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EXPERIMENTAL PUZZLES BEYOND THE STANDARD MODEL

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ABSTRACT

A number of selected topics describe the main features of the present experimental puzzles beyond the Standard Model. They include the search for supersymmetric particles as carried out at e^+e^- colliders in the single-photon experiment (ASP) and at $p\bar{p}$ colliders in the missing-energy measurement (UA1), as well as a discussion of the fifth force from classical mechanics to the extended supergravity theories. This is to illustrate the answer of the present experiments to the possible existence of a superworld. The neutrino physics is then reviewed, starting with the single- and double-beta decay experiments and finishing with the large solar neutrino experiments (GALLEX). The non-accelerator side of the high-energy physics should at some time be able to clarify the nature of neutrinos (massive or not?, Majorana or Dirac particles? etc.). Finally, the Higgs sector is discussed. With the present experimental results it still remains untested. Whilst it is requested by the Standard Model, we show how it stands on the threshold of new physics (at the 1 TeV range) and of new technologies. We emphasize the fact that these experimental puzzles are everywhere and that we have to be very smart to solve them.

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1. INTRODUCTION

The Standard Model is, so far, a successful attempt to combine, within the gauge invariance

$$SU(3) \otimes SU(2) \otimes U(1) ,$$

the theories which try to explain the three fundamental forces between the elementary constituents [strong, weak, and electromagnetic (e.m.) forces]. In this scheme, the strong interactions are described by quantum chromodynamics (QCD)--the $SU(3)$ gauge theory--and the weak and e.m. interactions are unified by the Weinberg-Salam (WS) model within $SU(2) \otimes U(1)$ invariance.

How well does this model reproduce the present experimental observations? A good answer to this question is given, for instance, by the study of the results obtained by the UA1 and UA2 experiments at the CERN $p\bar{p}$ Collider. Among the various kinds of event produced in $p\bar{p}$ collisions at 630 GeV in the c.m. energy, are the events with 'jets'. They are produced with a measured cross-section of a few millibarns; the fraction of this cross-section due to heavy flavours is dominated by $b\bar{b}$ production and the corresponding cross-section is $\sigma^{b\bar{b}} \simeq 6 \mu\text{b}$. Jet events are mainly explained by QCD. Another type of event is that where intermediate vector bosons W and Z^0 are produced by the Drell-Yan mechanism in $p\bar{p}$ collisions. At the energy of the $p\bar{p}$ Collider at CERN, these events give a contribution of 600 pb to the total cross-section σ^{pp} , and they successfully reproduce the WS model expectations. DiLella in his lectures¹ gives a very detailed explanation as to how well these two types of event fit with the Standard Model. In addition to these two main standard processes, which have been measured to be 50 to 60 mb, the

most important part of the total cross-section $\sigma^{\bar{p}p}$ is provided by the so-called 'minimum bias events'. This means the events which have a rather large average charged multiplicity (say of the order of 30) and a rather small average transverse momentum (say 0.42 GeV/c) at the CERN $\bar{p}p$ Collider energy.

As shown by this example and, in fact, by a general overview of the present experimental results obtained in our field², the conclusion by now is: 'Everything fits well with the Standard Model'. So why pursue further; in other words:

Are there any puzzles beyond the Standard Model?

Despite this 'tout va très bien, Mme la Marquise' attitude, we think that we should not feel discouraged, mainly because nothing is perfect in this world; even the Standard Model! There are in fact many signs showing that 'the Standard Model does not qualify as the ultimate theory', such as:

- too many parameters (number of couplings: g_s , g_w , $\sin \theta_w$, fermion mass ratios, mixing matrix, Higgs, etc.),
- many unexplained features (charge quantization, baryon and lepton number conservation, P and C violations, iteration of families),
- many loose ends (Higgs sector, no gravity, hierarchy problem, no unification of forces).

These very important points which remain unexplained or are inexplicable by the Standard Model lead the theorist to look beyond this model. They do this in three different ways.

The first way is to 'extend minimally' the Standard Model by introducing new families (such as new heavy quarks, new heavy leptons, new heavy neutrinos), and new gauge levels:

$$SU(3) \otimes SU(2) \otimes U(1) \otimes G' ,$$

for instance,

$$SU(2)_L \otimes U(1) \quad \text{becomes} \quad SU(2)_L \otimes SU(2)_R \otimes U(1) ,$$

This means, in reality, new W's and new Z^0 's.

The second way consists in 'extending maximally' the Standard Model, by introducing a new concept: 'the world is composite'; so quarks and leptons are composite, W and Z^0 's are composite and even Higgs are composite (as, for instance, in technicolor)

The last way is even more radical. It considers that to find the really complete explanation we have to consider the whole energy scale (see Fig. 1); so the world is *super* ...; by ... we mean:

... *symmetric* (i.e. supersymmetry)

and also

... *gravitational* (i.e. supergravity with dimension $N \geq 1$)

and also

... *string* (i.e. superstring) .

I refer to the lectures given by Hinchliffe³ and Gross⁴ for the theoretical description of these various approaches. My point of view here will be that of the experimentalist. Let me say first that to talk about 'experimental puzzles beyond the Standard Model', is very much time- and fashion-dependent. Two years ago, on the basis of a few events found at the CERN $p\bar{p}$ Collider during the run of 1983⁵, compositeness, new families, unconventional Higgs, supersymmetry and why not technicolor were claimed to be discovered! (Superstring was not yet a 'commercialized' theory at that time.) Nowadays (July 1986), the general consensus of opinion is that the Standard Model agrees with all the experimental observations. So certainly the task is harder and the subject much less fashionable. However, the Standard Model has only been tested at the 5% level in the W-sector (see DiLella's lectures¹); the top quark has still to be established ($m_t \gtrsim 40 \text{ GeV}/c^2$?); the Higgs sector is untested; in the field of perturbative or non-perturbative QCD there are still a lot of remaining puzzles, see 'jet story' of DiLella¹; there remain a lot of fundamental questions concerning the ν -sector. For instance: Are the ν massive or not? How many are there? Are they Majorana or Dirac particles?, etc.

In the case of the experimentalists, the questions asked as well as the answers provided are not only dependent on the fact that a theoretical idea is correct or not, but also on the capability of the experimental apparatus to check it. So we will, in these lectures, discuss not only results and their possible non-standard interpretation, but also the *experimental techniques* to do this as well as the *improvements* from the detector point of view to achieve a better (and so more accurate) test.

These lectures could become a long and systematic review of all possible theoretical hypotheses and the corresponding experimental upper limits

Fig. 1. Description of the full energy scale in high-energy physics: from a few GeV to the Planck mass.

obtained so far. By personal taste, I prefer to focus on some selected topics and study, in more detail, their specific features both from a theoretical and an experimental point of view. So these lectures have been divided into three sections. Section 2 is called 'Superworld?'. The first part of this section is devoted to the search for supersymmetry at e^+e^- and $p\bar{p}$ colliders. For this purpose two 'typical' experiments, namely single photon search at e^+e^- (ASP) and missing energy measurement at $p\bar{p}$ (UA1) are described; the second part is devoted to the discussion of the fifth force to show how antigravity is related to supergravity.

Section 3, called: 'Extended world?' is mainly devoted to a review of the ν physics including a non-accelerator section. The last section, 'Beyond the 1 TeV world' reports on the Higgs sector and includes also a section about new accelerators at very high energy, the related new experimental techniques (i.e. an introduction to the high-energy physics domain at the dawn of the 21st century.)

As you will see, there are still a lot of experimental puzzles beyond the Standard Model: Good for us!

2. SUPERWORLD?

2.1 Supersymmetry at e^+e^- and $p\bar{p}$ Colliders

The $N = 1$ supergravity model (SUGRA) makes definite predictions at the low-energy level [i.e. the W-mass range, namely from a few GeV/c^2 to $O(100) \text{ GeV}/c^2$]. There are a lot of possibilities to test its experimental consequences. This is true both at e^+e^- and $p\bar{p}$ colliders⁶.

We want to describe here two main techniques, used to search for supersymmetric particles at these machines. Each of these techniques is, in some sense, specific to each accelerator. They are the single-photon search at the e^+e^- collider and the missing-energy measurement at the $p\bar{p}$ collider.

The results obtained so far by both experiments are negative. However, we may hope that all the new e^+e^- and $p\bar{p}$ colliders (SLC, LEP, ACOL, Tevatron) are going to completely scan the W-scale and give a final answer about the possible existence of supersymmetric particles in this mass range.

2.1.1 Single photon searches at PEP. I will define the principle of these searches and give a description of the related experiments.

i) Principle

We discuss here the study of the process^{*}):

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^{*}) We will come back to this experiment in the next section when discussing it in terms of a neutrino counting experiment [process (3)].

$$e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$$

by an exchange of a virtual scalar electron $\tilde{e}$. So it can be used to search for $\tilde{e}$ with a mass larger than $\sqrt{s}$. The single-photon differential cross-section is given by:

$$\frac{d\sigma}{dx d\cos\theta} = \frac{\alpha^2 s(1-x)}{3x \sin^2\theta} \left[\left(1 - \frac{x}{2}\right)^2 + \frac{x^2 \cos^2\theta}{4} \right] \left[\frac{1}{m_{e_R}^4} + \frac{1}{m_{e_L}^4} \right]$$

where $x = 2E_\gamma/\sqrt{s}$. So it peaks at small θ and small E_γ . This implies that it is mandatory to have an e.m. calorimeter down to small θ to perform such searches. Moreover, the main backgrounds are the following QED processes:

$$e^+e^- \rightarrow e^+e^-\gamma \quad (1)$$

$$e^+e^- \rightarrow \gamma\gamma\gamma, \quad (2)$$

where e^+e^- or $\gamma\gamma$ escapes into the small polar angle region not covered by veto counters and, also,

$$e^+e^- \rightarrow \gamma\nu\bar{\nu}. \quad (3)$$

The predominant quantum electrodynamics (QED) background (1), requires a rejection factor of the order of 10^{-4} to reach a sensitivity to the ν pair production [process (3)]. By using the three-body final-state kinematics, as shown schematically in Fig. 2, we get a way to eliminate the other QED backgrounds [processes (1) and (2)]. For simple kinematical reasons, the transverse energy of the photon, E_T^γ , relative to the beam line, must be balanced by the e^- pair; thus for a detected photon with transverse momentum E_T^γ , at least one of the other particles will be at an angle larger than

$$\sin\theta_{\text{recoil}}^{\text{min}} = E_T^\gamma / (2E_{\text{beam}} - E_\gamma).$$

So θ_{recoil} must be larger than $E_T^\gamma / 2E_{\text{beam}}$ to achieve the desired degree of rejection.

Fig. 2. Three-body final-state kinematics $ee\gamma$, used to eliminate QED backgrounds.

There only remains then, the two 'conflicting processes':

Their cross-section can be parametrized in the following way:

$$\sigma(e^+e^- \rightarrow \gamma\nu\bar{\nu}) \simeq \alpha G_F^2 s \left(1 + \frac{N_V}{4}\right)$$

$$\sigma(e\tilde{\gamma} \rightarrow e\tilde{\gamma}) = \frac{8\pi}{3} \alpha^2 \frac{s}{m_e^4}$$

So the ratio of these two cross-sections is given by:

$$\frac{\sigma_{\tilde{\gamma}}}{\sigma_{\nu}} \simeq 50 \left(\frac{40 \text{ GeV}}{m_e^{\tilde{\gamma}}} \right)$$

Therefore if $m_e^{\tilde{\gamma}}$ is of the order of a few tens of GeV, the $\tilde{\gamma}$ will escape detection. Moreover, as the final states and the corresponding Feynman diagrams are the same, both cross-sections can be parametrized in the following way:

$$\frac{d^2\sigma}{dx dy} = K \frac{1}{x} \frac{1}{1-y^2} s(1-x) \left[\left(1 - \frac{x}{2}\right)^2 + \frac{x}{4} y^2 \right]$$

where

$$K_{\gamma\nu\bar{\nu}} = \frac{G_F^2 \alpha}{6\pi^2} [N_V(g_V^2 + g_A^2) + 2(g_V + g_A + 1)]$$

$$K_{\gamma\tilde{\gamma}\tilde{\gamma}} = \frac{4\alpha^3}{2m_e^4}$$

$$y = \cos \theta_{\gamma}$$

Therefore, the limit on the single-photon cross-section probes the sum of the ν -pair and supersymmetric sources; for $m_e^{\tilde{\gamma}} > \sqrt{2} m_W$, the process $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ dominates. The only way to separate both processes is to do a careful study of the $\sqrt{s}$ dependence of σ , since the weak cross-section has a resonance, while the supersymmetric cross-section does not. Because of this fact, it will not be possible to interpret the results of SLC and LEP studies of the Z^0 width without using the lower limit provided by PEP data.

ii) Description of the experiments and their results

Taking into account these different points, two experiments have tried to perform such a search at PEP: the upgrade of the MAC experiment⁷ and a special-purpose detector, ASP⁷. We now summarize the main features of these detectors as well as the results they have obtained.

The MAC detector (Fig. 3) has, in its central region, a drift chamber (CD) and a shower counter (SC) consisting of 32 lead plates interspersed with proportional wire chambers giving a total of 14 radiation lengths. It goes down to 40° for photon detection, with $E_T^\gamma > 4.5$ GeV. An end-cap hadron calorimeter (EC) covers the region down to 10°; it consists of 28 1-in. steel plates, each followed by planar proportional chambers constructed in 30° wedges. The upgrade of the MAC detector has been done essentially by adding an SAV detector. It is a set of proportional chambers and lead plates altogether 8.5 radiation lengths thick, and allowing the detection of photons down to 5° with $E_T^\gamma > 3$ GeV.

The ASP detector has been specially built to do a single-photon search experiment. Figure 4 reproduces a view along the beam axis of this detector. Drift chambers are placed in the region in front of the low-angle calorimeters, in order to measure the exit angle of charged particles in the three-body QED final states. By measuring the angles and corresponding energies,

Fig. 3. Schema of the MAC detector.

Fig. 4. View along the beam axis of the ASP detector.

Fig. 5. Transverse view of the ASP detector.

it solves the rejection problem of the $ee\gamma$ background. Figure 5 shows the details of the lead-glass array which can detect photons down to 20° and veto down to 10° . The lead glass has been chosen for its good intrinsic resolution and favourable signal-to-noise ratio. Inside this photon calorimeter, two systems are designed to reject events with accompanying charged particles and to distinguish e^- and γ . The first of these systems is a central tracker made of 0.4 in. $\times$ 0.4 in. $\times$ 88 in. Al tubes read at each end (so the coordinate is determined by the charge conjugation); the second of these systems is made of 2 cm thick scintillator and surrounds the central tracker. Figure 6 shows a typical $ee\gamma$ event used to provide a source of constrained single photons.

The main result is provided by the ASP experiment, which allows a much more accurate measurement than the upgraded MAC experiment. It has been measured by ASP that:

$$\sigma(ee \rightarrow \gamma + \text{new sources}) < 0.0062 \text{ pb}$$

$$\sigma(ee \rightarrow \gamma + \text{weakly interacting particles}) < 0.094 \text{ pb} ;$$

Fig. 6. Typical $ee\gamma$ event in the ASP detector.

Fig. 7. Scatter plot of m_e^{γ} versus $m_{\gamma\gamma}$:
a) for the ASP detector,
b) for the MAC detector.

and assuming $m_{\gamma}^{\gamma} = 0$, this states an upper limit on m_e^{γ} of 50 GeV/c² (90% CL). The corresponding scatter plot of m_{γ}^{γ} versus m_e^{γ} is reproduced in Fig. 7a for ASP and Fig. 7b for MAC.

2.1.2 Missing-energy measurement at the CERN $p\bar{p}$ Collider

(UA1 experiment). The first monojet plus missing-energy events found in the run of 1983 have triggered a lot of enthusiasm⁸. They were interpreted as a sign of new physics. They corresponded to a total integrated luminosity of 130 nb⁻¹. Once the statistics have increased by about a factor of 5 (UA1 has recorded a total of 715 nb⁻¹), the evidence for 'new phenomena' has dramatically decreased⁹. However, what has been developed by UA1 in its pioneering work is a special technique. It is based on the fact that many new phenomena are predicted to produce ν 's or ' ν -like' particles which escape recognition by the detector thus creating missing energy. Provided the detector has a full angular coverage (4π) and is hermetic enough (i.e. has reduced cracks and dead regions as much as possible), it is able to measure quite accurately the energy missed in the event. Let me describe this method in more detail.

i) Missing-energy technique in the UA1 detector.

The first important remark, when starting this discussion, concerns the fact that in $p\bar{p}$ (or pp) colliders, it is not possible to measure properly the total missing energy of an event, but only the transverse component of

Fig. 8a Vector sum of x components of the energy vector $\sum_i \vec{E}_{xi}$ versus E_T^{tot} for minimum bias events (UA1).

Fig. 8b Vector sum of the y components of the energy vector $\sum_i \vec{E}_{yi}$ versus E_T^{tot} for minimum bias events (UA1).

the missing energy: E_T^{miss} . This is clear when looking at the plots of Fig. 8, where we note that owing to the beam jets produced in such collisions, a large fraction of the energy is lost in the beam pipe. So the component of the energy along the beam axis is very badly measured. We are restricted then to defining a transverse missing energy, by considering the component along the two axes in the plane perpendicular to the beam axis (i.e. components E_y and E_z). By projecting the energy of each calorimeter i-cell onto the transverse plane, we obtain the transverse energy vector $\vec{E}_{Ti}$ given by:

$$\vec{E}_{Ti} = \vec{E}_{yi} + \vec{E}_{zi}.$$

The corresponding total energy E_T^{tot} of the event is defined as the scalar sum of the transverse energy of each i-cell:

$$E_T^{tot} = \sum_i ||\vec{E}_{yi} + \vec{E}_{zi}||,$$

and the total transverse missing energy is given by

$$E_T^{\text{miss}} = -E_T^{\text{tot}} = - \sum_i ||\vec{E}_{Ti}||$$

This method may be applied, if and only if the calorimeter is really 4π and hermetic. In the case of the UA1 detector, 'good 4π coverage' is ensured by the central, forward, and very forward calorimetry which covers the range down to 2° with respect to the beam axis, plus a μ -detector (able to detect μ 's down to about 20° from the beam axis), plus a good handling of the cracks and dead region (which are inevitable in any 4π -detector technology). There is in UA1 a main dead region. It is defined as a cone of $\pm 15^\circ$ around the vertical up and down axis in the central calorimeter (covering the region in pseudorapidity η defined by $|\eta| \leq 1.5$). This dead zone is due to the separation into two gondola hemispheres. Some energy may flow in this region without being detected by the calorimeter. However, this leakage may be detected by the central detector (CD) (which is able at least to see the charged component of this possible energy flow). This information from the CD may be used to tag a good fraction of the so-called vertical events. This fact is taken into account to validate or not the total missing transverse energy measured in an event.

Moreover an estimate of the resolution on E_T^{miss} has been made by measuring the resolution on E_T^{tot} on a sample of minimum-bias data and of high- E_T jet triggers. The result is plotted in Fig. 9; the resolution on E_T^{miss} derived from this measurement is given by $\sigma = 0.7/E_T^{\text{tot}}$. This parameter is used to validate the transverse missing energy measured in an event; a cut, which is a function of σ , is applied to E_T^{miss} . We will consider two types of cut, a loose cut which is equivalent to 2.5σ or 3σ and a

Fig. 9. Resolution on E_T^{tot} in the UA1 experiment for minimum bias data and jet triggered events.

tight cut which corresponds to 4σ . Most of the results we are discussing later on refer to this tight cut.

Historically, the missing-energy technique has been first used in UA1 to search for $W \rightarrow e\nu$ events. The fact of being able to look both for the e^- and for the ν in such event has been very powerful in identifying the $W \rightarrow e\nu$ signal (see L. DiLella's lectures¹). This technique has then been extended to look for other processes which also produced ν 's or ν -like particles. We are considering this case now.

ii) *Definition of the missing-energy selection in UA1.*

The various filters applied to select missing-energy events in UA1 are presented here. The first level of selection is, of course, given by the trigger.

a) *Missing-energy trigger:*

Until 1984, no such first-level trigger was set. From 1984 on, a missing-energy has been introduced both at the first level (i.e. in the hardware processor) and at the second level (i.e. using on-line 168E or 3081E emulators). It is done by requesting an imbalance in the total transverse energy between the left and right sides of the central calorimetry of at least 17 GeV, together with at least one jet; in the trigger processor a jet is defined as a minimal amount of 15 GeV of transverse energy deposited in eight adjacent e.m. cells and the two hadronic cells behind. The estimate of E_T^{miss} in this first-level trigger is biased by the left-right symmetry of the central e.m. calorimetry in UA1 (so-called gondolas). At the second-level trigger, the on-line emulators recompute E_T^{miss} by using the information provided by all the calorimeter cells in the apparatus; a cut on E_T^{miss} of 3.5σ (where $\sigma = 0.7/E_T^{\text{tot}}$) is applied on these data.

b) *Off-line filter:*

Apart from this on-line selection of missing-energy events, an off-line filter is applied on all the recorded data (i.e. the 10 millions of triggers which correspond to the total integrated luminosity of 715 nb^{-1}). It is this selection, which finally retains 1 % to 2 % of the data, which provides the complete sample of missing-energy data. It includes all the different types of triggers which may be set by the first-level trigger¹⁰. It also implies that all these data have been completely preprocessed, which means that the calorimetry information has been reconstructed (including all the constants of calibration, bookkeeping of dead channels, etc.). It retained, independently of the first-level trigger bit, each event which had a computed transverse missing energy of 15 GeV and validated at 2σ (where $\sigma = 0.7/E_T^{\text{tot}}$). It also rejects spurious events such as cosmic rays and beam halo, which fake missing-energy events. We show in Fig. 10 a diagram of the complete data selection from the on-line trigger to the off-line filter. The tight

Fig. 10. Flow diagram of the data selection for missing energy events in the UA1 experiment.

selection obtained by applying a 4 σ cut on E_T^{miss} finally gives 56 events out of the initial 10 million triggers); the work on the loose filter selection is still in progress. We will discuss here the results provided by the 4 σ filter.

iii) *Physical interpretation of the 4 σ sample; τ -signal.*

When looking at the 56 events obtained in this sample, it is obvious that a clear monojet signal is seen for 53 out of the 56 events (see Fig. 11) and that few multijet events are found: only three bijet events which are not back to back (Fig. 12). These favoured jet topologies (monojets and bi-jets not back to back) are simply due to our peculiar filtering conditions, which forbid the activity back to the jet trigger in the event.

The distribution of the total missing transverse energy in these events (Fig. 13) as well as of the transverse energy E_T of the jet trigger (Fig. 14) show a concentration of events between 15 and 40 GeV. There are few events above 40 GeV. The distribution of the second highest E_T jet of the event is shown in Fig. 15. Most of these jets have E_T below 12 GeV; only three events (the bijet candidates) have the second jet above this value. The rates for such events, given by all possible known sources, have been estimated; they take into account both the UA1 detector limitations and any possible physical process. So there are two types of background: the processes from the Standard Model which may generate such signatures and the so-called QCD jet-jet fluctuations. This last process is the one corresponding to $p\bar{p} \rightarrow (q \text{ or } g) 2\text{-jet QCD events}$, where one of the two jets is mismeasured because of apparatus limitations and provides a faked missing energy. All these contributions to the background have been calculated using both real data and ISAJET Monte Carlo¹¹; they are summarized in Table 1. The predominant background is due to the process $W \rightarrow \tau \nu_\tau$, where τ decays hadronically. So before trying to go further, i.e. to look for new signals, one has to find the rules to get rid of the τ -sample.

As in the case of the search for new signals in e^+e^- (subsection 2.1), we see here that it is mandatory to exclude the background due to standard physics and, in particular, that due to the τ -signal. Perhaps it is even trickier in the case of $p\bar{p}$ collisions. To the question of how to separate τ 's from the rest, we will give an answer in two steps; the first step consists in defining a variable called ' τ -likelihood' able to separate τ 's from non- τ events. The second step tries to make use of all the information provided by the detector and to refine the τ -signal. As the identification of τ 's is an important issue at $p\bar{p}$ colliders, let us spend some time to describe it.

The ' τ -likelihood method', considering that no single cut provides adequate separation between τ 's and standard QCD jets, tries to find a set

Fig. 11. View of a typical monojet plus missing energy event in the UA1 experiment (1985 data).

Fig. 12. View of a typical bijet non back to back and missing energy event in the UA1 experiment (1985 data).

Fig. 13. E_T^{miss} distribution for the 56 events selected in the 4σ sample in the UA1 experiment.

Fig. 14. Distribution of the transverse energy, E_T^{jet} , of the trigger jet for the 56 events selected in the 4σ sample in the UA1 experiment.

Fig. 15. Distribution of the transverse energy of the second E_T jet for the 56 events selected in the 4σ sample in the UA1 experiment.

Fig. 16. a) Distribution of the variable F ('narrowness of the jet'), for generated τ 's and QCD real jets in the UA1 experiment.
 b) Distribution of the variable ΔR ('matching between the central tracking and the calorimeter jets') for generated τ 's and QCD real jets in the UA1 experiment.
 c) Distribution of the charged multiplicity n_{CD} for generated τ 's and QCD real jets in the UA1 experiment.

of independent variables, each of which provides some separation between these two types of event. The variables used in this approach are: F , the 'narrowness' of the jet^{*)}; ΔR , the 'matching in space' between the highest- p_T track and the calorimeter jet axis; and n_{CD} , the track multiplicity defined here by counting all the tracks which have p_T bigger than 1 GeV/c and are contained in a cone in ΔR less than or equal to 0.4. The plots of these three parameters F , ΔR , and n_{CD} , as obtained in the case of τ 's generated by Monte Carlo or QCD jets given by real jet data, are shown and compared in Fig. 16.

*) The variable F is given by the ratio:

$$\frac{\sum_{\Delta R < 0.4} E_T^{\text{cell}}}{\sum_{\Delta R < 1} E_T^{\text{cell}}},$$

where the numerator sums over all the cells belonging to the trigger jet inside a cone in $\Delta R = 0.4$ with respect to the calorimeter jet axis and the denominator sums over all the cells inside a cone in $\Delta R = 1$ with respect to the same axis: $\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$, where $\Delta\eta$ is the difference in pseudorapidity and $\Delta\phi$ the difference in azimuthal angle between the highest- p_T track and the calorimeter jet axis.

Fig. 17. τ log-likelihood distribution for generated τ 's (solid line), QCD real jets (broken line), and for the 56 events selected in the 40 sample in the UA1 experiment.

One then defines a τ log-likelihood variable L in the following way:

$$L = \ln (P_F P_{\Delta R} P_{n_{CD}}) ,$$

where the distributions of F , ΔR and n_{CD} as obtained from the τ -Monte Carlo have been used to calculate the relative probabilities (P_F , $P_{\Delta R}$, $P_{n_{CD}}$) for an event to fit the τ -hypothesis. The corresponding L -distributions for τ 's as generated by Monte Carlo and QCD jet data have been used to define a cut at $L = 0$ (Fig. 17). If L is negative that means that the events are classified as $W \rightarrow \nu_\tau$ decay candidates, whereas if L is positive they are classified as non- τ -candidates. The L -distribution given by the 56 events (Fig. 17), leads to 32 events classified as τ -candidates and a sample of 24 events considered as non- τ -events.

However, one may make the following remarks concerning this classification.

- The 'contamination' of the τ -sample by non- τ -events and vice versa is non-negligible (see Fig. 17), as can be seen from the number reported in Table 1 which gives an estimate that 9.5 ± 1.0 events out of the 24 so-called non- τ -events are in fact τ 's.
- At the c.m. energy of the CERN $p\bar{p}$ Collider the QCD jets show essentially the same features as the τ 's in what concerns the chosen variables n_{CD} , ΔR , F (as already pointed out¹² and shown in Fig. 18).
- To study the process $W \rightarrow \nu_\tau$, where τ decays into a single charged pion plus some possible additional π^0 's, it is essential to ensure the hadronicity of the charged track, otherwise there is a non-negligible

Table 1. Expected Contributions from 'Standard Background'
in the UA1 Experiment

Background process	Expected contribution (No. of events)	
	for all data (56 events)	for $L < 0$ data (24 events)
$W \rightarrow \tau \nu_\tau \rightarrow \text{hadrons}$	39.7 ± 1.8	9.5 ± 1.0
All leptonic decays of W or Z^0 (except $W \rightarrow \tau \nu \rightarrow \text{hadrons}$)	9.7 ± 1.3	7.5 ± 1.2
Heavy flavour (b, c) production from $p\bar{p} \rightarrow Q\bar{Q}$ and from W and Z^0 decays	0.2 ± 0.8	0.2 ± 0.8
QCD jet-jet fluctuations	3.8 ± 1.7	3.8 ± 1.7
Total	53.4 ± 2.4	21.0 ± 1.7

Fig. 18. a) Effective mass of charged tracks of an experimental jet, with $E_T > 25 \text{ GeV}$ passing the requirements of the τ -selection.
 b) Multiplicity spectrum for jets which have $E_T^{\text{jet}} > 15 \text{ GeV}$ passing the requirements of the τ -selection.
 c) Multiplicity spectrum for jets which have $E_T^{\text{jet}} > 25 \text{ GeV}$ passing the requirements of the τ -selection.

contamination of $W \rightarrow e\nu$ events (estimated to be 7.5 ± 1.2 events out of the 24 events).

This becomes even more important when relaxing the cut on E_T^{miss} (loose filter selection). These facts are taken into account in the second step.

The 'refined τ -selection' imposes stricter requirements on the narrowness of the jet and on the matching between the jets as defined in the calorimeter and in the central tracking device (CD). But the main point concerns the charged multiplicity.

Depending on the charged multiplicity (defined by counting all tracks with p_T larger than 0.5 and not 1 GeV/c) of the event two cases are considered in this approach.

The first case concerns the events where the jet trigger has a charged multiplicity equal to 1. If so, it is required, in addition, that the track should be well isolated both in terms of central tracking and calorimetry, that it should have a momentum larger than 2 GeV/c; this is correlated with a maximum transverse-energy deposit of 7 GeV in the corresponding e.m. cells and a minimum transverse-energy deposit of 15 GeV in the corresponding hadronic cells (by corresponding cells we mean the cells which are in a cone in $\Delta R < 0.4$ with respect to the track). Moreover, strong requirements on the hadronicity of the track are demanded. This is a crucial issue as, contrary to the case of $W \rightarrow e\nu$ events, most of the $\tau^{\pm} \rightarrow \pi^{\pm}(n\pi^0's)\nu_{\tau}$ correspond to low p_T tracks (i.e. lower than 10 GeV/c) and E_T in e.m. cells lower than 15 GeV; so the e/π rejection becomes quite tricky. This problem is discussed in more detail in Appendix I.

The second case concerns the events where the track multiplicity is larger than 1. There, to ensure the τ -character of the events (namely the case $\tau \rightarrow \pi^+\pi^-\pi^+ + n\pi^0's + \nu_{\tau} : \tau_3$), a set of requirements are imposed. The multiplicity equal to 3 is not a stringent enough condition; as shown in Fig. 19, at this c.m. energy most of the QCD jets have an average multiplicity of 3 also. So a requirement on the fragmentation properties of the jet is defined¹³ (following a study reported in Appendix II), which allows τ_3 to be well identified from QCD. Half of the real τ_3 events pass these cuts and only 3% of the QCD jets (including heavy flavour). Owing to the heavy contamination of τ_3 events by standard QCD, such strict cuts are requested. We show in Fig. 20 a typical τ_3 candidate as found in the UA1 detector.

In conclusion, $W \rightarrow \tau\nu_{\tau}$ events may be detected by the UA1 experiment^{12,14}. This however requires very accurate handling of the information and the corresponding systematics given by the e.m. and hadronic calorimeter, as well as the central detector which is a major tool also in this game.

Fig. 19. Multiplicity distributions for
a) $\tau \rightarrow 3\pi^{\pm} + n\pi^0 + \nu_{\tau}$, as generated by ISAJET MC.
b) $p\bar{p} \rightarrow b\bar{b}$ or $c\bar{c}$, as generated by ISAJET MC.
c) $p\bar{p} \rightarrow g, u, d, s$, real data events.

Fig. 20. $(\tau \rightarrow 3\pi^{\pm} + n\pi^0 + \nu_{\tau})$ candidate in UA1 data.

This process is the dominant standard process which contributes to the missing-energy sample. Moreover the contribution of all the standard backgrounds is estimated to be 53.4 ± 2.4 , corresponding to the 56 events selected out of all the data recorded from 1983 to 1985 in the UA1 experiment. Not much room is left for anything other than a Standard Model explanation for these events.

iv) Supersymmetry at $p\bar{p}$ colliders¹⁵.

One of the main reasons for studying events with missing energy and one or several jets is the search for supersymmetric particles. They are produced mainly through the following three reactions:

$$p\bar{p} \rightarrow \tilde{g}\tilde{g} \quad (5)$$

$$p\bar{p} \rightarrow \tilde{g}\tilde{q} \quad (6)$$

$$p\bar{p} \rightarrow \tilde{q}\tilde{q} \quad (7)$$

The mass range accessible at the CERN $p\bar{p}$ Collider or at the Tevatron is the W-mass range, namely a mass from a few GeV/c^2 to $100 \text{ GeV}/c^2$. In this case, the minimal supergravity model (SUGRA), provides a complete framework within which the supersymmetric particles are given by simple relations such as:

$$m_{\tilde{q}} = m_{3/2} (1 + 1.67\xi^2)^{1/2}$$

$$m_{\tilde{g}} = 2.88\xi m_{3/2}$$

$$m_{\tilde{\gamma}} = 0.4\xi m_{3/2}$$

where the quantity $\xi m_{3/2}$ is equal to $m_{\tilde{\gamma}}$ (mass of the photino) and to $m_{\tilde{g}}$ (mass of the gluino), measured at the Planck mass, and the parameter $m_{3/2}$ (mass of the gravitino) is equal to $m_{\tilde{q}}$ (mass of the squark) measured at the Planck mass too. The factors $1.67\xi^2$, 2.88 , and 0.4 measure the renormalization effects. Moreover, these models provide two alternatives¹⁶; the first one assumes that the gluino mass is larger than the scalar quark mass. This is realized if, and only if, ξ is bigger than 0.8 but, in addition, the mass of the gluino must always be smaller than 1.1 times the mass of the scalar quark. Therefore, in this framework, the masses of the gluino and of the scalar quark are almost degenerate. As a consequence, the gluino decays into an antiquark plus a scalar quark, and the scalar quark decays into a quark and a photino; so the processes $p\bar{p}$ (or pp) going to $\tilde{g}\tilde{g}$ or $\tilde{g}\tilde{q}$ or $\tilde{q}\tilde{q}$ have almost the same signature. The corresponding rates have been computed¹⁶. This first alternative of the SUGRA model is particularly favourable for the low-energy case (i.e. masses less than or equal to $100 \text{ GeV}/c^2$). The second alternative assumes the squark mass to be bigger than the gluino mass; in this case, the discrepancy between both masses can be quite large¹⁶. The most probable decay mode for the squark is then that the scalar quark decays into the corresponding quark and a gluino. The gluino decays into quark plus antiquark and photino. The photino is assumed to be the lightest supersymmetric particle and therefore is stable. The main consequences of this second

picture is that the signatures of the processes (5), (6), and (7) are rather different and that the rates are different too.

Here different supersymmetric scenarios, defined within this framework, have been applied to the UA1 detector. Therefore, events corresponding to the supersymmetric processes (5), (6), and (7) have been generated by the Monte Carlo ISAJET. These events are then simulated through the whole UA1 detector. They are finally analysed in the same way as the missing-energy sample of real data, using, in particular, the same filters.

The various cases considered in this study are summarized in Table 2. The rates corresponding to these different cases, and the effect of the different filters applied, are also listed in Table 2. Table 2a concerns the case where the $\tilde{g}$ and $\tilde{q}$ masses are non-degenerate. In Table 2b we report a case where the $\tilde{g}$ and $\tilde{q}$ masses are very much different (strongly non-degenerate), and in addition the gluino mass is very small: $m_{\tilde{g}} = 10 \text{ GeV}/c^2$. In this special case, we have looked at both the dominant decay mode of the $\tilde{q}$ in $q\tilde{q}$ (93% of branching ratio) and the case where $\tilde{q} \rightarrow q\tilde{\gamma}$ (which represents about 7% of the branching ratio). Finally, in Table 2c, we deal with the scenario where $\tilde{g}$ and $\tilde{q}$ are degenerate in mass; in this latter case, the process $\tilde{g}\tilde{q}$ is higher, by a factor of about 5 to 10, than the other two.

Typical supersymmetric events simulated in the UA1 detector are shown in Figs. 21 and 22. The different jet topologies obtained in each scenario, for the various filters, are summarized in Table 3. This table compares, for the case of the process $p\bar{p} \rightarrow \tilde{g}\tilde{q}$, the effect of no filter (i.e. trigger only), and of the 4σ inclusive filter (i.e. where a cut of 4σ is applied on E_T^{miss}), on the jet-structure of the events. Table 3a summarizes the percentage of events which belong to each category, in the case where the $\tilde{g}$ and the $\tilde{q}$ masses are non-degenerate. We note that the multijet structure is then favoured, especially when the masses increase (see for instance the case: $m_{\tilde{g}} = 50 \text{ GeV}/c^2$ and $m_{\tilde{q}} = 100 \text{ GeV}/c^2$). If the two masses are strongly non-degenerate and if, in addition, the gluino mass is very low (see Table 3b), the bijets back-to-back are the dominant topology, followed closely by ≥ 3 -jet events. When the cut at 4σ in E_T^{miss} is applied, the back-to-back topologies are dramatically decreased, by about 50%. In the case where $\tilde{q} \rightarrow q\tilde{\gamma}$, the non-back-to-back structures are the most important ones, and remain also when the cut on the missing energy is applied. When the two SUSY particles are degenerate in mass (see Table 3c), the main jet-structures are the non-back-to-back ones (i.e. the monojets and the bijets not back to back); this effect is even enhanced when applying the cut in missing energy. So for the same process, depending on the mass and the decay scenarios, jet topologies may change a lot (and also the effect of the cut on E_T^{miss}).

Table 2a: Non-Degenerate Mass Scenarios, Cross-Sections, Rates, and Effect of the Various Filters

Mass (GeV/c ²)	Process		σ^* (nb)	Expected rates [*] (No. of events)	Percentage of events passing each filter		
	Decay mode	Reaction			Trigger	4 σ inclusive	2.5 σ non-b/b 4 σ non-b/b
$m_{\tilde{g}} = 25$ $m_{\tilde{q}} = 50$	$\tilde{g} \rightarrow q\bar{q}\gamma$	$p\bar{p} \rightarrow \tilde{g}\tilde{g}$	0.40×10^{-4}	28,600	33	3.5	2
	$\tilde{q} \rightarrow q\bar{g}$	$p\bar{p} \rightarrow \tilde{q}\tilde{q}$	0.30×10^{-4}	21,450	55	3.9	0.5
		$p\bar{p} \rightarrow \tilde{q}\tilde{q}$	0.70×10^{-6}	500	78	3.9	0.5
$m_{\tilde{g}} = 40$ $m_{\tilde{q}} = 60$	$\tilde{g} \rightarrow q\bar{q}\gamma$	$p\bar{p} \rightarrow \tilde{g}\tilde{g}$	0.24×10^{-5}	1,716	63	9.3	1.4
	$\tilde{q} \rightarrow q\bar{g}$	$p\bar{p} \rightarrow \tilde{q}\tilde{q}$	0.55×10^{-5}	3,932	76	9.8	1.4
		$p\bar{p} \rightarrow \tilde{q}\tilde{q}$	0.24×10^{-6}	171	88	8.6	-
$m_{\tilde{g}} = 50$ $m_{\tilde{q}} = 100$	$\tilde{g} \rightarrow q\bar{q}\gamma$	$p\bar{p} \rightarrow \tilde{g}\tilde{g}$	0.40×10^{-6}	286	85	18.3	2.9
	$\tilde{q} \rightarrow q\bar{g}$	$p\bar{p} \rightarrow \tilde{q}\tilde{q}$	0.27×10^{-6}	193	97	17	0.27
		$p\bar{p} \rightarrow \tilde{q}\tilde{q}$	0.52×10^{-8}	3.7	100	19	-

* The cross-sections are computed with ISAJET 5.20; the quoted rates are the total expected rates for the total integrated luminosity of 7.15 nb⁻¹; the effect of the various filters is not included in these rates.

Table 2b: Strongly Non-Degenerate Mass Scenario, Cross-Section, Rates and Effect of the Various Filters

Mass (GeV/c ²)	Process		σ^* (mb)	Expected rates [*] (No. of events)	Percentage of events passing each filter		
	Decay mode	Reaction			Trigger	4 σ inclusive	2.5 σ non-b/b 4 σ non-b/b
$m_{\tilde{g}} = 10$ $m_{\tilde{q}} = 100$	$\tilde{g} \rightarrow q\bar{q}\gamma$ $\tilde{q} \rightarrow q\bar{g}$	$p\bar{p} \rightarrow \tilde{g}\tilde{q}$	0.74×10^{-5} ($\times 0.93$)	4,920	89	7.8	0
$m_{\tilde{g}} = 10$ $m_{\tilde{q}} = 100$	$\tilde{g} \rightarrow q\bar{q}\gamma$ $\tilde{q} \rightarrow q\bar{\gamma}$	$p\bar{p} \rightarrow \tilde{g}\tilde{q}$	0.74×10^{-5} ($\times 0.07$)	370	86	64	17.5

* The cross-sections are computed with ISAJET 5.20; the quoted rates are the total expected rates for the total integrated luminosity of 7.15 nb⁻¹; the effect of the various filters is not included in these rates

Table 2c: Degenerate Mass Scenarios, Cross-Sections, Rates, and Effect of the Various Filters

Mass (GeV/c ²)	Process Decay mode	σ^* (mb)	Expected rates [*] (No. of events)	Percentage of events passing each filter		
				Trigger	4 σ inclusive	2.5 σ non-b/b 4 σ non-b/b
$m_{\tilde{g}} = 21$ $m_{\tilde{q}} = 19$	$\tilde{g} \rightarrow q\bar{q}$ $\tilde{q} \rightarrow g\gamma$	0.04×10^{-3}	286,000	26	3	6.5 2.5
$m_{\tilde{g}} = 42$ $m_{\tilde{q}} = 40$	$\tilde{g} \rightarrow q\bar{q}$ $\tilde{q} \rightarrow q\gamma$	0.15×10^{-4}	10,725	62	24	10.2 7.1
$m_{\tilde{g}} = 63$ $m_{\tilde{q}} = 57$	$\tilde{g} \rightarrow q\bar{q}$ $\tilde{q} \rightarrow q\gamma$	0.14×10^{-5}	1,001	83	47	11 7
$m_{\tilde{g}} = 84$ $m_{\tilde{q}} = 80$	$\tilde{g} \rightarrow q\bar{q}$ $\tilde{q} \rightarrow q\gamma$	0.11×10^{-6}	78.6	95	64	12 10.6

* The cross-sections are computed with ISAJET 5.20. We only consider here the case $p\bar{p} \rightarrow g\tilde{q}$ which is the dominant reaction; the other two have a lower cross-section by a factor of 5 to 10, but pass the filters in the same way as the process $g\tilde{q}$. The expected rates do not include the effect of these filters

Fig. 21. Monojet plus missing-energy event, generated by $pp \rightarrow \tilde{g}\tilde{g}$ (ISAJET MC) with $m_{\tilde{g}} = 42 \text{ GeV}/c^2$, $m_{\tilde{q}} = 40 \text{ GeV}/c^2$, simulated in the UA1 detector: $E_T^{\text{miss}} = 43 \text{ GeV}$; $E_T^{\text{jet}} = 40.9 \text{ GeV}$; $p_T^{\text{jet}} = 28.7 \text{ GeV}/c$. a) Full detector view; b) Transverse view; c) Lego plot from calorimetry; d) Lego plot from the CD.

By comparing the rates obtained for the different jet topologies with the results of UA1 on the $4\sigma\text{-}E_T^{\text{miss}}$ selection, we may exclude the scenario corresponding to $m_{\tilde{g}} = 25 \text{ GeV}/c^2$ and $m_{\tilde{q}} = 50 \text{ GeV}/c^2$ and that corresponding to $m_{\tilde{g}} = 42 \text{ GeV}/c^2$ and $m_{\tilde{q}} = 40 \text{ GeV}/c^2$. The scenario where $m_{\tilde{g}} = 84 \text{ GeV}/c^2$ and $m_{\tilde{q}} = 80 \text{ GeV}/c^2$ and the one with $m_{\tilde{g}} = 50 \text{ GeV}/c^2$ and $m_{\tilde{q}} = 100 \text{ GeV}/c^2$ cannot be excluded.

The case where $m_{\tilde{g}} = 10 \text{ GeV}/c^2$ and $m_{\tilde{q}} = 100 \text{ GeV}/c^2$ is also rejected by present UA1 data. Moreover, if we consider the $(m_{\tilde{g}}, m_{\tilde{q}})$ plot we may define a certain number of zones; the first one is defined by $m_{\tilde{g}} > 1.1m_{\tilde{q}}$ and is excluded by the supergravity models. The second area is that defined in the

Fig. 22. Non-back-to-back bijet plus missing-energy event generated by $p\bar{p} \rightarrow \tilde{g}\tilde{g}$ (ISAJET MC) with $m_{\tilde{g}} = 42 \text{ GeV}/c^2$; $m_{\tilde{q}} = 40 \text{ GeV}/c^2$, simulated in the UA1 detector: $E_T^{\text{miss}} = 20.9 \text{ GeV}$; $E_T^{\text{jet1}} = 28.5 \text{ GeV}$; $p_T^{\text{jet1}} = 13.7 \text{ GeV}/c$; $E_T^{\text{jet2}} = 20.8 \text{ GeV}$; $p_T^{\text{jet2}} = 19.2 \text{ GeV}/c$. a) Full detector view; b) Transverse view; c) Lego plot from calorimetry; d) Lego plot from the CD.

range $m_{\tilde{q}} < m_{\tilde{g}} < 1.1m_{\tilde{q}}$ (i.e. the degenerate-mass case); in this scenario, with the present UA1 data, we may set an upper limit on both masses around $60 \text{ GeV}/c^2$ (this is using only monojet events; bijet events are compatible with such a limit, but the error made on this estimation is still worse than in the monojet case because of the lack of statistics). In the remaining area, it is less easy to set a definite limit on both masses. Therefore, we may conclude that the present experimental $p\bar{p}$ results allow us to exclude some supersymmetric scenarios, within certain limited regions of the $(m_{\tilde{g}}, m_{\tilde{q}})$ plot; these limits are strongly model-dependent, i.e. mass and decay-mode dependent.

Present e^+e^- and $p\bar{p}$ colliders have both done pioneering work concerning the search of possible supersymmetric particles. It is quite sure that, with the help of SLC, LEP, and the Tevatron, and with an increased luminosity at the CERN antiproton collector (ACOL), a definite answer will be given in the next five years to the question of the existence of such particles with masses of the order of $100 \text{ GeV}/c^2$. Otherwise we will have to wait for the next generation of pp colliders.

Table 3a: Various Jet Topologies for Events with no Filter (i.e. Filter 1) or 4σ Inclusive Filter (i.e. Filter 2) and Considering a Non-Degenerate Mass

Mass (GeV)	Filter No.	Monojets (%)	Monojets b/b (%)	Bijets b/b (%)	Bijets non-b/b (%)	≥ 3 jets
$m_{\tilde{g}} = 25$	1	2.8	7.6	22	20	4.5
$m_{\tilde{q}} = 50$	2	6.2	25	9.3	9.3	3.1
$m_{\tilde{g}} = 40$	1	4.5	8.6	22	21	23
$m_{\tilde{q}} = 60$	2	19	4	13.5	10.8	4
$m_{\tilde{g}} = 50$	1	1.1	-	1.6	15.8	8.9
$m_{\tilde{q}} = 100$	2	3.1	3.9	8.7	4.7	20.5

Note that the remaining percentages are rejects and that only the process $p\bar{p} \rightarrow \tilde{g}\tilde{q}$ is considered here

Table 3b: Various Jet Topologies for Events with no Filter (i.e. Filter 1) or 4σ Inclusive Filter (i.e. Filter 2) Applied and Considering Strongly Degenerate Mass and a Small Gluino Mass ($m_{\tilde{g}} = 10 \text{ GeV}$; $m_{\tilde{q}} = 100 \text{ GeV}$)

Decay Mode	Filter No.	Monojets (%)	Monojets b/b (%)	Bijets b/b (%)	Bijets non-b/b (%)	≥ 3 jets
$\tilde{q} \rightarrow q\tilde{g}$	1	2.6	10.2	39	11	25.5
	2	4.6	15.6	9.3	10.9	12.5
$\tilde{q} \rightarrow q\tilde{g}$	1	27.6	14.5	8.6	25	8.5
	2	33	14	5	26.6	8

Note that the remaining percentages are rejects and that only the process $p\bar{p} \rightarrow \tilde{g}\tilde{q}$ is considered here

Table 3c: Various Jet Topologies for Events with no Filter (i.e. Filter 1), or 4σ Inclusive Filter (i.e. Filter 2) Applied, and Considering Degenerate Mass

Mass (GeV)	Filter No.	Monojets (%)	Monojets b/b (%)	Bijets b/b (%)	Bijets non-b/b (%)	≥ 3 jets
$m_{\tilde{g}} = 21$	1	15	10	18.5	8.5	2
$m_{\tilde{q}} = 19$	2	50	-	-	-	-
$m_{\tilde{g}} = 42$	1	14.5	9	12.5	19	6.5
$m_{\tilde{q}} = 40$	2	40.1	10.7	3.2	27.8	3.2
$m_{\tilde{g}} = 63$	1	11.5	9	19	3.7	13.6
$m_{\tilde{q}} = 57$	2	14.8	8.5	9.6	30.8	25.5
$m_{\tilde{g}} = 84$	1	11.8	7.6	14	36	7.8
$m_{\tilde{q}} = 80$	2	13.5	6.3	3.6	45	9.4

Note that the remaining percentages are rejects and that only the process $p\bar{p} \rightarrow \tilde{g}\tilde{q}$ is considered here

2.2 Antigravity and Supergravity

The fifth force, even if it is only a crazy idea, gives an attractive example of how the concept of antigravity may link classical mechanics (Newton and Galileo) to elementary particle physics (K^0 experiments) and to sophisticated theories such as supergravity at $N \geq 2$ dimensions. I have chosen this case mainly for this reason and I would like to warn the reader to take all that is reviewed here with a lot of care (including, of course, Newton's law of universal gravitation!).

2.2.1 Reminder of some fundamental notions of classical mechanics¹⁷.

Newton's law of universal gravitation says that 'The gravitational interactions between two bodies can be expressed by an attractive central force, proportional to the masses of the bodies and inversely proportional to the square of the distance between them'; in other words this law can be expressed by the relation:

$$F = G \frac{mm'}{r^2},$$

where the proportionality constant G must be determined experimentally. Measuring the force F between two known masses, m and m' , at a known distance r , yields the value of $G = 6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2\cdot\text{kg}^{-2}$ or

$$G = \frac{hc}{m_p^2},$$

where m_p is the Planck mass and is equal to $1.221045(46) \times 10^{19} \text{ GeV}/c^2$.

The experiment of Cavendish measured this according to the schema of Fig. 23.

Moreover, the principle of equivalence, which expresses the fact that the inertial and gravitational masses are the same for all bodies, gives rise to an important result: 'All bodies at the same place, in a gravitational field, experience the same acceleration' *).

One example is that all bodies fall to Earth with the same acceleration. To verify the above statement, we note that in a place where the gravitational field is G , the force on a body of mass m is:

$$F = mG$$

and the body acceleration is $a = F/m = G$, which is independent of the mass m of the body subject to the action of the gravitational field. Because of the principle of equivalence, the laws of Nature must be written in such a way that it is impossible to distinguish between a uniform gravitational field and an accelerated frame of reference. This is a statement which constitutes the basis of the 'general principle of relativity' proposed by Einstein in 1915.

Fig. 23. Schema of the Cavendish measurement. When masses m' are placed close to masses m , their gravitational attraction produces on the horizontal rod a torque that results in a torsion of the fibre (OC). Equilibrium is established when the gravitational and torsional torques are equal. The torsional torque is proportional to the angle θ , which is measured by the deflection of a ray reflected from a mirror attached to the fibre. By repeating the experiment at several distances r , and using different masses m and m' , we can verify the law: $F = G(mm'/r^2)$.

*) Remember this principle when discussing in particular the $K^0 - \bar{K}^0$ system.

2.2.2 How experimental tests of gravity lead to antigravity. A set of experiments have measured the constant G , both by redoing the experiment of Cavendish (G_{Cav}) or by measuring G within a mine (geophysical experiments: G_{mine})¹⁸. The results obtained by each experiment is reported in Fig. 24; a discrepancy is seen between G_{Cav} and G_{mine} :

$$G_{\text{Cav}} < G_{\text{mine}} .$$

Why? A way to explain this is by adding to the potential of gravity, $V_0 = V_{\text{gravity}} = -g(m_1 m_2 / r)$, another potential ΔV , which is a Yukawa potential:

$$\Delta V \propto \frac{1}{r} e^{-\mu r} ,$$

such that in fact $V = V_0 + \Delta V = -g(m_1 m_2 / r)(1 + \alpha e^{-\mu r})$; so:

$$G_{\text{Cav}} = g(1 + \alpha) \quad \text{and} \quad G_{\text{mine}} = g .$$

As $G_{\text{Cav}} < G_{\text{mine}}$, this implies that α must be negative so the additional force corresponding to ΔV must be *repulsive* for like objects; this means it is a vectorial-type force.

So, in addition to gravitational forces, there exists an antigravitational force also called the fifth force.

Fig. 24. Modern geophysical measurements of G .

2.2.3 How can the fifth force be related to particle physics? If this extra force exists, it is mediated by a *light vector boson* that we call *graviphoton* and represent by the symbol λ^*).

To take into account this extra force in particle physics, there are two ways. One is conventional, the second one is fancy. I will discuss the second one first, as it offers a way to relate *antigravity* to extended supergravity theories. Certainly the ideas summarized here are still controversial from the theoretical point of view. (Extended supergravity theories are far from being in their definite form and still have no realistic formulation; it is not the purpose of these lectures to discuss the real validity of such an approach.) However from a didactic point of view, they can be used to show how, ultimately, the high-energy physicist should be able to relate all forces of Nature within a global and unique description. Note that what I report below is *directly* derived from the inspired lectures¹⁹ given by Scherk in 1979. [At that time the fifth force or antigravity was not at all fashionable as it has been the last few months²⁰ and supergravity, of which Scherk was one of the pioneers, was still in its infancy.]

i) Antigravity and extended supergravity

I reproduce here the arguments developed by Scherk¹⁹, since I am interested in the attempt he made at relating a very abstract idea (such as supergravity) to real life^{**}).

Discussing antigravity, Scherk remarks that 'antigravity is an inescapable consequence of extended supergravity; many attempts to get rid of this "crazy photon" have failed so that it may be wiser to learn to live with it'.

This is due to the fact that, in extended supergravity models, gravity will proceed not only through a tensorial exchange, but also through vectorial and scalar exchanges. This is indeed the case, if one takes for instance the $N = 2$ supergravity model coupled to a massive scalar multiplet but in which supersymmetry is unbroken. Zachos¹⁹⁾ has discovered that a remarkable phenomenon occurs in such a model. In the weak field limit, the potential between a pair of massive particles can be obtained from the Born diagrams where both a graviton and a graviphoton can be exchanged. If several scalar multiplets are introduced, with masses m_i and coupling constants g_i to the vectorial particle, one finds in the static limit the amplitude:

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*) This symbol has been invented by Scherk and Nahm. According to them, it is an Egyptian hieroglyph with phonetic value šn (shen) which is an inversion of the Egyptian hieroglyph γ , phonetic value šš (shess).

**) More recent developments of these ideas have been proposed, for instance by Barbieri and Bars.

$$A = 4\kappa^2 \frac{m_i m_i'}{q^2} \left(m_i m_i' - \frac{g_i g_i'}{\kappa^2} \right).$$

The resulting potential in the static limit is given by:

$$V(r) = - \frac{\kappa^2}{4\pi r} \left(m_i m_i' - \frac{g_i g_i'}{\kappa^2} \right).$$

In $N = 2$ supergravity, $g_i = \epsilon \kappa m_i$ where $\epsilon = +1$ for a particle and -1 for an antiparticle. So one finds:

$$V(r) = - \frac{\kappa^2}{4\pi r} m_i m_i' (1 - \epsilon \epsilon'),$$

which vanishes between a pair of particles and a pair of antiparticles, whilst the gravitational attraction is doubled between a particle-antiparticle pair. Therefore, the extra-vectorial force is repulsive between like particles and attractive between unlike particles. This phenomenon is called 'antigravity'. Once we understand the inevitability of antigravity in extended supergravity, we may ask also, Why do we not see it?

Scherk gives the beginning of an answer to such a question in the following way. Derived from the previous equation, in the static limit, if a graviton is exchanged between two particles, we find the amplitude:

$$A = - \frac{4\kappa^2}{q^2} m^2 m'^2 (1 - \epsilon \epsilon')^2.$$

If we now consider the static force between two protons which are $u\bar{u}d$ bound states, as the graviton couples not to the masses but to $T_{\mu\nu}$, it sees the total energy of the quarks as the mass of the proton; this mass is mostly the kinetic energy of the quarks and the gluons. So its contribution to the force is given by $4\kappa^2 m_p^2/r^2$, where m_p is the proton mass.

The graviphoton λ is coupled to $2\kappa m \bar{\chi} \gamma^\mu \chi$, where m is the mechanical mass of the quark in question and $\bar{\chi} \gamma^\mu \chi$ is the conserved e.m. current. So λ sees directly the quark mass and not the proton mass and its contribution is:

$$- \frac{4\kappa^2}{r^2} (2m_u + m_d)^2.$$

The ratio of the graviphoton contribution to that of the graviton is then of the order of $3m_u^2/m_p$, i.e. 10^{-4} ; so it is much smaller.

By applying then the principle of equivalence (see Appendix III, or do it as an exercise!) and if we consider the fall of K^0 , $\bar{K}^0$ towards the Earth one finds that the relative difference in acceleration between K^0 and $\bar{K}^0$ is:

$$\frac{a(K^0) - a(\bar{K}^0)}{a(K^0)} \simeq 6 \frac{m_u}{m_p} \frac{m_s}{m_{K^0}} \simeq 10^{-2} !$$

So to save antigravity, Scherk assumes that the graviphoton λ acquires a mass, presumably through radiative corrections. It is rather likely since is universally coupled to scalar fields through the action

$$L = -\frac{1}{4} F_{\mu\nu}^\lambda F^{\mu\nu\lambda} - \frac{1}{2} \left| \gamma_\mu - 2i\kappa m_A \frac{\lambda}{\mu} \right|^2 - \frac{1}{2} m^2 \phi^* \phi ,$$

if there are no radiative corrections:

$$V(\phi) \simeq \frac{1}{2} m^2 |\phi|^2 \quad \text{at } m_\lambda = 0 .$$

The radiative corrections are proportional to g_{strong}^2 , or α or g^2 ; so $m_\lambda = 2\kappa m_\phi \langle \phi \rangle$. If $\langle \phi \rangle$ is due to $SU(2) \otimes U(1)$ breaking, $\langle \phi \rangle$ is equivalent to 1 to 100 GeV; so with $m_\phi \simeq 1$ GeV we get

$$m_\lambda \simeq 10^{-19} \text{ GeV}/c^2$$

and the associated Compton wavelength is thus $\lambda_\lambda \sim 1$ km. This means that the graviphoton, if it exists, is a light object associated with a short-range force²¹.

ii) Other approaches

Let us come back now to a more conventional approach. The question is, if such a force exists, mediated by a light vector boson, to what current does this light vector boson couple? and thus what is the associated charge.

In the case of a vectorial boson with vectorial current^{*)}: $j_\mu = A_\mu j^\mu$, the corresponding charge is:

$$Q = d^3x j_0(x) .$$

Apart from choosing the weak hypercharge Y as first candidate for Q , the most general way to define the charge is by taking any combination of $B - L$ and $L_i - L_j$ (where $L_i - L_j$ is successively: $L_e - L_\mu$, $L_e - L_\tau$, $2L_e - L_\mu - L_\tau$). On macroscopic stable matter:

*) Warning: Remember that if we want to build an anomaly-free theory, we have to choose a current which is vectorial (i.e. couples equally to left and right particles) and not chiral. Otherwise the required anomaly cancellation is model dependent.

$$B \equiv P + N \equiv N + Z, \quad L_e \equiv -Z.$$

So the most general linear combination is given by

$$'Q' = \text{const} \times (\cos \theta N + \sin \theta Z)^{22}.$$

Another way to formulate these ideas is by considering the alternative proposed by Fayet²³. In 1979, he introduced a new light neutral spin 1 gauge boson, called U. This extra U(1) factor responsible for spontaneous supersymmetry breaking, has vector couplings. They could lead to a new macroscopic force of intermediate or long range, usually repulsive, which would manifest itself as a derivation from Newton's law of gravitation. The vector in the U current purely originates from Z^0 -U mixing, which is a linear combination of the conserved (B-L) and electromagnetic currents:

$$J_U^\mu \text{ vector} = [(1 - x^2)/(1 + x^2)] \left[-\frac{1}{4} J_{B-L}^\mu + \left(\frac{1}{2} - \sin^2 \theta \right) J_{em}^\mu \right].$$

The U charge is then defined as follows:

$$Q^U \equiv Q^Z = (B - L) + (4 \sin^2 \theta - 2)Q.$$

In particular, for a nucleus, $Q^U = Q^Z = N + (4 \sin^2 \theta - 1)Z$; this coincides with the weak charge which may be measured in atomic physics experiments on parity violation.

An upper bound on the relative strength of the U force compared with gravitation is calculated as a function of its range λ_U ; Fayet found it to be $\leq 0.16/\lambda_U^2$. Therefore, only short-range gravity experiments at various distances between a few centimetres and ~ 10 m should give really measurable effects. Otherwise the antigravitational force becomes too small compared to gravity.

To summarize, if an antigravitational force exists, from the high-energy physics point of view, this means that there is a light vector boson (that we call λ denoting a graviphoton) which mediates this force. It couples to a charge, which in its more general form can be associated with any linear combination of the conserved B - L and e.m. currents. Its mass is of the order of 10^{-19} GeV/c² and it is a short-range force as the associated Compton wavelength is at most 0(1 km).

2.2.4 Experimental tests of antigravity. We have assumed so far that the antigravitational force exists and so we have tried to characterize its properties and define its consequences concerning particle physics.

We should, however, come back to the fundamental problem which is in fact: *Do we have any serious experimental proof of the existence of such a fifth force?*

We should say that, at the present time, the answer to this question is no.

The interest in such a subject has been revived a few months ago by the results of a re-analysis of the Eötvös experiment.

i) Re-analysis of the Eötvös experiment²⁰

The Eötvös experiment²⁴, performed in 1922, used a torsion balance to compare the acceleration of different materials in a gravitational field (Fig. 25). The Earth was used as a source of gravitational field and the conclusion was that there was no sign of antigravity.

Fishbach, Aronson et al., motivated by results obtained in a $(K^0 - \bar{K}^0)$ experiment²⁵ (see next subsection) and the geophysical results (Subsection 1.1.2), re-analyse Eötvös's results. They argue about the fact that this measurement is, according to them²⁶, sensitive to 'local horizontal mass anomalies' (buildings, mountains, etc.); so they say that the Earth should not be considered as an 'idealized uniform density sphere, but that one has to introduce also the effects of local matter distribution'.

By applying such a trick they find that the relative acceleration between two objects made of different materials is different from zero (in contradiction with the equivalence principle) and moreover that it varies with the materials.

Fig. 25. Schema of the Eötvös experiment: the torsion is used as a balance. It compares the acceleration of different materials in a gravitational field (the Earth).

ii) Antigravity and anomalies in the $(K^0-\bar{K}^0)$ system

Aronson et al.²⁵ performing a K^0 regeneration experiment have found that the characteristic parameters of the $(K^0-\bar{K}^0)$ system, such as the mass difference Δm between K_L and K_S , the K_S lifetime τ_S , and the CP non-conserving parameter η_{+-} , present an anomalous behaviour with energy. This means that instead of being constant with respect to energy, they vary. Between two different ranges in energy, 2 to 10 GeV and 30 to 130 GeV, the mean corresponding values differ by 2 to 9%.

They interpret these results by stating that no simple long-range field can account for this difference; so there is room for an intermediate range force (among possible explanations).

But these results have not been confirmed by the E617/731 experiment at FNAL²⁷, which measured no such discrepancy for η_{+-} at $\langle E_K \rangle = 65$ GeV.

Two experiments should be able to clarify this point quite soon; the E621 experiment at FNAL, which could measure τ_S up to 200-300 GeV and the NA31 experiment at CERN²⁸ which should be ideal for measuring $(K-\bar{K})$ parameters at 100 GeV.

iii) Experimental tests of the existence of the fifth force

The results presented in (i) and (ii) have triggered a renewed interest in experimentally proving the existence or non-existence of antigravity.

The main ways to test this hypothesis remain the classical measurements such as the balance experiment (i.e. Cavendish measurement), the torsion balance (à la Eötvös or Dicke, where either the Earth or the Sun are used as gravitational field), and Galileo's experiment. In this last case, the experiment consists in comparing the times of flight of different test masses dropped from the same height.

To achieve a sensitivity within desired requirements, say $\Delta a/g \approx 0(10^{-10})$, it is necessary to measure the time of flight to within 0.1 ns over a distance of 10 m. This should be feasible. An impressive list of proposals to perform one of these three types of measurement has been proposed since a few months (of the order of 20 experiments). Let us hope that some time they will give a final answer, as 'Few experiments are simpler in principle, harder in practice and so far reaching in implication' (Dicke²⁹).

In addition to these classical measurements, high-energy physics may provide another way to test this hypothesis than the one provided by looking at the $(K^0-\bar{K}^0)$ system. It consists in a direct search for the graviphoton λ^{30} by the study of a possible process such as:

$$K^0 / + / - \rightarrow \pi^0 / + / - \lambda. \quad (4)$$

The graviphoton may be produced also in $K^0 \rightarrow 2\pi^0\tilde{\lambda}$ but it cannot compete with the corresponding background provided by $K^0 \rightarrow 2\pi^0\gamma$; whereas the decays for γ corresponding to reaction (4) are strictly forbidden by angular momentum conservation since spin of massless γ is necessarily perpendicular to γ - π orbital momentum. However, as $\tilde{\lambda}$ is massive, there is an additional ($S_z = 0$) spin degree of freedom which allows process (4).

As the decay of $\tilde{\lambda}$ in 3γ is highly suppressed, the signature for the process $K \rightarrow \pi\tilde{\lambda}$ is one single π of fixed energy in the c.m. of the K and nothing else. So it is equivalent to an experiment in a K^+ stopping beam looking for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K^+ \rightarrow \pi^+ + \text{axion}$. Recently the branching ratio $\text{Br}(K^+ \rightarrow \pi^+ a^0)$ has been measured to be less than 4.6×10^{-8} at 90% CL³¹. Soon BNL experiments³² will be able to reach 10^{-10} or 10^{-11} . No such limits exist for the K^0 case; there is only an old limit³³, $\text{Br}(K_L^0 \rightarrow \pi^0\gamma) < 3 \times 10^{-3}$. This indicates that the Compton wavelength λ_γ for a possible $\tilde{\lambda}$ is ≤ 25 m. Note that the Eötvös and geophysical experiment give $\lambda \lesssim 200$ m.

2.2.5 Conclusion on the existence of the fifth force? There are three as yet unexplained classes of phenomena:

- i) The slight discrepancies between the values obtained for the Newtonian constant of gravity from laboratory measurements and geophysical data.
- ii) The results of the Eötvös experiment, which seem to show that the observed accelerations of various bodies to the Earth are not universal but depend on the ratio of their hypercharges (or baryon numbers) to their masses.
- iii) The energy dependence of the parameters of the neutral K system.

While each one of these phenomena may not be statistically very significant, the combination of the three may be taken as a first sign of evidence for a graviphoton. However, it is clear that the real and definite answer will be given by the experiments of classical mechanics.

3. EXTENDED WORLD?

We have seen, in the Introduction, that a theoretical way to go beyond the Standard Model is to introduce new families, i.e. new heavy leptons, heavy quarks, etc. We will show in this section how this can be done experimentally; but our main concern will be to concentrate especially on one object which is a wonderful probe to see whether or not the standard world must be extended. This probe is the *neutrino*.

It was in 1933 that the neutrino ν was predicted for the first time, by Pauli, at the Solvay conference. In 1942, J.S. Allen, following the

suggestion of K.C. Wang, gave the experimental evidence by observing ${}^7\text{Li}$ recoil after the K-capture in ${}^7\text{Be}$. The same year, the idea of ν_μ was theoretically introduced by Sakata and Inoue. In 1958, Feinberg suggested that if the weak interaction is mediated by intermediate vector bosons, then, two neutrinos must be introduced to explain the small mass of the ratio:

$$\frac{\mu \rightarrow e + \gamma}{\mu \rightarrow e \nu \bar{\nu}} \leq 10^{-8}.$$

In 1959, Reines and collaborators observed directly the neutrino in the reaction $\bar{\nu}_e + p \rightarrow \beta^+ + n$ at a reactor experiment. In 1962, both Columbia and CERN groups observed, for the first time, a μ neutrino ν_μ in the reaction $\pi \rightarrow \mu \nu$. In 1980, the existence of three neutrinos, ν_e , ν_μ , ν_τ , with the following mass limits, was known: $m_{\nu_e} \leq 60$ eV, $m_{\nu_\mu} \leq 570$ keV and $m_{\nu_\tau} \leq 250$ MeV. The same year at ITEP, Lyubimov et al. measured, in the reaction ${}^3\text{T} \rightarrow {}^3\text{He} + \nu_e + e^-$, the following mass limit for the neutrino ν_e :

$$14 \text{ eV} \leq m_{\nu_e} \leq 46 \text{ eV at } 99\% \text{ CL}.$$

This result is still very controversial.

This 'historical' review is to show that the neutrino is an old pal. But despite that, the fundamental questions concerning the nature of the neutrinos still remain unanswered. These questions are:

Are neutrinos massive?

Is ν_e a mixture of several neutrinos?

What is the precise relationship between ν_e , ν_μ , and ν_τ ?

Are neutrinos Dirac particles (so that ν is different from $\bar{\nu}$) or

Majorana particles (so that ν and $\bar{\nu}$ are the same particle)?

Are there more than three neutrinos?

The Standard Model claims that ν 's are massless and that there are only three neutrinos: ν_e , ν_μ , and ν_τ ; that is why neutrinos are a splendid probe to look beyond the Standard Model: it is, so far, a real experimental puzzle.

Many of the questions listed above are going to be answered by *non-accelerator* experiments; the main experimental ways to study the nature of ν 's are single and double β -decay and ν -oscillation experiments (using, as the source of neutrinos, reactor, atmospheric or solar ν 's). The different corresponding techniques and results will be reviewed here. It will be shown that neutrino physics is always a very active and attractive area of high-energy physics as well as a very original one.

Apart from the section on neutrino physics, another short section will be devoted to the search for fourth-generation heavy charged or neutral leptons in e^+e^- and $p\bar{p}$ colliders; it is another example of extending the Standard Model.

3.1 The Nature of Neutrinos and Non-Accelerator Physics³⁴

We are reporting here the main technique used in this experimental field essentially to determine the mass of the neutrinos, and their possible couplings with ν_1 and ν_2 neutrino states. This search is done by studying single or double β -decay reactions or possible ν oscillations.

3.1.1 Single β -decay experiment. The single β -decay is a direct way to measure the mass of the ν_e and to test whether or not it is coupled with several neutrinos.

i) Principle of this method

The nuclear β -decay is defined by the process

$$(A, Z) \rightarrow (A, Z \pm 1) .$$

The electron e^- can couple with several neutrinos with different coupling constants; suppose for instance, that the e^- couples with two neutrinos, ν_1 of mass m_1 and ν_2 of mass m_2 ; we write ν_e as a linear combination of both neutrinos ν_1 and ν_2 :

$$\nu_e = \nu_1 \cos \theta + \nu_2 \sin \theta .$$

By convention, we choose $|\sin \theta| \leq |\cos \theta|$, so

$$\nu_e = \nu_1 + \epsilon \nu_2 ,$$

which means that ν_e couples mostly with ν_1 ; in other words the branching ratio ϵ of ν_e in ν_2 is small.

Experimentally, one measures the energy spectrum of the emitted e^- in the reaction

$$(A, Z) \rightarrow (A, Z \pm 1) + e^{\mp} + \begin{pmatrix} - \\ \nu_e \end{pmatrix} .$$

The Fermi theory gives the corresponding β spectrum: $dN(E_\beta)/E_\beta$, where E_β is the kinetic energy of the β -electron. Instead of plotting directly the distribution $dN(E_\beta)/E_\beta$, it is preferable to use the so-called Kurie plot, which is the best way to illustrate the dependence of the spectrum shape on the neutrino mass.

This plot is derived from the $dN(E_\beta)/E_\beta$ plot by the following transformation:

$$\frac{dN(E_\beta)}{E_\beta} \rightarrow \frac{dN(E_\beta)}{\sqrt{F(Z, E_\beta)} p_\beta E_\beta dE_\beta} \propto \sqrt{W_0 - E_\beta} [(W_0 - E_\beta)^2 - m_\nu^2]^{1/4} ,$$

Fig. 26. Equivalence between the Fermi plot (a) and the Kurie plot (b) obtained for a single- β -decay reaction.

where $F(Z, E_\beta)$ is a Coulomb factor

p_β is the momentum of the β -electron

$$W_0 = m_i c^2 + m_f c^2 - m_e c^2 - E_R$$

(with m_i and m_f being, respectively, the initial and final nuclear masses and E_R the recoil energy), so W_0 is the end-point energy.

Figure 26 shows the main features of the Kurie plot.

ii) Experimental situation

The measurement of single β -decay processes is rather difficult. There exist mainly two techniques: one using spectrometers, the other using calorimetry.

The ITEP experiment³⁵, using a radioactive source of valine ($C_5H_{11}NO_2$) containing 18% of tritium, has shown evidence for an electron antineutrino mass between 14 and 46 eV, with a best fit at 35 eV. However, the use of a tritiated valine source gives systematic uncertainties which are comparable to the size of the neutrino mass observed; the main systematic uncertainty is due to the energy given up in final-state excitations of the molecule following the β -decay of one of the tritium atoms. It is difficult to evaluate this effect in a molecule as complex as valine.

A way to get rid of these problems is by using calorimetry. Simpson³⁶, for instance, implanted tritium in a Si(Li) detector. Because the whole energy in each decay is measured (β -energy and X-rays), the spectrum recorded in the crystal always corresponds to ground-to-ground-state transition. He studied the reaction

with a corresponding end energy $W_0 = 18.6$ keV. He found that ν_e can be analysed as a linear combination of two neutrinos ν_1 and ν_2 : $\nu_e \simeq \nu_1 + \epsilon \nu_2$, with a measured value of $\epsilon \simeq 2$ to 4% and a mass of ν_2 of 17 keV.

This result (despite many controversies) seems in total disagreement with those competitors using the same technique but looking at the reaction:

This process has a much larger end energy: $W_0 \simeq 166.8$ keV. No ν_2 of 17 keV was found by these experiments³⁷.

At the present time, the most common agreement on the limit of the $\bar{\nu}_e$ mass as given by single β -decay experiments may be summarized by the results obtained by Bowles et al.³⁸. They measure the $\bar{\nu}_e$ mass in free molecular tritium β -decay (to get rid of the problems when using more complex molecules), using a sophisticated spectrometer as shown in Fig. 27. In the case of a tritium molecule, final-state effects may be accurately calculated. The Los Alamos group³⁸ has estimated that these effects do not generate a spurious neutrino mass greater than 1 eV. They find, with present restricted statistics, an upper limit on the mass of the $\bar{\nu}_e$ of 29.3 eV at the 95% CL or 25.4 eV at the 90% CL. The Kurie plot (Fig. 28) does not support the existence of a neutrino ν_2 'à la Simpson'. It does not support the central value reported by Lyubimov and collaborators, but neither does it exclude the lower part of the range 17 to 40 eV. Improvements to the apparatus transmission and resolution now in progress are expected to result in a sensitivity to neutrino mass in the vicinity of 10 eV.

Fig. 27. Spectrometer for a single β -decay experiment. Cross-sectional view of the Los Alamos gaseous tritium beta-decay experiment³⁸).

Fig. 28. Kurie plot for the molecular tritium β -decay experiment³⁸⁾. The line through the data in this plot is the calculated best fit for $m_v = 0$.

At the present time, the β -decay experiments do not give any evidence of the neutrinos being massive and a mixture of several ν_i 's ($\nu_{i=1,2,\dots}$), but a lot of work is in progress.

3.1.2 Double β -decay (DBD) and Majorana neutrinos. The double β -decay corresponds to the processes

$$(Z, A) \rightarrow (Z + 2, A) + 2\beta^- + 2\bar{\nu}_e$$

$$(Z, A) \rightarrow (Z - 2, A) + 2\beta^+ + 2\nu_e ,$$

where two neutrinos are produced. We call it $\text{DBD}_{2\nu}$. However, if the ν is a Majorana and massive particle, the neutrinoless double β -decay reaction $\text{DBD}_{0\nu}$ is also possible:

$$(Z, A) \rightarrow (Z + 2, A) + 2\beta^-$$

$$(Z, A) \rightarrow (Z - 2, A) + 2\beta^+$$

There are two ways of measuring these processes: the *direct counting experiments*, where both DBD_{2v} and DBD_{0v} are possible; and the *geochemical method*, which cannot distinguish between DBD_{2v} and DBD_{0v} decays. Let me describe the two methods and their present results.

i) Geochemical method³⁹

The double β -decay is a rare process; 'favourable' half-lives are of the order of 10^{21} years, which corresponds to about 1 decay per 3 months in a 1 g source of a DBD-active isotope.

The geochemical method overcomes this difficulty by applying the *accumulation principle*. By accumulation principle, we mean, firstly, that the decay product is collected during geological times (up to about 10^9 years) in suitable natural mineral crystals; and, secondly, their integral effect on the isotopic composition of the daughter element in the sample is detected by mass spectrometry (i.e. using radiometric age determination methods).

Geochronologically, Te and Se mineralizations have occurred from the early Precambrian to the Quaternary period. But very ancient minerals are particularly scarce. So it is very difficult to provide the 'ideal' sample of a DBD experiment; 'ideal' means here old, rich in Te, low in U, well-crystallized, coarse-grained, and plentiful.

The measurement is done by getting the mass spectrum of Xe extracted from an old tellurium ore (Fig. 29). The large ^{130}Xe anomaly observed in this spectrum indicates the double β -decay of ^{130}Te in ^{130}Xe . The decay constant $^{130}\lambda_{\text{DBD}}$ of such a decay of ^{130}Te is

$$^{130}\lambda_{\text{DBD}} = \frac{N(^{130}\text{Xe})}{N(^{130}\text{Te})} \frac{1}{t},$$

where t is the accumulation time determined by the radiometric age determination method, $N(^{130}\text{Xe})$ is measured by mass spectrometry, and $N(^{130}\text{Te})$ is obtained by standard chemical analysis. The results obtained by the

Fig. 29. Isotopic contribution of xenon extracted from a native tellurium ore. The horizontal lines indicate the maximum contribution of the atmospheric xenon.

Table 4. Half-Lives ($T^{1/2}$)
from Geochemical
Experiments

Isotope	$T^{1/2}$ (years)
^{130}Te	$(2.55 \pm 0.2) \times 10^{21}$
^{128}Te	$> 8 \times 10^{24}$
^{82}Se	$(1.7 \pm 0.3) \times 10^{20}$

Table 5. Limits on the Mass of the Neutrino
 $\langle m_\nu \rangle$ and the Parameter η , from
Geochemical Experiments

Isotope	$\langle m_\nu \rangle$ (eV)	η
^{82}Se	≤ 33	$< 4 \times 10^{-5}$
^{130}Te	≤ 100	$\leq 15 \times 10^{-5}$
^{128}Te	< 8.7	$\leq 3.5 \times 10^{-5}$
^{130}Te and ^{128}Te combined	< 5.6	$\leq 2.4 \times 10^{-5}$

geochemical experiments are summarized in two tables. Table 4 gives the half lives $T_{1/2}$ for ^{130}Te , ^{128}Te , and ^{82}Se . Table 5 gives the limit on the mass of the neutrino $\langle m_\nu \rangle$, as found by the geochemical method, and on the value of the parameter η . This parameter η is the amplitude corresponding to an admixture of a right-handed ($V+A$) component, which happens in the case where ν is a Majorana particle. In such a case the lepton-number-violating DBD may occur. This method cannot measure the ν -mass to better than 1 or 2 eV, and cannot really be much more improved, so let us direct our attention now to the other DBD method.

ii) Direct counting experiments in DBD⁴⁰

The direct counting experiments in DBD are mainly based on the study of the double β -decay of ^{76}Ge which follows the schema given below.

Natural germanium contains 7.76% (in atoms) of ^{76}Ge , which decays on the ground state of ^{76}Se ($0^+ \rightarrow 0^+$) transition with a transition energy ϵ_0 equal to 2040.71 ± 0.52 keV. An alternative decay corresponds to the transition $0^+ \rightarrow 2^+$ to the excited state of the ^{76}Se at 559.1 keV with a transition energy of 1481.6 ± 0.5 keV.

So the $\text{DBD}_{0\nu}$ would be revealed by the presence, in the background spectrum of a germanium detector, of peaks corresponding to the $0^+ \rightarrow 0^+$ and $0^+ \rightarrow 2^+$ transitions. The spectra obtained in the region ($0^+ \rightarrow 0^+$) $\text{DBD}_{0\nu}$

Fig. 30. a) Spectra in the regions of $0^+ \rightarrow 2^+$ neutrinoless double β -decay in the Milan experiment.
 b) Spectra in the regions of $0^+ \rightarrow 0^+$ neutrinoless double β -decay in the Milan experiment.

(Fig. 30a) and the region $(0^+ \rightarrow 2^+)$ $\text{DBD}_{0\nu}$ (Fig. 30b) as measured by the Milan group⁴¹ do not show such evidence.

In conclusion, the present limit provided by DBD measurements on m_ν are confined to a few electronvolts: $m_\nu \lesssim 6$ eV. This is somehow in contradiction with single β -decay results, which at the present stage of accuracy give $m_\nu \gtrsim 10$ eV. There are prospects for improving this limit using the DBD direct counting method. New experiments are planned using very sophisticated technologies, such as ^{136}Xe inside a TPC⁴² and an ^{81}Kr source in an ionization resonance spectrometer using a yag laser⁴³ or superconducting tunnel junctions.

But if one wants to look for lower mass regions, certainly other methods must be used.

3.1.3 Study of neutrino oscillations. The principle of such a measurement is based on the hypothesis of neutrino oscillations between the different flavours: ν_e, ν_μ, ν_τ .

The neutrinos ν_e, ν_μ, ν_τ , eigenstates of the weak interactions, are not eigenstates of the mass, but linear combinations of ν_1, ν_2 , and ν_3 , which are the eigenstates of the mass:

$$|\nu_1\rangle = \sum U_{1i} |\nu_i\rangle$$

where

$$l = e, \mu, \tau \quad \text{and} \quad i = 1, 2, 3.$$

The fraction of neutrinos of flavour m at a distance L from the source of neutrinos of flavour l can be written as:

$$P(\nu_l \rightarrow \nu_m) = \sum U_{li}^2 U_{mi}^2 + 2 \sum_{i < j} U_{li} U_{mi} U_{lj} U_{mj} \times \cos(2\pi L/l_{ij})$$

where $l_{ij}(m)$, the oscillation length, is

$$l_{ij}(m) = 4\pi p_\nu / |m_i^2 - m_j^2|.$$

If there is only a mixture of two flavours, the U matrix is, in fact, a rotation matrix of angle θ and

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2} \sin^2 2\theta (1 - \cos 2\pi l/l_\nu),$$

where l is the vacuum oscillation length and:

$$l = 2.53 \text{ m} \frac{P}{1 \text{ MeV/c}} \frac{1 \text{ eV}^2}{\Delta m^2} \quad \text{and} \quad \Delta m^2 = m_1^2 - m_2^2.$$

So there remain only two parameters to characterize the neutrino oscillations, namely $\sin^2 2\theta$ and Δm^2 .

The neutrino oscillations are studied with nuclear reactors or atmospheric ν 's or solar ν 's. We are now going to discuss each case.

i) Nuclear reactor experiments

The nuclear reactor is a pure source of $\bar{\nu}_e$ emitted isotropically from β -decay of fission products. The experimental area has to be well shielded from the reactor core and associated activities. There are two possible options. The first one is to push the detector as far as possible from the reactor so that one gets cleaner conditions but lower statistics; this is the choice made by the Gösgen experiment⁴⁴. The second option is to keep the apparatus near the reactor, as is required for high statistics, optimizing the signal/background ratio as well as possible; this is the option taken by the Le Bugey experiment⁴⁵. The last results from the Gösgen experiment contradict the previous results from the Le Bugey group who claimed experimental evidence for ν oscillations.

The Gösgen experiment has measured the positron spectrum from the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$, at distances of 64.7 m, 45.9 m, and 35.9 m from

counts
MeV·h

Fig. 31. Positron spectrum measured by the Gösigen experiment at the following distances from the reactor: 64.7 m, 45.9 m and 35.9 m.

Fig. 32. Scatter plot of Δm^2 versus $\sin^2 2\theta$ as measured by the Gösigen experiment and comparison with the results from the Le Bugey experiment.

the core of the reactor. The three spectra are equivalent (Fig. 31); so there is no evidence for ν oscillations. Moreover, the oscillation parameter region ($\sin^2 2\theta$, Δm^2) favoured by the Le Bugey experiment is not supported by the Gösigen data (Fig. 32). The Le Bugey group are redoing their measurement.

ii) Atmospheric neutrinos

Neutrinos produced in the atmosphere can also be used to look for ν oscillations. These ν 's are produced by π^- and μ^- -decays by interaction of cosmic rays with the atmosphere. Below 10 GeV, these ν 's prevail over the extraterrestrial ν -flux. They are a well-known source of background for proton-decay experiments. The IMB experiment has taken advantage of this and has measured possible ν oscillations⁴⁶.

Fig. 33. Detection of Cherenkov light in the IMB experiment. The pattern of the hit PMs plus the timing allow us to reconstruct the direction; ν_μ interactions produce less light (for CC) than ν_e interactions.

The IMB detector⁴⁶ is a large imaging water Cherenkov detector, with the largest fiducial mass (3300 t) available at present, well shielded at a depth of 610 m (1600 m water equivalent). The detector is based on the detection of Cherenkov light produced by 2048 photomultipliers (see Fig. 33). The distance a neutrino has travelled is a function of its zenith angle:

$$L = [r^2 - (r - d)^2 \sin^2 \theta]^{1/2} - (r - d) \cos \theta ,$$

where r is the Earth's radius (~ 6380 km), d is the scale height of atmosphere $\simeq 10$ km. In the lower hemisphere: $L \simeq -2r \cos \theta$. If ν oscillations occur, there will be a difference between ν 's in the upward-going fifth of the solid angle (as sketched in Fig. 34), which travel a mean distance of

Fig. 34. Schema of upward versus downward atmospheric neutrinos.

Fig. 35. Visible energy spectrum measured in the IMB experiment, for
a) upward atmospheric neutrinos, b) downward atmospheric neutrinos.

10^7 m, and those in the downward-going fifth of the solid angle, which have only travelled $\sim 10^4$ m.

The IMB experiment has collected 135 atmospheric ν events in 420 days of running. By comparing the visible energy of upward-going neutrino interactions (Fig. 35a) and the downward-going neutrino interactions (Fig. 35b), the analysis cannot reject the fact that the two distributions are just the same. The corresponding neutrino energy E_ν is defined by

$$E_\nu \simeq 0.758 E_{\text{vis}} + 410 \text{ MeV} ,$$

which gives an average value for E_ν of about 920 MeV. From the comparison of the two spectra above, an exclusion contour is obtained in the $(\Delta m^2, \sin^2 2\theta)$ plot (Fig. 36). No evidence for ν oscillations is observed in this experiment.

Fig. 36. Scatter plot of Δm^2 as a function of $\sin^2 2\theta$ as measured by the IMB experiment (exclusion contour).

iii) Solar neutrinos

A new field starts to be actively investigated; it is the range of solar neutrinos. As shown in Fig. 37, they allow one to go a step further in the study of the $(\Delta m^2, \sin^2 2\theta)$ plot, by reaching Δm^2 values smaller still (i.e. $\leq 10^{-8} \text{ eV}^2$).

Fig. 37. Δm^2 range available for each technique to measure ν -oscillations.

a) Origin of solar neutrinos

Most of the energy produced in the Sun comes from the pp fusion reaction chain:

or

Electron or proton capture on the ${}^7\text{Be}$ may also give:

A small fraction comes from the pep reaction:

The neutrino flux, at Earth level, as predicted by the Standard Solar Model (SSM) is shown in Fig. 38. But there is a 'solar neutrino puzzle'. Some experiments have found many fewer solar neutrinos than predicted by the SSM.

Fig. 38. Neutrino flux diagram as predicted by the Standard Solar Model.

Mikheyev and Smirnov⁴⁷ have explained this fact by showing that electron neutrinos, above a certain minimum energy E_m , may all be converted into μ -neutrinos on their way out through the Sun. The results of Mikheyev and Smirnov have been derived in a different but equivalent way by Bethe⁴⁸; he draws additional conclusions from this phenomenon concerning the masses of μ , e , and τ neutrinos, Δm^2 , and a very minor restriction on the value of the neutrino mixing angle.

So there also the theoretical situation is very unclear as to whether the Sun is 'standard' or 'non-standard'. Again experiments may clarify the situation. Let us see how. So far, the Brookhaven experiment⁴⁹ is the only one to have observed solar neutrinos by detecting ^{37}Ar atoms produced via $\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$ in a 600 t tank filled with C_2Cl_4 . There is now an impressive list of very important experimental projects.

b) 'New generation' of solar neutrino experiments: GALLEX

Somewhere in the middle of Italy, there is the Cave of 'Zichi Baba' also known as the Gran Sasso Laboratory, Fig. 39. It is an impressive experimental area. Several huge experiments are planned to run there by the end of the 80's (MACRO, GALLEX, etc.).

We take as an example^{*}) the GALLEX experiment⁵⁰. It is based on the counting of ^{71}Ge atoms produced in the reaction

Fig. 39. Schema of Zichi Baba's cave (Gran Sasso).

^{*}) Another gallium experiment is going to be performed at the Baksan Neutrino Observatory (USSR), at an approximate depth of 3800 m of rock, using 50 tons of solid gallium⁵⁰.

which has a threshold of 233 keV and is sensitive to almost the whole spectrum of solar neutrinos.

The main goals of the GALLEX experiment are:

- Experimental verification (for the first time) that nuclear fusion is the principal solar energy source.
- Search for ν -flavour oscillations down to ν -mass difference as small as $\Delta m^2 \simeq 10^{-12} \text{ eV}^2$.
- Test of the Standard Solar Model versus the non-standard one, which has the potential of being able to affect drastically the fluxes of ^8B and ^7Be neutrinos (cf. Standard Model results).

The schema of the detector is shown in Fig. 40. The main phases of this experiment can be summarized in the following way:

Fig. 40. Schema of the GALLEX experiment.

- The target: This is a single tank of about 55 m³. The gallium target is a highly concentrated GaCl₃ solution. As soon as the Ge atom is formed in this solution, it gives GeCl₄ (germanium chloride), which is highly volatile; so it is easily swept out from the solution by a circulating stream of air and helium.
- The extraction of the ⁷¹Ge: This is done with gas scrubbers. The ⁷¹Ge is confined in a small volume and reduced to gaseous germane (GeH₄); so it is admixed with the counting gas of proportional counters.
- Detection of the ⁷¹Ge: This is done through the schema shown in Fig. 41; via its decay by Compton effect (EC), it comes back to ⁷¹Ga in extremely background-free counting devices. We show in Fig. 42 some results on the study of the rejection efficiency of Compton background, as simulated by a ⁶⁰Co source in ⁷¹Ge.

This experiment also requires:

- Accumulation of sufficient statistics: This means 2 to 4 years of running with about 25 runs per year.

Fig. 41. Schema of the ⁷¹Ge decay process.

Fig. 42. Results obtained by the GALLEX Collaboration when studying the rejection efficiency of the Compton background, as simulated with a ⁶⁰Co source in ⁷¹Ge counting (the pulse-form parameter G·I is a function of the pulse height).

- Constant monitoring: This is a crucial issue in order to demonstrate the combined performance of all experimental components and processes; it is done by means of a strong artificially-produced low-energy neutrino source, inserted into the target tank. The best choice is considered to be a ^{51}Cr , 600 kCi source. The ^{51}Cr is produced by activation of ^{50}Cr . It decays by e^- capture ($T_{1/2} = 27.7$ days) into ^{51}V . It emits mono-energetic neutrinos of 745 keV (90%) and 426 keV (10%). The actual source is made of 120 kg of natural Cr powder in a sealed cylindrical container of 1 m length and 10 cm radius; it is surrounded by a Pb shield of 10 cm thickness. One source could be used, during about 60 days, for four to six Ge extractions.

This experiment is expected to have started running by 1989. This domain of high-energy physics is certainly very challenging. From the point of view of size, required performance, and complexity of the technology applied, these non-accelerator physics experiments are very comparable with the experiments running at present at $p\bar{p}$ colliders (CERN $p\bar{p}$ Collider or the Tevatron), or even with those projected for the next generation of pp colliders (see last section).

3.1.4 Conclusion. We may make the following concluding remarks:

- i) We have been reviewing a large number of experiments which allow scanning of a wide range in mass; namely from a few tens of electron-volts (with β -decay and DBD) down to 10^{-4} or 10^{-5} eV with solar neutrino experiments.
- ii) An impressive variety of experiments are implied, all working in the non-accelerator domain. They are either 'simple detectors' in a laboratory (such as a magnetic spectrometer experiment) or quite huge detectors inside enormous experimental halls (GALLEX at Gran Sasso).
- iii) All these experiments are far reaching from the technological point of view.
- iv) At the present time, the main questions about the nature of the neutrinos still remain unanswered.

So a lot of activity, and research and development, is going on in this domain of high-energy physics.

3.2 How Many Generations?

If there are more than the three generations stated by the Standard Model, this would imply, in particular, that there are sequential heavy charged (L) or neutral leptons (ν_L) of the fourth generation. Both e^+e^- and pp colliders may perform such searches, as will be described below.

3.2.1 Heavy-charged-lepton search.

i) In e^+e^- experiments the main way to look for such new objects is to consider the process

$$e^+e^- \rightarrow L^+L^- ,$$

where L then decays, via charged current, into:

$$L^\pm \rightarrow \nu_L W^\pm$$

where $W^\pm$ decays leptonically or hadronically. Such an explanation (among others) has been proposed for the eight events observed by the MARK J experiment at PETRA⁵¹. These events were produced by the reaction:

$$e^+e^- \rightarrow \mu + \text{hadrons} ,$$

during the run with a c.m. energy of $46.3 \leq \sqrt{s} \text{ (GeV)} \leq 46.78$ and with an average luminosity of 50 nb^{-1} per day. The running conditions corresponded, in the case of PETRA, to a relatively high background. The Lego plots characterizing these events are reproduced in Fig. 43. Their main features are a broad e.m. and hadronic energy flow, and muons isolated from the main energy flow with a low average momentum of about 3 to 4 GeV. The missing energy in these events is small, about 10 to 20% of the total c.m. energy. The energy flow is broad and could be divided into three or more jets and clusters. In most of these events, the e.m. shower is about 10 GeV. Such events were not observed by the other PETRA experiments (but no such high-energy beam was available any longer). So we have to wait for SLC, LEP, and $p\bar{p}$ results to solve this puzzle.

ii) At $p\bar{p}$ Colliders, the search for such an object may proceed by looking at the process

$$p\bar{p} \rightarrow W \rightarrow L\bar{\nu}_L$$

where

$$L \rightarrow q\bar{q}'\nu_L .$$

This is in fact another 'by-product' of the missing-energy measurement.

Such an analysis has started at the UA1 experiment and very preliminary results have been obtained⁵². Again the main limitation, at the present time, is the lack of statistics.

Fig. 43. Lego plots of the 8 MARK J events characterized by one muon (indicated by a black tower) and hadronic activity. The energy scale is different for each event. Event E has two muons.

Fig. 44. Expected number of monojets plus missing-energy events produced by $W \rightarrow L\nu_L$ in the UA1 experiment, for an integrated luminosity of 715 nb^{-1} , as a function of the decay lepton mass.

The main experimental signatures of such events are monojet plus missing energy or bijets non back-to-back plus missing energy. An estimate of the number of expected heavy leptons corresponding to the total integrated luminosity recorded on tape by the UA1 experiment (715 nb^{-1}) has been made as a function of the mass of the possible new heavy lepton L . It includes a detailed Monte Carlo generation of the corresponding decay of the W , a full detection simulation, and a 4 σ filter as the one applied to the data. The corresponding result is reported in Fig. 44. An upper limit on the mass of a possible heavy lepton L is calculated by comparing the expected number of monojet events (coming from heavy leptons) with the number of monojets obtained in the data (after subtracting the standard background). This gives an upper limit on the mass of this possible heavy lepton:

$$m_L \gtrsim 41 \text{ GeV}/c^2 \text{ at } 90\% \text{ CL} .$$

More definite answers in this mass range again imply a factor of 10 more in statistics; so we need to wait for ACOL and Tevatron results as well as SLC and LEP.

3.2.2 Search for the neutral heavy lepton. One way to search for such a new particle is by the neutrino-counting technique at e^+e^- colliders. It is based on the following principle; in the Standard Model, events with a single photon and no other observed particles will be produced by radiative corrections to the production of ν -pairs:

$$\sigma(e^+e^- \rightarrow \gamma\nu\bar{\nu}) \propto G_F^2 s \left(1 + \frac{N_\nu}{4}\right).$$

This process goes through the two diagrams (charged and neutral currents) given below:

So it is a good way to count the number of neutrinos. It has the advantage of being insensitive to the masses of the associated charged leptons.

Present results are given by two experiments already described in Section 1, namely MAC and ASP; ASP has been especially designed for such a search. The results are an upper limit on the number of neutrinos, amounting to 41 for MAC and 14 for ASP at the 90% CL (see Fig. 45).

Proton-antiproton colliders also have various ways to furnish this number, among which is the study of the process $Z^0 \rightarrow \nu\bar{\nu}$. This is also a

Fig. 45. Corrected $\nu\bar{\nu}\gamma$ cross-section as a function of the number of neutrino generations, as obtained by the ASP experiment.

by-product of the missing-energy analysis. The statistics are at the present time much too low to really give some plausible information. I refer to the lectures of DiLella for the discussions of the other possibilities¹.

We could review many other examples of experimental puzzles beyond the Standard Model which refer to this section on an 'extended world', such as the search for new W's and new Z⁰'s which could be a sign of a (L-R)-handed symmetry etc.

However, we have chosen to restrict ourselves to the case of the neutrinos, since this is still a very puzzling domain in many respects and involves mainly non-accelerator physics and a lot of different and special techniques. In addition, the example we have quoted, concerning the search for heavy leptons, shows the other aspect which essentially implies pp and e⁺e⁻ colliders. Again there, most of the work remains to be done.

4. BEYOND THE 1 TeV/c² MASS RANGE: NEW WORLD?

The question as to whether or not there is a threshold for new physics, somewhere around 1 TeV/c² in the mass scale of high-energy physics represented in Fig. 1, is certainly one of the most if not the most puzzling point that has to be clarified. This new physics scale is directly connected with the Higgs sector and the hierarchy problem. This problem is discussed in detail in Hinchliffe's lectures at this school³. Let me summarize some facts.

The Standard Model expects a scalar Higgs boson H⁰, with a mass somewhere between a few GeV/c² and about 1 TeV/c², decaying into a fermion and antifermion pair (f $\bar{f}$). Whereas the Higgs is the 'inseparable' companion of the intermediate vector boson W and Z⁰ discovered at the CERN pp Collider, it has not yet been found: the Higgs sector remains untested. Moreover, the presence of these fundamental scalars leads to the hierarchy problem. In the Standard Model, all masses are fixed by the Higgs potential mass scale, in the following way:

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 + \text{loops} ,$$

where $\langle \phi \rangle$ is equal to $\sqrt{-\mu^2/\lambda}$, that is to say it is equivalent to $G_F^{-1/2} \simeq 300$ GeV. The W and Z masses are related to $\langle \phi \rangle$ by $m_{W,Z} \simeq g_{W,Z} \langle \phi \rangle$. The masses of the fermions f are related to $\langle \phi \rangle$ by $m_f \simeq g_{\phi f \bar{f}} \langle \phi \rangle$, and the Higgs mass is $\sqrt{\lambda} \langle \phi \rangle^2 = \sqrt{2} \mu$.

Now $\langle \phi \rangle \sim \mu$ is very much smaller than the Planck mass m_P ; but even if μ^2 is small at the tree level⁵³, in general the loops which are quantum-radiation corrections can become divergent too. A new symmetry at $\mu^2 = 0$ could enforce $\delta\mu^2 \simeq 0(\mu^2)$; but it is not possible to do so with scalars in

the Standard Model. Only supersymmetry is able to solve this problem, the so-called hierarchy problem, by introducing a new symmetry which relates bosons and fermions.

As the Standard Model cannot extend its validity up to the Grand Unification scale (i.e. 10^{15} GeV) or to the Planck mass scale (i.e. 10^{19} GeV) and as the great desert is implausible:

'Something must happen in between'!

(See how in Gross's lectures.) The parameter Λ we have just introduced above can then be interpreted as the scale of new physics beyond the Standard Model; and it is natural to expect: $\Lambda \simeq O(1 \text{ TeV})$: so new phenomena are expected thereon.

The Higgs sector, predicted by the Standard Model, and still totally unexplored, is a very fundamental sector, at the border line of the Standard Model and new thresholds: It is a main concern for the experimentalists: we have to search for it everywhere (i.e. with all possible types of experiments and machines and in a very wide mass range). As we shall see, it is not an easy task.

This introduction to the $1 \text{ TeV}/c^2$ mass sector explains why we will consider two points in this section; the first subsection will concentrate on how to explore the whole Higgs sector. We will start from the very-low-mass Higgs range (say $m_{H^0} \lesssim 20 \text{ GeV}/c^2$), then the range in mass which goes up to twice the W mass, and finally we will look at the high-mass Higgs scale, say $m_{H^0} > 2m_W$ and mainly around $1 \text{ TeV}/c^2$. This last point will connect immediately with the second subsection. There, we will review what are the means we need, in terms of machines and detectors, to scan this high-mass region.

4.1 Experimental Exploration of the Higgs Sector

As we have seen, the Higgs mass can extend from a few GeV/c^2 to about $1 \text{ TeV}/c^2$. To explore experimentally this tremendously wide range we have to go step by step, as a function of the accelerators and the detectors we have or will have at our disposal. So we have divided this subsection into three parts. The first part is concerned with presently running machines and detectors and is mainly restricted to the scanning of the very-low-mass region: $m_{H^0} \lesssim \text{few GeV}/c^2$. The second part will discuss the capabilities of new e^+e^- colliders (TRISTAN, SLC, LEP I and II, and the Tevatron) to scan the mass range from a few tens of GeV/c^2 up to twice the W mass. The last part will be devoted to the high-mass range, where the Higgs decays into intermediate vector boson pairs and has a mass larger than twice the W mass.

4.1.1 'Prehistorical search for Higgs': $m_{H^0} < 10 \text{ GeV}/c^2$. In summer 1984, the Crystal Ball experiment⁵⁴ claimed experimental evidence for a narrow state with a mass of $8.3 \text{ GeV}/c^2$ called ζ and observed in the decay of $\Upsilon(1s) \rightarrow \zeta + \gamma$. The corresponding branching ratio of $\Upsilon(1s)$ into $\zeta + \gamma$ was measured to be 0.5%. It is 100 times higher than the one expected for a minimal Higgs H^0 . So ζ was thought perhaps to be a non-standard H^0 . (Remember, this was the year when everything was non-standard physics!). Moreover, the decay of $\Upsilon(2s)$ into $H^0 \gamma$ was not seen. In autumn 1984⁵⁵, with higher integrated luminosity at DORIS II, the experiments CESR and CUSB did not see ζ at the $\Upsilon(1s)$ resonance. This result follows a well-known experimental law: 'as the statistics increase, the evidence decreases'. Later, the CLEO, CUSB, ARGUS and Crystal Ball experiments studied the process of the production of a minimal Higgs at the Υ resonance. The branching ratio for this decay of the Υ (where there is emission of a monochromatic γ) is related to the branching ratio of the decay of Υ into two μ 's by

$$B(\Upsilon \rightarrow \gamma H^0) = B(\Upsilon \rightarrow \mu\mu) \frac{G_F m_b^2}{\sqrt{2}\pi\alpha} \left(1 - \frac{m_{H^0}^2}{m_Y^2}\right),$$

and is of the order of 10^{-4} if the mass of the minimal H^0 is small (without including QCD radiative corrections). To improve the energy resolution on photons, the calorimeter of CUSB has been upgraded. The NaI modules have been partially replaced by BGO counters. The energy resolution for photons achieved by the BGO counters, $\sigma(E_\gamma)/E_\gamma = 0.018/E_\gamma^{1/4}$, has to be compared with $\sigma(E_\gamma)/E_\gamma = 0.038/E_\gamma^{1/4}$, which is the energy resolution for photons obtained with NaI. The measured photon-energy spectra after event topology cuts both for BGO and NaI data are shown in Figs. 46a and b. No monochromatic photon

Fig. 46. Inclusive photon spectra obtained by CUSB for photons (a) in the BGO array and (b) in the NaI array.

Fig. 47. The CUSB 90% CL upper limit of the branching fraction for radiative Υ decay into minimal Higgs bosons.

signals are observed for a photon with an energy between 0.7 and 5 GeV. So combining NaI and BGO results, CUSB has estimated an upper limit for the branching ratio of Υ in ΥH^0 , as a function of m_{H^0} and at the 90% CL, which is reproduced in Fig. 47. This excludes the mass range which goes from 1.2 to 4.2 GeV/c², for a minimal Higgs. However, as pointed out by Vysotsky, the QCD radiative corrections, which have not been taken into account in this analysis of the CUSB experiment, can be as important as 50%. So the limits obtained by CUSB are no longer valid; more data are needed.

Another example of the search for Higgses of very small mass is the one motivated by the 'supermonojet' events found in 1983 by the UA1 experiment⁸. Glashow and Manohar⁵⁶ interpreted these events as a possible decay of Z^0 into two non-standard Higgses h_1^0 and h_2^0 ; h_1^0 would be a stable particle with a mass less than or equal to twice the μ mass; h_2^0 would decay into $f\bar{f}$ or $f\bar{f}h_1^0$ (where f is a fermion). Such objects, if true, should also be produced in e^+e^- colliders via the reaction $e^+e^- \rightarrow Z^0 \rightarrow h_1^0 h_2^0$. No such experimental evidence has been found at PETRA and PEP. Moreover, as already seen in Section 2 the supermonojets have become simple monojet events.

So let us see what are the real hopes of finding the Higgs.

4.1.2 Search for low-mass Higgses, i.e. $0(10 \text{ GeV}/c^2) < m_{H^0} < 2m_W$. If the Higgs mass is at most around the mass of the W , say $\lesssim 0(100) \text{ GeV}/c^2$, the e^+e^- colliders, such as TRISTAN, SLC, and LEP I and II, have the best chance of discovering them. Depending on the luminosity, SLC will be able to discover a Higgs with a mass of the order of $20 \text{ GeV}/c^2$ ⁵⁷; LEP I will

certainly be able to look for Higgses with masses of the order of 30 or 40 GeV/c^2 ; LEP II will be able to scan the 100 GeV/c^2 mass range. They will do it by looking at the process:

$$e^+e^- \rightarrow Z^0 + H^0,$$

where Z^0 or H^0 will be virtual; Z^0 decays into l^+l^- and H^0 into $f\bar{f}$ where $f = c, b, \tau$, and Q . For very low mass Higgses--say $< 20 \text{ GeV}/c^2$ -- $\tau^+\tau^-$, $c\bar{c}$, and $b\bar{b}$ decay modes are the most important ones; $\tau^+\tau^-$ gives the cleanest signature. If the top mass is around 40 GeV/c^2 , $t\bar{t}$ becomes the dominant decay mode once the Higgs mass is larger than twice the top mass, say 100 GeV/c^2 .

Despite the fact that e^+e^- colliders are certainly the best ones to look for Higgses in this mass range, pp colliders may also actively participate in this search. A study is under way⁵⁸ to see how the Tevatron $p\bar{p}$ collider with a c.m. energy of 2 TeV or a pp collider with higher c.m. energy, say 10 TeV, would be able to search for this object. At these energies the dominant mode to produce H^0 is through the qq or gg fusion mechanism; WW fusion starts to become of the same order when dealing with 10 TeV or 18 TeV pp machines and a Higgs mass of 200 GeV/c^2 . Another production mechanism is through the hadroproduction:

$$u\bar{d} \rightarrow W \rightarrow W + H^0 \quad \text{or} \quad d\bar{d} \rightarrow Z^0 \rightarrow Z^0 + H^0.$$

This type of process is lower by a factor of at least 10 than the dominant mode, but if we consider the decay of W into $q\bar{q}$ or Z^0 into $\nu\bar{\nu}$ we may then obtain quite interesting signatures. This is shown in Fig. 48, where some displays (Lego plots) corresponding to such events are presented. These events have been submitted to a simulation program which reproduces the Collider Detector Facility (CDF) at Fermilab. In Table 6 we present the cross-section for different Higgs masses, say 20, 50, and 70 GeV/c^2 and different luminosities of the Tevatron. We consider only the case where the Higgs decays into $\tau^+\tau^-$ and each τ decays into a charged pion; this gives a rather clean signal in the case of pp collisions, much cleaner than if the Higgs decays into $b\bar{b}$ (which is certainly the dominant decay mode at this mass range). The numbers quoted in this table include all the branching ratios and are computed using PYTHIA Monte Carlo calculations⁵⁹. In Table 7 we quote the case of a 10 TeV pp collider working with a luminosity of 10^{32} and look at the possibility of producing Higgses of 50 or 100 GeV/c^2 . The rates obtained are not unreasonable. However, much more work is needed because, as we will see in the next subsection, the main problem with pp

a) $p\bar{p} \rightarrow W^{\pm} \rightarrow W^{\pm} + H^0$
 at $\sqrt{s} = 2$ TeV and
 $m_{H^0} = 20$ GeV/c²;
 $W^{\pm} \rightarrow q\bar{q}$ and $H^0 \rightarrow \tau^+\tau^-$;

b) $p\bar{p} \rightarrow Z^0 \rightarrow Z^0 + H^0$
 at $\sqrt{s} = 2$ TeV and
 $m_{H^0} = 70$ GeV/c²; $Z^0 \rightarrow$
 $\nu\bar{\nu}$ and $H^0 \rightarrow \tau^+\tau^-$;

c) $p\bar{p} \rightarrow H^0 \rightarrow W^{\pm}W^{\mp}$ at
 $\sqrt{s} = 10$ TeV and $m_{H^0} =$
 200 GeV/c²; $W^{\pm} \rightarrow q\bar{q}$
 and $W^{\pm} \rightarrow l^{\pm}\nu_l$.

Fig. 48. Pictures of Higgs events simulated in the CDF detector and generated by the PYTHIA MC according to different processes.

Table 6. Production of Low-Mass Higgses at the $p\bar{p}$ Tevatron Collider ($\sqrt{s} = 2$ TeV): Estimate of Cross-Section and Rates (corresponding to an integrated luminosity L for 1 year of run of 10^{36} or $5 \times 10^{38} \text{ cm}^{-2}$)

Process	Mass (H^0) (GeV/ c^2)	σ^* (pb)	Rates (No. of events per year)	
			$L = 10^{36}$	$L = 5 \times 10^{38}$
$p\bar{p} \rightarrow H^0 \rightarrow \tau^+ \tau^-$	20	5.5	1	500
$p\bar{p} \rightarrow H^0 \rightarrow \tau^+ \tau^-$	50	0.3	-	85
$p\bar{p} \rightarrow H^0 \rightarrow \tau^+ \tau^-$	70	0.16	-	40

* The cross-sections quoted in this table are computed with PYTHIA M.C. and include the branching ratio of H^0 in $\tau^+ \tau^-$ (or $W^+ W^-$) and the branching ratio of each τ in $\pi^-(n\pi^+) \nu_\tau$.

Table 7. Production of Low-Mass Higgses at a pp Collider ($\sqrt{s} = 10$ TeV): Estimate of Cross-Section and Rates (for an integrated luminosity per year of 10^{39})

Process	Mass (H^0) (GeV/ c^2)	σ^* (pb)	Rates (No. of events per year)
$pp \rightarrow H^0 \rightarrow \tau^+ \tau^-$	50	3.2	600
$pp \rightarrow H^0 \rightarrow \tau^+ \tau^-$	100	0.15	40
$pp \rightarrow H^0 \rightarrow W^+ W^-$	200	4	4000

* The cross-sections quoted in this table are computed with PYTHIA M.C. and include the branching ratio of H^0 in $\tau^+ \tau^-$ (or $W^+ W^-$) and the branching ratio of each τ in $\pi^-(n\pi^+) \nu_\tau$.

colliders is the very high background provided by standard processes which mimic well the signals.

Concerning ep colliders, very similar remarks to those made for pp colliders are applicable; moreover their main constraint is the e beam energy which is difficult to get higher than 100 GeV energy (lectures of Wolf⁶⁰).

4.1.3 Search for high-mass Higgses: $m_{H^0} > 2m_W$ ⁶¹. It may well happen that, even in the Standard Model, the Higgs is a heavy object; by heavy we mean $\geq 2m_W$.

In this case, the dominant decay modes for the Higgs is $H^0 \rightarrow W^+ W^-$ or $Z^0 Z^0$. Moreover, to produce such massive Higgses a very-high-energy machine is needed. LEP 200 (if built by 1995) would be at the limit of producing a

Higgs of about $200 \text{ GeV}/c^2$ mass; we know that with our present technological knowledge it is not possible to build a $1 \text{ TeV } e^+e^-$ collider, whereas we are able to design a very-high-energy pp collider such as an SSC (i.e. 40 TeV in c.m. energy). So the $1 \text{ TeV}/c^2$ range becomes 'the mass scale' of such high-energy pp colliders.

This domain is, at the present time, only reserved for prospects. But it is clearly a very active field as it is an introduction to the physics and the technologies of the end of this century in high-energy physics. So we will outline, in this subsection, the ways these studies are being made to prepare the work that will be done in about 10 years from now.

Computations from Ref. 61, as summarized in Table 8, give the Higgs-mass discovery limit as a function of the c.m. energy and the luminosity in the reaction $pp \rightarrow H^0 \rightarrow W^+W^-$. The schema reproduced in Fig. 49 gives the different mass ranges accessible to the various machines which should be running by the end of this century. It shows that a machine such as the SSC pp collider, i.e. high energy and high luminosity would be able to scan masses in the range from $200 \text{ GeV}/c^2$ to $1 \text{ TeV}/c^2$ with a favoured range around $1 \text{ TeV}/c^2$.

Table 8. Higgs-Mass Discovery Limit as a Function of $\sqrt{s}$ in $pp \rightarrow H(+W^+W^-)$

$\int L dt$ (cm^{-2})	$\sqrt{s}$ (TeV)	m_{H^0} discovery limit (GeV/c^2)
10^{38}	20	-
	40	200
10^{39}	20	250
	40	400
10^{40}	20	700
	40	1000

Fig. 49. Higgs mass range accessible to all the machines which are built or are going to be built by the end of this century.

Table 9. Main Scenarios of the Search for the High-Mass Higgs
at a pp Collider ($\sqrt{s} = 40$ TeV)

Process	Rate			Backgrounds
	$m_H = 150$ (pb)	$m_H = 300$ (pb)	$m_H = 800$ (pb)	
$q\bar{q} \rightarrow H \rightarrow W^+W^-$ where $W^\pm \rightarrow l^\pm \nu$ $W^\pm \rightarrow q\bar{q}$	-	1.32	0.156	$pp \rightarrow q\bar{q}, qg, gg + W$ $pp \rightarrow W^+W^-; WZ$ $pp \rightarrow W + \text{jets}$
$q\bar{q} \rightarrow H \rightarrow Z^0Z^0$ where $Z^0 \rightarrow \nu\bar{\nu}$ $Z^0 \rightarrow l^+l^-$ or both Z^0 's $\rightarrow l^+l^-$ or $Z^0 \rightarrow l^+l^-$ $Z^0 \rightarrow q\bar{q}$	- - -	0.081 0.013 0.22	0.0095 0.0016 0.026	$pp \rightarrow ZZ, WZ$ $pp \rightarrow Z + \text{jets}$ $pp \rightarrow qg + \text{jets}$
$q\bar{q} \rightarrow H + W, Z$ where $W, Z \rightarrow q\bar{q}$ $H \rightarrow \tau^+\tau^-$ or $H \rightarrow t\bar{t}$	0.0052 6.9	- -	- -	$pp \rightarrow W + \text{jets}$ and/or $pp \rightarrow Z + \text{jets}$

The main scenarios to search for Higgs at high-energy pp colliders are listed in Table 9. For the time being, people are mainly concentrating on the study of the following two processes:

$$pp \rightarrow H^0 \rightarrow W^+W^-, \quad (8)$$

where one W decays leptonically and the second one decays hadronically; and

$$pp \rightarrow H^0 \rightarrow Z^0Z^0, \quad (9)$$

where one Z^0 decays leptonically and the second one into $\nu\bar{\nu}$.

We should like to review briefly what are the main difficulties of detecting such particles in a high-energy pp collider such as the SSC. This will serve as an introduction to the last part of this section. All the results given in this subsection are from Ref. 62.

i) Main characteristics of these events

They are very rare processes, with cross-section less than or equal to 1 nb. They are hidden by large backgrounds (typically the ratio signal/background $\lesssim 10^{-3}$), mainly due to Standard Model processes which mimic the signal quite well. They may be produced in pp interactions through different processes, but all these processes give signatures characterized by jet(s),

missing energy, and lepton(s); plus the fact that the H^0 decays into W or Z^0 pairs which are *longitudinally polarized* (this imposes an important additional constraint as we will see later). So, apart from this last point, the search for Higgs particles will have very similar points to the search for other new particles such as heavy supersymmetric particles⁶³. The main requirements are high luminosity, sophisticated trigger (with different levels) and a very performing 4 π detector.

Moreover, we may estimate quantitatively the characteristics of events by generating these processes by a Monte Carlo program⁵⁹ and simulating them through a detector.

We report in Table 10, as an example, the results of this estimate on a sample of events reproducing W-pairs, produced in a 4 π fine-grained

Table 10. Characteristics of W-pair and W + jets Events as given by PYTHIA⁵⁹ and ISAJET

MC Process *)	$\langle E_T^{miss} \rangle$ (GeV)	$\langle E_T^l \rangle$ (GeV)	$\langle n_{jet}^{E_T > 50 \text{ GeV}} \rangle$
a	171.3	194.5	3.2
b	204.5	235.9	3.3
c	62.1	61.8	2.4
	$\langle E_T^{isol} \rangle$ (GeV)	$\langle m_T^{l+v} \rangle$ (GeV/c ²)	
a	6.5	70.0	
b	6.2	97.7	
c	2.8	64.5	
	$\langle E_T^{j_1} \rangle$ (GeV)	$\langle E_T^{j_2} \rangle$ (GeV)	$\langle E_T^{j_3} \rangle$ (GeV)
a	371.4	40.8	14.6
b	410.4	69.0	18.8
c	107.2	24.0	11.3
	$\langle m_{jj} \rangle$ (GeV/c ²) **	$\langle m_{WW} \rangle$ (GeV/c ²)	$\langle \delta m_{WW} \rangle$ (GeV/c ²)
a	90.3, 82.7, 76.1	992.0	4.0
b	83.7, 76.8, 71.2	796.0	8.1
c	30.7, 23.9, 17.1	40.0	346.6

*) Process (a) refers to $pp \rightarrow W^+W^-$ as generated by ISAJET.

Process (b) refers to $pp \rightarrow W^+W^-$ as generated by PYTHIA.

Process (c) refers to $pp \rightarrow W + \text{jet}$ as generated by ISAJET.

**) For different threshold values (0, 0.5, and 1 GeV) on the E_T of each cell

calorimeter. We apply also the same simulated detector to Z^0 -pair events. One of the main parameters in this last case is the missing transverse energy produced by the decay of one of the Z^0 's into a $\nu\bar{\nu}$ pair. We show in Figs. 50a, b, and c the missing-energy spectra we may expect for Higgs with a mass of 0.3 or 0.6 and 1 TeV/c^2 .

Fig. 50. Transverse missing energy spectrum provided by the process $pp \rightarrow Z^0 Z^0$, where one $Z^0 \rightarrow \nu\bar{\nu}$ and the other $Z^0 \rightarrow l^+ l^-$ at $\sqrt{s} = 40 \text{ TeV}$
 a) for $100 \leq p_T^{Z^0} (\text{GeV}/c) \leq 200$, which corresponds to the case of an H^0 with a mass of $\sim 300 \text{ GeV}/c^2$;
 b) for $300 \leq p_T^{Z^0} (\text{GeV}/c) \leq 400$, which corresponds to the case of an H^0 with a mass of $\sim 600 \text{ GeV}/c^2$;
 c) for $400 \leq p_T^{Z^0} (\text{GeV}/c) \leq 600$, which corresponds to the case of an H^0 with a mass of $\sim 1 \text{ TeV}/c^2$.

Such studies give an idea of the spectrum as well as the average value of the main parameters describing each type of event [namely, missing energy, electron momentum, jet momentum, and number of jets in the case of the process (8); missing energy and lepton momentum in the case of the process (9)].

These studies can also be used to define a trigger strategy.

ii) Triggering on high-mass Higgs candidates at high-energy pp colliders

Preliminary studies⁶⁴, have allowed a trigger strategy to be defined in order to select W-pair candidates. This strategy is sketched in Fig. 51 and is defined in the three following steps.

A first-level trigger will consist of the two following requirements. First it selects the electron candidate as a calorimeter cell with a transverse energy $E_T^{\text{cell}} > 25 \text{ GeV}$, at least 80% of this energy being electromagnetic. Secondly, it requires a total missing transverse energy of more than 40 GeV for the event.

The second-level trigger also works in two steps. It requires the electron candidate to be isolated, with a surrounding region of ± 5 calorimeter cells in both pseudorapidity and azimuth, containing less than 20% of the transverse energy of the electron candidate cell. It asks, in addition, that in the 'opposite hemisphere' to the (electron + missing energy) system, there is either one jet with a transverse energy greater than 80 GeV or two jets each having a transverse energy greater than 40 GeV.

Finally, a third-level trigger requires the matching of a track with $p_T > 10 \text{ GeV/c}$ with the candidate electromagnetic cell.

Such requirements lead, at the end, to a trigger rate of $\sim 1 \text{ Hz}$.

Fig. 51. Schema of the strategy to trigger on high-mass W pairs at the SSC.

iii) Main detection problems

The appropriate detector to perform such a search is certainly a 4 π detector, which should be able to make a precise measurement of the total missing transverse energy, to tag electrons and make an accurate measurement of their characteristics (i.e. momentum, charge and very good e/π rejection), and to measure precisely the jet content of the events. Let us now consider this last point.

Most of the physics which will be studied at the SSC implies new particles which decay into $q\bar{q}'$ or $q\bar{q}$ (plus sometimes additional neutrinos). This is the case, for instance, of new heavy quarks, new heavy leptons, supersymmetric particles, etc. This is why the problem of recognizing tricky jet patterns is a main concern⁶⁵.

The present problem, that we take here as an example, is to differentiate events as given by

$$pp \rightarrow H^0 \rightarrow W^+ W^- \rightarrow (q\bar{q}) + (l^+ \nu_l)$$

from those given by the following standard backgrounds:

$$\left\{ \begin{array}{l} pp \rightarrow W^\pm + (g \text{ or } q) \text{ jet} \\ \quad \downarrow \\ \quad l^\pm \nu_l \\ pp \rightarrow W^\pm + q\bar{q} \text{ (where } W \text{ is radiated by one of the partons)} \\ pp \rightarrow W^\pm W^\mp \rightarrow q\bar{q} + l^\pm \nu_l \end{array} \right.$$

It is essential there to measure properly both W's and, in particular, to be able to reconstruct a W from its hadronic decay products. This is not an easy problem. As we see from the plot in Fig. 52, which shows the distribution of the invariant mass of the two jets m_{12} it is not sufficient to

Fig. 52. Distributions of the invariant mass of two jets produced in the case of W's decaying hadronically (solid line) and of a QCD jet (dashed line).

cut on $m_{1,2}$ around the W mass as the standard background is about 200 times higher than the signal⁶⁶. So a much more tricky game has to be played.

We show here some aspects of this game, namely we will discuss how the energy spectrum of an event may be reproduced and also how to reproduce the polarization properties.

By projecting the transverse energy of each cell of the calorimeter onto the main axis s of the event in the (η = pseudorapidity, φ = azimuth) plane E_T^S we obtain an energy spectrum related to the jet structure of this event. This is shown in Fig. 53a where we have plotted the E_T^S spectrum of

E_T^S spectrum of event $pp + W + \text{jet}$

Corresponding Lego plot

E_T^S spectrum of a $(W + q\bar{q})$ system only

E_T^S spectrum of a typical QCD jet only

Fig. 53

an event generated according to the process $pp \rightarrow W + \text{jet}$; the transverse energy of the recoil jet is required to be $> 300 \text{ GeV}$ (in order to correspond to a Higgs mass of $\sim 700 \text{ GeV}/c^2$). We clearly see a three-peak structure in this energy spectrum (Fig. 53a); one peak corresponds to the QCD jet (recoil jet), the other two correspond to the $(W \rightarrow q\bar{q})$ system. The Lego plot in Fig. 53b is another way to represent the three-jet structure of the event we are discussing. If we now expand on the W system of the same event, we get the E_T^S spectrum corresponding to the two quarks that are the decay products of the W (Fig. 53c). It contrasts with the E_T^S spectrum of a typical QCD jet as shown in Fig. 53d.

However, gluon bremsstrahlung may distort such nice two-jet structure topologies by adding extra very neighbouring jets to the $q\bar{q}$ system we are looking at (Fig. 54). So Fig. 55 shows a sample of a typical $q\bar{q} E_T^S$ spectrum we may get in reality.

We can then conclude that in order to search for hadronic decays, we may use the ' E_T^S -spectrum technique' to select the events which have the expected 2-jet structure.

Fig. 54. Effect of gluon bremsstrahlung in the display of an event, $pp \rightarrow W^+W^+$, where one of the W 's decays into $c\bar{s}$ (see corresponding Lego plot shown in this picture) and each quark, c and $\bar{s}$, emits gluons.

Fig. 55. E_T^S spectrum of different $(W + q\bar{q})$ systems.

There are also some ways to recognize an important property of the event we are looking at, namely the polarization effects.

Whereas usually W's are transversely polarized, the ones produced by H^0 decays are longitudinally polarized. This provides a very useful piece of information that we can define by a parameter

$$\cos \theta^* = \frac{p_L^1 - p_L^2}{p_L^1 + p_L^2},$$

where $p_L^{1,2}$ are the longitudinal momentum of the jets 1 and 2 along the W-axis in the laboratory system. A W produced with a transverse polarization will have an angular distribution in $1 + \cos^2 \theta^*$, whereas a W produced with a longitudinal polarization will have an angular distribution in $\sin^2 \theta^*$, Fig. 56.

These two examples show that the detection of massive Higgses in a high-energy pp collider will require very performing detectors and sophisticated analysis; perhaps this will be possible.

To conclude this subsection, I would like to say that it is very unlikely that we will discover the Higgs (if it exists) with the present

Fig. 56. Distribution of $\cos \theta^* = (p_L^1 - p_L^2)/(p_L^1 + p_L^2)$ as given by the $(W + q\bar{q})$ system and standard QCD jets.

machines. We have to wait first for a new generation of e^+e^- colliders and, in particular, for LEP 200, but maybe the Higgs mass is such that it will not yet be discovered by 1995 and will need much-higher-energy machines such as the SSC pp collider. Whereas the Higgs is predicted by the Standard Model, it is in fact intimately related to new thresholds for unconventional physics, staying somewhere beyond the 1 TeV range. For the next generation of high-energy physics, 'puzzles beyond the Standard Model' are related to the construction of new machines and new detectors able to scan the TeV range.

4.2 New Accelerators, New Detectors, and New Technologies for the New Physics beyond the 1 TeV Range

This subsection is essentially to give a brief introduction on how, at the present time, we imagine the high-energy physics will be, from the experimental point of view, in 10 years from now. We could be totally wrong in our predictions; however, we have already to think in terms of this time scale. Ten years is not too much, as we will see, to prepare and design all the future projects.

Figure 57 shows the machines which have been built since the very beginning of high-energy physics and also the ones which are planned.

Fig. 57. Centre-of-mass energy accessible to all the machines which have been built up to now or are going to be built by the end of this century.

Table 11. Summary of the SSC Parameters

Parameter	Value	Parameter	Value
Type of machine	pp collider	β max. (m)	332
Beam energy (TeV)	20	β min. in arc (m)	111
Circumference (km)	82.944	Horizontal dispersion: maximum (m)	3.92
Revolution frequency (Hz)	3614	minimum in arc (m)	2.36
Luminosity: at $\beta^* = 0.5$ m ($\text{cm}^{-2} \cdot \text{s}^{-1}$)	10^{33}	Crossing angle: typical value (μrad)	75
at $\beta^* = 10$ m ($\text{cm}^{-2} \cdot \text{s}^{-1}$)	5.6×10^{31}	maximum value (μrad)	150
Bunch separation (m)	4.8	Distance between adjacent interaction points (km)	2.40
Nominal interaction point space between magnetic quad ends (m)	20	Angle between adjacent interaction points (mrad)	10.6
Number of bunches per ring	1.71×10^4	Magnetic field dipole (T)	6.6
Average number of reactions per bunch crossing at $10^{33} \text{ cm}^{-2} \cdot \text{s}^{-1}$ for a total cross-section of 90 mb	1.4	Magnetic radius of curvature (km)	10.1
Number of protons: per bunch	7.3×10^9	Dipole length: magnetic (m)	16.54
per ring	1.27×10^{14}	slot (m)	17.34
Beam current: peak value (A)	2.0	Arc quadrupole length: magnetic (m)	3.32
average value (mA)	73	slot (m)	4.32
Beam energy per ring (MJ)	405	Number of regular SC dipoles (both rings)	7680 (horizontal dipoles)
Normalized transverse emittance ($\text{rad} \cdot \text{m}$)	1.0×10^{-6}	Number of quadrupoles (both rings)	1776
Luminosity lifetime (d)	~ 1	Acceleration period (s)	1000
Synchrotron radiation power (kW per ring)	9.1	Energy gain per turn per proton (MeV)	5.26
Synchrotron radiation energy damping time (h)	12.5	Peak RF voltage (MV)	20
Beam-beam tune shift (max. value)	0.8×10^{-3}	Total RF power ring (MW)	2
r.m.s. energy spread: at injection	1.75	RF system slot length (per ring) (m)	25
at 20 TeV	0.5×10^{-4}	r.m.s. bunch length (cm)	6.0-7.3

Fig. 58. SSC collider: a) SSC collider ring layout, and b) injector.

Concerning the possibility of scanning the $1 \text{ TeV}/c^2$ mass range, there are two main projects: the LHC pp collider⁶⁷ in Europe and the SSC machine⁶⁸ in the States.

We reproduce in Fig. 58a a view of the SSC collider ring layout as well as the injector (Fig. 58b) and, in Table 11, the main characteristics of such a machine as defined by the SSC central design group⁶⁸. In Fig. 59 the LHC project is shown as it could be designed inside the LEP tunnel and we report in Table 12 its main characteristics. Both projects are now in their final form and, in particular, the SSC project is waiting for final approval.

Fig. 59. Transverse view of the LHC collider in the LEP tunnel.

Table 12. Main Characteristics of the LHC Project

a) Performance

No. of bunches	3564	
Bunch spacing (ns)	25	
No. of crossing points	8	
β value at crossing points (m)	1	
Normalized emittance $4\pi\gamma\sigma^2/\beta$ (μm)	5 π	
r.m.s. beam radius (μm)	11.76	
Full bunch length ($4\sigma_s$) (m)	0.31	
Full crossing angle (μrad)	96	
Maximum energy (TeV)	8.488	
Circulating current (mA)	86	167
Particles per bunch	1.34×10^{10}	2.56×10^{10}
Beam-beam tune shift	1.3×10^{-3}	2.5×10^{-3}
Stored beam energy (MJ)	64.91	126.01
Luminosity half-life (h)	16.6	8.7
Luminosity ($\text{cm}^{-2}\cdot\text{s}^{-1}$)	4.14×10^{32}	1.56×10^{33}
Luminosity per collision (cm^{-2})	1.03×10^{25}	3.89×10^{25}
$\langle n \rangle$ at $\Gamma = 100$ mb	1.03	3.89

b) Magnets

Maximum dipole field (T)	10
Maximum quadrupole gradient ($\text{T}\cdot\text{m}^{-1}$)	250
Effective gap between dipoles (m)	1.15
Effective gap between dipoles and quads (m)	2
Horiz. dipole corrector strength ($\text{T}\cdot\text{m}$)	2.5
Vert. dipole corrector strength ($\text{T}\cdot\text{m}$)	2.5
Maximum sextupole strength ($\text{T}\cdot\text{m}^{-1}$)	2000
Ramping time (min)	10
Vacuum chamber inner diameter (mm)	~ 40
Coil inner diameter (mm)	50
Horiz. separation between orbits (mm)	180

The main characteristics of these projects are very-high-energy beams: 8.5 TeV for LHC or 20 TeV for SSC, and high luminosity from 4.1×10^{32} to 1.5×10^{33} at LHC or 1×10^{33} at SSC. A lot of activity is going on in relation to these projects to study the physics issues and the detectors to achieve them.

Among the various detectors that are projected to work in the SSC collider, there is the one shown in Fig. 60 which represents a 'classical' 4π detector directly extrapolated from the present detectors such as UA1, CDF, and D0. It is certainly not the final design and we hope that new

Table 12. Main Characteristics of the LHC Project (cont.)

c) RF system

Harmonic No.	35640	
Frequency (MHz)	400.8	
Momentum compaction	4.595×10^{-4}	
Energy	Injection = 450 GeV	Operation = 8.488 TeV
Bunch area (eV·s)	1.0	2.5
Bucket area (eV·s)	1.73	7.5
Circumferential voltage (MV)	16.89	16.89
Synchrotron tune	9.89×10^{-3}	2.28×10^{-3}
Synchrotron frequency (Hz)	111.2	25.6
Bucket half-height	1.21×10^{-3}	2.78×10^{-4}

d) Typical periods

Cell length (m)	119.463	
Bending angle (mrad)	34.195	
Phase advance	$\pi/2$	
No. of quadrupoles	2	
Effective quad. length (m)	2.72	
Number of dipoles	10	
Effective dipole length (m)	9.68	
Maximum β value (m)	202.8	
Minimum β value (m)	35.2	
Maximum dispersion (m)	2.762	
Minimum dispersion (m)	1.329	
Bending radius (m)	2831.4	
Normalized emittance $4\pi\gamma\sigma^2/\beta$ (μm)	5π	
Energy	Injection = 450 GeV	Maximum = 8.488 TeV
Vert. beam radius (4σ) (mm)	2.91	0.67
Horiz. beam radius ($4\sigma + D\delta_b$) (mm)	6.25	1.44

Fig. 60. Design of a conventional SSC 4π detector (project).

techniques will in fact be used for such a detector. However, we may use it to give a first idea of the sizes and main parameters such as SSC detector will have (Table 13) and also the amount of electronics that will be required.

Table 13. Summary of the Main Characteristics which Describe a Conventional 4π Detector at the SSC

a) Calorimetry

Calorimeter	e.m	hadronic
Depth (X_0) [λ]	25 [0.8]	6.2
Rapidity range η	-6 to 6	-6 to 6
$\Delta R^{\text{cell}} = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$	0.03	0.06
No. of towers	60,000	14,500
Weight (U + LAr) (t)	~ 375	~ 4000

b) Superconducting magnet

Field (T)	1.5
Length (m)	9
Radius (m)	2.5

c) Tracking parameters

Vertex detector		Silicon	Wire chamber
Rapidity range η		-1.5 to 1.5	-1.5 to 1.5
Length (cm)		10 or 20	100
No. of layers		2	25
No. of strips or sense wires		18,000	8,000
Resolution (μm)		10	100
Tracking	Central	End cap	Forward
Rapidity range $ \eta $	≤ 1.2	1 to 3	3 to 5
No. of wires	100,000	10,000	12,000
Resolution (μm)	≤ 175	≤ 200	≤ 200
Muon detector (drift tubes)			
Rapidity range η		-5 to 5	
No. of wires		87,000	
Total weight (t)		30.700	
Resolution (μm)		≤ 200	

d) Electronics (No. of electronic channels, in thousands)

Wire vertex detector	16
Central tracking	min 132 max 232
End-cap tracking	20
Forward tracking	24
e.m. calorimeter	220
Hadronic calorimeter	58
Muon system	184
Total	min 654 max 754

Another major experimental issue when working at very-high-energy, very-high-luminosity pp colliders is the trigger; this is not the case in e^+e^- colliders. So let us also look at some general features about triggering events at the SSC. In the earlier part of this section we have defined, as an example, a trigger strategy to trigger on W-pair events.

A collider of 40 TeV c.m. energy with $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and a corresponding inelastic cross-section of about 100 mb corresponds to a rate of 10^8 collision, per second. This is a rate much too high to be acceptable for a first-level trigger so it has to be decreased to 10^4 or 10^5 Hz. The second-level trigger is able then to decrease this rate to 10 or 10^2 Hz. Finally, a third-level trigger refines the rejection of the second-level trigger but does not cut so much on the final rate which is typically between 1 and a few hertz for most of the physics trigger of interest⁶⁴. To achieve these different rejection levels the following strategy is foreseen at present; the first-level trigger relies on very fast signals, coming directly from the calorimetry. The main example is given by the CDF first-level trigger derived from the structure of the calorimetry (4 π fine-grained calorimeter)⁶⁹. The energy or transverse energy of each calorimeter cell is considered, provided it is higher than a predefined threshold. Then by adding, subtracting, clustering, and comparing the signals, the following elementary basic trigger levels are built; the missing-energy trigger is defined by calculating the total missing transverse energy in the event as derived from the sum of the energy of each cell and requiring a minimal amount of ~ 50 GeV. The e^- trigger is defined by requiring that a cell has more than a certain amount of transverse energy E_T (say > 25 GeV) and that 80% of this energy is electromagnetic. Clusters are identified in the event by summing each cluster of adjacent hit cells around the highest E_T cell energy. Muon signals are defined by matching the information given by the hadronic cell equivalent to a minimum ionizing particle with a signal in the μ -detector. Total transverse energy triggers are defined by summing all the hit cells in the events and requiring the total transverse energy to be higher than a predefined threshold, say for instance 300 GeV. The total trigger rate corresponding to these types of trigger and associated thresholds has been estimated to be $\leq 10^5$ Hz⁷⁰. The required thresholds are low enough so that it would be no problem (from the physics requirements point of view) to higher them a little bit such that the trigger rate at the first level can go down to 10^4 Hz.

The ideas for constructing a second-level trigger are mainly based on the use of digitized information, microprocessors for local responsibility, and tracking information to some extent. The tracking information, for instance, quick stiff track reconstruction (as designed for the CDF

detector⁷¹) can be used to ensure a muon track or an electron. There are also proposals to use information from the transition radiation detectors (TRDs) to reconstruct e^- at a second-level trigger⁷². The use of microprocessors allows the refinement of the first-level trigger action and the introduction of sophisticated algorithms using the various sources of digitized information and possibly matching some of them together. This gives refined levels of decision, by access in particular to refined parameters. The third-level trigger could be considered like a park of computers and almost an on-line reconstruction level at least for certain types of events. These are very preliminary ideas, mainly based on our present knowledge and technological capabilities⁶⁴. Certainly a lot of progress is going to be made in this domain, particularly in the next 10 years.

5. CONCLUSION

In these lectures, I have tried to cover a set of specific subjects that are still, nowadays, very puzzling. They include the search for supersymmetric particles in the W-mass range, done at both e^+e^- and $p\bar{p}$ colliders. So far, there is no sign that such particles exist. Some limits may be set, within specific models. However, there is real hope to get a definite answer, in this mass range, by e^+e^- and $p\bar{p}$ machines with higher luminosity, higher c.m. energy and improved detectors. The proof that there is an antigravitational force has still to be given. It is up to the classical experiments (remake of Cavendish's, Eötvös', and Galileo's measurements) to solve the problem. It will certainly be amusing and trivial, then, to verify that antigravity is an unescapable consequence of extended supergravity theories. The β -decay measurements (in the tens of eV range) and the large solar neutrino experiments (in the $\Delta m^2 \simeq 10^{-8}$ eV range) should be very active and interesting fields of high-energy physics. They should succeed in filling in the identity card of an old friend, the neutrino (mass, nature, how many relatives, ...?). This last question about the number of neutrinos will also be answered, hopefully soon, by the new generation of e^+e^- and $p\bar{p}$ colliders. Is there a scalar neutral Higgs as predicted by the Standard Model? If yes, what is its mass? Are there other Higgses? The clarification of all these questions related to the crucial Higgs sector may take a certain time and a lot of effort.

These various puzzling aspects of high-energy physics have been expressed here in their experimental form--they address very fundamental questions; they require most of the detection techniques used in our field of physics; they imply the use not only of most of the accelerators we have built or are going to build (in particular the e^+e^- and $p\bar{p}$ colliders) but

also of the sky (non-accelerator neutrino physics). They are very far reaching from the technological point of view.

We are a long way from having answered the main questions of particle physics--and we will need to be really smart to do so. Yes, particle physics is a puzzling field!

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APPENDIX I: HADRONICITY IN THE UA1 DETECTOR

The main concern in this appendix is to show that to identify a charged pion, it is necessary to have an accurate measurement of the hadronicity, i.e. a precise e/π rejection.

To measure the hadronicity in the UA1 detector, one may make use of various quantities. On the one hand, there are the quantities which are directly measured by the apparatus. These include, first of all, the energy deposited in the hadronic cell (E_{had}), behind the e.m. cell candidates. The energy deposited by an e^- at various energies and different incident angles has been measured in a beam test (see Fig. I.1). It allows us to calibrate the corresponding E_{had} . One also uses the energies deposited in each of the four samples in depth of the central e.m. calorimeter (gondolas); namely: E_{S1} , E_{S2} , E_{S3} , E_{S4} ; moreover the momentum (p^{track}) of the charged track associated to the e.m. cluster and measured by the central tracking is a very useful piece of information; it is compared to the energy measured in the corresponding e.m. cell(s).

On the other hand, there are the quantities which are derived from beam test measurements and/or obtained by a fit. These include the evaluation of

Fig. I.1. Probability ϵ that a pion, with an incident momentum p (GeV/c) and an incident angle θ , gives an energy deposit $E_C(\pi)$, in the corresponding C-cell, smaller than a threshold value (E_C^{THR}). (The quoted values are derived from a beam test measurement.)

the difference (S1) between the energy deposited in the first sample of the e.m. cell and that deposited in this sample by an e^- of same incident energy and angle (this is given by beam test measurements). The corresponding difference obtained in the case of the fourth sample (S4) is also considered. The difference between the position along the beam axis ($\Delta x/\sigma_x$) measured in the CD and that measured in the calorimeter, is computed; this is done by taking the barycentre of the energy deposit in each sample, performing a fit of the points obtained. The difference between the azimuthal angle defined by the CD and that defined in the calorimeter ($\Delta\phi/\sigma_\phi$) is also used; finally, the chi-square value (χ^2_{relic}) which measures the shower development in the calorimetry is computed by taking into account the energy deposit in each sample of the e.m. calorimeter.

These various parameters are sketched in Fig. I.2. They are presented in a projection of the central e.m. calorimeter cells, in the (ϕ = azimuth,

Fig. I.2. Schema of the central e.m. calorimetry, in the plane (x = beam direction, ϕ = azimuthal angle), with the various parameters defining the 'hadronicity' of an event.

x = beam axis) plane. They are all used to identify the e^- candidate in the search for $W \rightarrow e\nu$ events, by imposing on them the following set of cuts:

$$E_{\text{had}} \leq 500 \text{ MeV (main constraint)}$$

$$\Delta(1/p - 1/E)/\sigma_{p,E} \leq 3$$

$$\Delta x/\sigma_x \leq 3$$

$$\Delta\phi/\sigma_\phi \leq 3$$

$$\chi^2_{\text{relic}} \leq 20$$

Thus the identification of the τ -signal, when τ decays into a single charged pion plus possible π^0 's, could be simply defined by taking a logical OR of the reverse of each one of the conditions listed above. But whereas, in the case of the $W \rightarrow e\nu$ events, most of the tracks have a momentum bigger than 10 GeV/c (see Fig. I.3a), in the case of the τ it is just the contrary (see Fig. I.3b).

So a trickier analysis must be done. It consists in distinguishing three regions, according to the p_T of the charged track. In each of these regions, various sets of parameters have to be considered (they are those, among the quantities we have listed before, which may be effectively measured in the particular p_T -range considered). Moreover a strict matching between the three parts of the detector which are involved in this game, must

Fig. I.3. Transverse momentum distribution of the leading track for:
a) $W \rightarrow e\nu$ events, and b) $W \rightarrow \tau\nu$, $\tau^\pm \rightarrow \pi^\pm(n\pi^0)\nu_\tau$ events.

be defined. The following cases are considered: the first one corresponds to the situation where $p_T^{\text{track}} > 10 \text{ GeV/c}$: the whole set of parameters has to be used. If, in the second case, p_T^{track} is between 5 and 10 GeV/c, the parameter E_{had} is no longer available or its handling becomes too bad. If, in the last case, p_T^{track} is lower than 5 GeV/c and higher than 2 GeV/c, the only quantities which remain reliable are the mismatches in energy and in azimuthal angle between the CD and the calorimetry.

This measurement and the corresponding analysis make wide use of the information provided by the central tracking ($+B$), the e.m. and hadronic calorimetry. They rely on an accurate calibration of these three parts of the detector (in particular of the calorimetry).

We have considered here a special case (i.e. the UA1 detector), and therefore have been dealing with the corresponding systematics. However, 'the moral of this tale' is that in a pp collider environment, the search for τ 's [even when considering its cleanest signatures: $\tau^\pm \rightarrow \pi^\pm (n\pi^0)'s) \nu_\tau$] requires in fact to exploit all the resources of a detector to ensure the e/π rejection, and to handle very well the corresponding systematics. Another example of this statement is given in Appendix II.

APPENDIX II: USE OF THE FRAGMENTATION PROPERTIES OF THE JETS,
TO IDENTIFY A $\tau^{\pm} \rightarrow 3\pi^{\pm}(n\pi^0's) \nu_{\tau}$ signal.

Based on a study reported in Ref. 13, we want to show here how one may use the properties of fragmentation of the trigger jet to enhance the signal provided by the τ_3 events produced by:

$$p\bar{p} \rightarrow W^{\pm} \rightarrow \tau^{\pm} \nu_{\tau} ,$$

where:

$$\tau^{\pm} \rightarrow 3\pi^{\pm} + (n\pi^0's) + \nu_{\tau} .$$

It has already been mentioned in Subsection 2.1.2 (iii) that the multiplicity argument in this case (namely $n_{CD} = 3$), is not strong enough to distinguish τ_3 events from standard QCD jets; about 50% of the QCD jets have a charged multiplicity ≤ 3 . Moreover, at this energy, a standard QCD jet which passes the same 'narrowness' requirement and good matching both in space and in energy between the CD jet and the calorimeter jet as a selected τ_3 candidate, has an effective mass equal to that of a typical τ_3 event.

Therefore, more sophisticated properties have to be emphasized. They imply mainly properties of the charged part of the jet, given by the tracking device and the $\vec{B}$ field.

We plot the transverse momentum measured for each of the three tracks of the trigger jet. We compare the corresponding distributions provided by τ_3 events (as generated by the ISAJET Monte Carlo), by standard QCD jets (mainly due to light constituents) as given by real data, and by heavy quark jets (generated by the process: $p\bar{p} \rightarrow b\bar{b}$ or $c\bar{c}$, using the ISAJET Monte Carlo). These distributions are shown in Figs. II-1, II-2, and II-3. We may derive a set of cuts which allow to enhance the τ -signal. Once the charged multiplicity of the trigger jet is equal to 3, we impose that:

$$p_T \text{ (leading track)} > 5 \text{ GeV/c}$$

$$\text{and } p_T \text{ (next to leading track)} > 3 \text{ GeV/c}$$

$$\text{and } p_T \text{ (next to next to leading track)} > 2 \text{ GeV/c} .$$

By applying this recipe we obtain that 45% of the τ_3 sample is left, whereas only 2% of the heavy-flavour jets and 1% of the light-constituent jets survive these conditions.

If we now consider the τ -sample estimated out of the 56 events found by UA1 (i.e. 39 τ candidates), this means that only 3 τ_3 events are expected; but only 0.04 event from light constituents and 0.004 heavy-flavour events

will remain. This gives a signal/background ratio of 3/60, which is quite reasonable.

We thus have a good way to distinguish τ_3 events from standard QCD background (both light and heavy constituents). On the other hand, we cannot, so far, define a precise strategy to distinguish τ_3 from heavy-flavour jets since we have no real experimental knowledge about the fragmentation properties of b-, c- or t-quark jets.

Fig. II.1. Transverse momentum distribution of the leading track for:
a) $W + \tau \nu_\tau$ events; $\tau \rightarrow 3\pi^\pm(n\pi^0)\nu_\tau$ (ISAJET Monte Carlo); b) QCD jets (real data), mainly light constituents; c) QCD jets, b- and c-quark jets only (ISAJET Monte Carlo).

Fig. II.2. Transverse momentum distribution of the next-to-leading particle for: a) $W + \tau \nu_\tau$ events; $\tau \rightarrow 3\pi^\pm(n\pi^0)\nu_\tau$ (ISAJET Monte Carlo); b) QCD jets (real data), mainly light constituents; c) QCD jets, b- and c-quark jets only (ISAJET Monte Carlo).

Fig. II.3. Transverse momentum distribution of the next-to-next-to-leading particle for: a) $W \rightarrow \tau \nu_\tau$ events; $\tau \rightarrow 3\pi^\pm(n\pi^0)\nu_\tau$ (ISAJET Monte Carlo); b) QCD jets (real data), mainly light constituents; c) QCD jets, b- and c-quark jets only (ISAJET Monte Carlo).

APPENDIX III: GRAVIPHOTON AND EQUIVALENCE PRINCIPLE

This computation has been done by Scherk²⁰. Two atoms of atomic number A and A' having Z and Z' protons, respectively, and of charge zero, fall with different accelerations towards the Earth. The force between them is given by:

$$F = \frac{G}{r^0} [mm' - m^0 m'^0] .$$

The negative term $m^0 m'^0$ is due to the exchange of the graviphoton. We get

$$m = Z(m_p + m_e - \Delta) + (A - Z)(m_n - \Delta)$$

$$m^0 = Z(2m_u + m_d + m_e) + (A - Z)(m_u + 2m_d) ,$$

where m_p is the proton mass, m_e is the electron mass and m_n is the neutron mass in the expression of the usual gravitational mass m ; whereas m^0 has only to do with quarks and electron masses, m_u is the u-quark mass, and m_d is the d-quark mass.

The acceleration of the atom characterized by (Z, A) is given by

$$a(Z, A) = \frac{G}{r^2} m' \left[1 - \frac{m^0}{m} \frac{m'^0}{m'} \right] .$$

If (A', Z') represent the Earth, we can safely replace m'^0/m' by $3m_u/m_p$. So the acceleration of the atom (Z, A) towards the Earth is

$$a(Z, A) = \frac{G}{R_E^2} m_E \left[1 - \frac{m^0}{m} \frac{3m_u}{m_p} \right] ,$$

where R_E is the radius of the Earth and m_E its mass. The relative difference in the acceleration of the two atoms is given by

$$\begin{aligned} \frac{\delta a}{a} &= \frac{a(Z, A) - a(Z', A')}{a(Z, A)} - \frac{3m_u}{m_p} \left(\frac{m^0}{m} - \frac{m'^0}{m'} \right) \\ &= \frac{3m_u}{m_p} \frac{Z'A - ZA'}{mm'} \times . \end{aligned}$$

$$\left[m_e(m_n - \Delta - m_u - 2m_d) + \frac{3}{2} (m_u + m_d)(m_n + m_p) + \frac{1}{2} (m_u + m_d)(m_n + m_p) \right] .$$

In the square bracket, the dominant contribution is given by $m_e m_n$, so that

$$\frac{\delta a}{a} \simeq \frac{3m_u}{m_p} \left(\frac{Z'}{A'} - \frac{Z}{A} \right) \frac{m_e}{m_p} .$$

If we consider, for instance, two atoms such as H and ${}^4\text{He}$, we get $\delta a/a \simeq 10^{-6}$, which is unacceptable.

The situation is even worse if we consider the fall of K^0 and $\bar{K}^0$ towards the Earth; we get

$$\frac{a(K^0) - a(\bar{K}^0)}{a(K^0)} \simeq 6 \frac{m_u}{m_p} \frac{m_s}{m_{K^0}} \sim 10^{-2} !$$