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Hadronic Final States in Diffractive Scattering at HERA

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Outline:

- Introduction
- Event Shapes
- Energy Flow
- Hadron Production
- Dijet Production
- Open Charm Production
- Rapidity Gap Between Jets
- Summary

Introduction

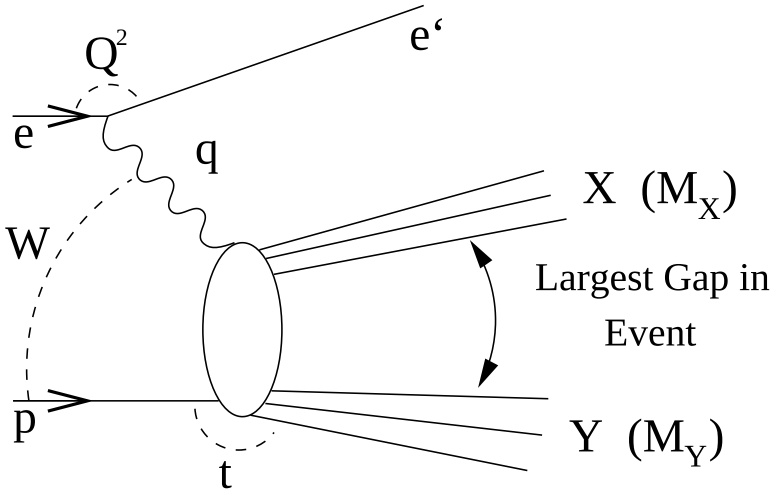
- Hard scattering in diffractive processes have been observed in $p\bar{p}$ (UA8, Tevatron) and ep (H1, ZEUS) collisions.

- The contribution of diffractive processes to the ep interaction cross-section has been measured in terms of a diffractive structure function $F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$.

- These measurements were sucessfully interpreted in terms of resolved Pomeron ($I\!P$) model with diffractive parton densities which are dominated by gluons at the starting scale and evolved with DGLAP.
  A Pomeron model with only quarks at starting scale is not able to describe the measurements.

- The many hadronic final state observables are sensitive to the QCD structure of diffraction and provide independent tests of the pomeron structure extracted from $F_2^{D(3)}$.

Kinematics of Diffractive ep scattering



$Q^2 = -q^2$	**photon virtuality**
$x = \frac{Q^2}{2q\cdot p}$	**Bjorken scaling variable**
$W^2 = (p+q)^2$	$\gamma^* p$ **CM energy squared**

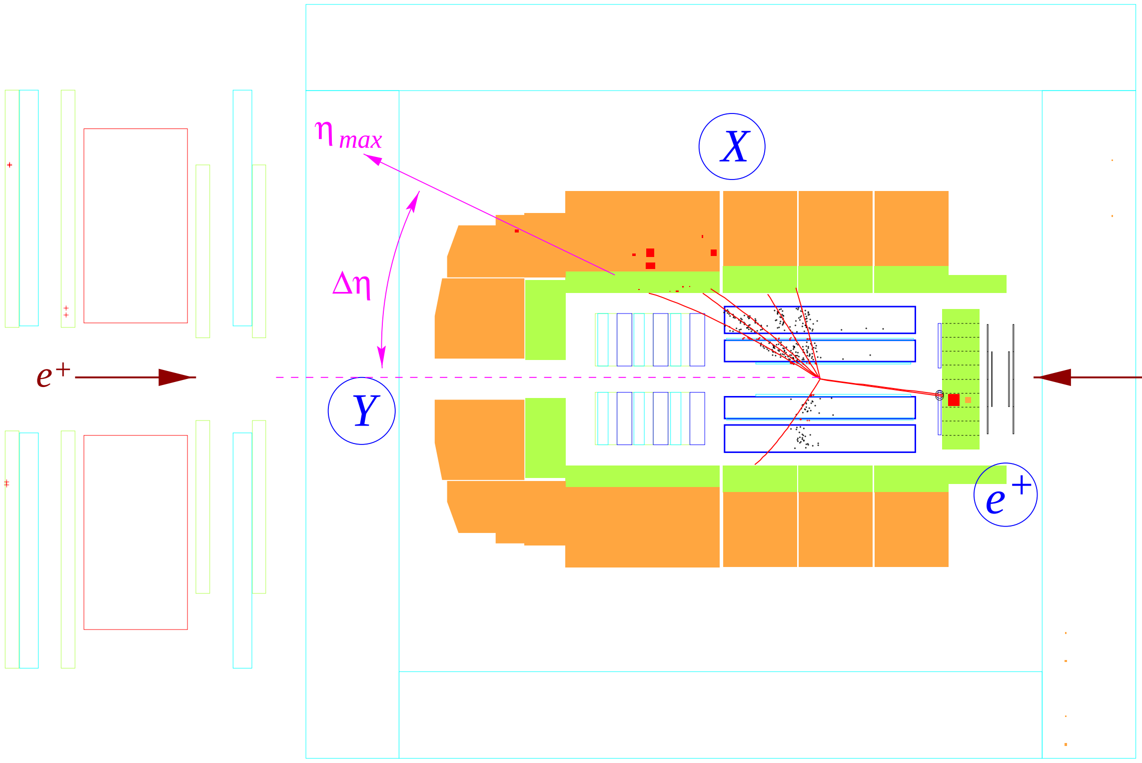
$t = (p - p_Y)^2$	**4-momentum transfer squared**
M_X, (M_Y)	**Inv. mass of system** X (Y)
$\beta = \frac{Q^2}{2q\cdot(p-Y)}$	**fraction of** $I\!P$ **momentum carried by struck quark**
$x_{I\!P} = \frac{q\cdot(p-Y)}{q\cdot p}$	**fraction of** p **momentum transferred to** $I\!P$ $x_{I\!P} \simeq 1 - E_Y/E_p$

$x_{I\!P}\beta = x$

$$\boxed{M_X \ll W\text{, small } M_Y\ (\simeq m_p)\text{, small } |t|\ (\lesssim 1\ GeV^2)}$$

- $Q^2 \approx 0$, $|t| \approx 0$: similar to soft hadron-hadron interactions
- $Q^2 \gg 0$: γ^* probes $I\!P$ structure
- large $|t|$: search for perturbative $I\!P$

Selection of diffractive events



Selection: Leading Proton Tag

- **Leding Proton is measured in very forward detectors**

- **Proton with** $z \simeq E'_p / E_p \gtrsim 0.97$ $(x_{I\!P} \lesssim 0.03)$
  $\Longrightarrow M_Y = M_p$ **(pure single diffraction)**

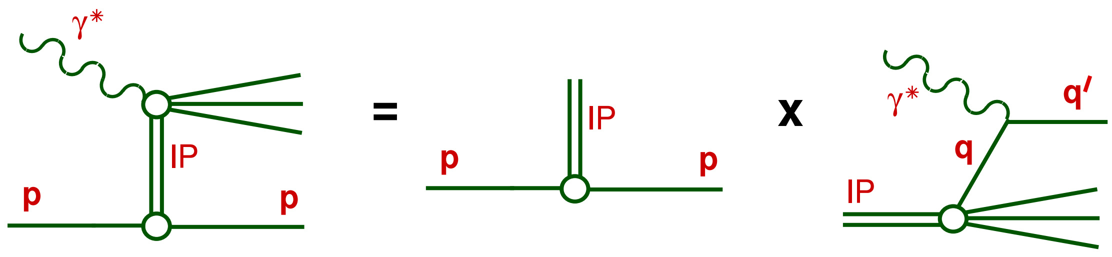
Selection: Large Rapidity Gap Events

No colour field between hadronic subsystems X and Y
$\Longrightarrow$ **no hadronic activity in the forward part of detector**
$\Longrightarrow$ **Large Rapidity Gap** $\Delta\eta \simeq ln(W^2/M_X^2)$
(pseudorapidity $\eta = -ln\ tan\ \theta/2$)

- **Proton is not directly measured**
- $x_{I\!P} \lesssim 0.05$

Models for diffractive hard scattering

- **factorizable models:**
  - Monte-Carlo programs:
    RAPGAP (Jung), POMPYT (Bruni,Ingelman)
  - also Alvero, Collins, Terron, Whitmore;
    Kunzst, Stirling;...
  - flux of spacelike $I\!\!P$ from proton
  - γ^* couples to parton from $I\!\!P$

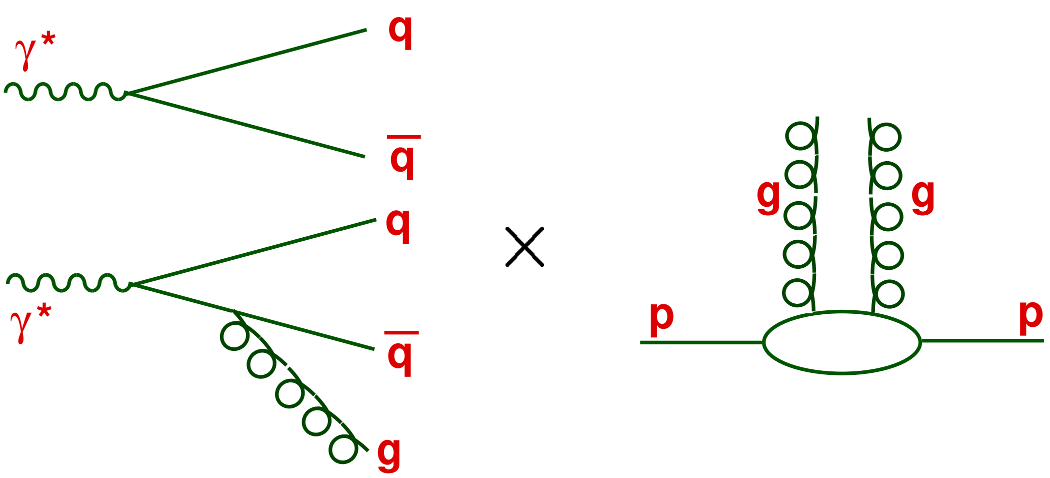


$$F_2^{D(3)}(x_{I\!\!P}, \beta, Q^2) \;\propto\; f_{I\!\!P/p}(x_{I\!\!P}) \;\times\; F_2^{I\!\!P}(\beta, Q^2)$$

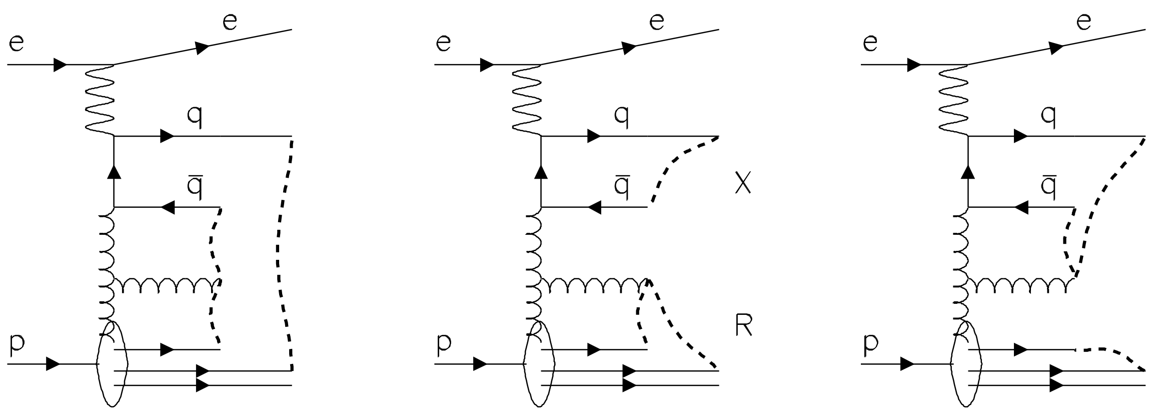
  - parton densities in $I\!\!P$ can be taken from the QCD fits to $F_2^{D(3)}$ data:
    * "leading gluon" distribution (fits 2 and 3)
    * "quark-based" distribution (fit 1)

    $\Longrightarrow$ test universality of parton distributions

- **2-gluon exchange models:**
  - Monte-Carlo programs:
    RIDI (Ryskin, Solano), RAPGAP
  - Nikolaev, Zakharov, Genovese, Ryskin, Diehl, Bartels, Ellis, Kowalski, Wüsthoff, Lotter, Bialas, Peschanski,..
  - $q\bar{q}$, $q\bar{q}g$ production vias gg-exchange/BFKL ladder

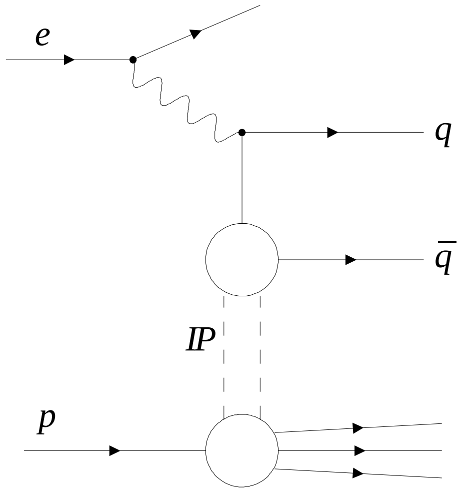


- **Soft Colour Interactions:**
  - Monte-Carlo programs:
    LEPTO (Edin, Ingelman, Rathsman)
  - Alternative model without $I\!P$ concept
  - Start from standard DIS (dominantly BGF at low x)
  - Colour rearrangement on the hadronic final states
  - Attempt of unifying standard DIS and diffraction



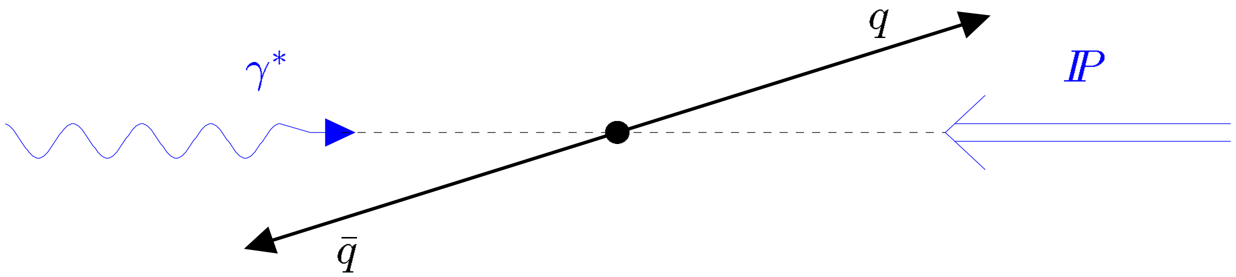
Expectations for hadronic final states

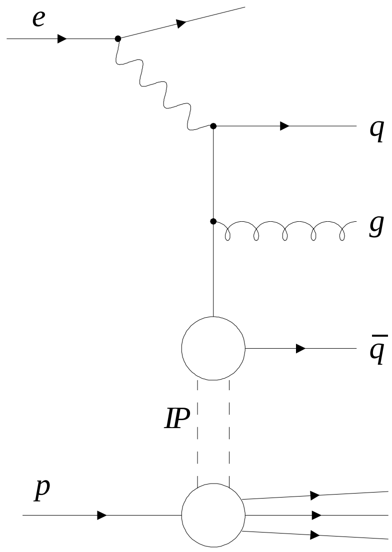
Quark-dominated $I\!\!P$



Lowest order $\mathcal{O}(\alpha_{\rm em})$

- Aligned-jet (AJM) configuration
- Triplet-antitriplet system with low p_T
- Small p_T from intrinsic k_T of quarks
- Some p_T from hadronization and particle decays

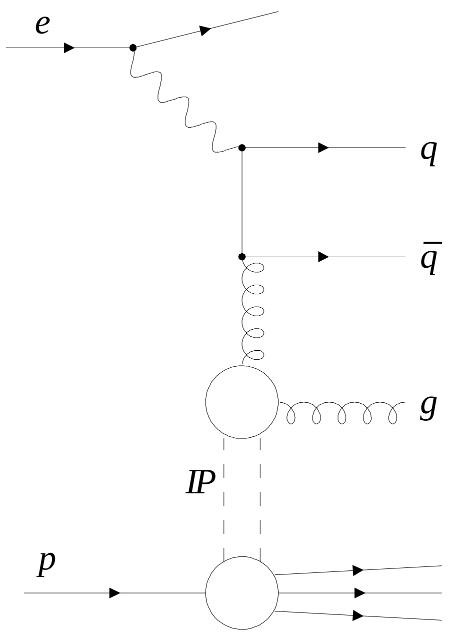




Higher order $\mathcal{O}(\alpha_{\rm em}\alpha_s)$ — QCD-C

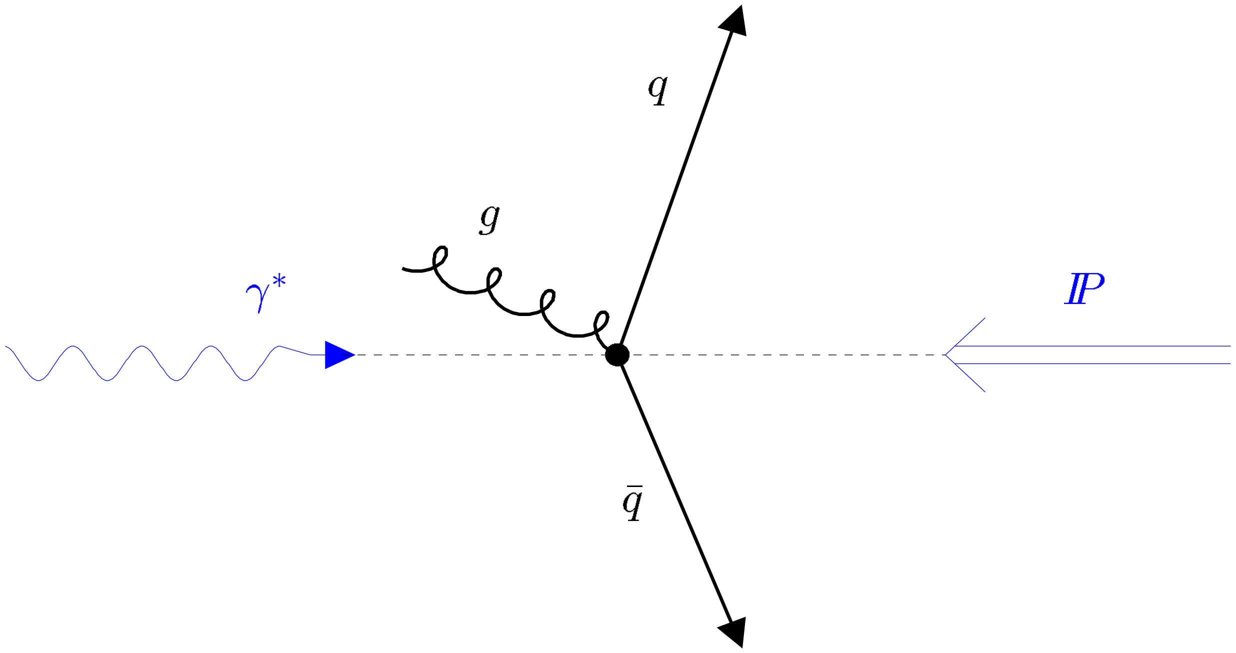
- Three-parton topology
- Significant p_T

Gluon-dominated $I\!P$

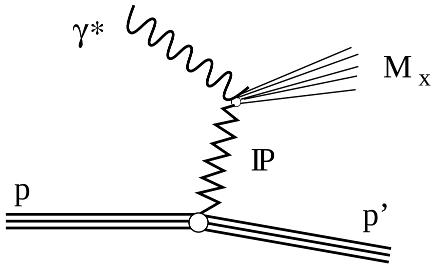


Lowest order $\mathcal{O}(\alpha_{\rm em}\alpha_{\rm s})$ — BGF

- BGF: q and $\bar{q}$ not aligned along $\gamma^* I\!P$ axis $\rightarrow$ large p_T
- Higher parton multiplicity in final state
- Additional octet-octet colour field



Global Event Shapes: Definition of variables

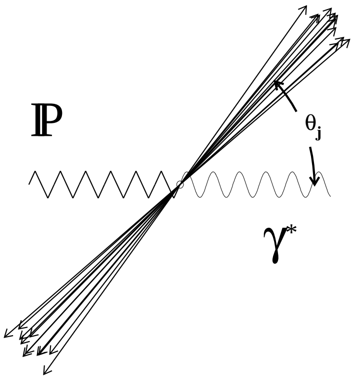


- Thrust

$$T = \max \frac{\Sigma_i \left|\mathbf{n} \cdot \mathbf{p}_i\right|}{\Sigma_i \left|\mathbf{p}_i\right|}$$

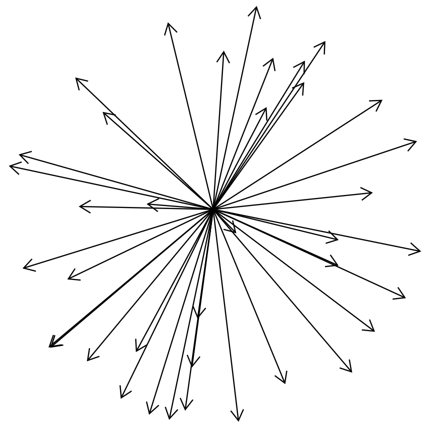
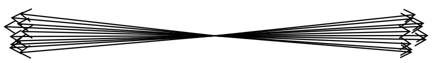
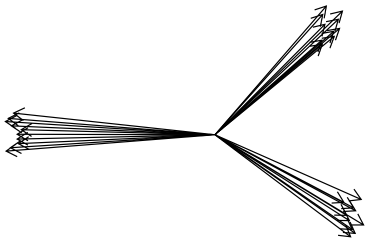
- Sphericity

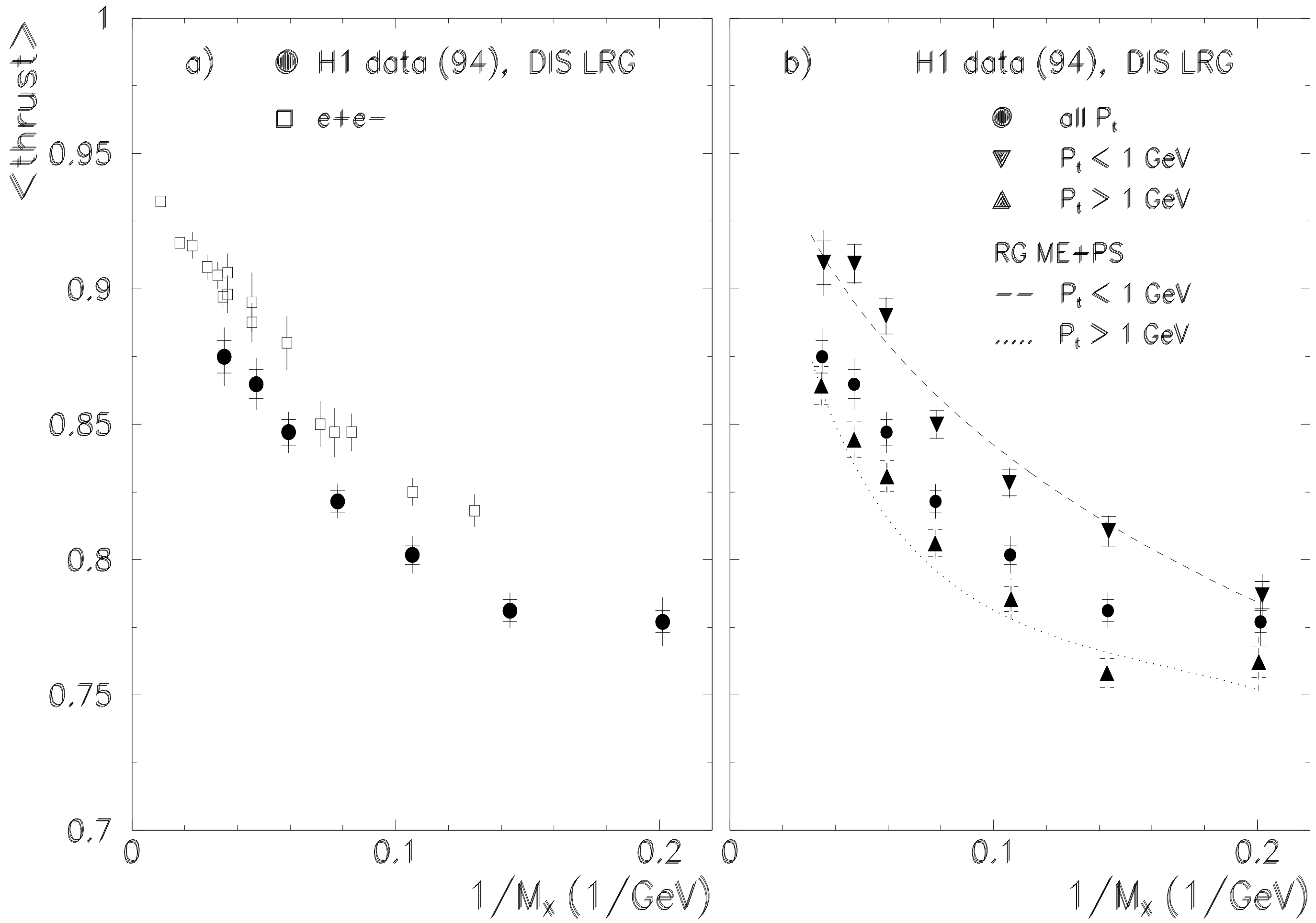
$$S^{\alpha\beta} = \frac{\Sigma_i \, p_i^\alpha p_i^\beta}{\Sigma_i \left|\mathbf{p_i}\right|^2} \qquad \alpha, \beta \;\epsilon\; x, y, z$$



eigenvalues of $S^{\alpha\beta}$: $\quad \lambda_1 \geq \lambda_2 \geq \lambda_3$

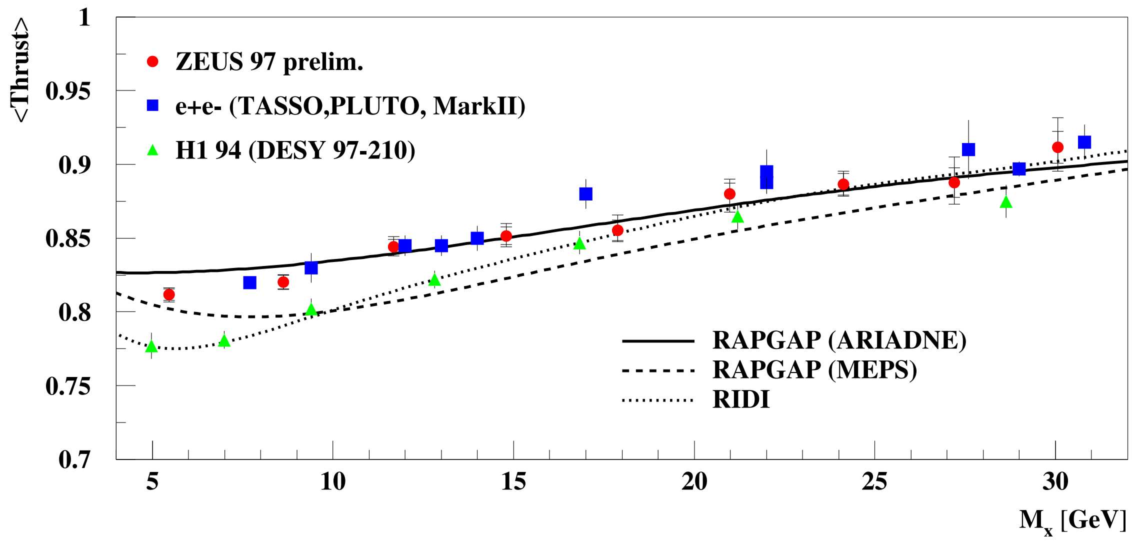
$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

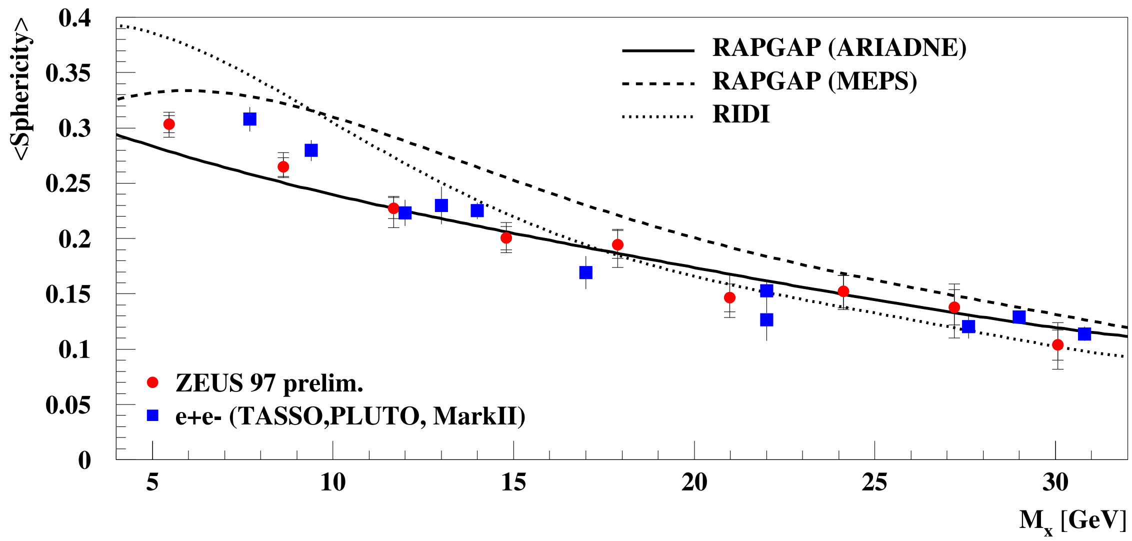
Particle Trajectories	Thrust	Sphericity
	$\to \frac{1}{2}$	$\to 1$
	$\to 1$	$\to 0$
	$\simeq \frac{3}{4}$	$\simeq \frac{1}{2}$



H1: large rapidity gap
$10 < Q^2 < 100\ GeV^2,\ y < 0.5$
$x_{I\!P} < 0.05,\ 4 < M_X < 36\ GeV$
$|t| < 1\ GeV^2,\ M_Y < 1.6\ GeV$

- $\langle T \rangle$ increases with M_X $\Longrightarrow$ increasing of back-to-back correlations, dominant two jet topology of the final state
- For fixed M_X average thrust is lower for larger P_t (w.r.t. incoming proton direction) $\Longrightarrow$ ≥ 3 parton configuration
- $\langle T \rangle_{LRG} < \langle T \rangle_{ee}$ $\Longrightarrow$ $q\bar{q}$ states with limited p_T hadronization are not sufficient: higher parton multiplicities are more important in DIS LRG events than in e^+e^-
- RAPGAP–factorizable Pomeron model, with gluon dominated $I\!P$ parton densities from H1 fits to $F_2^{D(3)}$ data, gives good description of $\langle T \rangle$.





ZEUS: leading proton

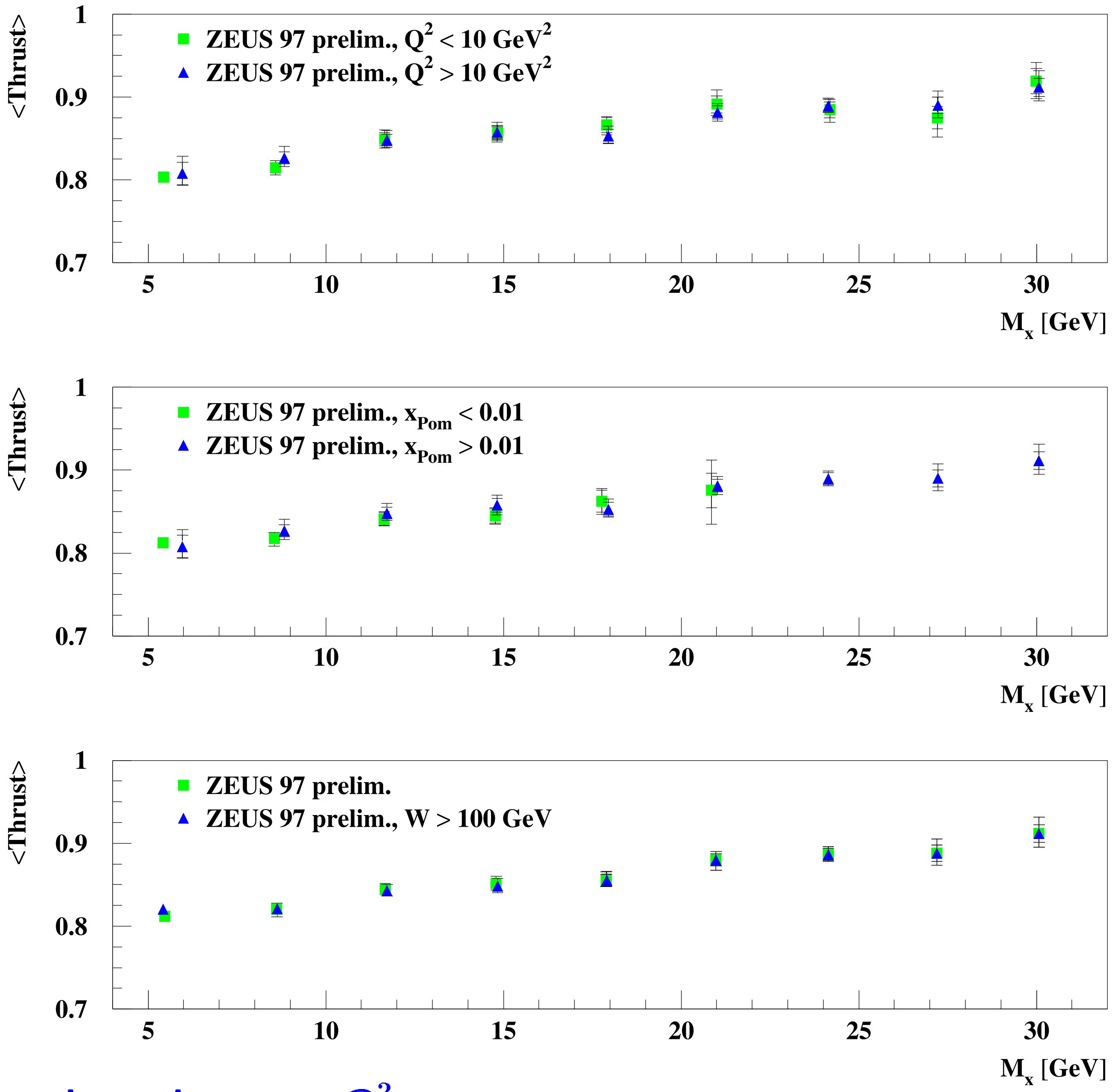
$4 < Q^2 < 90\ GeV^2,\ 0.03 < y < 0.95$

$0.0003 < x_{I\!P} < 0.03,\ 4 < M_X < 35\ GeV$

- ZEUS measurement consistent with e^+e^-
- H1 sees less collimated events than ZEUS (need more gluons) $\Longrightarrow$ discrepancy between experiments !
  (might be due to different event selection/kinematics: H1-Large rapidity gap, ZEUS- leading proton)

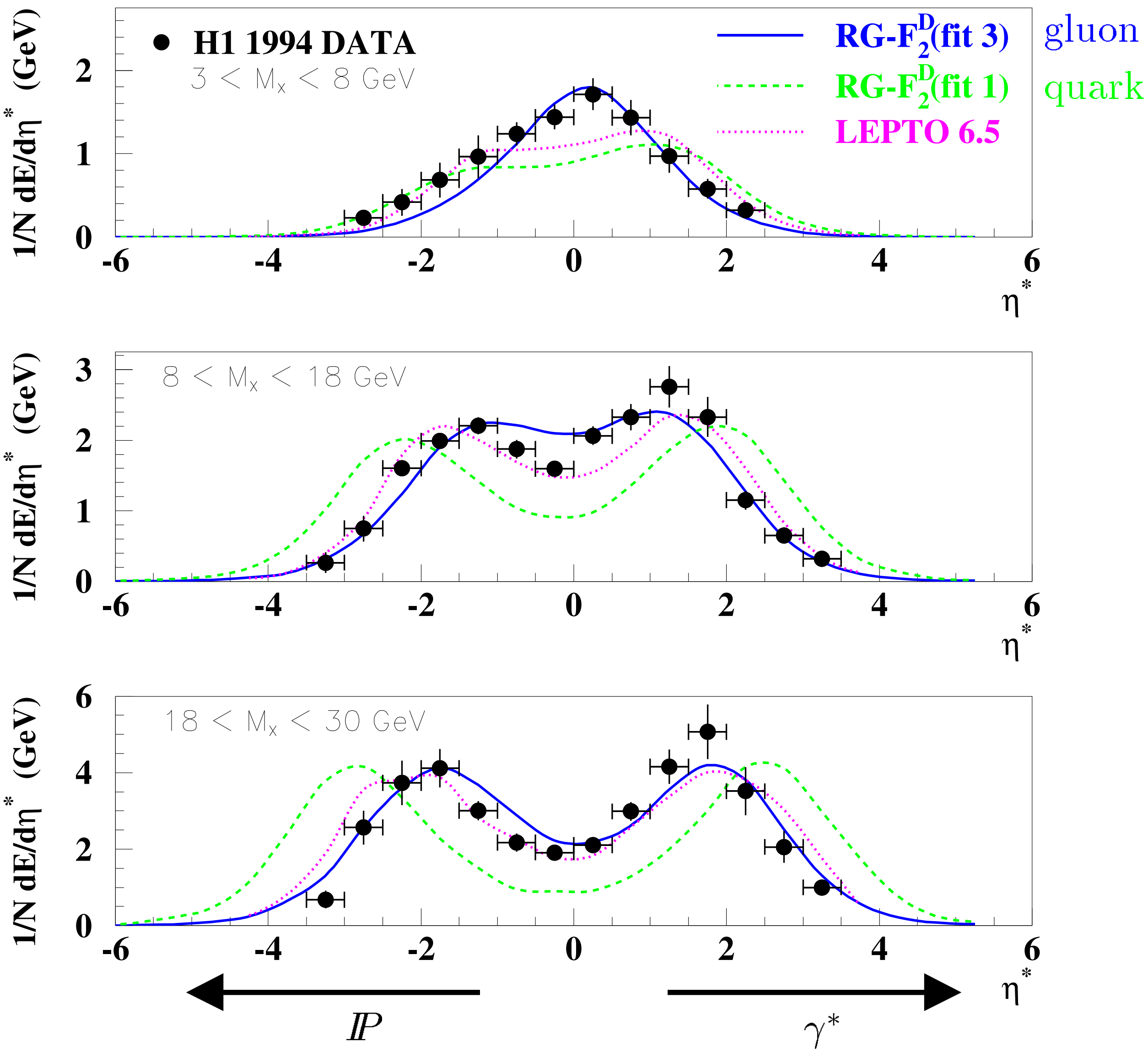
- RIDI fails at low M_X, but closer to H1
- RAPGAP (Ariadne) gives best description. Difference between ARIADNE and MEPS $\Longrightarrow$ Fragmentation mechanism is important

Global Event Shape Q^2, $x_{I\!P}$ and W dependence



- no dependence on Q^2
- no dependence on $x_{I\!P}$
- no influence from low W contribution
- (same holds for Sphericity)

Energy flow in $\gamma^* I\!P$ CMS– $1/N\ dE/d\eta^*$



H1: large rapidity gap

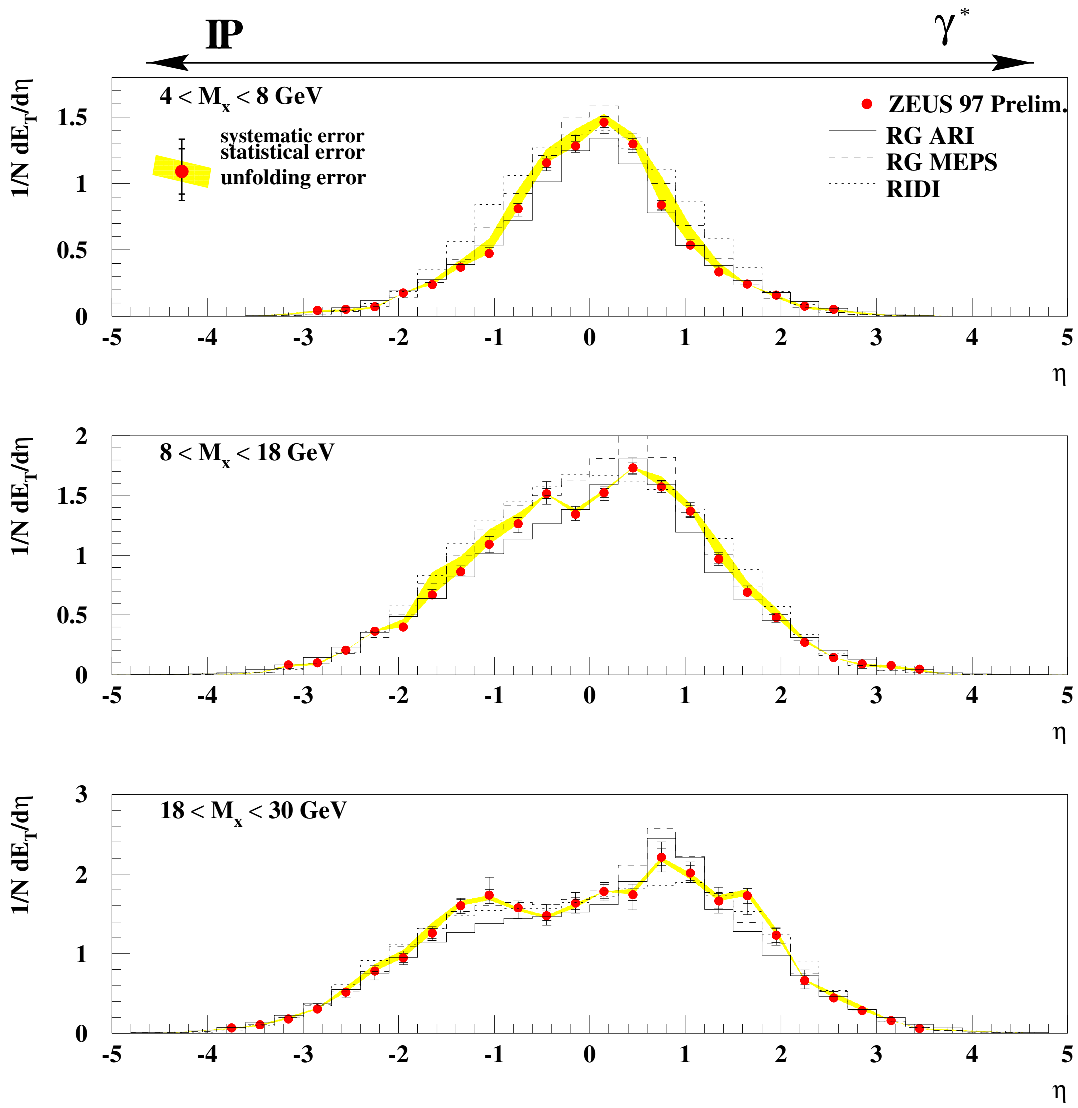
$7.5 < Q^2 < 100\ GeV^2,\ 0.05 < y < 0.6$

$x_{I\!P} < 0.025,\ 3 < M_X < 30\ GeV$

$|t| < 1\ GeV^2,\ M_Y < 1.6\ GeV$

- **General agreement between H1 and ZEUS-leading proton data**
- **"Two jet" structure develops at higher M_X**
- **Slight enhancement of energy in the current hemisphere**
- **Well described by RAPGAP (gluon), but not by RAPGAP (quark)**
  $\Longrightarrow$ **large contribution from gluons !**

Transverse Energy Flow $1/N \; dE_T/d\eta^*$



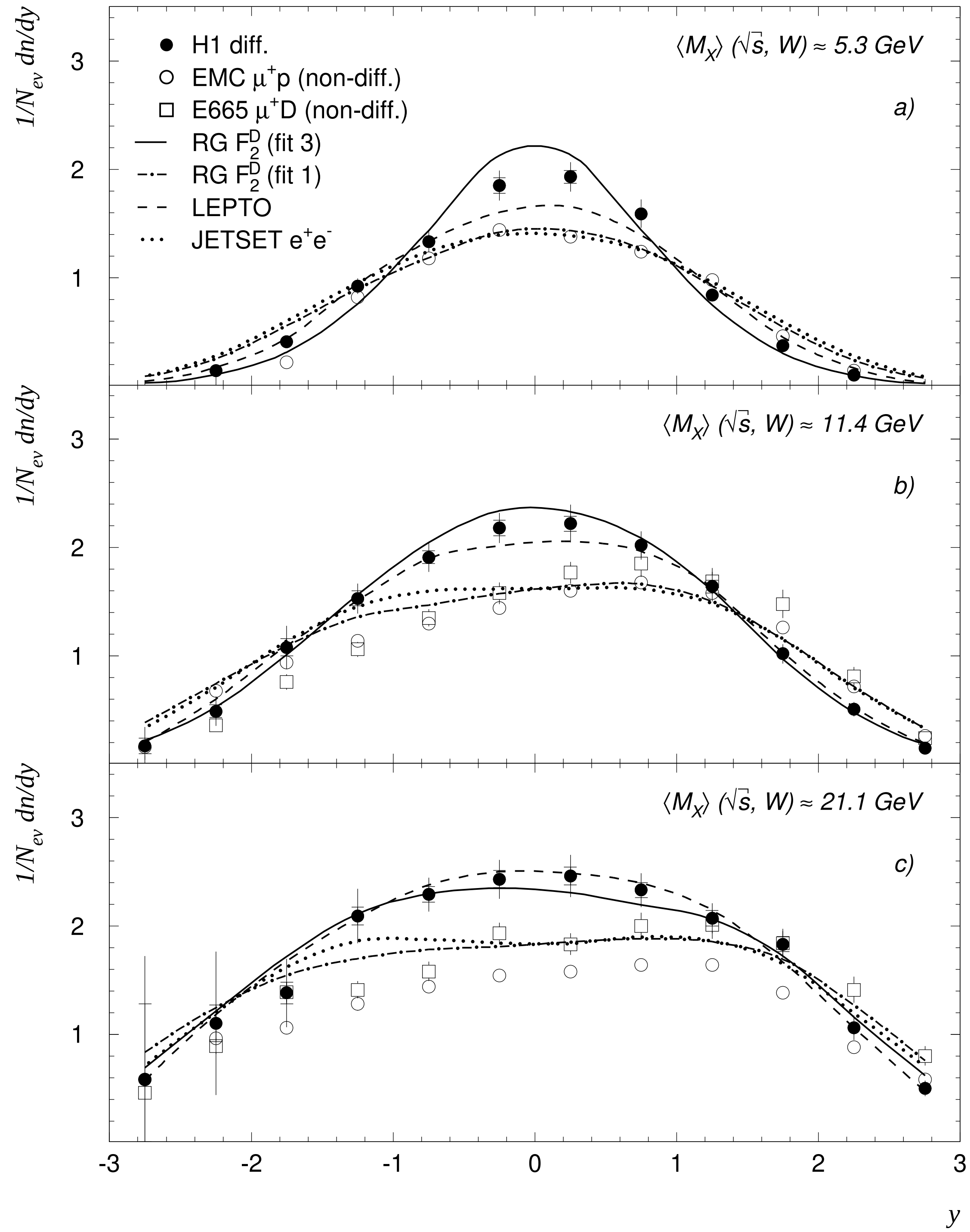
ZEUS: leading proton

$4 < Q^2 < 90 \; GeV^2, \; 0.03 < y < 0.95$

$0.0003 x_{I\!P} < 0.03, \; 4 < M_X < 30 \; GeV$

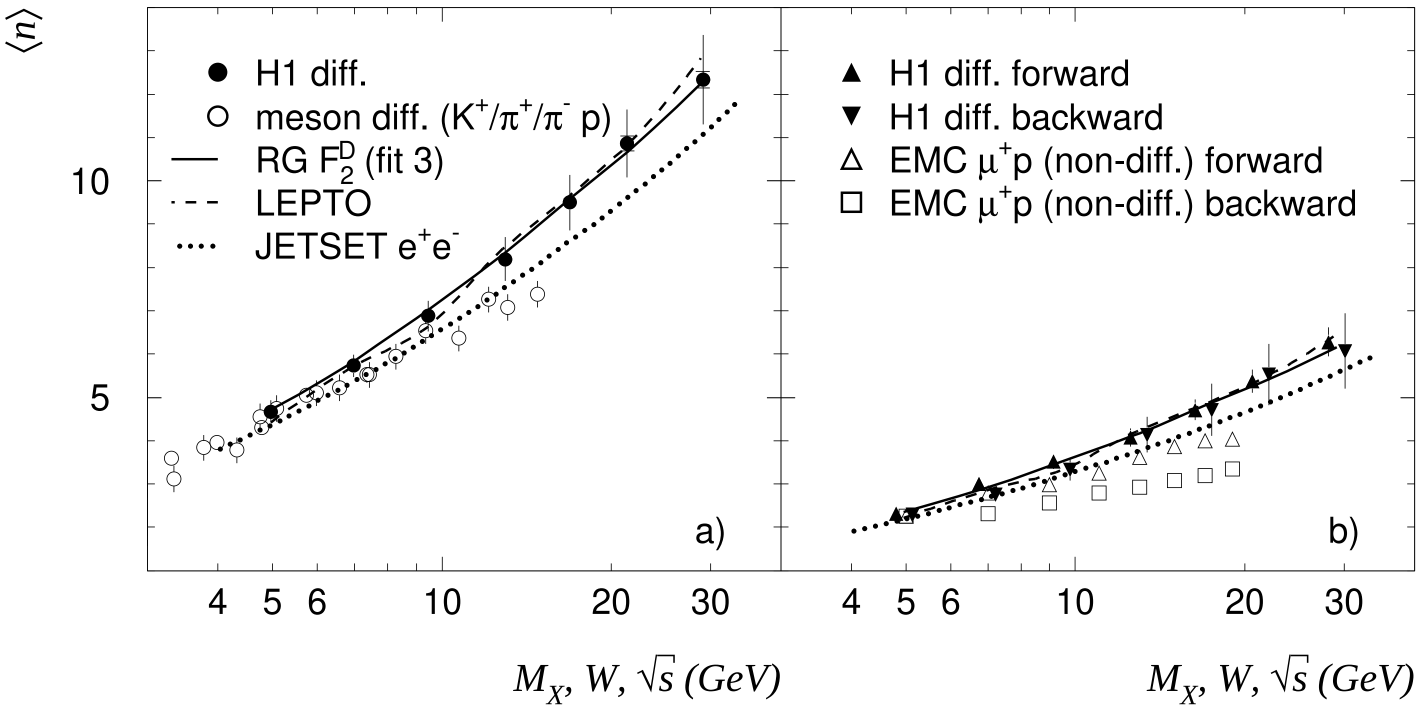
- "Two jet" structure is visible at higher M_X
- Enhancement of transverse energy in the current hemisphere (γ^*-side)

Charged Particle Rapidity Distribution



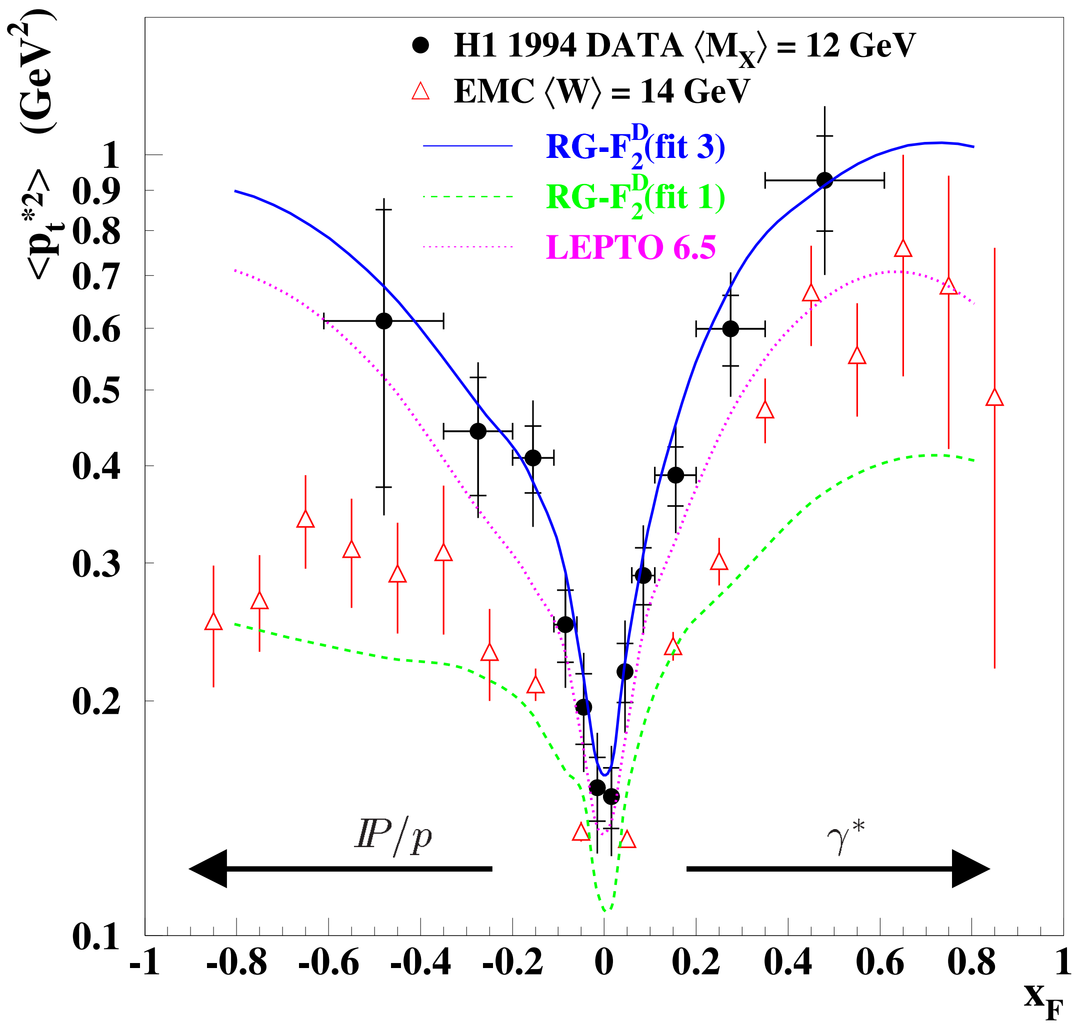
- **In central region particle density is larger than in μN interactions at $W^2 \approx M_X^2$**
- **Symmetrical about $y = 0$**
- **RAPGAP with a quark based $I\!P$ predicts the rapidity spectra close to e^+e^- and $\mu N \Longrightarrow$ $q\bar{q}$+gluon radiation is not suffieicent**
- **RAPGAP with hard gluon dominated $I\!P$ and LEPTO describe the rapidity spectra (but deviations in the lowest M_X bin).**

Charged particle multiplicity



- **Average multiplicity $\langle n \rangle$ rises with M_X (W, $\sqrt{s}$)**
- **At low masses ($M_X < 10\ GeV$) similar to e^+e^- and meson diffraction $\Longrightarrow$**
  hadronisation of single string between the quark and antiquark
- **At higher masses ($M_X > 10\ GeV$) $\langle n \rangle$ rises faster than in e^+e^- and meson diffraction $\Longrightarrow$**
  contribution from more complex ($q\bar{q}g$) parton configuration
- **Forward-backward symmetry (unlike the μp data)**

"Seagull plot" ($\langle p_T^{*2} \rangle$ vs x_F)

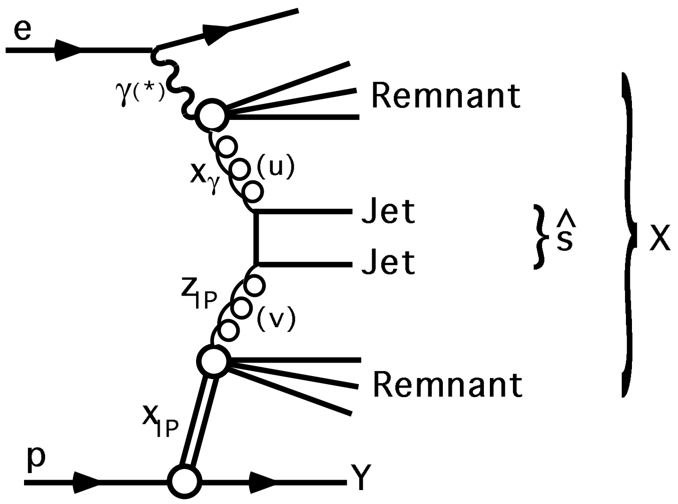


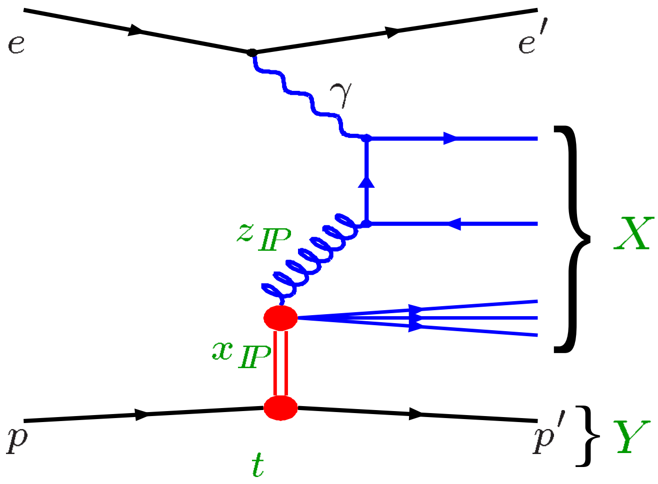
- $\langle p_T^{*2} \rangle$ is higher in diffractive data than in $\gamma^* p$
  $\Longrightarrow$ Larger contribution from scattering from gluons, increasing role of BGF processes
- Symmetry between target and current hemispheres $\Longrightarrow$
  in non-diffractive $\gamma^* p$ the high p_T radiation is suppressed from extended p remnant
  in diffractive $\gamma^* p$– more point-like partonic system in the target fragmentation region
- Good agreement between H1 and ZEUS

- Well described by RAPGAP (gluonic $I\!P$), LEPTO and RIDI
- Predictions of RAPGAP (quark based $I\!P$) are too low for all x_F

Charm and high p_T Jet production

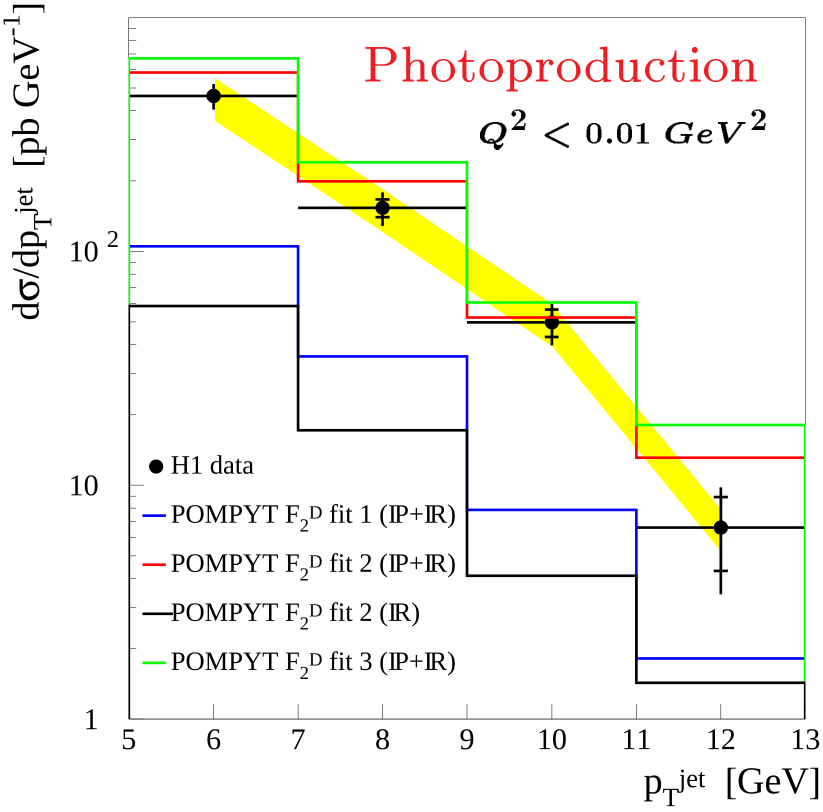
- **Ideal test of underlying dynamics of diffaction:**
  - **Cross-sections are calculable.**
  - **Production mechanism sensitive to the gluon content.**





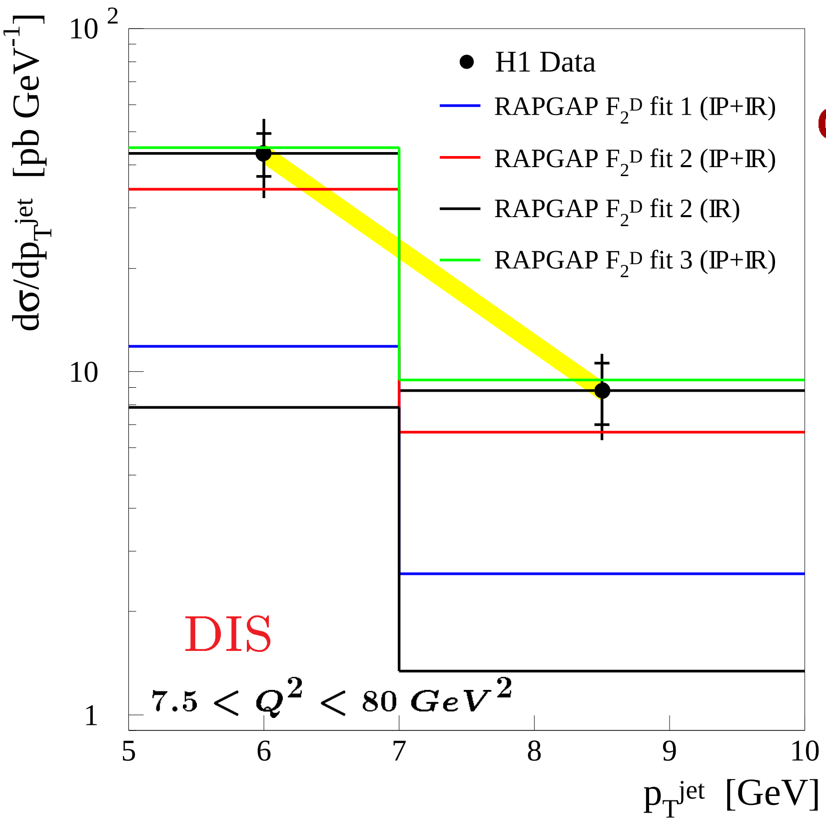
- **2-Jets are reconstructed in the central detectors.**
- **Jets are identified as a collimated energy deposited in $\eta - \phi$ space, within the cone of $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 1$.**
- **p_T^{jet} is defined relative to γ^* axis in the rest frame of X.**
- **Measurements are made both in photoproduction $Q^2 \simeq 0$ and in DIS regimes**
- **In photoproduction regime distinguish between the 'direct' ($x_\gamma = 1$) and 'resolved' ($x_\gamma < 1$) processes: ($x_\gamma -$ fraction of γ momenta involved in the hard interaction).**

p_T^{jet}-spectra



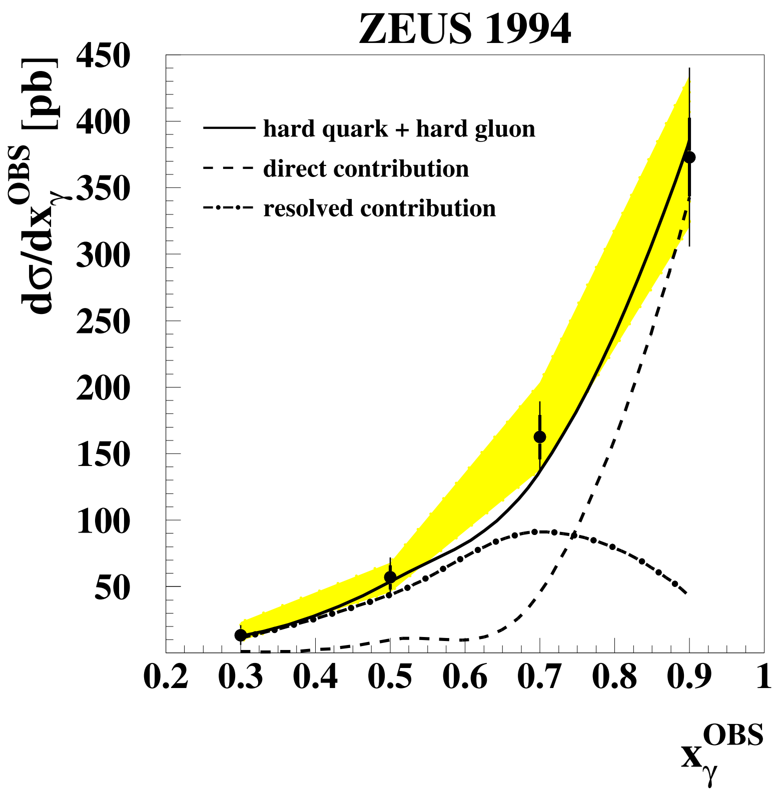
Data reasonably well described by gluon dominated $I\!P$

Quark dominated $I\!P$ is too low by a factor ~ 5

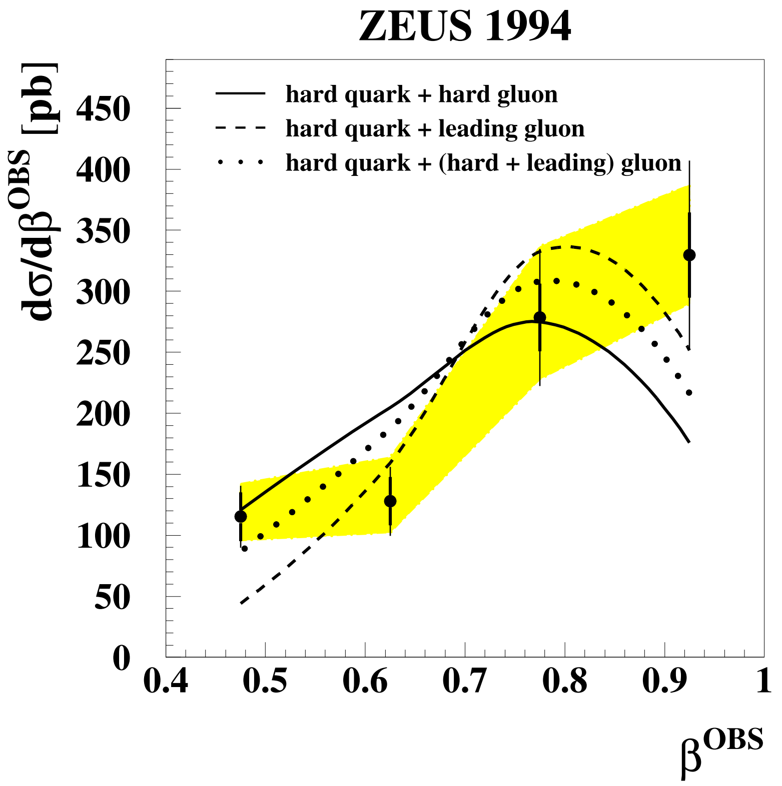


Contribution of sub-leading exchange $\sim 15\%$

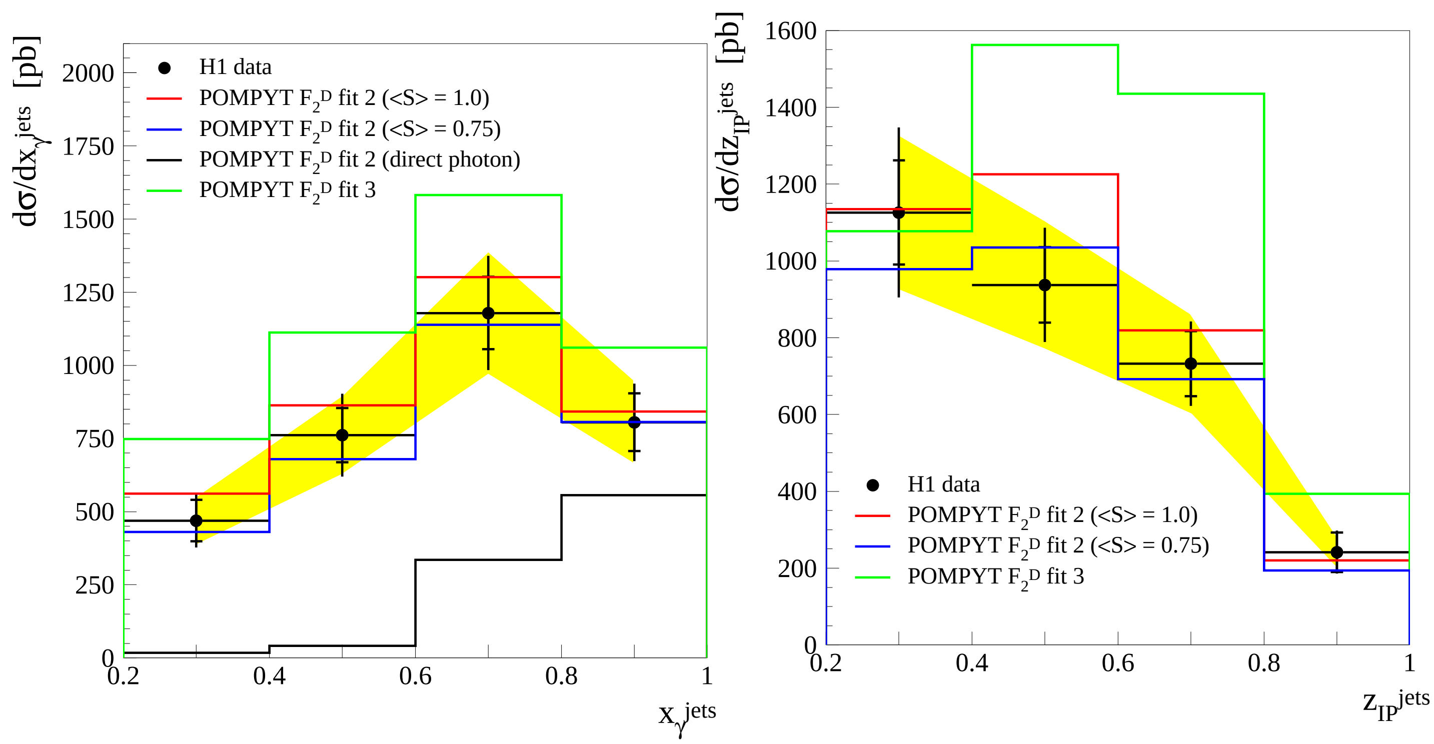
$\underline{x_\gamma^{jets}, z_{I\!P}^{jets}}$: fraction of γ, $I\!P$ momentum transfered to the system X (i.e. entering the hard scattering)



ZEUS: Large rapidity gap: $0.001 < x_{I\!P} < 0.03$, $p_T^{jet} > 6\ GeV$



- Both Direct ($x_\gamma = 1$) and Resolved ($x_\gamma < 1$) photon contributions observed
- Gluon dominated $I\!P$ gives good descrpition of ZEUS data



H1: Large rapidity gap: $x_{I\!P} < 0.05$, $p_T^{jet} > 5\ GeV$

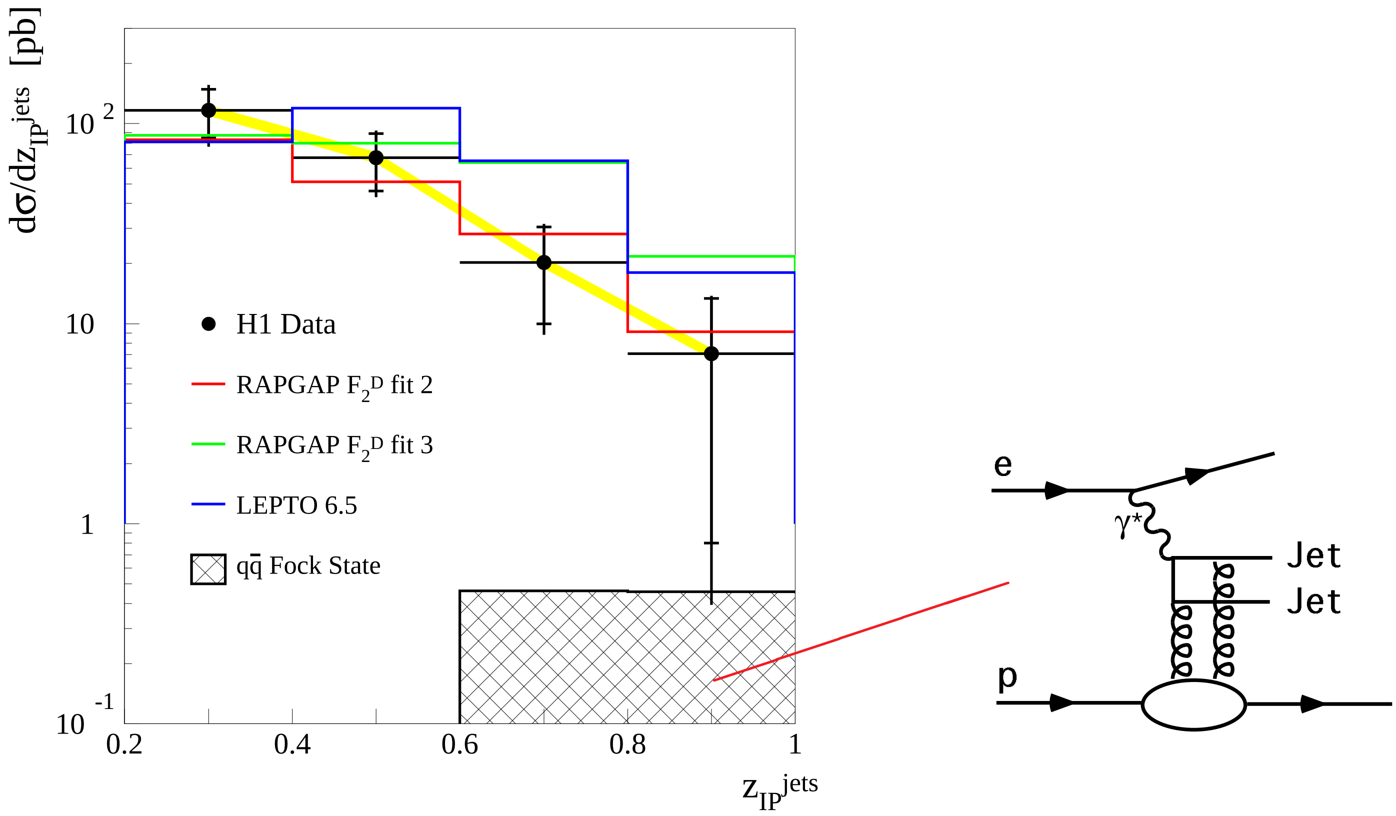
- MC predicts too high cross-section for H1
- H1 and ZEUS- different kinematic ranges (H1: lower p_T, higher $x_{I\!P}$ $\Longrightarrow$ lower x_γ, more resolved photon contribution)
- In diffractive resolved photoproduction additional interactions between the extended beam remnants would be expected to destroy rapidity gaps $\Longrightarrow$ breaking of diffractive factorization.

$$d\sigma^D_{true}(ep \to epX) < d\sigma^D(ep \to epX)$$

$d\sigma^D_{true} = \langle S \rangle \cdot d\sigma^D$, where $\langle S \rangle$ – rapidity gap survival probability, $\langle S \rangle \leq 1$

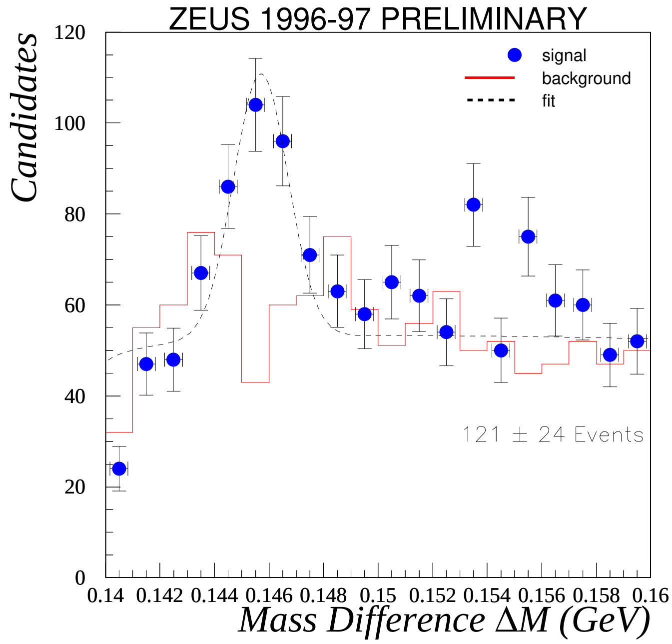
- To estimate: apply a constant weight $\langle S \rangle$ to the MC events with $x_\gamma < 0.8$.
- $\langle S \rangle$ at the order of 0.4–0.8 gives reasonable description of data (~ 0.1 at Tevatron !).

$z_{I\!P}^{jets}$ distribution in DIS



- Gluon dominated $I\!P$ gives good description
- In 2 gluon exchange model the $q\bar{q}$ state alone cannot describe data $\Longrightarrow$ $q\bar{q}g$ states are required
- No evidence for a large 'super-hard $I\!P$' contribution ($z_{I\!P} = 1$)

Open Charm Production

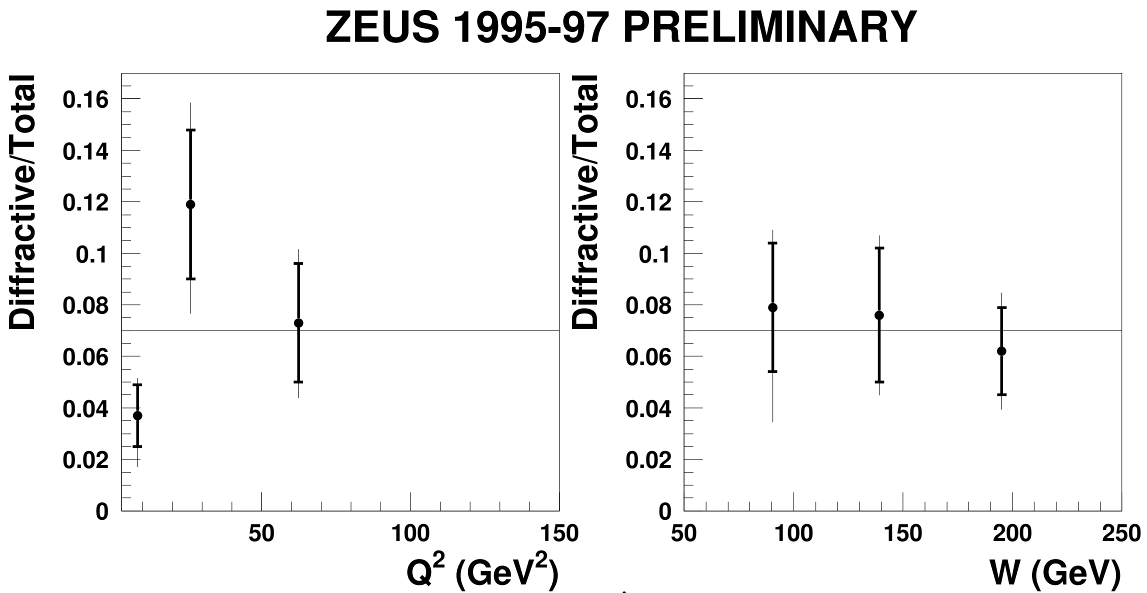


$$D^{*\pm} \longrightarrow D^0\pi^{\pm}$$
$\longrightarrow$ $(K\pi)\pi^{\pm}$ (bf=2.63%)
$\longrightarrow$ $(K\pi\pi\pi)\pi^{\pm}$ (bf=5.19%)

Ratio of diffractive $D^{*\pm}$ to total $D^{*\pm}$ production

$$\boxed{\text{Ratio } (D^* \to K\pi\pi) = 7.0 \pm 1.3^{+1.7}_{-1.8}\%}$$

$$\boxed{\text{Ratio } (D^* \to K4\pi) = 8.9 \pm 2.4^{+1.7}_{-1.6}\%}$$



- Ratio of diffractive to total D^* production is consistent with ratio of diffractive to inclusive DIS ($\sim 10\%$)

- no significant Q^2 or W dependence

$D^* \to K4\pi$

(ZEUS preliminary)

$1 < Q^2 < 480\ GeV^2$, $0.04 < y < 0.7$

$2 < p_T(D^{*\pm}) < 9\ GeV$, $|\eta(D^{*\pm})| < 1.5$

$x_{I\!P} < 0.015$, $\beta < 0.8$

$N_{D^*} = 121 \pm 24$

$$\boxed{\sigma = 526 \pm 110^{+200}_{-240}\ pb}$$

$D^* \to K\pi\pi$

(ZEUS preliminary)

$3 < Q^2 < 150\ GeV^2$, $0.02 < y < 0.7$

$p_T(D^{*\pm}) > 1.5\ GeV$, $|\eta(D^{*\pm})| < 1.5$

$0.002 < x_{I\!P} < 0.012$, $\beta < 0.8$

$N_{D^*} = 59 \pm 9$

$$\boxed{\sigma = 379 \pm 66^{+99}_{-140}\ pb}$$

interpolate $D^* \to K4\pi$ to this kinematic region:

$$\boxed{\sigma = 398 \pm 83^{+154}_{-180}\ pb}$$

ZEUS: good agreement between different decay channels !

$D^* \to K\pi\pi$

(H1 preliminary)

$2 < Q^2 < 100\ GeV^2$, $0.05 < y < 0.7$

$p_T(D^*) > 2.\ GeV$, $|\eta(D^*)| < 1.5$

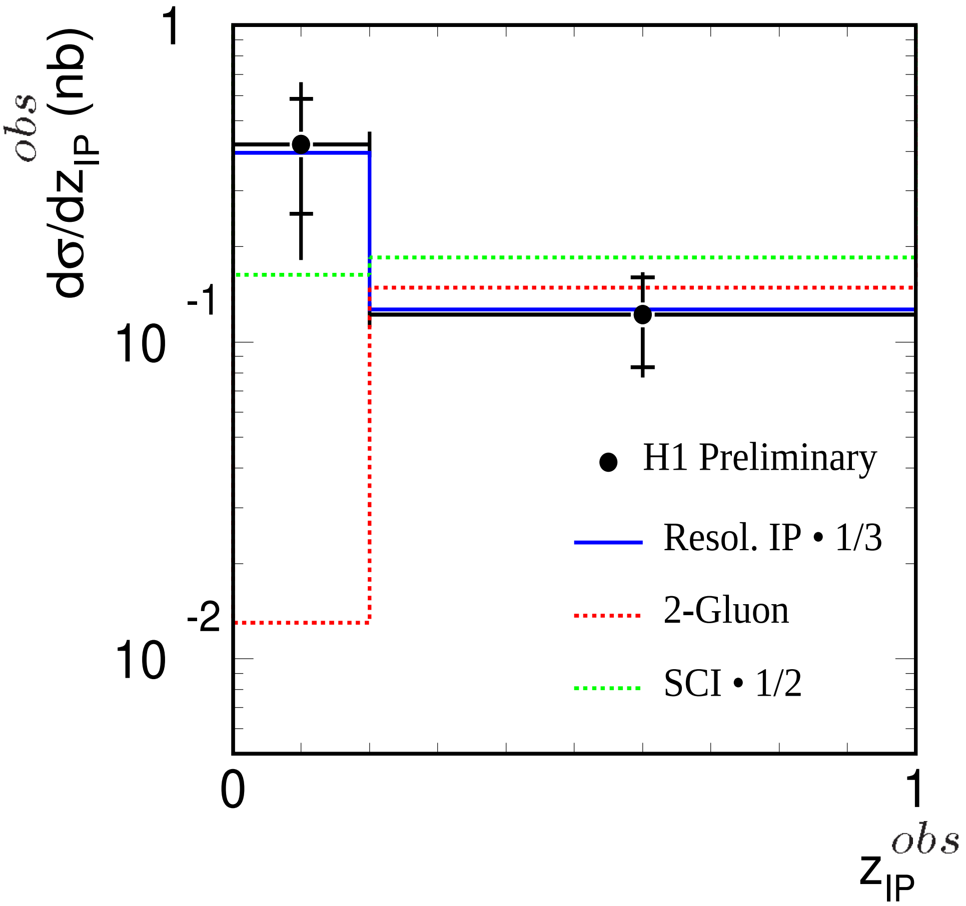
$x_{I\!P} < 0.04$, $M_Y < 1.6\ GeV$

$|t| < 1\ GeV^2$

$N_{D^*} = 38 \pm 10$

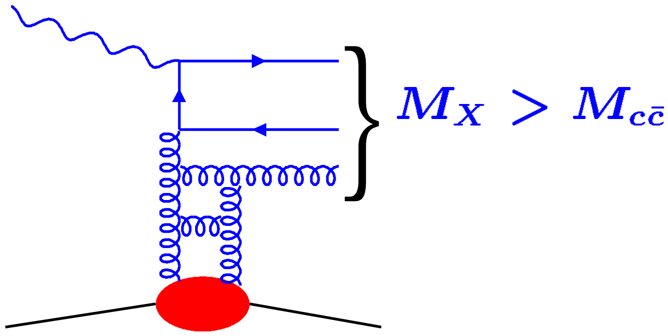
$$\boxed{\sigma = 154 \pm 40 \pm 35\ pb}$$

Differential cross section $d\sigma/dz_{I\!P}^{obs}$ (H1)



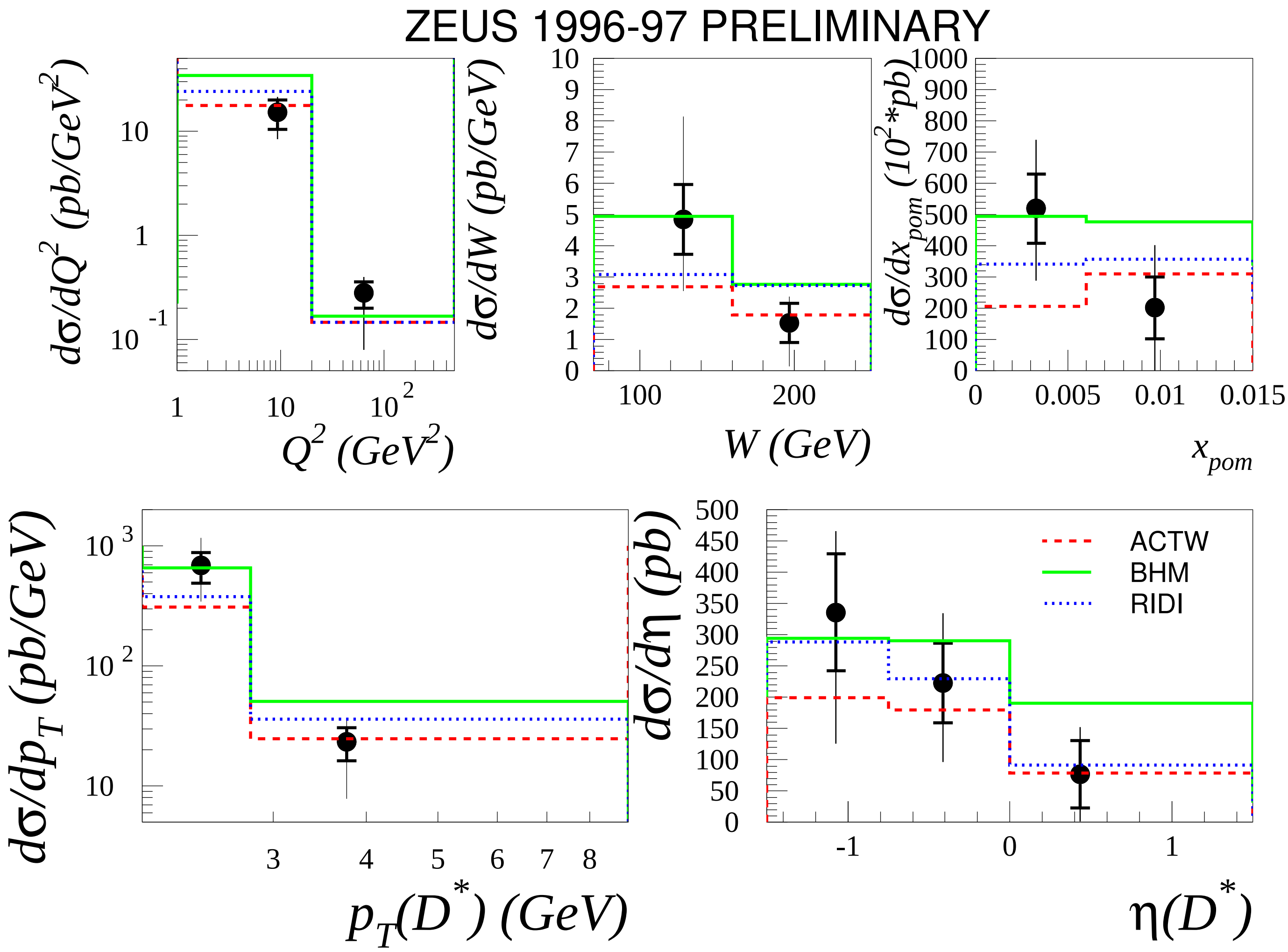
$$z_{I\!P}^{obs} = \beta \cdot \left(1 + \frac{\hat{s}}{Q^2}\right) = \frac{(M_{c\bar{c}}^2 + Q^2)}{(M_X^2 + Q^2)}$$

- **The large fraction of charm production at low $z_{I\!P}^{obs}$ (resolved $I\!P$)**
- **The 2-gluons model with only $c\bar{c}$ configuration is disfavoured**
  $\longrightarrow$ **higher order contributions (e.g. gluons) are required**



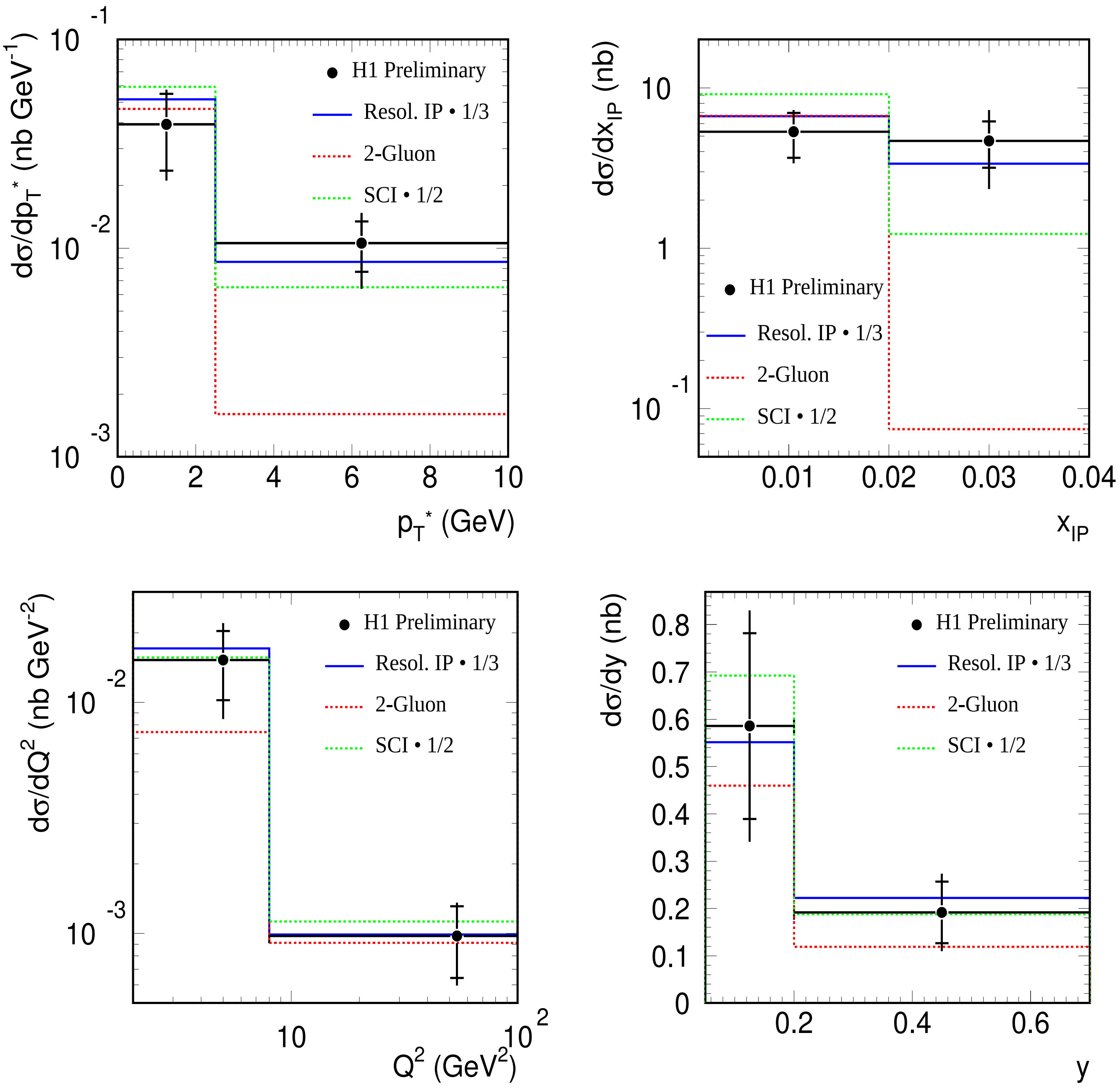
Differential cross sections– $D^* \to K4\pi$

(ZEUS)



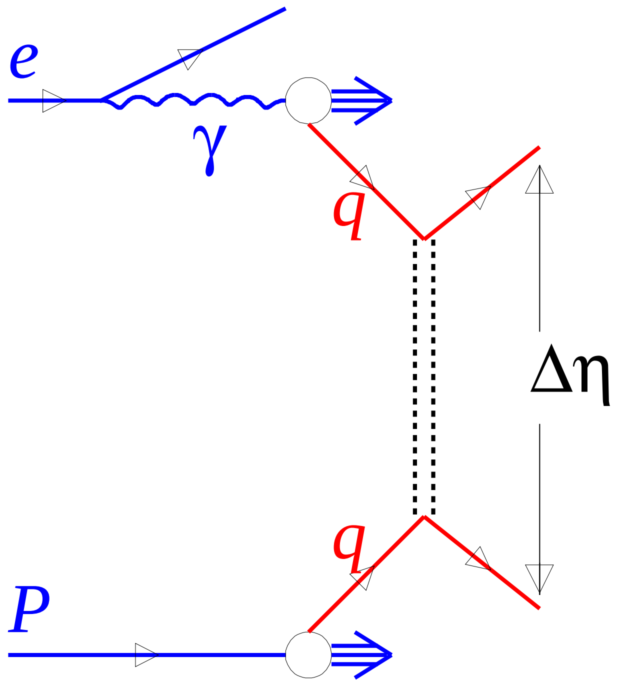
- **Models:**
  - **ACTW (Alvero, Collins, Terron, Whitmore) – gluon dominated resolved $I\!P$ model**
  - **BHM (Buchmüller, Hebecker, McDermott) – Semi-classical model**
  - **RIDI (Ryskin) – pQCD model with higher order corrections**
- **Agreement in normalization $\Longrightarrow$ $I\!P$ is gluon dominated object**
- **Similar conclusions are for differential cross-sections for $D^* \to K\pi\pi$ ZEUS measurement**

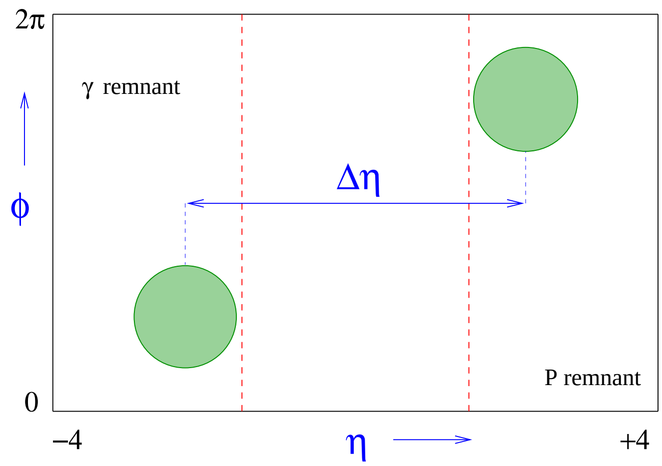
Differential cross sections: $D^* \rightarrow K\pi\pi$ (H1)



- Shape of distributions agree well with resolved $I\!P$ model.
- 2-gluon model ($q\bar{q}$) fails in high p_T, high $x_{I\!P}$ (M_X) range
  $\longrightarrow$ need $q\bar{q}g$ states !
- Resolved $I\!P$ and SCI models fail in normalization (factor 2-3 !)
- Parton densities from $F_2^{D(3)}$ do not describe open charm
  $\Longrightarrow$ in contrast to other H1 measurements !
- Disagreement between H1 and ZEUS results !
- large uncertainties of g densities in $I\!P$?
  breaking of factorization ?

Rapidity gap between jets in photoproduction

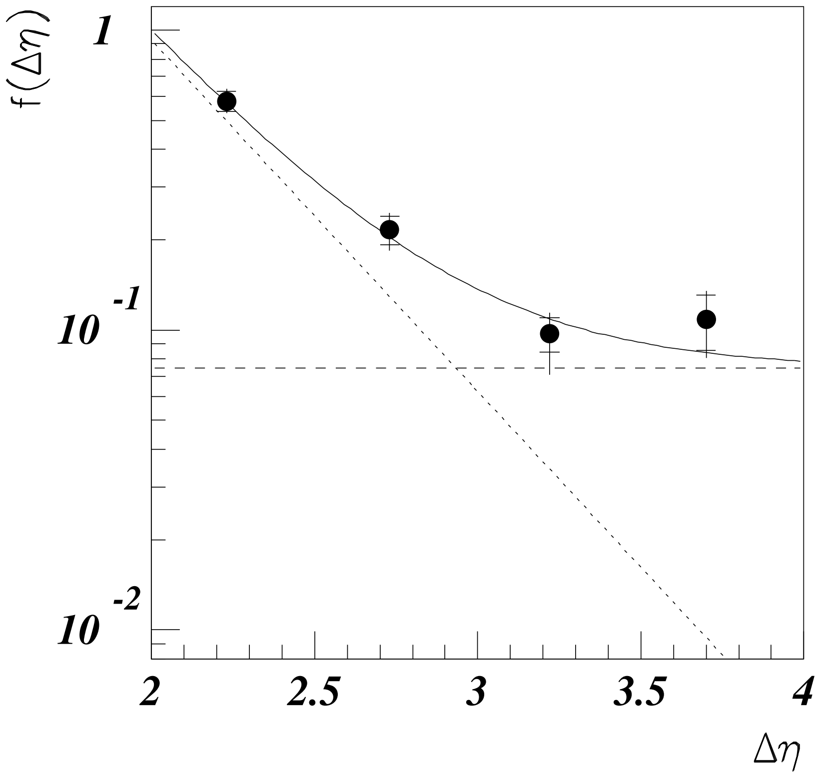




- Phase space is restricted to the region where QCD is applicable (square of the four momentum transfer $|t|$ is large)
- Elastic parton–parton scattering is calculated with LLA of BFKL (Mueller & Tang)

$$\frac{d\hat{\sigma}}{dt} = (\alpha_s C_F)^4 \frac{2\pi^3}{t^2} \frac{e^{2w_0 Y}}{(7\alpha_S N_c \zeta(3) Y)^3}, \qquad w_0 = N_c\ 4\ ln\ 2 \frac{\alpha_s}{\pi}$$

- 'Gap fraction'–$f(\Delta\eta)$– proportion of events containing high P_t jets for which there is a gap in rapidity between the jets as a function of the jet-jet separation $\Delta\eta$.
- For colour non-singlet exchange: exponential fall-off with increasing $\Delta\eta$
  $\Longrightarrow$At sufficiently large $\Delta\eta$, a colour singlet exchange will dominate.

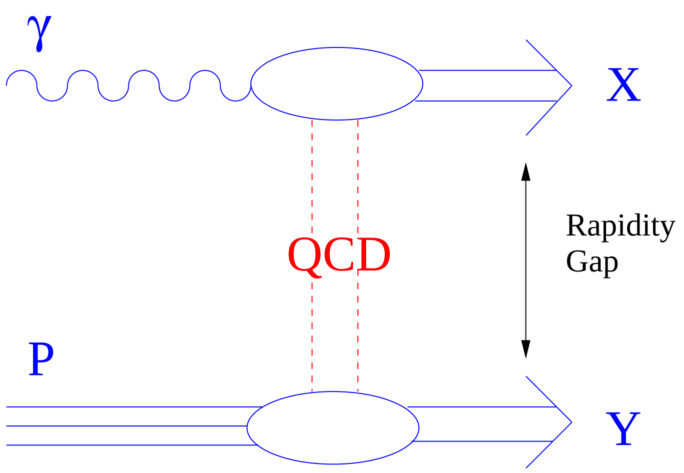


(**ZEUS**, Phys.Lett. B369 (1996) 55)
$Q^2 < 4\ GeV^2$
$135 < W < 280\ GeV$
$E_T^{jet} > 5\ GeV$
$\eta^{jet} < 2.5$

- **Di-jet photoproduction events contain an excess of events with rapidity gap between two jets over the expectations of colour exchange processes at the level of $f(\Delta\eta) = 0.11 \pm 0.02^{+0.01}_{-0.02}$.**
- **In $p\bar{p}$ collisions at Tevatron $f(\Delta\eta) \simeq 0.01$**
$\Longrightarrow$ difference in rapidity gap survival probability at γp and $p\bar{p}$.

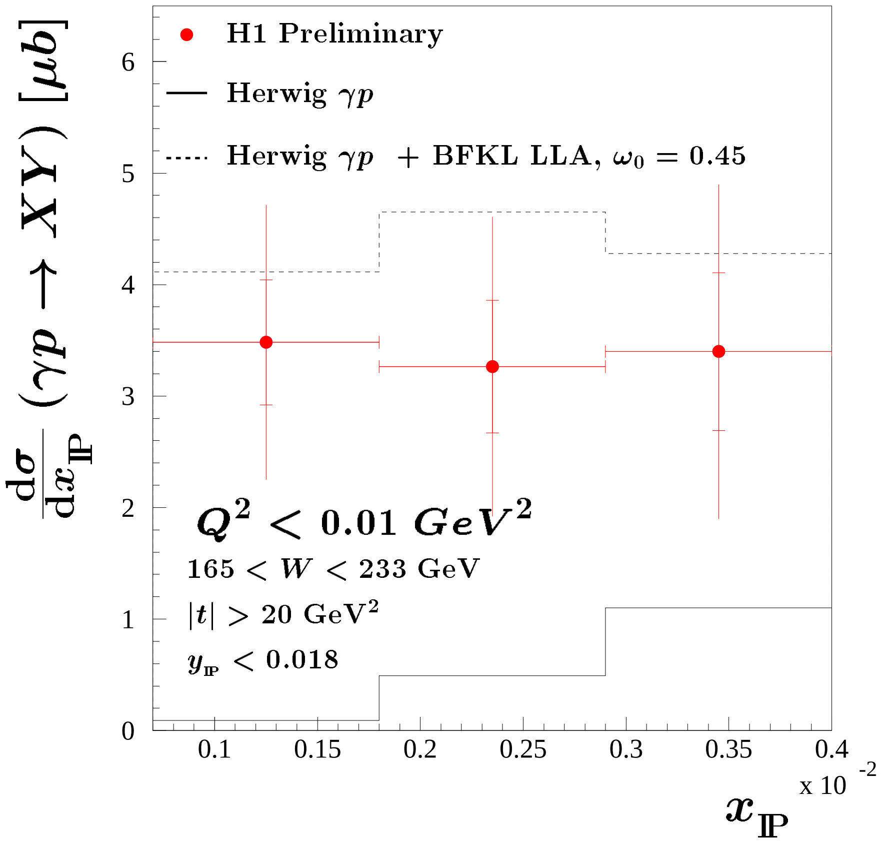
- **Disadvantage of the "rapidity gap between jet" method:**
the accessible gap size is limited by detector acceptance

A new approach: study inclusive $\gamma p \to XY$ double dissociative process at high $|t|$.



$$W^2 = (\gamma + P)^2 \qquad t = (P - Y)^2$$

$$x_{I\!P} = \frac{\gamma\cdot(P-Y)}{\gamma\cdot P} \simeq \frac{M_X^2 - t}{W^2} \qquad y_{I\!P} = \frac{P\cdot(\gamma-X)}{\gamma\cdot P} \simeq \frac{M_Y^2 - t}{W^2}$$



- Good agreement between data and Monte-Carlo (γp+ BFKL LLA) in shape and normalization for value of parameter $w_0 = 0.45$.

Summary

The different hadronic final state observables have been studied in diffractive ep interactions at HERA.

- Measurements of event shape evolution with M_X, the energy flow, charged particle multiplicities are in general consistently described by resolved $I\!P$ model with gluon dominated parton densities evolving with DGLAP.
  $\longrightarrow$ Same model gives consistent description of hadronic final state and inclusive $F_2^D(3)$ measurements.
- Several 2-gluon models exist, free parameters can be tuned to describe H1 and ZEUS data. $\longrightarrow$ need $q\bar{q} + q\bar{q}g$ states !
- The 'rapidity gap survival probability' for resolved γp interactions at HERA is larger that for $p\bar{p}$ interactions at Tevatron.
- For production of D^*, the shapes of distributions are well reproduced by models, but
  $\longrightarrow$ H1 sees discrepancy to results of other hadronic final states and to ZEUS results:
  breaking of factorization ? $\longrightarrow$ need understanding.
  Luminosty upgrade at HERA will allow precise measurement of open charm in diffractive DIS.
- An excess of events with a large rapidity gap between jets is observed over the expectations of colour exchange processes.
- The double dissociation photoproduction cross-section is measured at large $|t|$ and is in agreement with the model based on the exchange of a strongly interacting colour singlet object.