Non–diffractive and Diffractive Real and Virtual Photoproduction of Hadrons and Jets

THE UNIVERSITY of LIVERPOOL

ZEUS Collaboration

H1 Collaboration

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Outline

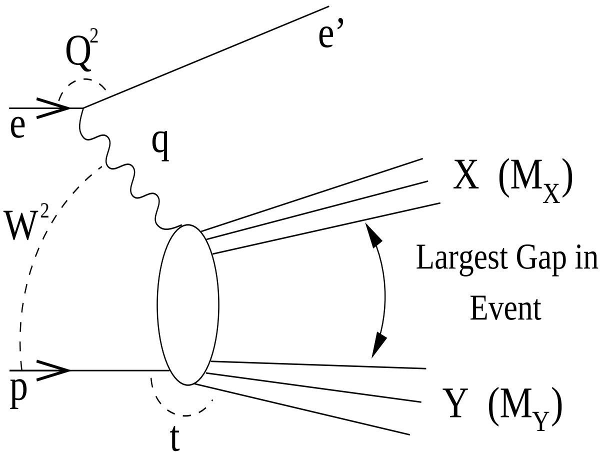
Based mostly on material selected from the following abstracts:

248,249,255,269.273,380,648,655,660,661...

...with apologies to the researchers for all the omitted...

- Introduction
- The hadronic final state in diffractive events and the partonic structure of the Pomeron.
- The photoproduction of jets with rapidity gaps.
- Jet production and the structure of real and virtual photons.
- Conclusions

Introduction to Diffraction



- The H1 definition of diffraction requires that the hadronic final state consists of a system X and Y seperated by the largest gap in pseudo–rapidity (η).

- Kinematics Standard deep–inelastic scattering variables:

$$Q^2 = -q^2;\ x = \frac{Q^2}{2P \cdot q};\ y = \frac{q \cdot P}{e \cdot P};\ W^2 = (q+P)^2$$

- Diffractive Kinematics for systems X and Y

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

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

- Interpretation in terms of an exchanged object (e.g. Pomeron):

$\beta \equiv$ Fraction of the exchanges momemtum carried by a constituent

$x_{I\!P} \equiv$ Fraction of protons momentum carried by exchage

Diffraction: Introduction

- Interpret events as involving the exchange of a *colourless* object.

- Data has been analysed in terms of structure function of exchanged object. Shown that

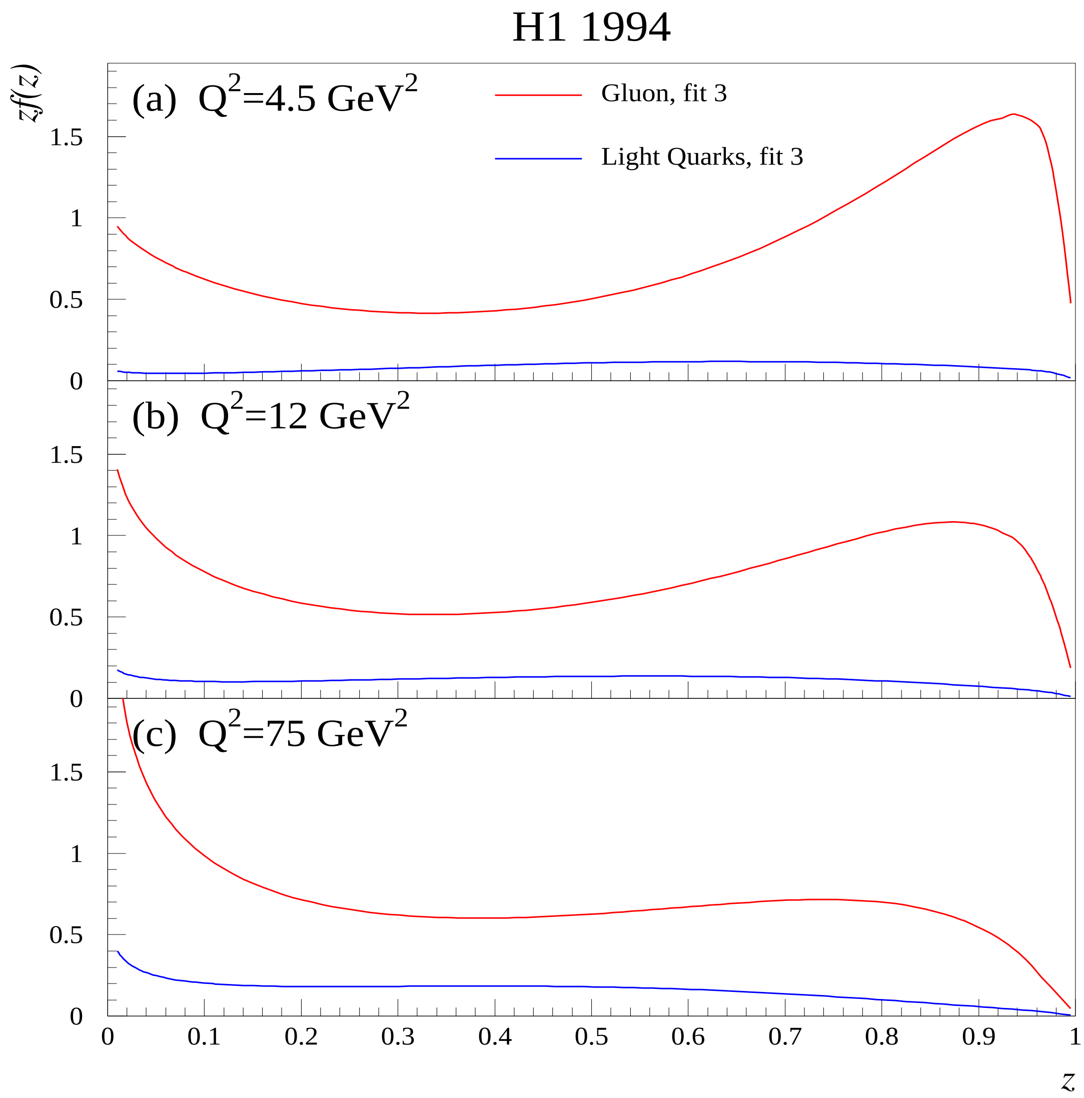
  Data indeed consistent with combination of factorisable Pomeron and meson exchange.

  Exchanged object contains significant gluon content. $\Rightarrow$

  (For details, see talk by A. Mehta this conference.)

- Is this picture corroborated by details of the hadronic final state?

Pomeron Parton Densities



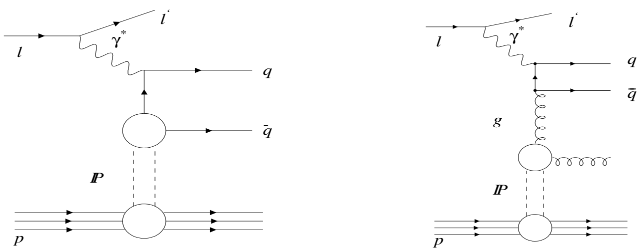
- "Hard" gluon behaviour seen $x_{g/I\!P} \to 1$ as $Q^2 \sim Q_0^2$
- Significant fraction of the Pomeron's momentum is carried by gluons
- Rapid evolution of the gluon density. Important for the hadronic final state

Diffraction: Final State Expectations

Measurements in $\gamma^* I\!P$ C.M.S.

- Energy Flow and Charged track spectra
- Event shapes – Thrust

- Consider energy and momentum flow in $\gamma^* I\!P$ c.m.s.



For Quark dominated object, expect:

- strong alignment with $\gamma^* I\!P$ axis. Limited p_T from:
- intrinsic k_T, soft gluon bremsstrahlung, hadronisation
- Only QCD–Compton process can provide high p_T radiation (suppressed by $\mathcal{O}(\alpha_s)$)

For Gluon dominated object, expect:

- From matrix element $q, \bar{q}$ from quark box do not have to be aligned along $\gamma^* I\!P$ axis
  $\rightarrow$ In fact a significant fraction of events can have high p_T $q\,/\bar{q}$
- Enhanced E_T flow at $\eta^* = 0$. (+ Colour factor)

Monte Carlo Models

- H1 + ZEUS Collaborations use RAPGAP (Author H. Jung)
  $\rightarrow$ based on Ingelman–Schlein Model:
  - proton couples to a spacelike $I\!P$
  - $I\!P$ has a partonic structure
  - probed by virtual photon

- H1 Parton densities obtained from fit to $F_2^{I\!P}(\beta, Q^2)$
- ZEUS Parton densities of the form:

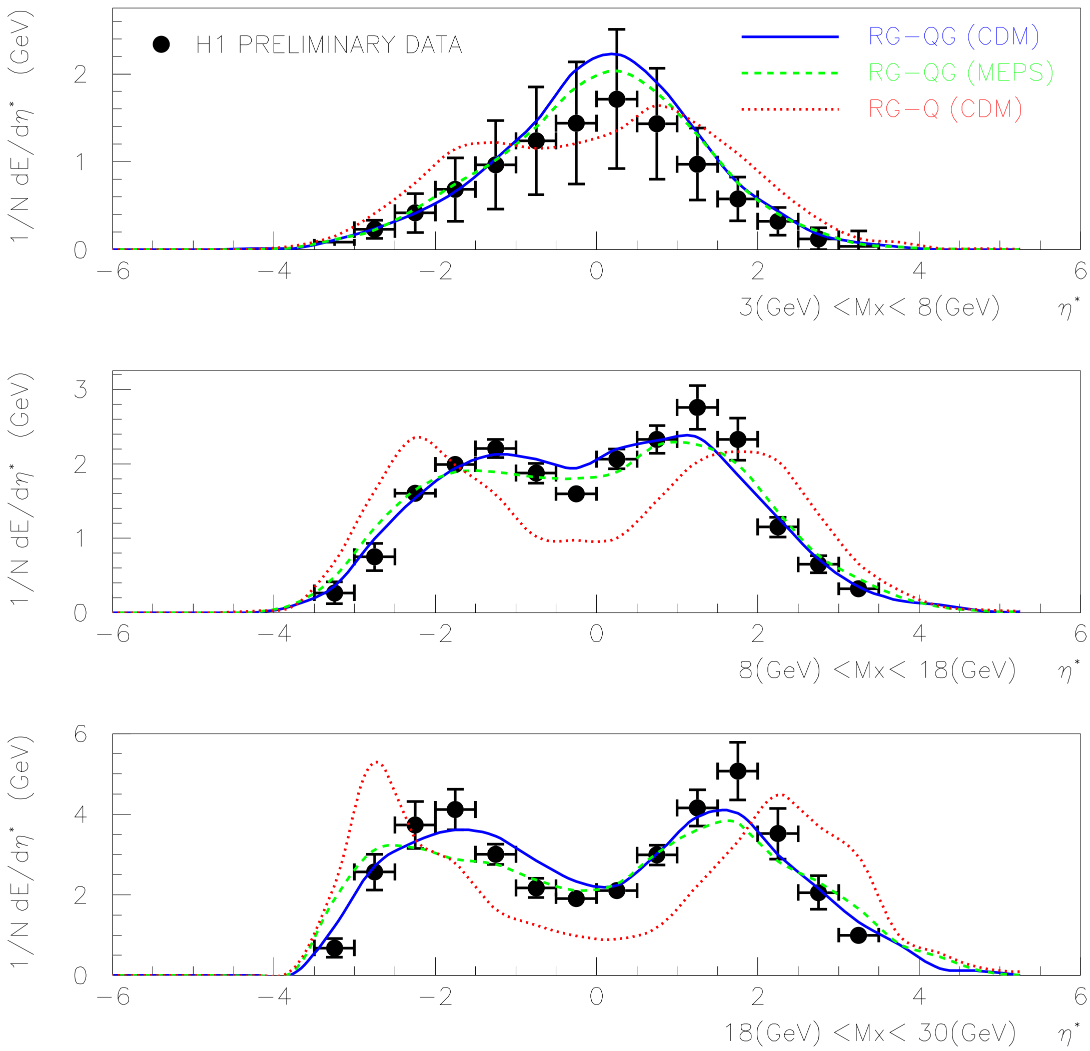
  $\beta f_{u/I\!P} = a_2\beta(1-\beta)$, $\beta f_{g/I\!P} = b_2\beta(1-\beta)$ "hard quark + hard gluon"

  $\beta f_{u/I\!P} = a_3\beta(1-\beta)$, $\beta f_{g/I\!P} = b_3\beta^8(1-\beta)^{0.3}$ "hard quark + singular gluon"
- Full Q^2 evolution included

Final State Modelling

- $\mathcal{O}(\alpha_s)$ QCD matrix elements (BGF, QCD–Compton)
- Fragmentation Schemes (perturbative)
  1. LLA parton showers (DGLAP)
  2. colour dipole model (CDM c.f. ARIADNE)
- hadronisation $\rightarrow$ LUND string model (JETSET)

Energy–Flow in $\gamma^* I\!P$ C.M.S.



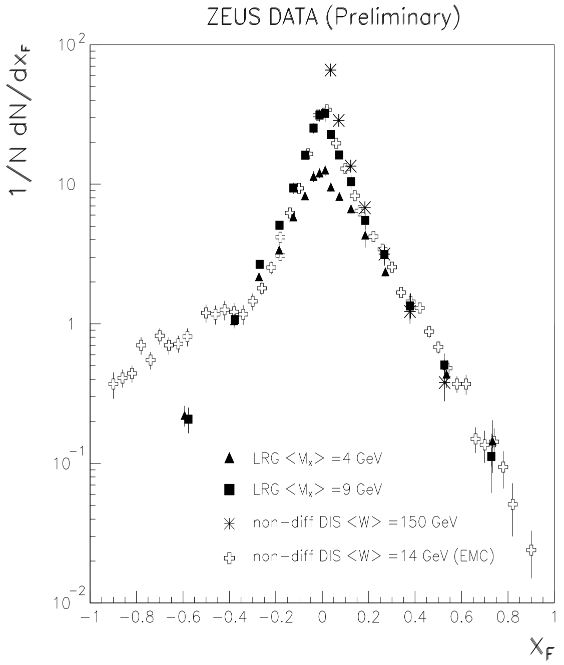
- E–flow distributions rather symmetric about $\eta^* = 0$
  $\rightarrow$ Indicative of leading 2–body process

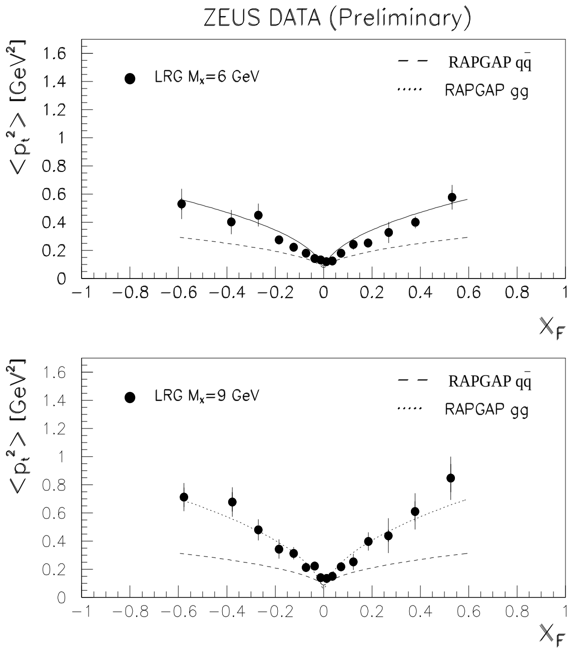
- High level of E–Flow at $\eta^* \approx 0$
  $\rightarrow$ Cannot be reproduced by quark only Pomeron
  $\rightarrow$ Well described by "hard" gluon Pomeron

Charged Track Spectra in the $\gamma^* I\!P$ C.M.S.

In Diffraction the relevent mass scale is M_X

$$\rightarrow x_F = \frac{2p_z^*}{M_X}$$





- Symmetry between photon and Pomeron hemispheres
  $\rightarrow$ In the kinematic domain of the EMC data the $\gamma^* p$ interactions are dominated by valence and sea quark interactions

- No suppression of high p_T QCD radiation in the remnant direction
  $\rightarrow$ More "point" like "partonic remnant" than the extended proton remnant in EMC $\gamma^* p$ data.

- Seagull Plot
  Higher $< P_T^{*2} >$ than predicted from quark
  $\rightarrow$ significant contribution from hard subprocess
  $\rightarrow$ consistent with "hard gluon" prediction

See also H1 results on particle production presented at ICHEP Warsaw '96

THRUST

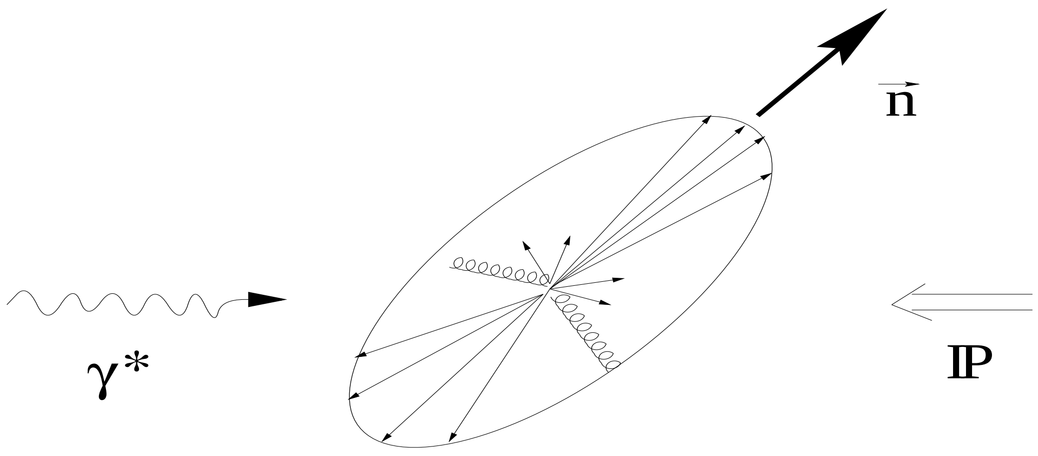
$$T = \frac{1}{\Sigma_{i=1}^{N} |\vec{p}_i|} \times \max\left\{\Sigma_{i=1}^{N} |\vec{p}_i \cdot \vec{n}|\right\}$$

- Information from Thrust:

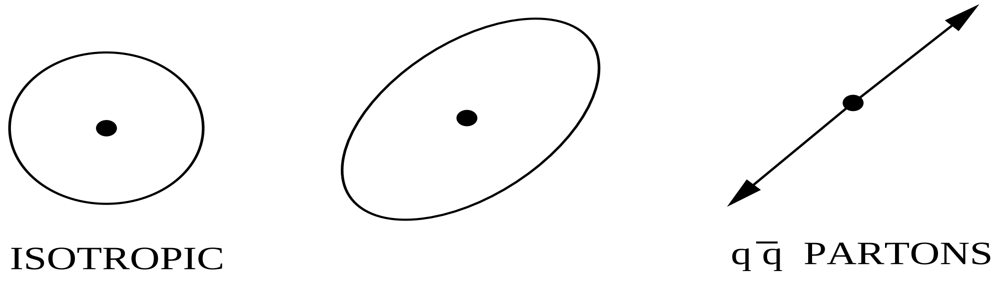
Thrust finds the direction in the C.M.S. along which the energy flow is maximal

- For each event obtain information on:

1. Orientation $\vec{n}$ w.r.t. $\gamma^* \; I\!P$ axis
2. Shape given by T

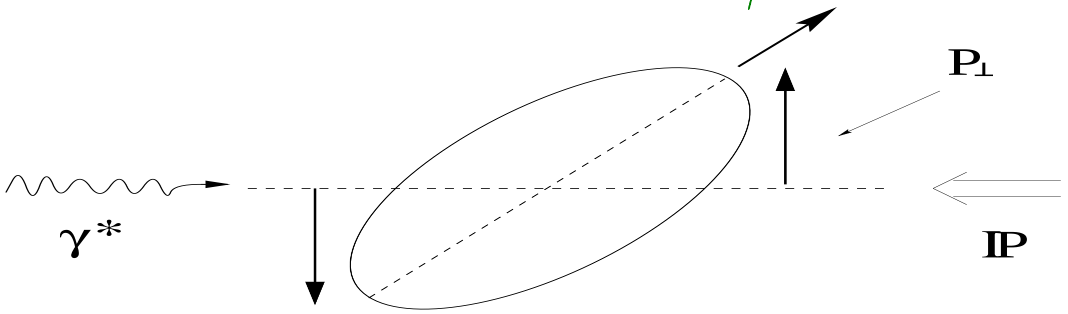


$$1/2 \; < \; T \; < \; 1$$



THRUST $P_\perp$

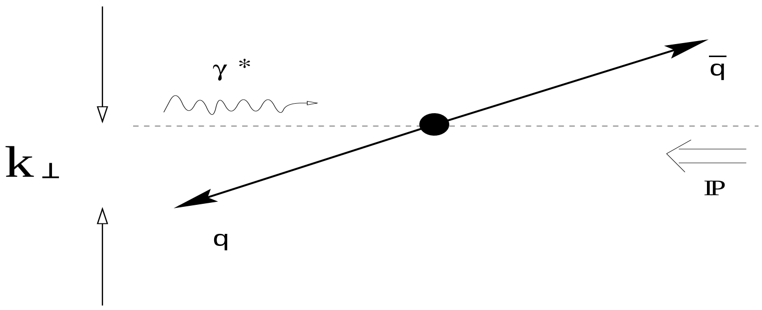
- From $\vec{n}$ w.r.t. γ^* $I\!P$ axis



$P_\perp = \left| T \times \frac{M_X}{2} \right|$

Final State Expectations:

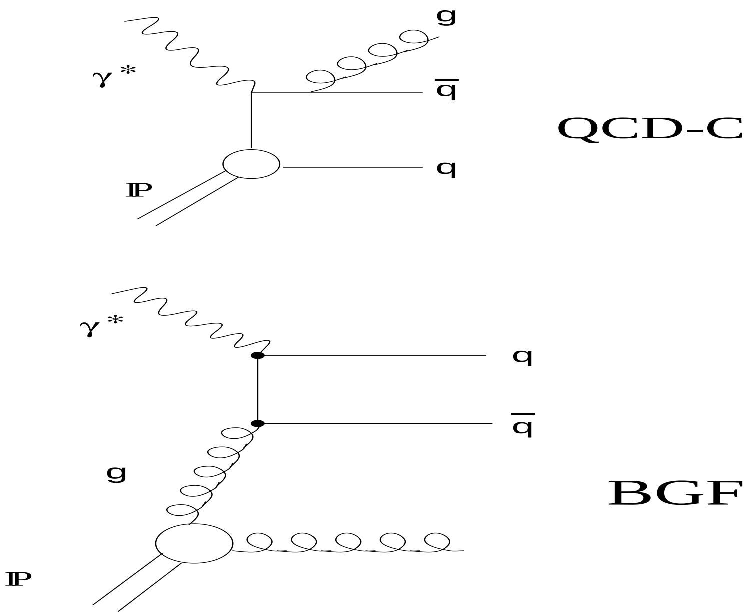
Quark dominated Pomeron



Small $k_\perp$ $q, \bar{q}$ Aligned
~ 2 Jet Topology $T \sim 1$

Only Soft QCD Radiation
$p_\perp \sim k_\perp$, $p_\perp^2 < 1\,\mathrm{GeV}^2$

High $P_\perp$ processes

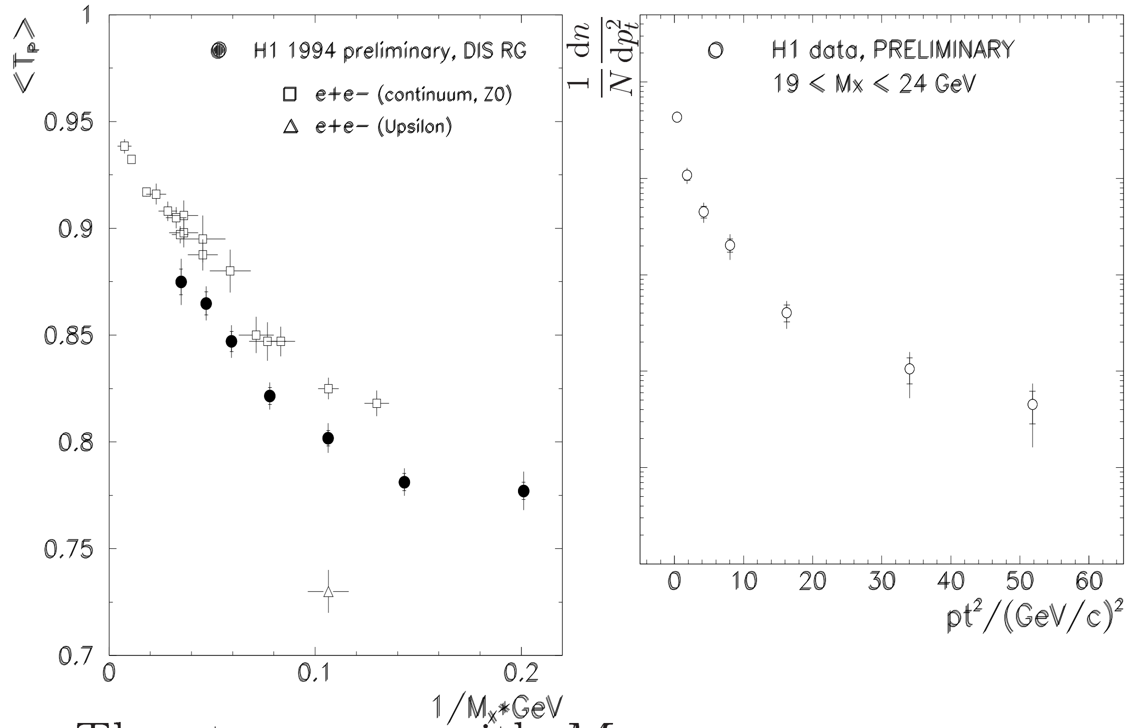


~ 3 Jet Topology
$T < 1$

Hard $q, \bar{q}, g$
$p_\perp^2 \gg 1\,\mathrm{GeV}^2$

THRUST

$\rightarrow$ Fully corrected with systematic + statistical errors in quadrature.



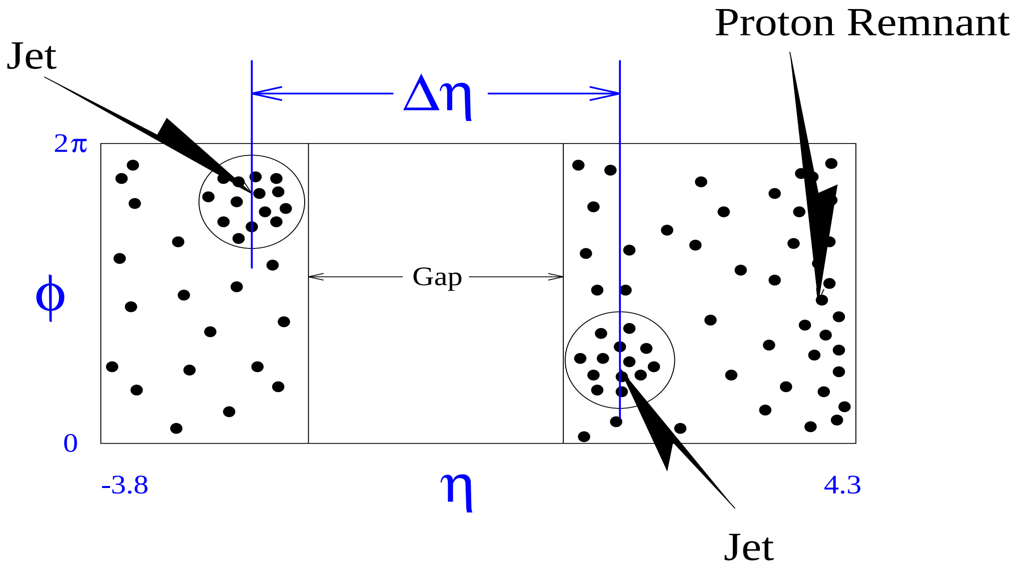
- $<$ Thrust $>$ grows with M_X
  $\rightarrow$ Final state not isotropic but exhibits a growing back to back correlation in the energy flow
  $\rightarrow$ 2–Jet is the leading topological property

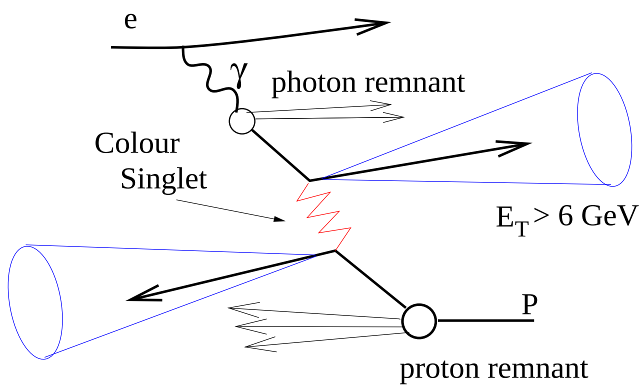
- $<$ Thrust $>$ in diffraction is systematically below that of the e^+e^-
  $\rightarrow$ Diffractive data require larger number of higher parton multiplicity processes (e.g. BGF)

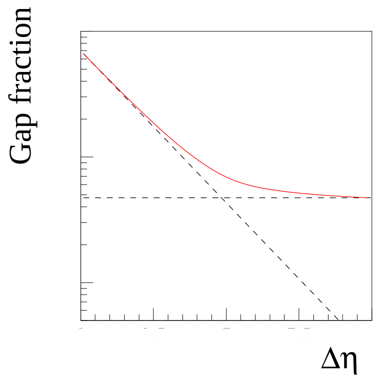
P_T^2 Distribution

- P_T^2 distribution peaked at low P_T^2 values
- Substantial P_T^2 tail
  $\rightarrow$ Significant contribution from high P_T hard processes

Rapidity Gaps Between Jets in Photoproduction



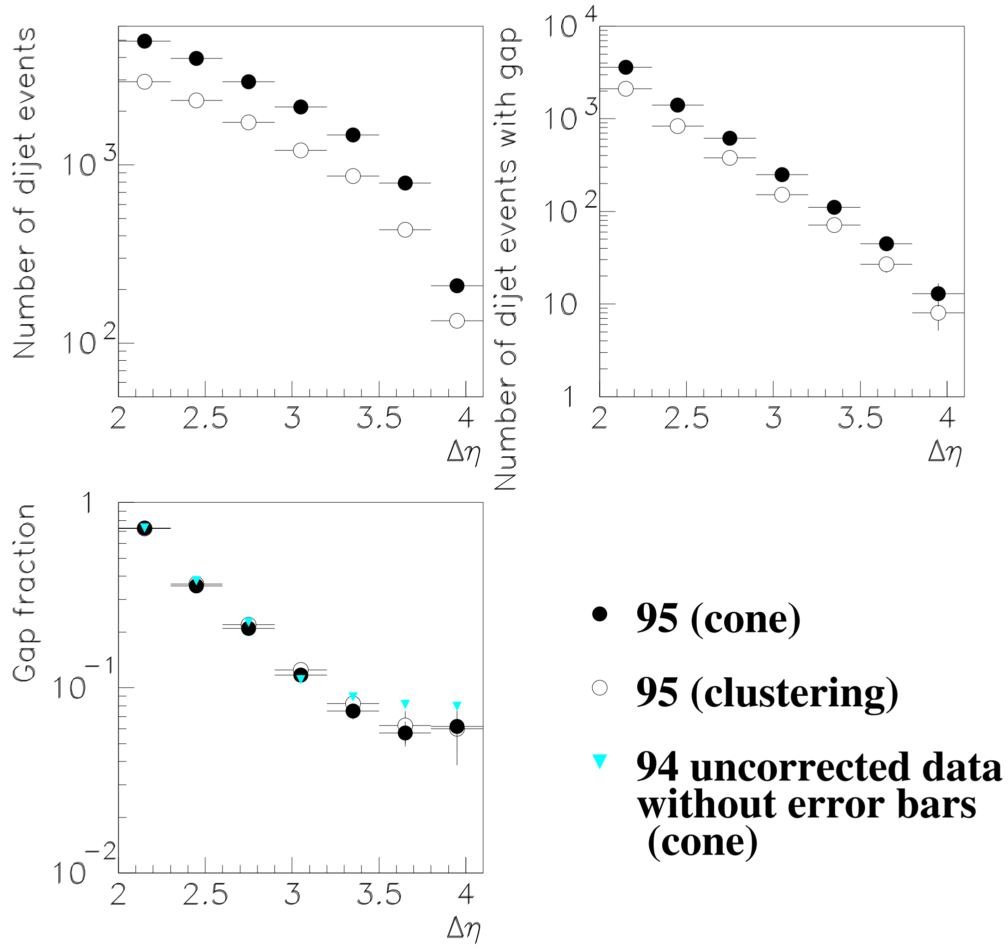




- Gaps from random multiplicity fluctuations decrease exponentially
- Excess over exponential decrease indicative of *colourless exchange*

Rapidity Gaps Between Jets

ZEUS: Uncorrected Preliminary '95 data:

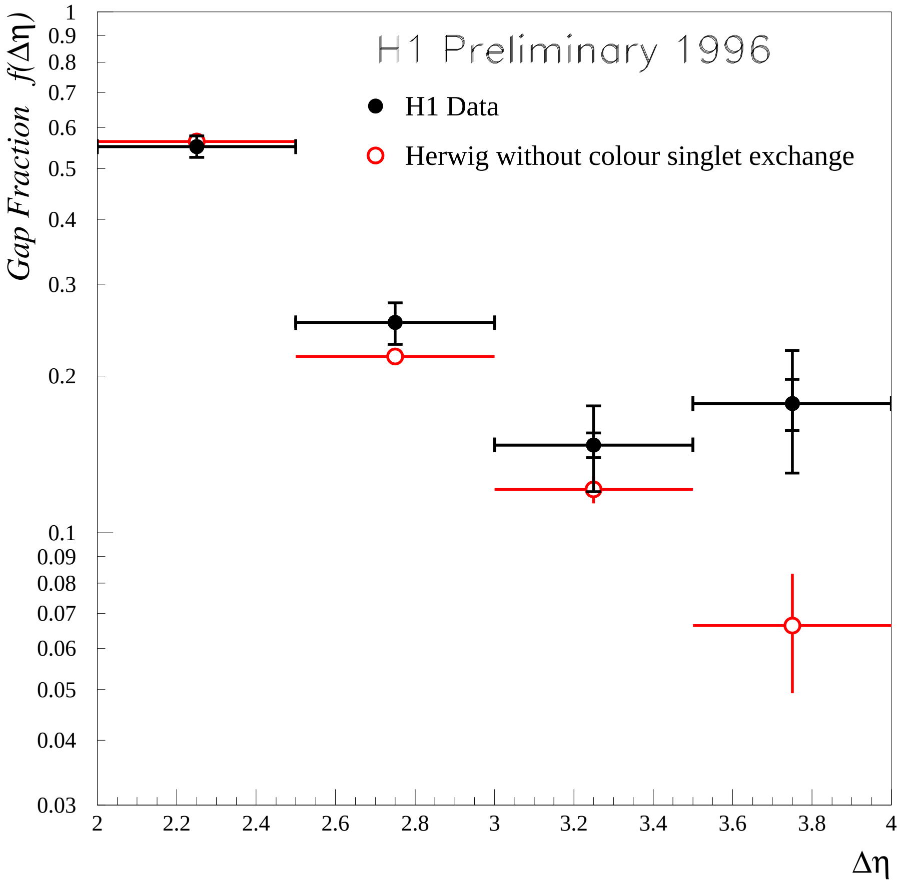


- Agrees with 1994 published results.
- Gap fraction insensitive to choice of jet finder
- Excess over exponential fall-off ⇒ colour-singlet exchange

Rapidity Gaps Between Jets

H1: Corrected Preliminary '96 data: $\rightarrow$ Statistical + Systematic errors in quadrature

$E_T > 4.5\,\mathrm{GeV}$ and $158\,\mathrm{GeV} < W < 247\,\mathrm{GeV}$



- Qualitatively Consistent with the ZEUS result
- Excess over exponential fall-off
  $\Rightarrow$ colour-singlet exchange

ZEUS: Diffractive Photoproduction Di–jet Cross Sections

Di–jet cross sections with a large rapidity gap

$$e \; + \; p \rightarrow (jet \; + \; jet + X_r) \; + \; e^{'} \; + \; Y$$

Kinematic Range

- $0.2 < y < 0.85$ ($134\,\mathrm{GeV} < W < 277\,\mathrm{GeV}$)
- $Q^2 < 4\,\mathrm{GeV}^2$ (mean $Q^2 \approx 10^{-3}\,\mathrm{GeV}^2$)
- $\eta_{max} < 1.8$

Jet Algorithm

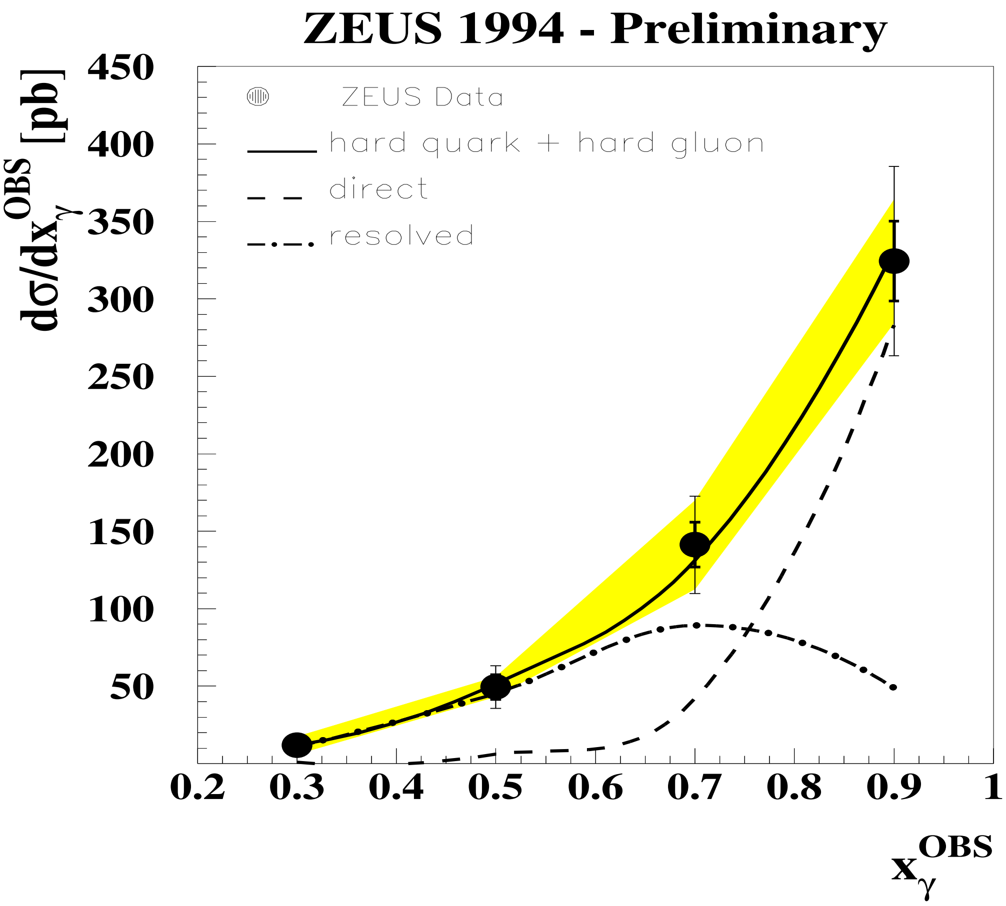
- Cone algorithm in $\eta - \phi$ space
  $\rightarrow$ Radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 1$
- Require at least 2 jets with
  $\rightarrow -1.5 < \eta^{jet} < 1$
  $\rightarrow E_T^{jet} > 6\,\mathrm{GeV}$

See also H1 results on di–jet production presented at ICHEP Warsaw '96

ZEUS: Resolved and Direct Contributions

$$x_\gamma^{OBS} = \frac{\Sigma_{jets} E_T^{jet} e^{-\eta^{jet}}}{2yE_e}$$

$\rightarrow$ Fraction of the photon's momentum participating in the production of the two jets

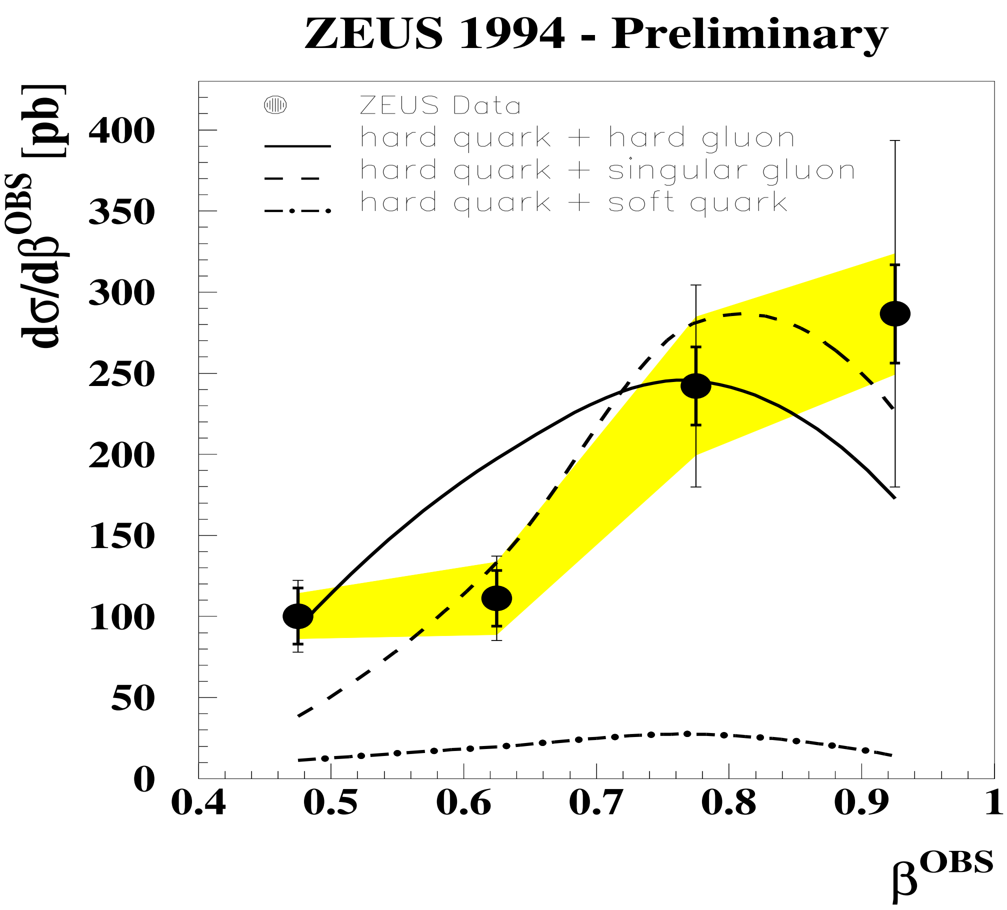


- x_γ^{OBS} strongly peaked at $\sim$ 1
  $\rightarrow$ Significant contribution from direct processes
- Resolved contribution needed for low x_γ^{OBS}

ZEUS: β Distribution

$$\beta^{OBS} = \frac{\Sigma_{jets} E_T^{jet} e^{-\eta^{jet}}}{2 x_{I\!P} E_p}$$

$\rightarrow$ Fraction of the $I\!P$ momentum participating in the production of the two jets



- β^{OBS} strongly peaked towards $\beta^{OBS} \sim 1$
  $\rightarrow$ Significant fraction of the Pomeron's momentum is involved in the hard scattering.
- Gluon parton params give a moderate description of data
  $\rightarrow$ Quarks only at the starting scale fail to describe the data

$\rightarrow$ Hard Gluon and singular gluon params. better

Diffraction Summary

- **Energy Flow, Particle Spectra, Thrust and Jets** have been measured in deep–inelastic diffraction and photoproduction
- The large quantity of energy observed in the central region ($\eta^* \approx 0$) can only be explained by partonic models of the pomeron in which its momentum is largely carried by gluons.
- This is borne out in the observation of large P_T^{*2} tail
- The striking symmetry of the X_F and "seagull" plots and high $< P_T^{*2} >$
  $\rightarrow$ "hard" gluon behaviour gives best description of data
- Comparing $\gamma^* I\!P$ data with the higher Bjorken–x EMC data
  $\rightarrow$ Provides a direct comparison with a quark dominated structure
- **Event Shapes** measurement show that alignment and 2–jettiness are the leading topological properties
- Large fraction of high P_T events

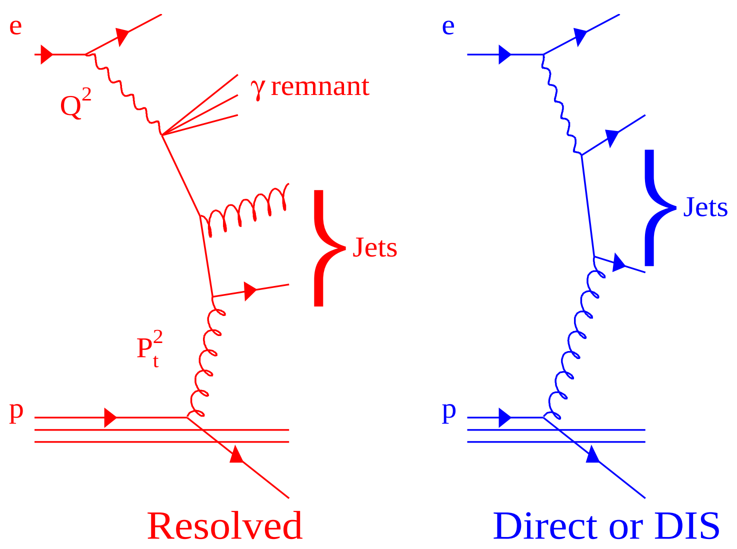
- **Jets** Significant cross section towards $x_\gamma^{OBS} \sim 1$
  $\rightarrow$ Large cross section for $\beta^{OBS} \sim 1$
  $\rightarrow$ Quark only does not describe any aspects of the data

Models in which the moemtum of the Pomeron is carried mainly by gluons give best description of data

$\rightarrow$ Data prefer "hard" Gluon param.

Inclusive Jet Production and Virtual Photons

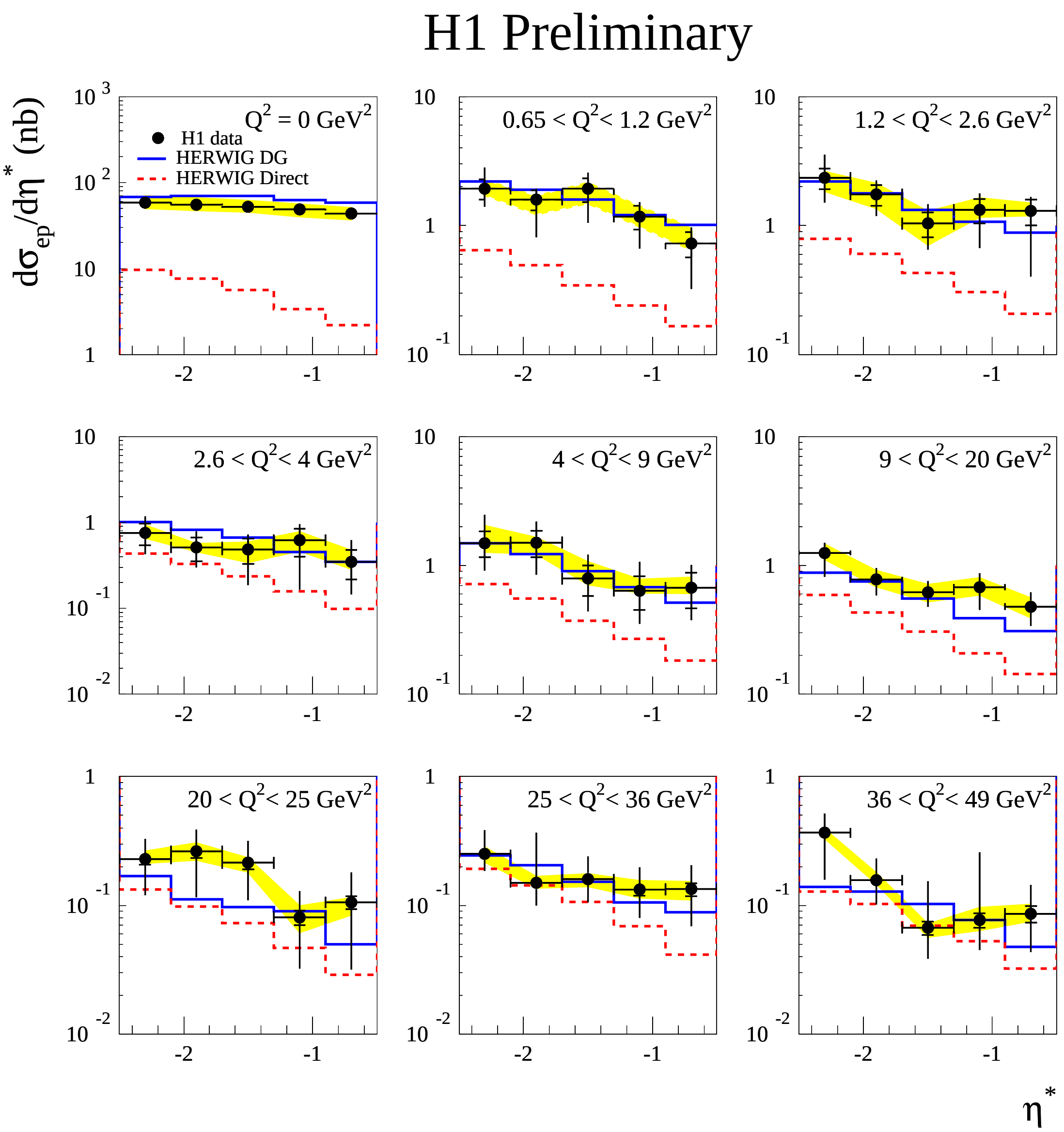
- Photoproduction of jets sensitive to parton densities in both photon and proton:
- Quasi-real photons ($Q^2 \sim 0\,\mathrm{GeV}^2$) interact either as a point-like object (“direct” processes) or as an object composed of partons (“resolved” processes).
- In deep-inelastic scattering $Q^2 >> 0\,\mathrm{GeV}^2$, a pointlike photon probes structure in the proton.



- Suggests parton densities in the photon *suppressed* as Q^2 increases

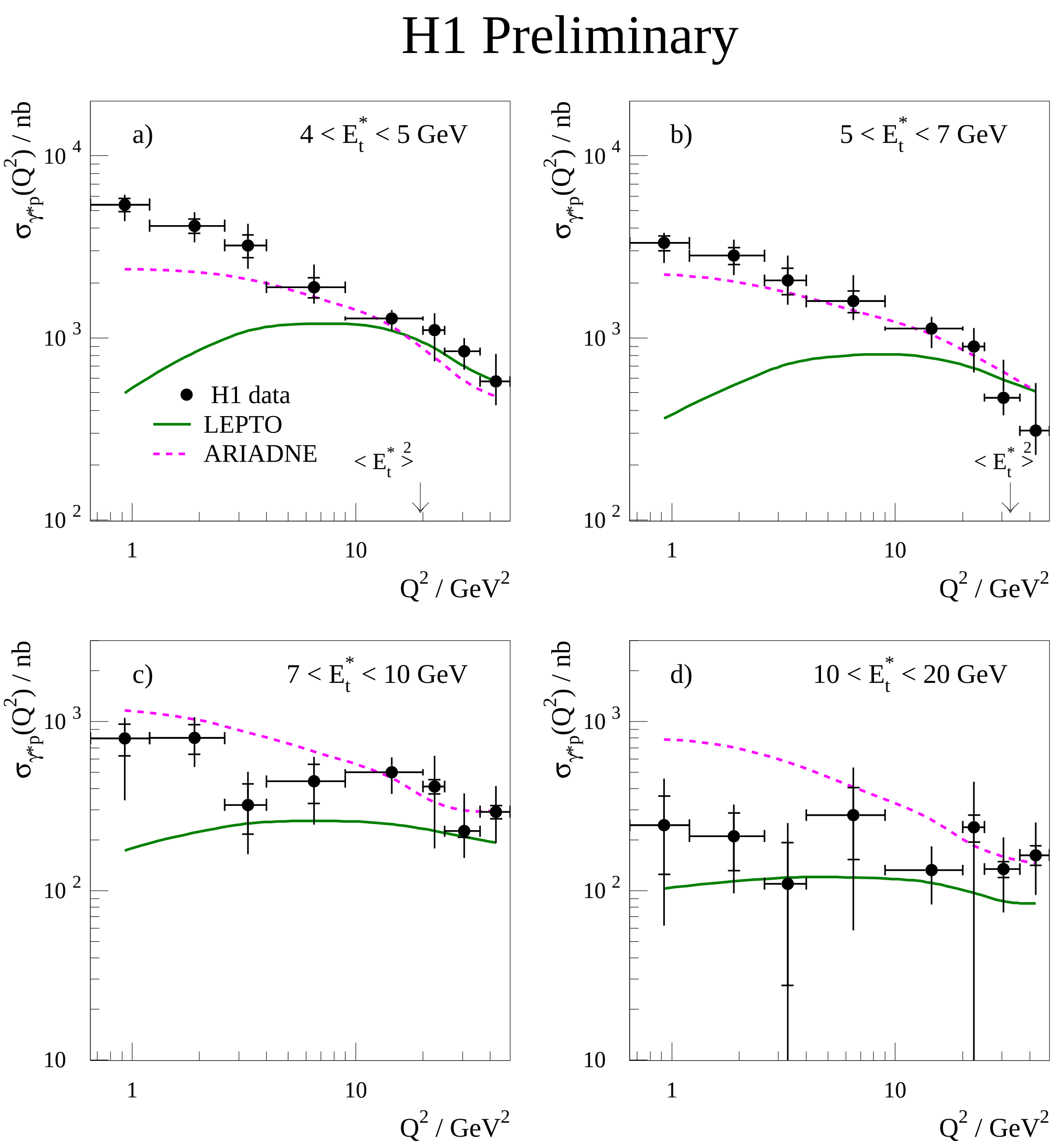
Jet η^* Distribution as a Function of Q^2

Use k_T factorising algorithm $E_T^* > 5\,\mathrm{GeV}^2$ and
$0.3 < y < 0.6$



- Comparing with HERWIG-DG
  rightarrow Direct photon processes alone significantly underestimate the cross section
- Data described well by HERWIG model
  $\rightarrow$ Includes a resolved component that is suppressed with increasing Q^2

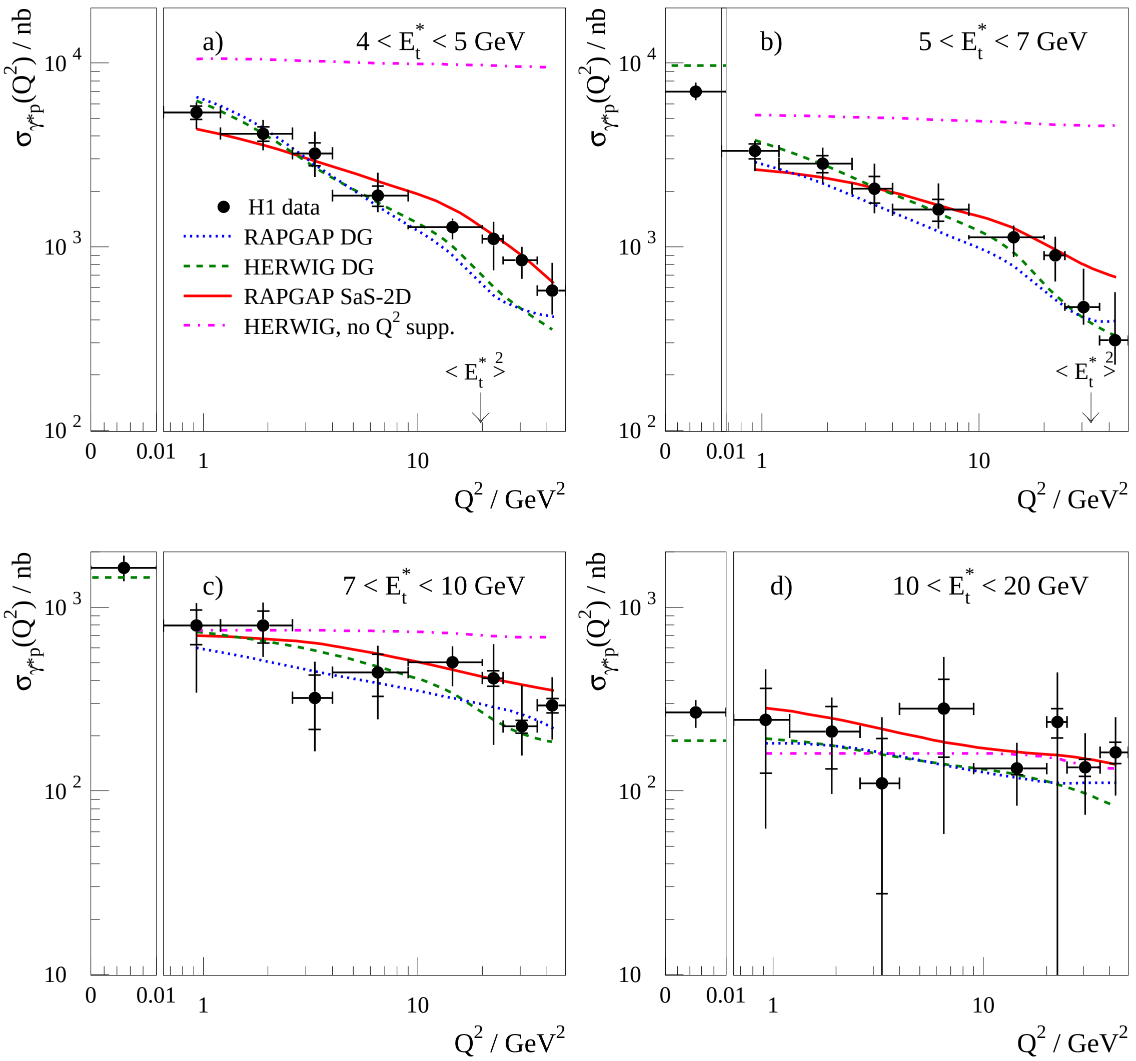
Jet X–Section vs Q^2



- $E_T^* < 10\,\mathrm{GeV}$ $\rightarrow$ significant decrease of jet cross section as Q^2 increases.
- Standard DIS models (LEPTO, ARIADNE) only valid when $Q^2 >> p_T^2$
- Neither model can describe the data when $Q^2 < p_T^2$

σ vs Q^2

H1 Preliminary



- Comparisons with models incorporating partonic structure for the γ^*
- Models are in good agreement with each other and describe the data well
- Data best described by the RAPGAP model which uses the Schuler and Sjöstrand parameterisation of the virtual photon.
  $\rightarrow$ SaS the photon parton densities do not vanish when $Q^2 > p_T^2$

Virtual Photons: Conclusions

- The single inclusive jet–cross section has been measured for $Q^2 = 0\,\mathrm{GeV}^2$ and $0.65 < Q^2 < 49\,\mathrm{GeV}^2$, $0.3 < y < 0.6$.
- In the region $p_T^2 >> Q^2$, where the photon can be resolved, the data is inconsistent with models which treat the photon as a pointlike object.
- A phenomenological model which includes a resolved component of the photon suppressed *logarithmically* with its virtuality describes the data at all Q^2.