Diffraction:An Experimental Perspective

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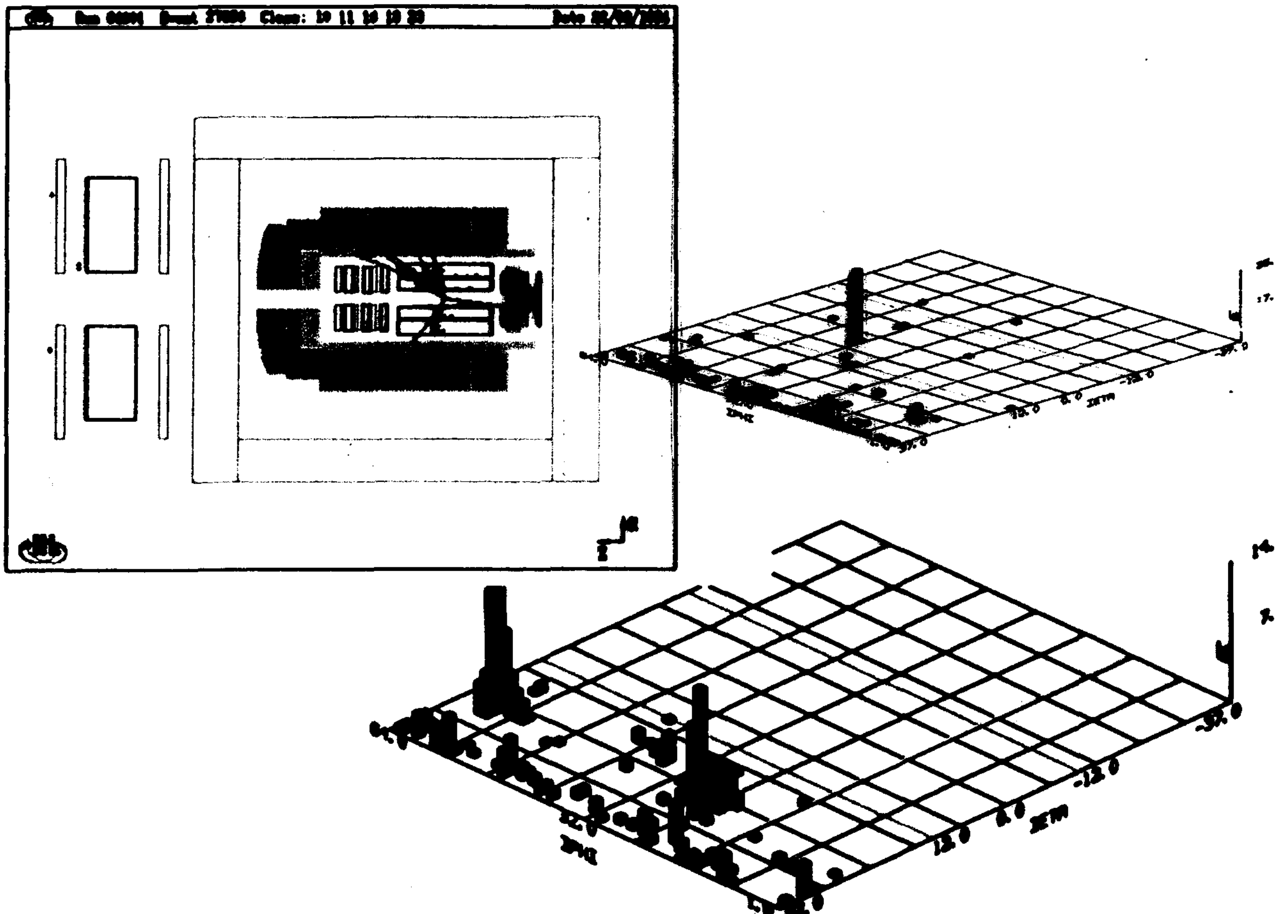
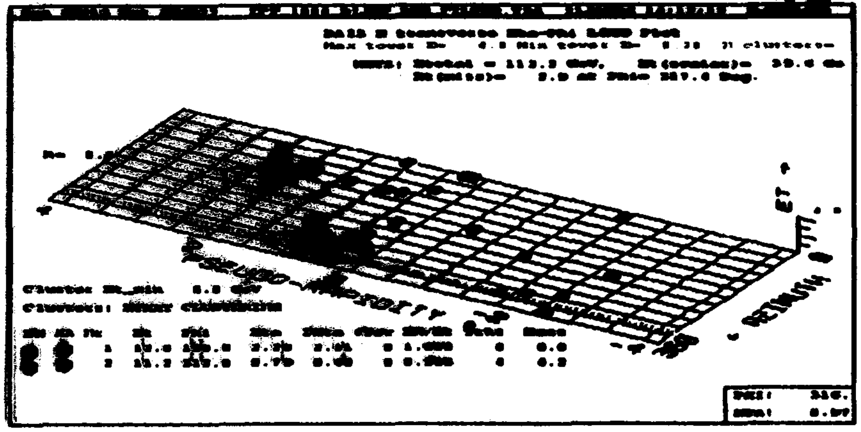
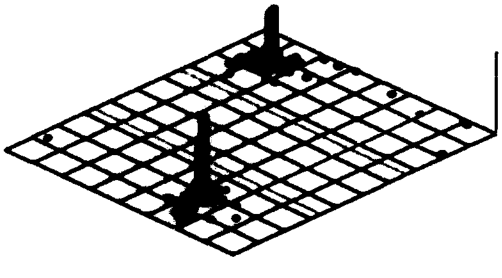


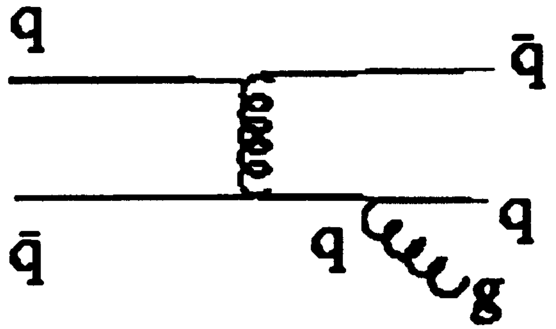


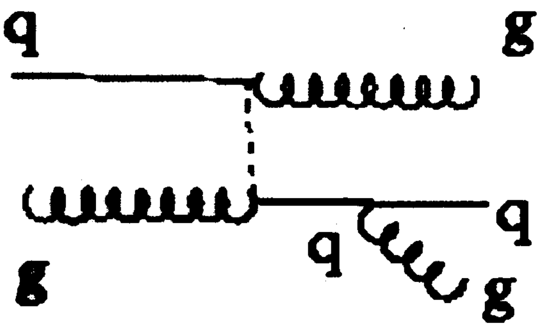


CTEQ Summer School
June 3,4 2002
Madision, WI

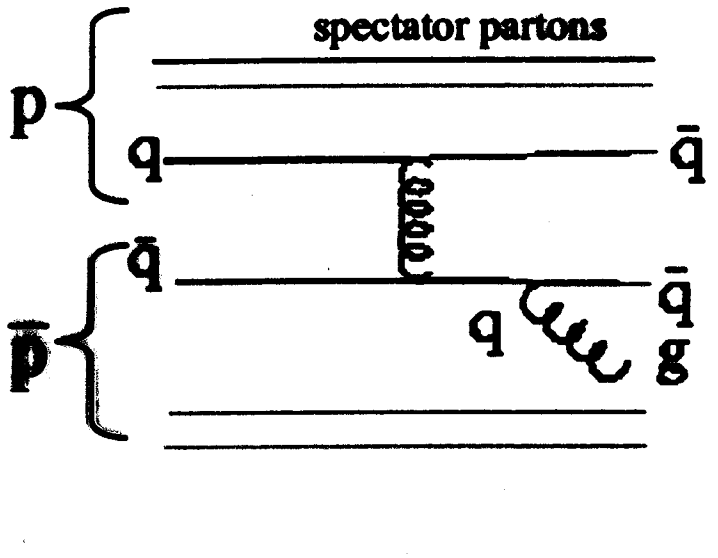
Typical QCD Event

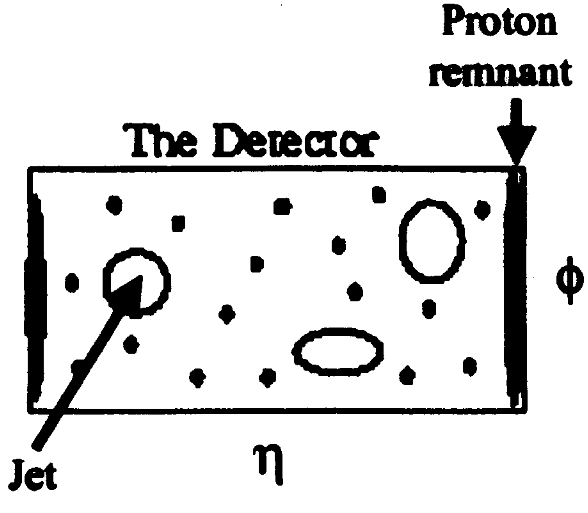
In a $p\bar{p}$ collision, a gluon or quark may be exchanged:





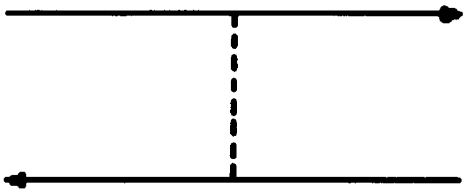
Due to the color flow in the event, particles are produced throughout phase space, and concentrated in regions around the struck partons (jets).



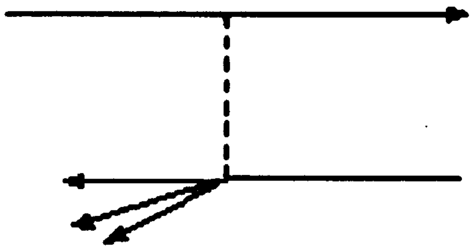


Diffraction

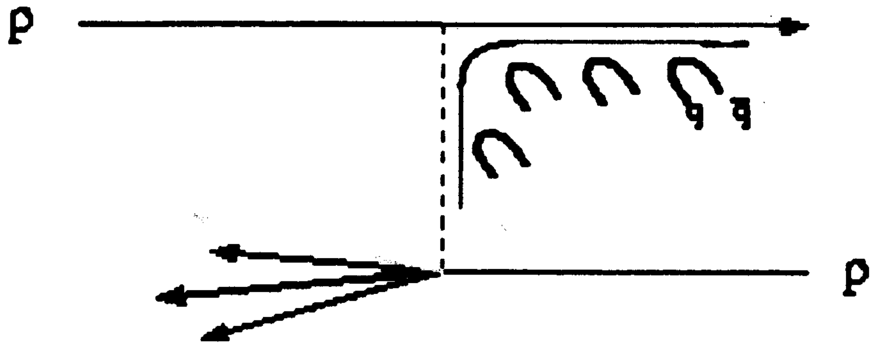
Elastic Scattering



Single Diffraction



If exchanged particle had color:



The event is no longer diffractive!

The exchanged particle must be colorless
for diffractive event!

What Is Diffraction?

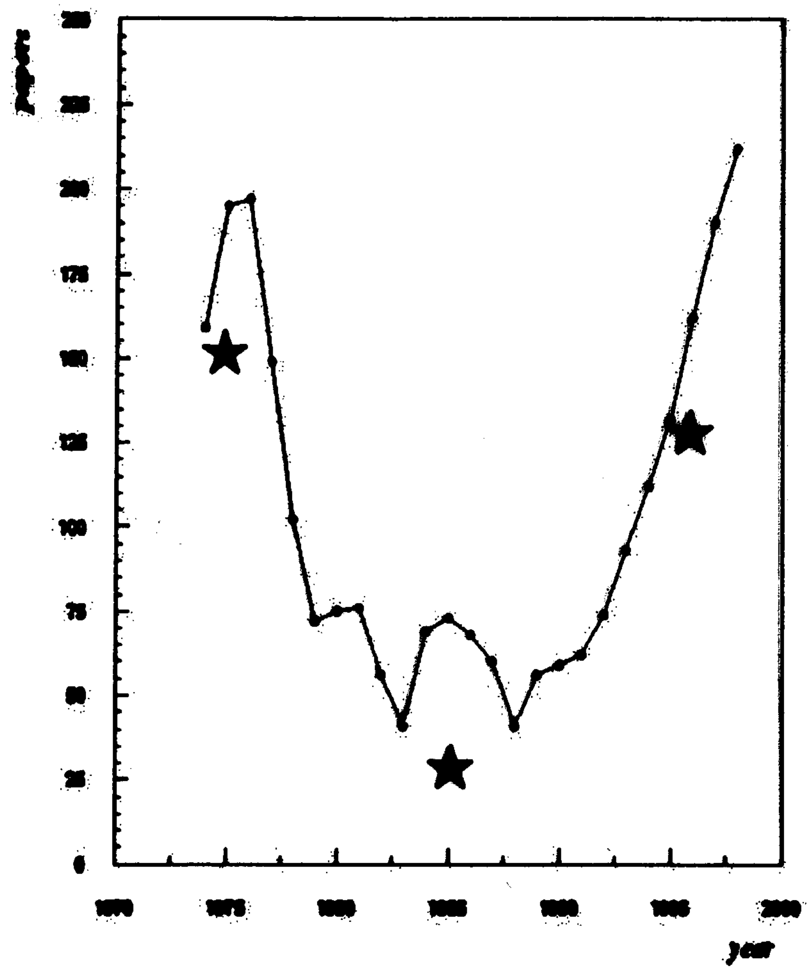
- Diffraction in high energy hadron physics encompasses those phenomena in which no quantum numbers are exchanged between interacting particles
  - Diffused particles have same quantum numbers as incident particles

- Exchanging quanta of the vacuum is synonymous with the exchanging of a Pomeron
  - Named after Russian physicist I.Y. Pomeranchuk
  - Virtual (pseudo) particle carries no charge, isospin, baryon number or color
  - Couples through internal structure

- Can be studied in occur in p-p, p-$\bar{p}$, and e-p collisions

40 years of Diffraction

60's: First evidence for hadronic diffraction, S matrix
Regge theory, Pomeron



70's: DIS, High p_T processes. Parton model, QCD,
c, τ, b, gluon

80's: Ingelman-Schlein, BFKL

90's: Hard Diffraction (UA8), Rapidity Gaps (Bjorken),
HERA (diffraction in ep), Tevatron

Outline

- Diffraction
- Regge Theory
- Ingelman-Schlein Model
- Hard Diffraction (UA8)
- BFKL Theory
- HERA
- Color Evaporation
- Tevatron
- Future

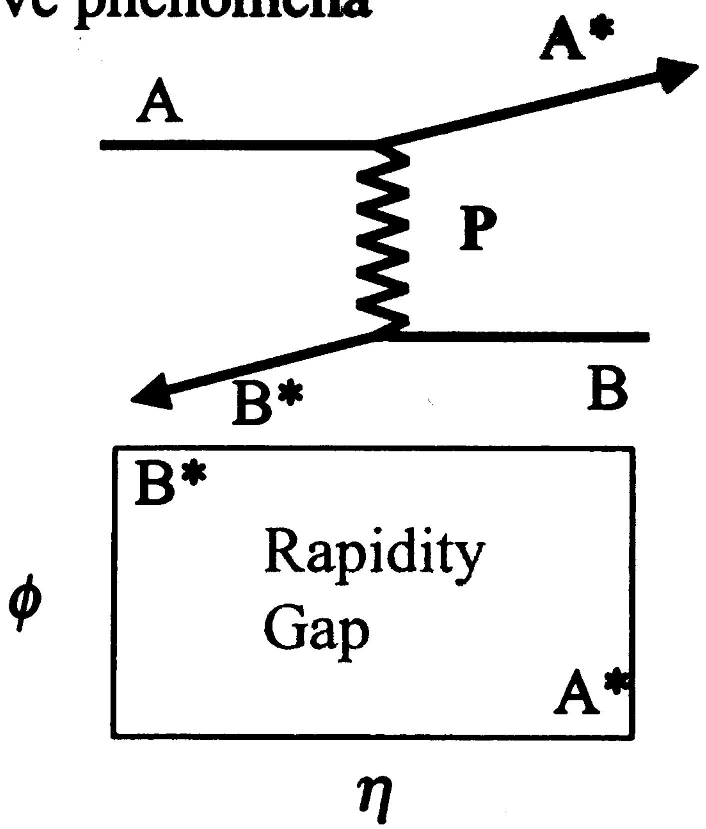
Thanks to many people for contributions to this talk including Michael Strang, Christophe Royon, Sergio Novaes, Kaushik De, Ken Hatakeyama, Brian Cox, Paul Newman, and Risto Orava

Elastic Scattering

- The particles after diffraction are the same as the incident particles
- The cross section can be written as:

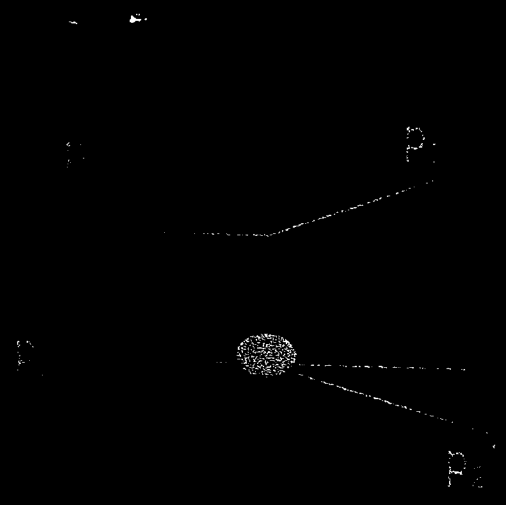
$$\frac{d\sigma/dt}{\left(d\sigma/dt\right)_{t=0}} = e^{bt} \cong 1 - b(p\theta)^2$$

- This has the same form as light diffracting from a small absorbing disk, hence the name diffractive phenomena



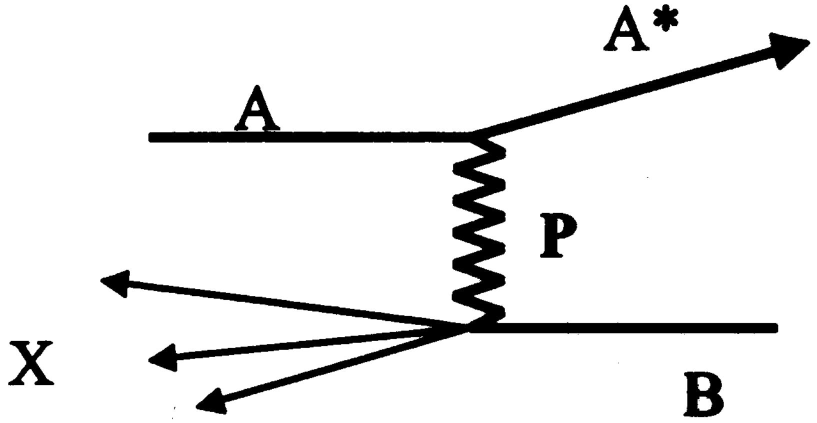
$$A + B \rightarrow A^* + B^*$$

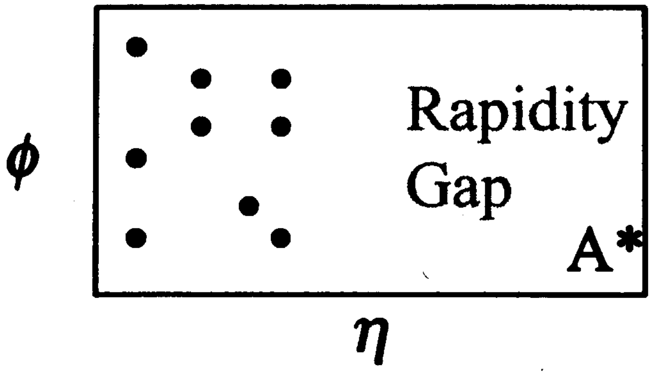
Elastic Scattering is Complex!



Soft Single Diffraction

- One particle continues intact while the other becomes excited and breaks apart

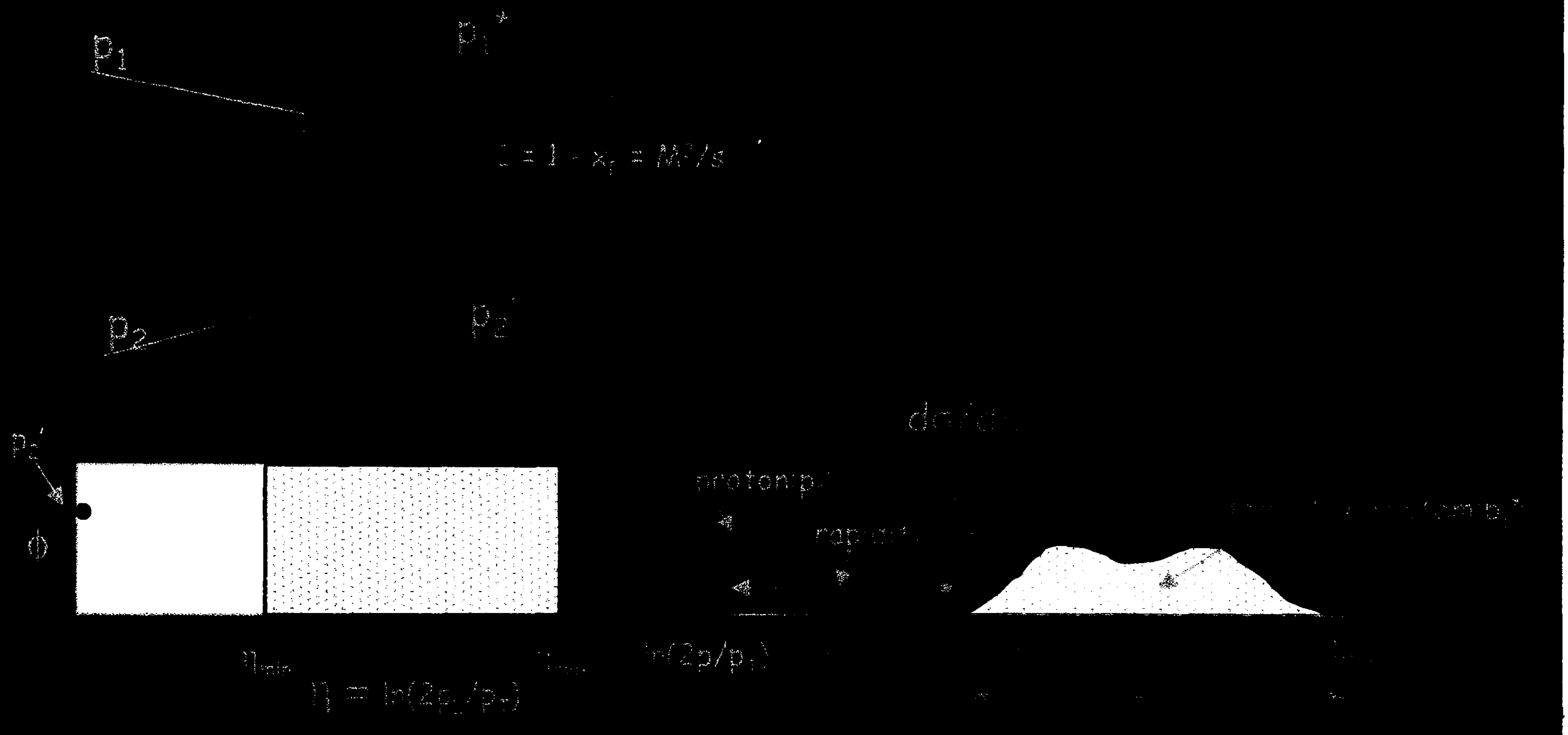




$$A + B \rightarrow A^* + X$$

Experimentally, can tag outgoing beam particle or rapidity gap as signature of diffraction

In Single Diffractive Excitation mass of the diffractive system depends on the momentum loss, ξ, of the incident proton. The size of a rapidity gap is ~ $\ln\xi$.



Cross section: $d^2\sigma_{sd}/d\xi dt = (A/\xi)b\exp(-bt)$ [illegible]

Regge Theory (pre-QCD)

- A Reggeon is a pole in the partial wave in the t-channel of the scattering process in the complex angular momentum plane.
- At high energy, the asymptotic scattering amplitude becomes

$$A_R(s,t) = g_1 g_2 \frac{s^{\alpha_R(t)} + (-s)^{\alpha_R(t)}}{\sin \pi\alpha_R(t)}$$

- This has the important property that at $t = m_R^2$ where m_R is the mass of resonance with spin j ($j = \alpha_R(t = m_R^2)$) this formula describes the exchange of the resonance.
- The function $\alpha_R(t)$ is the Reggeon trajectory and has experimental form

$$\alpha_R(t) = \alpha_R(0) + \alpha'_R(0)t$$

- The trajectories correspond to "particles" :

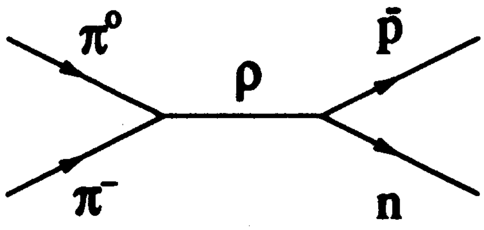
$$\alpha_P(t) \cong 1.08 + \alpha'_P(t)t \text{ (Pomeron)}$$

$$\alpha_R(t) \cong 0.5 + t \text{ (Reggeon)}$$

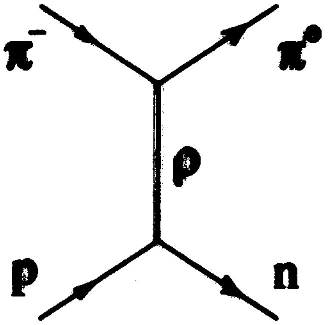
$$\alpha_\pi(t) \cong 0.9t \text{ (Pion)}$$

In The Days Before QCD ...

Scattering processes are visualised in terms of meson / nucleon exchange



s channel 'resonance production'



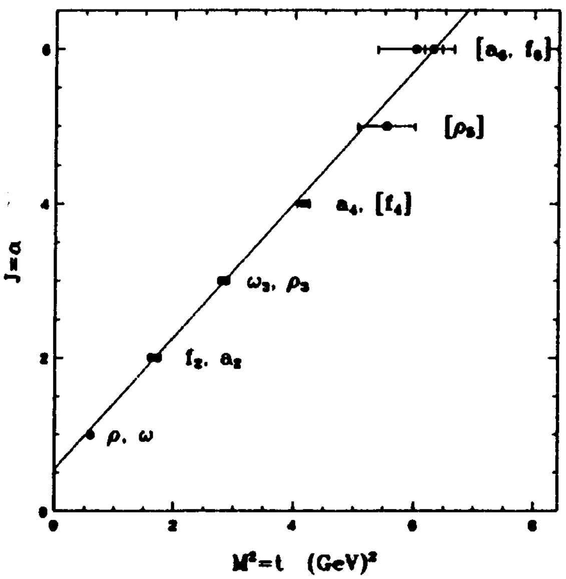
t channel 'ρ meson exchange'

$s = (\pi^- + p)^2$, $t = (\pi^- - \pi^0)^2$

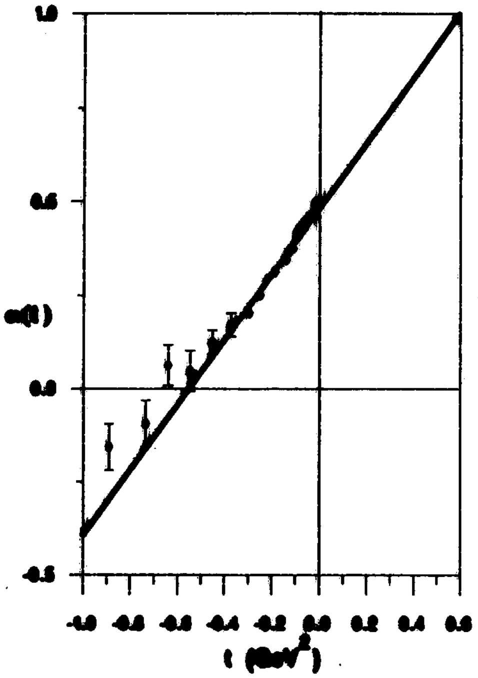
- Crossing symmetry :
  $A_{\pi^- p \to \pi^0 n}(s,t) = A_{\pi^- \pi^0 \to p\bar{n}}(t,s)$
- Regge Theory :
  Based on very general assumptions about $A(s,t)$
  In the Regge limit (for $s \gg$ all other scales)
  $A(s,t) \to \beta(t) s^{\alpha(t)}$
  $\alpha(t)$ is a kind of 'complex angular momentum'
  Scattering process viewed as the exchange of a 'reggeon' with angular momentum $\alpha(t)$

In The Days Before QCD ...

$\pi^- \pi^o \rightarrow$ meson



$\pi^- p \rightarrow \pi^o n$

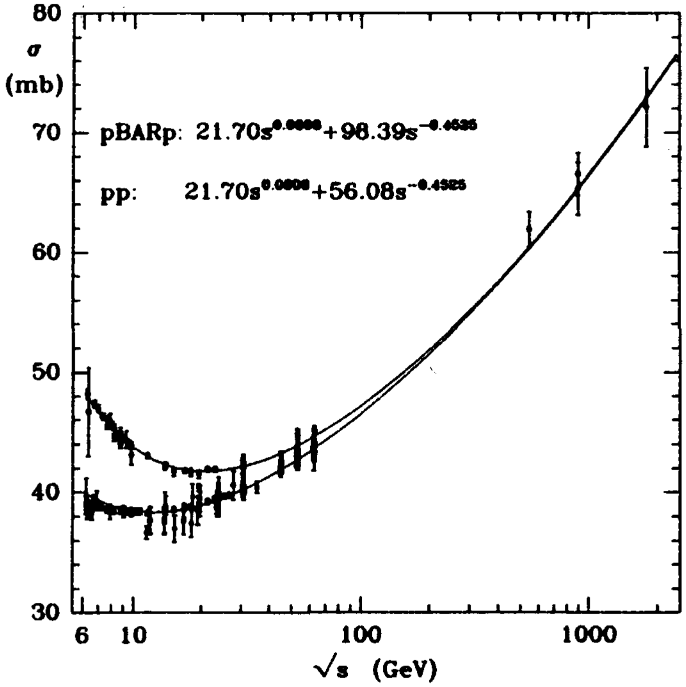


- Straight line $\rightarrow \alpha(t) = \alpha(0) + \alpha^{'} t$
  From figure, $\alpha(0) = 0.55$, $\alpha^{'} = 0.86$ GeV^2

- Prediction from Regge Theory for crossed process:
  $A(s,t) \simeq s^{(\alpha(0)+\alpha^{'} t)}$
  and hence, since
  $\frac{d\sigma}{dt} \simeq \frac{|A(s,t)|^2}{s^2}$
  then the cross section for $\pi^- p \rightarrow \pi^o n$ is
  $\frac{d\sigma}{dt} \simeq s^{2(\alpha(0)-1+\alpha^{'} t)}$

Total Cross Sections and the Pomeron

- **The Optical Theorem**
  From ONLY Unitarity and time reversal symmetry :
  $\frac{\Im m A(s,0)}{s} = \sigma_{tot}$
- **The prediction from Regge theory is therefore :**
  $\sigma_{tot} \simeq s^{\alpha(0)-1}$
  where $\alpha(0)$ is the intercept of the trajectory with the correct quantum numbers
- **For any process which involves charge exchange, the Regge intercept < 1 (Pomeranchuk (1956))**
- **BUT all hadronic σ_{tot} rise with $s \rightarrow$ POMERON**



Ingelman-Schlein Model

G. Ingelman and P. Schlein, Phys. Lett. B 152, 256 (1985)

- This model is an attempt to blend Regge phenomenology with QCD

- Applying perturbative QCD tools, propose the cross section for diffractive hard scattering can be factorized as:

$$\frac{d^2\sigma(AB \to AX)}{d\xi dt} = F_{P/A}(\xi,t)\sigma(PB \to X)$$

- The first term is the Pomeron flux factor (probability of finding a Pomeron in particle A), while the second is the cross section of the Pomeron interacting with particle B to give X

- The important variables are, $\xi = 1 - p_A/p_{A^*}$, the momentum fraction of hadron A taken by the Pomeron (diffraction dominates for $\xi < 0.05$) and t, the standard momentum transfer. M_X for the resultant system is given by $\sqrt{\xi s}$

Ingelman-Schlein II

- The flux factor term has been derived by Donnachie and Landshoff after comparison to global data:

$$F_{P/p}(\xi,t) = \frac{9\beta_o^2}{4\pi^2}\xi^{1-2\alpha(t)}\left[\frac{4m^2-2.8t}{(4m^2-t)(1-t/0.71)^2}\right]^2$$

$\beta_o^2 \approx 3.5\ \mathrm{GeV}^{-2}$ (Pomeron - Quark Coupling)

$a(t) = 1.08 + 0.25t$

- The remaining cross-section can be found from standard factorization processes to be

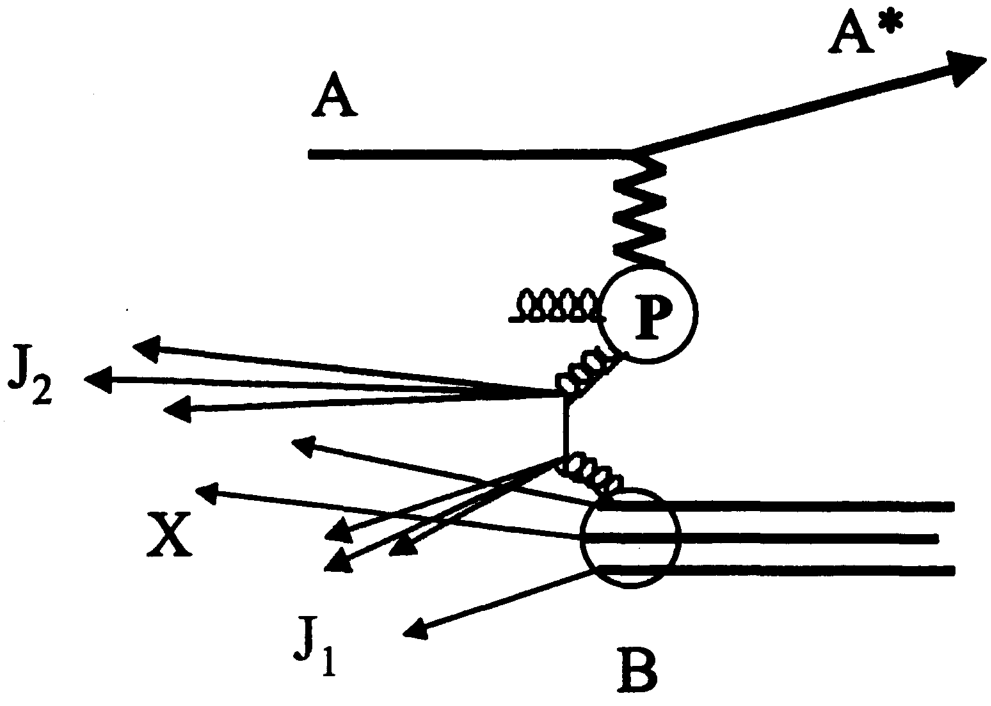
$$\sigma(PB \to X) = \sum_{ab}\int d\beta dx_b f_{a/P}(\beta) \times f_{b/B}(x_b)\hat{\sigma}(ab \to X)$$

- The only unknown is the structure function of parton *a* (with momentum fraction *β*) in the Pomeron so measurements of the cross section allow us to probe this structure function

Ingelman-Schlein III

- The factorization allows us to look at the diffractive reaction as a two step process. Hadron A emits a Pomeron then partons in the Pomeron interact with hadron B.

- The Pomeron to leading order is proposed to have a minimal structure of two gluons in order to have quantum numbers of the vacuum



Ingelman-Schlein IV

- The partonic structure of the Pomeron can be probed through hard diffractive reactions and a structure function can be proposed similar to that for a proton.
  - Inititially considered two possible gluon structure functions:

$$\beta f_{g/P}(\beta) = 6\beta(1-\beta) \quad \text{(hard gluon)}$$

$$\beta f_{g/P}(\beta) = 6(1-\beta)^5 \quad \text{(soft gluon)}$$

  - The momentum sum rule is used for normalization:

$$\int_0^1 \beta f(\beta) d\beta = 1$$

  - Later extended to include other structures such as:

$$\beta f_{g/P}(\beta) = \delta(1-\beta) \quad \text{(super - hard gluon)}$$

$$\beta f_{q/P}(\beta) = \frac{6}{4}\beta(1-\beta) \quad \text{(quark)}$$

Learning about the Pomeron

- **QCD** is theory of strong interactions, but **40%** of total cross section is attributable to **Pomeron** exchange -- not calculable and poorly understood

- Does it have partonic structure?
  Soft? Hard? Quark? Gluon?
  Is it universal -- same in *ep* and $p\bar{p}$?
  Is it the same with and without jet production?

- Answer questions in HEP tradition -- collide it with something that you understand to learn its structure

- Note: variables of diffraction are *t* and $\xi \sim M^2$

⇨ with proton tagger measure $\dfrac{d^2\sigma}{dt\,d\xi}$

without, just measure σ

UA8 EXPERIMENT

UCLA (P. SCHLEIN et al)

$$\underbrace{p\bar{p}}_{s} \to \underbrace{p_f}_{x_p} + (\text{jet} \underbrace{+\,\text{jet}}_{s'=s(1-x_p)} + X) + \text{c.c.}$$

$\sqrt{s} = 630\ \text{GeV}$ ∴ $x_p = 0.9 \Rightarrow \sqrt{s'} = 200\ \text{GeV}$

p_f DETECTED IN ROMAN POT SPECTROMETER (MOMENTUM CALCULATED ONLINE WITH DATA DRIVEN PROCESSOR)

JETS IN UA2' CALORIMETER

JET $E_T > 8$ GeV IN CONE $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1$

BASIC JET TRIGGER = PROTON (UA8) + ΣE_T (UA2)

HARD DIFFRACTION ISSUES

- DOES IT EXIST? $p\bar{p} \to p + \text{JETS}$

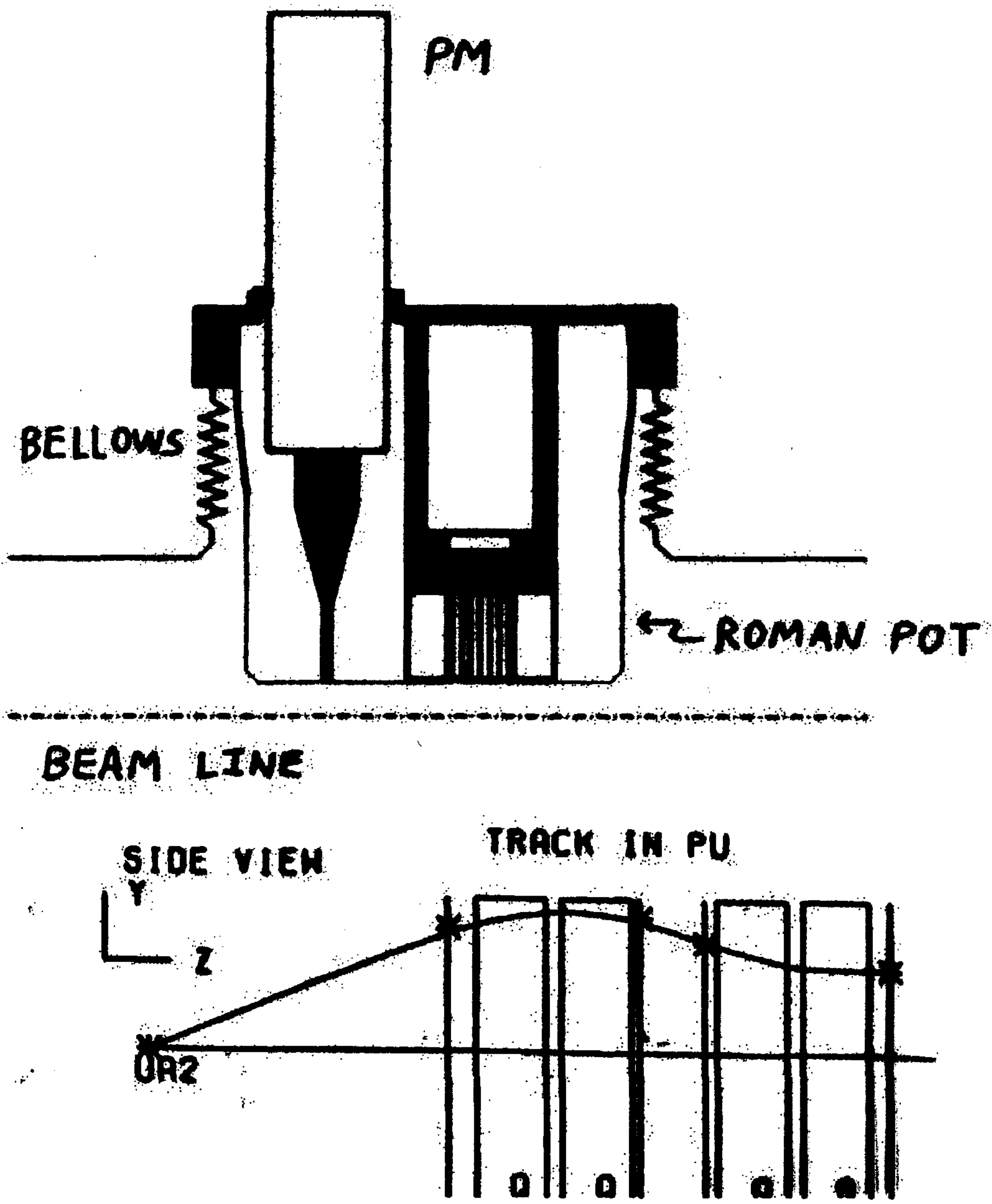
- DOES $(1-x_p)$ COMPONENT (POMERON) HAVE PARTONIC STRUCTURE?

- IS IT REASONABLE TO THINK OF $\mathbb{P}$ AS STATE IN p ON WHICH $\bar{p}$ SCATTERS?

$\Rightarrow$ UNIVERSAL "FLUX FACTOR" FOR $\mathbb{P}$ IN PROTON INDEPENDENT OF INTERACTION

SHOULD COMPARE DIFFERENT INTERACTIONS $p\bar{p} \to pX$
$e^-p \to e^-pX$
$\bar{p}p \to \bar{p}pX$
AT DIFFERENT ENERGIES

UA8 ROMAN POT



MONTE CARLO SIMULATION

PYTHIA 4.8 (MODIFIED BY G. INGELMAN)

POMERON DEFINED AS BEAM PARTICLE WITH SWITCHES CONTROLLING STRUCTURE

Ex $xG(x) \sim (1-x)^5$ SOFT GLUON
$xG(x) \sim x(1-x)$ HARD GLUON
$xQ(x) \sim x(1-x)$ $q\bar{q}$

GENERATE POMERON-PROTON COLLISIONS WITH $\sqrt{s'}$
JET PRODUCTION FROM STANDARD QCD 2→2

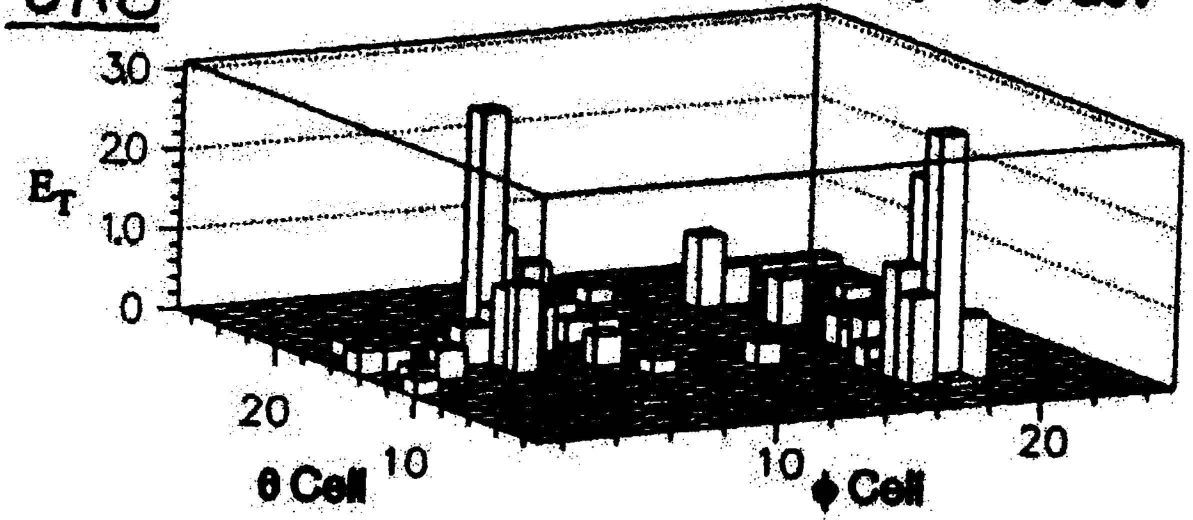
JETSET 6.3 HADRONIZATION ACCORDING TO LUND MODEL (INCLUDE I.S + F.S RADIATION)

BOOST TO LAB FRAME + PASS THROUGH UA2 DETECTOR SIMULATION

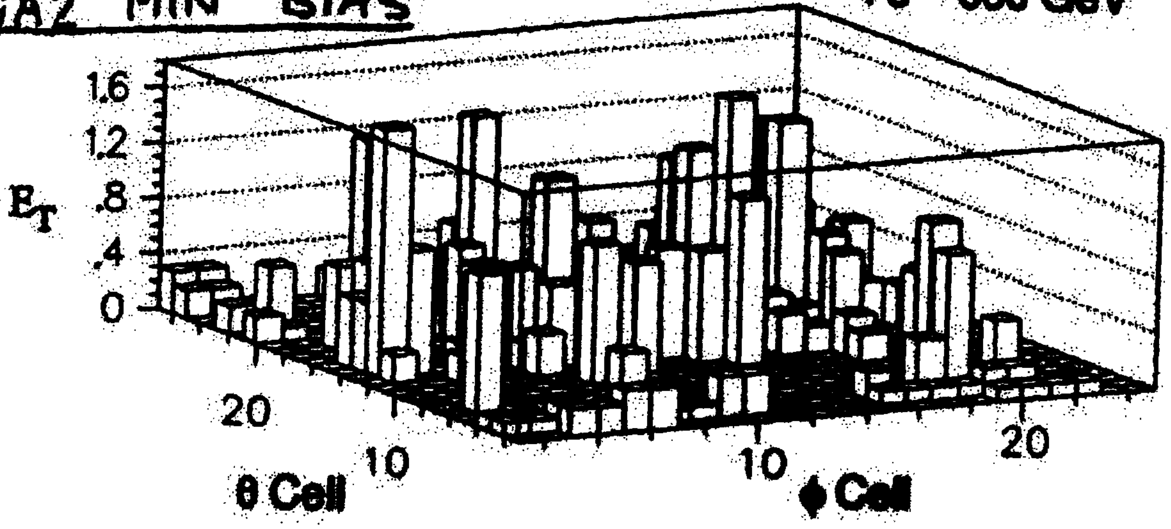
COMPARE WITH DATA

2-JET EVENTS ($E_T > 8$ GeV)

UA8 $\sqrt{s'} = 150$ GeV $p p$



UA2 MIN BIAS $\sqrt{s} = 630$ GeV $p \bar{p}$



UA8 2-JET EVENTS HAVE TYPICAL BEHAVIOR $\Delta\phi$, ENERGY FLOW, $\cos\theta^*$ INVARIANT MASS REASONABLY MODELLED BY MC WITH LITTLE DIFFERENCE BETWEEN $(1-x)S$
$x(1-x)$ q or g

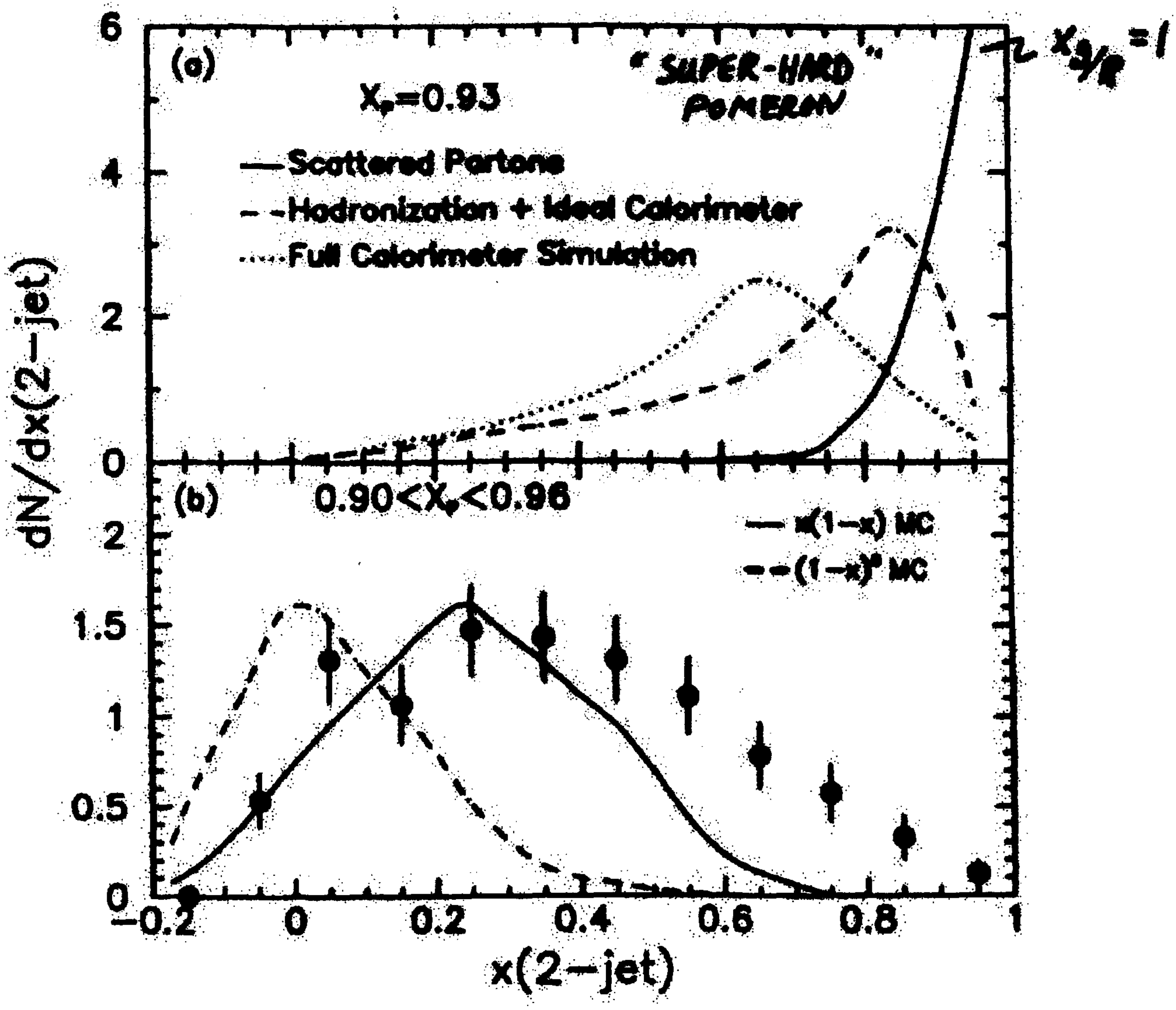
DATA SAMPLE		
x_p	$\sqrt{s'}$ GeV	2 Jets [illegible]
.9-.92	189	94
.92-.94	167	103
.94-.96	141	100

$$x(2\text{-JET}) = x_{g/\mathbb{P}} - x_{g/p}$$

$$= 1 - x_{g/p}$$

if whole $\mathbb{P}$ interacts

UA8 Collaboration, A. Brandt et al
Phys Lett. B 297 417 (1992)



FIT ⇒ 30% CONTRIBUTION FROM "SUPER-HARD" POMERON

CONCLUSIONS

- JETS OBSERVED IN EVENTS WITH TAGGED p ($\bar{p}$) SHOW TYPICAL QCD JET PROPERTIES
- $(1-x_p) = I\!P$ STRUCTURE APPEARS VERY HARD

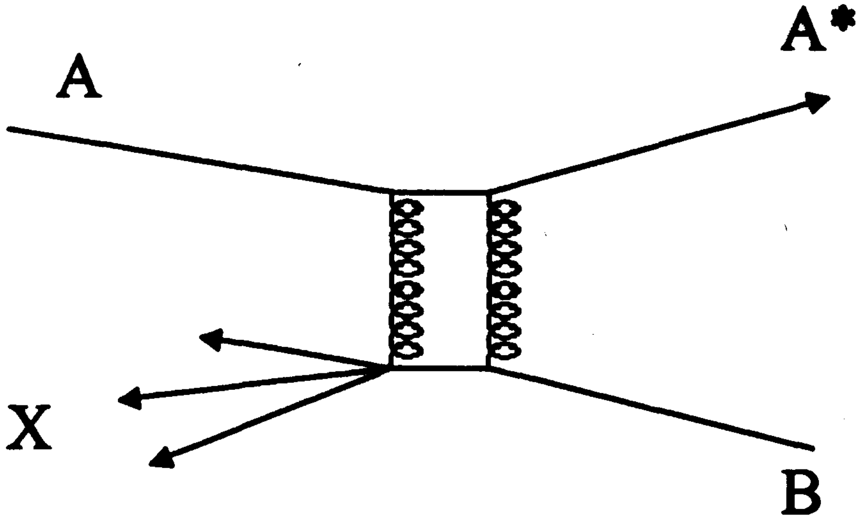
  x(2-JET) ⇒ 30% OF TIME ENTIRE $I\!P$ MOMENTUM GOES INTO HARD SCATTERING
  - EVIDENCE FOR PERTURBATIVE $I\!P$?

    FRANKFURT + STRIKMAN Phys Rev Lett 63 (1989)
    64 (1990)
  - $q\bar{q}$ $I\!P$ → 2-JETS WITH NO SPECTATOR D+L
- NO OBSERVED t-DEPENDENCE OF RESULTS
- CONCLUSIONS ROBUST
- $\sim 0.2 \times 10^{-3}$ OF S.D. EVENTS GIVE 2-JETS WITH $E_T > 8$ GeV (EVIDENCE FOR PARTONIC STRUCTURE OF POMERON)
  - VIOLATION OF MOMENTUM SUM RULE?
- NEED NEW EXPERIMENTS

  HERA, CDF + D0

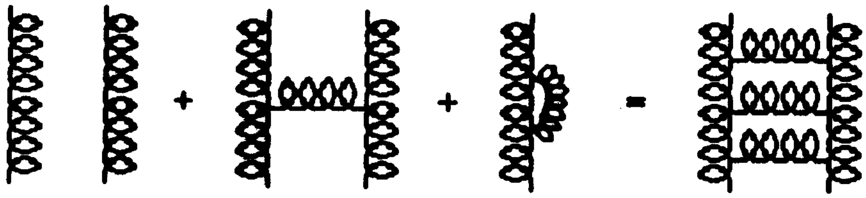
BFKL Theory

- Named after Balitsky, Fadin, Kuraev and Lipatov
- Proposes a more involved gluon structure of the Pomeron (higher order that Ingelman-Schlein)
- Basic Ingelman-Schlein proposes a two-quark structure which could be drawn as



BFKL II

- Starting with the two reggeized gluons we can add perturbative corrections of real ladder gluons and virtual radiative gluons to get a gluon ladder



- Mathematically, each successive order of correction adds a power of log *s* to the perturbative expansion and at sufficient energies will "break" the perturbation
- BFKL Proposes to fix this by isolating in each order the contribution with the highest power of log *s* and resumming these leading terms (leading logarithmic approximation)

BFKL III

- The ladders are resummed using an integral equation known as the BFKL equation. In the diffractive regime we can write $s \propto 1/\xi$ by introducing a dependence on k_T
- The resummed amplitude has a cut in the complex angular momentum plane which is called the perturbative or BFKL Pomeron
- The k_T dependence causes a different jet topology than the Ingelman-Schlein model proposes which could in theory be probed in a collider.
- Due to infrared-safety considerations, current detectors may not be sensitive enough to see the small corrections predicted by BFKL theory

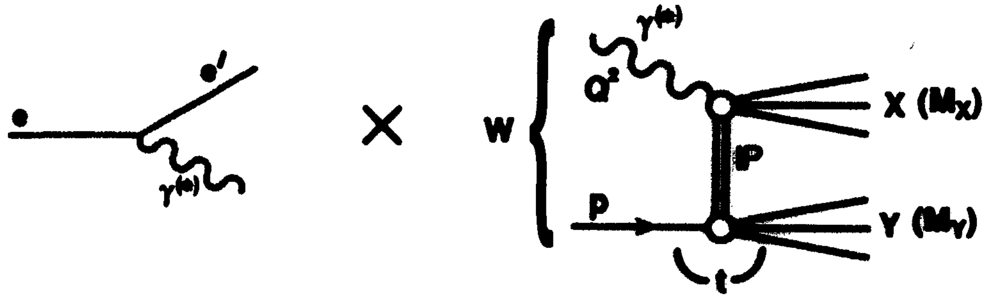
Hard Diffraction at HERA

courtesy of **Paul Newman, Birmingham**

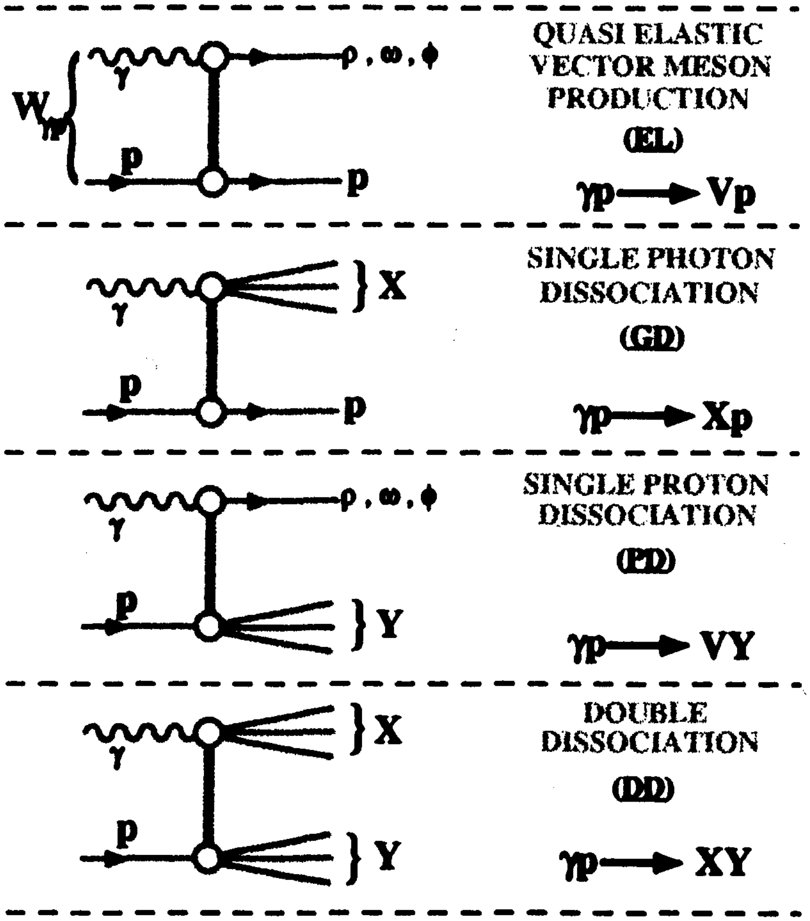
- Introduction to Diffraction at HERA.
- Latest Diffractive Structure Function Data
- QCD structure of $\gamma^* p$ Diffraction
- Energy Dependence of $\gamma^* p$ Diffraction
- Comparisons with Dipole Models
- Hadronic Final State Data
- Relation to hard diffraction in $p\bar{p}$ Scattering
- Prospects for the Future

Diffraction at HERA

At HERA, diffractive $\gamma^{(*)}p$ interactions can be studied ...



COLOUR SINGLET EXCHANGE PROCESSES IN γ^*-p INTERACTIONS



All four processes can be measured with varying Q^2, W, t, M_X, M_Y

- $Q^2 \sim 0$, $t \sim 0$

Similar to soft hadronic diffraction.

- Large $|t|$

pQCD calculation of IP?

- Large Q^2

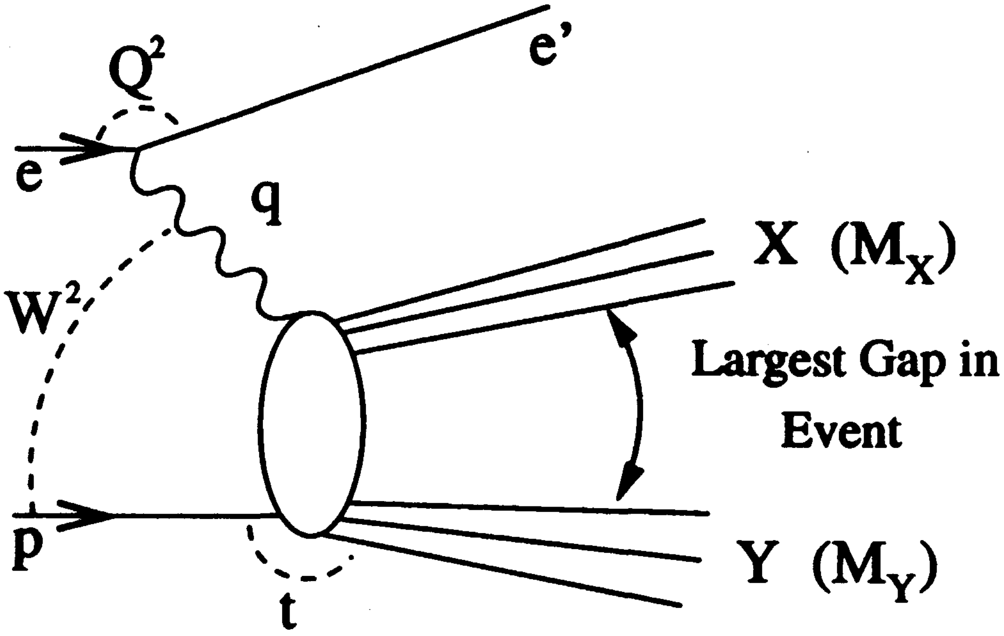
pQCD at γ^*IP vertex

γ^* 'probes' IP?

~ 60 H1 / ZEUS publications on diffraction so far!

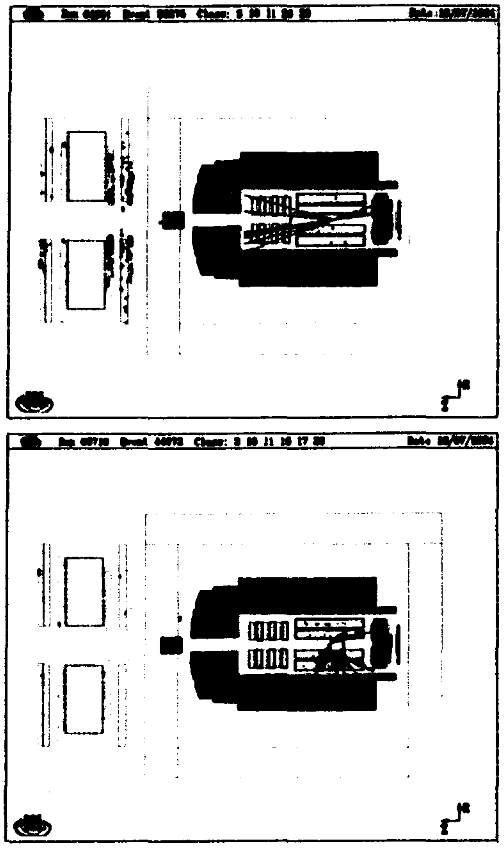
This talk mostly concerned with $\gamma^* p \to Xp$, large Q^2, small $|t|$

The Kinematics of Diffractive DIS



- The usual DIS kinematic variables are used
  $Q^2 = -q^2$, $W^2 = (q+P)^2$, $x = \frac{-q^2}{2P.q}$, $t = (P - p_y)^2$
- Plus two other useful variables
  $\beta = \frac{-q^2}{2q.(P-p-Y)} = \frac{Q^2}{Q^2+M_X^2-t}$
  $x_{\mathbb{P}} = \frac{q.(P-p_Y)}{q.P} = \frac{Q^2+M_X^2-t}{Q^2+W^2-M_p^2} = \frac{x}{\beta}$
- In the infinite momentum frame of the proton :
  $x_{\mathbb{P}}$: fraction of the proton momentum carried by the pomeron
  β: fraction of the pomeron momentum carried by the struck quark

Can one probe pomeron structure at HERA?

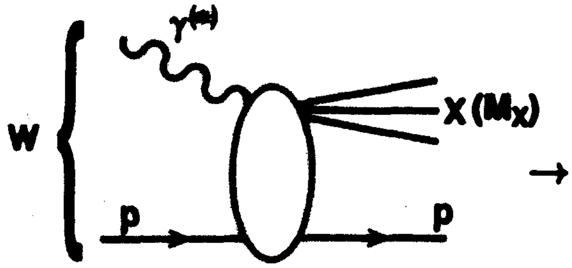


- At HERA the highly virtual photon is used to probe the structure of the proton
- The virtual photon probe can also be used to probe the structure of the pomeron
- There is much controversy about assigning parton distribution functions to this pseudo-particle, however, the measurement of F_2^D itself assumes nothing about the nature of diffraction

Experimental Techniques

Two complementary measurement techniques ...

1) Measure Hadrons Comprising X

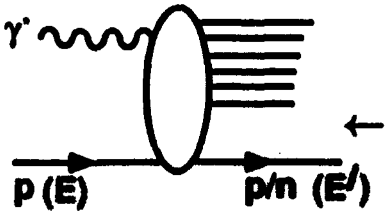


Largest rapidity
→ gap among
final state hadrons.

$\Delta\eta$ large when
$M_X \ll W$

- Ample statistics!
- Large systematics from unseen proton - elastic or dissoc'?
- t measurements not generally possible.
- Becoming harder to trigger

2) Tag and measure Leading Proton in Dedicated Detectors



No explicit
← gap requirement

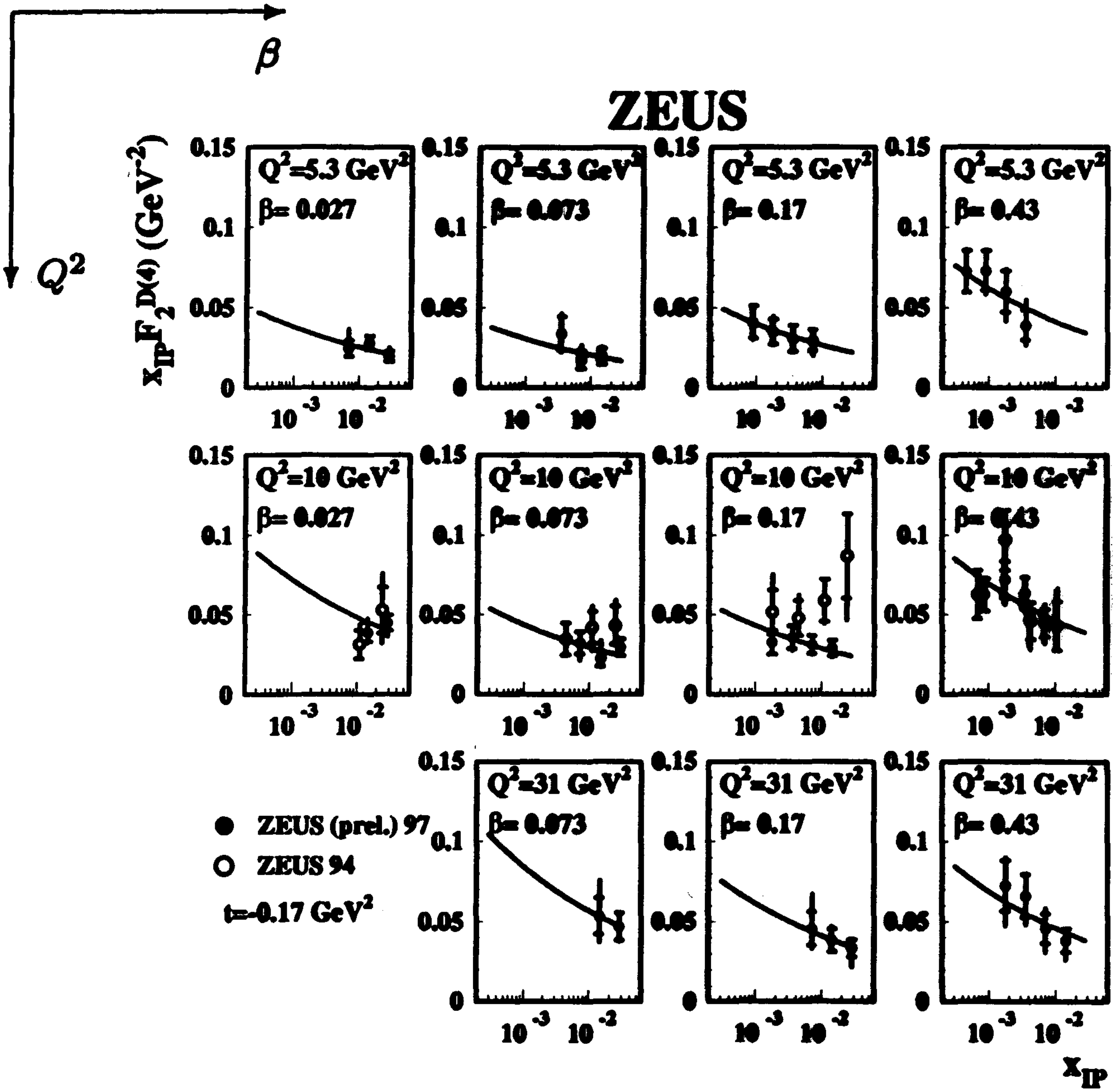
$x_{\mathbb{P}} = E'/E$
if exclusive p
at proton vertex.

- t measurements possible.
- Systematics can be reduced.
- Detector acceptance can be poor. → limited stats so far.

ZEUS $F_2^{D(4)}$ Data

Leading proton data allow 4-fold differential cross sections

$\rightarrow F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$

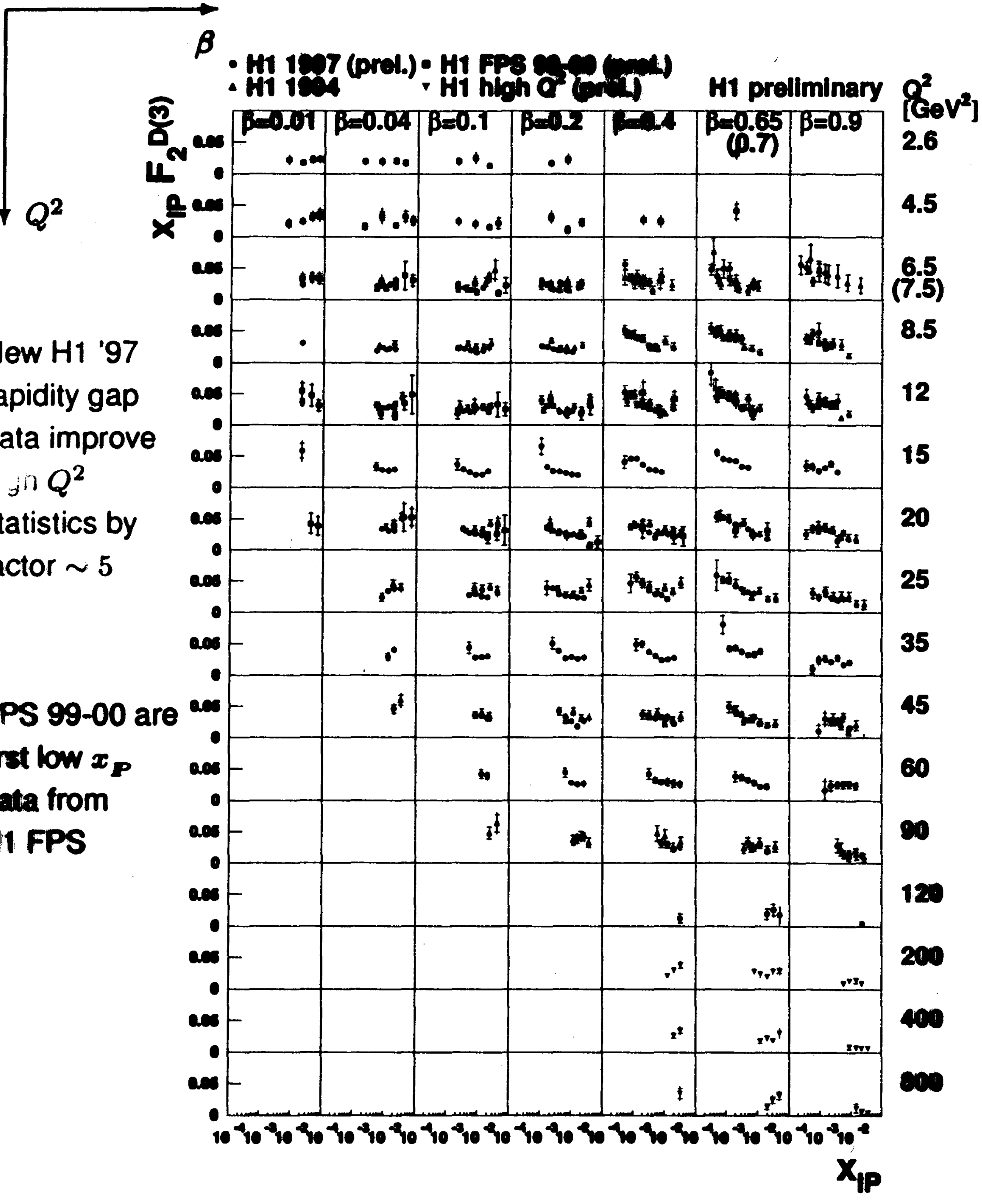


New ZEUS '97 LPS data give factor 6 increase in statistics

For non-proton tagged data, t poorly reconstructed.

$\rightarrow$ measure $F_2^{D(3)}(\beta, Q^2, x_{I\!P}) = \int \mathrm{d}t\, F_2^{D(4)}$

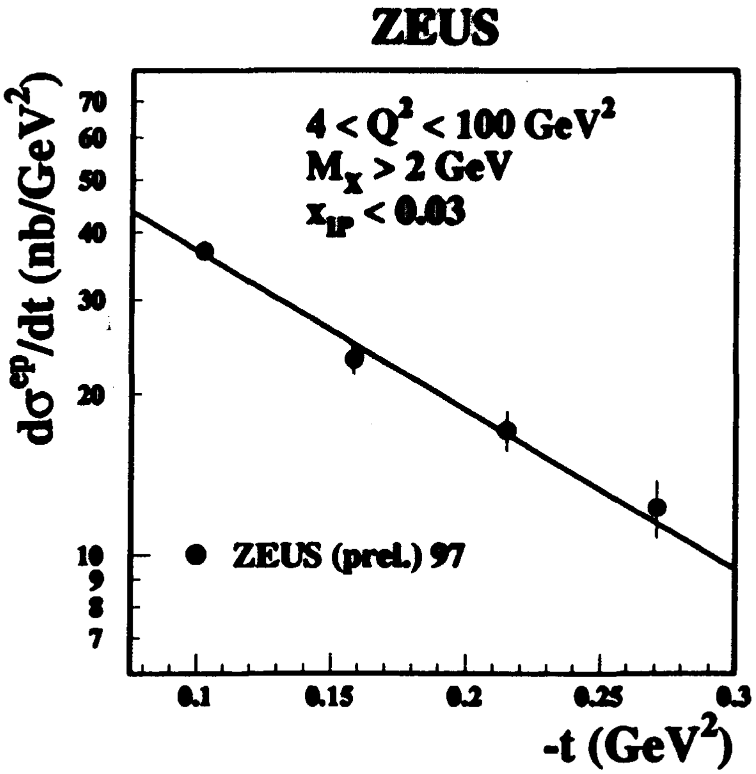
Compilation of H1 $F_2^{D(3)}$ Data



New H1 '97 rapidity gap data improve high Q^2 statistics by factor ~ 5

FPS 99-00 are first low x_{P} data from H1 FPS

t Dependence from Tagged Proton Data



Fit full ZEUS dataset to ...

$$\frac{d\sigma}{dt} \propto e^{(b\,t)}$$

$$b = 6.8 \pm 0.6\ (\text{stat.})\ {}^{+1.2}_{-0.7}\ (\text{syst.})\ \text{GeV}^{-2}$$

Highly peripheral p scattering

Slope larger than for e.g. elastic J/ψ → larger spatial extent at γ^* fluctuation?

Factorisation Properties of F_2^D

QCD Hard Scattering Factorisation for Diffractive DIS:-

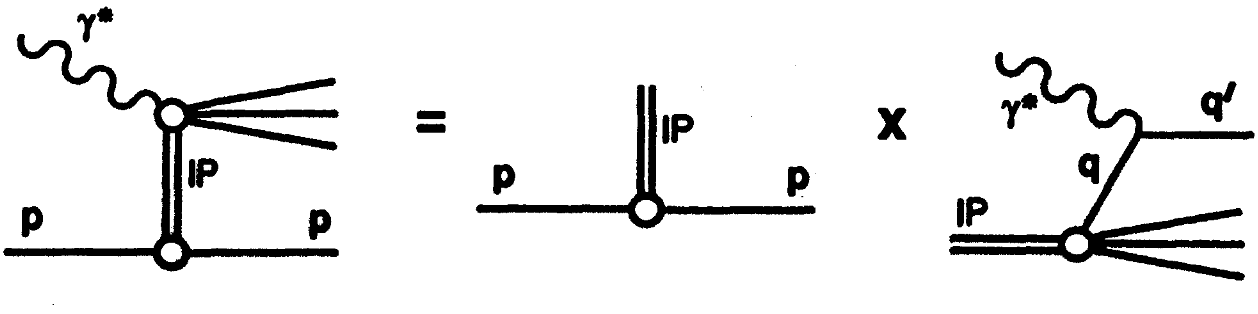
(Trentadue, Veneziano, Berera, Soper, Collins ...)
Diffractive parton densities $f(x_{\mathbb{P}}, t, x, Q^2)$ express proton parton probability distributions with intact final state proton at particular $x_{\mathbb{P}}, t \ldots$

$$\sigma(\gamma^* p \to Xp) \sim \sum_i f_{i/p}(x_{\mathbb{P}}, t, x, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(x, Q^2)$$

At fixed $x_{\mathbb{P}}, t,$ $f(x_{\mathbb{P}}, t, x, Q^2)$ evolve with x, Q^2 according to DGLAP equations.

'Regge' Factorisation ("resolved $\mathbb{P}$ model"):-

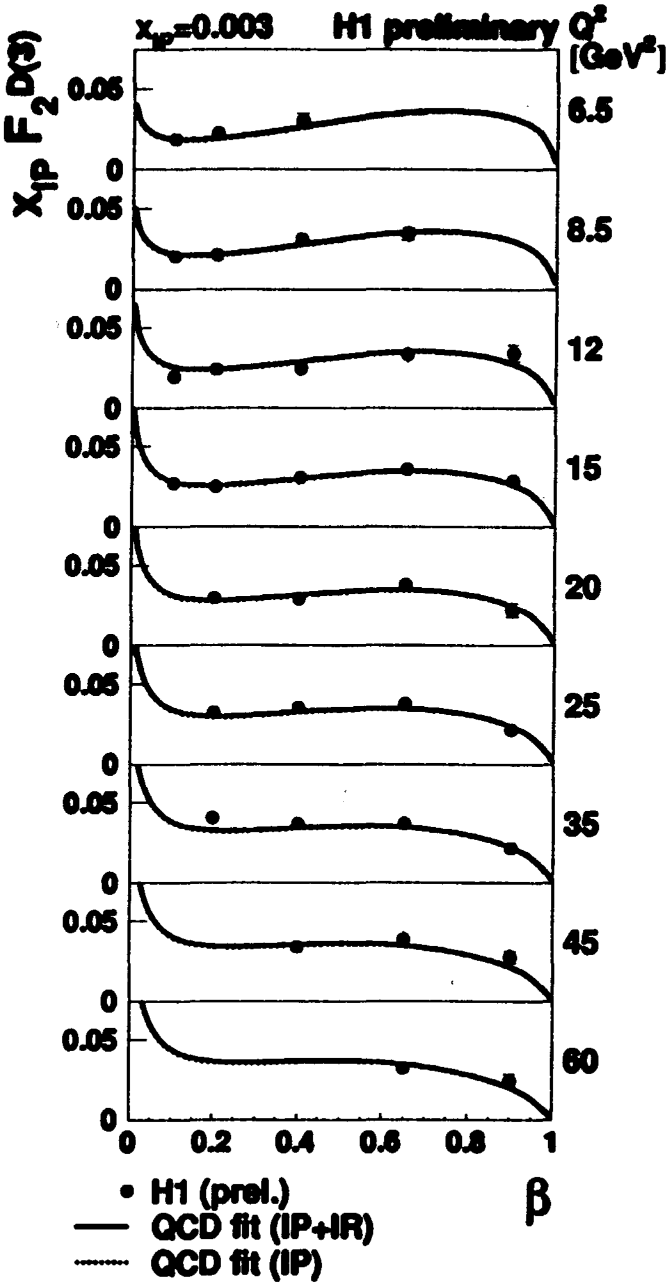
Soft hadron phenomenology suggests a universal *pomeron* ($\mathbb{P}$) exchange can be introduced, with flux dependent only on $x_{\mathbb{P}}, t$ (Donnachie, Landshoff, Ingelman, Schlein ...)

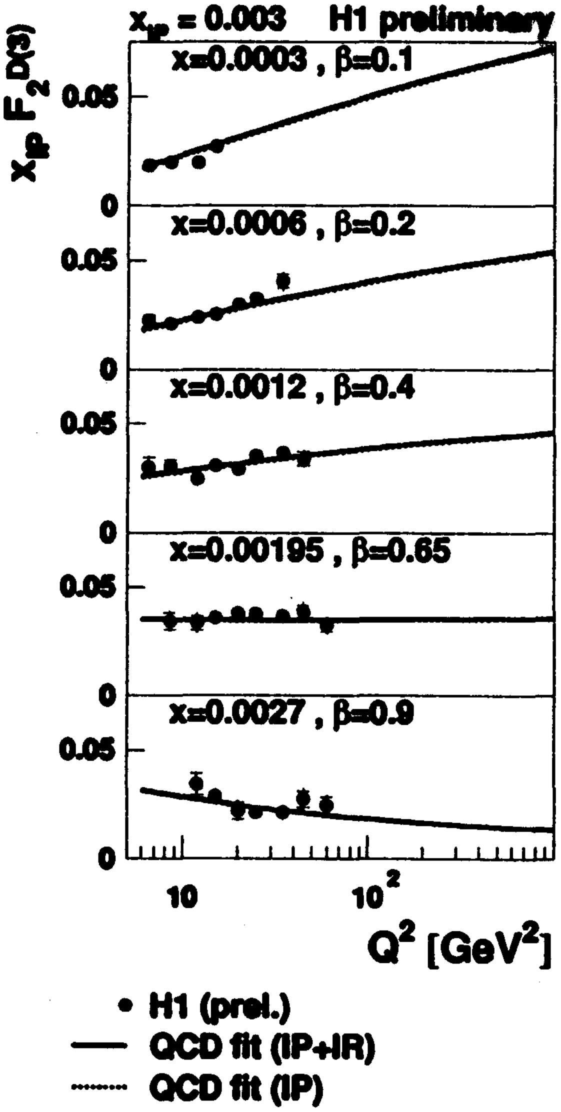


$$\begin{aligned} \sigma(\gamma^* p \to Xp) &\sim f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \otimes F_2^{\mathbb{P}}(\beta, Q^2) \\ &\sim f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \otimes \textstyle\sum_i f_{i/\mathbb{P}}(\beta, Q^2) \\ &\qquad \otimes \hat{\sigma}_{\gamma^* i}(\beta, Q^2) \end{aligned}$$

β, Q^2 dependence of $F_2^{D(3)}$

Example results at $x_{I\!P} = 0.003$





β dependence relatively flat.

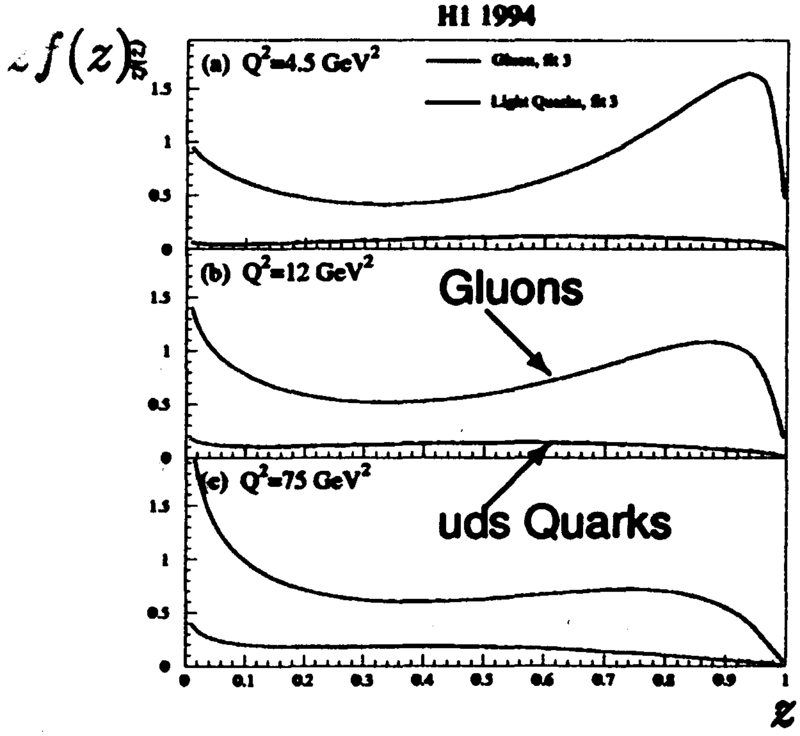
Rising scaling violations with $\ln Q^2$ up to large β

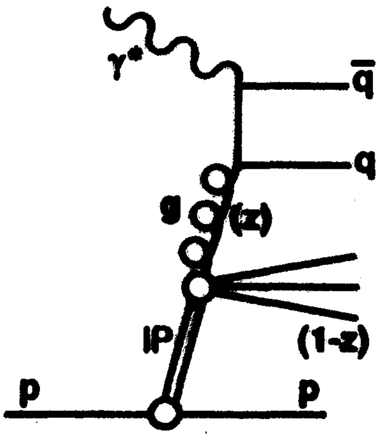
Require large gluon contribution in diffractive pdf's, extending to large fractional momenta (quark only gives no rise with Q^2)

Diffractive Parton Densities

Various sets of diffractive parton densities extracted from DGLAP fits to (β, Q^2) dependence of $F_2^{D(3)}$

Usually assume Regge factorisation for $x_{I\!P}$ dependence.





DGLAP analysis yields huge gluon distribution extending to high z

Complications:

- Poorly constrained high z region
- Higher twist contributions present?

Parton densities implemented in MC models for comparison with final state data

$F_2^{D(3)}$ in terms of Regge theory

Try a fit with two trajectories (pomeron and meson):

$$F_2^{D(3)} = f_{\mathbb{P}/p}(x_{\mathbb{P}})F_2^{\mathbb{P}}(\beta, Q^2) + f_{\mathbb{R}/p}(x_{\mathbb{P}})F_2^{\mathbb{R}}(\beta, Q^2)$$

where for the pomeron (similarly for the meson)

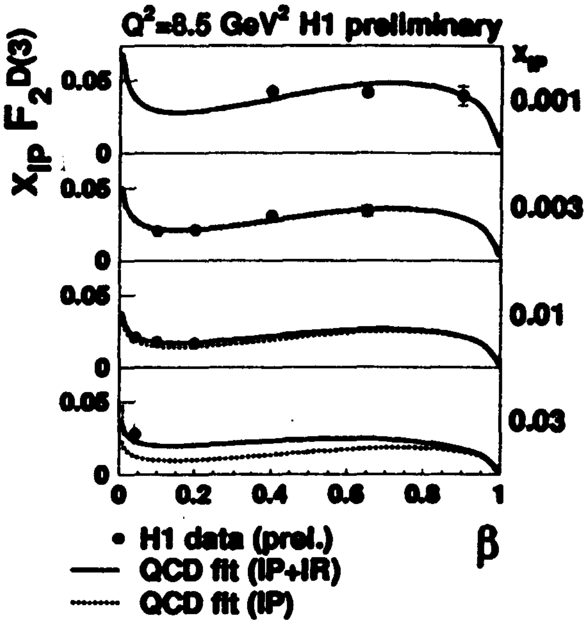
$$f_{\mathbb{P}/p}(x_{\mathbb{P}}) = \int_{t_{cut}}^{t_{min}} \frac{e^{B_{\mathbb{P}}t}}{x_{\mathbb{P}}^{2\alpha_{\mathbb{P}}(t)-1}} \mathrm{d}t,$$

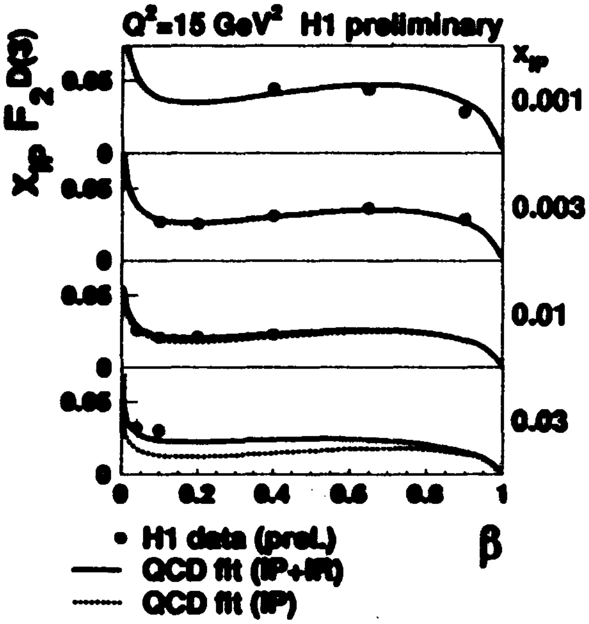
$$\text{with} \quad \alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t$$

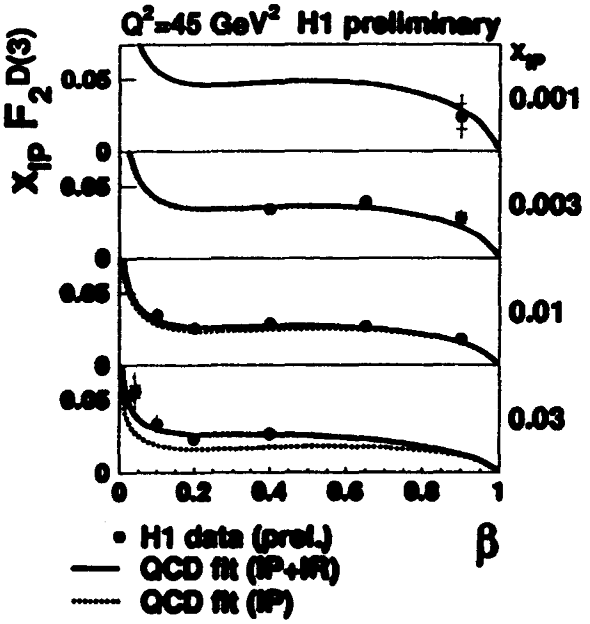
Fixed parameters, $\alpha'_{\mathbb{R}}$, $B_{\mathbb{R}}$, $\alpha'_{\mathbb{P}}$, $B_{\mathbb{P}}$ taken from pp experiments. $\alpha_{\mathbb{P}}(0)$, $\alpha_{\mathbb{R}}(0)$, $F_2^{\mathbb{P}}(\beta, Q^2)$ and $F_2^{\mathbb{R}}(\beta, Q^2)$ are left free.

- $\alpha_{\mathbb{P}}(0) = 1.203 \pm 0.020(\text{stat.}) \pm 0.013(\text{sys.})^{+0.030}_{-0.035}(\text{model})$
- $\alpha_{\mathbb{R}}(0) = 0.50 \pm 0.11(\text{stat.}) \pm 0.11(\text{sys.})^{+0.09}_{-0.10}(\text{model})$

Variation of diffractive pdf's with $x_{I\!P}$?







Variations with $x_{I\!P}$ well described by Regge flux factors.

Small sub-leading exchange ($I\!R$) contribution required at high $x_{I\!P}$, low β

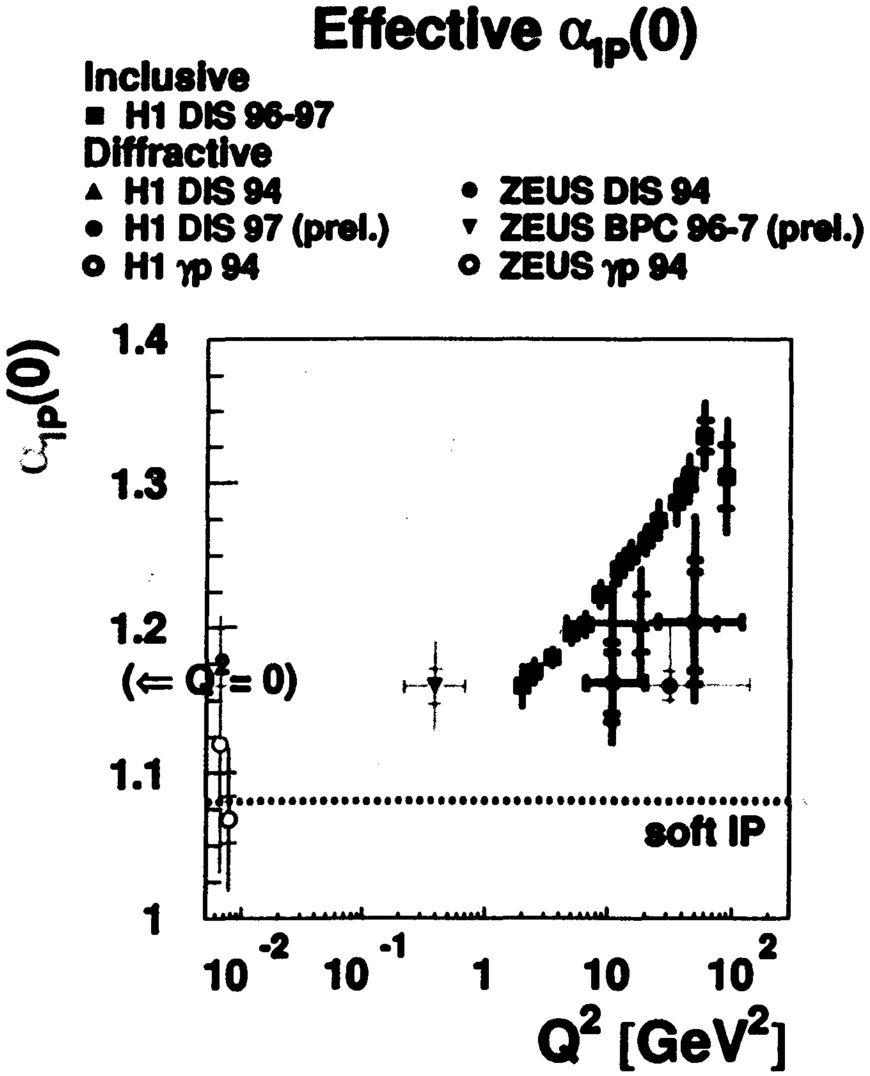
No evidence for breakdown of Regge factorisation hypothesis.

How Universal is the Pomeron?

Compare effective $\alpha_{\mathbb{P}}(0)$ from F_2^D and F_2 ...

Total x-section $\gamma^* p \to X$ $\quad F_2 \sim A(Q^2)\; x^{1-\alpha_{\mathbb{P}}(0)}$

Diss$^{\mathrm{n}}$ x-section $\gamma^* p \to Xp$ $\quad x_{\mathbb{P}} F_2^D \sim B(\beta, Q^2)\; x_{\mathbb{P}}^{2-2\langle\alpha_{\mathbb{P}}(t)\rangle}$



$\alpha_{\mathbb{P}}(0)$ grows with Q^2 → larger than soft $\mathbb{P}$ at large Q^2

Growth of effective $\alpha_{\mathbb{P}}(0)$ slower for diffractive than for inclusive cross section?

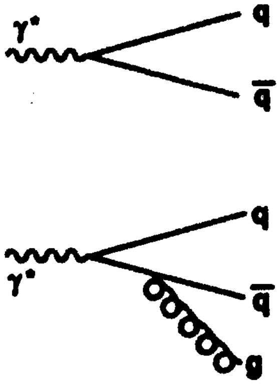
Energy dependences of diffractive and inclusive cross sections become similar at large Q^2

The pomeron as a single pole cannot describe all HERA F_2^D and F_2 data (also c.f. VM).

Colour Dipole Models

$\gamma^* \to q\bar{q}, q\bar{q}g$ well in advance of target ...

Partonic fluctuations scatter elastically from proton.



× Cross section for colour dipole to scatter elastically from proton

Simple relationships between σ_{tot}, σ_{el} and σ_{dif}

Describe diffraction beyond leading twist (high β?)

Joint description of F_2 and F_2^D ...

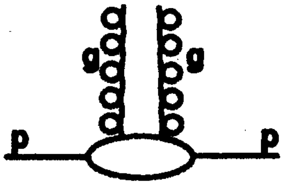
Different approaches to the dipole cross section ...

- Non-perturbative interaction with proton colour field

e.g. 'semi-classical' model
(Buchmüller, Gehrmann, Hebecker)

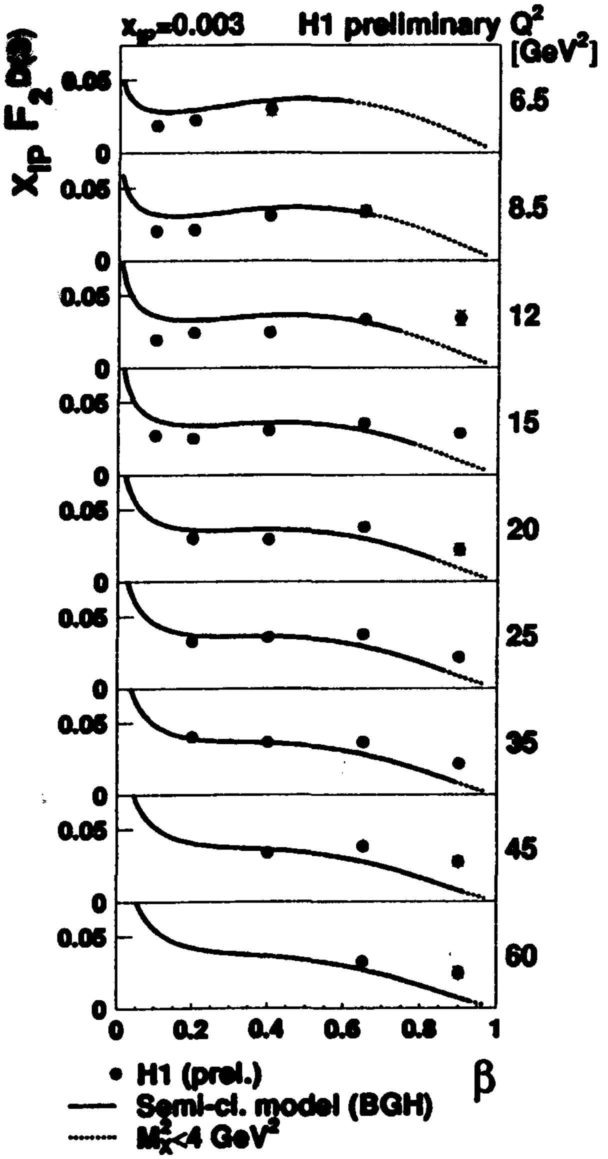
- Partonic - two gluon exchange

e.g. 'saturation' model
(Golec-Biernat, Wüsthoff)

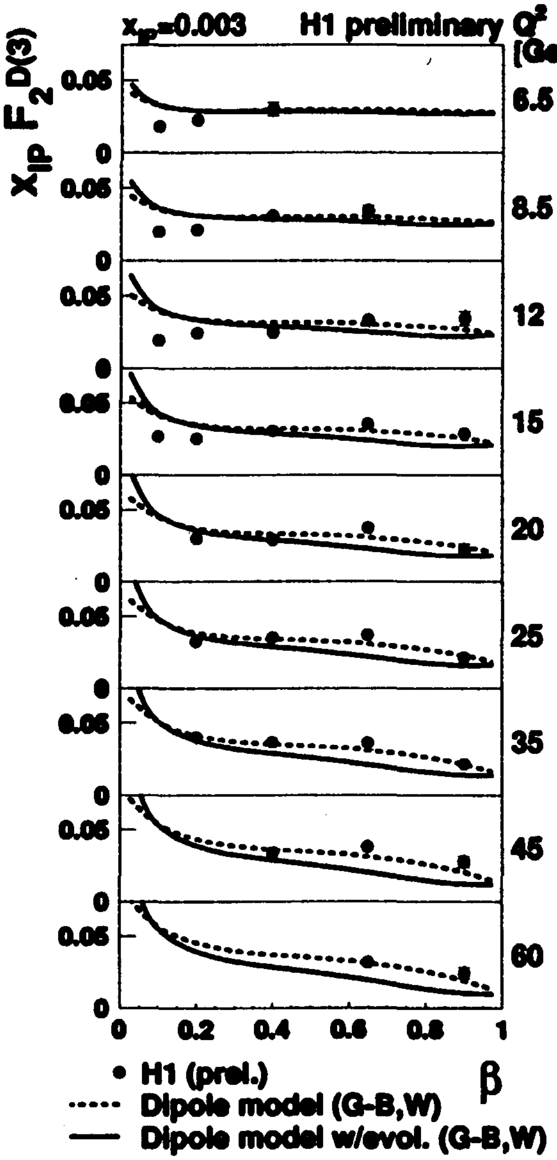


Colour Dipole Models

'Semi-classical'



'Saturation'



General features reproduced. Exceed data at low β, low Q^2.

Impressive given that models basically constrained by F_2 data!

'Saturation' model - higher twist at high β → better description

Inclusion of QCD evolution in 'saturation' model does not help.

Description improves with extra $4/9$ colour factor for $q\bar{q}g$

Diffractive Final State Data - Event Shapes

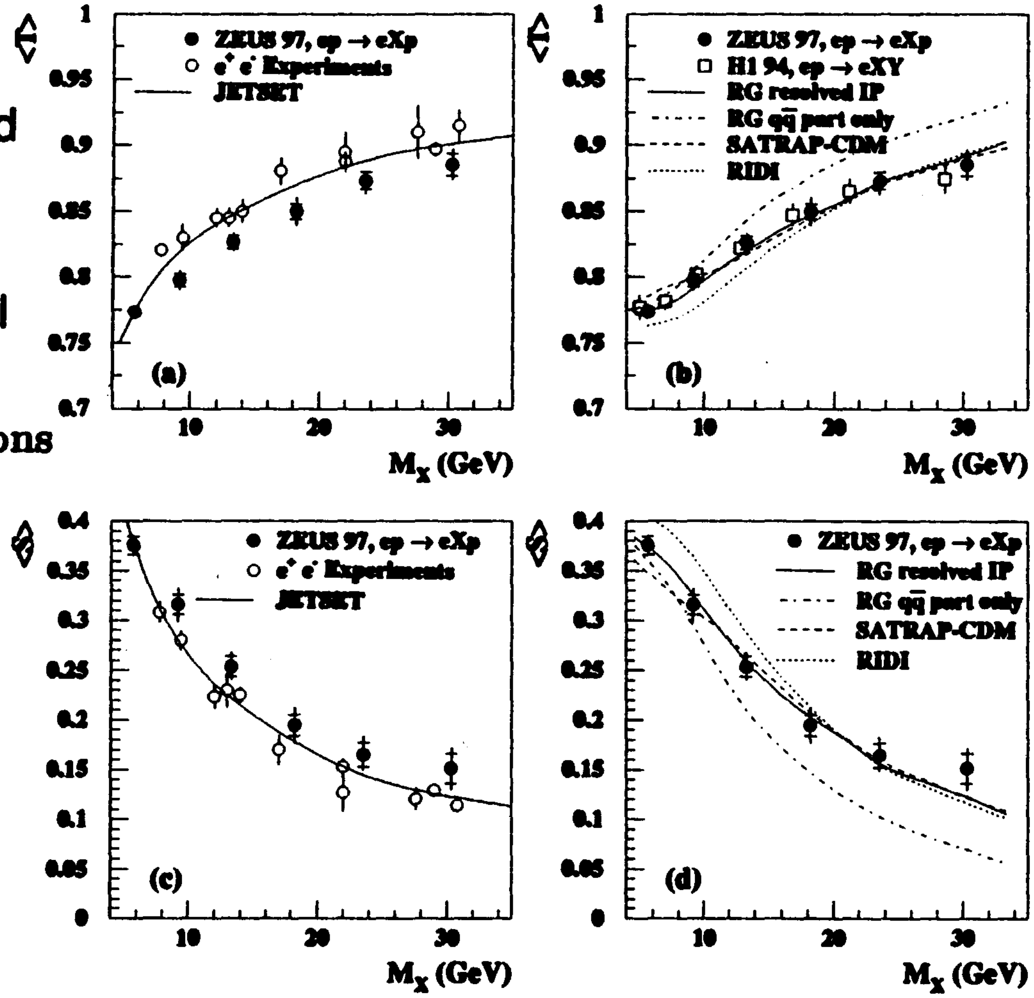
F_2^D only directly measures diffractive quark distribution

Many hadronic final state observables constrain the gluon distribution / event topology

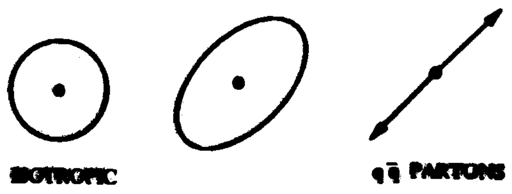
Very good agreement with diffractive parton densities from F_2^D in almost all cases.

e.g. Thrust and Sphericity indicate less collimated final state than $e^+e^- \to$ hadrons at similar energy.

ZEUS



$1/2 < T < 1$



$1 > S > 0$

Described by models with final states containing > 2 parton leading final state

- $q\bar{q}g$ in dipole models
- BGF in resolved $\mathbb{P}$ models

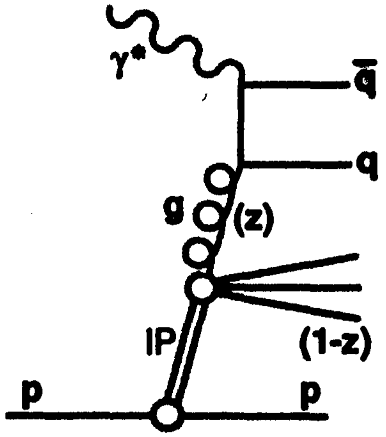
Diffractive Final State Data - Dijets

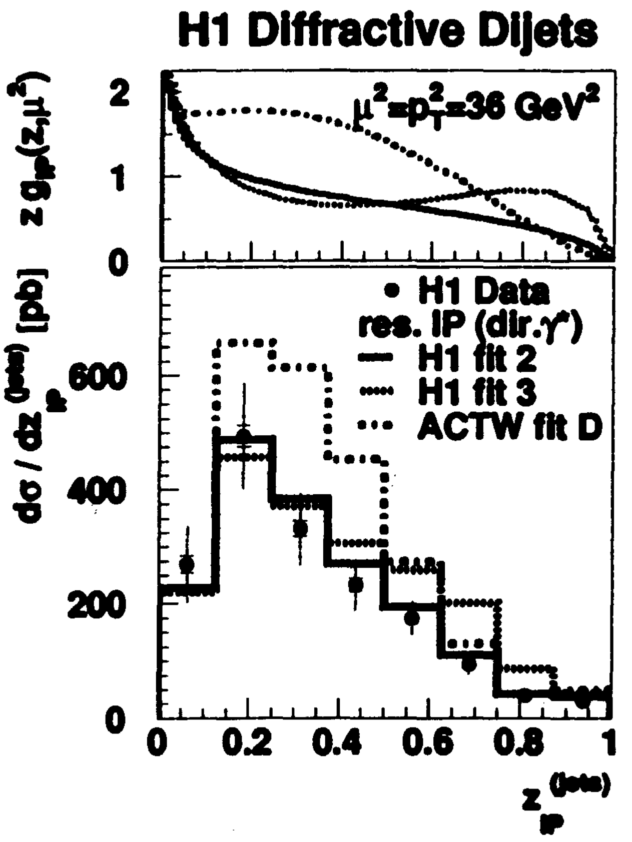
Best tests of gluon come in dijet and open charm studies.

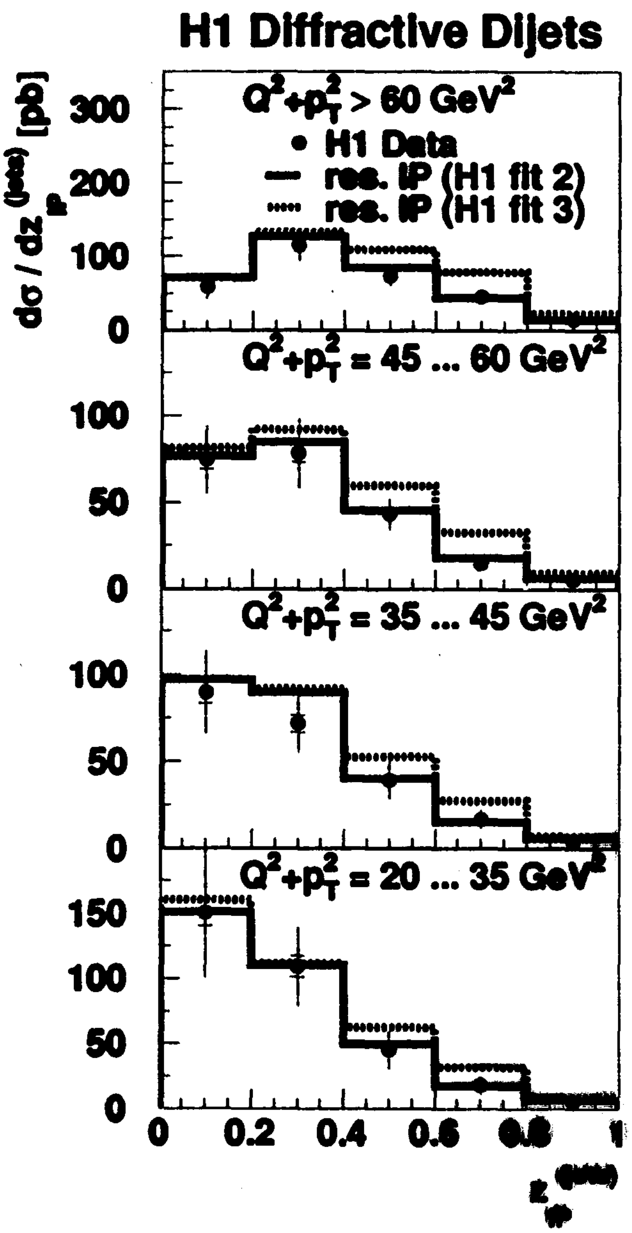
Gluon initiated processes

(boson-gluon fusion).

Rates ~ proportional to gluon density!







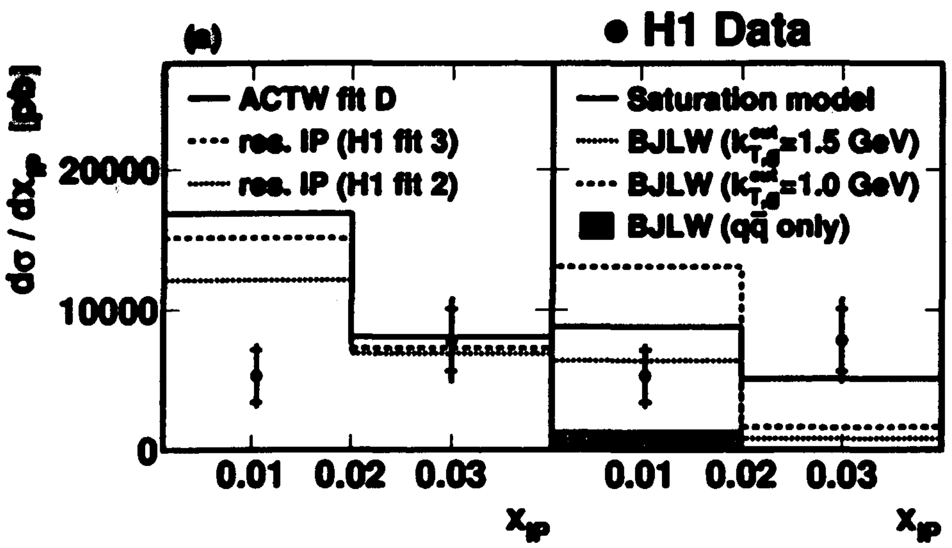
Can distinguish between different fits to F_2^D

H1 fit 2 ('flat' gluon) works spectacularly (too!) well.

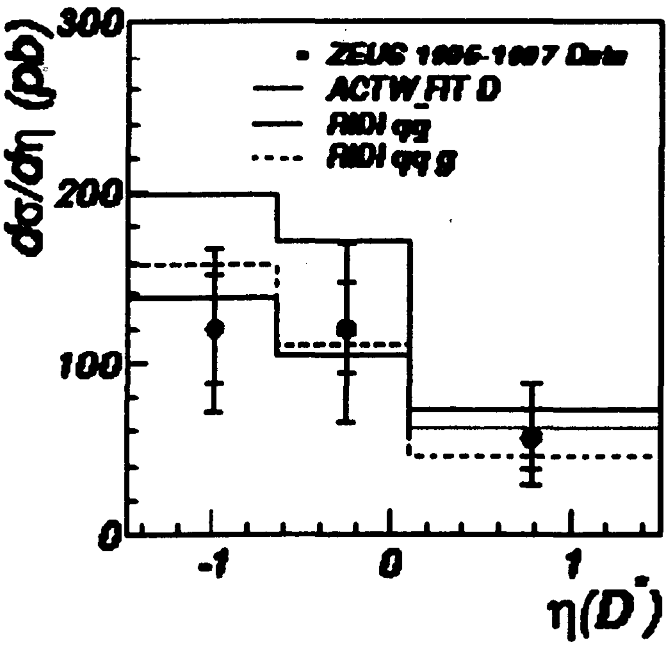
Also supports Regge factorisation (fits double differential $z_{\mathbb{P}}, x_{\mathbb{P}}$ cross secs with $\alpha_{\mathbb{P}}(0) \sim 1.2$)

Diffractive Final State Data - Open Charm

Even low statistics D^* cross sections can discriminate between models.



H1 DIS: $2 - 3\sigma$ discrepancy from resolved $\mathbb{P}$ model at low $x_{\mathbb{P}}/M_X$.



ZEUS γp: Predicted normalisation exceeds data by $\sim 2\sigma$

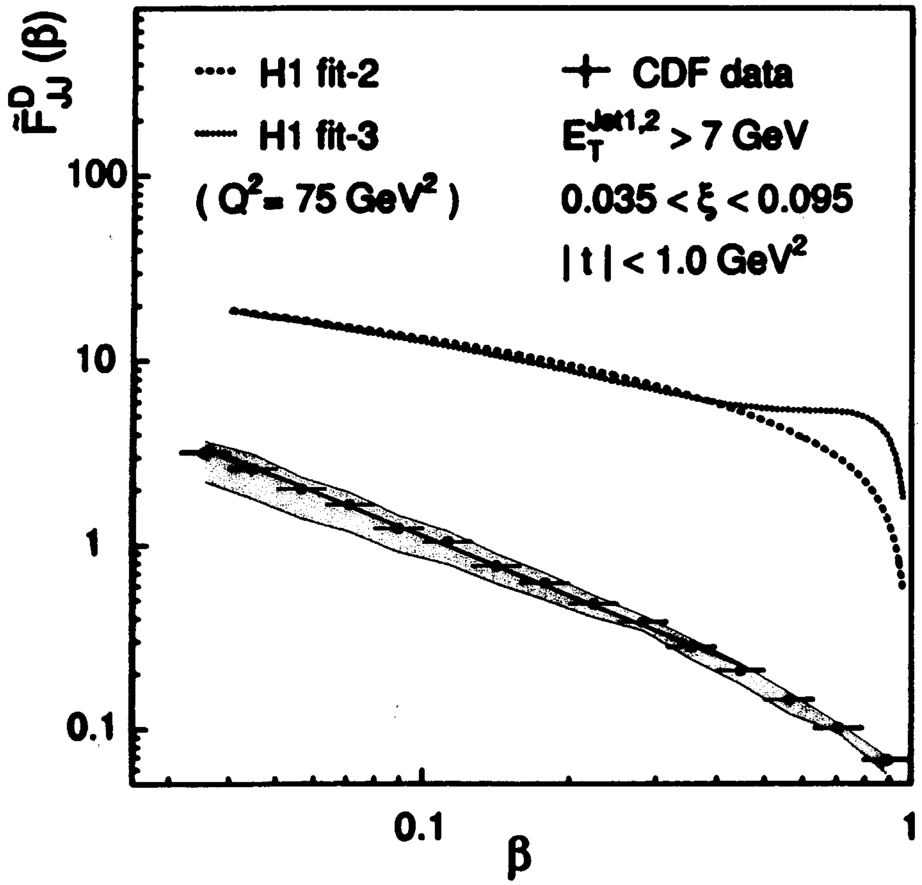
ZEUS DIS: Shapes and normalisation well described by resolved $\mathbb{P}$ models.

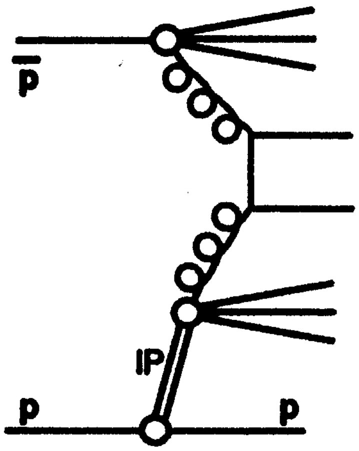
Situation not yet clear

- Statistical Fluctuations?
- First cracks in Resolved $\mathbb{P}$ model?

How Universal are Diffractive Partons?

Model Tevatron diffractive dijets using $\mathbb{P}$ partons from F_2^D.





Prediction inconsistent in both shape and normalisation.

Catastrophe?

Expected!

Discrepancies in all channels at the Tevatron (W, b, J/ψ, double pomeron exchange) . . .

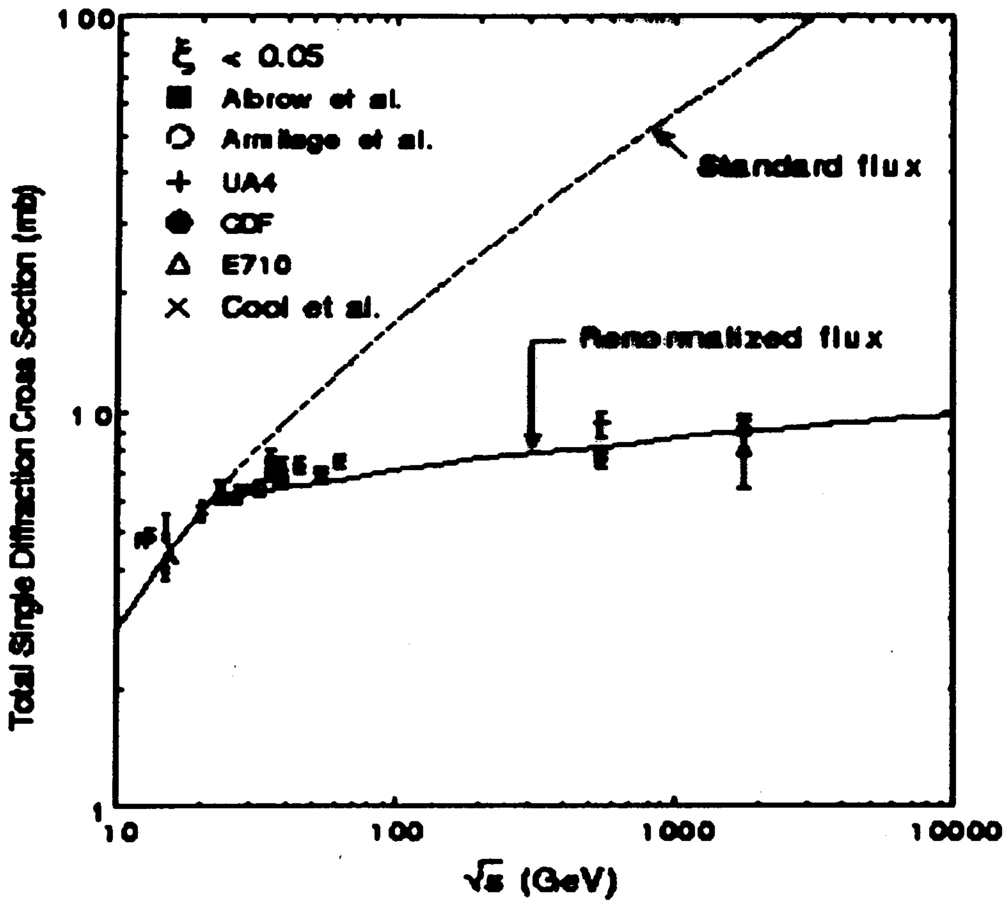
Discrepancies are process and kinematics dependent

Associated with hadronic remnant reinteractions (absorptive corrections?)

Phenomenological models can explain at least some data

Deeper understanding of ‘gap survival’ needed to explain connection between diffractive DIS and hadronic diffraction

Renormalization



- Failure of total single diffractive cross section to follow Regge prediction well-known, attributed to screening or absorbtive corrections (Levin+others) from multiple pomeron exchange

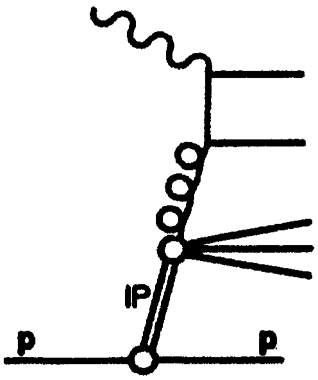
- Goulianos (PLB **358** 379 (1995)) explains discrepancy by "Flux Renormalization", only allowing one pomeron to be emitted, gives a phenomenological description of HERA vs. Tevatron discrepancy as well (√s dependent factor)

- Schlein and Erhan have alternate description (ξ damping)

Possible control experiment? - γp Dijets

Hard diffractive photoproduction provides photon interactions with and without remnants ...

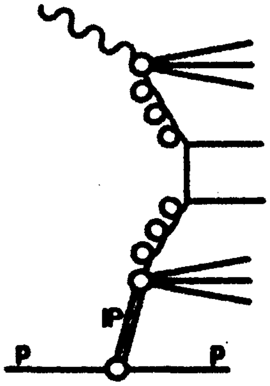
x_γ^{jets} = fraction of γ momentum entering the hard scatter.



DIRECT

$x_\gamma^{\text{jets}} \sim 1$

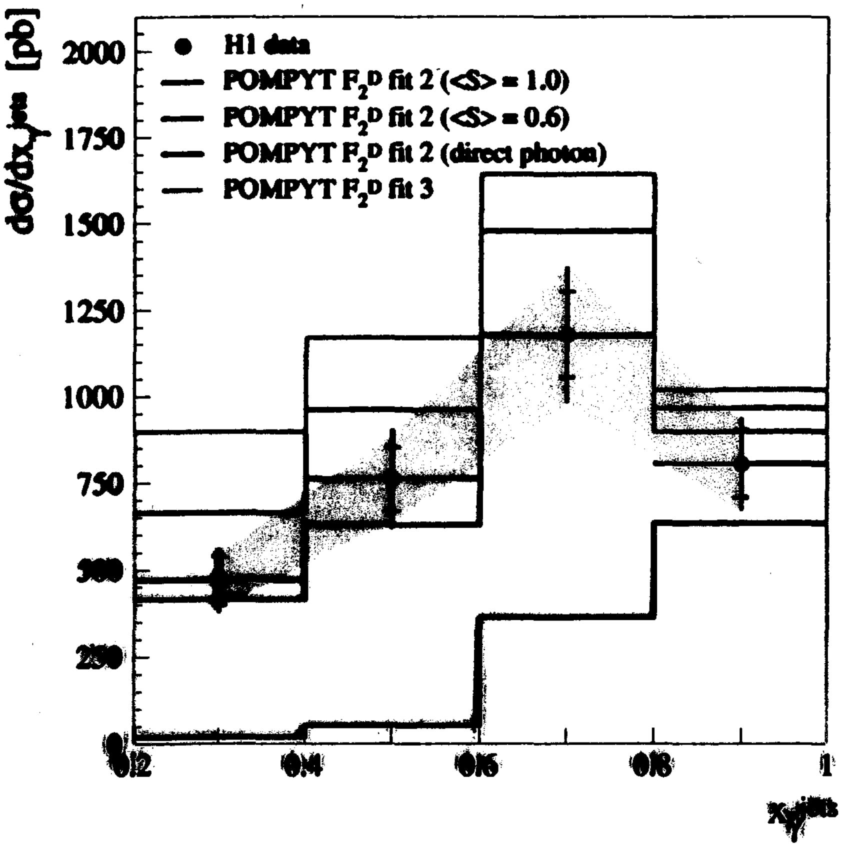
All gaps survive?



RESOLVED

$x_\gamma^{\text{jets}} < 1$

Some gaps destroyed?



Description based on diffractive partons improved by suppressing resolved interactions by 'gap survival probability' of 0.6

Improved data and MC modelling needed for firm conclusions.

No evidence (yet) for large factorisation breaking in resolved γp

Very Forward Proton Spectrometer

High acceptance direct tagging of leading protons →

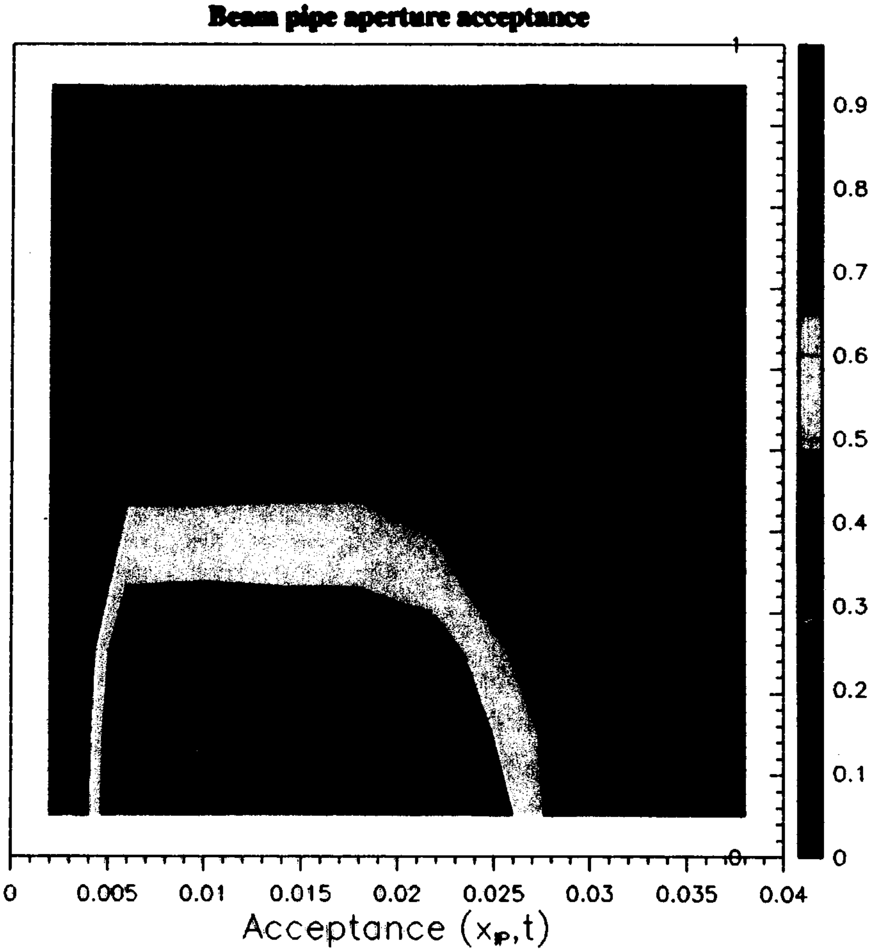
- Efficient triggering for 'rare' processes
- Removes rapidity gap selection systematics
- t dependences can be extracted

New tool for HERA-II

H1 VFPS

Roman pots at
$z \sim 200$ m
from 2002-3

Close to 100%
acceptance for
$x_{I\!P} \lesssim 0.02$
$|t| \lesssim 0.25\ \mathrm{GeV}^2$



Complements existing LPS / FPS . . .

Smaller $(x_{I\!P}, t)$ coverage, but higher tagging efficiency

Conclusion

- Hard diffraction is a Complex Subject!
- Hard *ep* diffraction tackles many fundamental questions in strong interactions
- This talk only scratched the surface (e.g. no VM discussion)

- Should be lots more data to come ...
  - HERA-I still under analysis ($> 100\ \mathrm{pb}^{-1}$ per experiment)
  - HERA-II ($\sim 1\ \mathrm{fb}^{-1}$ per experiment by 2006)
- New detectors - H1 VFPS ...
- Scope for much higher Precision!

- Many open questions remain.
- Lots of experimental / phenomenological challenges!

Color Evaporation

- This theory attempts to account for rapidity gaps in diffractive events without resorting to the use of a Pomeron
- Model has been successfully applied to onium production (charmonium, J/psi)
- Proposes that allowing soft color (non-perturbative) interactions can change the hadronization process such that color is bleached out and rapidity gaps appear
- Soft Color shows same exponential t-dependence as Ingelman-Schlein due to primordial k_T of the partons
- Suggests a formation rate of gaps in gluon-gluon sub processes which is less than or equal to the formation rate in quark-quark sub processes

Color Evaporation II

- Examples