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$p\bar{p}$ COLLIDER PHYSICS AT CERN: PRESENT AND PROSPECTS^{*)}

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ABSTRACT

Recent results originating from the $p\bar{p}$ collider at CERN are reviewed. The tests of the Standard Model provided by the present results are discussed. When reviewing prospects, emphasis is put on the relative potentials of the CERN programme and of the Fermilab Tevatron programme.

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1. FROM THE PAST SEVEN YEARS TO THE NEAR FUTURE

Experimentation at the CERN $p\bar{p}$ collider started in 1981, seven years ago. Over that period of time, there has been a long series of successful and spectacular rendez-vous with the Standard Model. They took place as the luminosity gradually increased and as one was thus able to probe for effects with smaller and smaller cross-sections.

In 1981 the integrated luminosity was 0.2 nb^{-1} . Clear evidence for hadronic jets was obtained; however, it was not high enough to find evidence for the W. Indeed, its production cross-section in the $e\nu$ leptonic mode was expected to be of the order of 0.5 nb , too small to yield events. In 1982, the integrated luminosity was 16 nb^{-1} , which was enough for the W $e\nu$ mode, and it was discovered. Yet this was still not a large enough luminosity for the Z in the e^+e^- mode,

since the expected cross-section was in this case of the order of 0.05 nb. In 1983, the integrated luminosity increased to reach 125 nb⁻¹, which was enough to permit the discovery of the Z e⁺e⁻ mode.

These beautiful experimental successes originated from the UA1 and UA2 collaborations¹, and have been reviewed at several major conferences^{2,3}.

In 1984, the integrated luminosity reached 300 nb⁻¹. It improved further in 1985 and 1986 and, by the end of 1986, a total integrated luminosity of 0.8 pb⁻¹ had been collected by UA1 and UA2. The luminosity eventually achieved was of the order of 5×10^{29} cm⁻²s⁻¹.

In 1984, the initial collision energy of $\sqrt{s} = 540$ GeV was raised to 630 GeV. Ramping runs were also able to cover the 200 GeV to 900 GeV range, though with relatively low luminosities. The UA5 collaboration, operating a streamer chamber, was able to quickly collect important pieces of information on typical hadronic collisions up to 900 GeV⁴. The UA4 collaboration, using the Roman pot technique, was able to study elastic scattering at small transfers⁵.

The extensive results on W and Z production and decay and on jet production obtained by UA1 and UA2 altogether provide an impressive test of the Standard Model.

It may even seem frustrating that all that was observed could be fairly accurately predicted⁶, and that everything was found to be in line with the Standard Model. One should, however, rather say that the collider results actually made the electroweak theory and chromodynamics, the Standard Model which we have today.

Nevertheless, there was one big surprise, which was the clarity of the event structure. Hard processes, testing the structure of matter at the level of 10⁻¹⁸m, where the Standard Model made such dramatic predictions, clearly stand out against the background associated with the vast quantities of debris left by proton-antiproton collisions at such energies. This is beautifully illustrated by the now well-known lego plots of Fig. 1.

Specific features associated with quark and gluon collisions at large transfers show up dramatically against a background which is no longer considered with awe. In order to expect this, one needed some optimism, which turned out to be justified.

Fig. 1: A sample of typical lego plots showing the angular distribution of the transverse energy for W ev production (a), Z e^+e^- production (b) and two-jet production (c). Results from UA1 and UA2.

It is the clarity of the event structure which quickly motivated the enthusiasm for studying hard processes at still higher transfers, but therefore with higher luminosity and also, of course, at much higher energies. At CERN, the possibility of increasing the luminosity by a factor of 10, as possible with a new antiproton source, the ACOL project, received strong attention in 1983, with completion in 1987. The goal is to achieve a luminosity of the order of $4 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$, which could yield an integrated luminosity of up to 10 pb^{-1} over a yearly run.

At the Fermilab Tevatron, the luminosity presently achieved is of the order of $5 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$. It should eventually increase beyond that soon to be available with ACOL, but only within a few years. As far as the more distant future is concerned, the SSC, with a centre-of-mass energy of 40 TeV and a luminosity of the order of 10^{33} stands as an instrument with great potential to probe the structure of matter

down to 10^{-19}m and beyond. At CERN, the LHC, a superconductor proton-proton collider of 17 TeV centre-of-mass energy, which could be installed alongside LEP in the the LEP tunnel, is being actively considered.

To come back to the present, the very important new fact is that the CERN collider has now lost its monopoly. The Fermilab Tevatron operates very successfully at $\sqrt{s} = 1800\text{ GeV}$, about three times the energy of the CERN collider, and an important crop of results has already originated from the CDF collaboration⁷. Over the next few years one will thus witness an intense, and certainly fruitful, competition between the CERN collider, reinforced by ACOL, and the Fermilab Tevatron. The Tevatron will eventually have an overwhelming lead but, for some time, CERN will have on its side a higher luminosity and the benefit of two large detectors running in parallel, as opposed to only one at Fermilab, until the D0 detector is completed.

It is well known that a lower energy can, to some extent, be compensated for by a higher luminosity, since what matters is the rate associated with quark and gluon collisions. The incident particles ($p\bar{p}$) are indeed broad band beams of quarks, antiquarks and gluons.

Figure 2 shows the differential luminosity for gluon-gluon collisions as a function of the gluon-gluon invariant mass M , for different machine energies. The quantity shown is⁸

$$\frac{d\sigma}{d\tau} = \frac{1}{M} \left(\tau \frac{dL}{d\tau} \right) \quad (1)$$

where $\tau = M^2/s$. It is directly relevant for the calculation of rates in perturbative QCD. Comparing the CERN collider to the Fermilab Tevatron one sees that, up to values of M of the order of 100 GeV, the difference in machine energy can be compensated for by an extra factor of ten in luminosity. As long as CERN maintains its luminosity advantage, it will keep the lead over the Tevatron, a mass range which may extend in some cases up to 100 GeV. The Tevatron is however the clear winner beyond this range. Nevertheless, the relevant cross-sections

Fig. 2: Differential cross-section normalized to unit coupling for the production of a system of invariant mass M in gluon-gluon collision. $d\sigma/d\tau = 1/M(\tau dL/d\tau)$, with $\tau = M^2/s$, is presented as a function of M for different $p\bar{p}$ (or pp) collision energies. Up to $M \approx 100$ GeV, a gain in luminosity by a factor ten compensates for the factor three between the CERN collider energy and the Tevatron energy.

at very large M are likely to be very small, and this advantage will be fully exploited only when the Tevatron luminosity has been considerably increased. This relative merit of luminosity versus energy will be our guideline when discussing prospects for the coming few years.

When this review was planned in late 1987, one anticipated a new important crop of results from the CERN collider. However, ACOL had some early problems and the integrated luminosity achieved over the 1987 run was only of 46 nb^{-1} , thus much lower than the total luminosity obtained earlier. As a result, the experimental situation did not change as one had hoped it might. Of course, older data could be analyzed and new results were obtained. However, there is now much less to report than an optimist could have expected a year ago. At the same time, CDF did obtain many results, which are presented in detail at this Conference⁷.

An important piece of news to report on the CERN side is that ACOL has now overcome most of its initial problems. It has achieved results which are only a factor two below design value, and further improvements are in sight. At present one can definitely hope for an integrated luminosity of the order of 5 pb^{-1} during the long 1988-1989 run, and an optimist would set that value at 10 pb^{-1} . During the coming two years, the CERN collider should therefore stand firm in the competition because of its higher luminosity. However, the Tevatron luminosity will also increase with time, and the advantages which CERN has today will eventually be lost.

The advantages provided by a higher energy are already clear with the W production results. Figure 3 shows the W production cross-section in the $e\nu$ mode as measured at CERN (UA1, UA2) and at Fermilab (CDF). The production rate increases by a factor of the order of three, in agreement with expectations^{6,9}. As long as it maintains its factor ten advantage in luminosity, CERN will collect more W's than Fermilab. They will also be less spread out in rapidity and produced with less transverse momentum, factors which both correspond to better experimental conditions. The mean transfer momentum of the W is expected to rise by a factor of order two between its present value of $7 \text{ GeV}/c$ at the CERN collider and its value at Fermilab. At equal luminosity, however, Fermilab will eventually become the clear winner in rate.

Mentioning W production as a bench-mark process, one should stress that within a few years, W production has become one of the best testing grounds for perturbative QCD. This is particularly the case for the transverse momentum distribution of the W shown in Fig. 4³. The observed behaviour is in very good agreement with expectations⁹.

At large p_T one finds a recoiling jet. Comparing the W jet to W rates, the UA2 collaboration was recently able to measure a value of α_s (at M_W^2). It is $\alpha_s = 0.13 \pm 0.03 \pm 0.02$.

Fig. 3: The cross-section for W production in the $e\nu$ mode as a function of energy. CERN collider data (UAl, UA2), new Tevatron data (CDF) and expectations based on QCD with present luminosity.

One should point out the anomalous high p_T point of UAl in Fig. 4. It corresponds to two events with two jets recoiling from the W, with a jet-jet invariant mass close to the W mass. The rate would, however, be too high for any expected W pair process. Statistics should eventually tell if this heralds new physics.

With the tenfold increase in luminosity provided by ACOL, one should obtain in a year about ten times as many W's as one has today. With a 10 pb^{-1} integrated luminosity, one should collect 3000 $W e\nu$ events and about 300 $Z e^+ e^-$ events. Information on the p_T distribution of W's and Z's will improve very much. This is a potentially interesting place to search for new effects.

Fig. 4: The transverse momentum distribution in W production. CERN collider results (UA1, UA2) and expectations based on QCD with present uncertainty.

The global production rate of W (Fig. 3) and Z is in good agreement with QCD. Figure 5 shows the present results of UA1 (in the three leptonic modes) and of UA2 (in the $e\nu$ mode) together with expectations. The shaded band denotes uncertainties at the $O(\alpha_s)$ level. The dashed curves show the uncertainty presently associated with $O(\alpha_s^2)$ effects¹⁰. The production rate in the leptonic mode depends on the mass of the top quark m_t and on the number of neutrino species. The curves in Fig. 5 are drawn for $N_\nu = 3$. At present, one cannot conclude anything about m_t . The theoretical uncertainties roughly match the experimental ones.

Fig. 5: The W and Z production cross-sections as measured at the CERN collider (UA1, UA2) and present standard model expectations which depend on the mass of the top quark. The shaded area corresponds to present uncertainties at the leading $[O(\alpha_s)]$ level. The dashed curves correspond to uncertainties which are associated with $O(\alpha_s^2)$ corrections, not yet fully under control.

2. THE HUNTING LIST

We are now entering a phase of lively competition between the Fermilab Tevatron and the CERN collider. For the reasons previously given it may last for a few years, as long as an excess in luminosity can compensate for lower energy.

There are clearly three main items on the present hunting list:

- i) Find the top quark.
- ii) Search for new physics.
- iii) More detailed study of electroweak properties and of hadronic jets.

With respect to the top quark, the present absolute upper limit from TRISTAN is $m_t > 26$ GeV. A reliable upper limit can be quoted from UA1¹¹ which is of the order of 40 GeV. The new accessible mass range in the near future will be $40 < m_t < 70$ GeV, at which point the looked-for signature is $t \rightarrow l\bar{\nu}$ jet, with a lepton, missing transverse

energy and a jet. The top quark can originate from $W \rightarrow t\bar{b}$ decay and from standard QCD processes such as $gg \rightarrow t\bar{t}$.

Luminosity is important in searching for the top. Rates are low and one should collect enough events to be able to distinguish them clearly from the background. Energy becomes a key factor if the mass is large, and in particular in the W-Z mass range or beyond. In that case, the top quark may be out of reach at CERN, although well within the reach of the Tevatron once its luminosity has increased.

With respect to new physics, supersymmetric partners to the known particles have long been actively sought. So far, all candidates associated with missing transverse energy (eventual decay involving a photino) and jet(s) have been interpretable in terms of standard physics¹². As previously stated, W production with associated jets may also offer an interesting trigger for new phenomena.

Luminosity is very important. Mass limits have already been pushed high, and expected rates are small¹². Since masses are high, energy is also a very important factor.

As regards further studies of Standard Model physics, it is clear that one should learn more about W and Z production (p_T dependence) and fragmentation. One would like to test for electroweak radiative corrections and thus also get constraints on the top quark mass. There is still much to learn about heavy quark production (c,b), something which may be needed in order to identify the top clearly, and also about hadronic physics and in particular jet fragmentation.

Here luminosity is the key factor. One may further study an invariant mass range where the energy of the Tevatron is not of overwhelming importance. Indeed, W and Z study is likely to turn out to be easier at the CERN collider. It is well known that prospects for the Higgs particle(s) are low³; rates are low and background is high.

We now come back to these three points in more detail.

The Hunt for the Top Quark

In the $W \rightarrow t\bar{b}$ mode, the sought-after signal is a lepton (electron in UA2, muon and later also electron in UA1), missing transverse energy and a jet (b) on one side. There should be a recoiling jet ($\bar{b}$)

on the other side. In the $t\bar{t}$ associate production mode, the recoiling $\bar{t}$ may show up as one fat jet or as three jets if they are all identified separately.

There is a background with similar features which comes from $W + \text{jet}$ events, with leptonic decay of the W . It also stems from $b\bar{b}$ associate production when an energetic gluon is also emitted, and the c jet associated with b semileptonic decay merges into the background. Figure 6a shows the expected production cross-section at the CERN collider, together with the limit obtained by UA1¹⁰. All the candidates obtained so far can be interpreted as originating from the background. There is of course some uncertainty in the calculation of the production cross-section. This is illustrated by Fig. 6b, which shows the ratio between the upper limit given and the expected rate as a function of the top mass. One may conclude that a top mass of less than 40 GeV is excluded, and one could push the limit a little higher (44 GeV) if one views the theoretical calculation with some optimism. The recent detailed analysis of Altarelli et al.¹³ shows that 40 GeV is an extremely reasonable lower limit.

There are indirect limits which are not very reliable since they are associated with important theoretical uncertainties. One of these comes from $B\bar{B}$ mixing. A top mass greater than 50 GeV is favoured¹⁴. Limits from W and Z decays are presently inconclusive, but that should not be the case when branching ratios are better known. The measured value of ϵ'/ϵ ¹⁵ favours a rather large top mass ($50 \text{ GeV} < m_t < 160 \text{ GeV}$), but without any stringent conclusion possible.

If the integrated luminosity achieved in the coming run reaches 10 pb^{-1} , UA2 should collect close to 100 clear top decay events if the mass is close to its present limit of 40 GeV. A possible conclusion is that at this level of luminosity, the top quark should be found if its mass is lower than 70 GeV.

Figure 7a shows the expected rate for top production in the semileptonic mode as a function of the top mass. The scale on the left corresponds to the presently achieved luminosity, and the scale on the right to what is expected with ACOL with an integrated luminosity of 10 pb^{-1} . Various contributions to top production are shown separately.

Fig. 6: The lower top mass limit set by UA1. (a) Expected rates as a function of the top quark mass and lower limit set by the UA1 analysis. (b) The ratio between the experimental upper limit and the calculated values for different sets of acceptable parametrizations. One concludes that the mass of the top has to exceed 40 GeV.

One sees that at the CERN collider the W decay mode dominates in the accessible mass range ($40 < m_t < 70$ GeV). Both UA1 and UA2 are on the hunt.

This is not the case at the Tevatron, where, for the same mass range, it is associated $t\bar{t}$ production which dominates. This is shown by Fig. 7b, which displays the production cross-section through the $W \rightarrow t\bar{b}$ and $t\bar{t}$ modes at $\sqrt{s} = 630$ GeV and at $\sqrt{s} = 1800$ GeV. The full top events should therefore look different, with b recoil at CERN and t recoil at Fermilab as the dominant feature.

Fig. 7: The top-quark production rate. (a) Number of events in the leptonic mode expected at collider energy as a function of the mass of the top. Different sources are separated out and combined into a global yield (solid curve). The left scale corresponds to the present integrated luminosity, and the right scale to an integrated luminosity of 10 pb^{-1} (ACOL).

If the mass of the top is higher than 70 GeV it will be extremely difficult to get evidence for the top at the CERN collider. One may quote 75 GeV as a reasonable upper limit for discovery. There is a question of rate and a question of background. The high mass range is of course where the Tevatron has a great advantage. With an integrated luminosity of 10 nb^{-1} (one expects $\sim 1 \text{ nb}^{-1}$ in the present Tevatron run), one should eventually be able to get evidence for the top quark if its mass is less than 180 GeV. If the top quark mass exceeds that of the W, the decay mode with a real W will give particularly striking signatures, which will help in the identification.

Fig. 7: The top-quark production rate. (b) The respective roles of W decay and of associate production in the top production cross-section, at the CERN collider and at the Tevatron. In the mass range accessible in 1988-1989, the dominant modes are different at the two machines.

Hunting for Sparticles

Events with large missing transverse energy and jet(s) have received a great deal of attention at CERN ever since they started appearing in sizeable numbers in 1983-1984. However, they could all be explained by the standard background¹². This led to lower limits for sparticle masses, which are obtained assuming that the decay of a squark or of a gluino eventually gives a low-mass photino which escapes unobserved.

The production of a squark-antisquark pair $\tilde{q}\tilde{q}^*$ or of a gluino pair $\tilde{g}\tilde{g}$ should eventually give an event with missing transverse energy and jets. Nevertheless, there is an important background with a similar signature which comes mainly from $W \rightarrow \tau\nu$ decay and $Z(\nu\bar{\nu}) + \text{jet}$ production. It is now well understood¹² and suffices to explain all observed effects.

Figure 8a gives the present limits on the $\tilde{q}$ and $\tilde{g}$ masses resulting from the UAl analysis. The two limits are correlated. One may confidently say that squarks have at least a mass of 45 GeV, and gluinos a mass of at least 50 GeV. If the two masses are equal, a more stringent limit of 75 GeV results (Fig. 8a). However, these limits have now been pulverized by CDF, though their results are still preliminary¹⁶. When it comes to massive objects, one quickly sees the power of having a much higher energy. Figure 8b gives the correlated upper limits for sleptons obtained by UAl from the analysis of W decays, assuming that some of them could go into $\tilde{e}\tilde{\nu}$.

The search for sparticles will continue. With ACOL, and an integrated luminosity of 10 pb^{-1} , the 75 GeV limit of Fig. 8a should be pushed to 120 GeV if nothing is found. It is, however, likely that such a limit will be even more quickly reached at Fermilab. With a luminosity of 10 pb^{-1} , Fermilab should eventually be able to push the limit to 200 GeV.

If supersymmetry is at work to solve the hierarchy problem, it would be puzzling that sparticles are so massive. A limit of 200 GeV can thus be deemed very high. In the coming few years, collider physics should thus provide a rather decisive test of supersymmetry.

Fig. 8: Limits on sparticle masses obtained by UA1. (a) The $m_{\tilde{q}}$, $m_{\tilde{g}}$ range excluded by the present results of UA1. (b) The $m_{\tilde{e}}$, $m_{\tilde{g}}$ range excluded by the present results of UA1.

3. PRESENT ELECTROWEAK PHYSICS AND PROSPECTS

We have already discussed W production. ACOL will allow for an important step further in our testing of QCD and exploring new grounds. Knowledge about Z production should eventually match our present knowledge about W production.

Mass values are already rather precise. Figure 9 shows the Jacobian peak distribution obtained by UA1 (9a) and UA2 (9b). The present values for the masses are¹⁶

$$\begin{aligned} M_W &= 82.7 \pm 1.0 \pm 2.7 \text{ GeV} & (\text{UA1}) \\ &= 80.2 \pm 0.6 \pm 1.8 \text{ GeV} & (\text{UA2}) \end{aligned}$$

The first error is statistical and the second is systematic in character.

There is good evidence for universality with $g_\mu/g_e = 1.01 \pm 0.07 \pm 0.04$ and $g_\tau/g_e = 1.01 \pm 0.11 \pm 0.06$ (UA1). The value of the Z mass obtained from the invariant mass of the lepton-antilepton final state is

$$\begin{aligned} M_Z &= 93.1 \pm 1.0 \pm 3.1 & (\text{UA1}) \\ &= 91.5 \pm 1.2 \pm 1.7 & (\text{UA2}) \end{aligned}$$

It is tempting to compare the width in order to obtain information about decay modes involving the top quark and new species of neutrinos which affect the W and the Z in different ways. Of particular interest is the directly-measured ratio between the $e\nu$ yield on the W and the e^+e^- yield on the Z:

$$R = \frac{\sigma_W B_{W e \nu}}{\sigma_Z B_{Z e^+ e^-}} \quad (2)$$

$$= \frac{\sigma_W \Gamma_{W e \nu}}{\sigma_Z \Gamma_{Z e^+ e^-}} \frac{\Gamma_Z}{\Gamma_W} \quad (3)$$

a

b

Fig. 9: Jacobian peak determination of the W mass.
 (a) UA1 distribution
 (b) UA2 distribution

The first term in (3) is determined theoretically and many uncertainties which appear in the calculation of the W and Z cross-sections disappear in the ratio. The second term is determined in the Standard Model. The measurement of R thus gives the ratio of the total width Γ_Z/Γ_W . One finds (UA1, UA2)

$$\frac{\Gamma_Z}{\Gamma_W} = 0.96 \begin{matrix} +0.14 \\ -0.10 \end{matrix} \pm 0.07 \quad (4)$$

the last error corresponding to theoretical uncertainties.

Figure 10 gives this ratio as measured and calculated as a function of the top mass, for different numbers of neutrino species. The shaded area indicates present theoretical uncertainties. The error bar drawn at the end of each curve shows the relatively very small uncertainty associated with $\sin^2\theta_W$. At present, one may conclude that if $N_\nu = 3$ there is no information on the top mass. If, however, the top mass is greater than 75 GeV, and is thus outside the range accessible with ACOL, then the number of light neutrinos is equal to three. In the minimal standard model ($\rho = 1$), one has

$$M_W = \left(\frac{\pi\alpha}{\sqrt{2} G_F} \right)^{\frac{1}{2}} \frac{1}{\sin\theta_W(1-\Delta r)^{\frac{1}{2}}} \quad (5)$$

$$M_Z = \frac{M_W}{\cos\theta_W} \quad (6)$$

where Δr comes from electroweak radiative corrections. It depends on the top quark mass and, to a lesser extent, on the Higgs meson mass. The value of ρ is in agreement with the minimal Standard Model (one neutral Higgs meson). One has (UA1, UA2) $\rho = 1 \pm 0.03$.

Within that model one may compare the W and Z masses and test for the presence of Δr . It is clear that some contributions to Δr are certainly there, since there is no doubt about the validity of the electroweak theory. In the one-loop approximation, the known piece is of the order of 0.07, and one may write

Fig. 10: The ratio of the widths of the W and Z as a function of the mass of the top quark for different numbers of light neutrino species. The small error bar at the end of each curve corresponds to the present uncertainty on $\sin^2\theta_W$. The grey zone corresponds to theoretical uncertainties in calculating σ_W/σ_Z .

$$\Delta r = 0.07 - \delta \quad (7)$$

where δ is very sensitive to the difference between the t and b quark masses. With a top mass of 45 GeV and a Higgs mass of 100 GeV, for instance, a recent calculation gives¹⁷:

$$\Delta r = 0.071 \pm 0.007 \quad (8)$$

Δr decreases from that value when the top mass increases.

At present the values of the W and Z masses given by UA1 and UA2 do not allow for a test of Δr . This is shown in Fig. 11a. One cannot distinguish $\Delta r = 0.07$ from $\Delta r = 0$.

The situation will change. The Z mass should be precisely measured at LEP. This will allow for the elimination of systematic errors affecting both the determination of the W and Z masses. The determination of the W mass will also benefit from a large increase in statistics, and a more detailed knowledge of the p_T dependence.

With ACOL and LEP, say in 1990, one should have a situation similar to that displayed in Fig. 11b, with the ratio of the W and Z mass known to a precision of half a per cent. One should then be able to test directly for the presence of radiative corrections.

Fig. 11a: The relation between M_Z and M_W in the Standard Model. The two curves correspond to no electroweak radiative corrections and radiative corrections at the expected level ($m_t \approx 45$ GeV) respectively. The UA1 and UA2 results are shown with their respective error zones.

At present, one may already conclude that they are there as expected, comparing the value of $\sin^2\theta_W$ as determined from the W and Z masses and as measured in deep inelastic neutrino scattering. This is shown in Fig. 12. Without radiative corrections ($\Delta r = 0$) there is a clear discrepancy. All values can, however, be brought into agreement if the radiative corrections are at the expected level ($\Delta r \approx 0.07$). A global fit of the values obtained from the W and Z masses and from deep inelastic neutrino scattering indeed gives:

$$\Delta r = 0.077 \pm 0.037 \quad (9)$$

In the one-loop approximation this already implies that the top mass cannot exceed 180 GeV.

Fig. 11b: The situation as it may look in 1990, after new results from ACOL and LEP have been combined. The expected error bar is shown. The location of the experimental point is arbitrary!

Fig. 12: The value of $\sin^2 \theta_W$ as measured from W and Z data and from neutrino scattering data:
(a) Without electroweak radiative corrections
(b) With the expected amount of radiative corrections.

4. JET PHYSICS

Clear evidence for jet production as expected in the framework of QCD was a major result at the CERN collider^{2,3}. Figure 13 provides a quick historical perspective. Figure 13a shows how jet production could be studied to larger and larger p_T , and therefore to lower and lower production cross-sections, as the luminosity increased from 1981 to 1983. The yields were in good agreement with predictions over several orders of magnitude. The yield was also much larger than at the ISR for the same p_T ³. Figure 13b shows the situation in 1982, when first evidence for jets could be obtained by UA2 and then UA1. Figure 13c shows how the situation had changed by 1986. The box in Fig. 13c corresponds to the zone covered by the 1982 data (Fig. 13b).

Experimental yields agree with theoretical expectations over ten orders of magnitude. However, one should not be blind to the uncertainties still present in these logarithmic plots. There are theore-

tical uncertainties in the calculation which stem from uncertainties in the structure functions, in the scale which should be chosen, and in the effect of still poorly-controlled higher-order effects. One may say that the theoretical predictions carry an uncertainty corresponding to typically a factor of two. However, there are also experimental uncertainties which correspond to the limited performance of calorimetry, in particular when dealing with steeply-falling cross-sections. One may say that this also corresponds to a typical uncertainty by a factor of two.

At present, the theoretical uncertainties thus match the experimental ones and, in both cases, it seems very hard to improve. Yet the global agreement shown in Fig. 13c is impressive. Jets are present as expected from quark and gluon hard scattering.

Perturbative QCD calculations in the leading log approximation are relatively simple. Calculations to higher orders very quickly become very difficult. Their effect is usually quietly disguised by a K factor which should simply multiply the lowest-order result to give the correct value, which is estimated to be of the order of 1.5 to 2 for large p_T jet ($p_T > 20$ GeV/c). However, before one can pin it down, comparing data to lowest-order predictions, one has to face uncertainties associated with the structure functions and the scale to be used in the calculation. Figure 14 shows the ratio between the experimental results and a particular leading-log calculation¹⁰, and then curves obtained varying the conditions under which the lowest-order calculation is performed. One clearly sees the relative value of the uncertainties coming from the experimental errors (limits of calorimetry) and from the computation inputs. Again, one may say that, even at the leading-order level only, theoretical uncertainties already match the experimental ones. The situation will only slowly improve.

In Fig. 13a one sees the jet yield increasing dramatically at fixed p_T when going from ISR to collider energy. With p_T values typically ten times higher one also finds a very sharp increase when going from the CERN collider energy to Tevatron energy. This is shown in Fig. 15^{3,7}. The observed rise is in good agreement with QCD. This clearly displays the big increase in yield obtained for large p_T jets.

Fig. 13: A historical snapshot of hadronic jets.
 (a) Inclusive jet yield at the ISR and as measured at the collider with increasing luminosity in 1982 and 1983. Also shown are predictions in leading log QCD.
 (b) The situation in 1982 when the first clear evidence was obtained. Reported values and predictions.
 (c) The situation in 1986. The box corresponds to the range covered by the 1982 results. Experimental value and leading log QCD predictions.

Fig. 14: The ratio between the measured jet yield and a particular QCD calculation in the leading-log approximation. Also shown are the changes in ratio expected from using other sets of acceptable parameters. Uncertainties in such lowest-order calculations match those coming from the limitation of calorimetry. (a) - UA2 results; (b) - UA1 results. Calculations from W.J. Stirling, Hamburg 1987.

For $p_T \sim 100$ GeV the increase in yield corresponds to a factor of the order of 50, and one sees again how a higher luminosity can only partly compensate for a lower energy.

The fact that the observed yield very well follows expectations from QCD allows one to put a mass or range limit on a new possible substructure, which would impose a lower fall-off with p_T when directly probed at high enough p_T value. This is usually parametrized in terms of a direct interaction with a mass scale Λ^{17} , present together with the standard interaction mediated by gluon or quark exchange. The limit obtained with the CERN results (UA1, UA2) is $\Lambda = 400 \text{ GeV}^3$. One may say that, up to such transfers, quarks and gluons have no visible structure. The Tevatron results have already pulverized this limit; they impose a value of Λ of at least 700 GeV^7 .

Fig. 15: Inclusive jet yields at present. CERN collider results (UA1 and UA2) and Tevatron results (CDF).

Fig. 16: Prompt photon production at large p_T . (a) The inclusive jet yield and the inclusive prompt photon yield. UA2 results and predictions from QCD to order α_s^2 .

The study of prompt photons is particularly interesting. The prompt photon yield was expected to follow the jet yield at typically a factor 10^3 below³, and eventually overtake the inclusive pion yield at $p_T \sim 40$ GeV/c. This was an important test of jet production in QCD. Figure 16a shows the inclusive jet and photon yield measured by UA2 (UA1 has very similar results), together with theoretical expectations^{18,19}. The calculation of the inclusive photon yield has been performed to $O(\alpha_s^2)$ and, in that case, experimental uncertainties on p_T

are much less than with hadronic jets. The prompt photon yield is very sensitive to the gluon structure function, the dominant process being $gq \rightarrow \gamma q$. This is beautifully verified experimentally by UA2, comparing the angular distribution of photons and π^0 at high p_T . In the former process quark exchange dominates, while in the latter it is gluon exchange, the π^0 being the fragment of a jet. One thus expects that the ratio of the two angular distributions should be

$$\frac{d\sigma/d\cos\theta (\gamma \text{ jet})}{d\sigma/d\cos\theta (\pi^0 \text{ jet})} \sim 1 - \cos\theta \quad (10)$$

As shown by Fig. 16b, this is verified^{16,19}.

Fig. 16: Prompt photon production at large p_T . (b) The ratio between the angular differential cross-section for γ production and for π^0 (jet) production. Results from UA2. The $\cos\theta$ behaviour ($1-\cos\theta$ solid curve) corresponds to the two different dominant modes (quark and gluon exchange respectively).

Heavy quark production is also a good testing ground for QCD. The inclusive muon yield was expected to follow the inclusive jet yield at typically a factor 10^4 below, with a relatively big bump associated

with W production²⁰. Excluding W's, it was also expected that b decay should be at the origin of most of the inclusive muon spectrum. The results of UA1 shown in Fig. 17a²¹ are in good agreement with these predictions. The observed yield is very well reproduced by detailed calculations, taking into account all known origins. The UA1 collaboration was able to isolate b production further and, after extrapolation from the kinematical range covered, obtained a value for the production of a $b\bar{b}$ pair of $\sigma(b\bar{b}) = 10.2 \pm 3.3 \mu\text{b}$ ²². This is in good agreement with the QCD value determined by Altarelli et al.¹³ of $12^{+7}_{-4} \mu\text{b}$ for $m_b = 5 \text{ GeV}$ and $19^{+10}_{-8} \mu\text{b}$ for $m_b = 4.5 \text{ GeV}$.

Fig. 17: Muon yield and b-quark yield - UA1. (a) The inclusive muon yield with its different origins. Separated out is the contribution from W decay.

Figure 17b shows the inclusive b spectrum for production with $p_T > p_{Tmin}$ as a function of p_{Tmin} . It is an ingenious analysis where different ranges of p_{Tmin} are best covered by the study of different contributions, namely $b \rightarrow J/\psi + X$, followed by $J/\psi \rightarrow \mu^+\mu^-$ at low p_{Tmin} , high mass muon pairs at higher p_{Tmin} (~ 6 GeV/c), low mass muon pairs at $p_{Tmin} \sim 10$ GeV/c and, finally, inclusive muons at $15 \text{ GeV/c} < p_{Tmin} < 30 \text{ GeV/c}$.

The overall spectrum is living up to expectations, but improvements should be made. The inclusive b yield has been calculated to $O(\alpha_s^3)$ and better data are needed²³. An important uncertainty in the connection between muon production and b production is still associated with imprecise knowledge of the b semileptonic fragmentation. This should be known precisely at LEP. With LEP and ACOL, one should also eventually know the b yield with good accuracy. This yield is very sensitive to the gluon structure function, since $gg \rightarrow b\bar{b}$ is the dominant process. One can therefore see that the combination of the prompt photon yield and the b-quark yield allows the isolation of contributions where experimental uncertainties will be minimal. Since for both processes next-to-leading order calculations have been carried over, one has a very good testing ground for QCD predictions beyond leading order, with a cross-check on the gluon distribution. Better data on b production should therefore be very useful²⁴.

An important aspect of b physics is the question of B - $\bar{B}$ mixing. The mixing parameter χ is defined by

$$\chi = \frac{\Gamma(B^0 \rightarrow \ell^- x)}{\Gamma(B^0 \rightarrow \ell^+ x)} \quad (11)$$

and can therefore be anything between 0 and 0.5. UA1 reported evidence for B - $\bar{B}$ mixing studying the relative abundance of like-sign and unlike-sign muon pairs²⁵. In this case, jet fragmentation gives a mixture of strange and non-strange B mesons, and one can only relate the mixing parameter for the d quark, χ_d , to that for the s quark, χ_s . The allowed region in the $\chi_d \chi_s$ plot determined by the UA1 result is shown in Fig. 18a. Since then, ARGUS has reported evidence for $B\bar{B}$ mixing in a configuration where only χ_d is relevant²⁶. The allowed

Fig. 17: Muon yield and b-quark yield - UAl. (b) The inclusive b-quark yield. Total yield for $p_T > p_{Tmin}$ as a function of p_{Tmin} . The curve is combined from data corresponding to different processes which are studied separately. The dashed curve is a QCD prediction (lowest-order calculation).

region determined by the ARGUS result, a band in χ_d , is also shown in Fig. 18a, along with the domain allowed in the CKM parametrization of the quark matrix¹⁴. All results are presently compatible. One can conclude that χ_s is high, indeed very close to its maximal value, and that the present range for χ_d and χ_s imposes a rather large top mass, heavier than 50 GeV¹⁴. The still wide error band associated with the UAl results should shrink considerably with ACOL and the highly-improved statistics which it will provide.

Figure 18b shows the presently allowed range now combining the UAl and ARGUS results (dashed zone), and also (dark zone) the range of values accessible if there are only three quark families (CKM matrix). Also shown as an ellipse is the size (not location!) of the experi-

mental zone which will result from further studies combining ACOL results with information still to come from e^+e^- colliders (DESY, Cornell, SLAC, LEP). This should be reached by 1990. One should therefore have a rather precise new test of the Standard Model with a three-quark family, or evidence for new physics.

UA2 has refined its analysis of four-jet events¹⁶, where one tries to separate the contribution of two-body induced processes, with four jets in the final state, from that of double-parton scattering, each scattering giving two jets. In the latter case, one can probe

Fig. 18: Presently allowed regions in the χ_d, χ_s plane obtained from the UA1 results, the ARGUS results and the three-quark family Standard Model analysis (CKM). (a) The three different regions.

Fig. 18: Presently allowed regions in the χ_d, χ_s plane obtained from the UA1 results, the ARGUS results and the three-quark family Standard Model analysis (CKM). (b) The present experimental and theoretical constraints. The ellipse gives the size of the experimentally allowed zone which one should have in 1990. The location is arbitrary!

correlations between partons in the transverse plane. The AFS collaboration at the ISR has reported evidence for the latter contribution²⁷. In that case, most of the jet production is due to quarks and the AFS result implies a rather strong correlation between quarks. The effective area with which one can express the probability of having a second parton-parton collision yielding jets in an event in which one has already been observed is of the order of 2.5 mb, much smaller than the proton area.

UA2 find that all their four-jet events can be interpreted in terms of two-body collisions¹⁹ and put a limit of 10 mb on the effective area. In that case, however, this should refer to gluon-gluon correlations rather than to quark-quark correlations. One should also remark that their event selection, with a transverse energy of at least 70 GeV within $\Delta y = \pm 1$, is such that double-parton scattering is very severely repressed. Indeed, one expects that the ratio between the double and single scattering rates for the same global E_T should vary as E_T^{-2} ²⁰. While it is realized that the present limitation of 70 GeV eliminates most of the double-parton scattering contribution if present, it is also realized that it would be very difficult to work with a lower limit. The transverse energy of each of the four jets has to be at least 10 GeV in order for the jets to be well individualized. This implies a rather large value for the minimum global transverse energy.

Fig. 19: Jet-jet invariant mass distribution with evidence for WZ decay into jets (UA2). This illustrates the present power and limitation of calorimetry.

To conclude this review of jet physics, one may show two figures which illustrate the present limitations of jet analysis. Figure 19 shows the invariant jet-jet mass distribution obtained by UA2 with evidence for W and Z jet decay. The yield agrees with expectations, but one sees the limit of present calorimetry. It has often been said

that the spectroscopy of tomorrow will be based on jets. This is unavoidable. However, much progress remains to be made in measuring the energy of jets.

Figure 20 shows the ratio between the fragmentation functions of quark and gluon jets as measured by UA1 from quark- and gluon-enriched samples, and also the ratio obtained by simulation²⁸. The gluon-jet fragmentation is indeed expected to be softer than the quark-jet fragmentation, with a larger multiplicity²⁹. While the data are in agreement with expectations, the precision is still very limited. One can see here also the present limitations of calorimetry. Yet separating gluon jets clearly from quark jets has long been a very important question.

Fig. 20: Ratio between the fragmentation functions in gluon- and quark-jet fragmentations. Z is the fraction of the jet momentum carried by the pion fragment in the inclusive pion yield. Results from UA1. The curve corresponds to a Monte Carlo shower calculation (QCD branching followed by Lund model hadronization).

5. MINIJETS AND SOFT PROCESSES

A minijet is a jet with a transverse momentum high enough for the jet to be recognized without ambiguity and yet small enough for the yield to be large. One may also say that minijets are jets seen in minimum bias events. The inclusive yield is at the level of 10 to 20 mb. However, one should repeatedly stress that it is an inclusive yield and not a cross-section!

The experimental definition of a minijet is somewhat ambiguous. Only at $p_T \sim 10$ GeV/c do jets stand out enough to meet the eye. One has to rely on a jet algorithm, collecting a minimum amount of E_T within a limited solid angle. The UA1 algorithm is $E_T > 5$ GeV over $\Delta r < 1$, with $\Delta r = \sqrt{|\Delta\eta|^2 + |\Delta\phi|^2}$, where η is the pseudorapidity and ϕ the azimuthal angle.

The theoretical problem is to relate the measured E_T value to a parton transverse momentum. This is tricky since a parton scattered at wide angle with a few GeV/c of transverse momentum implies some extra gluon radiation by the scattered gluons (dominant actors for minijets). This builds up a so-called pedestal in the E_T distribution and it contributes to a sizeable fraction of the transverse energy associated with a jet through the jet algorithm. It adds to the value known from minimum bias events, which is easily and rightfully subtracted away.

The UA1 collaboration reported a very sizeable yield for minijets ($E_T > 5$ GeV/c within $\Delta r < 1$). This is shown in Fig. 21a³⁰. At 900 GeV (highest energy in the ramping mode) the yield is close to 20 mb. This is of course $\langle n \rangle \sigma$ and not σ , where $\langle n \rangle$ is the mean minijet multiplicity.

It can be said that the measured value and the energy dependence are in agreement with QCD calculations exploiting the large gluon distribution at low x ($x \approx x_T = 2p_T/\sqrt{s}$ at wide angle) but, for the reasons previously given, one can claim only a rough agreement, within an uncertainty of the order of a factor two. What is clear is that the observed effect is associated with the incoherent scattering of the many low x gluons in the incident particles. This is the way minijets were expected to occur in the first place⁶.

The production of minijets can be related to the hard component of the pomeron³¹. Yet any relation between the energy behaviour of the minijet yield and of the total inelastic cross-section (Fig. 21a) is not clear. The rise of the total cross-section can be parametrized from very low (10 GeV) to very high (900 GeV) energy in terms of a pomeron intercept slightly above 1, with multi-pomeron exchange eventually adjusting to the Froissart bound. On the other hand, the production of minijets has some threshold effect. One has to break

Fig. 21: Minijets and associated effects. (a) The inclusive minijet yield measured by UA1 over the ramping run (200 GeV to 900 GeV). Plotted on the same graph is the total inelastic cross-section. Any simple relation between the two energy behaviours is misleading.

the coherence among gluons and one knows that this requires energies of at least a few GeV in the gluon-gluon centre of mass. While some connection exists, it is not the one which may be seen in Fig. 21a.

UA8 has recently reported the observation of wide-angle jets (studied through the UA2 detector) in events triggered by a quasi-elastically scattered proton, diffractive in character¹⁶. This is strong supporting evidence for a hard component in the pomeron.

Minijets were expected on general grounds, but were also expected to explain the appearance of events with both large rapidity density

and large $\langle p_T \rangle$ observed in cosmic ray emulsion chamber data³². This was the "Açu" class of events distinguished from the "Mirin" type associated with the smooth extrapolation of accelerator events (those seen in bubble chamber data at Fermilab at that time). It was argued that this dichotomy was an oversimplification and that the emergence of minijets should be the proper explanation⁶. Minijets clearly lead to both higher particle density (the different jets hadronize independently) and to higher $\langle p_T \rangle$, the probability of a large transverse momentum not being exponentially suppressed as in typical hadronic events. Figure 21b shows the variation of $\langle p_T \rangle$ as a function of central rapidity density combining ISR and collider (UA1) results³³. One sees a smooth rise, the more pronounced the higher the energy is. It is the behaviour expected from the production of minijets, as their yield sharply increases with energy.

Fig. 21: Minijets and associated effects. (b) An expected effect from minijets. The rise of the mean transverse momentum with central rapidity density. ISR and collider results.

Minijets offer an interesting transition between the soft hadronic processes, whose phenomenology is well known after the many results obtained at Fermilab and the ISR, and the hard processes on which we have been focusing so far. They can be put to several uses³¹.

I shall not say much about soft processes. At present one has too great a tendency to consider them as well-known, boring territory, the virgin new land lying in hard physics. What one should rather do is stress their interest and in particular in predicting background conditions at SSC (LHC) energies while looking for hitherto-unknown effects³⁴. The UA5 collaboration has studied many interesting features⁴; however, there is nothing strikingly new to report since I covered the subject last year³. I already mentioned the UA8 results on jets in diffractive events; more will soon be learned. New pieces of information will come from UA1 and CDF from the analysis of their minimum-bias samples. The new thing is that minimum-bias events are now receiving more attention.

A particularly interesting topic to me is the rise of strangeness excitation with energy, especially with a more abundant production of $\Lambda\bar{\Lambda}$, $E\bar{E}$ pairs in the central region⁴. This should also be linked to the emergence of minijets with "flavour-blind" gluons fragmenting in $s\bar{s}$ pairs shot at wide angles.

One may remark³⁵ that several features reported in minimum-bias events, and in particular the $\langle p_T \rangle$ dn/dy correlation (Fig. 21b) and the rise of strangeness production are identical to proposed signatures in the search for a quark-gluon plasma in heavy ion collisions³⁶. It is clear that a gluon-rich hot plasma and gluons shot aside as minijets could hadronize with very similar final states, once abundant pion production has partly averaged out many features. However, associating present collider results to a possible plasma formation and hadronization is puzzling to me. Evidence for a phase transition associated with plasma formation should imply a sizeable volume effect not accessible in $p\bar{p}$ collisions. One should also stress that when associated with minijets these effects appear at very high energy (> 500 GeV) when incoherent gluon scattering becomes important, whereas one looks for them as evidence for plasma formation in heavy ion collisions at much lower energies (≈ 20 GeV in each nucleon-nucleon collision). The transfer of the kinetic hadron energy in the initial state, to many gluon degrees of freedom in the final state, is

obtained very differently in the two processes. For that reason, the energy thresholds for their observation are very different.

There is one piece of soft physics which still offers a challenging question. It is the high value for ρ reported by the UA4 collaboration⁵. Parameter ρ is the ratio between the real and imaginary parts of the forward hadronic amplitude. The value given by UA4 is

$$\rho = 0.24 \pm 0.04$$

This is considered as very large when compared to the value expected from the analysis of ISR results⁶. One expected ρ to pass through a very wide maximum at collider energy of the order of 0.15, eventually decreasing logarithmically to zero. The UA4 value is puzzling. It would imply a sharp rise of the total cross-section between the top energies of the CERN collider and the Tevatron. This of course makes it all the more urgent to measure it there.

However, I should stress that the analysis is difficult and may depend more than anticipated on assumptions which have to be made about the behaviour of the hadronic forward amplitude. Figure 22 shows the variation with transfer momentum of the local slope (exponential parametrization) of the real part (upper curve) and the imaginary part (lower curve) obtained by C. Bourrely et al.³⁷ in their optical model analysis of the forward differential cross-section, which was actually done before the ρ value was measured. They obtained a total cross-section of 62 mb, in line with previous estimates⁶, and in agreement with the measured value³ and a value of ρ of 0.13. Their differential cross-section is in good agreement with the recent data. The non-exponential behaviour of the hadronic amplitude in the Coulomb interference region could lead to peculiar effects. As I already stated in Cargèse³, I think that the question of the value of ρ should still be considered open. It is still too early to speculate about a high value of ρ . Let us hope for a quick measurement of σ_{tot} at the Tevatron.

Knowing the value of ρ is very important for the estimation of the total cross-section in the multi-TeV range. Knowing ρ at the ISR, one could correctly predict the value of the total cross-section at

Fig. 22: The local slope for the exponential parametrization of the real and imaginary parts of the hadronic amplitude, as determined by Bourrely, Soffer and Wu. A detailed knowledge of the hadronic amplitude is needed to extract ρ from the Coulomb interference effects.

the collider. Extrapolating the value of σ_{tot} from present data without knowing ρ , one can merely say that $\sigma_{\text{tot}} = 110 \pm 30$ mb at $\sqrt{s} = 17$ TeV, which is not very precise. Yet one would like to know better the background conditions at SSC (LHC) energies.

6. THE PRESENT CERN COLLIDER PROGRAMME

The key to the higher luminosity which is so badly needed is ACOL (Antiproton Collector). The general layout of the new antiproton source is shown in Fig. 23.

The old AA (Antiproton Accumulator) ring in which collecting, cooling and stacking was performed, is now complemented by a new AC

Fig. 23: Layout of the ACOL project. The old AA ring is complemented by a new AC ring as part of the upgrade.

(Antiproton Collector) ring. The AC ring collects and precools. Antiprotons are then transferred to the AA ring which develops the cooling and stacks.

The AC ring collects $\bar{p}$ at 3.5 GeV/C from the target. It has a momentum bite of $\pm 3\%$ over 100 mrad. A new source provides 10^8 $\bar{p}$ /pulse as opposed to 6×10^6 in the previous setup. For that there is a new target and a new focusing device. The machine also has a new cooling system.

One thus expects 10^{12} $\bar{p}$ collected and stacked over ten hours as opposed to 5×10^{11} over 100 hours in the previous setup. If everything goes well, the collider luminosity should reach $4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. This is a gain by a factor ten as compared to the previous value.

Recent progress with ACOL has brought the achieved value within a factor two of the design value. Beam stability in the collider is very good and frequent refilling is more of a security than a necessity. The new run will start in September 1988 and extend until July 1989. One hopes to reach an integrated luminosity of 5 pb^{-1} at both the UA1 and UA2 intersections; one may even optimistically consider 10 pb^{-1} .

Both UA1 and UA2 will run. UA1 is developing a high-granularity calorimeter operating with uranium plates and TMP liquid at room temperature. It is a powerful electromagnetic and hadronic calorimeter, but it is not yet completed and will not be used in the forthcoming run. However, UA1 has ready a new muon-detector system covering $15^\circ < \theta < 165^\circ$, a new high-precision tracking device and a new data acquisition system suited to the increased luminosity. Even in its present limited form the detector is well adapted for the search for the top with muon triggers.

UA2 has been upgraded and has already run as such during the 1987 "low" luminosity run. The upgrade consisted of installing new end-cap calorimeters similar to the central one, a new tracking detector and a new triggering and data acquisition system suited to the increase in luminosity. It is a very powerful detector.

UA8, triggering on quasi-elastically scattered protons, is running in association with the UA2 detector.

The CERN programme can thus face the competition of the Tevatron with several trump cards in its hand. The key question is how long luminosity and detector efficiency will compensate for lower energy. We hope at CERN that this will be the case for a few years, long enough to find a great deal of new physics.

ACKNOWLEDGEMENTS

It was a great pleasure to present this review of CERN collider physics at the meeting of the Division of Particles and Fields of the APS, and I am very grateful for the invitation to do so. I would like to express my thanks to all the colleagues who have helped me enormously in preparing this report, in particular P. Darriulat, M. Della Negra, L. Di Lella and P. Landshoff. This text was written while I was visiting Brookhaven National Laboratory, and I would like to thank L. Trueman for his hospitality there.

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Helped by some, but not many, new results, I have tried here to minimize overlap with this extensive Cargèse survey which should be consulted for a more detailed discussion of several topics

which are only touched upon in this report. I benefited greatly from the summary talk given by L. Di Lella at the Fermilab $p\bar{p}$ Workshop (1988).

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