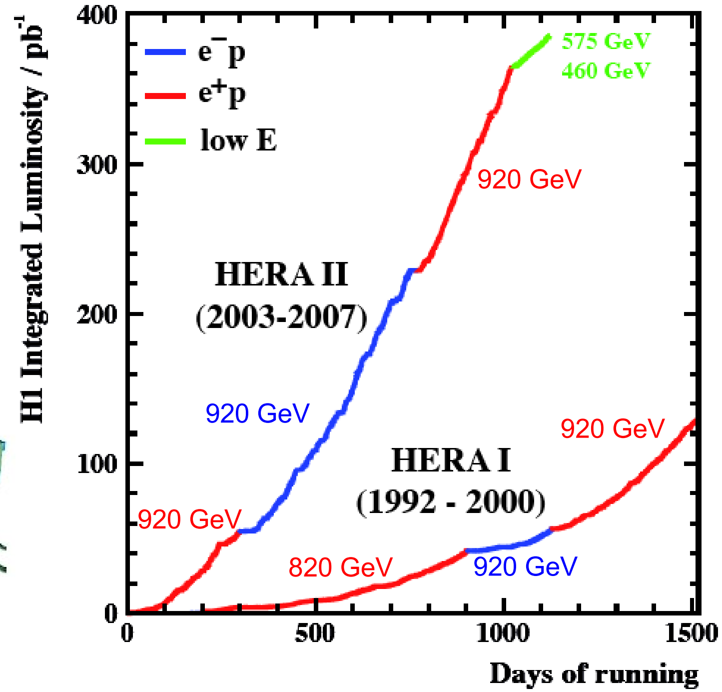
Xavier Janssen
On behalf of H1 and ZEUS Collaborations

Universiteit Antwerpen

Diffractive Physics at HERA



HERA collided 27.5 GeV electrons or positrons with protons of 460, 575, 820 and 920 GeV providing 0.5 fb^{-1} to H1 and Zeus between 1992-2007

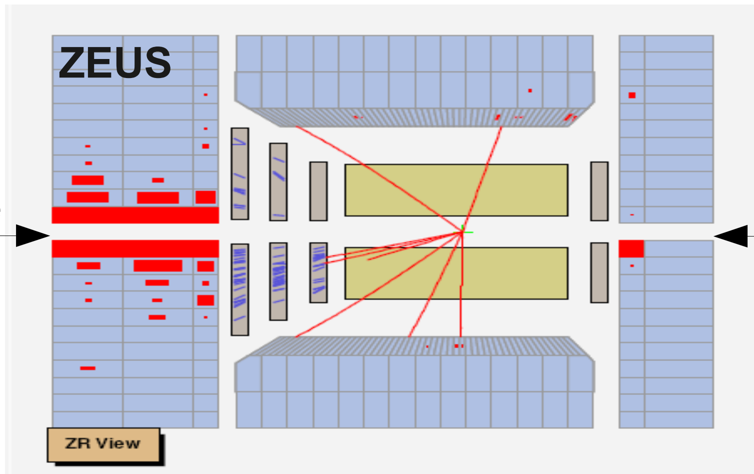
→ Final precision data analyses are being delivered

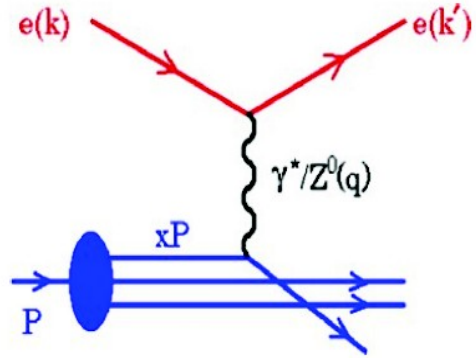
Hadron Collider Physics Symposium
Toronto, Canada, August 23-27, 2010

Deep-Inelastic Scattering and Diffraction

Inclusive DIS

$$\sigma_r(x,Q^2)=F_2-\frac{y^2}{Y^+}F_L$$



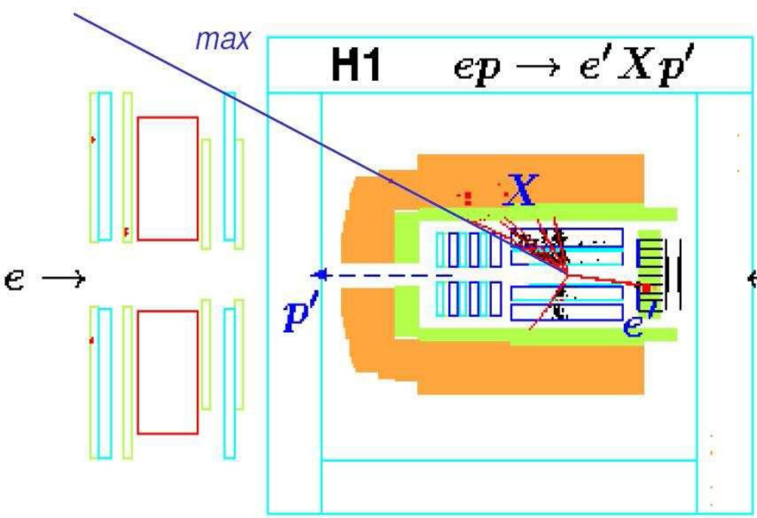


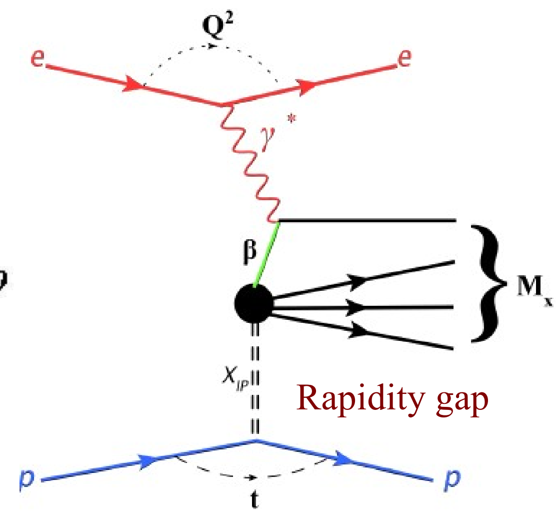
Q^2 Photon vituality
x Bjorken-x
W Photon-proton cms energy
$W = Q2\ (1/x-1)$

Photon probes internal proton structure:
- → Proton parton densities (see M. Wing)
- → Inclusive Jets, charm and beauty
- → Hadronic final states, fragmentation …
- → Electroweak: $e^\pm$ polarisation at HERA-II
- → BSM searches / limits

Diffractive DIS

$$\sigma_r^{D(4)}(\beta,Q^2,x_{IP},t)=F_2^{D(4)}-\frac{y^2}{Y^+}F_L^{D(4)}$$



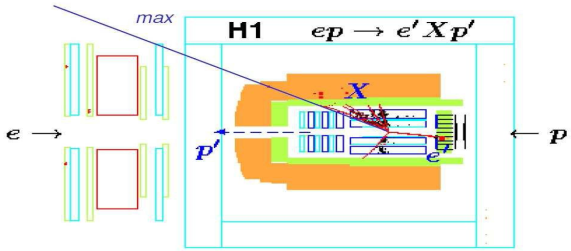


x_{IP} Momemtum fraction of colour singlet exchange
β Fraction of exchange momemtum of struck q
t 4-momemtum transfer at proton vertex squared
$x = x_{IP}\ \beta$

In 10% of events, proton stays intact and loses small momentum fraction
- ↔ Large rapidity gap / color singlet exchange (Pomeron at low x)
- → Diffractive PDF's → pQCD/PDF
- → Jets, Vector Mesons, DVCS ...

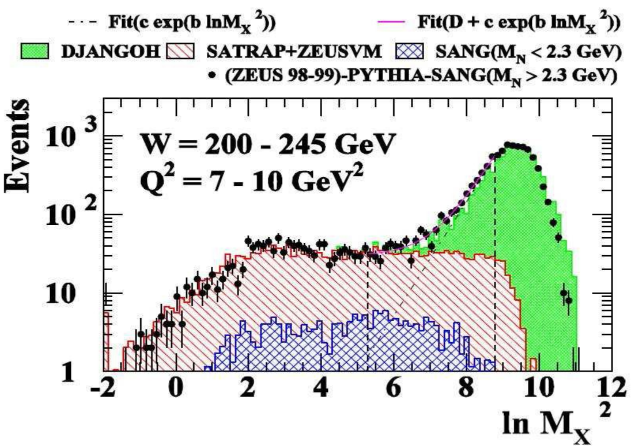
Diffraction: Selection methods

Large Rapidity Gap (LRG) Method:



- Request LRG in main detector (3.3<η<7.5)
- Meassure kinematic from $e^{\pm}$ and X system
  → No access to ***t***
- Some proton dissociation contamination
  → Corrected up to $M_Y < 1.6$ GeV

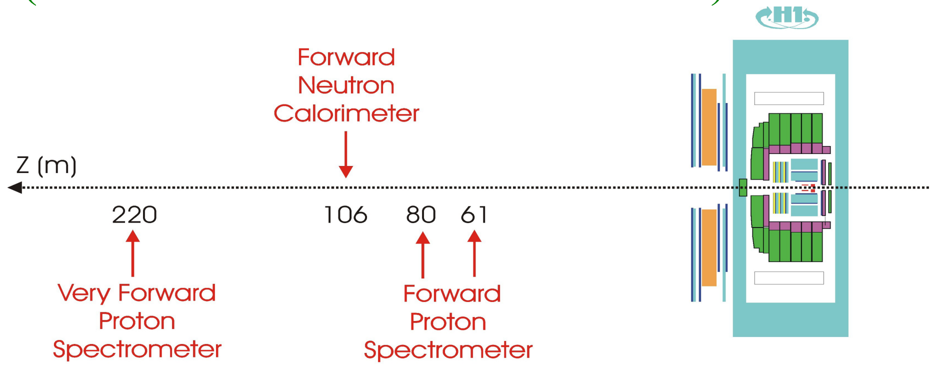
M_X Method:



- Flat (vs) ln M_X^2 for diffractive events
- Non diffractive events substracted from fits
  → Small proton dissociation contamination
  → No access to ***t***

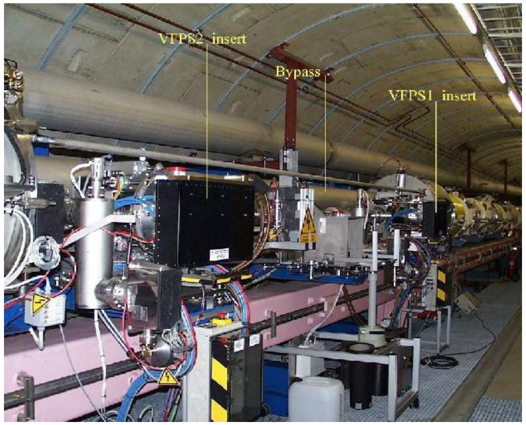
Tagged Leading Baryons Method:

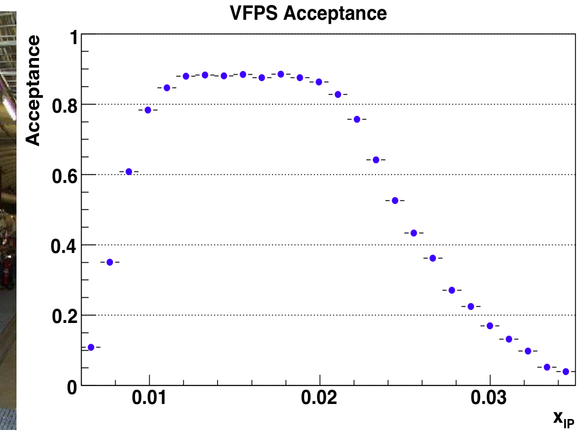
H1 (FPS) and ZEUS (LPS) have Proton Spectrometers (and Forward Neutron Calorimeters)



- Free of proton dissociation background
- Proton 4-momentum measurement → ***t***, x_{IP}
- Lower statistic (acceptance)

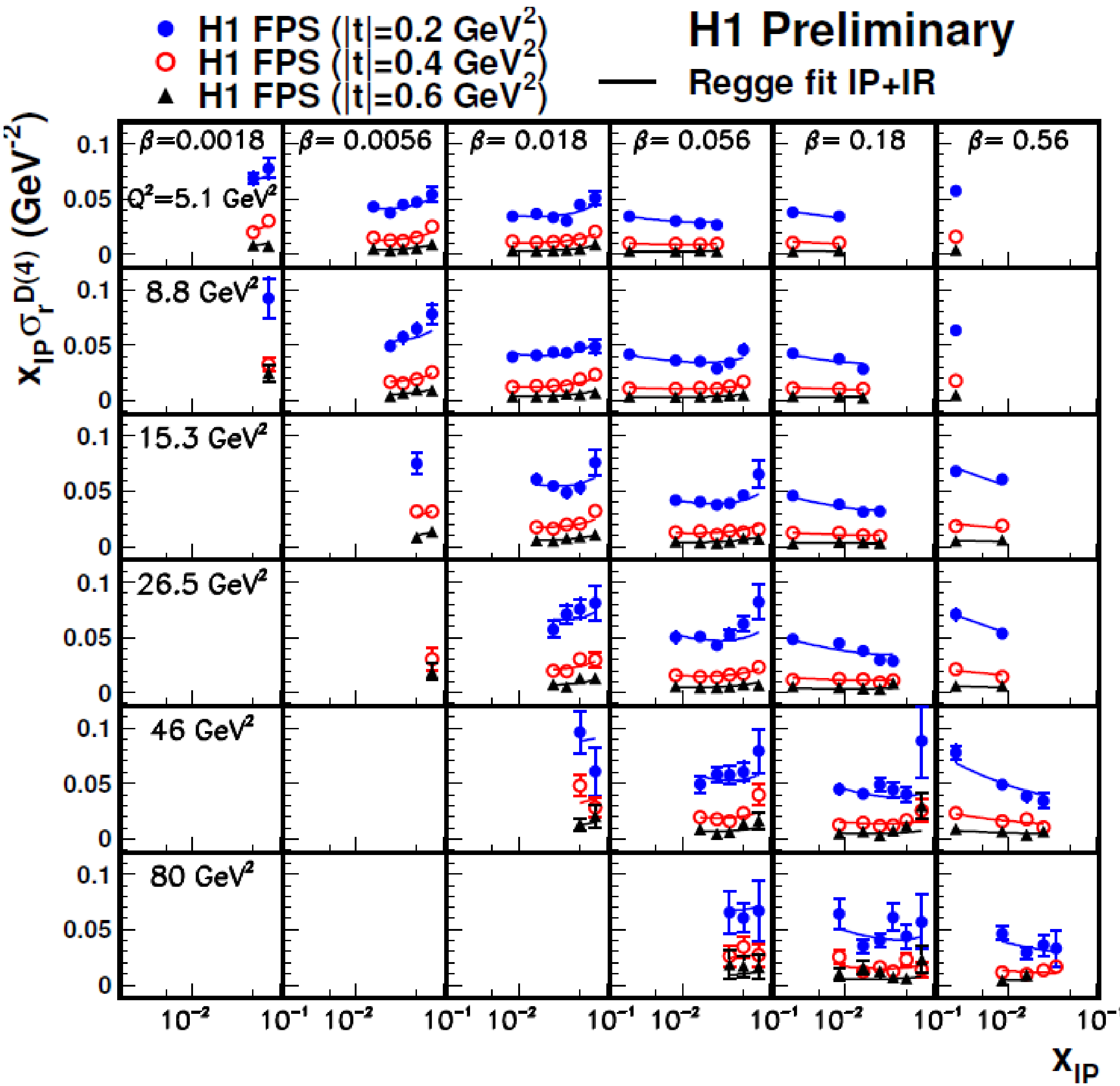
→ H1 VFPS @ HERA-II: Larger acceptance in x_{IP} & t



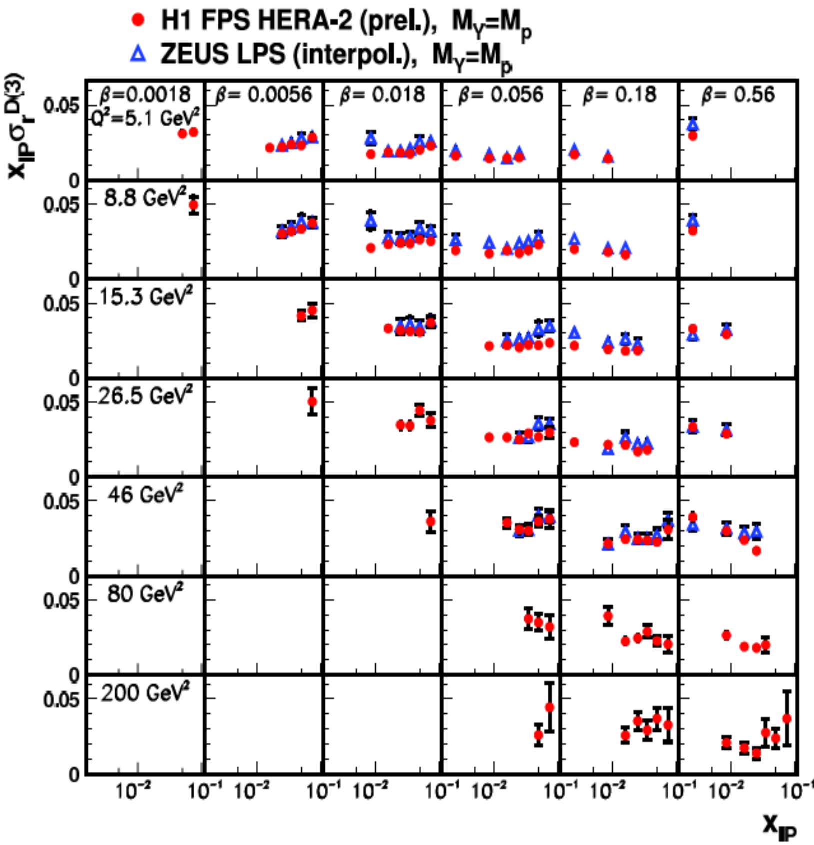


Leading Proton Results : $\sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)$

New H1 FPS results @ HERA-II (157 pb^{-1})



H1 vs ZEUS: Integrated over t

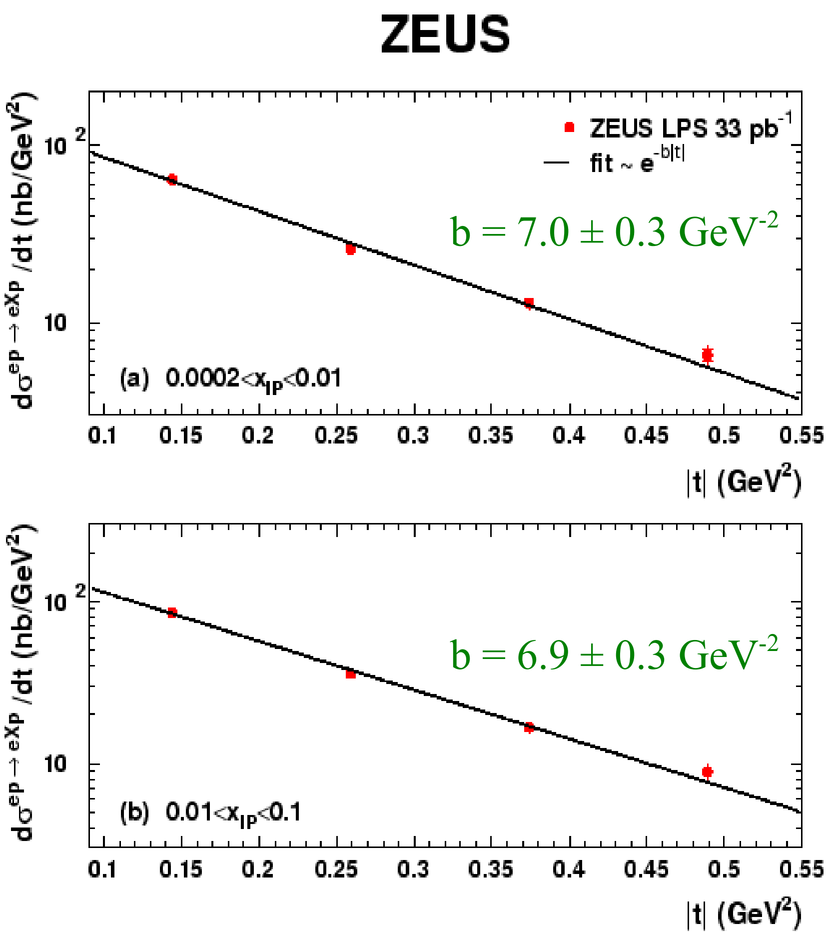


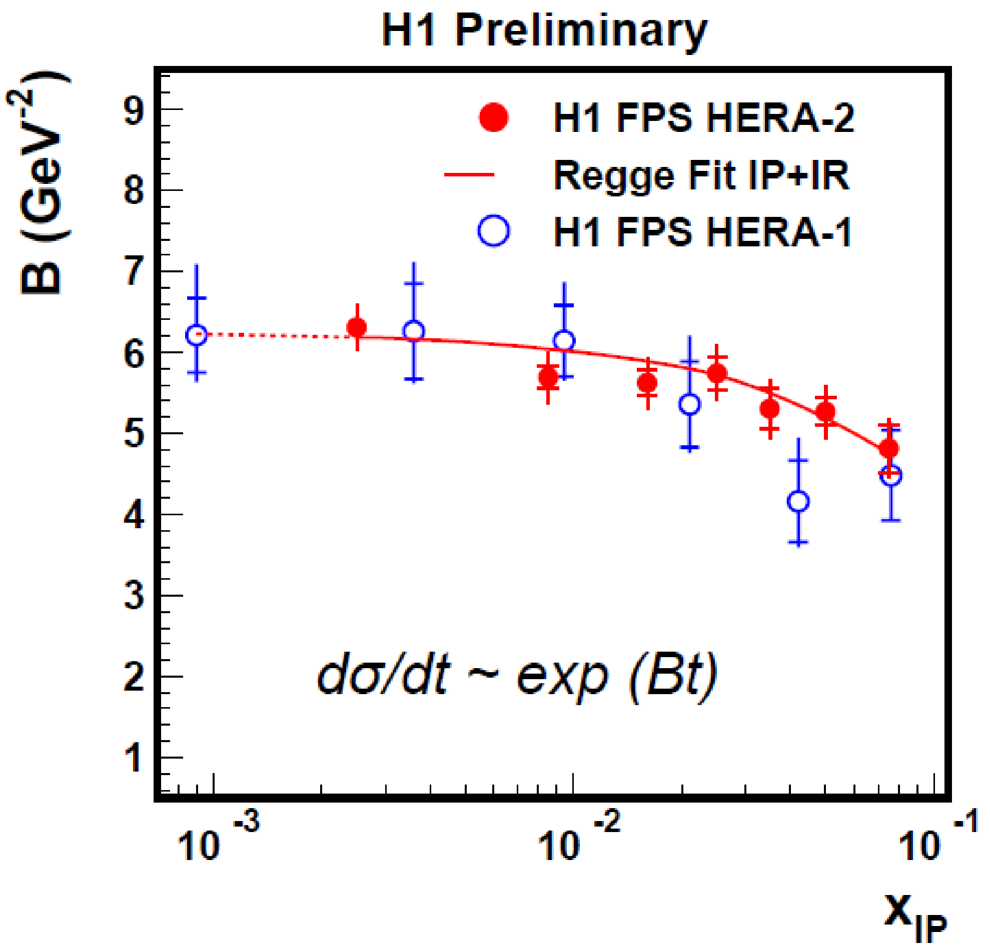
Good H1-ZEUS agreement on kinematic dependence

15% difference in overall normalization contained within both data uncertainties

Final datasets for both collaborations !

Leading Proton Results : $d\sigma_r^D / dt \sim \exp(-bt)$





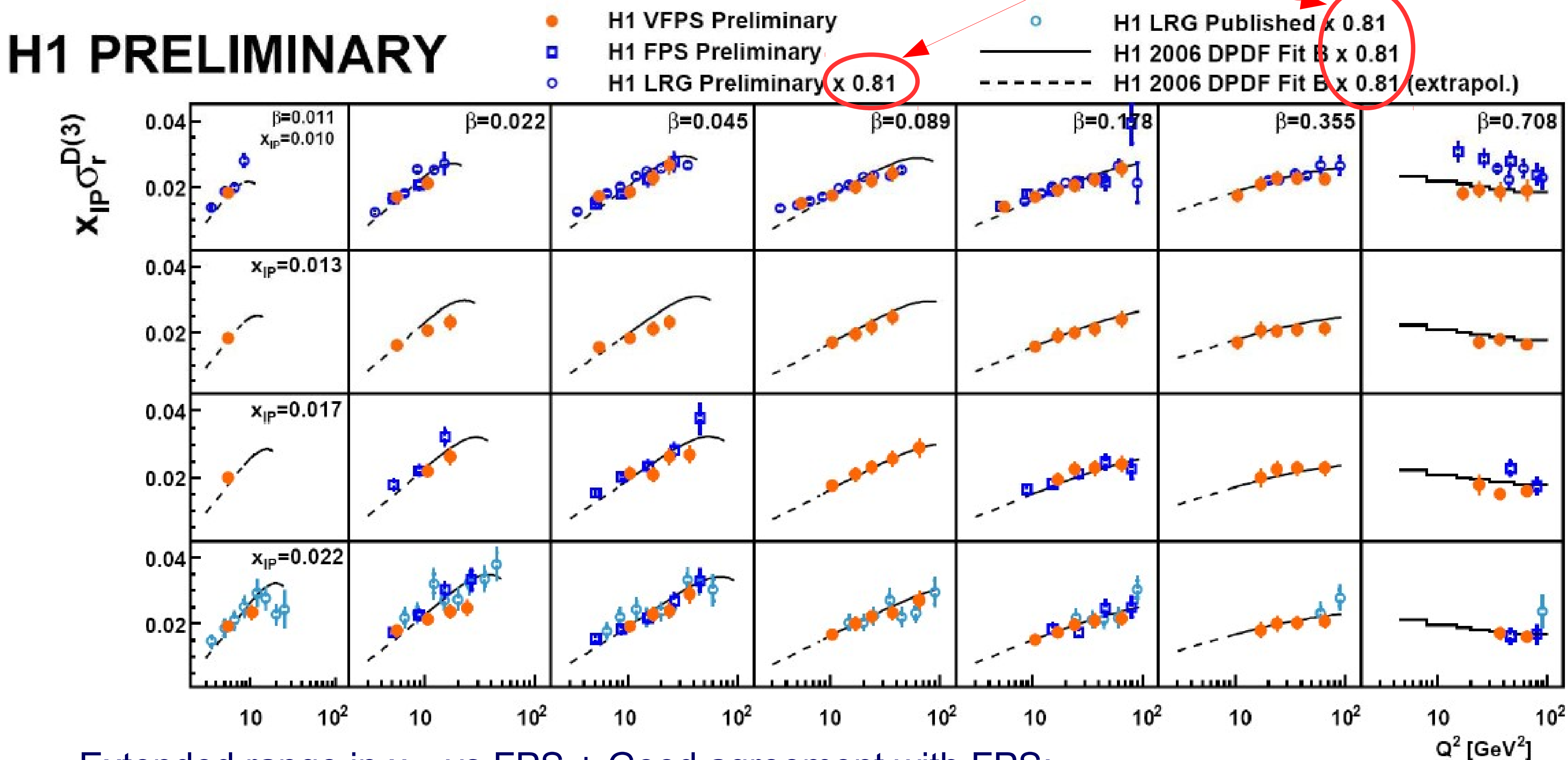
→ H1 and ZEUS results compatible (but ZEUS slightly higher than H1)

→ b-slopes ~ 6-7 GeV^2 for small x_{IP} (Pomeron exchange region)

→ At high x_{IP}, Reggeon exchange contribution leads to smaller b-slopes

First H1 VFPS Results : $\sigma_r^{D(3)}$

Correction for proton dissoc. contamination below $M_Y < 1.6$ GeV estimated from FPS/LRG ratio



→ Extended range in x_{IP} vs FPS + Good agreement with FPS:

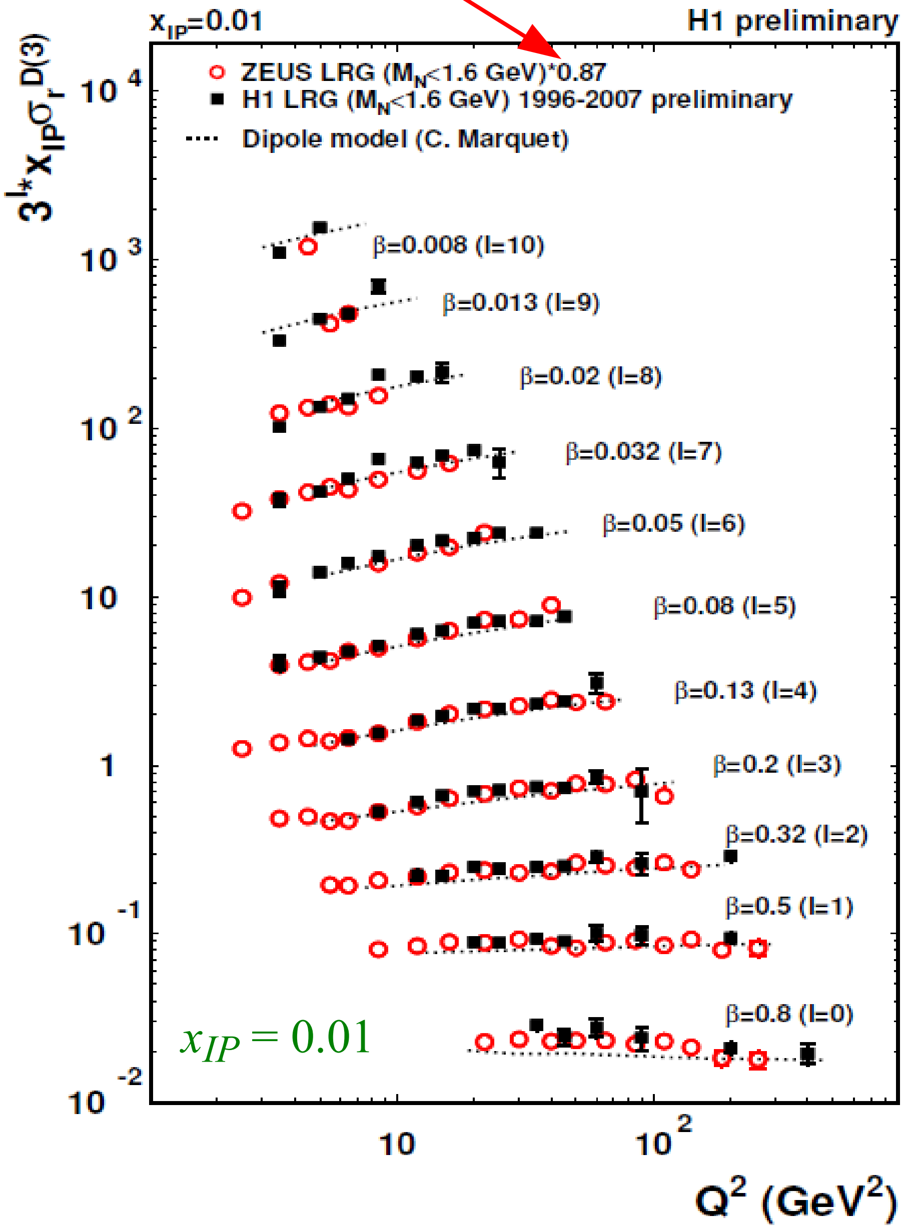
ratio VFPS / FPS = 0.96 +/- 0.02 (stat) +/- 0.11 (syst) +/- 0.08 (norm)

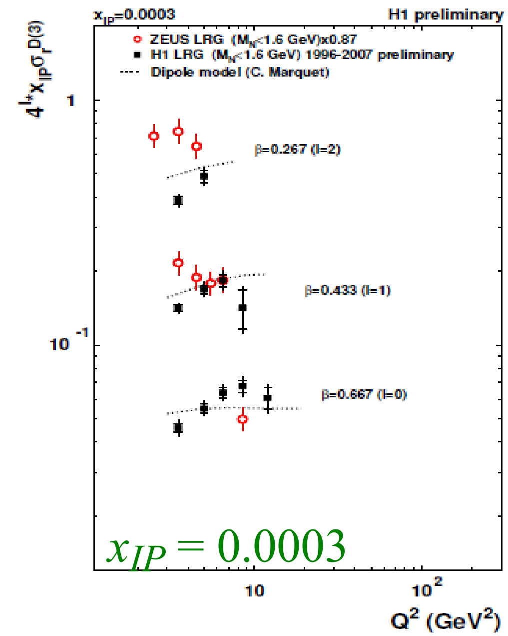
→ Agreement with H1 LRG data (and DPDF QCD fit) in most bins.

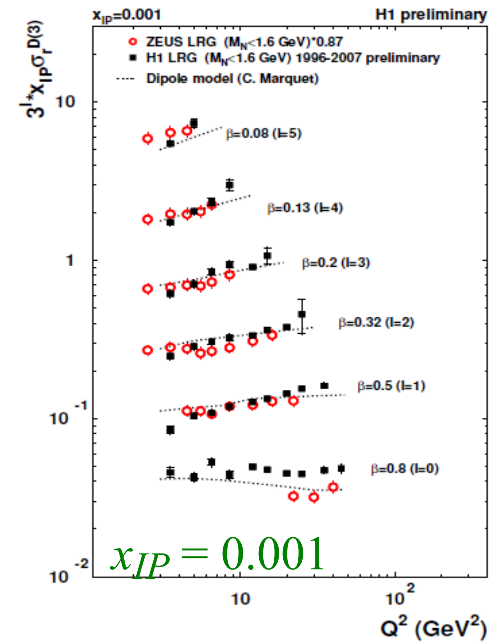
→ Positive scaling violations in most β bins. ↔ Diffractive DIS dominated by gluon exchange !

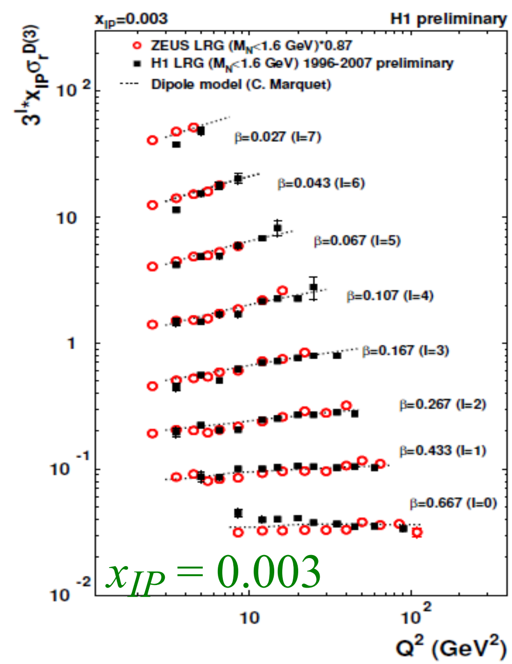
LRG Results from ZEUS and H1: $\sigma_r^{D(3)}$

ZEUS * 0.87 : on top of 0.91 factor to go from M_Y<2.3 (ZEUS) to M_Y <1.6 (H1) GeV









New H1 data (370 pb^{-1})

Positive scaling violation in most β bins (gluons)

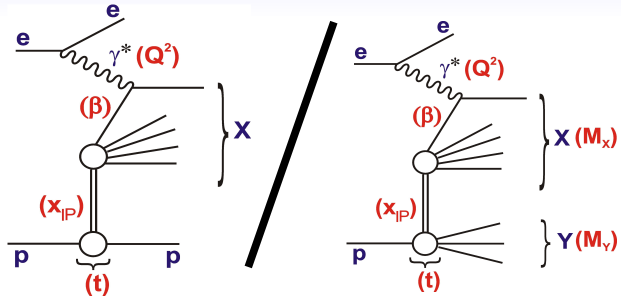
Precision of a few % over wide kinematic range

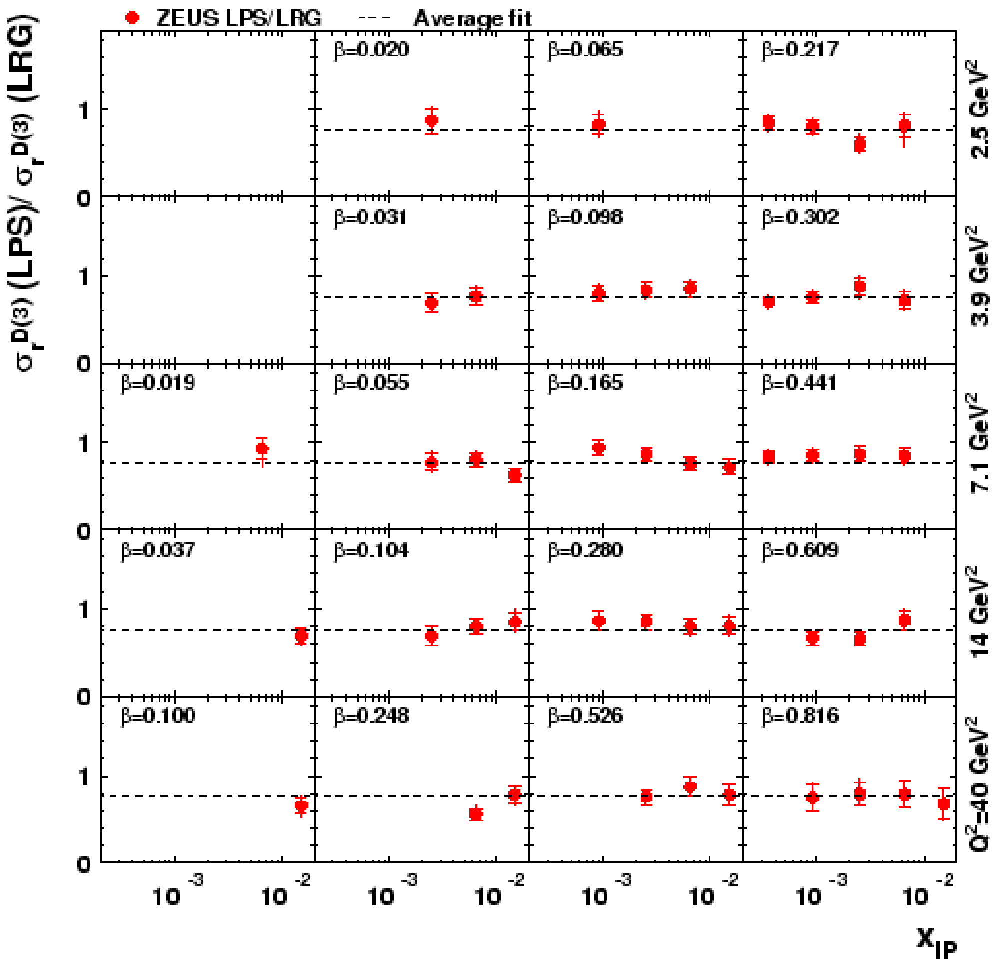
~13% difference between H1 and ZEUS, i.e. within normalization errors:

- Relative norm Err. ~ 7%
- ZEUS Proton diss. Err. ~ 8%

Comparisons between Methods

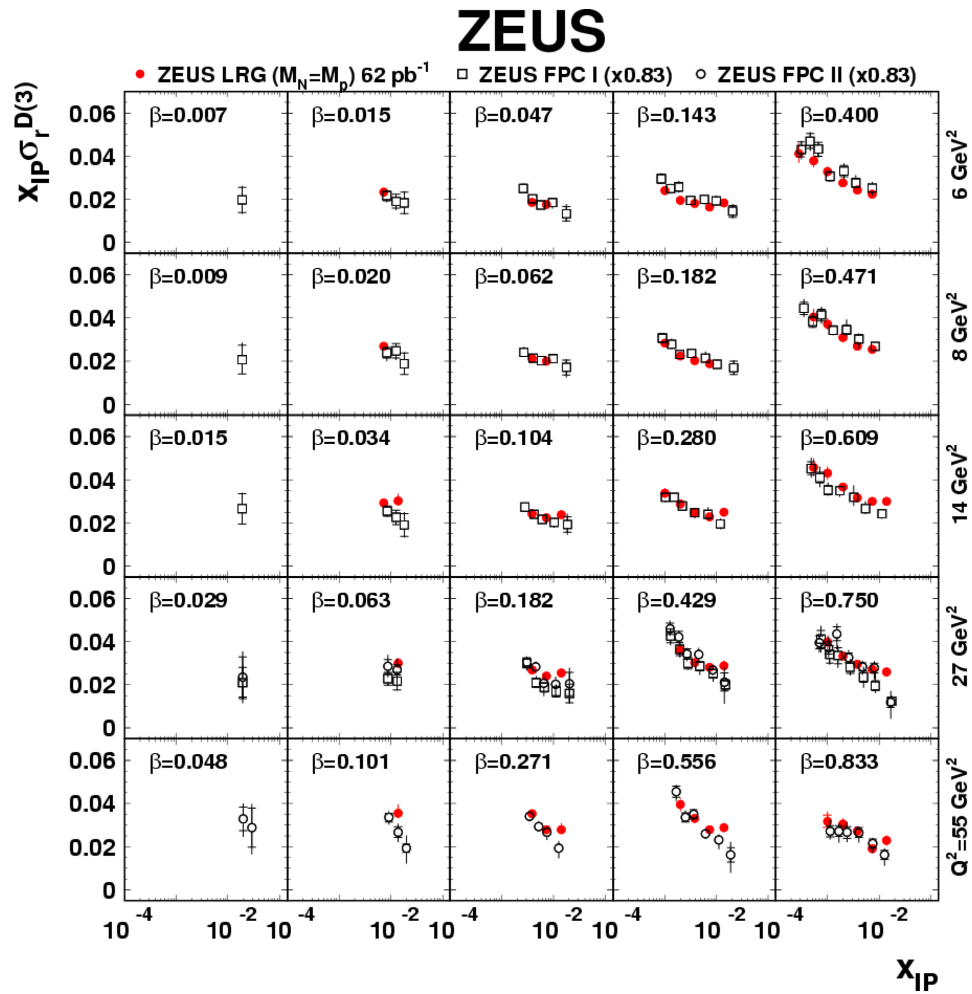
LPS / LRG =





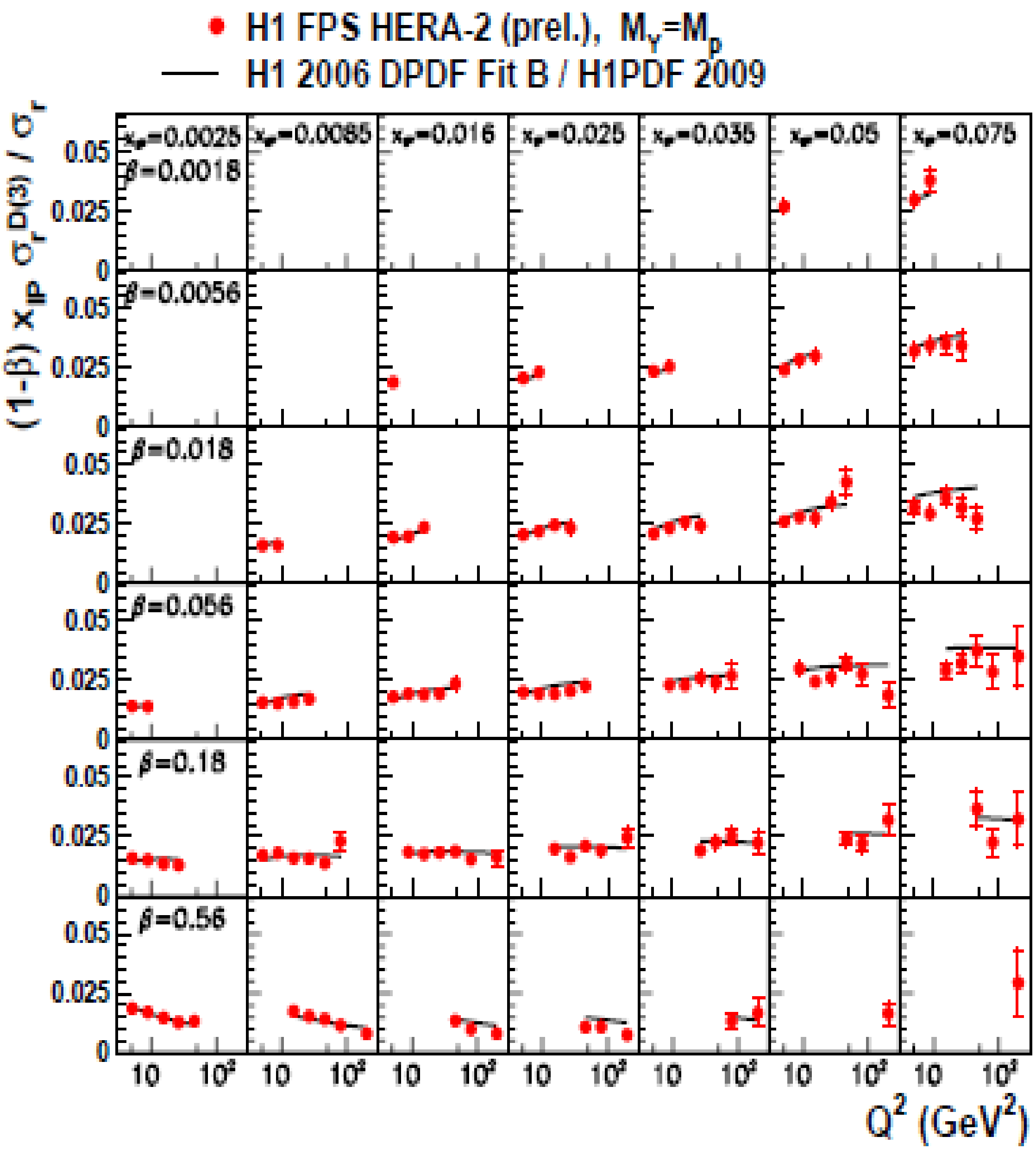
→ ~ 20% proton dissociation contamination in LRG data, independ of Q^2, β or x_{IP}

M_X (=FPC) Method (vs) LRG Method



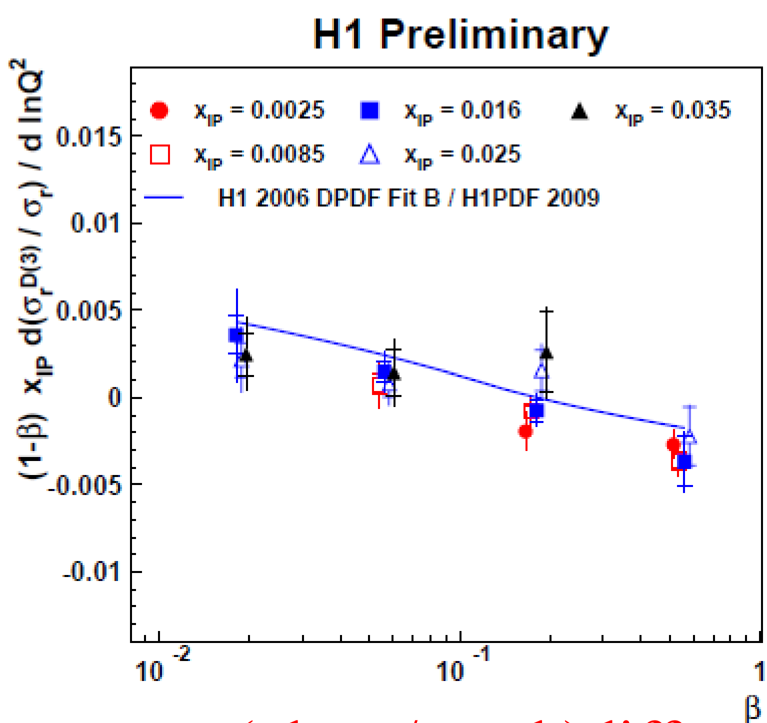
→ Results of M_X and LRG Methods in agreement (M_X scaled to correct for different proton dissoc. content)

Ratio $\sigma_r^{D(3)} / \sigma_r^{incl}$



Ratio is flat or weakly rises with Q^2 except at highest β

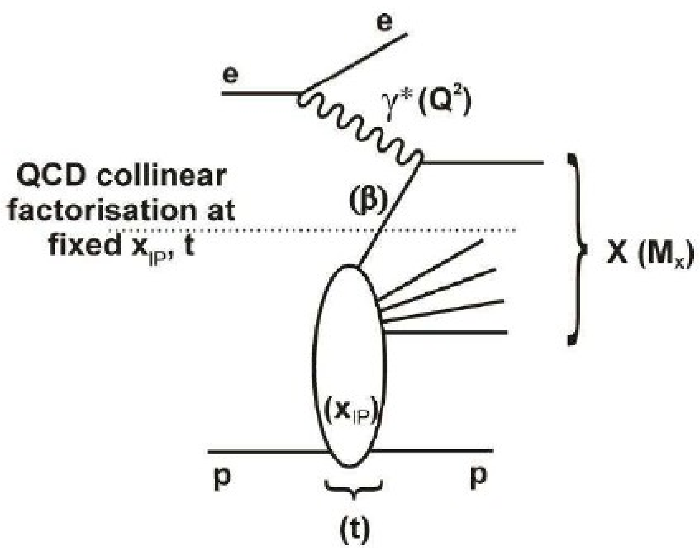
→ Extract log derivative:



→ (gluon/quark)diff ~ (gluon/quark)incl if measured at same (low) $x = x_{IP}\,\beta$

Factorization and DGLAP pQCD Fits

- QCD hard scattering collinear factorization theorem (Collins) at fixed x_{IP} and t



→ DGLAP applicable for Q2 evolution

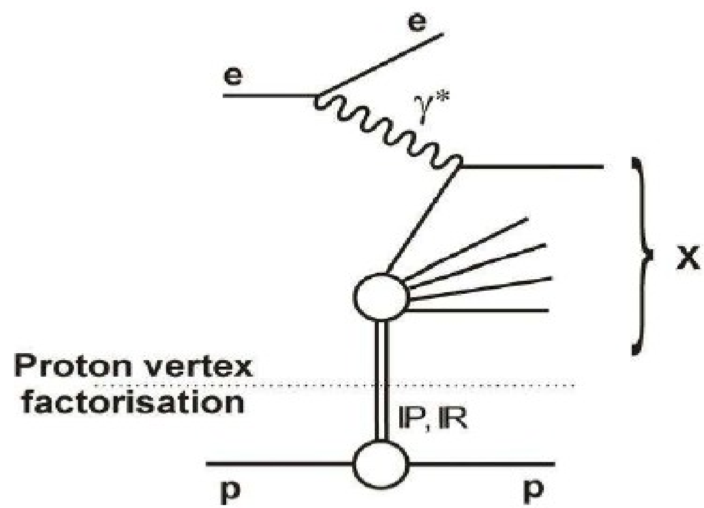
→ Can define diffractive parton densities:

$$d\sigma_i = f_i^D(\beta, Q^2, x_{IP}, t) \otimes d\hat{\sigma}^i(\beta, Q^2)$$

NB: Reggeon contribution at high x_{IP} parametrized according to π pdf's

- "Proton vertex" factorization of β, Q^2 from x_{IP} , t (and M_Y) dependences

No form basis in QCD !



→ Can define Pomeron parton densities:

$$f_i^D(\beta, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \times f_i^{IP}(\beta, Q^2)$$

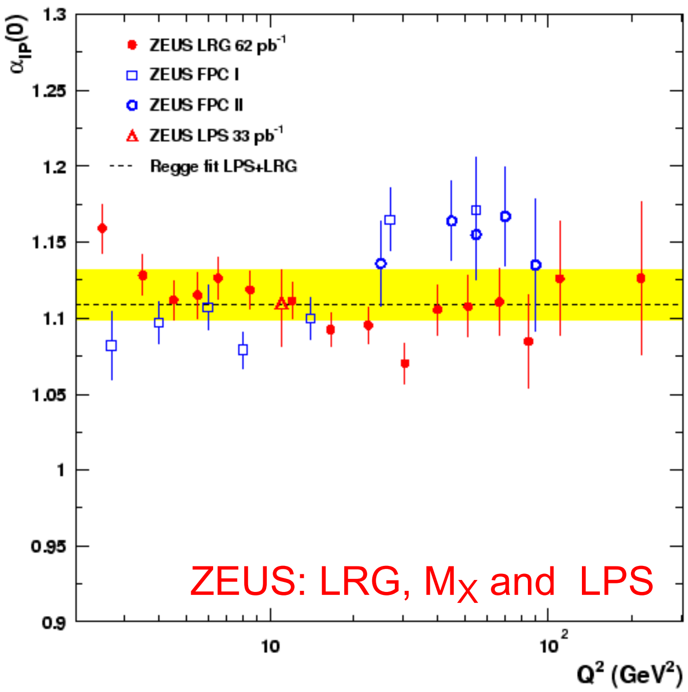
Pomeron flux $f_{IP/p}$ modelled by Regge theory:

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

Tests of Vertex Factorization

Assuming vertex factorization for IP:

$$F_2^{D(4)}(\beta,Q^2,x_{IP},t) = f_{IP}(x_{IP},t)\cdot F_2^{IP}(\beta,Q^2) + n_{IR}\cdot f_{IR}(x_{IP},t)\cdot F_2^{IR}(\beta,Q^2)$$



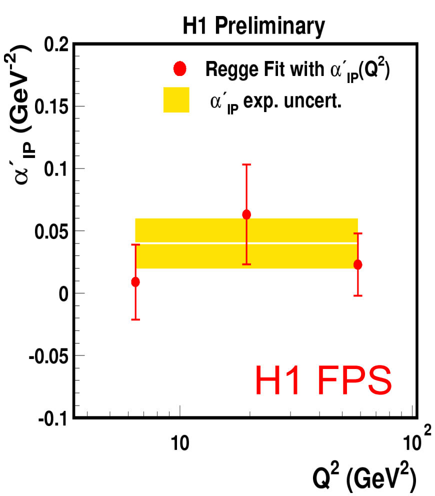
→ Perform Regge fit with as free parameters in every (β, Q2) bins:

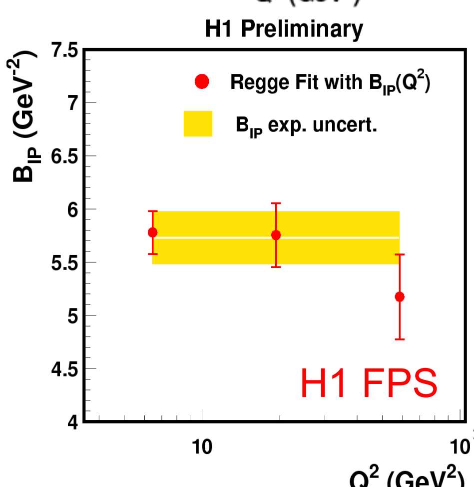
$\alpha_{IP}(0)$, α_{IP}' , b_{IP} , n_{IR} and $F_2^{IP}(\beta,Q^2)$

and fix $\alpha_{IR}(0)$, α_{IR}' , b_{IR} and $F_2^{IR}(\beta,Q^2)$

→ $\alpha_{IP}(0)$, α_{IP}' , b_{IP} independent of Q2

→ Supports vertex factorization





For H1 FPS fit:

$$\alpha_{IP}(0) = 1.10 \pm 0.02\,(\text{exp.}) \pm 0.03\,(\text{model})$$

$$\alpha'_{IP} = 0.04 \pm 0.02\,(\text{exp.}) \pm 0.03\,(\text{model})\ \text{GeV}^{-2}$$

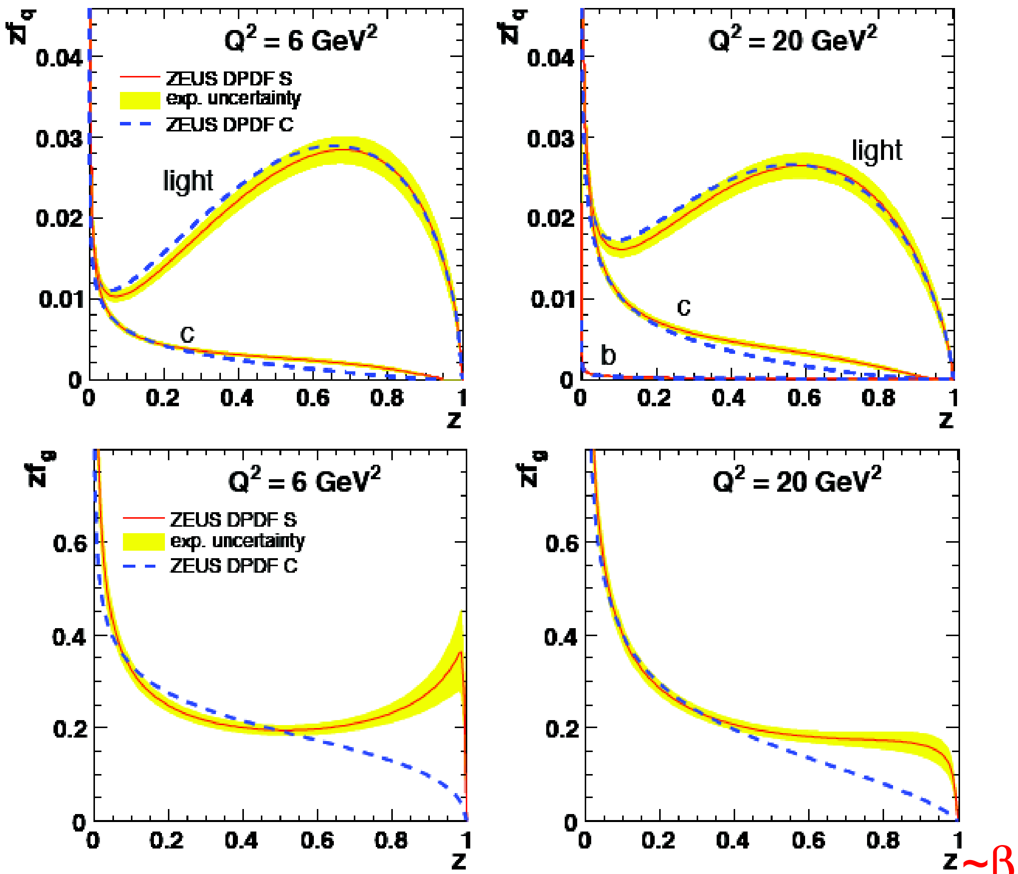
$$B_{IP} = 5.7 \pm 0.3\,(\text{exp.}) \pm 0.6\,(\text{model})\ \text{GeV}^{-2}$$

→ $\alpha_{IP}(0)$ consistent with soft IP (1.08)

→ α_{IP}' smaller than soft IP in hadron-hadron

Diffractive Parton Densities

Fit to ZEUS LRG+LPS: Only data $Q^2 > 5$ GeV^2



quarks: $z \sum (z, Q_0^2) = A_q z^{B_q} (1-z)^{C_q}$

gluons:

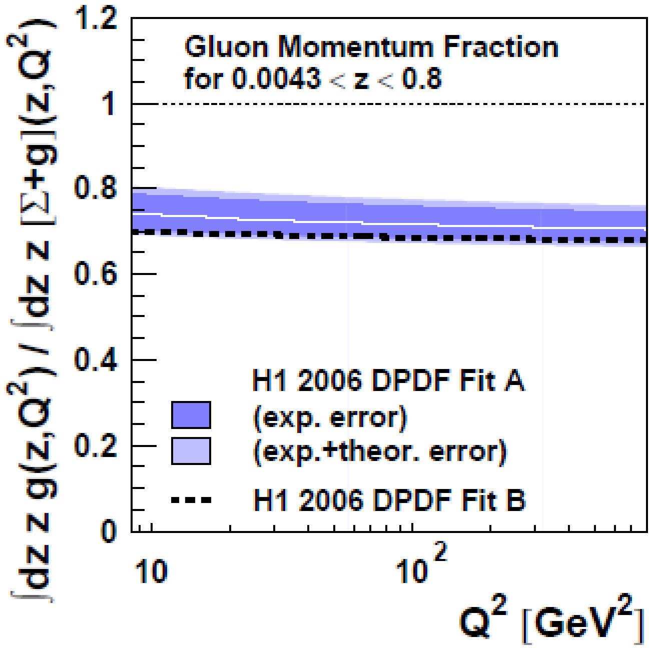
ZEUS S $zg(z, Q_0^2) = A_g z^{B_g} (1-z)^{C_g}$

ZEUS C $zg(z, Q_0^2) = A_g$

$\alpha_S(M_Z) = 0.118$ $Q_0^2 = 1.8\, GeV^2$ $\mu_F = \mu_r = Q$

Heavy quarks: general-mass VFNS scheme

$m_c = 1.35\, GeV,\ m_b = 4.3\, GeV$



→ quark PDFs well constrained

→ Large uncertainties for gluon PDF at large z

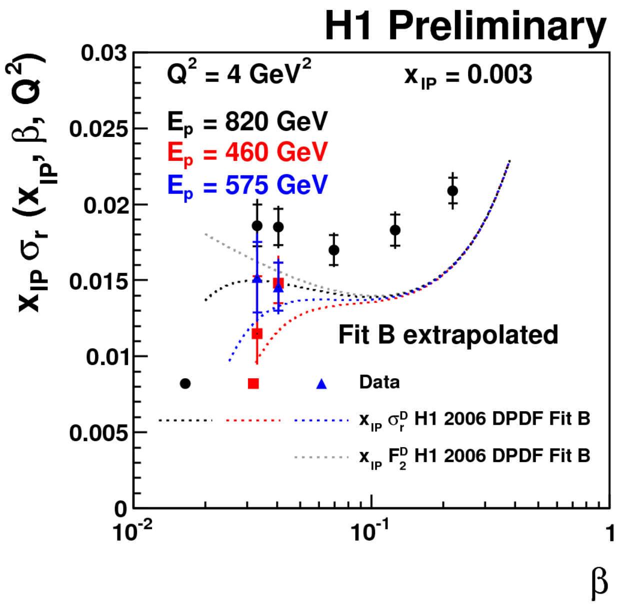
→ Not possible to do a fit to low Q^2 data !

→ quark:gluon ratio ~ 70%/30%

N.B.: Similar results from fits to H1 LRG data, see backup slides

First F_L^D Measurement

ZEUS



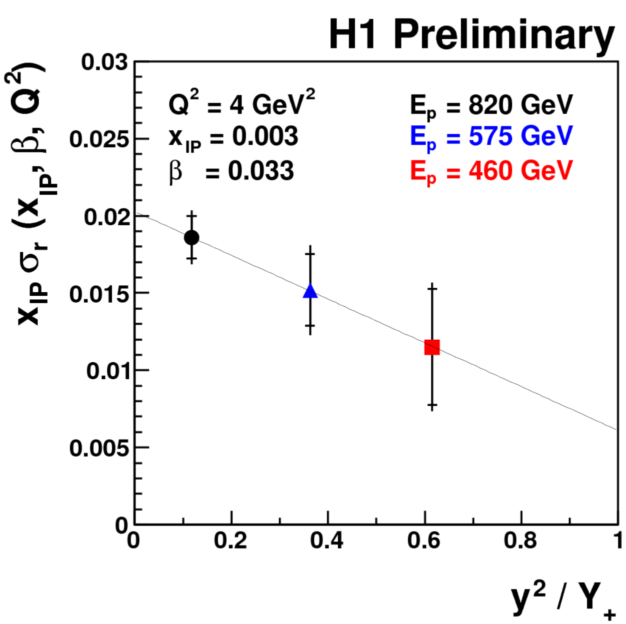
F_L^D probes directly the diffractive gluon density

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

→ Sensitivity to F_L^D at high y (low $E_e \sim$ 3-10 GeV)

→ Vary E_p to change y at fixed β, x_{IP} and Q^2

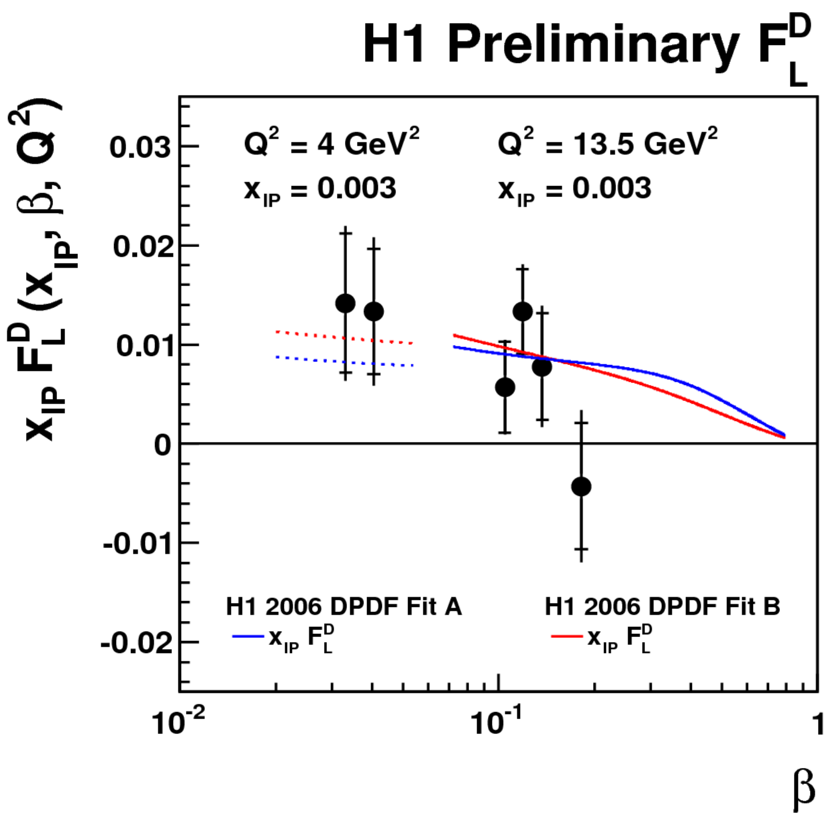
→ Low E_p run: 11 pb^{-1} @ 575 GeV , 6 pb^{-1} @ 460 GeV



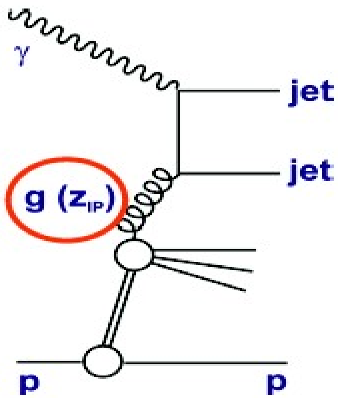
* F_L^D is a few σ away from zero

* F_L^D is compatible with NLO DGLAP fit to σ_r^D

* No access to high β !



Diffractive Dijets in DIS

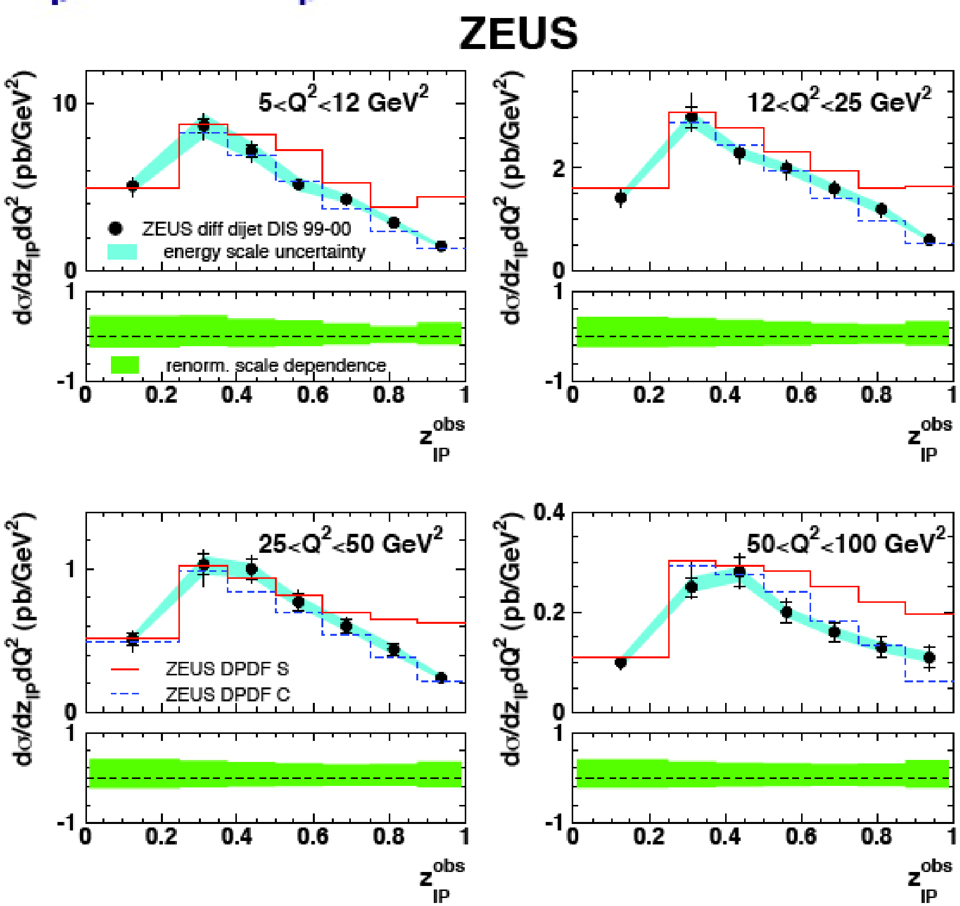


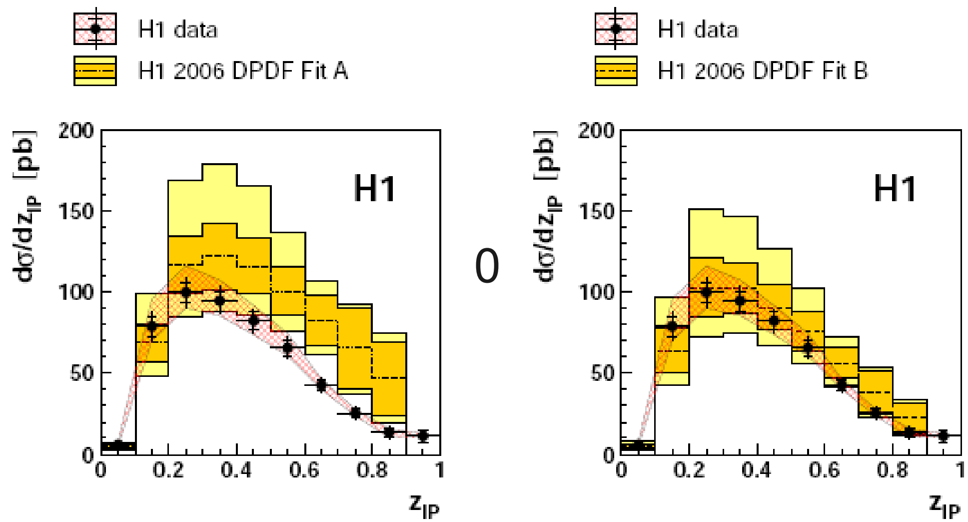
Select 2 jets in central detector + LRG

ZEUS:
$5 < Q^2 < 100$ GeV^2
$100 < W < 250$ GeV
E_T (jet1) > 5 GeV
E_T (jet2) > 4 GeV
$x_{IP} < 0.03$

$$z_{IP} = \frac{M_{12}^2 + Q^2}{M_X^2 + Q^2} \sim \beta$$

H1:
$4 < Q^2 < 80$ GeV^2
$0.1 < y < 0.7$
E_T (jet1) > 5 .5 GeV
E_T (jet2) > 4 GeV
$x_{IP} < 0.03$



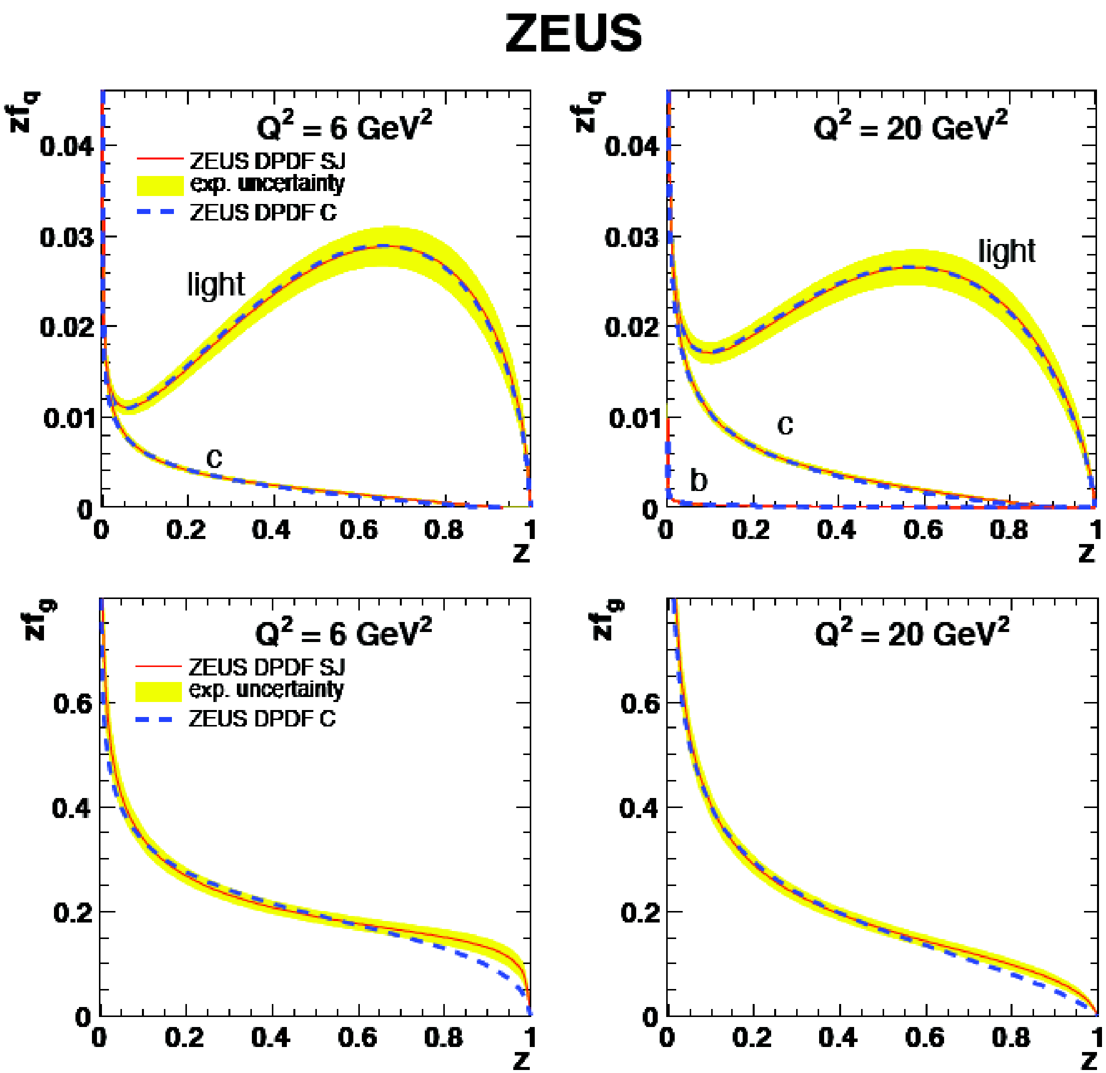


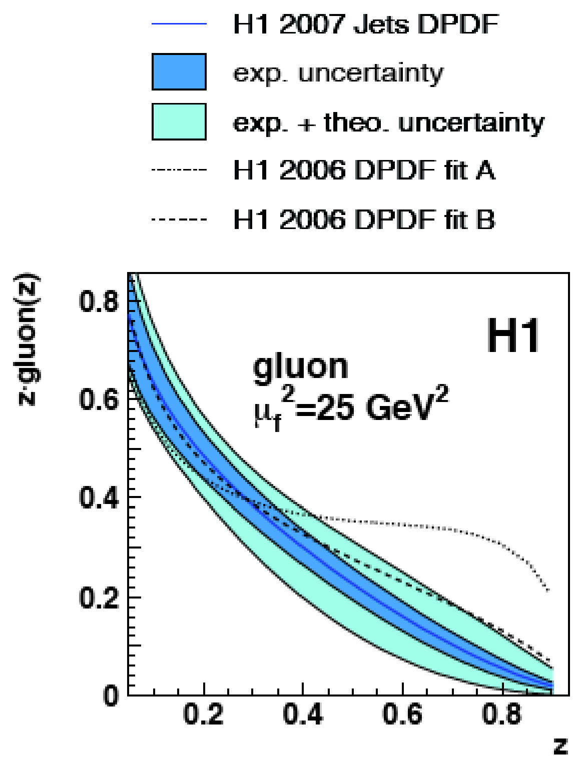
Different QCD fits give different predictions
→ Dijets cross-section sensitive to gluon at high z_{IP}
→ Include dijets data in QCD fit to constrain the gluon at high z_{IP}

Combined QCD Fits with Diffractive Dijets

ZEUS: LRG (Q^2>5 GeV^2) + LPS + DiJets , VFNS
H1 : LRG (Q^2>8.5 GeV^2) + DiJets , FFNS

$$\mu_F = \mu_r = Q(LRG, LPS), E_T(jet)$$

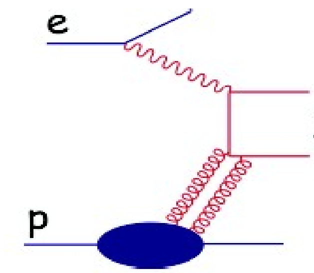


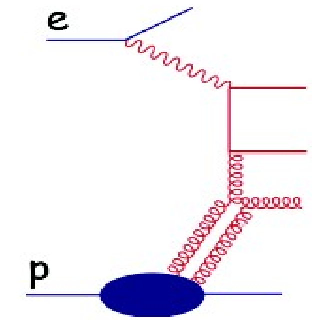


- No Change in quark PDF's
- Gluon PDF well constrained at high z
- Similar description of Inclusive DIS (Dijet fit similar to one of the standalone fits)

Selection: 1 Central Jet + 1 Forward Jet + proton in FPS

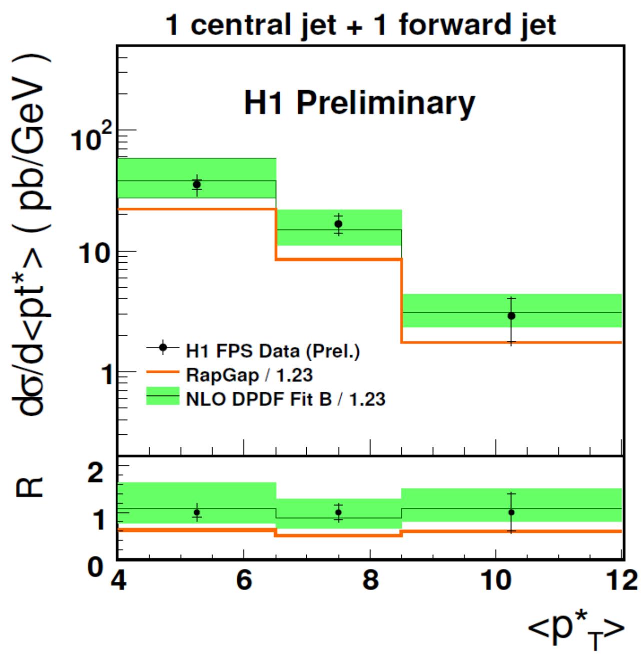
Forward jet: $p_t > 4.5$ GeV, $1 < \eta_{fwd} < 2.8$
Central jet: $p_t > 3.5$ GeV, $-1 < \eta_{cen} < \eta_{fwd}$
$2 < Q^2 < 110$ GeV^2, $|t| < 1$ GeV^2, $x_{IP} < 0.1$

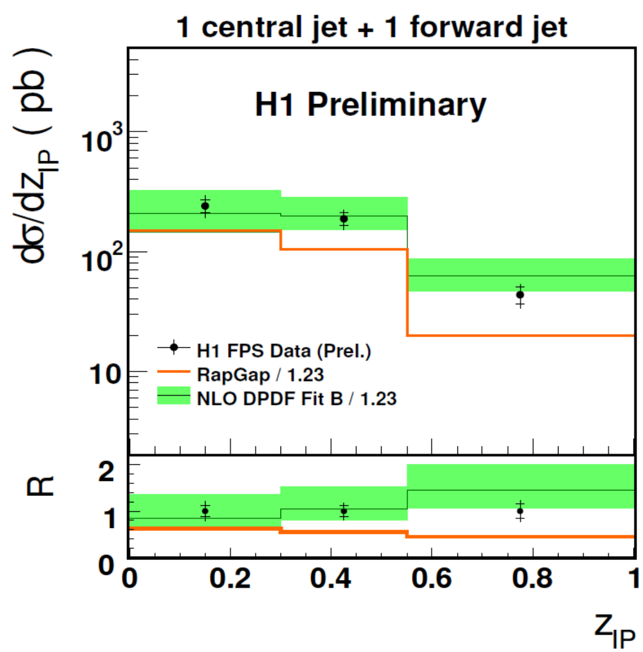


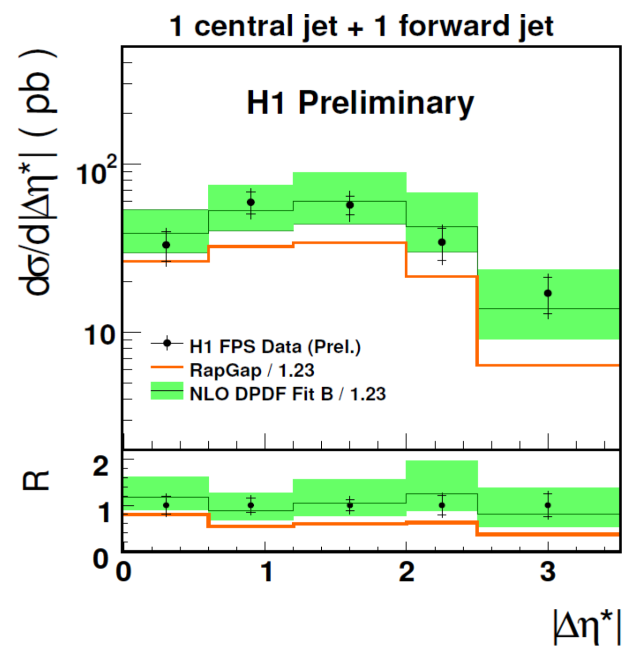


→ Search for "hard" pQCD contributions breaking DGLAP p_T ordering at low x (BFKL ...)

→ No evidence for effects beyond NLO DGLAP:

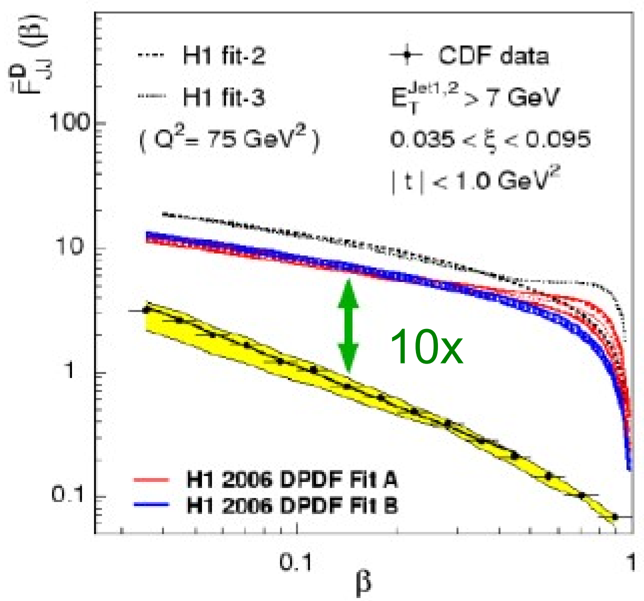






QCD Factorization Breaking in pp

H1 fits vs. Tevatron



DPDFs fail to predict Tevatron data

→ QCD factorization not expected to hold in pp diffraction !

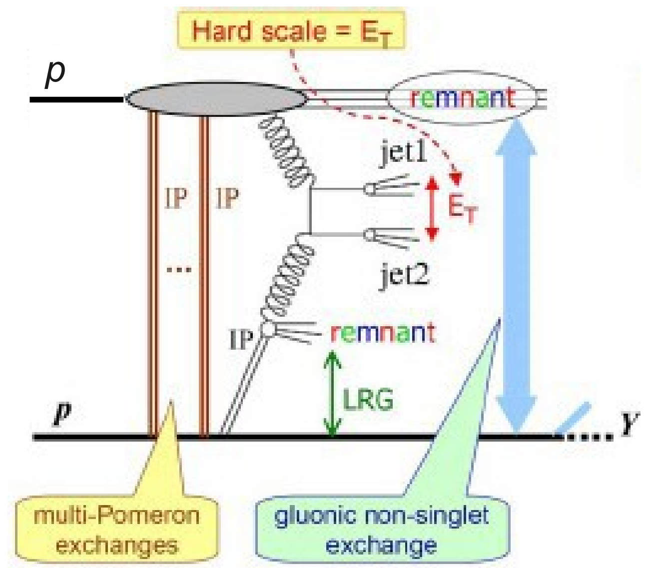
→ Several possible reasons:

– Multi-Pomeron exchange

– Remnant interactions

– Screening / Absorptive effects

→ "Rapidity Gap survival probability" at Tevatron: $S^2 \sim 0.1$

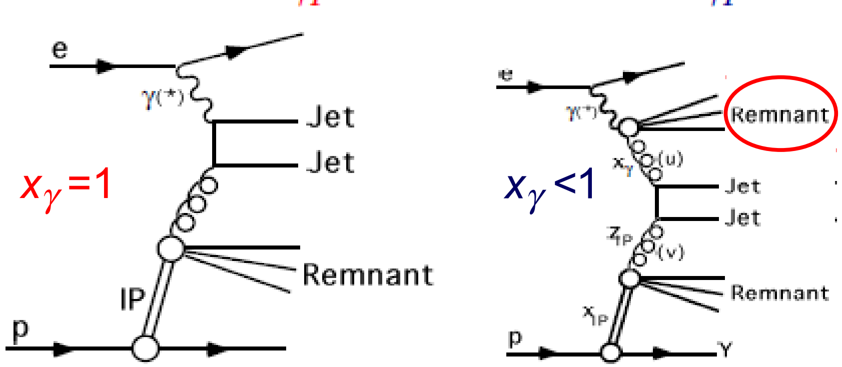


Can the Factorization Breaking be observed at HERA ?

→ Look at Diffractive Dijets in Photoproduction ($Q^2 \sim 0$)

DIS and direct γp

Resolved γp

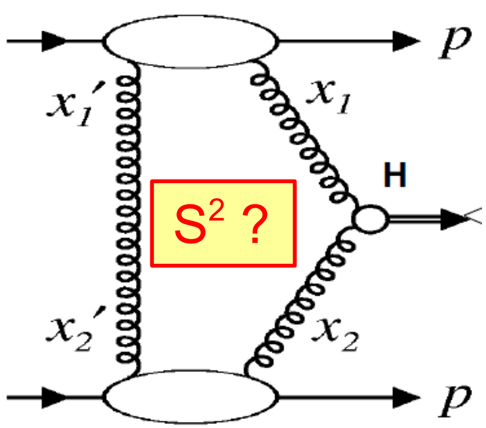


X_γ : Momentum fraction of γ entering hard process

N.B.: Separation between resolved and direct only possible at fixed order !

→ Factorization should hold → Suppression expected $S^2 \sim 0.34$ [Phys. Lett. B567 (2003) 61]

Central Exclusive Higgs Poduction at LHC ?

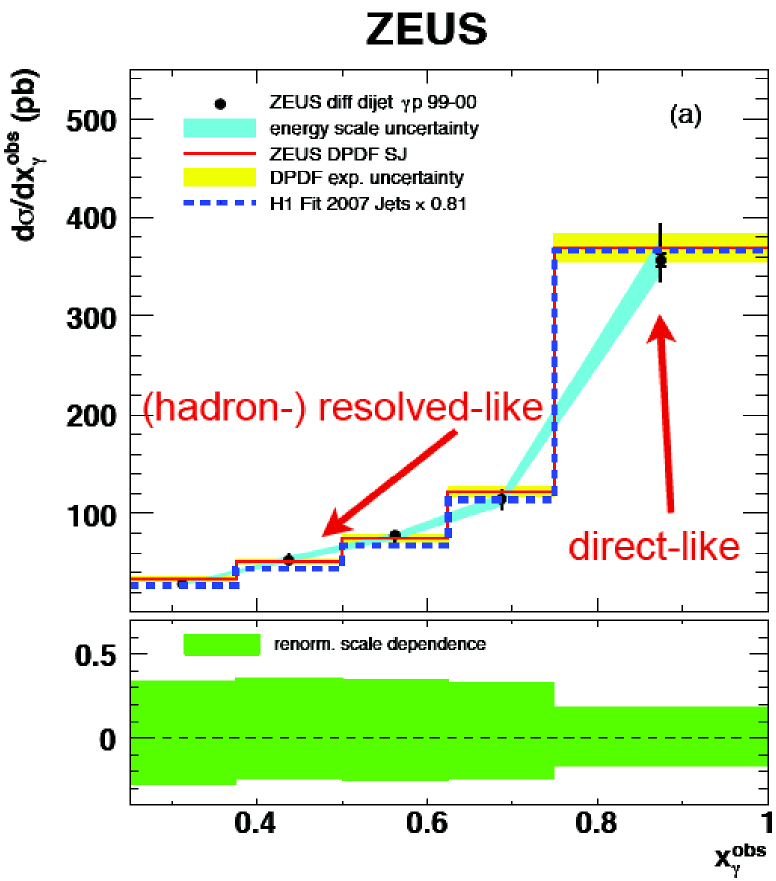


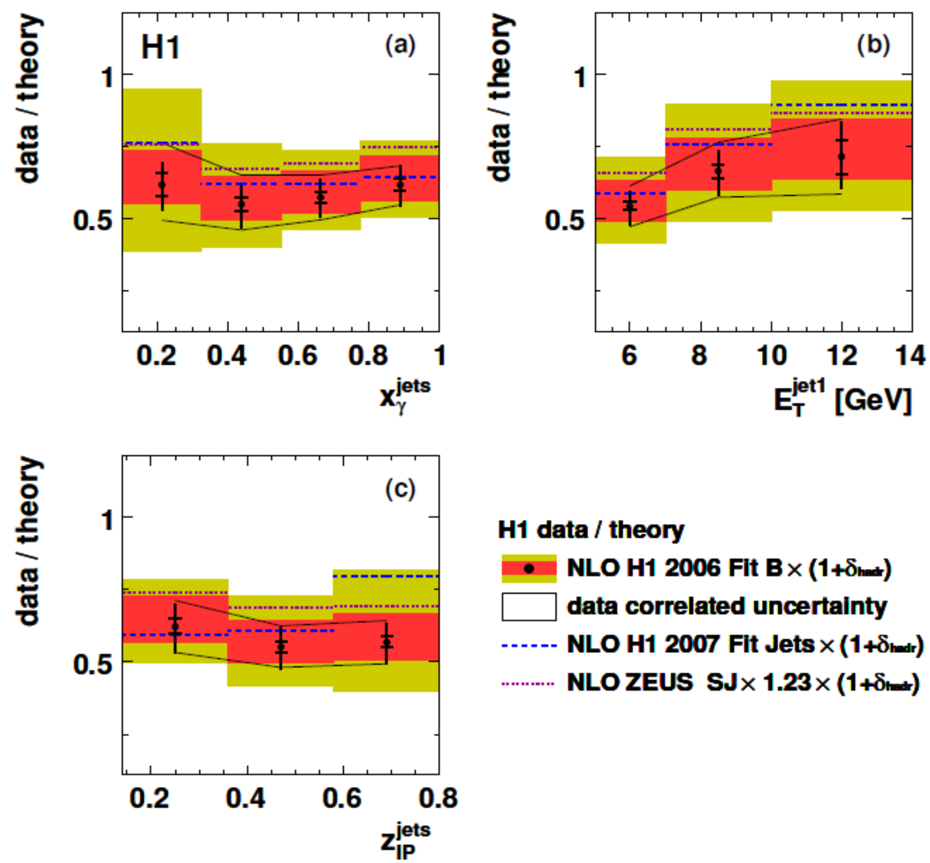
Diffractive Dijet Photoproduction → S^2 @ HERA

ZEUS [E_T(jet1) > 7.5 GeV] → No evidence for any gap destruction

H1 [E_T(jet1) > 5 GeV] → Survival probability < 1 at 2σ significance

σ(H1 data) / σ(NLO) = 0.58 ± 0.12 (exp.) ± 0.14 (scale) ± 0.09 (DPDF)

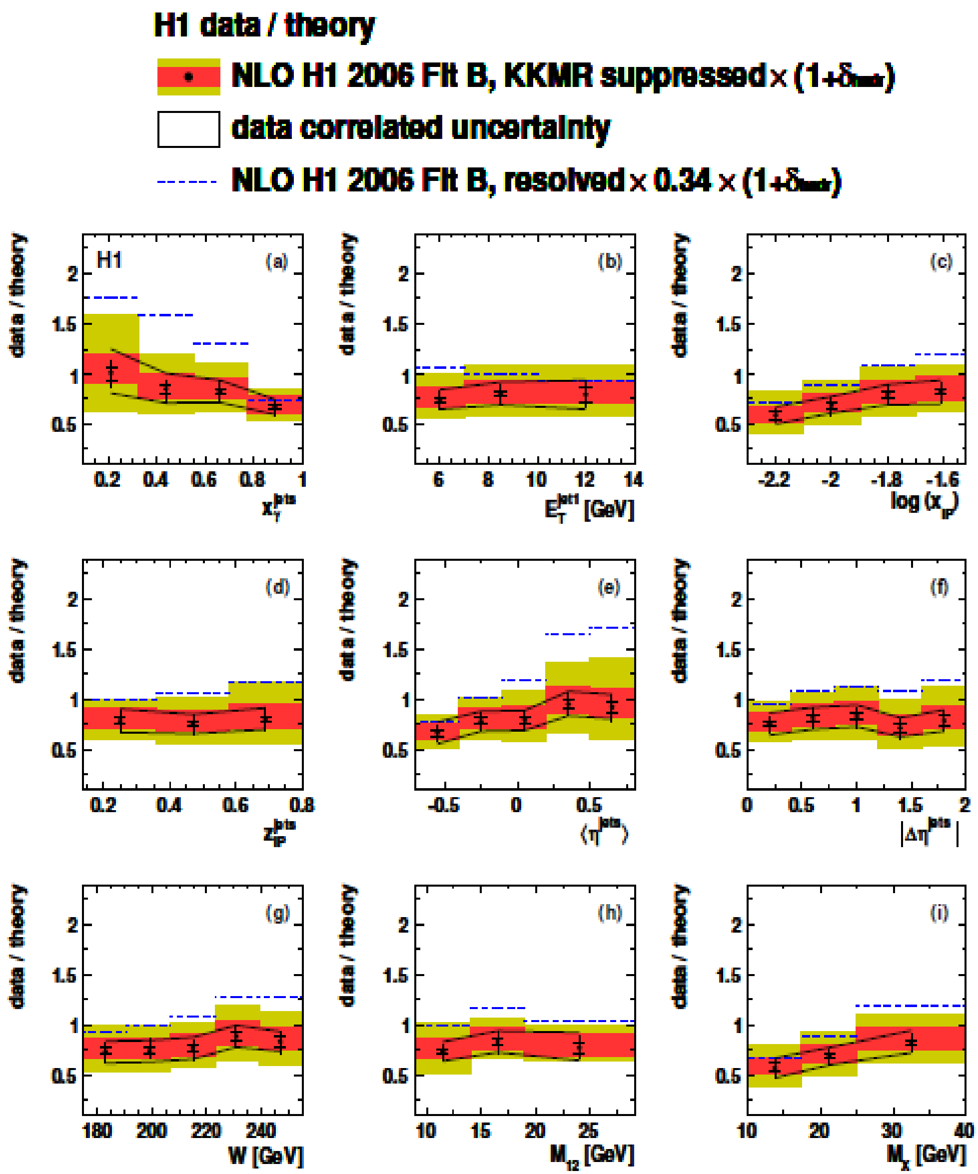




→ Gap survival has no or little dependence on x_γ

→ H1 vs ZEUS : Hint on a dependence on jet E_T ?

Diffractive Dijet Photoproduction ...



- Hadronization corrections migrations in x_γ
- NLO corrections mix direct and resolved

Refined Gap Survival Model (KMKR)
[arXiv:0911.3716]

- Direct contribution remains unsuppressed
- Suppression factor 0.34 applies to Hadron-like (VMD) part of photon structure only (low xγ < 0.1)
- Point-like (anomalous) part of photon structure has less suppression (~0.7-0.8)

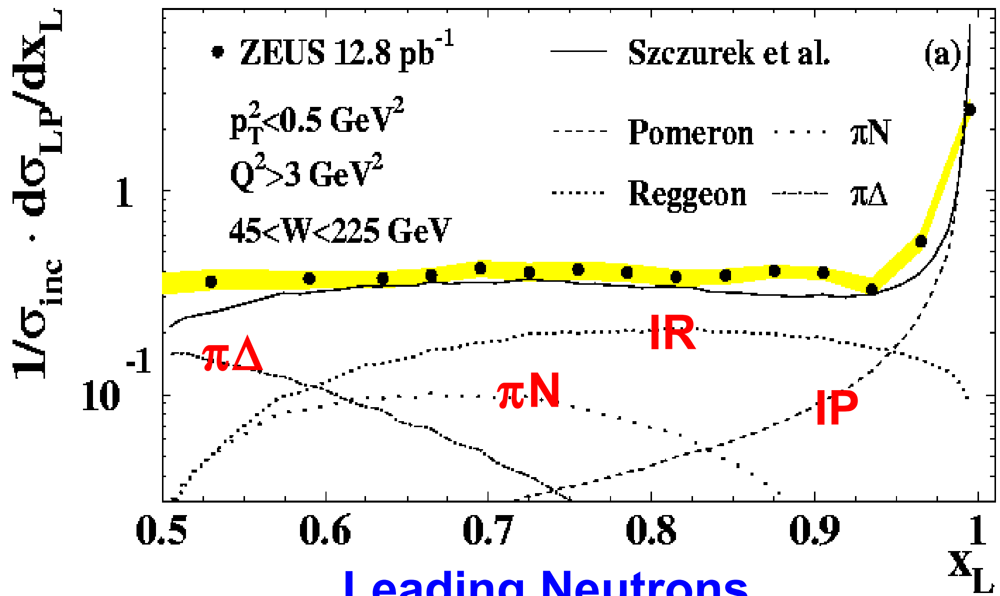
→ KMKR model (+experimental effects) accounts for flat with x_γ and smaller Rapidity Gap Survival Probability

→ KMKR model includes some E_T dependence allowing to describe both H1 and ZEUS

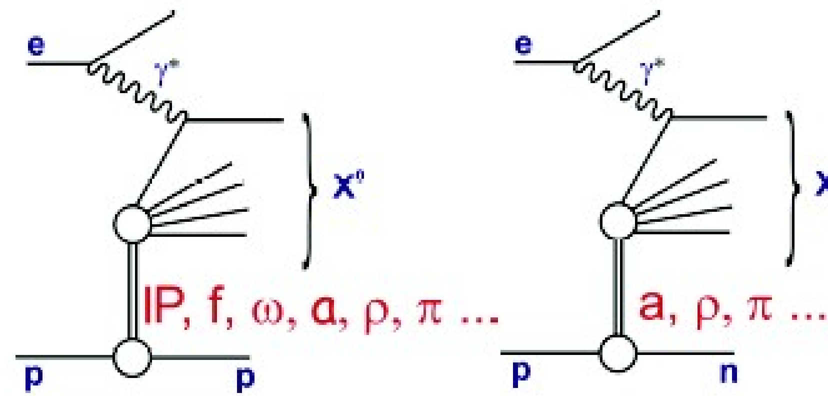
→ Progress in Diffractive Dijet Photoproduction and Rapidity Gap Survival Probability understanding at HERA

Beyond the diffractive peak: Leading Baryons

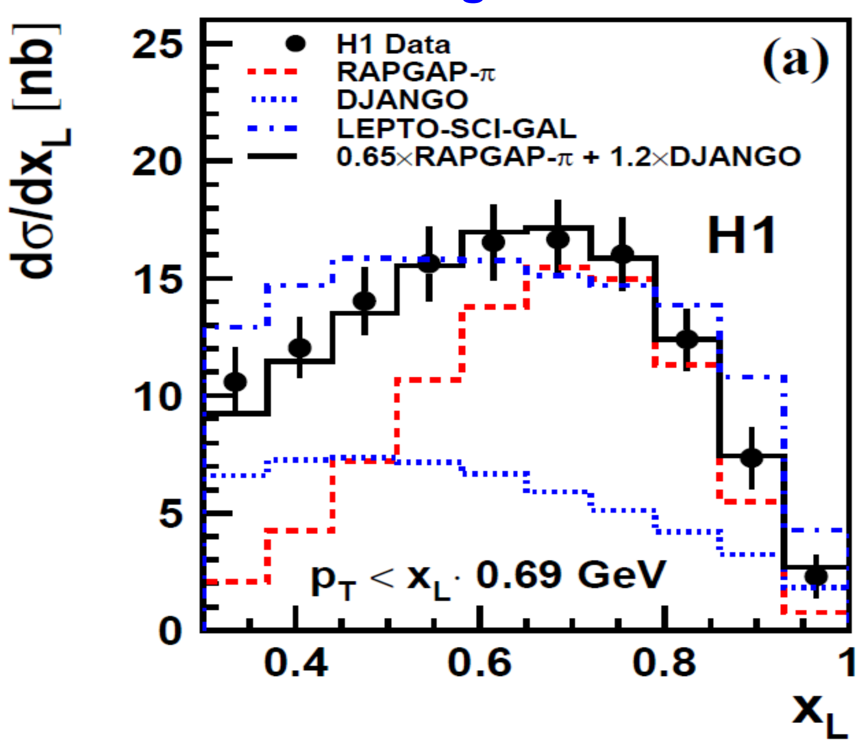
Leading Protons



- Diffractive peak at x_L (= 1-x_{IP}) = 1
- Flat at x_L<0.95
  → **Regge analysis:**
  Low x_L dominated by isoscalar meson exchanges with $\alpha_{IR}(0)$~0.5: ω, f ...
  (rather than isovector exchange: a, ρ ...)



Leading Neutrons



- Going to 0 at x_L (= 1-x_{IP}) = 1
- Drop at x_L= 0.7 due to acceptance
  → Large x_L: due to π exchange → $\alpha_\pi(0) \sim 0$
  → Low x_L: standard baryon fragmentation

Leading Neutron Structure Function

$$\sigma_r^{LN(3)}(\beta,Q^2,x_L)=F_2^{LN(3)}-\frac{y^2}{Y^+}F_L^{LN(3)}$$

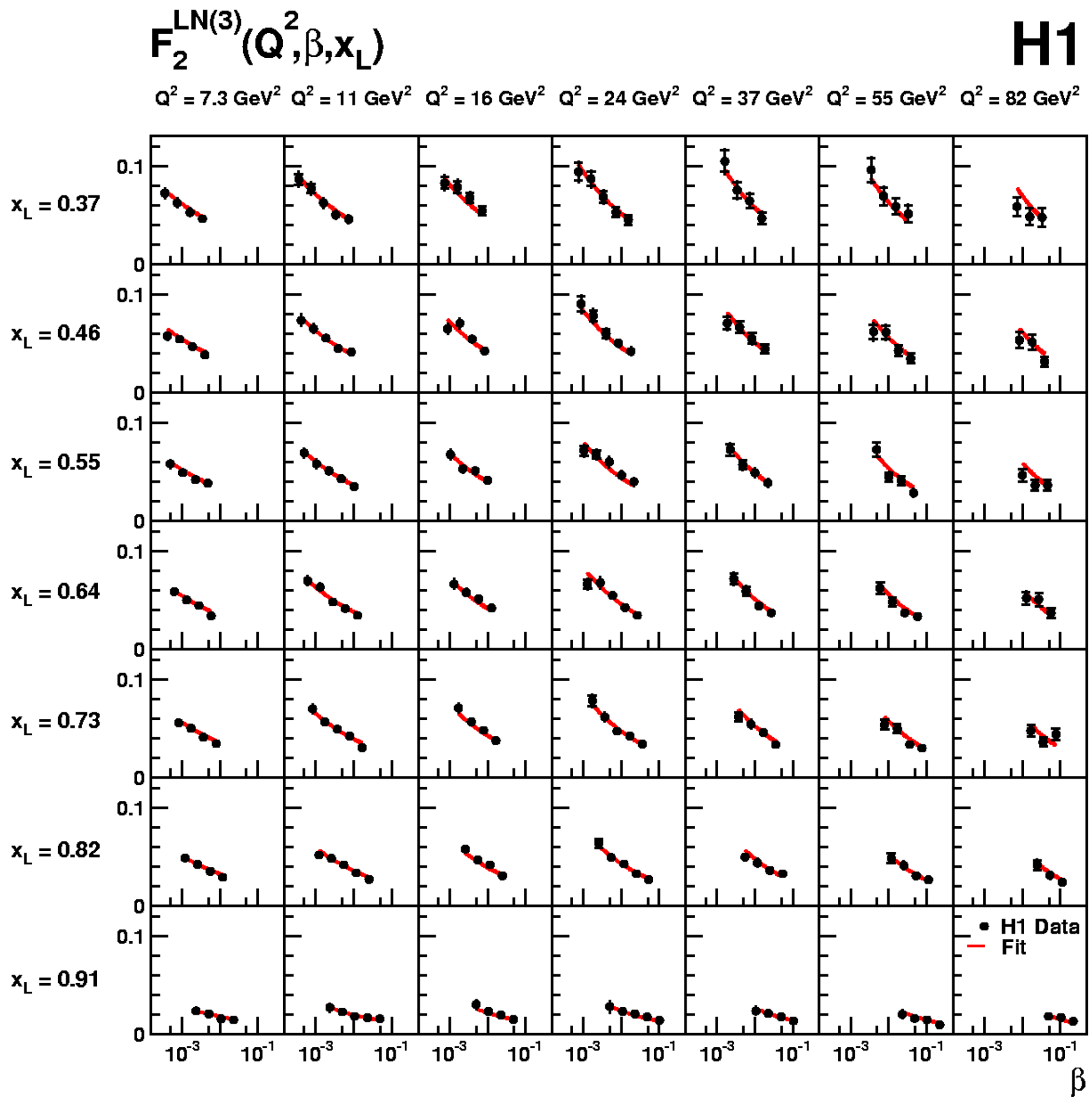
In particle exchange picture expect proton vertex factorization:

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

Fit $F_2^{LN(3)}(\beta,Q^2,x_L)$ by power law:

$$F_2^{LN(3)}(\beta,Q^2,x_L)\sim\beta^{-\lambda}$$

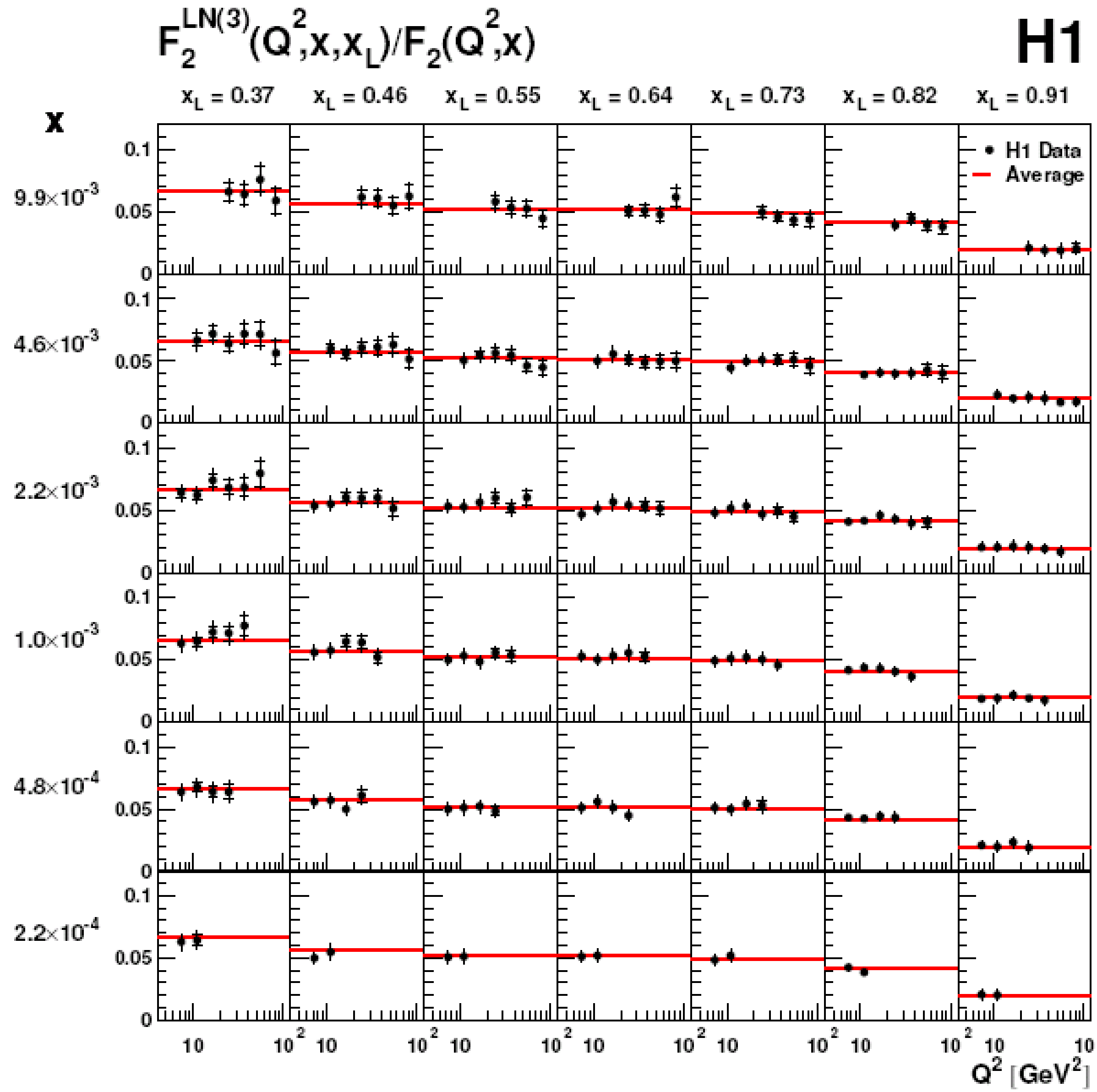
- λ is independent of x_L
  $\rightarrow$ consistent with vertex factorization
- λ increases with Q^2: from 0.23 to 0.3
  $\rightarrow$ similar Q^2 evolution of $F_2^{LN(3)}$ and proton structure function F_2



Leading Neutron Structure Functions

$$\sigma_r^{LN(3)}(\beta, Q^2, x_L) = F_2^{LN(3)} - \frac{y^2}{Y^+} F_L^{LN(3)}$$

→ Ratio to inclusive F_2:



In particle exchange picture expect proton vertex factorization:

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

Fit $F_2^{LN(3)}(\beta, Q^2, x_L)$ by power law:

$$F_2^{LN(3)}(\beta, Q^2, x_L) \sim \beta^{-\lambda}$$

- λ is independent of x_L
  → consistent with vertex factorization
- λ increases with Q^2: from 0.23 to 0.3
  → similar Q^2 evolution of $F_2^{LN(3)}$ and proton structure function F_2

→ leading neutron production in the proton fragmentation region in DIS is insensitive to Q^2 and x

LN: Pion Structure Function

$$\sigma_r^{LN(3)}(\beta, Q^2, x_L) = F_2^{LN(3)} - \frac{y^2}{Y^+} F_L^{LN(3)}$$

Assuming proton vertex factorization and the dominance of π+-exchange at high x_L, we estimate pion structure function at low x from measured $F_2^{LN(3)}$ at $0.68 < x_L < 0.77$:

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

where Γ_π is the integrated pion flux:

$$\Gamma_\pi = \int f_{\pi/p}(x_L = 0.73, t)\, dt$$

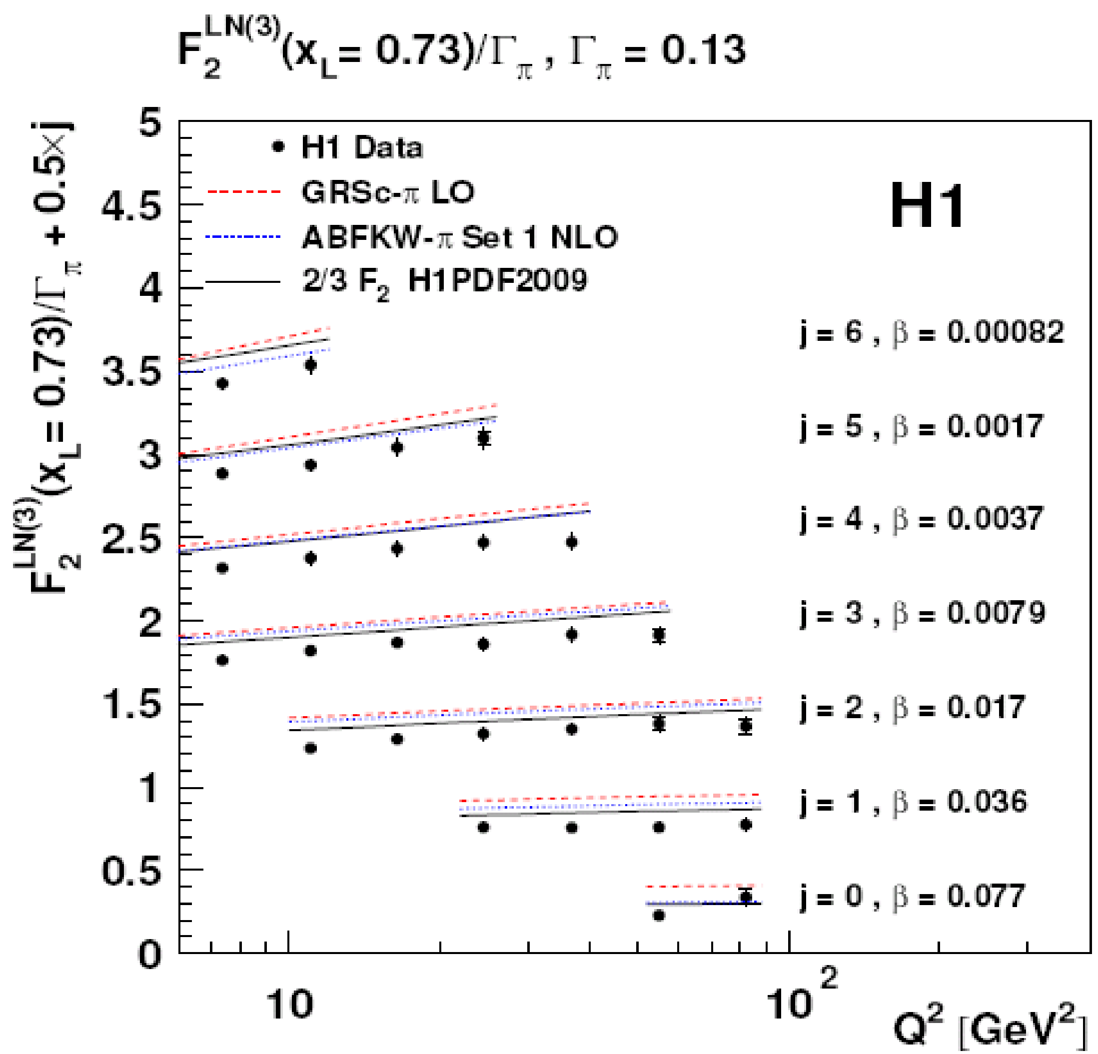
BUT several parametrization for Γ_π

→ 30% normalization uncertainties

→ F^π_2 following parametrization but a bit too low (30% uncertainties !)

→ F^π_2 following inclusive F_2 Q2 depend.

→ Universality of structure function at low x



CONCLUSIONS

Diffraction has been explored in details by the H1 and ZEUS experiments at HERA providing an unique sensitivity to strong color-singlet exchange in pQCD regime

Inclusive Diffraction and Diffractive PDFs:

- First H1 VFPS results (and recent FPS and LRG data)
- Proton Vertex Factorization holds with $a_{IP}(0) \sim 1.10$ and b-slope ~ 6–7 GeV^2
- Relative agreement between H1 and ZEUS (large normalization uncertainties)
  → Diffractive PDF's well constrained by combined fits with diffractive dijets in DIS

QCD Factorization Tests:

- QCD factorization broken in pp diffractive interactions:
  → Rapidity Gap Survival Probability at Tevatron: $S^2 \sim 0.1$
- At HERA, diffractive dijets in photoproduction shows smaller (or no) factorization breaking ($S^2 \sim 0.3$ expected for resolved photons)
  → Progress in theory side !

Leading Neutrons:

- Originating from both fragmentation (low x_L) and pion exchange (large x_L)
- Precise measurement of LN structure functions and F_2^{π} extracted

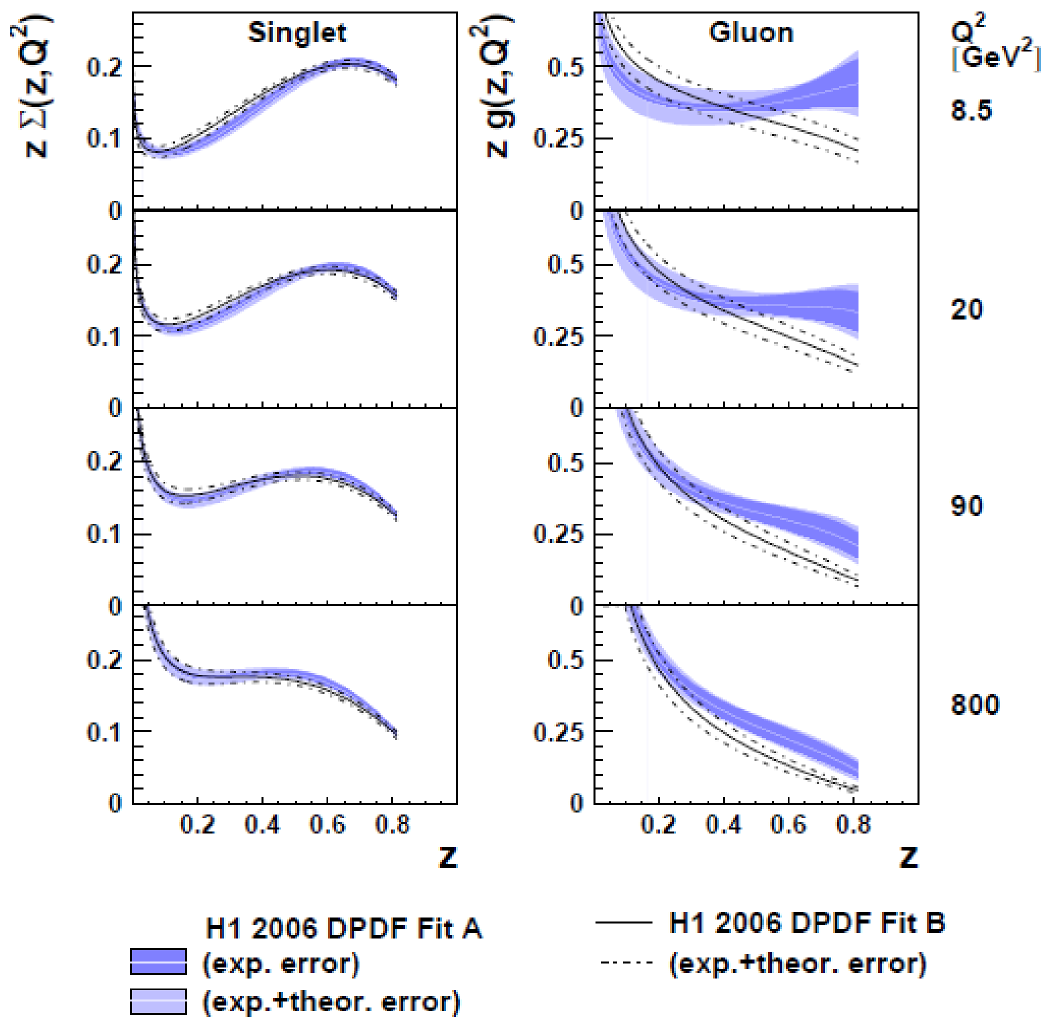
→ Input to diffraction, multi-parton interactions, LN studies … @ LHC

BACKUP SLIDES

QCD Analysis of H1 LRG Data

- Fit H1 LRG data in fixed $x_{I\!P}$ binning using NLO DGLAP evolution of DPDFs (massive scheme) to describe x, Q^2 dependences
- Proton vertex factorization framework assumed
- Fit all H1 LRG data with $Q^2 \geq 8.5\ \mathrm{GeV}^2, \mathrm{M_X} > 2\ \mathrm{GeV}, \beta \leq 0.8$
  $\longrightarrow$ Ensure stability of fit with variations of kinematic boundaries
- Parametrize:
  - quark singlet: $z\Sigma(z, Q_0^2) = A_q\ z^{B_q}\ (1-z)^{C_q}$
  - gluon density: $zg(z, Q_0^2) = A_g\ (1-z)^{C_g}$
    gluon insensitive to B_g
  - $\alpha_{I\!P}(0)$ (describes $x_{I\!P}$ dependence)
- Fix:
  - use world average for $\alpha_s(M_Z) = 0.118$
  - sub-leading $I\!R$ flux parameters taken from previous data
  - sub-leading $I\!R$ PDFs from Owens-π but free normalization
- Small number of parameters in DPDFs
  $\longrightarrow$ Need to optimize Q_0^2 wrt χ^2

H1 LRG QCD Fit Results



- Fit A: $Q_0^2 = 1.45\ \mathrm{GeV}^2$
  $\chi^2 \sim 158/183$ dof
  - Singlet constrained to $\sim 5\%$
  - Gluon to $\sim 15\%$ at low z
  - Gluon error band blowing up at highest z
- Fit B: $zg(z, Q_0^2) = A_g$
  $\chi^2 \sim 164/184$ dof
  - Singlet very stable
  - Gluon similar at low z
  - Gluon change at high z

$\longrightarrow$ New Diffractive PDFs available

$\longrightarrow$ Lack of sensitivity to gluon at high z

Pomeron Trajectory from H1 LRG QCD Fit

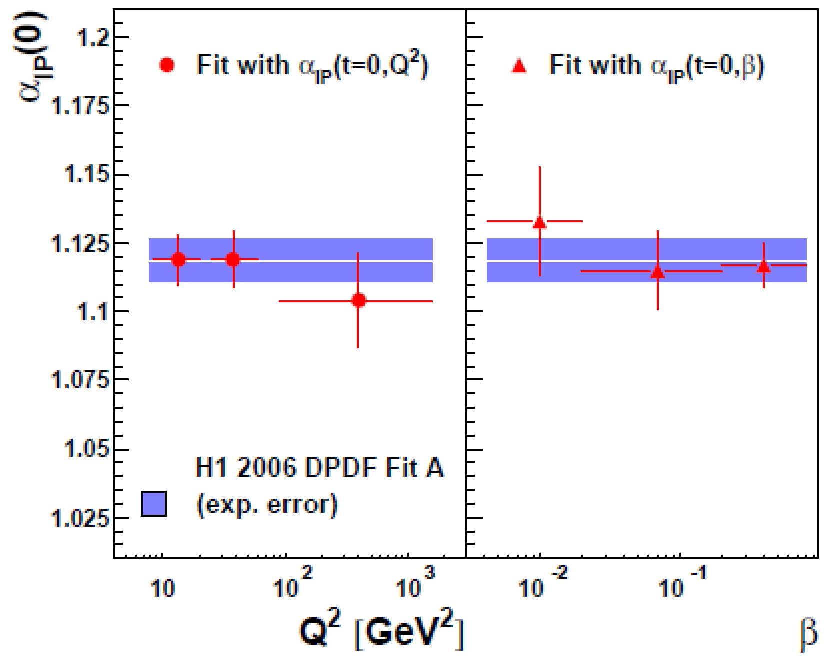
H1 Pomeron Intercept from QCD fit:

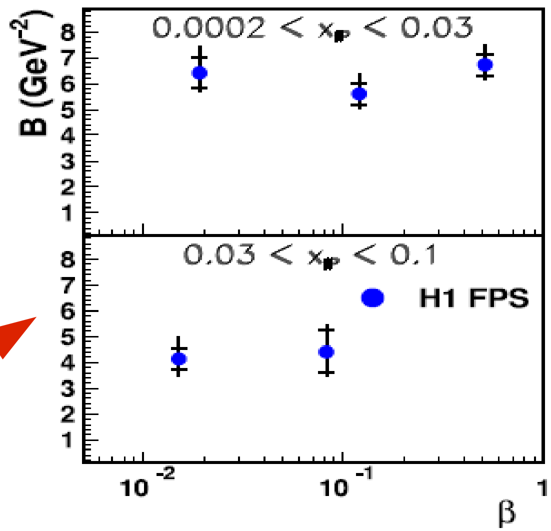
- $\alpha_{I\!P}(0) = 1.118 \pm 0.008(\text{exp.})^{+0.029}_{-0.10}(\text{th.})$
- Dominant uncertainty from strong correlation with $\alpha'_{I\!P}$
- No variation in Q^2 or β
  $\rightarrow$ support p vertex factorization
- Consistent with FPS result:

$$\alpha_{IP}(0) = 1.10 \pm 0.02\ (\text{exp.}) \pm 0.03\ (\text{model})$$

$$\alpha'_{IP} = 0.04 \pm 0.02\ (\text{exp.}) \pm 0.03\ (\text{model})\ \text{GeV}^{-2}$$

$$B_{IP} = 5.7 \pm 0.3\ (\text{exp.}) \pm 0.6\ (\text{model})\ \text{GeV}^{-2}$$





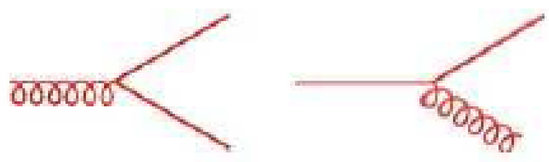
Regge fit to HERA-1 FPS data

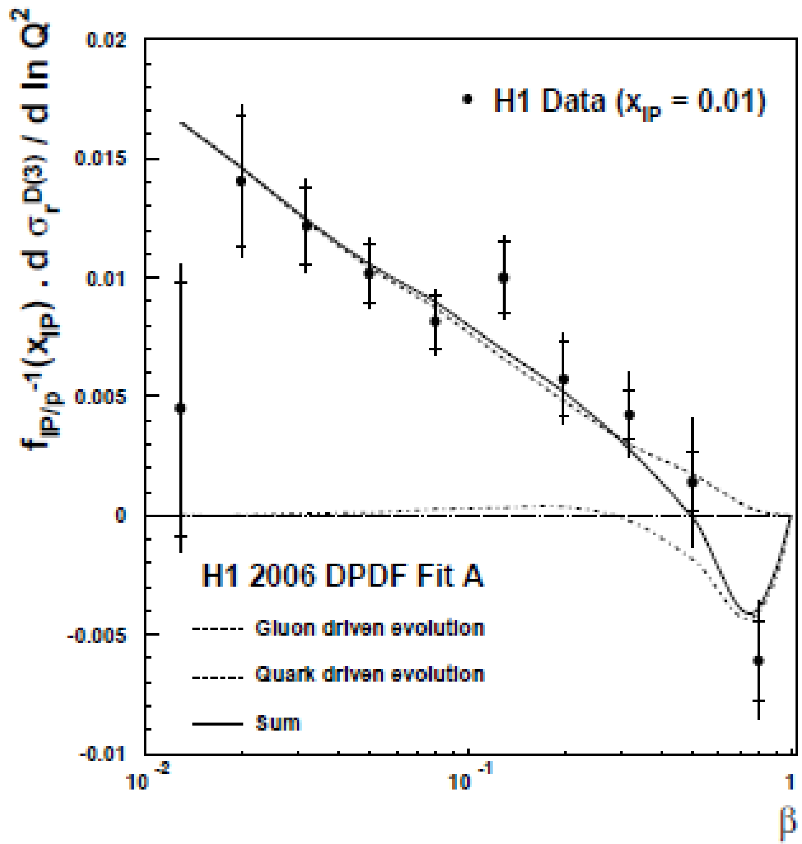
LRG Fits: High β sensitivity to gluon

- As there are only singlet quarks, the evolution eq. for F_2^D is

Log. Derivative wrt Q^2

$$\frac{dF_2^D}{d\ln Q^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg} \otimes g + P_{qq} \otimes \Sigma\right]$$

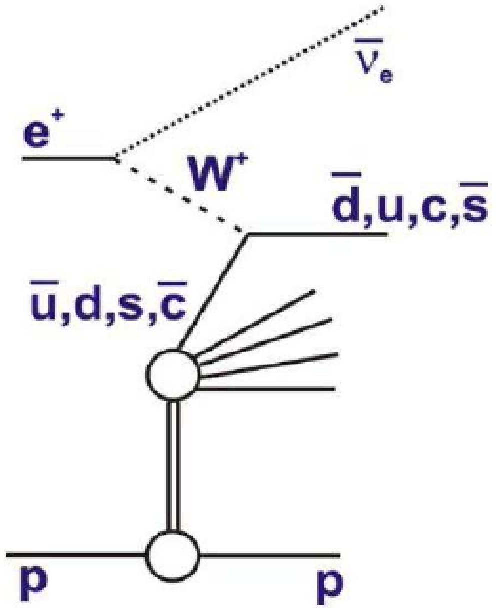


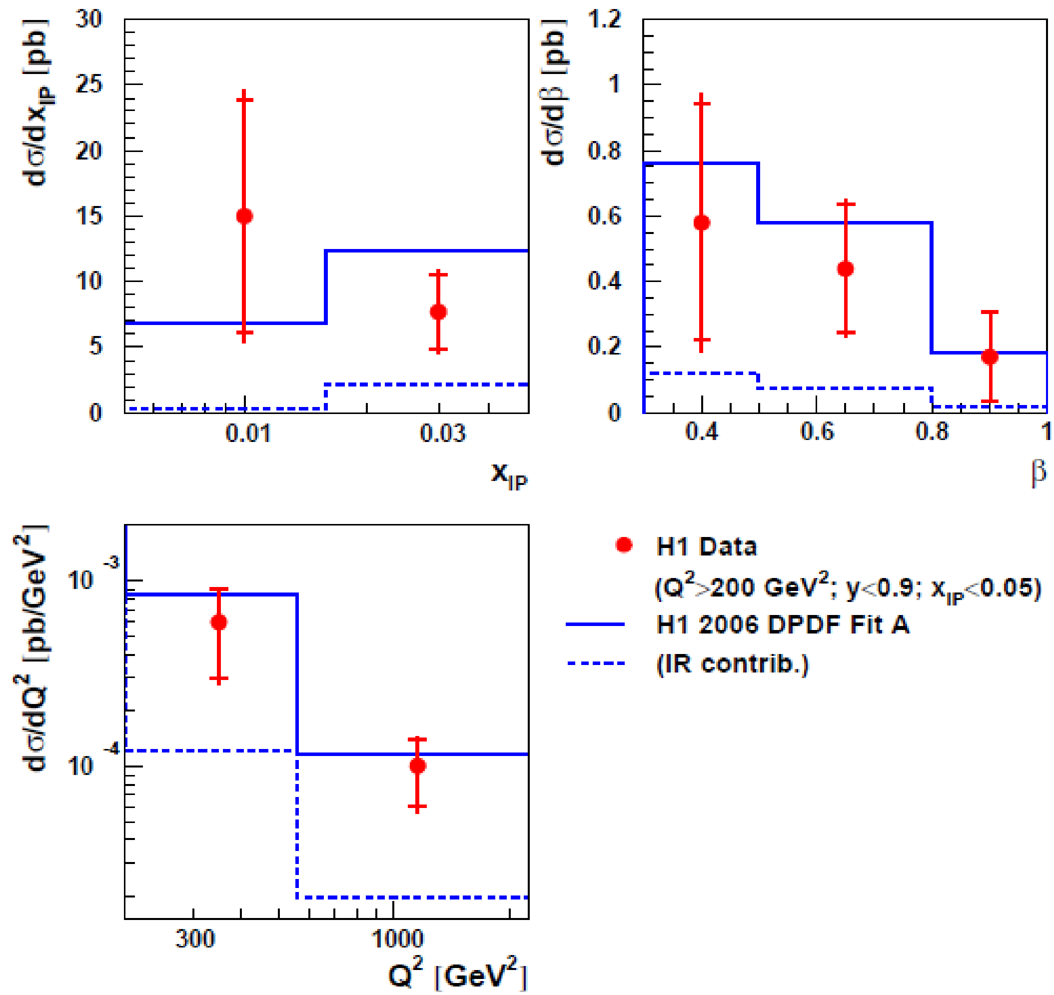


- At low β, evolution driven by $g \to qq$
  $\longrightarrow$ strong sensitivity to gluon

- At high β, relative error on derivative grows, $q \to qg$ contribution becomes important
  $\longrightarrow$ sensitivity to gluon is lost

Diffractive Charged Current Cross Section

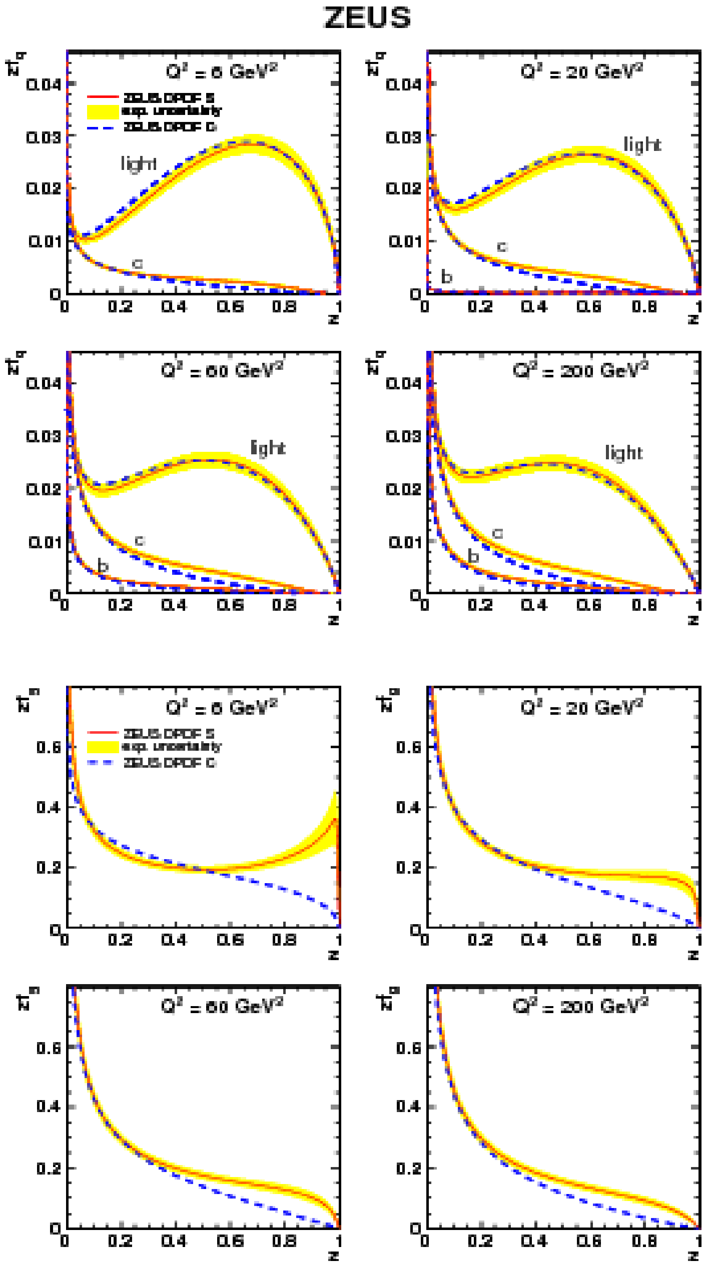




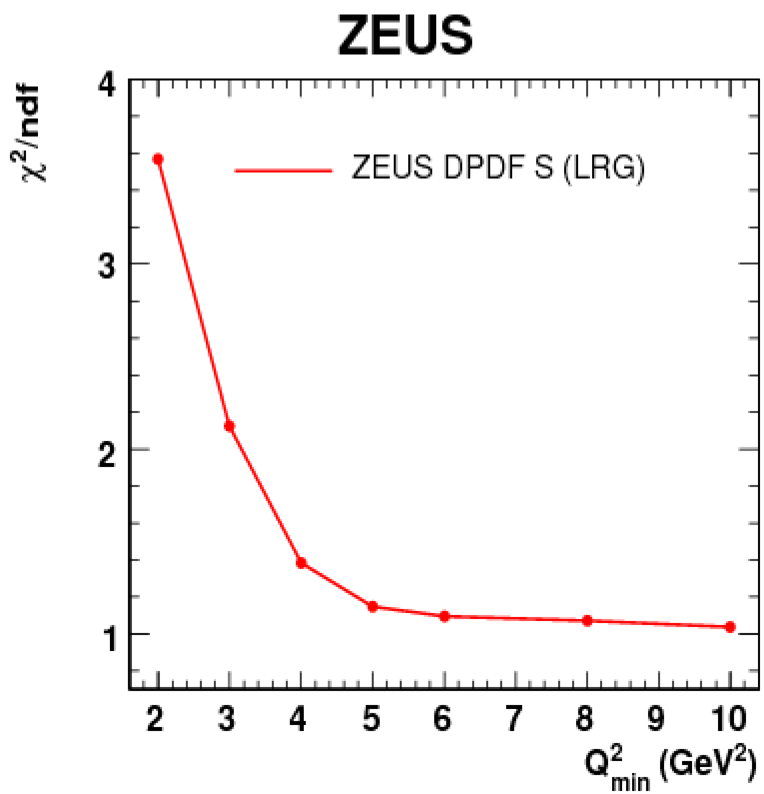
Sensitive to flavour decomposition of quark singlet (unconstrained by Neutral Currents)

Agreement with H1 2006 DPDFs (assumes $u = d = s = \bar{u} = \bar{d} = \bar{s}$)
but statistical precision very limited so far

ZEUS DPDF S: Results (1)

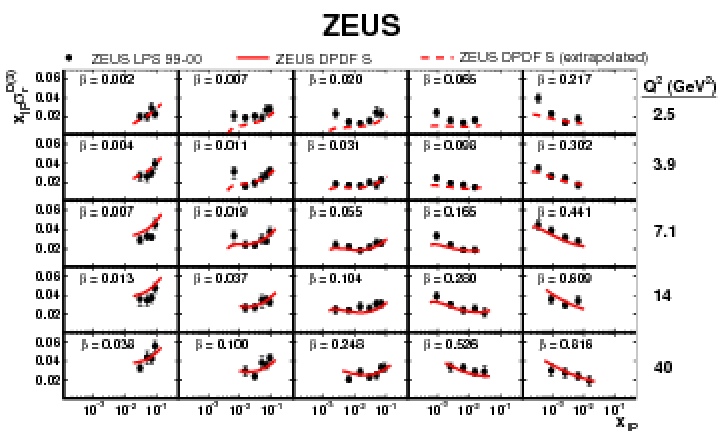


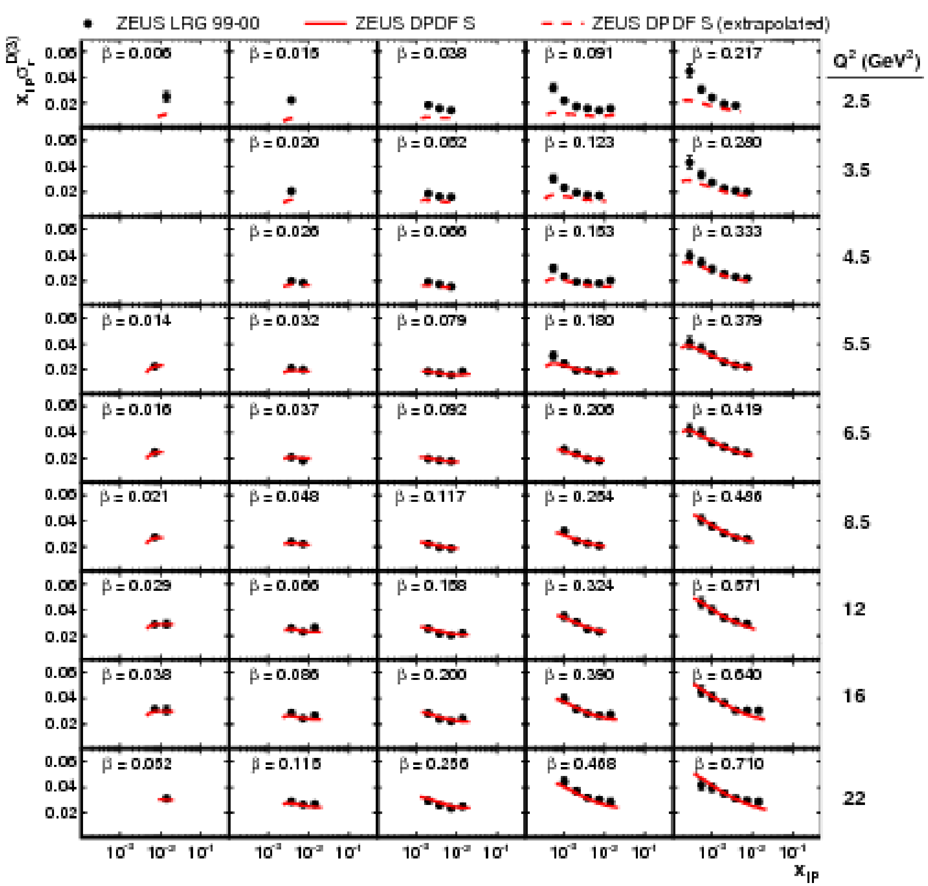
Chi2/ndof vs minimum Q^2 for ZEUS DPDF S Fit:



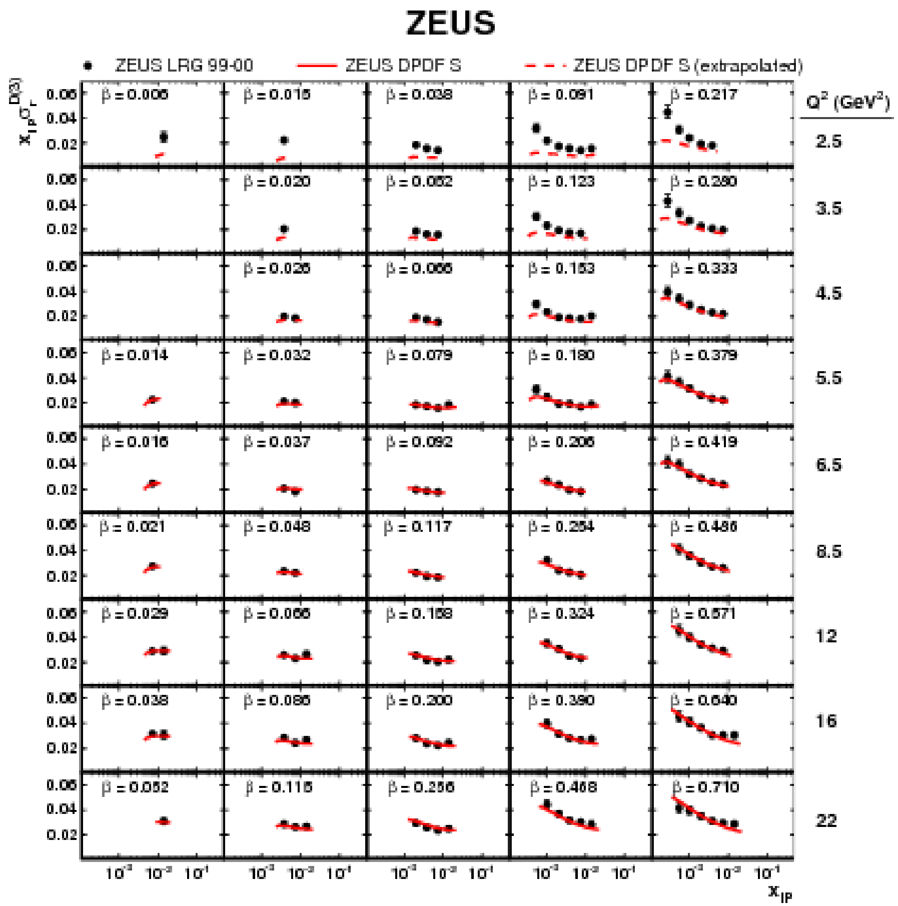
→ Fit quality bad below 5 GeV^2

ZEUS DPDF S: Results (2)

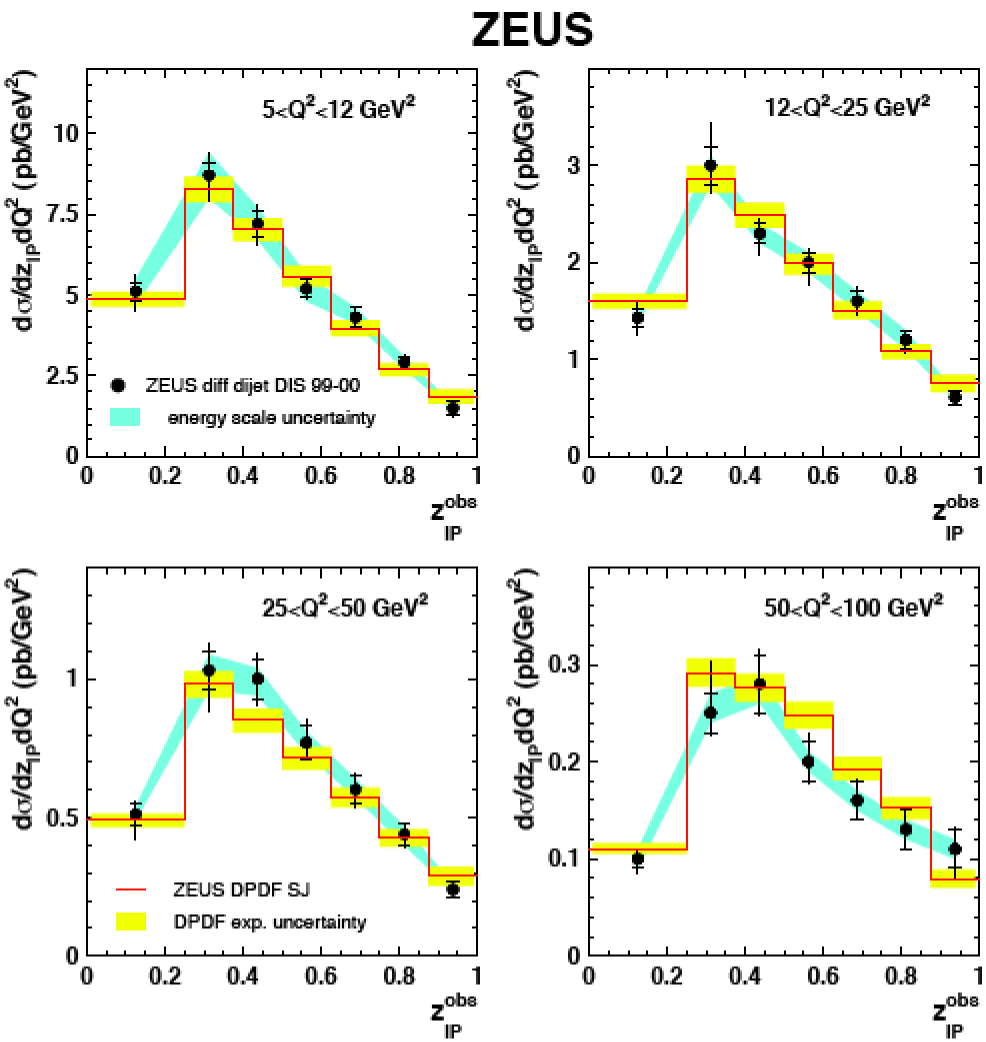


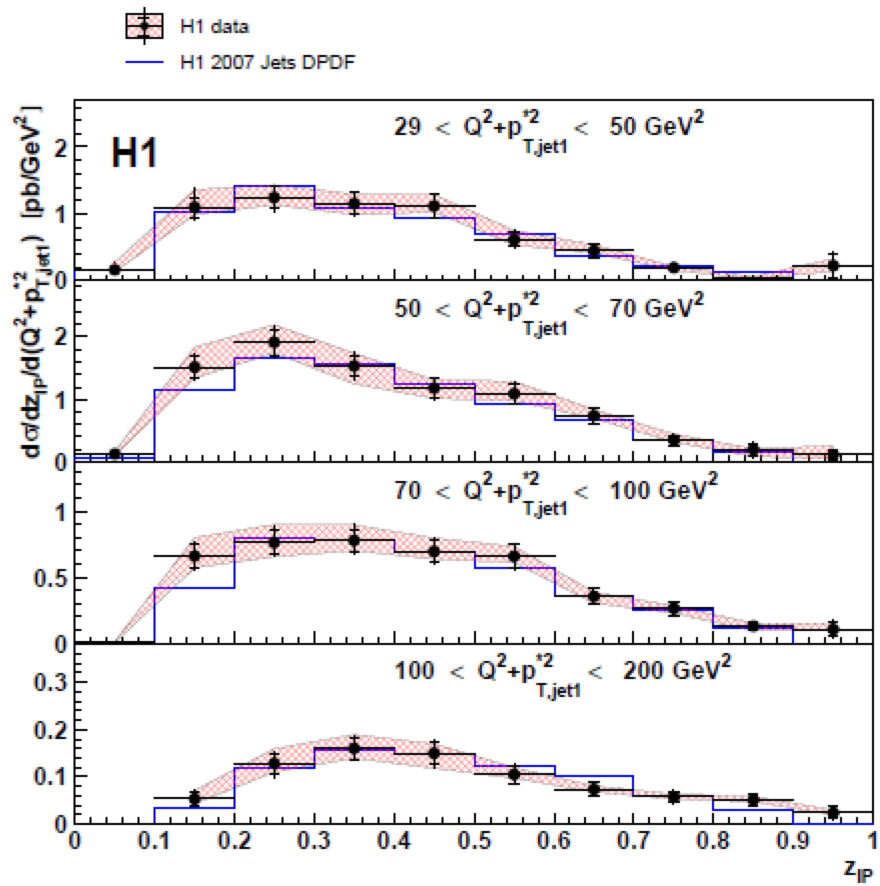


Comparison of ZEUS DPDF S Fit to ZEUS LRG and FPS data

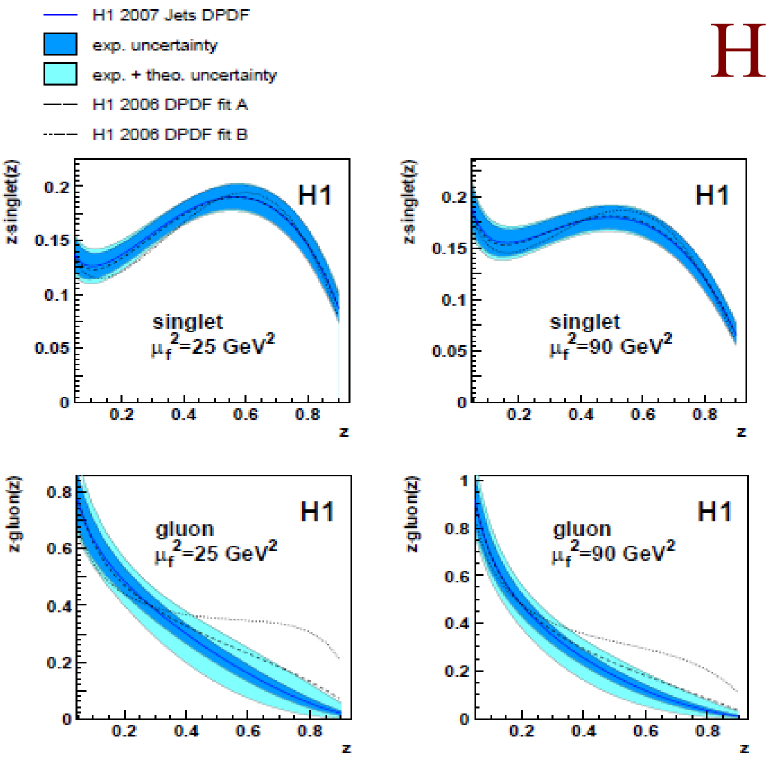


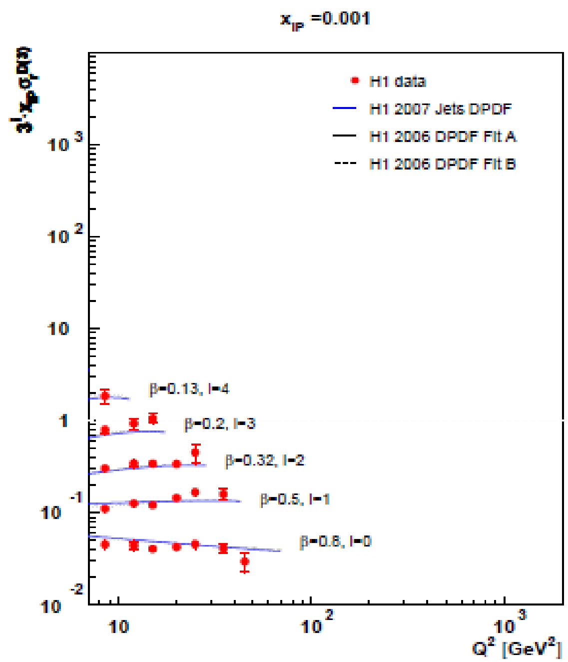
LRG-Dijets Fit Results

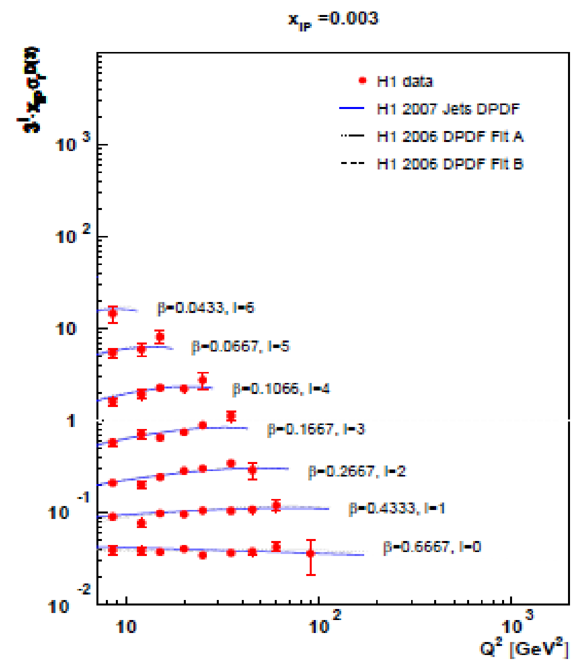


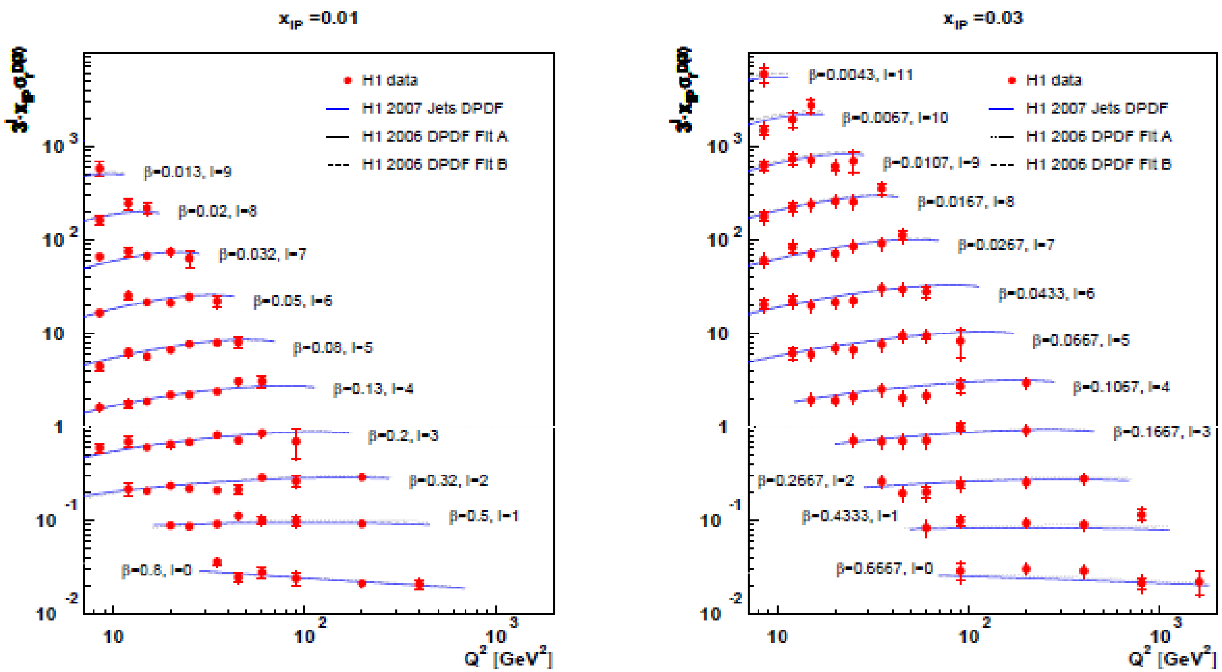


H1 LRG-Dijets Fit Results

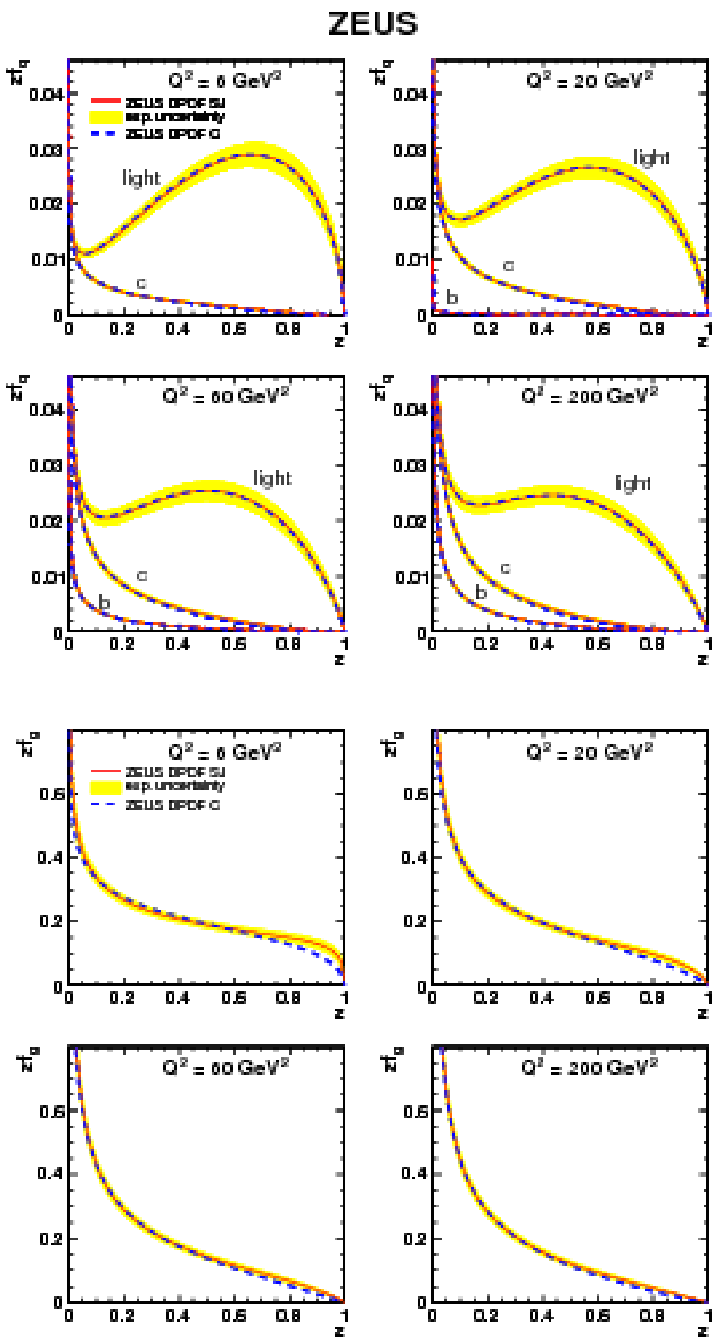


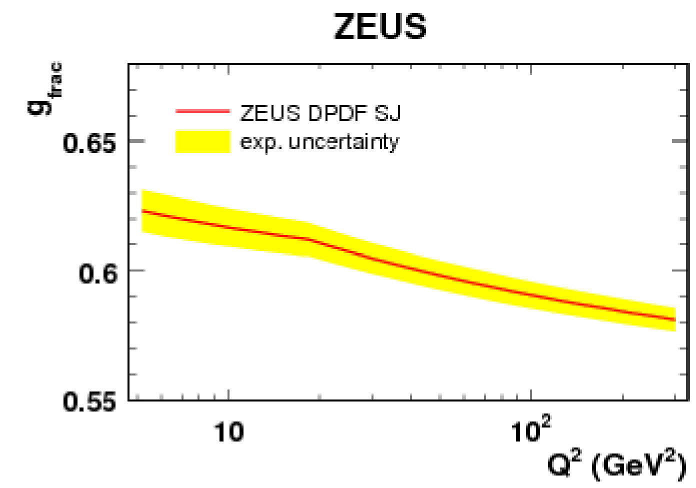


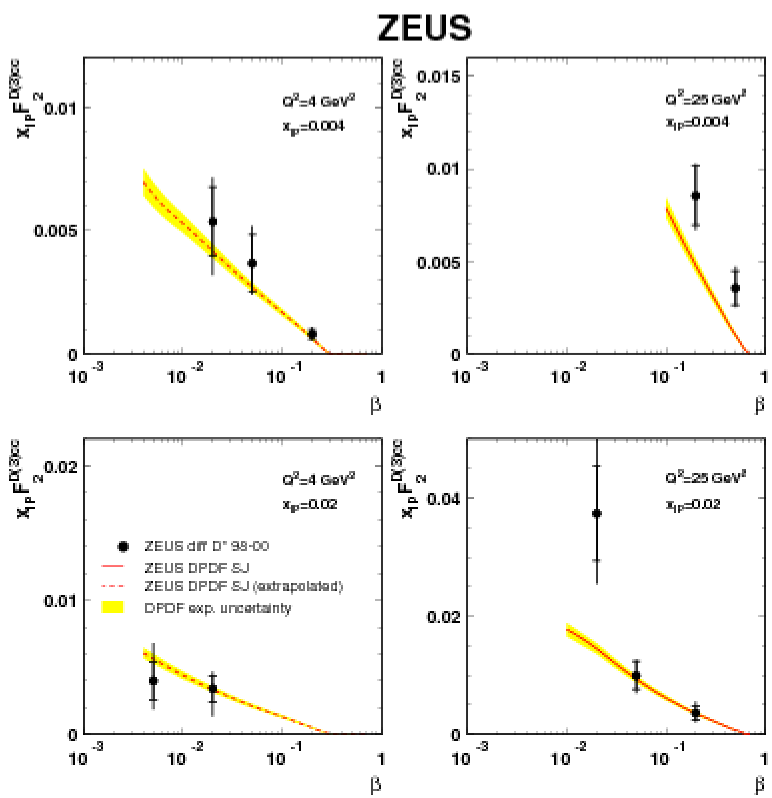




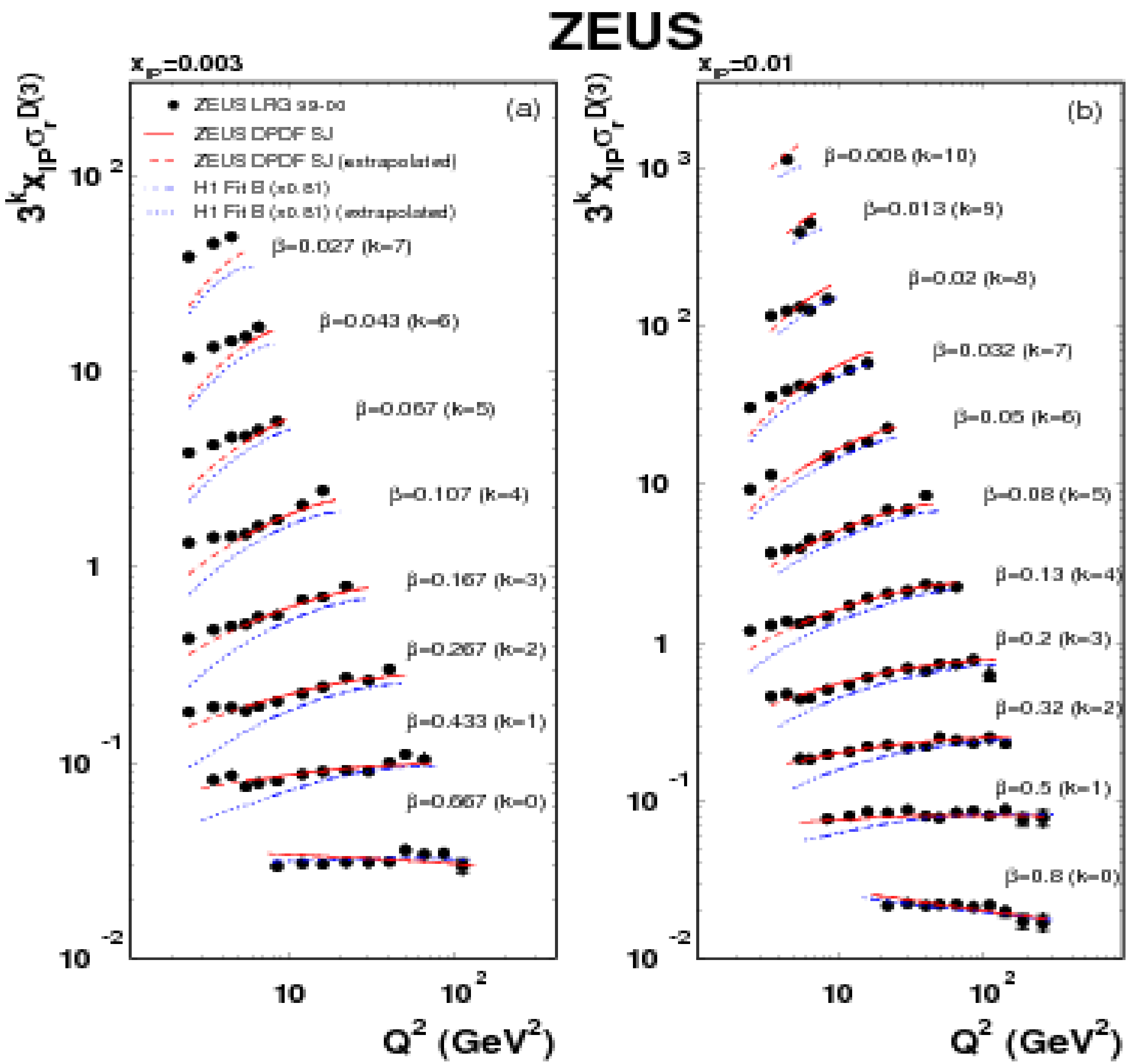
ZEUS DPDF SJ: Results







QCD Fits: H1 vs ZEUS



Differences ZEUS // H1 fits :

- VFNS // FFNS.
- $Q^2 > 5$ GeV^2 // $Q^2 > 8.5$ GeV^2.
- $M_N = m_p$ // $M_N < 1.6$ GeV; hence scaling 0.81.

Comparison :

- Agreement in shape for $\beta < 0.2$; ZEUS fit higher.
- At higher β and where extrapolated agreement worsens.
- Reflects degree of consistency between H1 and ZEUS data.

M. Wing, DIS2010

Leading Neutron Structure Functions

$$\sigma_r^{LN(3)}(\beta, Q^2, x_L) = F_2^{LN(3)} - \frac{y^2}{Y^+} F_L^{LN(3)}$$

In particle exchange picture expect proton vertex factorization:

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

Fit $F_2^{LN(3)}(\beta, Q^2, x_L)$ by power law:

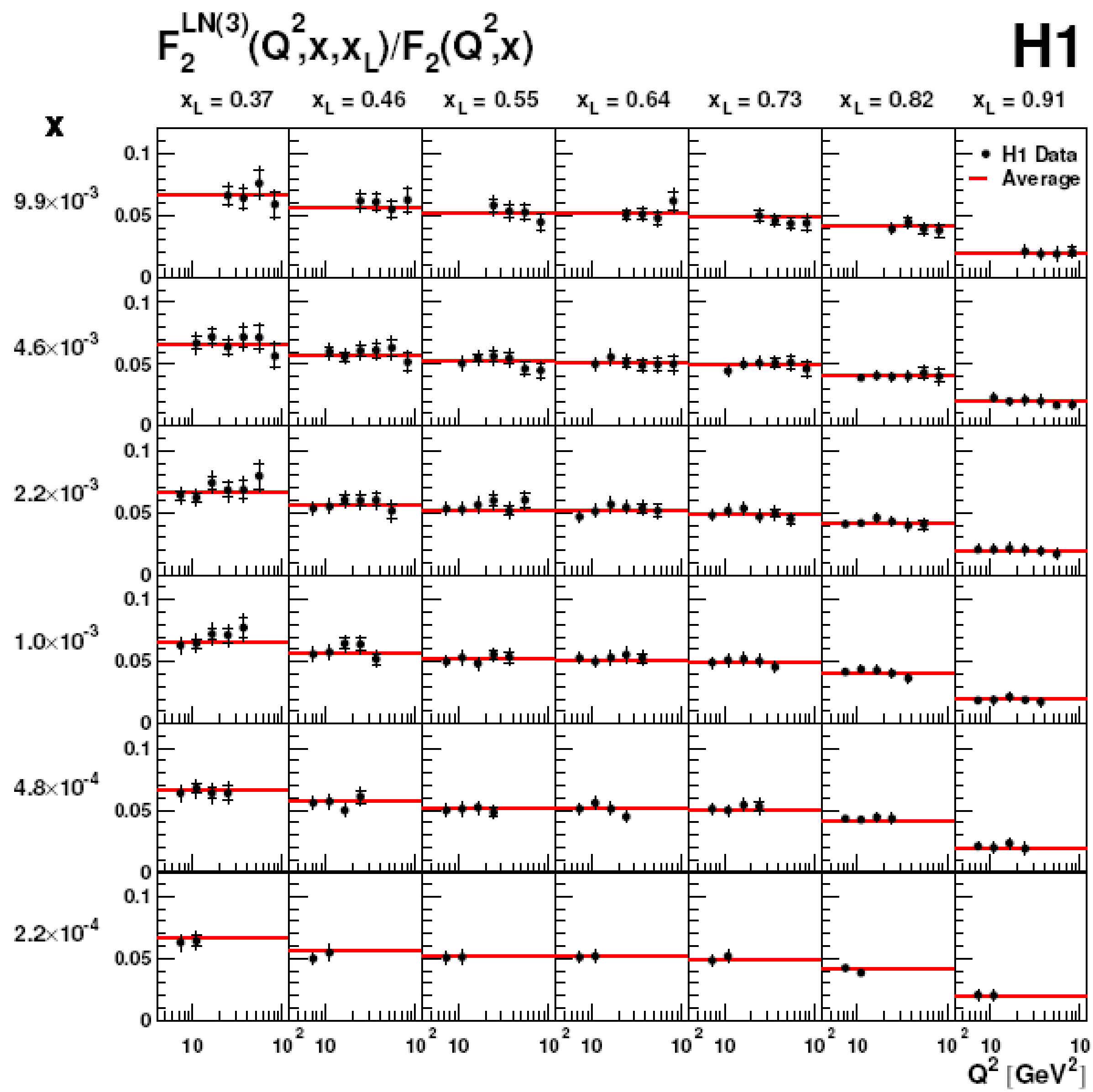
$$F_2^{LN(3)}(\beta, Q^2, x_L) \sim \beta^{-\lambda}$$

- λ is independent of x_L
  → consistent with vertex factorization

- λ increases with Q^2: from 0.23 to 0.3
  → similar Q^2 evolution of $F_2^{LN(3)}$ and proton structure function F_2

→ leading neutron production in the proton fragmentation region in DIS is insensitive to Q^2 and x

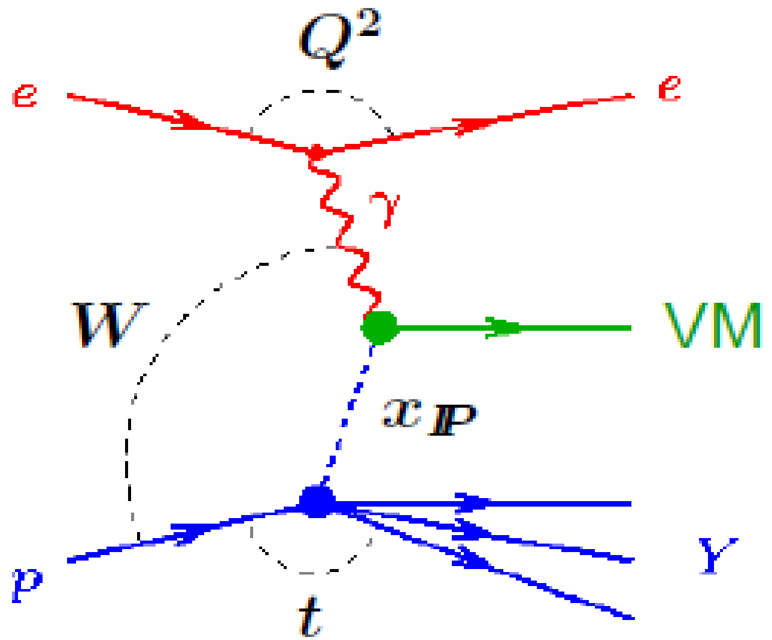
→ Ratio to inclusive F_2:



BACKUP SLIDES: VECTOR MESON PRODUCTION AND DVCS

Diffractive Vector Meson Production and DVCS

$$e + p \rightarrow e + VM \; (= \rho, \phi, J/\psi, ..., or\ \gamma) + Y \; (or\ p)$$



Q^2	Photon Virtuality Photoproduction: $Q^2 \sim 0$
W	γp CMS energy
t	4-momentum transfer squared
$x_{I\!P}$	Momentum fraction of the colour singlet exchange

Regge Theory

= Soft $I\!P$omeron exchange

$$\sigma \propto \left(\frac{W}{W_0}\right)^{4(\alpha_{I\!P}(t)-1)}$$

$$\alpha_{I\!P}(t) = 1.08 + 0.25\,t \text{ (DL)}$$

Light VM at low Q^2 and low $|t|$

pQCD Models

Exchange of $\geq$ 2 gluons

$$\sigma \propto (xG(x, Q^2))^2$$

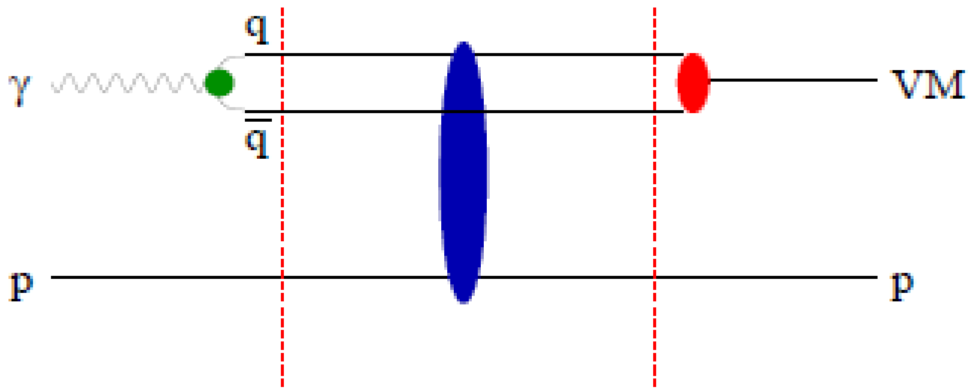
Steep rise of $xG(x, Q^2)$

Requires hard scale: Q^2, t or m_q

$\Longrightarrow$ Investigate transition between soft and hard regimes

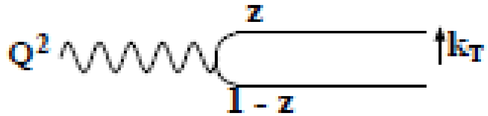
VM theory: Perturbative QCD approaches

Dipole approach (k_t factorisation)



$$\mathcal{A} = \Psi^{\gamma}_{q\bar{q}} \otimes \sigma_{q\bar{q}-p} \otimes \Psi^{V}_{q\bar{q}}$$

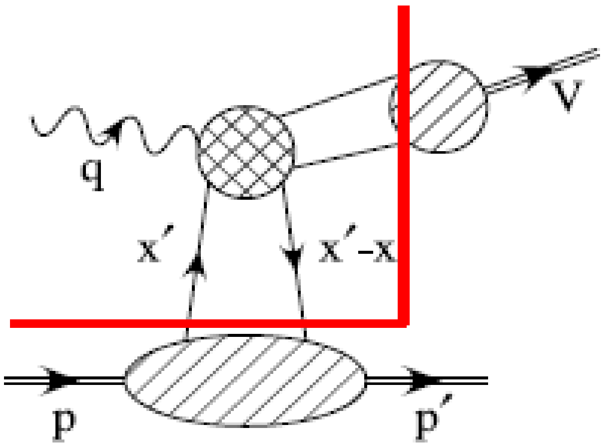
Scanning radius decrease with increasing
Q^2 or $M_V^2 \rightarrow \mu^2 = z(1-z)(Q^2 + M_V^2)$



$\longrightarrow \sigma_L \propto \frac{Q^2/M_V^2}{(Q^2+M_V^2)^4} [\alpha_s(\mu^2)\, G(x,\mu^2)]^2$
with $z \simeq 1/2 \rightarrow \mu^2 \simeq 1/4(Q^2 + M_V^2)$

$\longrightarrow \sigma_T \propto \frac{1}{(Q^2+M_V^2)^4} [\alpha_s(\mu^2)\, G(x,\mu^2)]^2$
with $z = 0, 1$ endpoints contributions
$\rightarrow$ hard scale damped

Collinear factorisation theorem



$$\mathcal{A}_L = f(x, x', t, \mu) \otimes H \otimes \Psi^V$$

where f_i: non-forward PDF ($x' \neq x$)
$\rightarrow$ Generalized Parton Density

Theorem proven for σ_L; often assumed for σ_T
Collins, Frankfurt & Strikman [hep-ph/9611433]

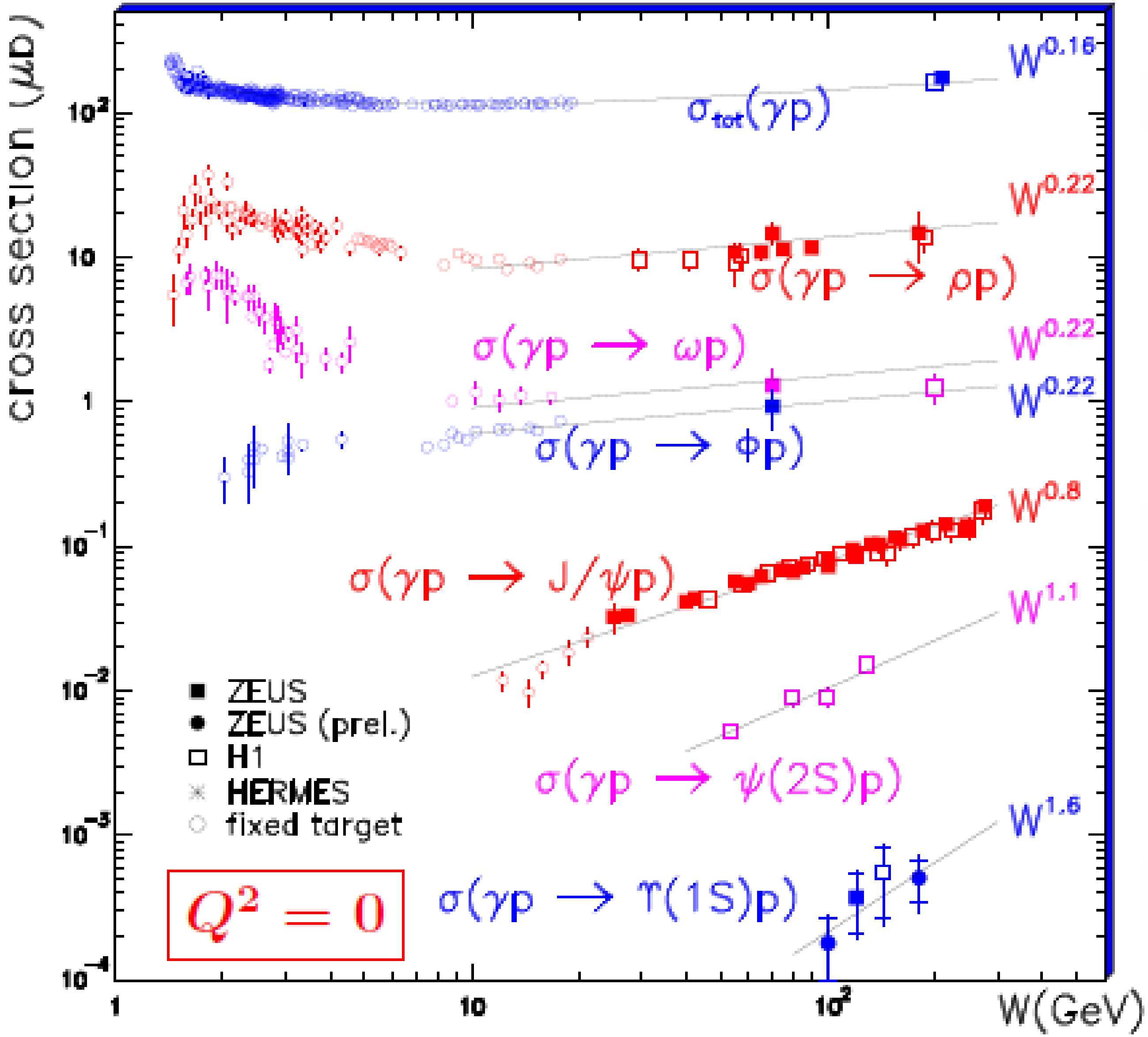
Dipole - Saturation:
- Kowalski, Motyka, Watt (KMW) [hep-ph/0606272]
- Marquet, Peschanski, Soyez (MPS) [hep-ph/0702171]

Dipole - k_T factorisation:
- Ivanov, Nikolaev, Savin (INS) [hep-ph/0501034]

Collinear - GPD:
- Goloskokov, Kroll (GK) [hep-ph/07083569]

Parton hadron duality:
- Martin, Ryskin, Teubner (MRT) [hep-ph/9609448]

Soft to hard transition: mass



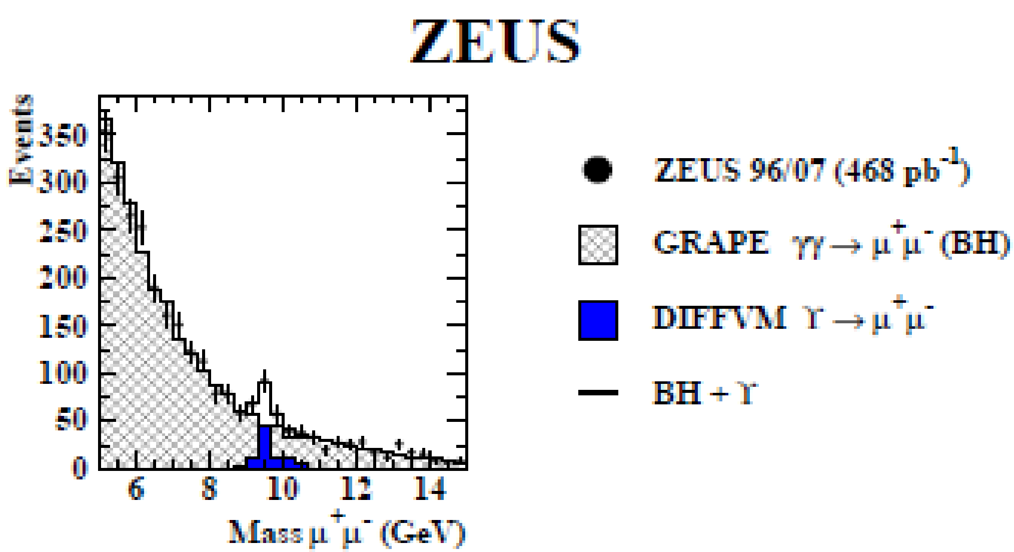
- Low mass (ρ, ϕ, ω; $M_V^2 \simeq 1$ GeV^2): no pert. scale → weak energy dep. (soft regime)
- High mass (J/ψ, υ): pert. scale → strong energy dep. (hard regime)
- Large mass (Υ) important skewing effect

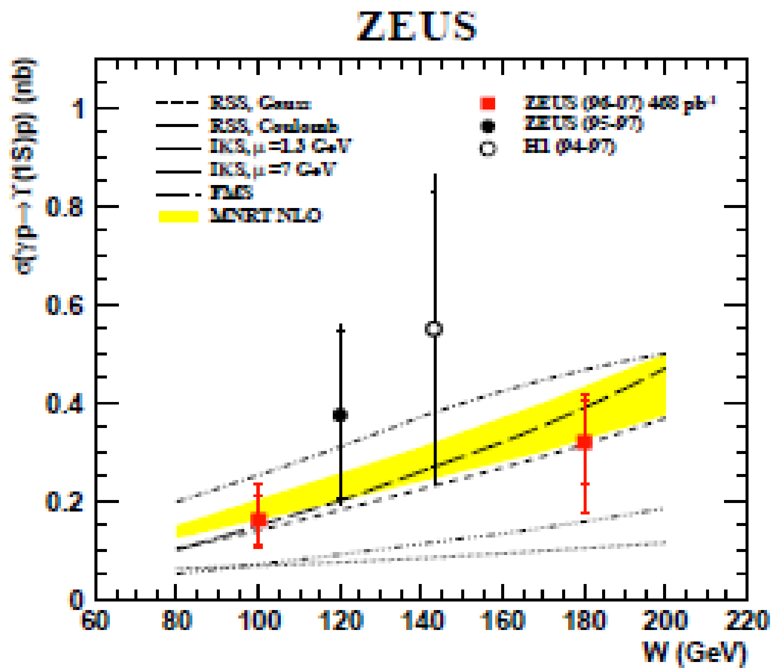
Upsilon Photoproduction

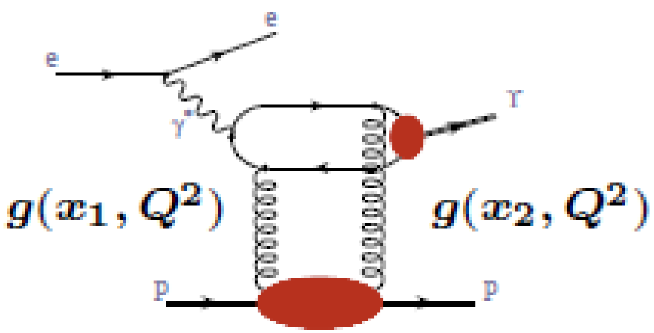
New ZEUS result:

1996-2007 data: 468 pb^{-1}
$60 < W < 220\ \mathrm{GeV},\ Q^2 < 1\ \mathrm{GeV}^2$
DESY-09-036 (accepted by PLB)

$$e + p \rightarrow e + \Upsilon + p$$
$$\Upsilon \rightarrow \mu^+ + \mu^-$$

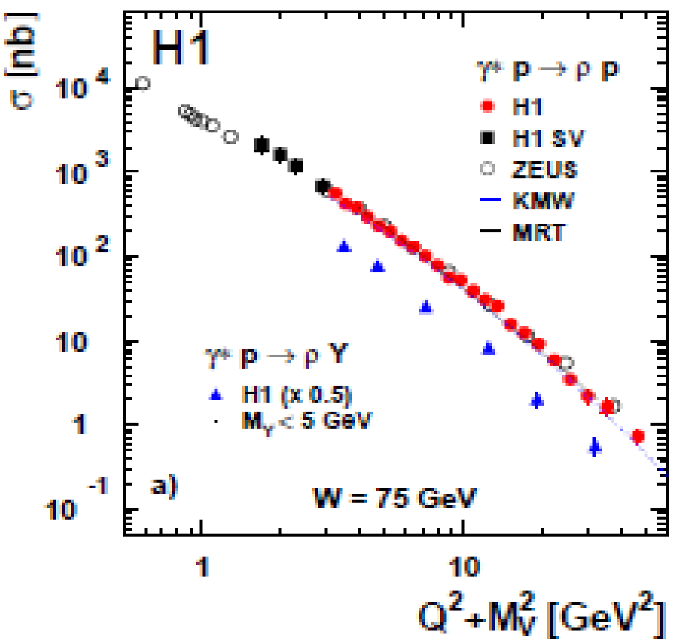


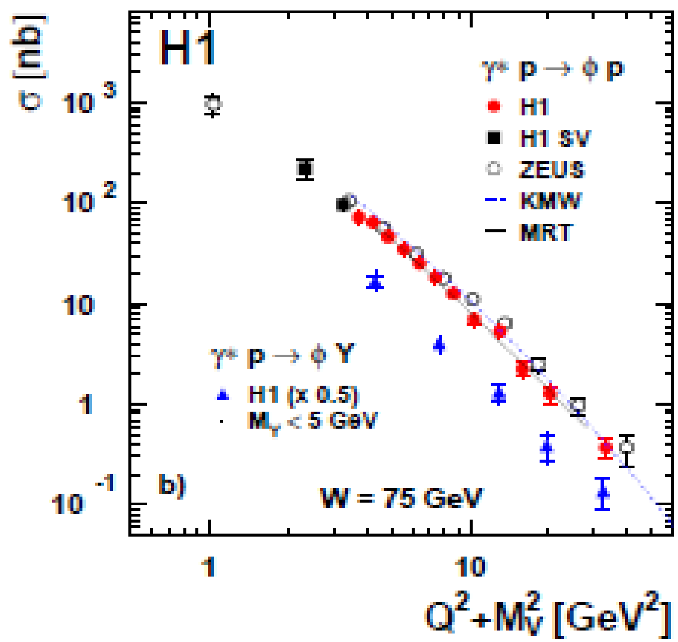




W dependence of the cross section is in agreement with pQCD models including skewing, i.e. $x_1 \neq x_2$

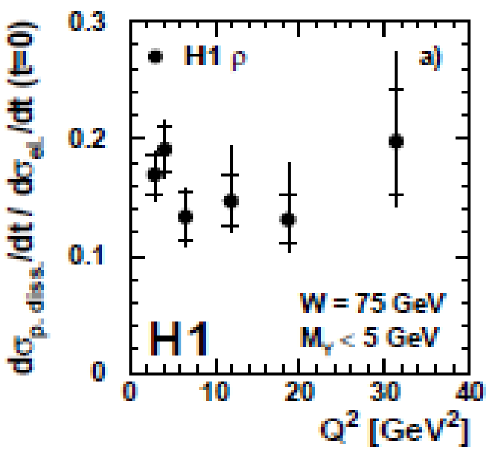
Q^2 dependence

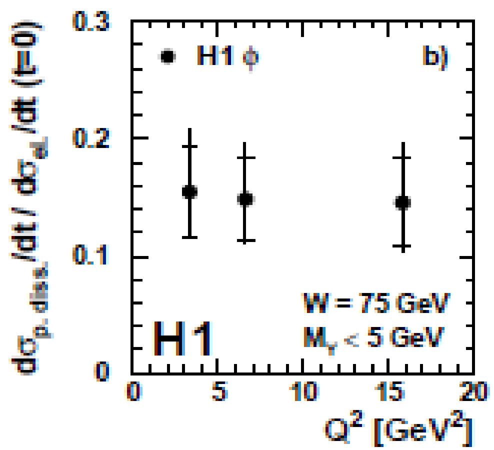


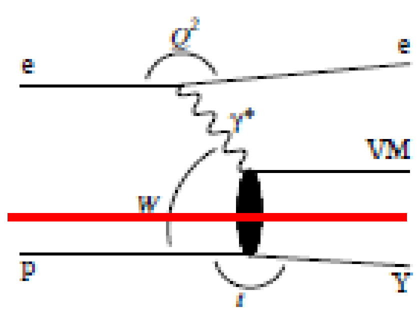


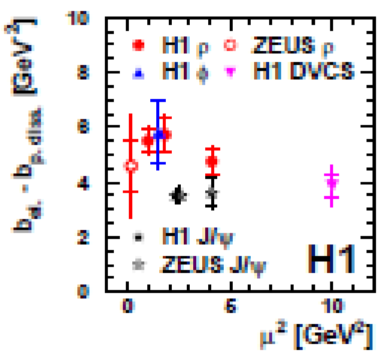
- High precision for elastic cross-sections
- First ϕ p-diss. cross-section
- H1 Zeus relative agreement

Test of vertex (“Regge”) factorisation:





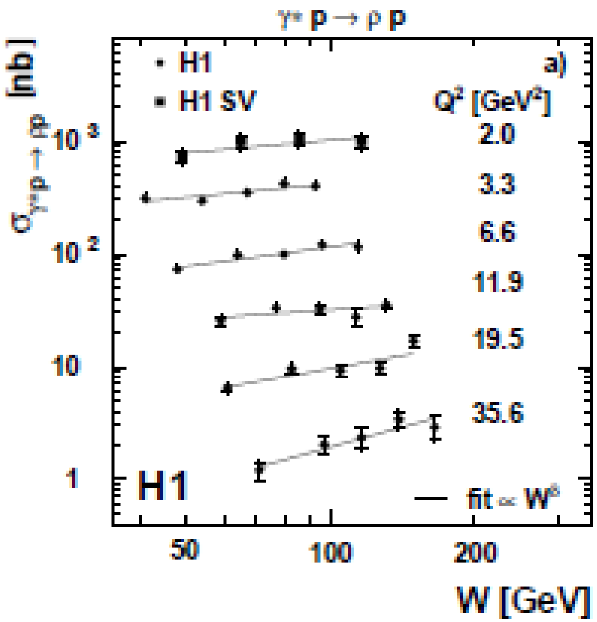




- p.diss/el : no Q^2 dep.
- t-depend. : no Q^2 dep.

$\longrightarrow$ vertex factorisation

Soft to hard transition - $\sigma(W)$



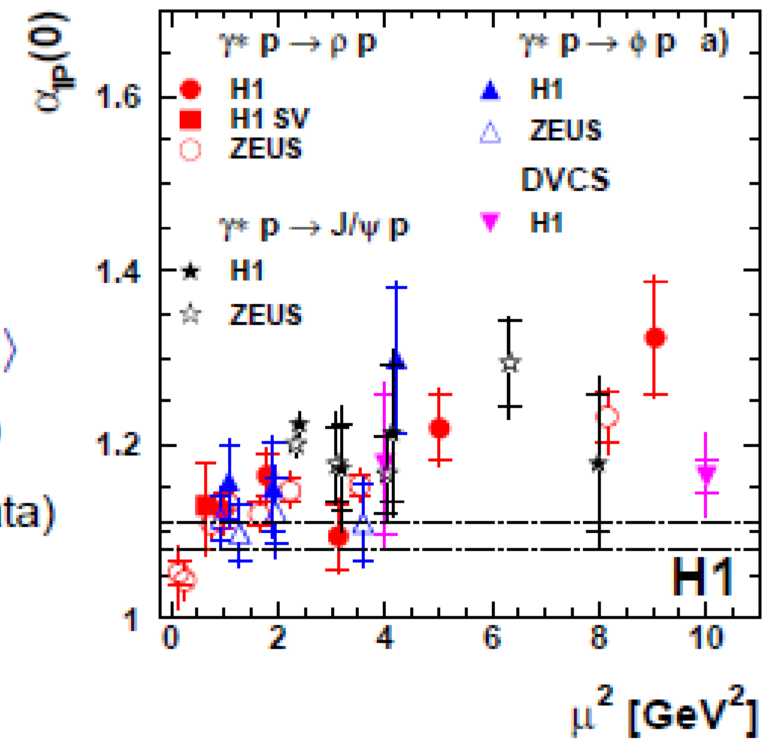
$$\sigma(W) \propto W^{\delta}$$

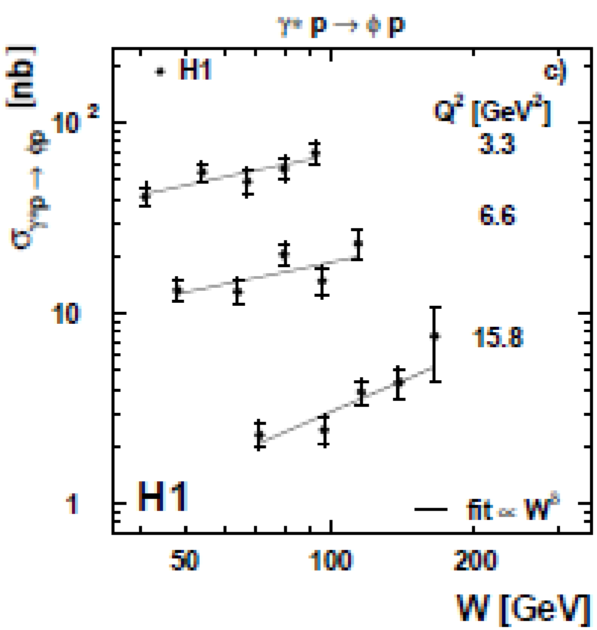
$$\alpha_{\mathbb{P}}(0) = 1 + \delta/4$$

$$+\alpha'_{\mathbb{P}}/\langle|t|\rangle$$

$\alpha'_{\mathbb{P}}$: 0-0.25 (⟶data)

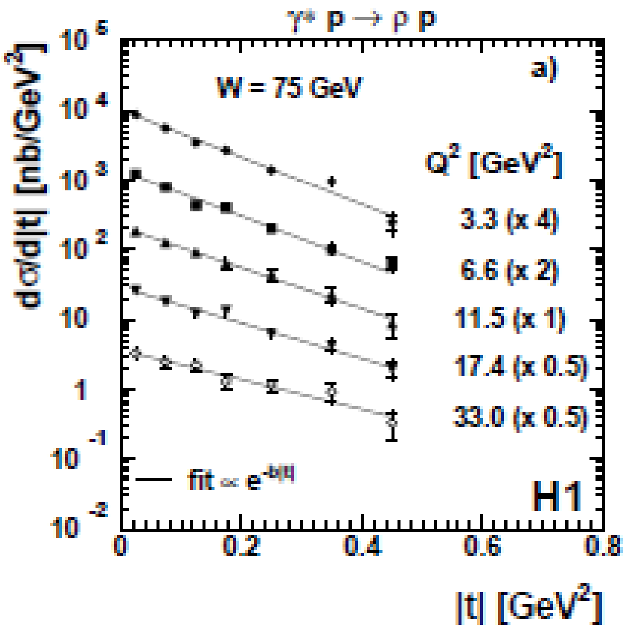
$\langle|t|\rangle$: b-slopes (⟶data)





- Common hardening of $\alpha_{\mathbb{P}}(0)$ with $Q^2 + M^2$ for all VM and DVCS
  $\Rightarrow$ Transition from soft to hard regime with $\mu^2 = (Q^2 + M^2)/4$
- Soft contributions (in σ_L ?) up to $\mu^2 \sim 5$ GeV^2 for ρ and ϕ

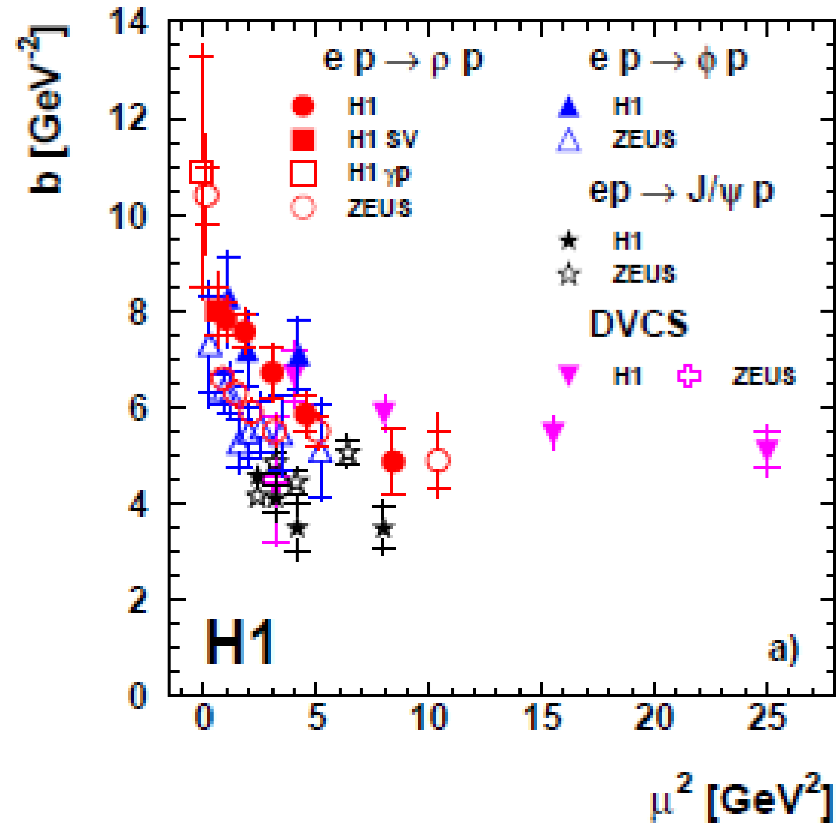
Soft to hard transition - t dependences

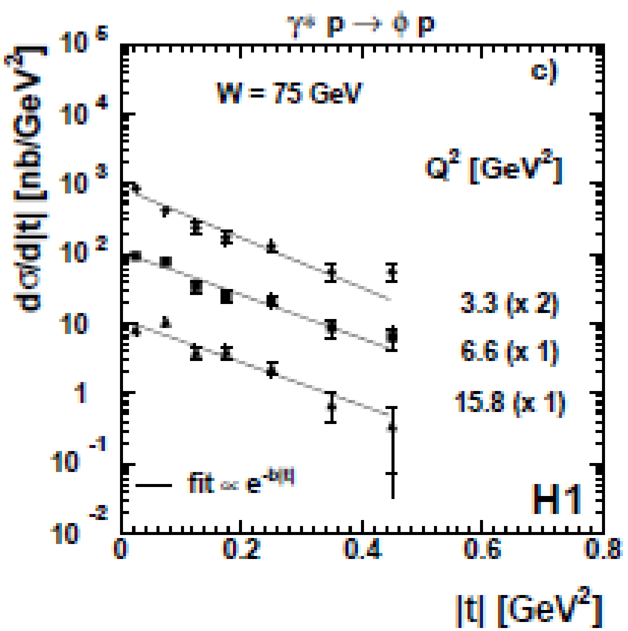


fit $e^{-b|t|}$

$b = b_p \otimes b_{q\bar{q}} \otimes b_{I\!P}$

$\rightarrow b \propto q\bar{q}$ dipole size

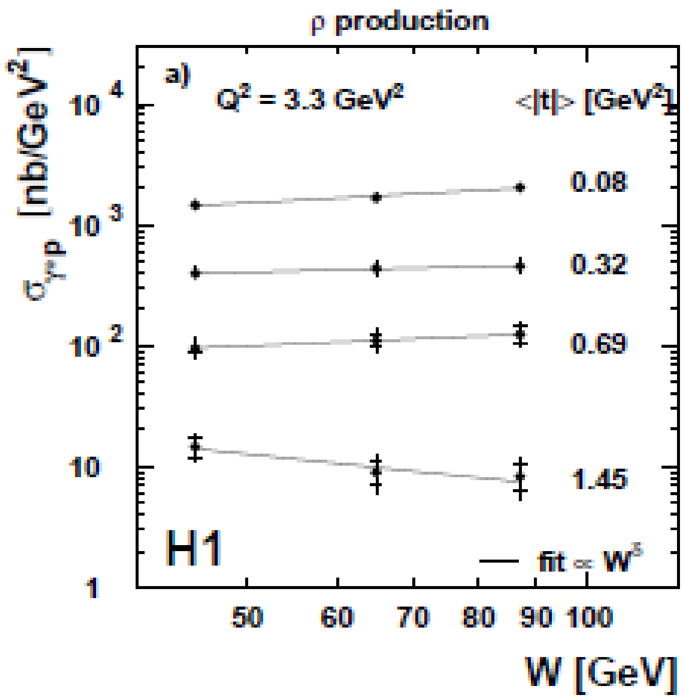


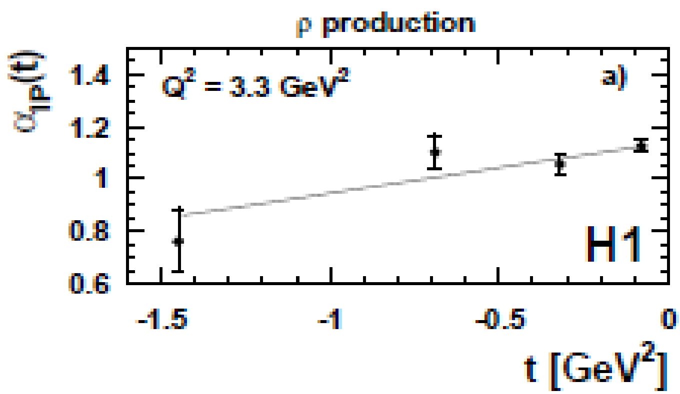


- b_ρ and b_ϕ decrease with μ^2
- Common value with J/ψ for $\mu^2 > 5\ \mathrm{GeV}^2$
- Large dipole for light VM at low Q^2

  $\Rightarrow$ Transition from soft to hard regime with μ^2

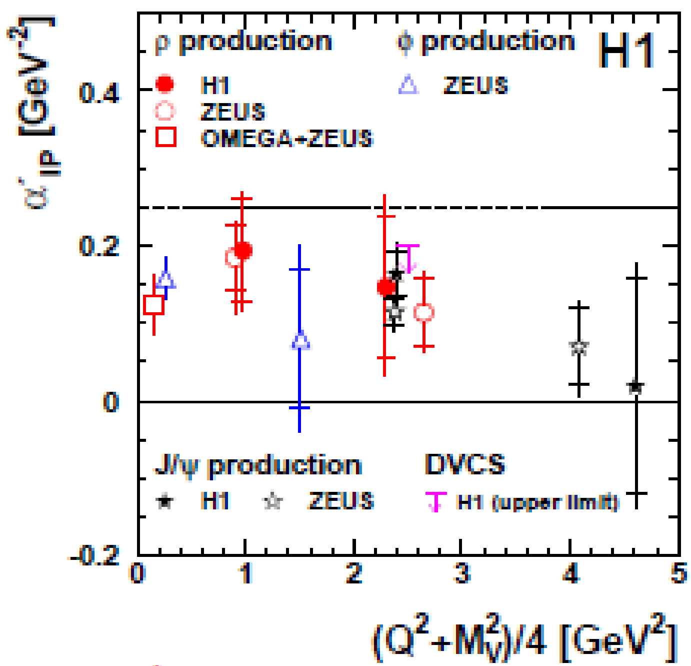
Shrinkage : $\alpha'_{I\!P}$ measurements





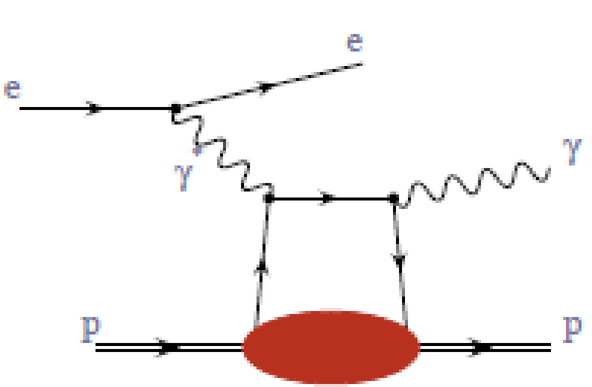
$$\frac{d\sigma}{dt}(W) \propto e^{b_0 t} W^{4(\alpha_{I\!P}(t)-1)}$$

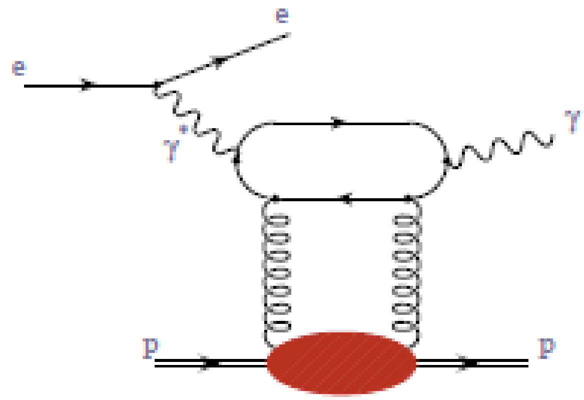
1. Study W depend. in bins of t:
   $\longrightarrow$ Fit: $W^{\delta} \longrightarrow \alpha_{I\!P}(t) = 1 + \delta/4$
2. Study $\alpha_{I\!P}(t)$ trajectories:
   $\longrightarrow$ Fit: $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t$

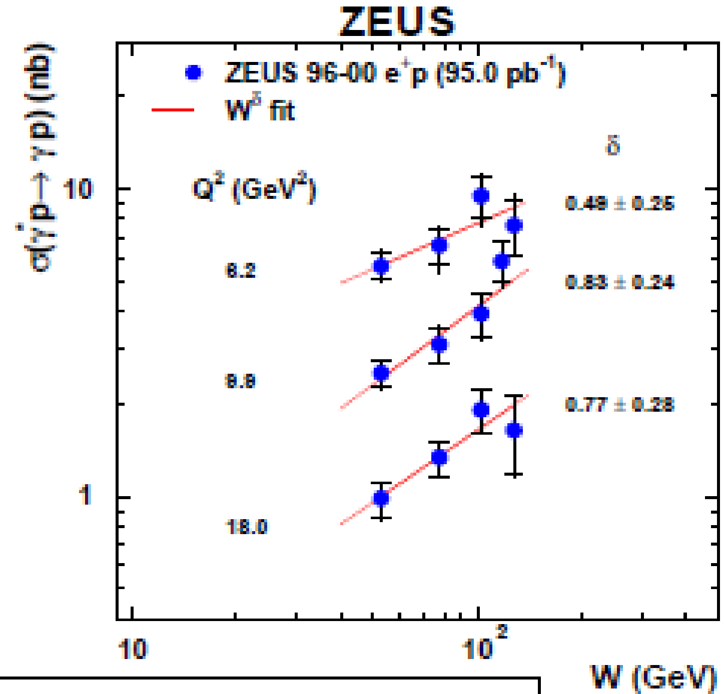


$\Rightarrow$ For all VM, $\alpha'_{I\!P}$ smaller than 0.25 (DL, $p\bar{p}$)
(cf BFKL, multiple $I\!P$ exchange)

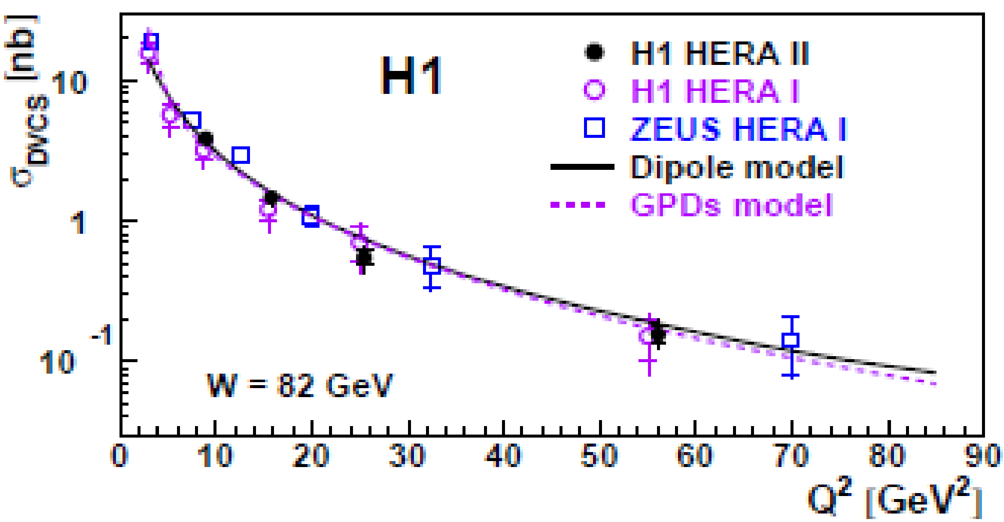
Deep Virtual Compton Scattering

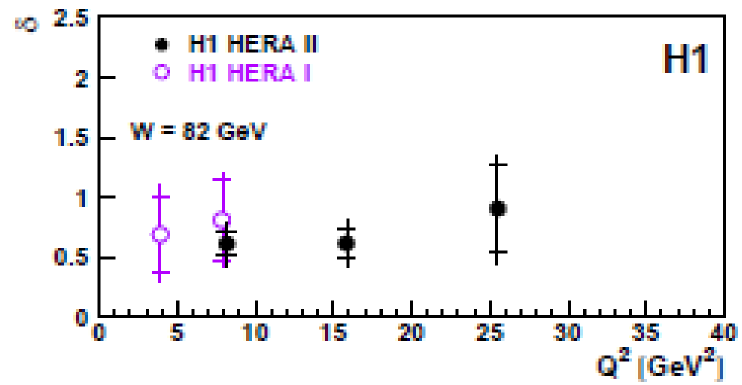






- fully calculable in pQCD
- Access to the full QCD amplitude
- Constrain gluon GPDs



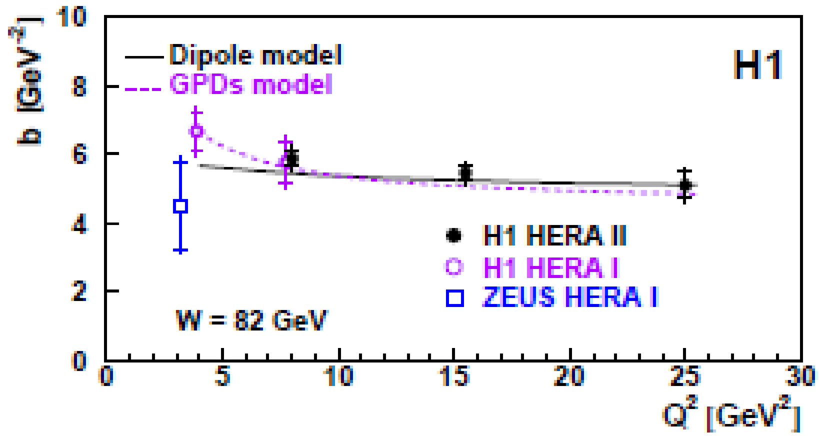


W dependence indicates a hard regime (similar to J/Ψ)

DVCS: t slope and Beam Charge Asymmetry

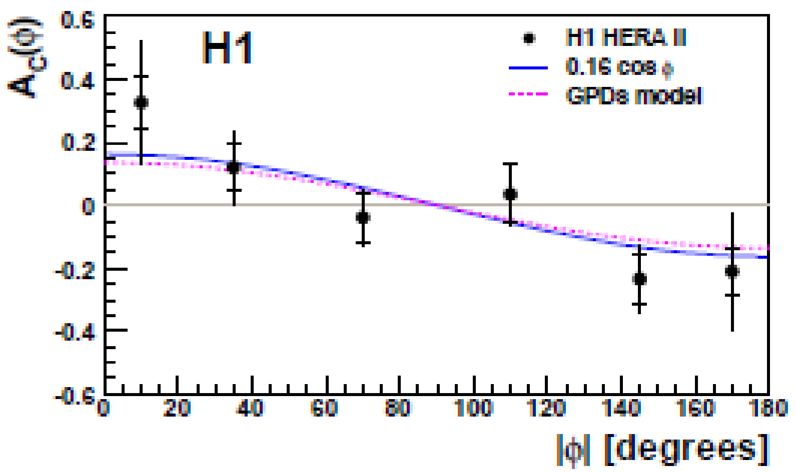
H1 measurement based on 291 pb^{-1} of HERA II data (e^+ and e^-).

- t slope as a function of Q^2



$\Rightarrow$ Similar behaviour with VM using the scale $Q^2 + M^2_{VM}$

- First DVCS BCA measured at HERA.



$$BCA \equiv \frac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)} \sim p_1 cos(\Phi)$$

DVCS: QCD interpretation

- correct Q^2 dependence of the propagator and of b in the cross section:

$$S = \sqrt{\frac{\sigma_{DVCS}\, Q^4\, b(Q^2)}{(1+\rho^2)}}$$

- skewing factor: around 2

$$R = \frac{\mathcal{I}m\, A(\gamma^* p \to \gamma p)}{\mathcal{I}m\, A(\gamma^* p \to \gamma^* p)}$$

$$= \frac{4\sqrt{\pi\, \sigma_{DVCS}\, b(Q^2)}}{\sigma_T(\gamma^* p \to X)\sqrt{(1+\rho^2)}}$$

$\Rightarrow$ important skewing factor

$\Rightarrow$ Q^2 evolution close to the one of DIS (pure DGLAP)