Diffractive Jet Production in DIS – Probing the Structure of Colour Singlet Exchange

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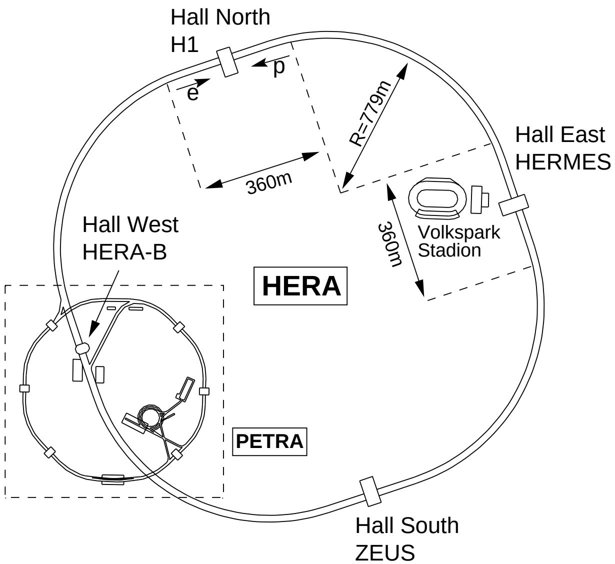
H1 Collaboration

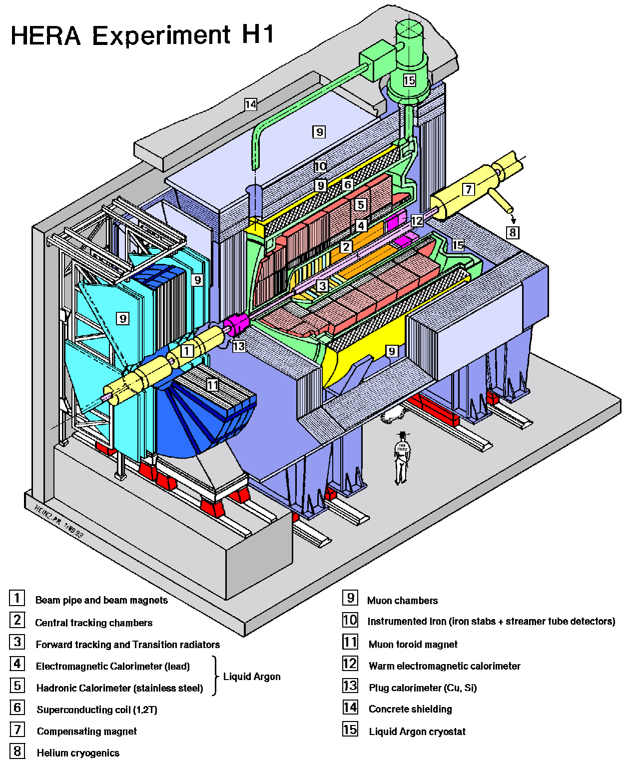
Fermilab and Madison

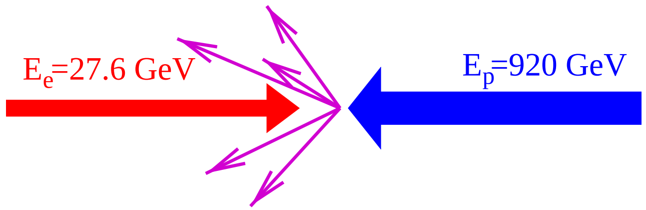
May 2001

- Introduction
- Diffractive DIS and $F_2^{D(3)}$
- Diffractive jet production
- Results
- Summary and conclusions

HERA and the H1 Detector





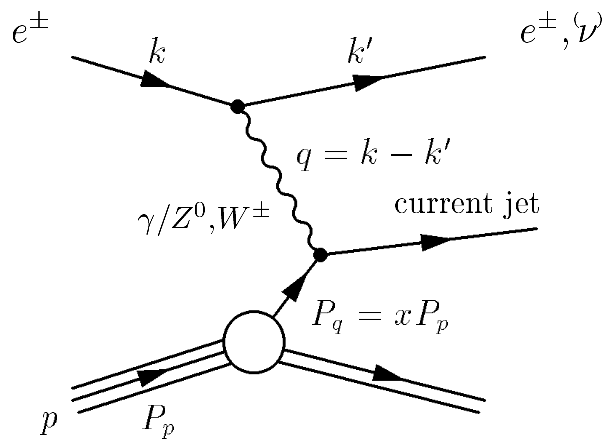


H1, ZEUS: ep collisions at $\sqrt{s} = 320$ GeV

HERA-B: p-beam on fixed target: CP violation in $B^0\bar{B}^0$

HERMES: e-beam on polarized target: Spin structure

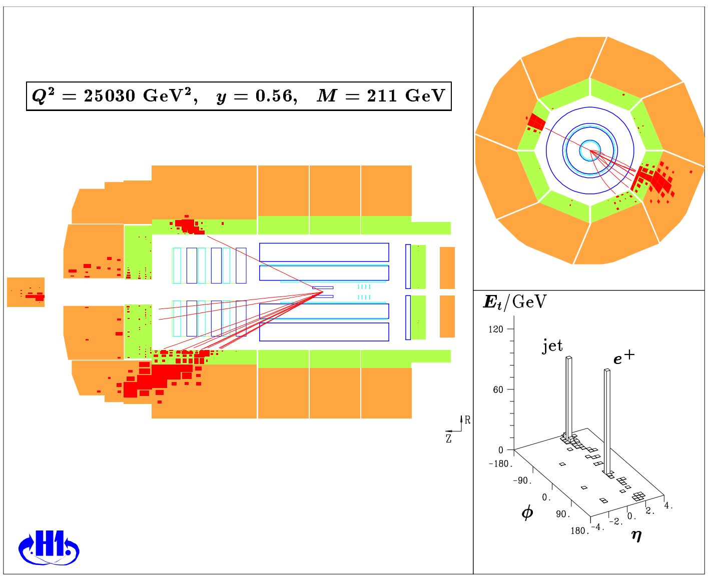
Deep Inelastic Scattering (DIS) at HERA

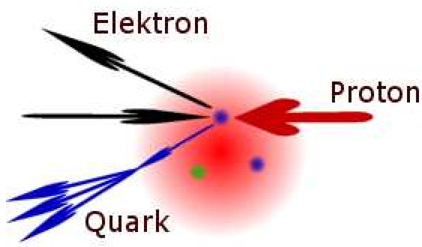


$Q^2 = -q^2 = (k - k')^2$
Photon virtuality,
"Resolution power"

$x = \frac{-q^2}{2P\cdot q}$ $(0 < x < 1)$
Parton momentum
fraction in p

- Highly virtual point-like photon γ^* in DIS at HERA probes proton structure with unprecedented resolution

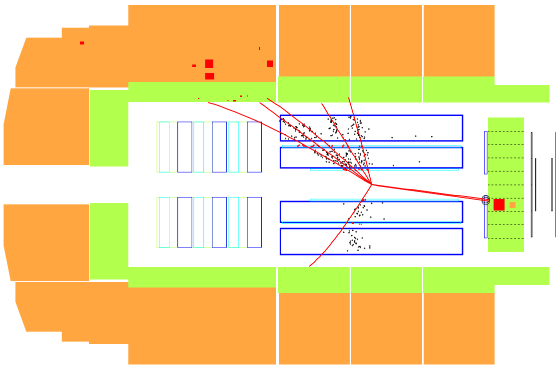




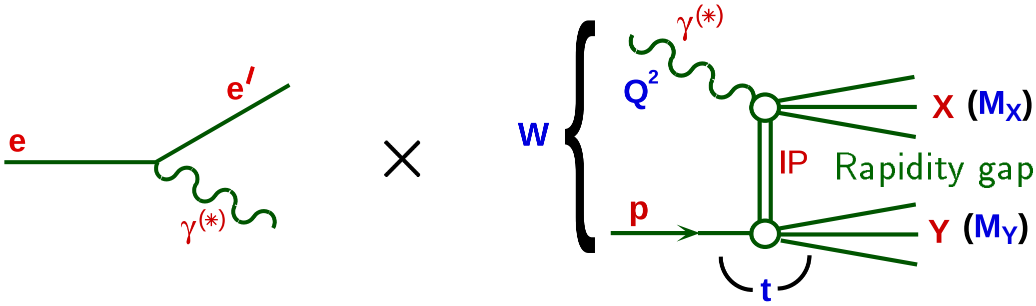
- Scattering off coloured object:
  $\longrightarrow$ p breaks up ("proton remnant")

Large Rapidity Gap (LRG) Events

- 10% of DIS events for exhibit large gap without hadronic activity in outgoing p region



- γ^* scatters off colorless state in p ("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

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

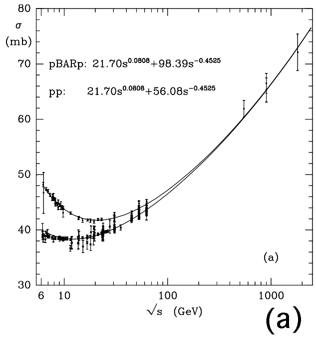
$\longrightarrow$ long. momentum fraction transferred from p to exchange

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

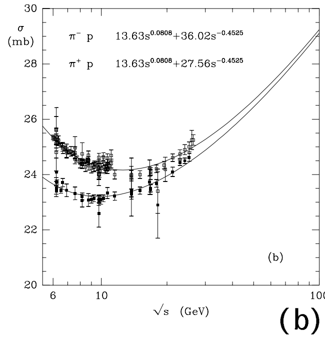
$\longrightarrow$ fraction of exchange momentum carried by q coupling to γ

Reminder: The “Pomeron”

- Introduced as pseudo-particle to parameterize elastic high energy scattering at small momentum transfers:

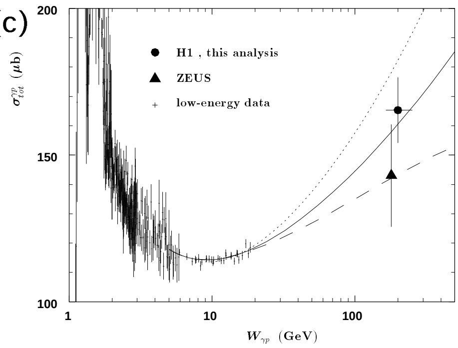


(a)



(b)

(c)



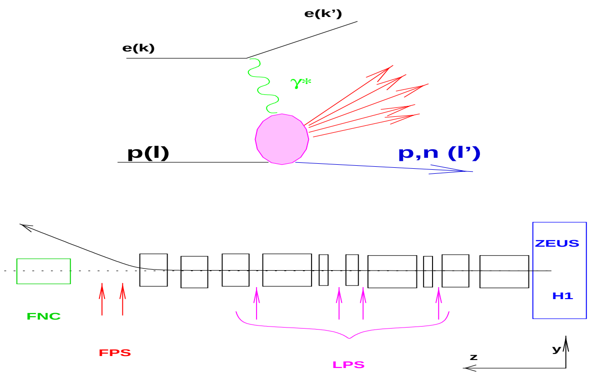
- Pomeron trajectory:
  $\alpha(t) = \alpha(0) + \alpha' t = 1.08 + 0.25\ t$

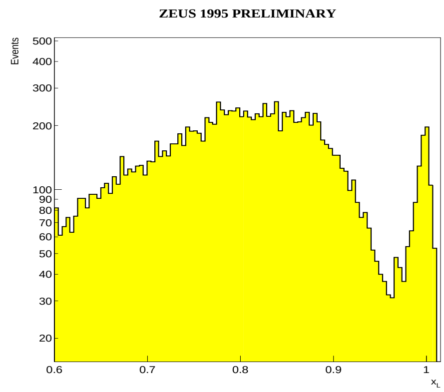
- Differential and total cross section:
  $\frac{d\sigma}{dt} \sim \frac{1}{s^2}|T(s,t)|^2 = f(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$
  $\sigma_{tot} \sim \frac{1}{s}\mathrm{Im}(T(s,t))|_{(t=0)} = s^{\alpha(0)-1}$

⇒ Today: Understand colour singlet exchange in terms of QCD (quark and gluon dynamics)!

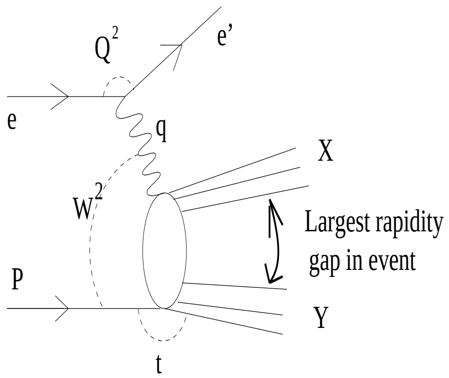
Selection of LRG Events

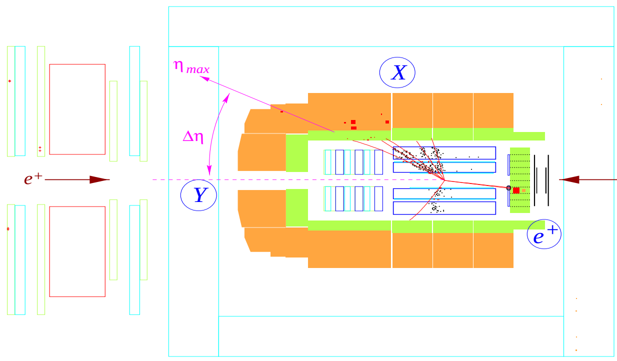
1. Tagging of p with "Roman Pots" (measure t, small stat.):



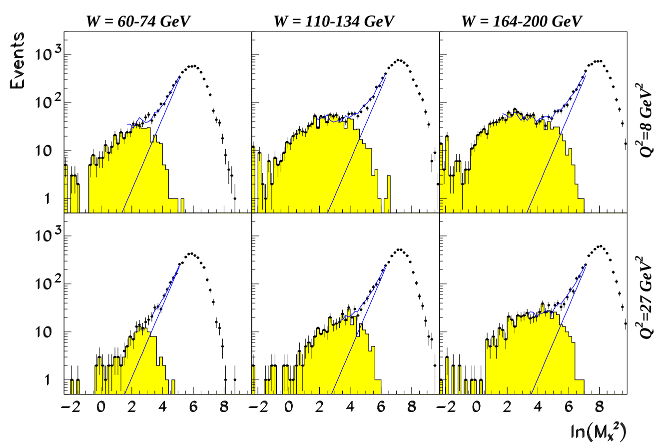


2. Large Rapidity Gap Requirement (integr. over M_Y, t):

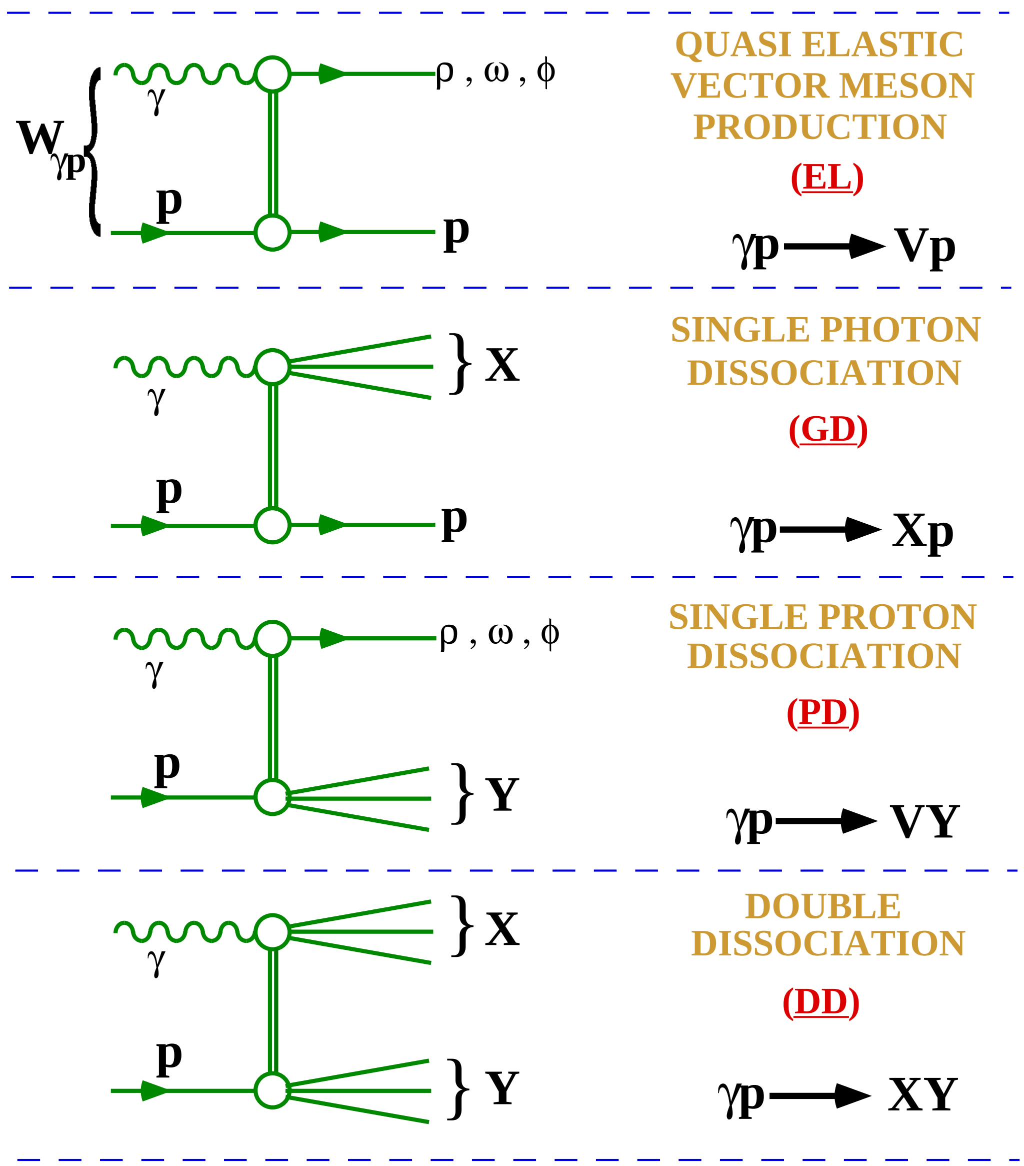




3. Analysis of final state M_X system (integr. over M_Y, t):



Colour Singlet Exchange Processes in $\gamma^* p$ Interactions



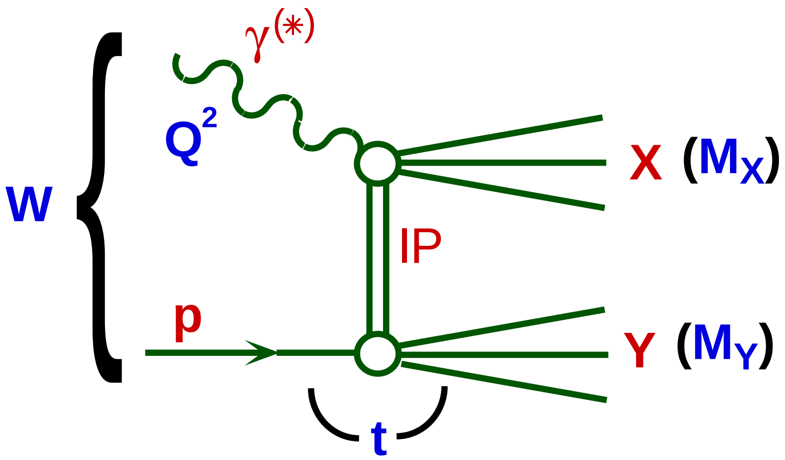
→ Photon γ^* can either fluctuate into vector meson or dissociate into high-mass system X

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

Diffractive DIS: Probing $I\!P$ Structure

Inclusive DIS: Structure function $F_2(x, Q^2)$:

$$\frac{\mathrm{d}^2\sigma(incl.)}{\mathrm{d}x\ \mathrm{d}Q^2} = \frac{4\pi\alpha^2}{xQ^4}\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2)$$



Diffractive DIS: Diffractive structure function F_2^D:

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

If Y is not measured, integrate over M_Y,t:

$$F_2^{D(3)}(\beta, Q^2, x_{I\!P}) = \int_{m_P}^{M_{Y,max}} \mathrm{d}M_Y \int_{t_2}^{t_1} \mathrm{d}t\ F_2^{D(5)}$$

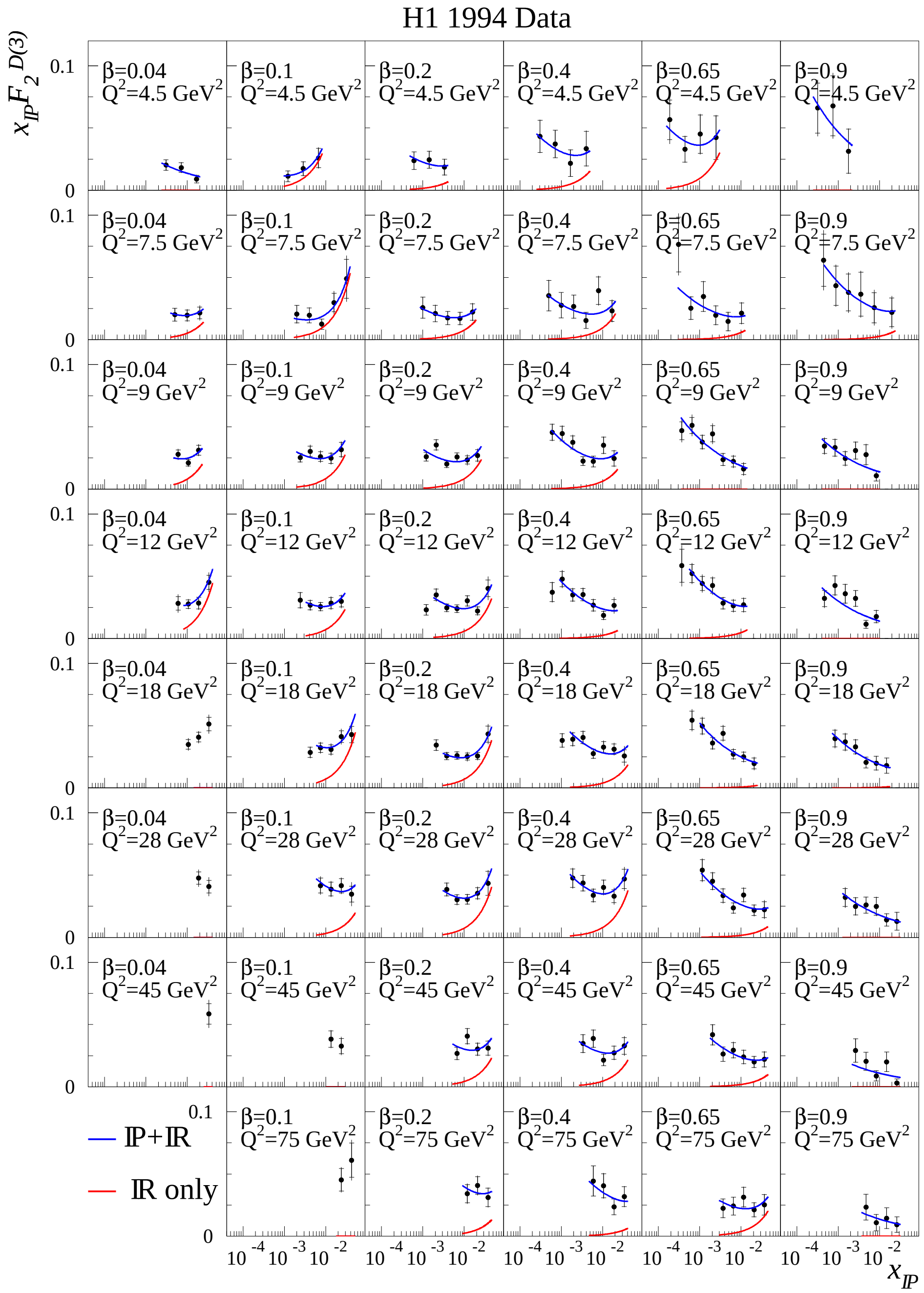
$\Rightarrow$ Large gap between X and Y $\Leftrightarrow$ M_X,M_Y,$x_{I\!P}$ small

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

H1 Measurement of $F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$:

$x_{I\!P} F_2^D$ $\beta \rightarrow$

$Q^2 \downarrow$



$x_{I\!P}$

Diffractive Parton Distributions

– Inclusive DIS factorization theorem:

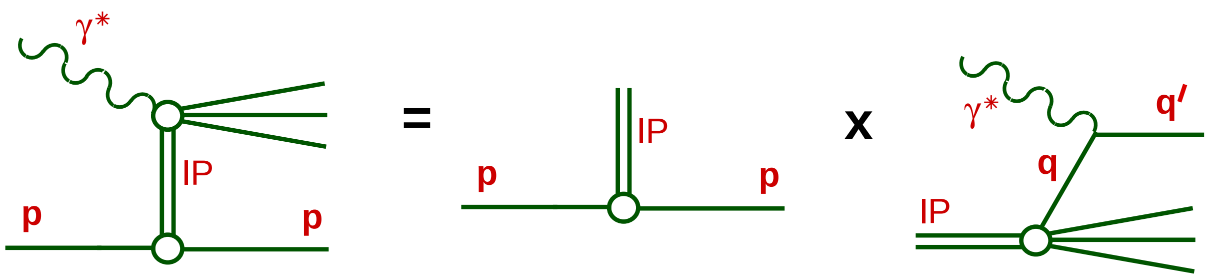
$$F_2(x, Q^2) \sim C_i \otimes p_i \quad (+\text{higher twist})$$

– Diffractive DIS [proof by J. Collins in 1998]:

$$F_2(x, Q^2, x_{I\!P}, t) \sim C_i \otimes p_i^D \quad (+\text{higher twist})$$

- valid at fixed $x_{I\!P}$, t
- p_i^D: 'conditional probabilities', obey DGLAP evolution
- determine p_i^D in inclusive diffr. scattering, then predict exclusive processes
- same C_i as in inclusive DIS

– Additional assumption: factorizing $x_{I\!P}$ dependence ['Regge factorization']

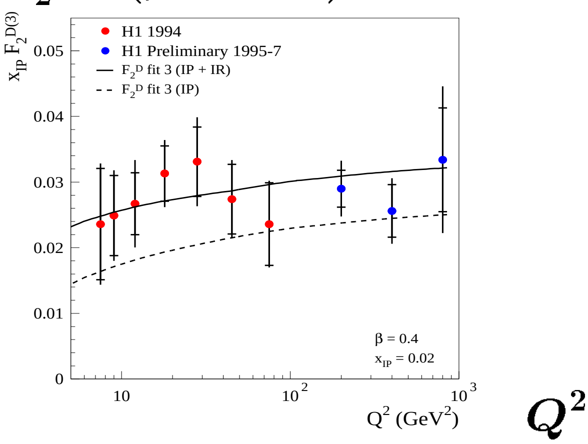


$$F_2^{D(3)}(x_{I\!P}, \beta, Q^2) = \quad f_{I\!P/p}(x_{I\!P}) \quad \times \quad F_2^{I\!P}(\beta, Q^2)$$

Diffractive PDF's from $F_2^{D(3)}$

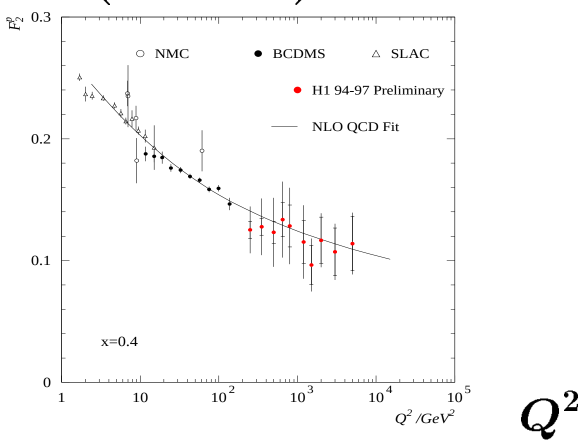
- Observation of (positive!) scaling violations:

$F_2^D \quad (\beta = 0.4)$



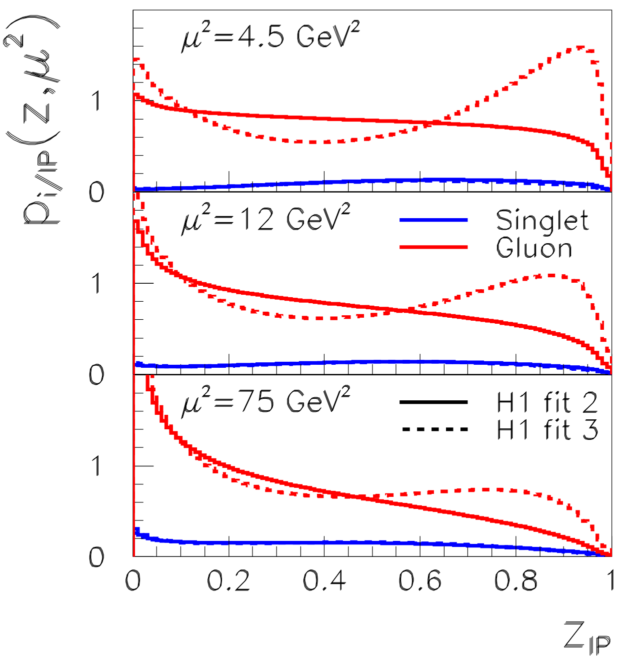
[flat/rising with Q^2]

$F_2 \quad (x = 0.4)$



[steeply falling with Q^2]

- Strongly suggestive of g dominated exchange !
- DGLAP QCD analysis of F_2^D yields diffractive PDF's:



Gluons

$\gg$

Quarks

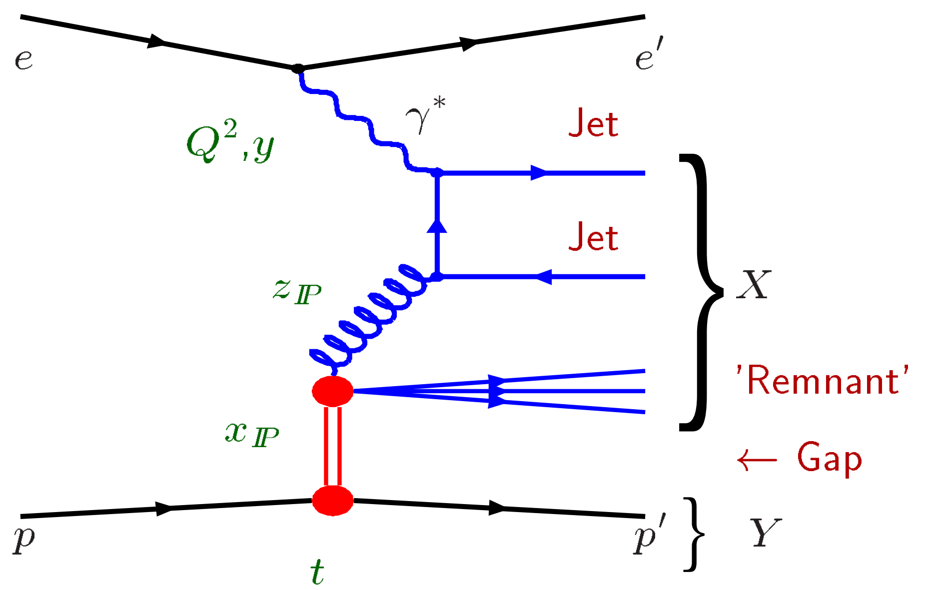
[g^D indirectly determined from scal. viol.
$\rightarrow$ large uncertainty]

Diffractive Dijet Production

Motivation:

- Direct sensitivity to g^D through $\mathcal{O}(\alpha_s)$ process (boson gluon fusion):
- Jet P_T provides second hard scale

Kinematics:



M_{12}

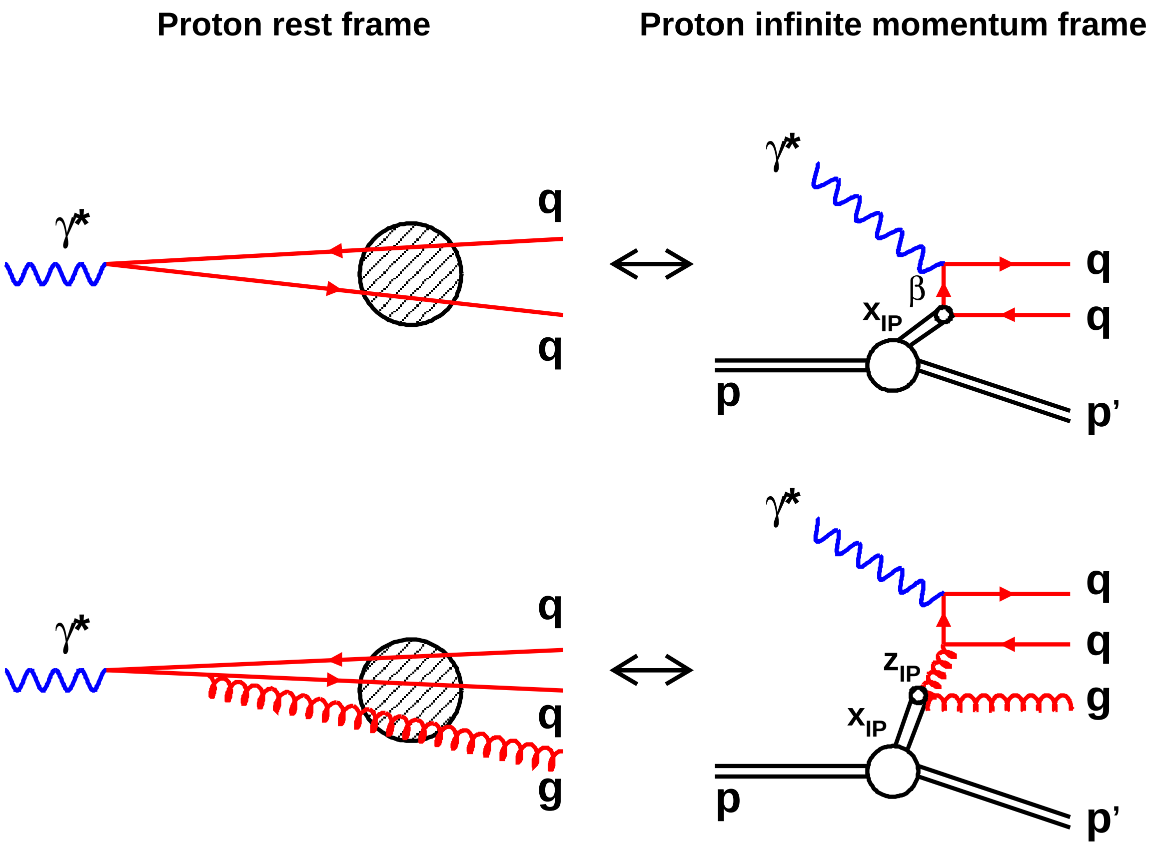
– Invariant mass of two leading jets

$$z_{I\!P}^{(jets)} \approx \frac{Q^2+M_{12}^2}{Q^2+M_X^2}$$

– Momentum fraction of exch. entering hard scattering

Proton Rest Frame Picture

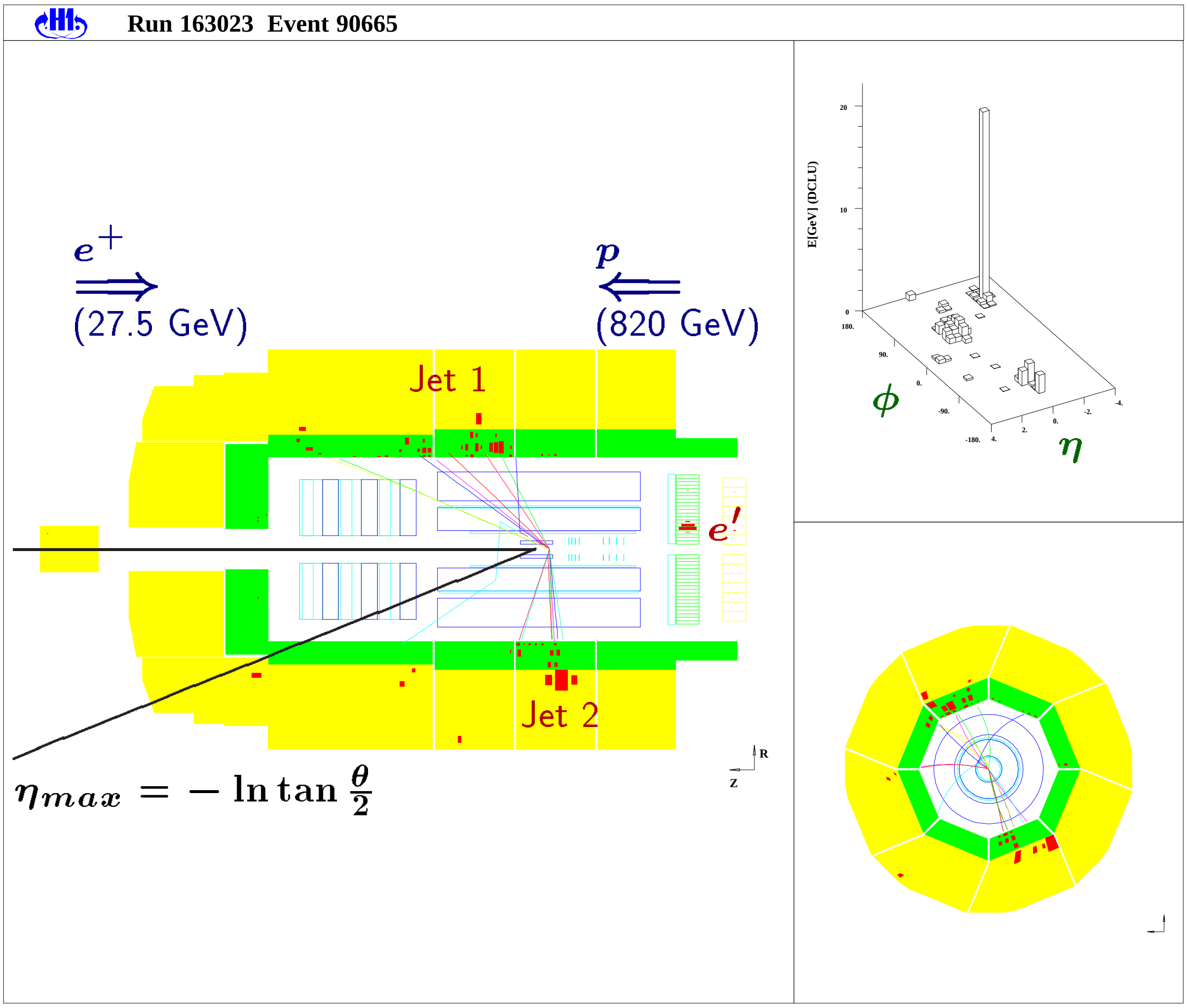
- Photon fluctuates into $q\bar{q}$ or $q\bar{q}g$ state long before interaction, then scatters elastically off proton at rest



$q\bar{q}$	$\Leftrightarrow$	diffr. q scattering (quark parton model)
$q\bar{q}g$	$\Leftrightarrow$	diffr. g scattering (boson gluon fusion)

- For large diffractive masses M_X or high p_T final states, $q\bar{q}g$ configurations are expected to dominate

Event 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 $(3.2 < \eta < 7.5)$
- 2-Jet Signature: $N_{\rm Jet} \geq 2$; $p_T > 4$ GeV
  CDF cone jet-algorithm in γp CMS

$\mathcal{L} = 18.0\ \mathrm{pb}^{-1}$ $N_{2-\rm Jet} = 2.500$ $N_{3-\rm Jet} = 130$

Cross Section Measurement

- Correction for detector effects to 'stable' particle level
- Correction for QED radiative effects at lepton vertex
- Bin-by-bin correction procedure

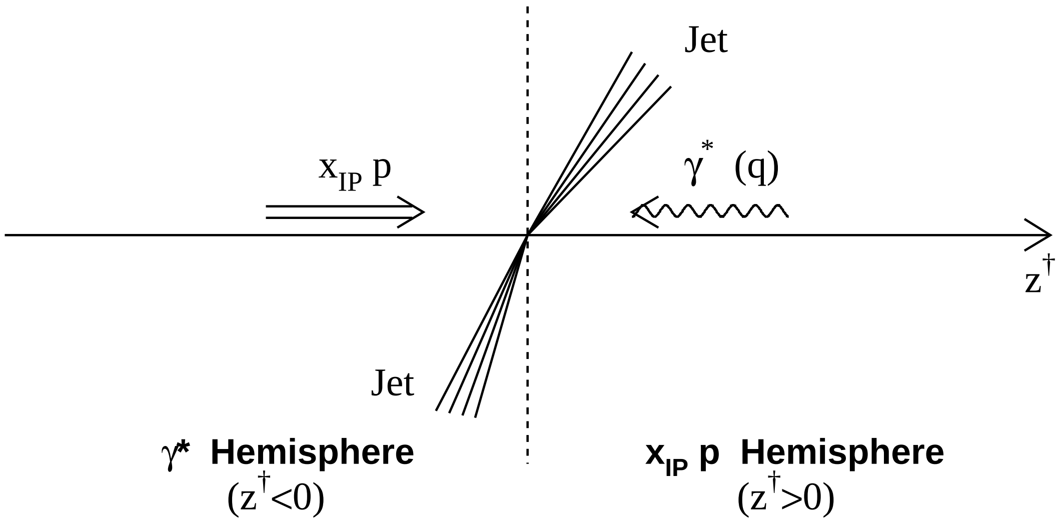
Kinematic Range of Hadron Level Cross Sections
$4 < Q^2 < 80\ \mathrm{GeV}^2$ $0.1 < y < 0.7$
$x_{I\!P} < 0.05$ $M_Y < 1.6\ \mathrm{GeV}$ $\lvert t\rvert < 1.0\ \mathrm{GeV}^2$
$N_{\mathrm{jets}} \geq 2$ or $N_{\mathrm{jets}} = 3$ $p^*_{T,jet} > 4\ \mathrm{GeV}$ $-3 < \eta^*_{jet} < 0$

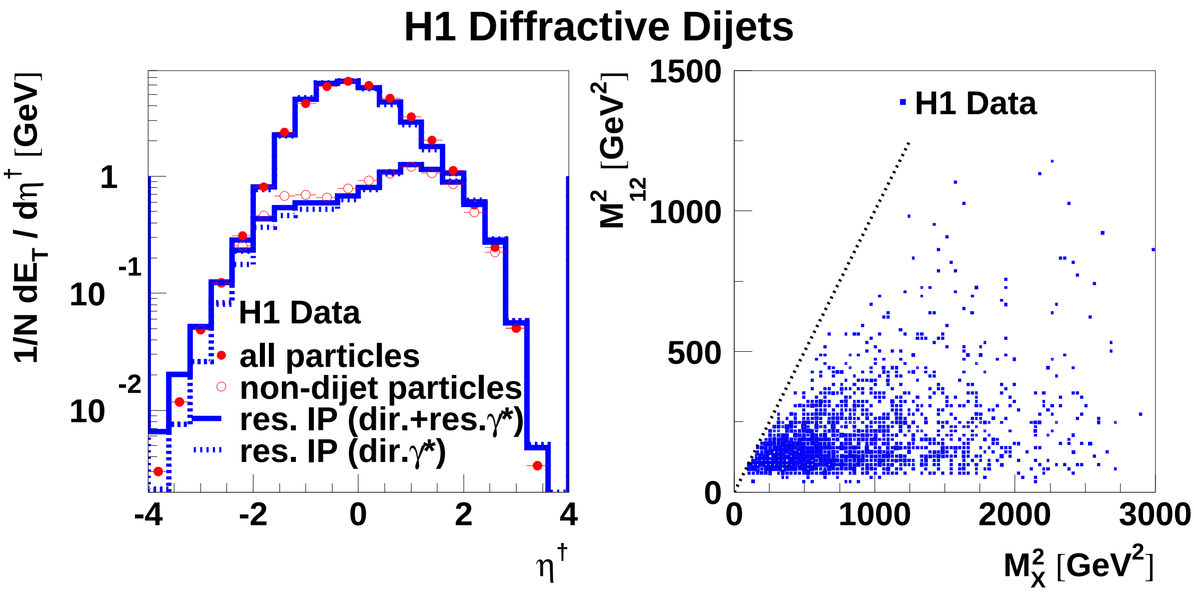
Main systematic uncertainties:

- Hadronic energy scales of calorimeters
- Trigger efficiency
- Model dependence of correcion
- Scattered electron measurement

$\Rightarrow$ Systematic error dominates $(15 - 30\%)$

Results: General Properties of Dijet Events





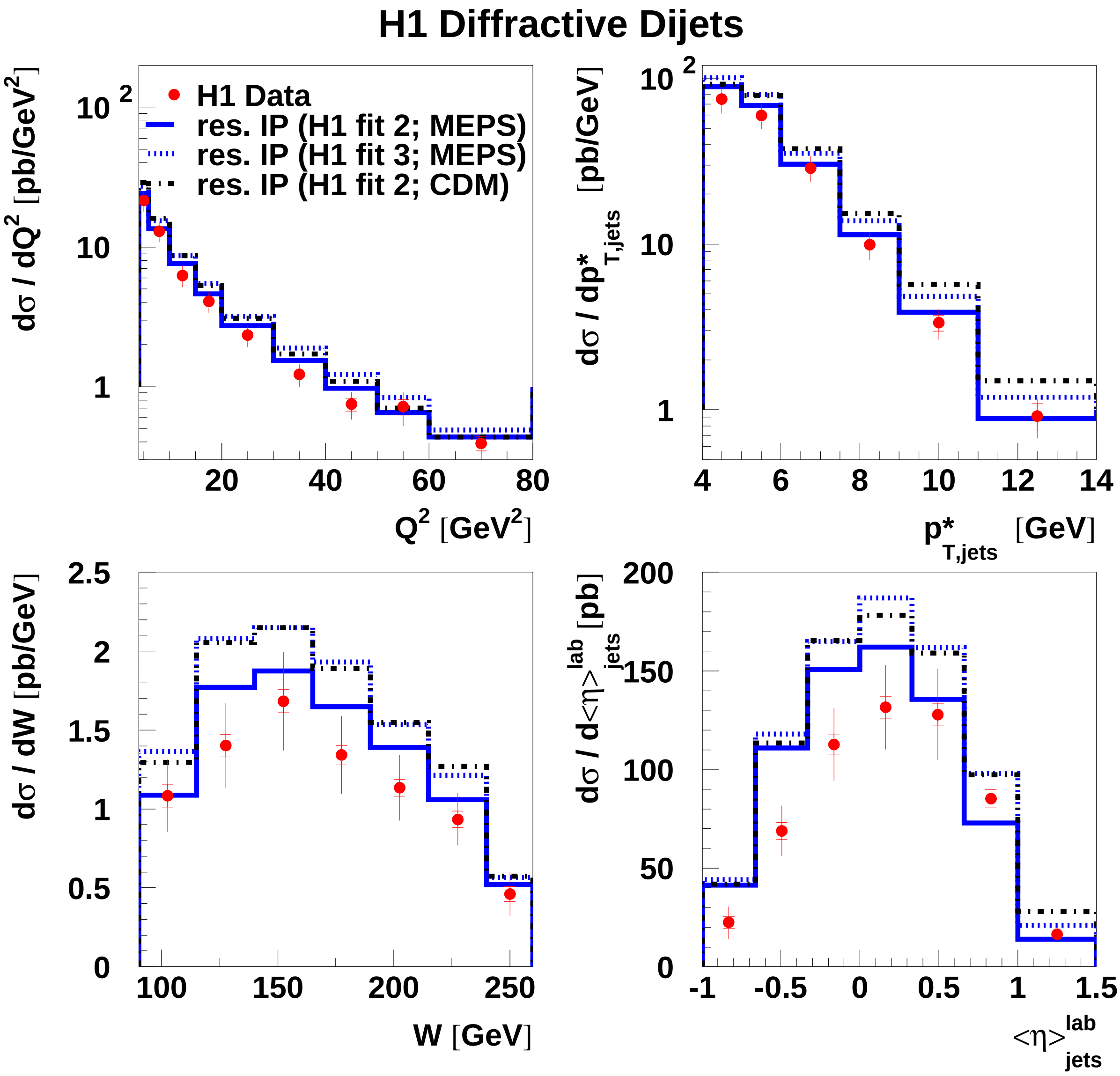
- Significant energy not contained in dijets, some preference for $I\!P$ hemisphere
- $M_{12} \ll M_X$ typically

$\Rightarrow$ exclusive 2-jets ($q\bar{q}$) just small part of cross section !

QCD Factorization at Work

Predict diffr. dijet cross sections with PDF's obtained from inclusive $F_2^{D(3)}$ measurement:

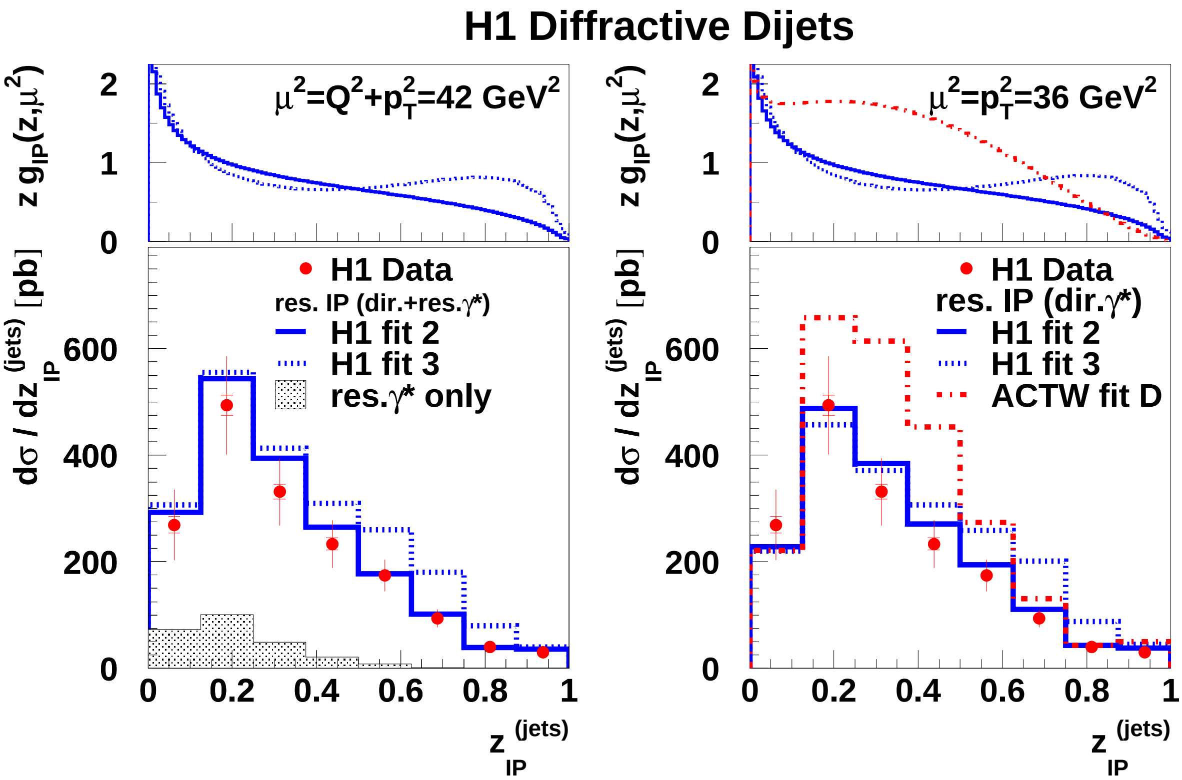
[resolved γ^* component included]



⇒ Consistent with QCD factorization in diffractive DIS

Diffractive Gluon Distribution

Dijets directly constrain shape and normalization of g^D:



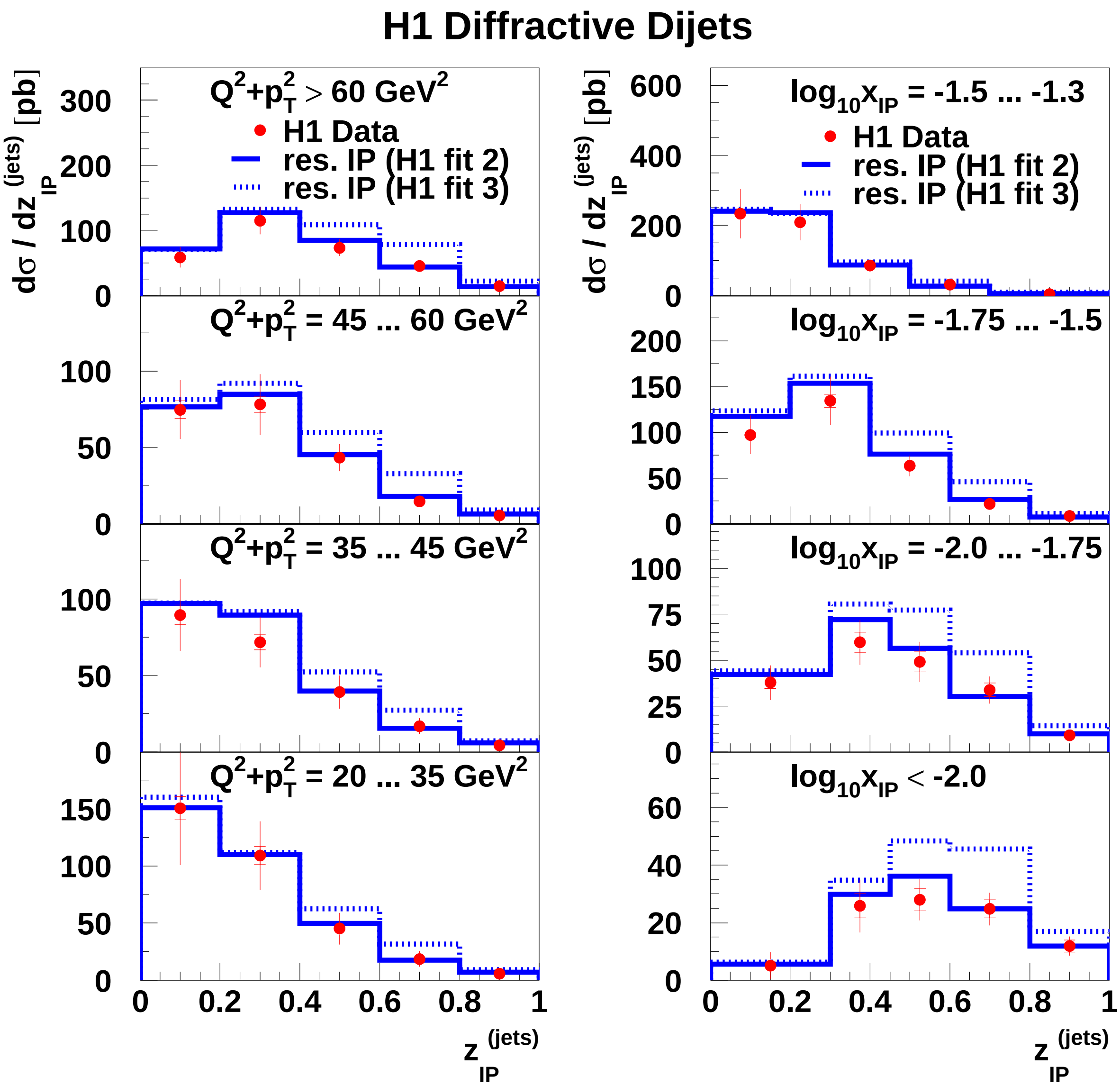
[res. γ^*, $I\!\!R$ and quark contributions small]

- H1 fit 2: very good agreement with data
- H1 fit 3: overshoots at high $z_{I\!P}$
- ACTW-D (Alvero, Collins, Terron, Whitmore fits): too high

$\Rightarrow$ Strong support for fully factorizable diffr. PDF's in DIS which are gluon-dominated with momentum distr. flat in z

Proton rest frame picture: $q\bar{q}g \gg q\bar{q}$ states

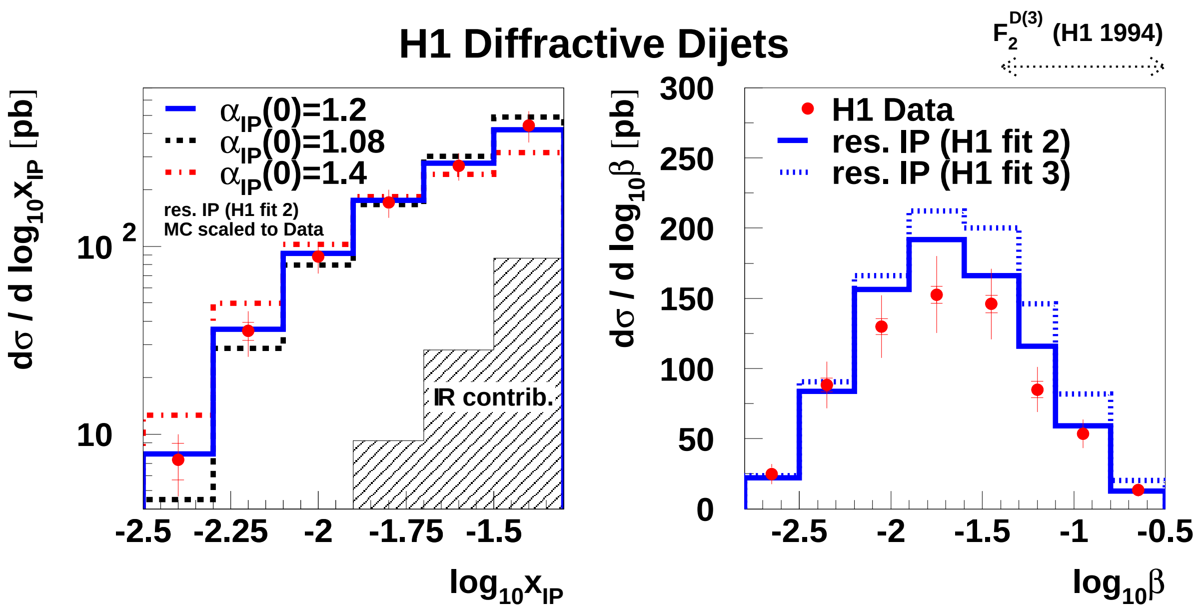
Features of Diffractive PDF's



- Data consistent with DGLAP evolution of PDF's with factorization scale $\mu^2 = Q^2 + p_T^2$
- Also compatible with factorization of $x_{I\!P}$ dependence $[f_{I\!P/P}(x_{I\!P}) \times p_i^D(z, \mu^2)]$
  No visible variation of $\alpha_{I\!P}(0)$ with $z_{I\!P}$

Energy Dependence $\alpha_{I\!P}(0)$

- Shape of $x_{I\!P}$ distribution sensitive to energy dependence of cross section:



Parameterization used (Regge motivated):

$$f_{I\!P/P}(x_{I\!P}, t) \sim \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(t)-1} e^{Bt}$$

$$\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t \quad [B = 4.6 \text{ GeV}^{-2}, \alpha'_{I\!P} = 0.26 \text{ GeV}^{-2}]$$

Fit Result:

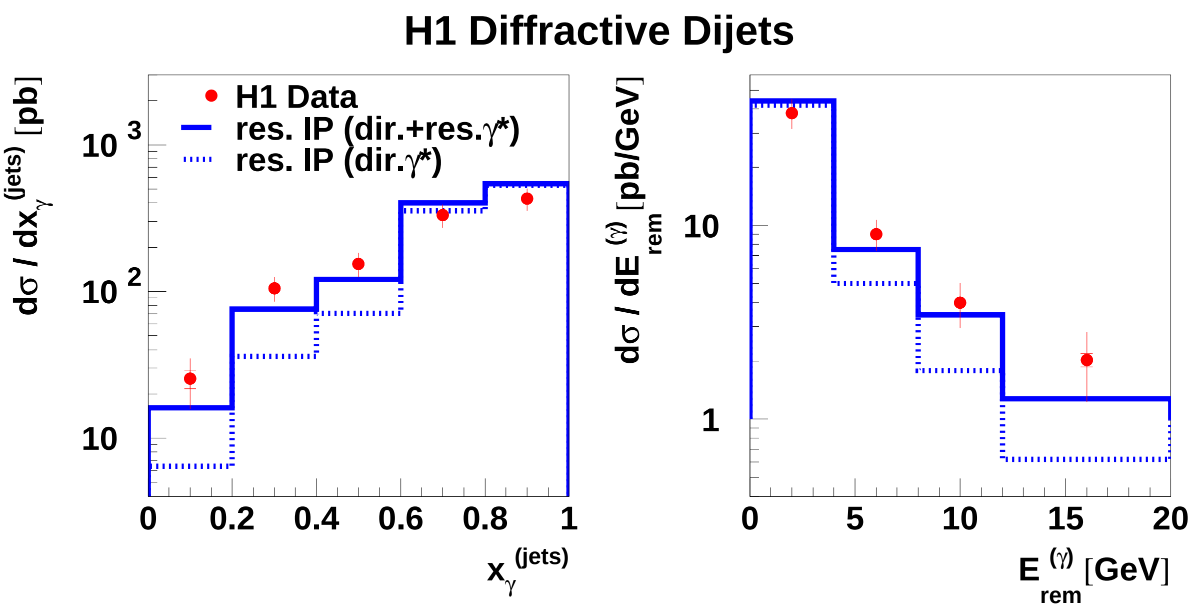
$$\alpha_{I\!P}(0) = 1.17 \,^{+0.03}_{-0.03}\,(\text{stat.})\,^{+0.06}_{-0.06}\,(\text{syst.})\,^{+0.03}_{-0.07}\,(\text{model})$$

$\Rightarrow$ Consistent with H1-$F_2^{D(3)}$ [Q^2 similar]

- β distribution: Jets are small β, compared with F_2^D

Resolved Virtual Photon Contribution

Since $Q^2 > 4\ \mathrm{GeV}^2$, $p_T^2 > 16\ \mathrm{GeV}^2$
$\Rightarrow$ Jets can "resolve" virtual photon
[expected from inclusive dijet production]



$x_\gamma^{(jets)} = \frac{(E-p_Z)_{jets}}{(E-p_Z)_X}$ E_{rem} in γ^* hemisphere

Resolved γ^* contribution according to
"SaS-2D" parameterization [Schuler,Sjöstrand]

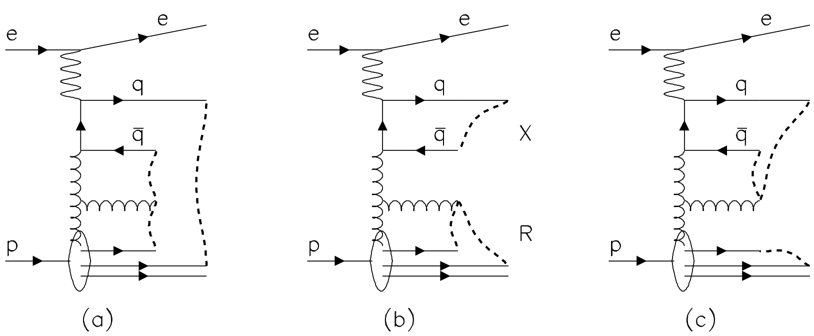
- $x_\gamma^{(jets)}$ cross section:
  Improvement at low $x_\gamma^{(jets)}$ if resolved contribution is added

- Corresponding improvement at high E_{rem}^γ

Soft Colour Neutralization

– Soft Colour Interactions (SCI)

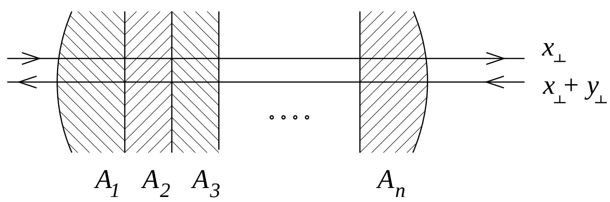
[Edin, Ingelman, Rathsman]



- Standard DIS, add. soft colour rearrangemens of final state partons may result in rapidity gap
- Two versions:
  - Original version: One additional parameter (rearrangement prob), tuned to F_2^D
  - Improved version: "Generalized area law"; improved description of F_2^D at low Q^2

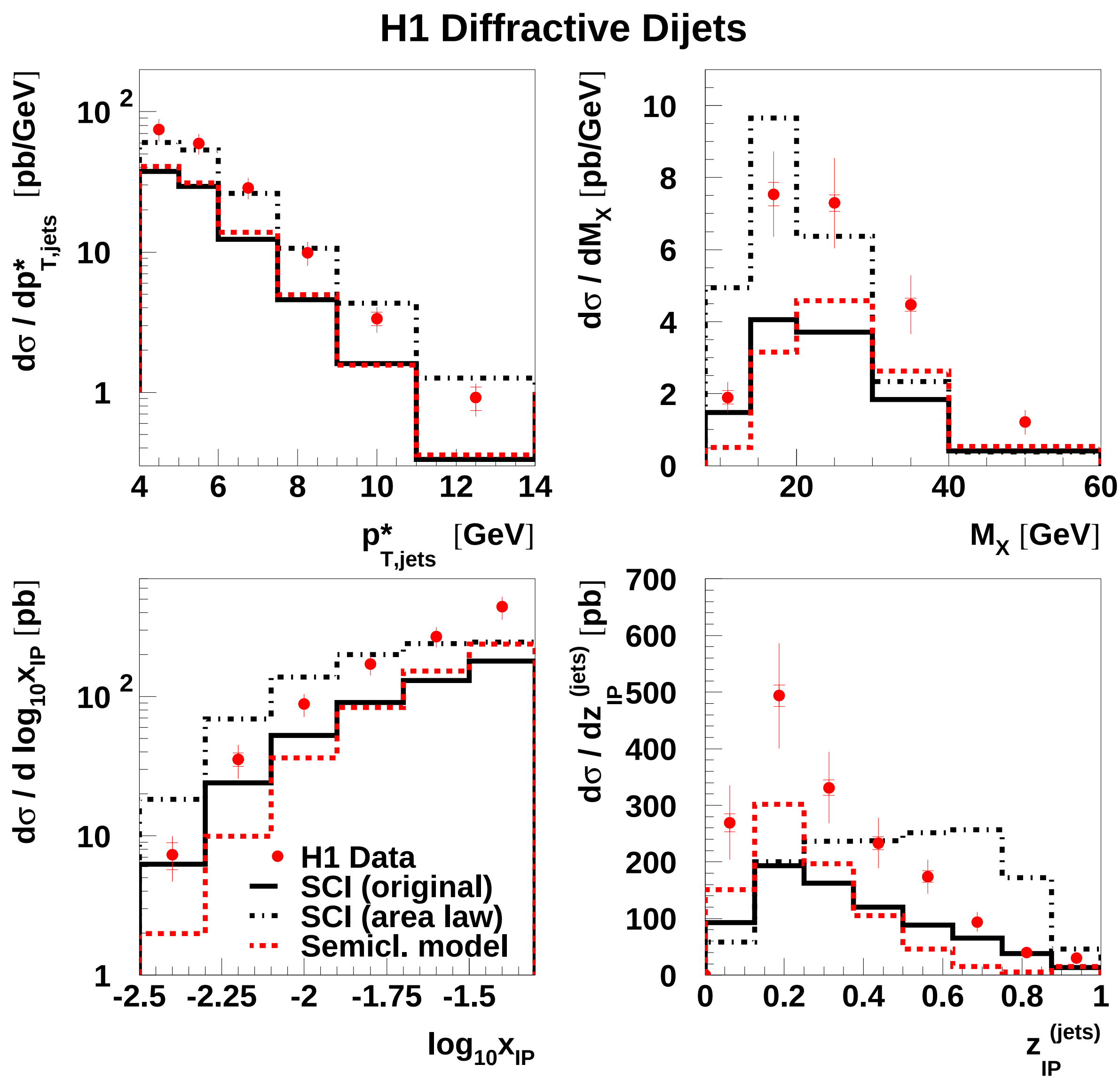
– Semi-classical model

[Buchmüller, Gehrmann, Hebecker]



- $q\bar{q}$, $q\bar{q}g$ states scatter elastically off large p, treated as superposition of uncorrelated colour fields

Results: Soft Colour Neutralization

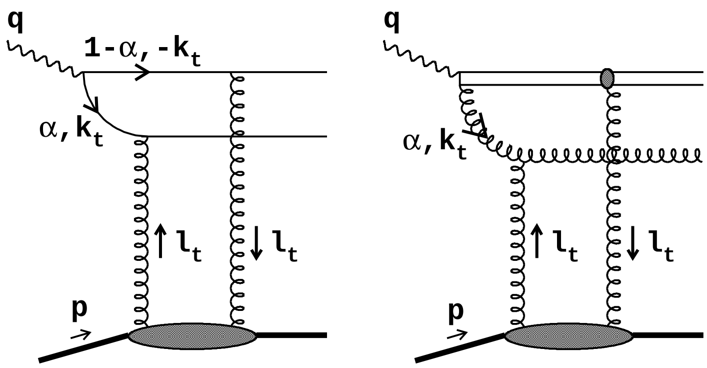


- SCI (orig.) and semi-classical model give reasonable shapes, but underestimate 2-jet cross section by factor 2
- SCI (area law) reproduces normalization, but fails in shapes

$\Rightarrow$ Sensitivity to differences between models which all (have been tuned to) describe $F_2^{D(3)}$!

Colour Dipole / 2-gluon Exchange Models

- Simplest parton level realization of colour singlet exchange: two gluons with cancelling colour charges



- 'Dipole picture': $q\bar{q}$,$q\bar{q}g$ configurations form (effective) colour dipole scattering off proton

Diffractive cross section:

$$\left.\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p}}{\mathrm{d}t}\right|_{t=0} \sim \int \mathrm{d}^2\mathrm{r} \int_0^1 \mathrm{d}\alpha |\Psi_{T,L}(\alpha,\mathrm{r})|^2 \; \hat{\sigma}^2(r^2, x, \ldots)$$

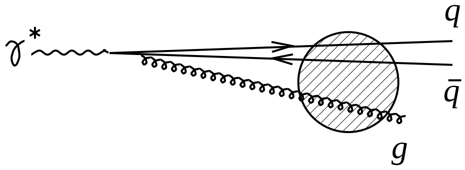
Dipole cross section may be expressed as:

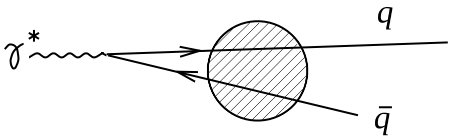
$$\hat{\sigma}(x,\mathrm{r}) \sim \int \frac{\mathrm{d}^2\mathrm{l}_t}{l_t^2} \left[1 - \mathrm{e}^{i\mathrm{r}\cdot\mathrm{l}}\right] \alpha_s(l_t^2)\mathcal{F}(x, l_t^2)$$

Where $\mathcal{F}(x, l_t^2)$ is un-integrated gluon density in proton

Colour Dipole / 2-gluon Exchange Models (II)

- Small P_T, large size dipoles: similar to soft hadron hadron scattering
- High P_T, small size dipoles: perturbation theory may be applicable





Saturation Model:
[Golec-Biernat, Wüsthoff]

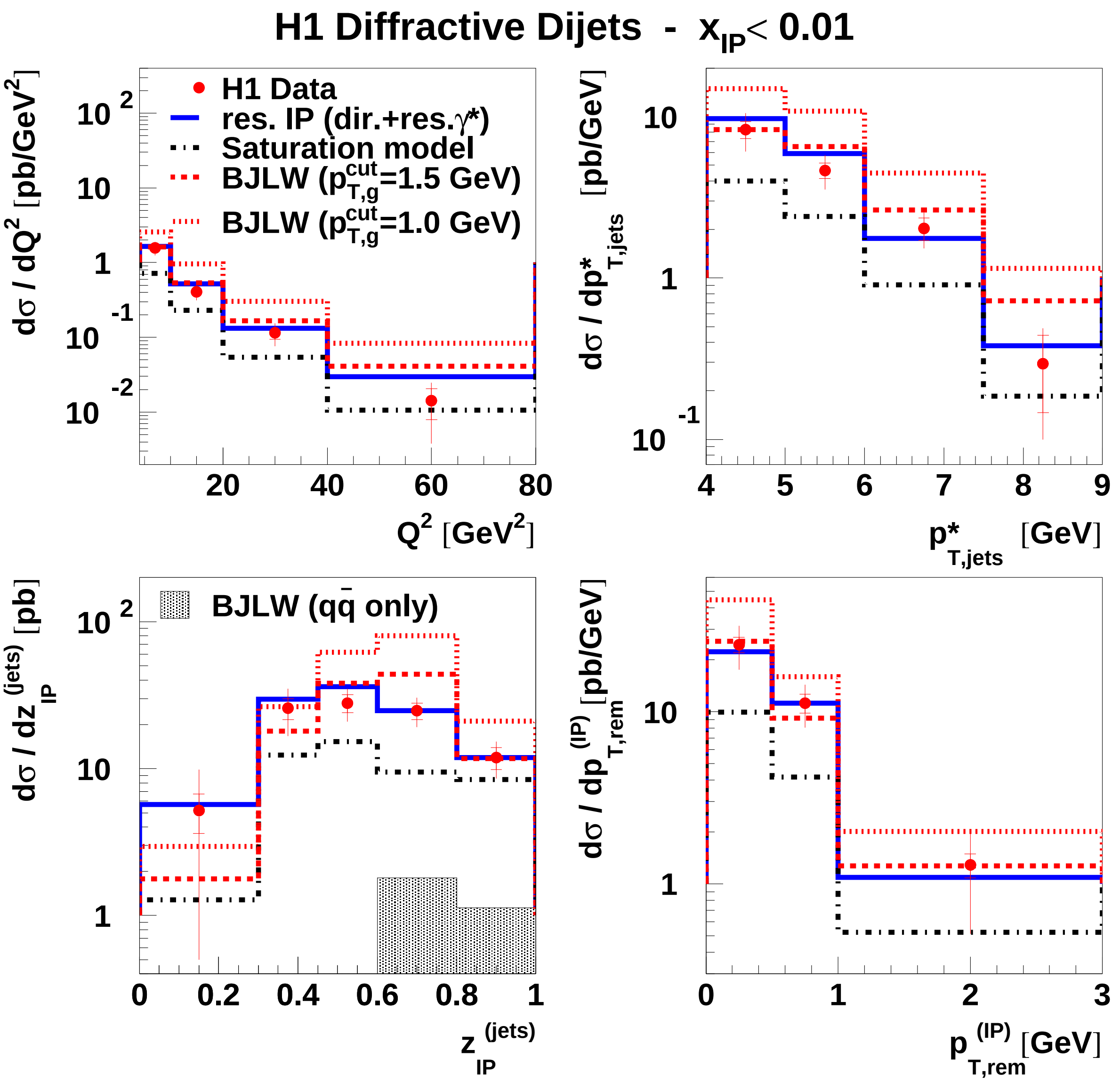
- Ansatz for σ_{Dipole} which interpolates between pert. ($\sim 1/Q^2$) and non-pert. ($\sim const.$) parts of inclusive $F_2(x, Q^2)$
- parameters fixed by fit to $F_2(x, Q^2)$, σ^D then predicted
- Strong p_T ordering assumed: $p_{T,g} \ll p_{T,q}$

2-gluon exchange calculation by Bartels et al. (BJLW):
[Bartels, Jung, Lotter, Kyrieleis, Wüsthoff]

- Perturbative calculation in low-β, low-$x_{I\!P}$ limit
- For $q\bar{q}g$ require high p_T of all 3 partons (only for jets!)
- non-p_T ordered configurations included, need cut-off for $p_{T,g}$

Results: 2-Gluon Exchange

$\boxed{x_{I\!P} < 0.01}$ $\Rightarrow$ avoid $I\!R$ exch.; p PDF's g-dominated

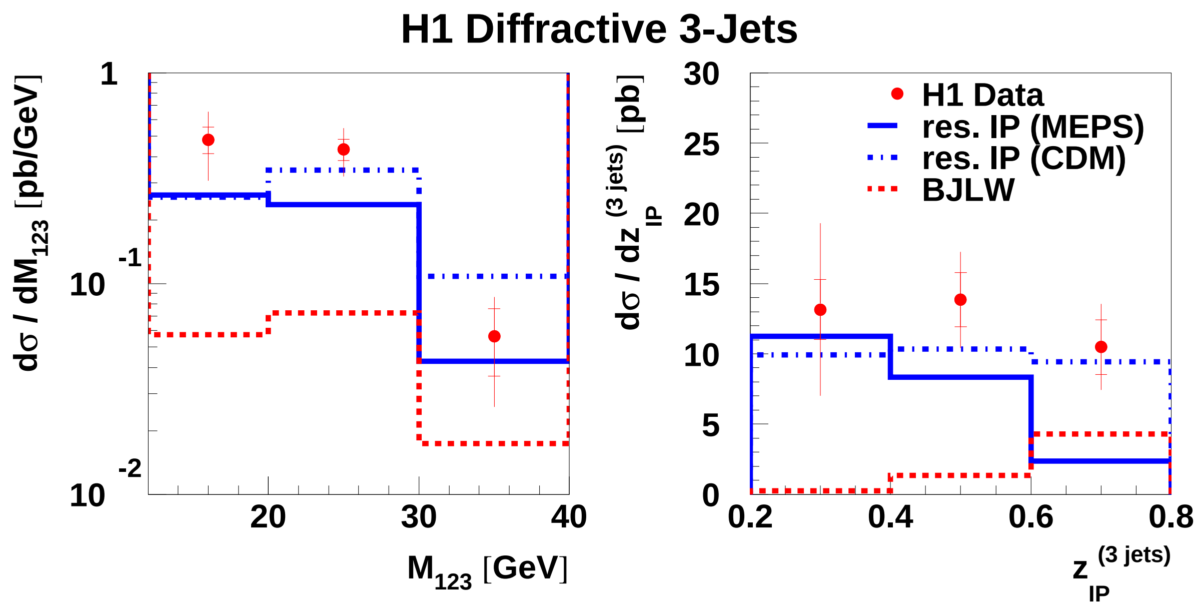


p_T of "$I\!P$ remnant"

- tiny $q\bar{q}$ contribution
- BJLW $\sim$ OK if $p_{T,g} > 1.5$ GeV
- Saturation Model too low
- $p_{T,rem}^{(I\!P)}$ not able to discriminate ;-(

3-Jet Production

Features:
- Limited statistics: 130 3-jets for $\mathcal{L} = 18.0\ \mathrm{pb}^{-1}$
- Kinematically forced to $x_{I\!P} > 0.01$



- Data above LO QCD prediction based on diffr. PDF's if MEPS is used for higher order approximation
- CDM does better job

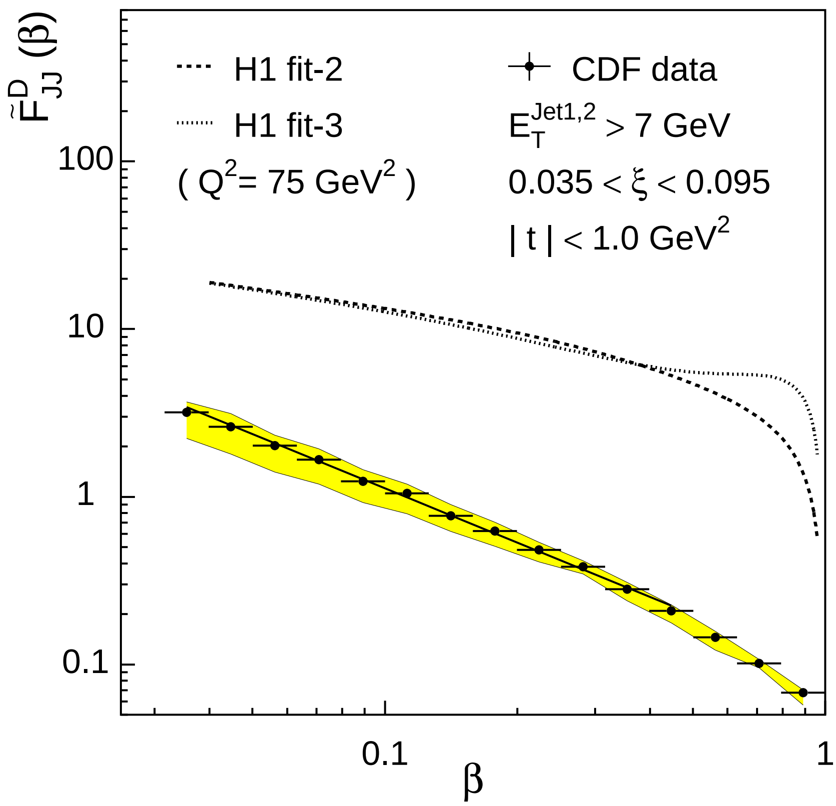
[Difference MEPS/CDM much smaller for dijets]

- 2-gluon exchange (BJLW) low

Comparison with Tevatron Results

CDF measurement of diffractive dijet production
with leading anti-proton in $p\bar{p}$ collisions:

Effective diffr. structure function $\tilde{F}^D_{JJ}(\beta)$



- Prediction based on diffractive PDF's extracted at HERA one order of magnitude above measured cross section!

⇒ Serious breaking of factorization!

Important to understand to get unified picture!

Summary

- Diffr. dijets tightly constrain diffractive gluon distribution g^D (shape and norm.), in contrast to $F_2^{D(3)}$ measurements

- Data favour diffr. PDF's, evolving with DGLAP, strongly dominated by gluons with momentum distribution rel. flat in z ("H1 fit 2")

- Consistent picture from $F_2^{D(3)}$ and jet measurements : Concept of factorizing diffr. PDF's in DIS [Collins] works.

- Consistent with factorizing $x_{I\!P}$ dependence with $\alpha_{I\!P}(0) = 1.17$ ("Regge factorization")

- In P rest frame: $q\bar{q}g \gg q\bar{q}$ configurations

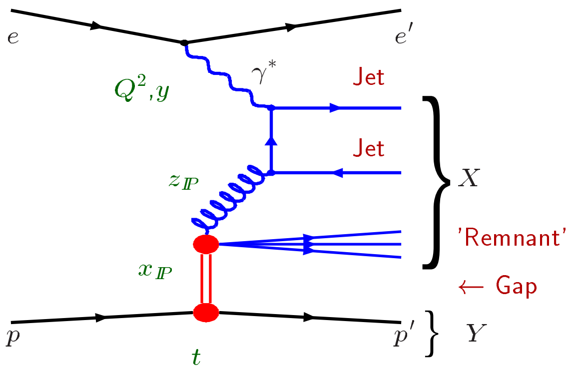
- SCI and Semiclassical models not yet able to simultaneously give correct shape and normalizations of jet cross sections

- Improved models calculations based on 2-gluon exchange can describe part of dijet cross section

Conclusion

Major step forward in understanding diffraction:

- Diffractive jet production is a powerful tool to illuminate QCD structure of colour singlet exchange, in particular the role of gluons !
- Sensitivity to discriminate between models which all describe inclusive diffraction (F_2^D) !
- 2-gluon exchange calculations in agreement with diffractive DIS data for the first time !



Results presented here are published by the H1 collaboration:

H1 Collaboration, C. Adloff *et al.*, "Diffractive Jet Production in Deep-Inelastic e^+p Collisions at HERA", DESY 00-174, `hep-ex/0012051`, acc. by Eur. Phys. J. **C**