DIS with Leading Protons in the Forward Proton Spectrometer of H1 at HERA

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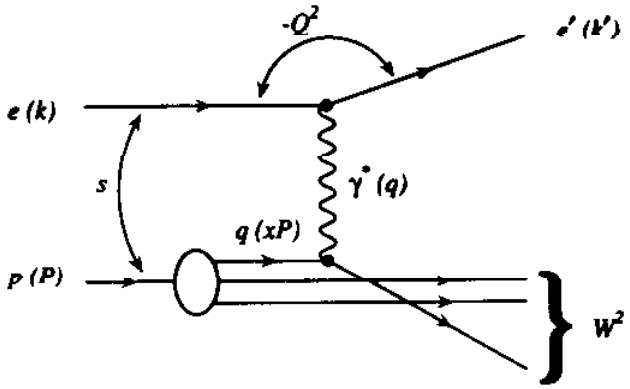
Working Group II: Diffraction

- Introduction
- Measurement of $\frac{\mathrm{d}^3\sigma\,(ep\to e'p'X)}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}x_\pi} \propto F_2^{LP\,(3)}$
- Fits to $F_2^{LP\,(3)}$, Factorization

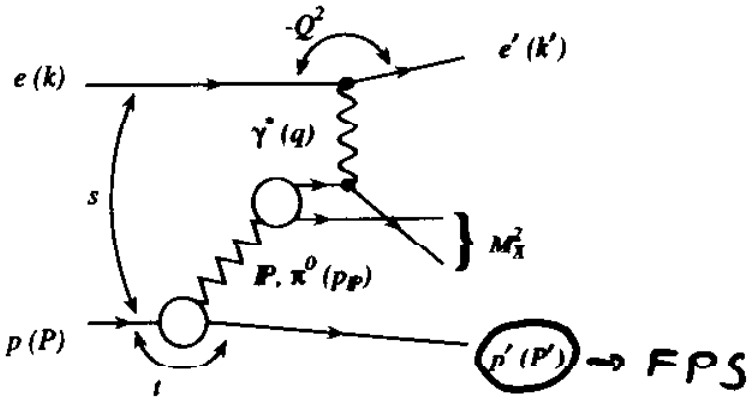
Kinematics



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

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

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



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

$\beta = \frac{Q^2}{2p_\pi \cdot q}$ Momentum fraction of quark out of "pion"

$$Q^2 = \beta \cdot x_\pi \cdot y \cdot s$$

$$\beta = \frac{x}{x_\pi}$$

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

Cross Section Definition

Semiinclusive cross section $\sigma\,(ep \to e'p'X)$
for DIS events with protons of $p_\perp < 200\,\mathrm{MeV}$.
Measured for $E'_p = 580 - 740\,\mathrm{GeV}$ $(x_\pi = 0.1 - 0.3)$.

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

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

$$\mathrm{d}x = x_\pi \cdot \mathrm{d}\beta \qquad x = x_\pi \cdot \beta$$

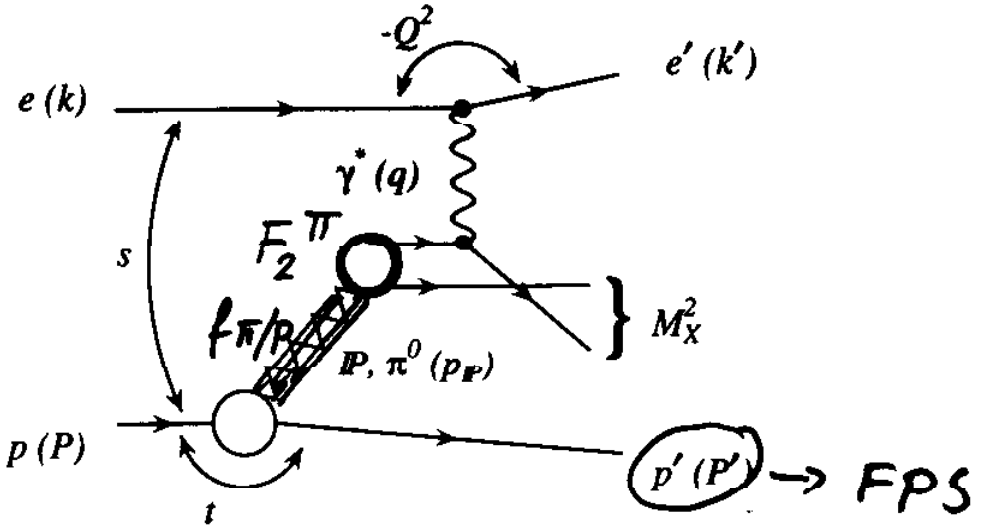
$$\frac{\mathrm{d}^3\sigma\,(ep \to e'p'X)}{\boxed{\mathrm{d}\beta}\,\mathrm{d}Q^2\,\mathrm{d}x_\pi} = \frac{4\pi\alpha^2}{\boxed{\beta}\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}\,(\beta,\, Q^2,\, x_\pi)$$

Cross section unambiguously* defined on hadron level

Model independent

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

Pion Exchange



Proton emits **virtual pion**

Momentum fraction $x_\pi = 1 - E'_p/E_p$ measured by FPS

$\beta = x/x_\pi$ momentum fraction of quark out of pion

Flux factor $f_{\pi/p}(x_\pi, t)$

Pion structure function $F_2^\pi(\beta, Q^2)$

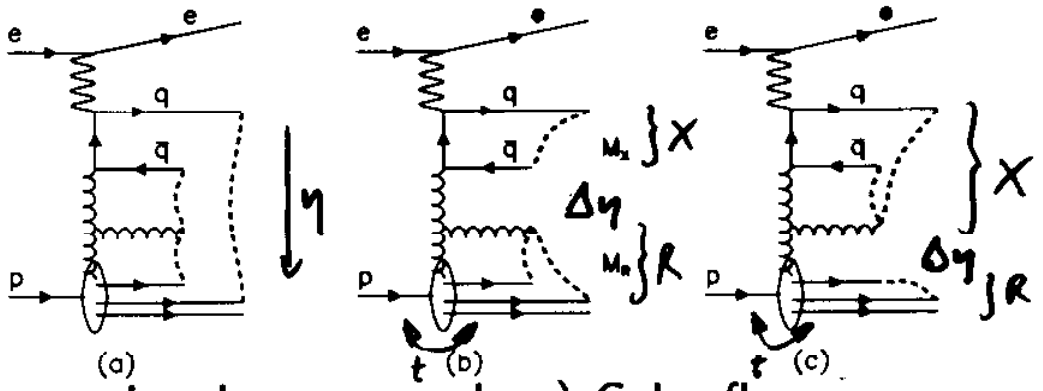
$$\begin{aligned}
\frac{\mathrm{d}^3\sigma(ep \to e'p'X)}{\mathrm{d}\beta\,\mathrm{d}Q^2\,\mathrm{d}x_\pi} &= \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}(\beta, Q^2, x_\pi) \\
&= f_{\pi/p}(x_\pi)\,\frac{\mathrm{d}^2\sigma(e\pi \to e'X)}{\mathrm{d}\beta\,\mathrm{d}Q^2} \\
&= f_{\pi/p}(x_\pi)\,\frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^\pi(\beta, Q^2)
\end{aligned}$$

Expect factorization

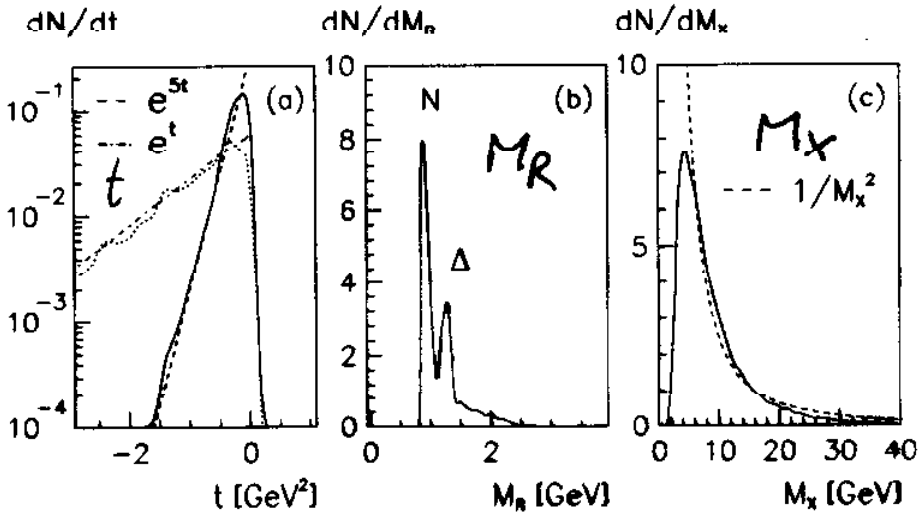
$$F_2^{LP\,(3)}(\beta, Q^2, x_\pi) = F_2^\pi(\beta, Q^2) \cdot \underbrace{\int_t f_{\pi/p}(x_\pi, t)\,\mathrm{d}t}_{f_{\pi/p}(x_\pi)}$$

Soft Color Interactions

Generator: LEPTO (6.3)



a) Conventional b, c) Color flow rearranged



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

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, ...)

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

The H1 Forward Proton Spectrometer

Objective:

Measure protons with $E'_p > 400\,\mathrm{GeV}$, $\theta_p < 1\,\mathrm{mrad}$

$\Rightarrow$ Detectors close ($\approx 4\,\mathrm{mm}$) to proton beam

HERA magnets act as magnetic spectrometer

$\Rightarrow$ Energy measurement by measuring offset and tilt of proton trajectory w.r.t. circulating beam at $85\,\mathrm{m}$

Forward Proton Spectrometer

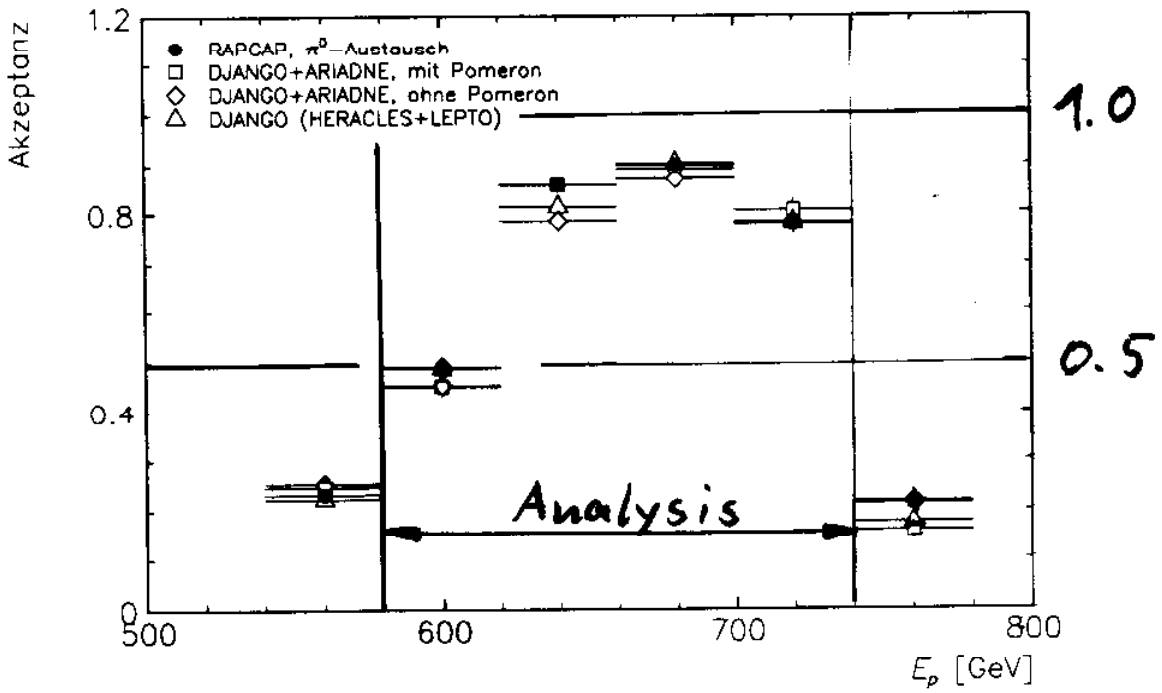
- Detectors in plunger vessels ("Roman Pots")
- Scintillating fiber hodoscopes
- Readout by multi channel photomultipliers
- 2 stations at 81 and 90 m
- Position resolution $\approx 0.1\,\mathrm{mm}$

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

Acceptance of the H1 FPS

Acceptance:

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



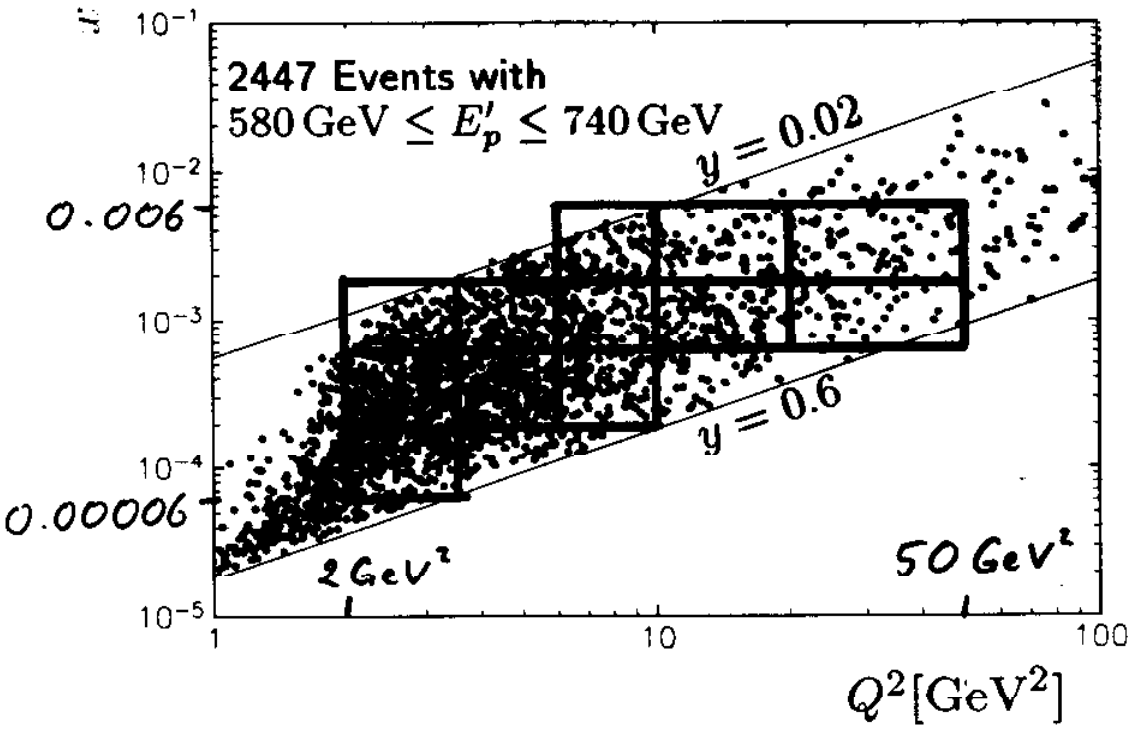
Acceptance $\gtrsim 50\,\%$ for $E'_p = 580 - 740\,\mathrm{GeV}$

Analysis:

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

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

DIS Analysis



1995 Data, $\int \mathcal{L} dt = 1.44\,\mathrm{pb}^{-1}$

Cuts:

- Electron energy: $E'_e > 12\,\mathrm{GeV}$
- Electron scattering angle: $155° < \theta_e < 177°$
- Inelasticity: $0.02 < y < 0.6$
- ≥ 1 track with $p_\perp > 450\,\mathrm{MeV}$ at $20° < \theta < 160°$
- + further quality cuts

Kinematics: Σ method combines Electron variables E'_e, θ_e with hadronic quantity $\Sigma = \sum_h (E_h - p_{z,h})$.

Q^2 resolution: 8 %

x resolution: 10 . . . 30 % at $y \approx 0.6 \ldots 0.02$

Radiative corrections small

Errors

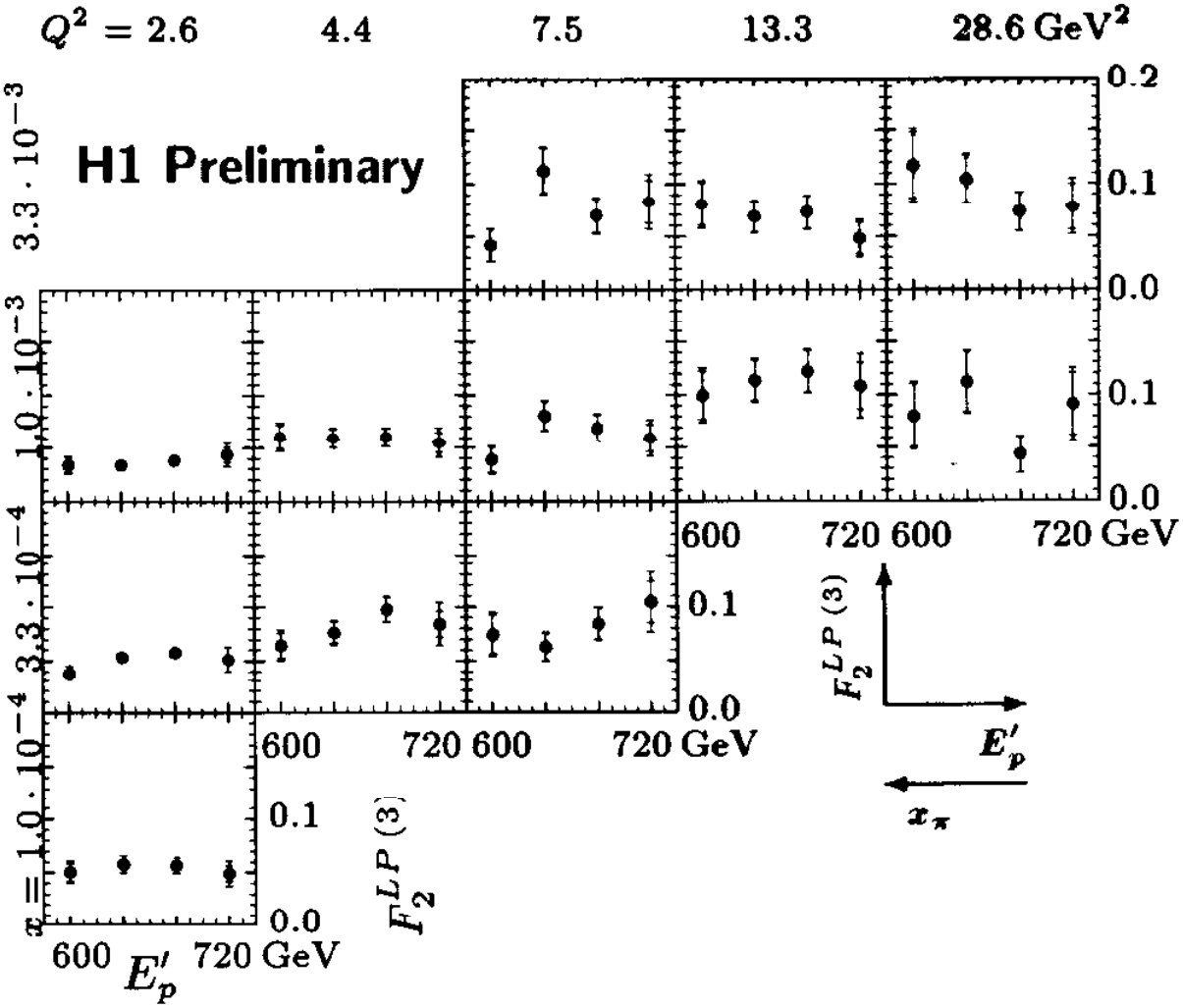
- Normalization: Common error
  - ▶ Luminosity: $1.14\,\%$
  - ▶ Track reconstruction in FPS: $5\,\%$
  - ▶ z position of vertex: $1\,\%$

  Sum: $\mathbf{5.2\,\%}$
- FPS induced: Dependent on E'_p (x_π)
  - ▶ Migration correction: $2.3 \ldots 18.9\,\%$
  - ▶ Acceptance: $3.7 \ldots 11.5\,\%$

  Sum: $\mathbf{4.9 \ldots 19.3\,\%}$
- x, Q^2 dependent
  - ▶ Trigger efficiency SpaCal: $5\,\%$
  - ▶ Trigger efficiency DC$R\phi$: $2\,\%$
  - ▶ ≥ 1 good track: $3\,\%$
  - ▶ Measurement of E'_e: $-1.0 \ldots +5.4\,\%$
  - ▶ Measurement of θ_e: $0.8 \ldots 4.0\,\%$
  - ▶ Measurement of Σ: $-5.7 \ldots +4.6\%$
  - ▶ Acceptance: $1.7 \ldots 8.3\,\%$

  Sum: $\mathbf{7.7 \ldots 12.3\,\%}$
- **Statistical error:** $\mathbf{9.4 \ldots 41\,\%}$

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



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

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

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

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

Hypothesis:

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

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

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

with $r\left(x_{\pi 3} = 0.171\right) = 1$,
$r\left(x_{\pi j}\right) = r_j$, take r_j as free parameters for $j \neq 3$.

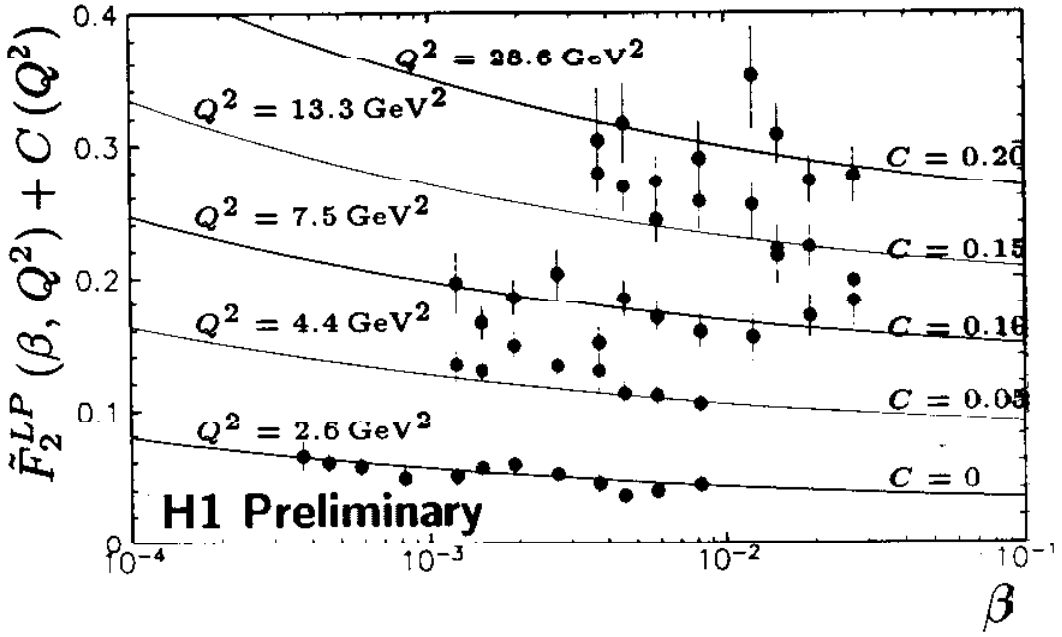
Fit to

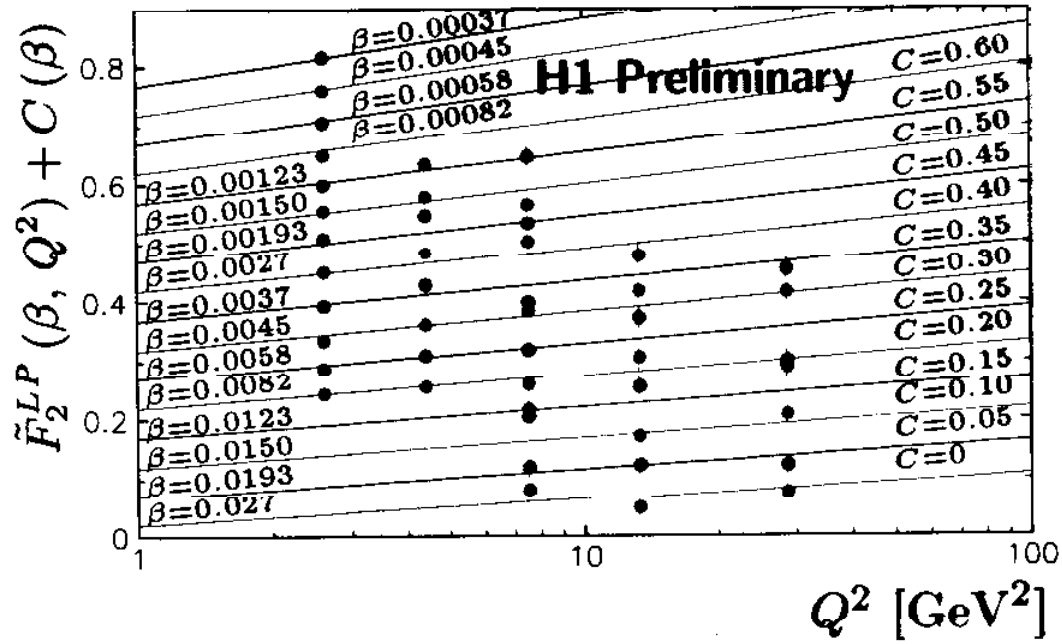
$$F_2^{LP(3)}\left(\beta,\, Q^2,\, x_\pi\right) = r_j \cdot \left(a \cdot \beta^b + c \cdot \beta^d \cdot \log Q^2\right).$$

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

Reminder:
$\beta = x/x_\pi$ Momentum fraction of quark out of "pion"
$x_\pi = 1 - E'_p/E_p$ Momentum fraction carried by "pion"

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





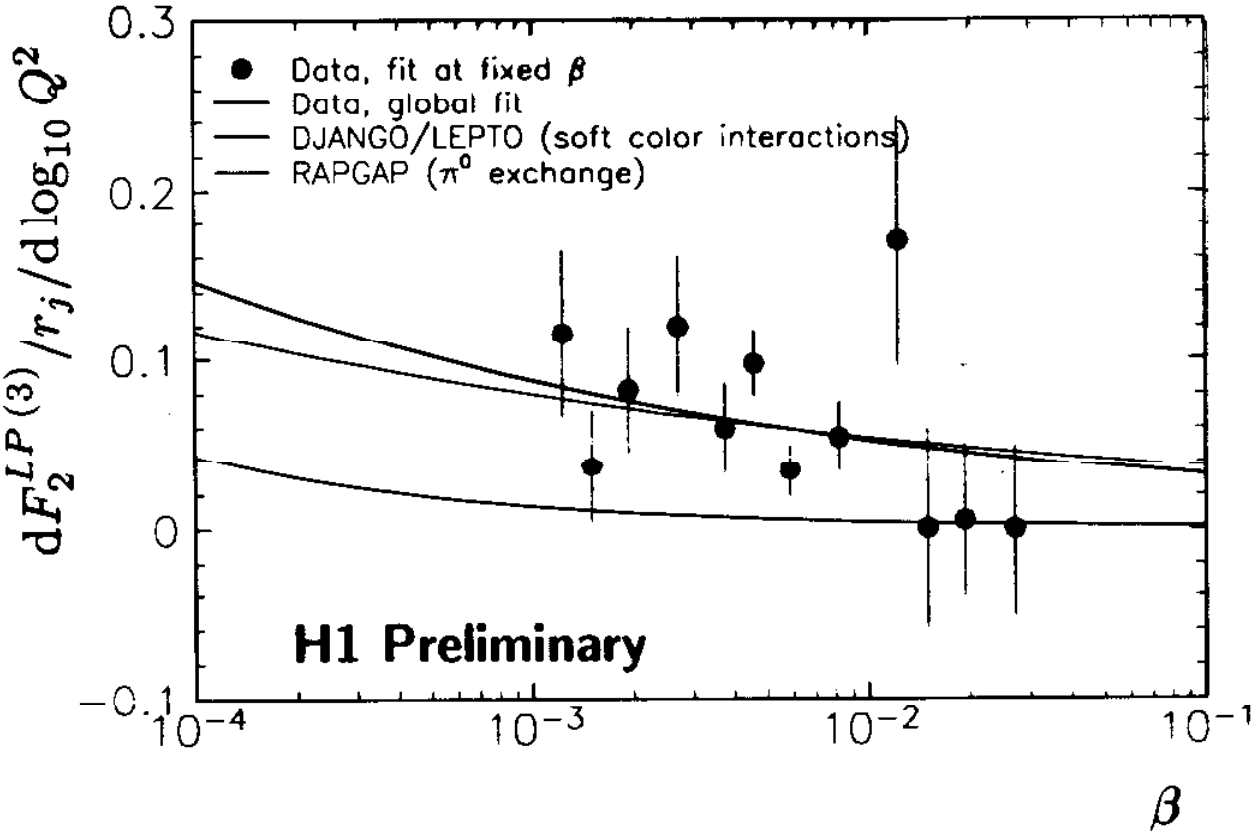
Factorisation:

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

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

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

Q^2 Rise



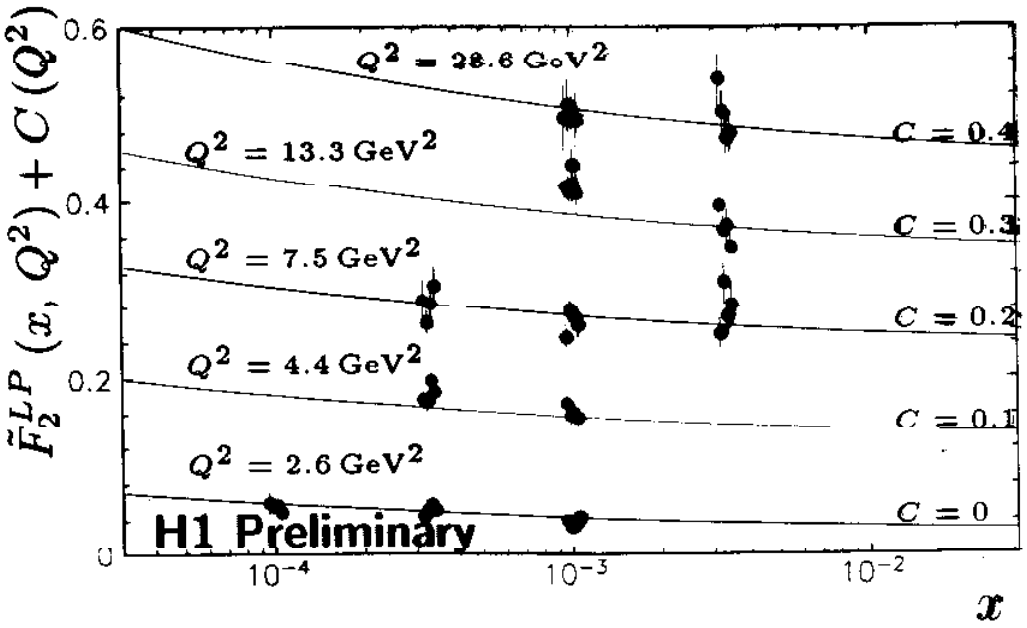
$\mathrm{d}F_2^{LP\,(3)}/\mathrm{d}\log_{10} Q^2$

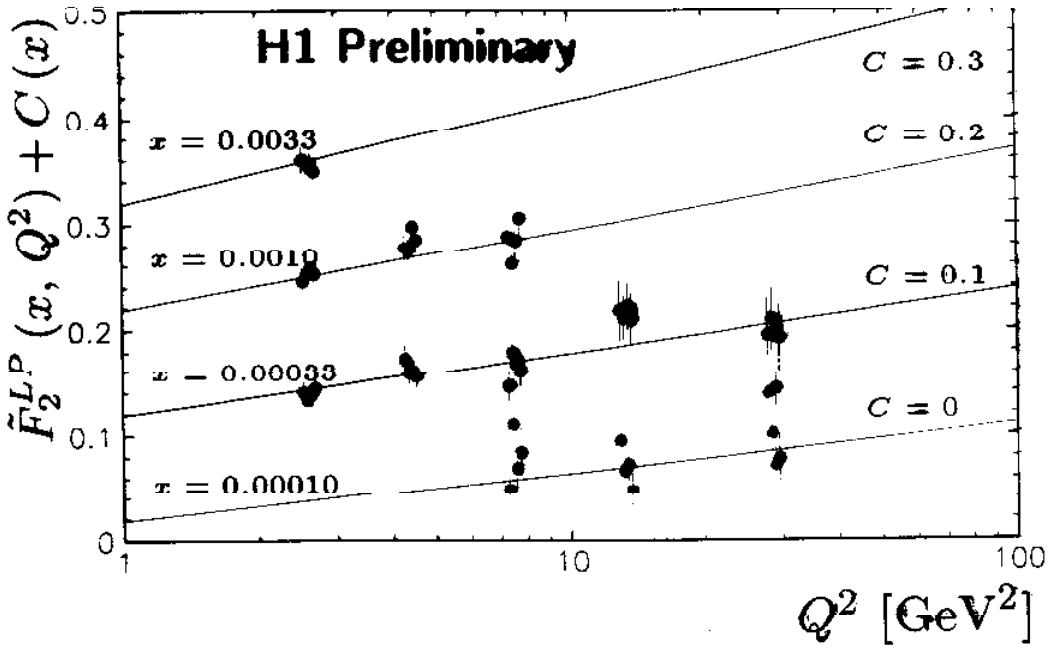
Red points:

Q^2 dependence fitted for each β bin independently

$F_2^{LP\,(3)}(\beta, Q^2) = a(\beta) \cdot \log_{10} Q^2 + b(\beta)$

Factorisation in x, Q^2, x_π?



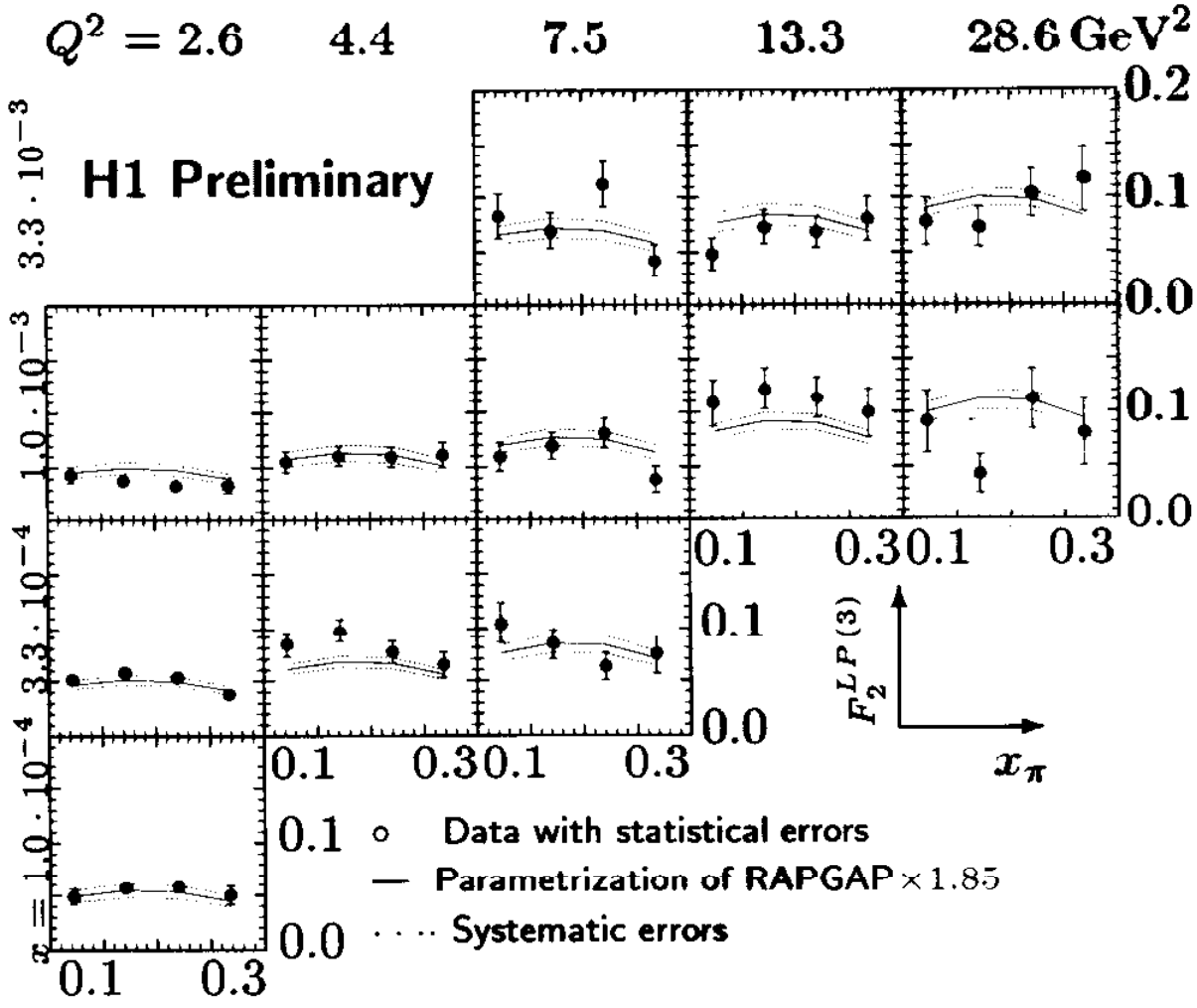


$$F_2^{LP\,(3)}(x, Q^2, x_\pi) = r(x_\pi) \cdot \tilde{F}_2^{LP}(x, Q^2)$$

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

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

Comparison with RAPGAP



RAPGAP: π^0 exchange

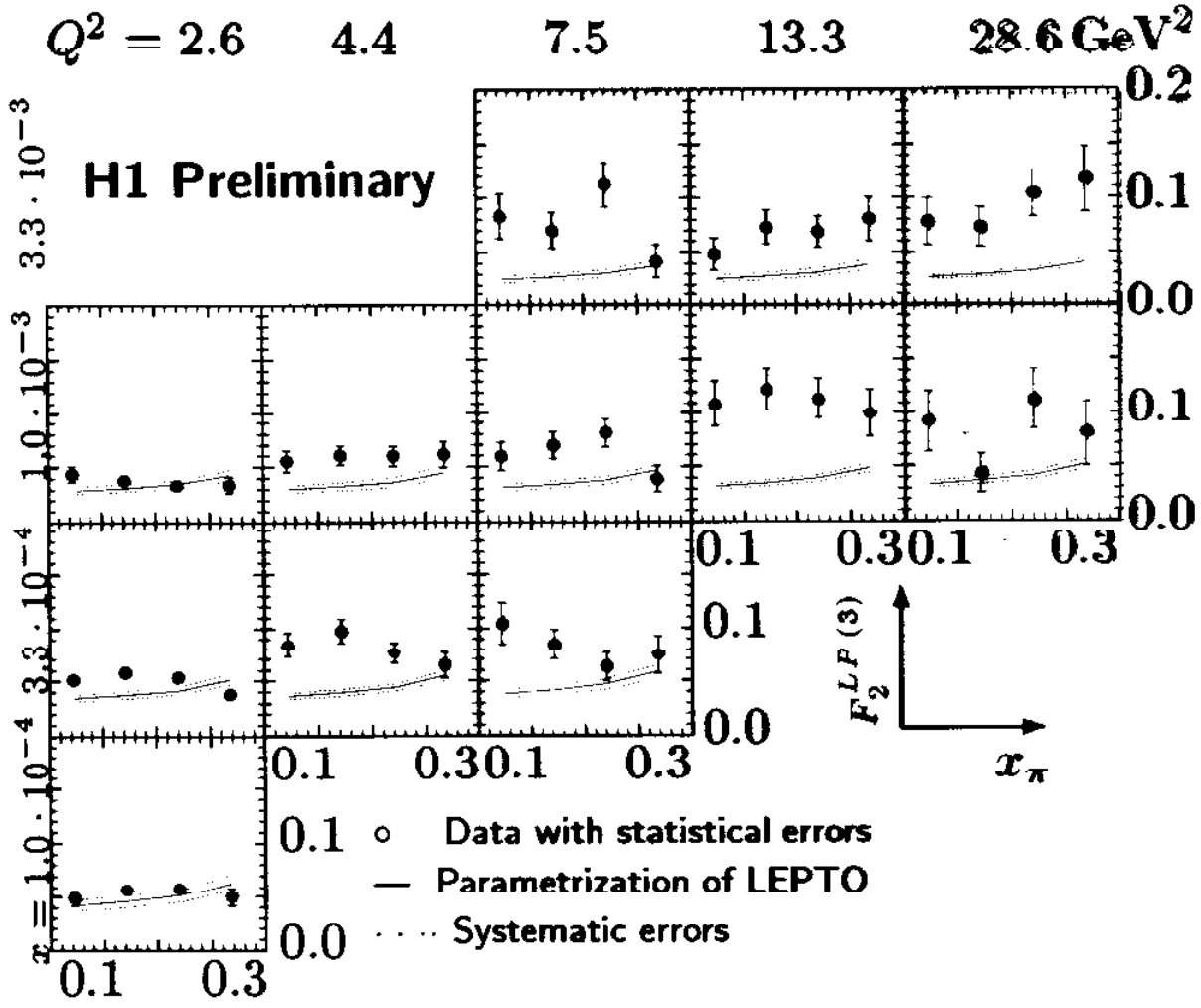
Pion structure function: GLÜCK, REYA, and VOGT

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

x_π spectrum rises too steeply

Q^2 rise of data not described

Summary

- Measurement of $\frac{\mathrm{d}^3\sigma\,(ep\to e'p'X)}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}x_\pi}$ for $p_\perp < 200\,\mathrm{MeV}$, parametrized by $F_2^{LP\,(3)}$
  Analysis: $E'_p = 580 - 740\,\mathrm{GeV}$ $(x_\pi = 0.1 - 0.3)$
- Rise of $F_2^{LP\,(3)}$ with Q^2 and with falling x
- Small x_π dependency
- Data compatible with factorization in β, x_π and x, x_π
- π^0 exchange (RAPGAP) describes shape of $F_2^{LP\,(3)}$, normalization too low
- Soft color interactions (LEPTO): Too shallow Q^2 rise