Energy Flow, Thrust and Charm and the Partonic Structure of the Pomeron

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H1 Collaboration

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Outline

- Introduction
- Diffraction
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- Hadronic Final State
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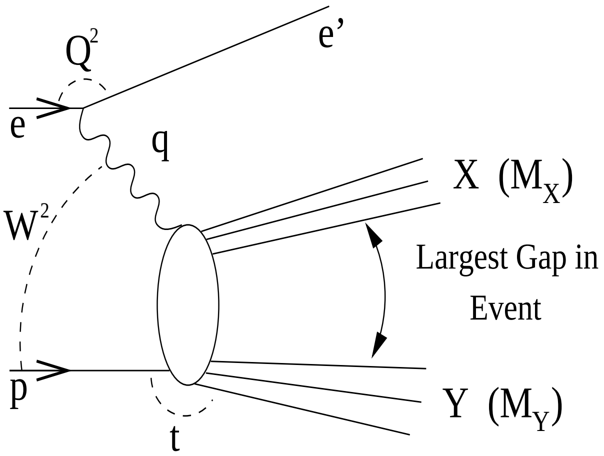
     (b) Thrust
     (c) Charm
- Conclusions

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:

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

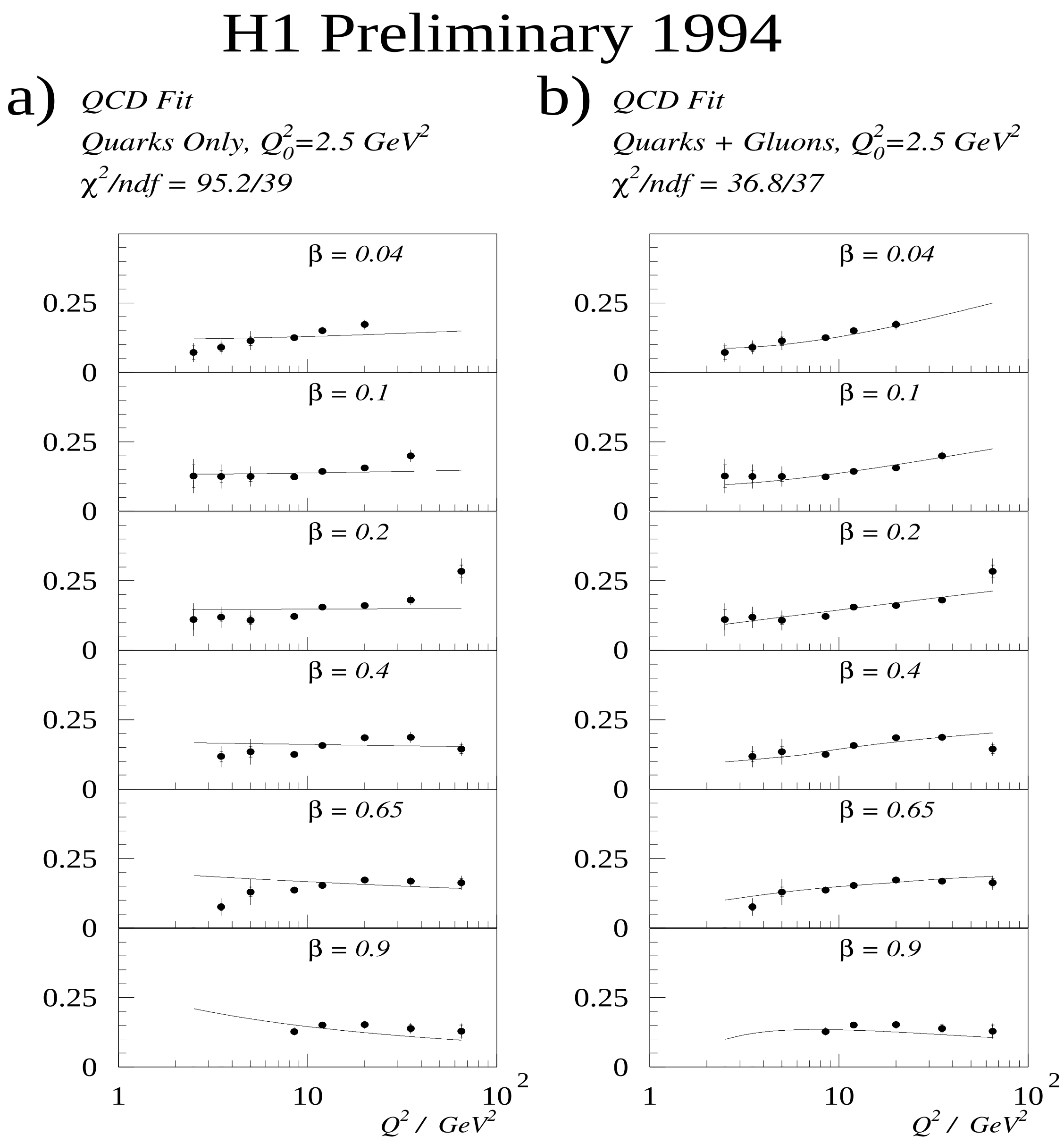
$f_{I\!P/p}(x_{I\!P}, t) \equiv$ Pomeron flux (non–perturbative)

$F_2^{I\!P}(\beta, Q^2)$ 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

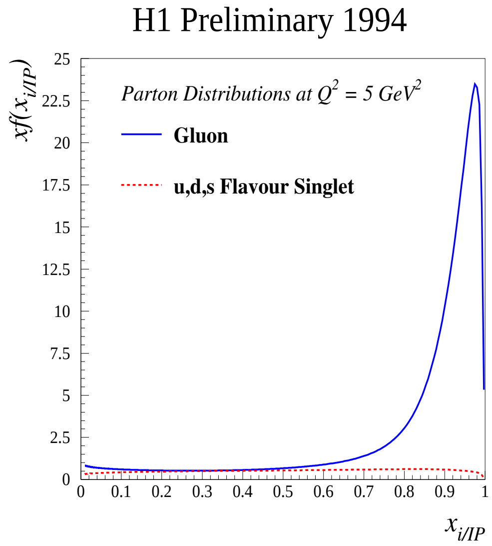
Partonic Structure of Diffractive Exchange

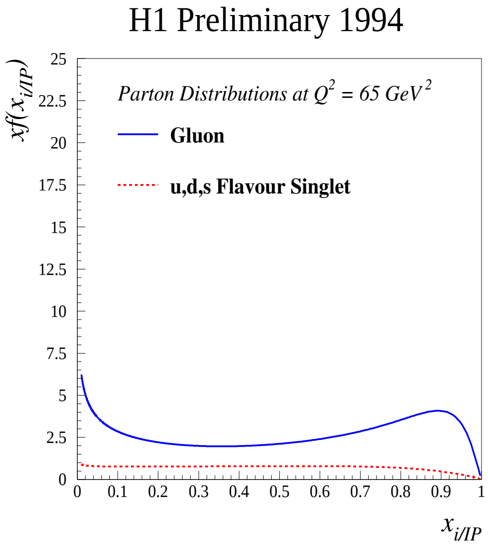


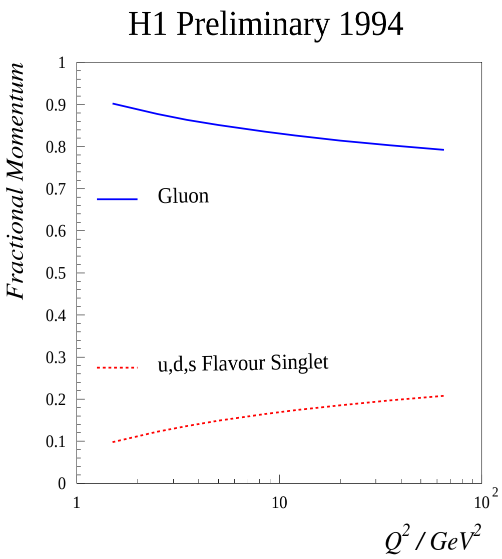
- $\tilde{F}_2^D$ Shows no evidence of a fall in Q^2 with increasing β
- Such strong Q^2 scaling violations
  $\rightarrow$ hint at very hard gluon density?

- 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)
  → based on Ingelman–Sclein 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 → LUND string model (JETSET)

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
- Open Charm production

Final State Selection

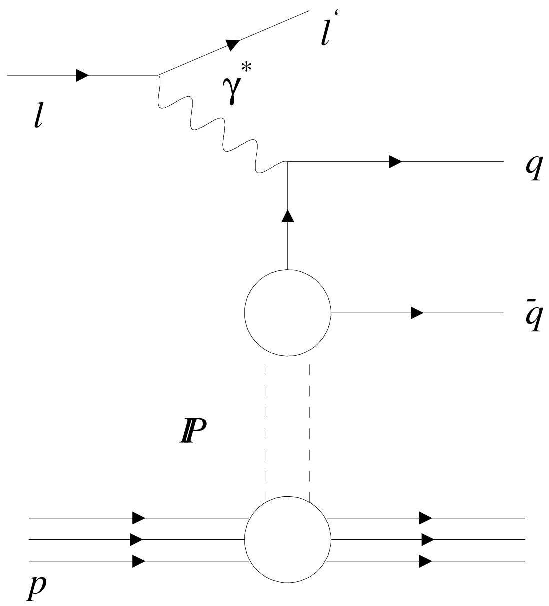
- Energy–Flow and Charged Track Spectra

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: <u>Quark</u> Dominated Object



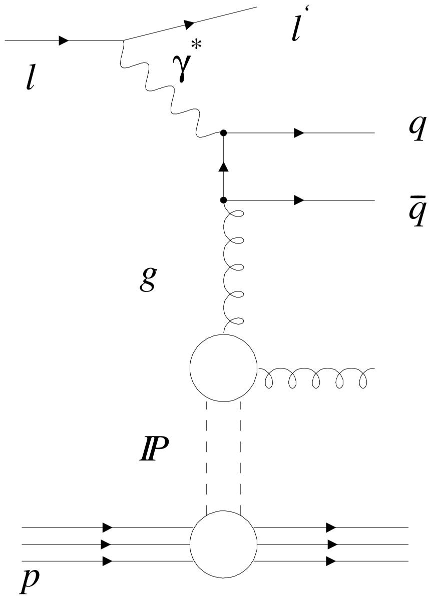
<u>Contribution to E_T, P_T, E–flow</u>

- In γ^* $I\!\!P$ C.M.S. Struck quark and 'remnant' are highly aligned along γ^* $I\!\!P$ axis

E_T May arise from:

- Intrinsic k_T of q + remnant
- Soft gluon bremsstrahlung
  $\rightarrow$ Highly collimated along q + remnant
  $\rightarrow$ 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 γ^* $I\!P$ axis

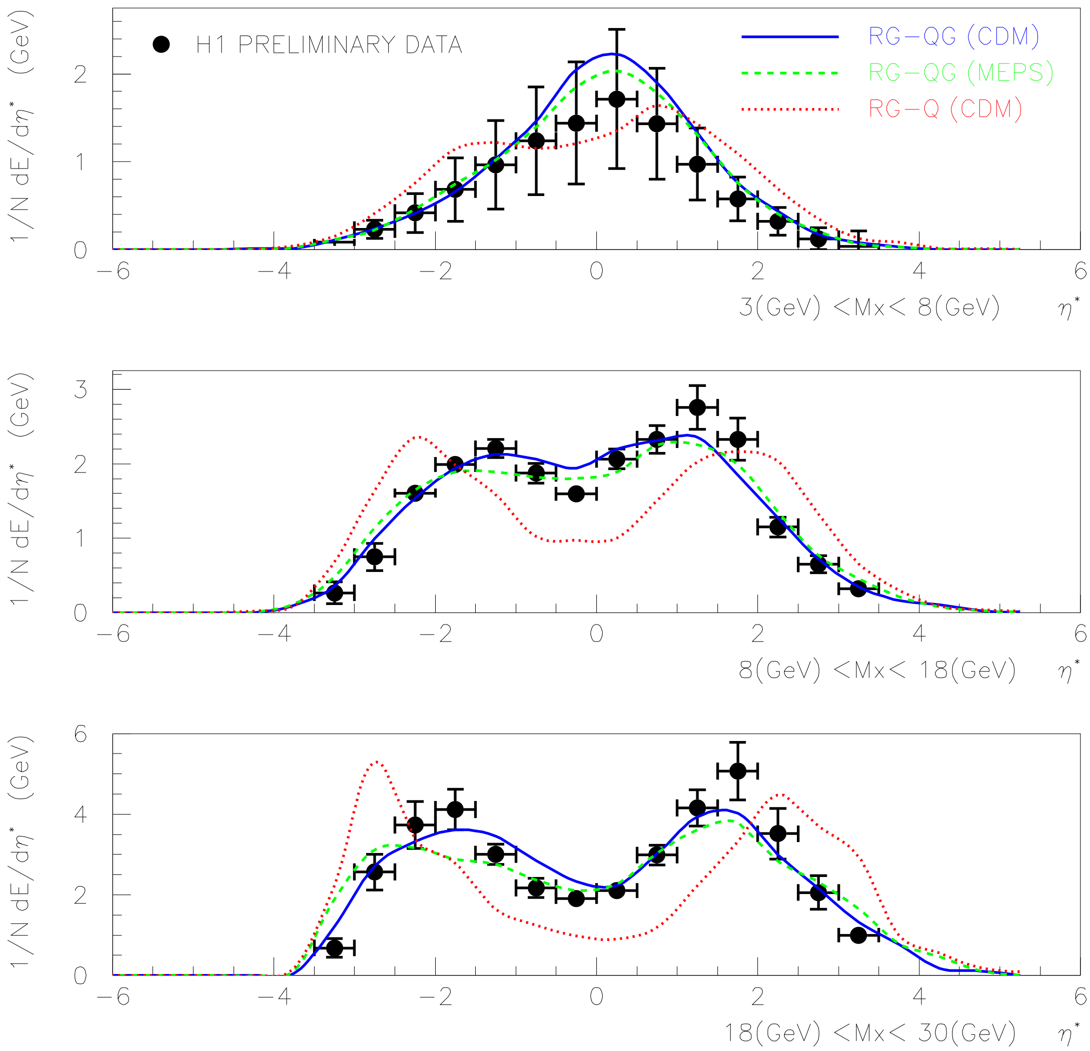
$\rightarrow$ In fact a significant fraction of events can have high p_T $q\,/\,\bar{q}$

$\Rightarrow$ Higher E-flow about $\eta^* = 0$

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

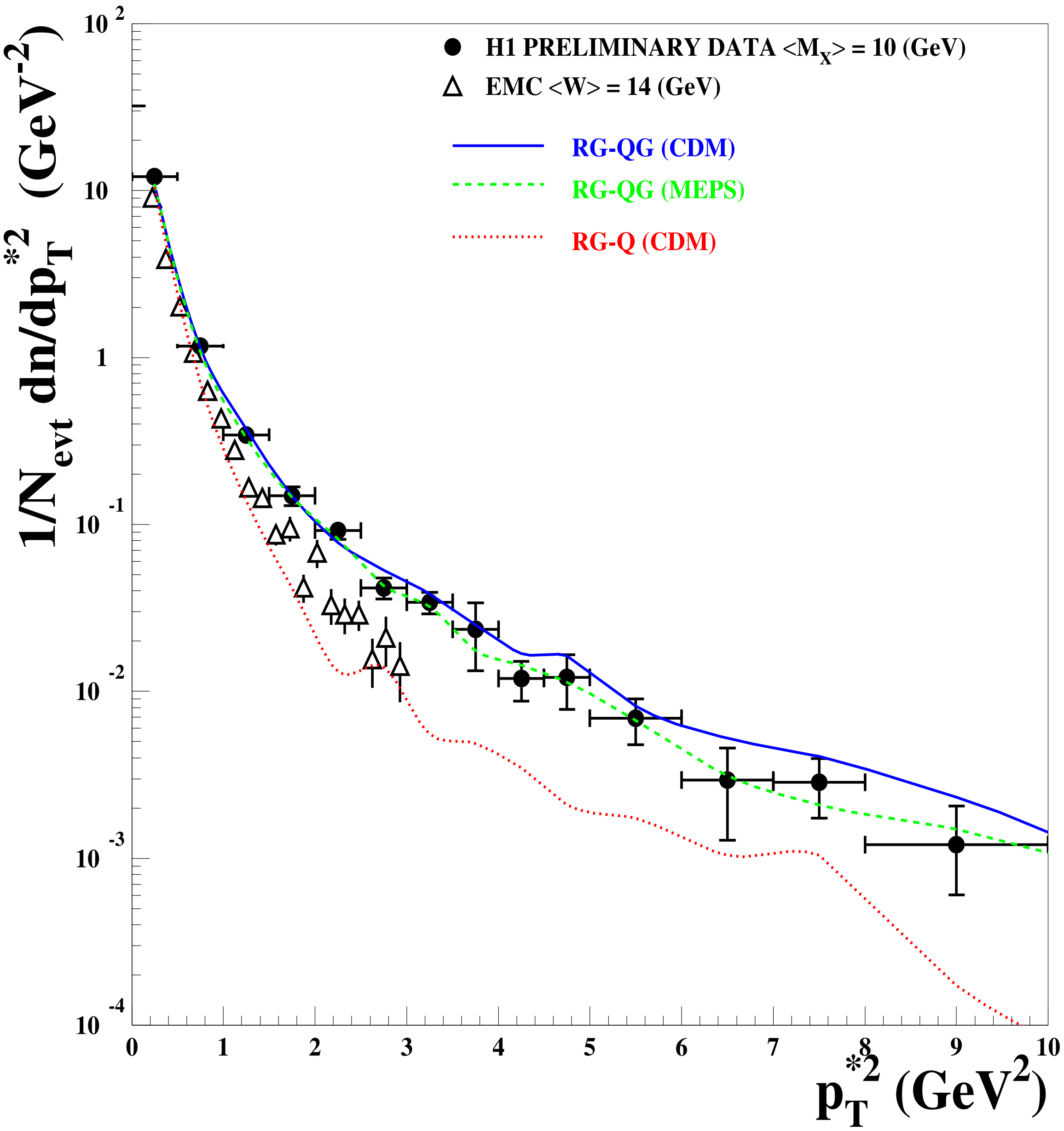
$\rightarrow$ Increased contribution to the energy flow in the central region of η^* in the γ^* $I\!P$ C.M.S.

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.

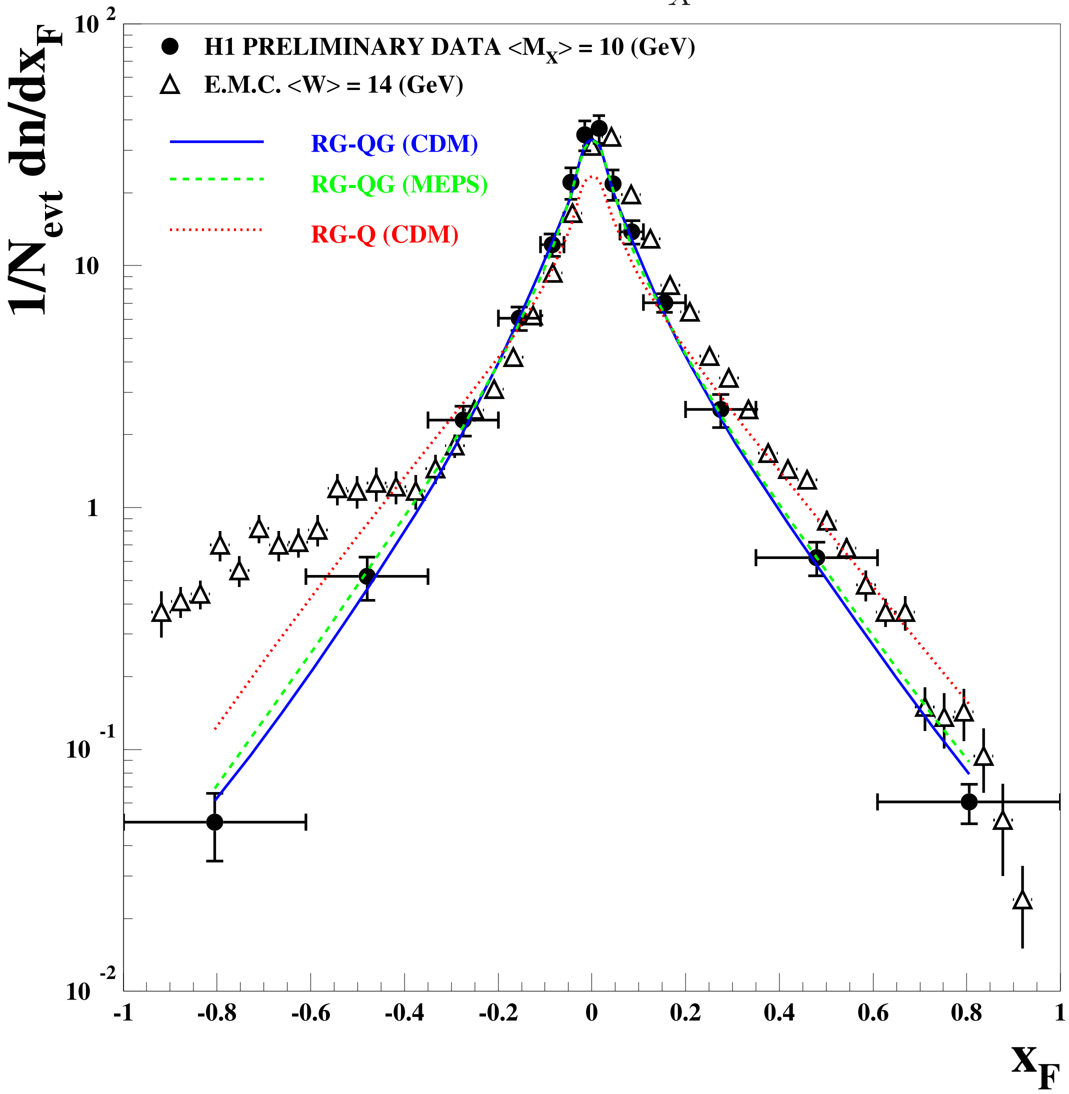


- Large tail to large P_T^{*2} over that observed in EMC at similar energy
  $\rightarrow$ In the kinematic domain of the EMC data the $\gamma^* p$ interactions are dominated by valence and sea quark interactions
- Quark dominated structure unable to reproduce high P_T^{*2} tail

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

In Diffraction the relevent mass scale is M_X

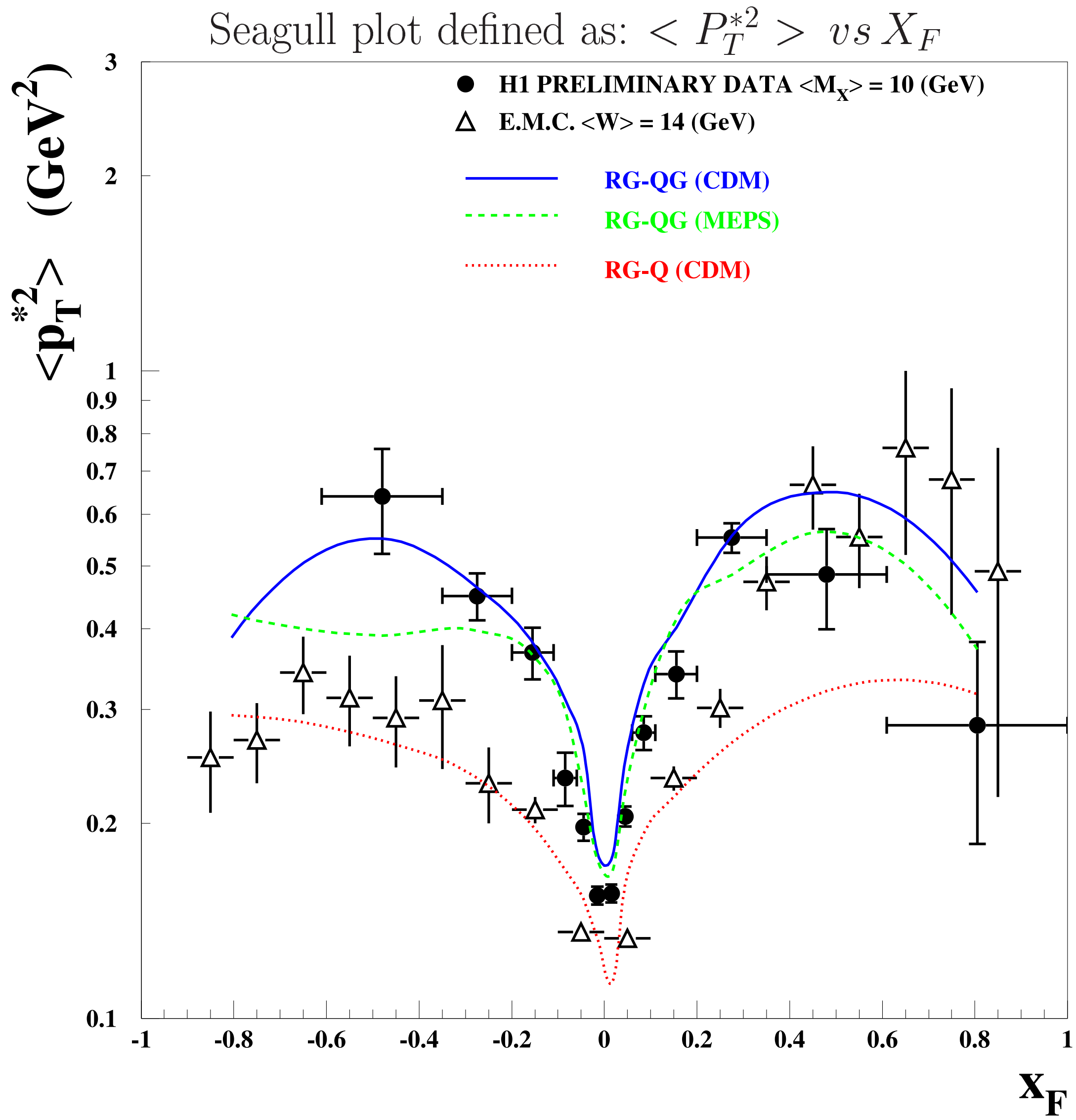
$$\rightarrow x_F = \frac{2p_z^*}{M_X}$$



- 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.



- 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

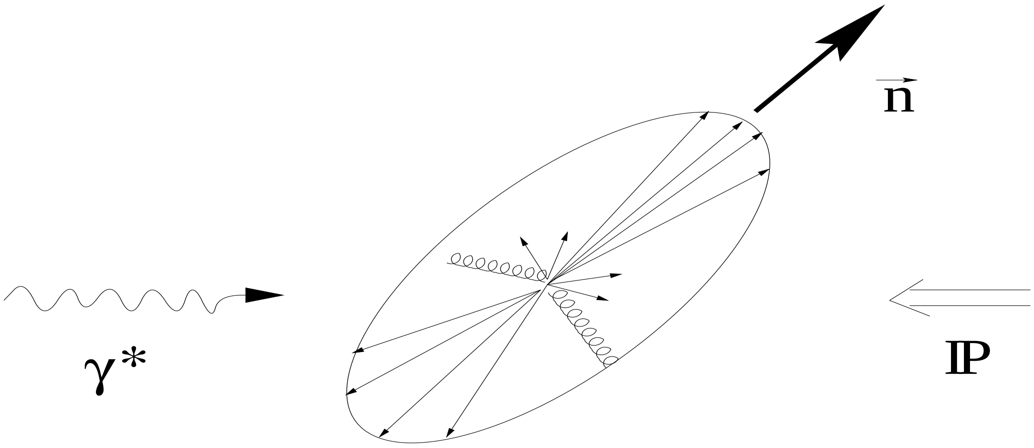
$$T = \frac{1}{\Sigma_{i=1}^{N} |\vec{p}_i|} \times \max\left\{\Sigma_{i=1}^{N} |\vec{p}_i \cdot \vec{n}|\right\}$$

- Information from Thrust:

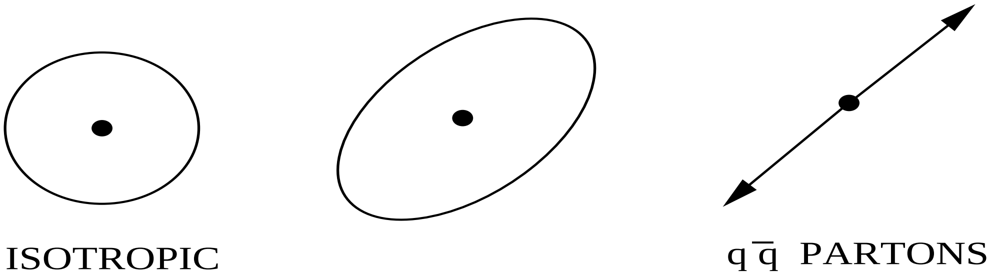
Thrust finds the direction in the C.M.S. along which the energy flow is maximal

- For each event obtain information on:

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

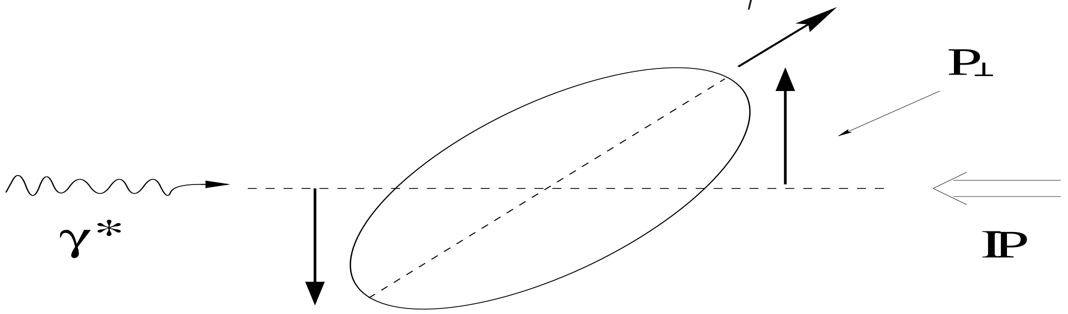


$$1/2 < T < 1$$



THRUST $\mathbf{P}_\perp$

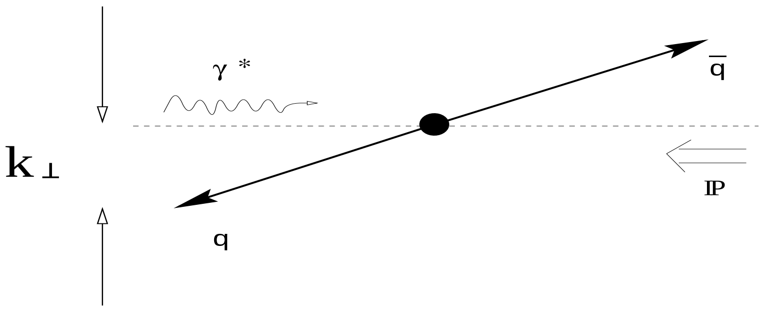
- From $\vec{n}$ w.r.t. $\gamma^*\ I\!\!P$ axis



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

<u>Final State Expectations:</u>

Quark dominated Pomeron



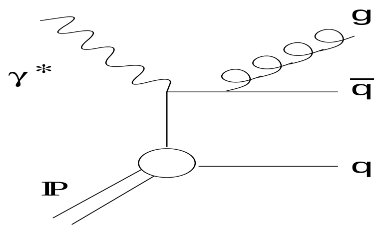
Small $k_\perp$ $q, \bar{q}$ Aligned

~ 2 Jet Topology $T \sim 1$

Only Soft QCD Radiation

$p_\perp \sim k_\perp$, $p_\perp^2 < 1\,\mathrm{GeV}^2$

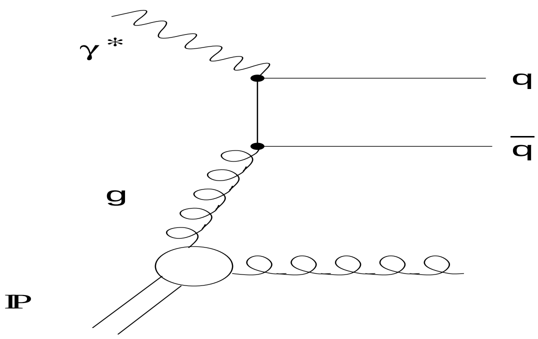
<u>High $P_\perp$ processes</u>



QCD-C

~ 3 Jet Topology

$T < 1$



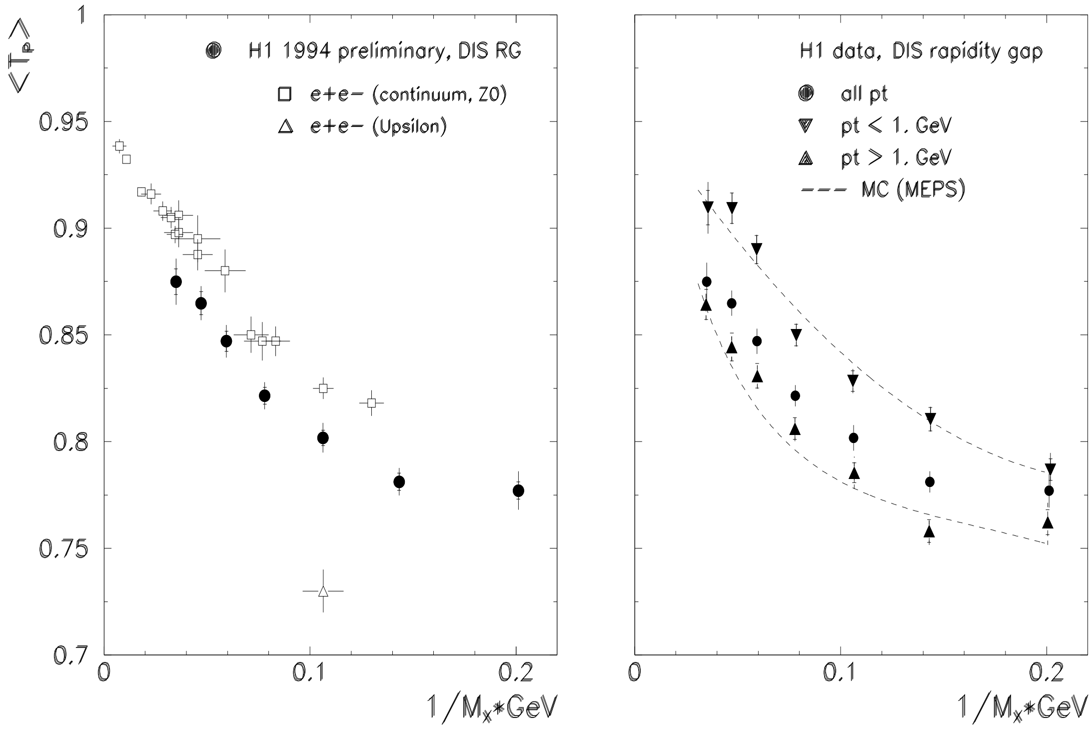
Hard $q, \bar{q}, g$

$p_\perp^2 \gg 1\,\mathrm{GeV}^2$

BGF

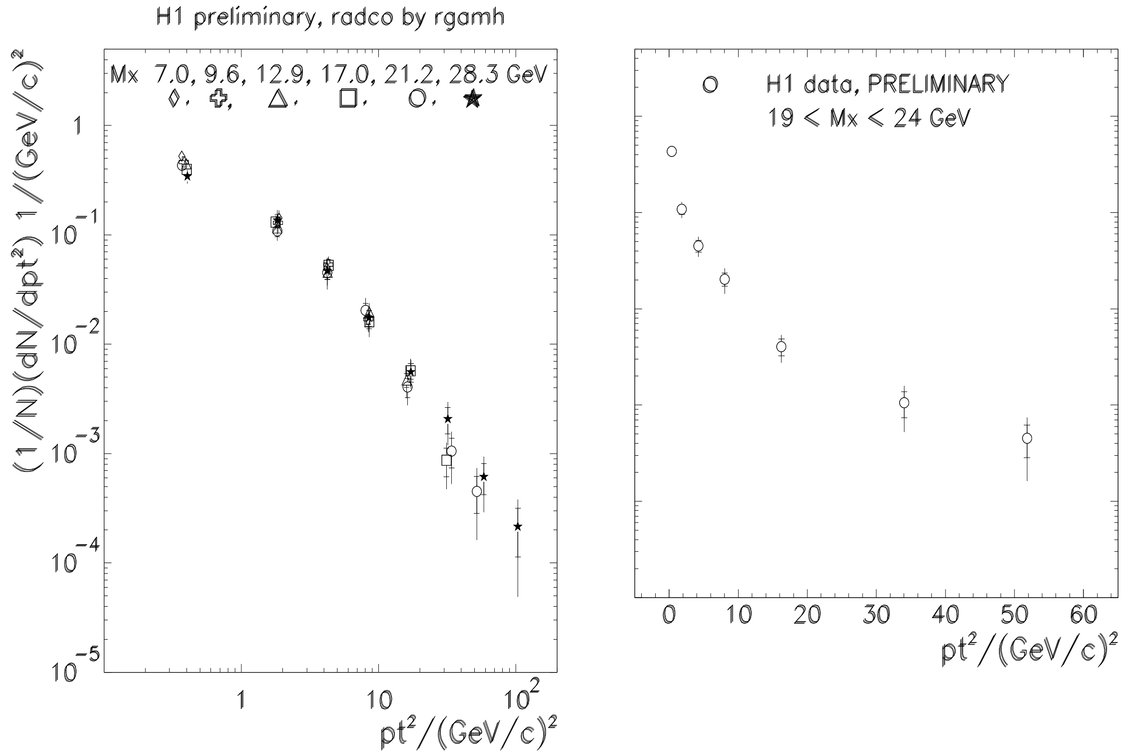
THRUST

→ Fully corrected with systematic + statistical errors in quadrature.



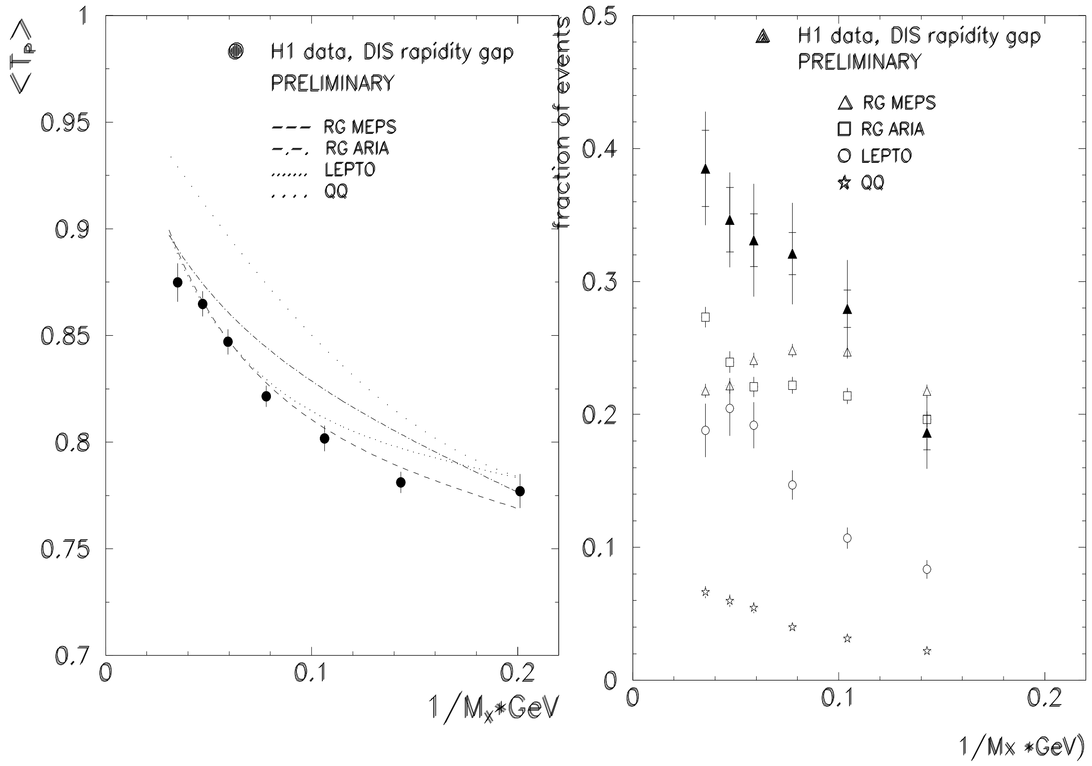
- < Thrust > grows with M_X
  → Final state not isotropic but exhibits a growing back to back correlation in the energy flow
  → 2–Jet is the leading topological property
- High $P_\perp$ data show strong collimation though lower $< T >$
  → Requirement of significant gluon radiation
- QCD Evolved M.C.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

THRUST P_T^2



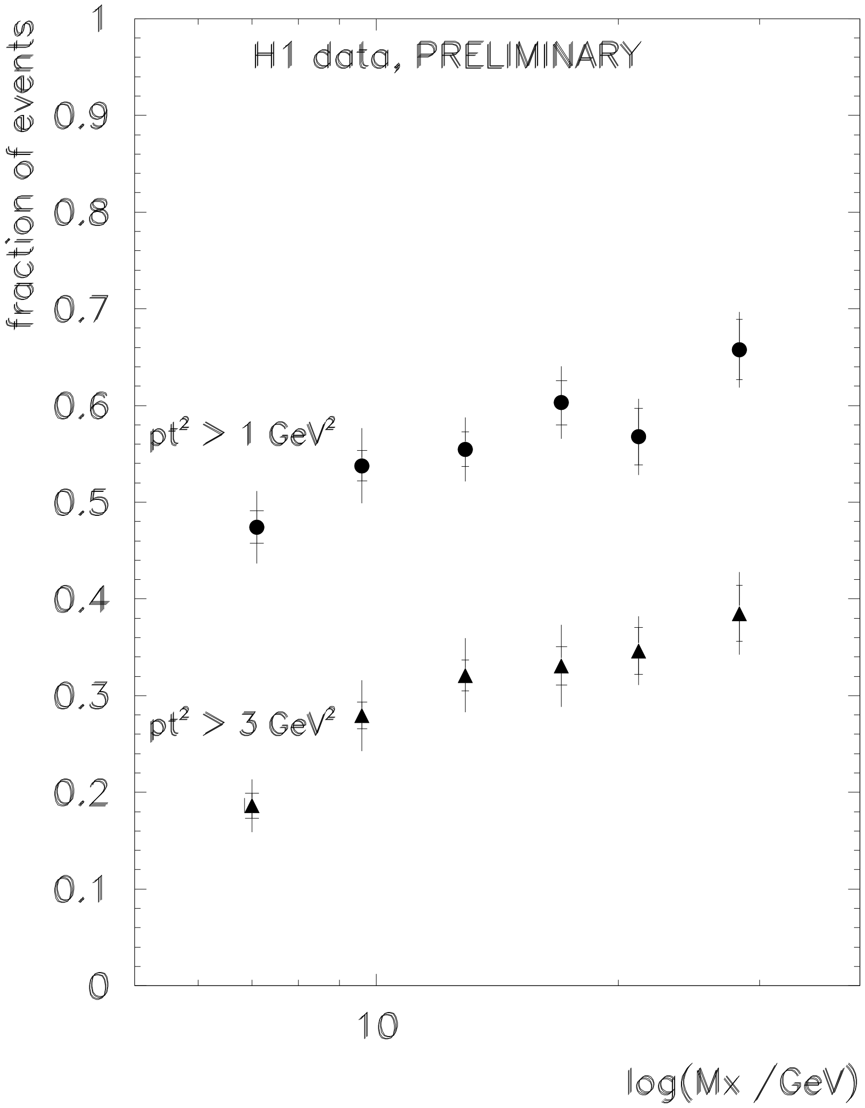
- P_T^2 distribution peaked at low P_T^2 values
- Substantial P_T^2 tail
  $\rightarrow$ Significant contribution from high P_T hard processes
- For all values of M_X the data show a universal shape in p_T

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

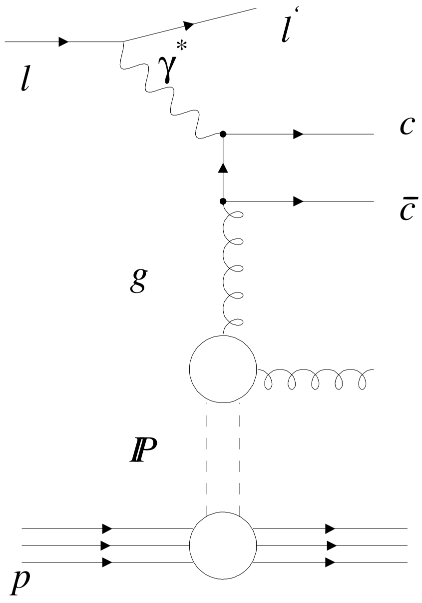


- $50 \rightarrow 60\%$ of data have $P_T^2 > 1\,\mathrm{GeV}^2$
- $25 \rightarrow 35\%$ of data have $P_T^2 > 3\,\mathrm{GeV}^2$
- Such a significant fraction of events requires large contribution from high p_T subprocesses

Thrust Summary

- 2–jettiness and alignment with $\gamma^* \mathbb{P}$ axis are the leading topological properties
- There is a large P_T^{*2} tail
  $\rightarrow$ 30 % of events have $P_T^{*2} > 3\,\mathrm{GeV}^2$
- Except near the kinematic end point P_T^{*2} distributions follow a universal shape independent of M_X
- Data consistent with "Leading" Gluon models and SCI model

CHARM



Expectations:

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

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

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 $\pi^{\pm}_{\mathrm{slow}}$

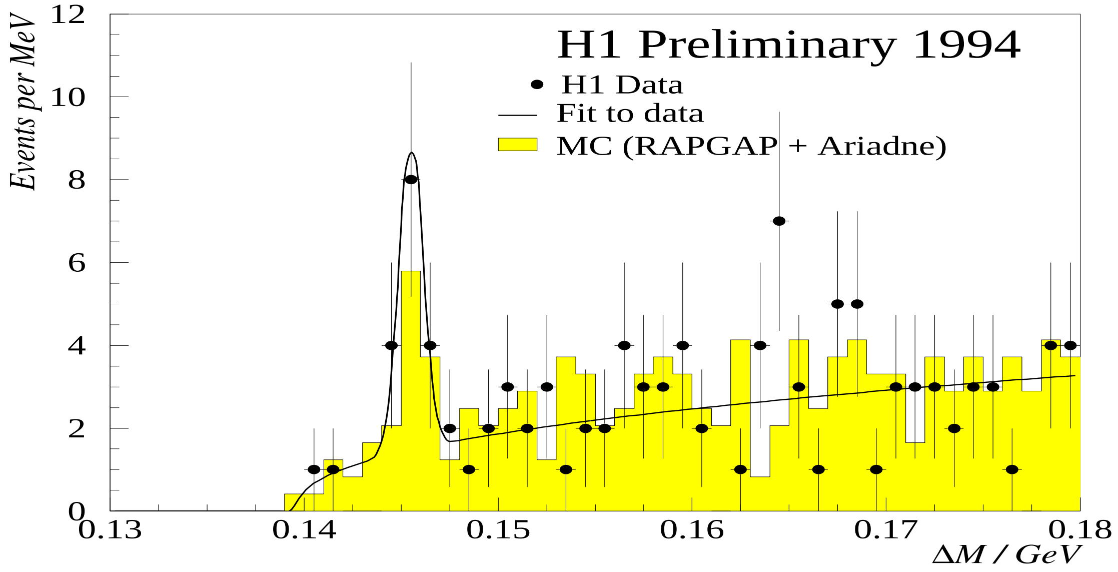
Kinematic range for $D^{*\pm}$

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

Event Kinematic Range:

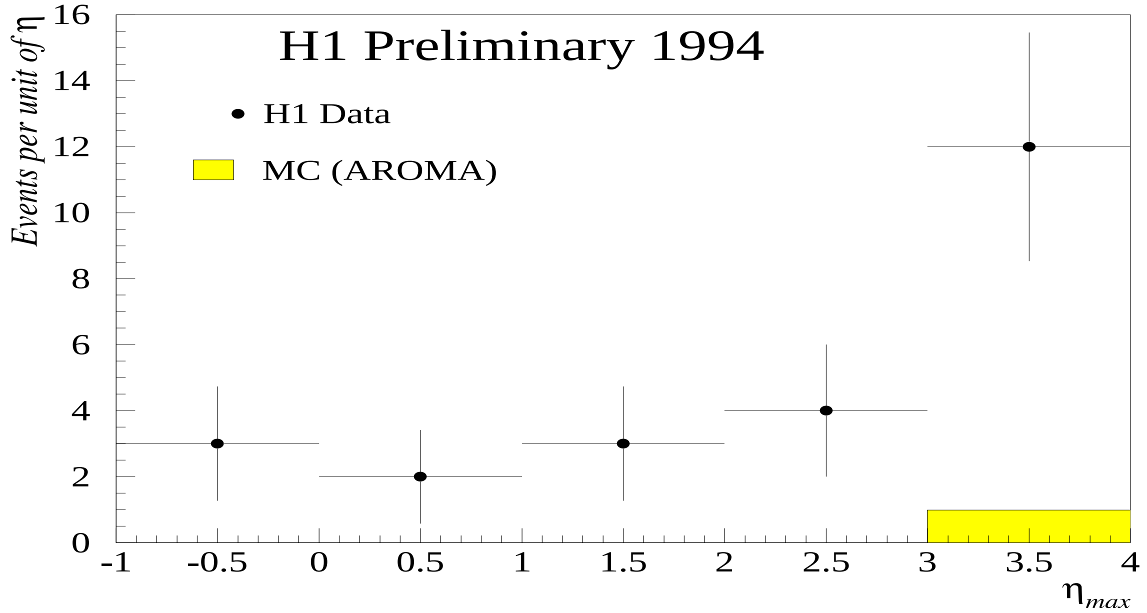
- $10 < Q^2 < 100\,\mathrm{GeV^2/c^2}$
- $0.06 < y < 0.6$
- $x_{I\!P} < 0.05$
- $M_Y < 1.6\,\mathrm{GeV/c^2}$

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 $\Delta M = M_{K\pi\pi^\pm_{slow}} - M_{K\pi}$



Charm Cross–Section and Conclusions

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

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

- 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 Charm** 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 born 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
- **Thrust** measurement show that alignment and 2–jettiness are the leading topological properties
- Large fraction of high P_T events
  $\rightarrow$ Large P_T^2 tails
  $\rightarrow$ Modelling of the final state not yet perfect (some surprises in-store?)
- **Charm** cross section consistent with QCD evolved prediction
  $\rightarrow$ Quark only does not describe data

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

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

Other "Leading" gluon models are also consistent (SCI, Buchmüller + Hebecker)