1984–1985 ACADEMIC TRAINING PROGRAMME

SPEAKER : L. DI LELLA / CERN
TITLE : Highlights on proton-antiproton collider results
DATES : 29, 30 and 31 May
TIME : 11.00 hrs - 12.00 hrs
PLACE : Auditorium

ABSTRACT

The purpose of these lectures is to review the main physics results obtained so far at the proton-antiproton collider. These include the study of high-\( p_T \) jets and the physics of the \( W^* \) and \( Z^0 \) bosons.

The level of these lectures will be such that any physicist should be able to follow them without difficulty.

Secretariat : tel. 2844 - 3364

COPIES OF TRANSPARENCIES
HIGHLIGHTS ON \( \bar{p}p \) COLLIDER RESULTS

Hard collisions:
\[
\bar{p}p \rightarrow \text{high } p_T \text{ secondaries}
\]

1. HADRONIC JETS
2. Production and decay of \( W^\pm, Z^0 \)

Data mostly from the historic runs of 1982–83 — with a small amount of preliminary results from the 1984 run.

THESE ARE LECTURES FOR PHYSICISTS NOT ACTIVELY INVOLVED IN COLLIDER EXPERIMENTS
General features of $\bar{p}p$ collisions at $\sqrt{s} = 546$ GeV (total centre-of-mass energy)

$\sigma_{\text{tot}} \approx 62 \text{ mb}$ \quad UA4

$\sigma_{\text{el}} \approx 13 \text{ mb}$

Distribution of charged particle multiplicity ($n_c$)

\[ \langle n_c \rangle = 29 \]

\[ \langle n_{\gamma\gamma} \rangle = 31 \]

*mostly from $\pi^0 \rightarrow \gamma\gamma$*
Need two variables to describe inclusive particle production

\[ p_T = p \sin \theta \quad \text{transverse momentum} \]

\[ y = \frac{1}{2} \ln \frac{E + p \cos \theta}{E - p \cos \theta} \quad \text{rapidity} \]

\[ \lim_{\beta \to 1} y = -\ln \tan(\theta/2) = \eta \quad \text{pseudorapidity} \]

\[ \frac{d^2 \sigma}{d^2 p} \quad \text{[cm}^2 \text{GeV}^{-2}] \]

\[ +(n+n)/2 \quad b<2.5 \ \text{UA1} \]

\[ \text{invariant cross-section} \]

\[ \langle p_T \rangle \approx 0.4 \ \text{GeV}/c \]
SOFT COLLISIONS $\equiv$ small $p_T$

HARD COLLISIONS $\equiv$ large $p_T$ or production of large $M$

Hard collisions are a small fraction ($\leq 10^{-3}$) of all $\bar{p}p$ collisions — but they are sensitive to the proton (antiproton) internal structure.

HISTORICAL EXAMPLE:

$\alpha$ - Nucleus scattering (1908$\rightarrow$1911)

Thomson's atom: $R \sim 10^{-8}$ cm, uniform charge distribution — expected fraction of $\alpha$ scattered at $\theta > 90^\circ \leq 1/10^{14}$

effect of atomic nucleus with $R \sim 10^{-13^{1/3}}$ cm

expected fraction of $\alpha$ scattered at $\theta > 90^\circ \approx 1/8000$

↑ in agreement with experimental results:

Geiger, Marsden 1908
Rutherford 1911
HIGH ENERGY $p, \bar{p}$ IN HARD COLLISIONS APPEAR AS BEING COMPOSED OF INDEPENDENT, POINT-LIKE CONSTITUENTS (PARTONS)

Each parton carries a fraction $x$ of the $p$ ($\bar{p}$) momentum.

PARTONS ≡ quarks ($q$)  
antiquarks ($\bar{q}$)  
gluons ($g$)

carry a new quantum number

COLOUR $q$ ($\bar{q}$) exist in 3 colour states  
gluons exist in 8 colour states

Structure functions $xdn/dx$ (depend on parton type)

QCD non-Abelian gauge theory: the best candidate to describe the strong interaction among partons
HARD $pp$ COLLISIONS AT COLLIDER ENERGIES ARE COLLISIONS BETWEEN TWO WIDE-BAND PARTON BEAMS

The relevant parameter is not $\sqrt{s}$ but the total energy in the parton-parton centre-of-mass:

$$\frac{x_1 \sqrt{s}}{2} \quad \frac{x_2 \sqrt{s}}{2}$$

$$\sqrt{s} = \sqrt{s x_1 x_2} \quad \text{ (neglecting masses and initial } p_T)$$

Parton-parton scattering $\rightarrow$ jets

$q\bar{q}$ annihilation $\rightarrow e^+e^-$ continuum, $W^\pm, Z^0$
HIGH-PT JETS: a 2-step process

Step 1

Many types of parton collisions:

\[
\begin{align*}
    q\bar{q} &\rightarrow q\bar{q} \\
    q\bar{q} &\rightarrow q'\bar{q}' \\
    qg &\rightarrow qg \\
    g\bar{q} &\rightarrow q\bar{q} \\
    gg &\rightarrow gg \\
    qg &\leftrightarrow q\bar{q} \\
\end{align*}
\]

all occurring to leading order in QCD

\( Q^2 \text{ large } \rightarrow \text{collisions at short distance} \)

Perturbative calculations are possible because of "asymptotic freedom."

\[
\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\ln(4\pi^2/Q^2)}
\]

\( \alpha_s(Q^2) \to 0 \) if \( n_f < 16 \)
In general $x_1 \neq x_2$
\[ \rightarrow \text{final state high-}\mathbf{p}_T\text{ partons are not collinear} \]

Initial $p_T \approx 0 \rightarrow \text{final state high-}\mathbf{p}_T\text{ partons are coplanar with beams}$

**Step 2 Parton fragmentation (hadronisation)**

High-$\mathbf{p}_T$ parton $\rightarrow$ collimated system of high-$\mathbf{p}_T$ hadrons (jet). $\sum \mathbf{p} = \mathbf{P}(\text{parton})$

Final state interaction between the high-$\mathbf{p}_T$ partons and the other partons:

long distance $\rightarrow Q^2$ small $\rightarrow \alpha_s$ large

Need non-perturbative techniques (still missing at present)

Long-distance parton interaction is presumably responsible for parton confinement only colourless hadrons can exist as free particles

High-$\mathbf{p}_T$ jet production from hadronic collisions was predicted by Berman, Bjorken, Kogut (1971) as a consequence of the parton model.
1972 - ISR \((\sqrt{s} = 23 \rightarrow 63 \text{ GeV})\)

Observation of high-\(p_T\) \(\pi^0\) (ccr)

Parton model prediction \((\theta = 90^\circ)\)

\[
E d^3\sigma/dp^3 = p_T^{-4} F(2p_T/\sqrt{s})
\]

Experimentally \(p_T^{-8} F(2p_T/\sqrt{s})\)

Jet structure distorted by the single particle trigger - but "opposite side" jet was undistorted
1973- Bjorken suggests the use of calorimeters to trigger on the whole jet

Fermilab, $\sqrt{s} = 27$ GeV

- Jets
- $(\pi^+ + \pi^-)/2$

1973-80: events with high-$p_T$ hadrons compatible with two-jet structure — but calorimeters have limited solid angle ($\sim 1$ sr)

An extreme possibility: all jet structures observed are due to the trigger bias — the requirement of high-$p_T$ particles in limited solid angle.
1980-81: Experiment NA5 ($\sqrt{s}=24$ GeV)

Calorimeter with full azimuthal coverage:

$$\Delta \phi = 360^\circ$$

$$40^\circ < \theta^* < 140^\circ$$

$\theta^*$ polar angle in centre-of-mass system

- Selection of events with large total transverse energy:

$$\sum E_T = \sum E_i \sin \theta_i$$

sum over all particles entering the calorimeter

Result: events with large $\sum E_T$

(10–20 GeV) consist in general of many low-$p_T$ particles with uniform $\phi$-distribution

$\rightarrow$ no evidence for jet production
November-December 1981:
First physics run at the $\bar{p}p$ Collider
$\sqrt{s} = 540$ GeV, $\int L dt \sim 80 \mu b^{-1}$

December 1981: Workshop on Collider Physics,
Madison, USA

Among the conclusions of the Workshop:

Clean parton-model jets, it would appear, will be much more elusive in hadron-hadron scattering than in $e^+e^-$ collisions.

(Physics Today, Feb 1982)

July 1982 Paris Conference:
Clear evidence for high-$p_T$ jet-production in the UA2 experiment.
UA2

\[ \Sigma E_T = \Sigma E_i \sin \theta_i \]

all cells
Search for $E_T$ clusters in events with large $\sum E_T$

Cluster transverse energy:

$$E_T = \sum E_i \sin \Theta_i$$  (sum over all cluster cells)

Cluster ordering:

$$E_T^{(1)} > E_T^{(2)} > \ldots > E_T^{(n)}$$

For two-jet event expect

$$E_T^{(1)} \approx E_T^{(2)} \gg E_T^{(i)} \quad (i > 2)$$

\[\text{(coplanarity with beam axis)}\]
For two jets only
\( h_2 = 1 \)

For perfect \( p_T \) balance
\( h_1 = h_2 = \frac{1}{2} \)
Typical $E_T$ distribution in events with $\Sigma E_T > 100$ GeV

Main feature of events with large $\Sigma E_T$ at the $\bar{p}p$ collider:
$\Sigma E_T$ consists mainly of two narrow clusters, $E_T^{(1)} \approx E_T^{(2)}$, $\Delta \phi \approx 180^\circ$
as expected for two-jet final states
Event projection in plane perpendicular to beams

High density of charged particles

Energy deposition in first 17 rad. lengths ($E_{em}$)

Energy deposition in hadronic calorimeter ($E_{had}$)

For high $p_T$, $\pi^0$ ($\rightarrow \gamma \gamma$) expect $E_{had}/E_{em} \ll 1$

For high $p_T$ charged hadron: $E_{had}/E_{em} > 1$

For typical jet (~50% $\pi^0$, ~50% charged hadrons): $E_{had}/E_{em} \approx 1$
Why NAS did not see jets?
Study $\Sigma E_T$ vs $\sqrt{s}$ (Åkesson, Bengtsson 1982)

Two contributions:
- parton-parton scattering $\rightarrow$ 2 jets
- soft collisions: tail of multiplicity distribution

Contribution from hard parton-parton collisions increasing rapidly with $\sqrt{s}$ becomes dominant at Collider energies for $\Sigma E_T$ large
**Parton sub-processes**

**1st order QCD diagrams**

\[ \frac{d\sigma}{d(cos\theta^*)} = \frac{\pi [\alpha_s(Q^2)]^2}{2 \frac{\hat{s}}{s}} |M|^2 \]

\[ \hat{s} = (\text{total energy in the two-parton centre-of-mass frame})^2 \]

\[ = s x_1 x_2 \]
\[ t = - \frac{\hat{s}}{2} (1 - \cos \Theta^*) / 2 \]  
\[ u = - \frac{\hat{s}}{2} (1 + \cos \Theta^*) / 2 \]  
(neglecting quark masses)

Combridge, Kripfganz, Ranft (1977)

| Subprocess           | \(|M|^2 = f(\cos \Theta^*)\) | \(|M|^2 \) at \( \Theta^* = 90^\circ \) |
|----------------------|-------------------------------|------------------------------------------|
| \(q q' \to q q'\)   | \(\frac{4}{9} \frac{\hat{s}^2 + u^2}{t^2}\) | 2.22                                      |
| \(q q' \to q q'\)   | \(\frac{4}{9} \left( \frac{\hat{s}^2 + u^2}{t^2} + \frac{\hat{s}^2 + t^2}{u^2} \right) - \frac{8}{27} \frac{\hat{s}^2}{ut}\) | 3.26                                      |
| \(q q \to q q\)     | \(\frac{4}{9} \left( \frac{\hat{s}^2 + u^2}{t^2} + \frac{t^2 + u^2}{\hat{s}^2} \right) - \frac{8}{27} \frac{u^2}{\hat{s} t}\) | 2.59                                      |
| \(q q \to q q\)     | \(\frac{32}{27} \frac{u^2 + t^2}{ut} - \frac{8}{3} \frac{u^2 + t^2}{\hat{s}^2}\) | 1.04                                      |
| \(q q \to g g\)     | \(\frac{1}{6} \frac{u^2 + t^2}{ut} - \frac{3}{8} \frac{u^2 + t^2}{\hat{s}^2}\) | 0.15                                      |
| \(g g \to q q\)     | \(\frac{4}{9} \frac{u^2 + \hat{s}^2}{u \hat{s}} + \frac{u^2 + \hat{s}^2}{t^2}\) | 6.11                                      |
| \(q q \to g g\)     | \(\frac{9}{2} \left( 1 - \frac{ut}{\hat{s}^2} - \frac{u \hat{s}}{t^2} - \frac{\hat{s} t}{u} \right)\) | 30.38                                     |
| \(g g \to g g\)     | \(\frac{9}{2} \left( 3 - \frac{ut}{\hat{s}^2} - \frac{u \hat{s}}{t^2} - \frac{\hat{s} t}{u} \right)\) | 30.38                                     |

a q and q' denote quarks with different flavors.
**INCLUSIVE JET PRODUCTION**

Inclusive jet cross-section as a sum of convolution integrals

\[
\frac{d^2\sigma}{dp_T^2 d(cos\theta)} = \frac{2\pi p_T}{\sin^2\theta} \sum_{a,b} \int dx_1 dx_2 \, F_a(x_1, Q^2) F_b(x_2, Q^2) \times \left[\alpha_s(Q^2)\right]^2 \delta(s + t + m) \sum_f \frac{|M|_{ab \to f}^2}{s} \sum_{a,b} \sum_f \text{sum over all possible subprocesses}\]

\[a + b \rightarrow f \]

\(f \equiv \text{two-parton final state}\)

\[F_a(x, Q^2) = x \, \frac{dn}{dx} \text{ structure function for parton type } a - \text{ measured in deep inelastic lepton - nucleon scattering at } Q^2 \leq 100 \text{ GeV}^2 \text{ - extrapolated to } Q^2 \approx 10^3 - 10^4 \text{ GeV}^2 \text{ using QCD evolution (Altarelli – Parisi equation)}\]

**Theoretical uncertainties**

- Q^2 extrapolation of structure functions (gluon)
- Higher order QCD diagrams
- Definition of Q^2
- Final state interaction neglected (use QCD MonteCarlo to obtain relationship between parton p_T and jet E_T)

**Experimental uncertainties**

- Energy calibration of calorimeter (typically ±4%)
- Acceptance (jet angular dimensions)
- Luminosity

±50%
Proton Structure Functions
at $Q^2 = 10^4$ GeV$^2$

(Glück, Hoffmann, Reya)
QCD predictions are absolute — there is no adjustable parameter.
In parton-parton centre-of-mass:
\[ \theta^* = 90^\circ \quad p_T = \sqrt{\frac{s}{2}} = \sqrt{5x_1x_2/2} \]

For \( x_1 \approx x_2 \quad x = 2p_T/\sqrt{s} \)

- ISR (\( \sqrt{s} = 63 \))
- \( p_T \approx 20 \rightarrow x \approx 0.6 \)
- Dominance of valence quarks
- \( p_T \) Collider (\( \sqrt{s} = 630 \))
- 0.06
- Gluons

\[ \sqrt{s} = 546 \text{ GeV} \] (Antoniou et al.)

\( d\sigma/dp_T \) (cm\(^2\)/GeV/c\(^1\))

- \( gg \)
- \( qg \) or \( \bar{q}g \)
- \( \bar{q}q \)
Comparison of jet yields
\( \sqrt{s} = 546 \text{ GeV} \) vs. \( 630 \text{ GeV} \)
(UA2, 1985 Workshop on \( \bar{p}p \) Physics, St. Vincent)

Most theoretical and experimental uncertainties drop out in the ratio
For $Q^2$-independent structure function ("naive" parton model) expect ($\Theta=\pi$)

$$E d\sigma / dp^3 = p_T^{-4} f(x_T)$$

invariant cross-section

dimensionless function

of $x_T = 2 p_T / \sqrt{s}$

(can derive this relation using dimensional considerations only)

**ISR - $\bar{p}p$ Collider comparison**

→ evidence for scaling violations

$$f(x_T, Q^2)$$

$$Q^2 \approx 2 p_T^2 = \frac{s}{2} x_T^2$$

For a given $x_T$ $$\frac{Q_{\text{collider}}^2}{Q_{\text{ISR}}^2} \approx \left(\frac{630}{63}\right)^2 \approx 10^2$$
Good fit with form $E d \sigma / d p^3 = A p_T^{-n} (1-x_T)^m$

$A = (1.6 \pm 0.3) \times 10^{-26} \text{ cm}^2 / \text{ GeV}^{2-n}$

$\eta = 5.1 \pm 0.3 \quad m = 10.6 \pm 0.5$

A convenient parametrisation over a very large $\sqrt{s}$ range.
EVIDENCE FOR THE THREE-GLUON VERTEX (non-Abelian structure of QCD)

Expect three effects from 3-g vertex:
1. Through subprocess diagrams (gg → gg, etc.)
2. $Q^2$ dependence of structure functions
3. Dependence $\alpha_s(Q^2)$

Can these effects be seen in spite of theoretical and experimental uncertainties?

Furmanski, Kowalski (1984):

1. Consider a given theoretical prediction $[d\sigma/dp_T d\eta]_{TH}$ including or excluding the effects of the 3-g vertex

2. Multiply $[d\sigma/dp_T d\eta]_{TH}$ by normalisation constant $A$ and determine $A$ by best fit to data

3. Hope that fit is good for standard QCD — bad if effects of 3-g vertex are switched off.
Standard QCD - $\chi^2$/d.o.f. = 0.9 - 1.1 depending on structure functions, $Q^2$ definition, $\Lambda$, etc.

1.- QCD without subprocesses with 3-g vertex: $\chi^2$/d.o.f. = 1.8

2.- As 1, + suppression of 3-g vertex in $Q^2$ evolution of structure functions $\chi^2$/d.o.f. = 2.1

3.- As 2, + $\alpha_s = \text{constant}$: $\chi^2$/d.o.f. = 3.5

\[\frac{d\sigma}{d\rho_T} / (\Lambda \times \text{QCD})\]

→ switching off 3-gluon vertex (either partially or totally) changes \underline{shape} of $p_T$-dependence in disagreement with shape observed experimentally.
PARTON-PARTON SCATTERING

Determination of:
1. Angular distribution $d\sigma/d\cos\theta^*$
2. Structure functions

\[ \vec{P} = \vec{P}_1 + \vec{P}_2 \]
\[ M_{jj}^2 = 4P_1 P_2 \sin^2(\alpha/2) \]

For $P_T = 0$ (in practice for $P_T \ll P_{T1}, P_{T2}$)

\[ \theta^* = \sin^{-1} \left( \frac{2P_T}{M_{jj}} \right) \]
\[ x_1 = \left( \sqrt{P_L^2 + M_{jj}^2} + P_L \right) / \sqrt{s} \]
\[ x_2 = \left( \sqrt{P_L^2 + M_{jj}^2} - P_L \right) / \sqrt{s} \]

\[ \therefore \text{Events with two } P_T\text{-balanced jets allow determination of } x_1, x_2 \text{ and } \theta^* \text{ (scattering angle in two-parton centre-of-mass)} \]

For $P_T \neq 0$, $\theta^*$ is ambiguous — Collins-Soper convention shares $\vec{P}_T$ equally between the two incident partons.
\[
\frac{d^3\sigma}{dx_1 dx_2 d(\cos\theta^*)} = \sum_{a,b} \frac{F_a(x_1)}{x_1} \frac{F_b(x_2)}{x_2} \sum_f \frac{d\sigma}{d\cos\theta^*}(ab\to f)
\]

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Hopeless at first sight because of many subprocesses \(a,b\to f\)
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However the dominant subprocesses:
\(gg\to gg\)  \(gq\to gq\)  \(q\bar{q}\to q\bar{q}\)
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```
have very similar shapes for \(d\sigma/d\cos\theta^*\)
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```
\(\rightarrow\) As an approximation use \(d\sigma/d\cos\theta^*\) for \(gg\) scattering:
```

\[
d\sigma/d\cos\theta^* = \frac{\pi \alpha_s^2}{2 x_1 x_2 s} \cdot \frac{9}{8} \frac{(3 + \cos^2\theta^*)^3}{(1 - \cos^2\theta^*)^2}
\]

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Note \(\sin^{-4}\theta^*/2\) term (Rutherford) due to vector boson exchange
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present in \(gg\to gg\), \(gq\to gq\) because of 3-gluon vertex
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Also present in \(q\bar{q}\to q\bar{q}\)
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\[
\frac{d^3\sigma}{dx_1 dx_2 d(\cos\theta^*)} \approx \left[ \frac{d\sigma}{d(\cos\theta^*)} \right]_{gg\to gg} \sum_a \frac{F_a(x_1)}{x_1} \sum_b \frac{F_b(x_2)}{x_2}
\]
Approximate relations:

\[
\frac{d\sigma}{d\cos\theta^*} \big|_{gg \rightarrow gg} \approx \frac{4}{9} \left[ \frac{d\sigma}{d\cos\theta^*} \right]_{gg \rightarrow gg}
\]

\[
\frac{d\sigma}{d\cos\theta^*} \big|_{q\bar{q} \rightarrow q\bar{q}} \approx \left( \frac{4}{9} \right)^2 \left[ \frac{d\sigma}{d\cos\theta^*} \right]_{gg \rightarrow gg}
\]

- can define

\[
\sum_a F_a(x) = F(x) = g(x) + \frac{4}{9} \left[ q(x) + \bar{q}(x) \right]
\]

[global structure function]

and write:

\[
\frac{d^3\sigma}{dx_1 dx_2 d(\cos\theta^*)} \approx \left[ \frac{d\sigma}{d(\cos\theta^*)} \right]_{gg \rightarrow gg} \cdot \frac{F(x_1)}{x_1} \cdot \frac{F(x_2)}{x_2}
\]

Approximate factorisation is verified experimentally.

This analysis technique has been first used by UA1.
Angular distribution for parton-parton scattering

Note larger acceptance of UA1 calorimeter (larger |cosθ^*|)

- Good agreement with QCD
- Evidence for the Rutherford term \( \sin^{-4} \theta^* / 2 \)
- Scalar gluon exchange disagrees with data
\[
\frac{d^3\sigma}{dx_1 dx_2 d(\cos\theta^*)} \approx \frac{F'(x_1)}{x_1} \frac{F'(x_2)}{x_2} \int_0^{\cos\theta_{\text{min}}^*} \left[ \frac{d\sigma}{d\cos\theta^*} \right]_{gg \rightarrow gg} d(\cos\theta^*)
\]

\[\theta_{\text{min}}^* \text{ minimum angle for which both jets are within detector acceptance (depends on } x_1, x_2)\]

\[S(x_1, x_2) \approx x_1 x_2 \frac{d^2\sigma}{dx_1 dx_2} \int_0^{\cos\theta_{\text{min}}^*} \left[ \frac{d\sigma}{d\cos\theta^*} \right]_{gg \rightarrow gg} d(\cos\theta^*)\]

**Experimental uncertainties**
- Statistical errors
- Normalisation
- Calorimeter calibration

**Theoretical uncertainties**
- Higher order corrections (not yet calculated)
  \[\frac{d\sigma}{d\cos\theta^*} \rightarrow K \frac{d\sigma}{d\cos\theta^*}\]
  \[K \text{ unknown parameter believed to be } \leq 2\]

\[S(x_1, x_2) \approx F(x_1) F(x_2)\]

\[S(x, x) \approx [F(x)]^2\]

→ uncertainty on \(F\) ≈ (uncertainty on \(S\))/2
Assumptions:

\[ K = 1 \quad [\text{F}(x)\sqrt{K} \text{ is actually measured}] \]
\[ \alpha_s(Q^2) = \frac{12\pi}{23} \ln \left(\frac{Q^2}{\Lambda^2}\right), \quad \Lambda = 0.2 \text{ GeV} \]
Comparison with structure functions measured by the CHARM collaboration and extrapolated to $Q^2 \approx 2000$ GeV$^2$

Gluon density at small $x$
measured DIRECTLY for the first time [in deep inelastic scattering the gluon structure function is determined indirectly from the $Q^2$ dependence of $q(x), \bar{q}(x)$]
HIGHER ORDER QCD EFFECTS

Gluon radiation

\[ q \rightarrow g \rightarrow g \]
\[ g \rightarrow q \rightarrow g \]

\[ z = \text{gluon momentum/total momentum} \]

Radiation probability (\( z, w << 1 \)):

\[ \frac{d^2 R}{dz dw} \approx \frac{8\alpha_s}{3\pi} \frac{1-z}{zw} \quad (q \rightarrow qg) \]

\[ \approx \frac{3}{4} \frac{8\alpha_s}{3\pi} \frac{1-z}{zw} \quad (g \rightarrow gg) \]

Gluon radiation from initial partons

→ possibility of two-jet events with imbalanced \( p_T \) (jet from radiated gluon is emitted generally at small angle to beams)

In plane \( \perp \) to beams

\[ P_T^1 \]
\[ P_T^2 \]
\[ P_T^3 \]

\[ P_5 = \text{difference between two large components sensitive to measuring errors (calorimeter resolution)} \]

→ use \( P_T^2 \) to study \( p_T \) imbalance
$P_{\eta}$ distribution

Experimental data: UA2, $\sqrt{s} = 546$ GeV

\begin{align*}
&\text{QCD} \\
&\text{QCD, with} \quad R(q\rightarrow qg) = R(q\rightarrow gg) \quad \{ \text{M. Greco, 1985} \}
\end{align*}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{Graph showing $1/n \, dn/dp_\eta$ vs. $p_\eta$ (GeV).}
\end{figure}

--> further evidence for 3-gluon vertex

For $P_\eta < 15$ GeV/c, $dn/dP_T \sim P_T \exp(-a P_T^2)$

$\langle P_T \rangle = 7 \pm 1$ GeV/c
FRAAGMENTATION

Parton $\rightarrow$ jet

Two distinct regions:

1. Short distances ($\ll 10^{-13}$ cm)
   Perturbative QCD: gluon radiation, $q\bar{q}$ pair creation
   parton $\rightarrow$ jet of partons

2. Long distances ($\gg 10^{-13}$ cm)
   Non-perturbative QCD properties
   partons $\rightarrow$ colourless hadrons
   not calculable

Two "popular" models:

- independent jet fragmentation (each parton fragments independently of the other partons)
- lines of colour force (strings) stretched among all partons in final state (Lund model)

Variable definition:

hadrons: momentum $\vec{p}_i$

Jet momentum

$\vec{P} = \sum_i \vec{p}_i$

$Z = (\vec{P} \cdot \vec{P})/P^2$ fractional longitudinal momentum

$q_T$ component of $\vec{p} \perp \vec{P}$

$\text{dN/d}q_T \equiv D(q_T)$ fragmentation function
Measurement of $D(z)$ requires momentum measurement of individual jet fragments—possible in UA1 for charged fragment because of magnetic field.

Difficulty at small $z$: spectator particles not belonging to the jet $(e^+e^- \to 2 \text{ jets has no spectators})$

- $\circ$ UA1, $P_T > 30$ GeV (St. Vincent) mostly gluon jets
- $\nabla$ AFS (ISR), $<P_T> \approx 14$ GeV/c quark jets
- $\bullet$ $e^+e^- \to \text{jets, } \sqrt{s} = 34$ GeV quark jet

$\Rightarrow$ collider jets are softer: $<z>_{\text{collider}} < <z>_{e^+e^-}$
Two possible reasons:
- a real gluon jet/quark jet difference: 
  \[ R(q \rightarrow gg) = \frac{3}{4} R(q \rightarrow gg) \rightarrow \text{there is more gluon radiation from gluon jets than from quark jets} \]
- scale breaking effects in \( D(z) \) 
  (expected from gluon radiation)

Scale breaking effects are small:

Most likely, collider jets are softer because of a real gluon jet/quark jet difference.
Limited $q_T$ (transverse momentum $\perp$ jet axis)

$\langle q_T \rangle$ [GeV/c]

$z$

$E_T > 30$ GeV

$\text{d}N/\text{d}q_T$

$q_T$ [GeV/c]

$P_T$ distribution of secondaries from soft collisions with respect to beam axis.
Charged particle multiplicity in jets

In principle  \( \langle n_c \rangle = \int D(z) \, dz \)

but \( D(z) \) is poorly known at small \( z \) (spectators)

Method used by UA2:

Azimuthal density of charged particles

\[
\frac{d^2n}{d\phi \, d\rho} = \pi \langle n_c \rangle \left( \frac{d\phi}{d\rho} \right)_{\pi/2}
\]

\( m_{jj} \approx \sqrt{3} \)

Definition

\[
\langle n_c \rangle = \frac{1}{2} \left\{ \int_0^\pi \frac{dn}{d\phi} \, d\phi - \pi \left( \frac{d\phi}{d\rho} \right)_{\pi/2} \right\}
\]

average multiplicity of jet "core"
To compare with $\langle n_c \rangle$ measured in $e^+e^-$ collisions (quark jets) apply the same method to $e^+e^- \rightarrow$ hadrons

- Quark fragmentation model (Webber) fit to $e^+e^- \rightarrow$ hadrons
- Same model (with theoretical uncertainty) for gluon fragmentation

$m_{jj} \sim 50$ GeV mostly gluon jets $\langle n_c \rangle > \langle n_c \rangle$ collider $e^+e^-$

$m_{jj} > 100$ GeV mostly quark jets $\langle n_c \rangle \approx \langle n_c \rangle$
Transverse energy density in a jet vs $\phi$
($\phi = 0$ is the jet axis)

Note log ordinate - jet fragments at large $\phi$ are soft!

Field-Feynman fragmentation (no gluon radiation) predicts too narrow jets

**UA2**

$2\pi/\phi \, dE_t / d\phi$ (GeV rad$^{-1}$)

- $20 < E_t < 30$ GeV
- $30 < E_t < 40$ GeV
- $40 < E_t < 50$ GeV

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- Gluon jets
- Model (Webber) with quark jets
- Gluon radiation
SUMMARY

- High-$p_T$ jet production is the dominant phenomenon in hard collisions at the $\bar{p}p$ collider.

- Jet identification is easy (multi-cell calorimeters $\rightarrow E_T$ clusters).

- Jet production can be studied by (almost) ignoring fragmentation (as if the high-$p_T$ partons themselves were detected).

- Data are in good agreement with QCD:
  - inclusive cross-sections
  - angular distribution of parton-parton scattering
  - structure functions (first direct measurement of gluon density in proton)

- Need three-gluon vertex to describe data.

- Need gluon radiation to explain fragmentation.
PRODUCTION AND DECAY OF THE INTERMEDIATE VECTOR BOSONS $W^\pm$ AND $Z^0$

1. Expected properties
   (Masses, decay modes, production cross-sections)

2. $W$ and $Z^0$ detection

3. Measured properties
   Masses
   Cross-sections
   $Z^0$ width $\rightarrow$ number of neutrinos
   Charge asymmetry in $W \rightarrow e\nu$ decay
   QCD effects

4. Evidence for $W \rightarrow t\bar{b}$

5. Conclusions
Masses

\[ W^\pm \frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2} \]
\[ g^2 = \frac{e^2}{\sin^2\theta_W} = \frac{4\pi\alpha}{\sin^2\theta_W} \]
\[ G = (1.16638 \pm 0.00002) \times 10^{-5} \text{ GeV}^{-2} \]

Fermi coupling constant

From a precision measurement of \( \tau_\mu \): \( \tau_\mu = (2.19709 \pm 0.00005) \times 10^{-6} \text{ s} \)

\[ \alpha^{-1} = 137.03604 \pm 0.00011 \quad (\text{at } Q^2 = m_e^2) \]

\[ \Rightarrow M_W = \frac{37.28}{\sin\theta_W} \text{ GeV} \]

Taking radiative corrections into account:

\[ M_{W^\pm} = \frac{38.65}{\sin\theta_W} \text{ GeV} \]

Present world average from various low energy experiments [\( \nu N, \bar{\nu} N, \nu e, \bar{\nu} e, e(\text{pol.}) D, e^+e^-\rightarrow\mu^+\mu^-\): see K. Winter EP 84-137]

\[ \sin^2\theta(s=M_W^2) = 0.217 \pm 0.014 \]

\[ \Rightarrow M_W = 83.0 \pm 2.7 \text{ GeV} \]

\[ Z^0 \]

\[ M_Z = \frac{M_W}{\cos\theta_W} = \frac{38.65}{\sin\theta_W \cos\theta_W} = \frac{77.30 \text{ GeV}}{\sin 2\theta_W} \]

(from minimal Higgs scheme)

\[ \Rightarrow M_Z = 93.8 \pm 2.2 \text{ GeV} \]

(\( \Delta M_W, \Delta M_Z \) are not independent!)