Diffraction and Vector Meson Production at HERA

M.Kapishin, JINR

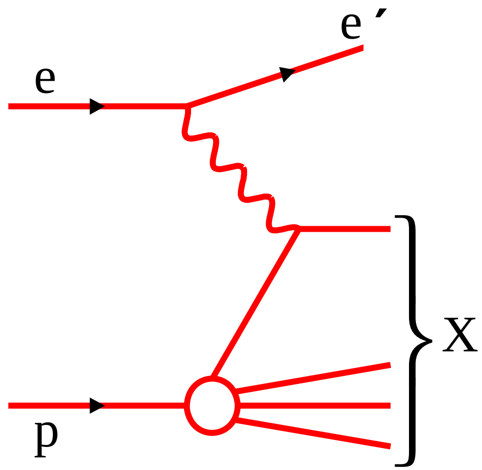
On behalf of the H1 and ZEUS Collaborations

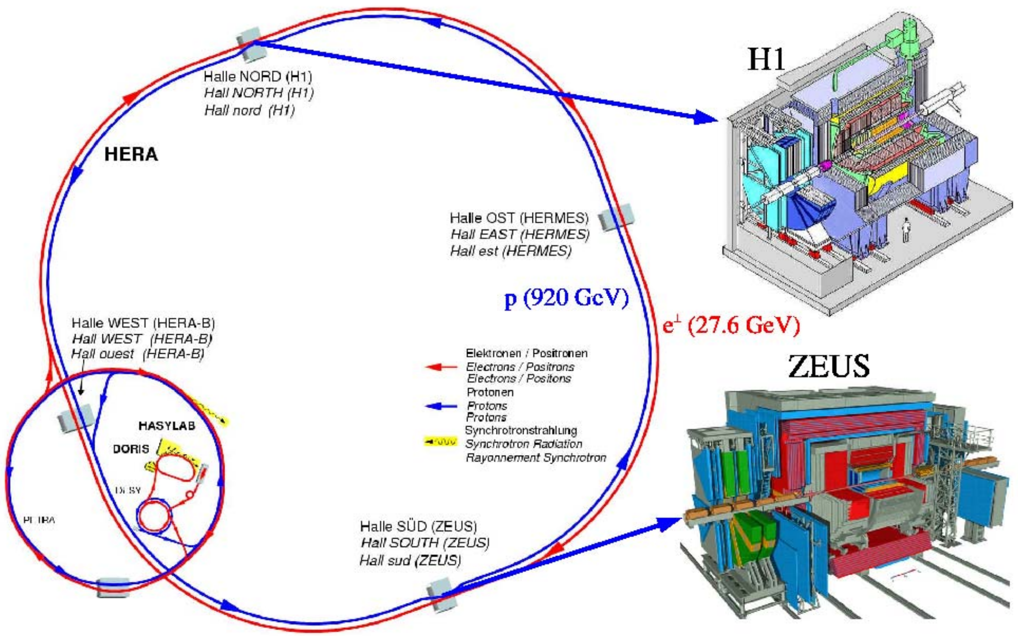
- Inclusive diffractive DIS
- Diffractive PDFs from combined QCD Fit to inclusive diffractive DIS and Dijets
- Dijets and open charm in DIS and photo-production: test of QCD factorization
- Exclusive vector meson production and DVCS

Diffractive DIS at HERA

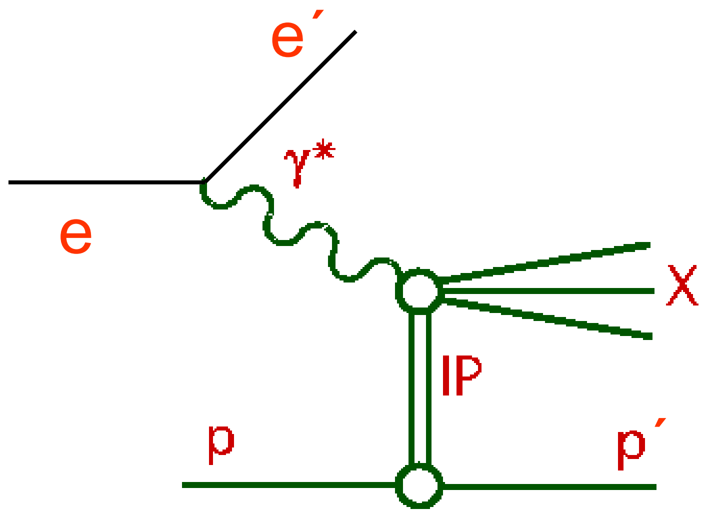
HERA: ~10% of low-x DIS events are diffractive

➔ study QCD structure of high energy diffraction with virtual photon





DIS: Probe structure of proton → F_2



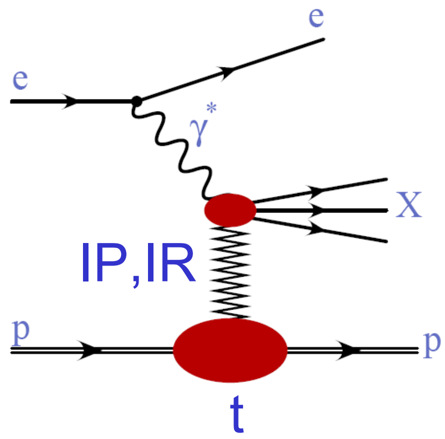
Diffractive DIS: Probe structure of color singlet exchange → F_2^D

Diffraction at HERA: from soft to hard

- **Soft processes at HERA**: $Q^2 \sim 0$, $|t|<1 GeV^2$

total γp cross section, low mass Vector Meson photo-production → similar to soft hadron diffraction

➔Regge approach to describe energy and t-dependences: exchange of IP and IR trajectories



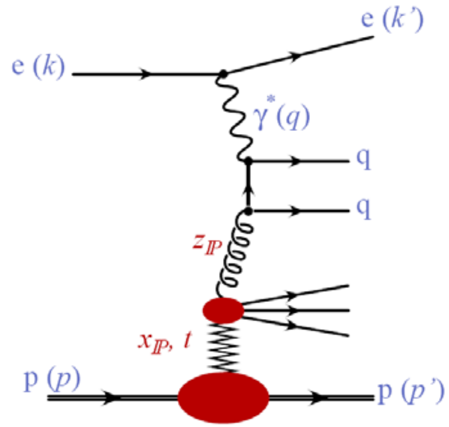
- **Transition to hard QCD processes:**

➔hard scales Q^2, E_t^{jet}, t, M_q

- **Diffraction in QCD:** color singlet exchange

Large Q^2 ➔ γ* probes parton structure of IP

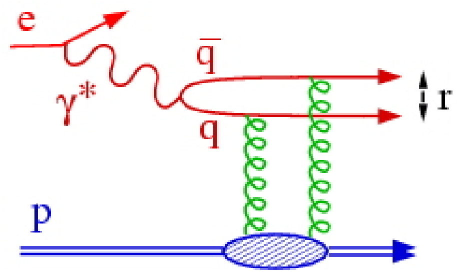
Large E_t^{jet} photo-production➔ test QCD collinear factorization



Large M_q ➔ charm, beauty photo-production

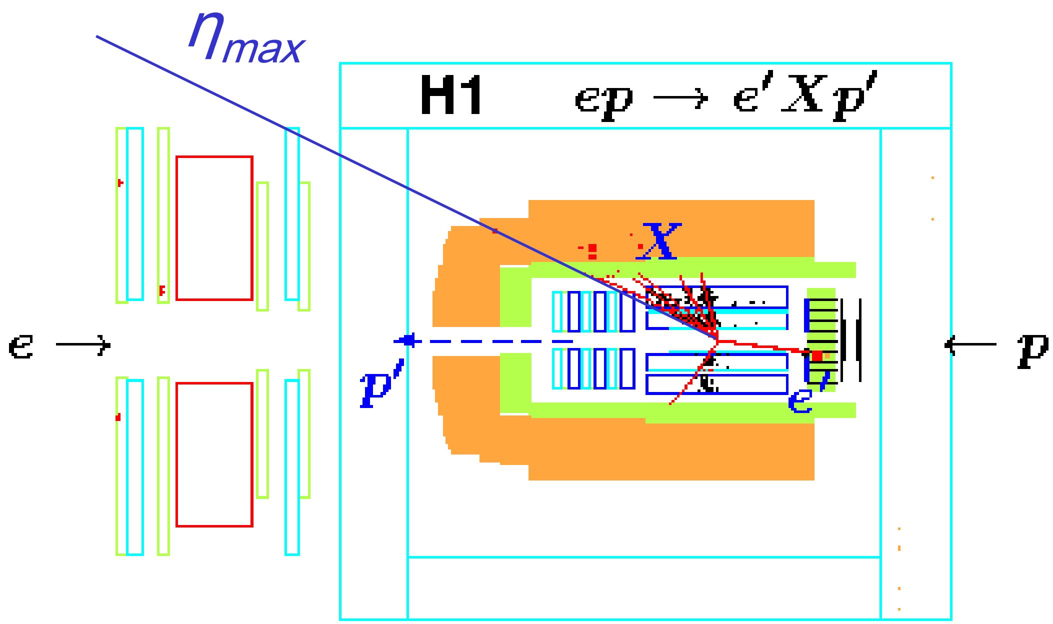
Large |t| ➔ sensitive to BFKL dynamics

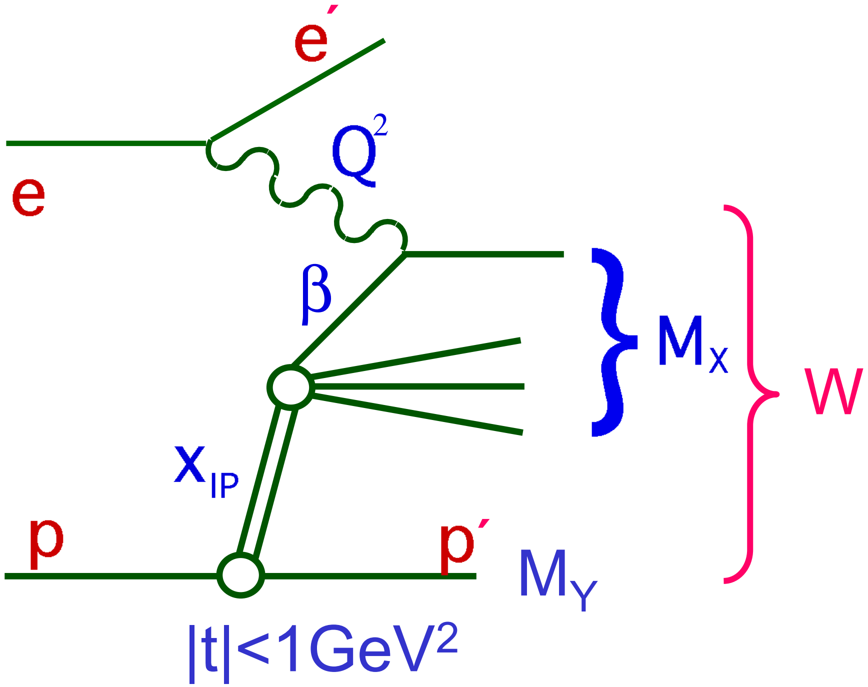
Color dipole approach ➔ 2 gluon exchange; transition to non pQCD → "saturation" at low Q^2



Selection of diffraction at HERA

Large rapidity gap between leading proton *p´* and *X*





Momentum fraction of proton carried by color singlet exchange:

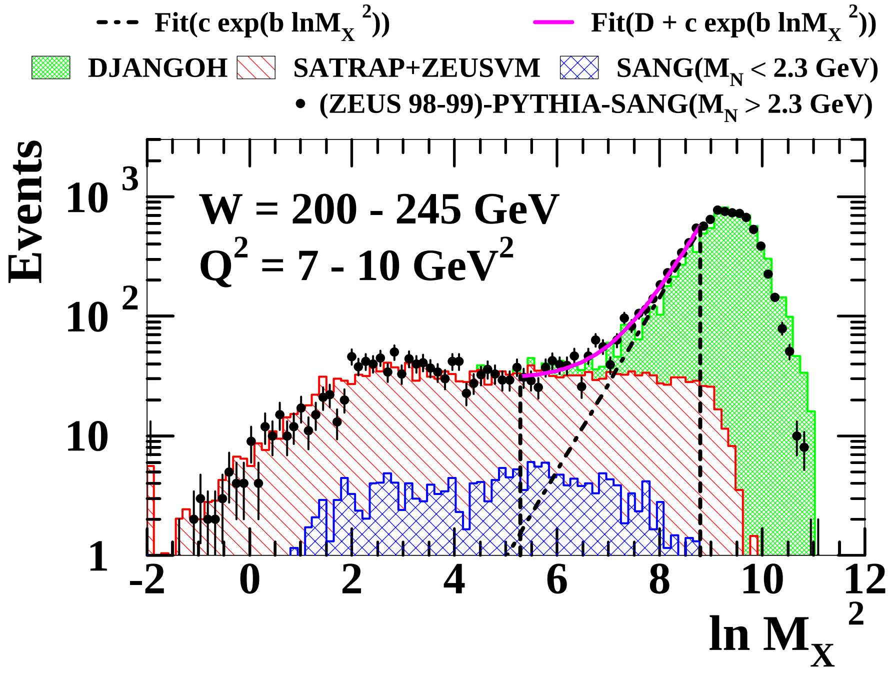
$$x_{\mathrm{IP}} = \frac{q \cdot (p - p')}{q \cdot p} \approx \frac{Q^2 + M_X{}^2}{Q^2 + W^2}$$

Momentum fraction of color singlet carried by struck quark:

$$\beta = \frac{x}{x_{IP}} \approx \frac{Q^2}{Q^2 + M_X{}^2}$$

Selection of diffraction at HERA

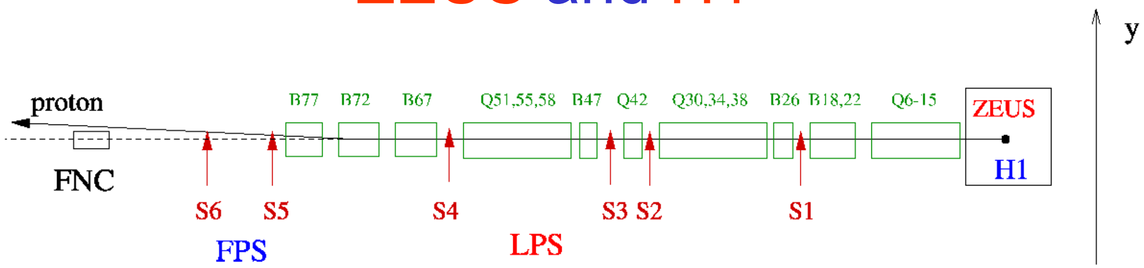
ZEUS: M_x method



$$\frac{dN}{dlnM_X^2} = D + c \cdot exp(b \cdot lnM_X^2)$$

- flat vs ln M_x^2 for diffractive events
- non-diffractive events subtracted from fit
- contamination from p-dissociation $ep \rightarrow eXY$, $M_Y < 2.3$ GeV

Leading Proton Spectrometers ZEUS and H1



- free of p-dissociation background
- t-measurement
- x_{IP} measurement

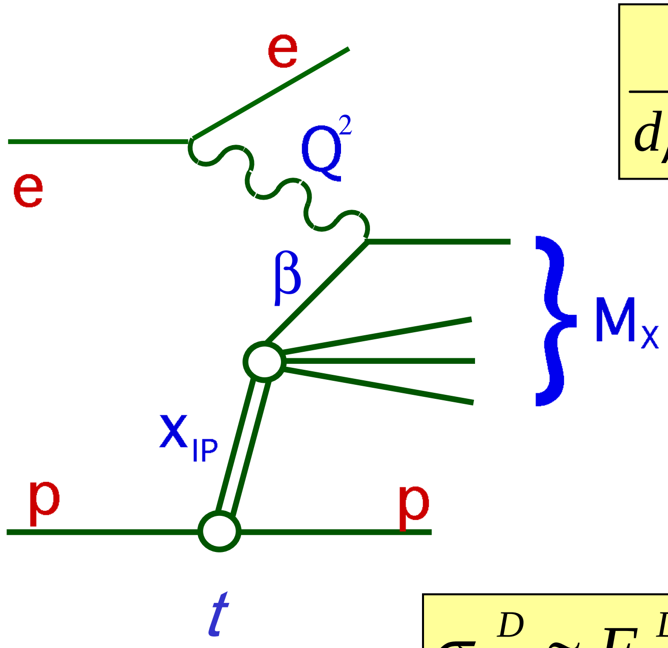
$$x_{IP} = 1 - \frac{E'_p}{E_p}$$

- access to high x_{IP} range (IP+IR)
- but low acceptance → low statistics

HERA-2: H1 Very Forward Proton Spectrometer at ~220m

➔ large acceptance at low x_{IP}

Diffractive Reduced Cross Section



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

Relation to F_2^D and F_L^D:

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

$\sigma_r^D \approx F_2^D$ at low and medium y $\qquad \sigma_r^D = F_2^D$ if $F_L^D = 0$

Assumption: proton vertex factorization for IP and IR

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

IP and IR flux (Regge motivated): $f_{IP}(x_{IP}, t) = \frac{e^{B_{IP} t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$ $\qquad \alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP}' t$

Integrate over t while proton is not measured $\rightarrow \sigma_r^{D(3)}$

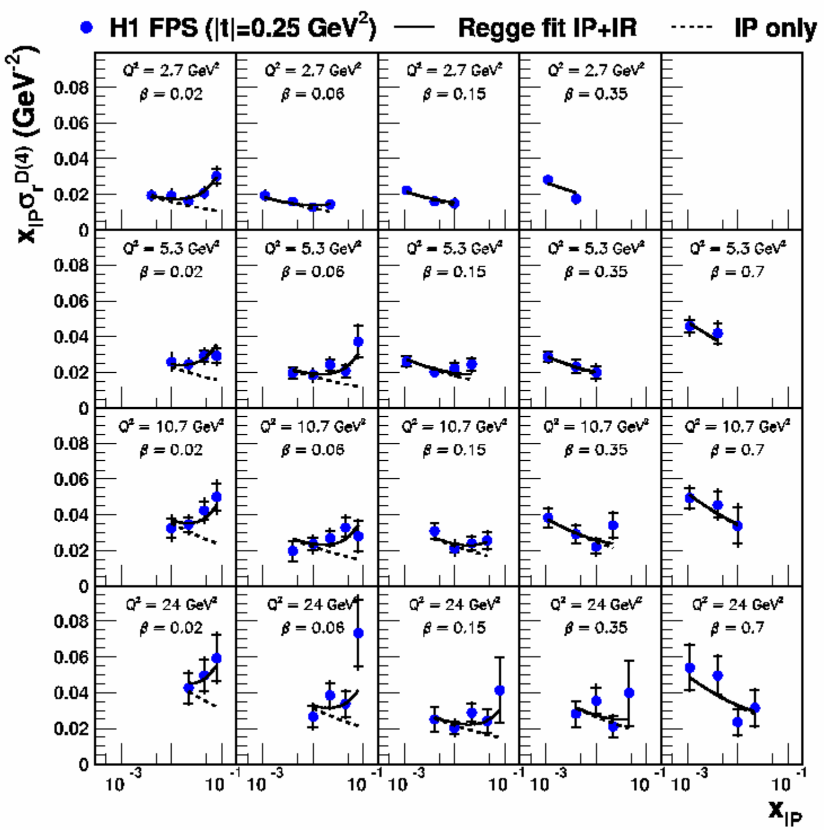
Diffractive DIS with LPS method

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

- Parameterization of x_{IP} dependence → IP intercept

H1:

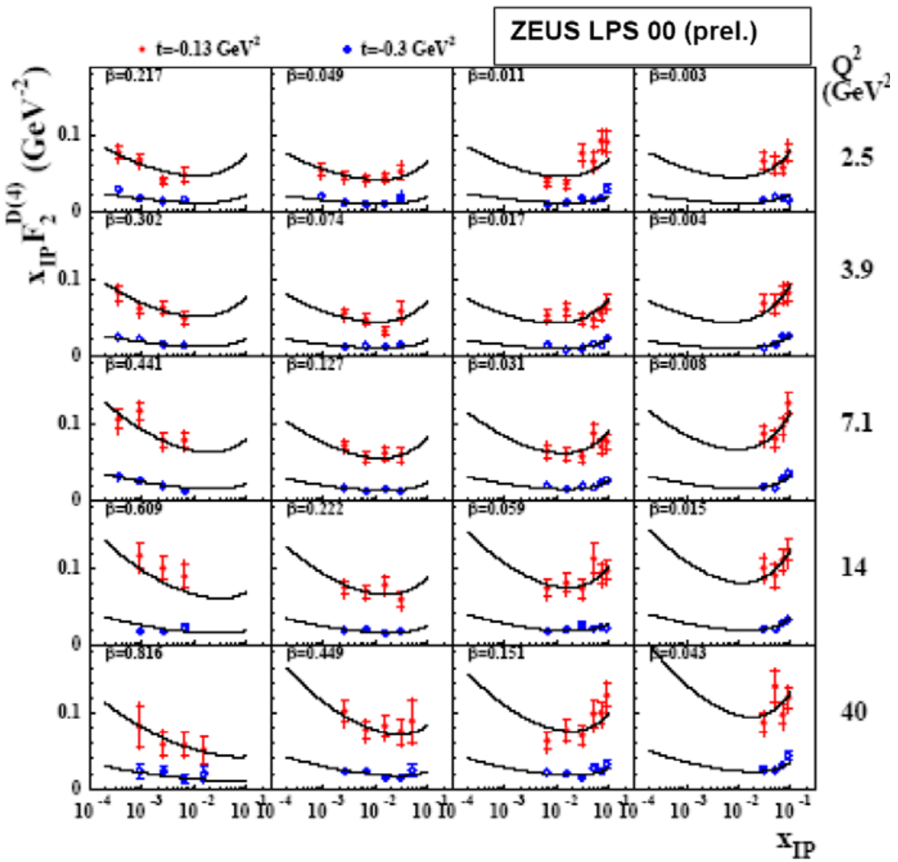
$$\alpha_{IP}(0) = 1.118 \pm 0.008\ (\text{exp.})\ ^{+0.029}_{-0.010}\ (\text{theory})$$



ZEUS:

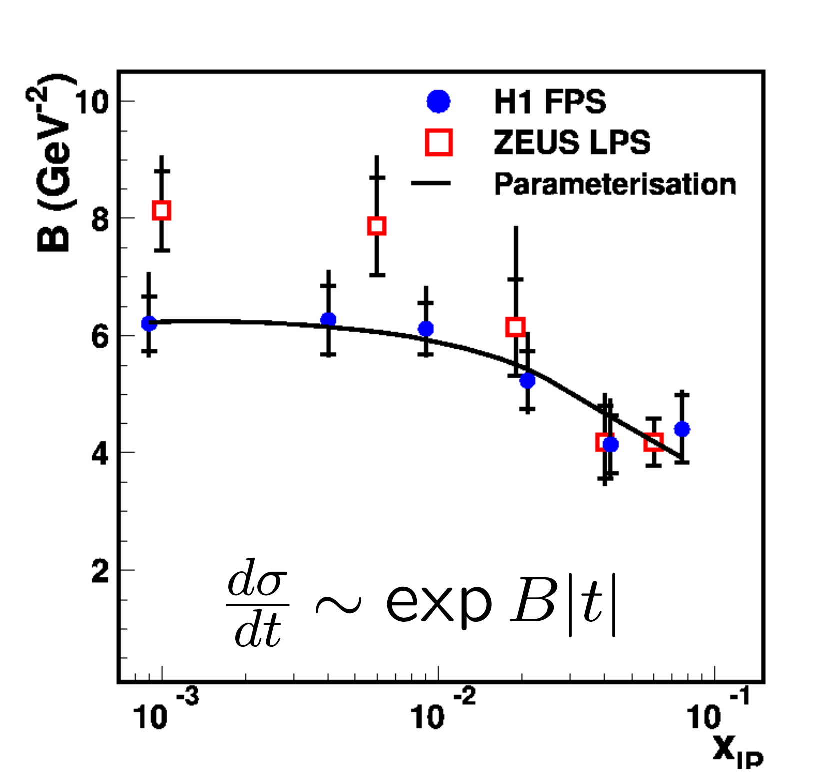
$$\alpha_{IP}(0) = 1.117 \pm 0.005\ (\text{stat.})\ ^{+0.024}_{-0.007}\ (\text{theory})$$

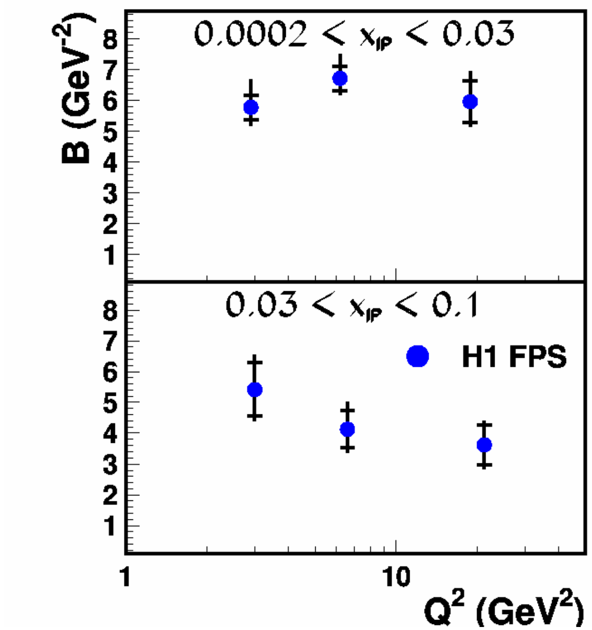
● t = -0.13 GeV² ● t = -0.3 GeV²



Diffractive DIS: t-dependence

- LPS measurements





- t dependence does not change with β or Q^2 at fixed $x_{IP} \rightarrow$ consistent with proton vertex factorization
- α'_{IP} is not "soft" (α'_{IP}(soft)~0.25 GeV^{-2})

$$B = B_{IP} + 2\alpha'_{IP} \ln(1/x_{IP})$$

H1: $\alpha'_{IP} = 0.06^{+0.19}_{-0.06}\ \mathrm{GeV}^{-2}$

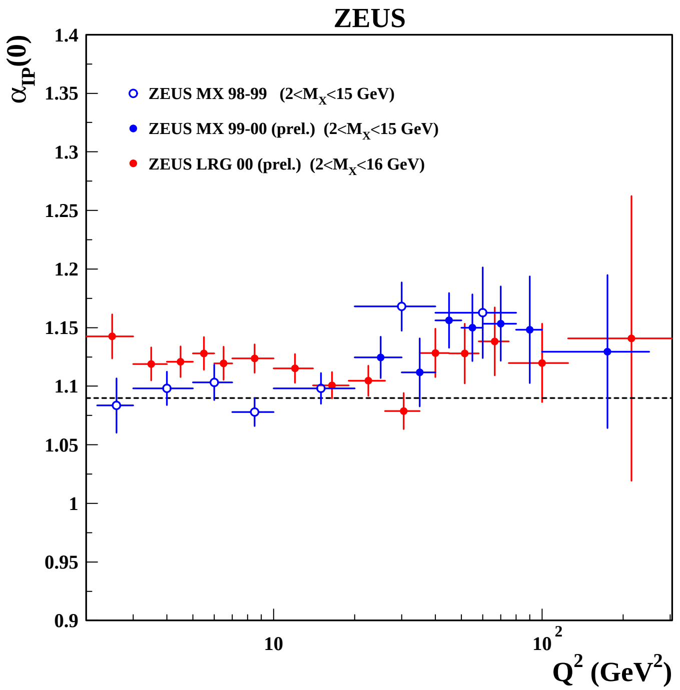
$B_{IP} = 5.5^{-2,0}_{+0.7}\ \mathrm{GeV}^{-2}$

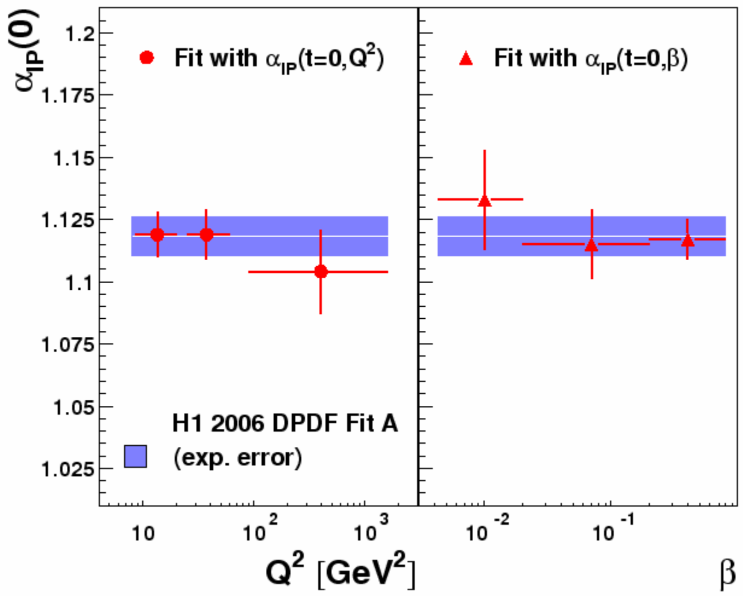
ZEUS: $\alpha'_{IP} = -0.03 \pm 0.07(stat.) \pm^{0.04}_{0.08} (syst.) GeV^{-2}$

$B_{IP} = 7.2 \pm 0.7(stat.) \pm^{1.4}_{0.7} (syst.) GeV^{-2}$

from Regge fit of $F_2^{D(4)}$

Pomeron intercept vs Q^2 and β





Diffractive cross section:

ZEUS Mx

$$\frac{d\sigma^{diff}}{dM_X^2} \propto (W^2)^{2\bar{\alpha}_{IP}-2}$$

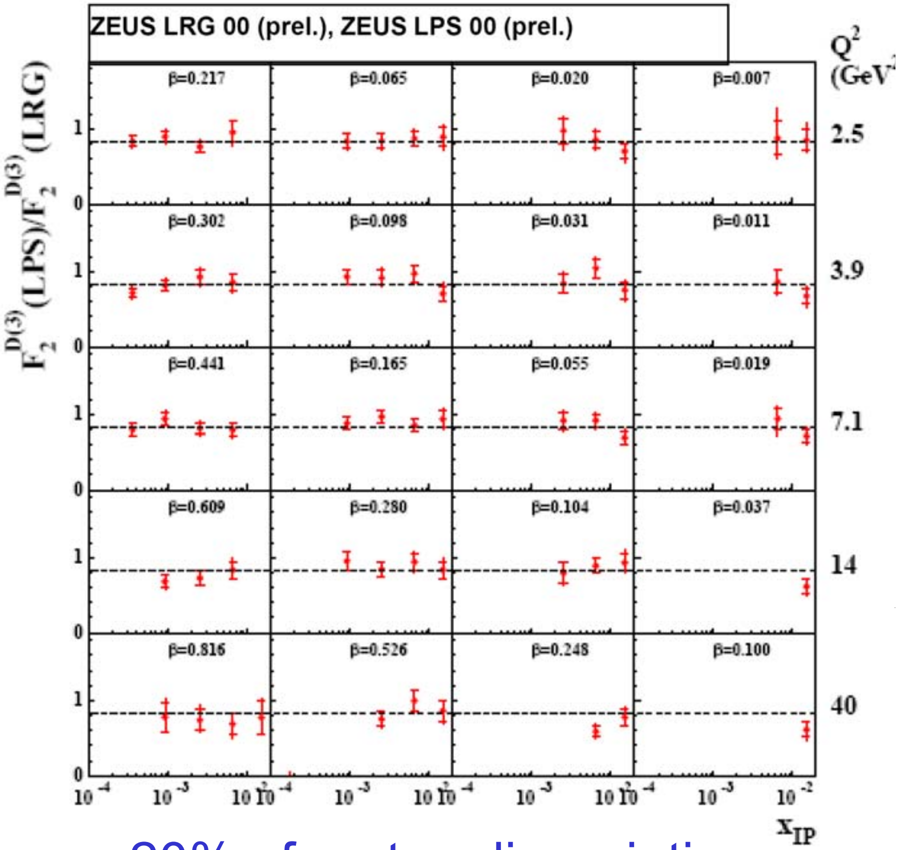
H1 / ZEUS LRG

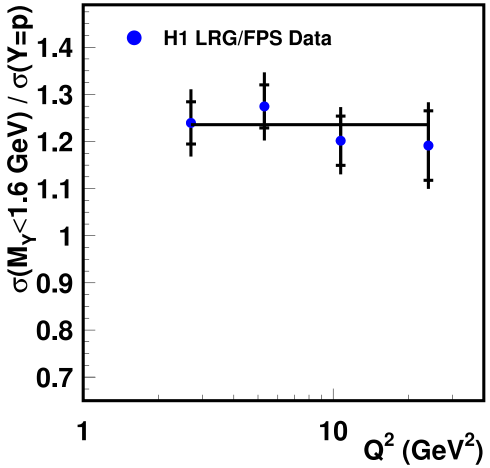
$$x_{IP}F_2^D \propto A(\beta,Q^2)\cdot x_{IP}^{2-2\alpha_{IP}(t)}$$

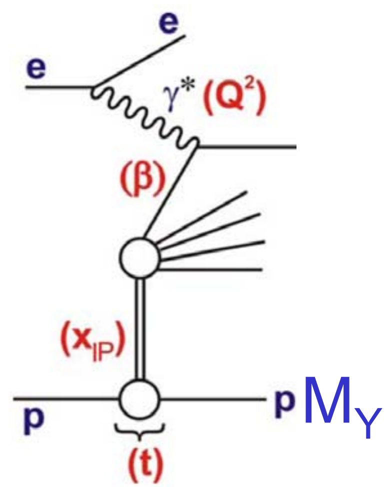
Pomeron intercept $\alpha_{IP}(0)$:

- data consistent within the errors with IP flux independent of Q^2 (H1 and ZEUS) and β (H1)→ support proton vertex factorization
- IP intercept is somewhat higher than α_{IP}(soft) ~1.096 extracted from soft hadron-hadron scattering

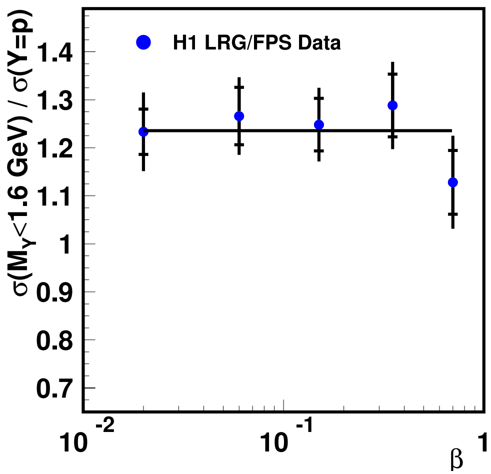
Comparing LRG with LPS data

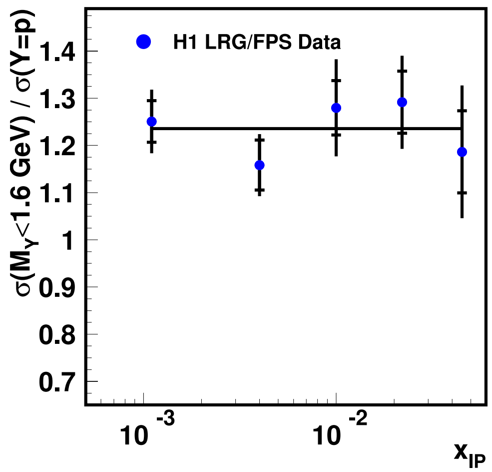






~20% of proton dissociation contribution in LRG data





LRG/LPS ratio independent of Q^2, β, x_{IP} within errors

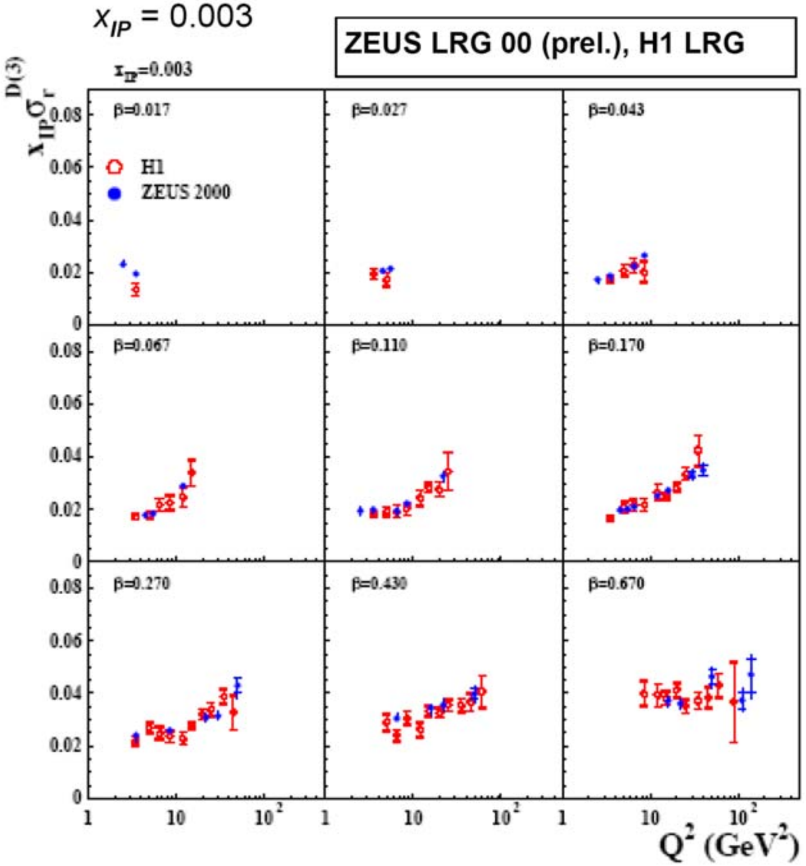
LRG and LPS data are consistent with proton vertex factorization →

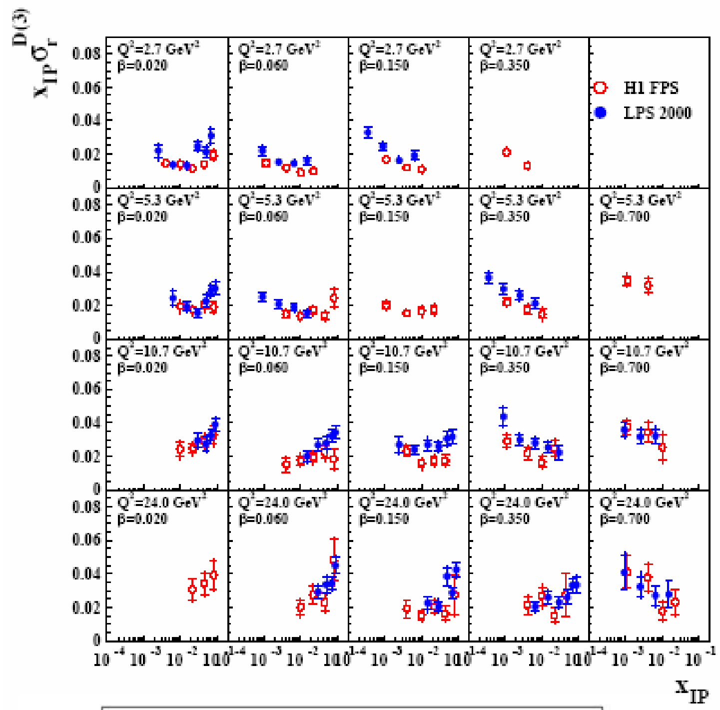
- x_{IP}, t and M_Y dependences factorise from the Q^2 and β dependences

Comparing H1 with ZEUS data

LRG data: H1 vs ZEUS

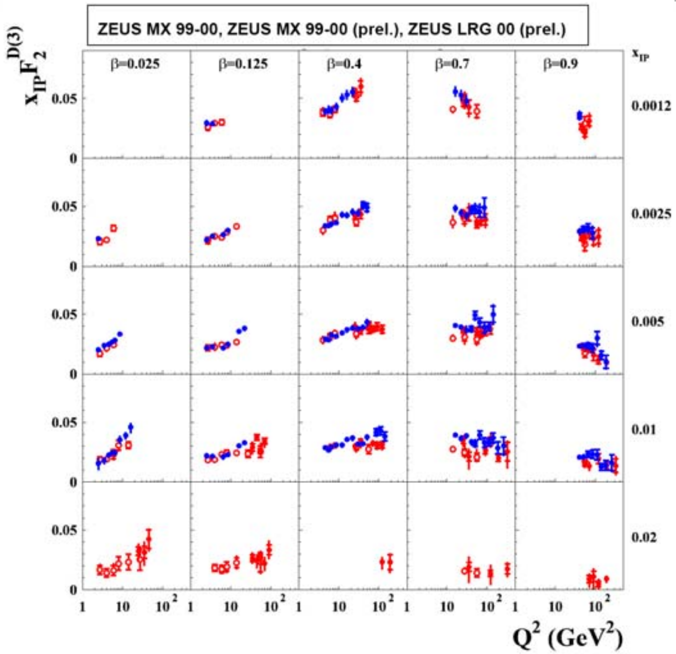
x_{IP} = 0.003





LPS data:

H1 vs ZEUS



ZEUS:

M_x vs LRG

Fair agreement between H1 and ZEUS results obtained with LRG, M_x and LPS methods (difference in normalization within 20%)

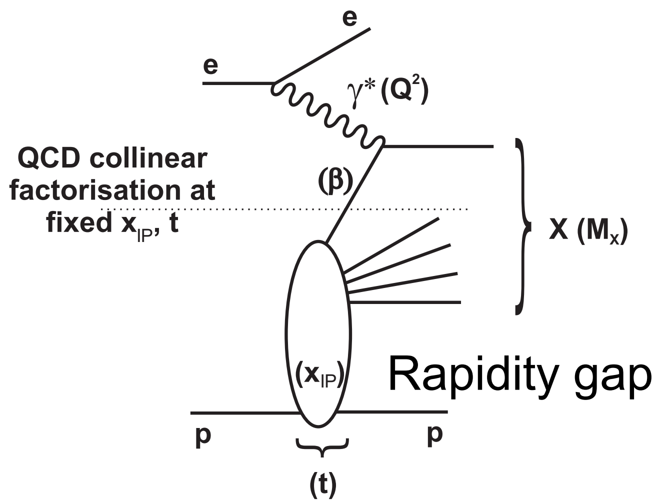
Factorization in Diffractive DIS

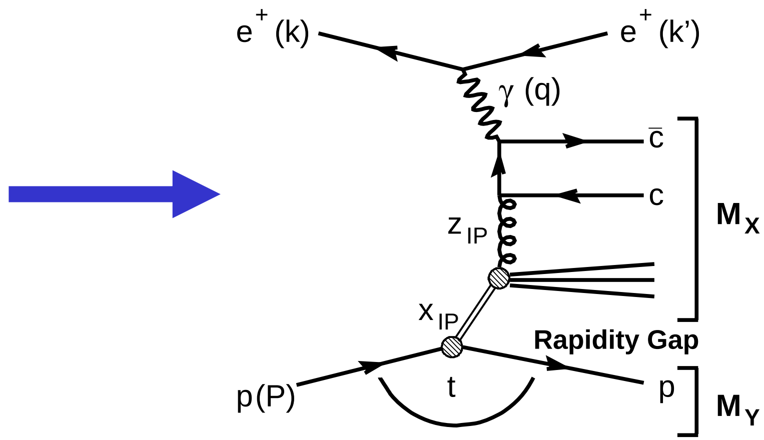
QCD hard scattering collinear factorization:

$$\sigma^D(\gamma^* p \to Xp) = \sum_{parton\_i} f_i^D(x, Q^2, x_{IP}, t) \cdot \sigma^{\gamma^* i}(x, Q^2)$$

$\sigma^{\gamma^* i}$ - universal hard scattering cross section (same as in inclusive DIS)
f_i^D - Diffractive Parton Distribution Function ➔ obey DGLAP, universal for diffractive *ep* DIS (inclusive, Dijets, Charm)

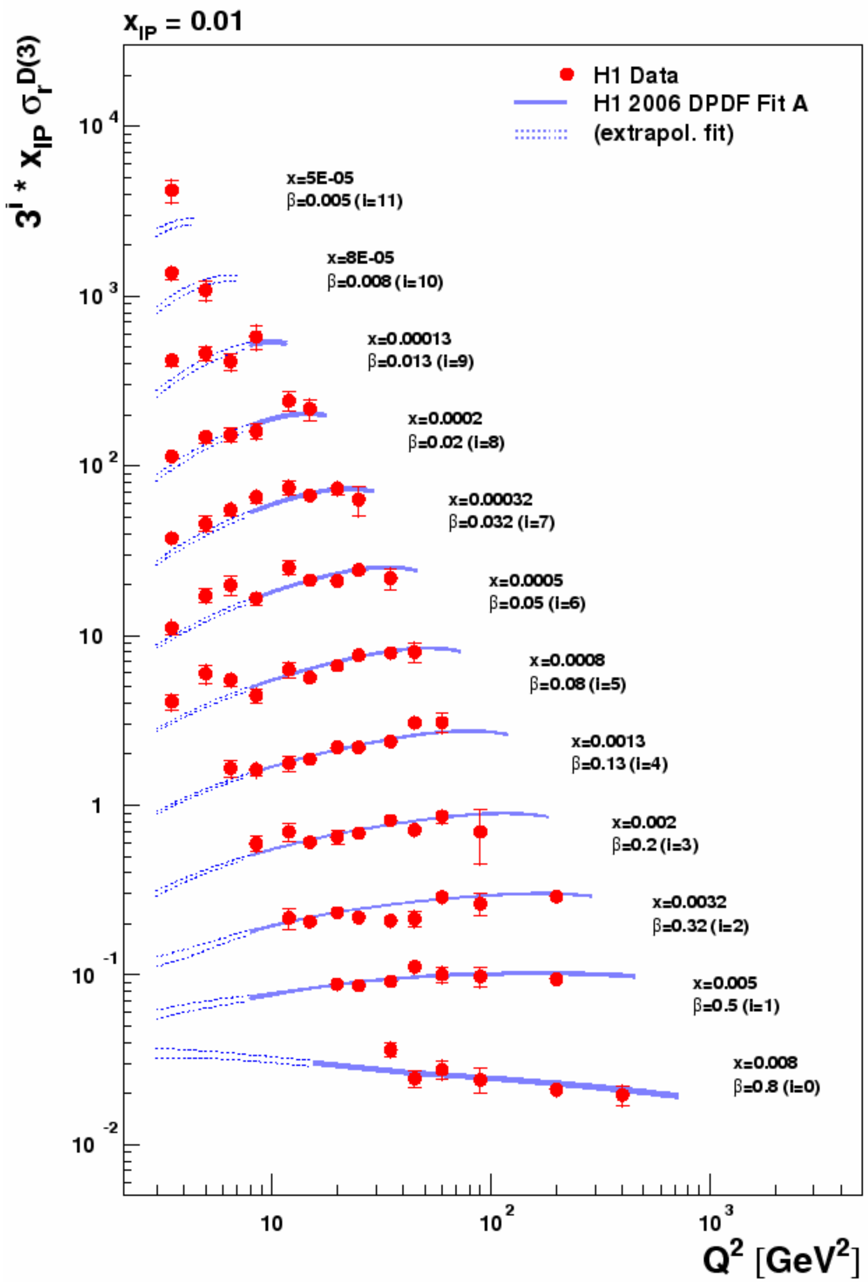
- ❑ Extract DPDFs from QCD fit to inclusive diffractive DIS
- ❑ Test DPDFs in diffractive Final States (Boson Gluon Fusion)

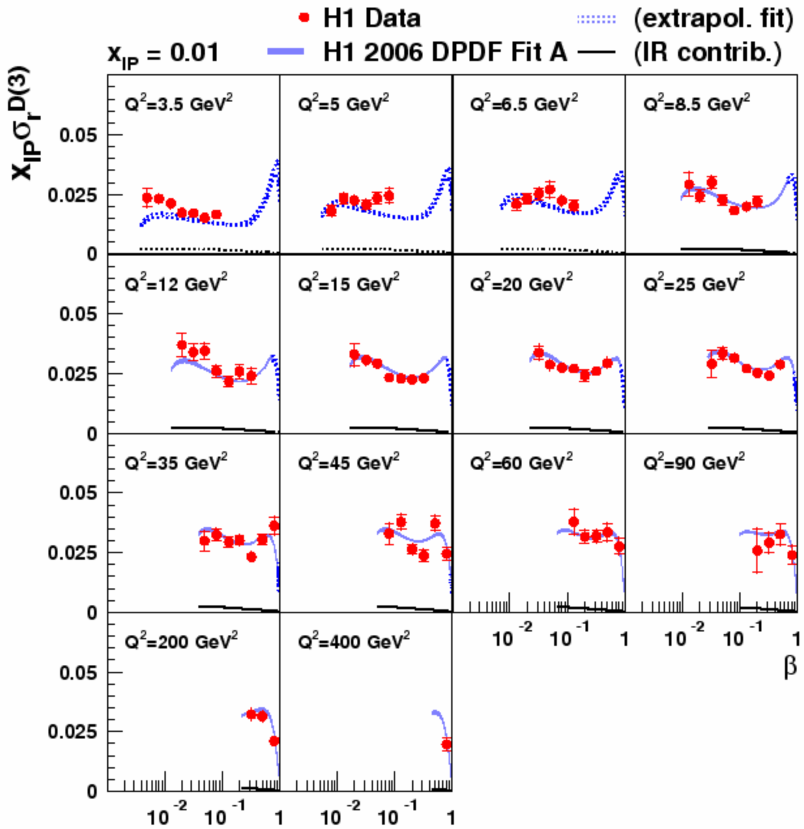




- ❑ Assumption: Proton vertex factorization ➔ shape of diffractive PDFs independent of x_{IP} and t

DGLAP Fit to Diffractive DIS data



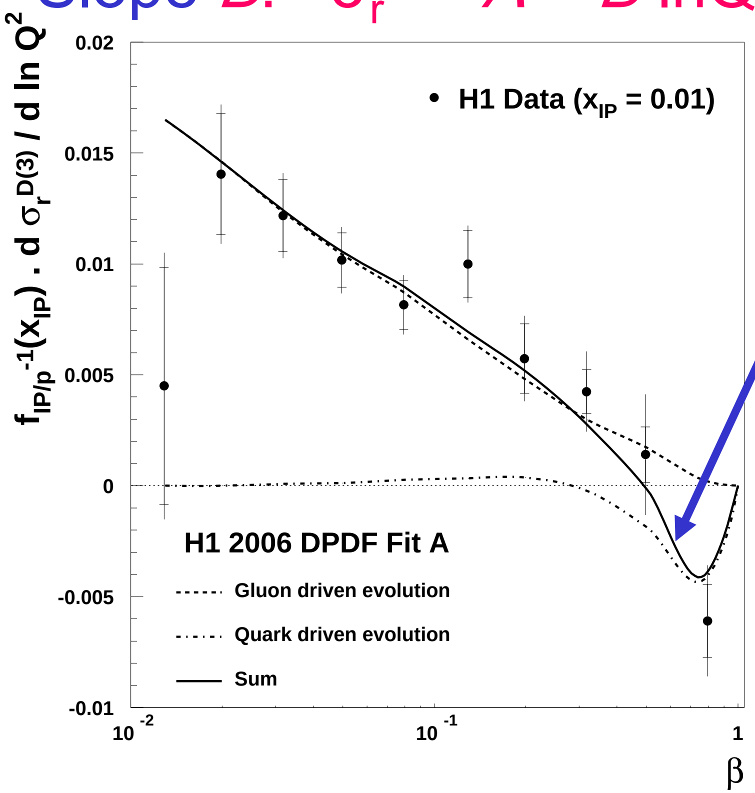


- LRG measurements: → best precision: 5% (stat), 5%(syst)
- Study β and Q^2 dependence at fixed x_{IP} → NLO DGLAP fit to extract diffractive PDFs for quark singlet and gluon

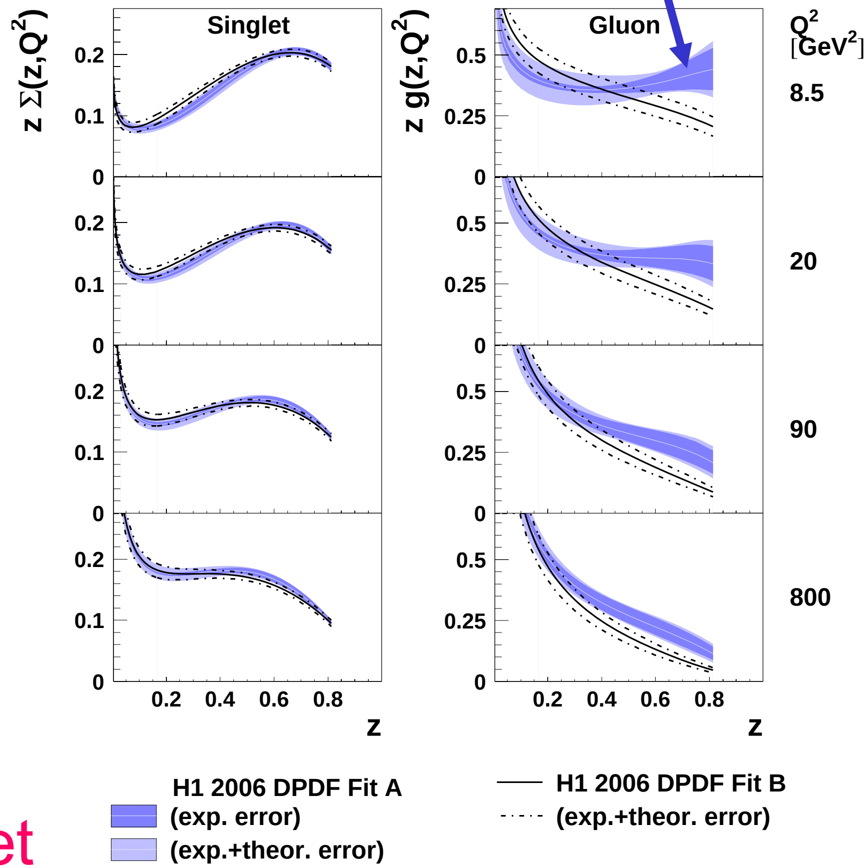
DPDFs from Inclusive Diffractive DIS

- Gluon DPDF ➔ from positive scaling violations ➔ larger uncertainty

Slope B: $\sigma_r^D = A + B \ln Q^2$



- At high momentum fraction QCD evolution is driven by quark radiation ➔ no sensitivity to gluon DPDF

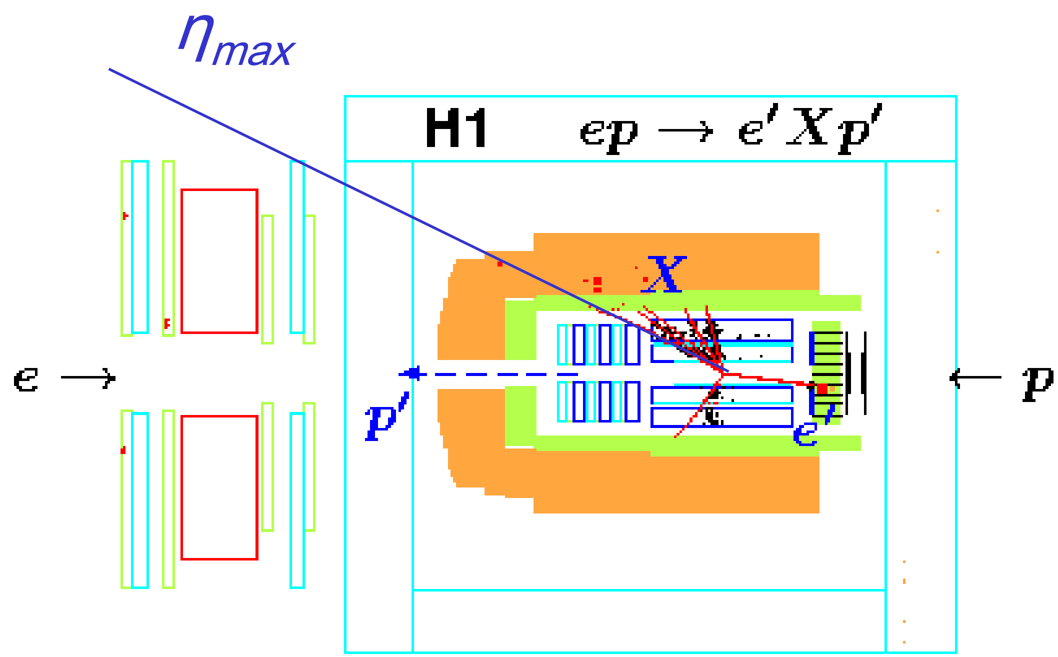


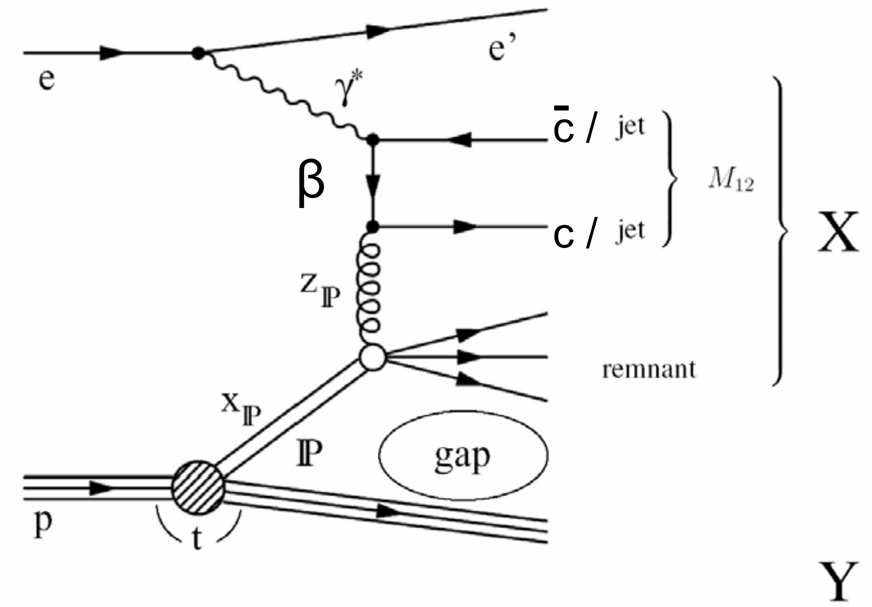
- DGLAP Fit constrains quark singlet DPDF and gluon DPDF at low z

Two DPDF parameterizations: Fit A and Fit B

Diffractive Final States at HERA

- Focus on LRG method: Large rapidity gap between leading proton *p´* and *X*
- *X* includes Diffractive Final States: Dijets, Charm



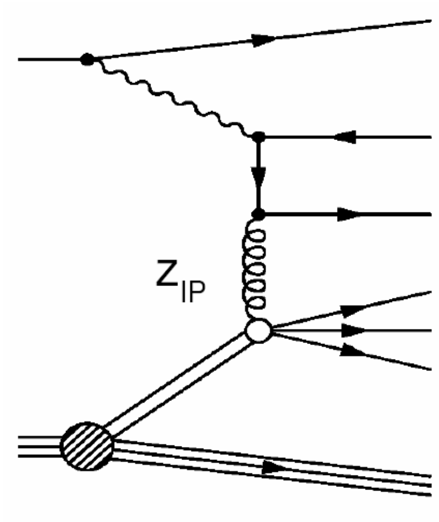


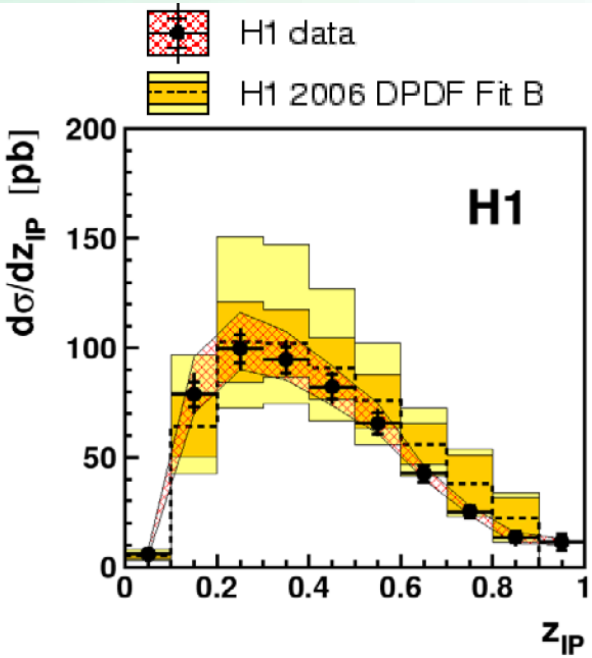
x_{IP}<0.04, |t|<1 GeV^2

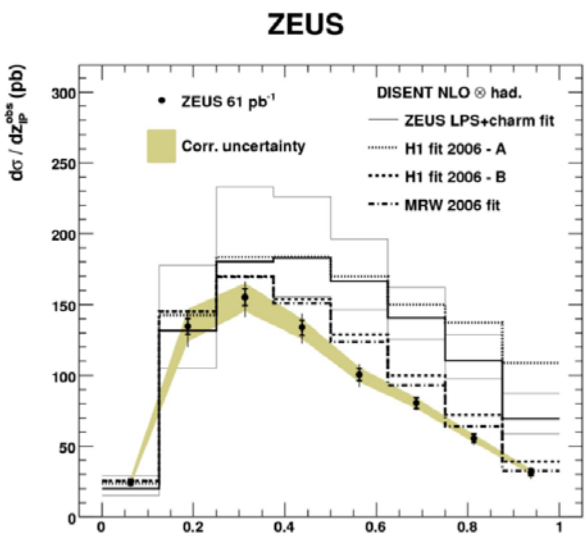
x_{IP} - momentum fraction of proton carried by color singlet exchange

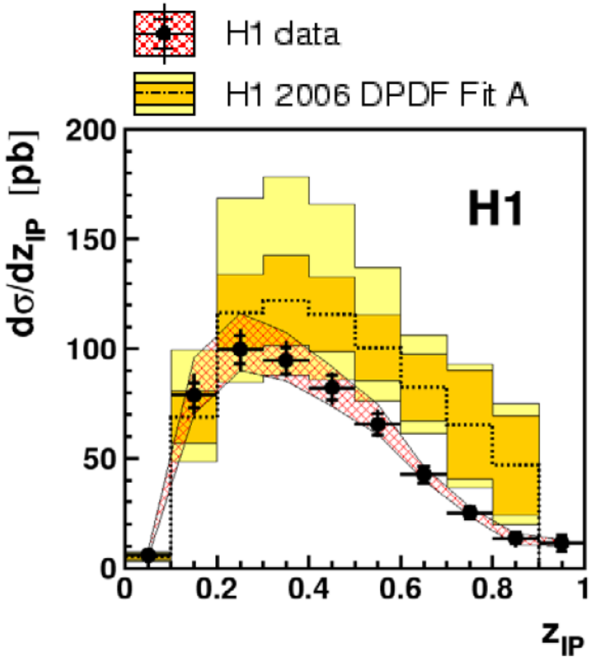
z_{IP} - momentum fraction of color singlet carried by parton entering hard sub-process

DPDFs from Diffractive DIS vs Dijets









- z_{IP} distribution is the most sensitive to gluon DPDF
  ➔difference between NLO H1 2006 Fit A and Fit B at high z_{IP}
- H1 Dijet data are in better agreement with NLO predictions based on Fit B
- ZEUS Dijet data are consistent with DPDFs from H1 2006 Fit B and LPS data (ZEUS LPS Fit)
- Statistics sufficient to make combined QCD Fit to inclusive diffractive DIS and Dijets

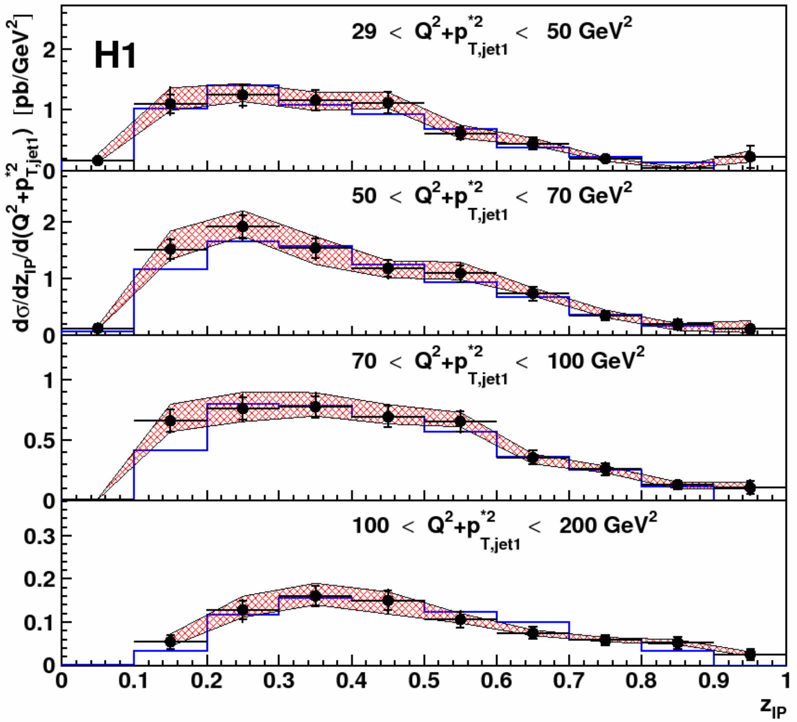
Combined Fit to Diffractive DIS and Dijets

Aim: one set of NLO DPDFs which describes inclusive and Dijet data

- Parameterization of quark and gluon DPDFs at Q_0^2:

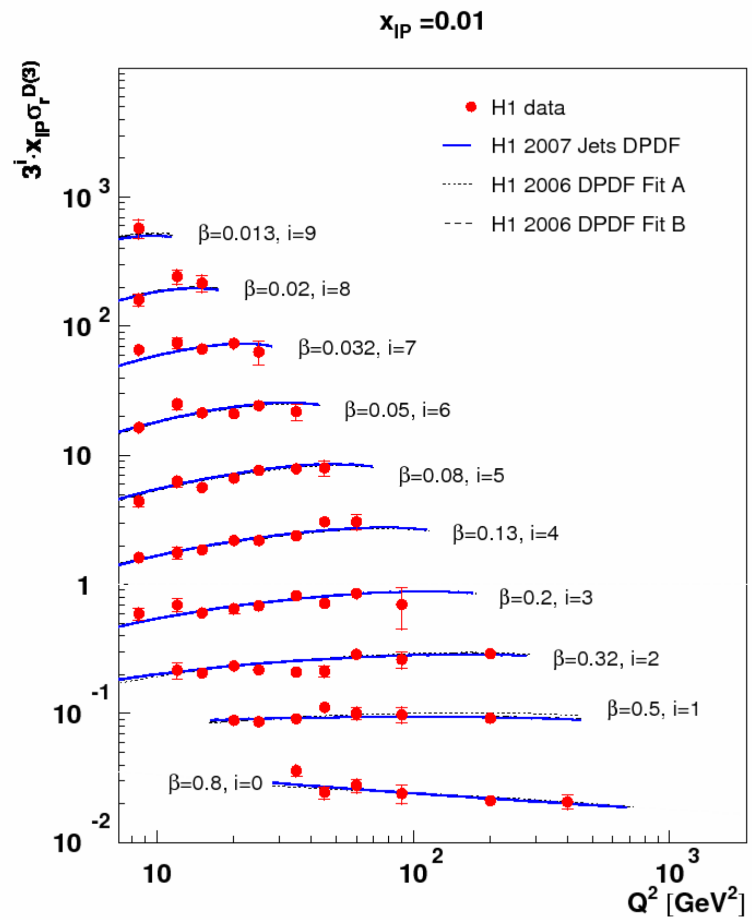
$$PDF(z,Q_0^2) = Az^B(1-z)^C$$

- NLO DGLAP evolution:



$\mu_r = Q^2+p_t^2$

+



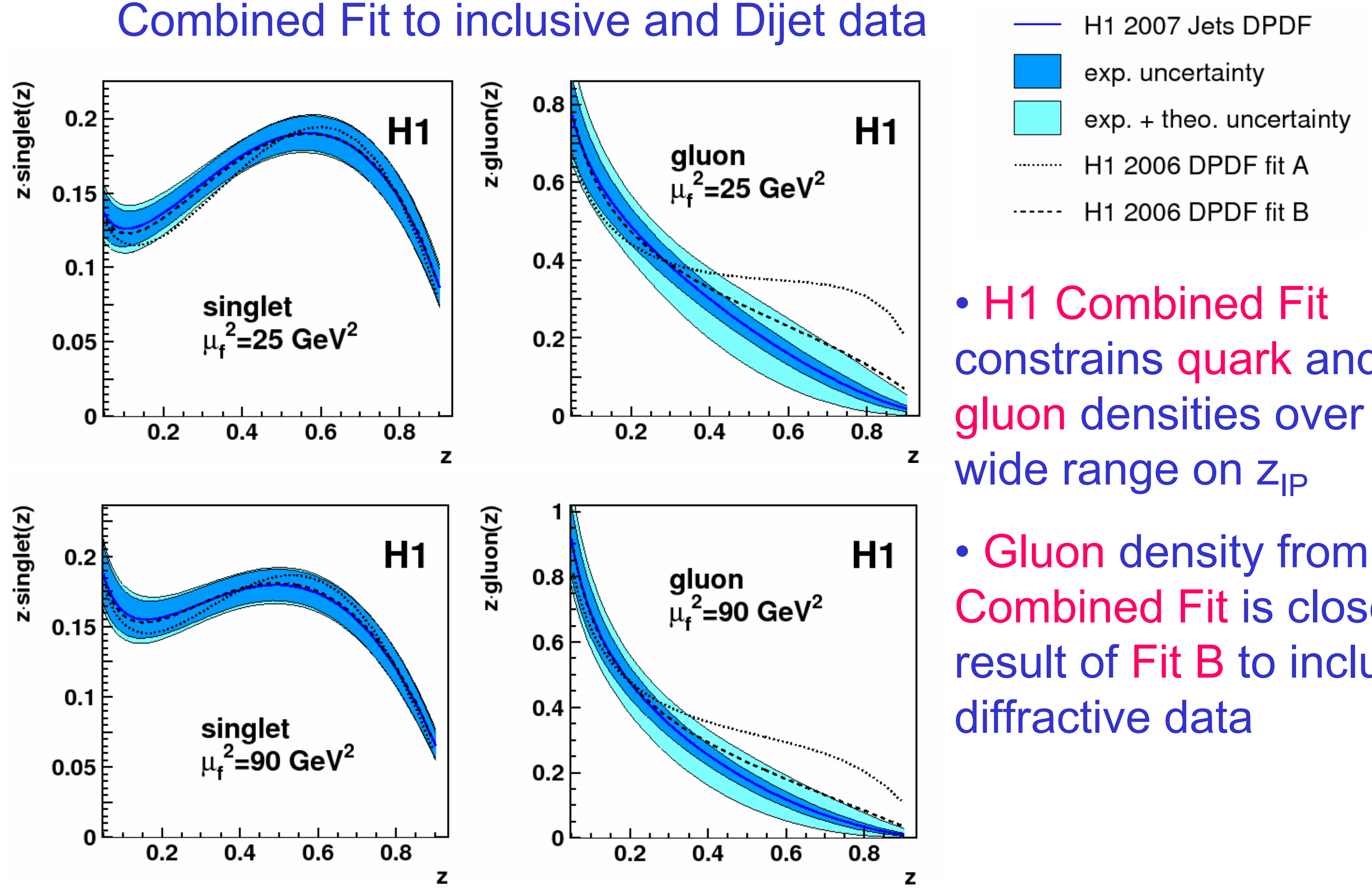
Combined Fit vs Dijet data

Combined Fit vs inclusive data

➔ Data are consistent with QCD collinear factorization

DPDFs from Diffractive DIS and Dijets

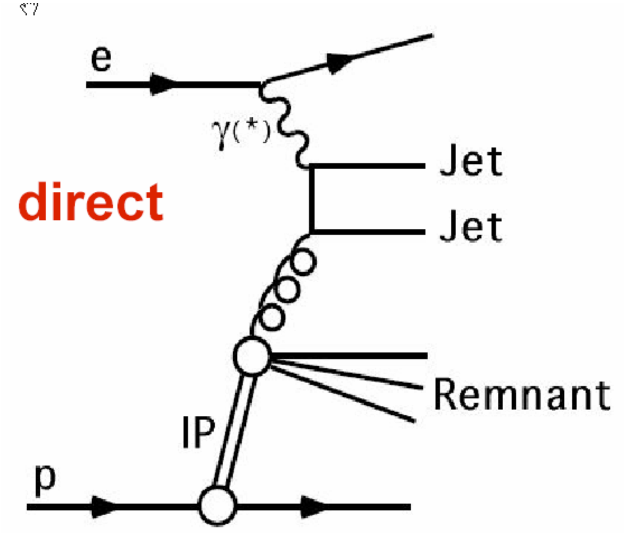
Combined Fit to inclusive and Dijet data



- H1 Combined Fit constrains quark and gluon densities over wide range on z_{IP}
- Gluon density from Combined Fit is close to result of Fit B to inclusive diffractive data

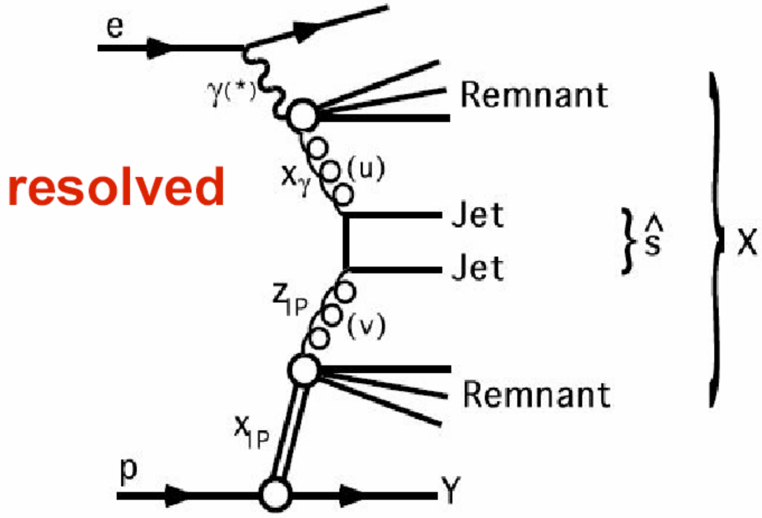
Test of Factorization: Dijet Photo-production

small point-like photon

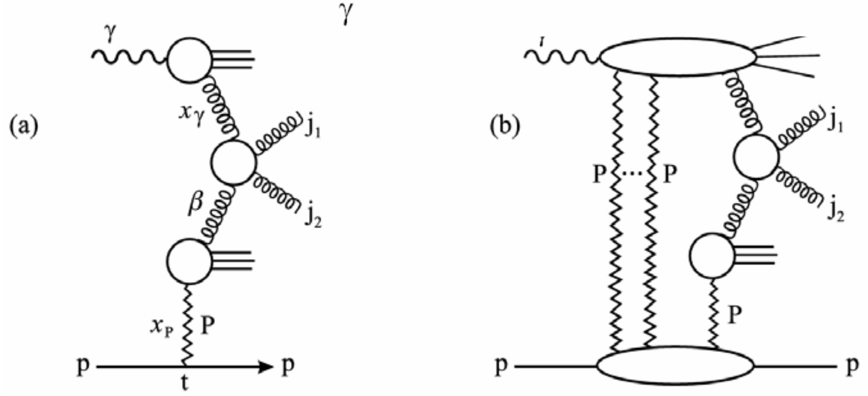


$x_\gamma = 1$

large hadron-like photon



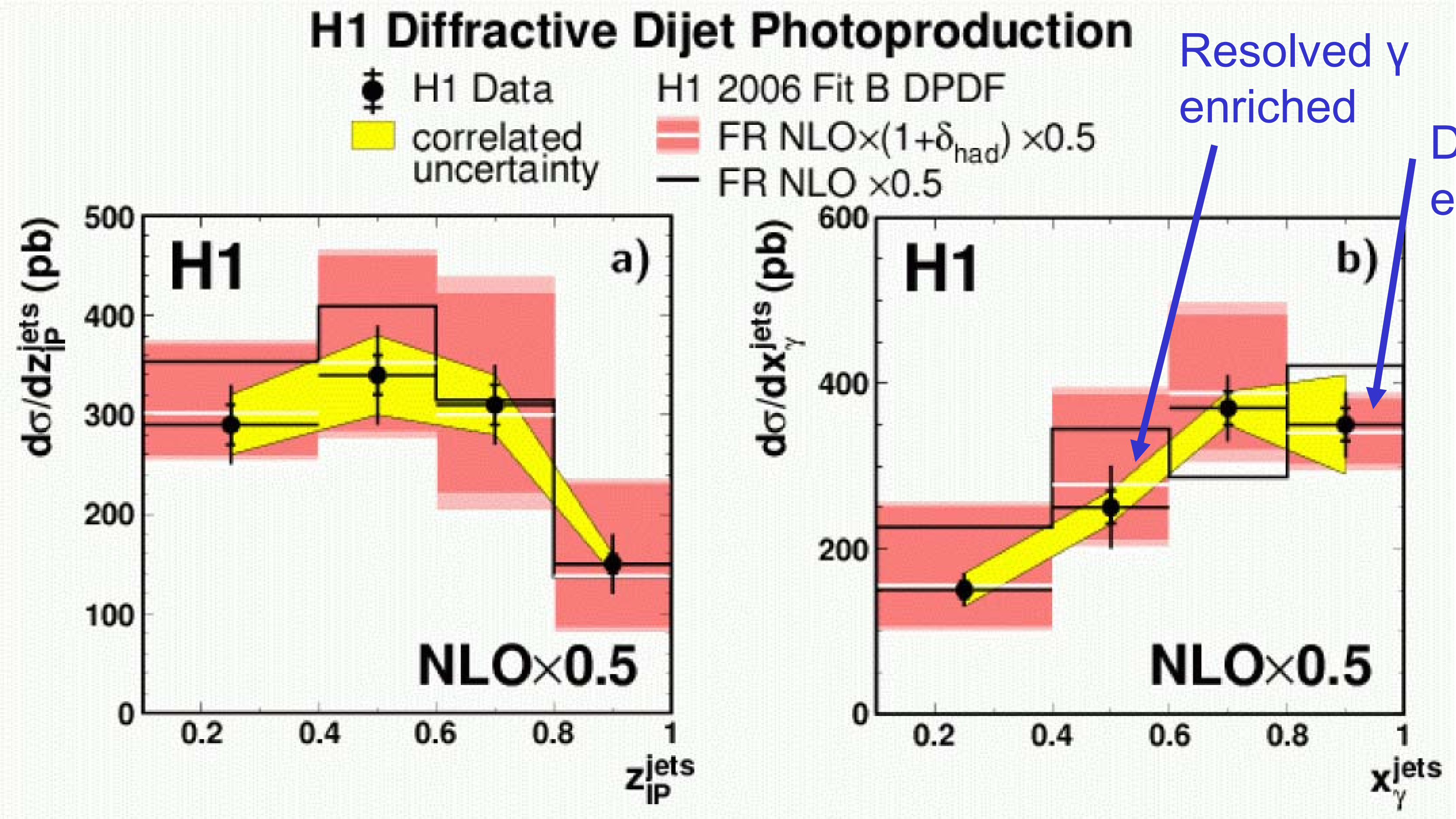
$x_\gamma < 1$



direct resolved

- Q^2~0, hard scale → E_t^{jet} process sensitive to gluon density
- Factorization in Dijet PhP expected to be valid in direct photo-production but broken in resolved photo-production (secondary re-scattering, multi-pomeron exchanges)

Diffractive Dijet Photo-production



- NLO QCD (Frixone): H1 2006 Fit B; $\mu^2 = (E_t^*)^2$
- Dijets in PhP are described in shape by NLO QCD predictions, but suppressed by a factor ~0.5 for direct and resolved γ

➔Factorization breaking for Dijets in PhP

Diffractive Dijet Photo-production

- NLO QCD (Klasen&Kramer): H1 2006 Fit A & B, ZEUS LPS Fit $\mu^2 = (E_t^*)^2$

- Dijets in PhP are only weakly suppressed by a factor of ~0.8 for direct and resolved γ

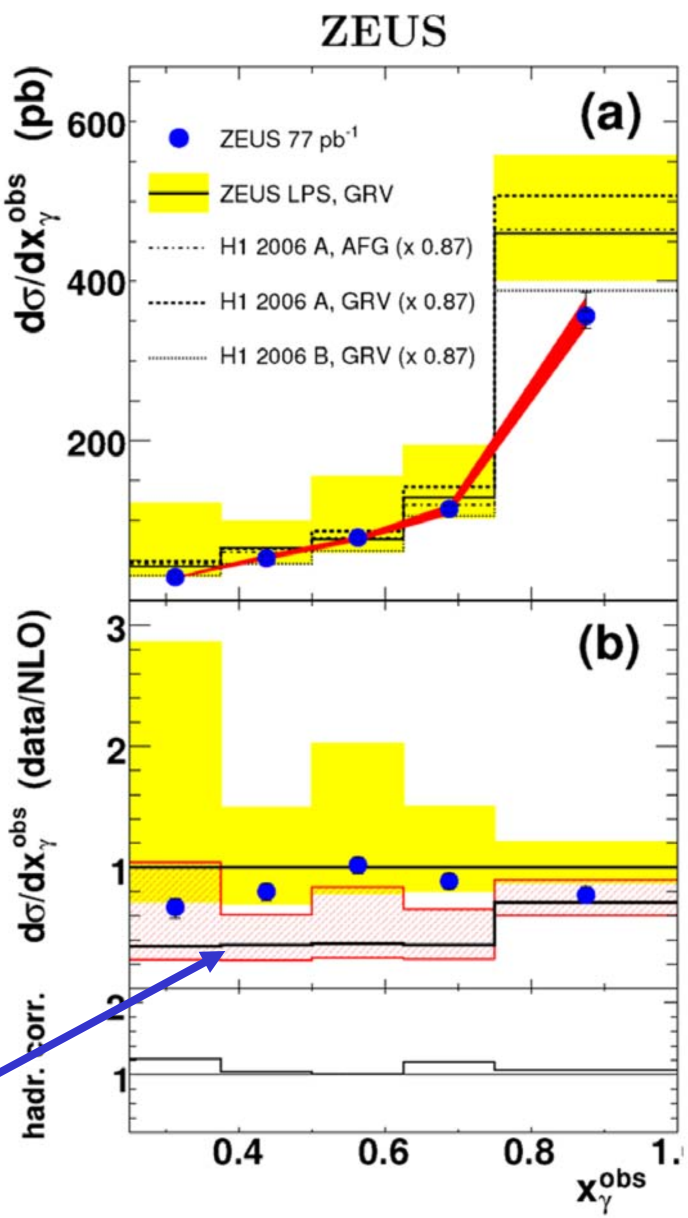
→ No factorization breaking

Comparison ZEUS with H1:

- harder E_t^{jet} cut

ZEUS: $E_t^{jet} > 7.5$ GeV, H1: $E_t^{jet} > 5$ GeV

- 20% H1/ZEUS LRG normalization uncertainty
- 20% difference in H1/ZEUS NLO calculations

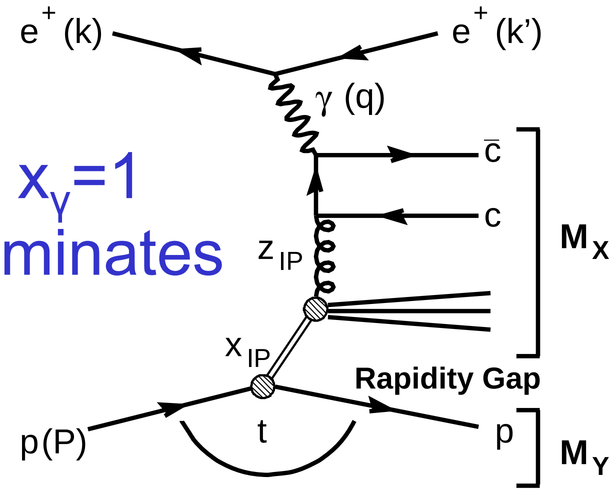


Kaidalov & Khoze R=0.34 suppression for resolved γ

Test of Factorization: Charm in DIS and PhP

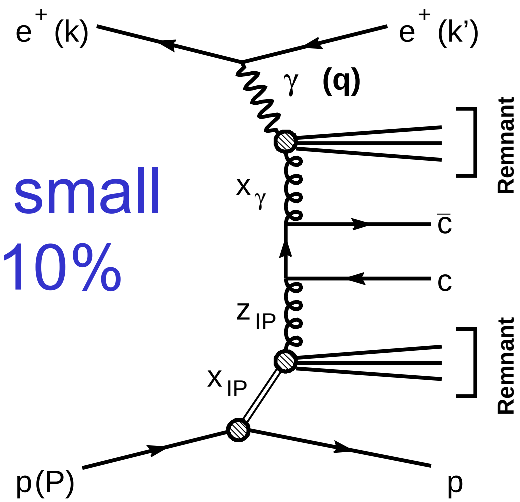
DIS and direct photo-production

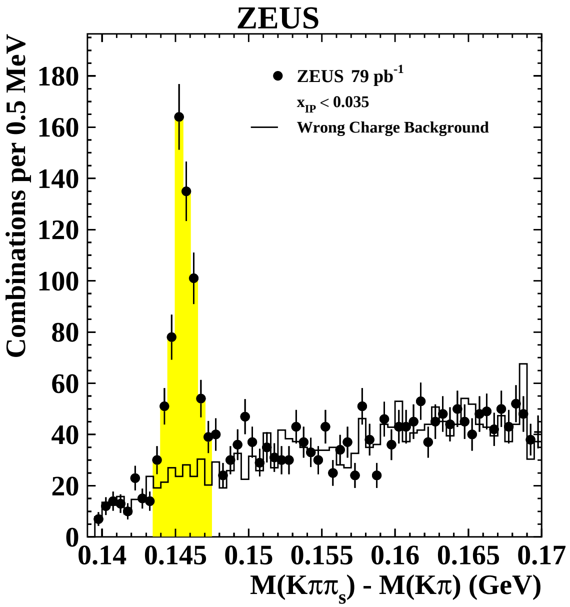
$x_\gamma=1$ dominates



Resolved photo-production

$0<x_\gamma<1 \rightarrow$ small fraction <10%





- Dominating process: Boson Gluon Fusion
➔ directly sensitive to gluon DPDF

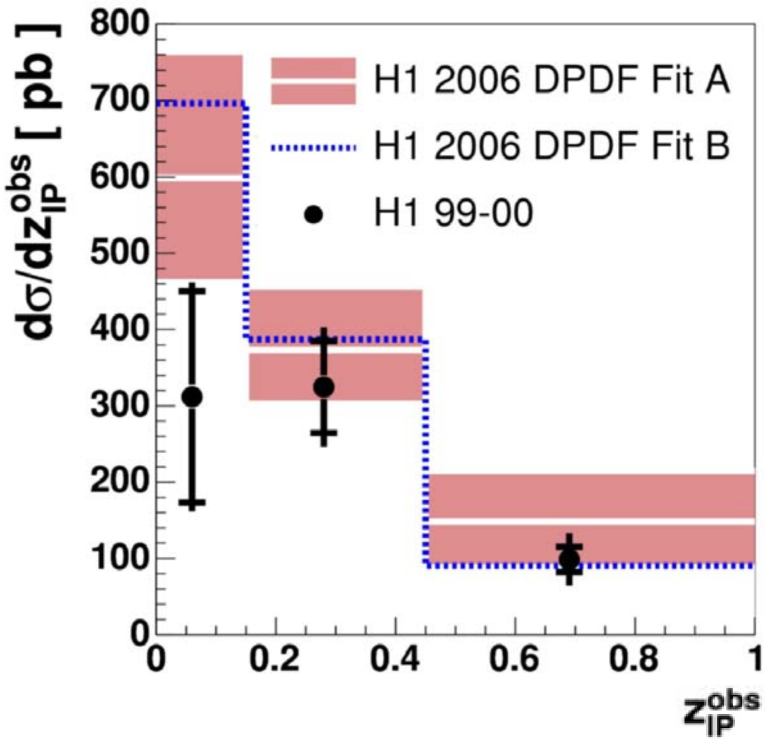
- Hard scale is provided by mass of Charm quark
➔ probing low and medium range on z_{IP}

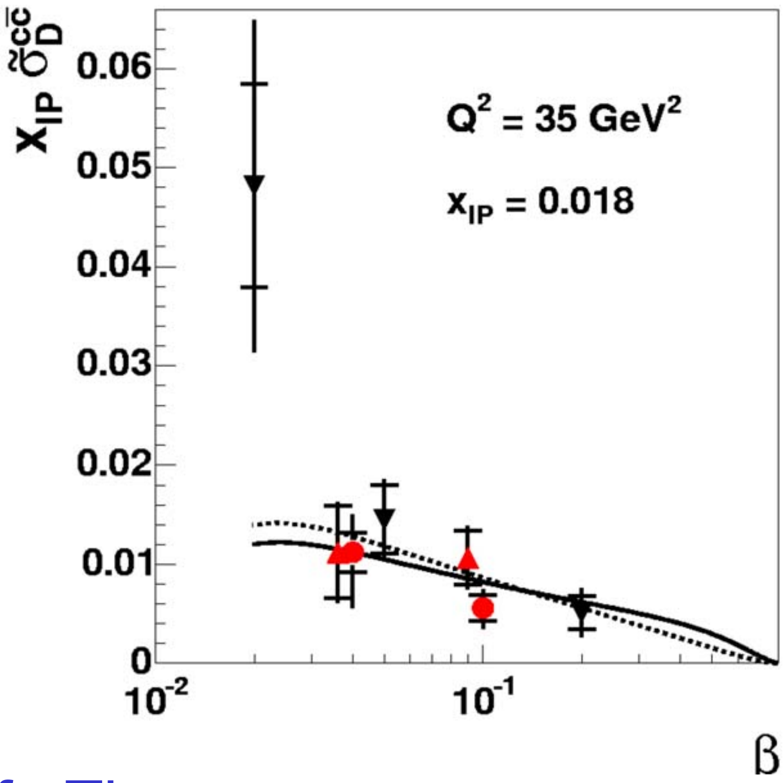
- H1 and ZEUS: Diffractive D*

- H1: First measurement of diffractive Charm using complimentary Lifetime method (impact parameter to primary vertex)

Diffractive Charm in DIS

Charm contribution to F_2^D ~20% ➔ comparable with charm fraction in inclusive DIS





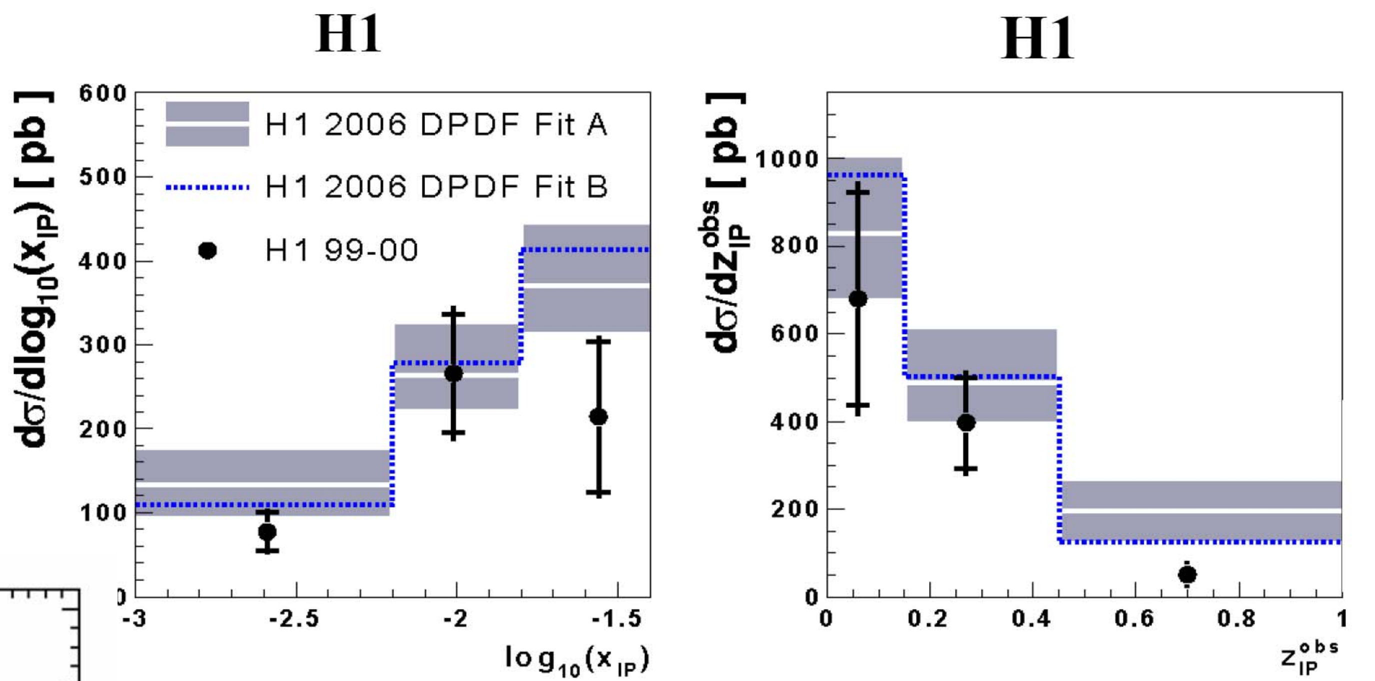
❑ Diffractive Charm in DIS (D* and Life Time method):

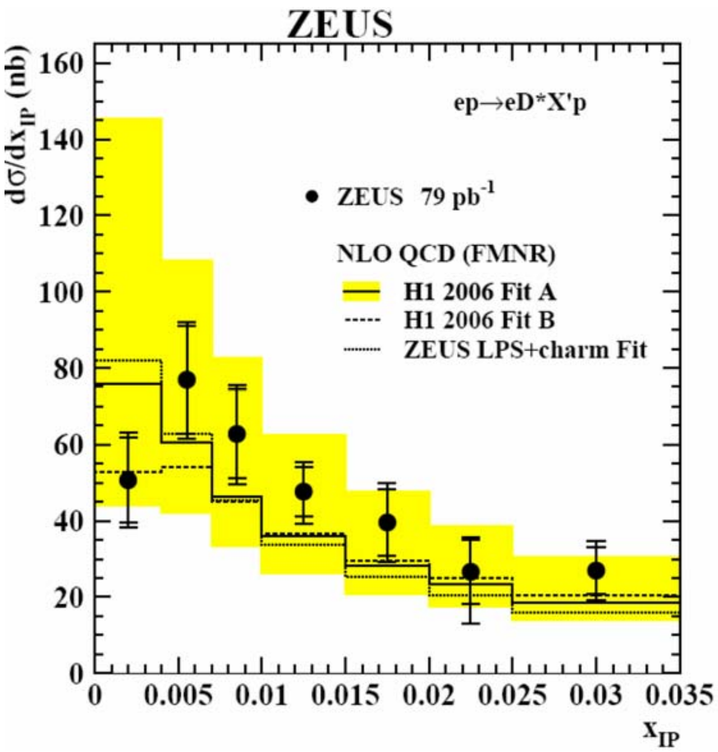
- data consistent with NLO QCD predictions

➔ support QCD collinear factorization

Diffractive Charm in Photo-production

• NLO QCD:
H1 2006 Fit A & B,
ZEUS LPS Fit
$\mu^2 = m_c^2 + p_t^2$





❑ Diffractive Charm (D*) in photo-production:

▪ data consistent with NLO QCD predictions within scale uncertainties

➔ no evidence for suppression of Charm direct photo-production

Diffractive DIS / hadron final states: Summary

❑ Many new measurements of inclusive diffraction at HERA

➔ good agreement between different methods and experiments

➔ data are consistent with proton vertex factorization

❑ Combined QCD Fit to inclusive diffractive DIS and Dijets constrains quark and gluon DPDFs in a wide range on fractional momentum

➔ consistent picture of diffractive inclusive DIS and Dijets within QCD factorization approach

❑ Diffractive Dijet photo-production results need clarification

➔ breaking of QCD factorization in Diffractive Dijet photo-production?

➔ difference between experiments or NLO calculations?

❑ Diffractive Charm DIS and photo-production data are consistent with predictions based on NLO QCD Fit to inclusive diffractive DIS

Vector Meson production and DVCS

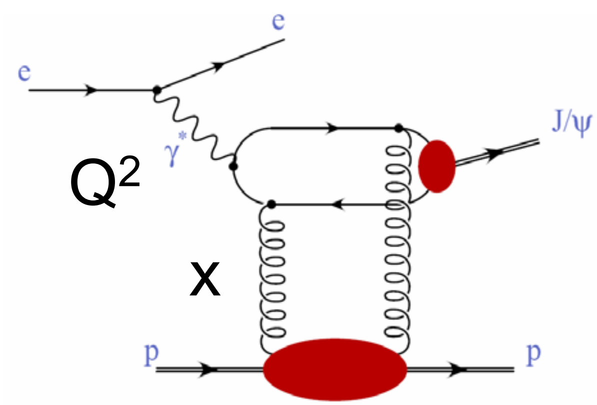
Exclusive VM production:

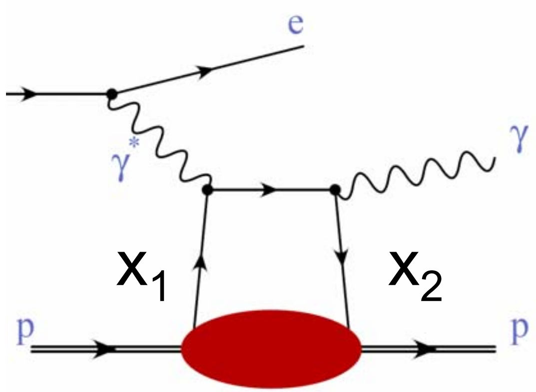
- transition from soft to hard IP exchange with increasing of M_{VM}, Q^2, t
- Regge theory for soft processes (IP trajectory)
- pQCD description → two gluon exchange

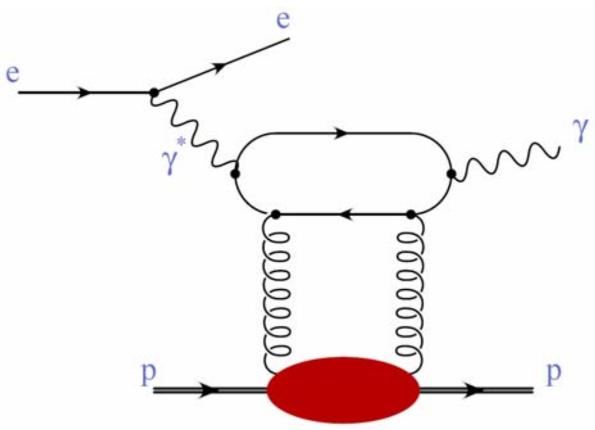
$$\sigma \sim |x\ g(x, Q^2)|^2$$

Deeply Virtual Compton Scattering (DVCS):

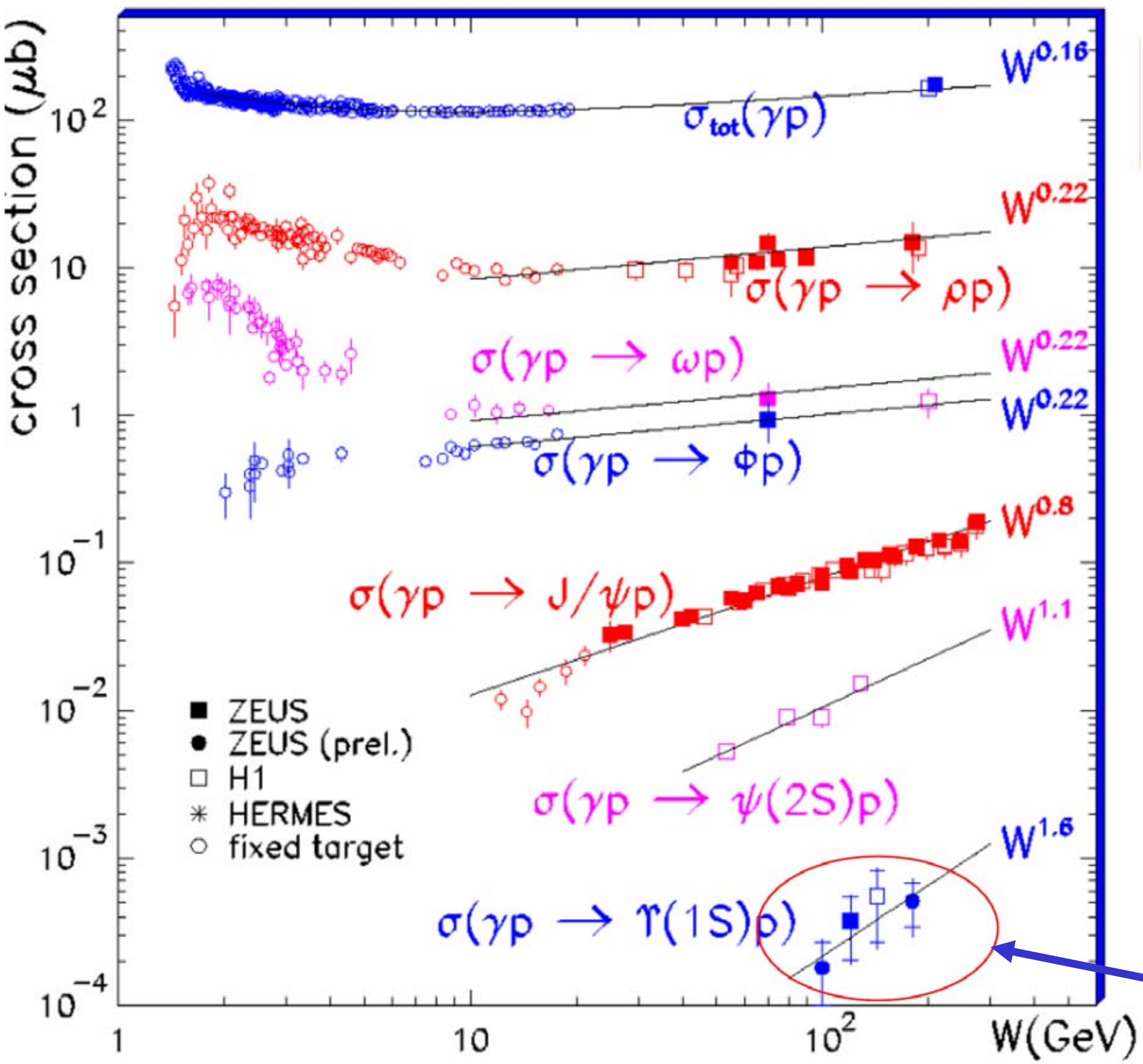
- fully calculable in pQCD
- no uncertainty due to VM wave function
- access to generalized (skewed) Parton Distributions → $GPD(x_1,x_2)$







VM photo-production: W-dependence

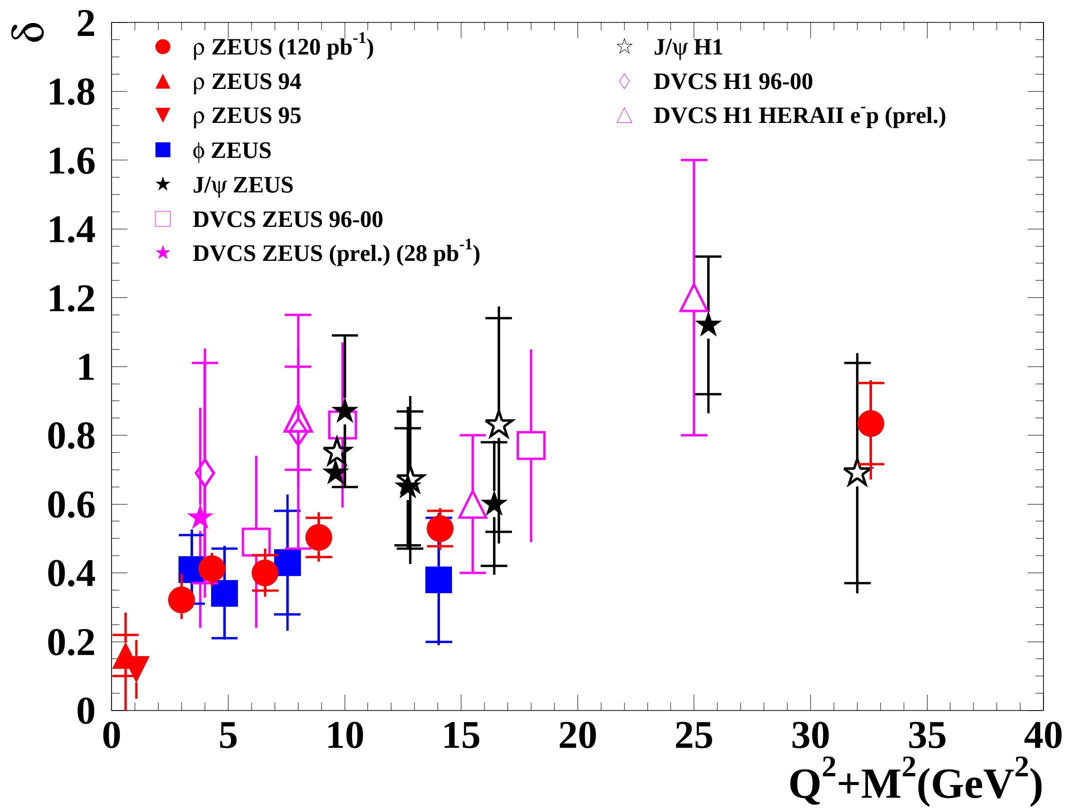


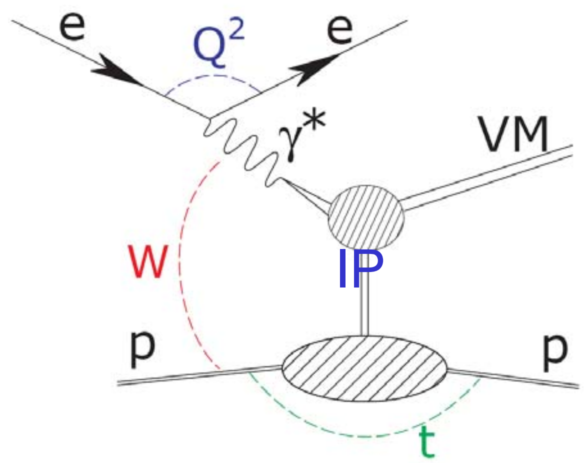
$\sigma \propto W^{\delta}$ ($\rho,\varphi,\omega,J/\psi,\Upsilon$)

- transition from weak W^{δ} dependence for low mass VM (ρ,φ,ω) to strong W^{δ} dependence in presence of hard scale M_{VM} ($J/\psi,\Upsilon$)

new Υ-photo-production data

VM production and DVCS: $\delta(Q^2+M^2)$

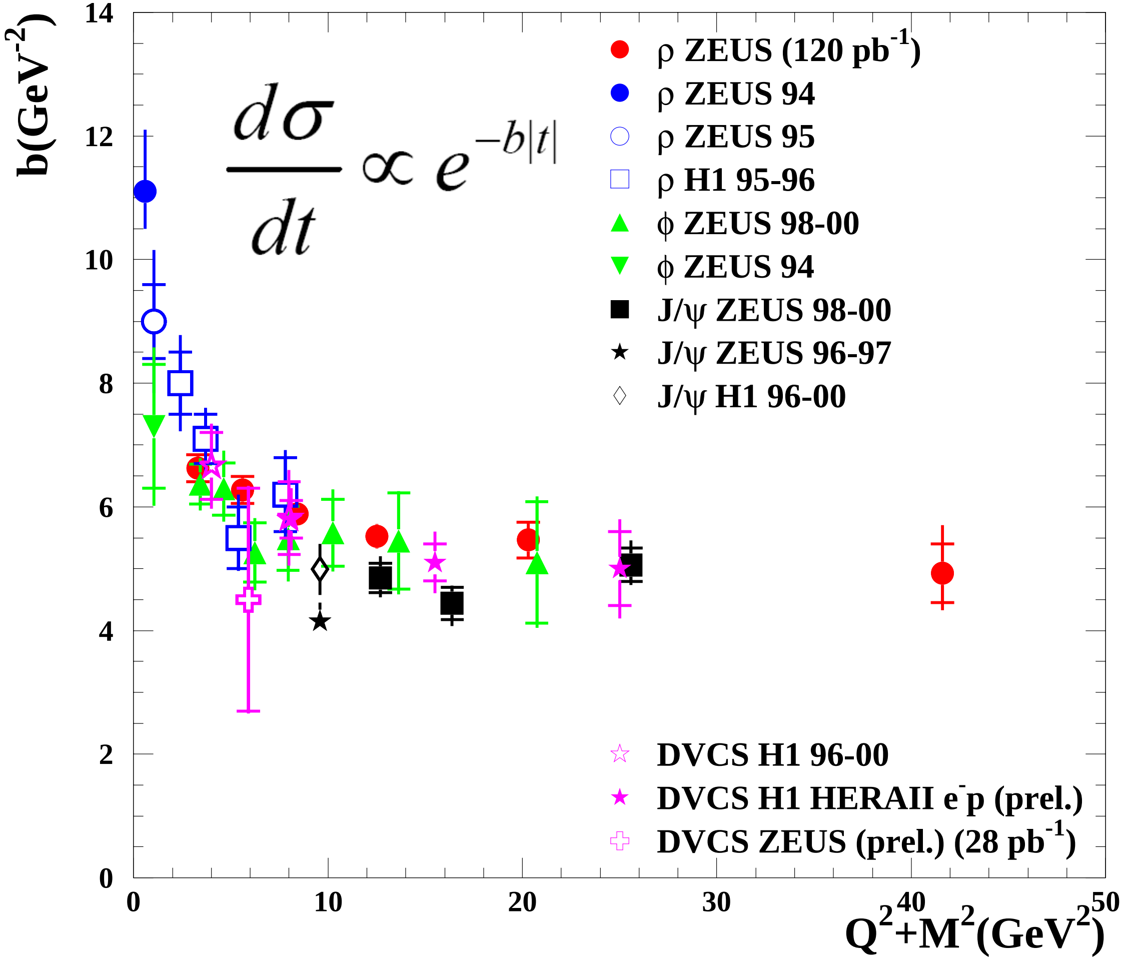




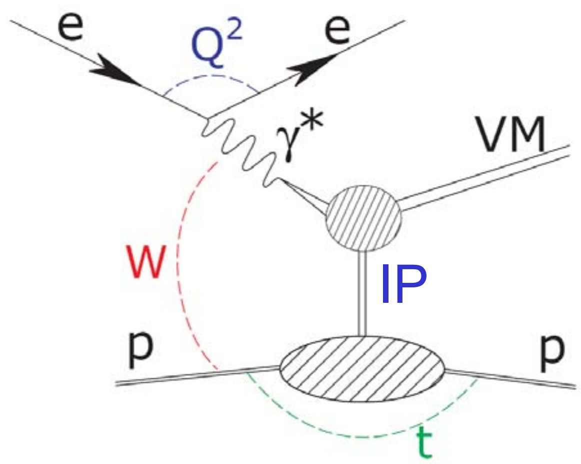
$\sigma \propto W^{\delta}$ (ρ,φ,J/ψ,DVCS)

- Transition from soft to hard regime when Q^2+M^2 increases
- Saturation at high $Q^2+M^2 \rightarrow$ different from F_2 behavior at low x

VM production and DVCS: $b(Q^2+M^2)$



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



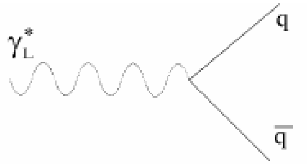
- b reflects transverse size of interaction
- b decreases with Q^2+M^2 from ~10GeV^{-2} (soft process) to ~5 GeV^{-2} (hard process)

Universal behavior with scale Q^2+M^2 for ρ,φ,J/ψ,DVCS

Elastic ρ-mesons in DIS: $R = \sigma_L/\sigma_T\ (Q^2, W)$

- Elastic ρ-meson production in DIS

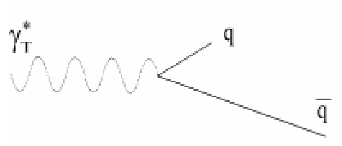
longitudinally polarized γ_L^*



Small spatial configuration (large k_T).

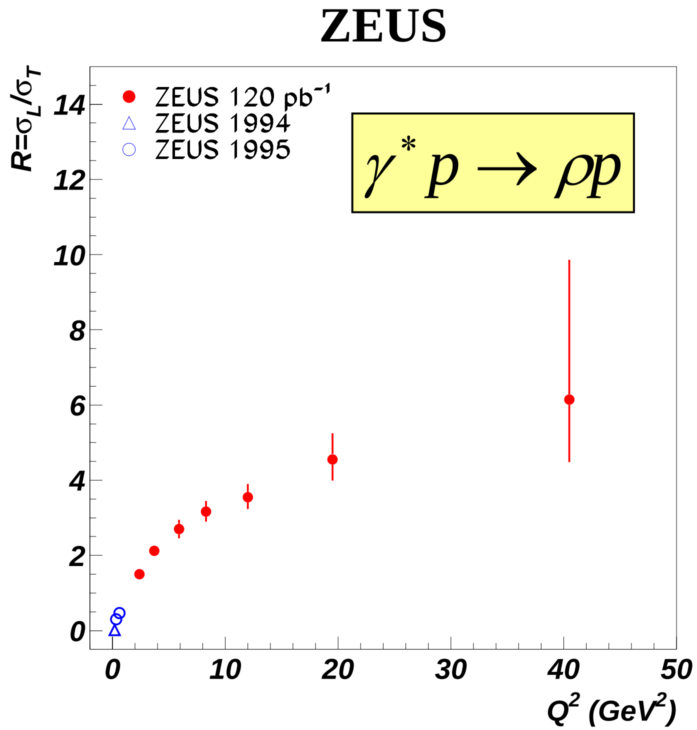
σ_L steep rise with W

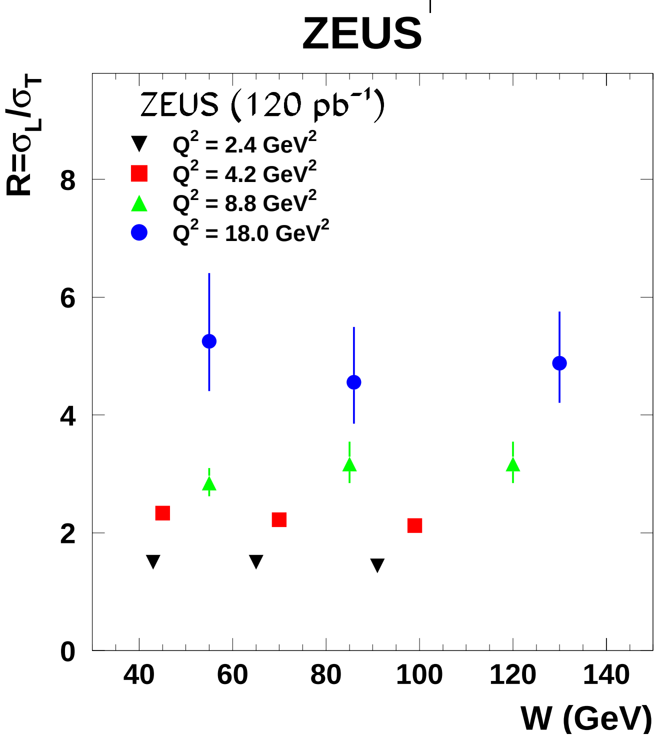
transversaly polarized γ_T^*



Large spatial configuration dominates (small k_T)

σ_T slow rise with W





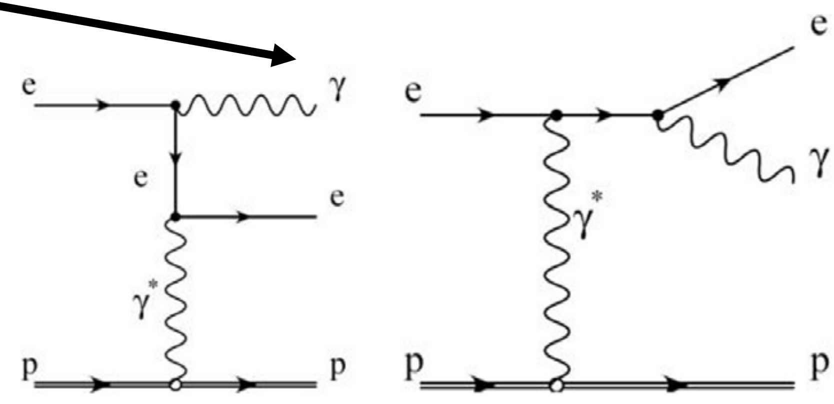
s-channel helicity conservation (SCHC) → VM retains helicity of γ*

$$R = \sigma_L / \sigma_T = r_{00}^{04} / \varepsilon(1 - r_{00}^{04})$$

- R increases with Q^2 → σ_L dominates
- σ_L and σ_T have same W dependence

DVCS: Beam Charge Asymmetry

Interference between DVCS (QCD process) and Bethe-Heitler (QED process)

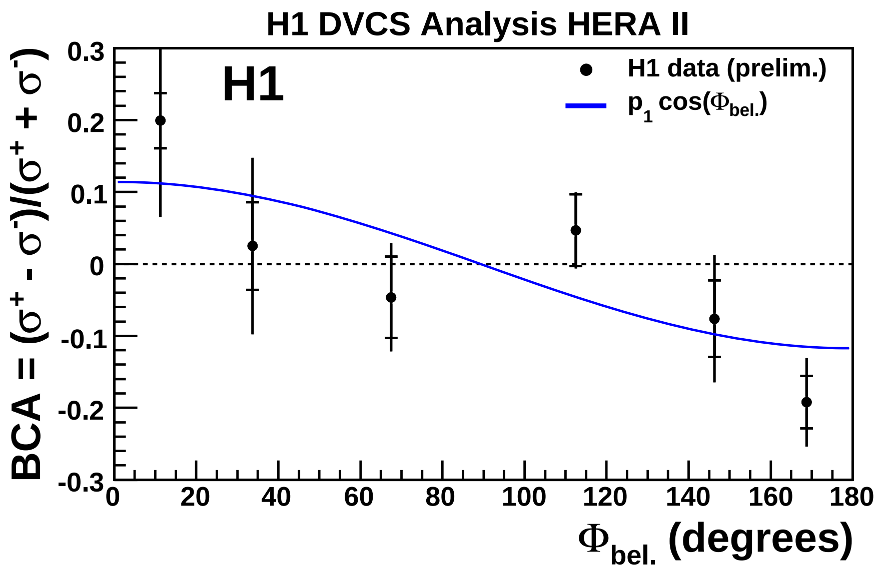


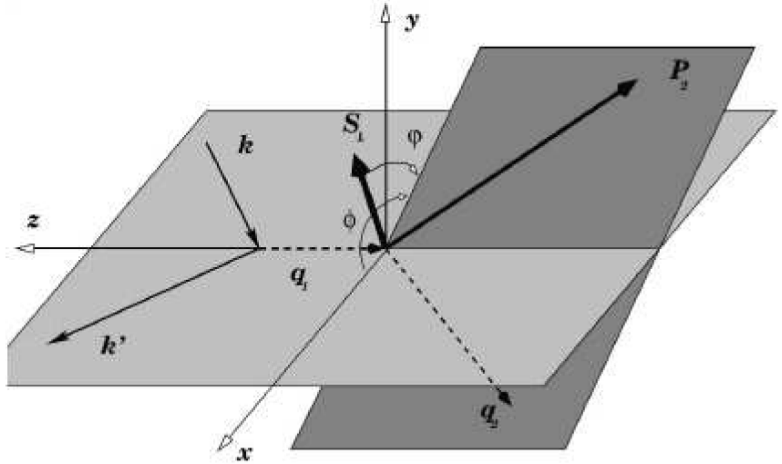
$d\sigma = d\sigma^{BH} + d\sigma^{DVCS} \pm$ Interference

for beam lepton charge (+/-)

$BCA = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-) = p_1{}^* \cos(\varphi) + \ldots$

$p_1 \sim GPD$



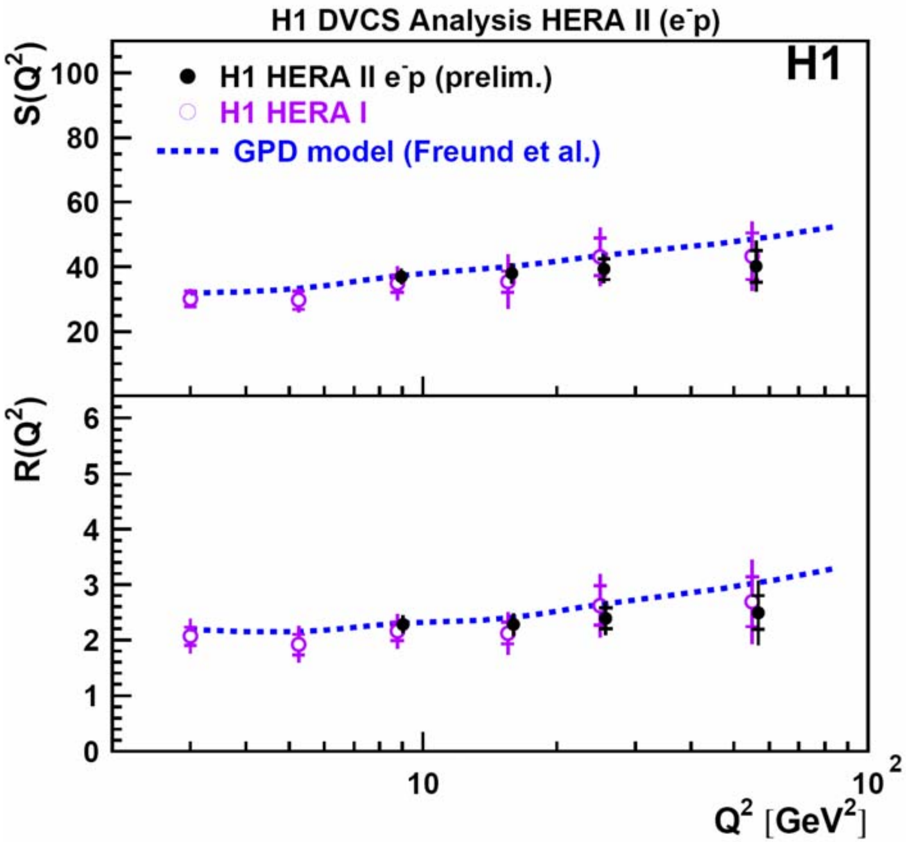


DVCS: QCD interpretation

•Correct for Q^2 dependence of propagator term and b-slope

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

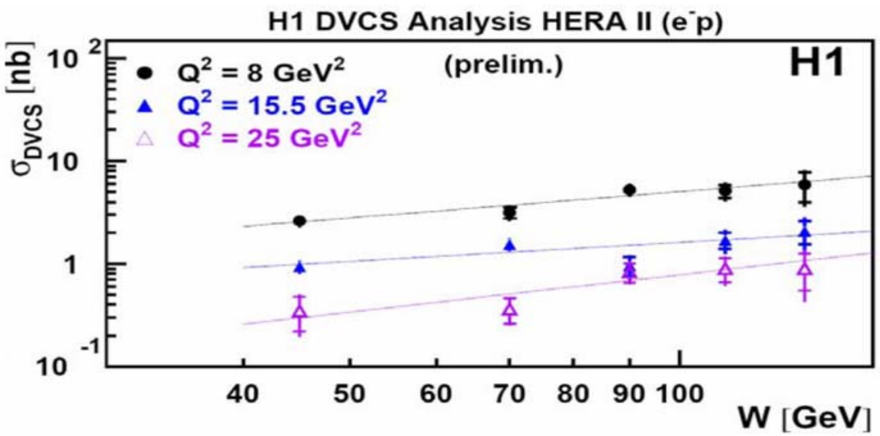
$$R = \frac{\mathcal{I}m\ A(\gamma^* p \to \gamma p)}{\mathcal{I}m\ A(\gamma^* p \to \gamma^* p)} = \frac{4\sqrt{\pi\ \sigma_{DVCS}\ b(Q^2)}}{\sigma_T(\gamma^*\ p \to X)\ \sqrt{(1+\rho^2)}}$$

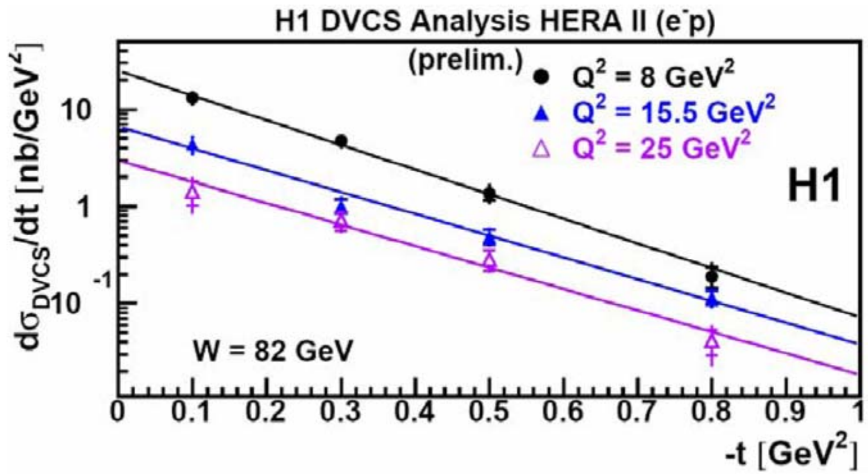


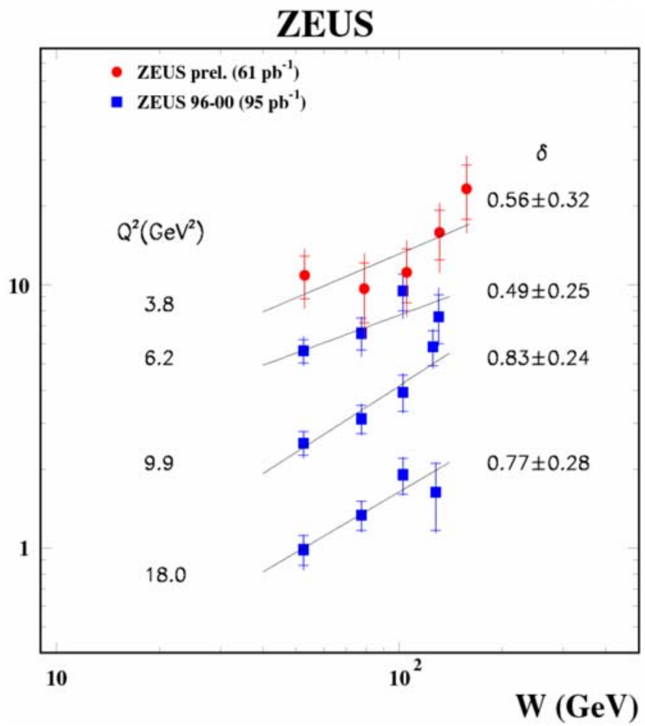
• Skewing factor R~2 for DVCS, for inclusive DIS expected R=1

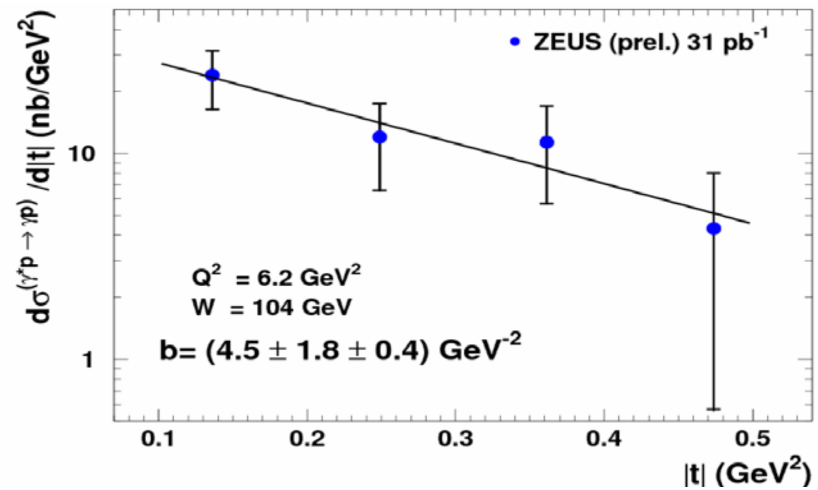
• QCD based model is able to describe Q^2-dependence of S and R

DVCS: t and W-dependences







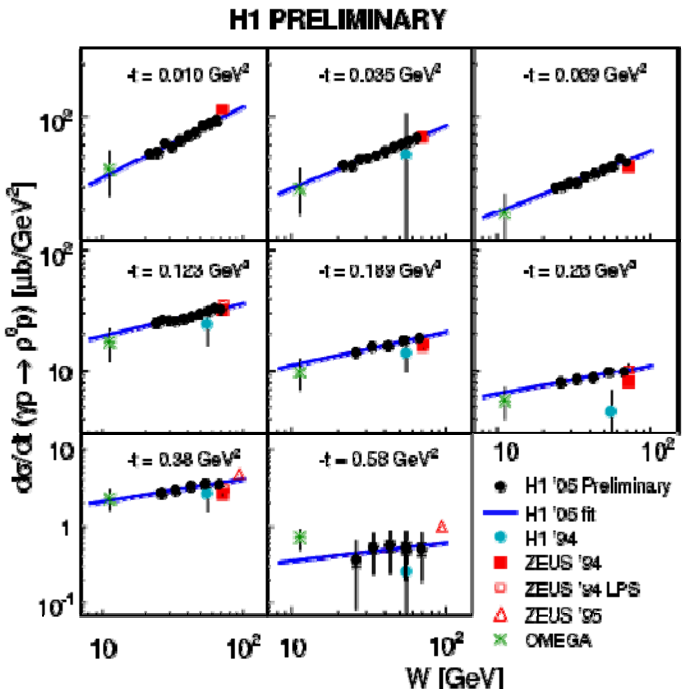


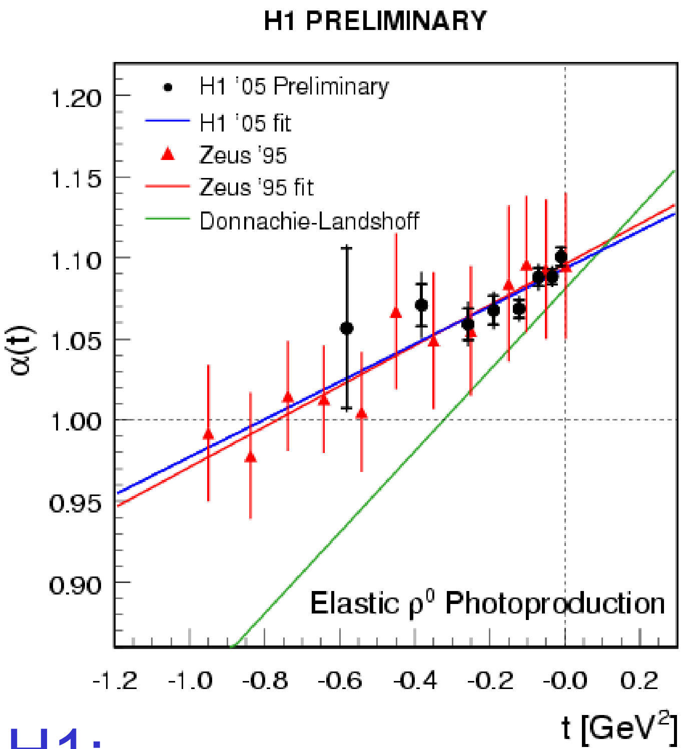
- W and t-dependences indicate hard process (similar to J/ψ)

Effective Pomeron trajectory

- Elastic ρ-meson photo-production

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





ZEUS:

$\alpha_P(0) = 1.096 \pm 0.021$

$\alpha'_P = 0.125 \pm 0.038\ \mathrm{GeV}^{-2}$

H1:

$\alpha_P(0) = 1.093 \pm 0.003^{+0.008}_{-0.007}$

$\alpha'_P = 0.116 \pm 0.027^{+0.036}_{-0.046}\ \mathrm{GeV}^{-2}$

- slope α'_P is smaller than value 0.25 GeV^{-2} extracted from soft hadron-hadron scattering

VM production and DVCS: Summary

New high statistics measurements of Vector Mesons in DIS and photo-production and DVCS process at HERA:

• W-dependence of cross section becomes stronger with increasing of hard scale Q^2+M^2

• Exponential slope of t-distribution decreases with Q^2+M^2

• σ_L/σ_T ratio increases with Q^2 and is independent of W

• Effective Pomeron trajectory has smaller slope than that extracted from soft hadron-hadron scattering

• W and t dependences of DVCS indicate hard process

• First measurement of DVCS beam charge asymmetry at HERA, process is sensitive to GPDs