The **pp** collider at the CE?IN-GPS will soon be ready for experimentation up to 540 GeV center-of-mass energy. Aiming at an evaluation of the physics in this new energy range we assemble significant results from present accelerators and from cosmic-ray analyses together with the theoretical interpretations. Their extrapolation to collider energies leads to a wealth of predictions which await to be tested.

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1. Introduction

The proton-antiproton (pp) collider at the CERN SPS\(^{1}\) will soon be operational. The systematic exploration of a new energy range up to 540 GeV center-of-mass energy will subsequently begin by several detector systems\(^{2}\). We therefore aim to form an opinion about the physics to come as based on our present-day knowledge. Our main sources of information are: observations from cosmic-ray experiments, extrapolation of results from existing accelerators, present theory framework of strong and electro-weak interactions supplemented by phenomenological models\(^{3-5}\).

Clarification about the Centauro events is expected and the possibility to find surprising new phenomena is again open. The large-\(p_t\) inclusive reactions, with jets of up to 100 GeV/c transverse momentum, will test the dynamical consequences of perturbative QCD; signatures of glueballs are anticipated. The low-\(p_t\) inclusive data are described by several phenomenological models which, at collider energies, differ in their predictions for the central plateau height and the mean multiplicity. The rise of the total cross section and the characteristics of the (quasi) elastic reactions will hopefully provide a better understanding of diffraction. One of the main motivations for constructing the pp collider is the production of the weak bosons \(W^\pm\) and \(Z^0\) with the leptonic decay modes considered best for their detection. Weak interaction modelling, and the \(SU_2 \times U_1\) model in particular, predict their masses around 100 GeV. If they indeed are found, present weak interaction theory will be certified and possibly further constrained. Two other fundamental features await to be verified: the non-abelian nature of weak gauge theories via the coupling of three gauge bosons, and the Higgs- or technicolor particles which generate the gauge boson (and quark) masses. The processes for their verification have a low cross section and experiments with a very high statistics are needed. The current studies of the Drell-Yan process and the production of direct photons, continued in the pp energy region, will test present theoretical concepts at higher energies and provide more detailed information on the constituent
from particular at low $x$ values. More massive quarks are expected manifesting themselves by new hidden-flavor states (onia) in the lepton-pair spectrum, and by the associated production of new open-flavor states. Once they are found, present phenomenological QCD analyses can again be applied. There are two principle themes in this presentation which are repeatedly encountered: perturbative QCD and electro-weak gauge theory.

The paper is organized as follows: Section 2 assembles the main results from cosmic-ray experimentation and introduces the Centauro events. The INR/PNPI data and characteristics of the large-$p_T$ inclusive processes are presented in Section 3 together with an overview about the theory-analyses and predictions. Section 4 covers the rapidly developing experimental and phenomenological understanding of the small-$p_T$ reactions. Details of the $W$ and $Z$ boson detection, and possible subsequent analyses, are discussed in Section 5. Section 6 touches massive lepton-pair production, the discovery of hidden- and/or open-flavor states, and the production of prompt photons. To establish clear signatures for Higgs- or technicolor-particles will be difficult in this class of rare processes, discussed in Section 7. Figures also the hadronic production of gauge-boson pairs such as $W^+W^-$, $WZ$. Section 8 summarizes this study.

2. Results from Cosmic Ray Experiments

Cosmic ray experiments have already provided some information about particle interactions beyond presently available accelerator energies, despite the problem of low flux. The research has mainly been motivated by the fundamental astrophysical question of origin, acceleration and propagation of cosmic rays. With the advent of the new generation of colliding beam machines at CERN and FNAL hadronic interactions at several hundred TeV will be abundantly produced and their systematic study should clarify the general features of particle production sufficiently, so that further progress can be made in the indirect determination of the primary cosmic ray composition around 1000 TeV.
from air shower measurements. On the other hand, hints for new phenomena \(^2\) have emerged from cosmic ray studies at very high energies which might be confirmed and their characteristics subsequently analyzed by the CERN-SPS \(\bar{p}p\) collider.

### 2.1 General Features of Hadronic Events Above 10 TeV

Multiplicities and rapidity densities for charged secondaries have been reported at 20 TeV which corresponds to a total C.M. energy of about 300 GeV. The average multiplicity measured in two experiments is found to be \(19 \pm 5\) \(^7\) and \(25 \pm 7\) \(^8\) respectively. A logarithmic extrapolation from accelerator data yields \(18 \pm 1\) \(^9\). The data may indicate an increase of the charge multiplicity proportional to \(s^{1/4}\). The large statistical errors and systematic uncertainties however forbid any premature conclusion. The rapidity density at \(x=0\) is reported to be \(3.9 \pm 0.6\) \(^8\). This value is larger than that obtained at the ISR. The ISR values range from 1.4 to 1.9 in the range \(23.6 \text{ GeV} < s^{1/2} < 62.5 \text{ GeV} \(^2\).

Because cosmic ray experiments cannot precisely determine the interaction energies event by event, it is not possible to make a very significant test of hadronic scaling. Analyses of results at 20 TeV \(^7\) and of air shower measurements up to \(10^3\) TeV \(^10\) indicate that the data are not consistent with scaling in the fragmentation region.

A recent study of hadronic interactions around 50 TeV \(^11\) has shown that many of their features can be understood in terms of conventional ideas extrapolated from accelerator energies. The inclusion of a large fraction of hard scattering is needed to describe the large \(p_t\) characteristics and the increasing multiplicity. The falling energy spectrum and the fixed threshold in the experiments, however, favor selection of high-multiplicity events.

The analysis of only 1000 events, generated by the \(\bar{p}p\) collider, will suffice to settle most of the mentioned items at the c.m. energy of 540 GeV which corresponds to a lab-energy of about 150 TeV. The events can be collected within a few minutes.
2.2 New Long-Lived Heavy Objects

The presence of new long-lived ($\gamma > 10^{-7}$s) heavy objects is suggested by experiments that study simultaneously the distribution of energies and delay times of hadrons near air-shower cores. Several events were observed with delays greater than 30 nsec and energies greater than about 45 GeV; these events constitute a fraction of about $3 \times 10^{-4}$ of the events, and could indicate the production of relatively stable particles with mass $\geq 5$ GeV/c$^2$. Such massive stable particles could be seen with a time-of-flight system which provides sub-nanosecond resolution over a path length of about 3 m.

2.3 Anomalous Hadron Attenuation

Results reported from the very large calorimeter at Tien Shan show that the attenuation length of hadrons in lead increases significantly around 50-100 TeV. Above 100 TeV most of the events are air shower cores. At lower energies a significant subset of events are unaccompanied hadrons interacting in the calorimeter. Because of the small ratio of radiation length to nuclear mean free path ($1/30$) the incident electromagnetic component is in equilibrium with the hadronic core, and the rate of energy deposited is characterized by the nuclear absorption length. In a normal cascade, energy deposition in the calorimeter is expected to be dominated by pions. The corresponding attenuation length is calculated to be $\sim 700$ g/cm$^2$. This is the value found experimentally up to about 50 TeV. Above 100 TeV, however, the attenuation length is about $1100$ g/cm$^2$.

Such an effect could be due to copious production of unstable particles (including leptons) if by chance they had decay modes and life times appropriate to the calorimeter. Further studies of the calorimeter would, however, be useful to eliminate the possibility of energy dependent biases.

Although the $p\bar{p}$ collider will surpass the 100 TeV threshold, it is not a priori clear how the anomalous hadron attenuation will manifest itself. The used calorimeters do not widely differ from the Tien Shan set up, but the latter operates in the laboratory frame while $p\bar{p}$ collisions...
will be observed in their center-of-mass frame. The fact that the production of the new component has to be exceptionally copious will probably be the best experimental clue.

### 2.4 Hadron-to-Photon Ratios in Events Around 500 TeV.

The large ratio between hadron and photon energies in the original Centauro events continues to defy a conventional interpretation. The primary interaction responsible for the event happened to be close enough to the emulsion chamber so that its height could be estimated by triangulation. Because of the lack of photons incident from the atmosphere, it happens that at most one $\pi^0$ was produced in the atmospheric interaction which produced at least 49 hadrons. Correcting for hadrons not interacting in the chamber, one estimates 74 hadrons were produced in the original interaction. Keeping in mind that only the electromagnetic portion of hadronic interactions in the chamber is seen, the interaction energy is estimated to be somewhat greater than 500 TeV.

A recent analysis of the data on atmospheric interactions of 100–1000 TeV cosmic rays suggests that there could indeed exist a larger group of anomalous events with very little energy in secondary pions. The group comprises two of the five Centauro events from the Brazil-Japan experiment and three mini-Centauros, including one event from the Panir experiment. At least 5% of the events around 1000 TeV appear to be anomalous. The fraction could be much higher, since Centauro interactions high in the atmosphere would probably be obscured by subsequent atmospheric cascading.

Two classes of explanations for Centauro events can be imagined: (a) those involving exotic cosmic projectiles such as exploding blobs of ultra-dense matter, metastable high-strangness states, or condensed nuclei, and (b) those involving a new kind of interaction of ordinary hadrons beyond some threshold energy. Assuming that explanation (b) is the one to hold, Centauros could be produced at the $pp$ collider and were seen by the detectors, if their production threshold is not too sharp and below the energy range of the machine.
Their discovery would pose uncomfortable problems since a point-like production mechanism can already be excluded. The flux of high energy quarks carrying a fraction of the primary cosmic ray energy does not suffice to explain the observed number of relativistic heavy Centauro-fireballs \(^{19}\), and the absence of neutral pions from the fragmentation of the spectator jet is too peculiar. Violent hadronic processes have to be invoked which do not proceed via point-like constituent scattering.

3. Large-\(p_t\) Physics

Hadron production at large \(p_t\) is considered to probe hadronic short-range interactions. The point-like constituents undergo hard scattering processes and subsequently fragment into jets of hadrons. Perturbative QCD predicts the jet and the particle cross sections, with scale dependent momentum and fragmentation distributions being used.

3.1 QCD Predictions

Characteristic features are: (1) the jet cross section depends on the parton momentum distributions and the differential cross section of the perturbative subprocesses between quarks and/or gluons, (2) at fixed \(p_t\), the cross section increases with energy, (3) since \(50\%\) of the hadron momentum is carried by gluons at low \(x_G\), their influence grows substantially at higher energy, (4) due to the production of infrared-suppressed gluons (which becomes more important with growing energy), a simple scale breaking pattern emerges at fixed c.m. angle, (5) at fixed \(p_t\), the single hadron yield is 2-3 orders of magnitude below the jet yield, details depend on the steepness of the \(p_t\) spectrum of the jet, and on the fragmentation function, (6) the two-jet events are coplanar, and so are their leading hadrons, at higher energies the coplanarity is spoiled by multijet production, (7) the Fermi motion of the partons manifests itself in the primordial transverse momentum, (8) gluon jets are different from quark jets. Gluon jet characteristics are: higher multiplicity due to the larger color charge, a soft hadron spectrum and the absence of number which vanish at higher quark energy.

All practical suffering from the uncertainty of scaling transverse momenta.

The smallest solution is to consider...
absence of leading fragments, the overall compensation of its quantum numbers, and a growing jet cone with increasing jet $k_T$. Quark jets have a smaller jet cone and a lower multiplicity, and their non-vanishing 'charge retention' \(^{21}\) reflects in the mean the quark charge. Quark jets are occasionally accompanied by a gluon jet.

Although this picture is well defined, approximations are needed in practical applications. The comparison between theory and experiment suffers from ambiguities due to the problems; higher order QCD corrections \(^{23}\), uncertainties in the parton distributions \(^{24}\), nuclear and multiple scattering corrections \(^{25}\), higher twist effects \(^{26}\), large primordial transverse momenta \(^{27}\).

3.2 Experimental Features at FNAL and ISR Energies \(^{28}\)

The typical configuration involves two jets at wide angles, and the small-$p_T$ forward and backward spectator jets. One of the wide angle jets is associated with the jet trigger particle (towards-jet), and the other with the recoiling constituent (away-jet).

(1) Jets involve a burst of neutral and charged hadrons (mostly pions) which are isotropically distributed around the jet axis. The mean multiplicity of the charged jet-fragments increases from 4 to 12 in the $\sqrt{s}$ range 5-25 GeV of the two wide angle jets. The positive-to-negative charge ratio increases with the momentum fraction $z$ in pp collisions. Among the leading jet fragments pairs of opposite charge are favored. The mean transverse momentum with respect to the jet-axis is $\langle k_T \rangle \approx 0.55$ GeV/c. Jet fragmentation reveals approximately scaling. The $z$-distributions are well described by an exponential form with the slope as in $e^+e^-$ annihilation. Identification of the gluon jet in the $e^+e^-$ planar three-jet events have so far been possible on a statistical basis only, and no dramatic differences between gluon and quark jets have yet been observed \(^{29}\).

(2) The jet cross section at fixed $p_T$ is typically two to three orders of magnitude above the single particle cross section, and their ratio increases with increasing $x_T (\approx 2p_T/\sqrt{s})$. Jet pionization dissipates about 1 GeV in mass and transverse motion to slow moving particles which...
introduces an uncertainty in its actual yield of up to an order of magnitude. Pions and kaons are more efficient producers of high-\( p_t \) jets than protons, with \( R( p_{}\pi) \approx R( p/\overline{p}) \) decreasing from 1.5 to 0.5 as \( p_t \approx 6 \text{ GeV}/c \) grows. Jets from pions are emitted more forward since their constituents take a larger momentum fraction. The density of opposite spectator fragments (all with \( p_t \approx 100 \text{ MeV}/c \)) decreases with growing transverse momentum of the trigger jet.

(3) Whenever triggering on a large \( p_t \) particle one is likely to select a particular and rare configuration; the characteristics of the towards-jet are severely distorted and the production cross section is greatly reduced.

The high-\( p_t \) event structure is compared to a normal inelastic event via the ratio \( \frac{dN_t}{dN_i} \). \( dN_t \) is the average number of particles per event emitted in some phase space direction \( \hat{p} \) in a high-\( p_t \) or normal inelastic event. One notices:
(a) around the trigger direction the ratio enhances,
(b) in the opposite direction the enhancement is even stronger and broader,
(c) at fixed azimuthal angle \( \phi \) the ratio decreases with growing \( p_t \), a sizable value of the ratio is limited to \( |\phi| < 1 \) near the towards (away-) direction,
(d) the large ratio on the away-side is due to a substantially higher overall multiplicity which follows from the trigger-bias effect.

Most of the jet momentum is absorbed by a single particle with less than 10% left to the accompanying secondaries. The associated momentum, originating to a large fraction 25-50% from prominent resonances, grows moderately with increasing \( p_t \).

The number of negative (positive) associates is bigger in a towards-side jet, triggered by a \( \pi^- \), than \( \pi^+ \) (\( \pi^+ \) than \( \pi^- \)). This compensation becomes more pronounced as the transverse momentum of the associates increases, with little dependence, however, on the \( p_t \) of the trigger pion. The charge compensation effect for the away-side secondaries is smaller and tends to die away as their transverse momentum increases.

There is essentially no correlation between the charge of the high-\( p_t \) trigger particle and the charge of the highest \( p_t \) particle on the away-side.
Within the away-side system itself one finds strong charge compensation similar to the towards-side system. The charge correlations for the trigger particles $K^+, p_T$ are similar.

The particle ratios $p/\pi^+, \bar{p}/\pi^-$, $K^+/\pi^-$ rise with increasing $x_t$ and fall off again beyond 0.2, the ratio $K^+/\pi^+$ however levels off. The large-$p_t$ $\pi^+/\pi^-$ ratio is practically $p_t$ independent in $K^- p$ collisions and seems to rule out the CIM mechanism. It increases in $pp$- (remains $\sim 1$ in $p\bar{p}$) collisions as expected from hard scattering models.

(4) The simultaneous production of two wide-angle jets, preferably in an azimuthal back-to-back configuration, was experimentally verified. The (away-side) particle density reveals a characteristic maximum around the rapidity $y$ of the away-side trigger, where $y$ determines its angle with respect to the beam axis. The momentum component out of the trigger plane gives a clue on the primordial $k_t$ and on the non-planer gluons. Perturbative QCD predicts $\langle p_{out} \rangle$ to increase with $p_t$ and $z$ which is observed for the unbiased away-jet. The transverse momentum imbalance between the two wide angle jets is roughly gaussian with a width of about 2.4 GeV. The production of symmetric pion pairs is considered to be a clean test of perturbative QCD, and the data are in good agreement with the predictions.

(5) The inclusive $\pi^\pm$ distribution at $90^\circ$ and $p_t \lesssim 6$ GeV/c is proportional to $p_t^{-n}(1-x_t)^m$ with $n=8, m=10.6$. As $p_t$ further increases, the $p_t$ exponent approaches $n \approx 4$ at larger $x_t$ (>$0.1$), the value predicted by the counting rules. Measurements at angles off the central region reveal "radial scaling". The angular dependence is accounted for by replacing $x_t$ by $x_R = (x_t^2 + x_L^2)^{1/2}$. Data in the lower $p_t$-range indicate for the inclusive production of $\pi^\pm$, $\bar{p}$ $n=8$, and for $p$ $n=12$.

(6) Some of the experimental results are not fully understood. The observed proton yield is an order of magnitude above QCD estimates. The $z$-distribution of the away-side $p^0$'s, triggered by a large-$p_t$ $p^0$, shows a departure from the exponential shape at low $z$ values. The
intrinsic transverse momentum of the colliding partons makes the observed \( p_t \) dependence steeper; phenomenological analyses hint at a value of 1 GeV/c which is far above the primordial transverse momentum as determined in other processes.

### 3.3 Theory Analyses

The production of large-\( p_t \) hadrons/jets is calculated in the framework of perturbative QCD. The hard-scattering process is described by the parton cross section using QCD Feynman-rules. Gluon gauge invariance is in the Feynman gauge maintained via the ghost graphs; the axial gauge, as an alternative, leads to more complicated intermediate expressions. The soft-gluon radiation causes via its renormalization group summation the scale dependence in the momentum distributions and gives rise to the running coupling constant in front of the parton cross sections. Nearly all phenomenological analyses use the leading-log parametrizations from deep-inelastic scattering where their normalization is fixed.

Present large-\( p_t \) phenomenology (in the ISR energy range) is to a large extent based on the gg and gg initiated order-\( \alpha_s^2 \) graphs whereby the gluon initiated processes contribute a significant fraction. Asymptotically each subprocess scales as \( p_t^{-4} \). For \( p_t \lesssim 3 \text{ GeV/c} \) the single particle cross section however falls off faster due to the scale dependence in the running coupling constant and in the momentum distributions. For \( p_t \gtrsim 3 \text{ GeV/c} \) the dominant subprocess is \( qg \) scattering with non-negligible \( gg \) and \( gg \) contributions. In the intermediate \( p_t \)-region the \( gg \) and \( gg \) contributions are responsible for the correct cross section size and fall-off; whereas at large \( p_t \)-values \( gg \)-scattering becomes predominant. The subprocess \( gq \rightarrow qg \), \( gq \rightarrow qg \) can for all \( p_t \)-values ignored. For \( p_t \gtrsim 4.5 \text{ GeV/c} \) the data are well described whereas for smaller \( p_t \)-values the predictions are too low.

In the above simple picture there are several particularities which we now consider:

1. The freedom to choose the dynamical expansion variable \( s^2 = t \) or \( 2 s t (s^2 + 2 s t + t^2) \), following from the ambiguity in mass factorization, influences the cross section size. \( s, t, u \) are the Mandelstam variables.
of the 2 \rightarrow 2 subprocesses. The second choice leads to smaller \( q^2 \) and a larger cross section (24e).

(2) The introduction of an intrinsic transverse momentum ("\( k_t \)-smearing") lifts the cross section substantially in the \( p_t \gtrsim 4 \text{ GeV/c} \) region and generates a steeper decrease. Fits with values \( \langle k_t \rangle \sim 1 \text{ GeV/c} \), larger than expected from other reactions, lead to qualitative agreement with the data. This procedure is theoretically motivated by the partons intrinsic transverse momentum due to their Fermi motion, and by their "effective \( k_t \)" from the Bremsstrahlung of gluons; the evaluation of the 2 \rightarrow 3 subprocesses will partially account for the latter reason. It should however be clearly realized that "\( k_t \)-smearing" serves as a cut-off for the mass and/or infrared singular parton cross sections, and the problems in the description of the low-p_\text{t} region still exist. The correct inclusion of primordial \( \langle k_t \rangle \) is unknown and different prescriptions for smearing lead to quite different results (27).

The inclusive cross section thus decreases as \( p_t^{-3} \) for \( p_t \lesssim 6 \text{ GeV/c} \), goes over to \( p_t^{-6} \) (the naive \( p_t^{-4} \) of qq-scattering plus the scale dependent \( \alpha_s^2(\mu^2) \) and \( u(x, Q^2) \)) in the intermediate region, and reaches \( p_t^{-4} \) at large \( p_t \)-values.

(3) Higher-twist mechanisms, contributing to each parton subprocess \( p_t^{-3}, p_t^{-6} \ldots \) terms (apart from the leading \( p_t^{-4} \)), might be another source of the theory-data discrepancy below \( p_t \lesssim 6 \text{ GeV/c} \). The constituent-interchange-model (CIM) (26a) ranges in this class of terms. Partons do not scatter point-like; pairs of quarks and/or gluons from a given hadron instead may jointly participate in a coherent manner in the hard-scattering process. Their influence in large-\( p_t \) reactions, in particular \( NN \rightarrow WX \), has been estimated via the subprocesses \( qg \rightarrow Xg \) and \( \bar{q} \rightarrow Xg \) which are the only 2 \rightarrow 2 processes giving \( p_t^{-6} \) contributions to the cross section. The absolute normalization is fixed by the pion weak decay constant, or in terms of the pion electromagnetic form factor at large \( q^2 \). The higher-twist cross section decreases less rapidly as \( x_t \rightarrow 1 \) and there is no trigger-bias suppression since the final X is produced without the necessity of jet fragmentation. They scale as \( s^{-1} \) and they
are qualitatively important for $p_t < 6 \text{ GeV/c}$ and $x_{V0} > 0.5$. At $\sqrt{s} = 10 \text{ GeV}$ the $q\bar{q}$ initiated contribution is roughly an order of magnitude more important than the analogous $qg$ subprocess. An overall correction to the inclusive cross section of at least $30\%$ is expected which grows with increasing $x_t$ and even dominates above $x_t > 0.65$. In $\pi^- N \rightarrow \pi^- N$ the higher-twist effects cause a charge-ratio substantially above unity. Spin–spin asymmetries in $p(\uparrow) p(\downarrow) \rightarrow \pi^- X$ might offer another possibility for their detection.

The search for high-twist effects lead recently to a special class of high-$p_t$ events which might allow for the isolation of a clean high-twist signal. The entire energy of an incident meson is delivered into production of a pair of large-$p_t$ jets at wide angle excluding any final state particles along the beam axis. At $\sqrt{s} = 20 \text{ GeV}$ the predictions account for $3-5\%$ of the reported inclusive jet yield. The veto, excluding particles along the beam direction, and the simple two-body kinematics simplify the goal.

(4) The existence of the Yang–Mills three-gluon vertex has been demonstrated through its dominance in the order $\alpha_s^3$ $g^3 \rightarrow g^2$ subprocess (fig.1). The single-particle cross section for $pp \rightarrow \pi^+ X$ was measured at $\sqrt{s} = 52 \text{ GeV}$. The significance of the $g^2$ subprocess as compared to simple $qg$-scattering is inferred from the charge ratios in the away-side jet and between the target and beam spectator jets accompanying the high-$p_t$ ($p_t > 2.5 \text{ GeV/c}$) trigger in the forward direction ($\phi > 20^\circ$). The ratio of the $g^2$ to $qg$ contributions is at the above conditions predicted by QCD to be $R = \frac{1}{2}$, in qualitative agreement with the experimental observation $R > 1$. The omission of the triple-gluon vertex (fig.1c) changes the $g^2$ contribution by more than an order of magnitude, leaving $R \approx 0.1$. Different choices of the moment and fragmentation distributions cannot change this insight.

(5) The leading-log phenomenology of the single particle inclusive processes assumes that the next-to-leading corrections from $\alpha_s^3$ expansion of the coefficient function are small. Their analysis needs consideration of all order-$\alpha_s$ QCD graphs with real as well as virtual gluon lines, and the resulting parton cross sections must
be evaluated up to the constant terms. The ultra-violet divergences are renormalized, and all infrared divergences are cancelled between the real- and virtual-glue graphs. The remaining mass singularities are via mass factorization absorbed in the momentum and fragmentation distributions. The resulting \( q_s \) correction term of the coefficient function has been determined for aa-scattering and was found to be large. In the present \( Q^2 \) range the non-leading corrections therefore are large and the leading-log approximation is without theoretical foundation.

\( q_s = 10 \text{ GeV} \)

In the present Cl-range the non-leading corrections therefore are large and the leading-log approximation is without theoretical foundation.

Might be this problem will disappear once the bound state nature of the quarks is taken into account. The analogous ag- and gg-parts, which are of prime importance at collider energies, are still missing. We point here also to the problems arising from the non-cancellation of the higher order QCD infrared divergences.

(6) The two-particle inclusive cross section allows for correlation studies. QCD calculations at \( p_t = 4 \text{ GeV/c} \), \( s = 53 \text{ GeV} \) reveal the following percentage for the trigger-recoil constituents: qa (27%), qa (25%), aa (11%), gg (17%). The trigger constituent is therefore mostly a quark (72%) and the recoil constituent is quite often a glue (62%). The away-side gluons produce equal number of positive and negative hadrons. Little variation of the away-side hadron multiplicity with growing trigger transverse momentum should occur.

The measurement of back-to-back large-p events disposes to a large extent of the \( k_t \)-smearing effects. Keeping the transverse momentum ratio \( z_p = p_t(aw)/p_t(tr) \) fixed (\( \sim 1 \)), the two-particle inclusive cross section increases smoothly with growing trigger transverse momentum. The \( k_t \)-smearing effects, strongly felt in the single-particle inclusive cross section at low-\( p_t \), do not influence its shape since the trigger bias, favoring the initial quarks moving towards the trigger, is removed. Thus, two-particle back-to-back cross sections reflect more closely the \( p_t \)-dependence of the basic subprocesses without the additional scale-breaking due to \( k_t \)-smearing.

The \( k_t \)-smearing also results in a momentum component \( P_{out} \) of the away-side constituent out of the trigger plane. \( P_{out} \) however is too
low and the discrepancy may be due to the $2 \Rightarrow 3$ constituent processes contributing to a large $P_{\text{out}}$-tail which at higher energies is more pronounced.

The experimental tests confirm these insights.

(7) Analysis of the three-jet processes based on the $2 \Rightarrow 3$ parton cross sections (with radiative gluon graphs only) are fruitful as long as the distributions differential in all three-jet momenta are considered. However, there are infrared singularities which in the kinematical region of their dominance must be cancelled by the virtual-gluon graphs, and there are mass singularities whose dominance signals the onset of confinement effects. In all $2 \Rightarrow 2$ versus $2 \Rightarrow 3$ comparisons their predominance is prevented by cuts on the angle and energy-fraction $(\theta, \epsilon)$ of the Sterman-Weinberg jets and/or by restricting the kinematical variables, such as for instance three-jet events in the transverse plane only.

With these uncertainties in mind we summarize the main insights from QCD three-jet analyses:

(i) With $\epsilon \approx 0.2$, $\theta \approx 0.25$ and $p_{t \text{(tr)} \geq 2.5 \text{ GeV}}$ one finds $\sigma(3j)/\sigma(2j) \sim 20-10^3$ for the $qg, gg$ and $gg$ initiated parton cross sections. The $gg \Rightarrow 3j$ processes instead are much larger than the corresponding $gg \Rightarrow 2j$ contributions. There is no qualitative change at higher energies if $x_g$ and the cut-off parameters are kept fixed.

(ii) The hadron initiated 3-jet as compared to the 2-jet cross section can by suitable cuts be enhanced or suppressed. Cuts on the transverse energy and azimuthal cause a suppression factor $3-10$, in addition to (i) above. A small $p_t$-cut (> 2 GeV/c) at fixed transverse energy ($E_t \approx 10$ GeV) however enhances the relative importance of the 3-jet events. Hard gluon emission is estimated to contribute a $\sim 20\%$ correction to the lowest order large-$p_t$ cross sections. At ISR energies the main contributions come from the $qg, qg \Rightarrow qgg$ subprocesses, whereas at collider energies $gg \Rightarrow gg$ will dominate.
(iii) The transverse thrust distribution offers in the ISR energy range little hope to find signatures of 3-jet events. At collider energies however, the gaussian tail of the smeared 2-jet contributions is 1-2 orders of magnitude below the significant 3-jet tail which essentially results from the $qg \rightarrow qgg$ subprocess and its anti-part [37](fig.2).

The $p_T^\perp$-distribution of $H^0 - p_T^\perp$ correlations cannot be explained by the smeared 2-jet contributions whereas the 3-jet curve, after smearing has been applied, can fit the data [28a](fig.3).

(iv) A detailed comparison of different $2 \rightarrow 3$ parton processes in the transverse plane reveals: three-jet events depend strongly on the particular production process. Process-dependent variations make the predictions based on "jet-universality" questionable, in particular so in the small-thrust region. The considerable variations with changing jet angular radii signal large differences in the jet-widths of quarks and gluons. Perturbative three-jet configurations are typically 2-4 times more important in hadronic production than in $e^+e^-$ annihilation. Jets from high-$p_T$ hadronic processes are considerably broader than those from $e^+e^-$ annihilation at the same energy, and sharply defined jet structures will be much less evident.

Thus, measurable jet properties can be largely process dependent leading to doubts on the concept of universal quark and gluon jets [37b].

3.4 Jets at the Collider

The inclusive $H^0$ spectrum as measured at the ISR is shown in fig.4. The cross section is several orders of magnitude above the naive extrapolation of the exponential shape seen in the small-$p_T$ region. Nevertheless, large-$p_T$ particles are rare. Roughly one $H^0$ at $p_T = 5 \text{ GeV/c}$ is seen in $10^7$ interactions in a $p_T$-bin of 1 GeV and per steradian. The jet-rate exceeds the single-particle rate by 2-3 orders of magnitude (see fig.5), but it is still small. Furthermore any jet trigger has to face considerable difficulties. Multiplicity fluctuations into the solid angle of the jet calorimeter may by far outnumber the "true" jets [38].
The situation at the $\bar{p}p$ collider may be drastically different. If the gluons continue to share $50\%$ of the momentum fraction, and if their distribution is proportional to $\sim (1-x)^5$, then their scattering will give rise to a large jet rate. A cross section of $\sim 2$ mb is expected for gluon jets of $p_t = 5-10$ GeV/c. No fancy jet trigger would be needed anymore since a large fraction of the events contains two $5-10$ GeV/c jets attached to the usual longitudinal phase space cigar. The inclusive jet yield at high transverse momenta is presented in fig.6. Assuming the luminosity $L = 10^{23}$ cm$^{-2}$ s$^{-1}$, one may expect about 250 jets/hour with $p_t(jet) \geq 20$ GeV/c.

The medium and large $p_t$ physics may be accessible in the very early phases of collider experimentation. An event with jets of 20 GeV/c, however, does not come for free: among $10^4$ minimum-bias events only 1 is expected. A calorimeter trigger is therefore needed. On the contrary, jets of 5-10 GeV/c are expected to be abundant.

The significant size of the jet yields at low $x_g$ ($< 0.25$, at 90$^\circ$) follows from the steep rise of the gluon momentum distribution. At $\sqrt{s} = 540$ GeV and $p_g = 7$ GeV/c the percentage of the different quark-gluon processes is estimated as: $qg \rightarrow q (2\%), qg \rightarrow g (8\%), qg \rightarrow g (13\%), qg \rightarrow q (25\%)$, $gg \rightarrow q (3\%)$, $gg \rightarrow g (45\%)$. The numbers vary for different gluon momentum distributions. The inclusive jet yields follow the ordering $g\rightarrow u\bar{d}d\bar{u}$ sea, with $61\%$ (15%) from gluons (quarks). The subprocesses are preferentially initiated by $gg$ (43%) and by $gq$ (41%) scattering. As $p_t$ grows the gluon-jet yields maintain their leading role up to rather large $x_g$-values ($x_g < 0.3$). Gluon jets are therefore expected to dominate over the full $p_t$-range covered by the collider at the luminosity of $L = 10^{20}$ cm$^{-2}$ s$^{-1}$.

Whilast looking at the $y$-distribution at fixed $p_t$ we vary the c.m. angle, since $y = -\ln(\tan \frac{\theta}{2})$. Over the wide angle region $|\Delta y| = 1$ gluon jets dominate. At forward angles ($\sim 60^\circ$) the valence quark jets are more likely with $u\bar{d}g\bar{d}\bar{u}$ sea, whereas at backward angles ($\sim 150^\circ$) the valence anti-quark jets $\bar{u}\bar{q}\bar{d}g\bar{d}$ sea take over. The angle $\theta$ is chosen with respect to the proton beam.
If quark and gluon jets are indeed produced as predicted by QCD, correlation measurements can provide detailed information about the underlying hard scattering processes. Using $p_T^*$ for instance as the trigger particle (around 90°) favors a u-jet. The away-jet in the forward region ($\sim 30-60°$) will originate from a gluon almost as frequent as from a u-quark at wide angles ($\sim 60-120°$), however, gluon jets will dominate. Choosing instead the trigger particle in the forward cone ($\lesssim 30°$) favors in the opposite wide (small) angle region the production of quark (gluon) jets. The initial and final partons in such collisions are (almost) the same since the $gg$ initiated processes are negligible. Since the $P_{out}$-distributions are broader for gluons than quarks one expects to see such broadening effect whilst passing from the wide to the small angle region 40).

Since large $p_T$ values can be reached, the QCD scaling violation effects are expected to be more pronounced in both the structure and the fragmentation functions. They dampen the single particle $p_T$ distributions by a factor 0.1-0.2 at the highest possible $p_T$ values.

The large amount of gluons initiating the large-$p_T$ reactions has three essential consequences: (a) excessive gluon processes in the low $x$ region, (b) likely production of glueballs, (c) heavy flavor creation in bound and unbound form. In the following we expand on (c) and (b).

### 3.5 Gluon Processes

In the lower $x_T$ region most of the subprocesses are initiated by gluons. Two aspects are of particular interest: the gluon momentum distribution and the interaction among gluons only.

The gluon momentum distribution can not be directly measured. Gravitons have been suggested as a probe in Gedanken experiments 41). Apart from the fact that $\sim 50\%$ of the nucleon momentum is carried by gluons there is little solid information. The measurement of the jet cross sections, in the $p_T$ region where the gluon initiated subprocesses dominate, will hopefully give more insight. Several theoretical models have been
suggested to describe the $x$-dependence of the gluon momentum distribution. The counting rule parametrization is in the $x \rightarrow 1$ limit fixed by the number of constituents left behind in the nucleon $^{30}$, and for $x \rightarrow 0$ it is related to a Pomeron dominated Regge parametrization, giving $xG(x) = 3 (1-x)^5$. The bremsstrahlung model follows from a convolution over the $q,g$ "irreducible" distributions, and the resulting parametrization is composed of several $(1-x)$ powers. Finally, the bag-bremsstrahlung model follows from a counting rule plus a bag-type parametrization, the latter with an exponential $x$-dependence $^{19a}$. The low-$x$ increase is strongest for the "bag", and relatively flat for the "bremsstrahlung" parametrization; the naive counting rule form lies in between.

However, these attempts are of limited value in the low momentum region. It will be necessary to extend the QCD calculations by including realistic bound state wave function and final state interaction effects. The influences of the coherence cancellations and of the hadron size have been analysed $^{24}$. An explicit dependence on the number of valence quarks was found. The coherence effects in the color singlet bound state eliminate the quark mass singularity. Such color cancellations are important for all $x$-values unless the gluon transverse momentum, as compared to the inverse hadron size, is large.

The $x$-dependence of the gluon distribution follows the qualitative rule: softer than the valence quark distributions, but harder than the sea-antiquark distributions. This wisdom was recently put to doubt by a new phenomenological analysis $^{24d}$ of the deep-inelastic data where the (so far ignored) charm threshold effects were taken into account. A very broad (i.e. hard) gluon input distribution emerged, similar to the one proposed in ref. $24e$. After the asymptotic freedom corrections have been applied, the familiar steep increase towards low $x$-values is, at the considered $Q^2$-values, seen again.

The gluon fragmentation function is even less known, and countingrule parametrizations are usually employed $^{42}$. 

...
Strong evidence for the existence of multi-gluon couplings has emerged from ISR large-\( p_T \) measurements since the three-gluon vertex in gg scattering dominates at large subenergies. Medium energy jets at the collider will predominantly originate from gg and qg collisions. Further tests on gluon self-interactions, with subprocesses as gg \( \rightarrow (n g) \), are therefore likely to become possible and to give more insight into the color octet dynamics of non-abelian gauge theories. Interesting theoretical aspects are: the vanishing of gluons of non-planer graphs, the (non-) cancellation of the infrared singularities, the influence of the asymptotic freedom corrections, the 'gluon-splitting,' the transition from the perturbative to the confinement region is marked by a phase transition whose characteristics are studied in lattice calculations, and in statistical models.

Due to the three- and four-gluon couplings, one expects cascades of gluons in the \( gg \) initiated subprocesses which generate a swarm of relatively slow moving hadrons with overall flavor-neutrality. The multiplicity of such events is anticipated to grow significantly with increasing energy reaching much higher values than for quark-jets. The particle ratios \( \pi^+/\pi^- \), \( K^+/K^- \), \( p/p \) should approach unity in the region where gluons dominate.

### 2.6 Glueballs

At short distances QCD involves color-octet spin-1 gluons which at large distances are expected to form color singlet composites, called glueballs. The detailed mechanism is unknown but a number of model calculations have given hints at their properties. The simplest bound states consist of 2 or 3 gluons. A pair of color-electric (or -magnetic) fields might bind to \( J^P = 0^+, 2^+ \) states, whereas color-electric and -magnetic gluons could form \( 0^-, 1^+, 2^- \) states. A rich spectrum of excited states is expected which decays into low mass hadrons via qq creation. There are several unknown aspects:

(a) Spectrum: Glueball masses have been estimated by several methods: field theory analyses, MIT bag models, potential models with massive spin-1 'lumps of gluons,' a relativistic wave equation with
a QCD motivated potential, lattice calculations, connection with the F-trajectory, phenomenology of OZI-rule violation, and partial wave analysis of the gg-channel. These calculations indicate the glueball mass spectrum in the 1-2 GeV range.

(b) Decays: The decay modes of the glueballs depend on their masses. Decays into the known low-mass hadrons and their excited states should occur without suppression of the strange quark states. Examples of two-body decays are: \( \pi \pi, K\bar{K}, \eta \phi, \eta' \rho, \eta' \phi, \eta_2, \zeta \), etc.

Phase-shift analyses for the \( \pi \pi \) and \( \eta \eta \) channels might reveal the \( J^{PC} = 0^{++}, 2^{++} \) low-lying states, whereas the \( 0^{--} \) has the \( \eta' \) quantum numbers and could mix. Many of the states have the \( \eta \), \( \pi \eta \), \( \phi \eta \) decay channels open which offers little hope for a significant signal.

(c) Widths: Glueball widths are either geometrically interpolating between the OZI-rule allowed and suppressed hadronic decays: \( \Gamma_0 \sim 10 \text{ MeV} \), or, since we are primarily dealing with a confinement problem, they could be \( \sim 1/3 \) of the typical hadronic widths: \( \Gamma_0 \sim 50 \text{ MeV} \).

Specific predictions thus become assumption dependent.

(d) Production: \( \gamma \)-initiated glueball production at the collider may be of significant size. Phenomenological analyses are, however, missing. Since large-\( p_T \) glue jets occur abundantly, it may be a promising place to look for glueballs in a specific jet decay mode. The missing mass system of inclusive \( \phi \) or \( \Upsilon \) production in e+e− annihilation or electroproduction could be another source. The \( \phi \) and \( \Upsilon \) radiative decays are expected to reveal such states in the \( E_{\gamma} \) spectrum as a measure of the invariant mass. The appearance of the \( K^0 \bar{K}^0 \) enhancement at 1440 MeV in the invariant mass spectrum of \( \Upsilon \rightarrow \gamma \chi \) has recently raised the question whether it could be interpreted as a glueball.

4. Low-\( p_T \) Decays

The glueball decays that are present at low-\( p_T \) are hadron decays. Regge theory gives that the low-\( p_T \) behavior should be described by the Pomeron, with the \( t \) dependence.

4.1 Phenomenology

There is evidence for a Regge trajectory, \( T^* \), about the \( p_T \) = 0 limit. The p+p limit for \( T^* \) at \( m_T \) = 1 should merge. There are forwardbackward asymmetries, and there may be several different types of \( T^* \) production.

The existence of the glueball, or a glueball, is also a consequence of a strong epsilon term perturbation theory. This perturbation theory to Regge theory is called the strong epsilon term. This is an important new aspect of the theory of color confinement. The Pomeron, as described by the \( t \) dependence of the cross-section, is not the total cross-section, pp ene...
4. Low-\(p_t\) Physics

The expectations for the total and elastic differential cross sections are presented and the attempts at an understanding of inclusive soft-hadron production covered. There are essentially two frameworks: Mueller-Regge theory \(^{60}\) and parton model \(^{61}\). Although the description of the low-\(p_t\) phenomena in the framework of perturbative QCD is lacking solid foundation there is considerable phenomenological progress.

4.1 Total and Elastic Cross Sections

Measurements of \(\sigma_\text{tot}^\gamma\) and \(Q = (\text{Re} \, A(0)/\text{Im} \, A(0))\) will decide about the dispersion analysis ln's-increase \(^{54}\) and the common pp and \(p\bar{p}\) limit. Similarly the elastic differential cross sections should merge. Will the low-\(\ln\) slope and dip-bump structure, moving as the forward peak shrinks, still obey geometrical scaling \(^{55}\)? Or will there be several dips as predicted by the factorizable eikonal model \(^{66}\)? One wonders about the proton shape as measured by the opacity and total/elastic cross section ratio \(^{53}\).

The consequences of a Pomeron viewed as an infinity of perturbative soft-gluon exchanges have been analyzed in (cut-off regularized) perturbative QCD \(^{57}\). In the asymptotic Regge-limit strong similarities to Reggeon-field-theory \(^{69}\) emerged which leads one to wonder whether this latter theory could perhaps provide information on the confinement aspect of QCD; for a layout of this program we refer to ref.\(^{67}\). QCD with color \(SU_3\) and 16 flavors—both necessary conditions for the critical Pomeron—may be the essentially unique theory giving factorization, asymptotically rising cross sections and equal particle-antiparticle differential cross sections. The scaling functions and critical exponents of the critical Pomeron are exactly calculable whereas the size of the non-leading terms is estimated with present-day data. The total and elastic differential cross sections, extrapolated into the \(p\bar{p}\) energy range \(^{68b}\), might eventually provide tests for this scheme.
In phenomenological investigations the Pomeron is approximated by two-gluon exchange (Low-Nussinov model \(^{69}\)), with the higher order gluon exchanges assumed to cancel out \(^{70}\). The exchanged gluons can interact with each of the two/three hadron-quarks giving rise to negative coherent besides of the incoherent contributions \(^{71}\) (fig. 7a). Immediate consequences of this picture are: multiparticle production follows from the separation of color and the consequent gluon radiation, zero flavor but color quantum number exchange, interference effects cancel infrared divergences, a constant or logarithmically increasing total cross section due to the vector nature of gluons, generalized quark counting, sensitivity on the size of the colliding bound states with a dependence on the (heavy) quark masses. The total cross section size is achieved at the expense of \(\alpha_s \approx 2\) \(^{67}\), and the non-perturbative effects are mostly ignored. The above insight were derived from simple model calculations based on gluon radiation \(^{72,71}\). Their extension to diffractive excitation \(^{73a,b}\) predicts a far bigger cross section and mean \(\langle p_\perp^2 \rangle\) if compared with traditional approaches \(^{73c}\).

### 4.2 Inclusive Soft-Hadron Production

The stability of the longitudinal phase space and the logarithmic increase of the average multiplicity, as predicted by Mueller-Regge theory \(^{74}\), are here of foremost interest. Could the rapid development of the central rapidity plateau and its increase with energy signal a new phenomenon (see section 2.1) and will the \(p_\perp\) distribution still be damped? Correlation measurements, giving insight into the process of cluster formation and fragmentation, are not expected to change drastically, and similarly -still based on ISR experience- particle ratios should vary little \(^3\).

The data of the single particle inclusive cross sections \(^{75}\) are in the fragmentation region parametrized as \(x_p (d\sigma/dx_p) = C (1-x_p)^n\).

\(x_p (= 2p_L/\sqrt{s})\) is the Feynman scaling variable and the exponent \(n\) changes for different processes, e.g. \(n(p\rightarrow K^+) \approx 3\), \(n(p\rightarrow \pi^-) \approx 4\), \(n(p\rightarrow K^+) \approx 2.5\).
Three characteristic observations emerge: (i) the fragmentation domain depends on the quantum numbers of the fragmenting and the produced hadrons but the momentum shape in the central region is quantum number independent; the cross section size can be understood from quark statistics, (ii) pion production in the nucleon fragmentation region reflects the valence quark distribution in the nucleon, (iii) the longitudinal, transverse and multiplicity behaviour of the produced hadrons are similar to the e^+e^- and deep-inelastic jets from quark fragmentation.

Whilst exposing the existing models, we first discuss the central and subsequently focus on the fragmentation region. Multiparticle production in QCD is presumed to occur as a result of color separation. After the (Low-Mussinov) two-gluon exchange has taken place the octet 'mesons' radiate gluons which in turn create qq pairs and/or multi-gluons; soft-gluons from the exchanged gluons can also occur (fig.7c). Ultimately these radiation products form through non-perturbative means the final state hadrons. Exactly how much radiation or particle production takes place and how the radiated particles are distributed is controlled by the relative momentum of the colored partons leaving the gluon-exchange process. Model calculations for hadron and e^+e^- initiated processes indicate characteristic asymptotic features: for transverse momenta q_t small as compared to the typical bound state momentum ε, the rapidity distribution dN/dy dη of the emitted gluon is uniform with a q_t^{-2} decrease as in e^+e^- annihilation. The difference in color-charge of the radiating octet jets results in a factor 9/4 larger hadron plateau than in e^+e^- annihilation. At large q_t there is a q_t^{-4} decrease due to the cancellations among the full gauge invariant set of hadronic subprocesses. The q_t^{-2}-tail in e^+e^- annihilation causes a logarithmically rising central rapidity plateau dh/dη with growing c.m. energy, whereas the central gluon plateau in hadronic collisions does not increase (in this order of perturbation theory). The hadron/ e^+e^- ratio thus decreases, with estimated values ~ 1.0 (~ 0.6) for \sqrt{s} = 18 (30) GeV. The fall-off at larger p_t-values is essentially responsible for the energy dependence of the central.
plateau. If \((q_t)^{\text{max}} \sim f \sqrt{s}\) the \(q_t^2\)-tail generates a logarithmic rise. Viewing particle production as \(^\text{color separation, stretched flux tubes, q\bar{q} creation,}\) the plateau height is anticipated to depend exclusively on the available energy of the separating color system. Such function, as well as the fraction \(f\), are expected to be independent of the particular physical process causing the color separation. As a result the "radiation" and resulting multiplicity are exclusively determined by the color structure and the available final-state c.m. energy. If \(q_t < \ell_t\) the competing contributions to \(dN/dy\) can cause a dip near \(y=0\), which is absent in \(e^+e^-\) annihilation. The hadron size influences \((\text{via } \ell_t)\) the plateau height, smaller hadrons give rise to a higher plateau. QED-like gluon radiation from separating color charges predicts the charge multiplicity to increase as a second order polynomial in \(\ln s\) \(^{76a}\) or even stronger \(^{76b}\).

At sufficiently high energies low-\(p_t\) collisions can generate partons with large invariant masses where perturbative QCD again applies. Assuming independent and coherent quark-quark scattering with a fixed momentum transfer \(\Delta \sim 1\text{ GeV}\) the main features (additional to the above) of such processes are \(^{77}\): the low-\(p_t\) hadronic system arises from two components, the "spectators" with fixed transverse spread, and the "struck" quarks (with \(\sqrt{p_t^2} \sim 10\text{ GeV}\)) giving rise to progressively broader hadron jets (similar to \(e^+e^-\)-jets), possibly of a forked structure. The \(\langle p_t^2 \rangle\) is thus expected to rise by a factor \(\sim 2\) as we go to collider energies and the longitudinal momentum distributions should soften with a possible violation of Feynman scaling. Gluon radiation from the incoming quarks causes a reduced invariant mass of the "struck" quarks and hence smaller \(\langle p_t^2 \rangle\) and \(\langle n \rangle\) than for events due to valence quark scattering.

The dual-topological-unitarization (DTU) approach \(^{78}\) to multiparticle production assumes that during hadron collision tube-like color-singlet systems are created consisting of 3 and \(\bar{3}\) color charge at the two ends. Their moving in opposite directions stretches the connecting gluon flux lines to rise. hadron production, treating the process as we perturb over the \(x_1\) and \(x_2\) distributions of the hadrons in the event. The tube-like model predicts a rise as a second order polynomial in \(\ln s\) \(^{76a}\) or \(^{76b}\).

In an event, the central \(3/2\) states at the center of the event are in valence quarks to a particle may be a singlet of the mean flux
lines, resulting in hadron production. Since in each colliding hadron there are minimal two quarks one may expect two (or more) such processes simultaneously to occur. The proton in these calculations is treated as a $3(q)$ and $\bar{3}(qq)$ system, the latter carrying most of its parent-hadron momentum. Practical calculations involve convolutions over the joint probability that the two-quark system takes fractions $x_1$ and $x_2$ of the incident momenta and over the $e^+e^-$ fragmentation functions. The Pomeron thus arises through unitarity as a reflection of two non-interfering "chains" of particles each with its own rapidity spectrum as found in $e^+e^-$ annihilation (at the corresponding energy). The two spectra can be different in shape and mutually displaced, and the central plateau region can consequently arise from different scenarios.

At present energies the heights follow: $(pp) < (\bar{p}p) < (\bar{p}p)$ where $(h_1, h_2)$ indicates the two hadrons initiating the single particle soft-inclusive process. $(pp)$ is the sum of heights of two shoulders while $(\bar{p}p)$ is the sum of two central maxima, the $(\bar{p}p)$ case, of $(pp)$ and $(\bar{p}p)$ type, falls in between (fig. 8 a, b). Further characteristics are: no spin-1 and color exchange and no dependence on the size of the initial hadrons; quark counting applies, at higher energies appearance of a rapidly rising bump in $(pp)$ near $y=0$, the hadronic central plateau heights eventually reach similar values about twice the $e^+e^-$ plateau (at the appropriately reduced energy). The partonic three-chain mechanism (fig. 8c) involving $(q, \bar{q})$ chains only (as opposed to $(qq, \bar{qq})$ and $(q, \bar{q})$ chains for the Pomeron) leads to a spectacular increase of the $pp$ central multiplicity height which at asymptotic energies lies a factor $\frac{3}{2}$ above the Pomeron expectations.

In the valon-recombination model, multi-hadron production in the central region is due to the glue and sea of the colliding hadrons. The valence quarks, on the contrary, will recombine with a parton from the sea to reproduce a hadron at large $x$. Since the sea parton has very small $x$, the momentum of the final state hadron will essentially be the same as that of the valence quark. In the further development of this model a distinction between the constituent quark ("valon") and the current quark ("quark") is made with a valon momentum distribution in the
nucleon $G_{v/p}(x)$ and a quark momentum distribution in the valon $F_{v}(x)$ constructed such that their convolution reproduces the deep-inelastic structure functions (fig. 9a). A valon is physically interpreted as a valence-quark plus its associated sea quarks and gluons due to the dressing process in QCD. A low-$p_t$ hadron-hadron collision is then viewed as a multi-stage process: initial hadron (1) → valons (2) → partons (3) → valons (4) → produced hadrons. Stage (4), giving the probability of two (three) valons to recombine into a final state meson (baryon) (fig. 9b), is governed by the recombination function (a joint multi-valon momentum distribution) whose open parameters are fixed by phenomenological analyses. This model describes successfully many single particle inclusive distributions in the fragmentation region and its application on other processes (e.g. quark fragmentation, form factors, pion decay constant) does not signal significant inconsistencies.

In order to understand hadron production in the fragmentation regions a description for quark and diquark fragmentation into hadrons is needed. Point-like QCD fragmentation \(^{72}\) of quarks assumes that $q\bar{q}$-pairs are created out of the vacuum by lowest order quark-gluon diagrams with subsequent two-quark association into mesons. The fragmentation functions follow from folding the perturbative process (motivated by the far off-shell mass of the quarks) with the meson bound state wave function. Simple analyses lead to $dN/dz \sim (1-z)^n$ where $n = 2 n_H + n_p - 1$ is specified by simple counting rules. $n_H$ = number of 'point-like' spectators to the emission and $n_p$ = number of 'hadronic' spectators. The analysis of simple graphs indicates $n=1,2$. This reasoning, extended to diquark fragmentation with higher $n$-values, permits a qualitative understanding of the data. Valon-recombination \(^{80}\) instead operates with QCD evolved valon momentum distributions. Using the rules of the jet calculus \(^{81}\), a two-quark momentum distribution is defined by valon-gluon splitting. The fragmentation function finally follows from a convolution over the two meson-quarks involving the recombination function. As a result $dN/dz \sim (1-z)\bar{s}(p^2)+1$ where $\bar{s}(p^2)$ is the standard evolution parameter in the quark distribution. The abovementioned model is used as a spectator exchange two-parton fragmentation function (fig. 9b), and its application on other processes (e.g. quark fragmentation, meson fragmentation distribution) is governed by the recombination function whose open parameters are fixed by phenomenological analyses. This model describes successfully many single particle inclusive distributions in the fragmentation region, and its application on other processes does not signal significant inconsistencies.
in the AP-corrections depending via the log-log function on the initial quark off-shell mass \( p^2 \); for typical values the exponent is \( \sim 2 \).

The above two methods are distinct. The \((1-z)\) power in the first one is due to the off-shell propagator in the tree-amplitude whereas it results from the convolution in the second one.

We turn to hadronic fragmentation. Three models exist: (a) gluon-exchange with point-like QCD fragmentation \( ^{72} \) is in practical calculations viewed as a two-step process: \( q \) (or \( 2q \)) emission from the fragmenting proton according to the QCD predicted momentum distribution and subsequent QCD bremsstrahlung leading to meson formation. The overall process is therefore a convolution over the probability \( Q(x) \) to find the fragmenting parton system with momentum fraction \( x \) and over its QCD fragmentation function discussed above. Since the fragmentation process is predominant, its counting rule powers appear again in the final result.

(b) DTU hadron formation \( ^{78} \) follows the same rules. The fragmentation function however is parametrized with a \( n = 1 - 2 \alpha(t) \) exponent as predicted by the triple-Regge limit. \( t \) is the squared momentum difference between the fragmenting and the inclusive hadron. (c) Valon-recombination \( ^{80} \) has been discussed earlier.

Significant differences of these approaches in the fragmentation regions are sparse. Definite conclusions about the validity of one or the other approach, which in the end even might merge, is premature. For a comparison of their predictions with the data we refer to recent reviews \( ^{75} \).

5. \( W^\pm \) and \( Z^0 \) Production

One of the main motivations for constructing the pp-collider was the experimental verification of the weak intermediate bosons: \( W^\pm \) and \( Z^0 \). Their discovery permits direct tests of gauge theory models. In the Weinberg-Salam model \( ^{32} \) their masses are uniquely fixed by the Weinberg-angle \( \sin^2 \theta_W = 0.23 \pm 0.015 \) with values: \( m_W = 77.9 \text{ GeV} \) and \( m_Z = 88.8 \text{ GeV} \). The total widths, proportional to \( m_W^3 \) and \( m_Z^3 \), depend on the number of lepton and quark pairs in the theory. Leptonic branching ratios are: \( B(W^\pm \to l^-\nu) \simeq 8\% \) and \( B(Z^0 \to l^-l^+) \simeq 3\% \). The production cross sections (see Table I) \( ^{83} \).
are estimated by the parton model where the scale dependent momentum distributions (in leading-log approximation) are fixed by deep-inelastic lepton-hadron-scattering.

At the "reasonable" luminosity of $L = 10^{29}$ cm$^{-2}$ s$^{-1}$ (which possibly will be reached during the first year) one expects to collect 5-10 events per day of the type $W^+ \rightarrow l^+ \nu$ (fig.10). Due to their weak coupling, the $W^\pm$ are expected to be produced with polarization which causes considerable asymmetry in the lepton spectra in the forward direction (fig.11). About 75% of the $W^\pm$ decay into hadronic channels; (heavy) quark and gluon jets are quite likely. The channel $Z^0 \rightarrow l^+ l^-$ is experimentally cleaner, but an order of magnitude lower in cross section (fig.12). The experimental effort is concentrated on the leptonic decays. They are thought to be the most promising ones with respect to signature and background because QCD jets of large $p_t$ will probably outnumber the quark-jet decays of the weak bosons.

Weak boson production and subsequent decay into leptons is a rare process. About one event of the type $W^\pm \rightarrow l^\pm \nu$ is hidden among $10^8$ normal hadronic events. The rarity is, however, compensated by effective triggering.

The discovery of the $W^\pm$ and $Z^0$ will open the possibility for several interesting investigations. As an example we mention the renormalization group summation of the perturbative QCD corrections. $Z^0$ production offers the possibility to test its predictions at a large $q^2$ point where $\alpha_s(q^2)$ is small and the next-to-leading corrections are sufficiently dampened. The collider will start running at the highest possibly energy. By decreasing $\sqrt{s}$ (at $q^2 = M_Z^2$) we vary $\alpha_s$ to larger values. The QCD corrections manifest themselves strongest at the smallest $\alpha_s$-values with substantial cross section decrease as $\tau$ grows. Comparing with the simple scaling predictions, where the cross section remains roughly constant, we notice a significant difference (fig.13), which can be verified by the experiment.
6. Drell-Yan and Related Processes

The study of Drell-Yan lepton-pair production with the collider is limited by the \(1/Q^4\) fall-off of the cross section (fig.14). By going to large \(s^\prime\)-values the small and smallest \(\sqrt{s^\prime}\)-range is therefore better tested than in earlier experiments. We further mention: the \(s^\prime\)-dependence of the \(\gamma^\prime\)-pair average transverse momentum, the QCD-modified parton distribution at smallest \(\sqrt{s^\prime}\)-values, the \(K\)-factor, correlations between the off-shell photon and a jet, and the dynamical behaviour of low-\(p^\prime_t\) hadrons associated with a Drell-Yan trigger.

The production of heavy-narrow \(Q\bar{Q}\)-states, such as \(J/\psi\), \(\Upsilon\), is of high interest. Several production mechanisms contribute: QZI-rule suppressed transitions from standard to heavy quarks, heavy quarks involved in the structure function of the colliding hadrons (particularly at large \(Q^2\)), two-gluon annihilation producing a \(C+1\) bound state which radiatively decays into vector mesons. The production cross sections for the presently known states follow a phenomenological scaling law \(^{89}\)\(\Gamma_h\)^1 \(s/M^2\text{d}^3\Gamma/\text{d}x_L = f(s/M^2,x_L)\). \(M\) is the meson mass, \(\Gamma_h\) the partial width of the meson decaying into ordinary hadrons, and \(x_L = 2p_{L}/\sqrt{s}\) is the Feynman scaling variable. The search for narrow vector states is limited by the overall production rate rather than by the background (fig.15). With sufficient counting rates, correlation measurements between the narrow states and opposite jets become possible giving more information about the underlying quark-gluon processes.

The production of open flavors is more copious than the production of massive lepton pairs. Perturbative QCD calculations assume either heavy flavor "creation" via quark/gluon annihilation or flavor "excitation" from the sea. They suffer from several shortcomings such as the precise knowledge of the distribution functions, the bound state effects, the influence of the primordial \(p^\prime_t\)-dependence etc. For an extended overview we refer to ref.92. The cross section for open-beauty production is estimated \(\sim 10 \mu b\) (fig.16). However, due to its chain-like decays into lower mass hadrons, the experimental signatures are not clear enough to permit efficient triggering. Multi-lepton signatures or measurements of dilepton correlations might possibly disentangle a beauty-signal from background.
The production of prompt photons is another clean source of information on the constituent dynamics. Its 0-th order constituent process is QCD hard scattering (confinement type effects are ignored) such as \(q \bar{q} \rightarrow \gamma + \text{g} \), \(qg \rightarrow q + \gamma\) and \(qq \rightarrow qq + \gamma\). As we go towards large \(x_t\) values the \(q\gamma\) final state is expected to dominate whereas at low \(x_t\) \(g\gamma\) is predominant. The \(\gamma/\pi^0\) ratio increases beyond 1 as \(p_t\) reaches 30–40 GeV/c. The single-photon inclusive distribution decreases roughly exponential. The order-\(\alpha_s\) QCD processes give rise to away-side quark/gluon jets whereas accompanying towards-jets can only come from the order \(\alpha_s^2\) QCD graphs. Several studies come to mind; the gluon distribution can be determined, \(x_t\)-scaling can be verified over a wide range, correlations with the away-side jets permit the study of their fragmentation functions, higher-twist effects might be isolated.


The standard SU\(_2\)xU\(_1\) model of the weak interactions describes successfully a wide range of phenomenological data with one single parameter \(\sin^2 \theta\), and it provides definite information about the \(\nu\) and \(Z^0\) masses. However, there is a corner of the model that is still obscure, i.e., how the mass-generation comes about. In the original form, the intermediate boson masses are generated by the fundamental scalar Higgs fields. Three of them are used up for the mass-generation, and a neutral Higgs boson \(\nu^0\) is left as a physical particle. Though its coupling to the intermediate bosons and quarks are given by the model, its mass is completely unconstrained.

Theoretical prejudices favor \(m_{\nu^0} \sim 10\) GeV.

Estimates of the decay modes as a function of its mass indicate a predominance of \(\nu^0 \rightarrow \nu + \ell^+\ell^-\), \(\nu + b\bar{b}\) in the mass range \(4\) GeV < \(m_{\nu^0}\) < 12 GeV, while for 12 GeV < \(m_{\nu^0}\) < 200 GeV it preferentially decays into the heaviest \(\nu\) (or \(L^+\ell^-\)) pairs. This suggests that \(\nu^0\)-decays may contain prompt leptons and/or strange particles. The cascade decay involving heavy quarks results in several final state leptons.

In hadron initiated reactions Higgs particles can be produced in several ways: (a) via two-gluon annihilation. The cross section in the collider energy range is estimated \(\sigma_{\nu^0} \sim 10^{-35}\) cm\(^2\) (fig.17). A recent study on trilepton detection of their decays is hindered by variable background. Several studies look at \(\nu^0\) bosons in hadronic events with a recombination constraint. A simple 3\(\nu^0\) decay range, decay in fragmentation on two jets.

The standard SU\(_2\)xU\(_1\) was reconsidered for nonmassless \(\nu\), which can have similar mass-breaking mass masses. Coldstone and Goldstone bosons can be left intact.

The Higgs boson is estimated 12 GeV, applied to detect heavy at the rate for heavy.

The decay of several into \(\ell\ell\) a heavy eta heavy quark study.
on trilepton events concluded that useful signatures emerge from
their dilepton mass spectrum and some newly proposed transverse momentum
variable. An overwhelming background could make such attempt rather
difficult. (b) via $Q\bar{Q}$ (or $Z^0$) $\rightarrow H^0 + \gamma$ with a peak in the photon
spectrum. The large number of $\gamma$ resulting from $H^0$-decay will form a
considerable background problem. (c) via Higgs-bremsstrahlung off vector
bosons (fig.18). The bremsstrahlung of the $H^0$ by a $Z^0$ produced in
hadronic scattering shows up as a bump in the di-lepton mass distribution
with a fast fall-off at $Q = m_{Z^0} - m_{H^0}$. This possibility is however
constrained by the large suppression factor of $10^{-3}\sim 10^{-4}$ as compared to
simple $Z^0$ production, quite apart from the fact that the number of $Z^0$
decaying into lepton pairs is restrained. (d) if $m_{H^0} \gg 2 m_{W}$ triggering
on two hadron jets could offer another possibility.

The system of spinless Higgs-particles generating masses in the standard
SU(2)\times U(1) theory is unsatisfactory as an alternative
was recently proposed. The essential ingredients are: (i) a new set of
massless technifermions, (ii) a corresponding set of gauge-technigluons,
which confine the techniquarks into technicolor singlet bound states -
similar to QCD though at the $\sim 1$ TeV mass scale, (iii) chiral symmetry
breaking of the technicolor Lagrangian leading to a large number of $O^-$
Goldstone bosons, (iv) they take over the role of the Higgs bosons. This
scheme predicts a wealth of new particles notably the color-singlet
bosons $P^0_{8,3}$ with masses $\lesssim 3$ GeV, and $P^\pm$ with their masses anticipated
in the 8-14 GeV range. The production of $P^0$ via two-gluon annihilation
is estimated to be predominant. The rate lies a factor 5 above analogous
H$^0$-expectations. The $t\bar{t}$ decay mode offers a possibility for $P^0$
detection although under a considerable background. Similar reasoning is
applied on the (techni-) color-octet states $P^0_{8,3}$, $P^\pm_8$. The production
rate for the neutral state, again estimated via two-gluon annihilation, is
at the pb-level; the rates for the other states are substantially below.
The dominant decays of $P^0_8$, its mass is estimated around 250 GeV, will be
into $gg$ and heavy $Q\bar{Q}$. A significant signal could be: events with pairs
of heavy quark jets.
Non-abelian gauge theories allow for tri-linear couplings such as \( W^+ W^- Z^0 \) or \( W^+ W^- X \). The next step after the intermediate bosons are discovered consists in an experimental verification of their existence. If, for the identification of these processes, the weak decay modes are used, one aims at the experimental verification of higher order weak interaction effects. Based on simple Drell-Yan \( qq \) annihilation the simultaneous production of two weak bosons (e.g. \( W^+ W^- + X \)) has been estimated (figs. 19, 20); the cross section rates are:

\[
\sigma(W^+ W^-) \sim 10^{-37} \text{ cm}^2, \quad \sigma(Z^0 Z^0) \sim 10^{-37} \text{ cm}^2 \quad \text{and} \quad \sigma(W^+ W^-) \sim 5 \times 10^{-35} \text{ cm}^2.
\]

We thus expect about 1 event in \( 10^3 \) \( W^+ W^- \) events to contain a second gauge boson. In \( pp \) collisions the \( W^+ (W^-) \) is preferably emitted along the proton (antiproton) initial direction; the \( Z^0 \), however, are emitted in both forward and backward cones. We have also indicated the rate for \( W^+ W^- \) production which allows for the determination of the \( W^\pm \) \( Z \) -factor appearing in its magnetic momentum:

\[
\mu_W = \left( \frac{\sigma_W}{\sigma_H} \right) (1 + \Delta)
\]

The angular distribution of \( pp \rightarrow W^- + X \), with \( \theta_W \) chosen as the \( p \rightarrow W^- \) angle, reveals a characteristic minimum around \( \cos \theta_W \approx -0.3 \); its size depends sensitively on \( \Delta \). The standard \( SU_2 \times U_1 \) model predicts \( \Delta = 1 \) with a vanishing cross section at the minimum point (fig. 21).

**8. Summary**

With this paper we aimed to sketch the physics at the \( pp \) collider by extrapolating from the present-day available theoretical and experimental information to the soon accessible energy range of maximum 540 GeV center-of-mass energy. The covered fields are: (a) insights from cosmic-ray data on the general features of hadronic events and possibly surprising new phenomena, (b) production of hadrons at large- and small-\( p_T \), (c) experimental verification of the weak bosons \( W^\pm \) and \( Z^0 \), (d) production of massive lepton pairs, new flavors and direct photons, (e) search for \( Higgs \) particles or technicolor, and the verification of the triple-boson couplings via boson-pair production. Our presentation repeatedly encountered perturbative QCD in its various applications, and it covered several key features of electromagnetic-weak unification.
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<table>
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<tr>
<th>Weak Bosons</th>
<th>$W^+$</th>
<th>$Z^0$</th>
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<tr>
<td>Mass</td>
<td>$M_W = 77.8$ GeV</td>
<td>$M_{Z^0} = 88.6$ GeV</td>
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<tr>
<td>Total Decay Width</td>
<td>$\Gamma_W = 2.47$ GeV</td>
<td>$\Gamma_{Z^0} = 2.49$ GeV</td>
</tr>
<tr>
<td>Production Rate at $\sqrt{s} = 540$ GeV</td>
<td>$\sim 3$ pb</td>
<td>$\sim 2$ pb</td>
</tr>
<tr>
<td>Lepton Events/Day ($L = 10^{30}$ cm$^{-2}$ s$^{-1}$)</td>
<td>50 - 100</td>
<td>5 - 10</td>
</tr>
</tbody>
</table>

Table 1
Figure Captions

Fig.1: Order-$g^2$ QCD diagrams contributing to $qg$-scattering with the triple-gluon vertex shown in (c).

Fig.2: Transverse thrust distribution for the different subprocesses; the dotted curves indicate the $p_T$-smeared two-jet contribution.

Fig.3: $p_T^\text{jet}$ distribution with a trigger momentum $p_T \sim 7-8$ GeV/c at various $x_T$-bins. The smeared 3-jet contribution is shown by the dashed curves.

Fig.4: Inclusive $\pi^0$ production at large-$p_T$ as measured at the ISR.

Fig.5: Comparison between the jet- and single particle rates.

Fig.6: Predicted jet-rates at the $pp$ collider.

Fig.7: a) Two-gluon exchange in the Low-Hussinov-model for the Pomeron.

b) Four of the 16 diagrams contributing to the coherent Low-Hussinov-model; the last two diagrams contribute with a negative sign.

c) Soft-gluon radiation in the low-Hussinov-model.

Fig.8: a) Two displaced chains in the DTU-model and the resulting $y$-distribution.

b) Short-long range chains in the DTU-model and the resulting $y$-distribution.

c) Three-chain contribution in $pp$ annihilation; the resulting $y$-distribution is compared with the analogous of the Pomeron.

Fig.9: a) Deep-inelastic scattering in the valon-recombination model.

b) Pion generation via valon-antivalon recombination.

Fig.10: $p_T$-spectrum of leptons originating from $W^\pm, Z^0$ and Drell-Yan.

Fig.11: Three dimensional distribution of the single-lepton spectrum in $pp$ collisions.

Fig.12: Total cross section for $Z^0$ production with (solid curves) and without (dashed curves) QCD corrections.

Fig.13: The $Z^0$- and $W^\pm$-production cross sections; $A$ and $B$ are defined in ref. 85.
Fig. 14: Invariant mass spectrum of lepton pairs via Z°, WW and heavy quarks.

Fig. 15: a) Inclusive cross sections for J/ψ(ψ) production, and scaled up φ(φ) and ψ(ψ) predictions.
   b) Production of lepton-pairs via heavy quark: inclusive cross section times branching ratio.

Fig. 16: Total cross section for beauty production in pp collisions.

Fig. 17: Inclusive Higgs-particle production via two-gluon annihilation at \( \sqrt{s} = 27, 50, 400 \) GeV (fine, horizontal, vertical shading).

Fig. 18: Rate of associated production of Higgs meson with Z or with Z° versus \( \phi \), expressed as a fraction of total Z or Z° production.

Fig. 19: The total cross section for \( p\bar{p} \to W^- + X \), \( p\bar{p} \to W^- Z + X \), and \( p\bar{p} \to Z Z + X \) (x = sin 2θ = 0.2).

Fig. 20: Total cross section for \( p\bar{p} \to W^- + X \) as a function of the \( W \)-mass.

Fig. 21: The differential cross section \( d\sigma/dcosθ \) for \( p\bar{p} \to W^- γ + X \) and \( p\bar{p} \to W^- γ + X \). \( θ \) is the angle between the \( W \) and the proton in the \( W \) rest system. \( \sqrt{s} = 540 \) GeV and \( M_W = 85 \) GeV. A photon cut \( E_γ > 30 \) GeV has been applied.

\( W \) and \( Z \) are fermions, while \( Z° \) is a boson.

(a) (b) (c)
\[ \sqrt{s} = 540 \text{ GeV}, \ p\bar{p} \rightarrow j_1 j_2 j_3 X \]

\[ E_L = 50 - 60 \text{ GeV}, \ p_L > 7.5 \text{ GeV/c} \]

Fig. 2
$7 < p_t < 8$

- $0.2 < x < 0.4$
- $0.4 < x < 0.6$
- $0.6 < x < 0.8$
- $0.8 < x < 1.0$

$d\sigma / dp_{out}$ (nbarn/GeV/c)

$P_{out}$ vs $GeV/c$

**Fig. 3**
INVARIANT CROSS SECTIONS FOR $p\bar{p} \rightarrow n^3$-ANYTHING VS TRANSVERSE MOMENTUM

**Figure 4**

**Table: Symbol and $V_t$ Values**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>$V_t$ (GeV)</th>
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<tbody>
<tr>
<td>o</td>
<td>23.5</td>
</tr>
<tr>
<td>a</td>
<td>30.6</td>
</tr>
<tr>
<td>o</td>
<td>44.0</td>
</tr>
<tr>
<td>v</td>
<td>52.7</td>
</tr>
<tr>
<td>o</td>
<td>62.4</td>
</tr>
</tbody>
</table>

$E \frac{d\sigma}{dp_t}$ cm$^2$ GeV$^{-2}$ ster$^{-1}$

$12 \times 10^{-25} \exp (-4p_t)$
$E(d^3\sigma/d^3p) \text{ nb}$

$P_\perp \text{ GeV/c}$

$E260 \text{ JET}$

$CP \left(\pi^+ + \pi^-\right)/2$
\[ \bar{p}p \rightarrow \mu^\pm + X \]
\[ \sqrt{s} = 540 \text{ GeV}, y = 0 \]

Fig. 10

\[ \frac{d\sigma}{dp_T} (\text{mb}/\text{GeV}^2) \]

-\( W, Z \rightarrow l\bar{l} \)
- heavy quarks
- direct leptons
- Drell-Yan
Fig. 12
Fig. 13


\[ \bar{p}p \rightarrow \mu^+ \mu^- + X \]

\[ \sqrt{s} = 540 \text{ GeV}, \ y = 0 \]

**Fig. 13**

---

**Fig. 14**
Total Cross Sections

\[10^{-36} \text{ cm}^2\]
Total cross sections

\[ \sigma(p\bar{p} \rightarrow W^+W^-X) \]

\[ \left[ 10^{-36} \text{cm}^2 \right] \]

\( M_w = 150 \text{ GeV}/c^2 \)
\( M_w = 100 \text{ GeV}/c^2 \)
\( M_w = 75 \text{ GeV}/c^2 \)
\( M_w = 50 \text{ GeV}/c^2 \)

\( \sqrt{s} \) (GeV)

Fig. 20
Fig. 21