CERN

Cours/Lecture Series

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 $W^\pm$ and Z^0 bosons.

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

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HIGHLIGHTS ON $\bar{p}p$ COLLIDER RESULTS

Hard collisions :

$\bar{p}p \rightarrow$ high p_T 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.

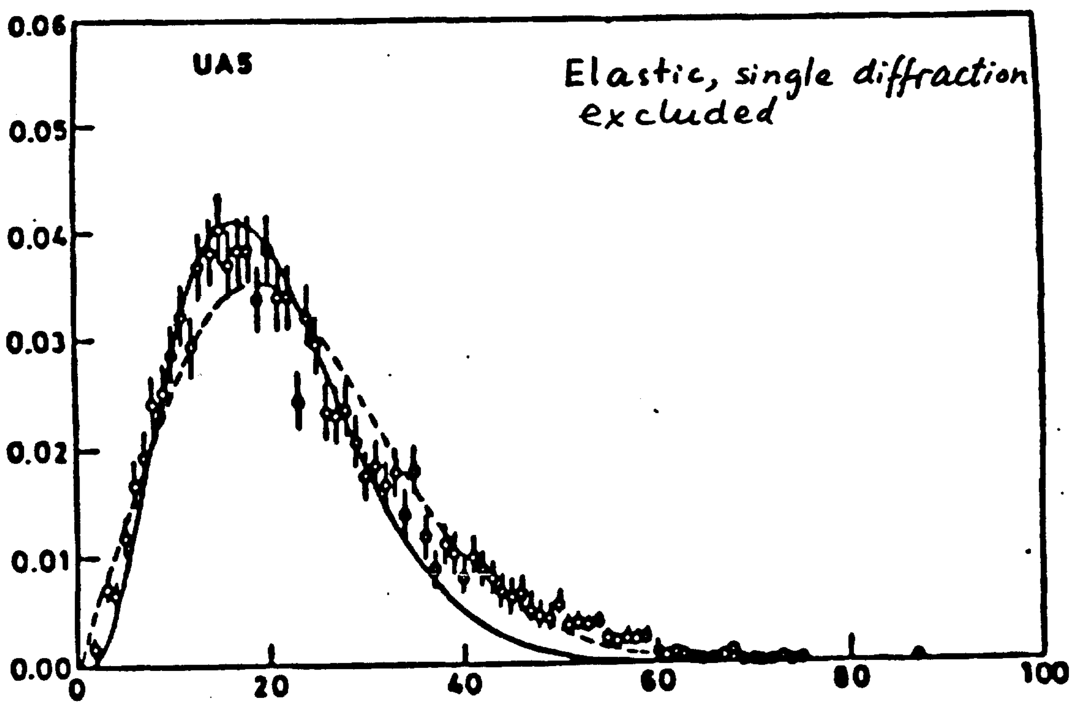
THESE ARE LECTURES FOR PHYSICISTS NOT ACTIVELY INVOLVED IN COLLIDER EXPERIMENTS

General features of $\bar{p}p$ collisions at $\sqrt{s} = 546$ GeV

$\underbrace{\sqrt{s}}$ ↳ total centre-of-mass energy

$$\left.\begin{aligned}\sigma_{TOT} &\approx 62 \text{ mb} \\ \sigma_{el} &\approx 13 \text{ mb}\end{aligned}\right\} \text{UA4}$$

Distribution of charged particle multiplicity (n_c)

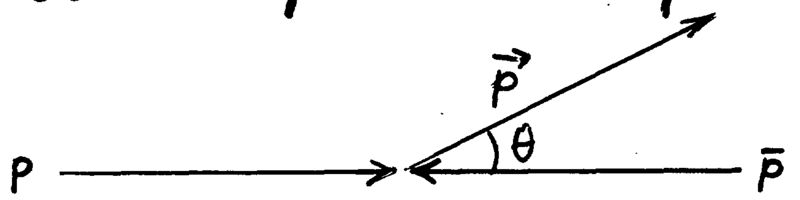


$\langle n_c \rangle = 29$

$\langle n_\gamma \rangle = 31$

↳ mostly from $\pi^0 \to \gamma\gamma$

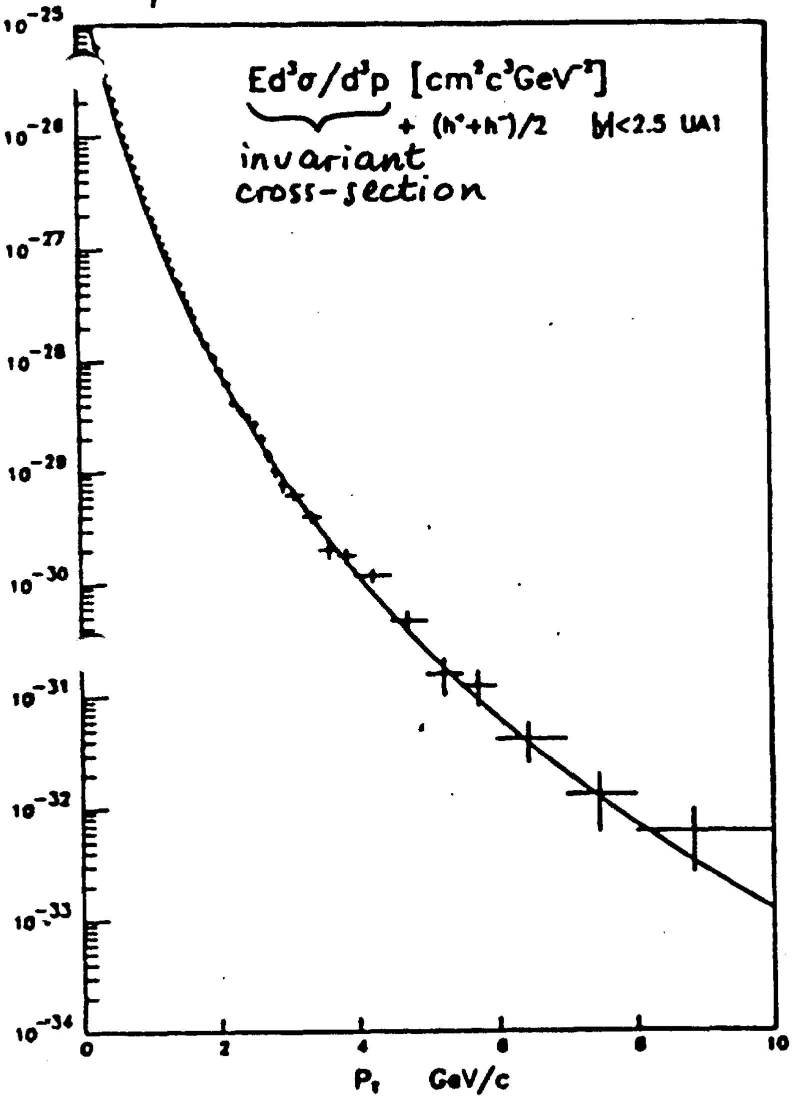
Need two variables to describe inclusive particle production

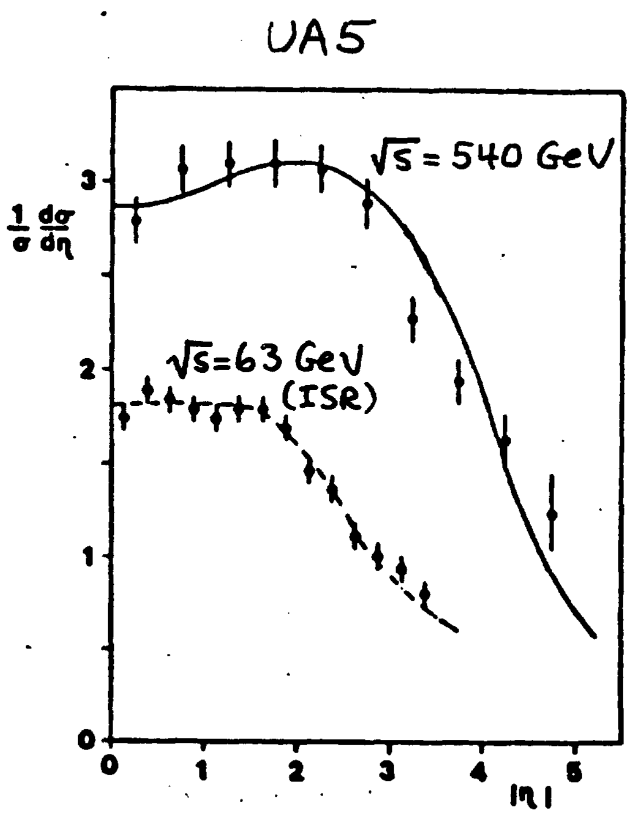


$p_T = p \sin\theta$ transverse momentum

$y = \frac{1}{2} \ln \frac{E + p\cos\theta}{E - p\cos\theta}$ rapidity

$\lim_{\beta \to 1} y = -\ln \tan(\theta/2) = \eta$ pseudorapidity





$\langle p_T \rangle \approx 0.4$ GeV/c

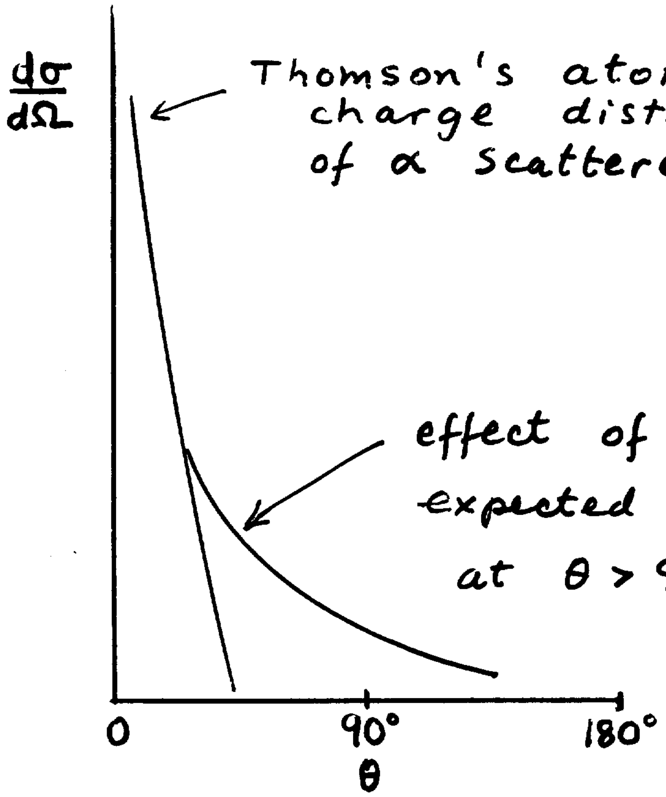
SOFT COLLISIONS ≡ small p_T

HARD COLLISIONS ≡ large p_T or production of large M

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

HISTORICAL EXAMPLE:

α – Nucleus scattering (1908 → 1911)



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

effect of atomic nucleus with $R \sim 10^{-13} A^{1/3}$ cm
expected fraction of α scattered at $\theta > 90° \approx 1/8000$

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 $\equiv$ 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 $x\, dn/dx$ (depend on parton type)

QCD non-Abelian gauge theory : the best candidate to describe the strong interaction among partons

HARD $\bar{p}p$ 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 : –

$$\xrightarrow{x_1\sqrt{s}/2} \; \xleftarrow{x_2\sqrt{s}/2}$$

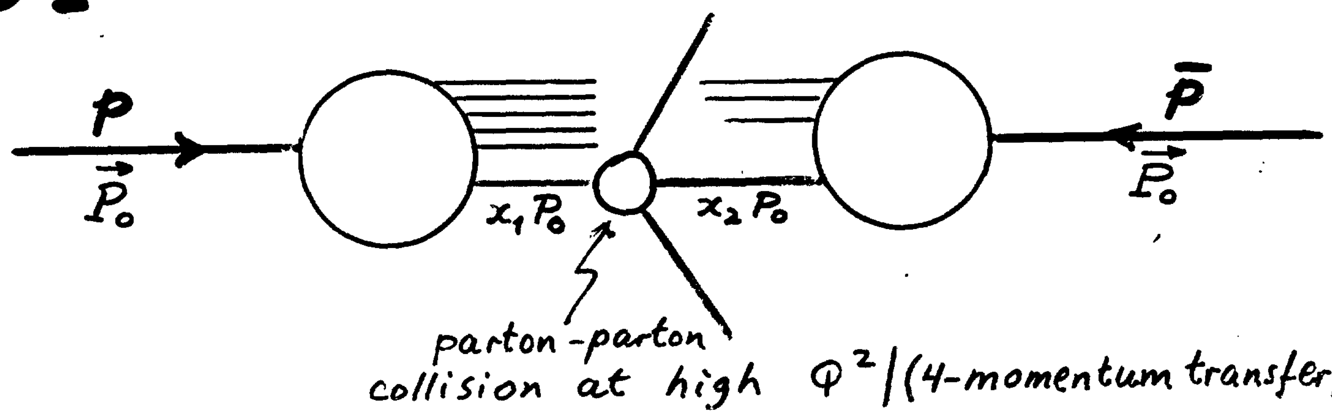
$\sqrt{\hat{s}} = \sqrt{s\, x_1 x_2}$ (neglecting masses and initial p_T)

Parton-parton scattering → jets

$q\bar{q}$ annihilation → $\ell^+\ell^-$ continuum, $W^\pm$, Z^0

HIGH - PT JETS : a 2-step process

Step 1



- Many types of parton collisions:

$$\left.\begin{array}{l} q\bar{q} \to q\bar{q} \\ q\bar{q} \to q'\bar{q}' \\ qq \to qq \\ qg \to qg \\ \bar{q}g \to \bar{q}g \\ gg \to gg \\ gg \rightleftarrows q\bar{q} \end{array}\right\}$$

all occurring to leading order in QCD

Q^2 large $\longrightarrow$ collisions at short distance

- **Perturbative calculations are possible because of "asymptotic freedom"**

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2)}$$

α_s: QCD coupling constant

n_f: number of quark flavours with $m^2 < Q^2$

Λ: scale parameter

$$\lim_{Q^2 \to \infty} \alpha_s(Q^2) = 0 \quad \text{if } n_f < 16$$

In general $x_1 \neq x_2$

→ final state high-p_T partons are not collinear

Initial $p_T \approx 0$ → final state high-p_T partons are coplanar with beams

Step 2 Parton fragmentation (hadronisation)

High-p_T parton → collimated system of high-p_T hadrons (jet). $\Sigma \vec{p} \approx \vec{P}$(parton)

Final state interaction between the high-p_T partons and the other partons:

long distance → Q^2 small → α_s large

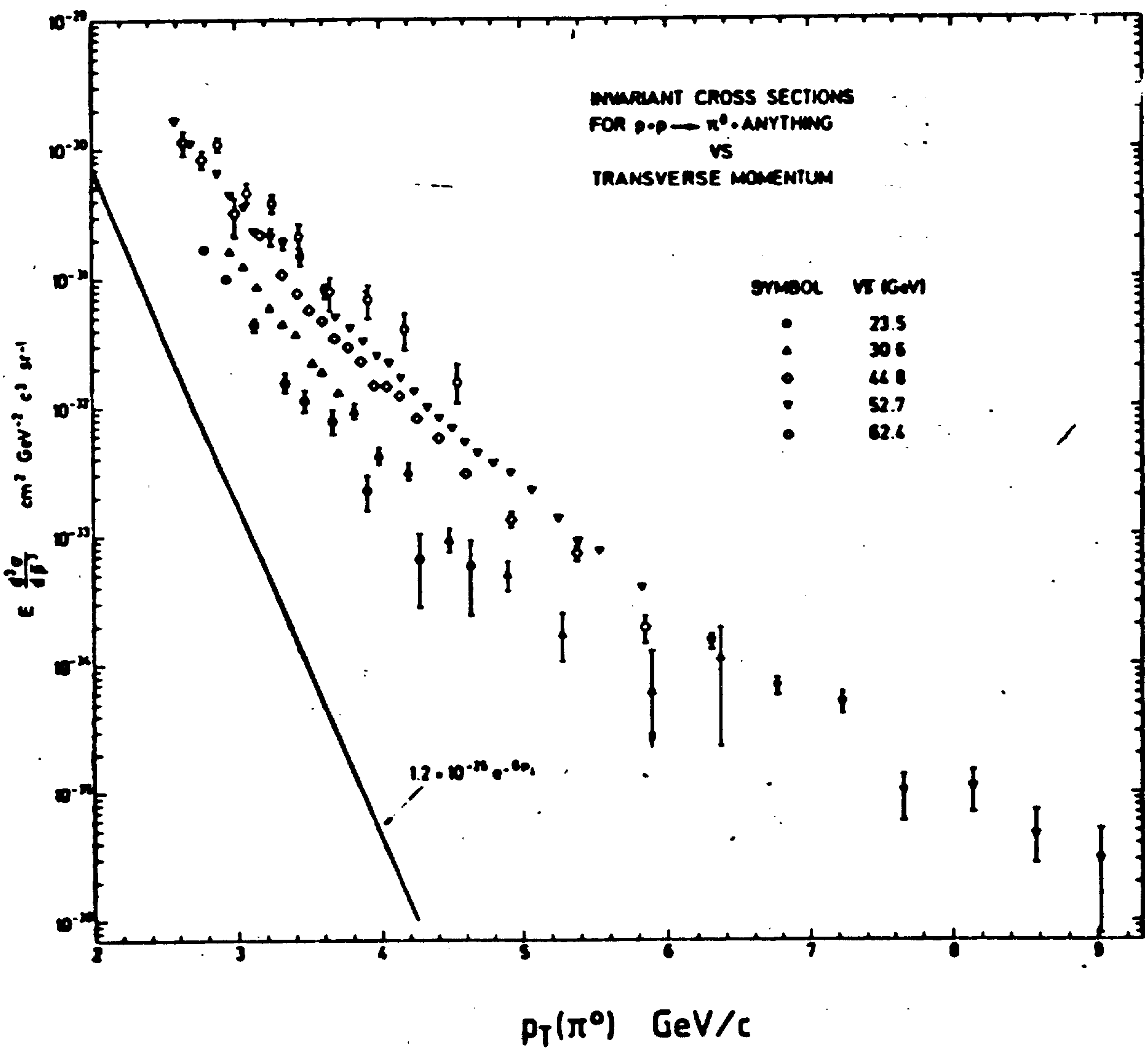
Need non-perturbative techniques (still missing at present)

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

High-p_T jet production from hadronic collisions was predicted by Berman, Bjorken, Kogut (1971) as a consequence of the parton model.

1972 – ISR ($\sqrt{s} = 23 \rightarrow 63$ GeV)

Observation of high-p_T π^0 (CCR)



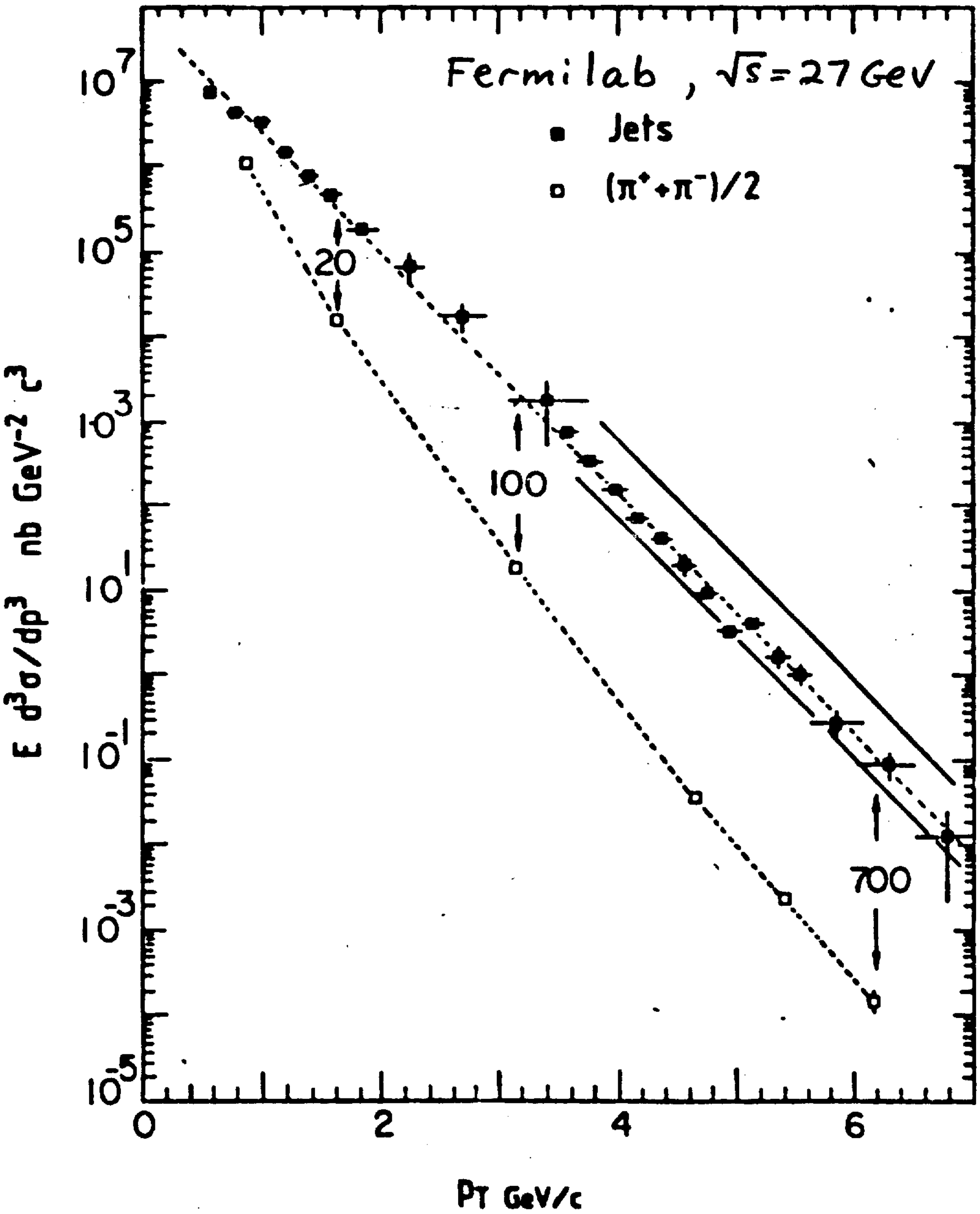
Parton model prediction ($\theta = 90°$)

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

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

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



1973 – 80 : events with high-p_T hadrons compatible with two-jet structure
— but calorimeters have limited solid angle (~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 :

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

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

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 ΣE_T (10-20 GeV) consist in general of many low-p_T particles with uniform ϕ-distribution

→ **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

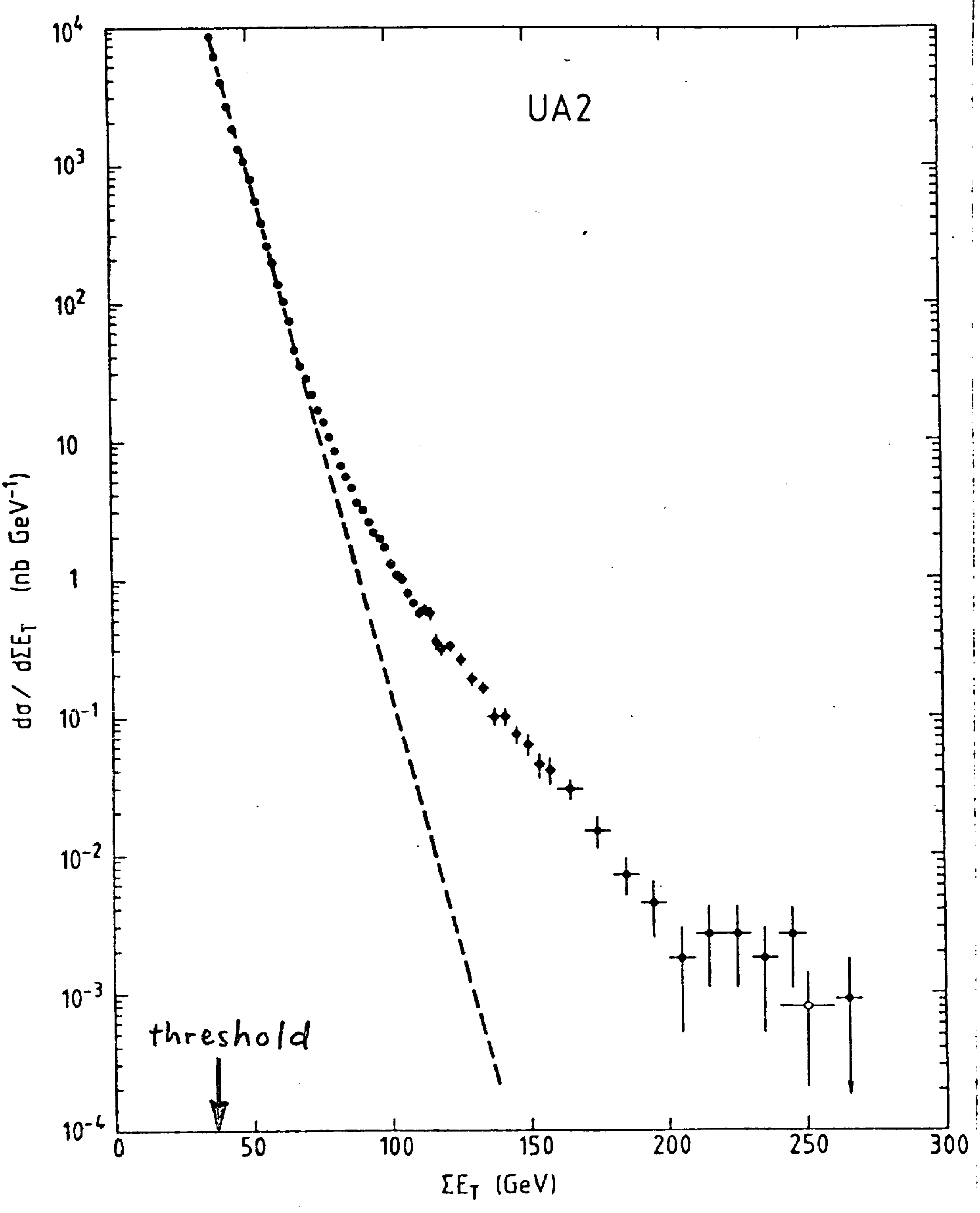
Among the conclusions of the Workshop:

> 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

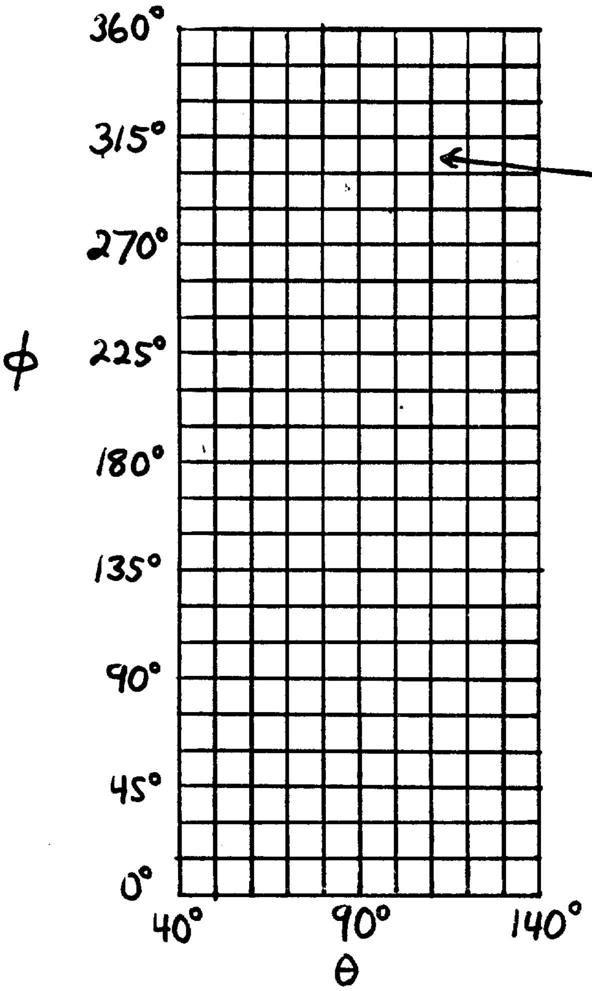
July 1982 Paris Conference :

Clear evidence for high-p_T jet-production in the UA2 experiment



$$\Sigma E_T = \sum_{\text{all cells}} E_i \sin\theta_i$$

Search for E_T clusters in events with large ΣE_T



cluster: $n (\geq 1)$ adjacent cells. each with $E > 0.4$ GeV

Cluster transverse energy:

$$E_T = \sum E_i \sin\theta_i \quad \text{(sum over all cluster cells)}$$

Cluster ordering:

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

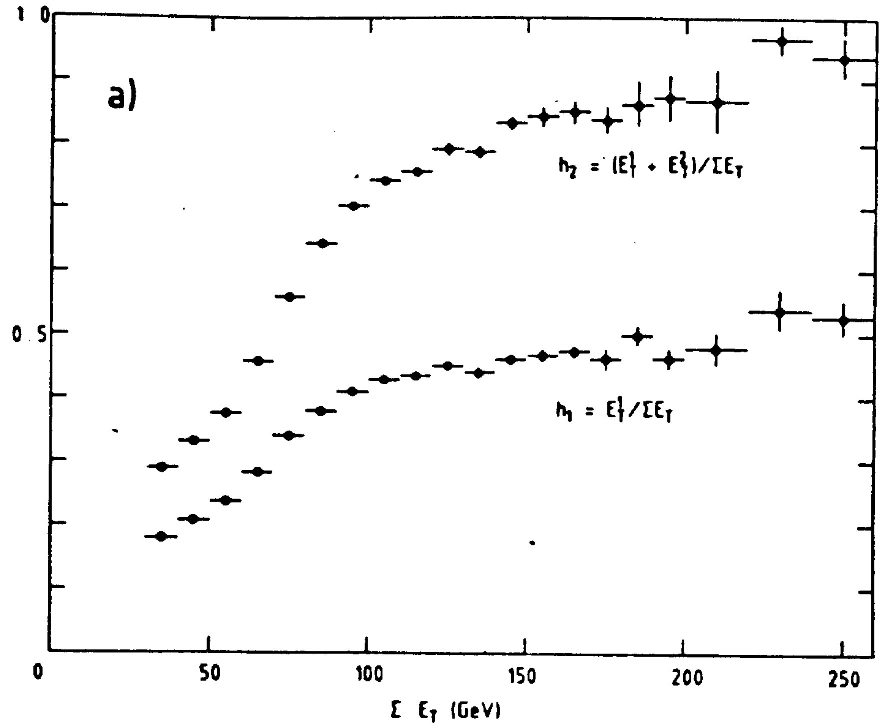
For two-jet event expect

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

$\Delta\phi \approx 180^\circ$ (coplanarity with beam axis)

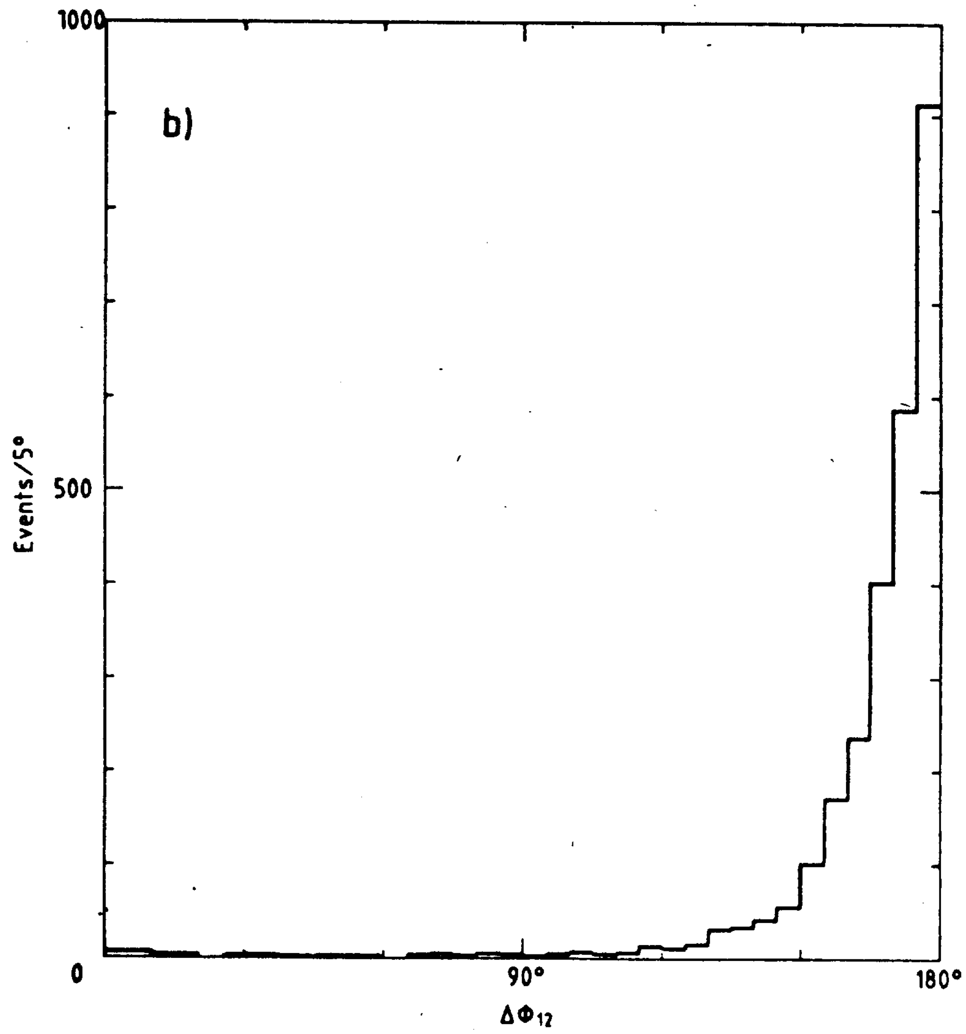
$\langle h_2 \rangle$

$\langle h_1 \rangle$

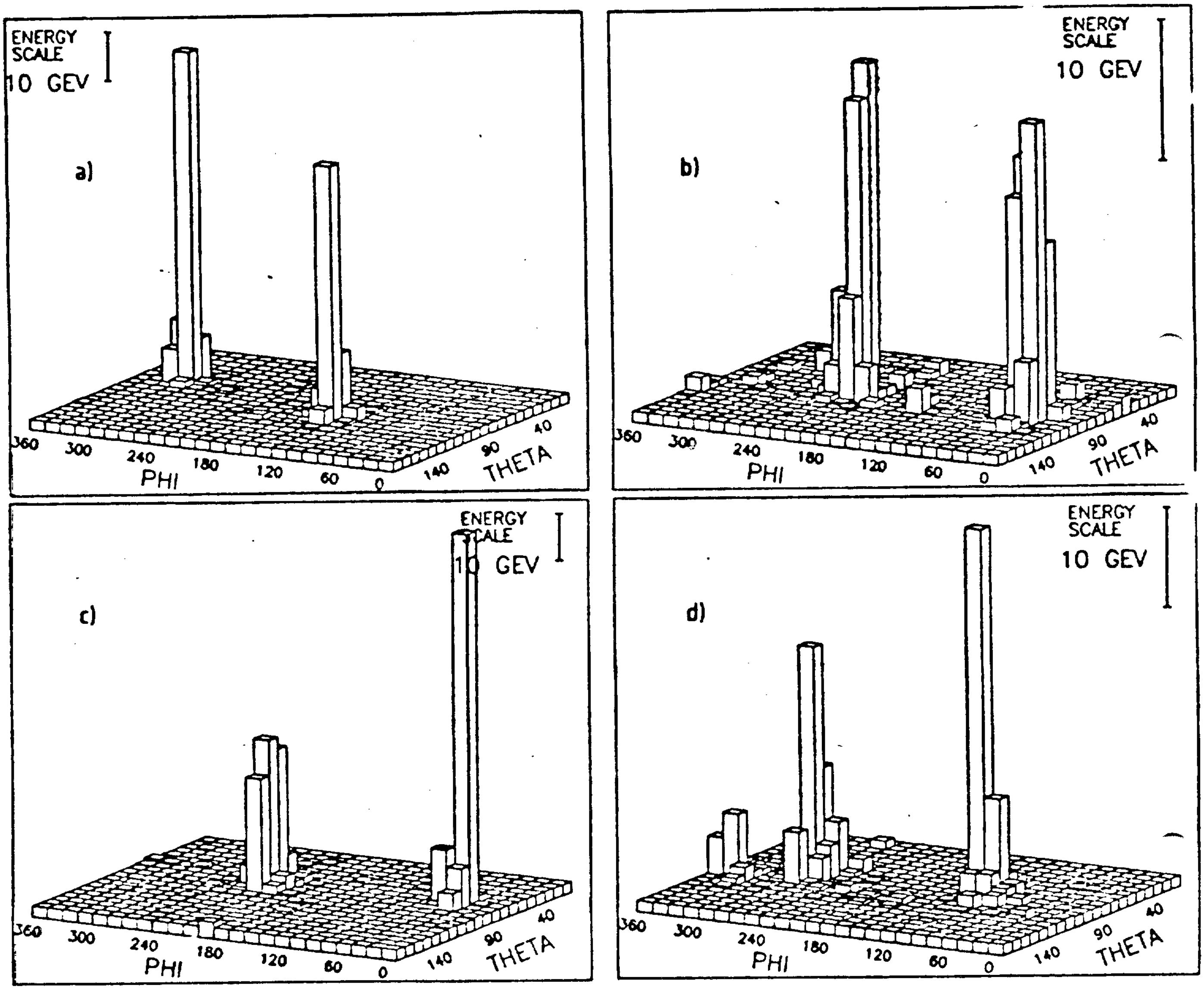


For two jets only $h_2 = 1$

For perfect p_T balance $h_1 = h_2 = 1/2$



Typical E_T distribution in events with $\sum E_T > 100$ GeV

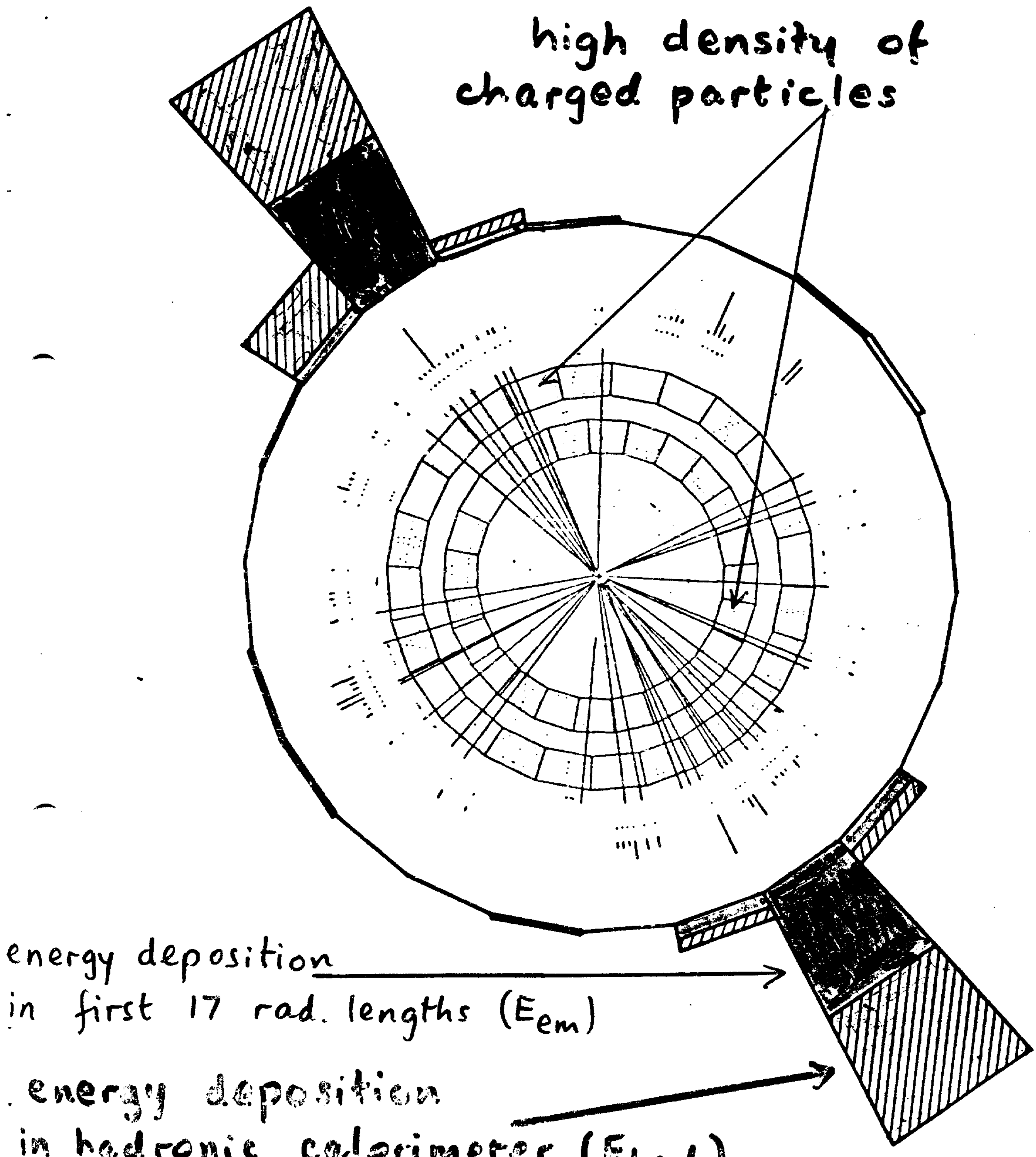


Main feature of events with large $\sum E_T$ at the $\bar{p}p$ collider:

$\sum E_T$ consists mainly of two narrow clusters, $E_T^{(1)} \approx E_T^{(2)}$, $\Delta\phi_{1,2} \approx 180^\circ$

as expected for two-jet final states

Event projection in plane $\perp$ to beams



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

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

For typical jet (~50% π^0, ~50% charged hadrons) : $\frac{E_{had}}{E_{em}} \gtrsim 1$

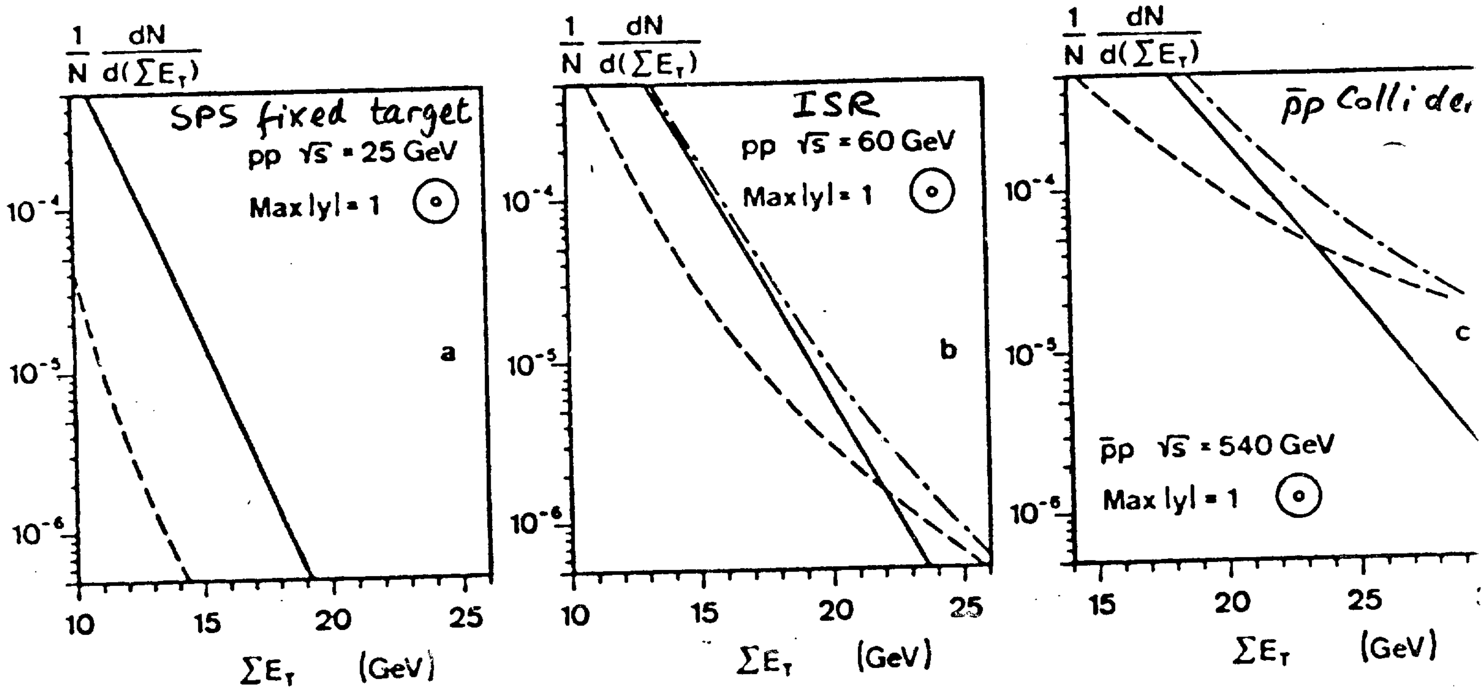
Why NA5 did not see jets?

Study ΣE_T vs $\sqrt{s}$ (Åkesson, Bengtsson 1982)

Two contributions:

------ parton-parton scattering → 2 jets

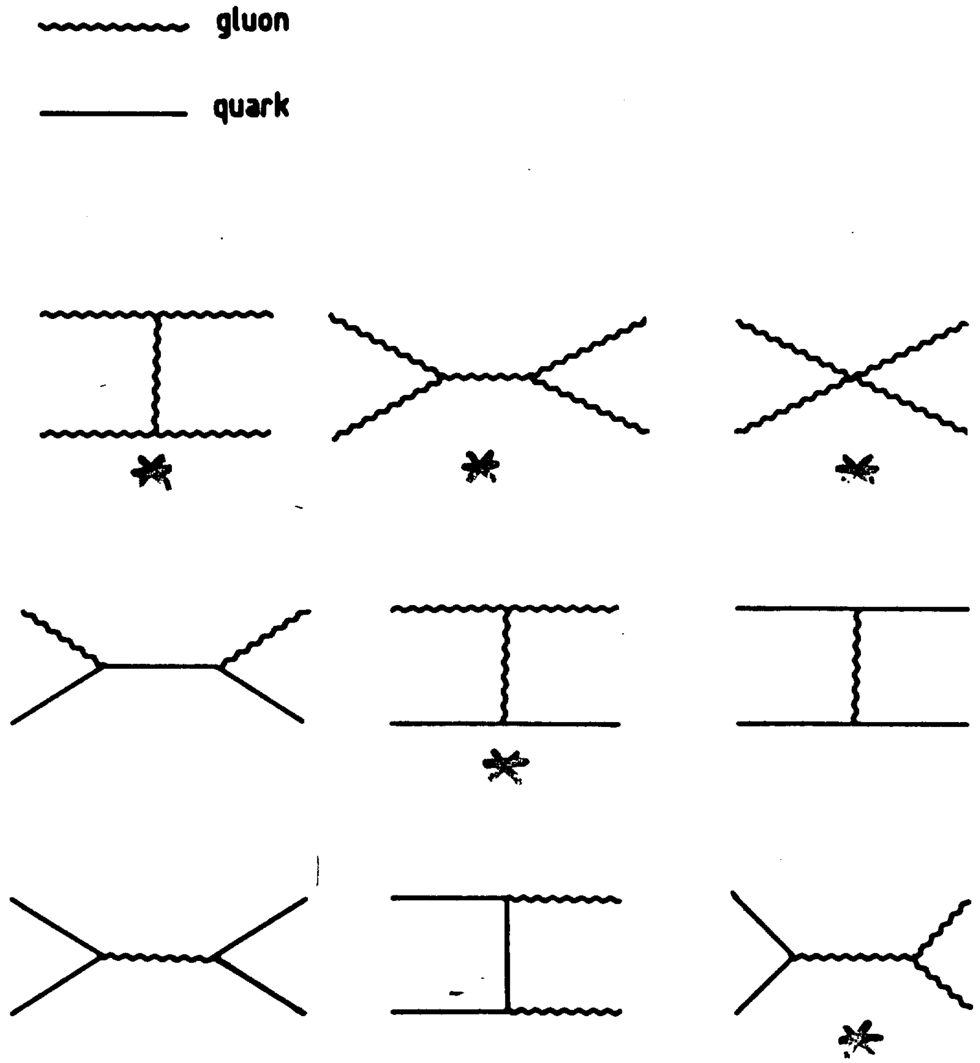
______ soft collisions : tail of multiplicity distribution



Contribution from hard parton-parton collisions increasing rapidly with $\sqrt{s}$ becomes dominant at Collider energies for ΣE_T large

Parton sub-processes

1st order QCD diagrams



* contains 3- or 4- gluon vertex (non-Abelian structure of QCD)

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

$\hat{s} \equiv$ (total energy in the two-parton centre-of-mass frame)^2

$= s x_1 x_2$

$$\left.\begin{aligned} t &= -\hat{s}\,(1-\cos\theta^*)/2 \\ u &= -\hat{s}\,(1+\cos\theta^*)/2 \end{aligned}\right\}\ \text{Mandelstam variables}$$

(neglecting quark masses)

Combridge, Kripfganz, Ranft (1977)

Subprocess	$\lvert M\rvert^2 = f(\cos\theta^*)$	$\lvert M\rvert^2$ at $\theta^* = 90°$
$qq' \to qq'$ [a] $q\bar{q}' \to q\bar{q}'$ [a]	$\frac{4}{9}\,\frac{\hat{s}^2+u^2}{t^2}$	2.22
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+u^2}{t^2}+\frac{\hat{s}^2+t^2}{u^2}\right)-\frac{8}{27}\,\frac{\hat{s}^2}{ut}$	3.26
$q\bar{q} \to q'\bar{q}'$ [a]	$\frac{4}{9}\,\frac{t^2+u^2}{\hat{s}^2}$	0.22
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+u^2}{t^2}+\frac{t^2+u^2}{\hat{s}^2}\right)-\frac{8}{27}\,\frac{u^2}{\hat{s}t}$	2.59
$q\bar{q} \to gg$	$\frac{32}{27}\,\frac{u^2+t^2}{ut}-\frac{8}{3}\,\frac{u^2+t^2}{\hat{s}^2}$	1.04
$gg \to q\bar{q}$	$\frac{1}{6}\,\frac{u^2+t^2}{ut}-\frac{3}{8}\,\frac{u^2+t^2}{\hat{s}^2}$	0.15
$gq \to gq$ $\bar{q}g \to \bar{q}g$	$-\frac{4}{9}\,\frac{u^2+\hat{s}^2}{u\hat{s}}+\frac{u^2+\hat{s}^2}{t^2}$	6.11
$gg \to gg$	$\frac{9}{2}\left(3-\frac{ut}{\hat{s}^2}-\frac{u\hat{s}}{t^2}-\frac{\hat{s}t}{u^2}\right)$	30.38

a q and q' denote quarks with different flavors.

INCLUSIVE JET PRODUCTION

Inclusive jet cross-section as a sum of convolution integrals

$$\frac{d^2\sigma}{dp_T\, d(\cos\theta)} = \frac{2\pi p_T}{\sin^2\theta} \sum_{a,b} \int dx_1 dx_2\, F_a(x_1, Q^2) F_b(x_2, Q^2) \times$$

$$\times \left[\alpha_s(Q^2)\right]^2 \delta(\hat{s} + t + u) \sum_f \frac{|M|^2_{ab \to f}}{\hat{s}}$$

$\sum_{a,b} \sum_f$ sum over all possible subprocesses

$$a + b \longrightarrow f$$

($f \equiv$ two-parton final state)

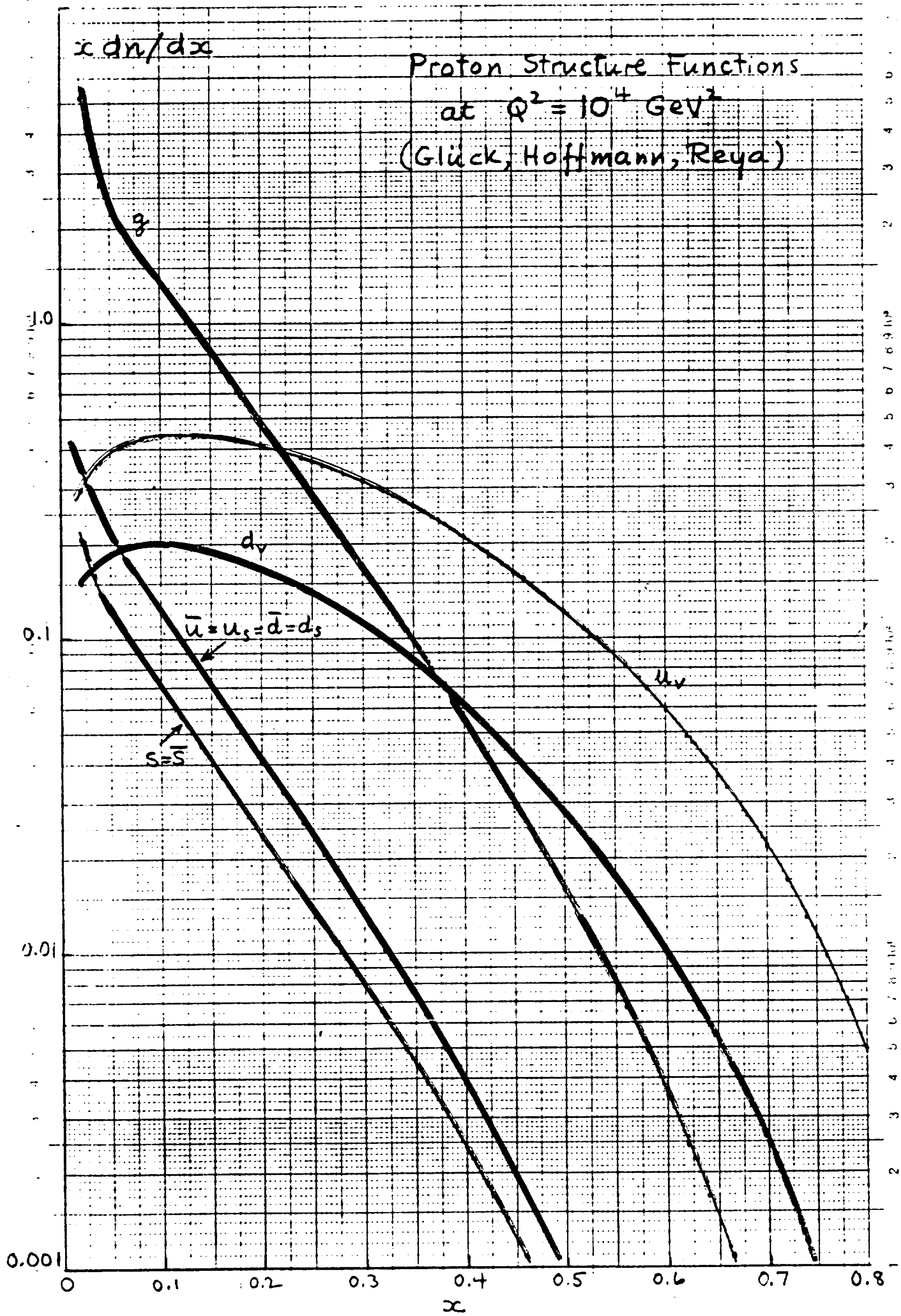
$F_a(x, Q^2) = x\, dn/dx$ structure function for parton type a — measured in deep inelastic lepton-nucleon scattering at $Q^2 \leq 100$ GeV^2 — extrapolated to $Q^2 \approx 10^3 - 10^4$ GeV^2 using QCD evolution (Altarelli-Parisi equation)

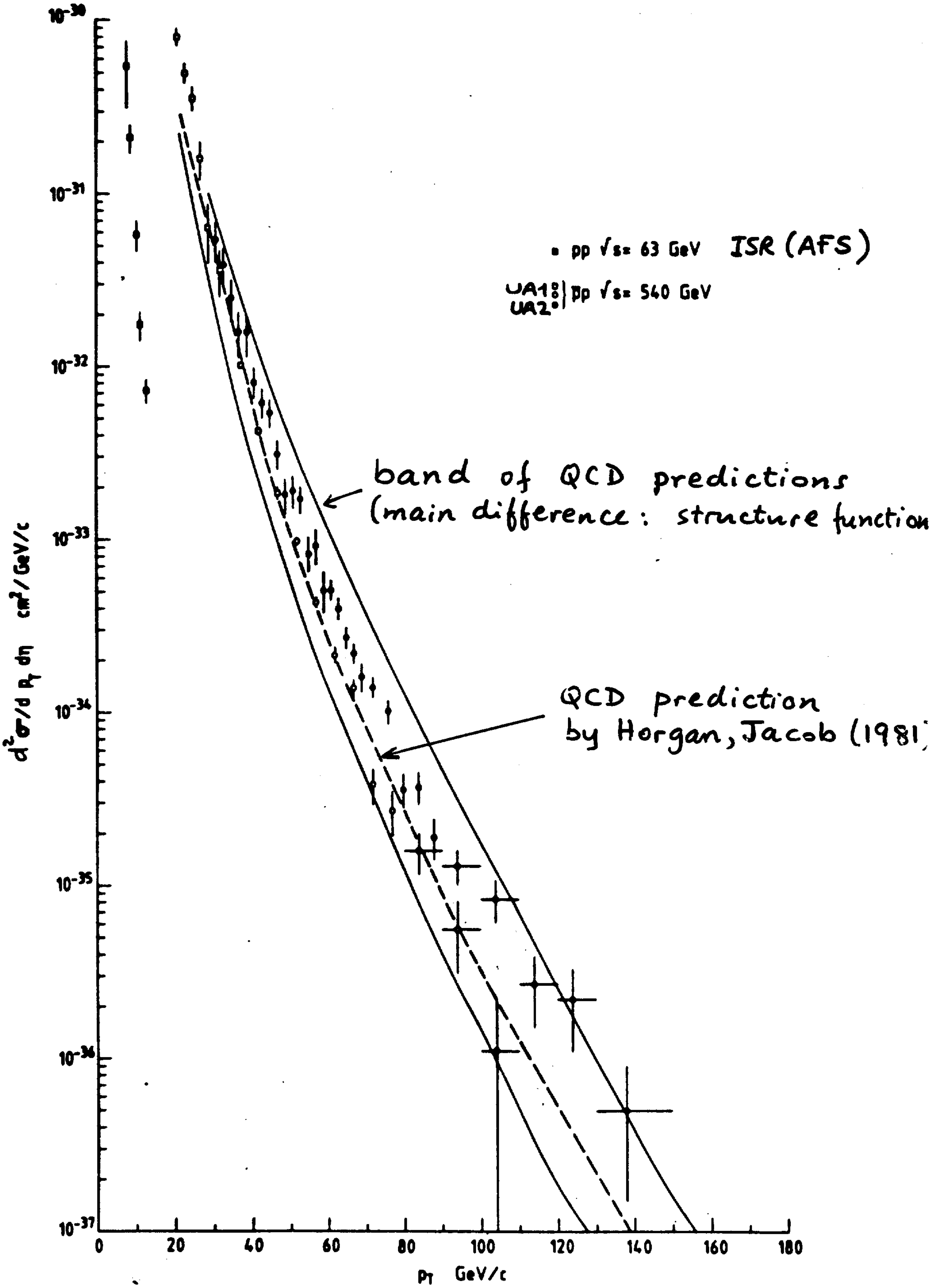
Theoretical uncertainties

$\pm 50\%$
- 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)

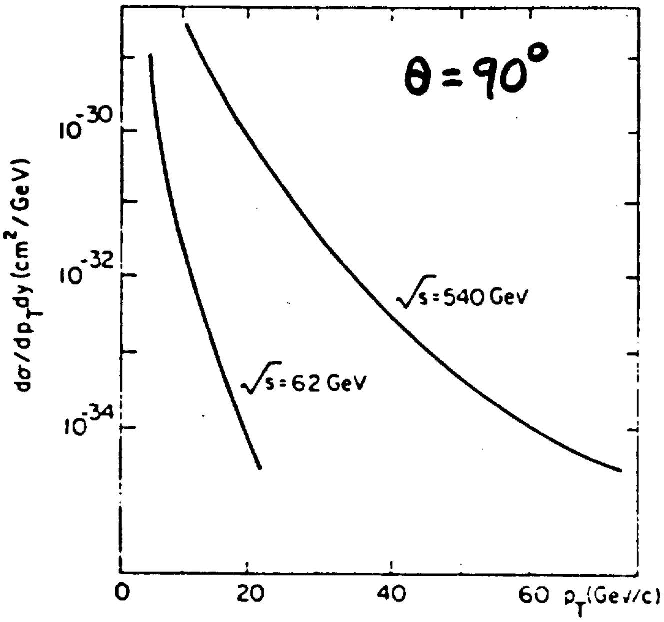
Experimental uncertainties

$\pm 50\%$
- Energy calibration of calorimeter (typically $\pm 4\%$)
- **Acceptance** (jet angular dimensions)
- Luminosity


x dn/dx
Proton Structure Functions
at Q² = 10⁴ GeV²
(Glück, Hoffmann, Reya)
g
1.0
d_v
$\bar{u} = u_s = \bar{d} = d_s$
0.1
u_v
$s = \bar{s}$
0.01
0.001
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x



QCD predictions are absolute — there is no adjustable parameter



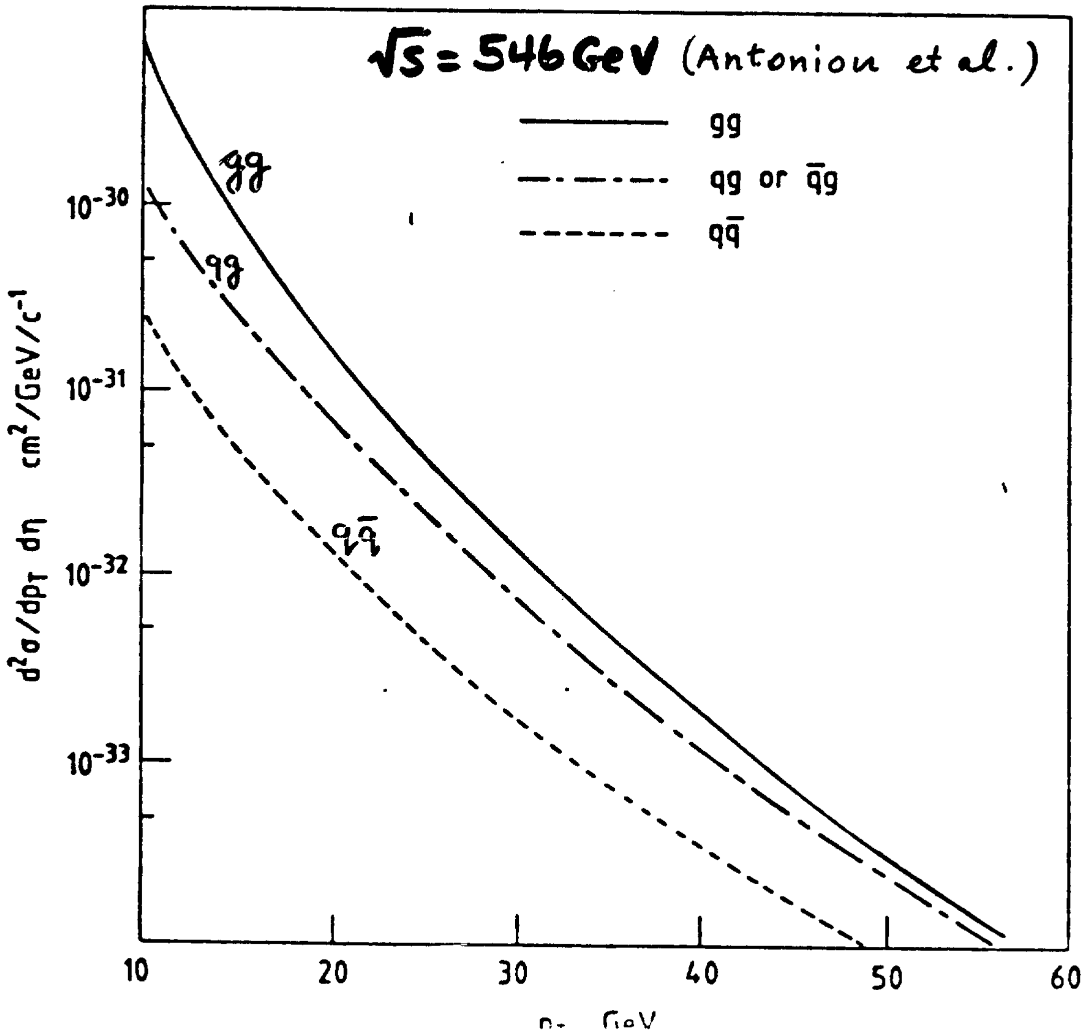
Horgan, Jacob 1981

In parton-parton centre-of-mass:

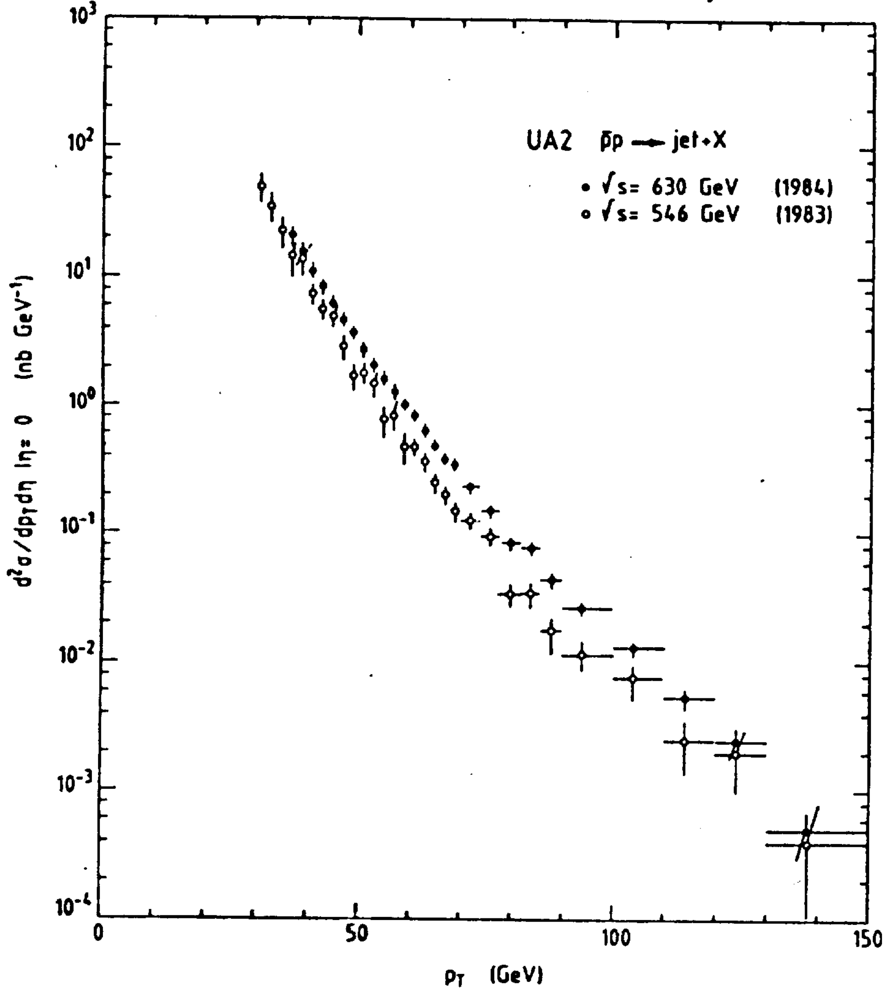
$\theta^* = 90°$ $\quad p_T = \sqrt{\hat{s}}/2 = \sqrt{s\, x_1 x_2}/2$

For $x_1 \approx x_2$ $\quad x \approx 2p_T/\sqrt{s}$

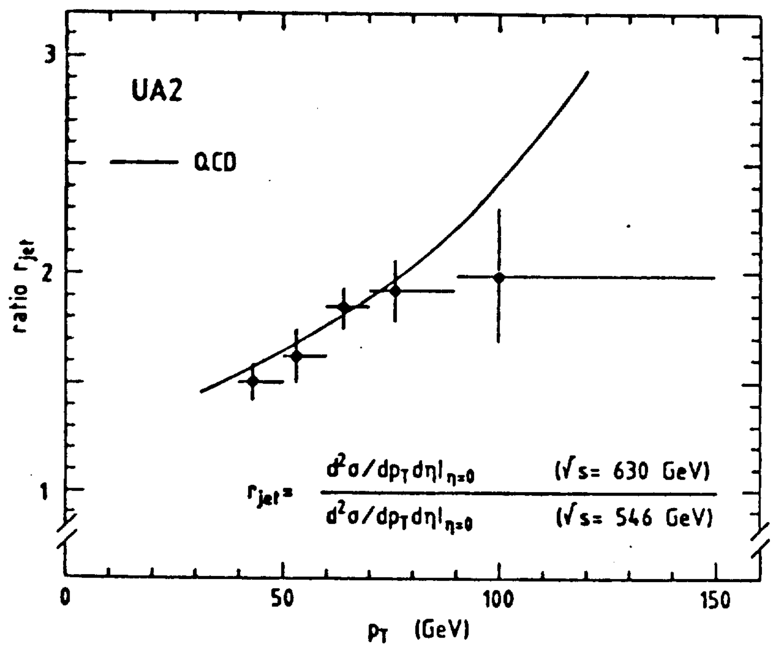
	ISR ($\sqrt{s}=63$)	$\bar{p}p$ Collider ($\sqrt{s}=630$)
$p_T \approx 20 \rightarrow x \approx$	0.6	0.06
Dominance of	valence quarks	gluons



Comparison of jet yields
$\sqrt{s} = 546$ GeV vs. 630 GeV
(UA2, 1985 Workshop on $\bar{p}p$ Physics, St. Vincent)



Most theoretical and experimental uncertainties drop out in the ratio

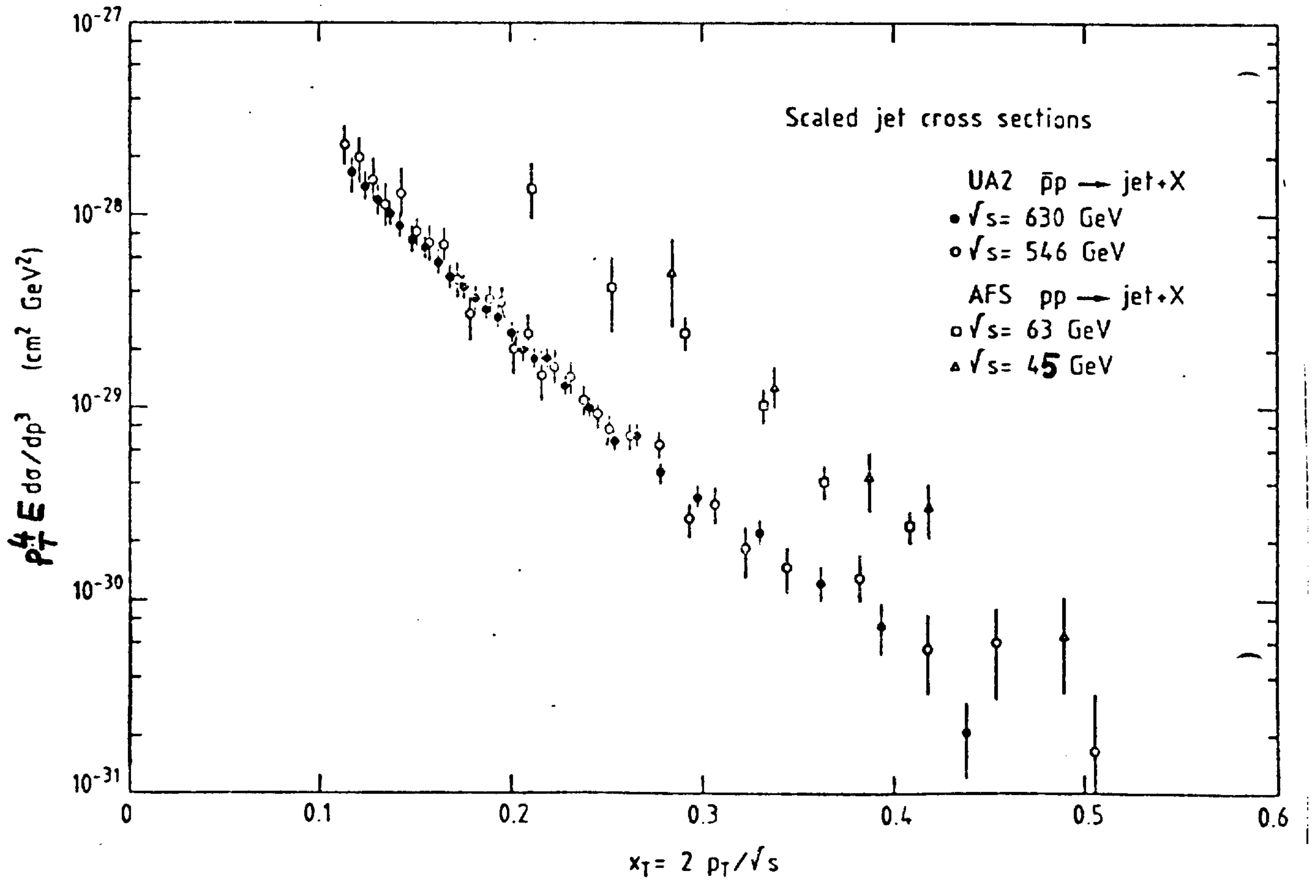


For Q^2-independent structure function: ("naive" parton model) expect ($\theta = 90$

$$E\,d\sigma/dp^3 = p_T^{-4}\,\underbrace{f(x_T)}_{\text{dimensionless function of } x_T = 2p_T/\sqrt{s}}$$

invariant cross-section

(can derive this relation using dimensional considerations only)



ISR – $\bar{p}p$ Collider comparison

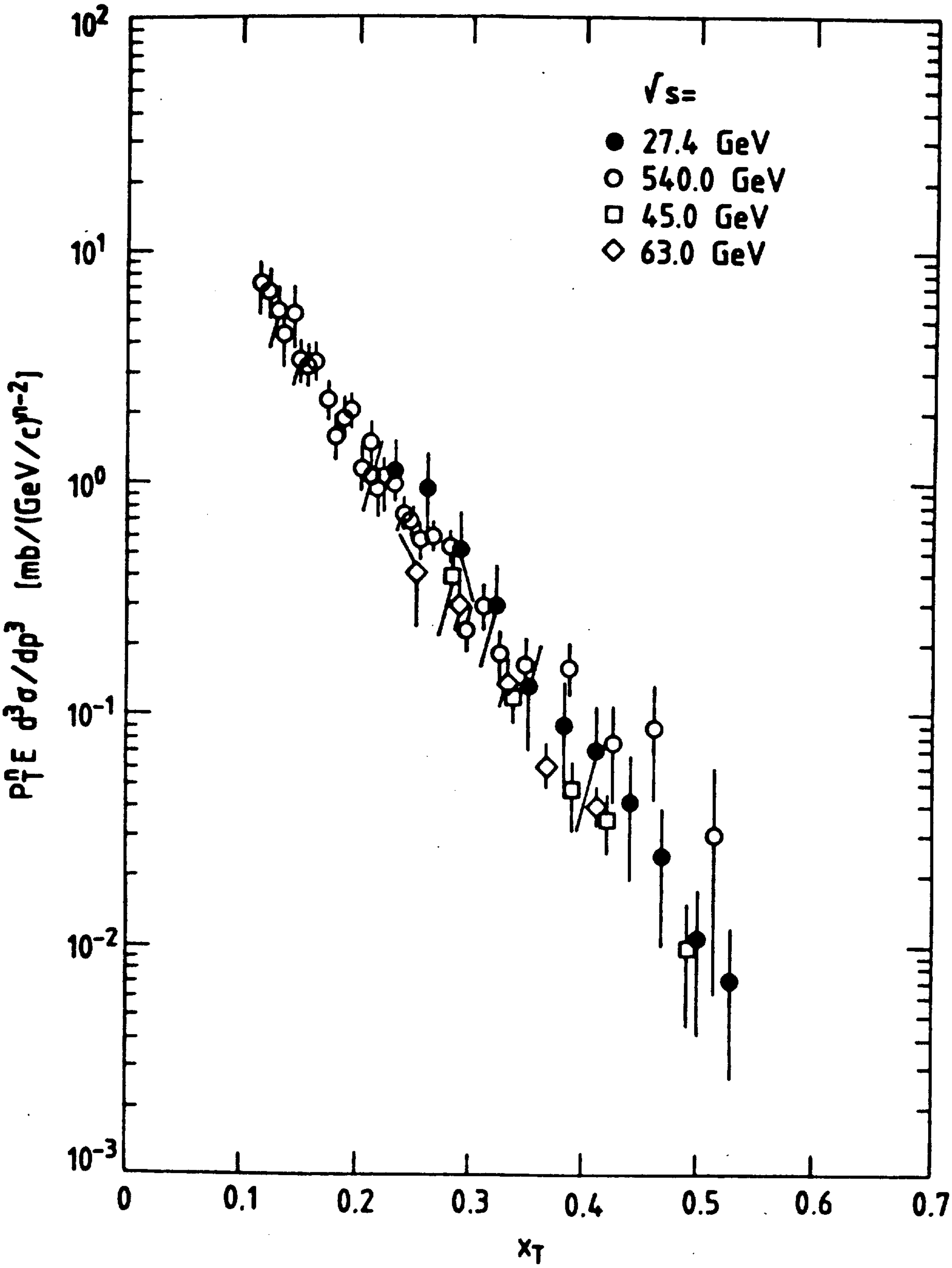
→ evidence for scaling violations

$f(x_T, Q^2)$

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

For a given x_T $\quad Q^2_{collider}/Q^2_{ISR} \approx \left(\frac{630}{63}\right)^2 = 10^2$

APPROXIMATE SCALING, $\sqrt{s} = 27 \rightarrow 540$ GeV



Good fit with form $E\dfrac{d\sigma}{dp^3} = A\, p_T^{-n}(1-x_T)^m$

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

$n = 5.1 \pm 0.3 \qquad m = 10.6 \pm 0.5$

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 ($gg \to gg$, 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

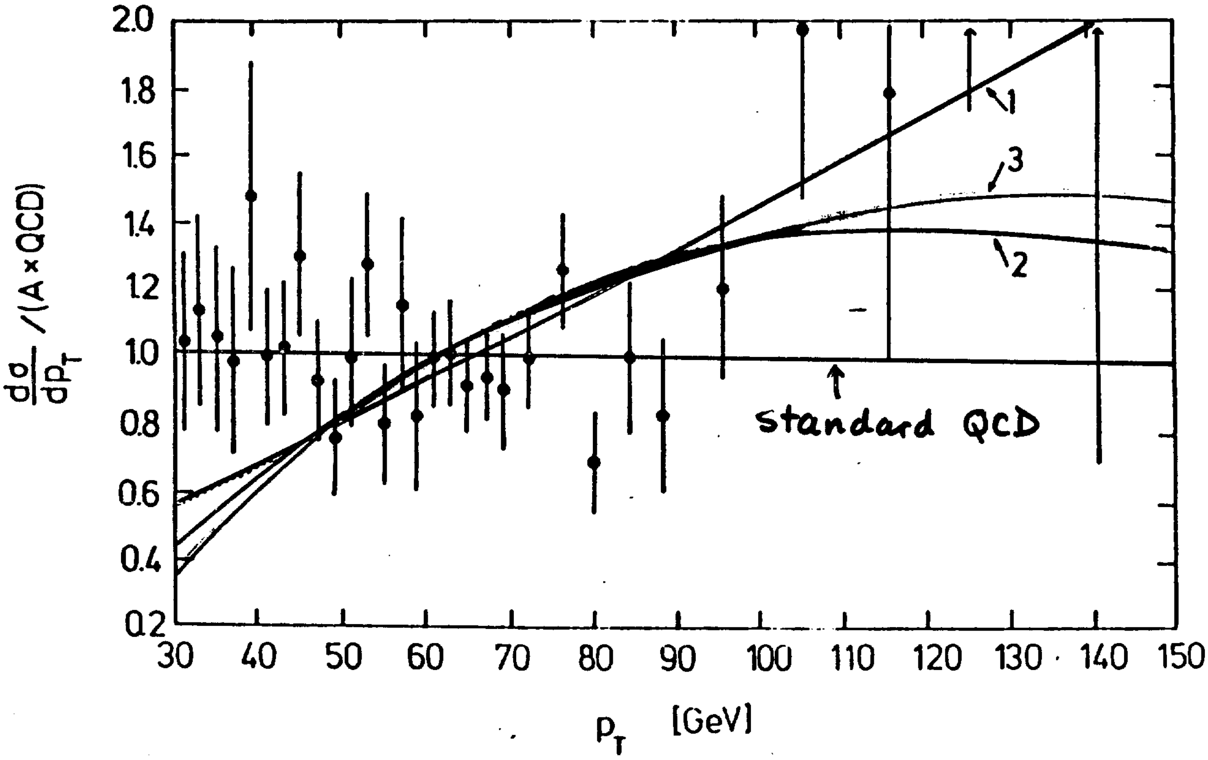
3.– Hope that fit is good for standard QCD — bad if effects of 3-g vertex are switched off.

Standard QCD – $\chi^2/d.o.f. = 0.9 - 1.1$ depending on structure functions, Q^2 definition, Λ, 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, + α_s = constant : $\chi^2/d.o.f. = 3.5$



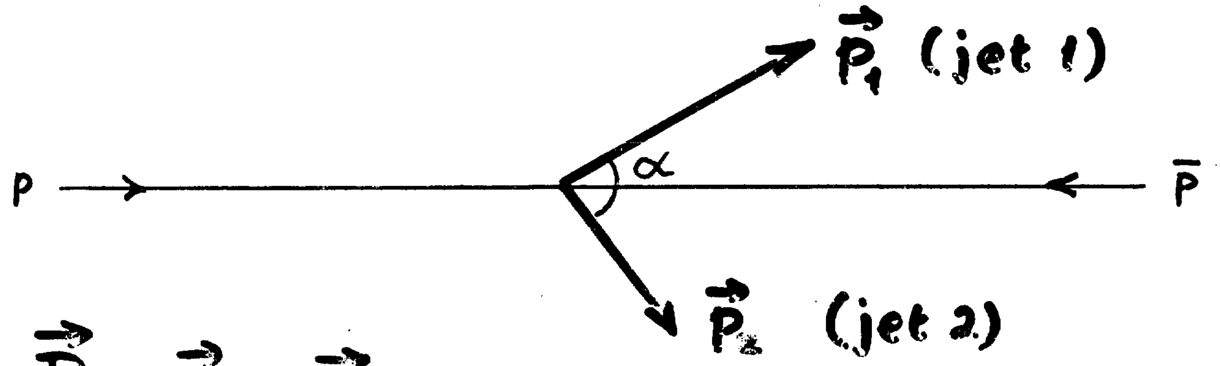
→ switching off 3-gluon vertex (either partially or totally) changes <u>shape</u> of p_T-dependence in disagreement with shape observed experimentally.

PARTON-PARTON SCATTERING

Determination of :

1.– Angular distribution $d\sigma/d\cos\theta^*$

2.– Structure functions



$$\vec{P} = \vec{P}_1 + \vec{P}_2$$

$$M_{jj}^2 = 4\,p_1 p_2 \sin^2(\alpha/2)$$

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

$$\theta^* = \sin^{-1}(2p_T/M_{jj})$$

$$x_1 = \left(\sqrt{P_L^2 + M_{jj}^2} + P_L\right)/\sqrt{s}$$

$$x_2 = \left(\sqrt{P_L^2 + M_{jj}^2} - P_L\right)/\sqrt{s}$$

∴ Events with two p_T-balanced jets allow determination of x_1, x_2 and θ^* (scattering angle in two-parton centre-of-mass)

For $P_T \neq 0$ θ^* is ambiguous — Collins-Soper convention shares $\vec{P}_T$ equally between the two incident partons

$$\frac{d^3\sigma}{dx_1\,dx_2\,d(\cos\theta^*)} = \sum_{a,b} \underbrace{\frac{F_a(x_1)}{x_1}\;\frac{F_b(x_2)}{x_2}}_{\substack{\text{densities } dn/dx \\ \text{for partons } a,\,b}} \sum_f \frac{d\sigma}{d\cos\theta^*}(ab\to f)$$

Hopeless at first sight because of many subprocesses $a,b \to f$

However the dominant subprocesses :

$gg \to gg$ $\quad$ $gq \to gq$ $\quad$ $q\bar{q} \to q\bar{q}$

$g\bar{q} \to g\bar{q}$

have very similar shapes for $d\sigma/d\cos\theta^*$

→ As an approximation use $d\sigma/d\cos\theta^*$ for gg scattering :

$$d\sigma/d\cos\theta^* = \frac{\pi\alpha_s^2}{2x_1x_2s}\cdot\frac{9}{8}\cdot\underbrace{\frac{(3+\cos^2\theta^*)^3}{(1-\cos^2\theta^*)^2}}$$

Note $\sin^{-4}\theta^*/2$ term (Rutherford) due to vector boson exchange present in $gg\to gg$, $gq\to gq$ because of 3-gluon vertex

Also present in $q\bar{q}\to q\bar{q}$

$$\frac{d^3\sigma}{dx_1\,dx_2\,d(\cos\theta^*)} \approx \left[\frac{d\sigma}{d(\cos\theta^*)}\right]_{gg\to gg} \sum_a \frac{F_a(x_1)}{x_1}\sum_b \frac{F_b(x_2)}{x_2}$$

Approximate relations :

$$\left[\frac{d\sigma}{d\cos\theta^*}\right]_{gq\to gq} \approx \frac{4}{9}\left[\frac{d\sigma}{d\cos\theta^*}\right]_{gg\to gg}$$

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

→ 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

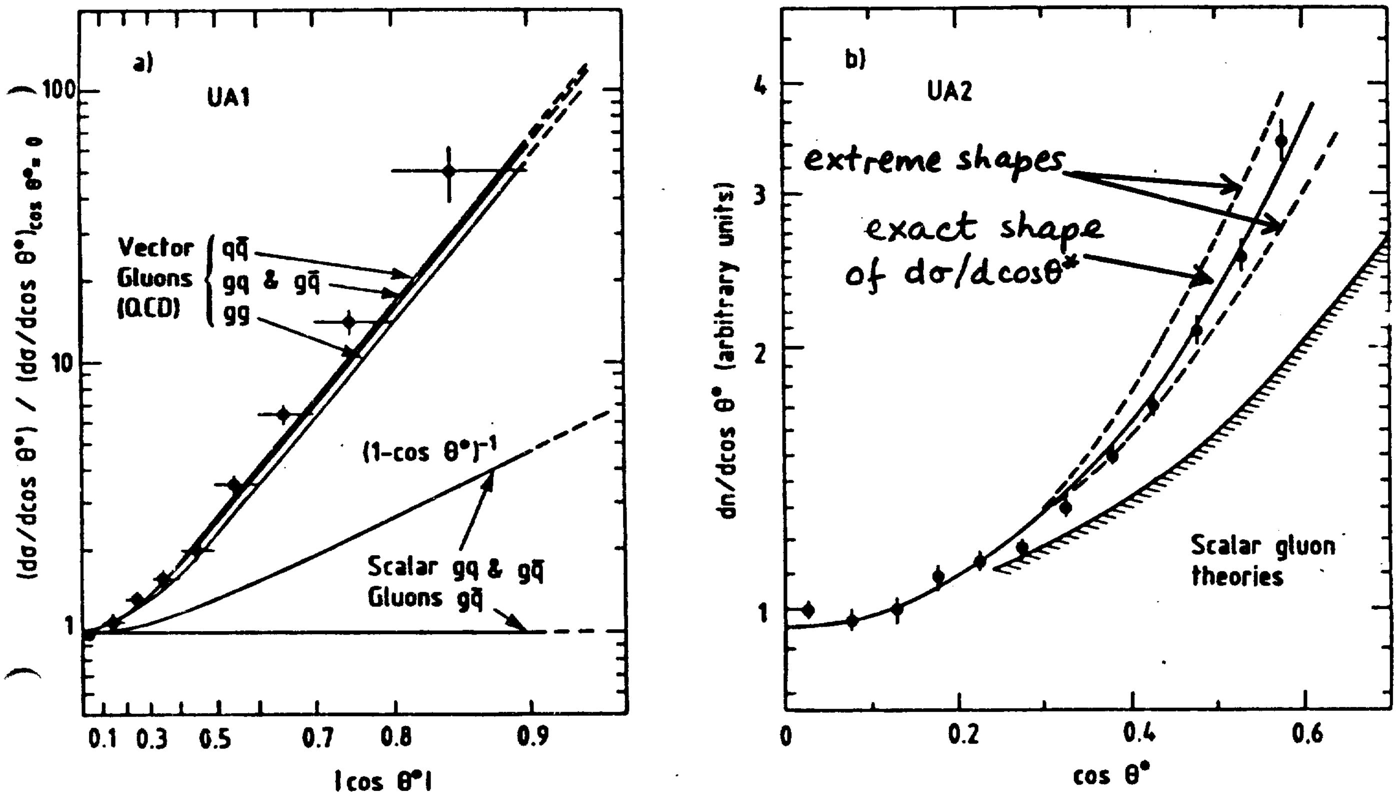
$$\frac{d^3\sigma}{dx_1\, dx_2\, d(\cos\theta^*)} \approx \left[\frac{d\sigma}{d(\cos\theta^*)}\right]_{gg\to gg} \cdot \frac{F(x_1)}{x_1} \cdot \frac{F(x_2)}{x_2}$$

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 $|\cos\theta^*|$)



- Good agreement with QCD
- Evidence for the Rutherford term $\sin^{-4}(\theta^*/2)$
- Scalar gluon exchange disagrees with data

$$\boxed{\int_0^{\cos\theta^*_{min}} \frac{d^3\sigma}{dx_1 dx_2 d(\cos\theta^*)} d(\cos\theta^*)} \approx \frac{F(x_1)}{x_1}\frac{F(x_2)}{x_2}\int_0^{\cos\theta^*_{min}}\left[\frac{d\sigma}{d\cos\theta^*}\right]_{gg\to gg} d(\cos\theta^*)$$

θ^*_{min} minimum angle for which both jets are within detector acceptance (depends on x_1, x_2)

$$S(x_1, x_2) \approx x_1 x_2 \boxed{\frac{d^2\sigma}{dx_1 dx_2}} \Big/ \int_0^{\cos\theta^*_{min}}\left[\frac{d\sigma}{d\cos\theta^*}\right]_{gg\to gg} d(\cos\theta^*)$$

<u>Experimental uncertainties</u>

Statistical errors
Normalisation
Calorimeter calibration

<u>Theoretical uncertainties</u>

Higher order corrections (not yet calculated)

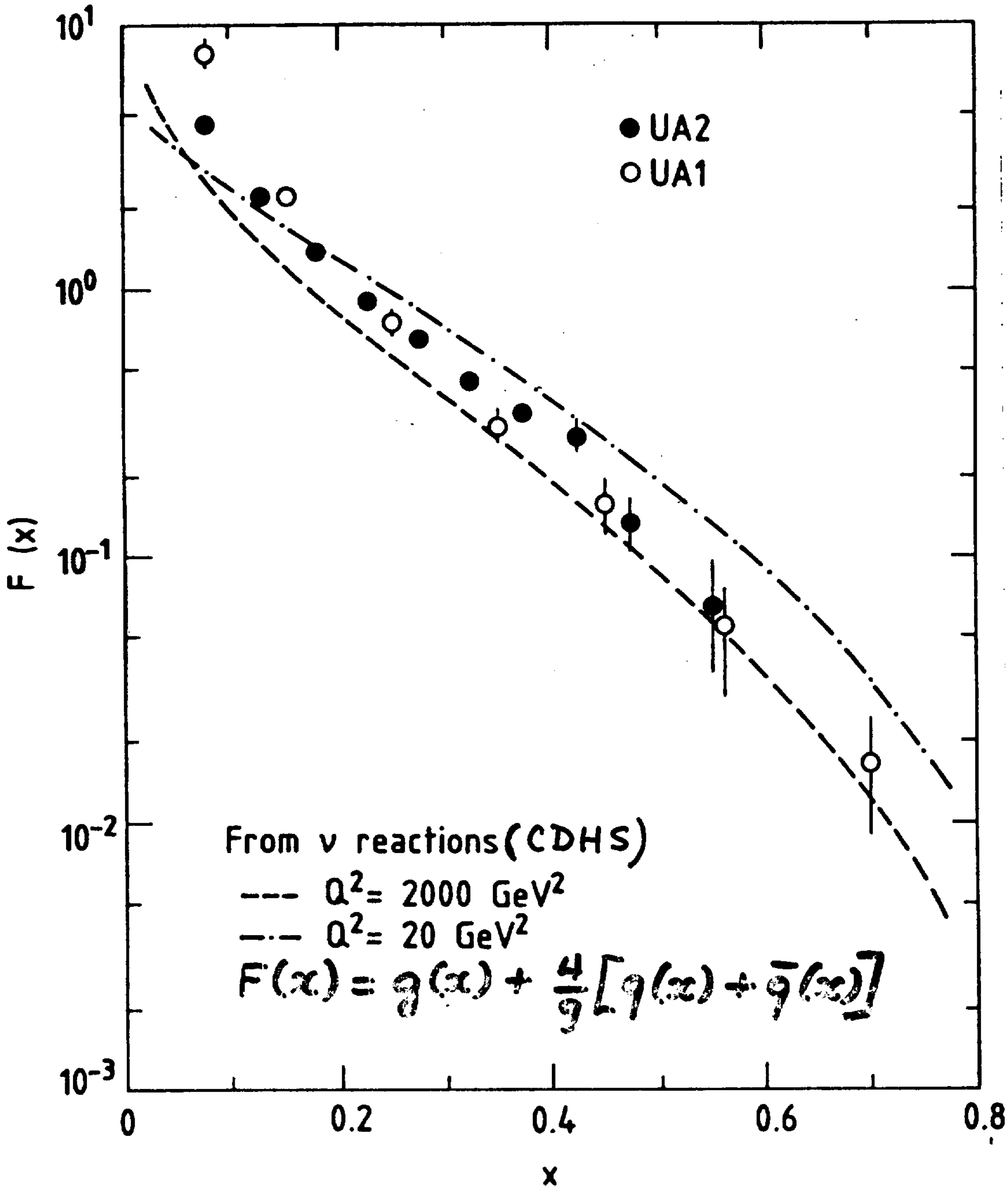
$$\frac{d\sigma}{d\cos\theta^*} \longrightarrow K\frac{d\sigma}{d\cos\theta^*}$$

K unkown parameter believed to be $\lesssim 2$

$$S(x_1, x_2) \approx F(x_1)\,F(x_2)$$

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

$\rightarrow$ uncertainty on $F \approx$ (uncertainty on S)/2

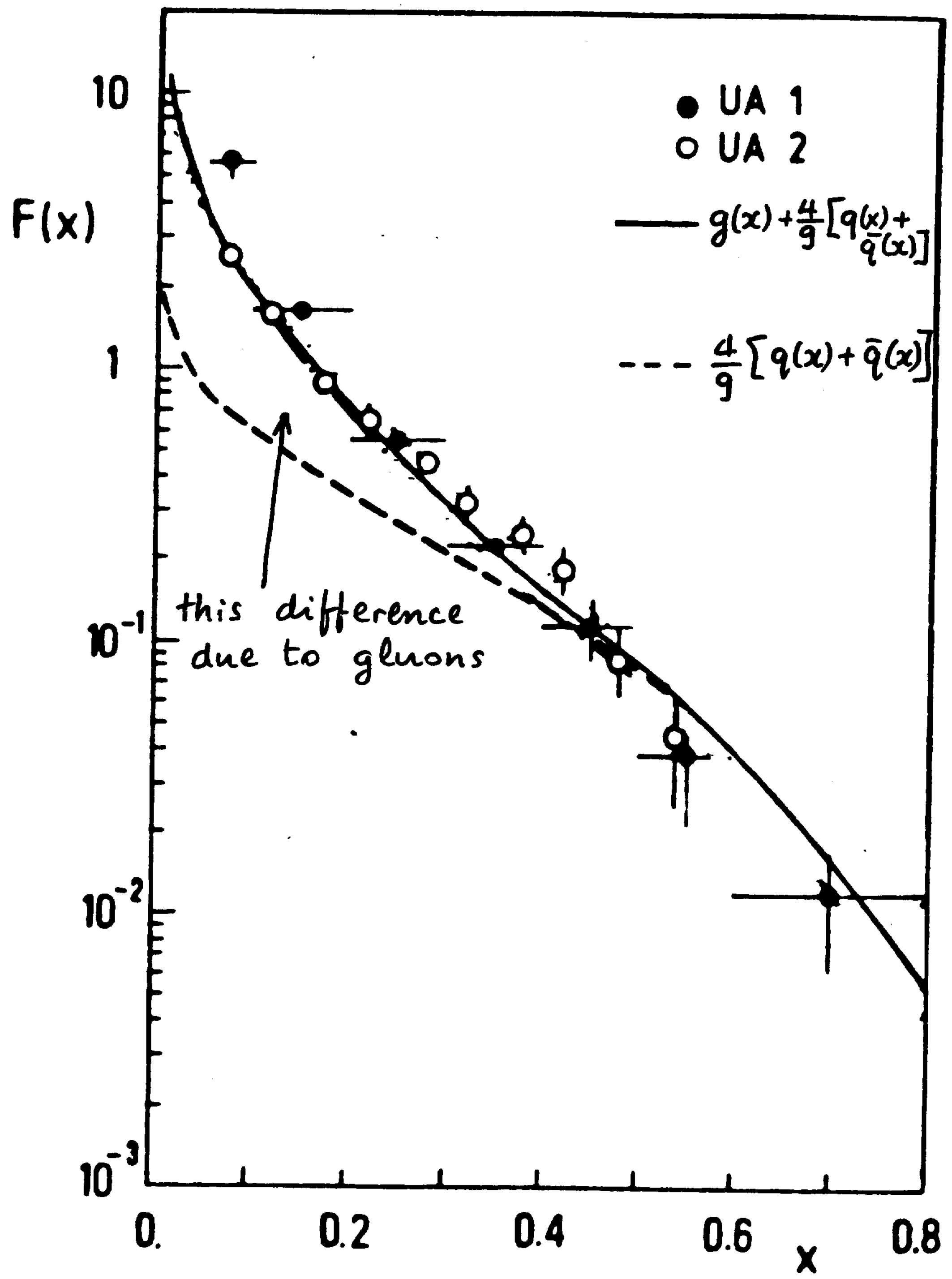


Assumptions:

$K = 1$ [$F(x)\sqrt{K}$ is actually measured]

$\alpha_s(Q^2) = 12\pi/23 \ln(Q^2/\Lambda^2)$, $\Lambda = 0.2$ GeV

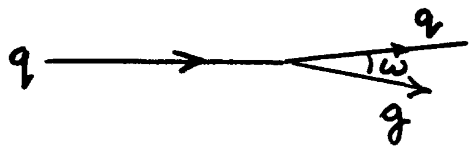
Comparison with structure functions measured by the CHARM collaboration and extrapolated to $Q^2 \approx 2000$ GeV^2

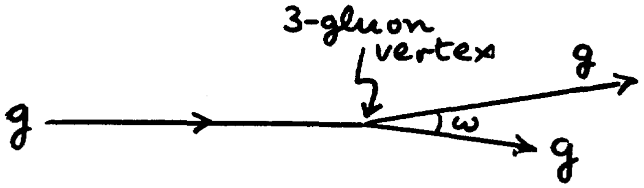


Gluon density at small x measured DIRECTLY for the first time [in deep inelastic scattering the gluon structure function is determined indirectly from the Q^2 dependence of $q(x)$, $\bar{q}(x)$]

HIGHER ORDER QCD EFFECTS

Gluon radiation





z = gluon momentum/total momentum

Radiation probability ($z, \omega \ll 1$):

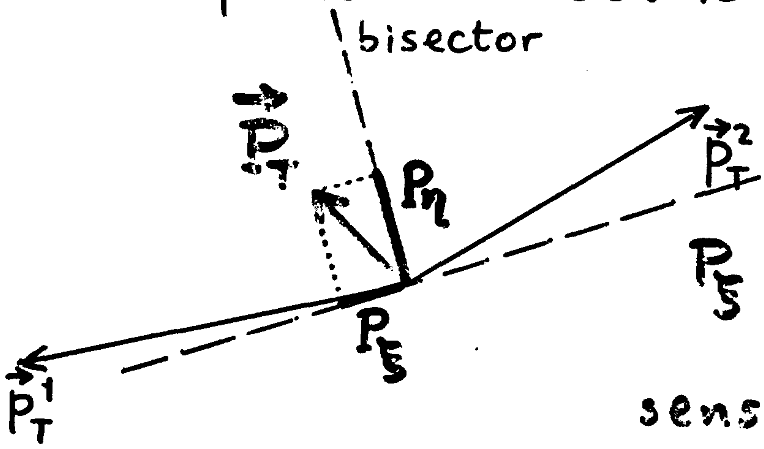
$$\frac{d^2R}{dz\,d\omega} \approx \frac{8\alpha_s}{3\pi}\,\frac{1-z}{z\omega} \qquad (q \to qg)$$

$$\approx \frac{9}{4}\,\frac{8\alpha_s}{3\pi}\,\frac{1-z}{z\omega} \qquad (g \to gg)$$

Gluon radiation from initial partons

→ **possibility of two-jet events with <u>imbalanced</u> p_T** (jet from radiated gluon is emitted generally at small angle to beams)

In plane ⊥ to beams



P_ξ = difference between two large components: sensitive to measuring errors (calorimeter resolution)

→ **use P_η to study p_T imbalance**

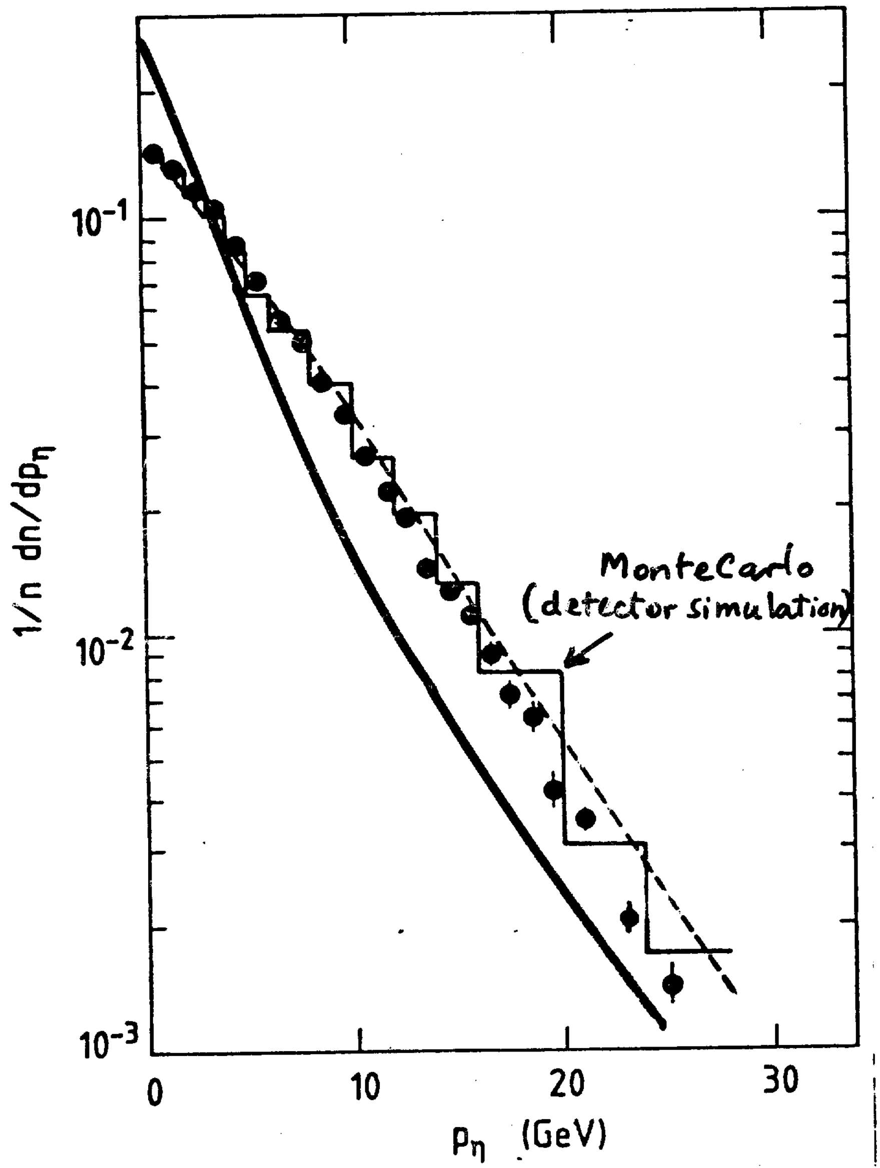
P_η distribution

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

——— QCD

——— QCD, with $R(q \to qg) = R(g \to gg)$

M. Greco, 1985



$\longrightarrow$ 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

FRAGMENTATION

Parton $\longrightarrow$ jet

Two distinct regions:

1.- **Short distances** ($\ll 10^{-13}$ cm)

Perturbative QCD : gluon radiation, $q\bar{q}$ pair creation

parton $\longrightarrow$ jet of partons

2.- Long distances ($\gtrsim 10^{-13}$ cm)

Non-perturbative QCD properties

partons $\rightarrow$ colourless hadrons

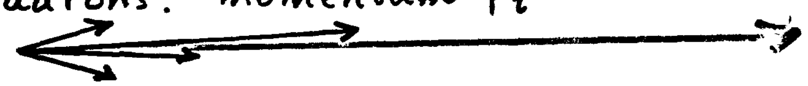
not calculable

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



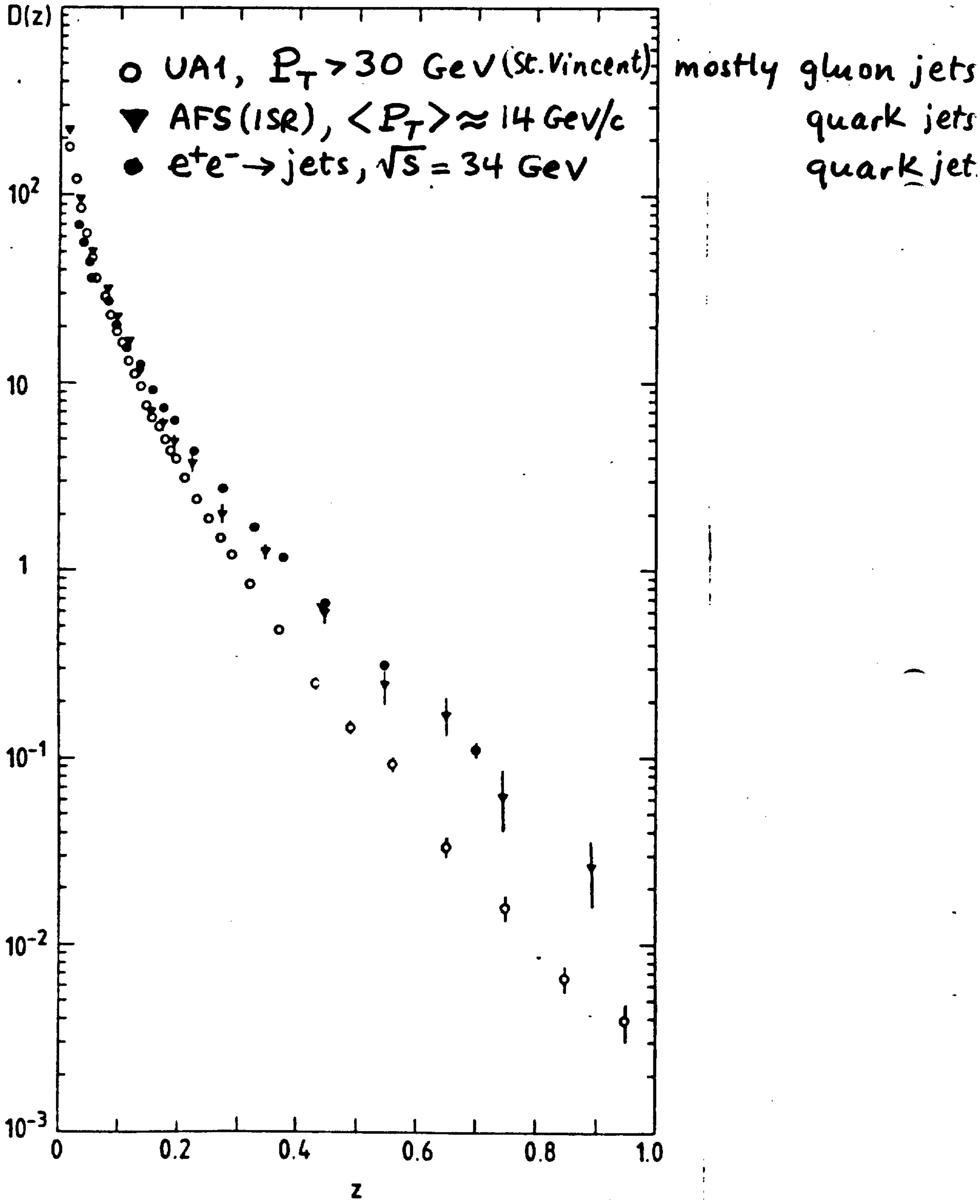
$z = (\vec{p} \cdot \vec{P}) / P^2$ fractional longitudinal momentum

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

$dn/dz \equiv D(z)$ fragmentation function

Measurement of D(z) requires momentum measurement of individual jet fragments — possible in UA1 for charged fragments because of magnetic field

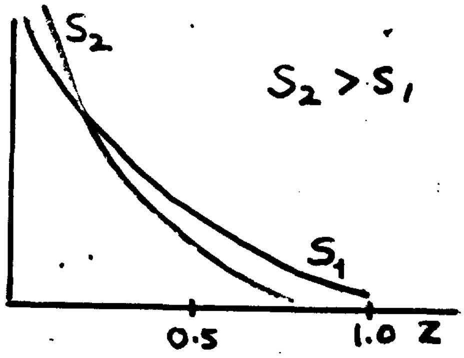
Difficulty at small z : spectator particles not belonging to the jet
($e^+e^- \rightarrow 2$ jets has no spectators)



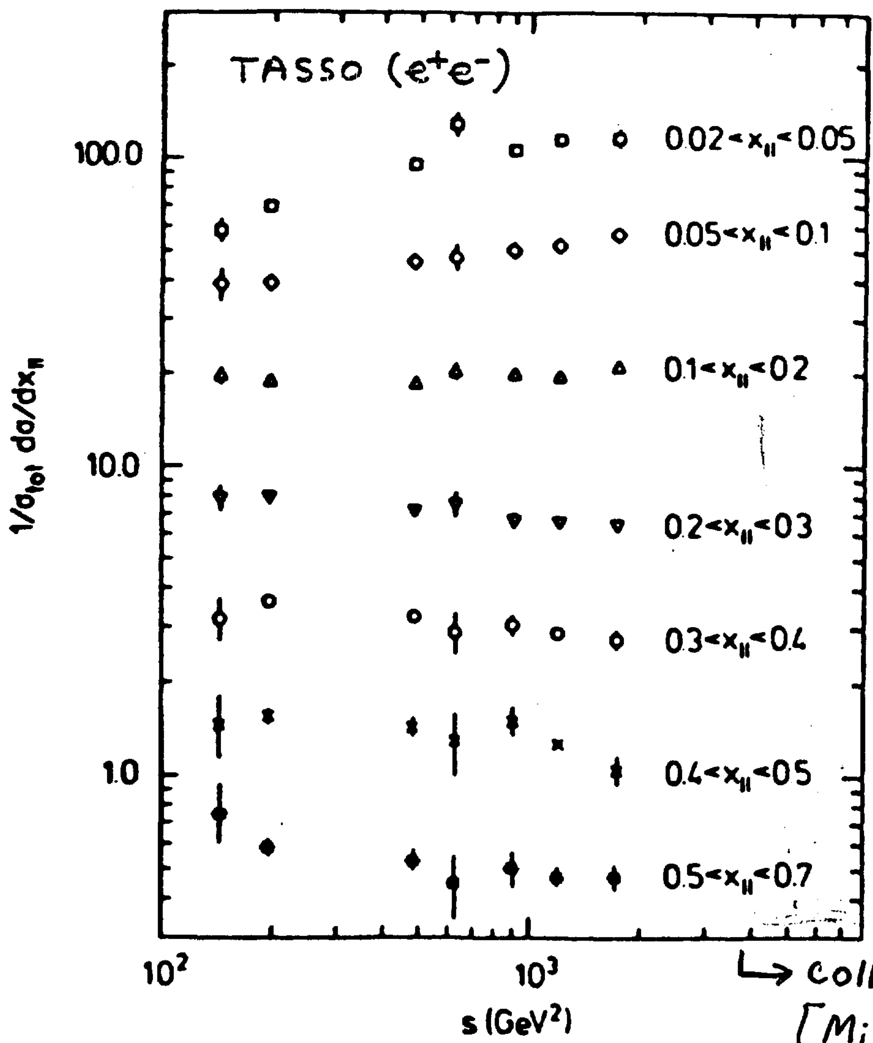
→ collider jets are softer : $\langle z \rangle_{collider} < \langle z \rangle_{e^+e^-}$

Two possible reasons:

- a real gluon jet/quark jet difference: $R(g \to gg) = \frac{9}{4} R(q \to qg) \to$ there is more gluon radiatio[n] from gluon jets than from quark jets
- scale breaking effects in $D(z)$ (expected from gluon radiation)



Scale breaking effects are small:

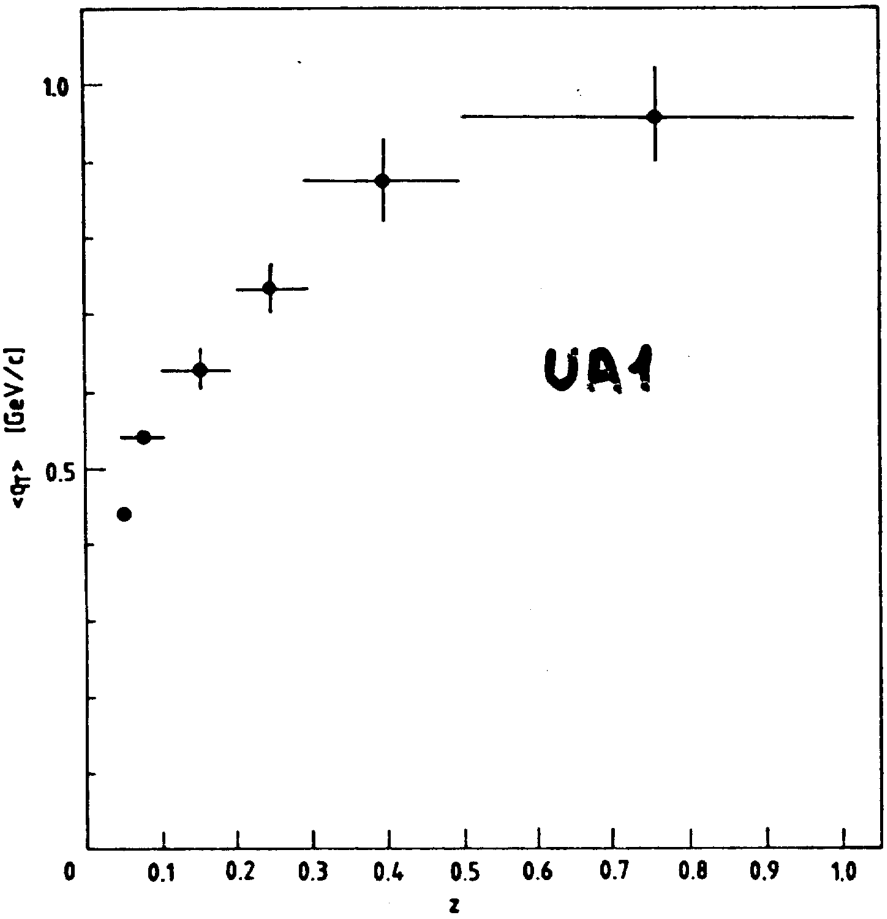


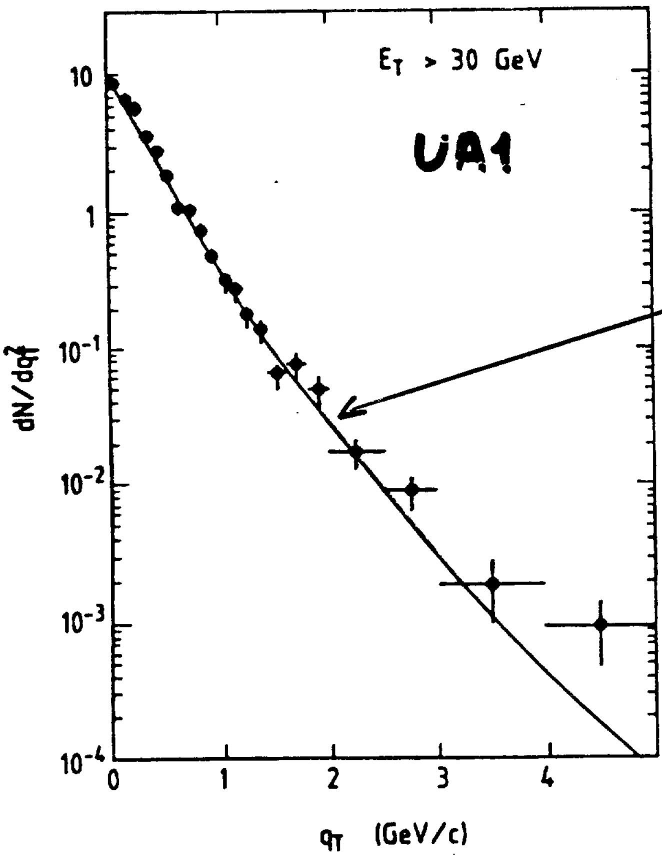
$x_{\parallel} \equiv z$

$\hookrightarrow$ collider jets $[M_{jj} = \sqrt{\hat{s}} = \sqrt{s_{e^+e^-}}]$

Most likely, collider jets are softer because of a real gluon jet/quark jet difference

Limited q_T (transverse momentum $\perp$ jet axis)





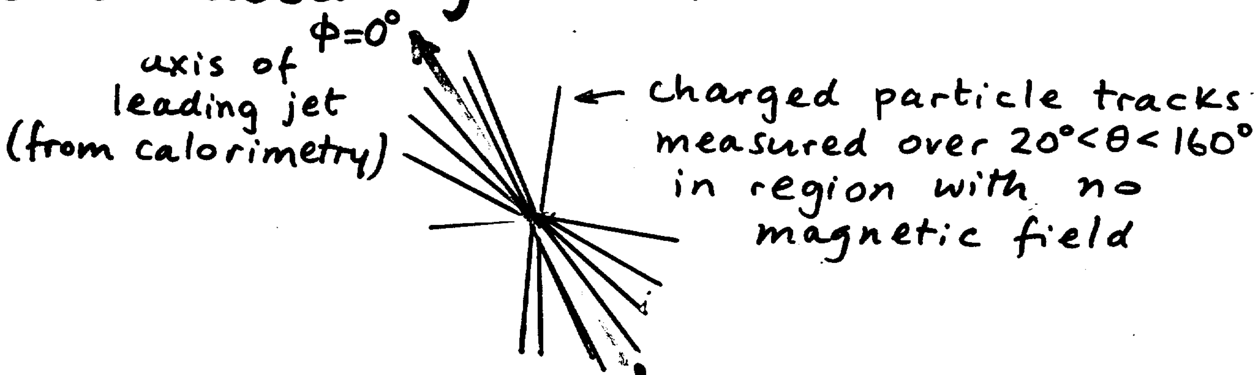
P_T distribution of secondaries from soft collisions with respect to beam axis

Charged particle multiplicity in jets

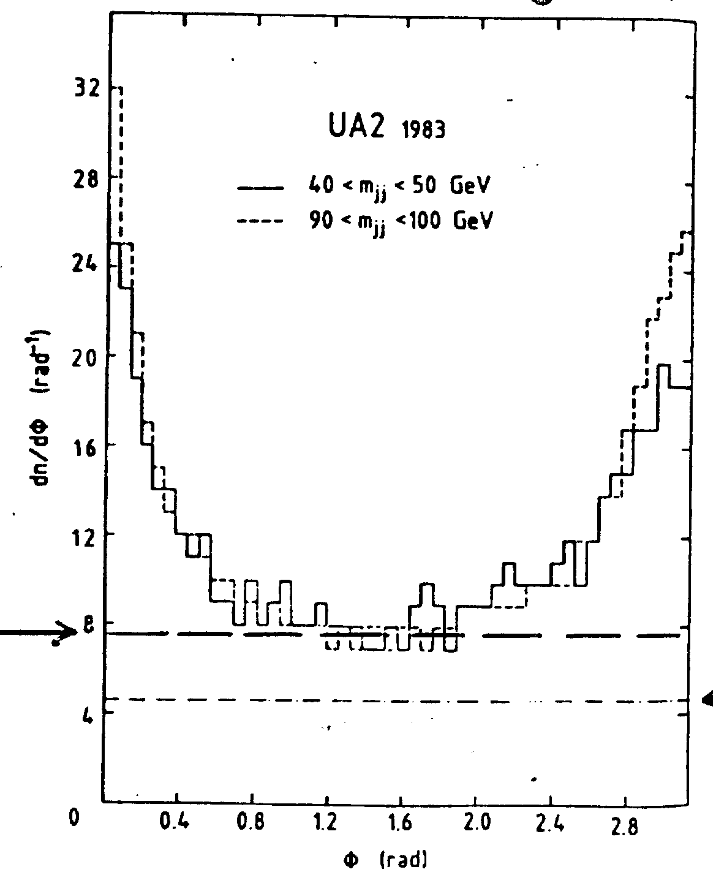
In principle $\langle n_c \rangle = \int_0^1 D(z)\, dz$

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

Method used by UA2 :



Azimuthal density of charged particles



$m_{jj} \approx \sqrt{\hat{s}}$

$\left(\frac{dn}{d\phi}\right)_{\pi/2}$

← average density in soft collision

Definition

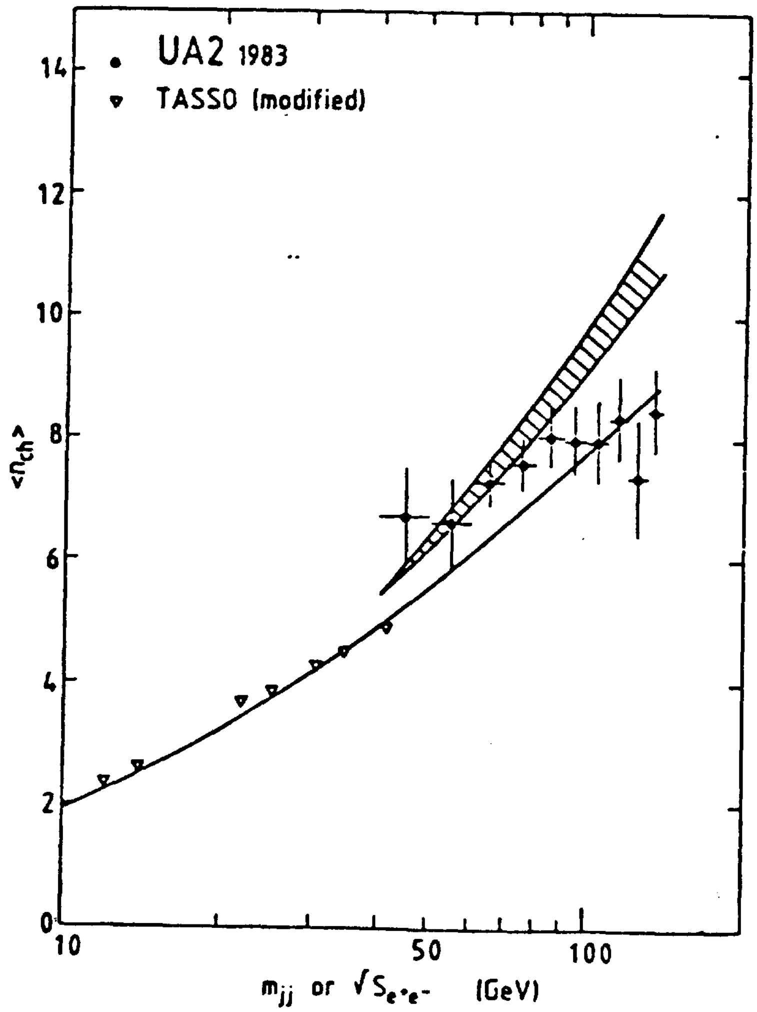
$$\langle n_c \rangle = \frac{1}{2} \left\{ \int_0^{\pi} \frac{dn}{d\phi}\, d\phi - \pi \left(\frac{dn}{d\phi}\right)_{\pi/2} \right\}$$

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

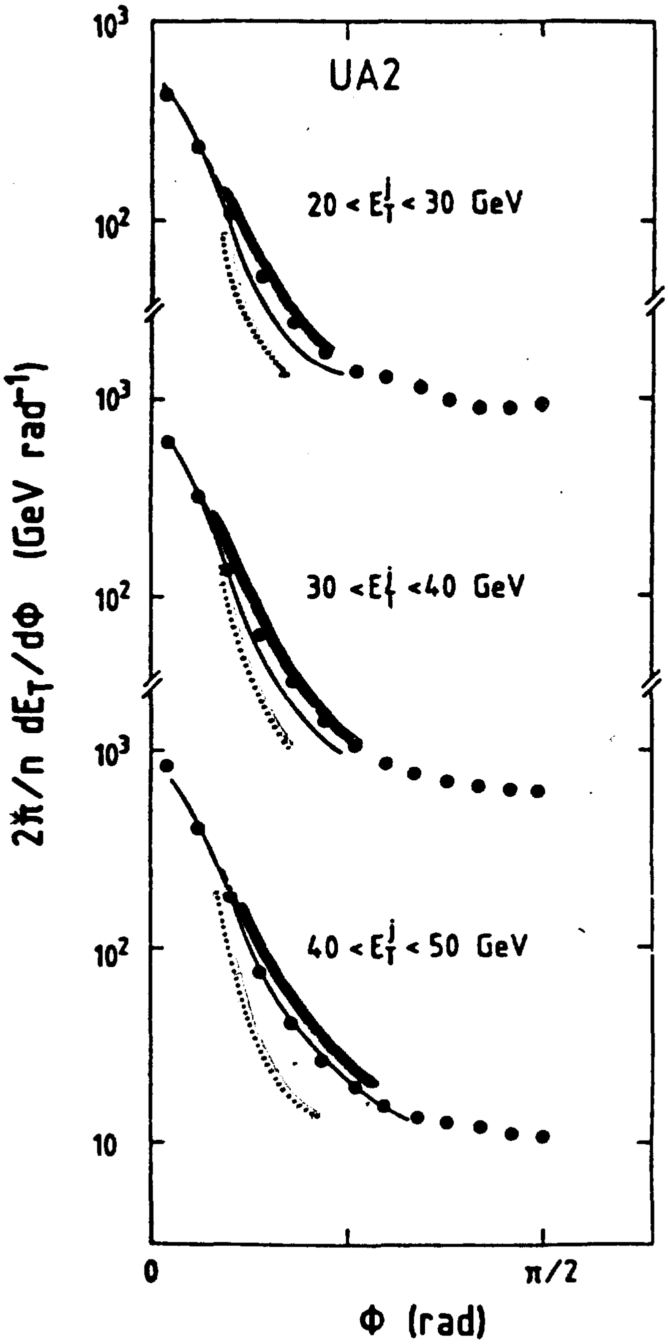


$m_{jj} \sim 50$ GeV mostly gluon jets $\langle n_c \rangle_{\text{collider}} > \langle n_c \rangle_{e^+e^-}$

$m_{jj} > 100$ GeV mostly quark jets $\langle n_c \rangle \simeq \langle n_c \rangle$

[illegible]

Transverse energy density in a jet vs ϕ
($\phi = 0$ is the jet axis)
Note log ordinate — jet fragments at large ϕ are soft!



gluon jets } model (Webber) with
quark jets } gluon radiation

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

SUMMARY

- High-p_T jet production is the dominant phenomenon in hard collisions at the $\bar{p}p$ collider
- Jet identification is <u>easy</u> (multi-cell calorimeters → 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 <u>direct</u> 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 → number of neutrinos
Charge asymmetry in $W \to e\nu$ decay
QCD effects

4.- **Evidence for $W \to t\bar{b}$**

5.- Conclusions

Masses

$W^{\pm}$ $\quad \dfrac{G}{\sqrt{2}} = \dfrac{g^2}{8M_W^2} \qquad g^2 = \dfrac{e^2}{\sin^2\theta_W} = \dfrac{4\pi\alpha}{\sin^2\theta_W}$

$G = (1.16638 \pm 0.00002) \times 10^{-5}\ \text{GeV}^{-2}$

Fermi coupling constant

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

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

$\longrightarrow \quad M_W = \dfrac{37.28}{\sin\theta_W}\ \text{GeV}$

Taking radiative corrections into account:

$$M_W = 38.65/\sin\theta_W \quad \text{GeV}$$

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

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

$$\longrightarrow \quad M_W = 83.0 \pm 2.7 \quad \text{GeV}$$

Z^0 $\quad M_Z = \dfrac{M_W}{\cos\theta_W} = \dfrac{38.65}{\sin\theta_W \cos\theta_W} = \dfrac{77.30\ \text{GeV}}{\sin 2\theta_W}$

(from minimal Higgs scheme)

$$\longrightarrow \quad M_Z = 93.8 \pm 2.2\ \text{GeV}$$

(ΔM_W, ΔM_Z are not independent !)