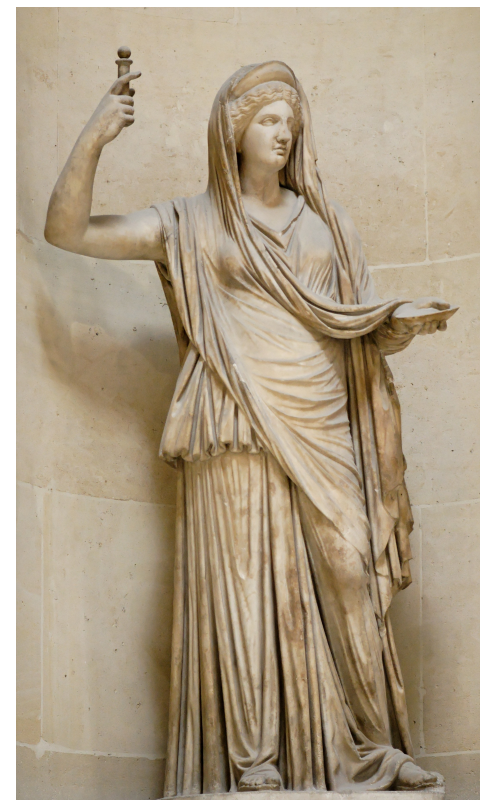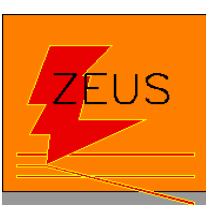# Diffraction at HERA

Richard Polifka

Charles University in Prague
On behalf of the
H1 & ZEUS Collaborations

25.09.2010
XL ISMD, 2010, Antwerp
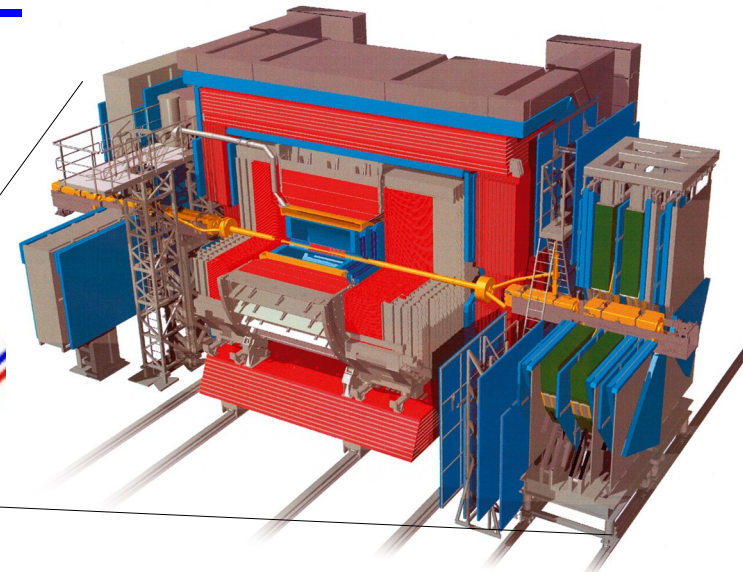
HERA
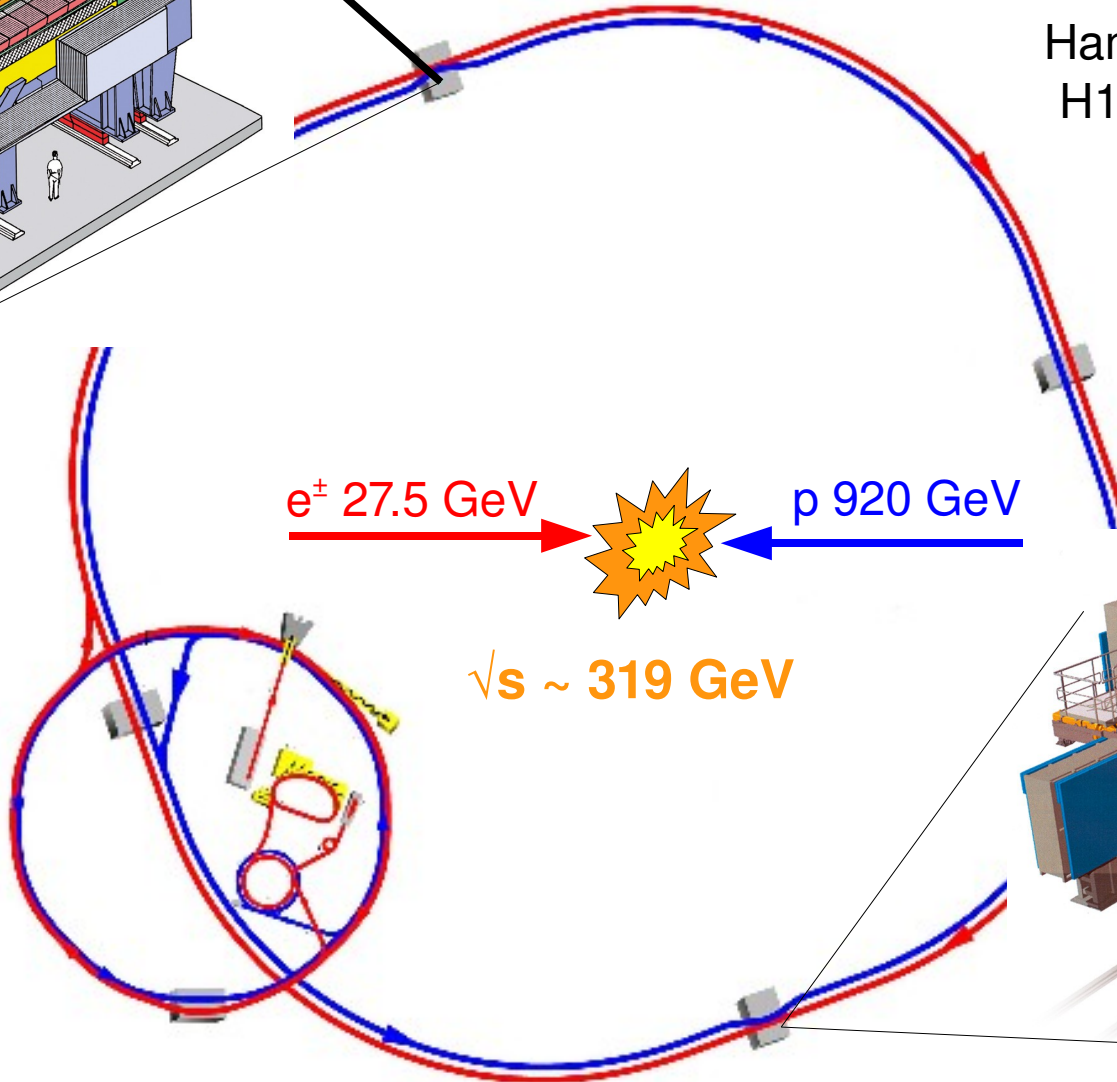

1992 – 2007
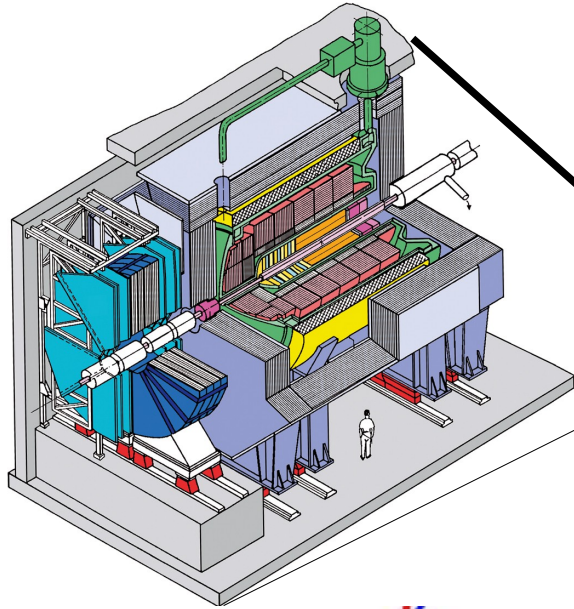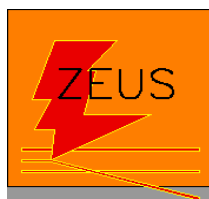**Deutsches Elektronen**
Synchrotron
Hamburg, Germany
H1 and ZEUS (4π)

e$^\pm$ 27.5 GeV   p 920 GeV

$\sqrt{s} \sim 319$ GeV

Data

L = 0.5 fb^{-1}

HERA 1:
  1992 – 2000

HERA 2:
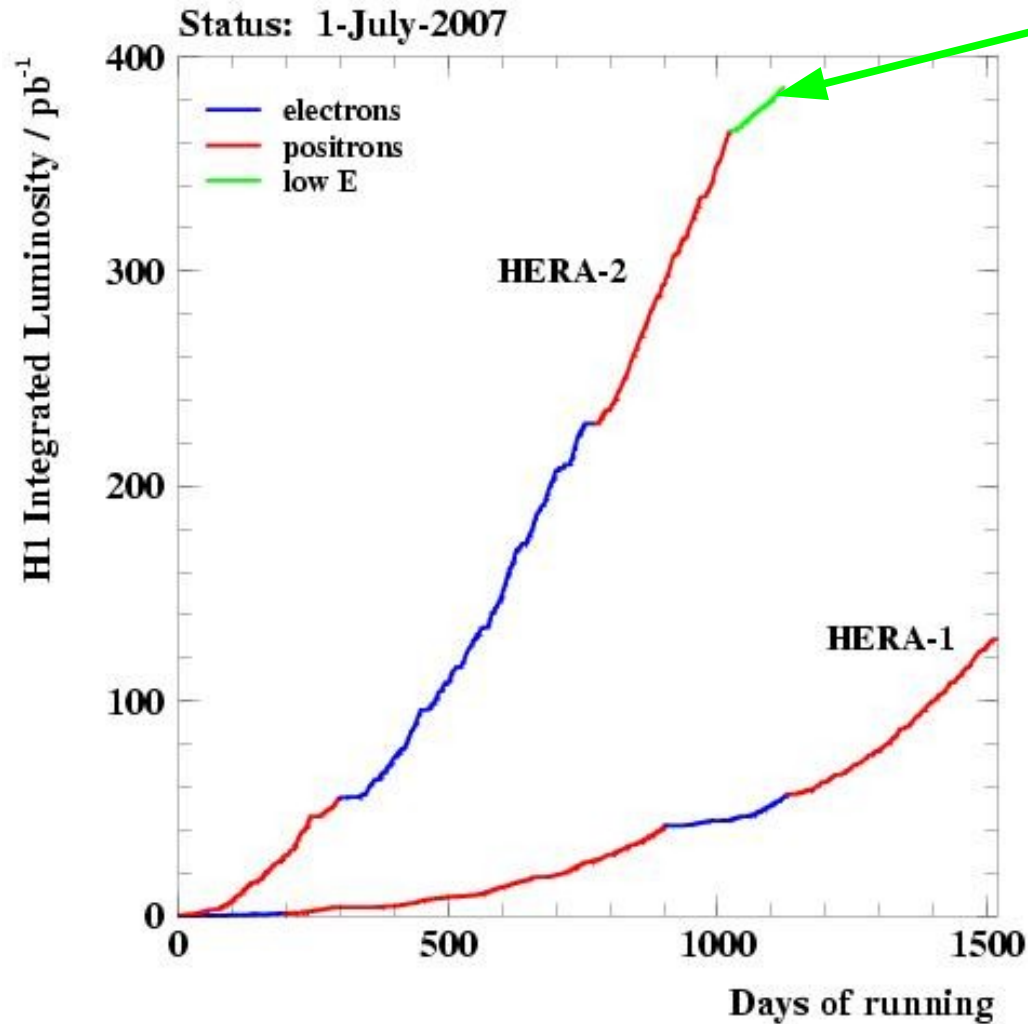 2003 – 2007

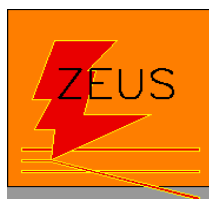E_p = 460 GeV
L = 12.4 pb^{-1}
E_p = 575 GeV
L = 6.2 pb^{-1}

460 and 575 GeV
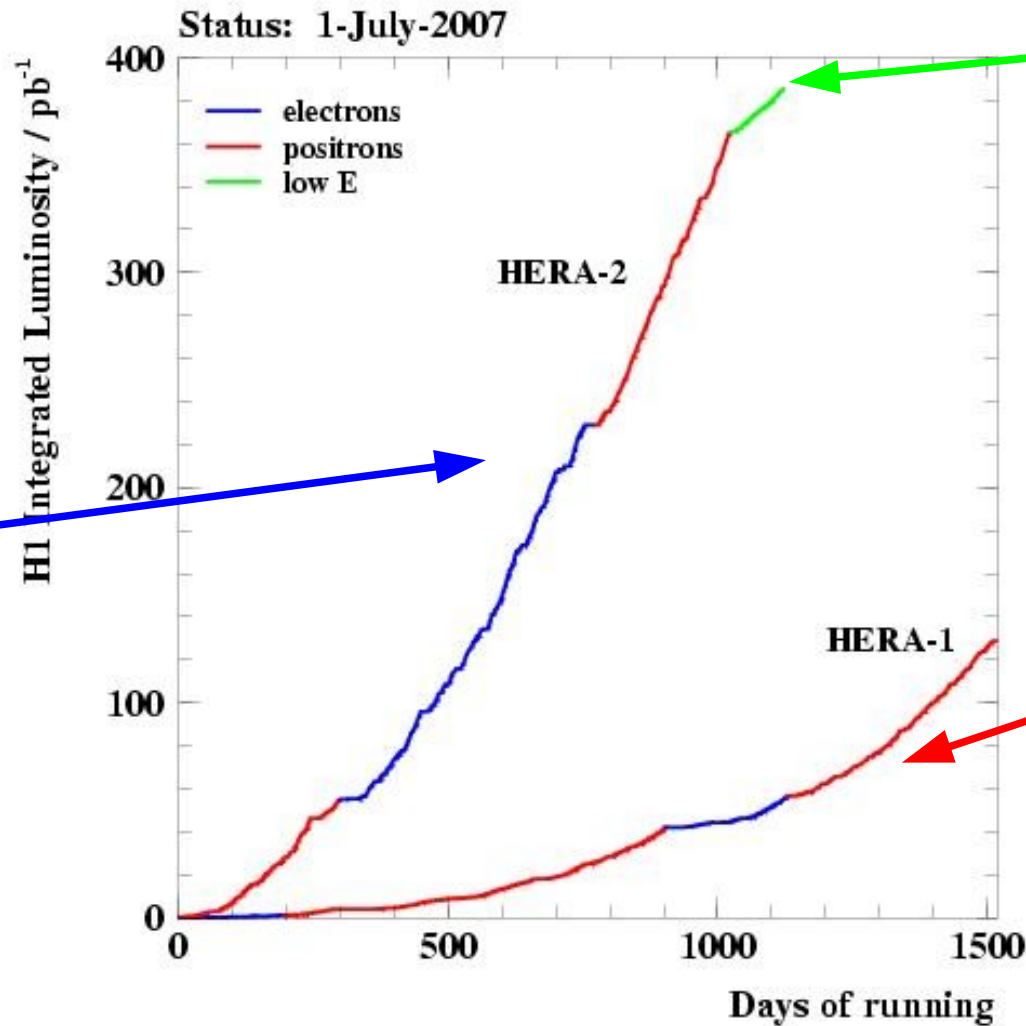Special dedicated
runs for
measuring F_L

3

Data

HERA 1:
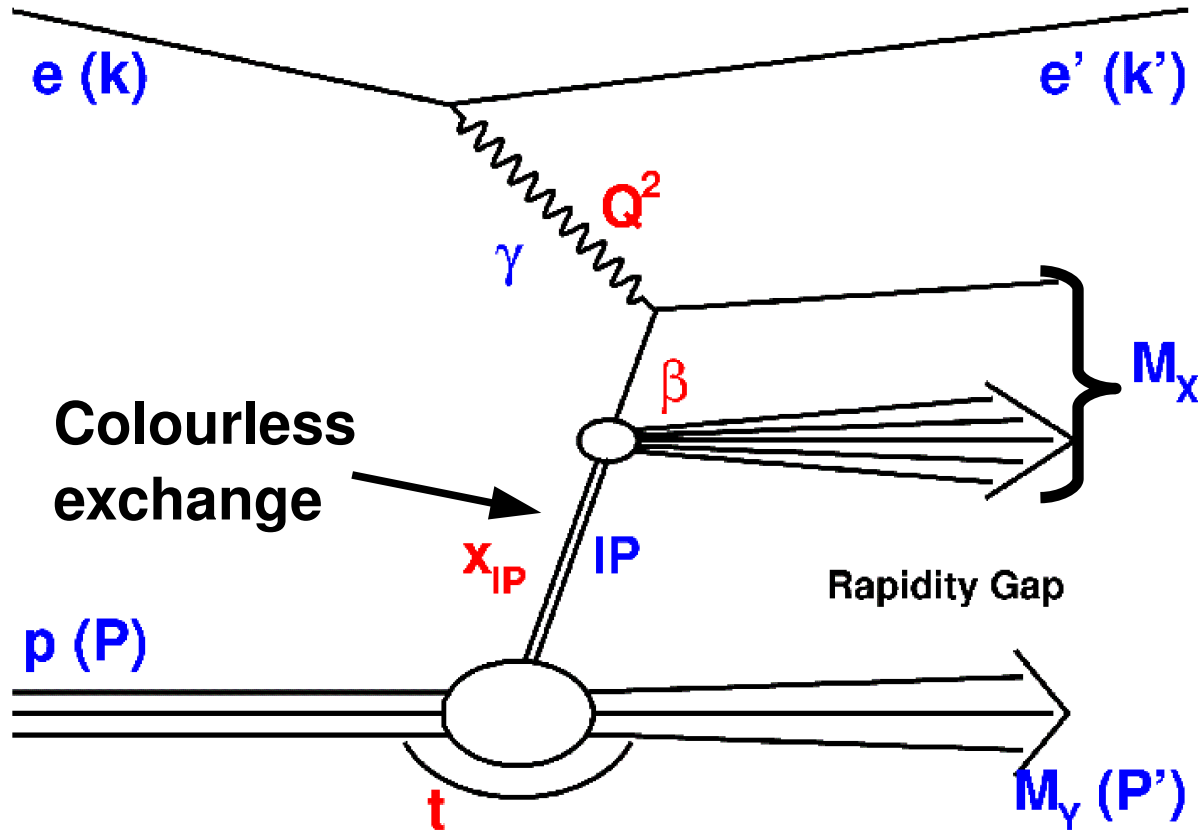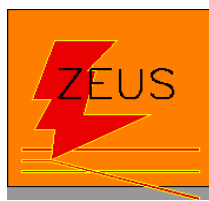 1992 – 2000
HERA 2:
  2003 – 2007

•Inclusive diffractive cross sections with leading proton and LRG
•Jet final states with leading proton

460 and 575 GeV - F_L^D measurement

•Inclusive diffractive cross sections with leading proton and LRG
•Jet final states with LRG

Status: 1-July-2007

electrons
positrons
low E

HERA-2

HERA-1

H1 Integrated Luminosity / pb^{-1}

Days of running

Diffractive kinematics

$$Q^2 = -q^2 = (k' - k)^2$$

$$x = Q^2/2Pq$$

$$x_{IP} = q(P' - P)/qP$$

$$= 1 - E_p/E'_p$$

$$\beta = x/x_{IP}$$

$$t = (P' - P)^2$$

$M_Y = m_p$

  proton stays intact

$m_p < M_Y < 1.6$ GeV

  proton dissociation

incl. nucleon resonances

$Q^2 >> 0$ GeV^2.... deep inelastic scattering

$Q^2 \sim 0$ GeV^2...... photoproduction (γp)

Experimental methods

LRG method:

Requirement of no activity in the forward part

+ high statistics

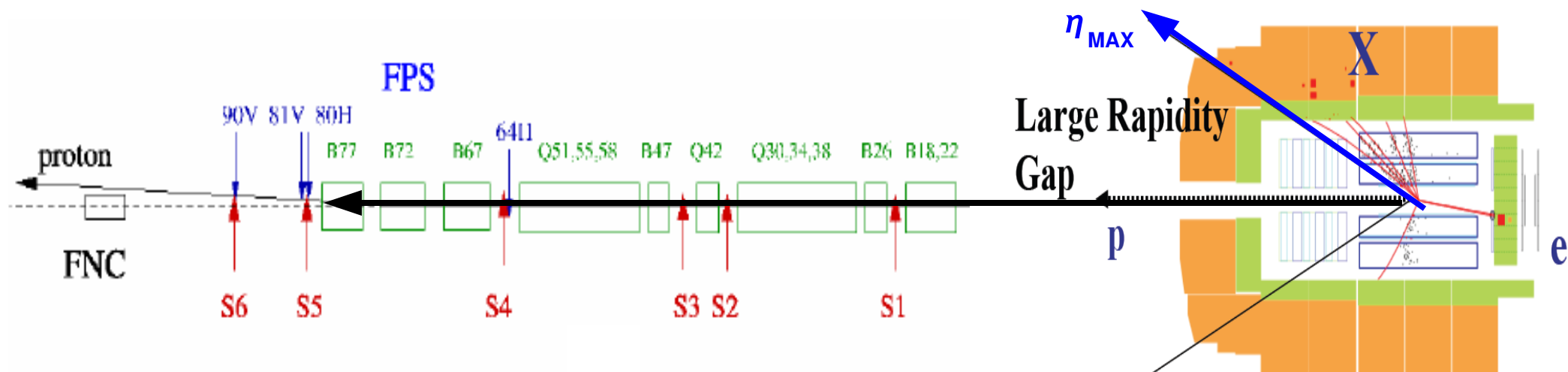-- proton dissociative background

Proton Tagging:

Detection of the leading proton in forward detectors - FPS (**H1**), VFPS(**H1**), LPS (**ZEUS**)

+ direct extraction of diffractive variables, t dependence measured

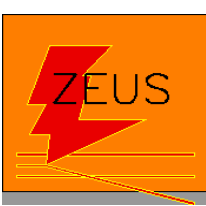+ free of proton dissociation background

-- small acceptance → low statistics

Neutron tagging:

Detection at z = +106m in FNC (**H1**, **ZEUS**)

Diffractive Cross Section

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

Where $\sigma_r^{D(4)}$ is diffractive reduced cross section:

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1 - y + y^2/2)}F_L^{D(4)}$$

Longitudinal diffractive structure function
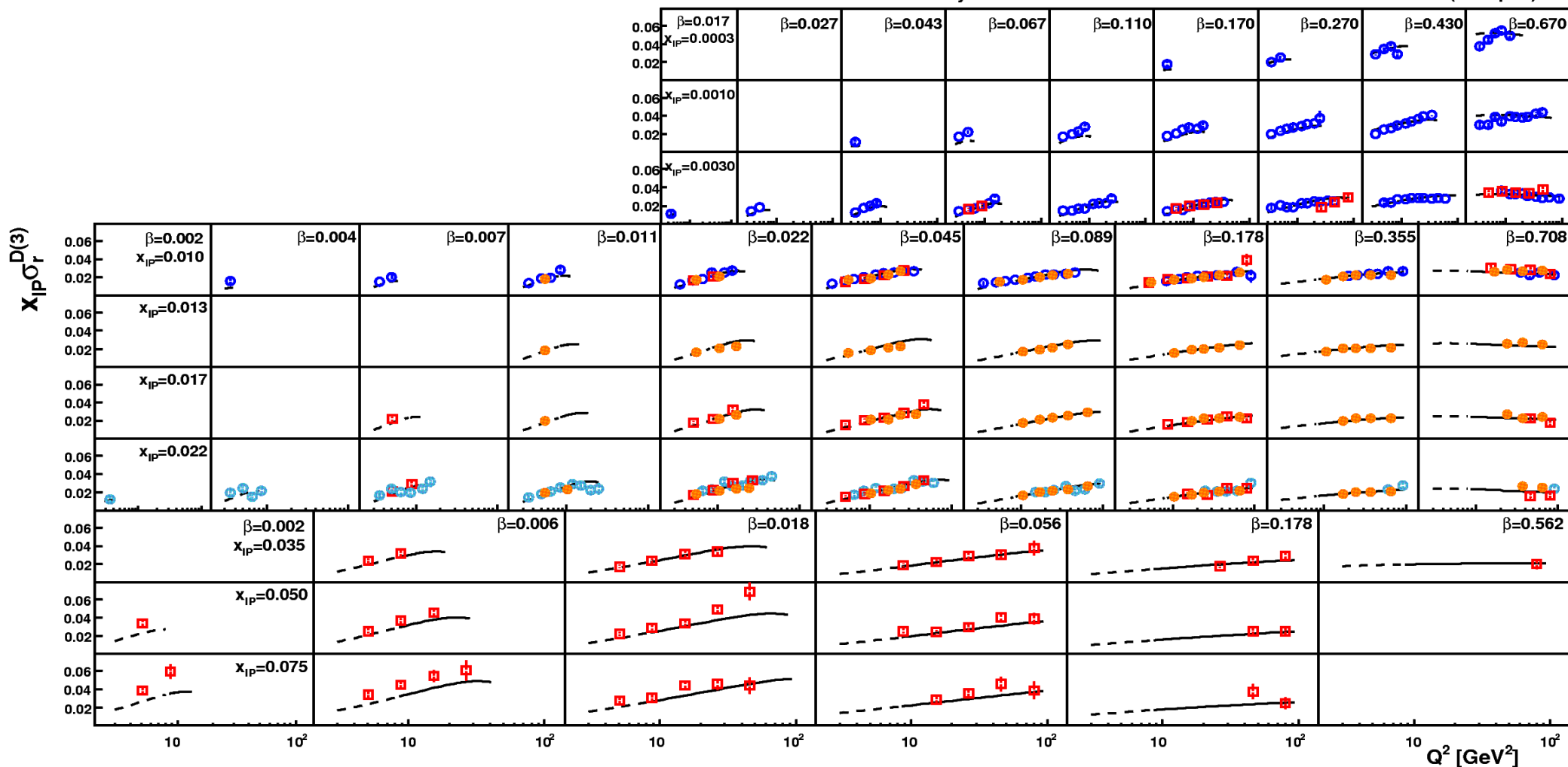
$$\sigma_r^{D(3)}(\beta, Q^2, x_{IP})$$

LRG method unable to measure the *t* dependence → integration

Reduced Cross Section

H1 PRELIMINARY

Legend:
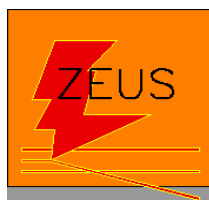- H1 VFPS Preliminary
- H1 FPS Preliminary
- H1 LRG Preliminary x 0.81
- H1 LRG Published x 0.81
- H1 2006 DPDF Fit B x 0.81
- H1 2006 DPDF Fit B x 0.81 (extrapol.)

- **Different measurements cover large region of phase space in x_{IP}, β and Q^2**
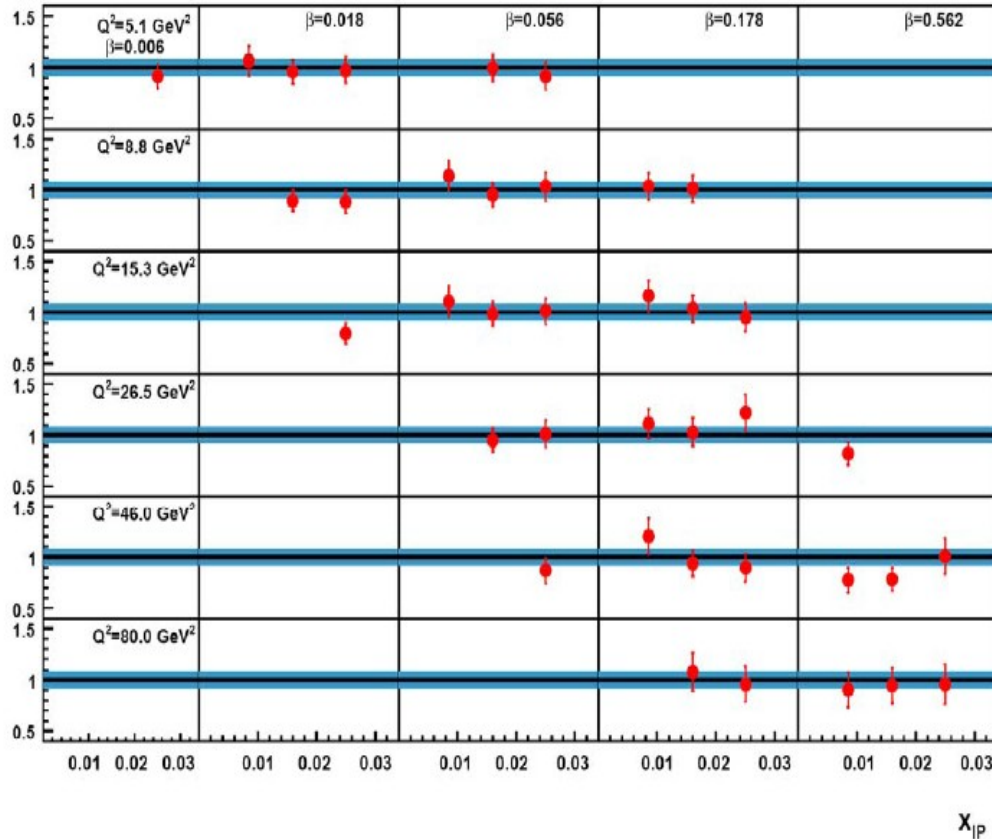- **Excellent agreement between different reconstruction methods in regions of overlap**
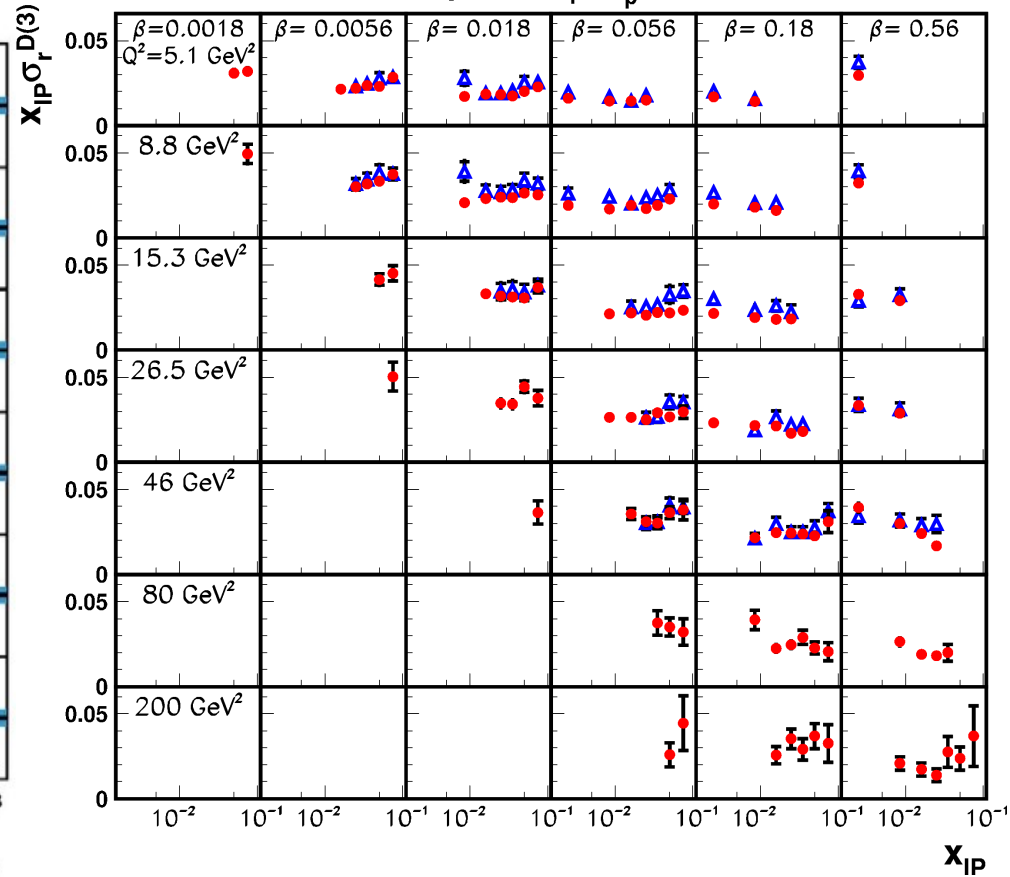
Leading Protons @ H1 and ZEUS

- **VFPS** / **FPS**, HERA 2 (157 pb^{-1})
- In the whole kinematical range in agreement within the errors
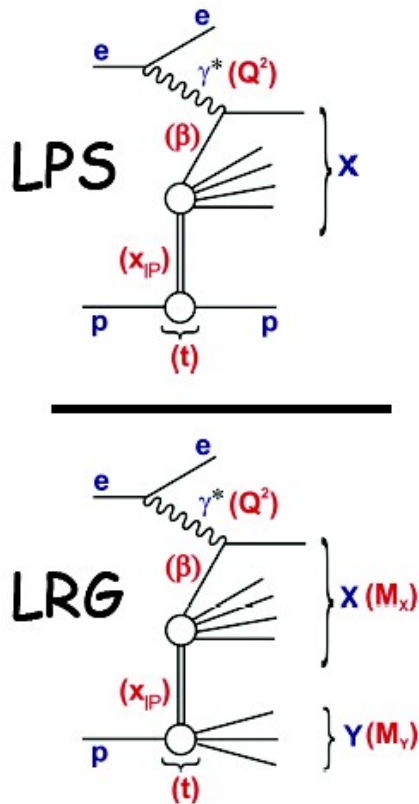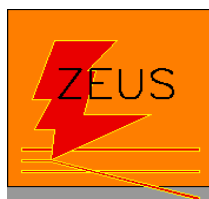
Successful consistency check in the region of overlap

- **FPS** x **LPS**
- H1 – ZEUS agreement within errors
- 15% difference in overall normalisation compatible with normalisation uncertainties (6% FPS, 10% ZEUS)
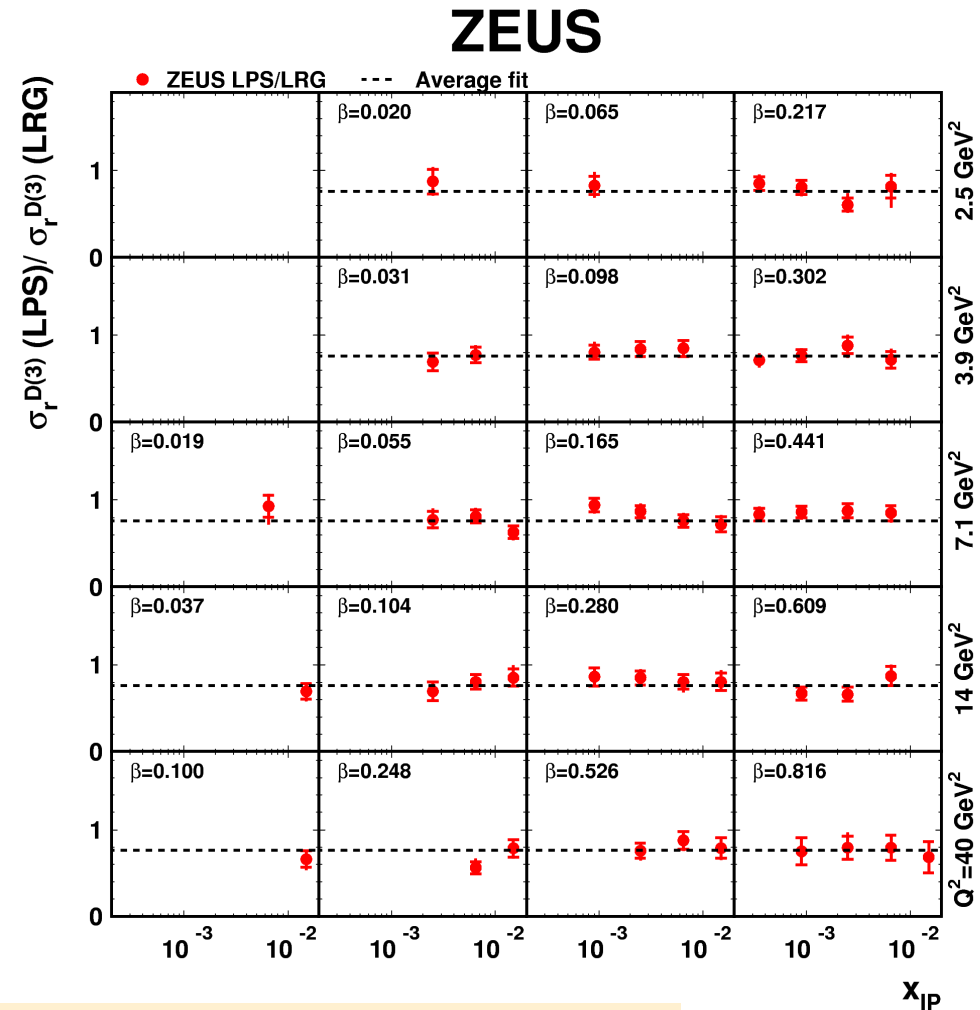
Leading Protons vs LRG
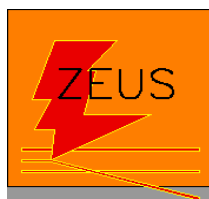

ZEUS   LPS/LRG: **0.76** ±0.01 ±0.03 ±0.08

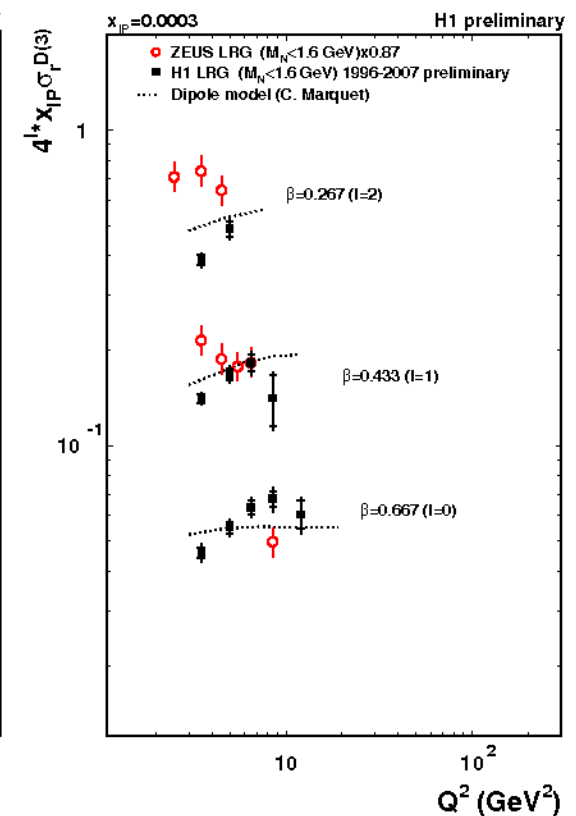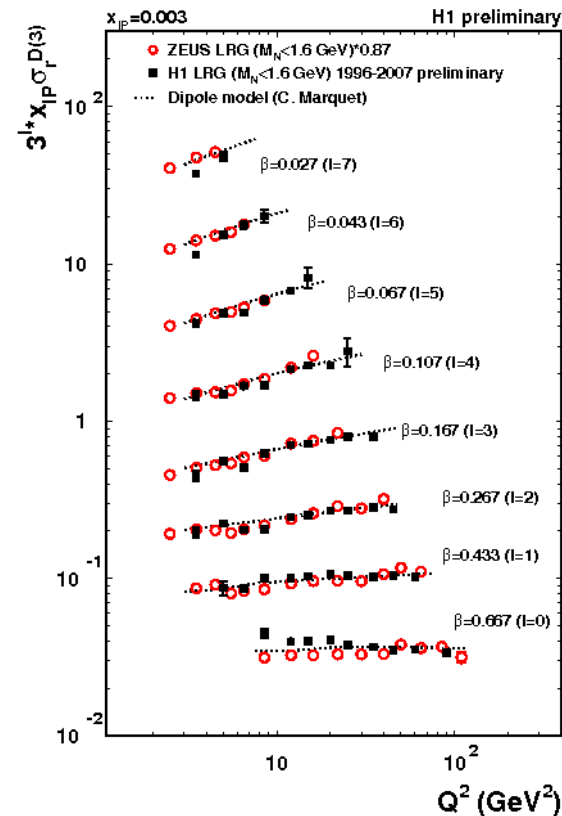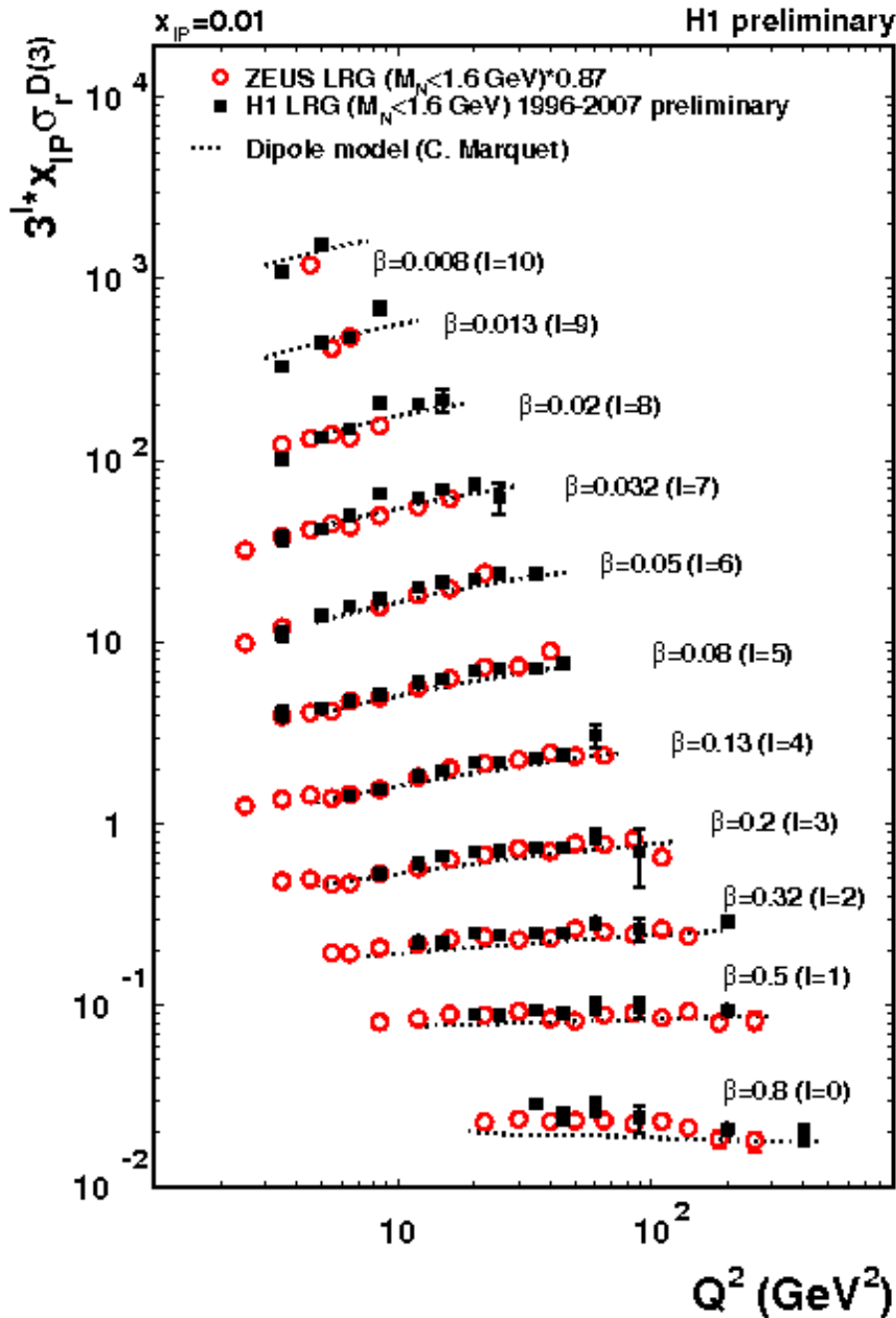**H1**   LRG/FPS: **1.18** ±0.01 ±0.06 ±0.1

**No dependence on any kinematic variable
Both measurements on 99/00 HERA 1 - Data
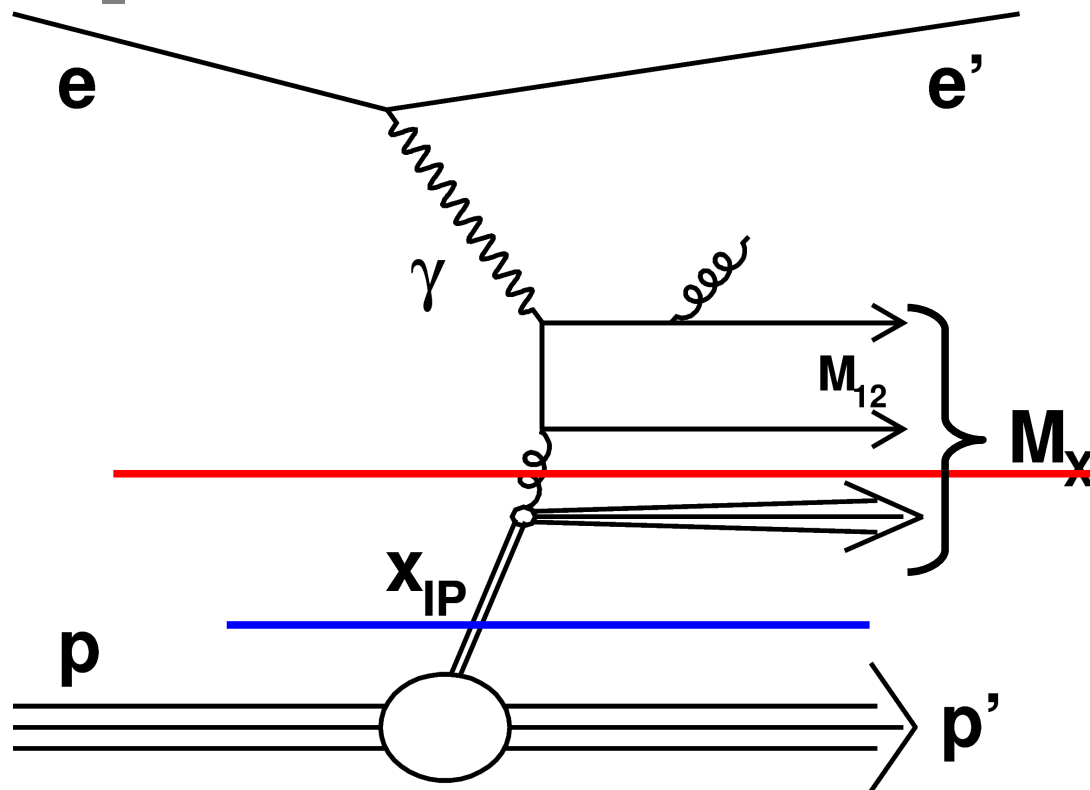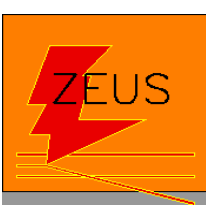Consistency between H1 and ZEUS within errors**

LRG @ H1 and ZEUS

- New H1 HERA 2 data with 370 pb^{-1}
- ZEUS data rescaled by 0.87 (normalisation difference)
- Agreement over wide kinematic range within normalisation errors

Factorisation

e   **e'**

γ

M_{12}

M_X

x_{IP}

p   **p'**

QCD collinear factorisation (Collins)

Proton vertex factorisation
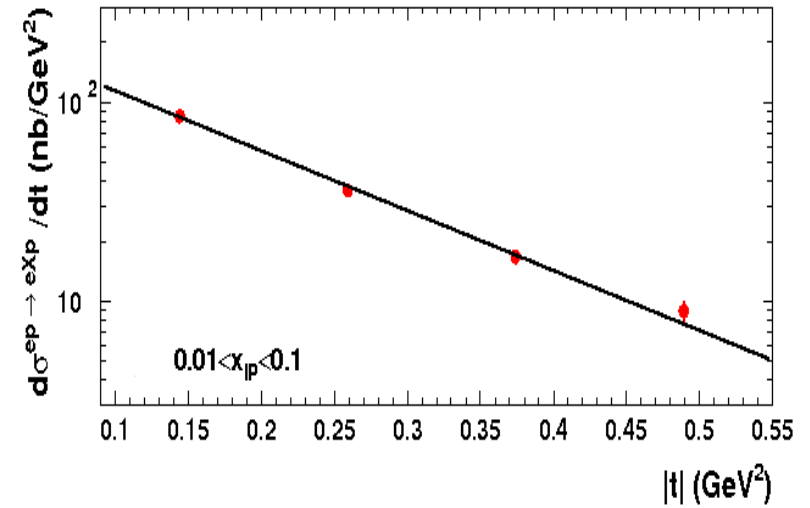
$$d\sigma^{ep \to eXp}(\beta, Q^2, x_{IP}, t) = \sum_i f_i^D(\beta, Q^2, x_{IP}, t) \cdot d\hat{\sigma}^{ei}(\beta, Q^2)$$

$$f_i^D(\beta, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i(\beta, Q^2) \qquad f_{IP/p}(x_{IP}, t) = A_{IP} \frac{e^{B_{IP} t}}{x_{IP}^{2\alpha(t)-1}}$$

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Proton Vertex Factorisation

Expectation of PVF: independence of **B**-slope on kinematical variables
FPS HERA 2 data, L = 157 pb^{-1}, LPS HERA 1 data L = 33 pb^{-1}
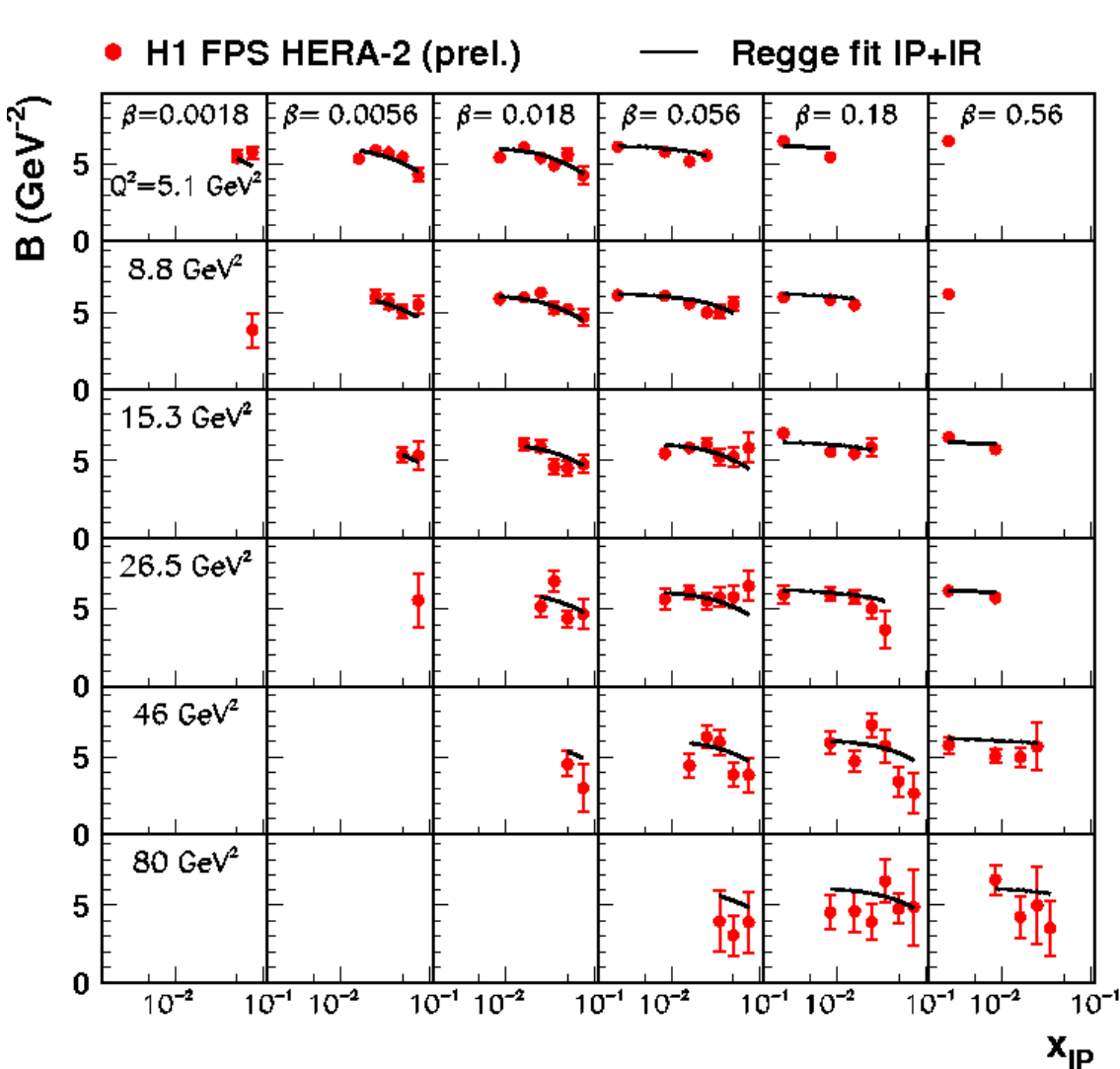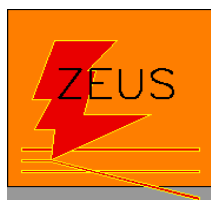

$$\frac{d\sigma}{dt} \sim e^{-B|t|}$$

- Data are consistent with **proton vertex factorisation**
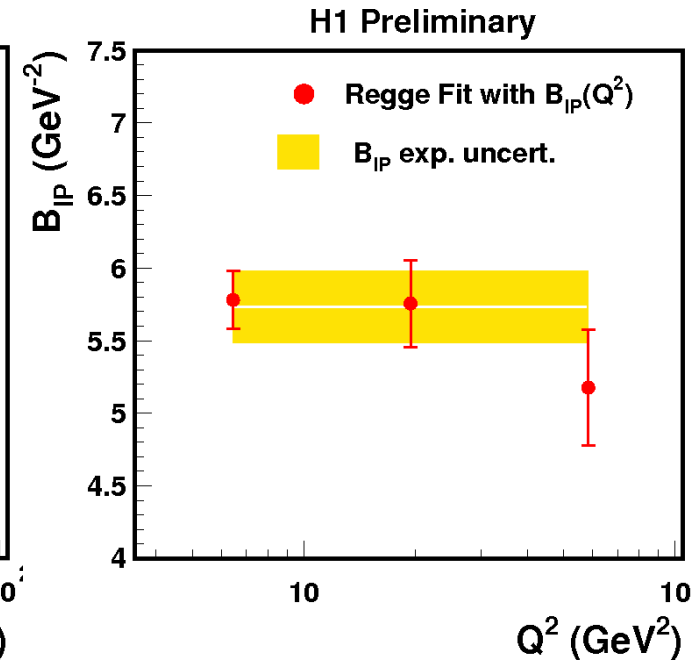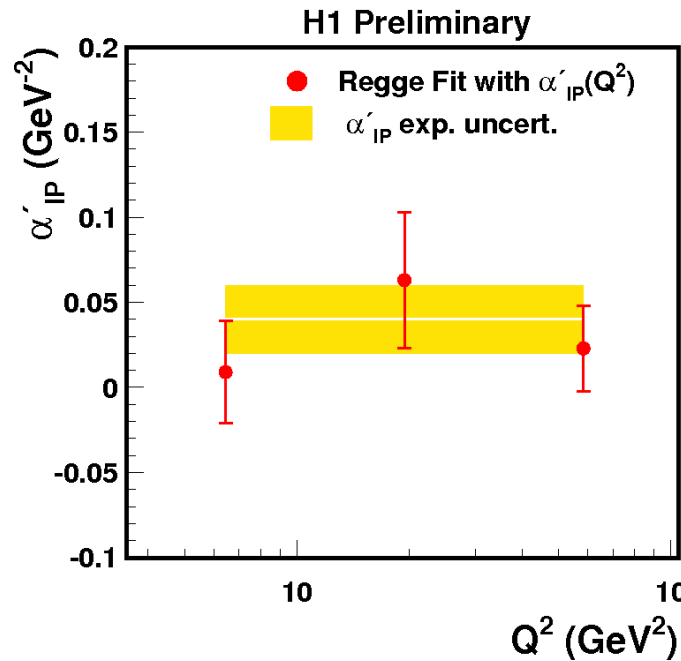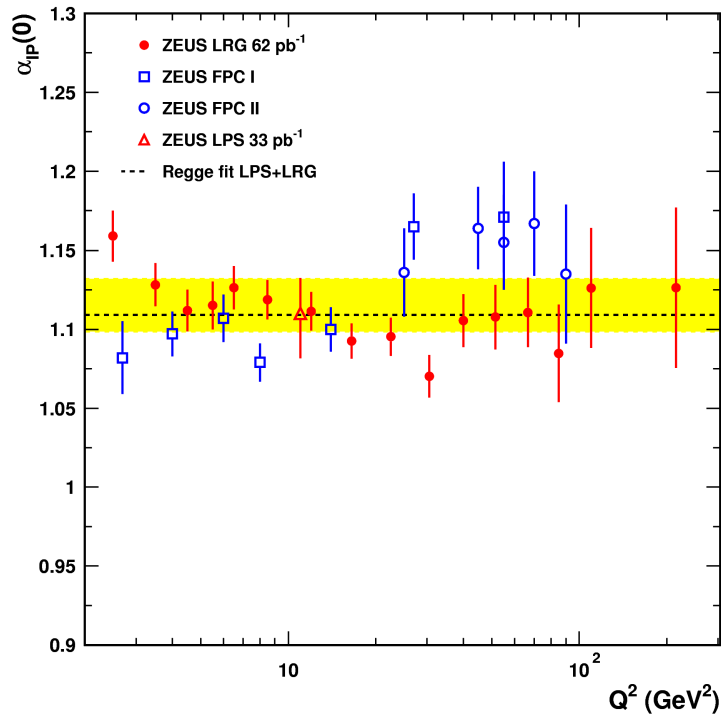- Weak dependence at high x_{IP} due to IR exchange

Proton Vertex Factorisation

$$f_{IP/p}(x_{IP}, t) = \frac{e^{B_{IP}t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$$
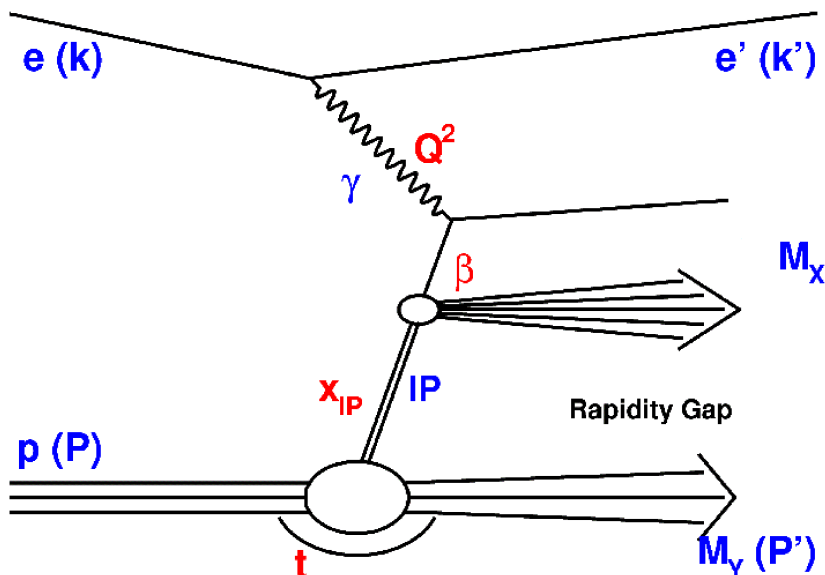
$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}\, t$$

ZEUS

	H1	**ZEUS**
$\alpha_{IP}(0)$	1.10 ± 0.04	1.11 ± 0.04
α'_{IP} [GeV^{-2}]	0.04 ± 0.04	-0.01 ± 0.11
B_{IP} [GeV^{-2}]	5.73 ± 0.26	7.1 ± 1.57

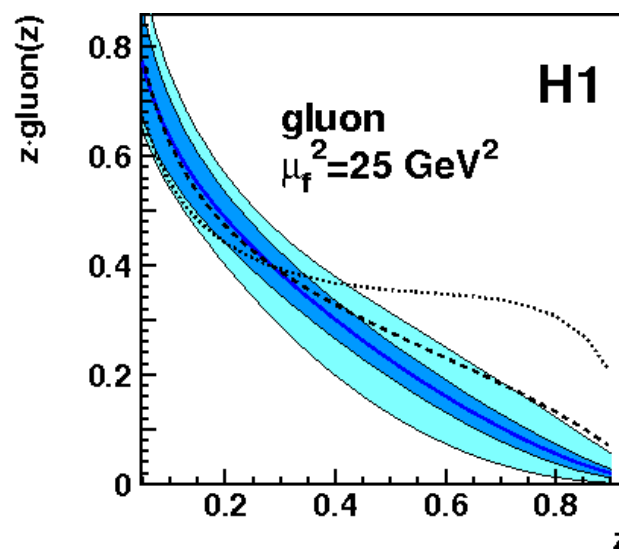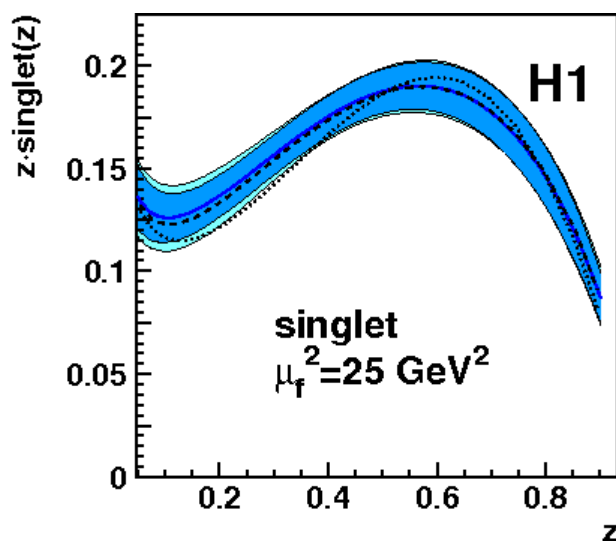**Independence on kinematical variables within errors favours proton vertex factorisation**
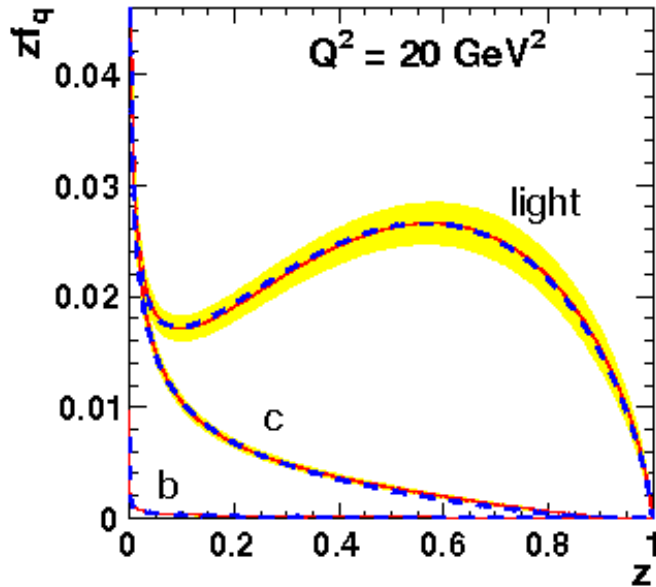**Good consistency between experiments**
$\alpha_{IP}(0)$ **prefers soft exchange**

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Extracting DPDFs

e (k)   e' (k')

Q^2

γ

β M_X

x_{IP} IP
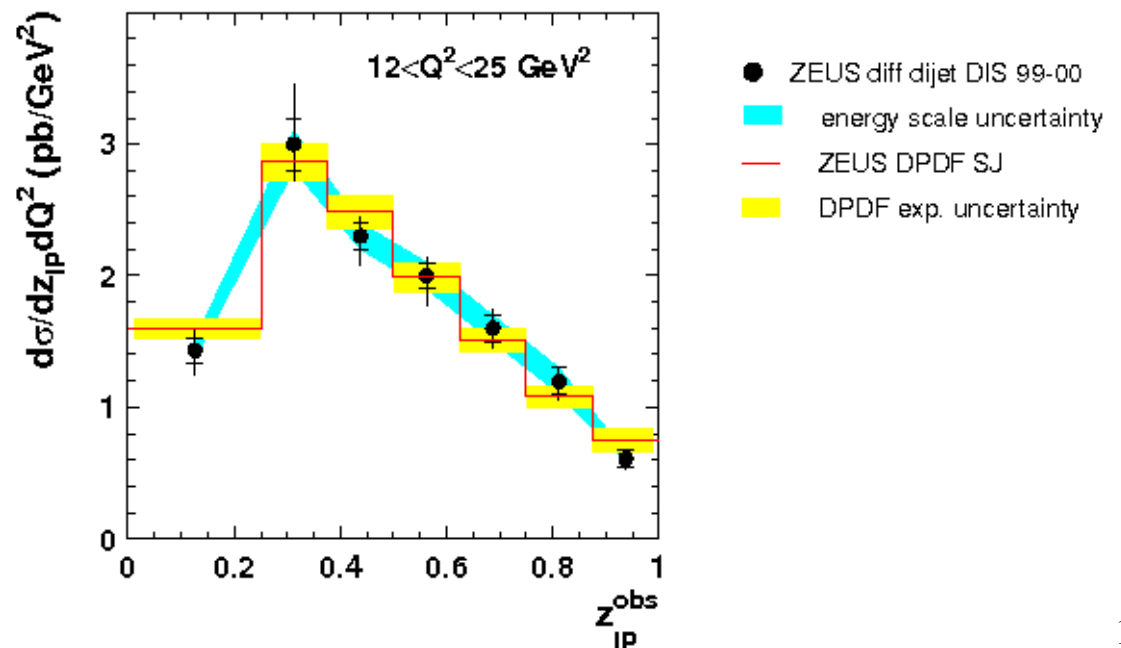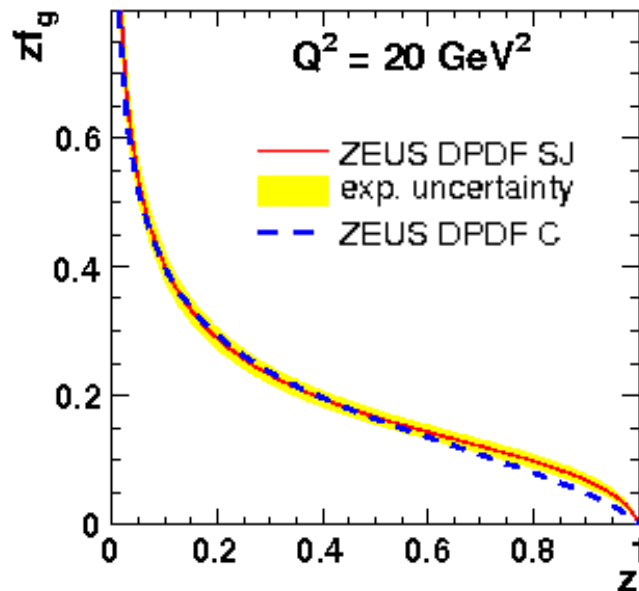
Rapidity Gap

p (P)

M_Y (P')

t

- Fit β and Q^2 dependence at fixed x_{IP}
- Parametrise at starting scale Q_0^2

and evolve using NLO DGLAP

- PVF allows to combine DPDFs with

pomeron flux Ansatz

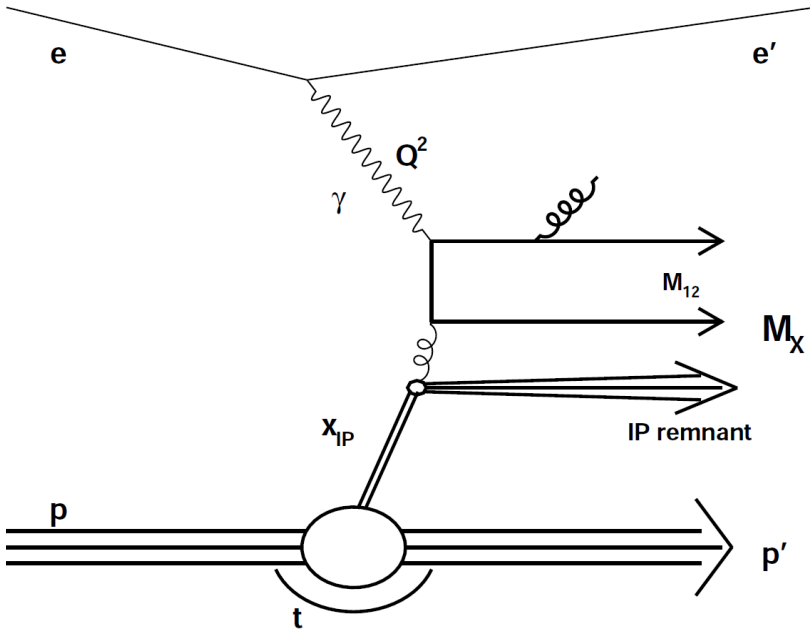- Diffractive Jets constrain gluon part

of DPDFs

H1 2007 Jets DPDF

exp. uncertainty

exp. + theo. uncertainty

H1 2006 DPDF fit A

H1 2006 DPDF fit B

z·singlet(z)

H1

singlet
μ_f^2=25 GeV^2

z·gluon(z)

H1

gluon
μ_f^2=25 GeV^2

DPDFs

$Q^2 = 20 \text{ GeV}^2$

light

c

b

zf_q

zf_g

ZEUS DPDF SJ
exp. uncertainty
ZEUS DPDF C

- Recent ZEUS fits to LRG and LPS inclusive and dijet data
- Improved heavy flavour treatment
- Good agreement with H1 up to normalisation uncertainty
- **Excellent** description of dijet data

$12 < Q^2 < 25 \text{ GeV}^2$

$d\sigma/dz_{IP}dQ^2$ (pb/GeV^2)

- ZEUS diff dijet DIS 99-00
- energy scale uncertainty
- ZEUS DPDF SJ
- DPDF exp. uncertainty

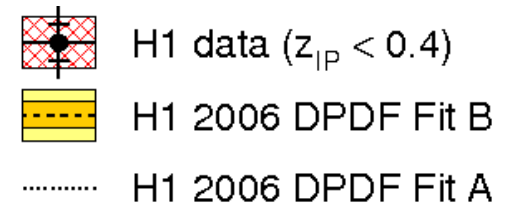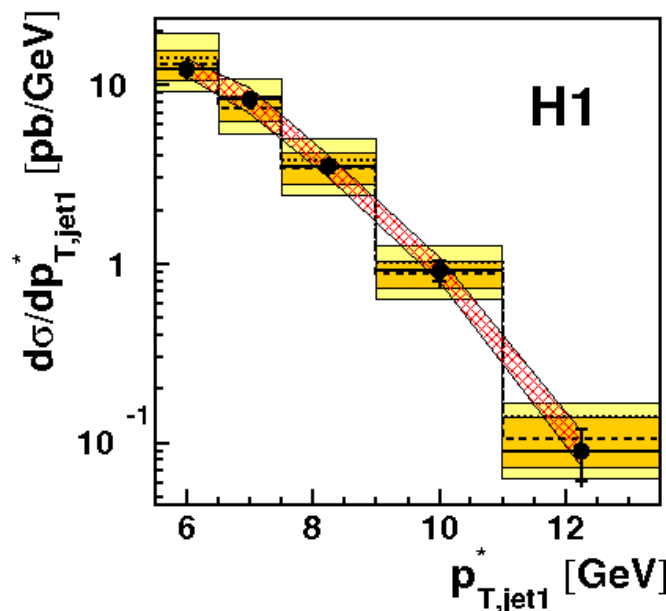z_{IP}^{obs}

Jes in Diffraction

- Presence of a hard scale
- Tool for proving QCD collinear factorisation – possible to test pQCD predictions convoluted with DPDFs
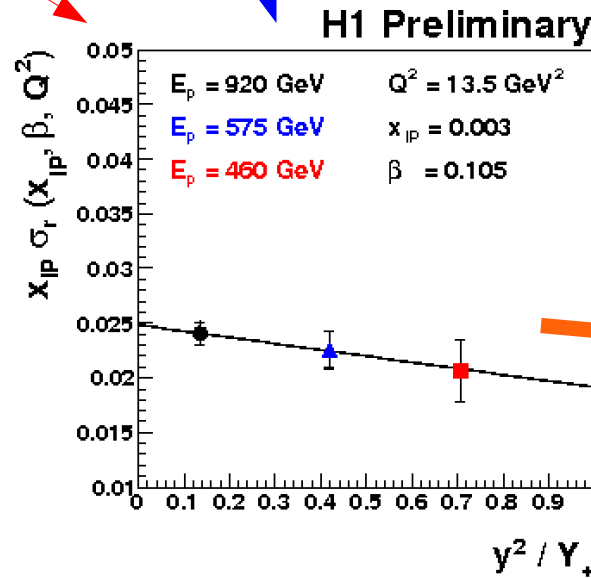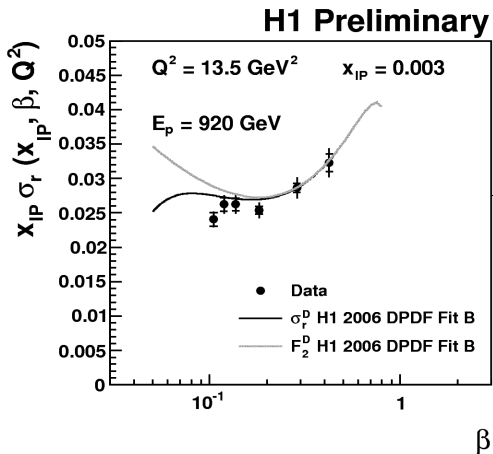- Direct extraction of gluon density in pomeron
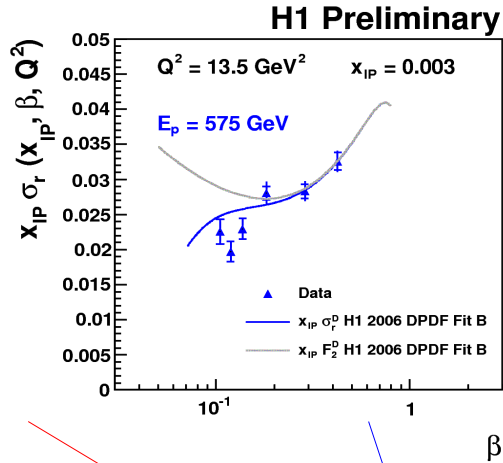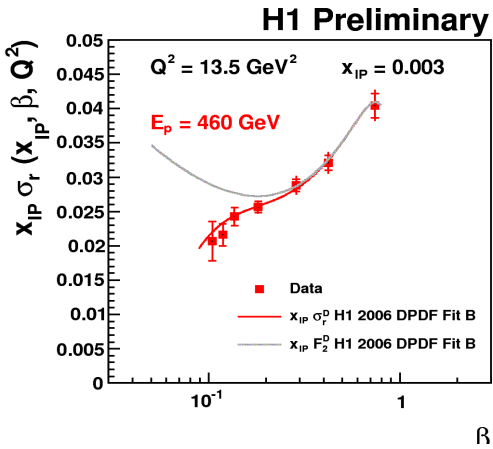- Study of parton evolution

FPS
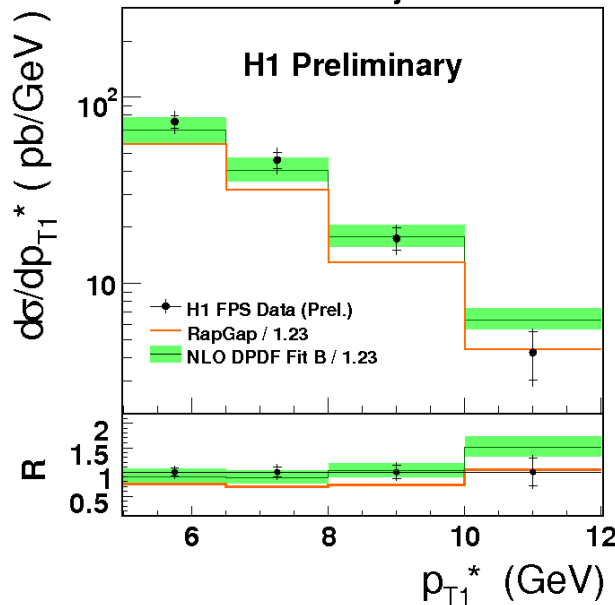
LRG

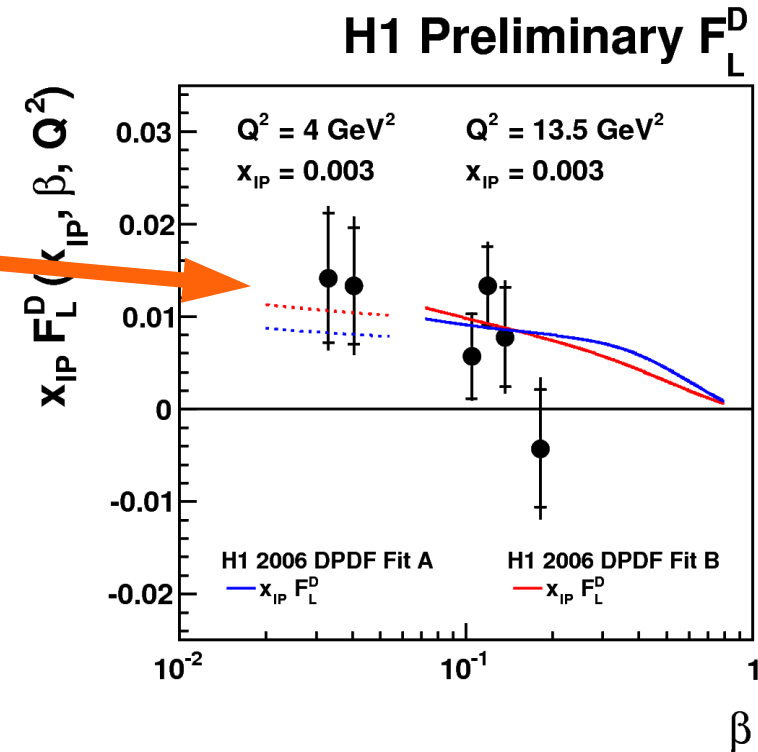DIS data (LRG and FPS Jets) support QCD factorisation

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Longitudinal Structure Function

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)}$$

- Sensitive to gluons
- Independent test of QCD factorisation
- For fixed β, Q^2 and x_{IP} different beam energies necessary

F_L^D significantly nonzero
Consistent with NLO DGLAP

Diffractive Forward Jets

- DGLAP assumes strong k_T ordering and neglects terms ~1/x

- Forward jets with leading proton in DDIS – search for physics beyond DGLAP

  - Possibly **only** in leading proton measurement

  - Possibility to investigate jets close to the proton direction

  - Low x region
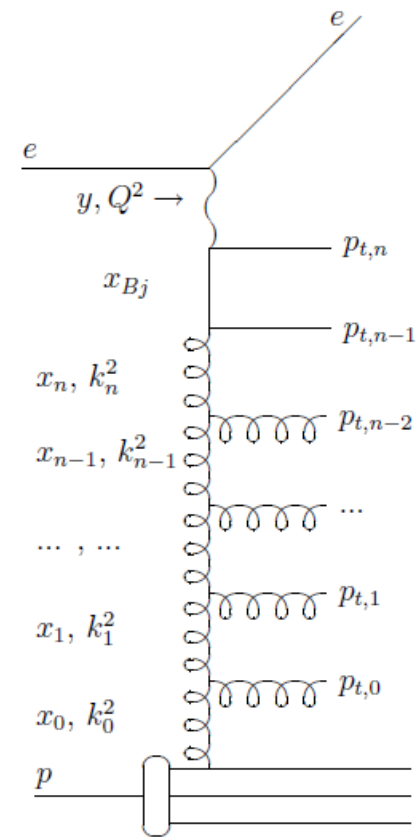
$p^*_{T,forward} > 4.5$ GeV

$1 < \eta_{forward} < 2.8$

$p^*_{T,central} > 3.5$ GeV

$-1 < \eta_{central} < 2.5$

Good description by DGLAP

Factorisation in photoproduction
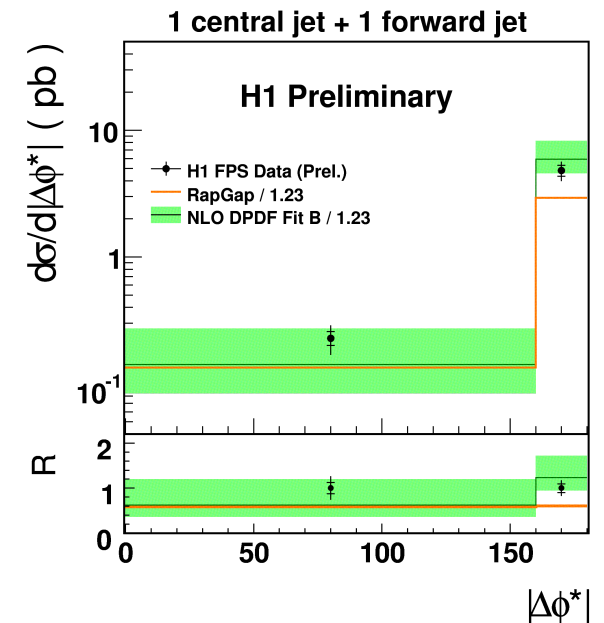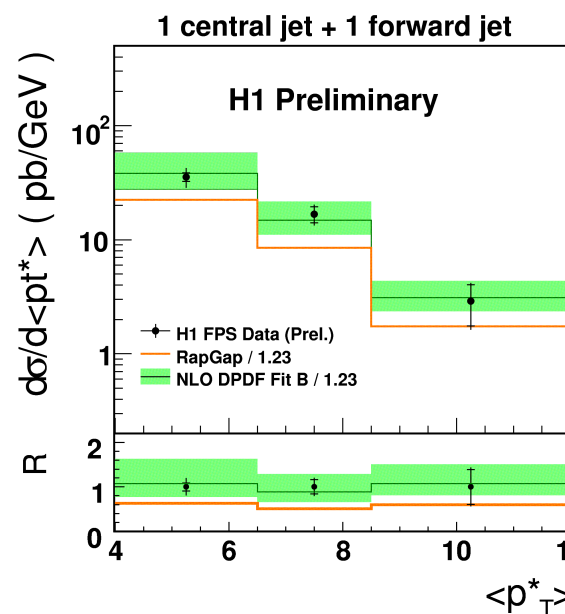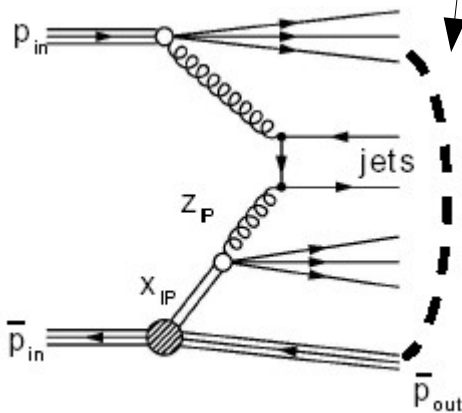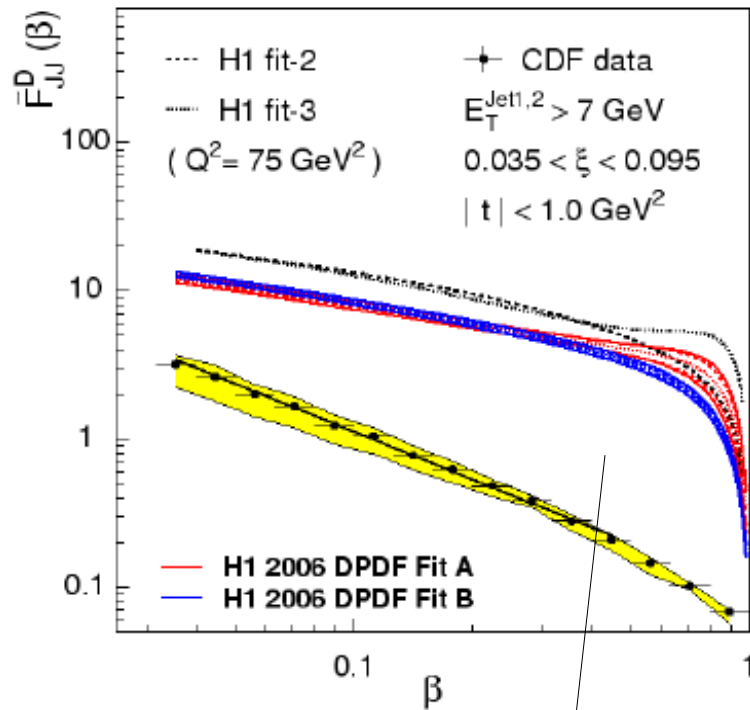
- CDF dijet cross section differs by factor 5-10 in comparison to predictions based on HERA DPDFs
- Soft interactions between proton remnants destroys the rapidity gap → **Survival Probability** ($S^2 \sim 0.1$ for CDF)
- Factorisation test at HERA → measurement of PHP dijets
- For HERA kinematics prediction S^2 (KKMR)~ 0.34 for resolved component
- Studied also at LHC

$$x_\gamma \approx x_\gamma^{OBS} = \frac{\sum (E - p_z)_{jets}}{(E - p_z)_{hadrons}}$$
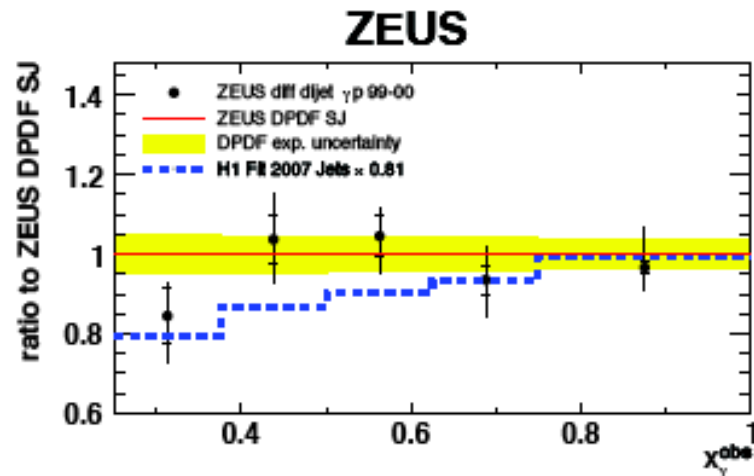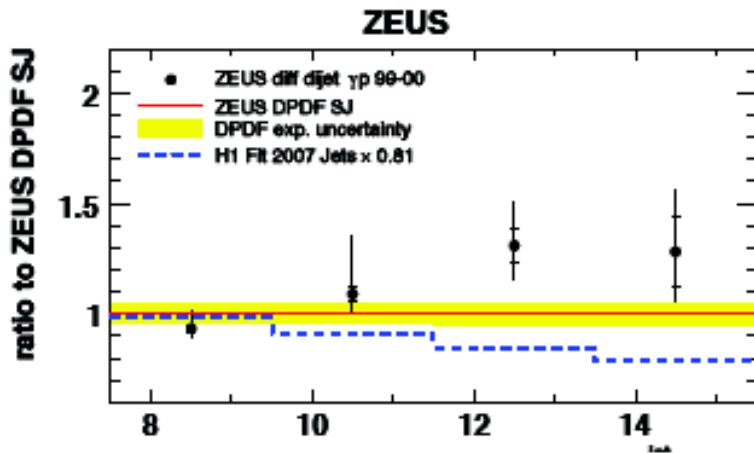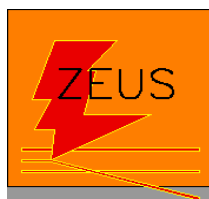
HERA conditions
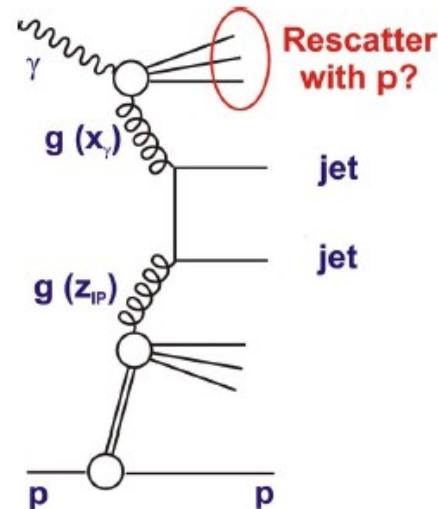
resolved, $x_\gamma < 1$ direct, $x_\gamma \sim 1$
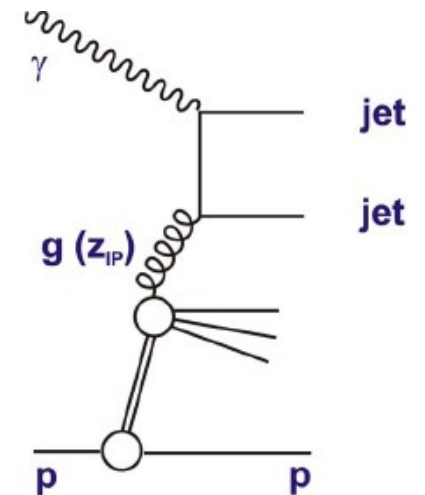
E$_T$ > 7.5 GeV

No factorisation breaking

E$_T$ > 5 GeV

E$_T$ dependence?

σ(data)/σ(NLO) = 0.58 $\pm$ 0.21 (tot)

Survival Probability in photoproduction revised

Revision (KKMR):

Direct process remains
unsuppressed

Previously predicted $S^2 \sim 0.34$
applies only to **Hadron-like**
photon structure function ($x_\gamma < 0.1$,
inaccessible in current analysis)

$0.1 < x_\gamma < 1$. „anomalous" part of
photon structure function, less
suppression ($\sim 0.7 - 0.8$)

KKMR: Better E_T dependence, x_γ
still unsatisfactory described,
additional suppression for x_γ
necessary in all cases –
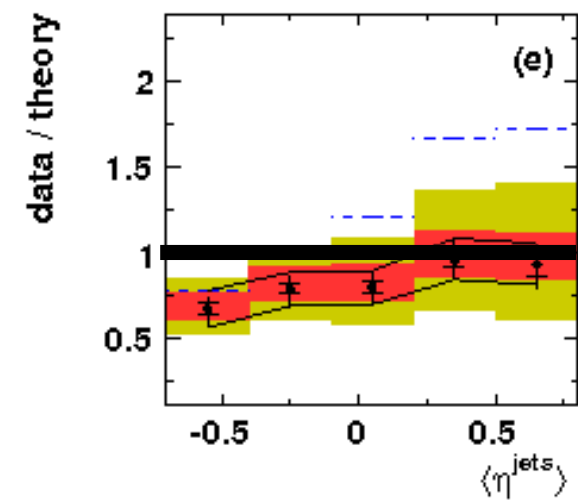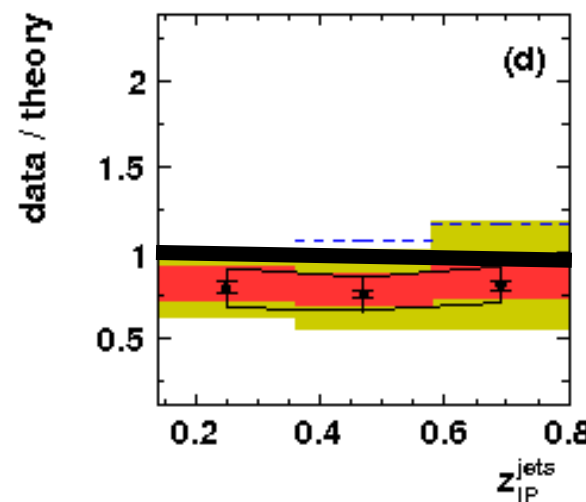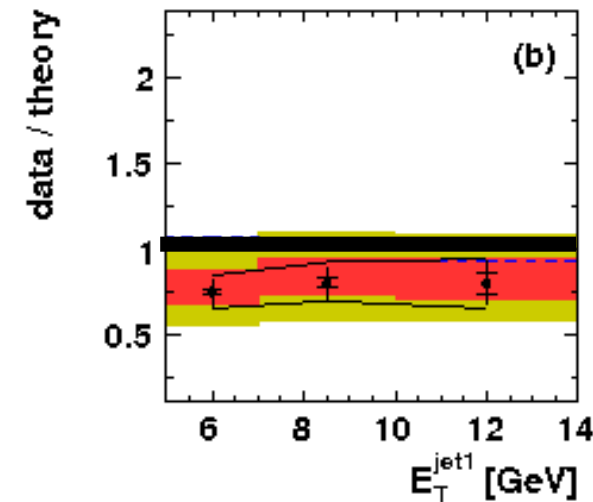**factorisation breaking?**

H1 data / theory

NLO H1 2006 Fit B, KKMR suppressed $\times (1+\delta_{hadr})$

data correlated uncertainty

NLO H1 2006 Fit B, resolved $\times 0.34 \times (1+\delta_{hadr})$

Leading Baryons

$e\pi \rightarrow e'X$

$p \rightarrow \pi^+ n$
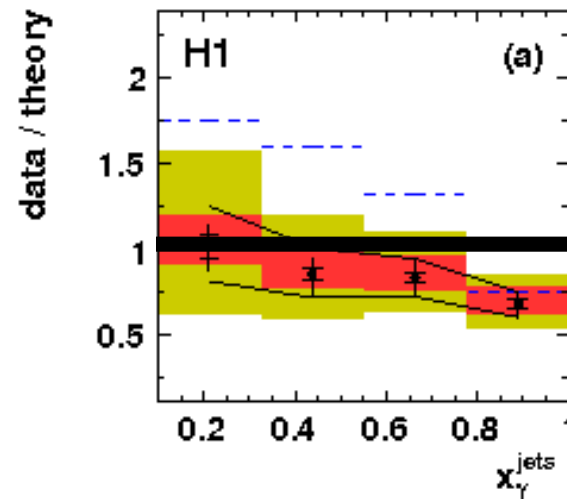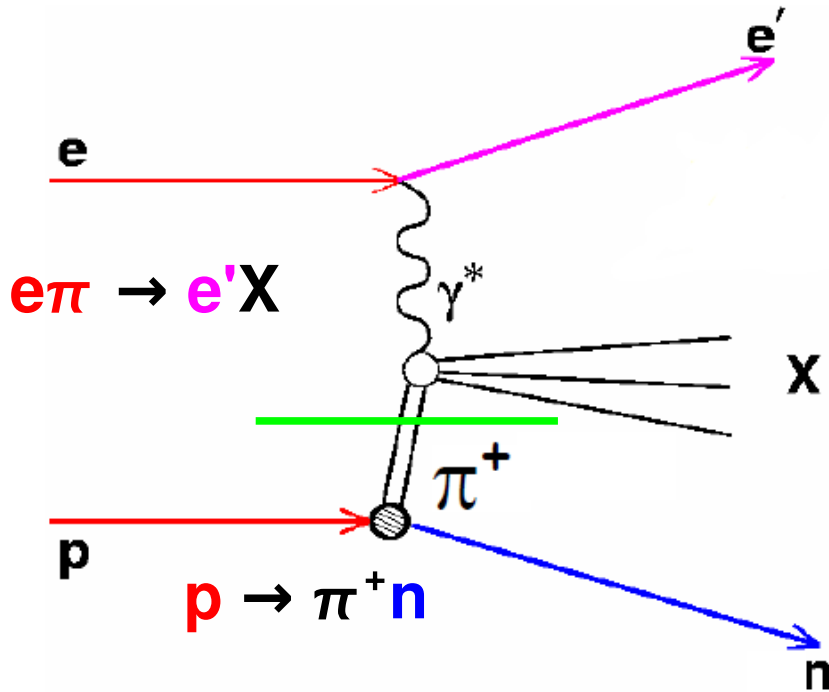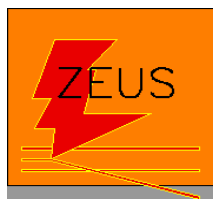
Pion structure function measurement

Tests of fragmentation models

$$x_L = E_n / E_p$$

In presence of a hard scale tests factorisation:

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

Pion flux factor – probability to find π in proton

Calculable cross section for $e\pi$ scattering

Model dependent, pion exchange as implemented in RapGap assumed

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Leading Baryons
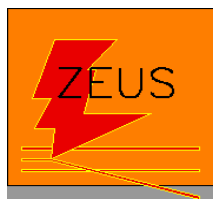
ZEUS
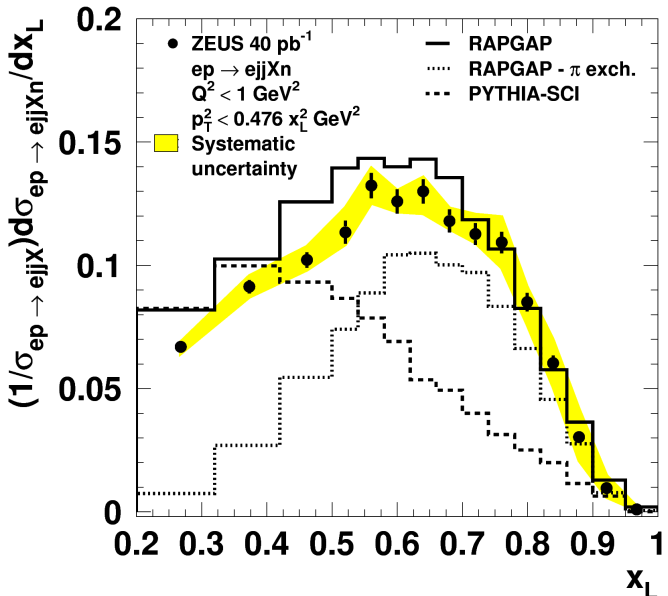
$$\frac{d^3\sigma(ep \to enX)}{dQ^2\, d\beta\, dx_L} = \frac{4\pi\alpha^2}{x\,Q^4}\left[1 - y + \frac{y^2}{2}\right] F_2^{LN(3)}(Q^2, \beta, x_L)$$

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

$F_2^{LN(3)}(x_L = 0.73)/\Gamma_\pi$, $\Gamma_\pi = 0.13$

H1

- Pion flux parametrization by Holtman et. al
- Integrated over t
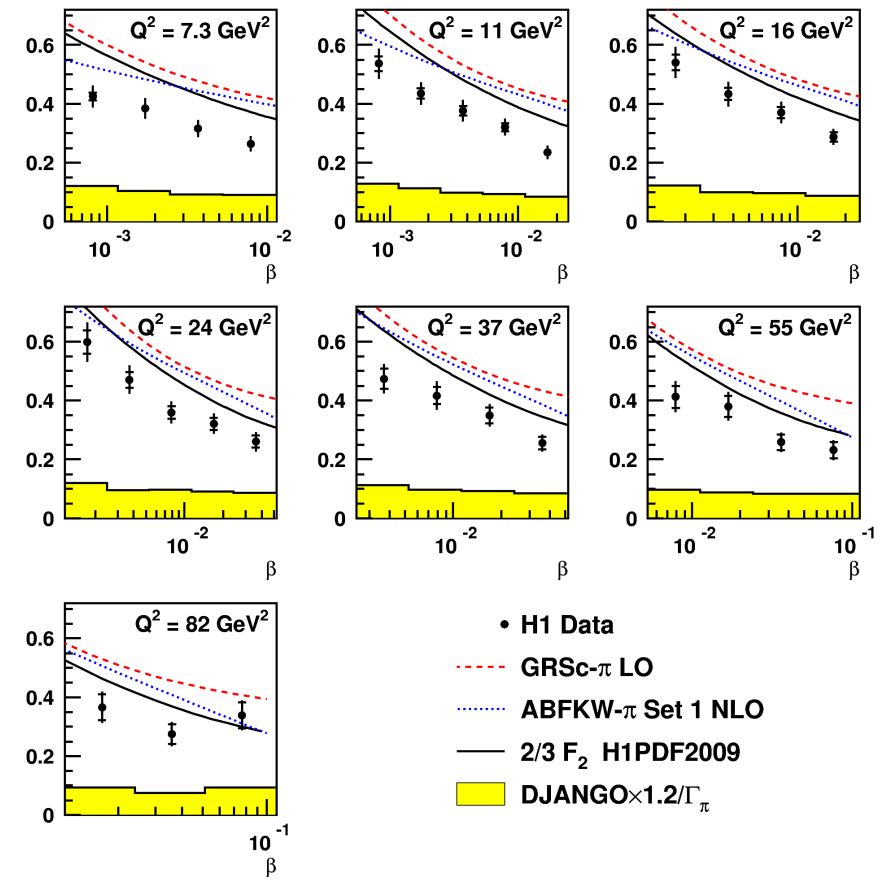
RapGap gives best description

Shape reasonably well described even by naive prediciton $F_\pi = 2/3\, F_2$

Consistent with proton vertex factorisation

Exlusive VM Production
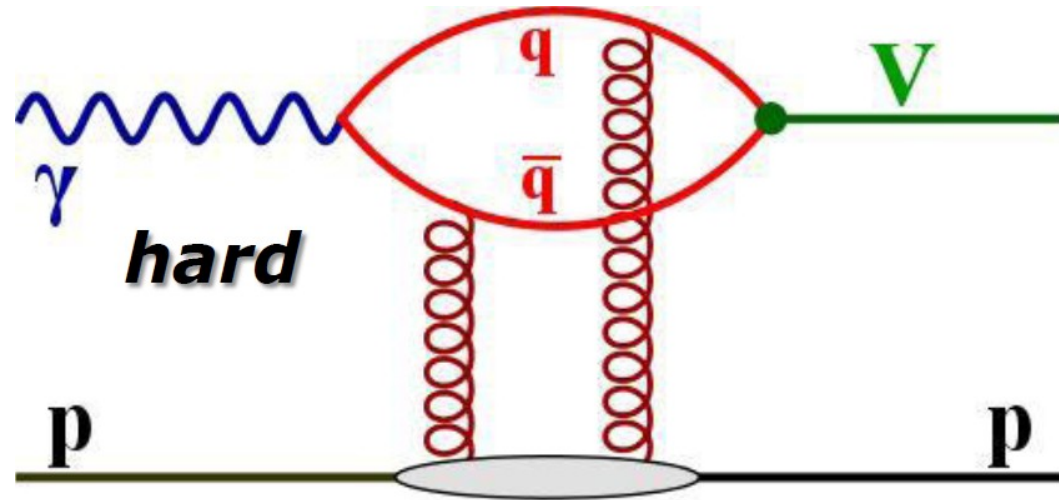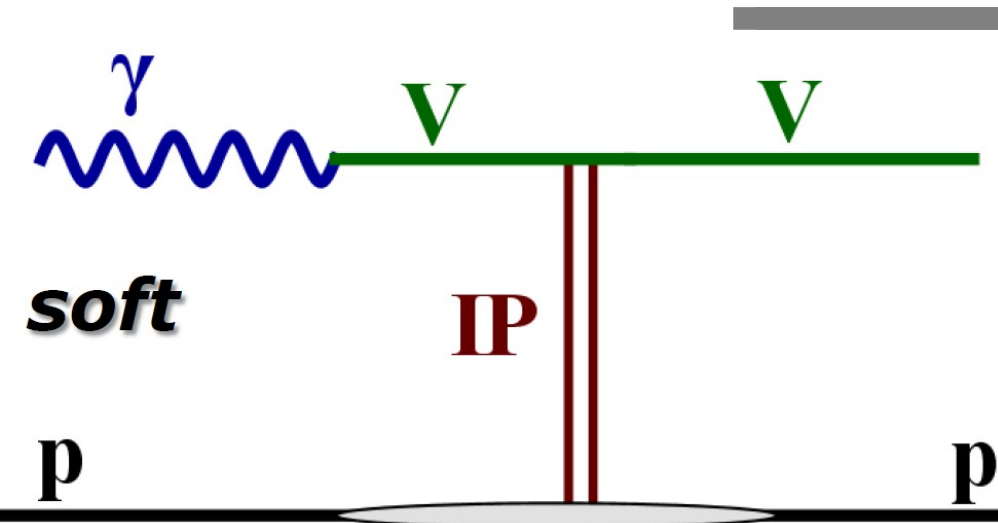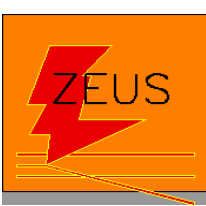
- Regge theory and Vector Dominance Model
- $\sigma \sim W^{\delta}$, $\delta_{soft} \sim 0.2$

$$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$$

- b ~ 10 GeV^{-2}

- Perturbative QCD
- Possible to calculate in presence of a scale: t, Q^2 or M_{VM}

- $\sigma \sim |x\,g(x,Q^2)|^2 \sim W^{\delta}$, $\delta_{hard} \sim 1$

$$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$$

- b ~ 4-5 GeV^{-2}

Exclusive VM – W-dependence
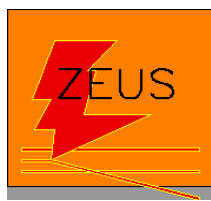
ZEUS

Data consistent with different QCD models
Measurements sensitive to different MC models

Dependence (δ) gets steeper with increasing VM mass

New Zeus Υ (DESY-09-036) measurement extends the phase space by factor of 2.5 in scale

Exlusive VM – *t* dependence
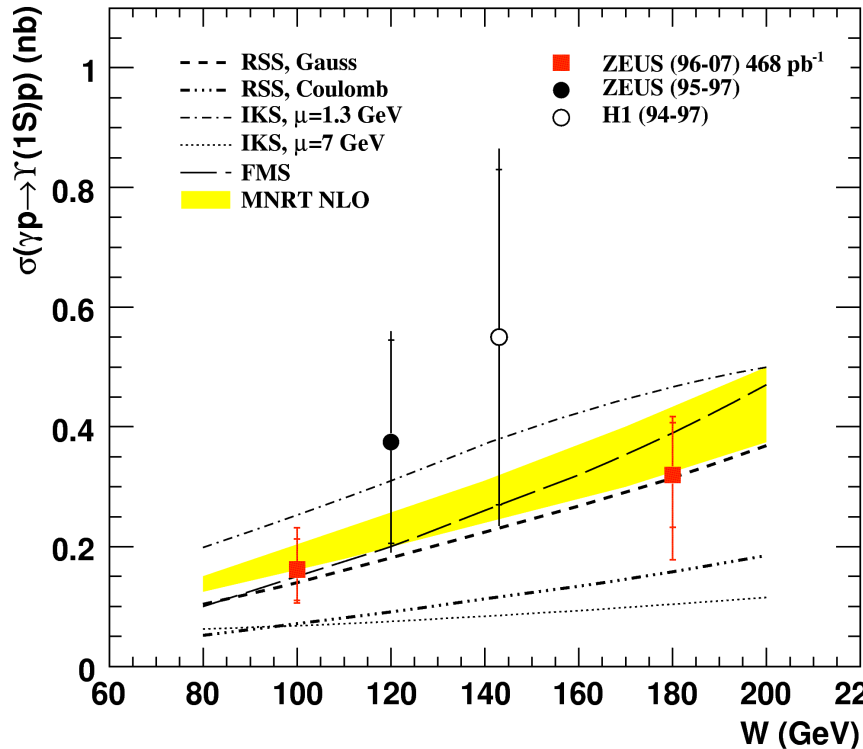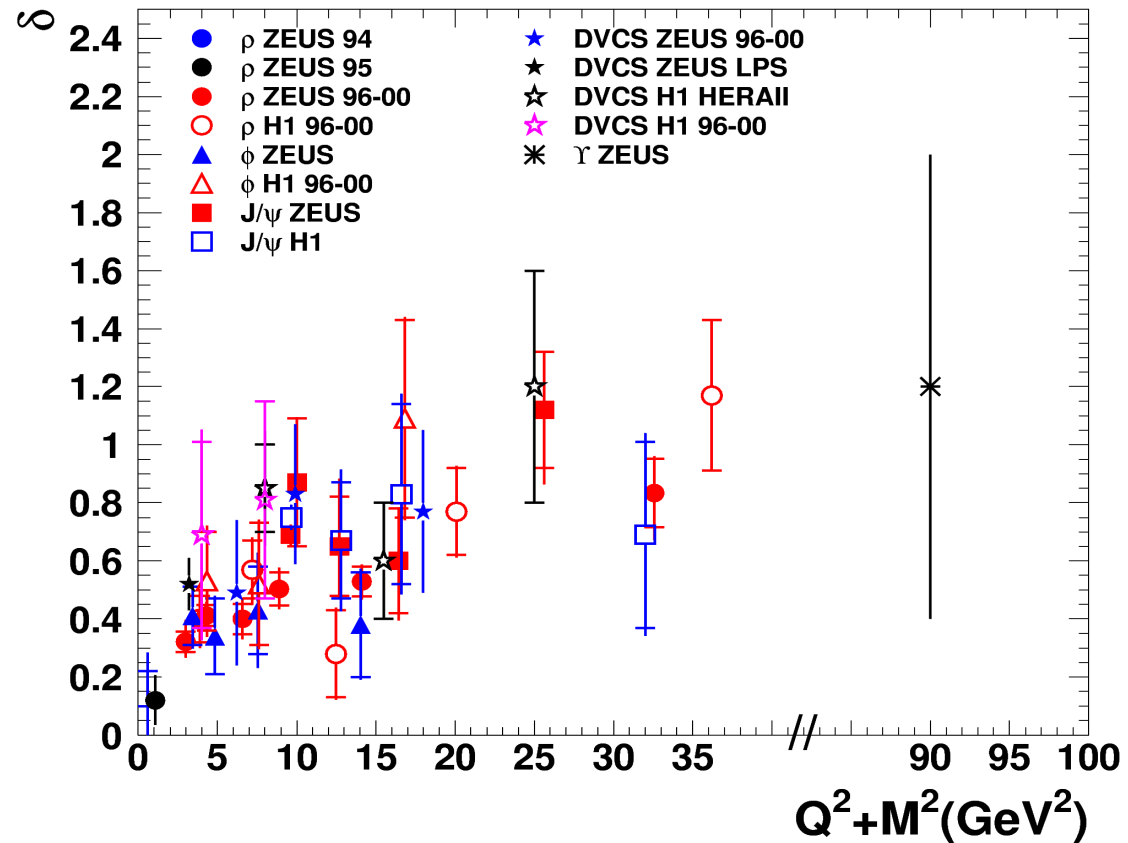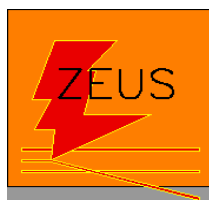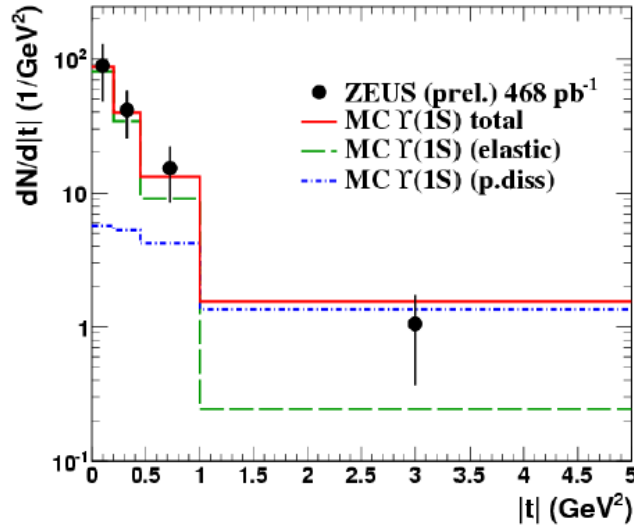
$$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$$

With increasing scale *b*-slope decreases, smooth transition from soft (ρ) to hard (Υ) meson physics

ZEUS

- ● ZEUS (prel.) 468 pb^{-1}
- — MC Υ(1S) total
- –·– MC Υ(1S) (elastic)
- ··– MC Υ(1S) (p.diss)

$$b_\Upsilon = 4.3^{+1.7}_{-1.1} \pm 0.5 \, [GeV^{-2}]$$

pQCD prediction in agreement with measurement within errors

Legend:
- ● ρ ZEUS 96-00 (120 pb^{-1})
- ● ρ ZEUS 94
- ● ρ ZEUS 95
- ○ ρ H1 96-00
- ▲ ϕ ZEUS 94
- ▲ ϕ ZEUS 98-00
- △ ϕ H1 96-00
- ■ J/ψ ZEUS 98-00
- ■ J/ψ ZEUS 96-97
- □ J/ψ H1 96-00
- ✳ Υ ZEUS (prel.)
- ☆ DVCS H1 96-00
- ☆ DVCS H1
- ★ DVCS ZEUS LPS (31 pb^{-1})
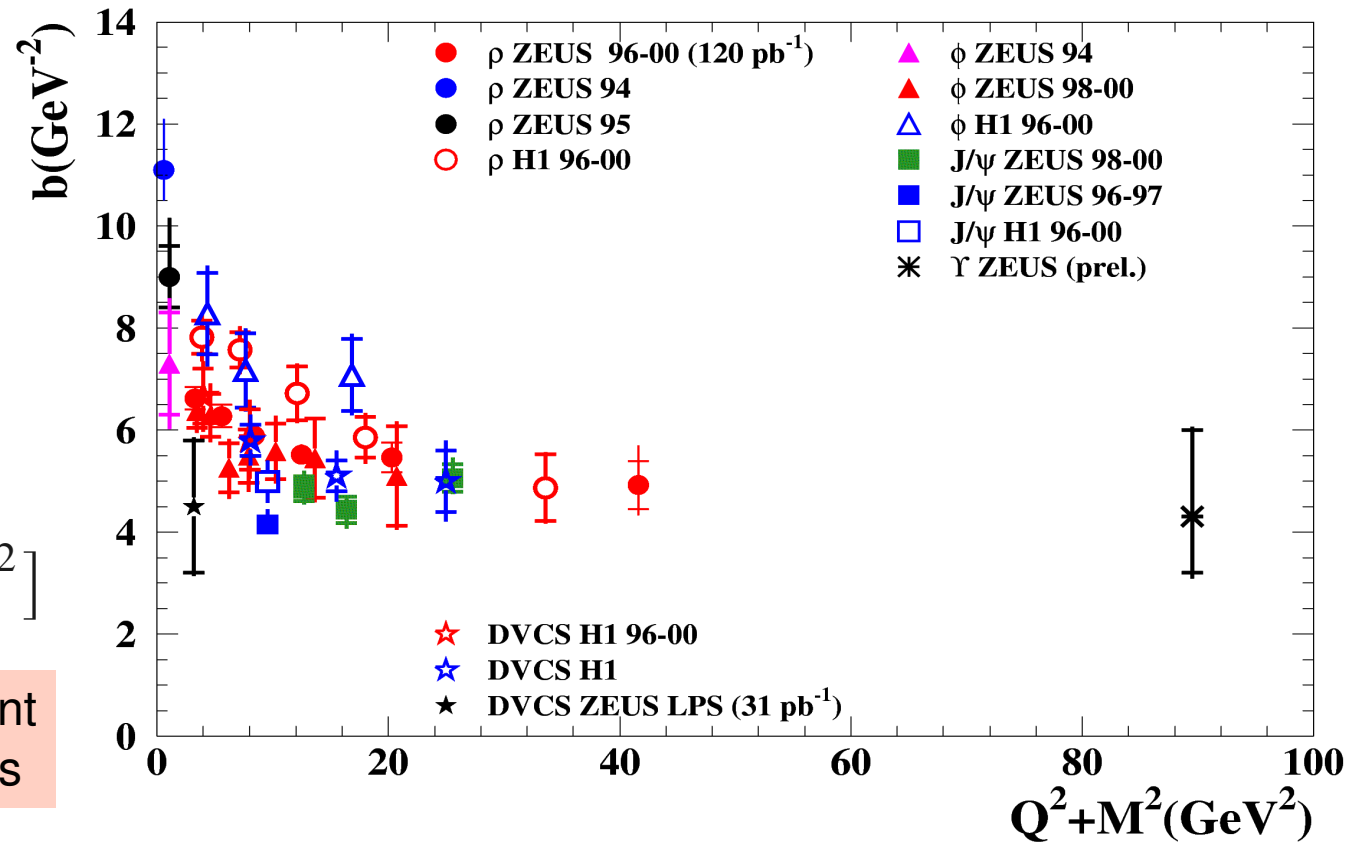
- • Recent DVCS (H1, DESY-09-109), ρ and ϕ (H1, DESY-09-093) results improve precision
- • *b*-slope decreases with scale as expected by smooth transition from soft to hard physics

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summary
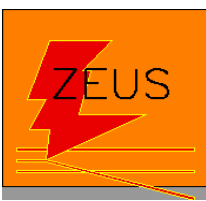
- New results from HERA-2 period have arrived and improved the measurements of diffractive structure functions

- Proton vertex factorisation with soft pomeron intercept of $\alpha_{I\!P} \sim 1.10$ and B-slope of ~ 6 GeV is a suitable model for diffraction

- DPDFs tested in extended phase space wrt previous measurements

- Progress in understanding of gap survival probability in photoproduction

- New unique measurements:
    - F_L^D – independent test of QCD factorisation and gluon density
    - Jets with leading proton – no physics beyond DGLAP observed

- Extension of phase space in exclusive VM measurement fits well in the picture of interplay between soft and hard physics