Physics Results on the Tagged Structure Functions at HERA

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DESY
on behalf of H1 and ZEUS

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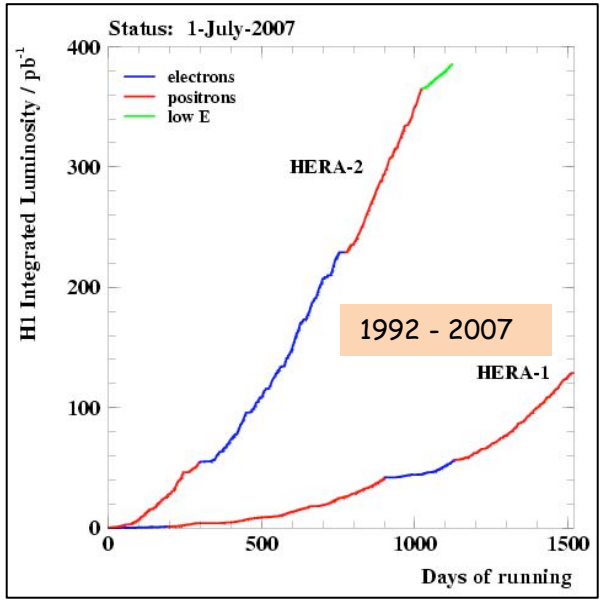
HERA, the H1 and the ZEUS Detector



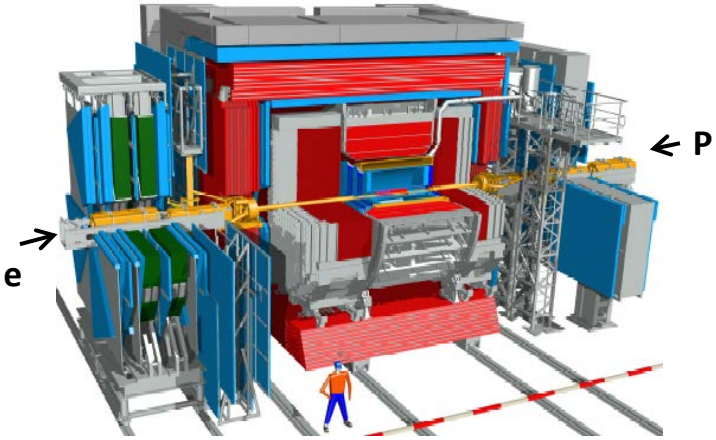
Three periods of data taking:

HERA I : ~120 pb^{-1}

HERA II : ~380 pb^{-1}

Low proton energy: ~65 pb^{-1}

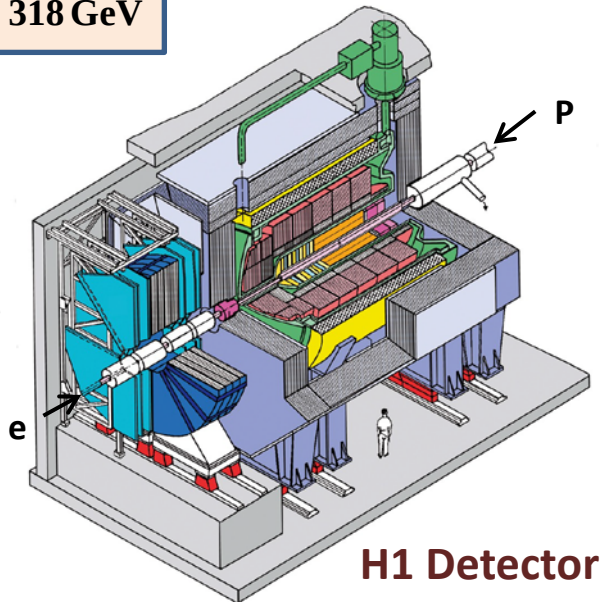
$$E_p = 920\,\text{GeV} \quad E_e = 27.5\,\text{GeV} \quad \sqrt{s} = 4E_pE_e = 318\,\text{GeV}$$



ZEUS Detector

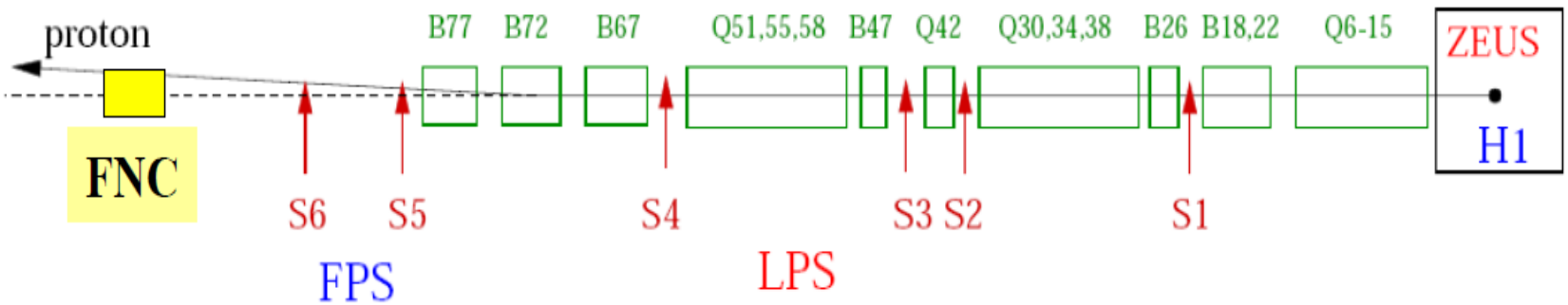
Inner tracking system
Superconducting solenoid
Calorimeter
Iron yoke
Muon chambers inside/outside yoke
Forward muon detector

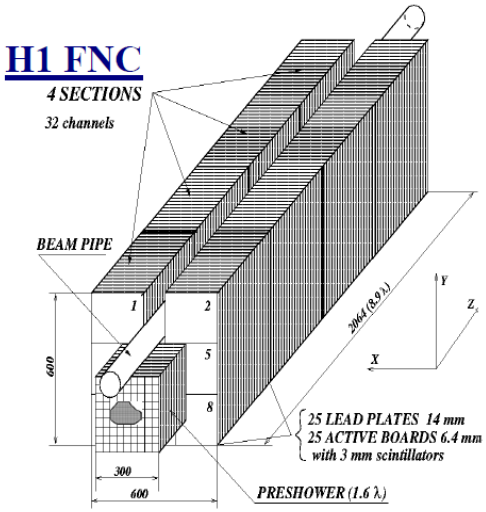
plus
Forward proton and neutron spectrometers
about 100m downstream



H1 Detector

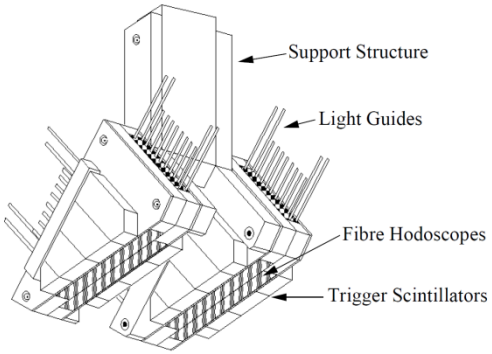
The Proton Taggers at HERA I





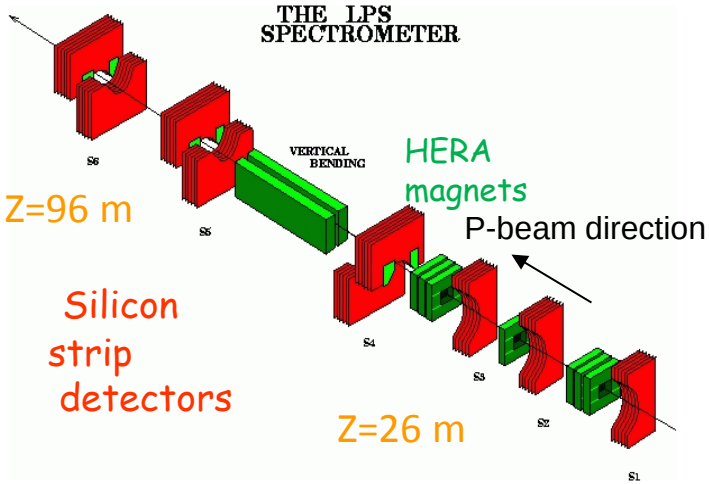
$\sigma_E/E \approx 0.63/\sqrt{E} \oplus 2\%$

Position resolution 2-3 mm



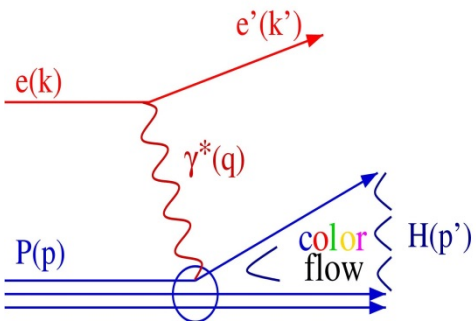
H1 FPS module

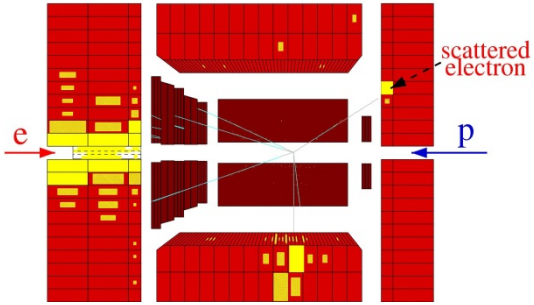
Scintillating fibers



Kinematics of DIS Events

Inclusive nondiffractive deep inelastic scattering (DIS) events





$s = (k+p)^2$ center of mass energy squared

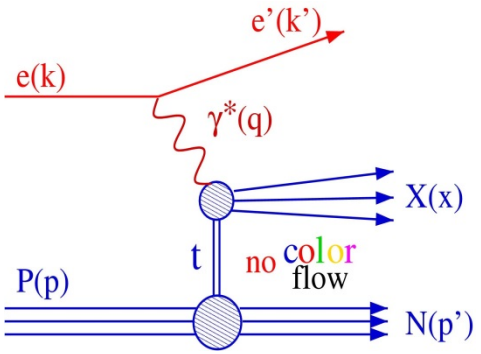
$W^2 = (q+p)^2$ photon-proton center of mass sqared

$Q^2 = -q^2 = -(k-k')^2$ virtuality, size of the probe

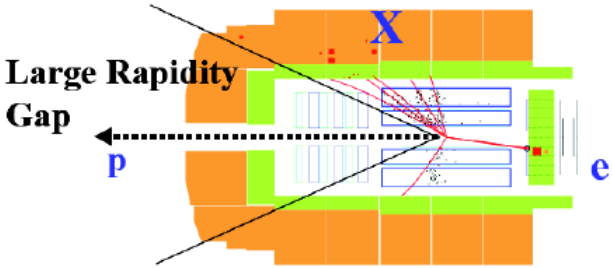
$x = \frac{Q^2}{2p \cdot q}$ x: fraction of the proton momentum carried by the struck parton

$y = \frac{p \cdot q}{p \cdot k}$ Y: inelasticity, fraction of the electron momentum carried by the virtual photon

Diffractive DIS events



Proton or dissociative system, measured in FPS/LPS



For diffractive events in addition:

M_x mass of the diffractive system x

$t = (p-p')^2$ four-momentum transfer squared at the proton vertex

$x_{IP} = \frac{(p-p') \cdot q}{p \cdot q} = \frac{M_X^2 + Q^2}{W^2 + Q^2}$ momentum fraction of the proton carried by the Pomeron

$\beta = \frac{Q^2}{2(p-p') \cdot q} = \frac{x}{x_{IP}} = \frac{Q^2}{M_X^2 + Q^2}$ fraction of the Pomeron momentum which enters the hard scattering

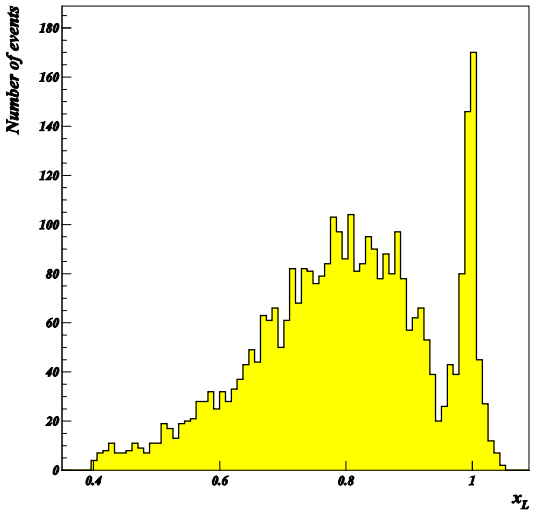
The tagged Proton Signal

$$x_L = \frac{p'}{p} \approx 1 - x_{IP}$$

$x_L \approx 1$ -> elastically (diffractively) scattered proton

$$t = -\frac{p_T^2}{x_L} - \frac{(1-x_L)^2}{x_L} M_p^2$$

Detecting the elastically scattered Proton is the only method to measure the four-momentum transfer, |t|, at the proton vertex.



X_L

Events with $x_L < 1$ originate from mainly from proton dissociative processes.

The resolution in X_L determines the background under the elastic peak.

Identification of Diffractive Events

Three methods have been used at HERA to select diffractive events:

- large rapidity gap selection -> p-dissociation background and Regge-contributions large acceptance;
- M_X method -> no Regge-contributions but p-dissociation background, large acceptance;
- detecting proton at $x_L \approx 1$ -> almost no background from p-dissociation but Regge-contributions, very small acceptance.

Inclusive DIS Proton Structure Functions

$$\frac{d^2\sigma_{\gamma^* p}}{dx dQ^2} = \frac{2\pi\alpha_{\mathrm{em}}}{x \cdot Q^4}\left[1-(1-y)^2\right]\cdot \sigma_r(x,Q^2)$$

$$\sigma_r(x,Q^2) = \mathrm{F}_2(x,Q^2) - \underbrace{\frac{y^2}{1+(1-y)^2}\mathrm{F}_{\mathrm{L}}(x,Q^2)}_{\text{sizeable only at high y}}$$

xF_3 can safely be neglected at not too high Q^2 for HERA data

For HERA data typically:

$$y = \frac{Q^2}{x \cdot s} \approx 0.1$$

Inclusive Diffractive Proton Structure Functions

Analogous to inclusive DIS:

$$\frac{d^4\sigma}{dQ^2 dt dx_{IP} d\beta} = \frac{2\pi\alpha_{em}}{\beta Q^2}\left[1-(1-y)^2\right]\cdot \sigma_r^{D(4)}(Q^2,t,x_{IP},\beta)$$

$$\sigma_r^{D(4)}(Q^2,\mathrm{t},x_{\mathrm{IP}},\beta) = \mathrm{F}_2^{\mathrm{D}(4)}(Q^2,\mathrm{t},x_{\mathrm{IP}},\beta) - \frac{y^2}{1+(1-y)^2}\mathrm{F}_{\mathrm{L}}^{\mathrm{D}(4)}(Q^2,\mathrm{t},x_{\mathrm{IP}},\beta)$$

If t is not measured and integrated over:

$$\sigma_r^{D(3)}(Q^2,x_{\mathrm{IP}},\beta) = \mathrm{F}_2^{\mathrm{D}(3)}(Q^2,x_{\mathrm{IP}},\beta) - \frac{y^2}{1+(1-y)^2}\mathrm{F}_{\mathrm{L}}^{\mathrm{D}(3)}(Q^2,x_{\mathrm{IP}},\beta)$$

Proton tagged DIS Cross-sections from H1

Regge fit $F_2^{D(4)} = f_{I\!P}(x_{I\!P},t)F_{I\!P}(\beta,Q^2) + n_{I\!R}\cdot f_{I\!R}(x_{I\!P},t)F_{I\!R}(\beta,Q^2)$

Pomeron contribution Reggeon contribution

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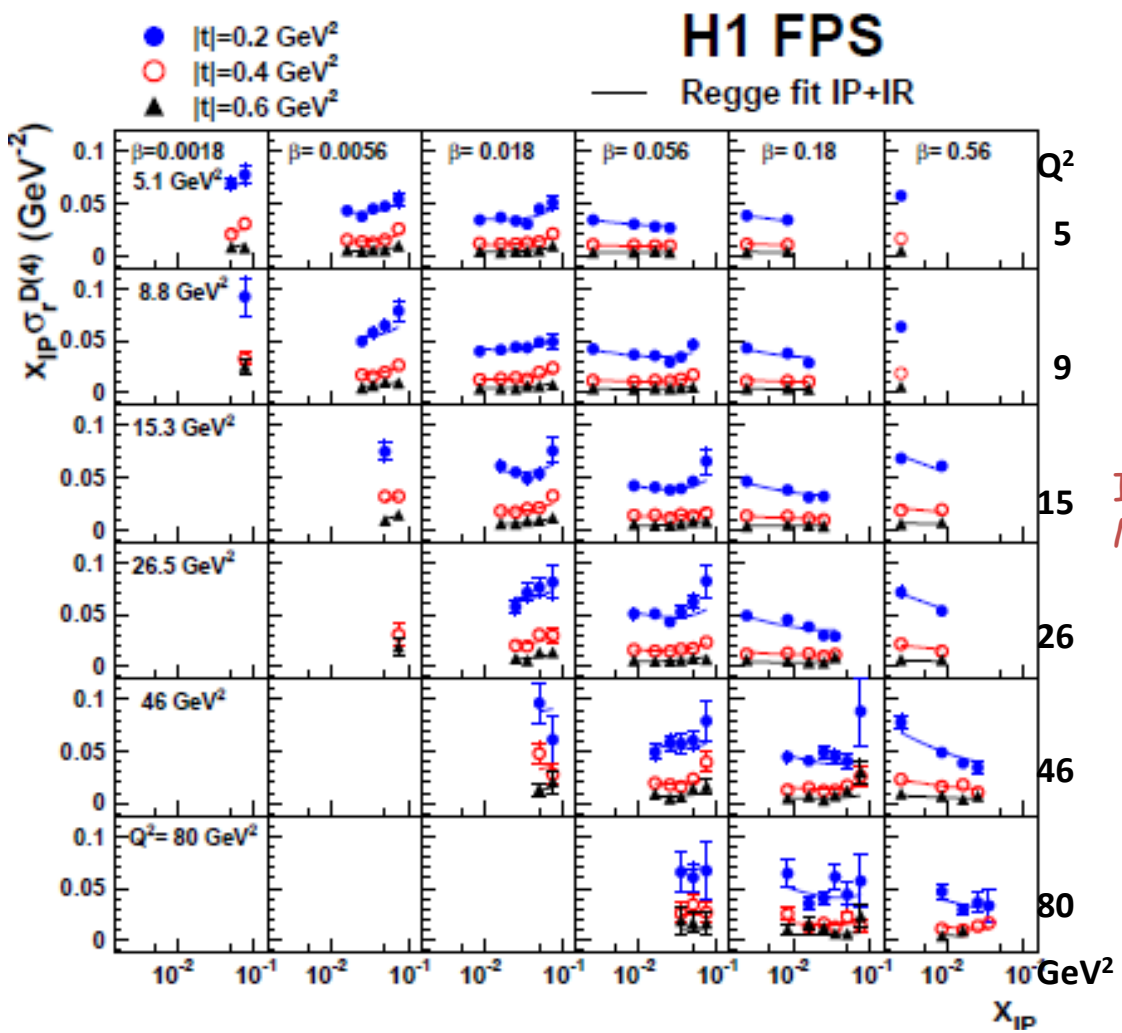
Eur.Phys.J. C71(2011) 1578

Assumption: Regge/vertex factorization



$$f_{I\!P}(x_{I\!P},t) = A_{I\!P}\cdot\frac{e^{B_{I\!P}t}}{x_{I\!P}^{2\alpha_{I\!P}(t)-1}}$$

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}t$$

$$f_{I\!R}(x_{I\!P},t) = A_{I\!R}\cdot\frac{e^{B_{I\!R}t}}{x_{I\!P}^{2\alpha_{I\!R}(t)-1}}$$

$$\alpha_{I\!R}(t) = \alpha_{I\!R}(0) + \alpha'_{I\!R}t$$

$F_{I\!R}(\beta,Q^2)$ from the parametrization of the pion trajectory

Input from other Measurements:

$$\alpha_{IR}(0) = 0.50$$

$$\alpha'_{IR} = 0.3\,GeV^{-2}$$

Fit Results

$$B_{IR} = 1.6\,GeV^{-2}$$

Parameter	Value
$\alpha_{I\!P}(0)$	$1.10 \pm 0.02\,(\text{exp.}) \pm 0.03\,(\text{model})$
$\alpha'_{I\!P}$	$0.04 \pm 0.02\,(\text{exp.})\,^{+0.08}_{-0.06}\,(\text{model})\ \text{GeV}^{-2}$
$B_{I\!P}$	$5.73 \pm 0.25\,(\text{exp.})\,^{+0.80}_{-0.90}\,(\text{model})\ \text{GeV}^{-2}$
$n_{I\!R}$	$[0.87 \pm 0.10\,(\text{exp.})\,^{+0.60}_{-0.40}\,(\text{model})]\cdot 10^{-3}$

p_T-Dependence of leading Proton Production

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JHEP06 (2009) 74

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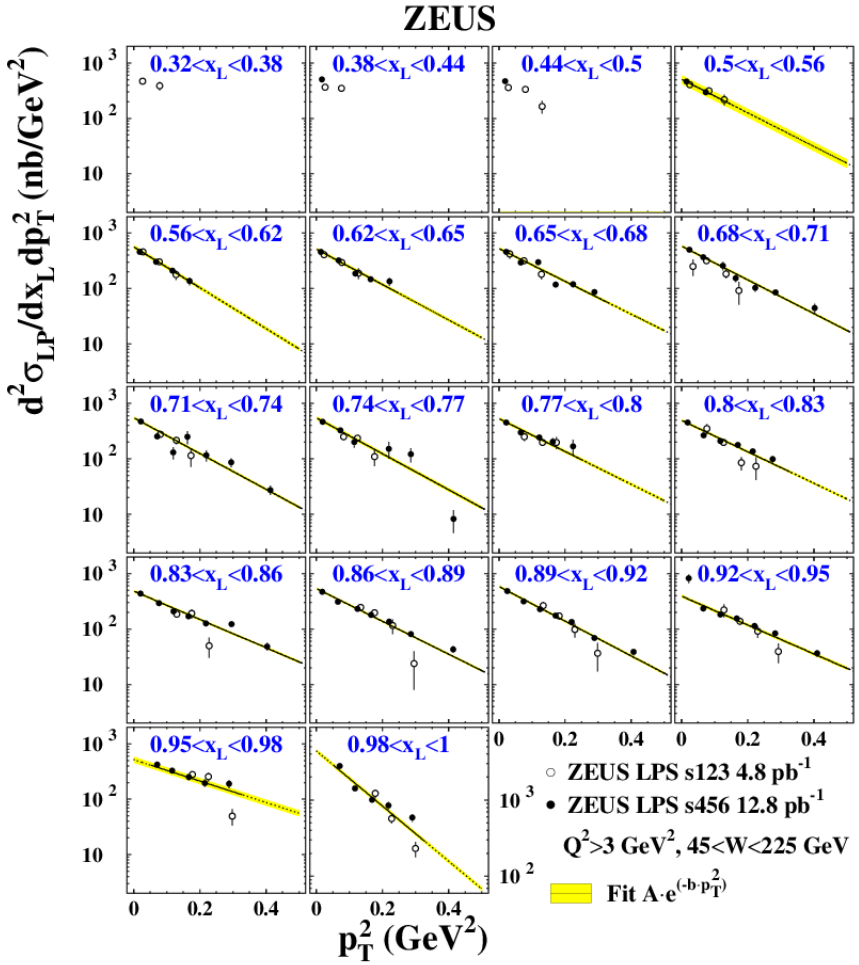
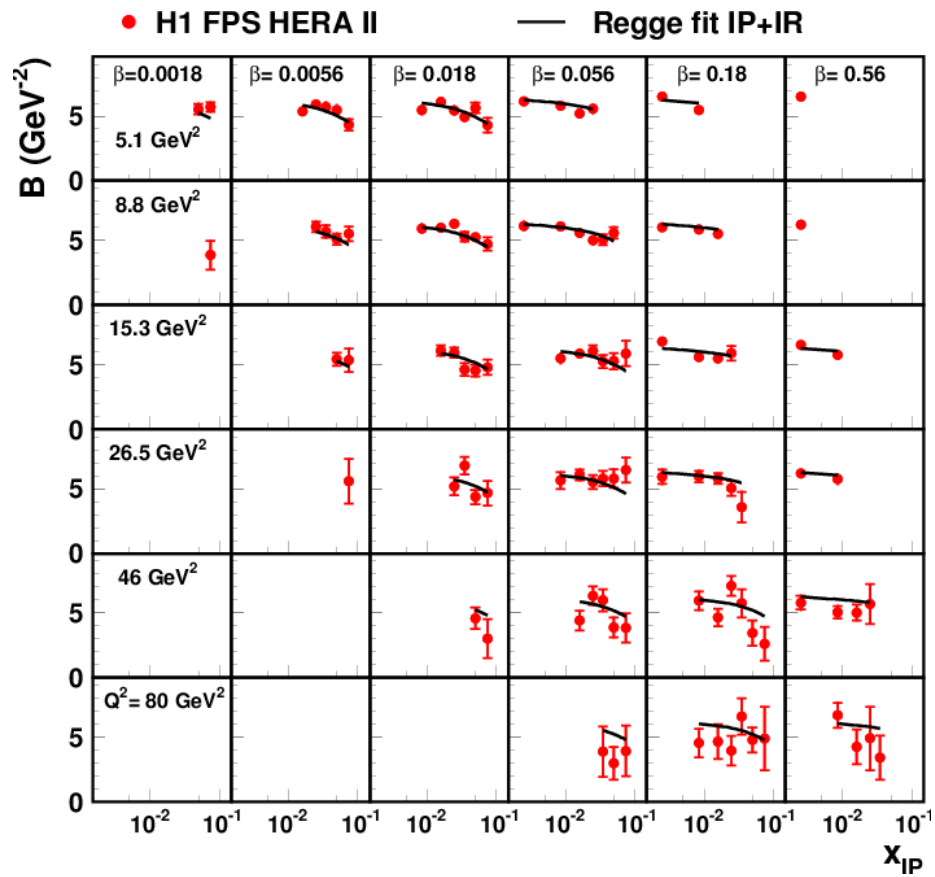
Eur.Phys.J. C71 (2011) 1578





$$\frac{d\sigma}{dp_T^2} = A\cdot e^{(-Bp_T^2)}$$

$$B(x_{I\!P},\beta,Q^2) = [1 - w_{I\!R}(x_{I\!P},\beta,Q^2)][B_{I\!P} - 2\alpha'_{I\!P}\ln x_{I\!P}] + w_{I\!R}(x_{I\!P},\beta,Q^2)[B_{I\!R} - 2\alpha'_{I\!R}\ln x_{I\!P}]$$

Proton tagged DIS Cross-sections from H1

H1 FPS data from HERA II ; comparison with fit from LRG data

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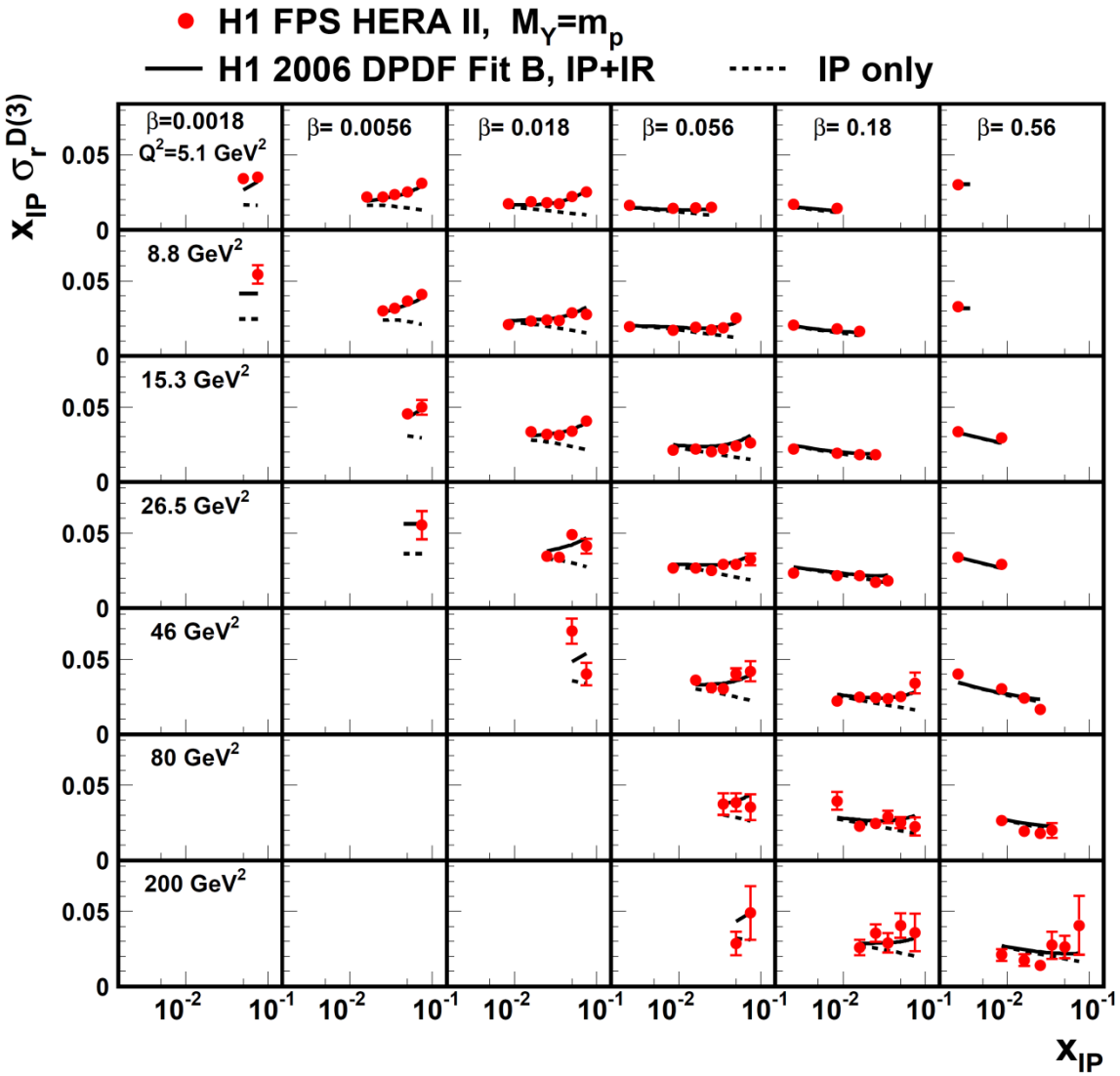


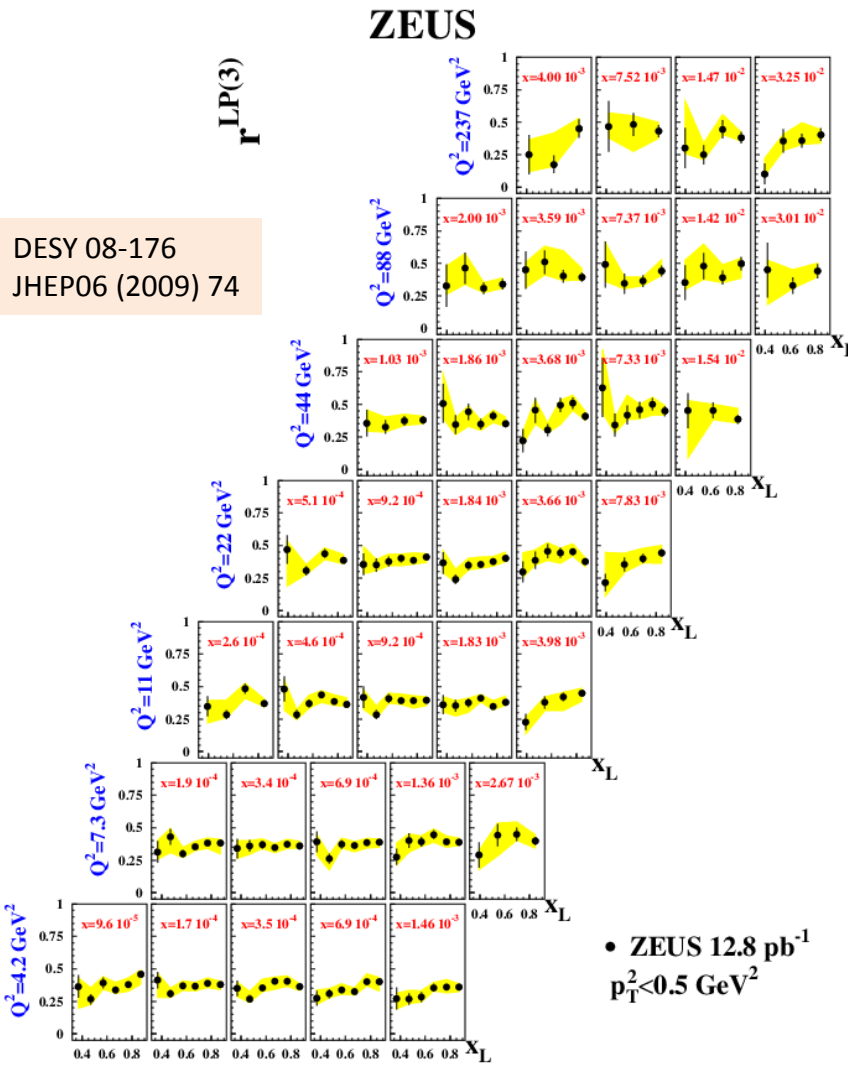
DPDF fit:
pQCD fit to earlier LRG dataset,
Eur.Phys.J. C50 (2006).

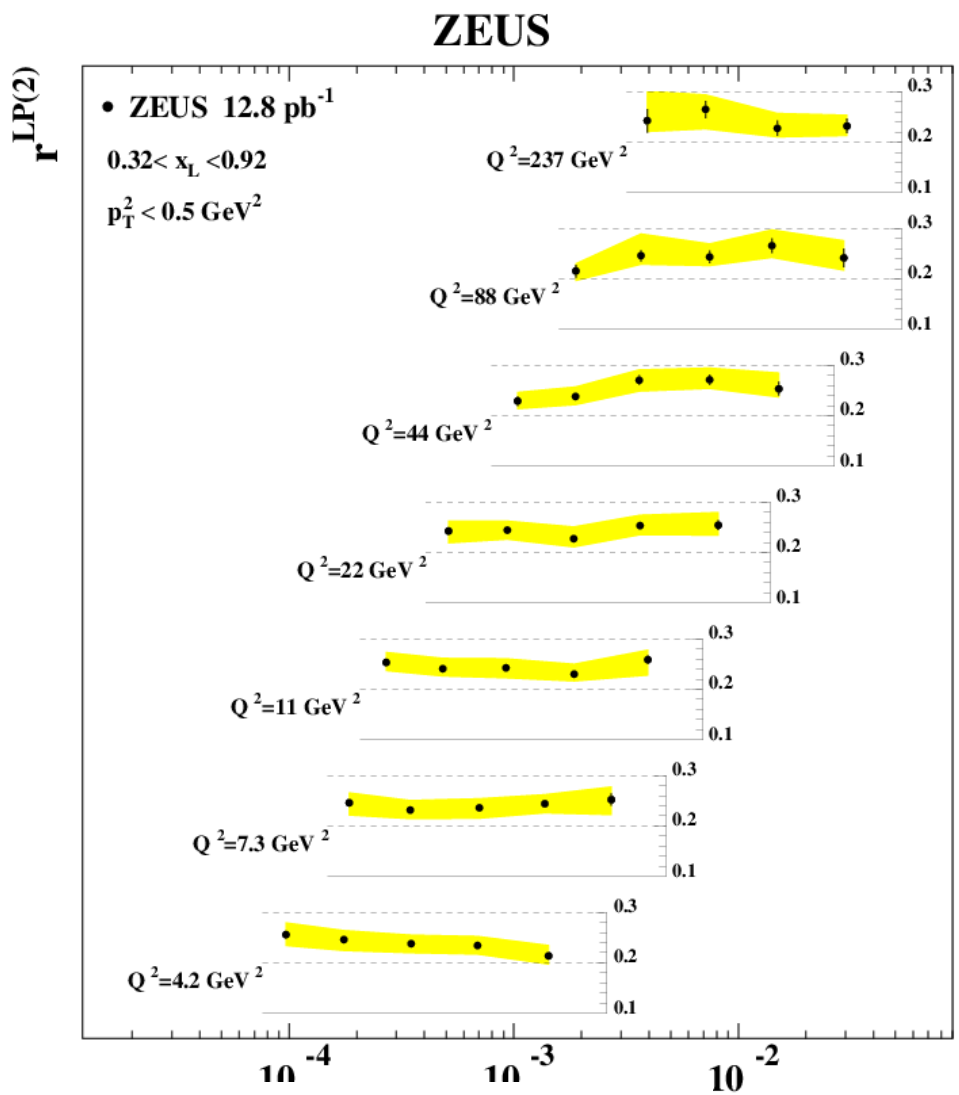
Dashed line shows the diffractive (Pomeron) contribution.

For $x_{IP} > 10^{-2}$ considerable contributions from Regge exchanges are present.

Ratio of Proton tagged Events at Low x_L to Inclusive DIS Events

DESY 08-176
JHEP06 (2009) 74





$$r^{LP(3)}(x, Q^2, x_L) = \frac{N^{LPS}(x, Q^2, x_L)}{N^{DIS}(x, Q^2)} \frac{A_{DIS}}{A_{LPS}} \frac{\mathcal{L}^{DIS}}{\mathcal{L}^{LPS}} \frac{1}{\Delta x_L}$$

$$r^{LP(2)}(x, Q^2) = \frac{F_2^{LP(2)}(x, Q^2)}{F_2(x, Q^2)}$$

pQCD Analysis of Diffractive Data

The concept of diffractive parton distribution functions (DPDF)

$$\sigma_r^{D(3)}(Q^2, x_{IP}, \beta) = F_2^{D(3)}(Q^2, x_{IP}, \beta) - \frac{y^2}{1+(1-y)^2} F_L^{D(3)}(Q^2, x_{IP}, \beta)$$

QCD-factorization theorem for diffractive DIS:

$$F_{2/L}^{D(3)}(\beta, Q^2, x_{I\!P}) = \sum_i \int_\beta^1 \frac{dz}{z} C_{2/L,i}\left(\frac{\beta}{z}\right) \underbrace{f_i^D(z, x_{I\!P}; Q^2)}_{\text{DPDFs obey DGLAP evolution}}$$

Regge-factorization assumption:

$$f_i^D(z, x_{\mathbb{P}}; Q^2) = f_{\mathbb{P}}(x_{\mathbb{P}}) f_i(z, Q^2) + f_{\mathbb{R}}(x_{\mathbb{P}}) f_i^{\mathbb{R}}(z, Q^2) \quad ; \quad f_{I\!P,I\!R}(x_{I\!P}, t) = \frac{A_{I\!P,I\!R} e^{B_{I\!P,I\!R} t}}{x_{I\!P}^{2\alpha_{I\!P,I\!R}(t)-1}}$$

Parametrisation of DPDFs at $Q_0^2 = 1.8\ \text{GeV}^2$

$$z f_{d,u,s}(z, Q_0^2) = A_q z^{B_q} (1-z)^{C_q}, \qquad z f_g(z, Q_0^2) = A_g z^{B_g} (1-z)^{C_g}$$

$$f_{\bar{q}} = f_q$$

Additional factor $e^{-\frac{0.001}{1-z}}$ included to ensure that distributions vanish for $z \to 1$.

Fit the DGLAP evolution with these parameterizations to inclusive diffractive data

9 parameters left free in fit: $A_{q,g},\ B_{q,g},\ C_{q,g},\quad \alpha_{I\!R}(0),\ \alpha_{I\!P}(0),\ A_{I\!R}.$

pQCD Analysis of Diffractive Data by ZEUS

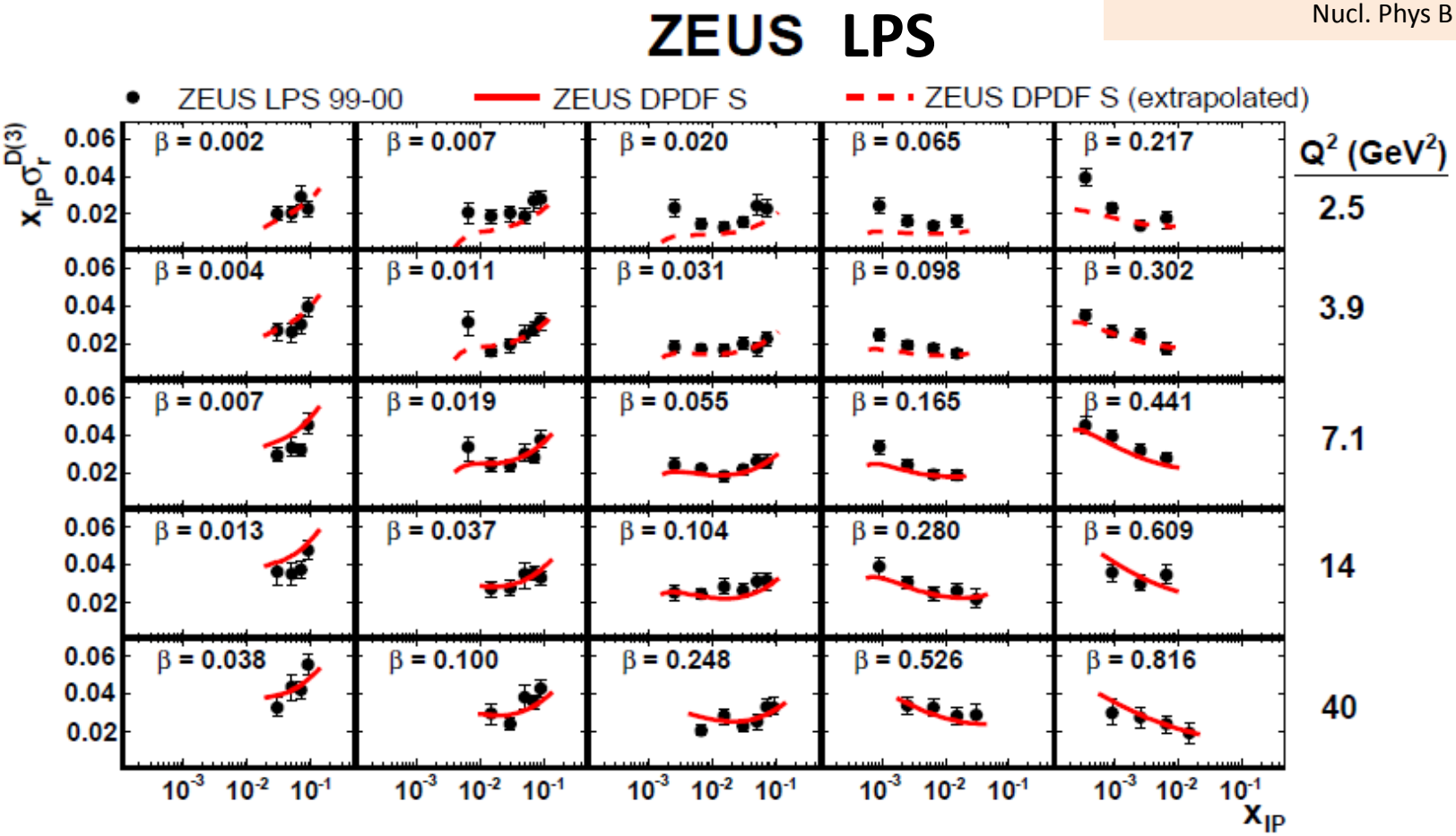
LRG sample: $2 < Q^2 < 305\ \text{GeV}^2$, $40 < W < 240$ GeV, $2 < M_X < 25$ GeV, $0.0001 < x_{IP} < 0.02$

LPS sample: $2 < Q^2 < 120\ \text{GeV}^2$, $40 < W < 240$ GeV, $2 < M_X < 40$ GeV, $0.002 < x_{IP} < 0.1$

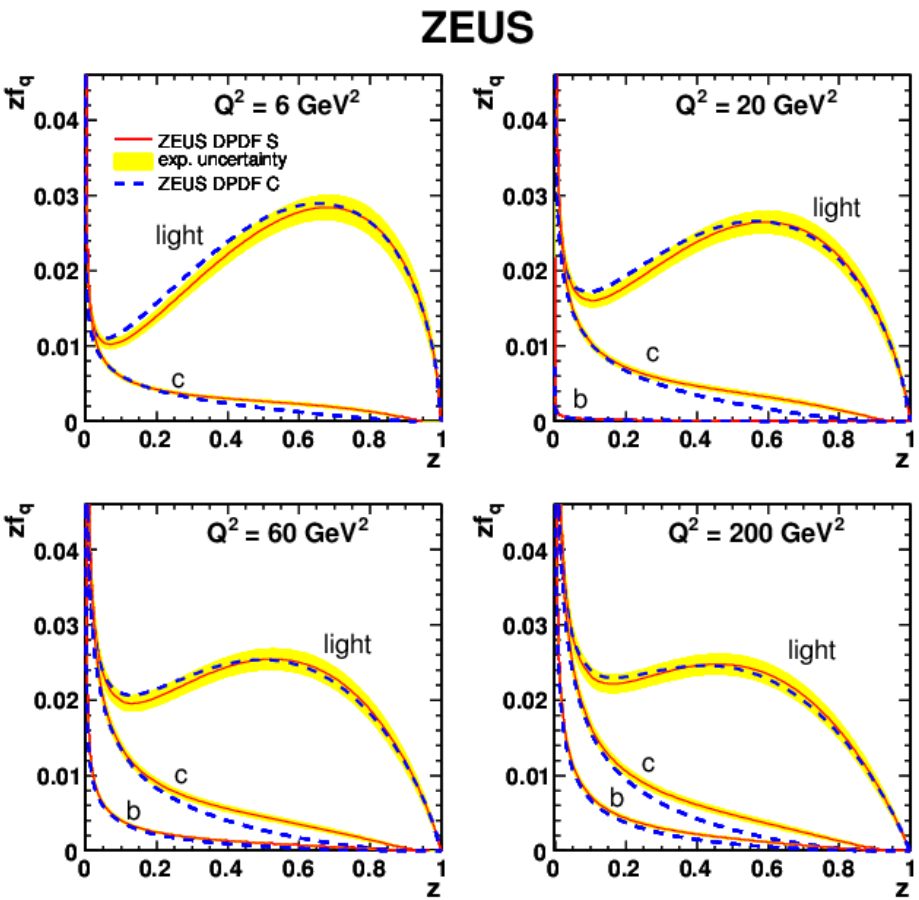
Samples are corrected for proton dissociation where necessary.

'Standard' Fit: A_g, B_g, C_g as free parameters → ZEUS DPDF S

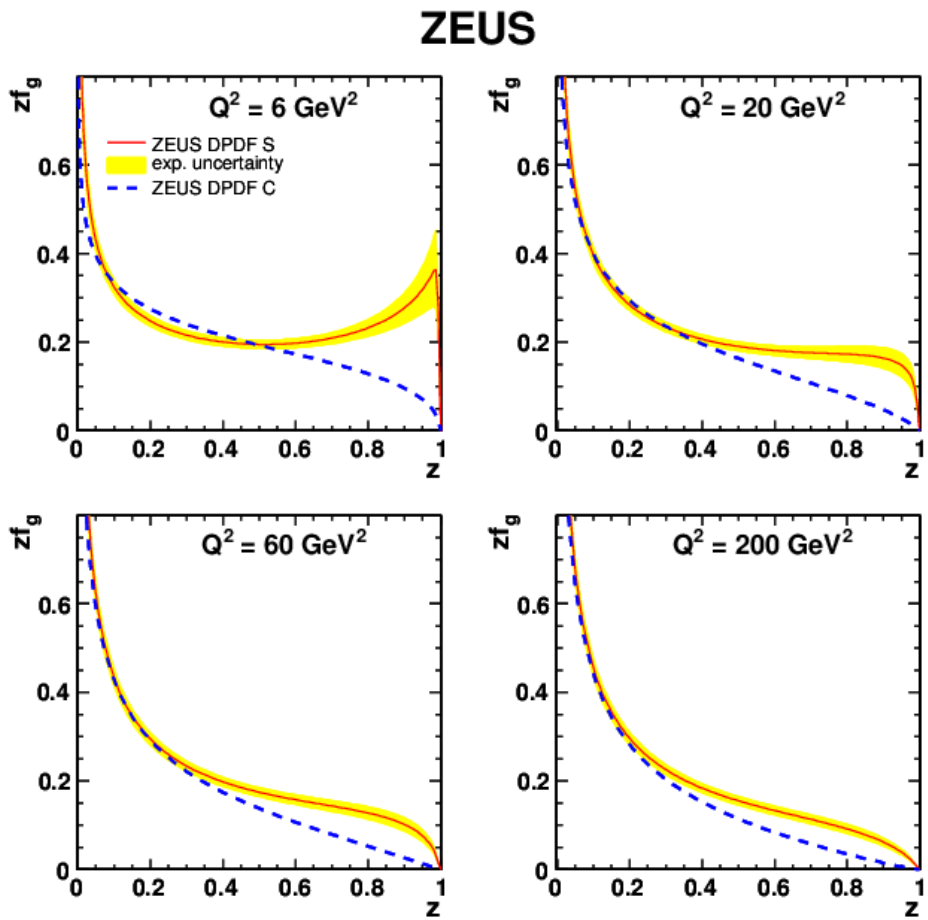
Data: DESY 08-175
Nucl. Phys. B 816 (2009)
pQCD analysis: DESY 09-191
Nucl. Phys B 831 (2010)



Diffractive Parton Density Functions (DPDF) from ZEUS



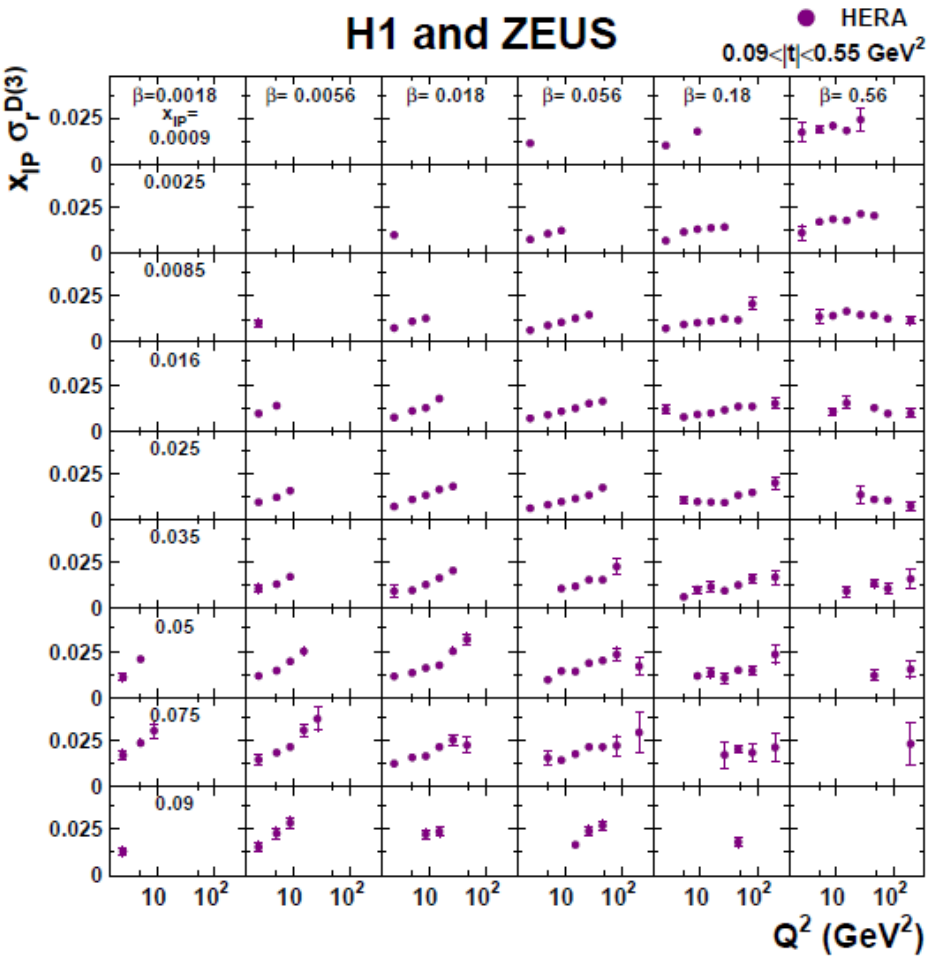
Diffractive quark density functions from the ZEUS DPDF S and DPDF C fits.



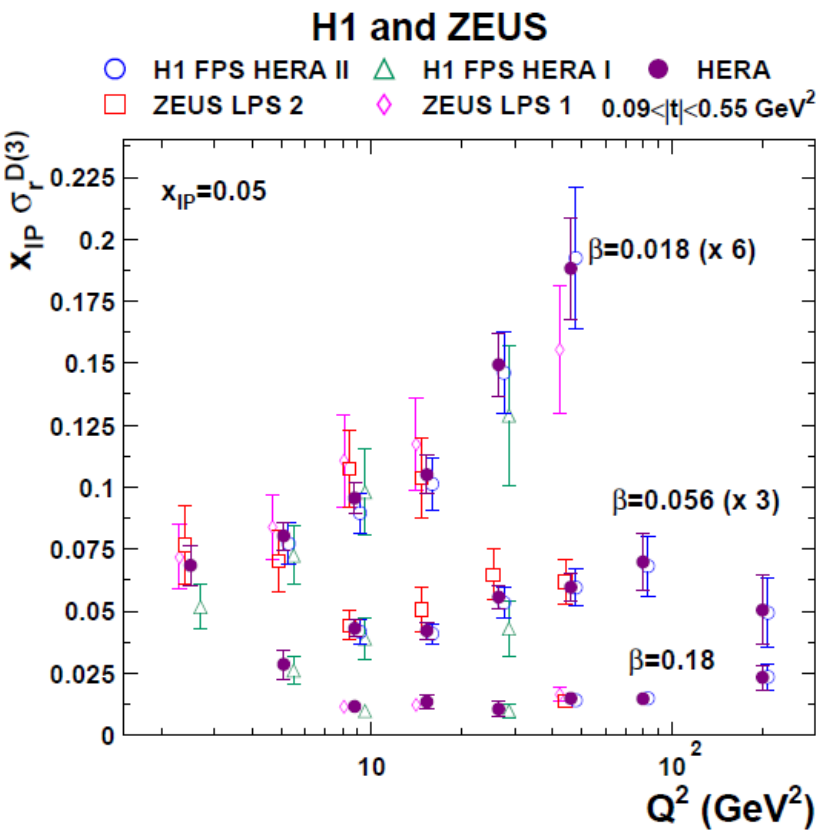
Diffractive gluon density functions from the ZEUS DPDF S and DPDF C fits.

Combination of H1 FPS and ZEUS LPS Data

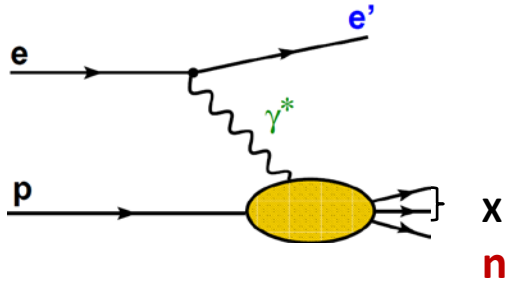
Choose a common (x,Q^2)-grid, if necessary swim data using fit of diffractive structure functions. Then combine data, taking into account correlations of systematic errors.



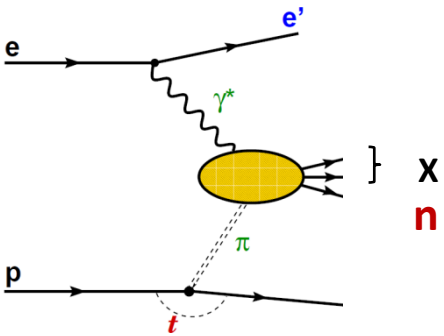
DESY 12-100
Eur.Phys.Journal C72(2012) 2175



Results from Events with a Leading Neutron

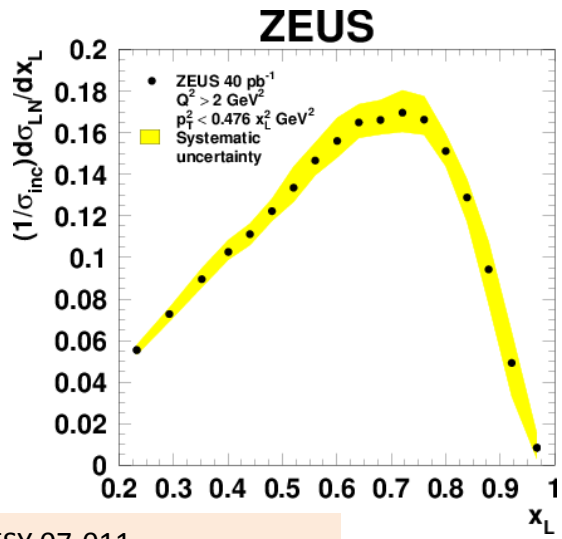


Final state neutron in the proton fragmentation system



Leading neutron production via an exchange process.

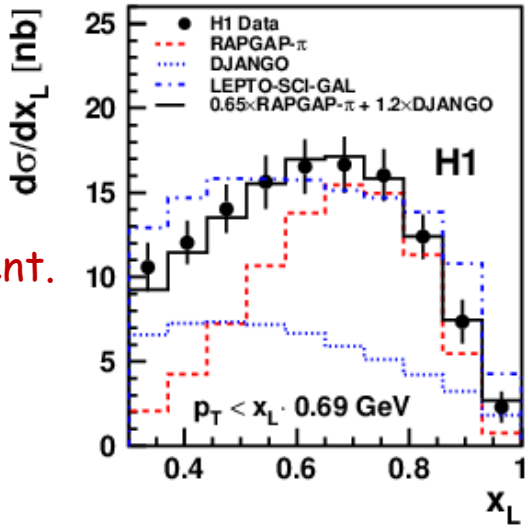
One pion exchange (OPE) is the dominating mechanism for the production of neutron tagged events.



DESY 07-011
Nucl.Phys.B776(2007) 1-37

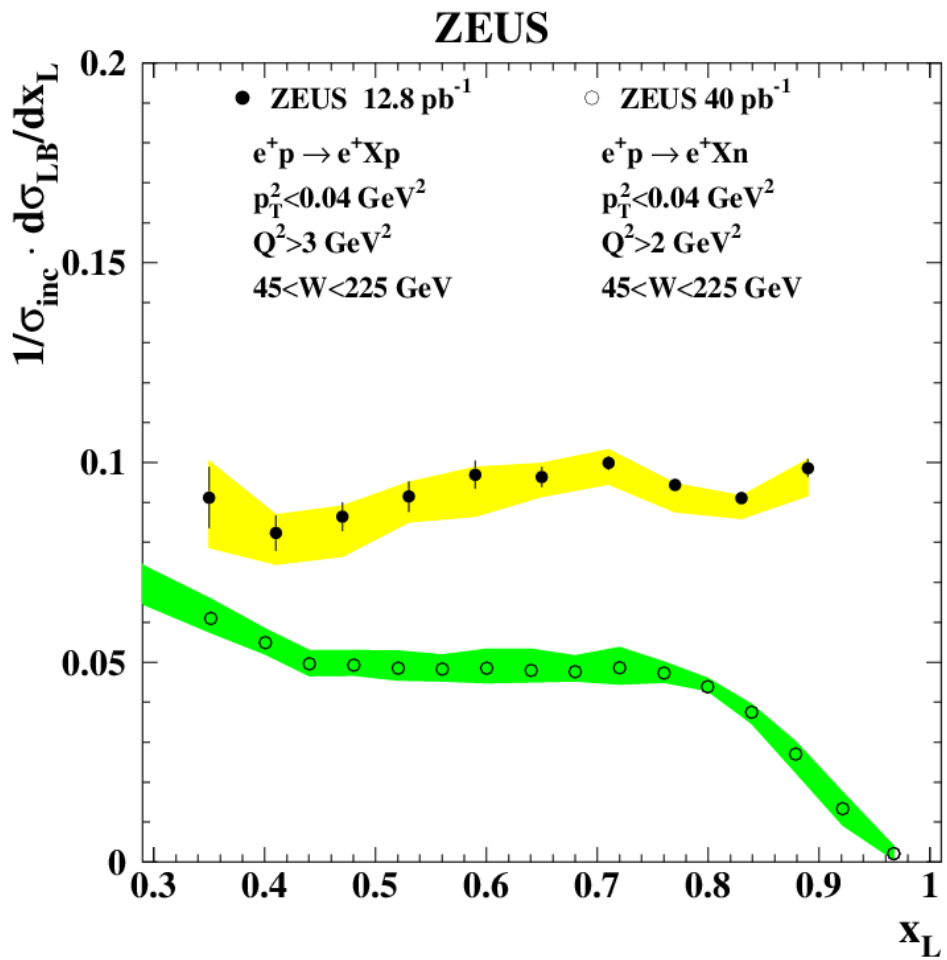
x_L Distributions

There is no elastic (diffractive) peak present.



DESY 09-185
Eur.Phys.J. C68 (2010) 381

Comparison of Leading Proton and Leading Neutron Cross-sections



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JHEP06 (2009) 74

The leading neutron rate is roughly a factor of two lower than the leading proton rate for x_L <1.

No diffractive processes, including dissociative events, contribute to leading neutron production.

Leading Neutron Cross-sections and Structure Functions

The semi-inclusive leading neutron cross-section can be written as, neglecting the longitudinal structure function.

$$\frac{\mathrm{d}^4\sigma(ep \to enX)}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}x_L\,\mathrm{d}t} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LN(4)}(Q^2, x, x_L, t)$$

$$\frac{\mathrm{d}^3\sigma(ep \to enX)}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}x_L} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LN(3)}(Q^2, x, x_L)$$

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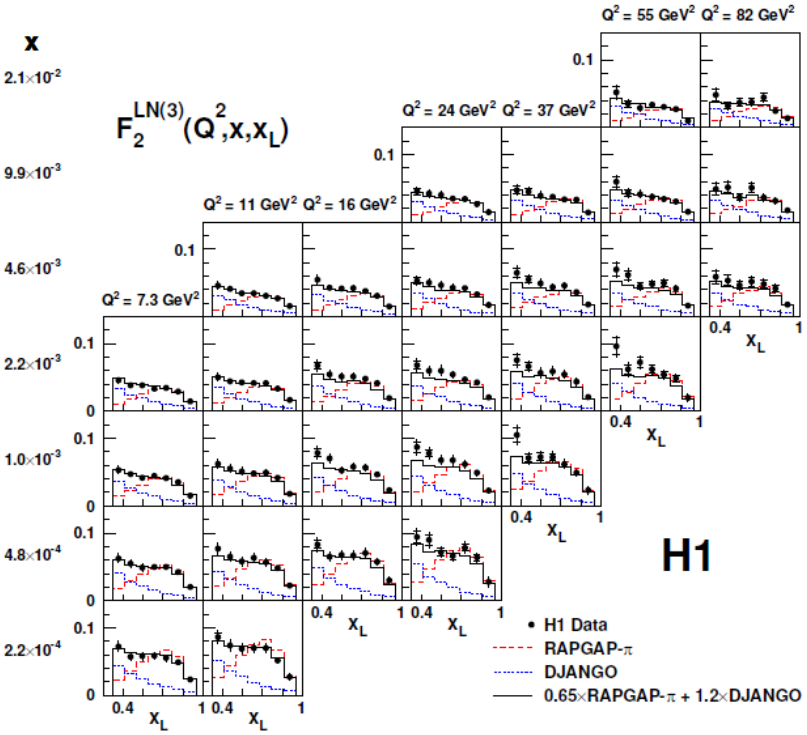

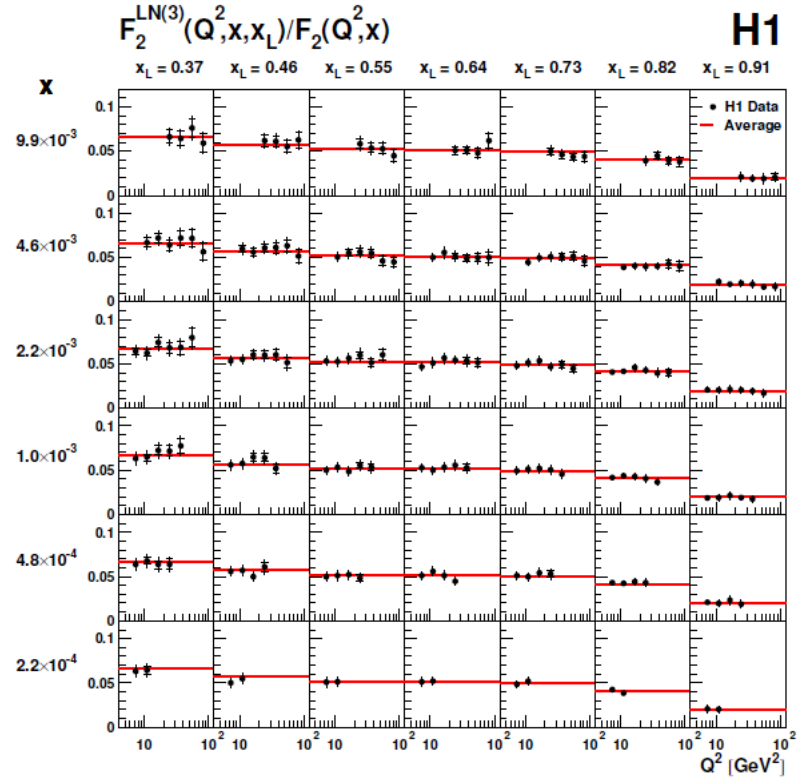

The neutron tagged structure function has the same Q^2 dependence as the inclusive structure function.

The Pion Structure Function

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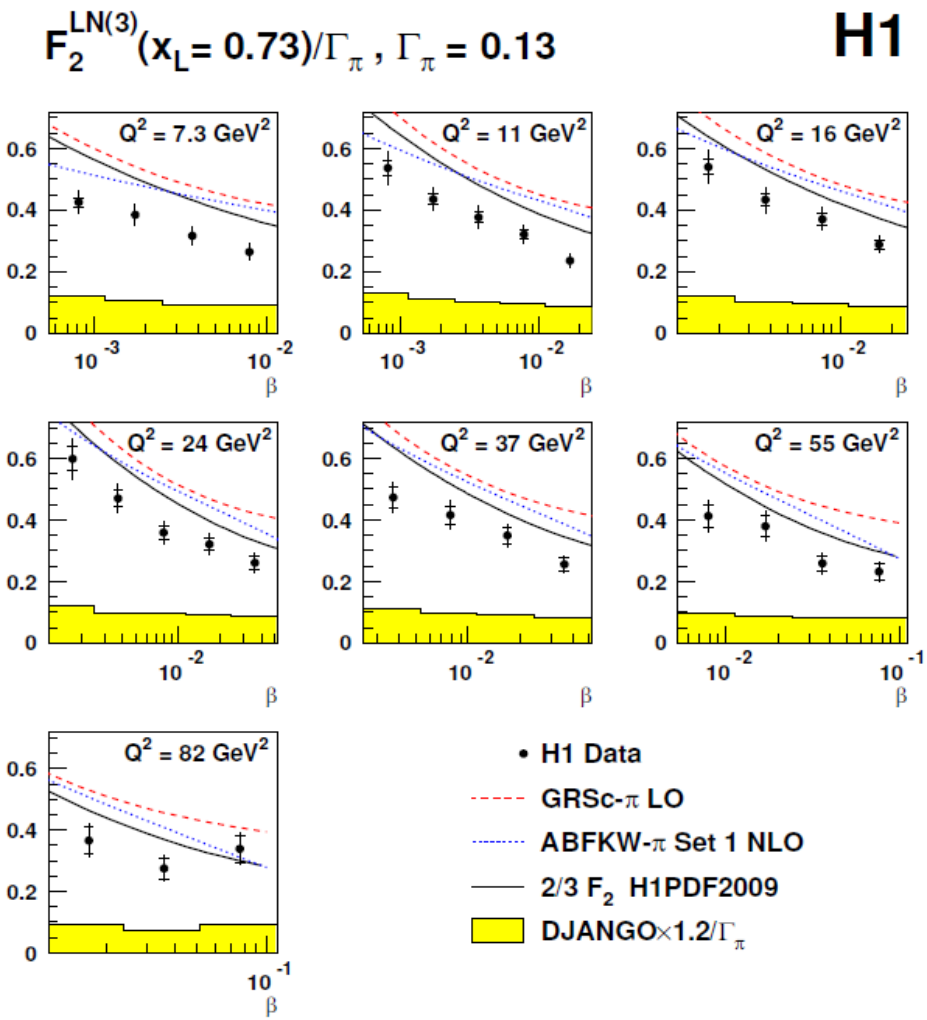
Assuming the validity of the vertex factorisation: $d\sigma(ep \to e'nX) = f_{\pi^+/p}(x_L, t) \cdot d\sigma(e\pi^+ \to e'X)$

with, e.g. $f_{\pi^+/p} = \frac{1}{2\pi}\frac{g^2_{p\pi\pi}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2 - t)^2}\cdot\exp\left(-R^2_{\pi n}\frac{m_\pi^2 - t}{1-x_L}\right)$

(various parametrisations exist)



Then one can write:

$$F_2^{LN(3)}(\beta, Q^2, x_L) = \Gamma_\pi(x_L)\cdot F_2^\pi(\beta, Q^2)$$

with $\Gamma_\pi(x_L) = \int_{t_0}^{t_{\min}} f_{\pi/p}(x_L, t)\,dt$

$F_2^\pi(\beta, Q^2)$ might be interpreted as the pion structure function.

The data are compared to two different parametrisatons of the pion structure function: Eur.Phys.J.C10 (1999), Phys.Lett. B 233 (1989), and the H1 parametrisation of the proton structure function scaled by a factor 2/3.

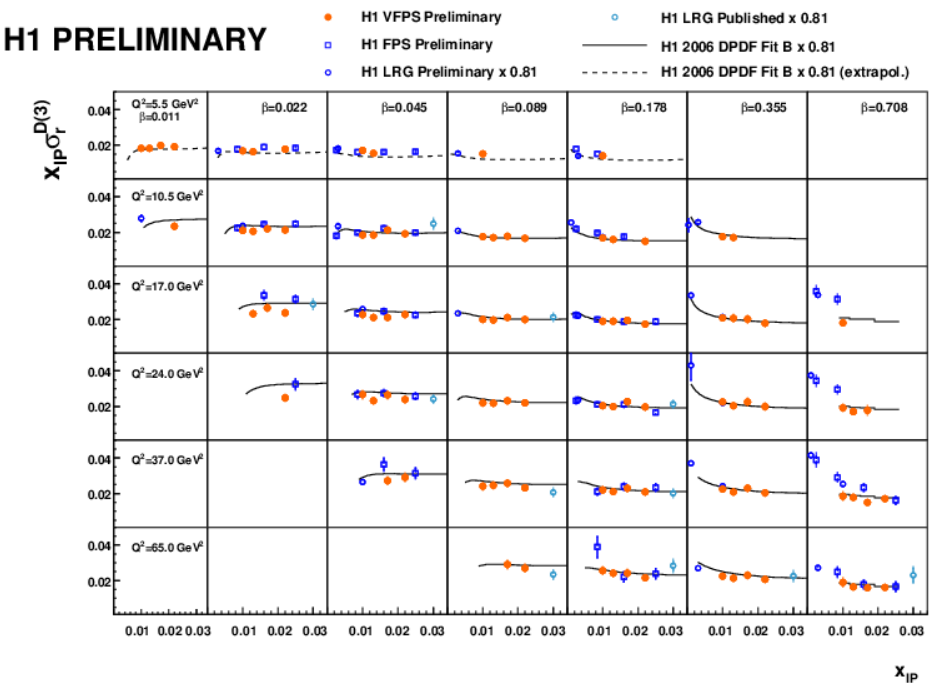
Summary

- Despite very low acceptance of the proton taggers a large amount of proton tagged data has been collected.
- The proton tagged data are mainly diffractive events for $x_{IP} < 10^{-2}$. For $x_{IP} > 10^{-2}$ Regge-exchange process contribute considerably.
- Proton tagged data can be described well by Regge theory inspired fits assuming vertex factorization.
- pQCD fits including Regge contributions deliver the Pomeron structure function assuming vertex factorization.
- From inclusive diffractive data measured with the LRG method and leading proton tagged events diffractive parton distribution functions can be extracted.

- Neutron tagged data are dominated by pion exchange processes. They are not diffractive.
- Assuming vertex factorization and taking the pion flux factor from hadronic scattering data the pion structure function can be extracted.

Backup Slides

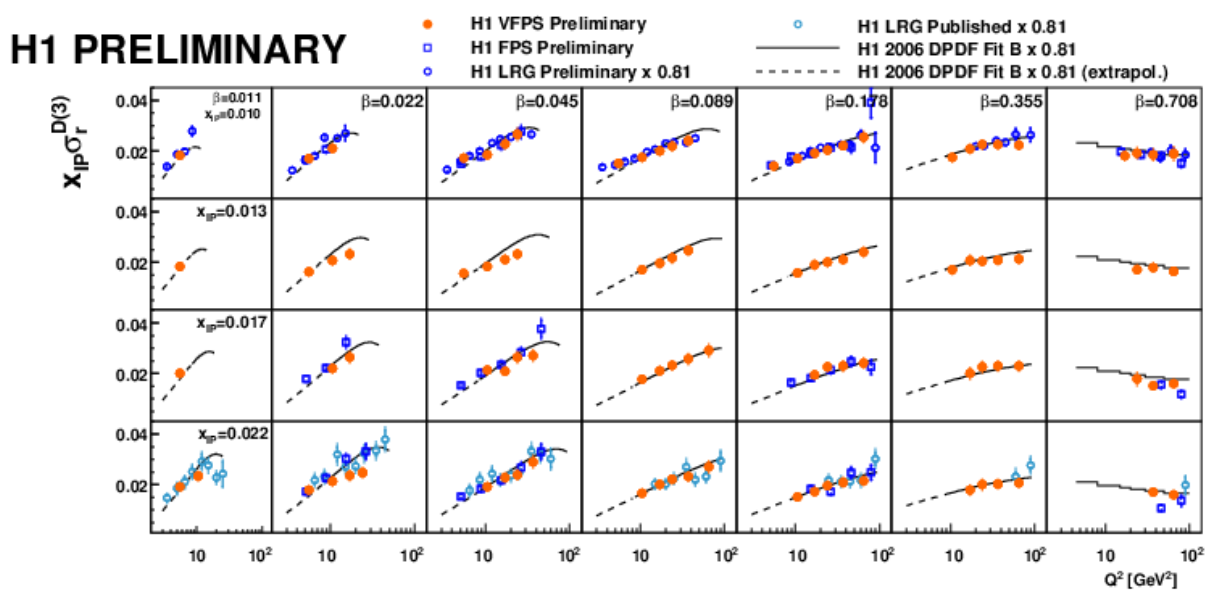
Results from the VFPS of H1



VFPS results are compared to Data from the FPS, LRG selected data, and DPDF fit.

The LRG data and the DPDF fit are scaled by a factor of 0.81 for the proton-dissociative contributions

H1 prelim-10-014



Diffractive Longitudinal Structure Function F_L^D

$$\sigma_r^{D(3)}(Q^2, x_{IP}, \beta) = F_2^{D(3)}(Q^2, x_{IP}, \beta) - \frac{y^2}{1+(1-y)^2} F_L^{D(3)}(Q^2, x_{IP}, \beta)$$

Measurements of σ_r^D done so far in kinematical regions where F_L^D can be neglected or it is corrected for by taking F_L^D from pQCD predictions.

F_L^D is strongly correlated to the diffractive gluon density → necessary to measure F_L^D directly

Need measurements of σ_r^D for different values of y at fixed (x, Q^2)

$$y = \frac{Q^2}{x_{IP}\beta} \cdot \frac{1}{s}$$

→ vary center of mass energy squared $s = 4 \cdot E_e E_p$

$$F_L^D = \frac{\partial \sigma_r^D}{\partial (y^2 / Y_+)}$$

with

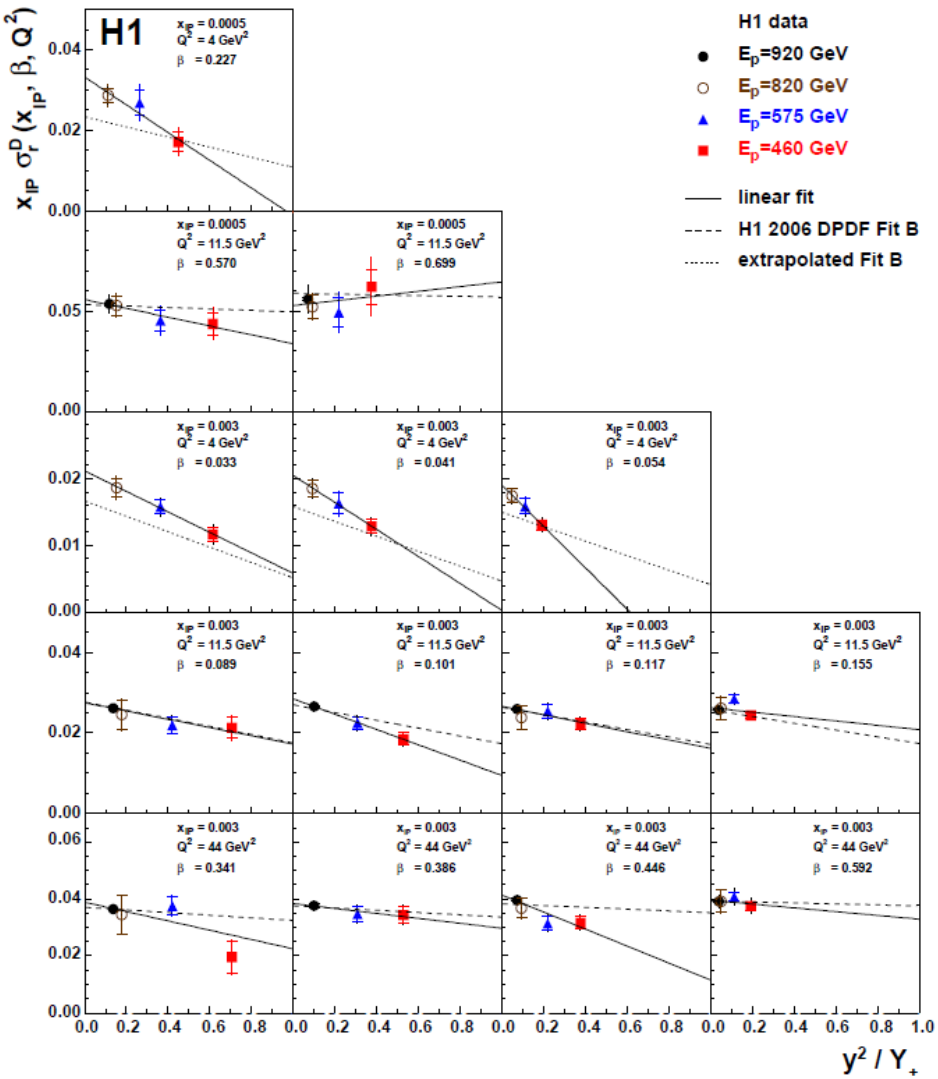
$$Y_+ = \frac{1}{1+(1-y)^2}$$

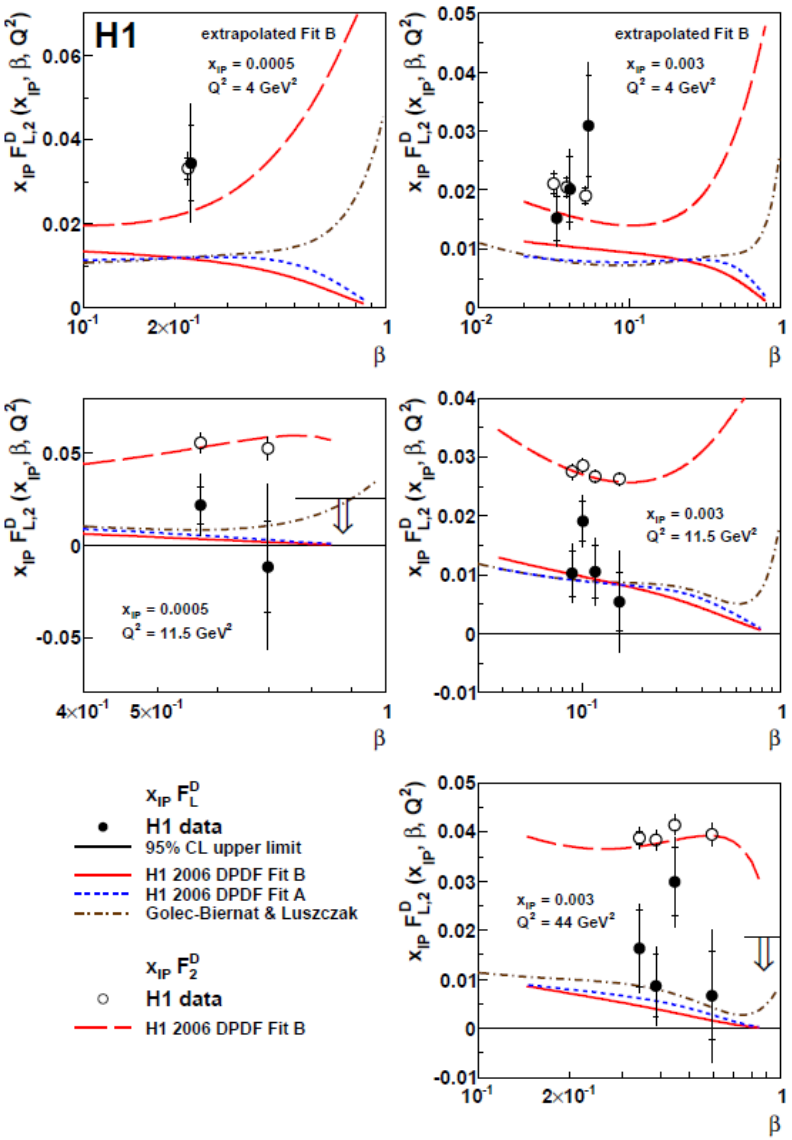
Keep electron energy E_e, vary proton energy E_p

E_p = 920 GeV, 575 GeV, 460 GeV

Measurement of the Diffractive Longitudinal Structure Function F_L^D by H1

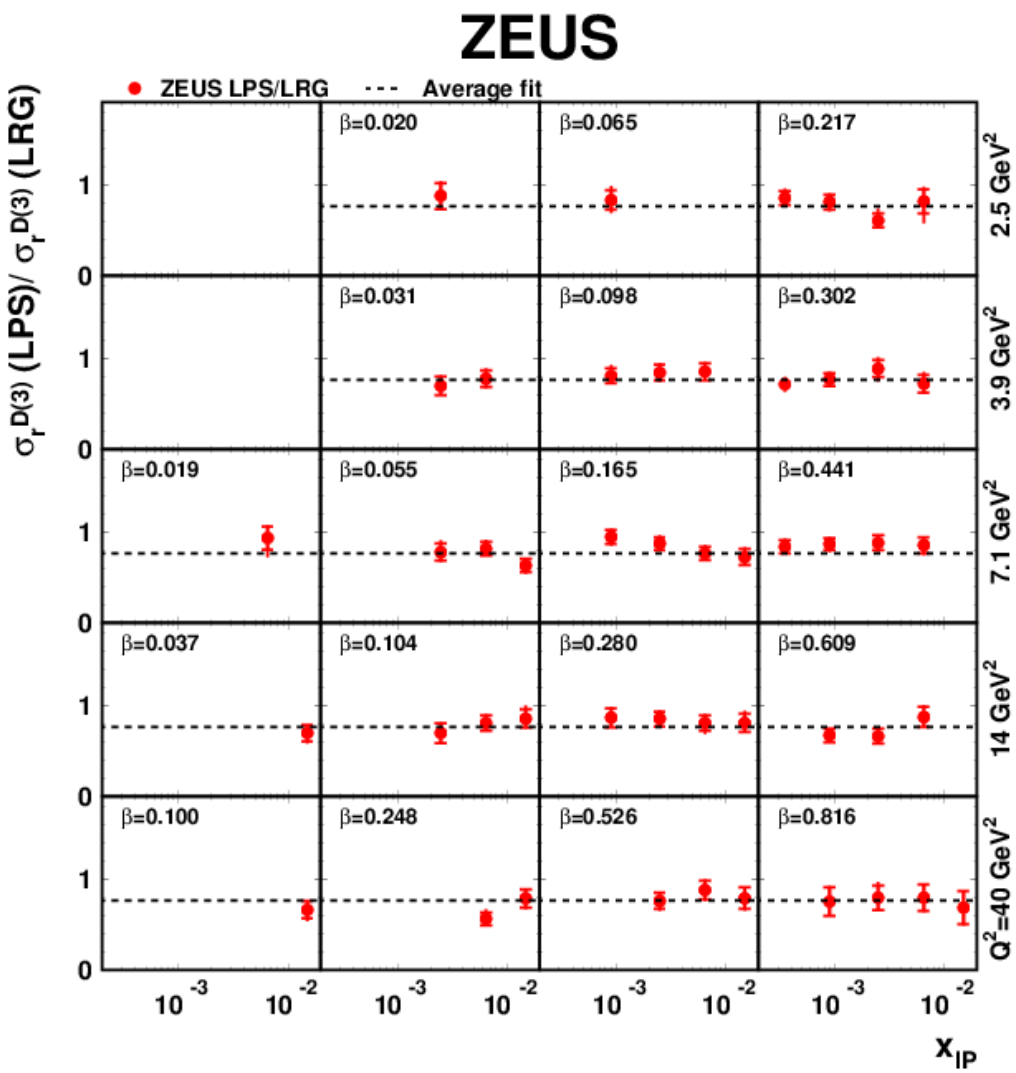
DESY 11-084
Phys.J. C72 (2012)





Ratio of LPS-tagged to LRG selected diffractive data

DESY 08-175
Nucl.Phys.B816(2009) 1-61



LRG selected data are plotted before subtraction of proton-dissociative background.

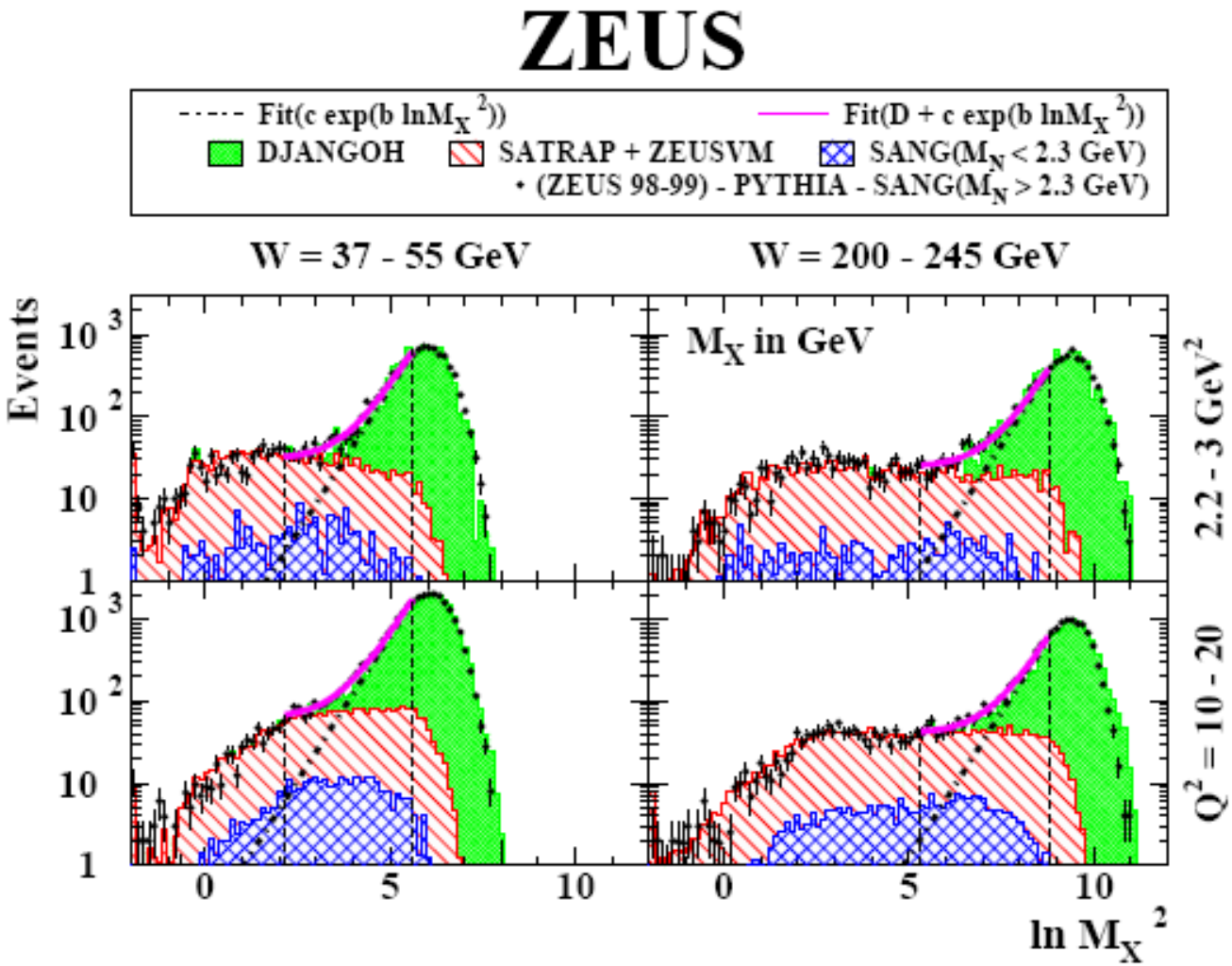
The ratio is independent of x_{IP} , Q^2, and β.

$$r = 0.76 \pm 0.01(stat.)^{+0.03}_{-0.02}(syst.)$$

The difference of r to one is due to the proton-dissociative contributions included in the LRG data.

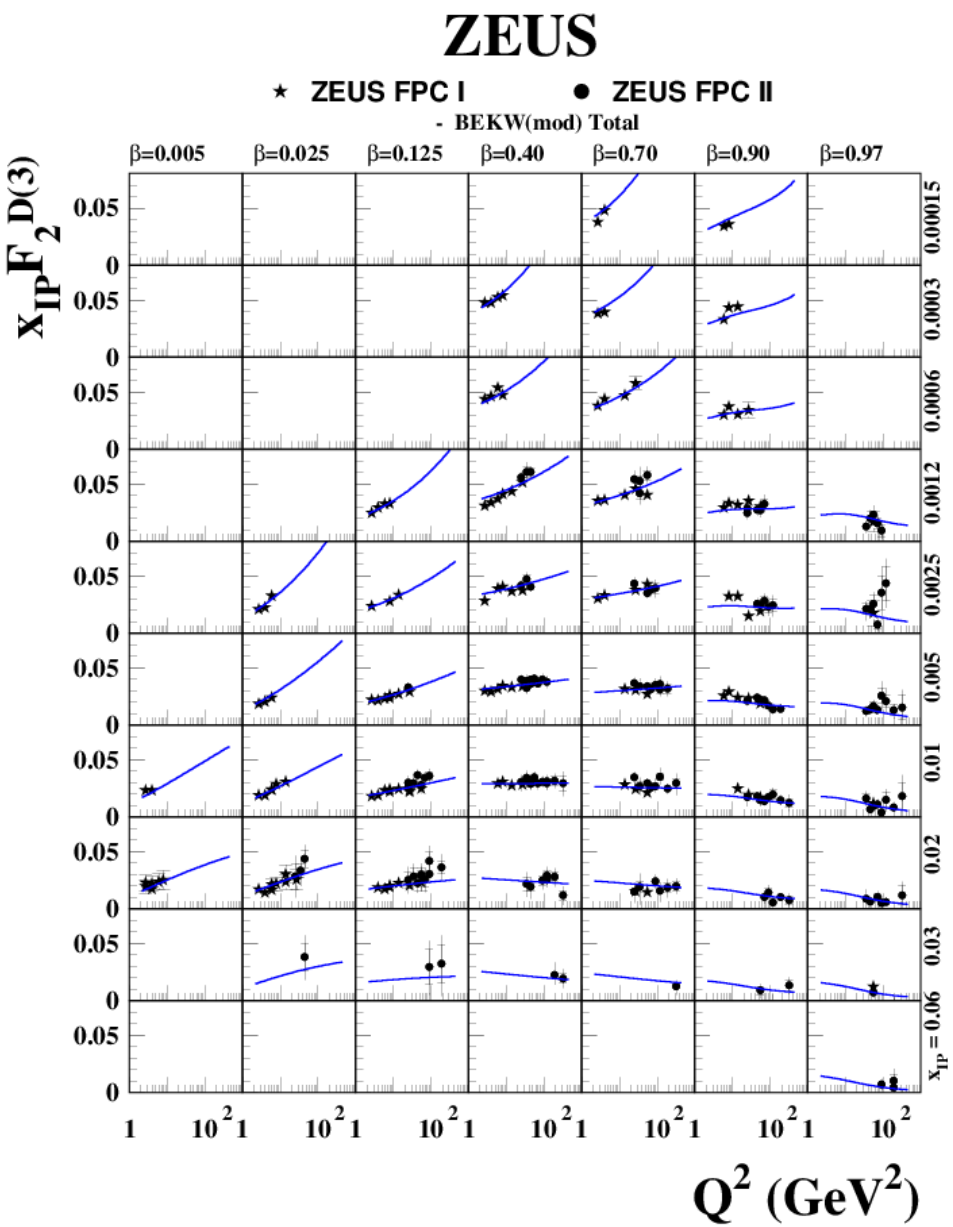
The M_X Method to extract Diffractive DIS Events

DESY 05-011
Nucl.Phys. B173 (2005) 3-80



Results from the M_X method

DESY 08-011
Nucl.Phys. B800 (2008) 1-76



Vertex factorization assumption:

$$F_2(x_{IP}, \beta, Q^2) = f_{IP}(x_{IP}) \cdot F_{IP}(\beta, Q^2)$$

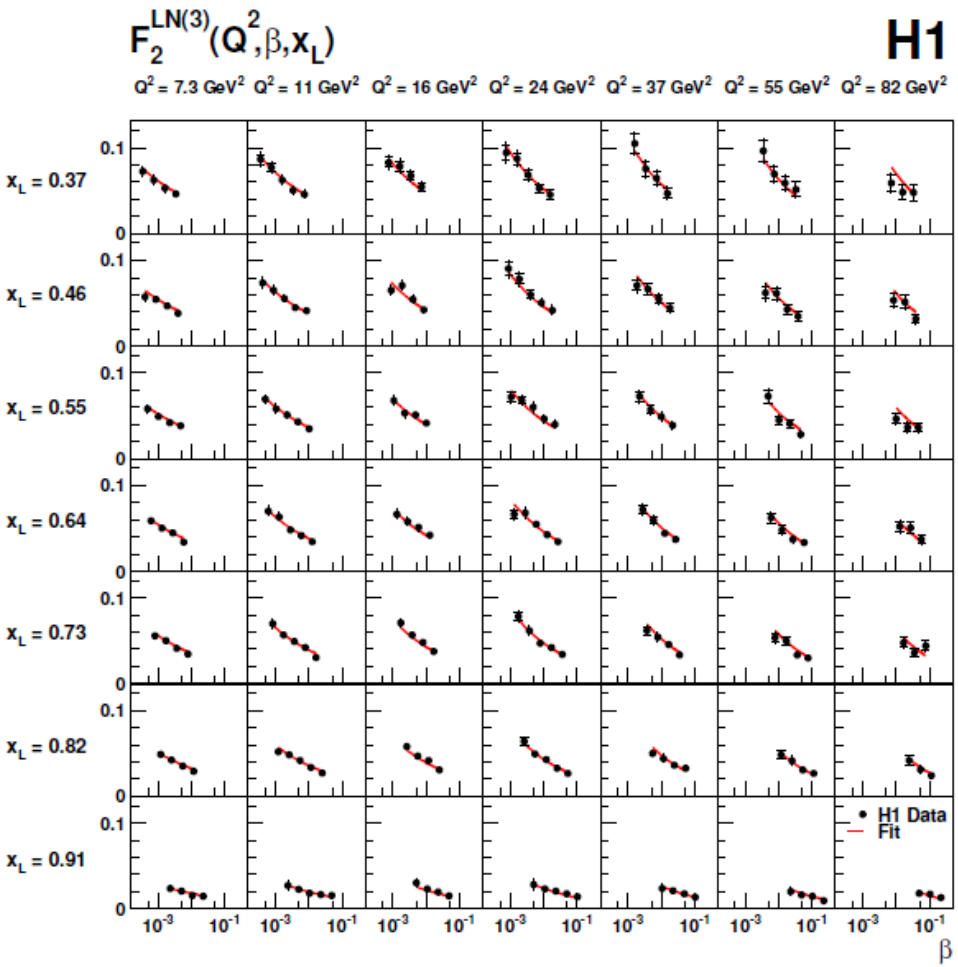
Consequence:

For fixed β, the Q^2 dependence should be independent of x_{IP}.

Within a column of fixed β, x_{IP} dependence results only in scale factors.

Visible are scaling violations:
At high x_{IP} the structure function falls with Q^2
whereas at low x_{IP} it rises with Q^2.

Leading Neutron Cross-section and Structure Function, cont.



DESY 09-185
Eur.Phys.J. C68 (2010) 381

In the OPE model, the cross-section for leading neutron production factorises:

$$d\sigma(ep \to e'nX) = f_{\pi^+/p}(x_L, t) \cdot d\sigma(e\pi^+ \to e'X)$$

The pion flux factor can be derived from hadron scattering data.
Various parametrisations exist, e.g.:

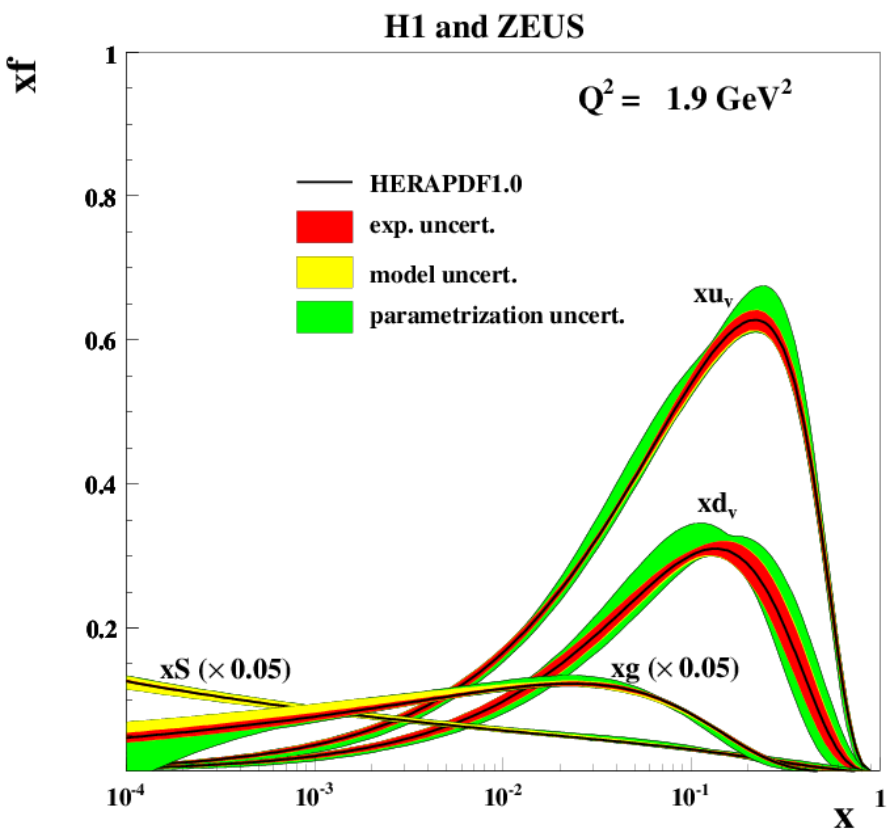
$$f_{\pi^+/p} = \frac{1}{2\pi}\frac{g^2_{p\pi\pi}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\cdot\exp\left(-R^2_{\pi n}\frac{m_\pi^2-t}{1-x_L}\right)$$

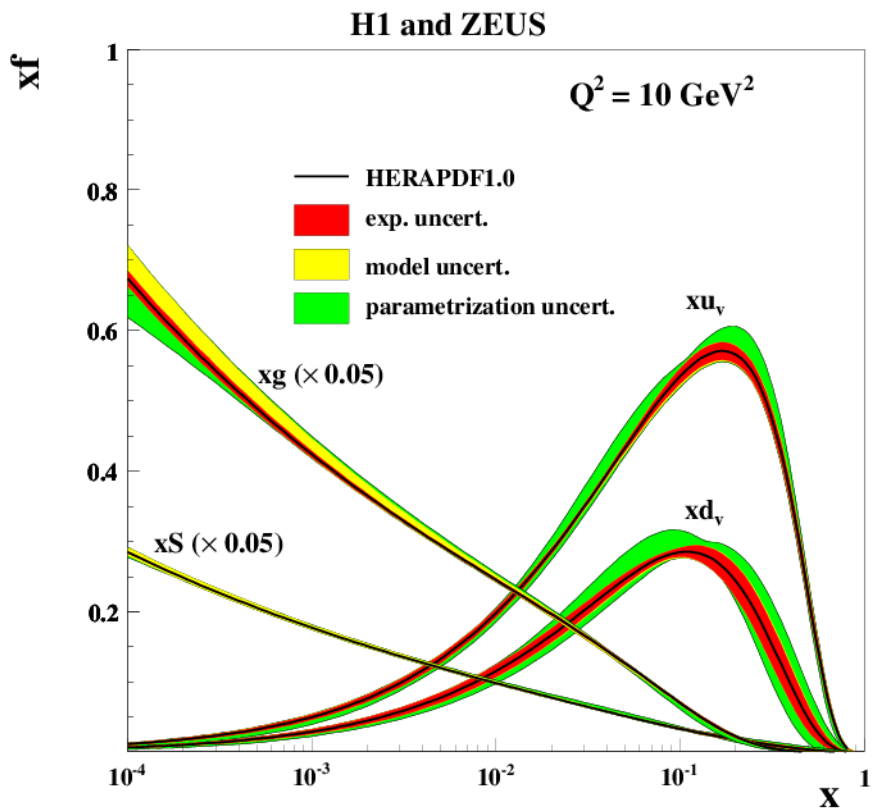
In the OPE model, β can be interpreted as the momentum fraction of the pion which takes part in the hard interaction with the virtual photon.

$$\beta = \frac{x}{1-x_L} = \frac{x}{x_\pi}$$

— Fit: $F_2^{LN(3)}(Q^2,\beta,x_L) = c(x_L)\cdot\beta^{-\lambda(Q^2)}$ with $\lambda = a\cdot\ln(Q^2/\Lambda^2)$

Inclusive DIS PDFs from H1-ZEUS combined data





Parton distribution functions from HERAPDF1.0 at $Q^2 = 1.9\ GeV^2$ and $Q^2 = 10\ GeV^2$
For xu_v, xd_v, xS(sea) and xg.