What is the Pomeron? Recent Results on Diffraction from the HERA ep Collider

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- HERA, H1 and Deep Inelastic Scattering
- Large Rapidity Gap Events
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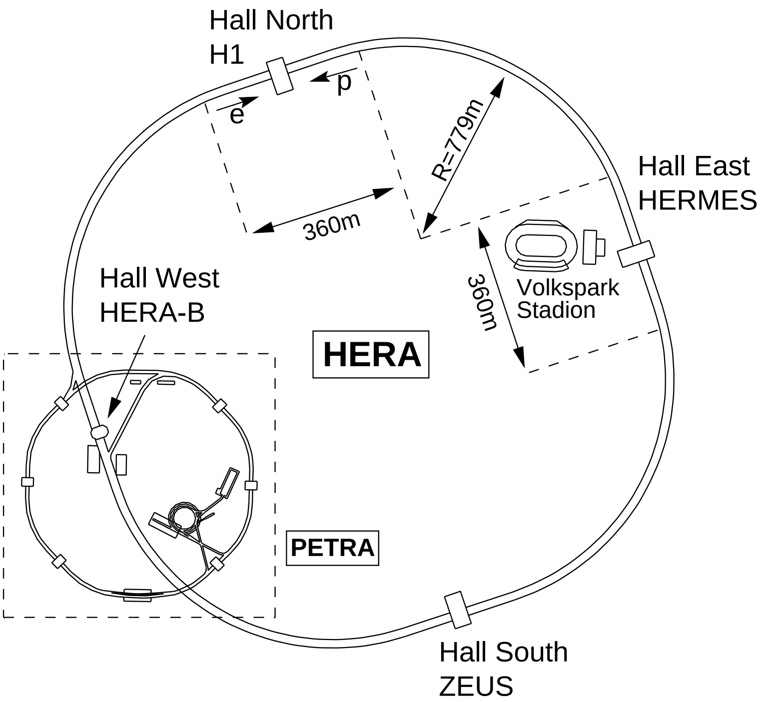
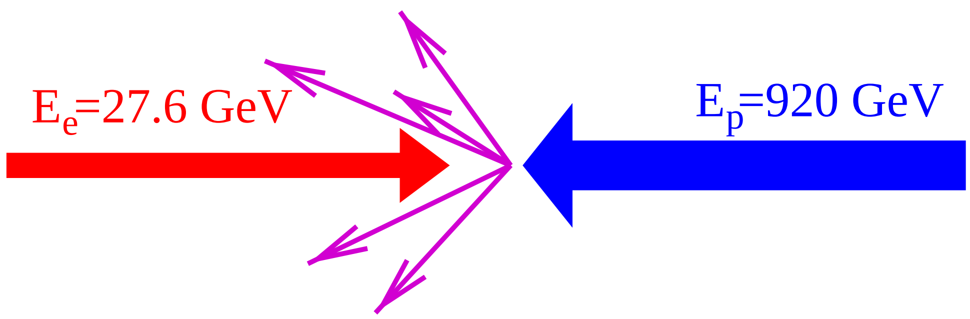
- Excursion to the Tevatron

The HERA ep collider



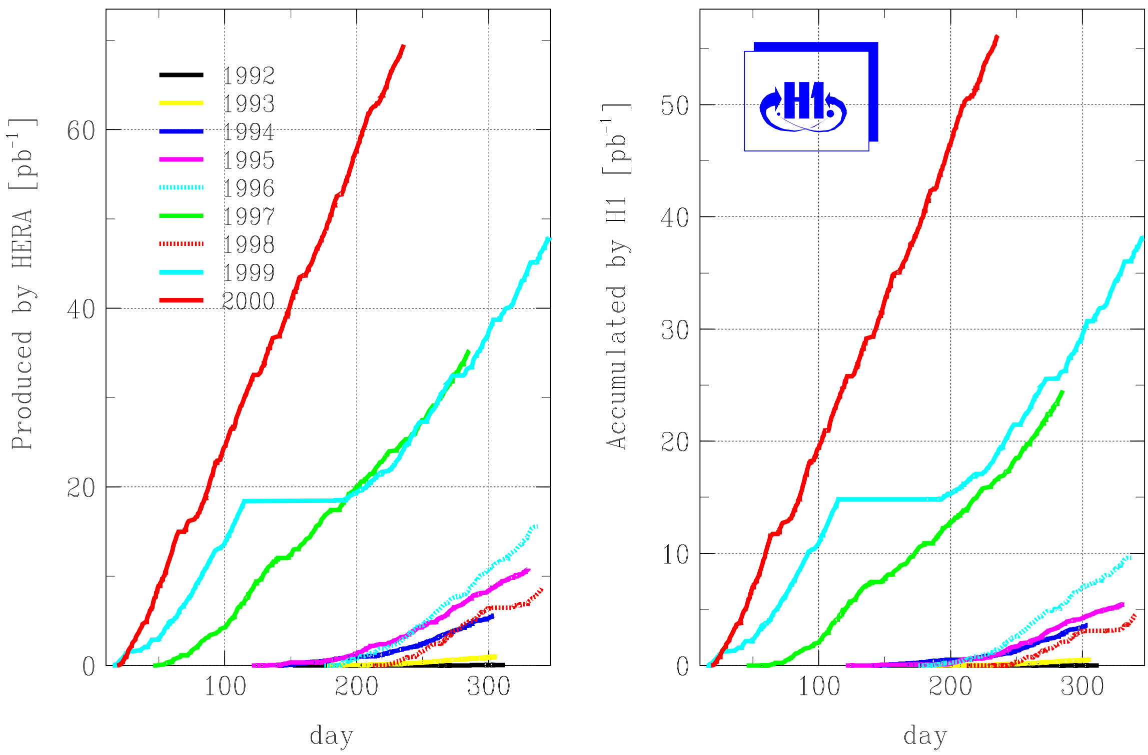
- HERA is the first and only accellerator in which electrons and protons are stored in two counterrotating beams



H1, ZEUS:	ep collisions at $\sqrt{s} = 320$ GeV
HERA-B:	p-beam on fixed target: CP violation in $B^0\bar{B}^0$
HERMES:	e-beam on polarized target: Spin structure

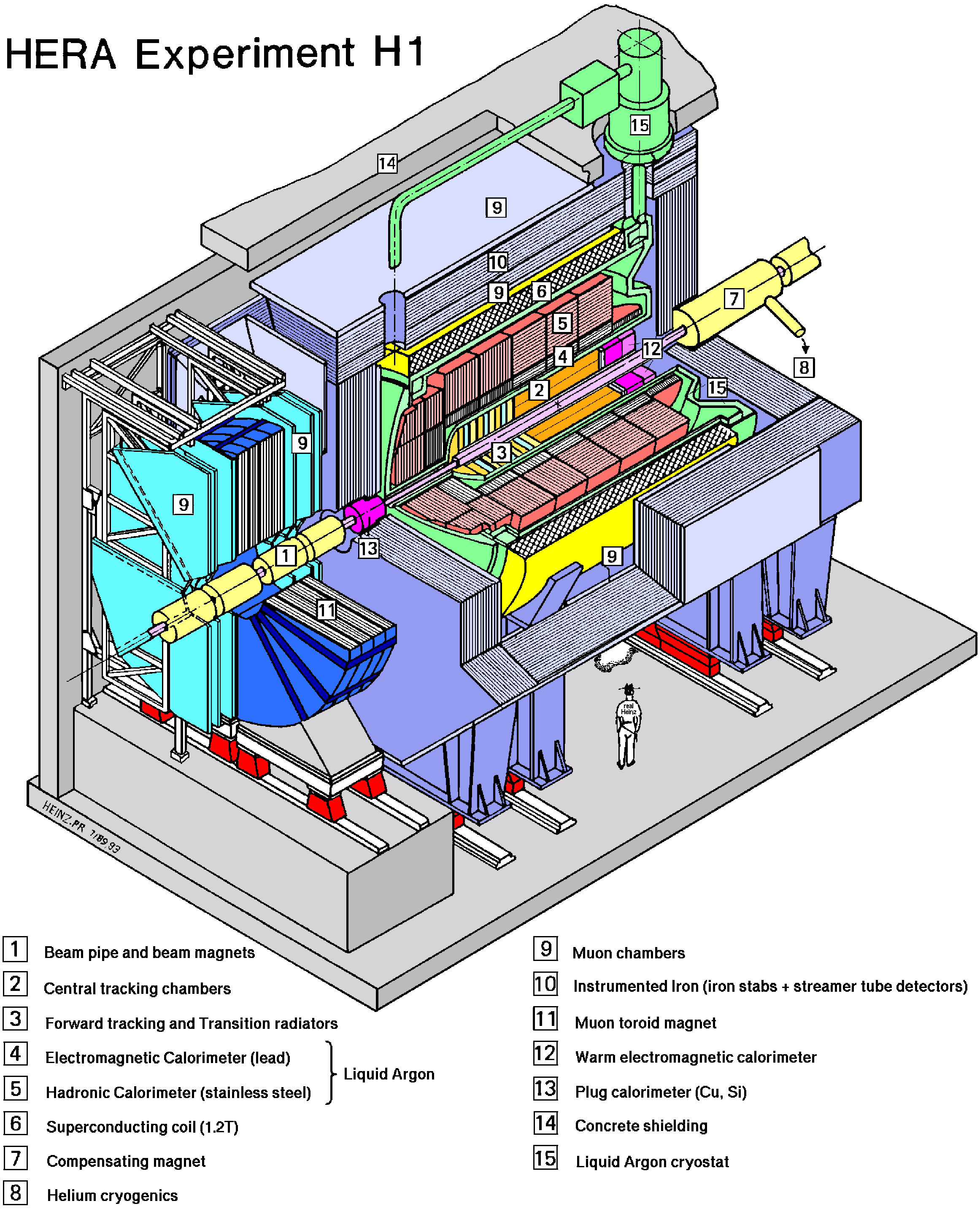
H1 and ZEUS: ep collisions

- HERA Run I (1993-2000) just completed in September
- Impressive Performance: HERA now performing at design parameters: $L = 1.5 \cdot 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- H1 and ZEUS now each have $> 100\ \mathrm{pb}^{-1}$ on tape

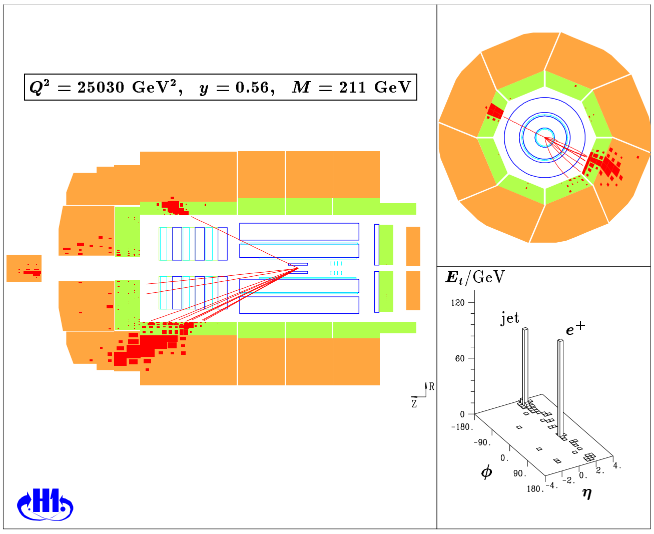


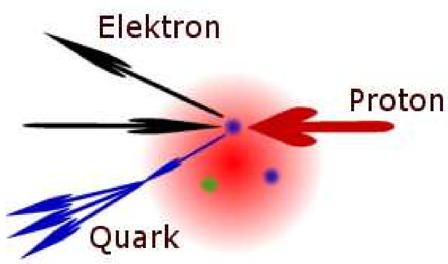
- Lumi upgrade program (Machine and Experiments) in progress to increase Luminosity by factor 5 !
- HERA Run II will start Summer 2001

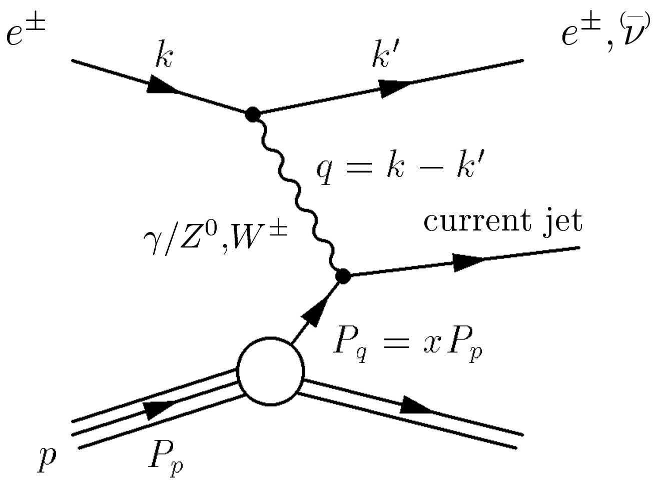
The H1 Detector at HERA



Deep Inelastic Scattering (DIS)







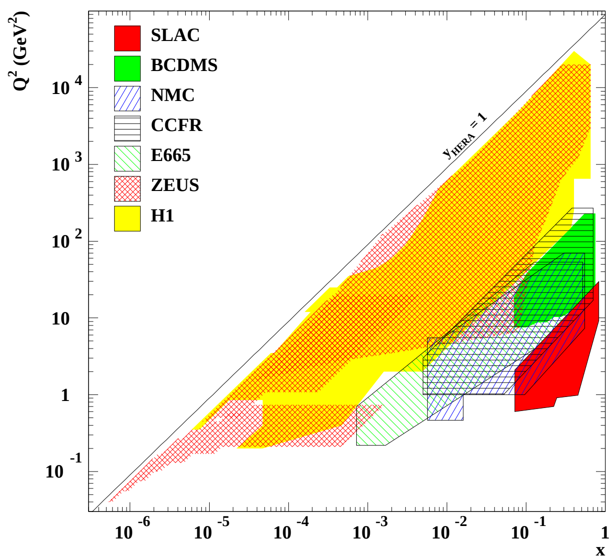
$$Q^2 = -q^2 = (k - k')^2$$

Photon virtuality,
"Resolution power"

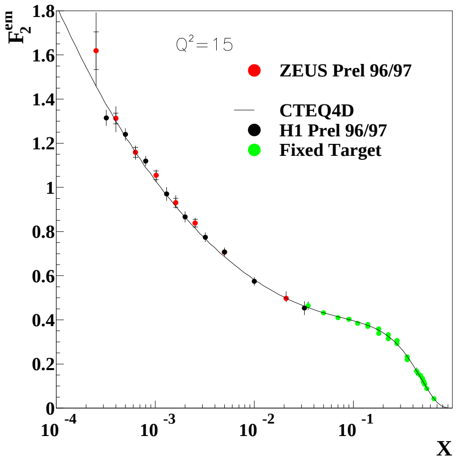
$$x = \frac{-q^2}{2P \cdot q} \quad (0 < x < 1)$$

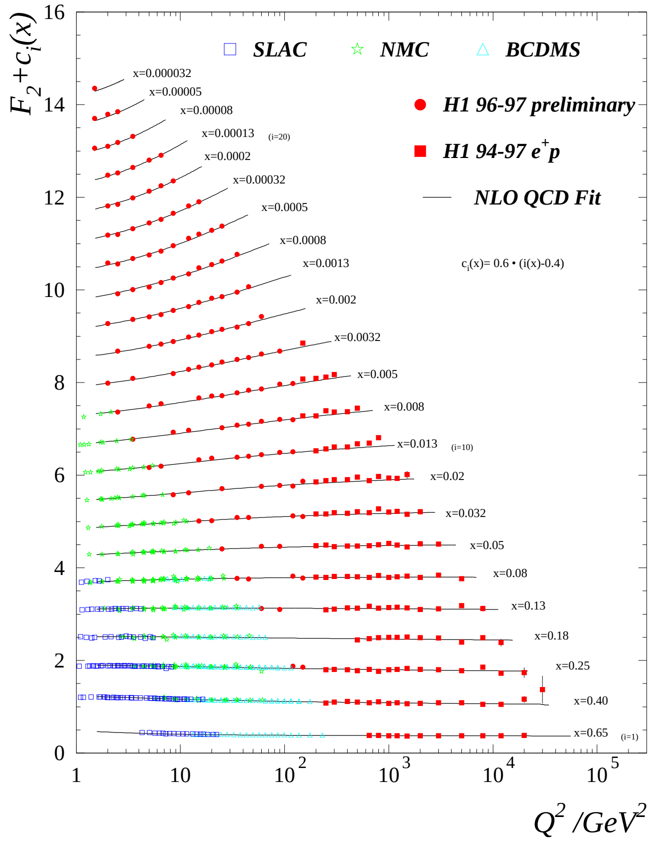
Parton momentum fraction in p

HERA probes p at two orders of magnitude higher Q^2 at fixed x than fixed target experiments



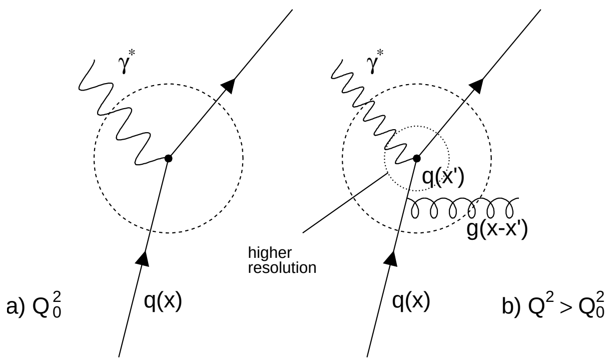
Proton Structure $F_2(x, Q^2)$

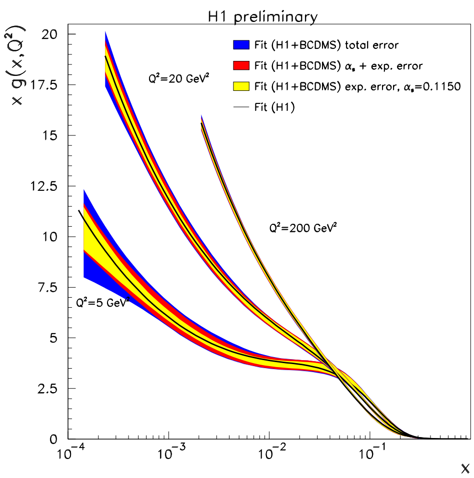




$$\frac{dq_i(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left[q_i(z,Q^2)P_{qq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

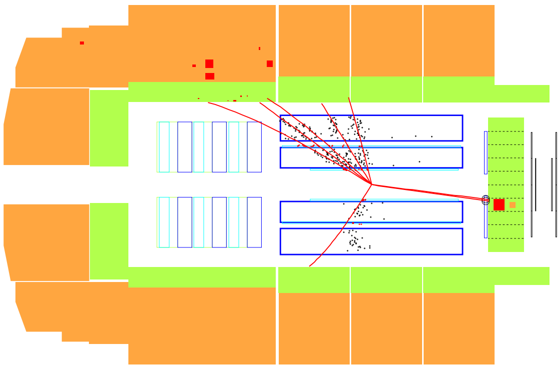
$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left[\sum_i q_i(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$



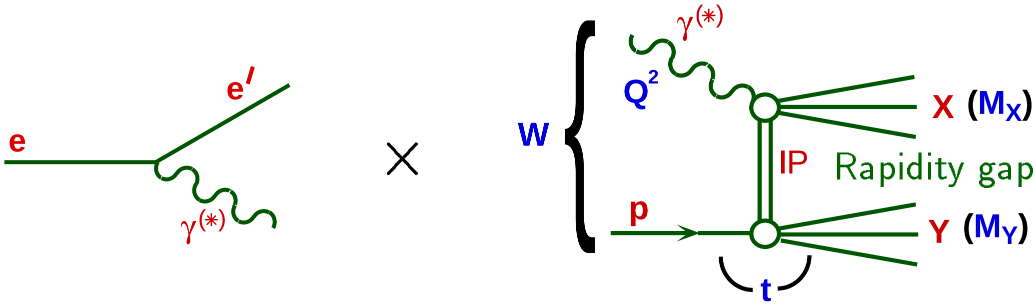


"Large Rapidity Gap" (LRG) Events

- 10% of DIS events at low $Q^2 = 4 \ldots 100\ \mathrm{GeV}^2$ exhibit large gap without hadronic activity in outgoing p region



- γ^* scatters off colorless state in p, the "Pomeron"
- p (or low-mass excitation) escapes through beampipe



$t = (p - p')^2$: (momentum transfer)^2 at p vertex
M_X, M_Y: Masses of X and Y

$x_{I\!P} = \frac{q\cdot(p-Y)}{q\cdot p} = \frac{Q^2+M_X^2-t}{Q^2+W^2-M_p^2}$

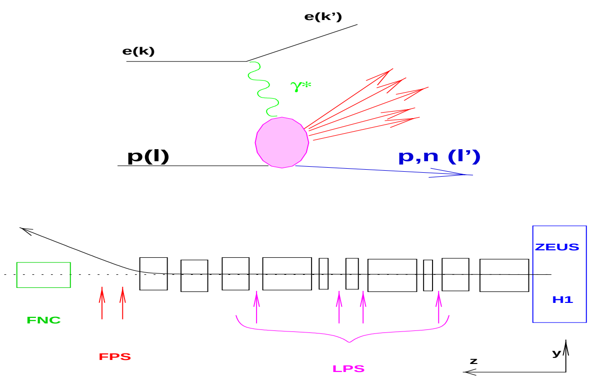
$\rightarrow$ long. momentum fraction transferred from p to exchange

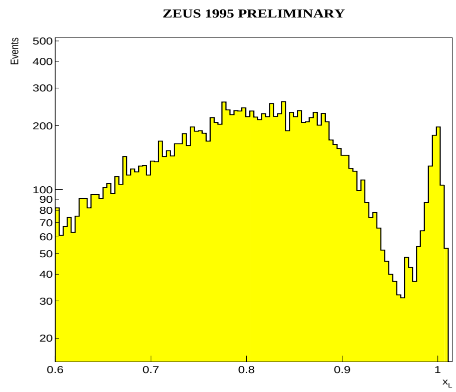
$\beta = \frac{-q^2}{q\cdot(p-Y)} = \frac{Q^2}{Q^2+M_X^2-t}$

$\rightarrow$ fraction of exchange momentum carried by q coupling to γ

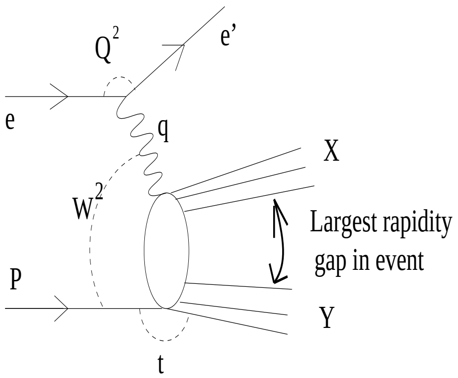
Selection of LRG events

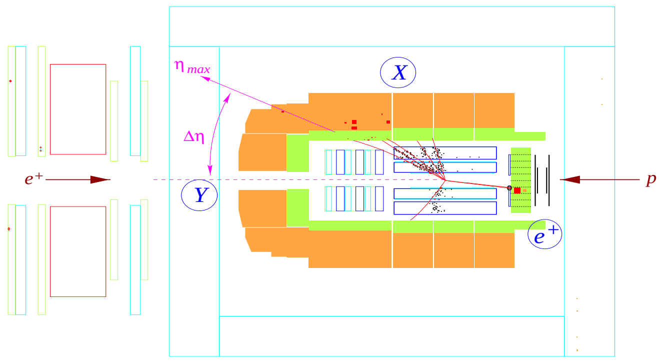
1. Tagging of p with "Roman Pots" (measure t, but low stat.):



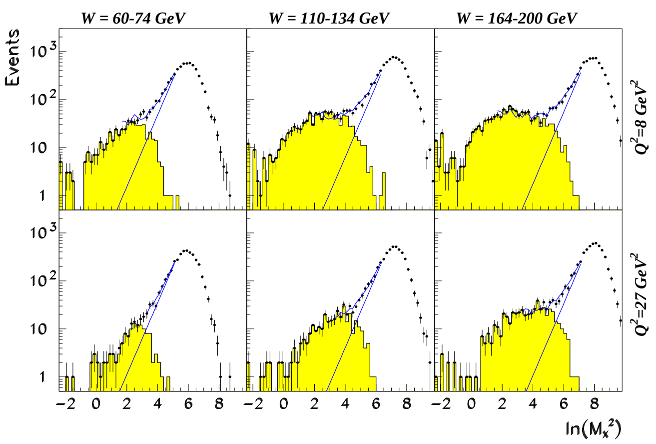


2. Large Rapidity Gap Requirement (integr. over M_Y, t):

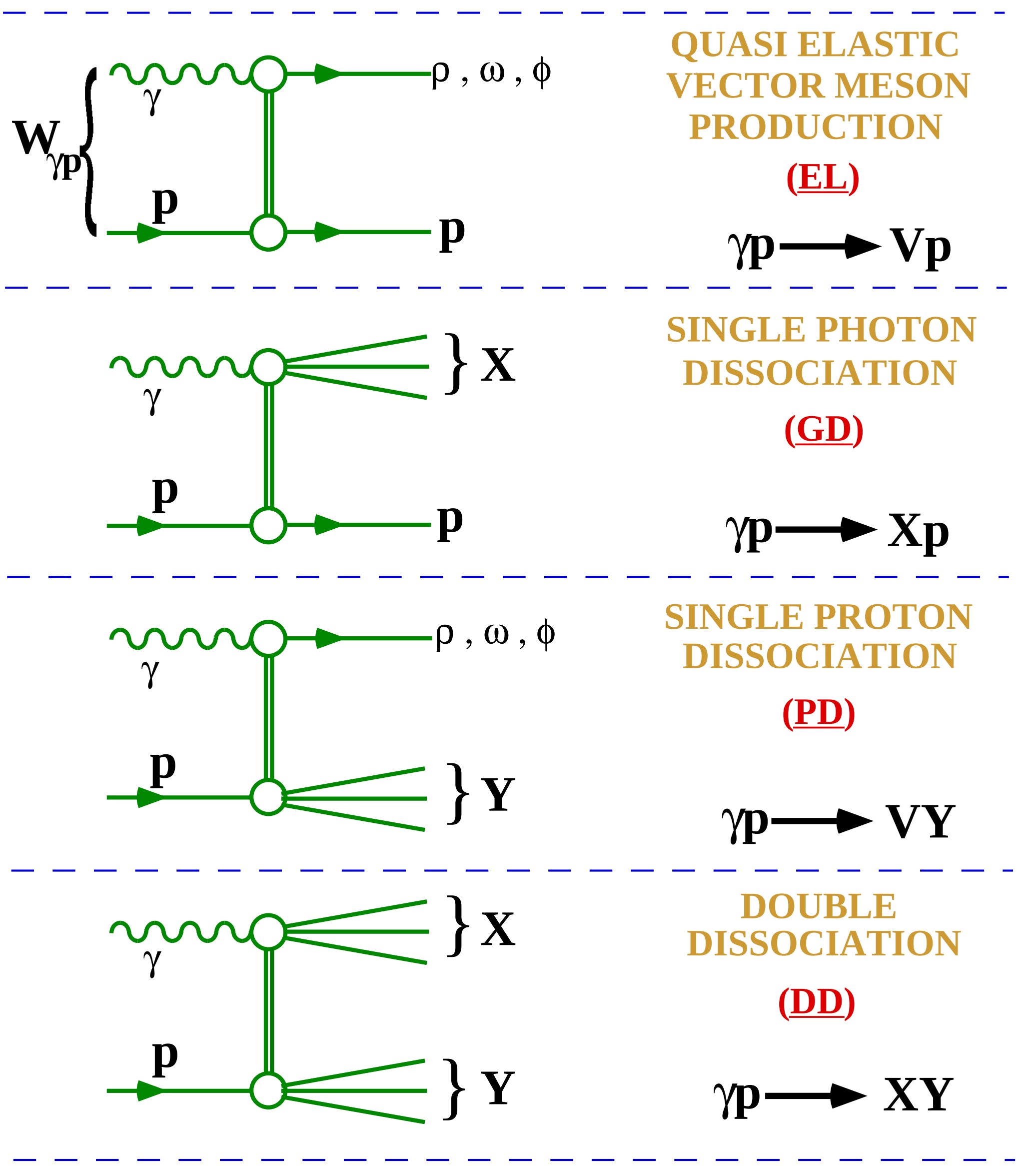




3. Analysis of final state M_X system (integr. over M_Y, t):



Colour singlet exchange processes in $\gamma^* p$ interactions

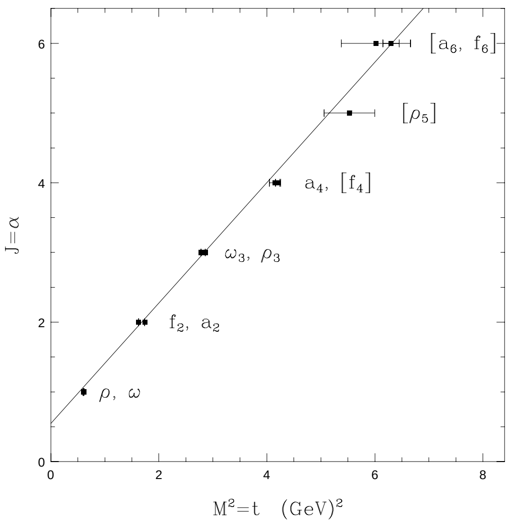


$\rightarrow$ Photon γ^* can either fluctuate into vector meson or dissociate into high-mass system X

$\rightarrow$ Proton p either stays intact (elastic scattering) or dissociates into low-mass baryonic system Y

History: The Pomeron in soft Hadron-Hadron Interactions

- 1960's: pre-QCD era
- Regge model: Describe soft hadron-hadron interactions by exchange of mesons with appropriate quantum numbers
- Observation: Family of mesons with same quantum numbers (except J) lie on "Trajectory" in (m^2, J) space:



$\alpha(t)$: generalized complex J

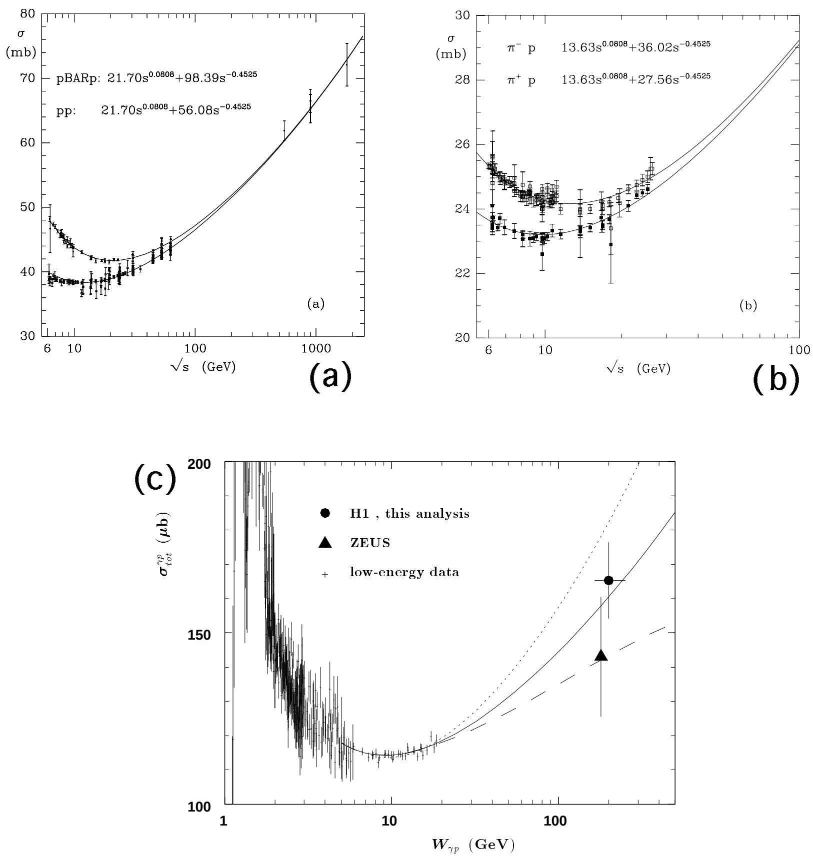
Parameterisation:
$\alpha(t) = \alpha(0) + \alpha' t$

- Express elastic and total cross sections in terms of $\alpha(t)$:

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}|T(s,t)|^2 = f(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$

$$\sigma_{tot} \sim \frac{1}{s} Im(T(s,t))|_{(t=0)} = s^{\alpha(0)-1}$$

Can Meson Trajectories fully describe soft hadronic hadrons?



$\rightarrow$ No! Increase of σ_{tot} at high energies can not be described by known Meson Trajectories

$$\sigma_{tot}(s) \sim s^{\alpha(0)-1} \sim s^{-0.5} \qquad (\alpha_{\mathrm{Mesons}}(0) = 0.5)$$

- New Trajectory invented, the "Pomeron"
- carries vacuum quantum numbers

$$\alpha_{IP}\ (t) = 1.08 + 0.25\ t$$

But today's question:
Can we understand the "Pomeron" in terms of QCD ??

LRG at HERA: DIS off the "Pomeron"

Most general case: Define five-fold differential cross section:

$$\frac{d\sigma(ep\to eXY)}{dx_{\mathbb{P}}\ dt\ dM_Y\ d\beta\ dQ^2} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1-y+\frac{y^2}{2(1+R^{D(5)})}\right)\times F_2^{D(5)}(x_{\mathbb{P}},t,M_Y,\beta,Q^2)$$

$R^{D(5)}$: Ratio σ_L/σ_T $\to$ neglected!

If Y is not measured, integrate over M_Y,t

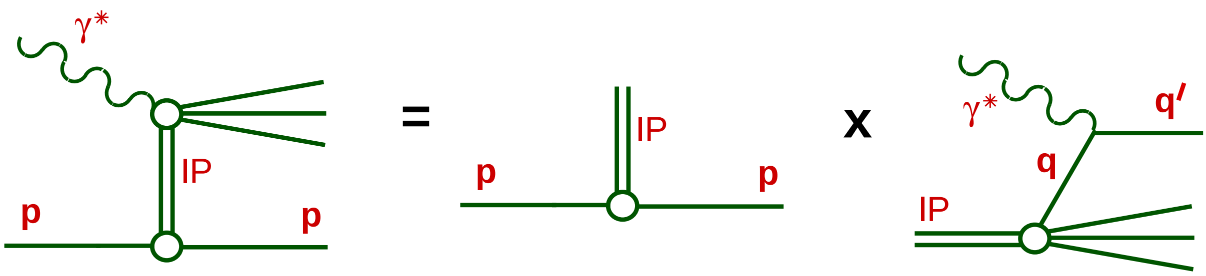
$$\frac{d\sigma^{ep\to eXY}}{dx_{\mathbb{P}}\ d\beta\ dQ^2} = \frac{4\ pi\alpha^2}{\beta Q^4}\left(1-y+\frac{y^2}{2}\right)\ F_2^{D(3)}(x_{\mathbb{P}},\beta,Q^2)$$

Inclusive diffractive DIS:

$Q^2 \gg 0\ GeV^2$, small M_X, small M_Y:

$x_{\mathbb{P}} \ll 1$	(H1: $x_{\mathbb{P}} < 0.05$)
small $\lvert t\rvert$	(H1: $\lvert t\rvert < 1\ GeV^2$)
small M_Y	(H1: $M_Y < 1.6\ GeV$)

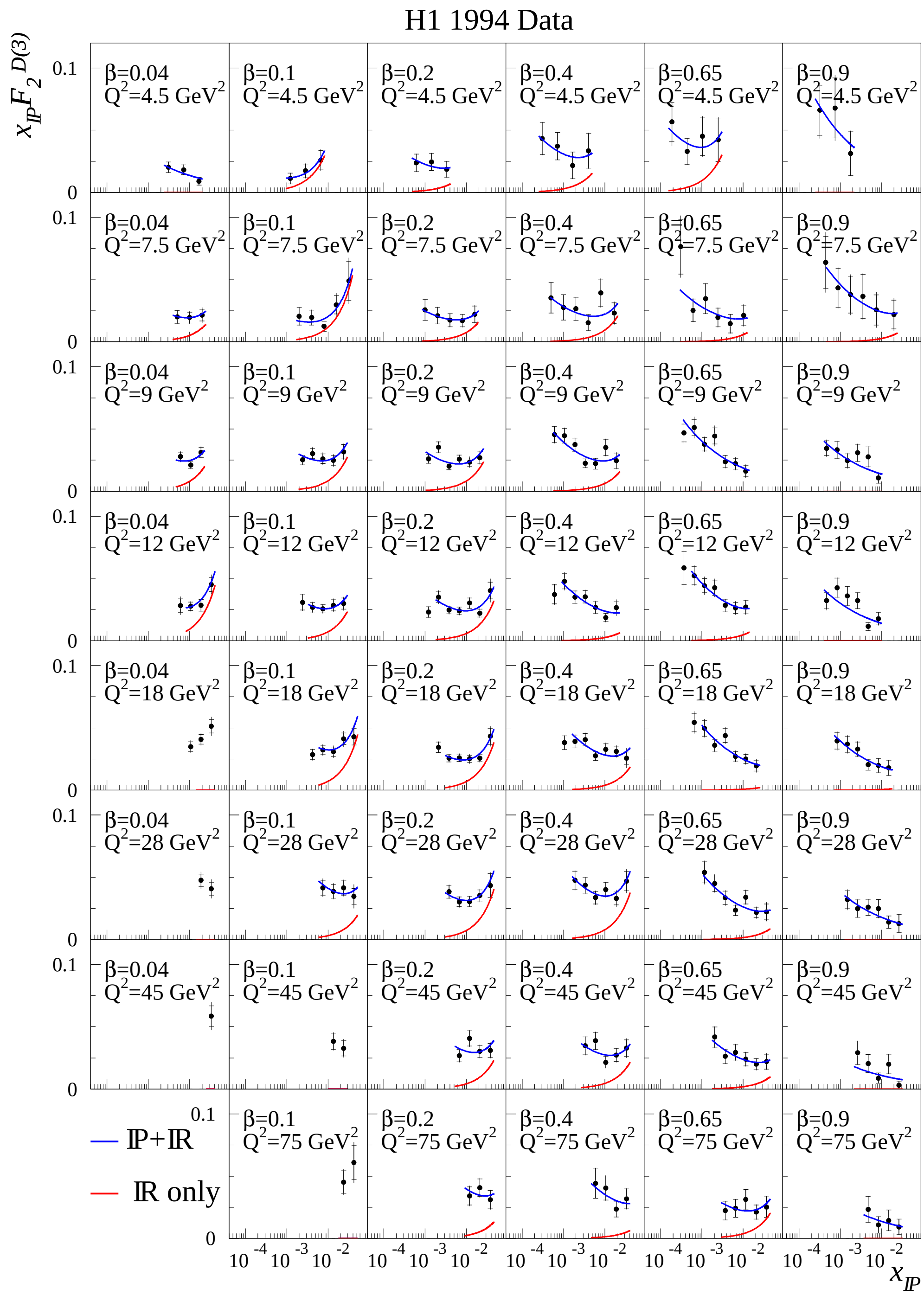
Factorizable Ansatz (Ingelman-Schlein, "resolved Pomeron"):



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

The diffractive Structure Function $F_2^{D(3)}$

Measurement of $F_2^{D(3)}(x_{IP}\ , \beta, Q^2)$ by H1:



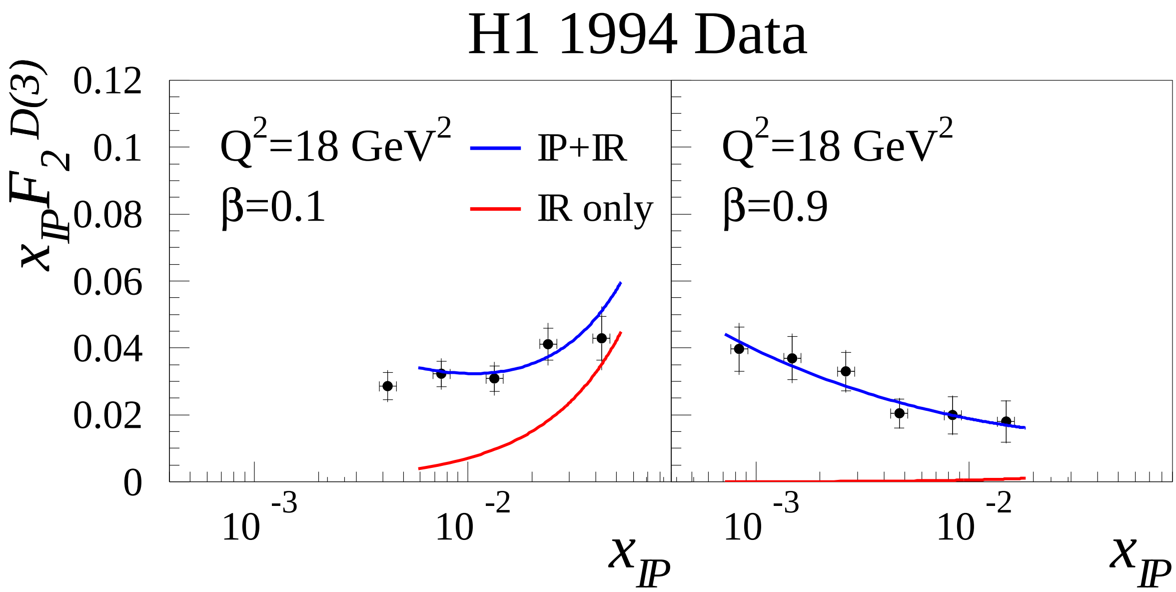
Regge parametrization of $F_2^{D(3)}$

Parametrize long-distance physics at p vertex using Regge phenomenology:

$$f_{I\!P/p}(x_{I\!P}) = \int_{-1\ GeV^2}^{t_{min}(x_{I\!P})} \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(t)-1} e^{b_{I\!P}t}\, dt$$

with $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t$

$F_2^{D(3)}$ (H1 1994): $x_{I\!P}$ dependence varies with β



$\rightarrow$ Additional sub-leading exchange necessary:

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

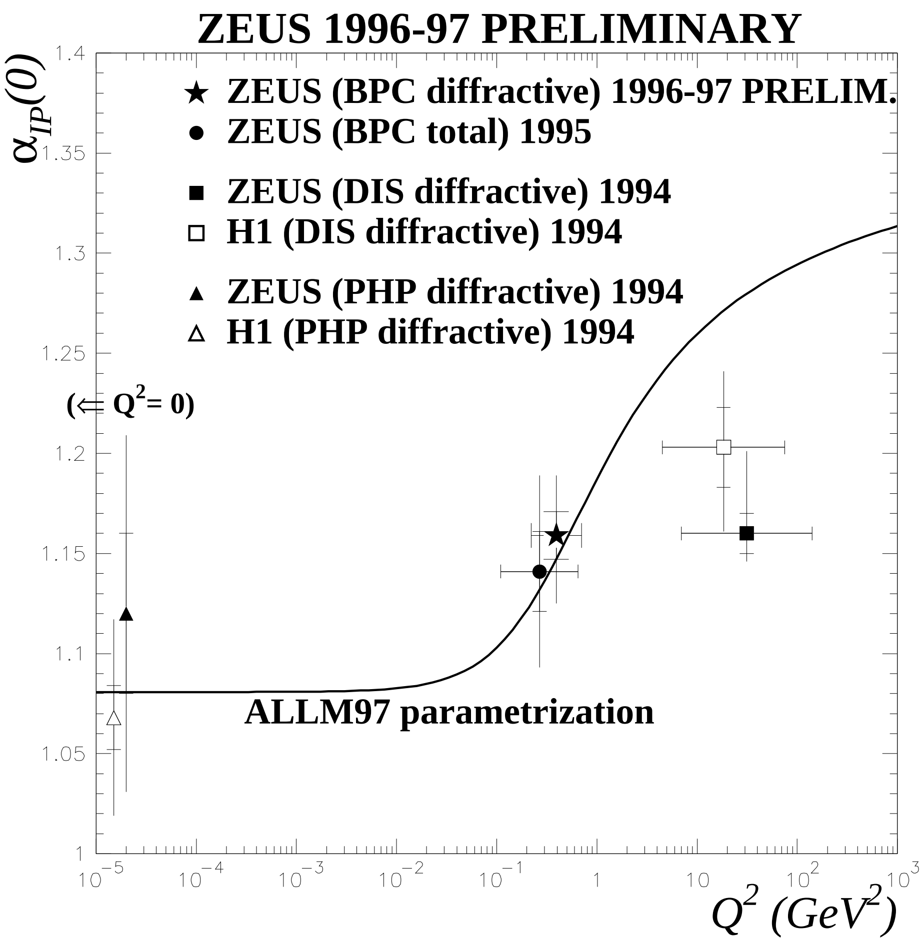
H1 phenomenological Regge fits with free parameters:
$\alpha_{I\!P}(0),\ \alpha_{I\!R}(0),\ F_2^{I\!P}(\beta, Q^2),\ F_2^{I\!R}(\beta, Q^2)$

The Pomeron intercept $\alpha_{I\!P}(0)$

Result from the H1 Regge fit:

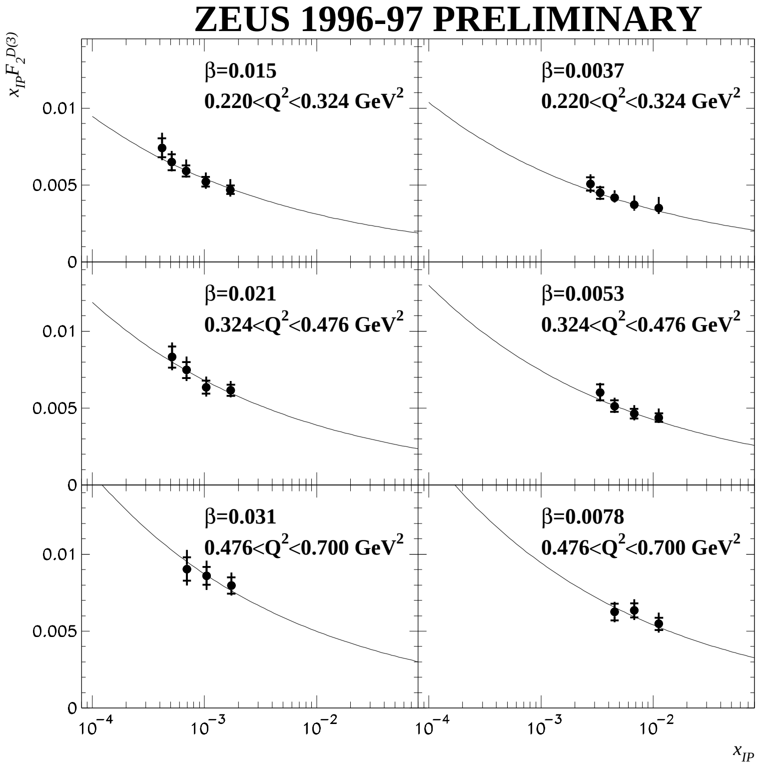
- $\alpha_{I\!P}(0) = 1.203 \pm 0.020 \pm 0.013 \pm 0.035$
  higher than in soft hadron-hadron physics ($\alpha_{I\!P}^{soft} = 1.08$)
- $\alpha_{I\!R}(0) = 0.50 \pm 0.11 \pm 0.11 \pm 0.10$
  consistent with f, ω, ρ, etc. exchange

$\rightarrow$ Diffractive DIS at HERA dominated by $I\!P$ exchange!

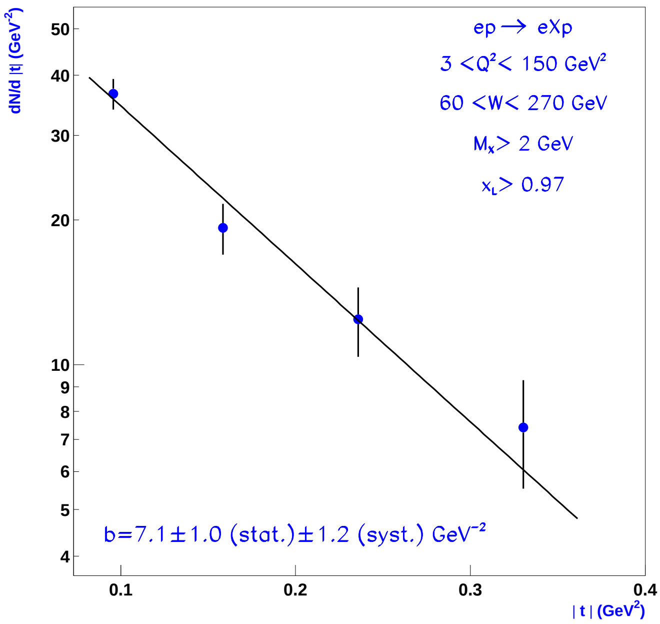


Does α_{IP} (0) vary with scale (Q^2) ?

ZEUS measurement of F_2^D at very low Q^2



Measurement of the t dependence



t measured tagging outgoing p in Roman Pots

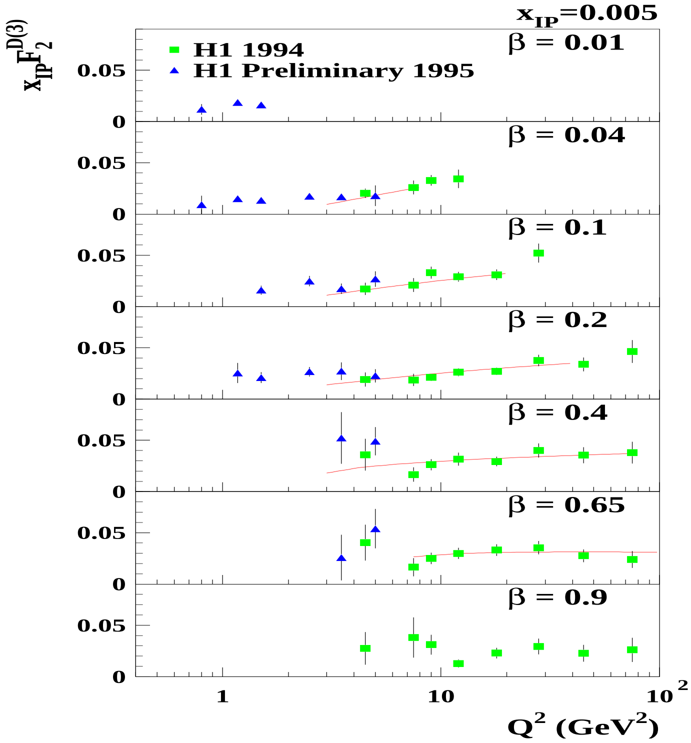
Fit to $\frac{d\sigma}{dt} \propto e^{bt}$ yields:

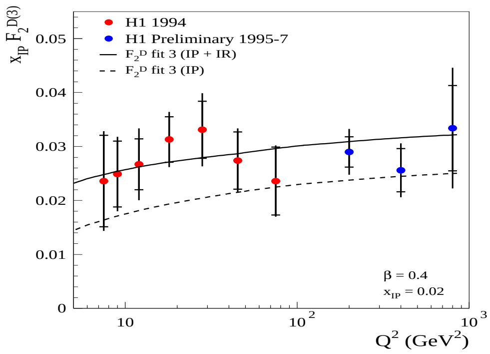
$$b = 7.1 \pm 1.0 \pm 1.2\ \mathrm{GeV}^{-2}$$

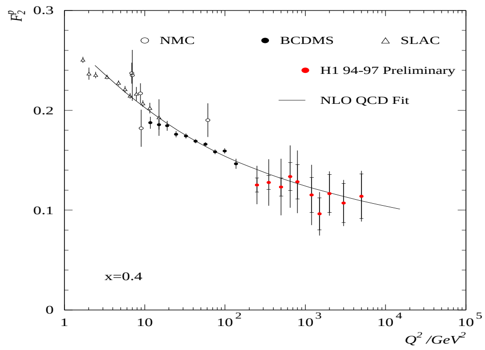
Consistent with hadron-hadron scattering

QCD Analysis of $F_2^{IP}(\beta, Q^2)$ (H1)

H1 observes scaling violations:

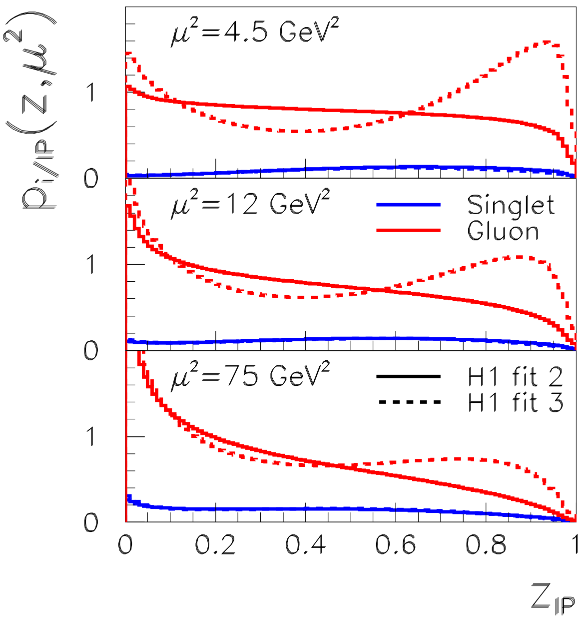






Strongly suggestive of exchange driven by gluons!

DGALP QCD analysis of scaling violations (a la $F_2(x, Q^2)$):



→ Gluons carry $80\ldots90\%$ of IP momentum!

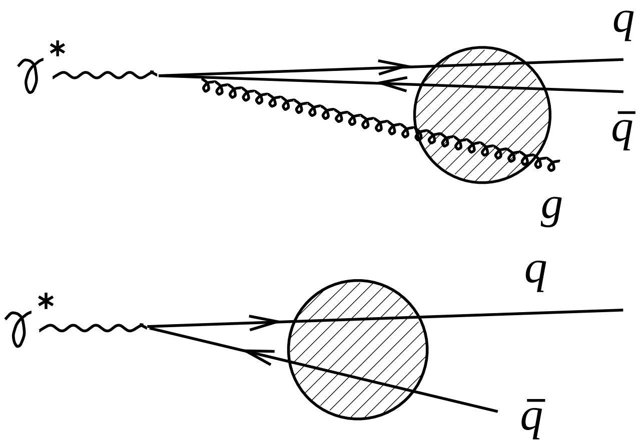
→ Large uncertainty in shape of gluon distribution!

Phenom. Models / QCD Calculations

"partonic Pomeron" model not only way to explain LRG events!

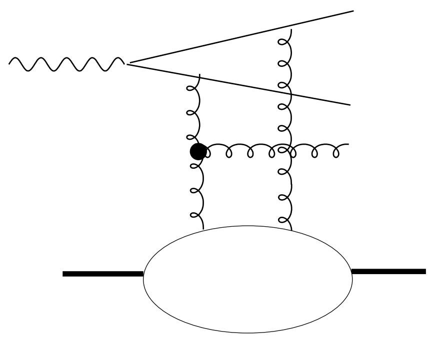
Color Dipole / 2-gluon Exchange Models:

- In proton rest frame: $q\bar{q}$ and $q\bar{q}g$ fluctuations of γ^*:



$$\sigma_{T,L}^{\gamma^* p}(x, Q^2) \sim \int d^2r \int_0^1 d\alpha |\Psi_{T,L}(\alpha, r)|^2 \ \hat{\sigma}(x, r^2)^2$$

- Simplest case: 2 gluons:
- $\hat{\sigma}^2 \sim |x_{I\!P} \ g(x_{I\!P}, \mu^2)|^2$



- Small size, high p_T dipole x.sec. should be calc. in QCD
- Large size, small p_T dipole x.sec. sim. to soft pp

Dipole models which treat interaction by 2-gluon exchange:

(1) Saturation Model

- by Golec-Biernat, Wüsthoff
- Ansatz for σ_{Dipole} which interpolates between pert. ($\sim 1/Q^2$) and non-pert. ($\sim const.$) parts of $F_2(x, Q^2)$
- parameters fixed by fit to $F_2(x, Q^2)$, σ^D then predicted
- ipmlemented assuming strong p_T ordering $p_{T,g} \ll p_{T,q\bar{q}}$

(1) BJLW Model

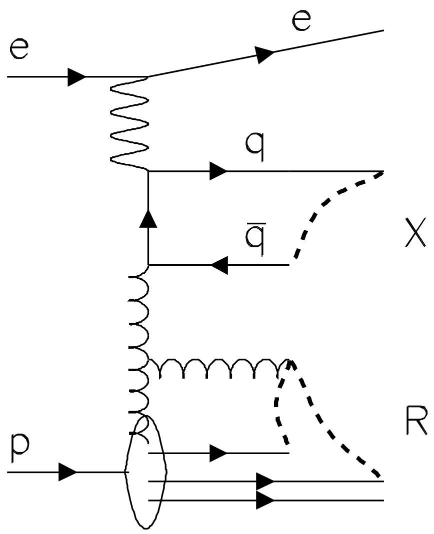
- by Bartels, Jung, Lotter, Wüsthoff
- calculation in low-β, low-x_{IP} limit
- for $q\bar{q}g$ require high p_T of all 3 partons (only for Jets!) i.e. NO soft $I\!P$ remant!
- non p_T-ordered contribs included

Dipole model with non-perturbative treatment of interaction:

(3) Semiclassical Model

- by Buchmüller, Gehrmann, Hebecker
- in p rest frame: $q\bar{q}$, $q\bar{q}g$ states scatter off soft colour field of large p

Soft Colour Interaction Model (SCI):



- by Edin, Ingelman, Rathsman
- standard DIS plus soft color rearrangements
- Version 1: simple, one parameter probability R_0 for color rearrangements
- Version 2: based on "Generalized Area Law" ansatz, better description of F_2^D at low Q^2

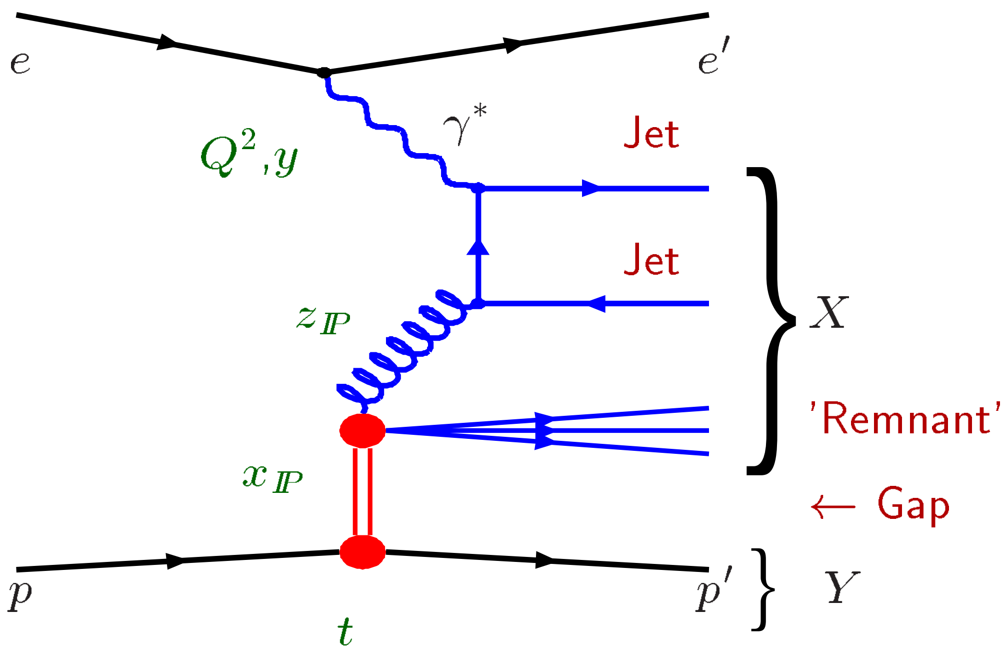
• All models (with exception of BJLW, which is tailored to high p_T processes) can describe $F_2^{D(3)}$ reasonably !

Diffractive Dijet Production

Why bother with Dijets?

- p_T of Jets introduces another hard scale, which may allow perturbation theory to be applied
- through $\mathcal{O}(\alpha_s)$ diagram (see below) direct sensitivity to gluons!

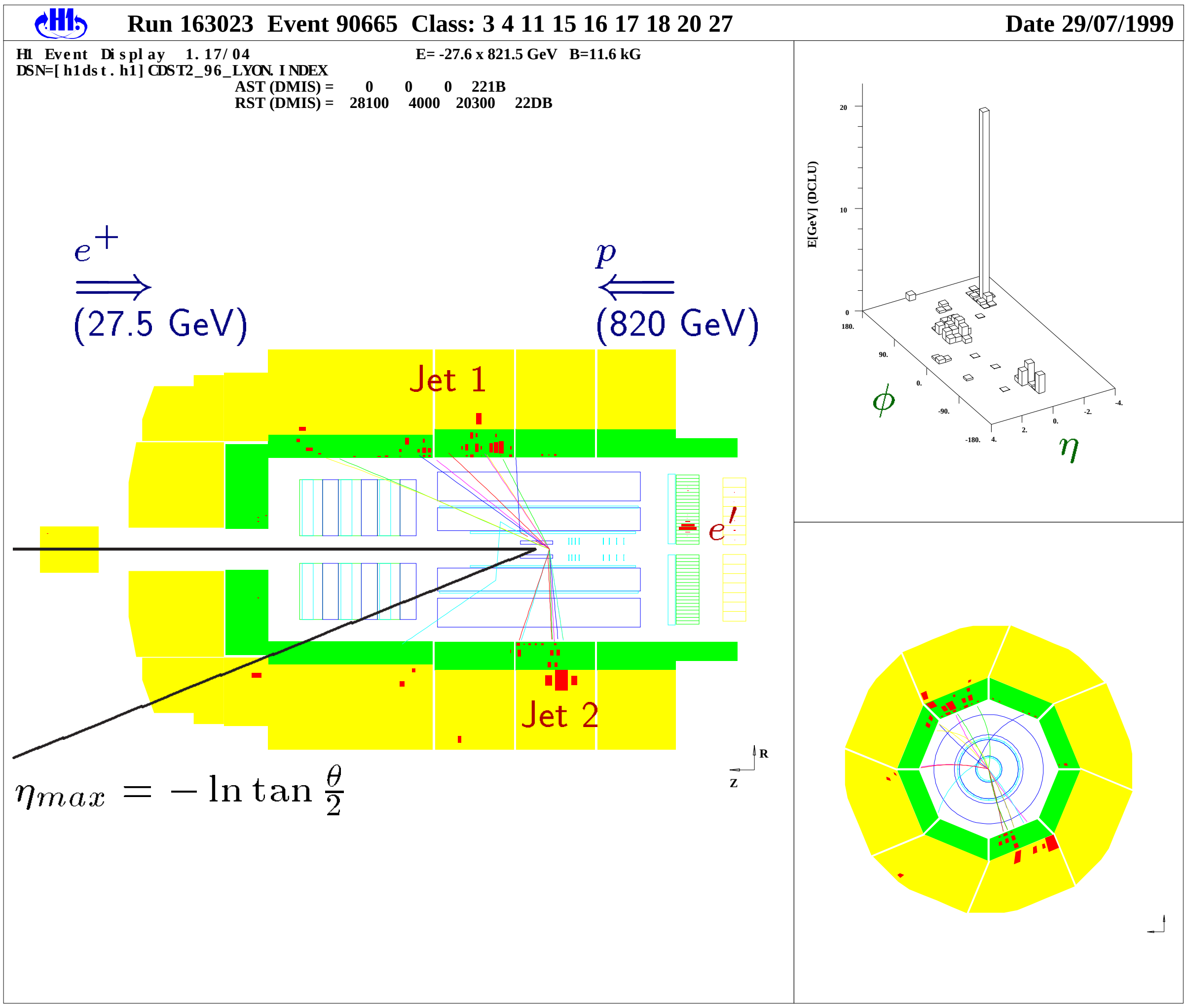
Kinematics, viewed in terms of a resolved "Pomeron" model:



$$z_{I\!P} \approx \frac{Q^2+M_{12}^2}{Q^2+M_X^2} \sim \frac{(\text{Dijet Mass})^2}{(\text{Total Mass})^2}$$

→ momentum fraction of exchange entering hard process

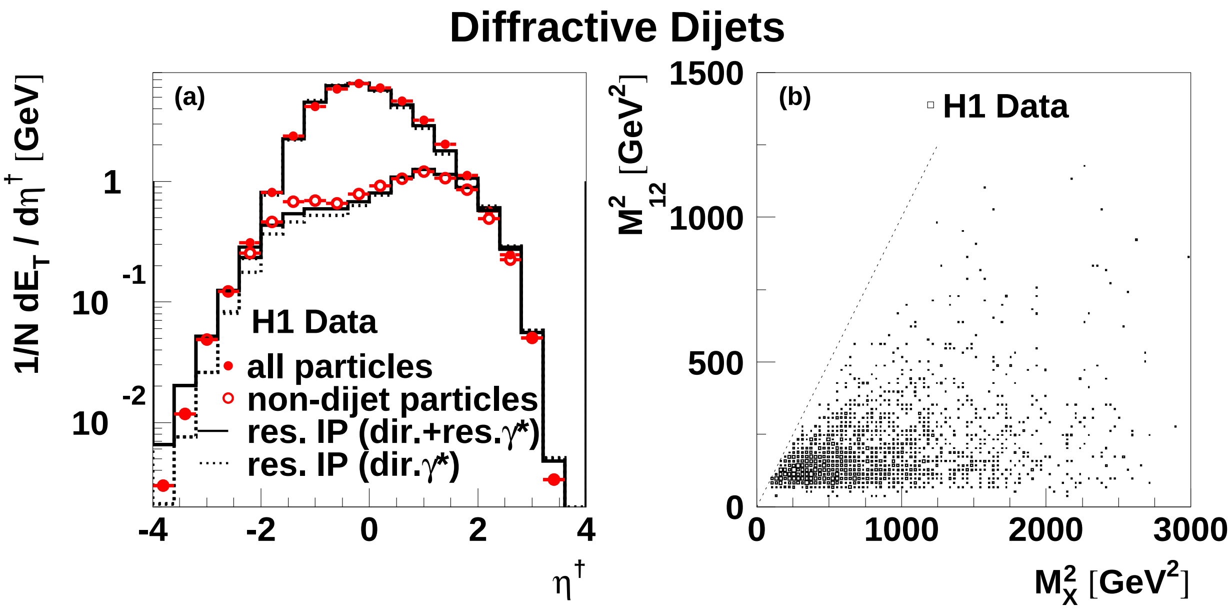
Data Selection



- DIS Signature: $4 < Q^2 < 80$ GeV; $0.1 < y < 0.7$
  Scattered electron e'
- Diffractive Signature: $x_{I\!P} < 0.05$; M_Y, t small
  Rapidity gap in outgoing p' direction
- 2-Jet Signature: $N_{\rm Jet} \geq 2$; $p_T > 4$ GeV
  Jet-Algorithm in γp Centre-of-mass frame

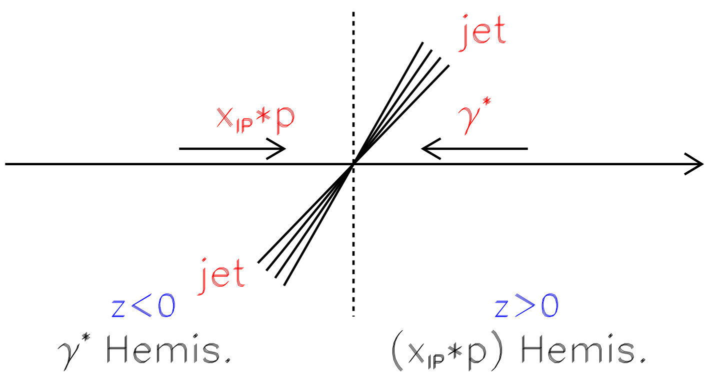
Data from 1996 to 1997: $\mathcal{L} = 18.0\ \mathrm{pb}^{-1}$
$N_{2\ \rm Jet} \approx 2.500$, $N_{3\ \rm Jet} \approx 130$

Reults for Diffractive Dijets



- Mean E_T flow in rest frame of X system (left):

- Significant energy NOT contained in 2-Jet system
- Remnant slightly asymmetric (towards IP dir.)



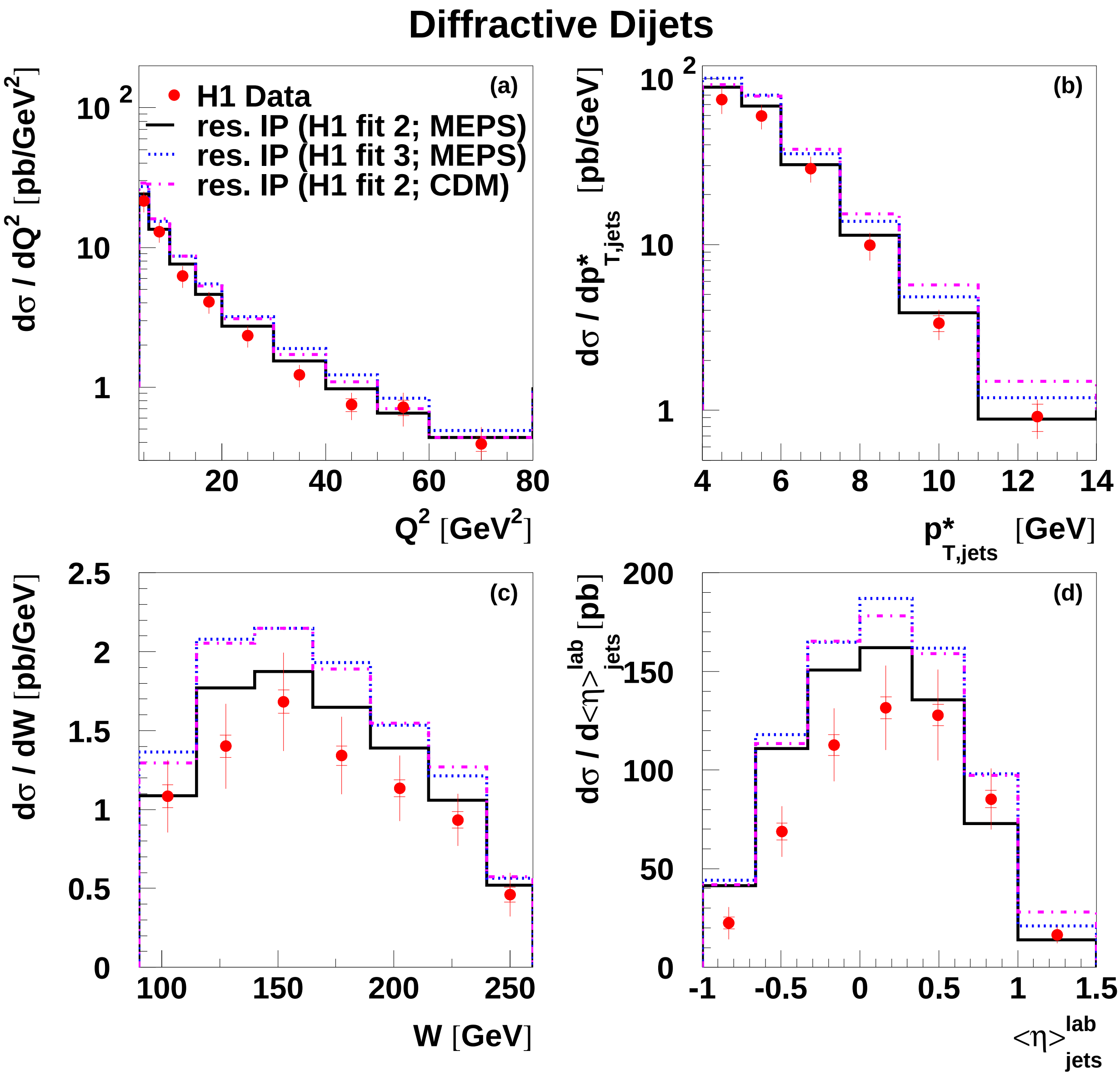
CMS of X
($\gamma^* IP$ CMS)

- Correlation M_x vs. M_{12} (right):

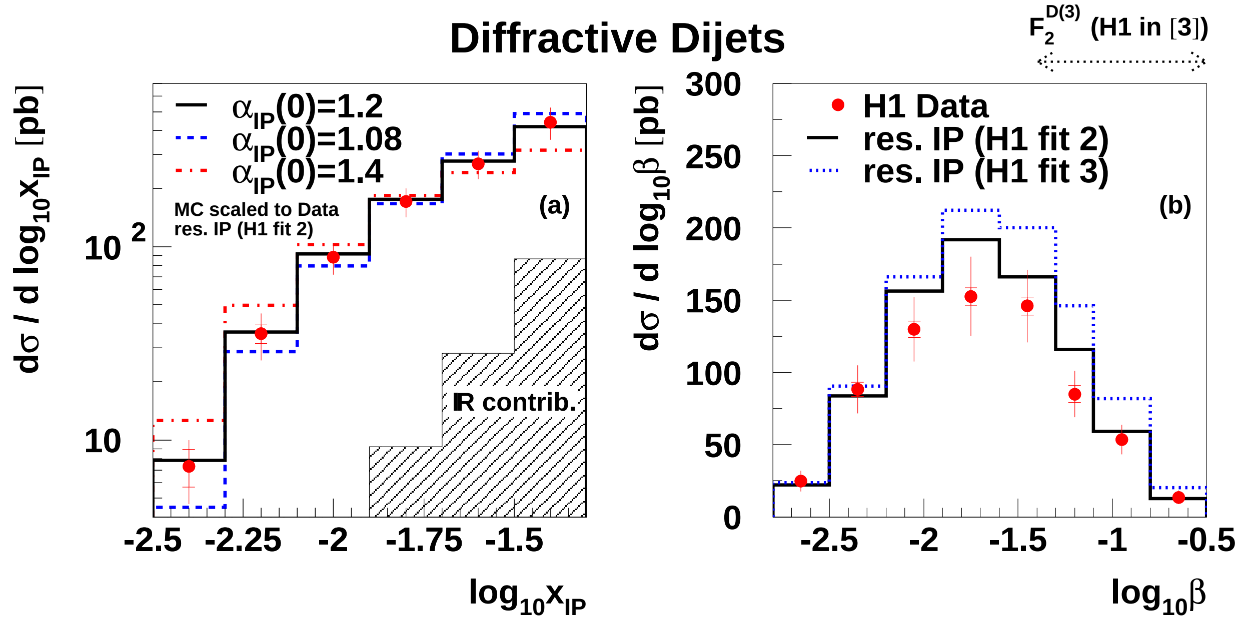
- Most events have $M_{12} < M_X$

$\longrightarrow$ In p rest frame: Dominance of $q\bar{q}g$ over $q\bar{q}\ \gamma$ fluctuations!

Interpretation in resolved Pomeron model



- Jet Cross Sections well described by resolved Pomeron model, where IP and IR fluxes and IP PDF's as obtained from the $F_2^{D(3)}$ analysis are used
- "H1 fit 2" in close agreement with data
- "H1 fit 3" overestimates cross section



x_{IP} distribution:

- Secondary exchange contribution (IR) small
- Sensitivity to Pomeron Intercept $\alpha_{IP}(0)$ value
  - not obvious that it should be same as for F_2^D
  - 1.2 preferred w.r.t. 1.08 (soft IP) and 1.4
- Explicit fit of $\alpha_{IP}(0)$ results in:

$$\alpha_{IP}(0) = 1.17\ ^{+0.03}_{-0.03}\ (\text{sta.})\ ^{+0.06}_{-0.06}\ (\text{sys.})\ ^{+0.03}_{-0.04}\ (\text{mod.})$$

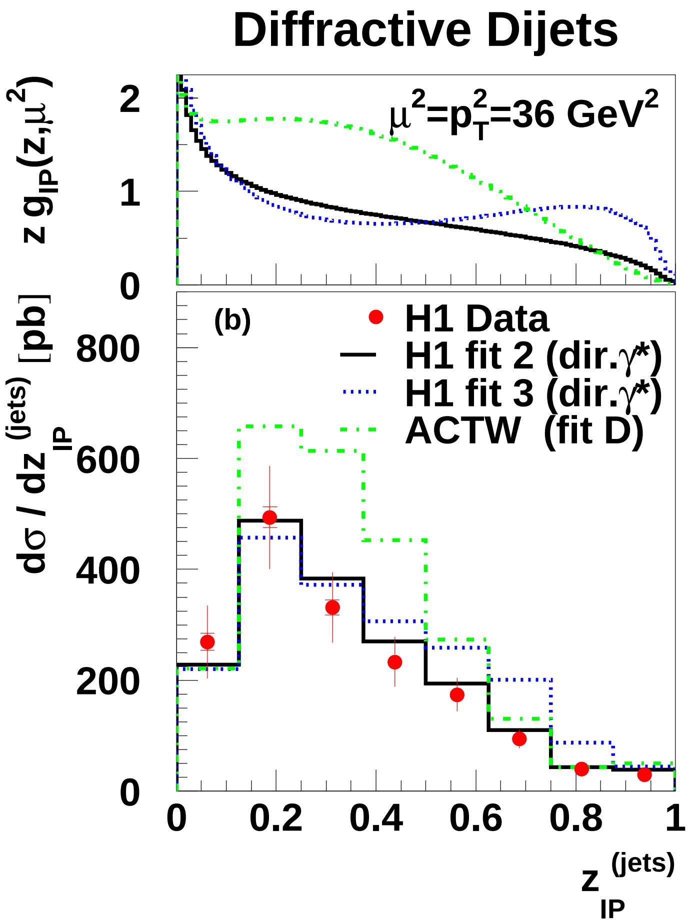
$\rightarrow \alpha_{IP}(0) < 1.32$ @ 95% C.L.

(for experts: Hard Pomeron (Lipatov) $\alpha_{IP}(0) = 1.4 \ldots 1.5$)

β distribution:

- β range is lower than accessed by F_2^D so far.

z_{IP} : Momentum fraction in IP entering hard interaction

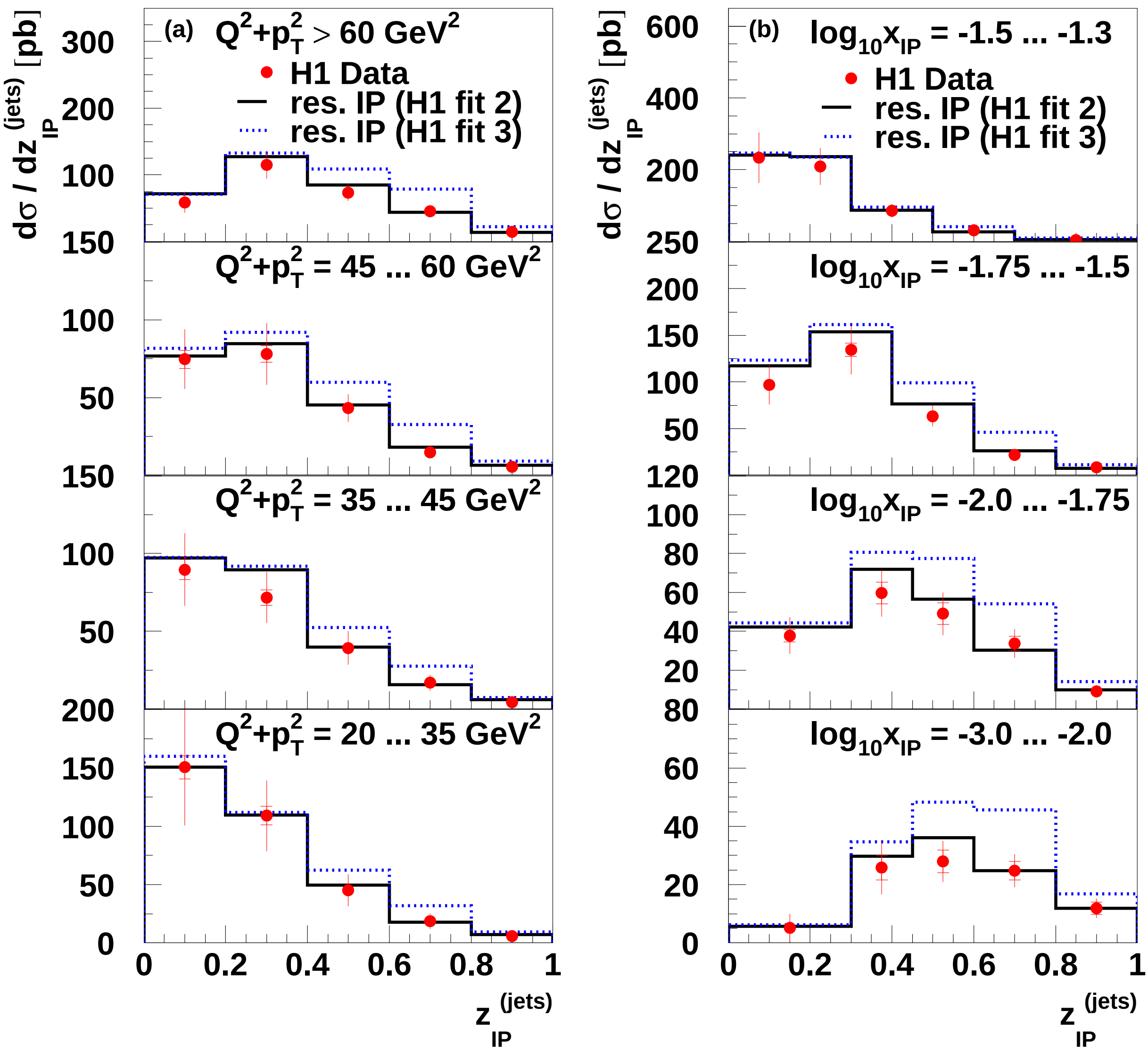


- q density is small (see F_2^D)
- Jets are directly sensitive to shape and norm. of g density!

- Parameterisation based on 'fit 2' (flat gluon) from incl. measurement in close agreement with data
- 'fit 3' (peaked gluon) too high at high z
- ACTW (comb. fit to H1 and ZEUS F_2^D and ZEUS γp jets) fails

$\longrightarrow$ Factorization in diff. lepton-hadron scattering!

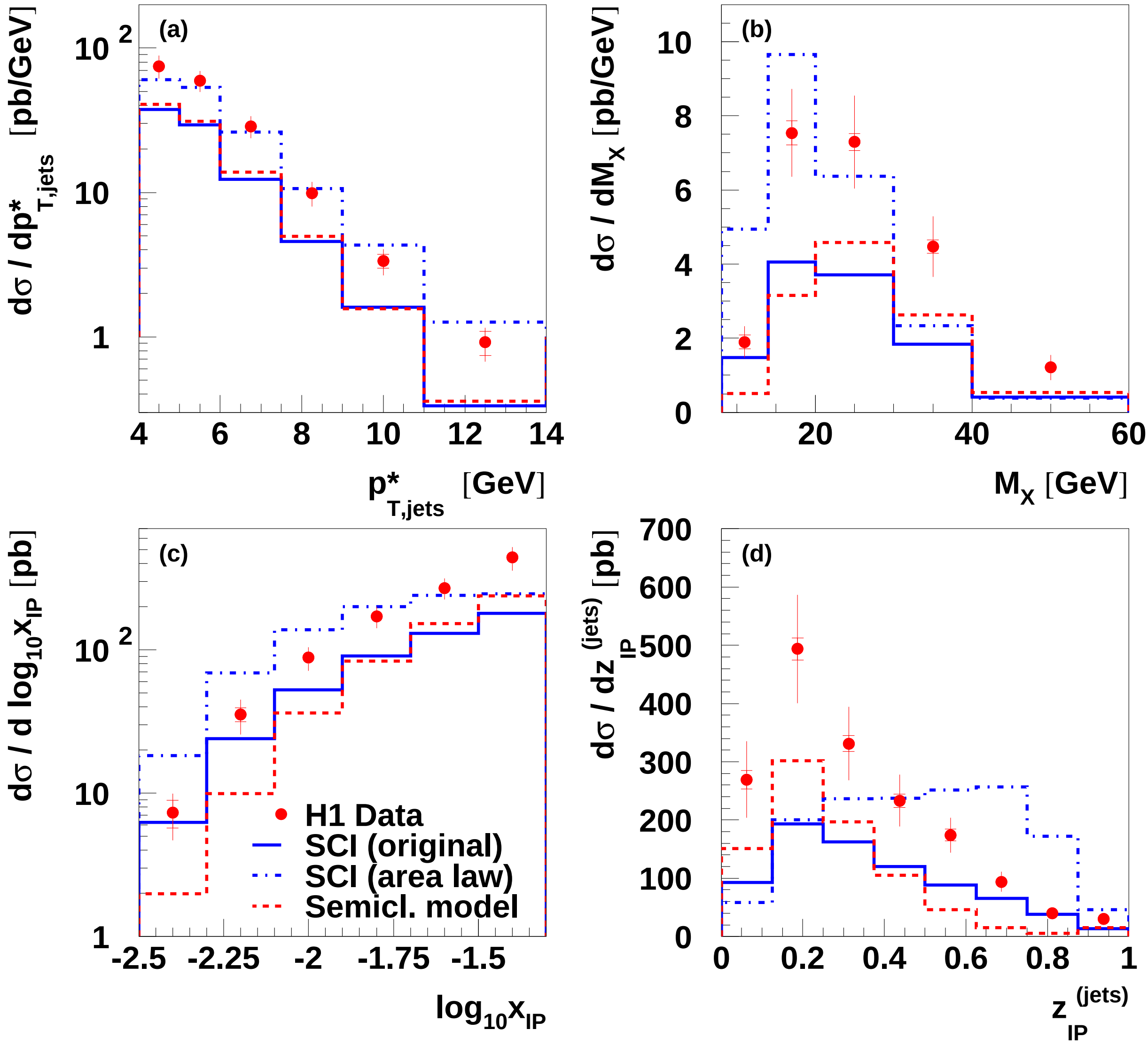
Diffractive Dijets



- $z_{I\!P}$ in $Q^2 + p_T^2$ bins (scale):
  - Fit 3 overshoots data at high z in all bins of $Q^2 + p_T^2$
  - Fit 2 in very good agreement

- $z_{I\!P}$ in $x_{I\!P}$ bins:
  - Data compatible with Regge Factorization
  - Only little freedom e.g. to change $g_{I\!P}(z, \mu^2)$ and compensate by adjusting $\alpha_{IP}(0)$

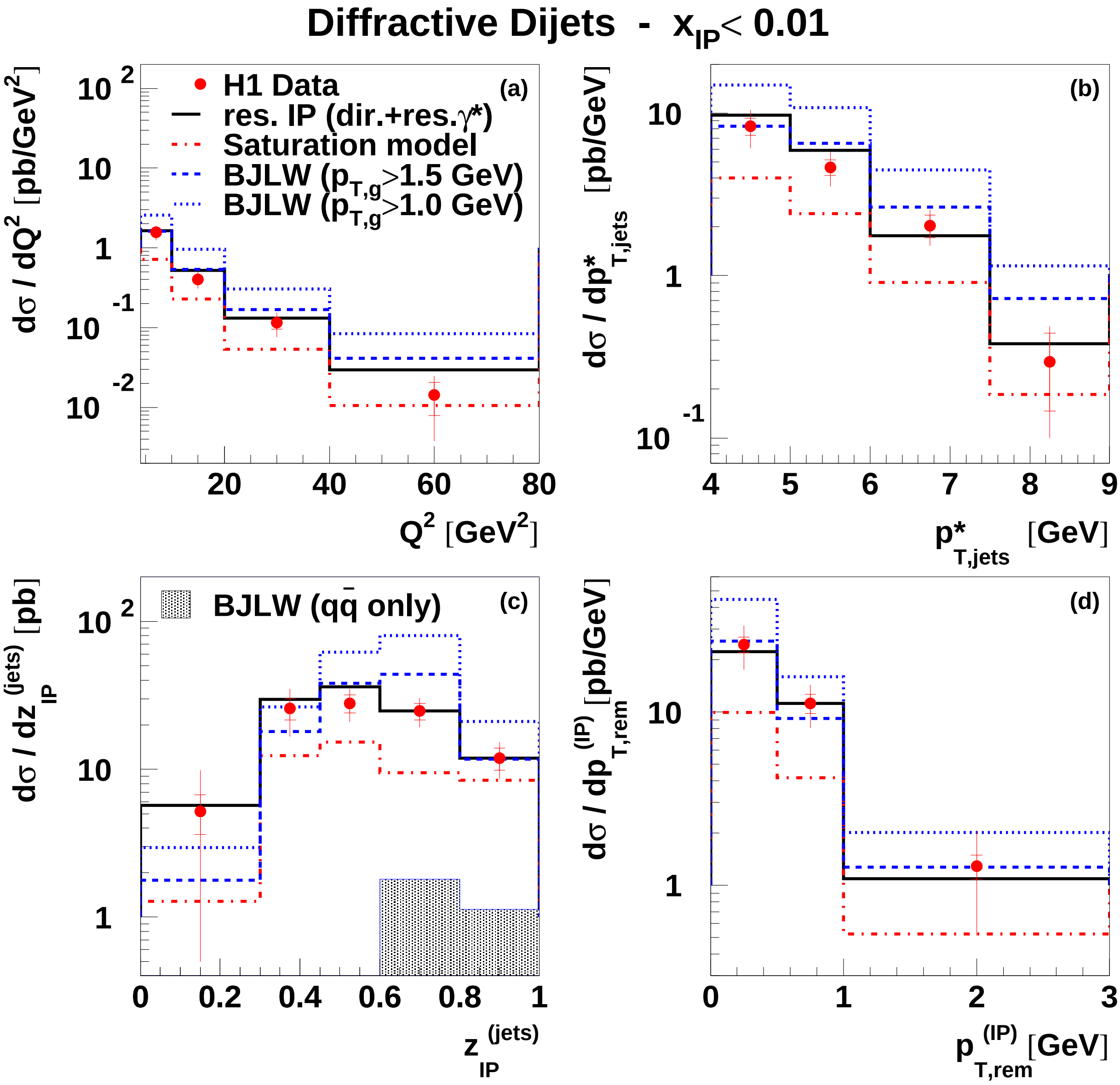
Diffractive Dijets



- Original Version of SCI:
  - Too low in normalization by Factor 2 , Shapes $\sim$ OK
- "Generalized area-law" Version of SCI:
  - Normalization $\sim$ OK , Shapes not described
- Semiclassical Model:
  - similar to SCI (original), Shapes OK

$\rightarrow$ Soft Colour Models in present cannot simultaneously describe shape and normalization!

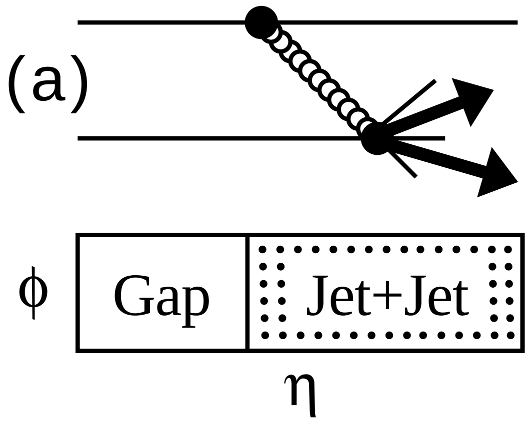
2-gluon exchange models



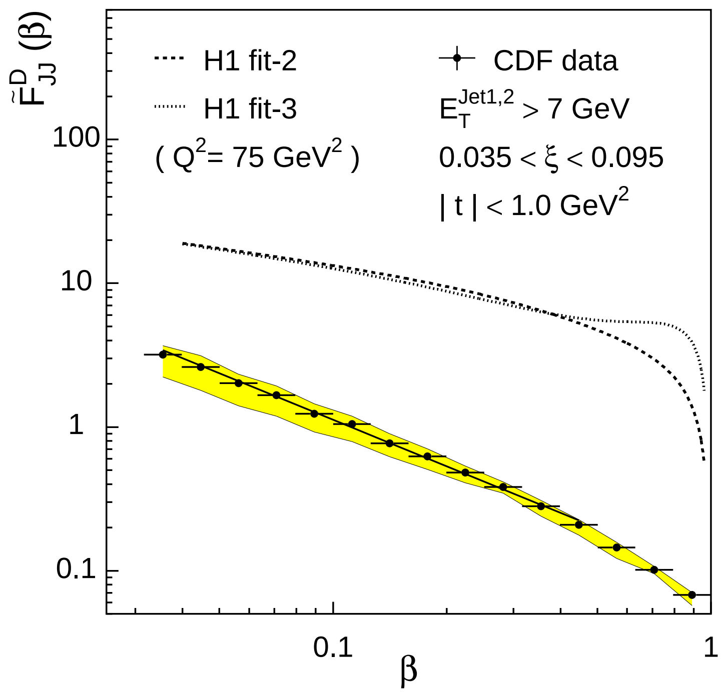
- $q\bar{q}$ alone very tiny !
- Saturation model low by factor 2 (strong p_T ordering)
- BJLW (Bartels et al.): roughly in agreement with cut-off for gluon: $p_T > 1.5$ GeV (no p_T ordering!)
- $p_T > 1.0$ GeV overshoots
- But: also res. IP (collinear IP remnant) describes Data!

New Results from the Tevatron (CDF)

Diffractive dijets in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV:



Extraction of diffr. Structure function of $\bar{p}$ and comparision with results from H1 $F_2^{D(3)}$:



- Serious breaking of factorization!
- "Survival Probability" due to remnant interactions, which are absent in lepton proton scattering ?!

Summary

- Inclusive diffractive DIS ($F_2^{D(3)}$) well described by factorizable "Pomeron exchange" with $\alpha_{IP}(0) = 1.2$ and Pomeron PDF's strongly dominated by gluons

- Diffractive Jet-Production confirms this picture: PDF's from inclusive measurement can describe exclusive process
$\rightarrow$ Diffractive hard scattering factorization
(non-trivial, see proof by Collins; broken at Tevatron)

- -Jets are highly sensitive to diffr. gluon distribution, in contrast to $F_2^{D(3)}$ (indirect via scaling violations)
- Best constraint so far on shape of $g_{IP}(z)$ at high z
- Compatible with factorizing x_{IP} dependence with $\alpha_{IP}(0) = 1.17 \rightarrow$ Regge factorization

- In proton rest frame, $q\bar{q}g$ states dominate over $q\bar{q}$

- Soft color neutralization models in present form cannot simultaneously describe shapes and normalization

- - 2-gluon exchange calculations can roughly describe shapes of distributions for $x_{IP} < 0.01$
- Normalization either low by factor 2 (saturation model) or free parameter (via p_T cut-off in BJLW)

- Diffractive Jets able to discriminate between models which all can describe inclusive measurements !