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

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DESY, H1

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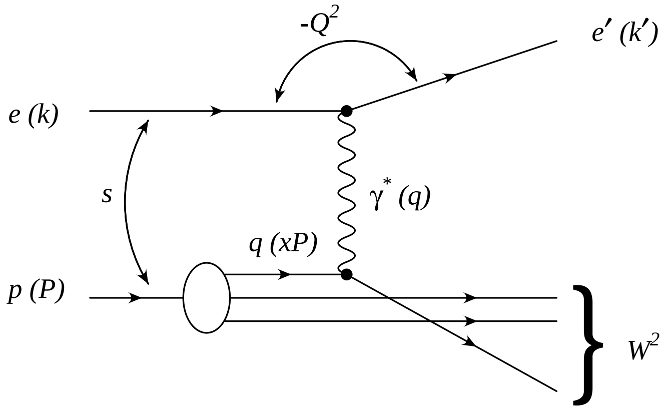
Working Group II: Diffraction

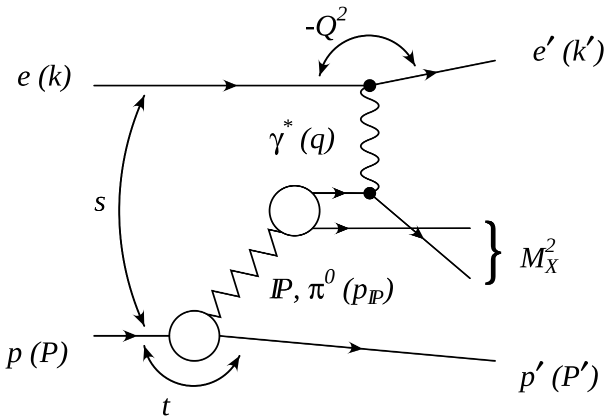
- Introduction
- Measurement of $\frac{\mathrm{d}^3\sigma\,(ep\to e'p'X)}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}x_\pi} \propto F_2^{LP\,(3)}$
- Fits to $F_2^{LP\,(3)}$, Factorization

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 $F_2^{LP\,(3)}$:

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

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

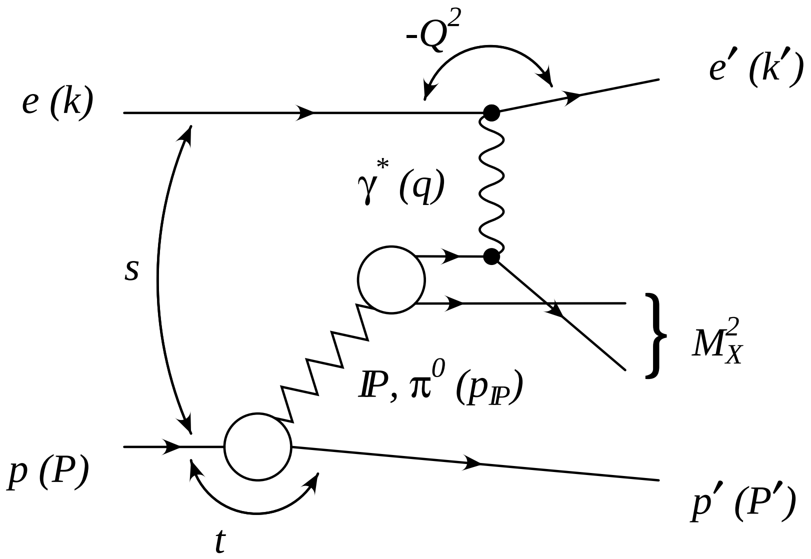
$$\frac{\mathrm{d}^3\sigma\,(ep \to e'p'X)}{\boxed{\mathrm{d}\beta}\,\mathrm{d}Q^2\,\mathrm{d}x_\pi} = \frac{4\pi\alpha^2}{\boxed{\beta}\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}\,(\beta,\, Q^2,\, x_\pi)$$

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 $F_2^\pi\,(\beta,\, Q^2)$

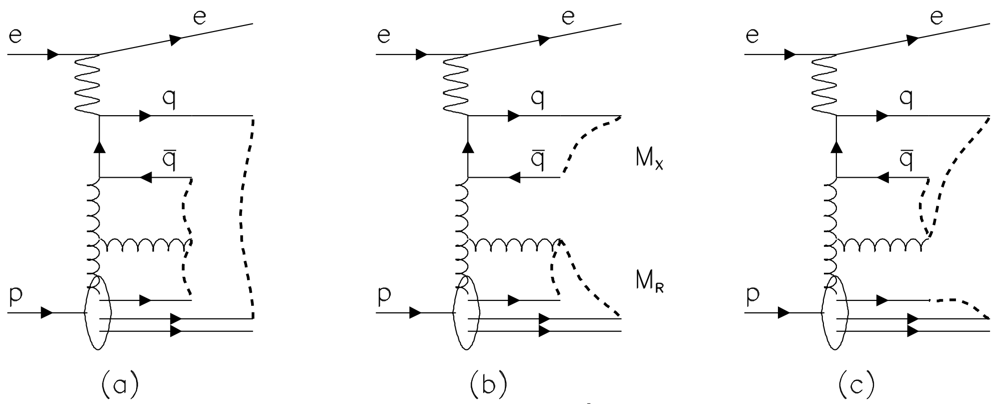
$$\begin{aligned}
\frac{\mathrm{d}^3\sigma\,(ep \to e'p'X)}{\mathrm{d}\beta\,\mathrm{d}Q^2\,\mathrm{d}x_\pi} &= \frac{4\pi\alpha^2}{\beta\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}\,(\beta,\, Q^2,\, x_\pi) \\
&= f_{\pi/p}\,(x_\pi)\,\frac{\mathrm{d}^2\sigma\,(e\pi \to e'X)}{\mathrm{d}\beta\,\mathrm{d}Q^2}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

Expect factorization

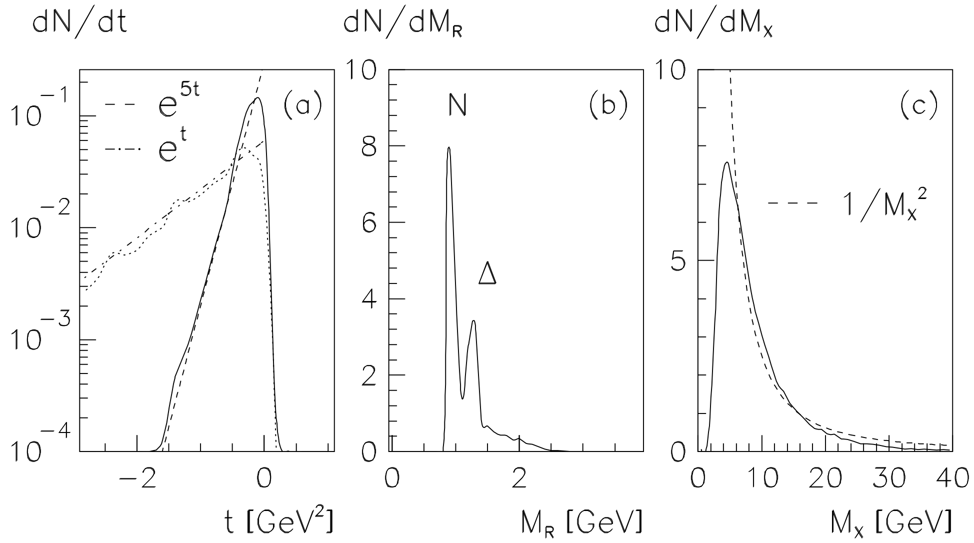
$$F_2^{LP\,(3)}\,(\beta,\, Q^2,\, x_\pi) = F_2^\pi\,(\beta,\, Q^2) \cdot \underbrace{\int_t f_{\pi/p}\,(x_\pi,\, t)\,\mathrm{d}t}_{f_{\pi/p}\,(x_\pi)}$$

Soft Color Interactions

Generator: LEPTO



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^+, $K, \ldots$)

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

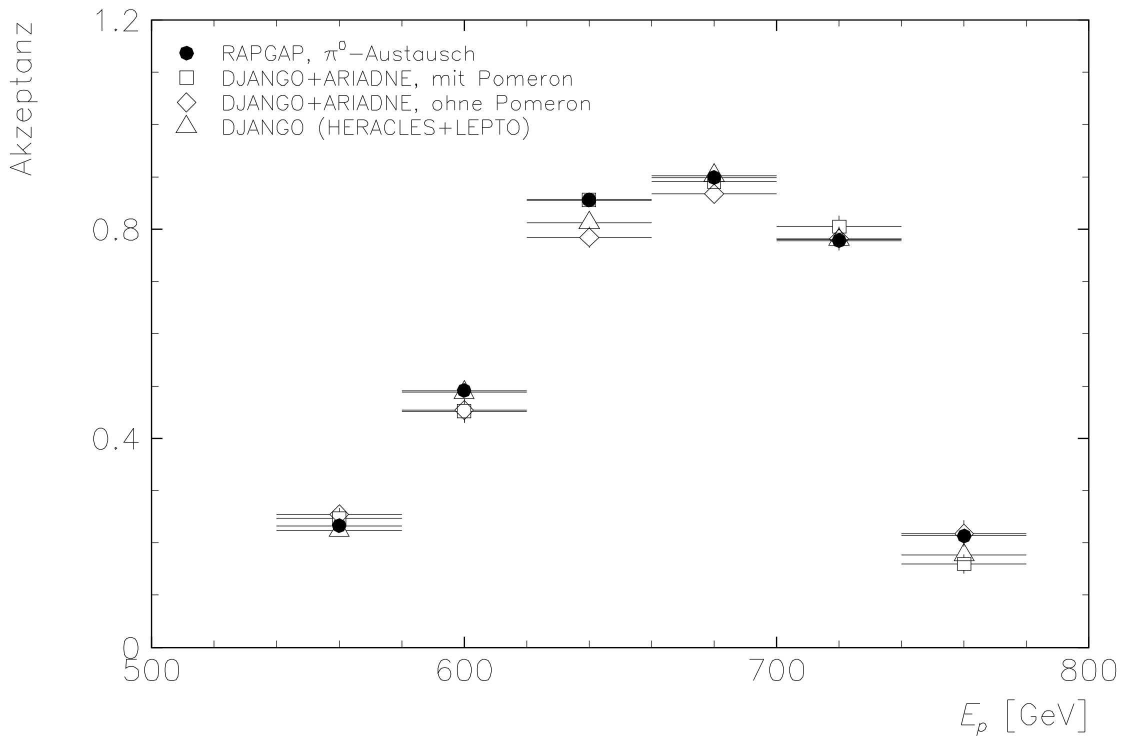
- Detectors in plunger vessels ("Roman Pots")
- Scintillating fiber hodoscopes
- Readout by multi channel photomultipliers
- 2 stations at 81 and 90 m
- Position resolution $\approx 0.1\,\mathrm{mm}$

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



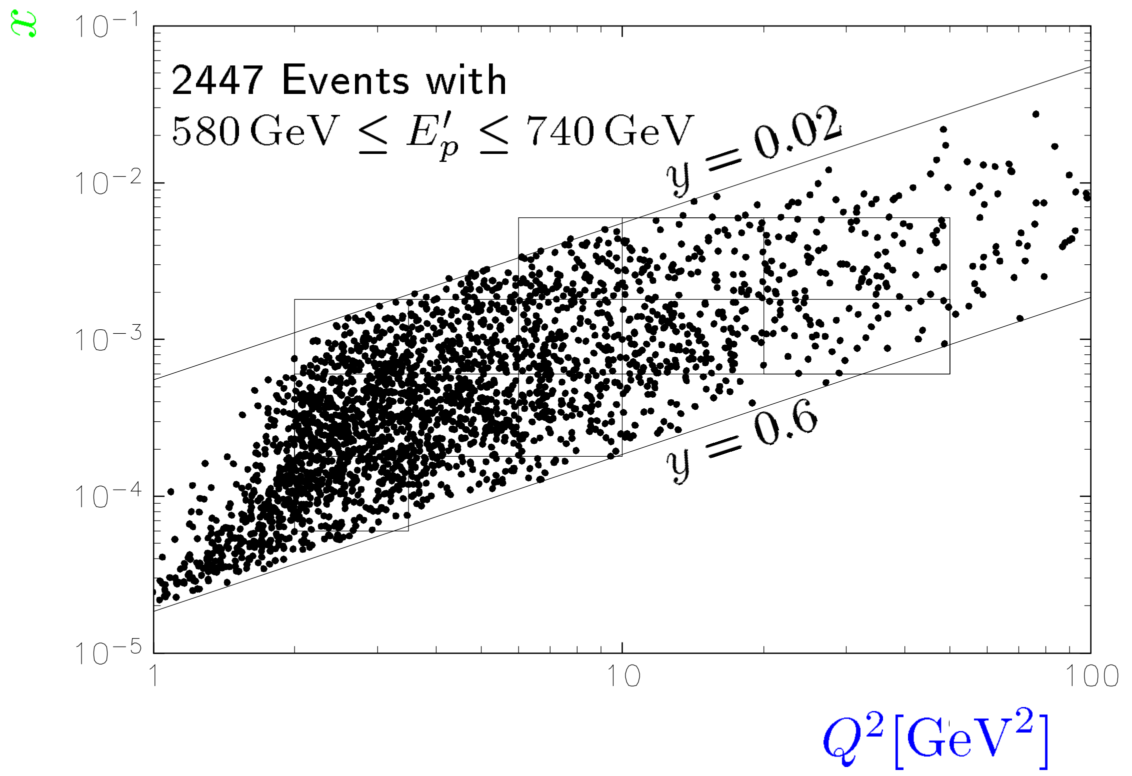
Acceptance $\gtrsim 50\,\%$ for $E'_p = 580 - 740\,\mathrm{GeV}$

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, $\int \mathcal{L}\mathrm{d}t = 1.44\,\mathrm{pb}^{-1}$

Cuts:

- Electron energy: $E'_e > 12\,\mathrm{GeV}$
- Electron scattering angle: $155^\circ < \theta_e < 177^\circ$
- Inelasticity: $0.02 < y < 0.6$
- ≥ 1 track with $p_\perp > 450\,\mathrm{MeV}$ at $20^\circ < \theta < 160^\circ$
- $+$ 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 $\ldots$ 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: $2.3\ldots18.9\,\%$
  - Acceptance: $3.7\ldots11.5\,\%$

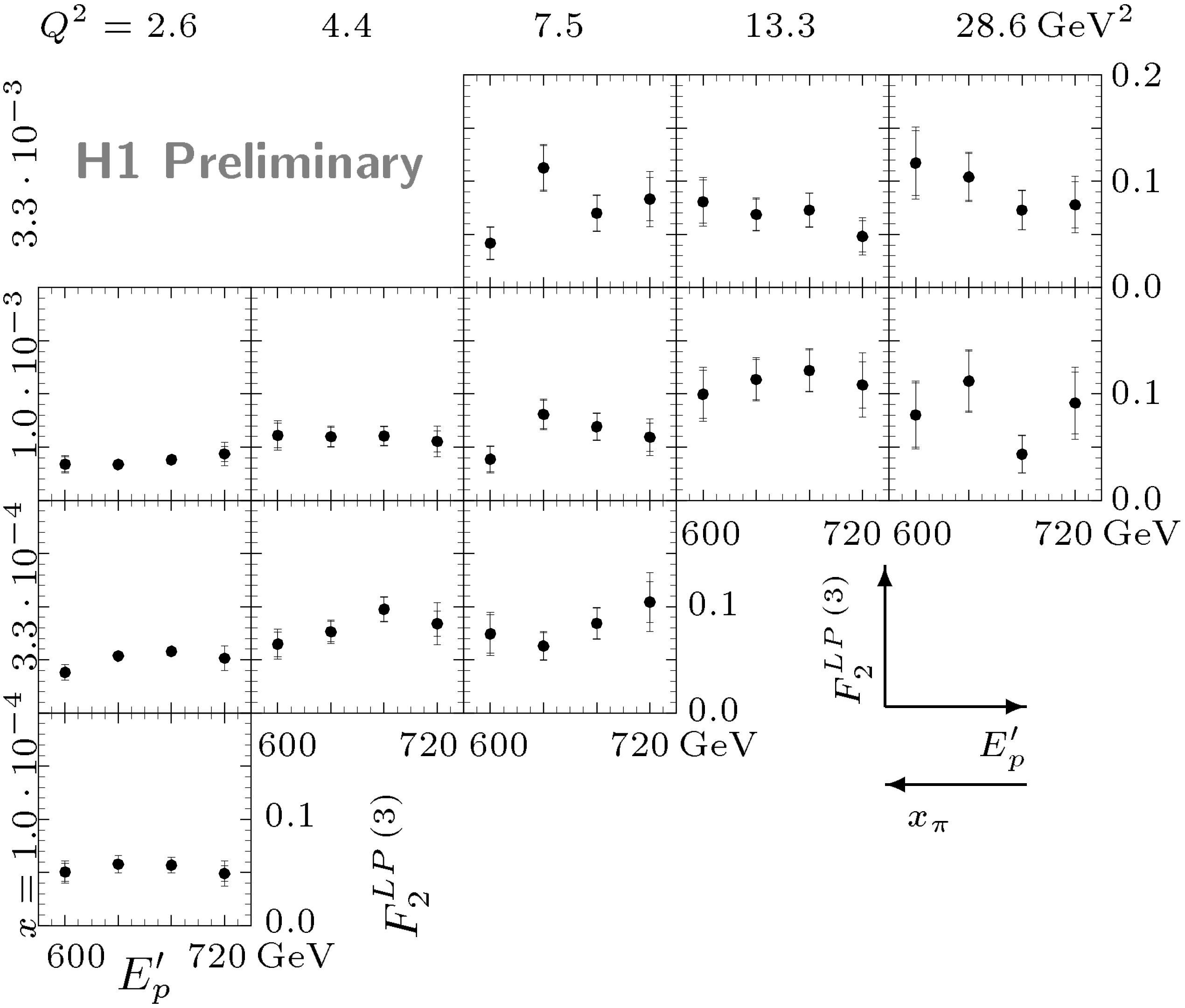
  Sum: $\mathbf{4.9\ldots19.3\,\%}$

- 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: $0.8\ldots4.0\,\%$
  - Measurement of Σ: $-5.7\ldots+4.6\%$
  - Acceptance: $1.7\ldots8.3\,\%$

  Sum: $\mathbf{7.7\ldots12.3\,\%}$

- **Statistical error:** $\mathbf{9.4\ldots41\,\%}$

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



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

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

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

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

Hypothesis:

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

Normalization of $f_{\pi/p}(x_\pi)$ uncertain

(additional trajectories)

Choose form

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

with $r(x_{\pi\,3} = 0.171) = 1$,

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

Fit to

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

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

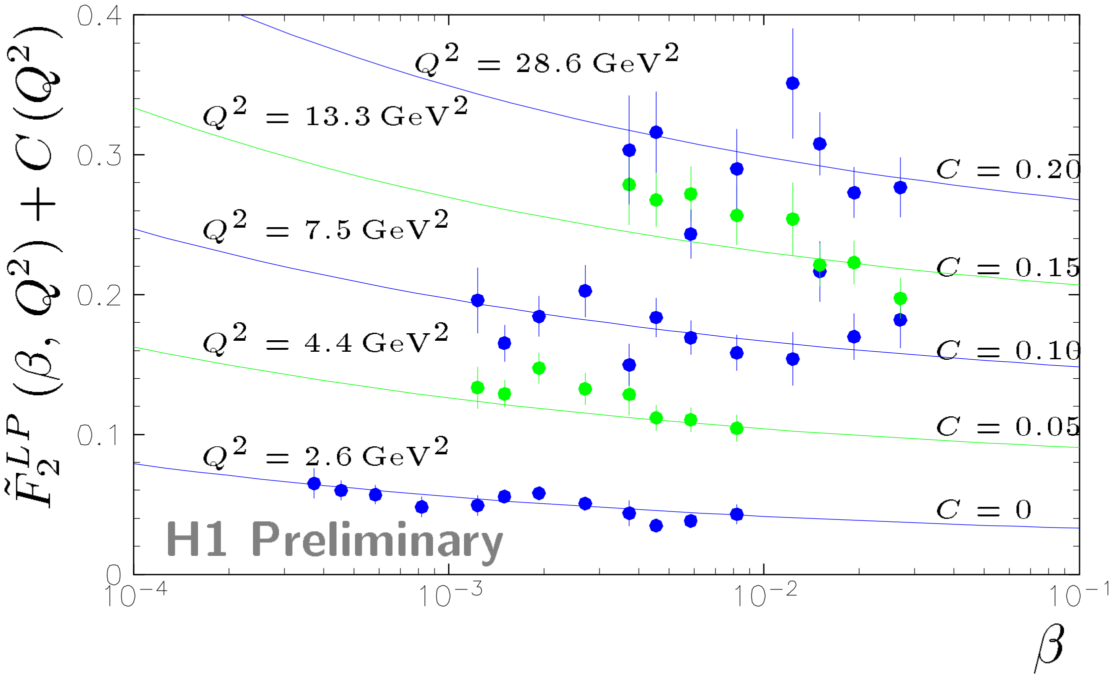
only statistical and x, Q^2 dependent errors

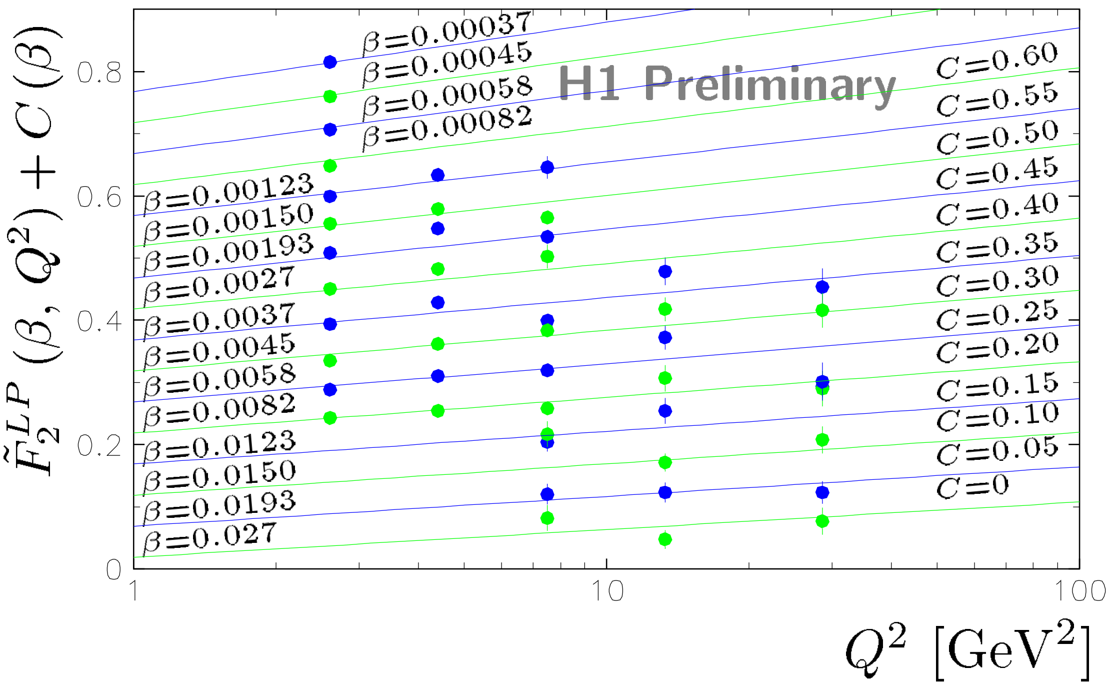
Reminder:

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

$x_\pi = 1 - E_p'/E_p$ Momentum fraction carried by "pion"

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





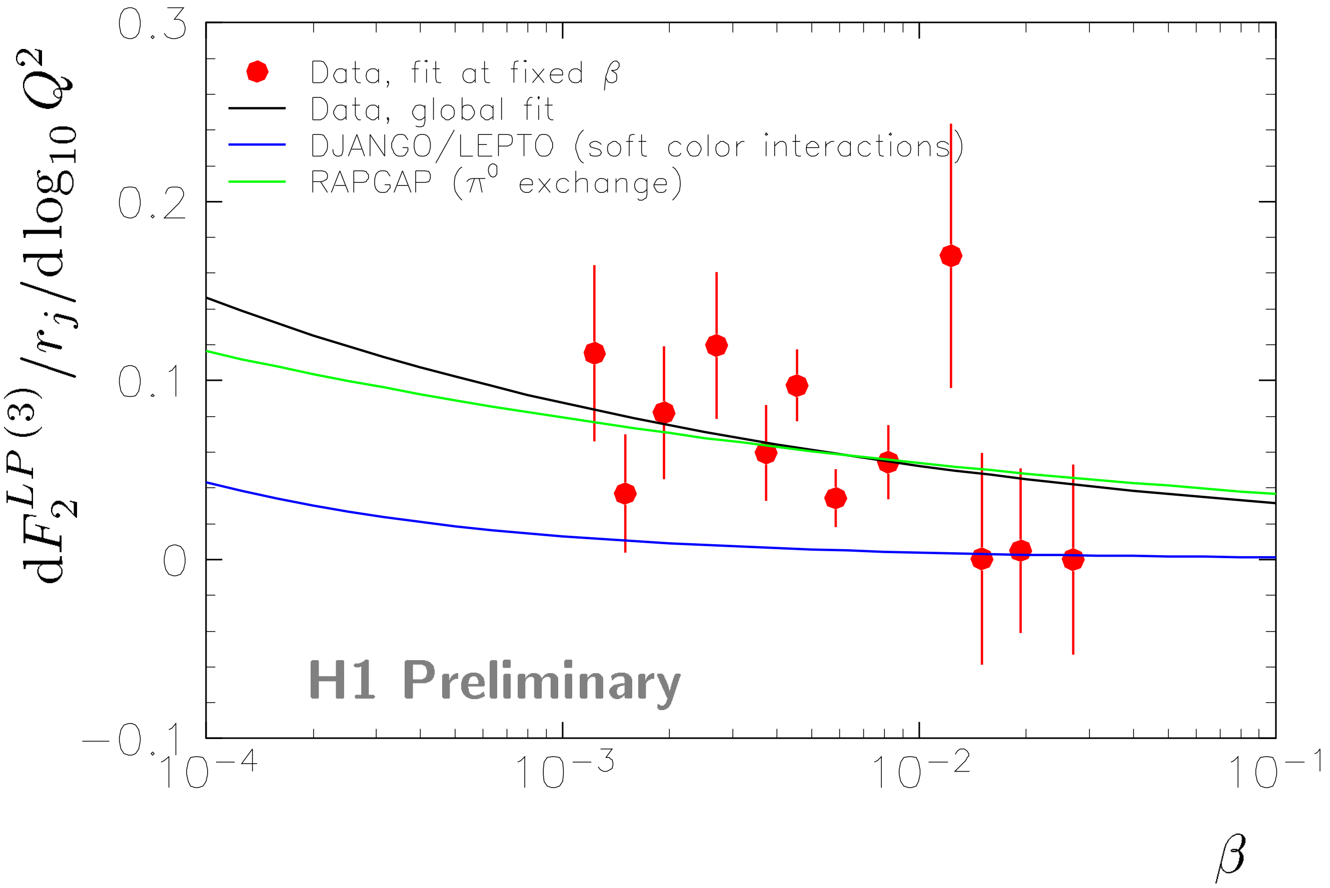
Factorisation:

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

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

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

Q^2 Rise



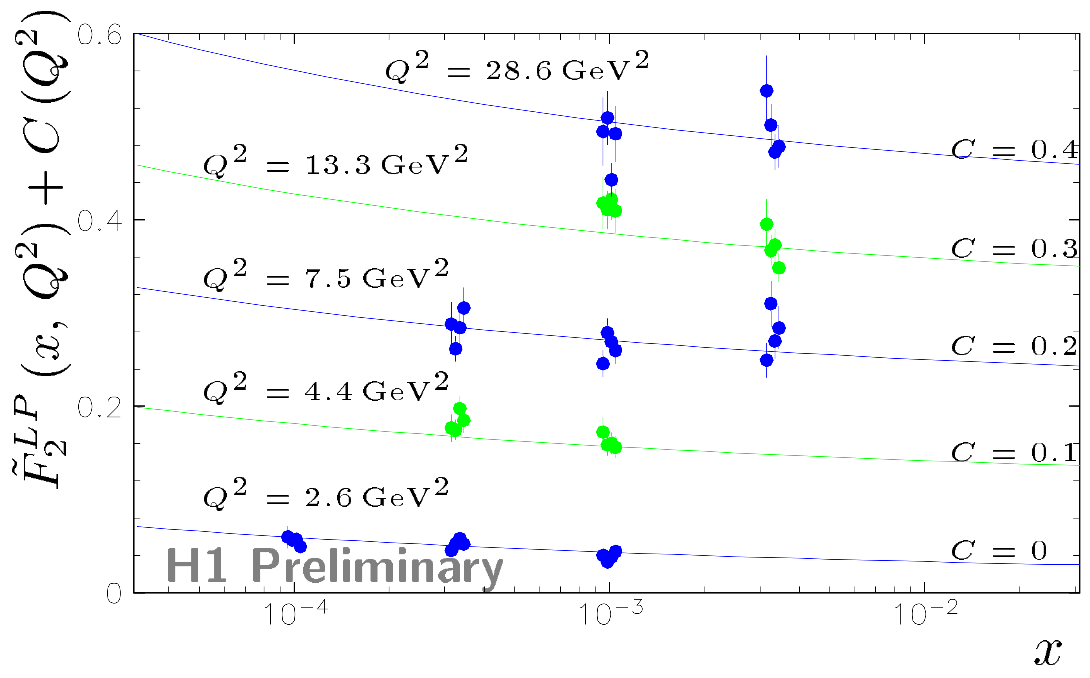
$dF_2^{LP\,(3)}/d\log_{10}Q^2$

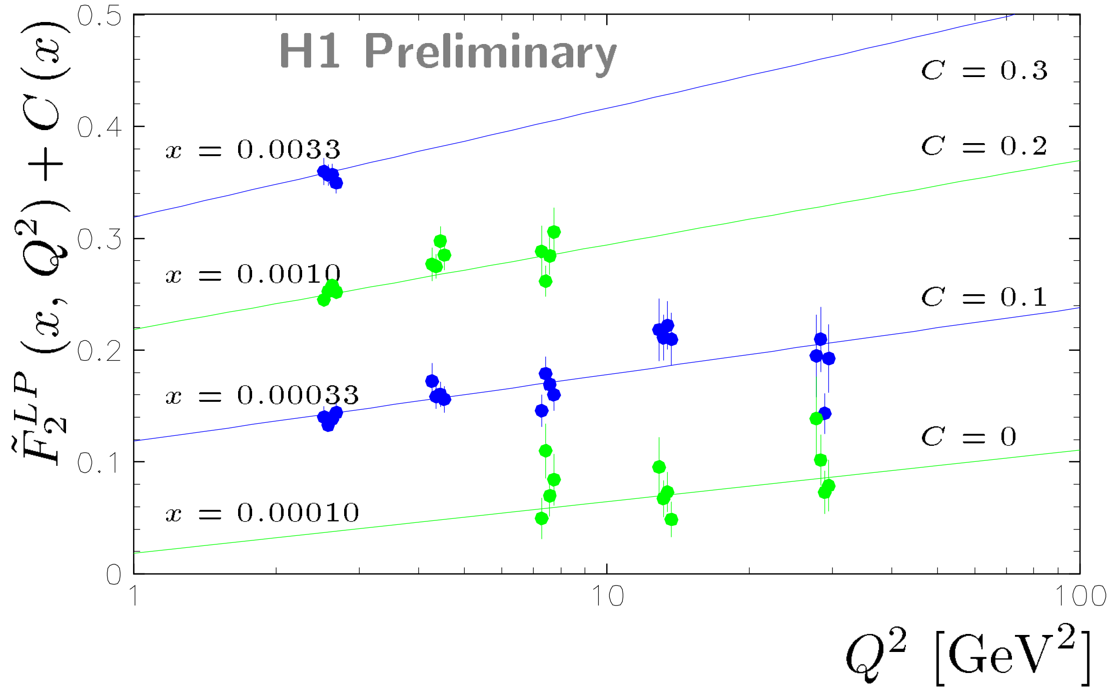
Red points:

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?



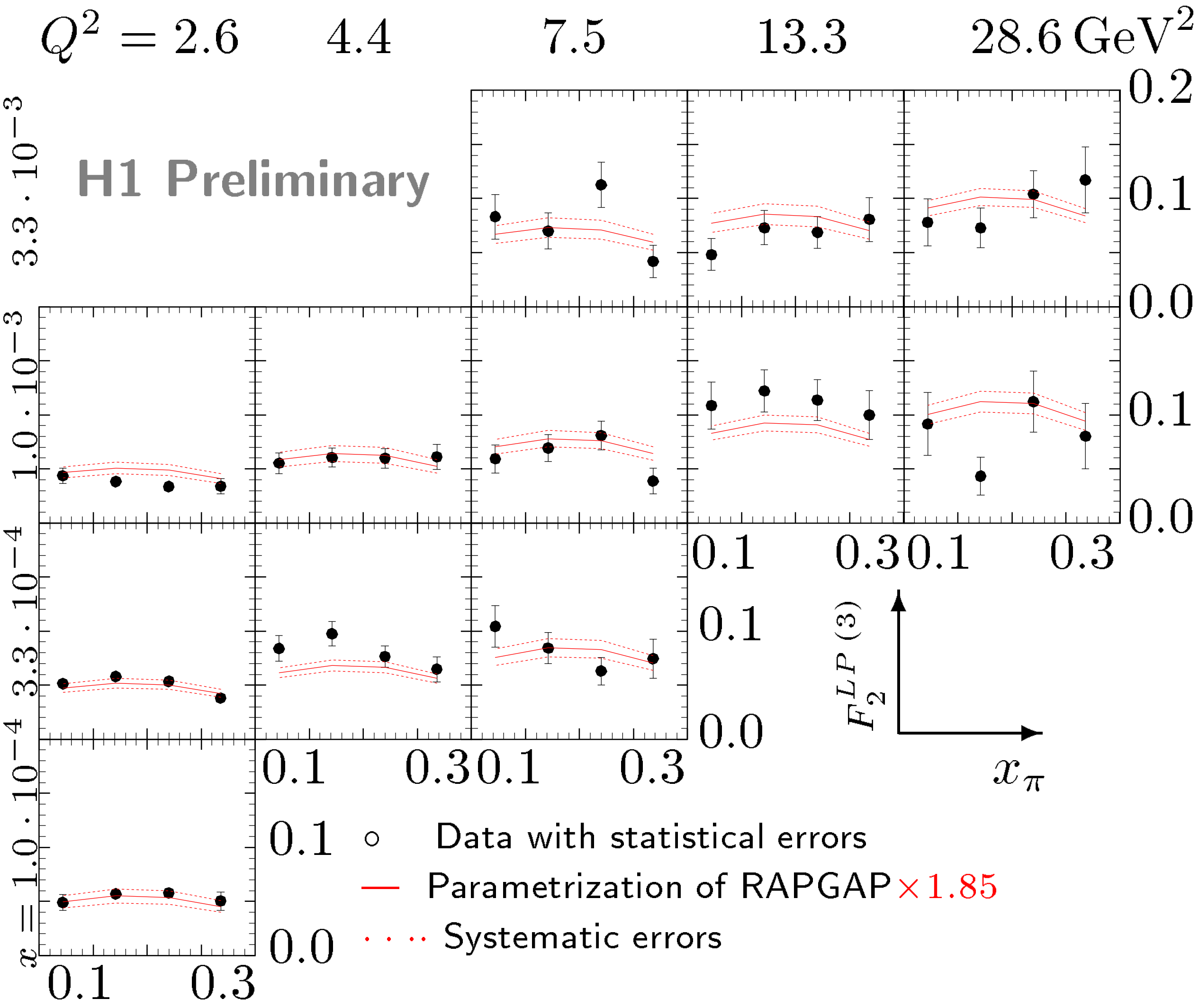


$$F_2^{LP(3)}(x, Q^2, x_\pi) = r(x_\pi) \cdot \tilde{F}_2^{LP}(x, Q^2)$$

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

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

Comparison with RAPGAP



RAPGAP: π^0 exchange

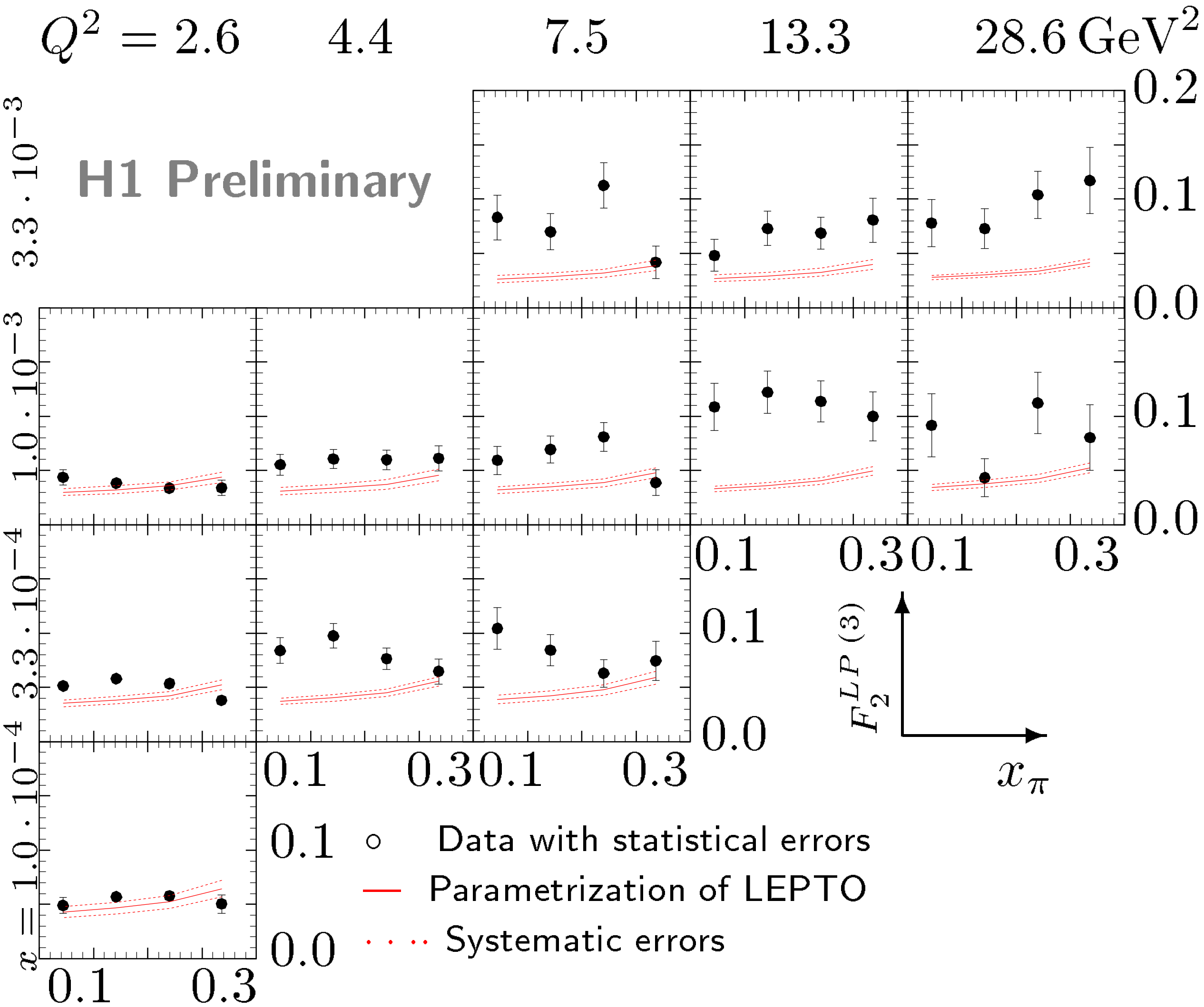
Pion structure function: Glück, Reya, and Vogt

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 $\frac{\mathrm{d}^3\sigma\,(ep\rightarrow e'p'X)}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}x_\pi}$ 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