Energy Flow, Event Shapes, Charm and the Structure of the Pomeron

THE UNIVERSITY
of LIVERPOOL

ZEUS Collaboration

H1 Collaboration

Christopher M. Cormack

Workshop on Small–x Physics

MADRID

18–21st June 1997

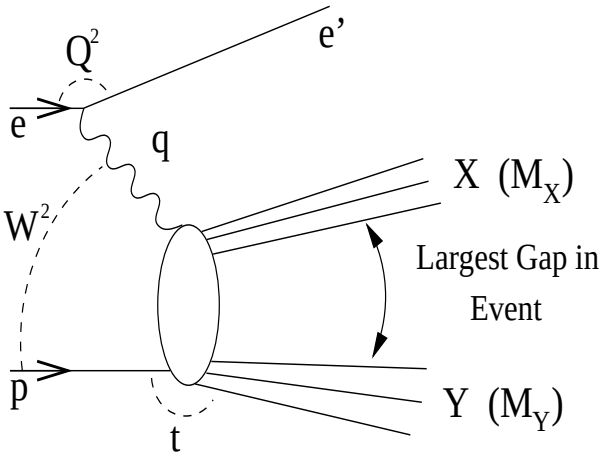
Outline

- Introduction
- Diffraction
- Modelling of the Hadronic Final State
- Hadronic Final State
  1. Kinematic Selection
  2. Final State Expectations
  3. Results
     (a) Energy Flow, Charged Track Spectra
     (b) Thrust, Event Shapes
     (c) Charm
- Conclusions

Introduction

- From '94 analysis of $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ diffractive contribution to the structure function is shown to be consistent with combined Pomeron and Meson exchange
- From $F_2^{I\!P}(\beta, Q^2)$ (the Pomeron component to $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$) large scaling violations. Strong increase in $F_2^{I\!P}(\beta, Q^2)$ with increasing Q^2
  $\rightarrow$ significant gluon contribution
- From QCD analysis of $F_2^{I\!P}(\beta, Q^2)$
  $\rightarrow$ "leading" gluon distribution
- What does the hadronic final state tell us about the diffractive interaction?

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

Factorisation and the "Pomeron Structure Function"

• From $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ it has been seen that the diffractive contribution to the cross section can be factorised in the form:

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

$f_{I\!P/p}(x_{I\!P}, t) \equiv$ Pomeron flux (non–perturbative)

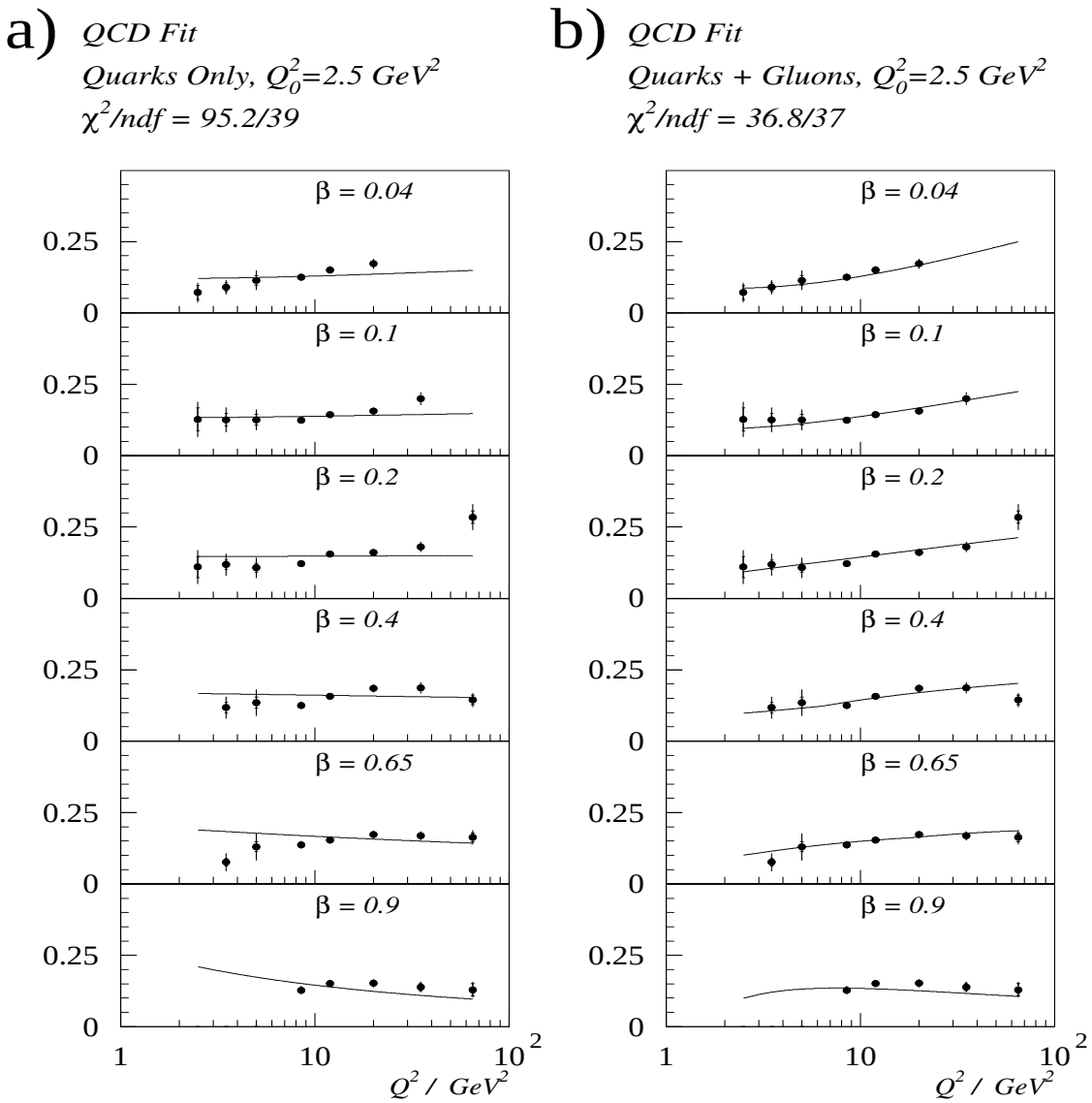
$F_2^{I\!P}(\beta, Q^2)$ can be thought of as the structure function of the "Pomeron"

• Ansatz of factorisation, it is possible to treat the Pomeron as an effective hadron. $\rightarrow$ Structure function.

$\Rightarrow$ Possible to parameterise the structure in terms of parton densities $\rightarrow$ DGLAP QCD fit

Partonic Structure of Diffractive Exchange

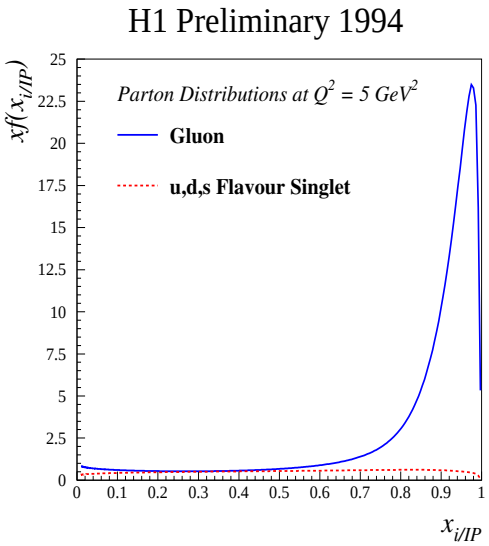
H1 Preliminary 1994

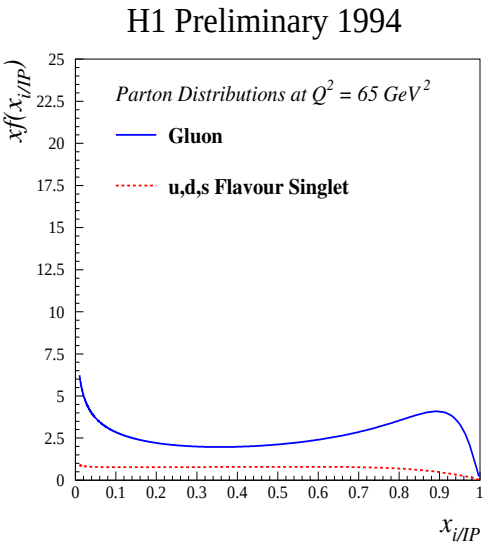


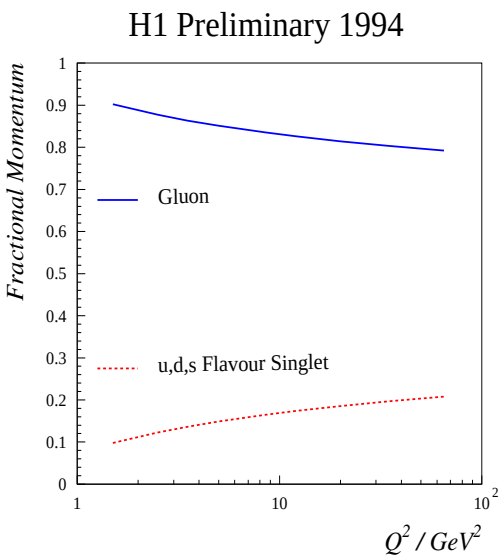
- $\tilde{F}_2^D$ Shows no evidence of a fall in Q^2 with increasing β
- Such strong Q^2 scaling violations
  $\rightarrow$ hint at very hard gluon density?

- DGLAP QCD fit including Quarks and Gluons at the starting scale gives best fit.
- Quark only gives a poor fit

Pomeron Parton Densities







- "Leading Gluon" 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

Monte Carlo Models

- H1 Collaboration uses 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

- Parton densities obtained from fit to $F_2^{I\!P}(\beta, Q^2)$
- Full Q^2 evolution included

Final State Modelling

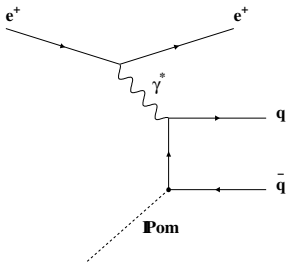
- $\mathcal{O}(\alpha_s)$ QCD matrix elements (BGF, QCD–Compton)
- Fragmentation Schemes (perturbative)
  1. LLA parton showers (DGLAP)
  2. colour dipole model (CDM c.f. ARIADNE)
- hadronisation $\rightarrow$ LUND string model (JETSET)

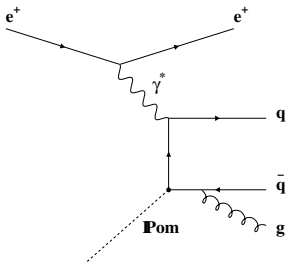
Monte Carlo Models: VBLY

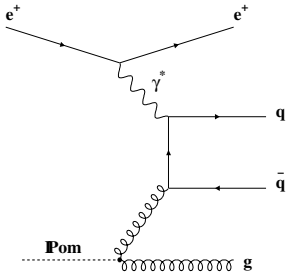
ZEUS: Vermaseren–Barreiro–Labarga–Yndurá*i*n

- The Pomeron has no structure
- Pomeron has point like coupling to quarks and gluons

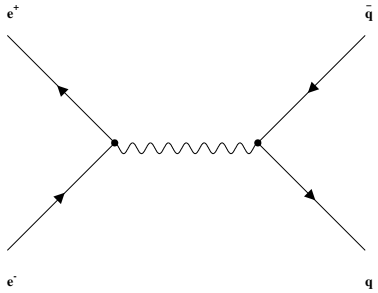
VBLY MC

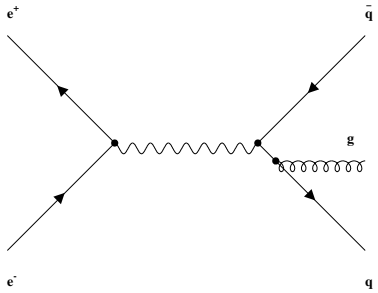






e^+e^-





Hadronic Final State

- From the fits to $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ and the subsequent QCD analysis

  $\rightarrow$ structure function of $F_2^{I\!P}(\beta, Q^2) \rightarrow$ strong Q^2 rise
  $\rightarrow$ gluons dominate the structure
  $\rightarrow$ "Leading Gluon" behaviour

- From measured parton densities

$\rightarrow$ Compare with predictions from RAPGAP

$\rightarrow$ Does the Hadronic final state concur with the structure function analysis?

Measurements:

- Energy Flow + Charged Track Spectra
- Thrust and Event Shapes
- Open Charm production

Final State Selection

- Energy–Flow and Charged Track Spectra

Kinematic Range Selected:

- $7.5 < Q^2 < 100\,\mathrm{GeV}^2$
- $0.05 < y < 0.6$
- $x_{I\!P} < 0.025$
- $M_Y < 1.6 GeV$
- $M_X > 3 GeV$

- All distributions are measured in the $\gamma^* I\!P$ C.M.S.

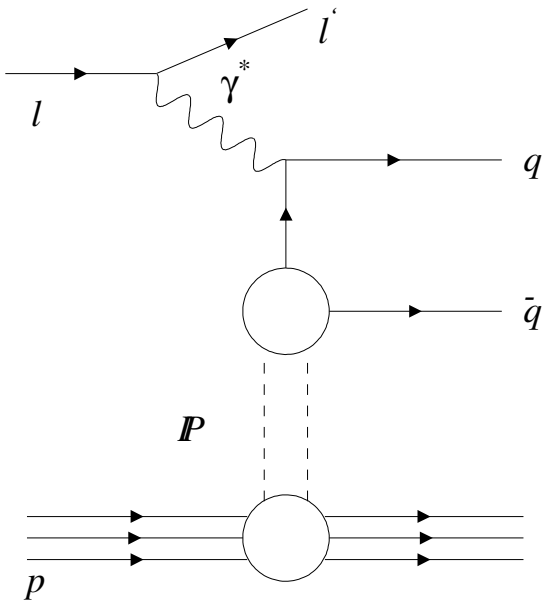
- Energy Flow uses Calorimeter Clusters

- Particle Spectra $\rightarrow$ Charged Tracks

- All objects boosted into the $\gamma^* I\!P$ C.M.S.

- All distributions fully corrected with statistical and systematic errors.

Final State Expectations: Quark Dominated Object

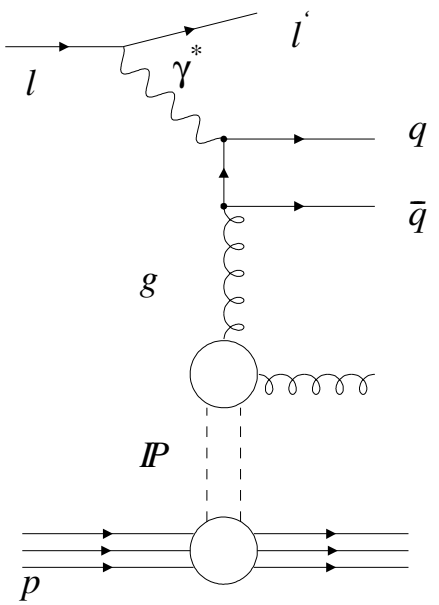


Contribution to E_T, P_T, E–flow

- In $\gamma^* I\!P$ C.M.S. Struck quark and 'remnant' are highly aligned along $\gamma^* I\!P$ axis E_T May arise from:

- Intrinsic k_T of q + remnant
- Soft gluon bremsstrahlung
  → Highly collimated along q + remnant
  → Very little large angle high energy radiation
- Hadronisation – particle decays (small contribution)
- Only QCD–Compton can provide high p_T radiation (suppressed by $\mathcal{O}(\alpha_s)$)

Final State Expectations: Gluon Dominated Object



Contribution to E_T, P_T, E–flow

- From matrix element $q, \bar{q}$ from quark box do not have to be aligned along $\gamma^* I\!P$ axis

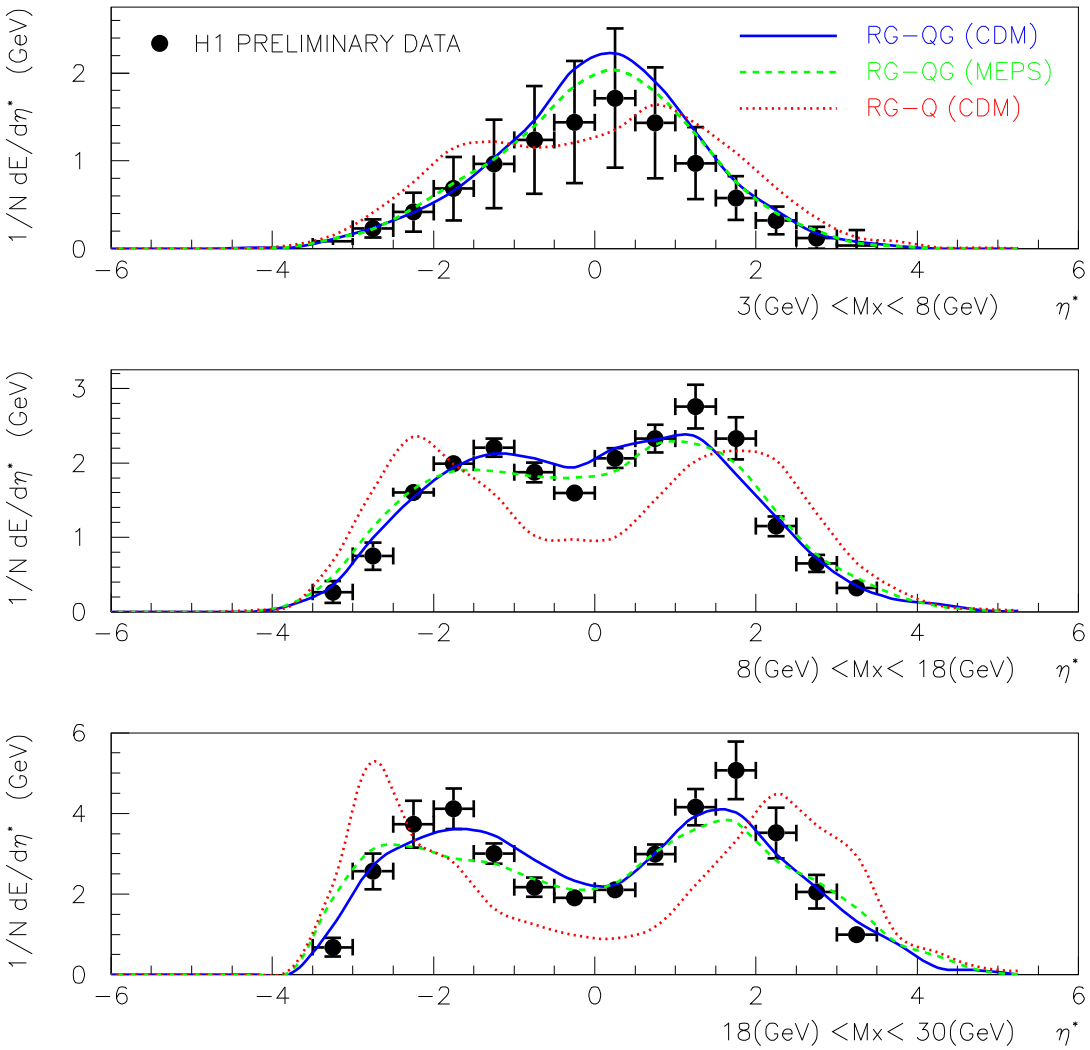
→ In fact a significant fraction of events can have high p_T q / $\bar{q}$

⇒ Higher E-flow about $\eta^* = 0$

- For t–channel gluon exchange there is enhanced (by the colour factor) large angle gluon emission

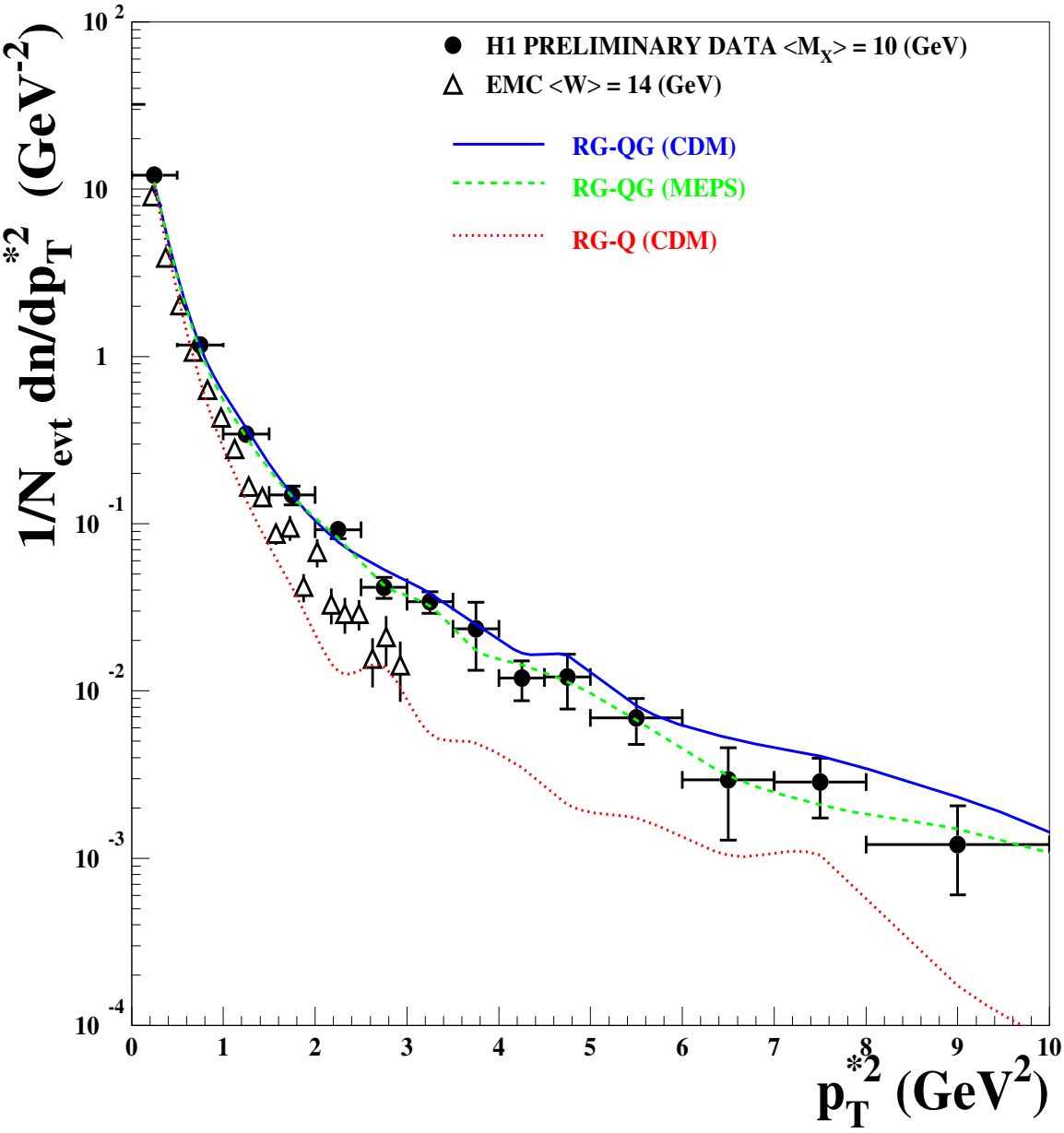
→ Increased contribution to the energy flow in the central region of η^* in the $\gamma^* I\!P$ C.M.S.

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 "leading" gluon Pomeron

Charged Track P_T^{*2} Spectrum in $\gamma^* I\!P$ C.M.S.

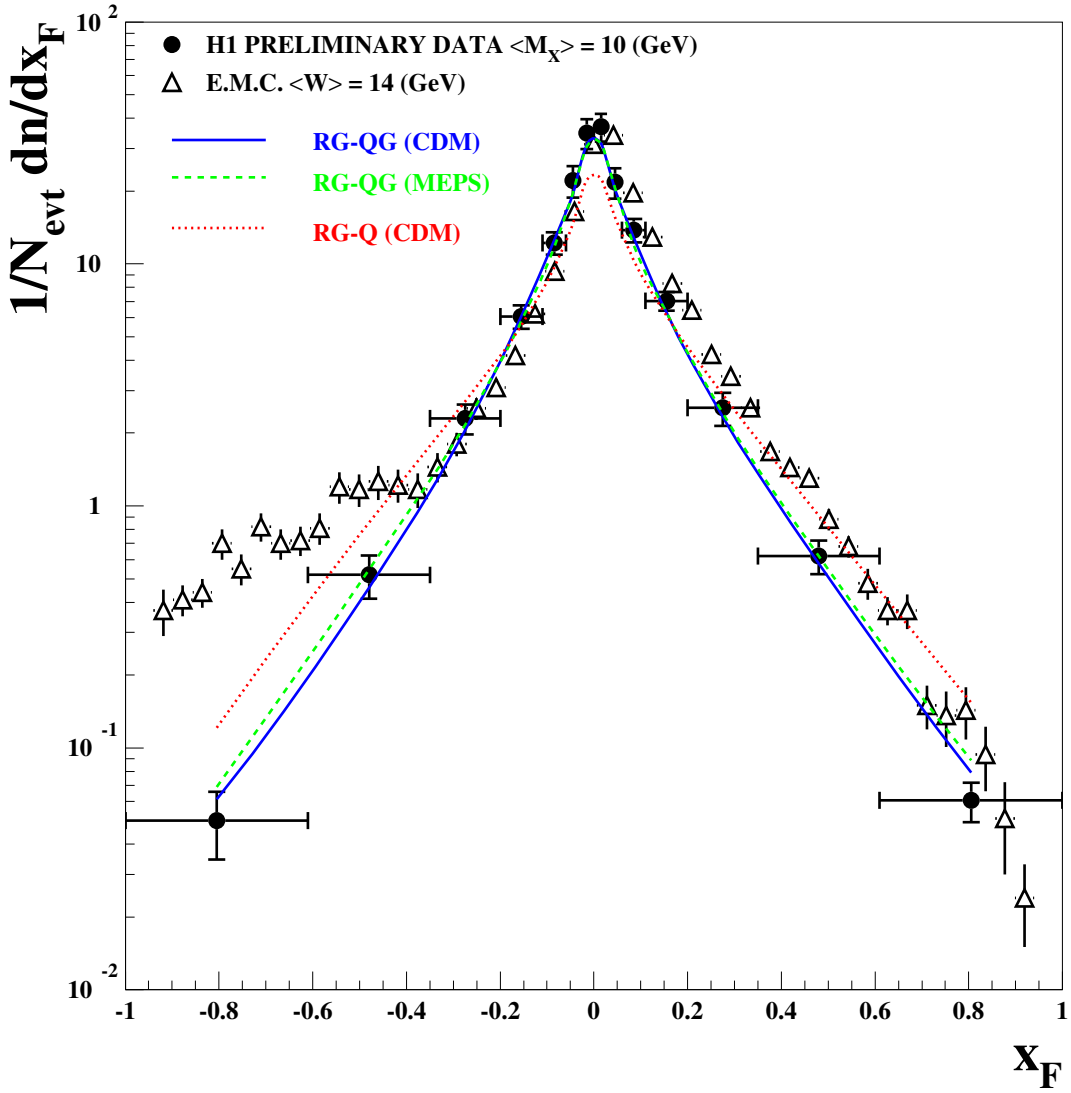


- Large tail to large P_T^{*2} over that observed in EMC at similar energy
  $\rightarrow$ In the kinematic domain of the EMC data the $\gamma^* p$ interactions are dominated by valence and sea quark interactions
- Quark dominated structure unable to reproduce high P_T^{*2} tail

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

In Diffraction the relevent mass scale is M_X

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

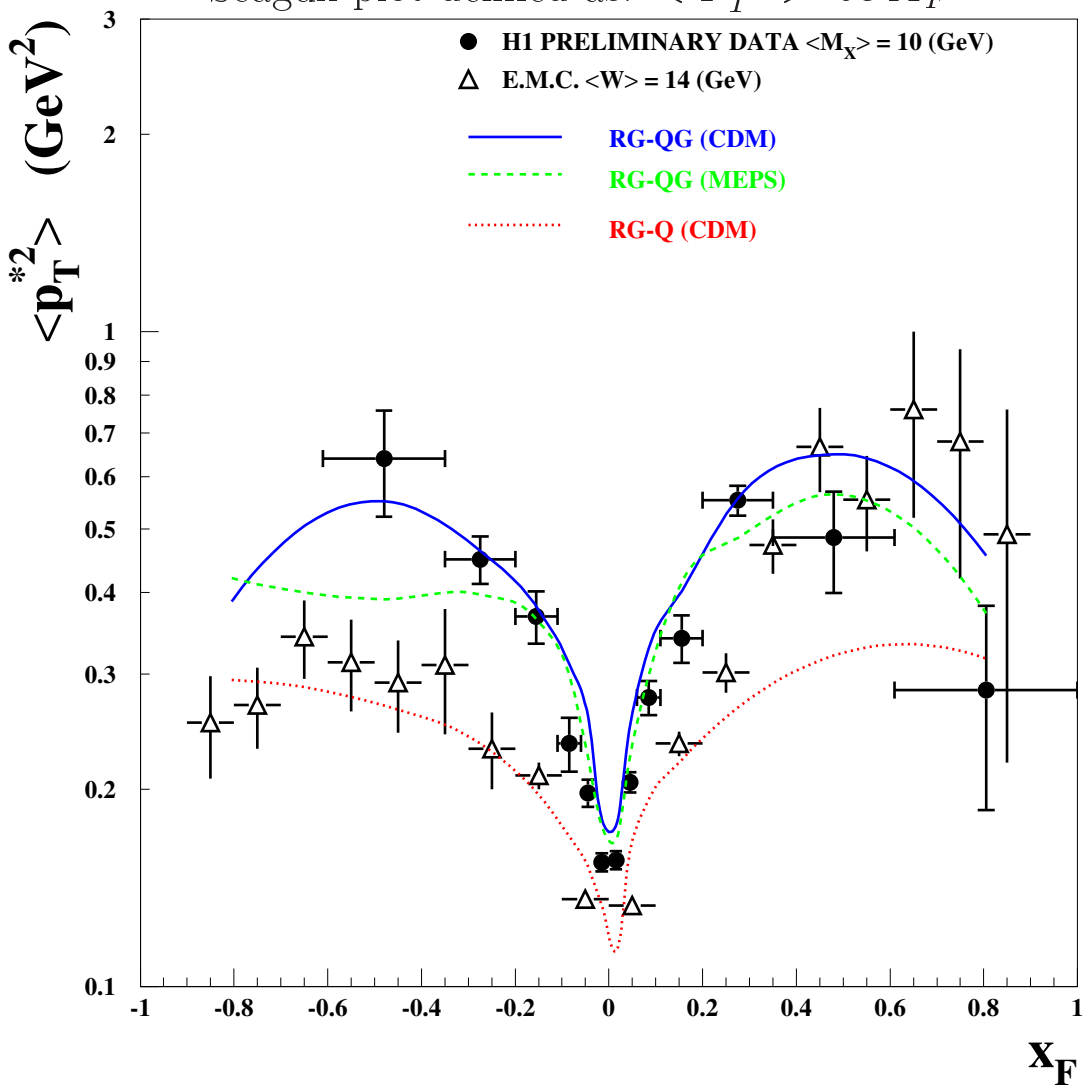


- Symmetry between photon and Pomeron hemispheres
  $\rightarrow$ In the kinematic domain of the EMC data the $\gamma^* p$ interactions are dominated by valence and sea quark interactions

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

"Seagull" plot in $\gamma^* I\!P$ C.M.S.

Seagull plot defined as: $< P_T^{*2} > \; vs \; X_F$



- Symmetry between photon and Pomeron hemispheres $\rightarrow$ More $< P_T^{*2} >$ in Pomeron remnant hemisphere (no suppression of radiation) $\rightarrow$ more point like remnant
- Higher $< P_T^{*2} >$ at $X_F \sim 0$ than EMC data $\rightarrow$ significant contribution from hard subprocess

Energy Flow Summary

- E–flow distributions symmetric about $\eta^* \approx 0$
  $\rightarrow$ High level of energy flow about $\eta^* \sim 0$
- High p_T^{*2} tail
  $\rightarrow$ H1 $\gamma^* I\!P$ data harder than EMC $\gamma^* p$ data
- X_F and "Seagull" plots rather symmetric about $X_F \sim 0$
  $\rightarrow$ More point like remnant than proton
- Well described by QCD evolved M.C. ("leading" gluon prediction)

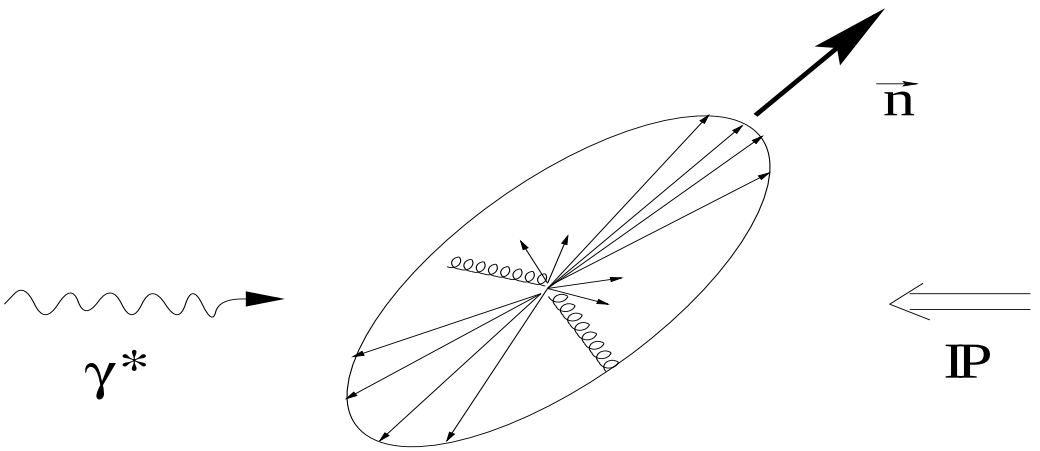
THRUST

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

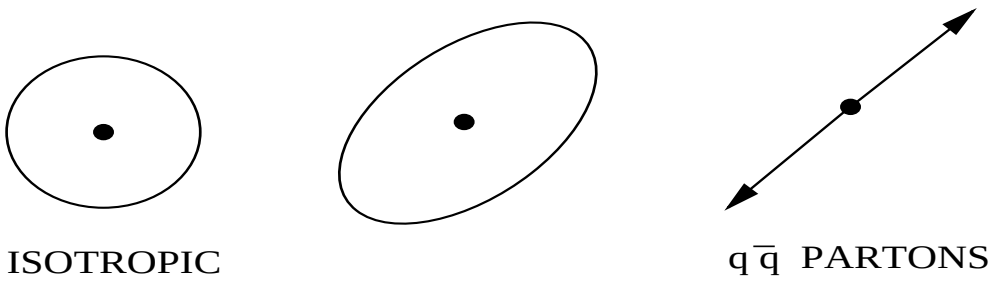
- Information from Thrust:

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. γ^* $I\!P$ axis
  2. Shape given by T

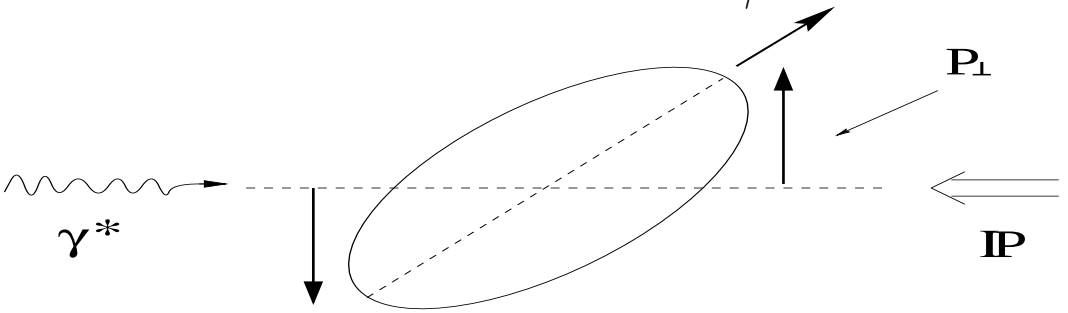


$$1/2 < T < 1$$



THRUST $\mathbf{P}_\perp$

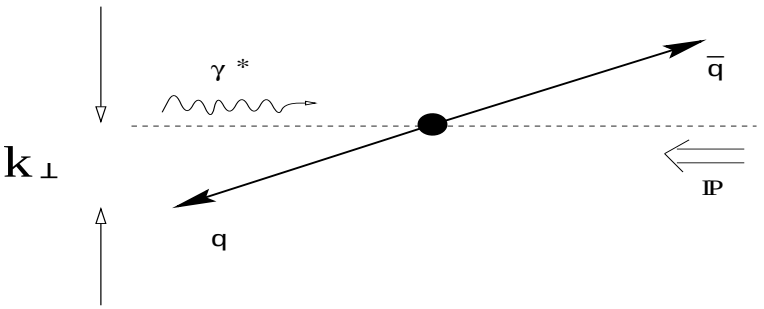
- From $\vec{n}$ w.r.t. $\gamma^* \mathbb{P}$ axis



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

Final State Expectations:

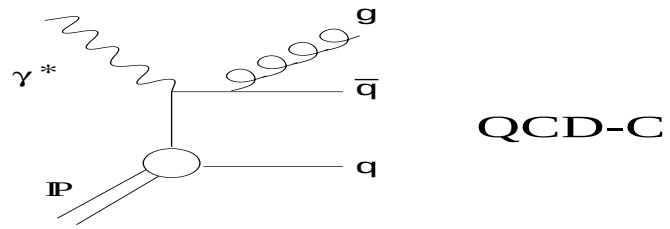
Quark dominated Pomeron



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

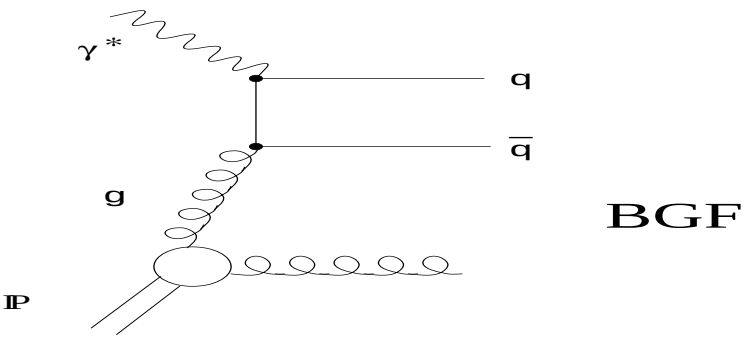
Only Soft QCD Radiation
$p_\perp \sim k_\perp$, $p_\perp^2 < 1\,\mathrm{GeV}^2$

High $P_\perp$ processes



QCD-C

$\sim$ 3 Jet Topology
$T < 1$

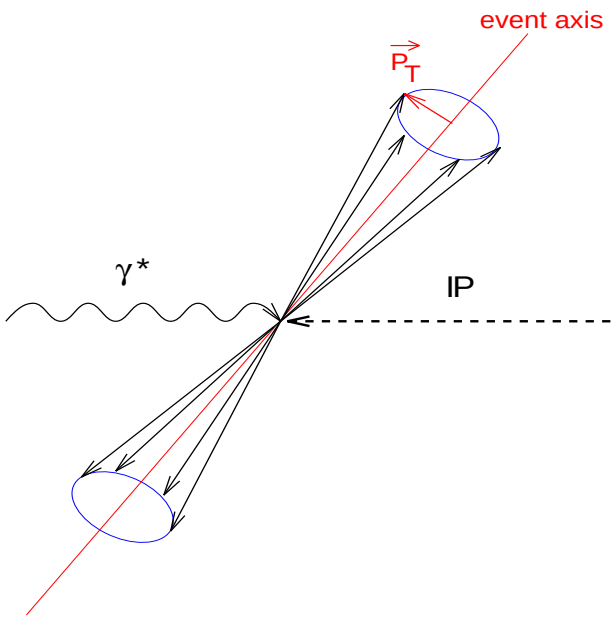


BGF

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

EVENT SHAPES: SPHERICITY

$$S = \frac{3}{2} min \frac{\Sigma p_{Ti}^2}{\Sigma p_i^2}$$



Event Shape Measurements:

- Sphericity (S) gives topology of the event:

  2–jet–like events: $S \to 0$

  spherical events: $S \to 1$

- Mean Squared Transverse Momentum w.r.t. $\vec{n}_S$

$$\langle p_T^2 \rangle = \frac{\Sigma p_T^2}{N}$$

$\to \langle p_T^2 \rangle$ sensitive to higher order gluon emission

$\to$ 3–jet structure

EVENT SHAPES: Kinematics and Event Selection

Event Kinematics

- $Q^2 > 5\,\mathrm{GeV}^2$
- $160 < W < 250\,\mathrm{GeV}$
- $7 < M_X < 25\,\mathrm{GeV}$
- $\eta_{max} < 1.8$

Hadronic Final State Selection

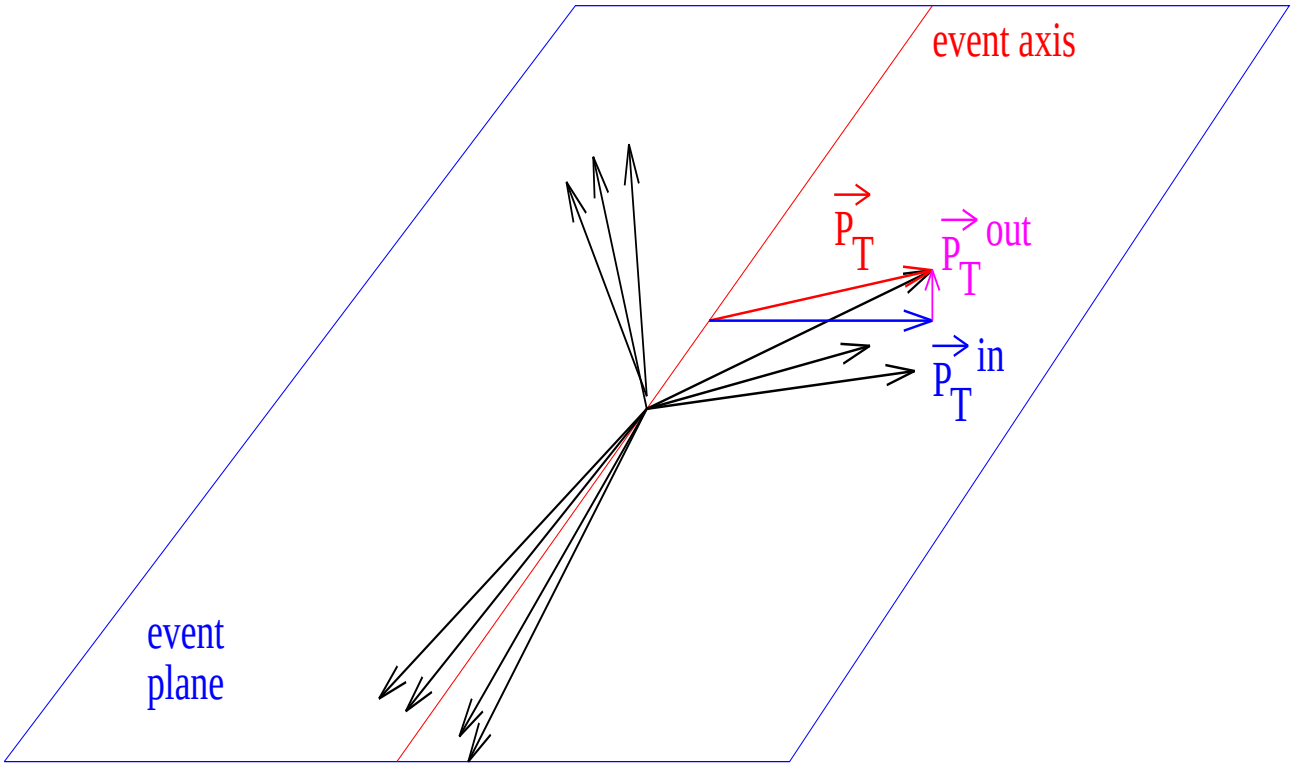
- $N_{part} > 3$
- $M_X > 7\,\mathrm{GeV}$
  $\rightarrow$ ensure sufficient hadronic activity
- $\eta_{max} < 1.8$
- $W > 160\,\mathrm{GeV}$ *and* $M_X < 25\,\mathrm{GeV}$
  $\rightarrow$ suppress non–diffractive DIS background

Correction to the hadron level:

$\rightarrow$ Subtract remaining non–diffractive DIS background

$\rightarrow$ Using Diff–MC correct the distributions to the hadron level to the above kinematic region.

EVENT SHAPES: Hadronic Plane



Measurements:

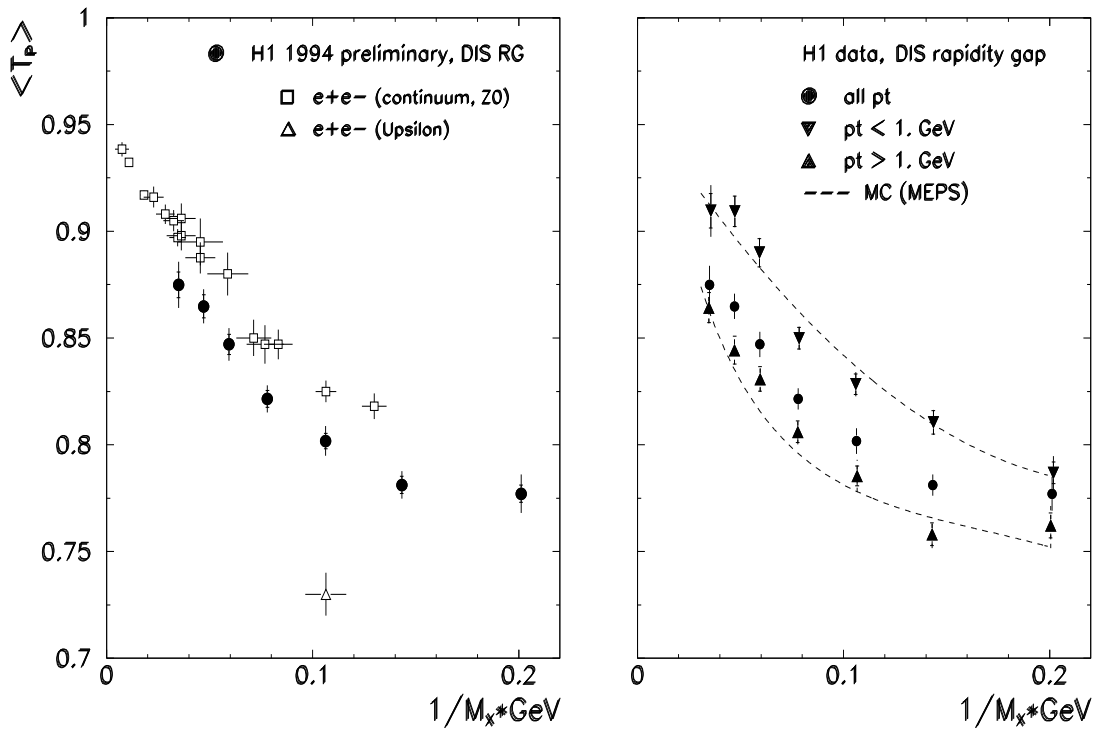
- Mean squared transverse momentum in and out of the event plane:
  $\langle p_{T\,in}^2 \rangle + \langle p_{T\,out}^2 \rangle = \langle p_T^2 \rangle$

For a 3–jet final state expect:

- Non–negligable $\langle p_T^2 \rangle$ w.r.t. the event axis
- The 3 jets must lie in the event plane
  $\Rightarrow \langle p_{T\,out}^2 \rangle$ must be small

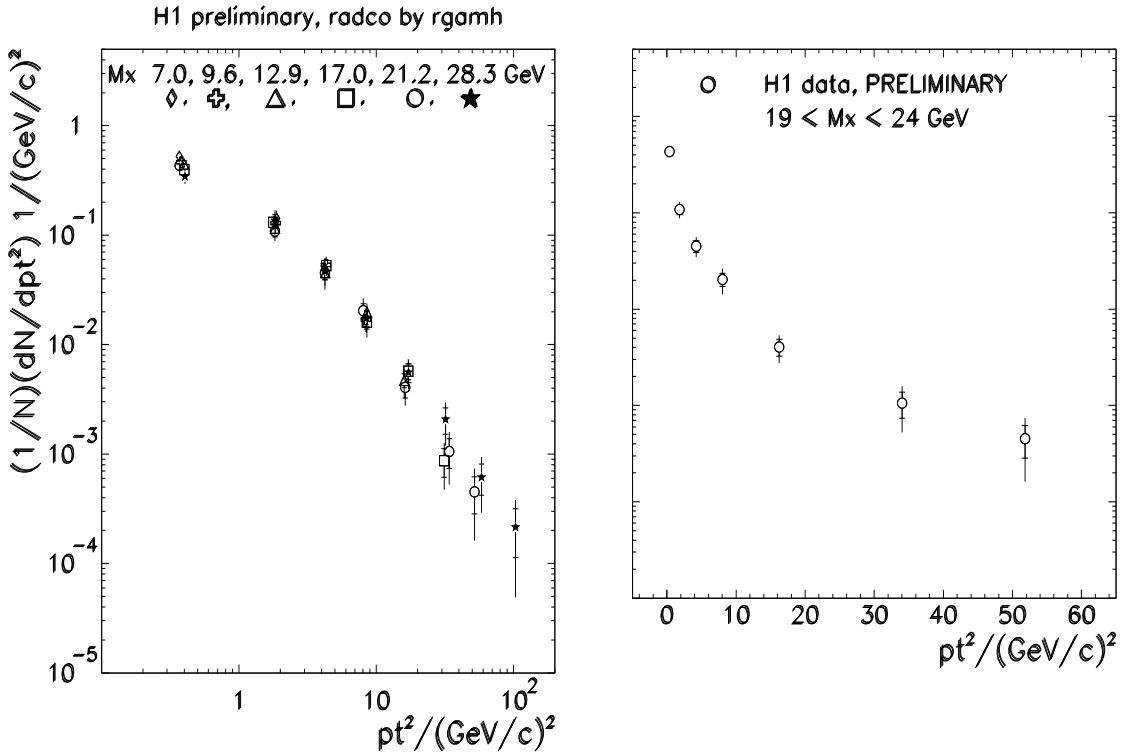
THRUST

→ Fully corrected with systematic + statistical errors in quadrature.



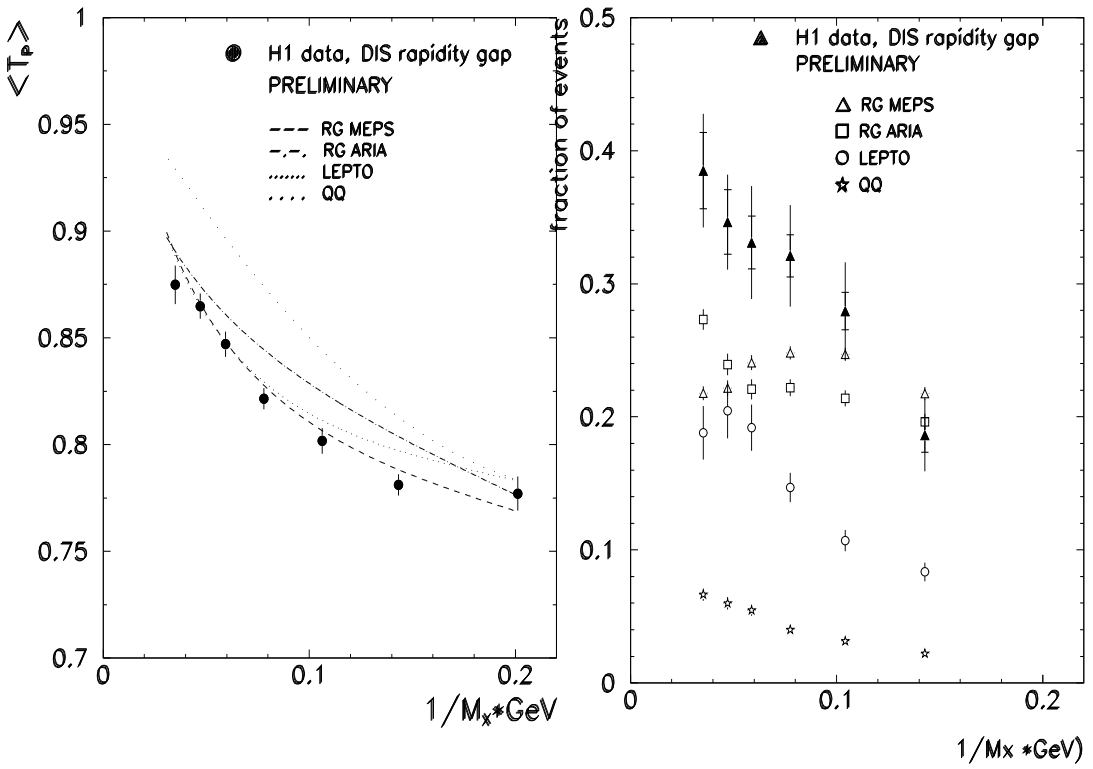
- $<$ Thrust $>$ grows with M_X
  → Final state not isotropic but exhibits a growing back to back correlation in the energy flow
  → 2–Jet is the leading topological property
- High $P_\perp$ data show strong collimation though lower $< T >$
  → Requirement of significant gluon radiation
- QCD Evolved M.C. describes data well

THRUST P_T^2



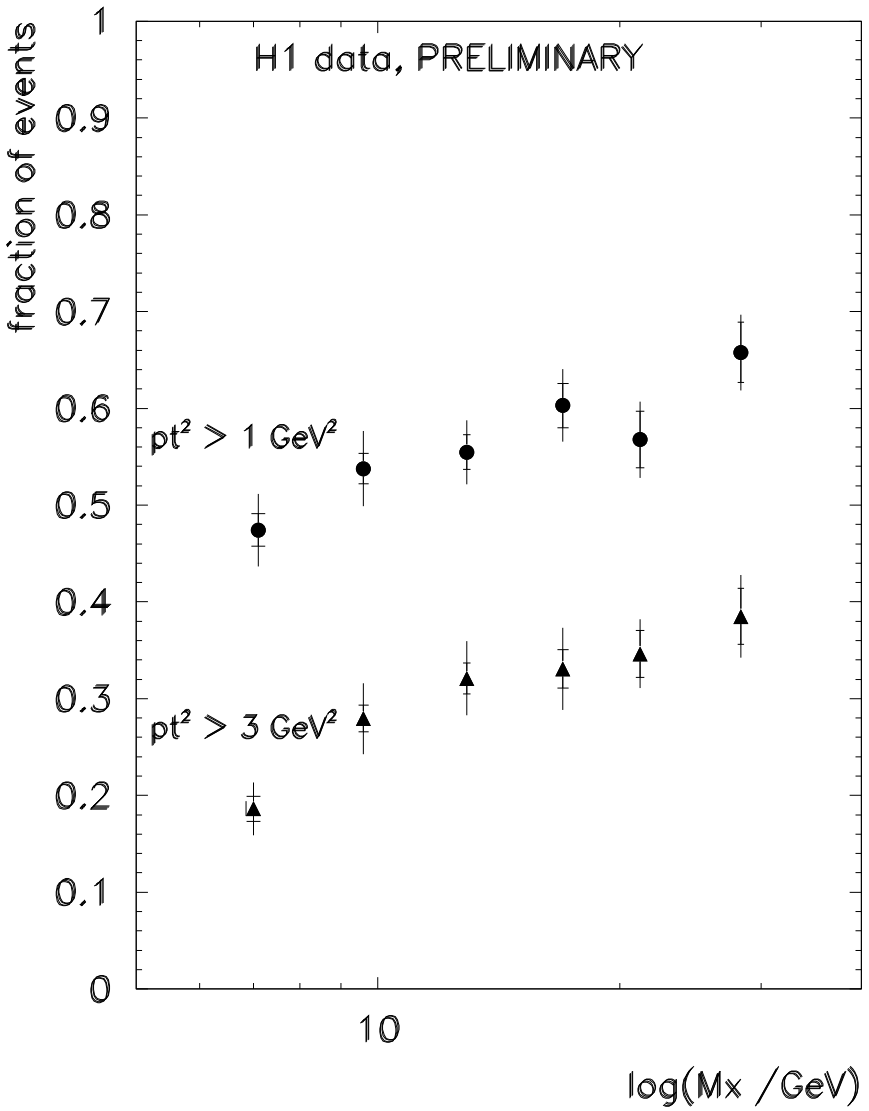
- P_T^2 distribution peaked at low P_T^2 values
- Substantial P_T^2 tail
  $\rightarrow$ Significant contribution from high P_T hard processes
- For all values of M_X the data show a universal shape in p_T

THRUST Model Comparisons



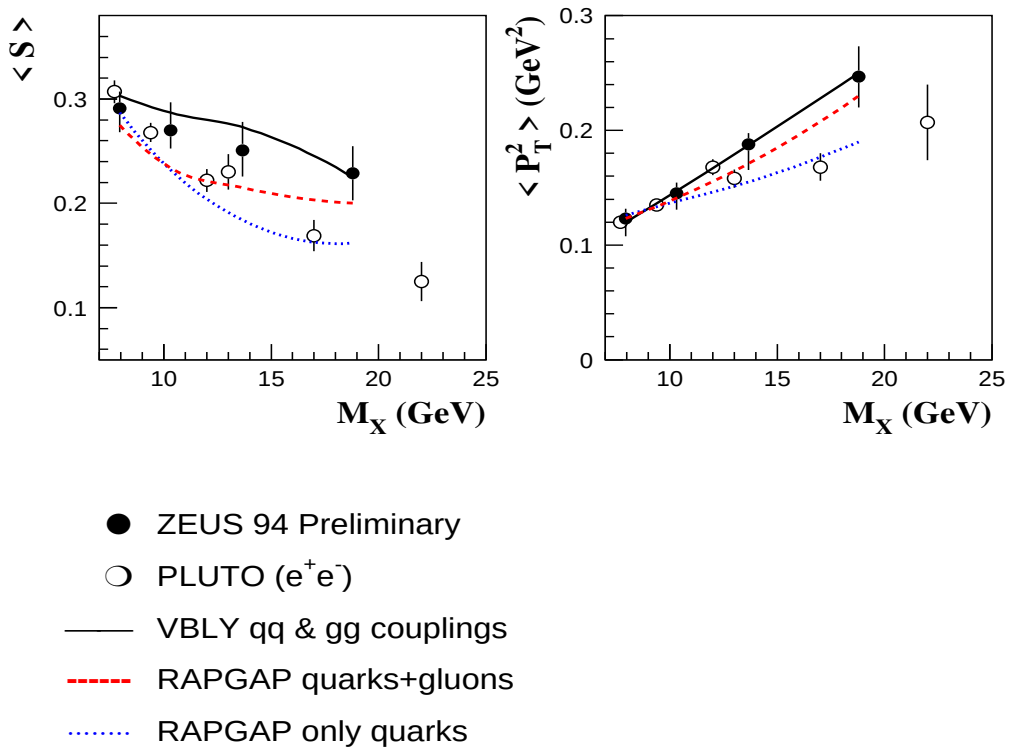
- "Leading" Gluon models describe the $< T >$ vs M_X well
  $\rightarrow$ Though description is not perfect
- No model is able to describe the M_X dependence of the high P_T data

% Of Events With High P_T



- $50 \rightarrow 60\%$ of data have $P_T^2 > 1\,\mathrm{GeV}^2$
- $25 \rightarrow 35\%$ of data have $P_T^2 > 3\,\mathrm{GeV}^2$
- Such a significant fraction of events requires large contribution from high p_T subprocesses

EVENT SHAPES: Sphericity



- ZEUS Data

  → $\langle S \rangle$ decreases with increasing M_X ⇒ Collimation

  → Strong rise in $\langle p_T^2 \rangle$ ⇒ Significant higher order gluon radiation (3–jet events)

- ZEUS–PLUTO Comparison

  → Diffractive DIS less collimated than e^+e^-

  → Stronger rise in $\langle p_T^2 \rangle$ in DIFF–DIS

  ⇒ Additional mechanism to hard gluon bremsstrahlung for three jet formation

- Monte Carlo Comparisons

  → Quarks only in $I\!P$ similar to e^+e^-

  → Factorisable MC $q + g$ closer to the data

  → Pointlike $I\!P$ coupling model gives good description of the data

Thrust and Event Shapes Summary

- 2–jettiness and alignment with $\gamma^* I\!P$ axis are the leading topological properties
- There is a large P_T^{*2} tail
  $\rightarrow$ 30 % of events have $P_T^{*2} > 3\,\mathrm{GeV}^2$
- Event Shapes

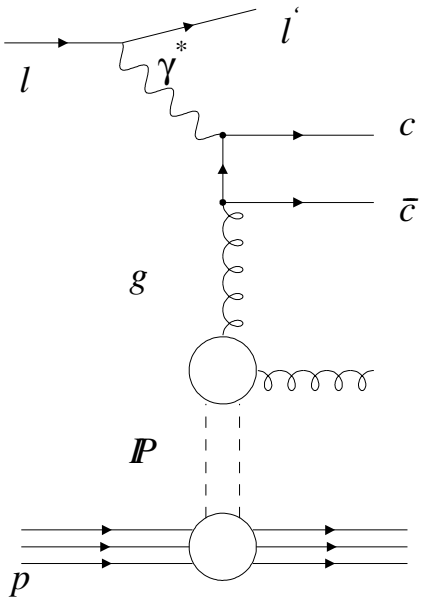
  $\rightarrow$ $\langle S \rangle$ falls less sharply than in e^+e^-

  $\rightarrow$ $\langle S \rangle$ Strong rise in $\langle p_T^2 \rangle$ steeper than in e^+e^-

  $\Rightarrow$ Requirement of additional mechanism for 3–jet like events

  $\rightarrow$ From MC models a gluonic $I\!P$ is needed to describe the data.

CHARM



Expectations:

- If Pomeron has a significant gluon content
  → BGF dominates
  ⇒ Increased open Charm production
- Charm contribution measured from $D^{*\pm}$ production
- Measure $ep \to e\ D^{*\pm}\ X'\ Y$ via:

$$D^{*\pm} \to (\bar{D}^0)\ \pi^{\pm}_{slow} \ \to \ K^{\pm}\ \pi^{\pm}\ \pi^{\pm}_{slow}$$

Charm Selection

Track Selection

- $|\eta_{track}| < 1.5$
- $p_T > 0.2\,\mathrm{GeV/c}$ for (K, π)
- $p_T > 0.1\,\mathrm{GeV/c}$ for $\pi^{\pm}_{\mathrm{slow}}$

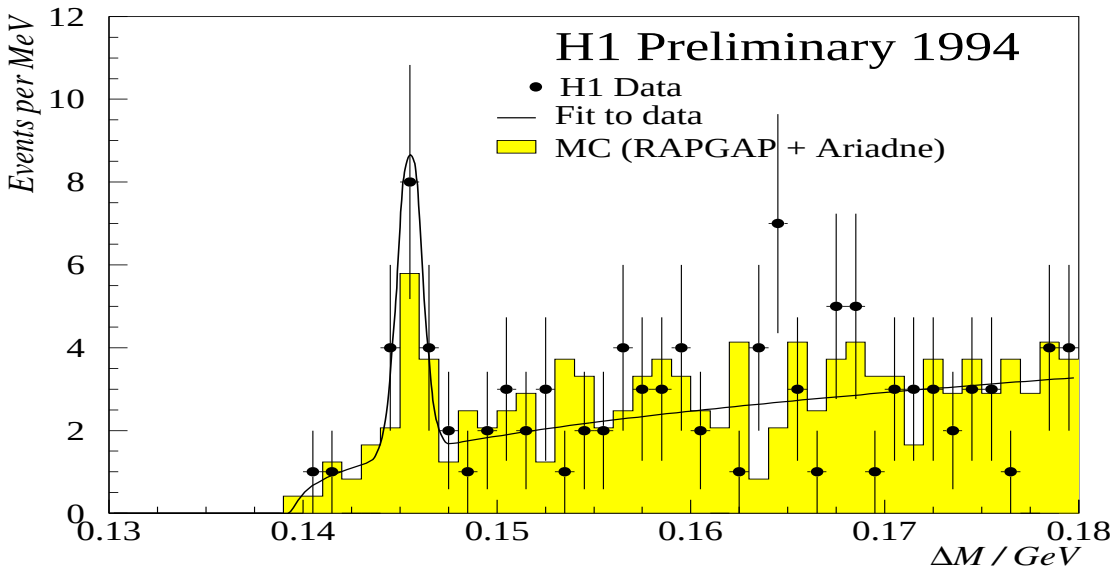
Kinematic range for $D^{*\pm}$

- $|\eta_{D^{*\pm}}| < 1.5$
- $p_T^{D^{*\pm}} > 1.0\,\mathrm{GeV/c}$

Event Kinematic Range:

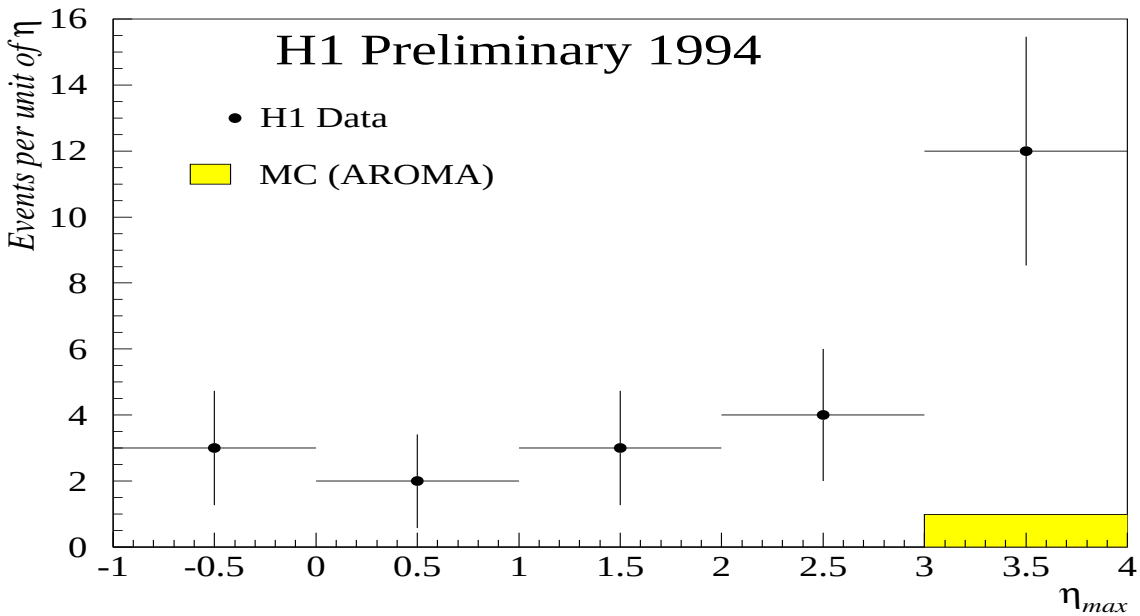
- $10 < Q^2 < 100\,\mathrm{GeV}^2/\mathrm{c}^2$
- $0.06 < y < 0.6$
- $x_{I\!P} < 0.05$
- $M_Y < 1.6\,\mathrm{GeV/c}^2$

Observation of Charm



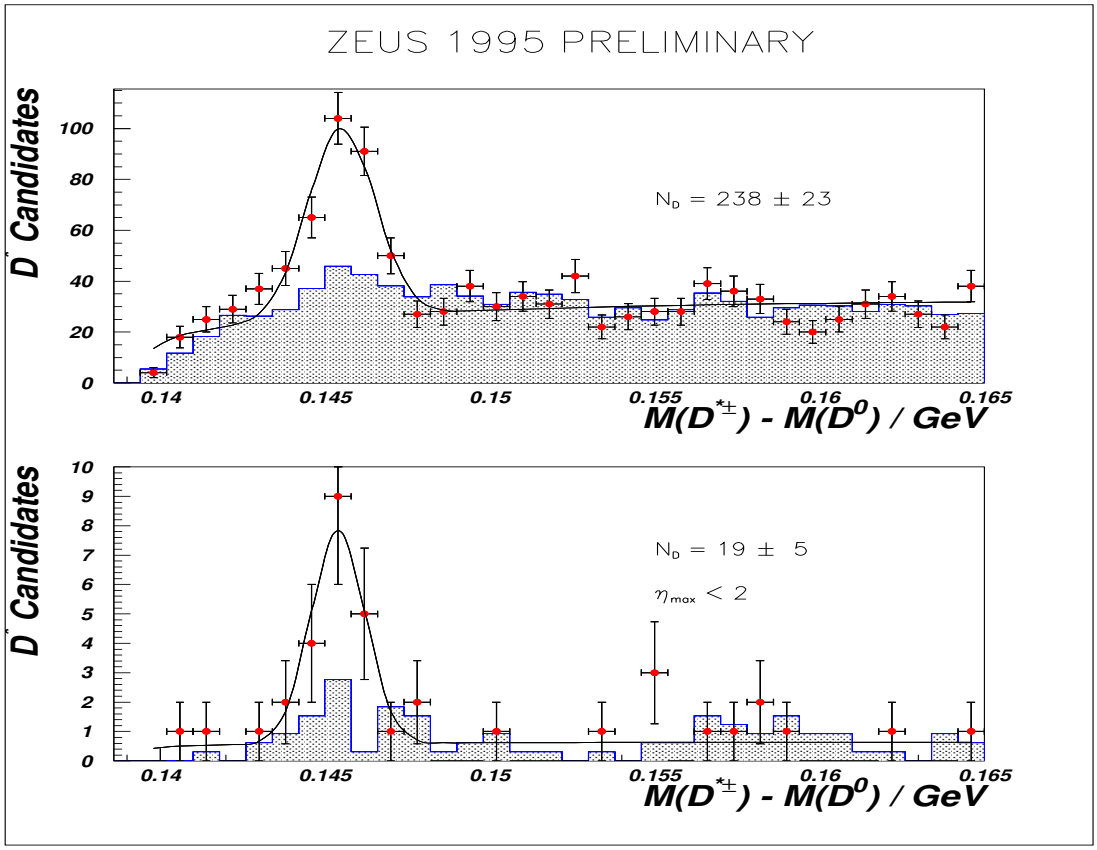
Analysis Method

- Search for pair of oppositely charged tracks ($K\pi$)
- accept if $|M_{K\pi} - M_{D^0}| < 80\,\mathrm{MeV/c^2}$
- combine with a third track ($\pi^{\pm}_{slow}$)
- Look at mass difference $\Delta M = M_{K\pi\pi^{\pm}_{slow}} - M_{K\pi}$



ZEUS: Observation of Charm

Mass Difference Distribution for Selected Samples



ZEUS: $D^{*\pm}$ Cross Section

- Acceptance corrections performed using RAPGAP and Nikolaev–Zakharov

- ZEUS 1995 Preliminary
  $\rightarrow$ Diffractive DIS $D^{*\pm}$ cross section:

$$\sigma_{diff}(D^{*\pm}) = 875 \pm 248(stat) \pm^{395}_{199} pb$$

- Cross section for DIS $D^{*\pm}$ production:

$$\sigma_{diff}(D^{*\pm}) = 3.9 \pm 0.4(stat.only)$$

- ZEUS see $\sim 20\%$ od $D^{*\pm}$ in DIS for $Q^2 > 10\,\mathrm{GeV}^2$ are diffractively produced.

Charm Cross–Section and Conclusions

- From the observed number of events possible to extract a cross section for the process:

$$\sigma(e^+ p \rightarrow \ e^+ D^{*\pm} X Y) = (380 \pm^{150}_{120} \pm^{140}_{110}) \,\mathrm{pb}$$

- QCD–RAPGAP M.C. predicts a value of $\sim 200\,\mathrm{pb}$
- From assumption of a quark dominated Pomeron the predicted cross section is less than $\sim 10\,\mathrm{pb}$
- This is inconsistent at the 2σ level with the measured cross section

Conclusions

- **Energy Flow, Thrust and Event Shapes** have been measured in deep–inelastic diffraction
- 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 $< P_T^{*2} >$
  $\rightarrow$ "leading" 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

- **Sphericity** Strong rise in $\langle p_T^2 \rangle$ above that seen in e^+e^-.
  $\rightarrow$ An enhancement of 3–jet like events over those from e^+e^-.
- **Charm** Significant cross section consistent with QCD evolved prediction (H1)
  $\rightarrow$ Quark only does not describe data

Model in which Pomeron's momentum is carried largely by gluons reproduces many aspects of the final states

Pomeron *seems* to behave like a 'single' gluon