DIS with Leading Baryons at ZEUS and H1 at HERA

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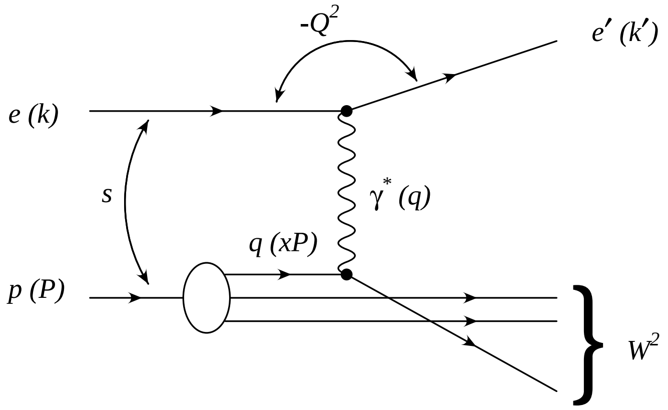
DESY –F11–
for the H1 and ZEUS Collaborations

Madrid Workshop on Low x Physics
Miraflores de la Sierra
June 18–21, 1997

- Introduction
- Results of the ZEUS and H1 Forward Neutron Calorimeters
- Results of the ZEUS Leading Proton Spectrometer for $x_{\mathrm{L}} = 0.6 - 1$
- Results of the H1 Forward Proton Spectrometer for $x_{\mathrm{L}} = 0.7 - 0.9$
- Summary and Conclusions

ps-file: `http://www-h1.desy.de/~blist/transp.madrid.ps.gz`

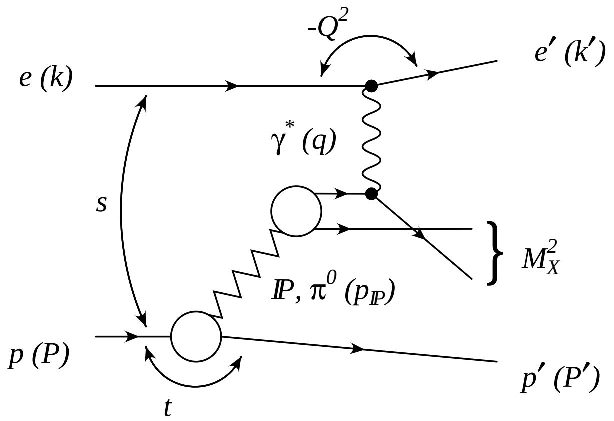
Kinematics



$x = \frac{Q^2}{2q \cdot P}$ Bjorken scaling variable= momentum fraction of quark

$y = \frac{q \cdot P}{k \cdot P}$ Inelasticity

$$Q^2 = x \cdot y \cdot s$$



$\xi = \frac{p_{\mathbb{P}} \cdot q}{P \cdot q}$ $= 1 - \frac{E'_p}{E_p}$ Momentum fraction of exchange

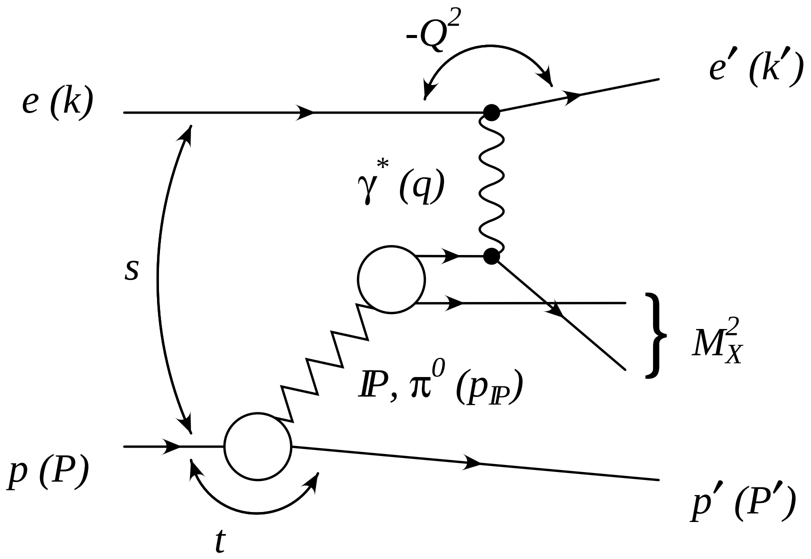
$\beta = \frac{Q^2}{2 p_{\mathbb{P}} \cdot q}$ Momentum fraction of quark out of $\mathbb{P}$, π

$t = p_{\mathbb{P}}^2$ Momentum transfer

$$Q^2 = \beta \cdot \xi \cdot y \cdot s \qquad \beta = \frac{x}{\xi} \qquad \xi = 1 - x_{\mathrm{L}}$$

Proton energy $E_p = 820\,\mathrm{GeV}$, CM energy $\sqrt{s} = 300\,\mathrm{GeV}$.

Regge Exchange: Pomeron, Pion



Proton emits **virtual pomeron, pion, etc.** "$\mathcal{P}$"

Momentum fraction $\xi = 1 - E'_p/E_p$ measured by FNC or LPS/FPS

$\beta = x/\xi$ momentum fraction of quark out of "$\mathcal{P}$"

Flux factor $f_{\mathcal{P}/p}(\xi, t)$

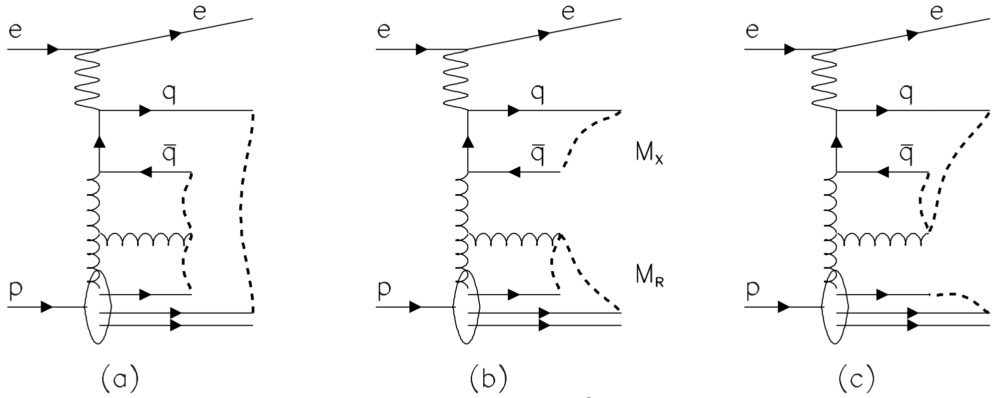
"$\mathcal{P}$" structure function $F_2^{\mathcal{P}}(\beta, Q^2)$

$$\frac{\mathrm{d}^4\sigma(ep \to e'p'X)}{\mathrm{d}\beta\,\mathrm{d}Q^2\,\mathrm{d}\xi\,\mathrm{d}t} = f_{\mathcal{P}/p}(\xi, t)\frac{\mathrm{d}^2\sigma(e\mathcal{P} \to e'X)}{\mathrm{d}\beta\,\mathrm{d}Q^2}$$
$$= f_{\mathcal{P}/p}(\xi, t)\frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right)F_2^{\mathcal{P}}(\beta, Q^2)$$

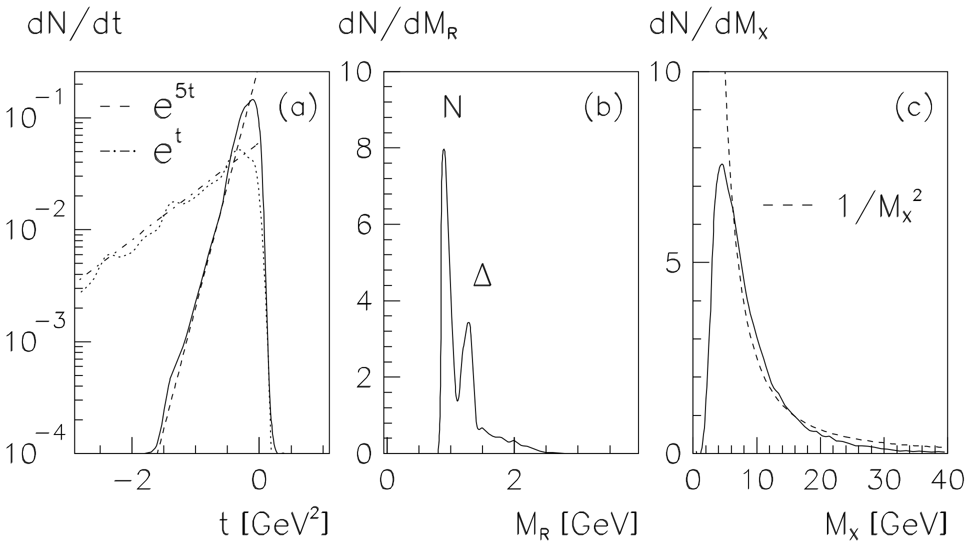
Prediction: Cross section factorizes into "$\mathcal{P}$" flux and e"$\mathcal{P}$" cross section.

Soft Color Interactions

Generator: LEPTO 6.5



a) Conventional b, c) Color flow rearranged



a) t spectrum: $d\sigma/dt \propto e^{bt}$

b) Mass of b) proton remnant c) central system

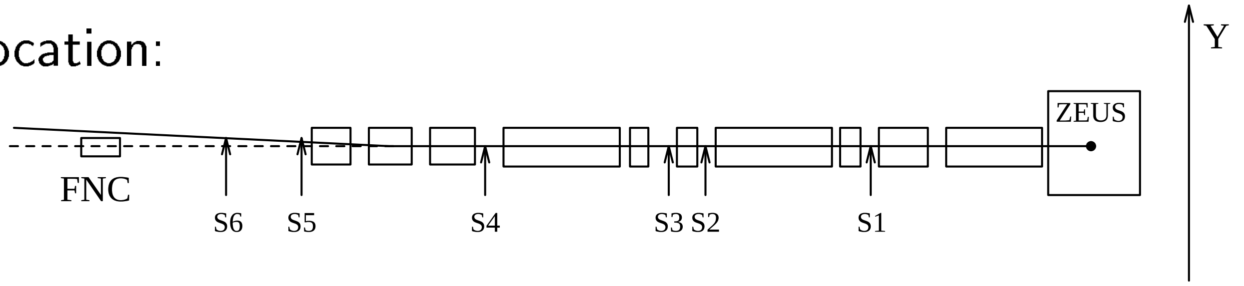
Soft color interactions + new seaquark treatment model

- Diffractive events (pomeron exchange)
- Diffractive proton dissociation
- Meson exchange (π^0, π^+, $K, \ldots$)

Figures from: A. Edin, G. Ingelman & J. Rathsman: DESY 96–060.

The H1 and ZEUS Forward Neutron Calorimeters

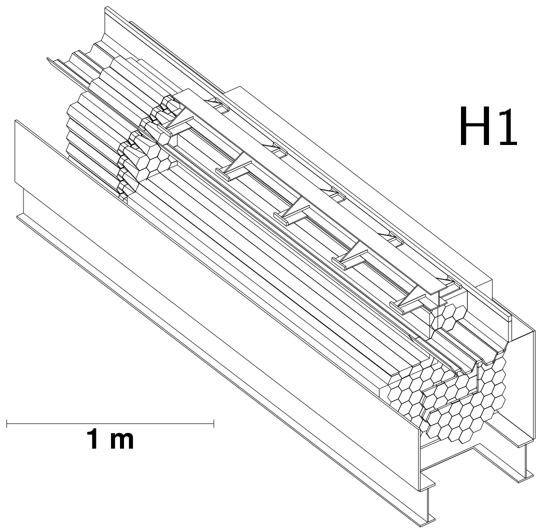
Location:



Measure high-energy neutrons emitted at $\theta \lesssim 0.5\,\mathrm{mrad}$

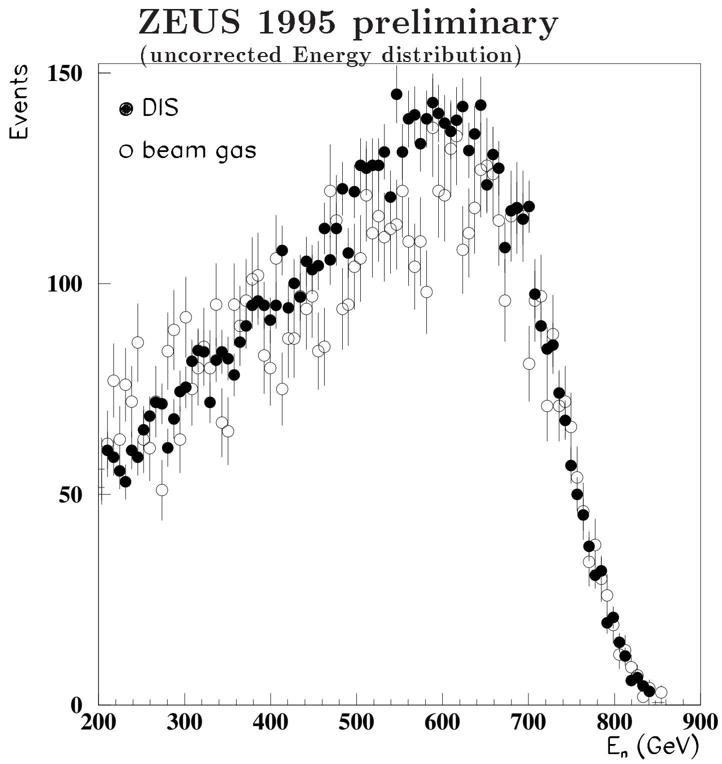
Properties:

ZEUS FNC III	H1 FNC
Pb–scintillator sandwich, wavelengthshifter readout	Pb–scintillating fiber spaghetti calorimeter
$L = 10.2\,\lambda_I$	$L = 9.5\,\lambda_I$
$\frac{\delta E}{E} = \frac{0.65}{\sqrt{E}}$	$\frac{\delta E}{E} = \frac{0.31}{\sqrt{E}}$ (testbeam)
$\frac{\delta y}{y} = \frac{12\,\mathrm{cm}}{\sqrt{E}}$, $\frac{\delta x}{x} = \frac{25\,\mathrm{cm}}{\sqrt{E}}$	$\frac{\delta x, y}{x, y} = \frac{3.1\,\mathrm{cm}}{\sqrt{E}} \oplus 2.4\,\mathrm{cm}$



H1 Forward Neutron Calorimeter

ZEUS 1995 FNC Results

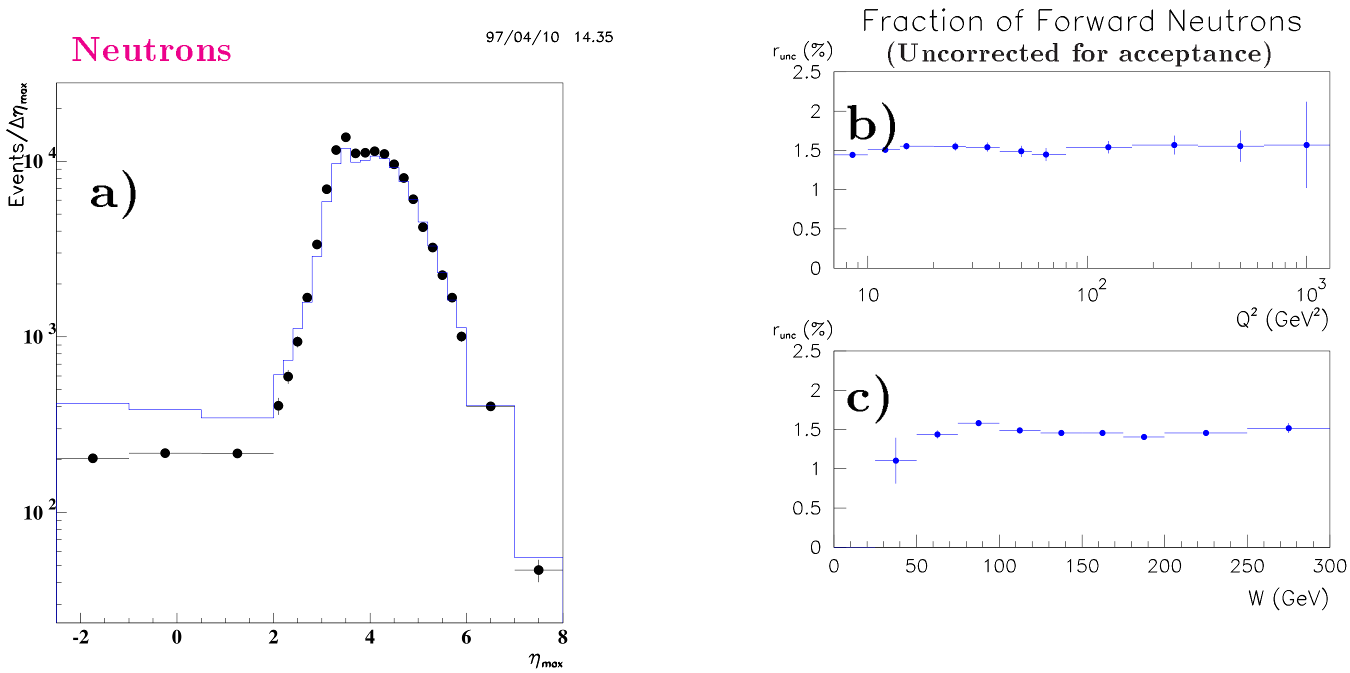


Energy spectra from ep and beam gas events are the same (arbitrary relative normalization).

$\Rightarrow$ Universal proton fragmentation, independent of the beam (e or A).

Events with Leading Neutron versus Inclusive DIS

1995 data, DIS: $E_n > 400\,\mathrm{GeV}$, $|t| < 0.5\,\mathrm{GeV}^2$



- Less rapidity gap events in sample with forward neutrons compared to total DIS sample (a)

  $\Rightarrow$ Neutrons do not come predominantly from diffractive proton dissociation

- Fraction of events with forward neutron to all events independent of Q^2 (b) and W (c)

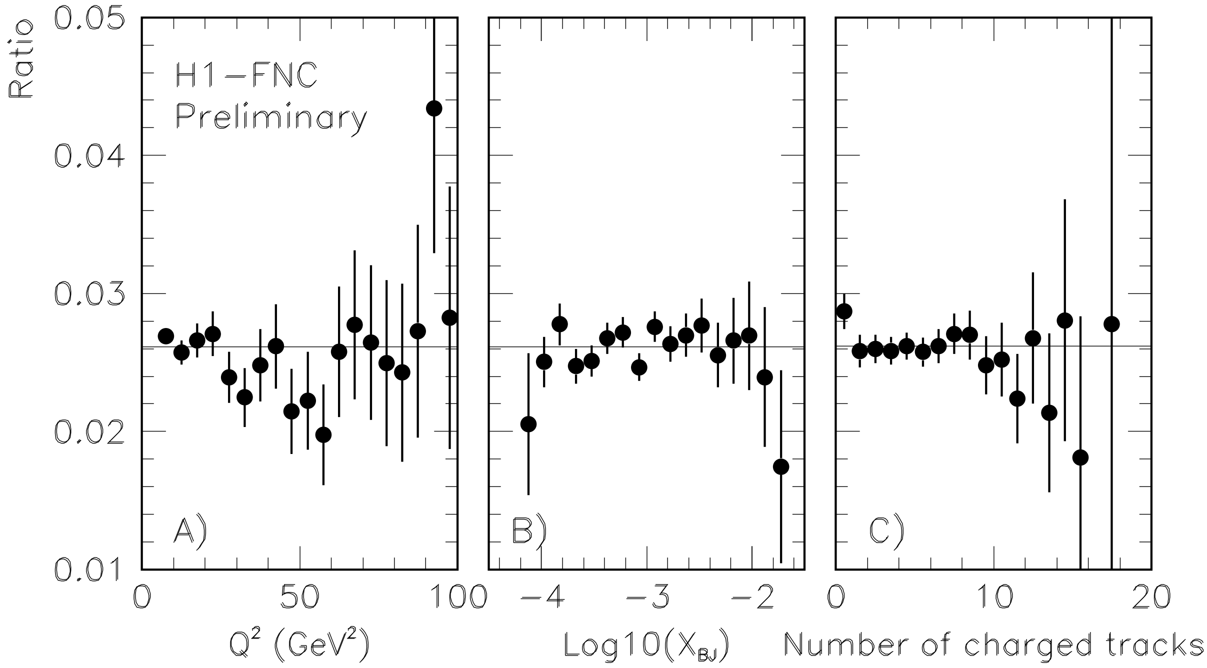
$9.1^{+3.6}_{-5.7}\,\%$ of all DIS events have a neutron with $E_n > 400\,\mathrm{GeV}$ and $|t| < 0.5\,\mathrm{GeV}^2$ (1994 data)[a].

[a] ZEUS Collab., Phys. Lett. **B384** (1996) 388.

H1 1996 FNC Results: Ratios

DIS events, $5 < Q^2 < 100\,\mathrm{GeV}^2$, $0.05 < y < 0.7$, $L = 1.98\,\mathrm{pb}^{-1}$

Ratio: events with leading neutron of $E_\mathrm{n} > 100\,\mathrm{GeV}$, $|t| < 0.5\,\mathrm{GeV}^2$ divided by all DIS events

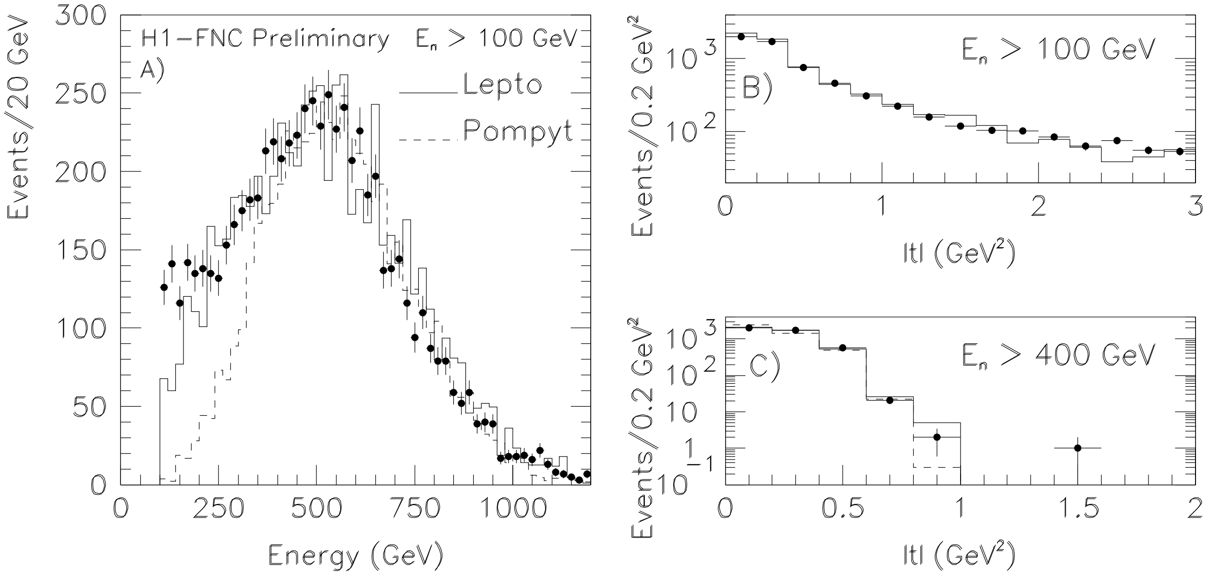


- Fraction of events with leading neutron to all DIS events is independent of Q^2 (A) and x (B)
- Fraction of events with leading neutron to all DIS events is independent of number of charged tracks (C)[a]

[a] cf. Frankfurt, Koepf & Strikman, hep–ph/9702236.

Comparison to Monte Carlo Models

DIS events, $5 < Q^2 < 100\,\mathrm{GeV}^2$, $0.05 < y < 0.7$, $L = 1.98\,\mathrm{pb}^{-1}$



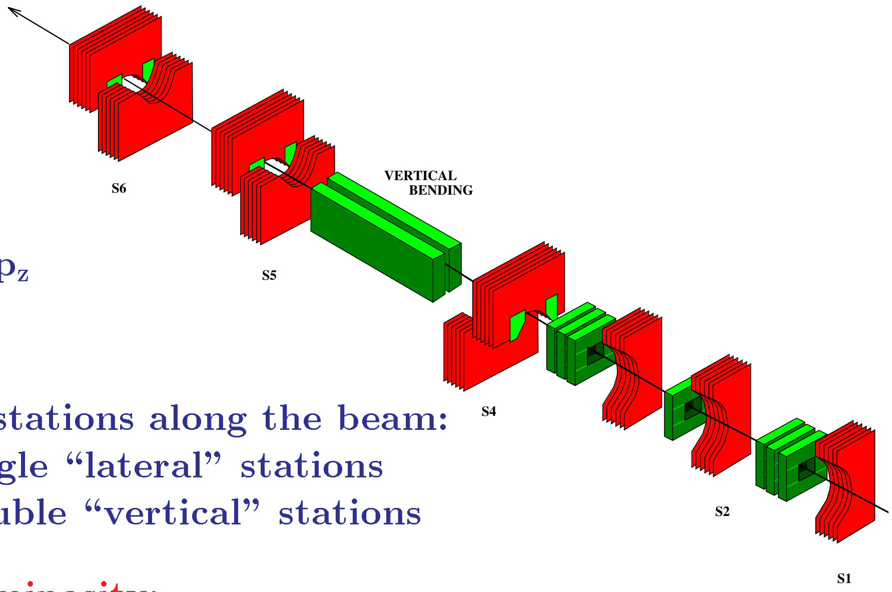
- LEPTO 6.5 (soft color interactions, new seaquark treatment) describes observed energy and t spectrum (A, B)
- POMPYT (pion exchange) describes energy and t spectrum for $E_n \gtrsim 350\,\mathrm{GeV}$ (A, C)

Monte Carlo predictions normalized to data.

Spectra are uncorrected for detector effects (acceptance, E_n and t resolution).

The ZEUS Leading Proton Spectrometer

LPS acceptance: $0.6 < x_L < 1.0$ and $0 < p_\perp^2 < 1$ GeV^2



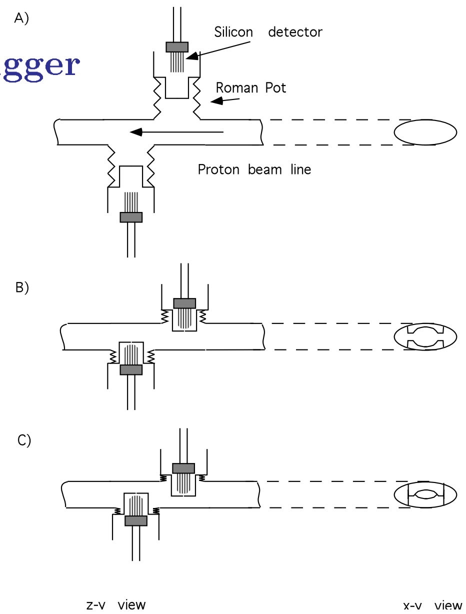
- **Resolution:**
  - $\simeq 0.3$ % on p_z
  - $\simeq 3$ % on $p_\perp$

- **Six detector stations along the beam:**
  S1 $\longrightarrow$ S3 single "lateral" stations
  S4 $\longrightarrow$ S6 double "vertical" stations

- **Collected Luminosity:**
  0.9 pb^{-1} in 1994
  2.5 pb^{-1} in 1995. Installed LPS Trigger
  4.0 pb^{-1} in 1996

- **Detector operations using Roman pots**

- **Six μstrip silicon detectors per pot**
  - **three different strip orientations $(0^o, +45^o, -45^o)$**
  pitch: 115μm $\to$ $0^o \sqrt{2}\mu$m $\to \pm 45^o$
  - **cut out to follow the 10σ beam profile**

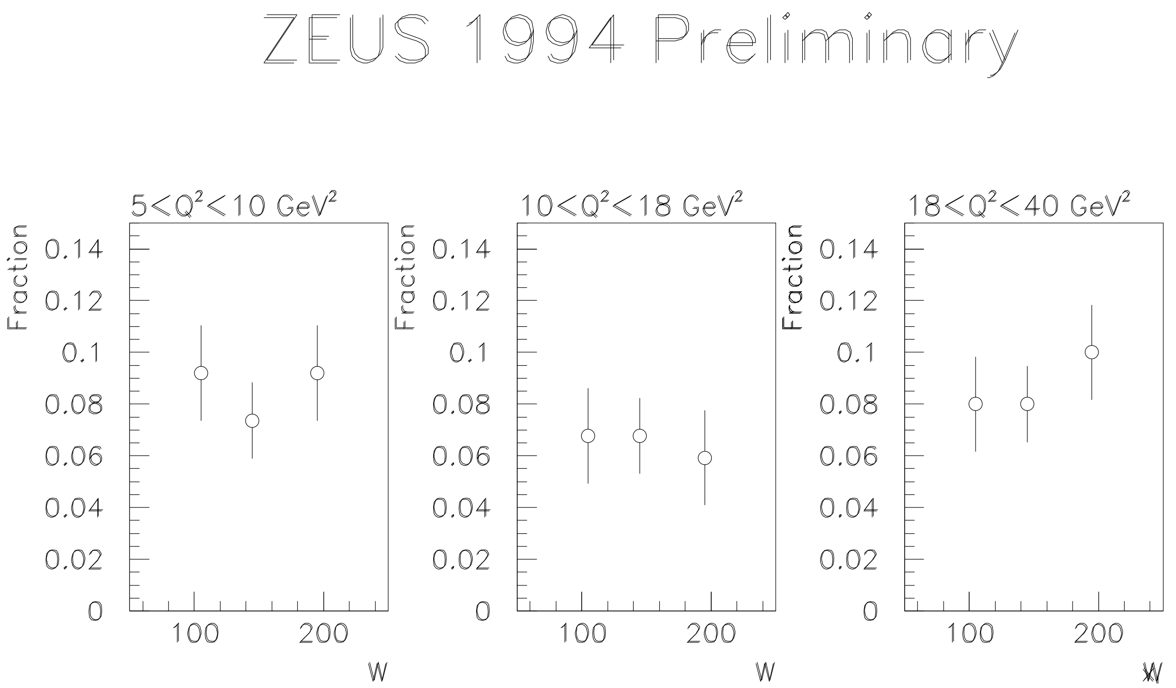


The deflection of the proton in the HERA magnets is used to reconstruct the momentum of the scattered proton.

Events with Leading Proton versus Inclusive DIS

Fraction: events with LP of $|t_{\rm inf}| < |t| < 0.5\,{\rm GeV}^2$ and $0.6 < x_{\rm L} < 0.92$, normalized to all DIS events

$|t_{\rm inf}| = \min\left(0.08\,{\rm GeV}^2,\ |t_{\min}|\right)$

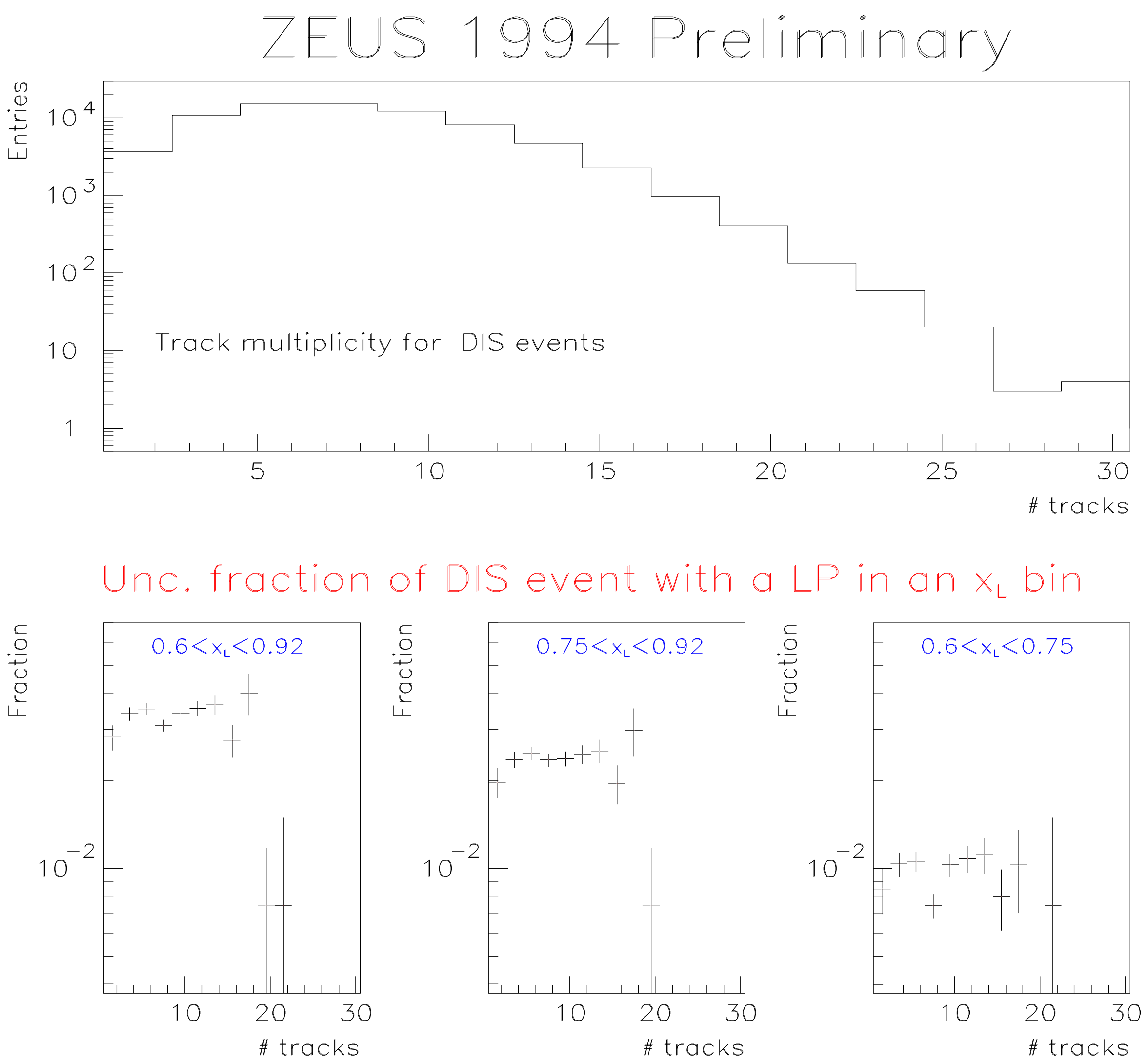


Only statistical errors shown

About 8 % of DIS events have a leading proton, independent of W or Q^2.

$x_{\rm L} = E'_p/E_p$

Track Multiplicities



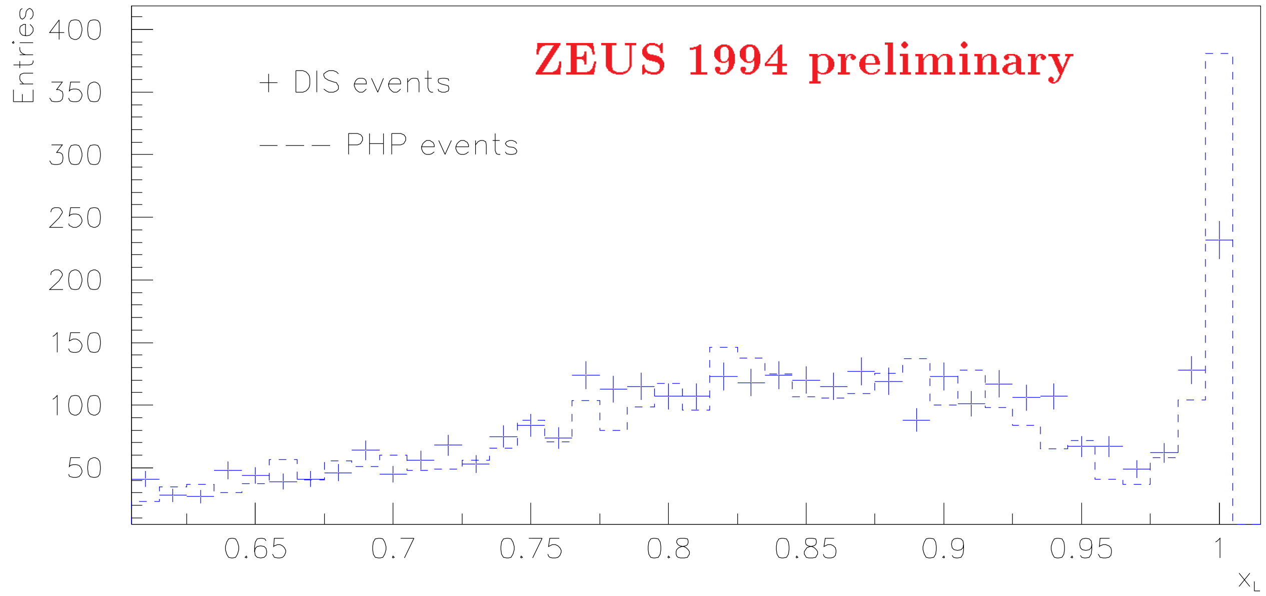
DIS events with a **leading proton** in the range $0.6 < x_{\mathrm{L}} < 0.92$ have the same charged track multiplicity as **inclusive DIS** events.

No breakdown of factorization observed.

Fraction: events with LP of $|t_{\mathrm{inf}}| < |t| < 0.5\,\mathrm{GeV}^2$ and $0.6 < x_{\mathrm{L}} < 0.92$, normalized to all DIS events

Energy Spectra in DIS and Photoproduction

$x_{\rm L}$ spectra, uncorrected for acceptance.



Shape of energy ($x_{\rm L}$) spectra for $x_{\rm L} < 0.98$ is the same in DIS and photoproduction.

Universal fragmentation, independent of Q^2.

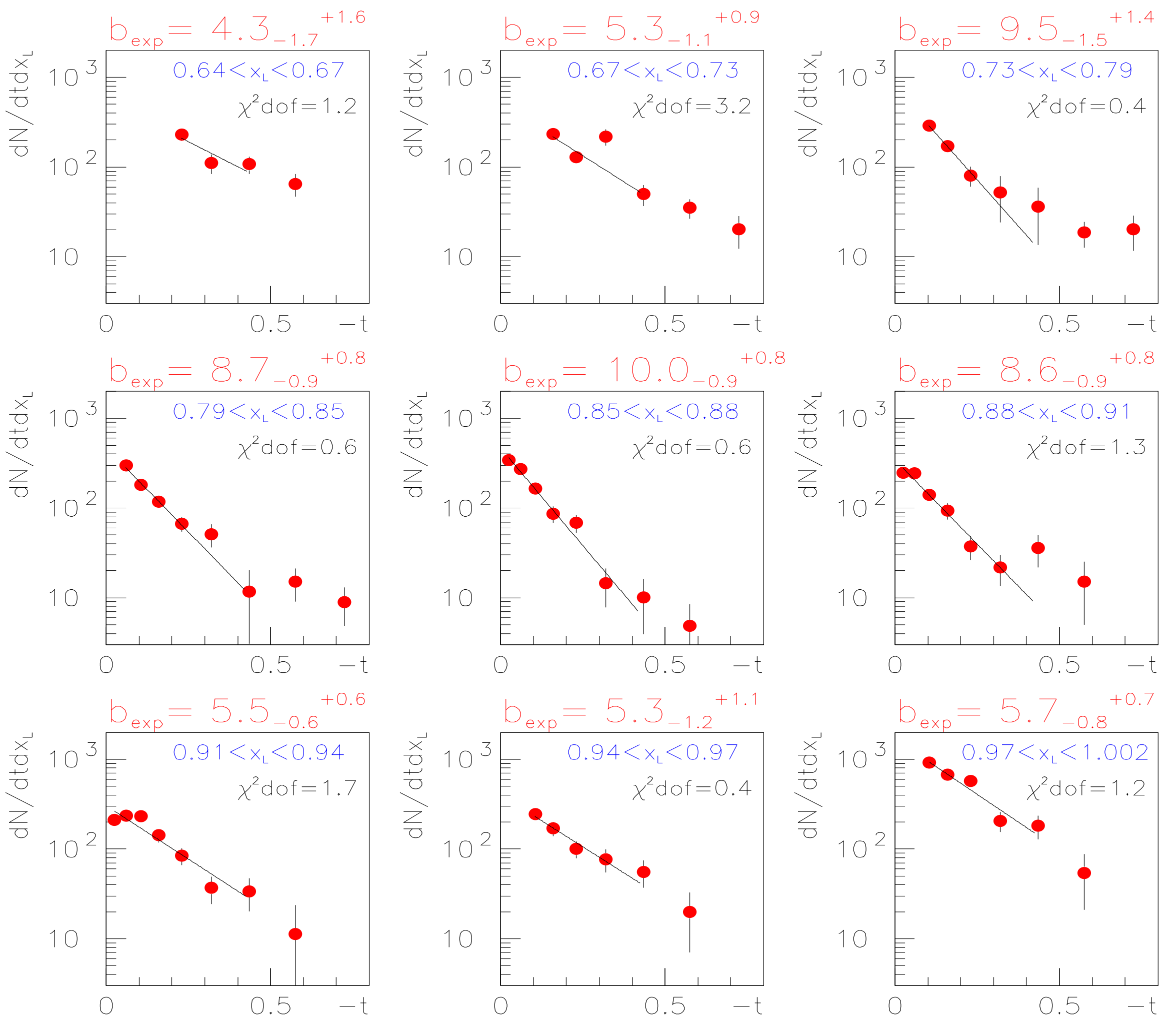
Measurement of $b\,(x_\mathrm{L})$

1994 data, $L = 900\,\mathrm{nb}^{-1}$, 3500 DIS events

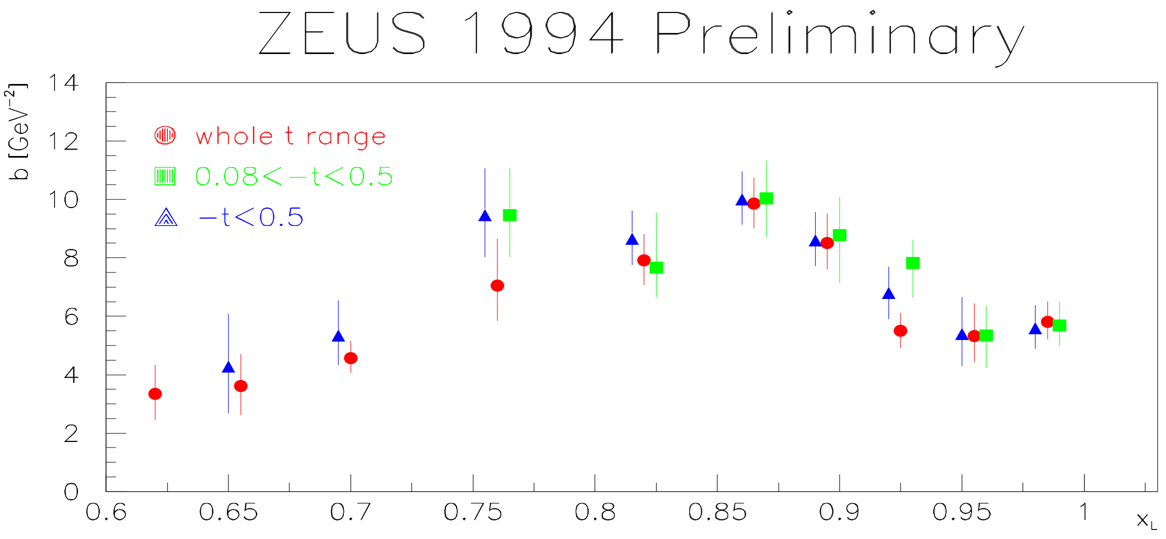
$|t_\mathrm{min}| < |t| < 0.7\,\mathrm{GeV}^2$

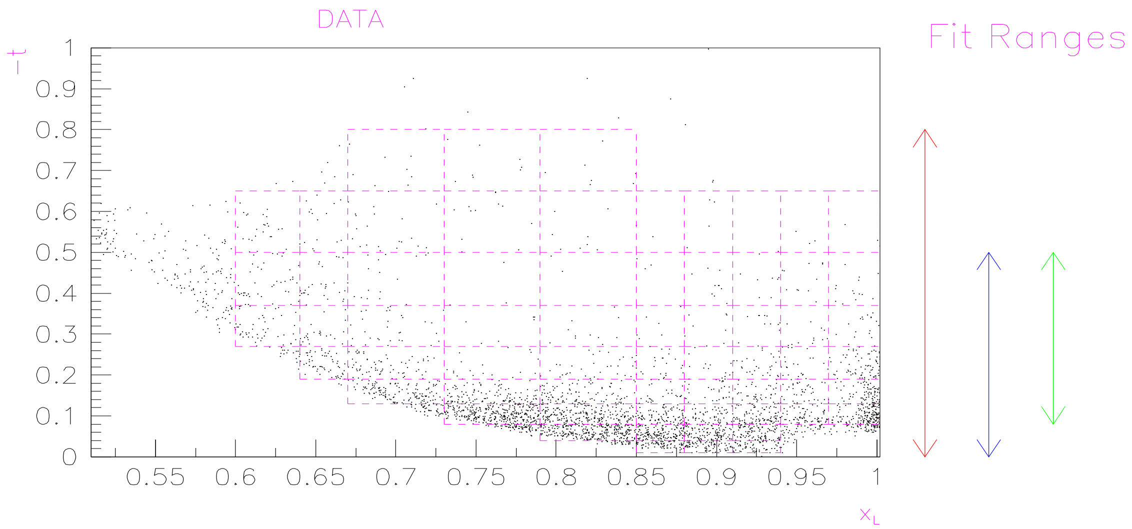
$0.6 < x_\mathrm{L} < 1$

Fit for $|t_\mathrm{min}| < |t| < 0.5\,\mathrm{GeV}^2$ using a single exponential



$x_{\rm L}$ Dependence of b Slope

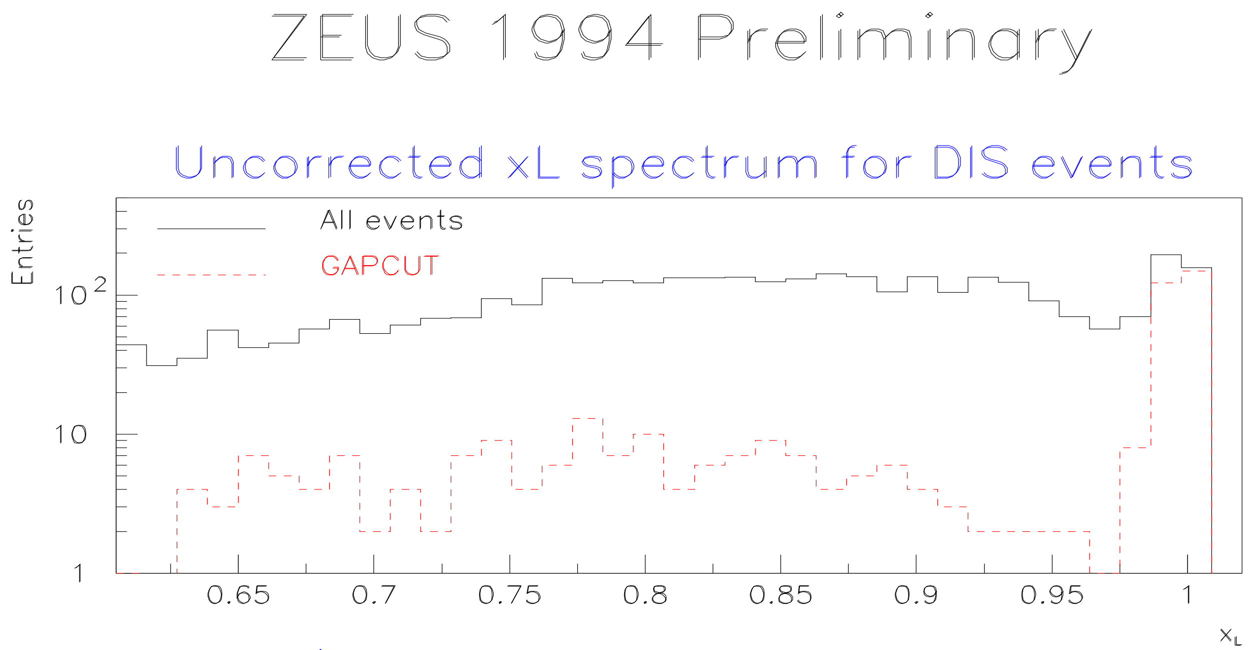


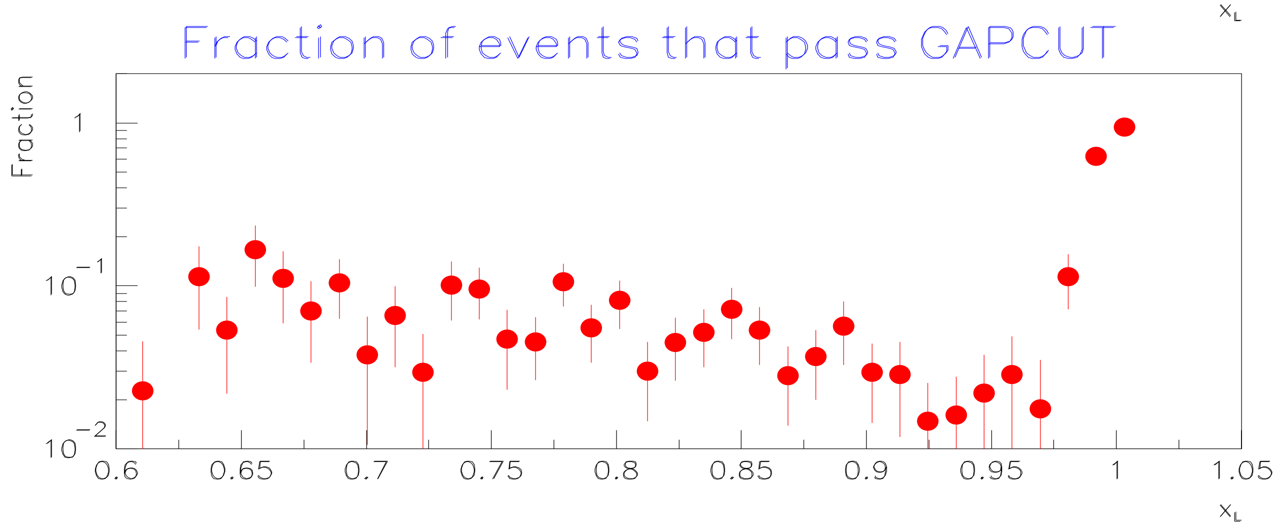


Fits over different t ranges yield compatible results.

- $b = 6\,\mathrm{GeV}^{-2}$ in diffractive region ($x_{\rm L} \approx 1$)
- b grows to $10\,\mathrm{GeV}^{-2}$ for $x_{\rm L} \approx 0.75 - 0.9$
- for $x_{\rm L} < 0.7$ the slope parameter b falls

Rapidity Gaps



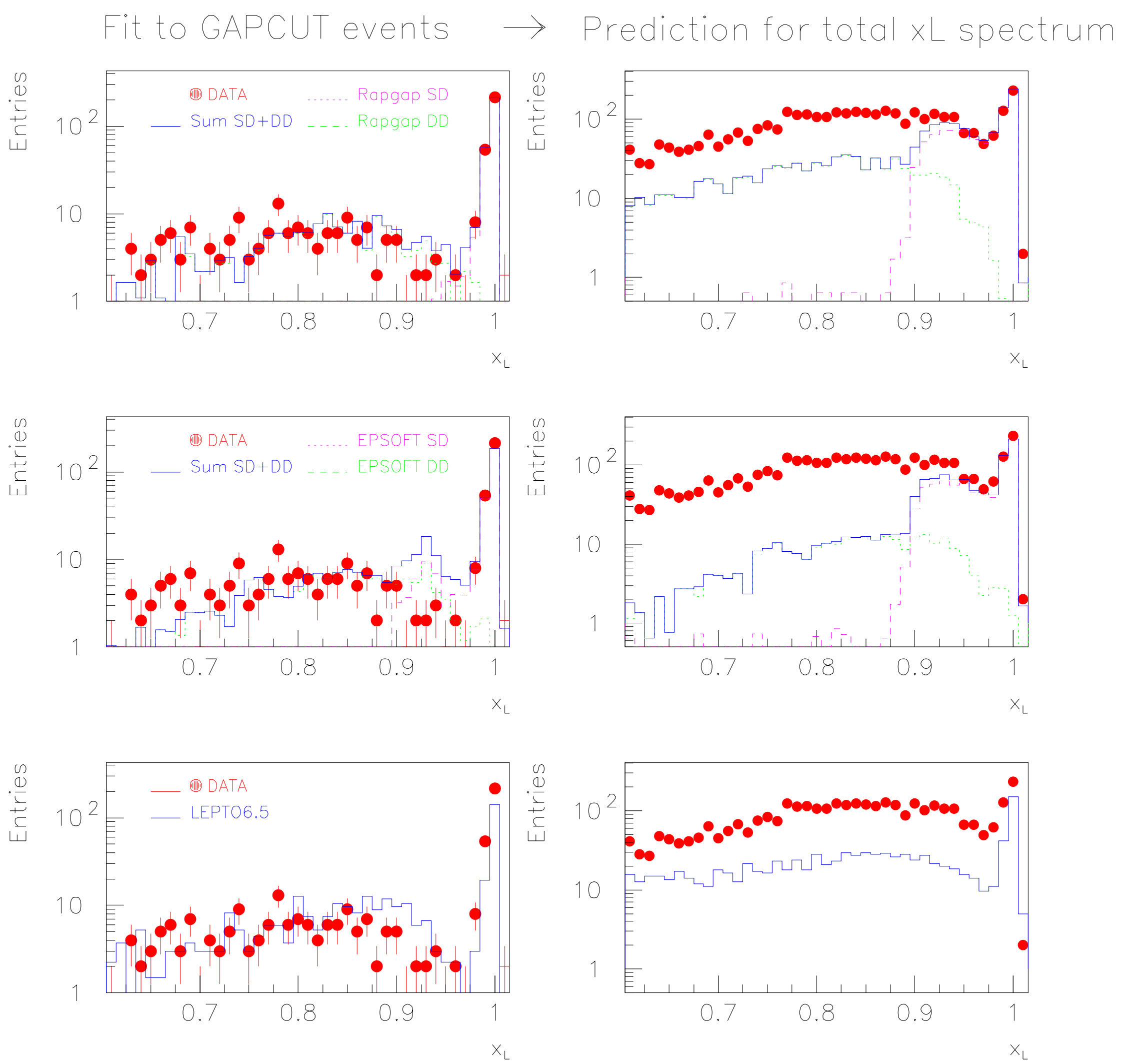


GAPCUT: Events with rapidity gap (single or double diffractive dissociation)

- Almost all events at $x_\mathrm{L} \approx 1$ have a rapidity gap.
- Only about 10 % of events at $x_\mathrm{L} \lesssim 0.97$ have a rapidity gap.

$\Rightarrow$ Protons at $x_\mathrm{L} \lesssim 0.97$ do not come predominately from proton dissociation, but 10 % do.

Comparison to Monte Carlo: x_{L}



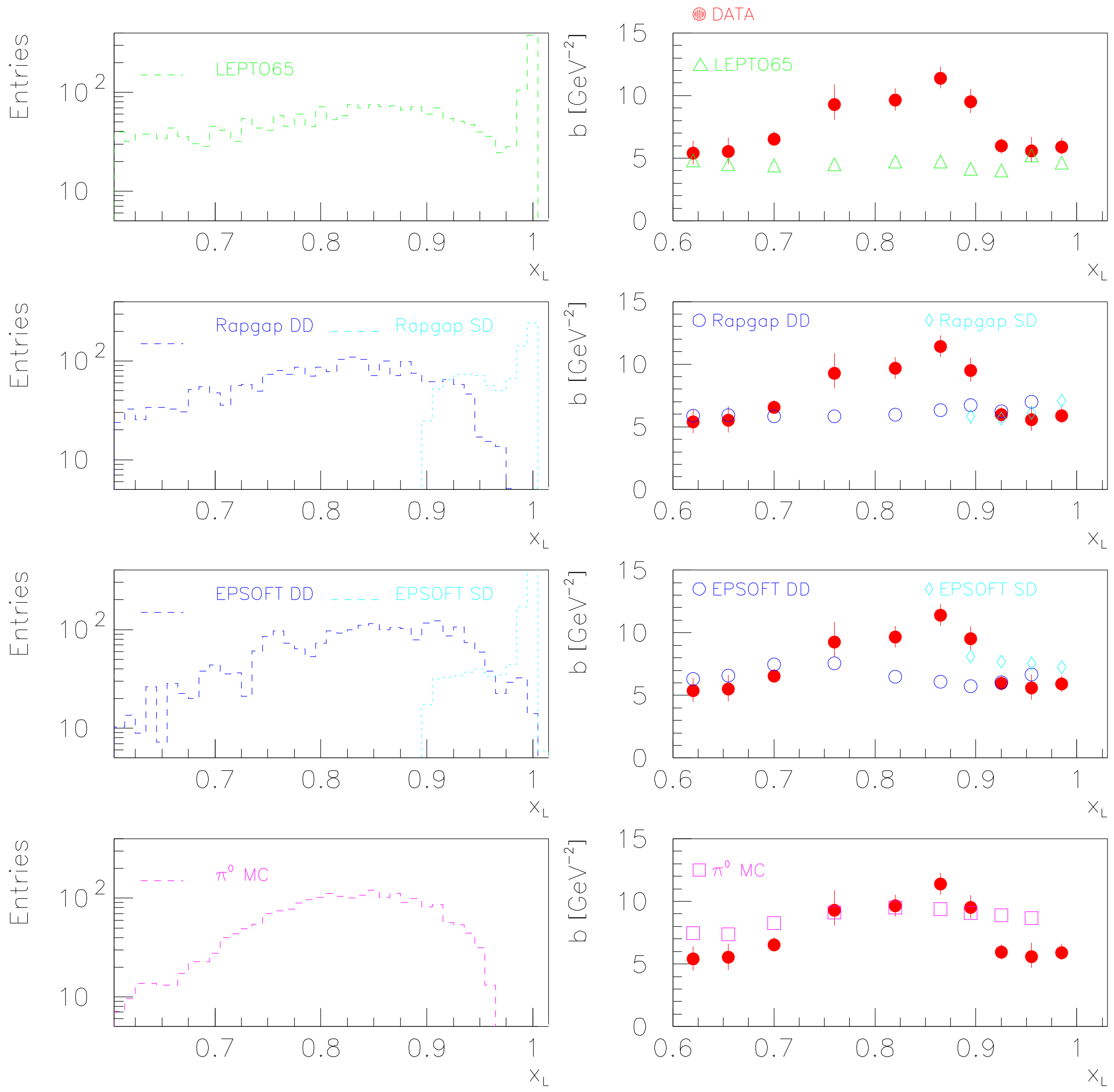
Tune Monte Carlo normalization to rapidity gap sample, compare prediction for total x_{L} spectrum.

- Both diffractive models with single + double diffr. dissociation can explain only 10 % of rate at $x_{\mathrm{L}} \lesssim 0.9$.

⇒ In Regge exchange models additional contribution (pion exchange?) is needed

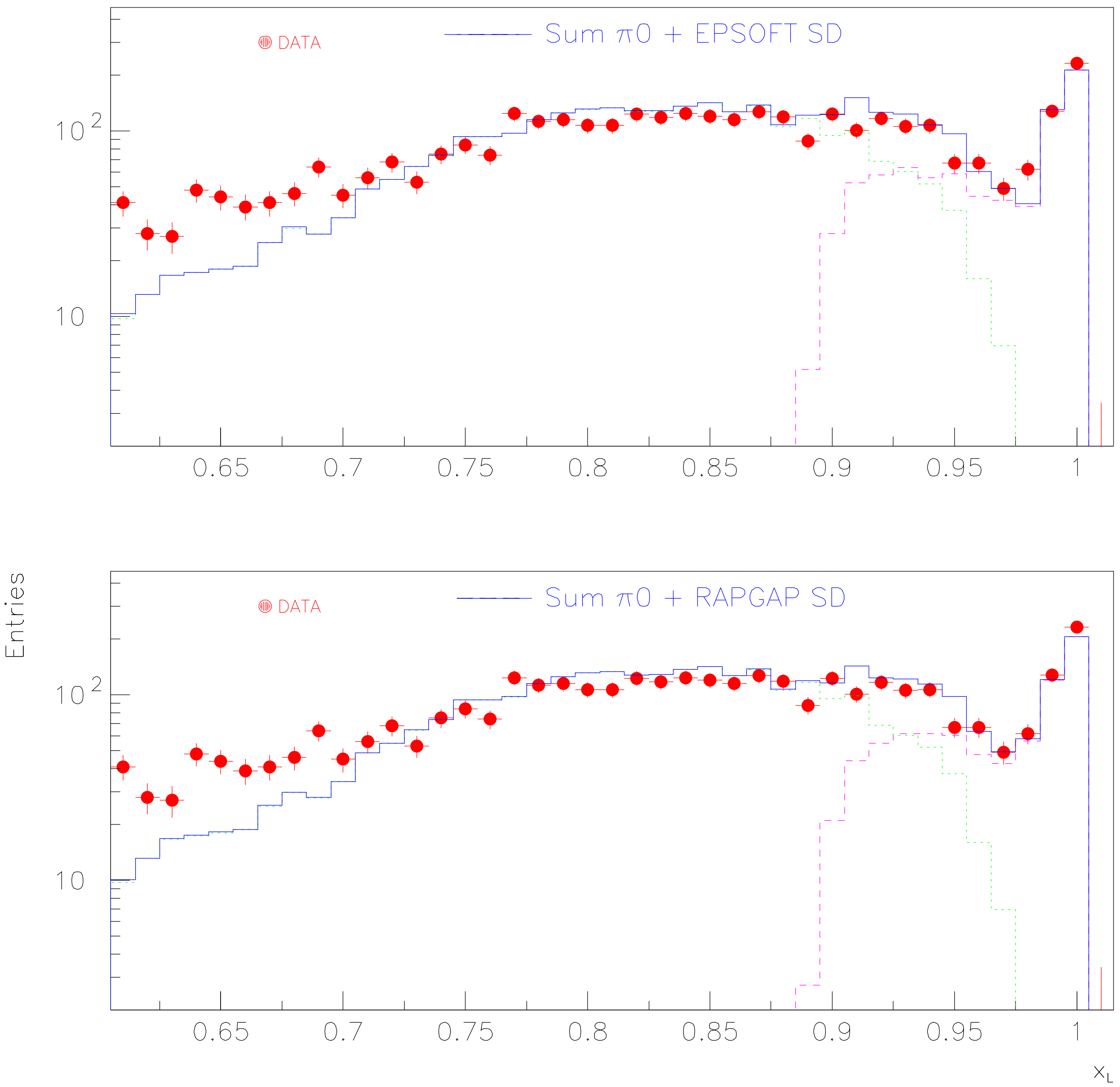
- LEPTO 6.5 predicts too many rapidity gap events and too few non–rapidity gap events at $x_{\mathrm{L}} \lesssim 0.95$.

Comparison to Monte Carlo: $b\,(x_{\rm L})$



No single mechanism (soft color interactions, diffraction, pion exchange) can explain the b slope variation and the $x_{\rm L}$ spectrum.

Comparison to Monte Carlo: Single Diffraction + Pion Exchange



The shape of the observed energy spectrum at $x_{\mathrm{L}} \gtrsim 0.7$ can be described by a sum of pomeron exchange and pion exchange Monte Carlos.

For $x_{\mathrm{L}} < 0.7$ additional contributions are needed.

Mind: Pion exchange does not explain GAPCUT events at $x_{\mathrm{L}} < 0.9$!

The H1 Forward Proton Spectrometer

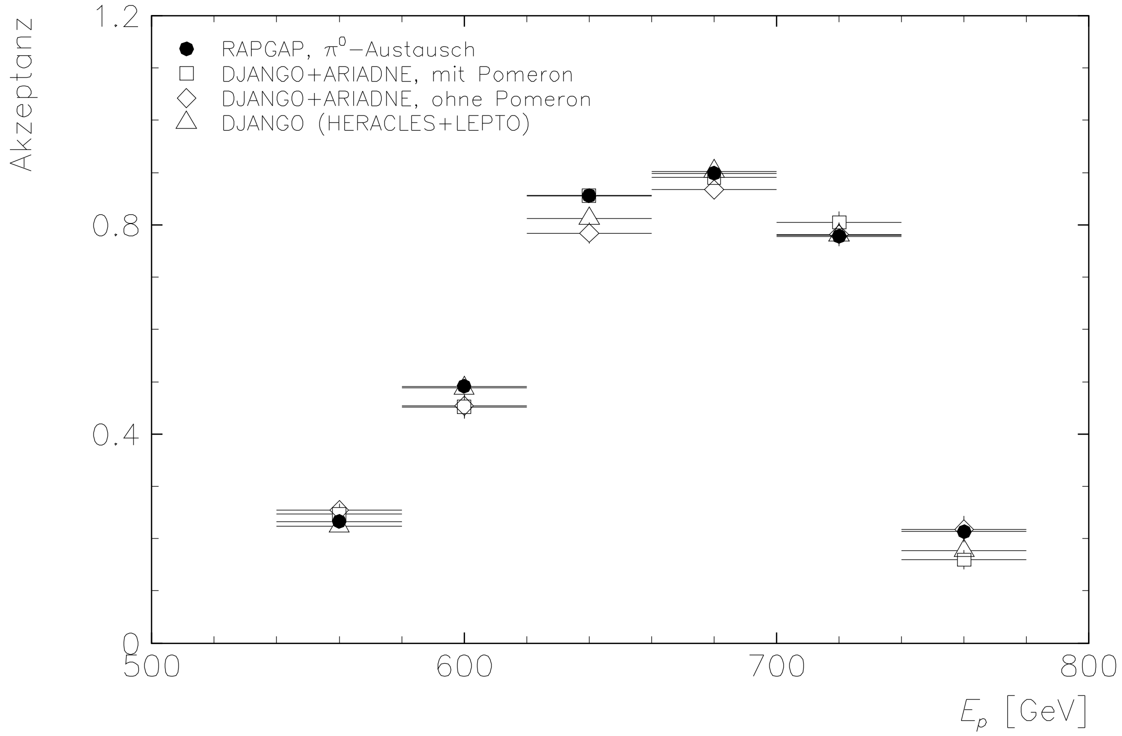
Since 1995: 2 Roman Pot Stations at $81\,\mathrm{m}$ and $90\,\mathrm{m}$

Scintillating fiber hodoscopes with position–sensitive photomultiplier readout

Resolution: $\delta E'_p = 6\,\mathrm{GeV}$ at $E'_p = 700\,\mathrm{GeV}$

Acceptance:

Fraction of protons with $p_\perp < 200\,\mathrm{MeV}$ in fiducial region



Acceptance $\gtrsim 50\,\%$ for $E'_p = 580 - 740\,\mathrm{GeV}$

Analysis:

4 Energy bins, $580 - 740\,\mathrm{GeV}$ ($\xi = 0.1 - 0.3$)

Bin size $40\,\mathrm{GeV}$ ($\Delta\xi = 0.05$)

Definition of $F_2^{LP\,(3)}$

Semiinclusive cross section $\sigma\,(ep \to e'p'X)$
for DIS events with protons of $p_\perp < 200\,\mathrm{MeV}$

Measured with 1995 data, $L = 1.44\,\mathrm{pb}^{-1}$,
$2\,\mathrm{GeV}^2 < Q^2 < 50\,\mathrm{GeV}^2$, $6 \cdot 10^{-5} < x < 6 \cdot 10^{-3}$
for $E'_p = 580 - 740\,\mathrm{GeV}$ $(\xi = 0.1 - 0.3)$.

Parametrized by semiinclusive structure function $F_2^{LP\,(3)}$:

$$\frac{\mathrm{d}^3\sigma\,(ep \to e'p'X)}{\boxed{\mathrm{d}x}\,\mathrm{d}Q^2\,\mathrm{d}\xi} = \frac{4\pi\alpha^2}{\boxed{x}\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}\,(x,\, Q^2,\, \xi)$$

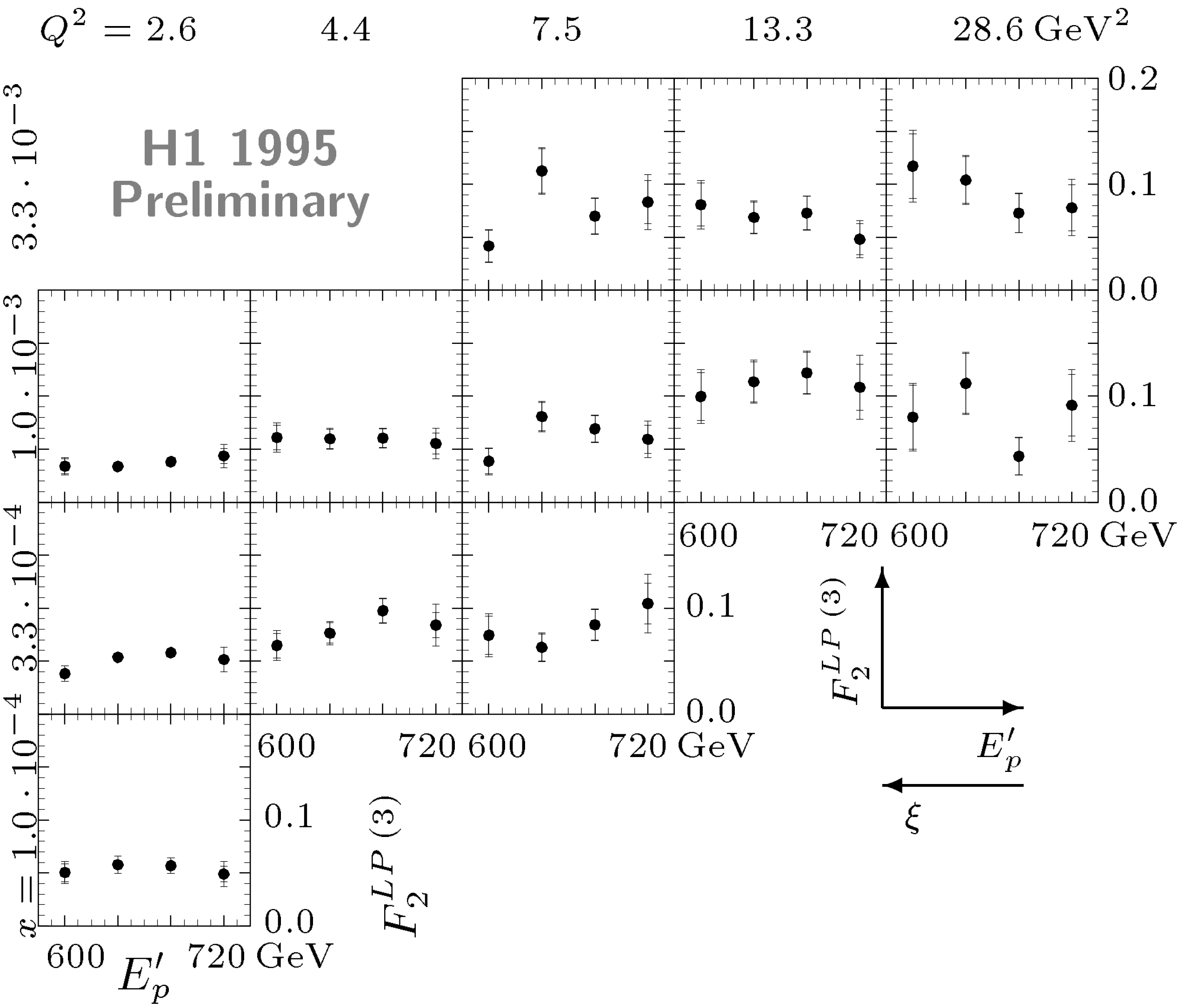
$$\mathrm{d}x = \xi \cdot \mathrm{d}\beta \qquad x = \xi \cdot \beta$$

$$\frac{\mathrm{d}^3\sigma\,(ep \to e'p'X)}{\boxed{\mathrm{d}\beta}\,\mathrm{d}Q^2\,\mathrm{d}\xi} = \frac{4\pi\alpha^2}{\boxed{\beta}\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}\,(\beta,\, Q^2,\, \xi)$$

Cross section unambiguously* defined on hadron level
Model independent

$*$: In the case where $\xi < 0.5$: there can be only one proton per event with $E'_p > 0.5 E_p$.

Results for $F_2^{LP\,(3)}$



- Weak ξ dependency
- Weak x dependency
- $F_2^{LP\,(3)}$ rises with Q^2

$$\frac{d^3\sigma\,(ep \to e'p'X)}{dx\,dQ^2\,d\xi} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}(x,\,Q^2,\,\xi)$$

for protons with $p_\perp < 200\,\mathrm{MeV}$

Global Fit to $F_2^{LP\,(3)}$

Hypothesis:

$$F_2^{LP\,(3)}\left(\beta,\,Q^2,\,\xi\right) = f_{\pi/p}\left(\xi\right)\cdot F_2^{\pi}\left(\beta,\,Q^2\right)$$

Normalization of $f_{\pi/p}\left(\xi\right)$ uncertain
(additional trajectories)
Choose form

$$F_2^{LP(3)}\left(\beta, Q^2, \xi\right) = r\left(\xi\right)\cdot \tilde{F}_2^{LP}\left(\beta,\,Q^2\right)$$

with $r\left(\xi_3 = 0.171\right) = 1$,
$r\left(\xi_j\right) = r_j$, take r_j as free parameters for $j \neq 3$.

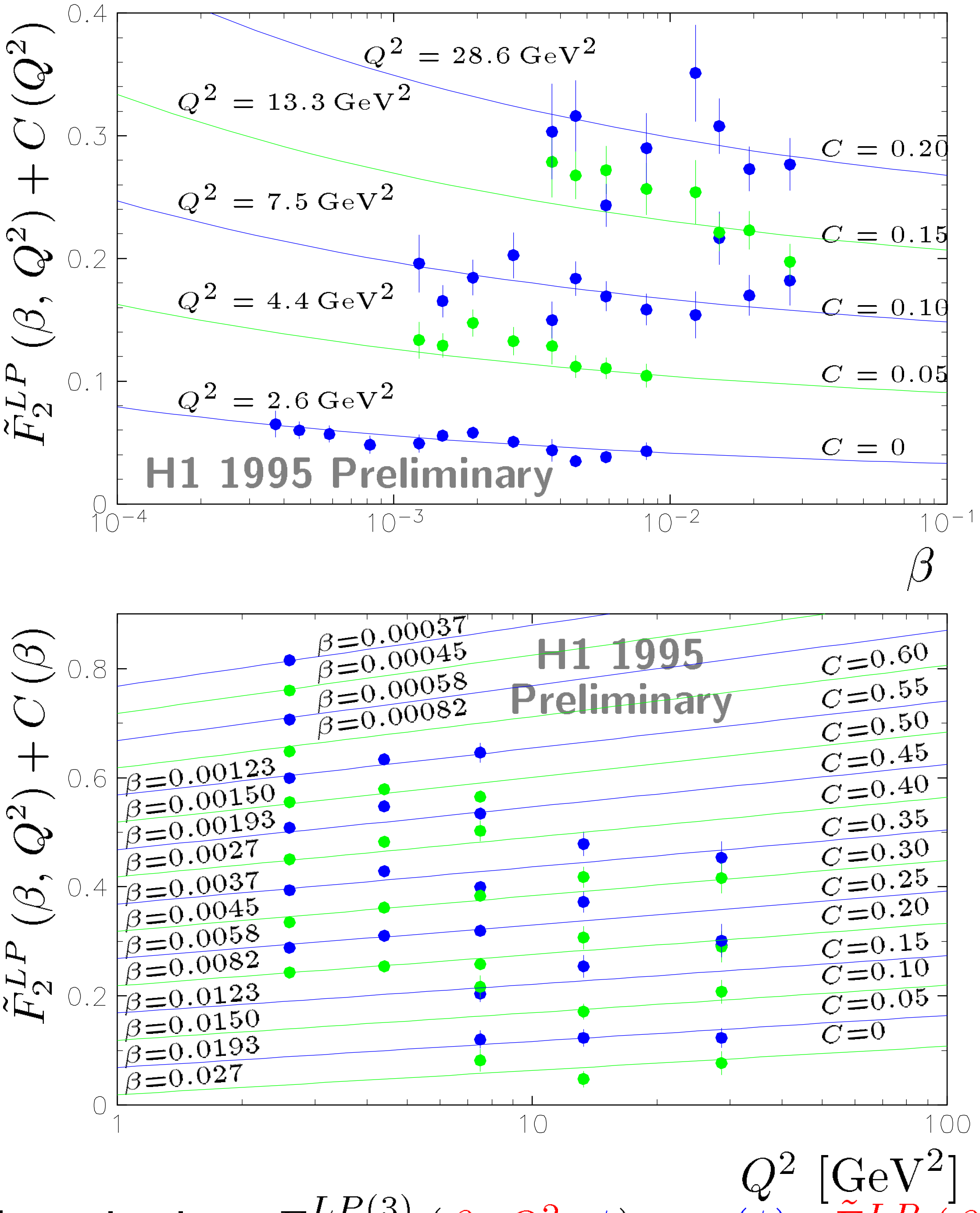
Fit to

$$F_2^{LP(3)}\left(\beta,\,Q^2,\,\xi\right) = r_j\cdot\left(a\cdot\beta^b + c\cdot\beta^d\cdot\log Q^2\right).$$

$\chi^2/df = 52.9/41$ $(CL = 10.1\,\%)$,
only statistical and x, Q^2 dependent errors

Reminder:
$\beta = x/\xi$ Momentum fraction of quark out of “pion”
$\xi = 1 - E_p'/E_p$ Momentum fraction carried by “pion”

Global Fit to $F_2^{LP\,(3)}$

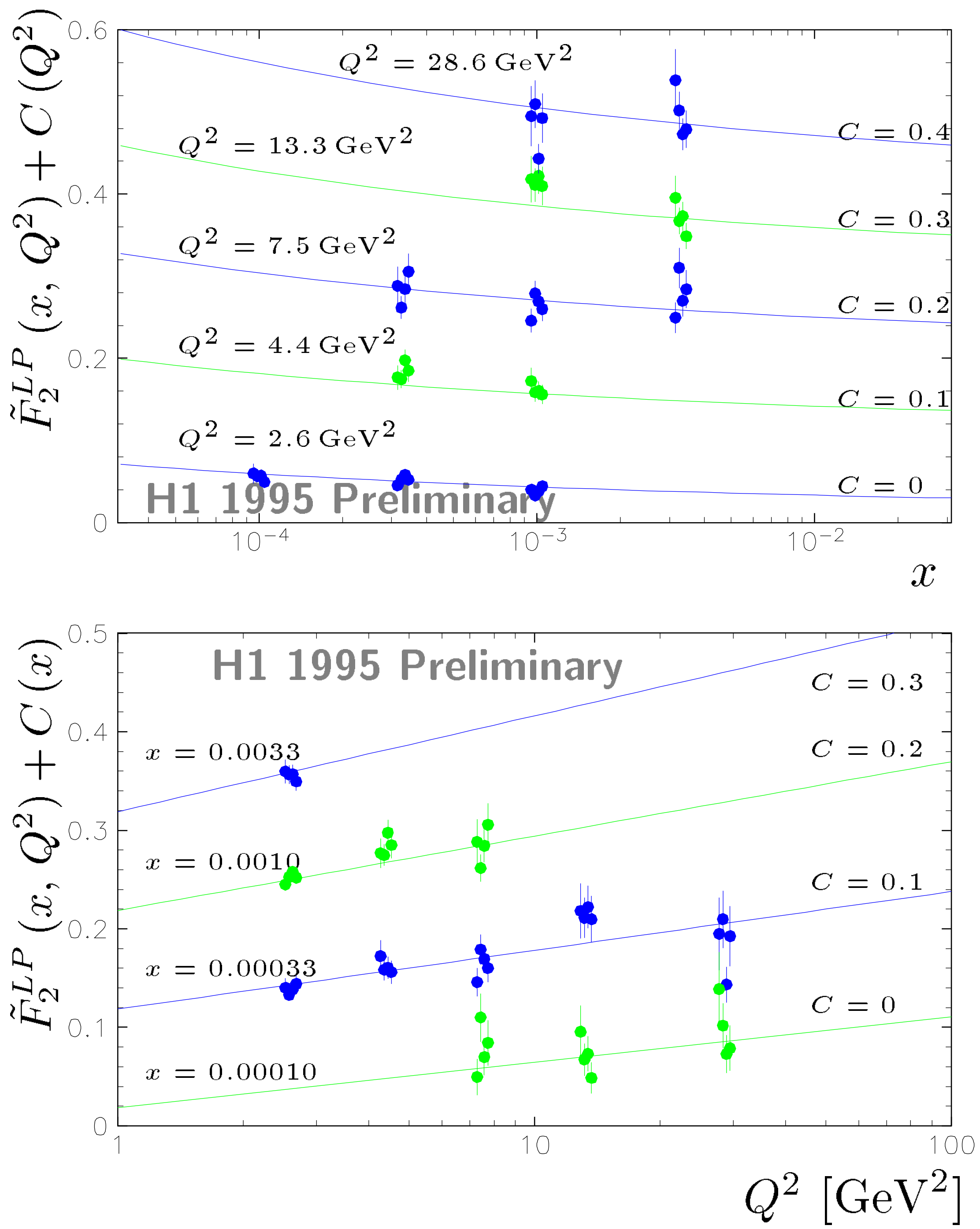


Factorisation: $F_2^{LP(3)}(\beta, Q^2, \xi) = r(\xi) \cdot \tilde{F}_2^{LP}(\beta, Q^2)$

$\tilde{F}_2^{LP}(\beta, Q^2)$ rises with Q^2 and falling β, like hadron structure function

$\chi^2/df = 52.9/41\ (CL = 10.1\,\%)$

Factorisation in x, Q^2, ξ?

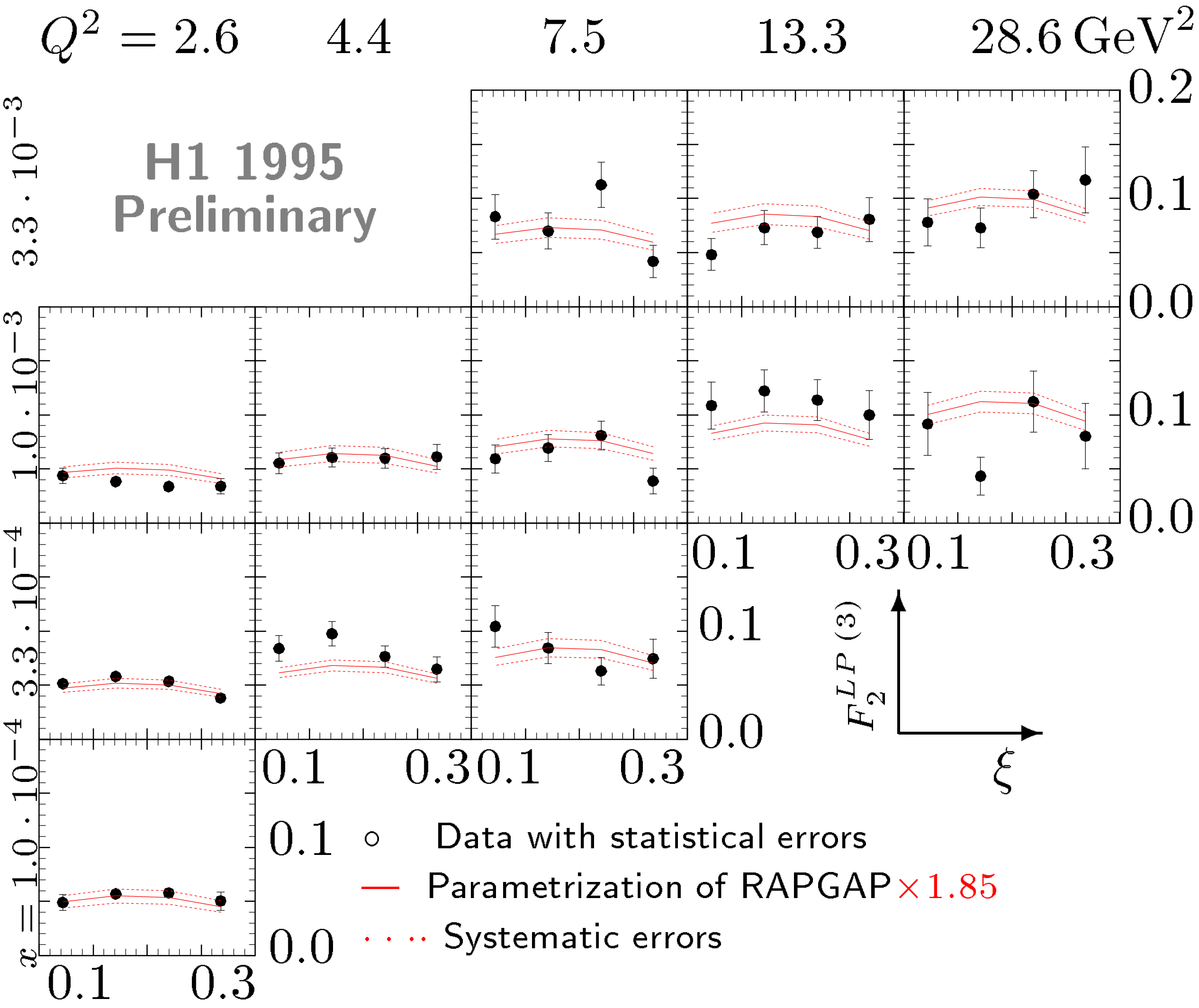


$$F_2^{LP(3)}(x, Q^2, \xi) = r(\xi) \cdot \tilde{F}_2^{LP}(x, Q^2)$$

$$\chi^2/df = 53.1/41 \; (CL = 9.8\,\%)$$

Answer: Factorisation as good as in β, Q^2, ξ

Comparison with RAPGAP



RAPGAP: π^0 exchange

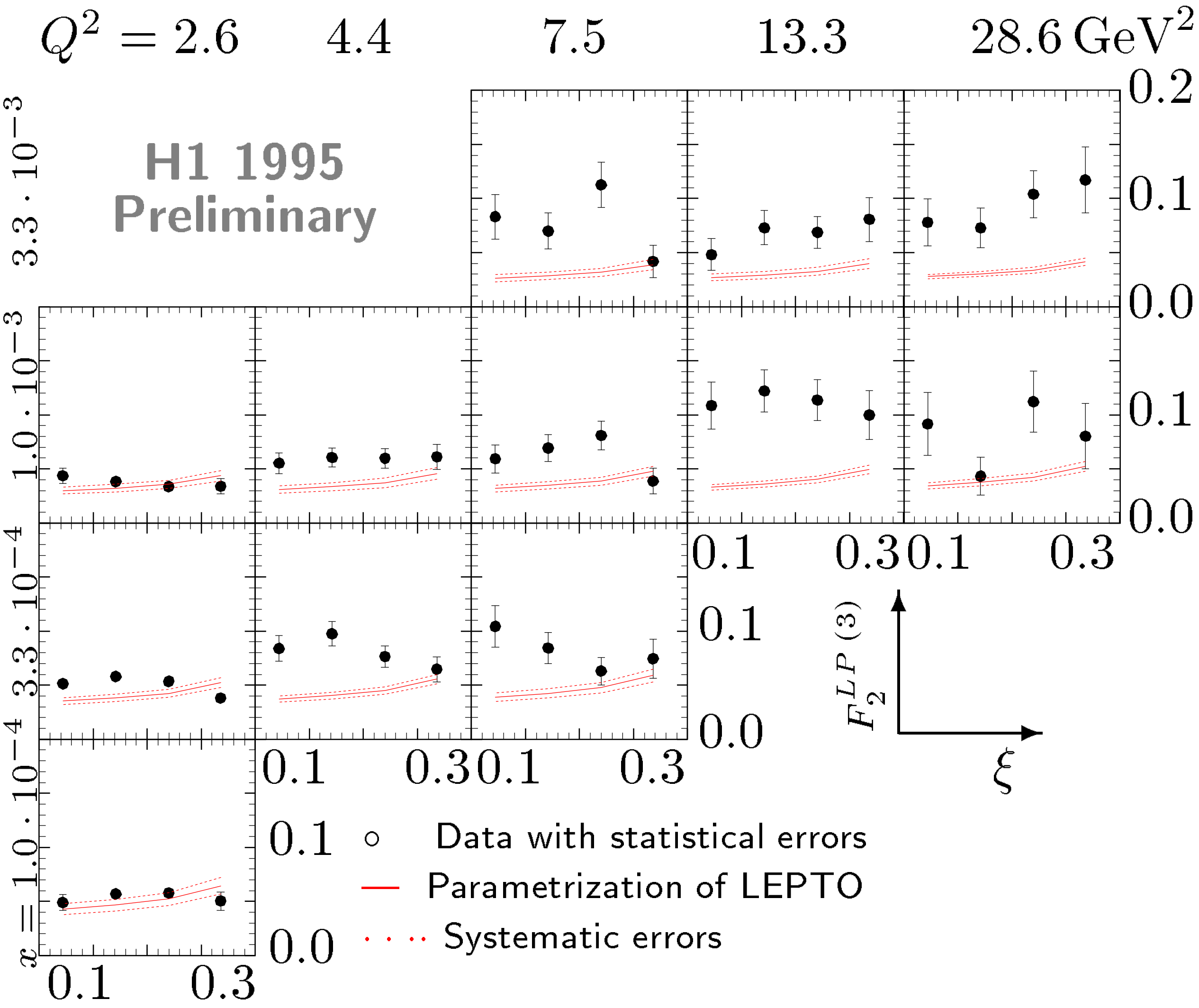
Pion structure function: Glück, Reya, and Vogt

Cross section prediction factor 1.85 too low,

Shape of distributions well described

$\chi^2/df = 54.2/47, \ (CL = 21.9\,\%)$

Comparison with LEPTO



LEPTO: Soft color interactions

Cross section at small Q^2 OK

ξ spectrum rises too steeply

Q^2 rise of data not described

Summary and Conclusions

- Ratio of events with leading baryon to all DIS events is independent of x, Q^2, and W and track multiplicity.

- Energy spectra of leading neutrons and protons at $x_\mathrm{L} < 0.98$ are independent of beam or Q^2.

- Leading neutrons and leading protons with $x_\mathrm{L} < 0.9$ are not predominantly produced by diffractive proton dissociation (few rapidity gap events).

- b slope for leading protons depends strongly on x_L.
  - LEPTO 6.5 fails to describe this dependency.
  - Pion exchange fits well for $0.7 \lesssim x_\mathrm{L} \lesssim 0.9$.
  - Proton dissociation needed to describe rapidity gap events at $x_\mathrm{L} \lesssim 0.9$.

- Measurement of $F_2^{LP\,(3)}$ for $0.7 < x_\mathrm{L} < 0.9$:
  - Factorization in β, ξ and x, ξ
  - π^0 exchange (RAPGAP) describes shape of $F_2^{LP\,(3)}$, normalization too low
  - Soft color interactions (LEPTO): Too shallow Q^2 rise