# Inclusive diffraction and tests of QCD factorisation at HERA


Karel Černý

(Charles University in Prague)


**on behalf of the H1and ZEUS collaborations**

37th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

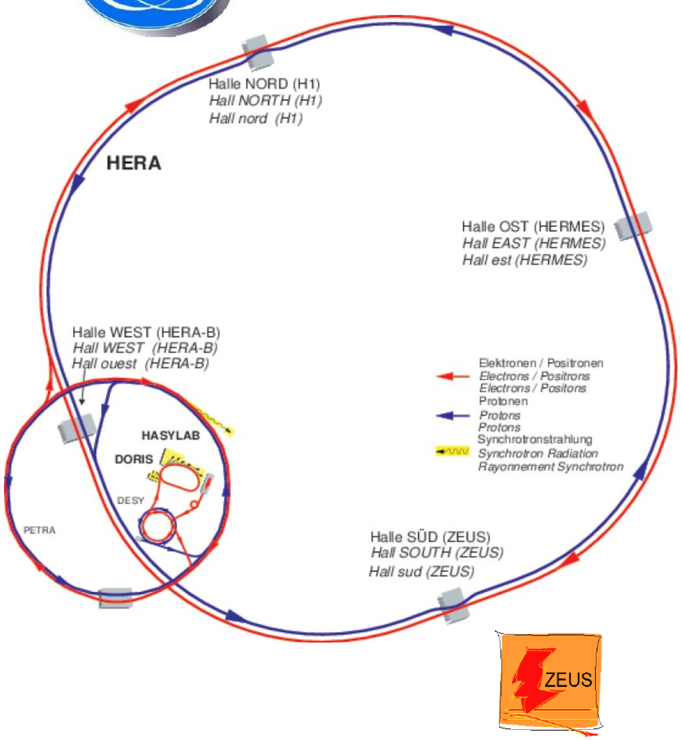
ICHEP 2014 VALENCIA

2 - 9 - JULY - 2014 - VALENCIA

# HERA

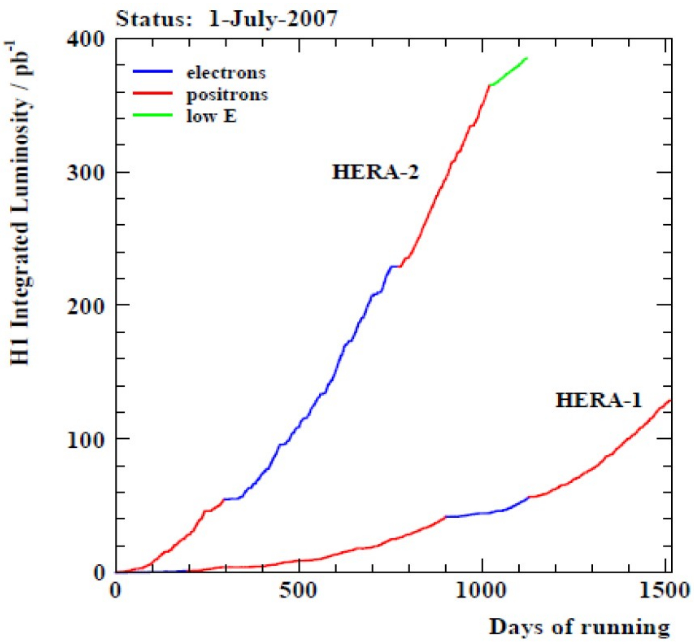
**HERA (DESY, Hamburg) ep collider in operation in 1993-2007**

**$E_p$ = 920 GeV     $E_{e^\pm}$ = 27.5 GeV**



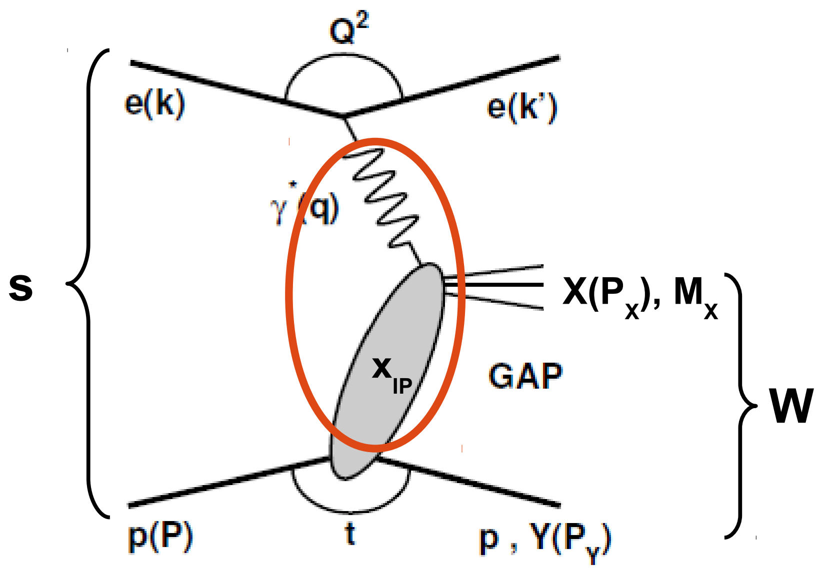

**two multipurpose experiments H1 and ZEUS**

**HERA I (1993-2000) ≈ 120 $pb^{-1}$**
**HERA II (2003-2007) ≈ 380 $pb^{-1}$**
**… per experiment**



# Hard diffraction at HERA

**Diffractive** deep inelastic scattering (DDIS) represents ~ 10% of DIS $\sigma$ at low x




ep → eXY

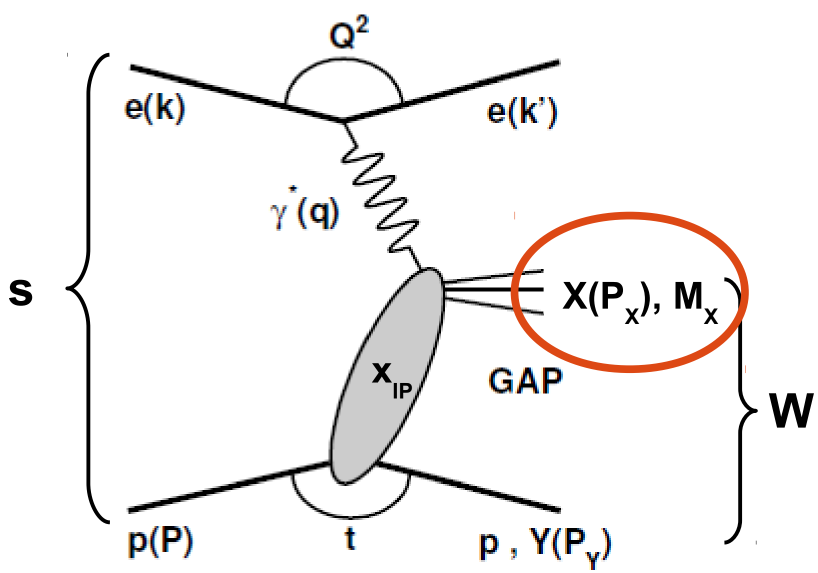
$$s = (k+P)^2$$
$$Q^2 = -q^2 = -(k-k')^2$$
$$y = \frac{q.P}{k.P}$$
$$x = \frac{Q^2}{2q.P}$$
$$W = \sqrt{(q+P)^2}$$
$$t = (P-P_Y)^2$$
$$M_X = P_X^2$$
$$M_Y = P_Y^2$$
$$x_{IP} = \frac{q.(P-P_Y)}{q.P}$$
$$\beta = \frac{x}{x_{IP}}$$

$Q^2$,t … four-momentum transfers
W … hadronic CMS energy
x … Bjorken x
X … photon dissociative system
Y … leading proton system
$x_{IP}$ … fractional proton mom. loss
$\beta$ … parton mom. frac. w.r.t. $x_{IP}$

can be viewed as coulour-singlet partonic state probed by exchanged $\gamma$

# Hard diffraction at HERA

**Diffractive** deep inelastic scattering (DDIS) represents ~ 10% of DIS $\sigma$ at low x




ep → eXY

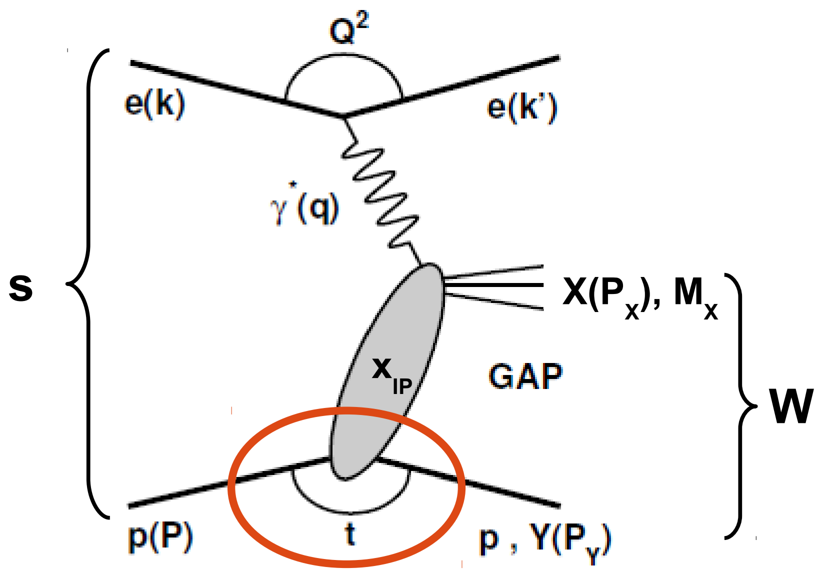
$$s = (k+P)^2$$
$$Q^2 = -q^2 = -(k-k')^2$$
$$y = \frac{q.P}{k.P}$$
$$x = \frac{Q^2}{2q.P}$$
$$W = \sqrt{(q+P)^2}$$
$$t = (P-P_Y)^2$$
$$M_X = P_X^2$$
$$M_Y = P_Y^2$$
$$x_{IP} = \frac{q.(P-P_Y)}{q.P}$$
$$\beta = \frac{x}{x_{IP}}$$

$Q^2$,t … four-momentum transfers
W … hadronic CMS energy
x … Bjorken x
X … photon dissociative system
Y … leading proton system
$x_{IP}$ … fractional proton mom. loss
$\beta$ … parton mom. frac. w.r.t. $x_{IP}$

virtual photon dissociates into X ($M_x^2 << W^2$)

# Hard diffraction at HERA

**Diffractive** deep inelastic scattering (DDIS) represents ~ 10% of DIS $\sigma$ at low x




ep → eXY

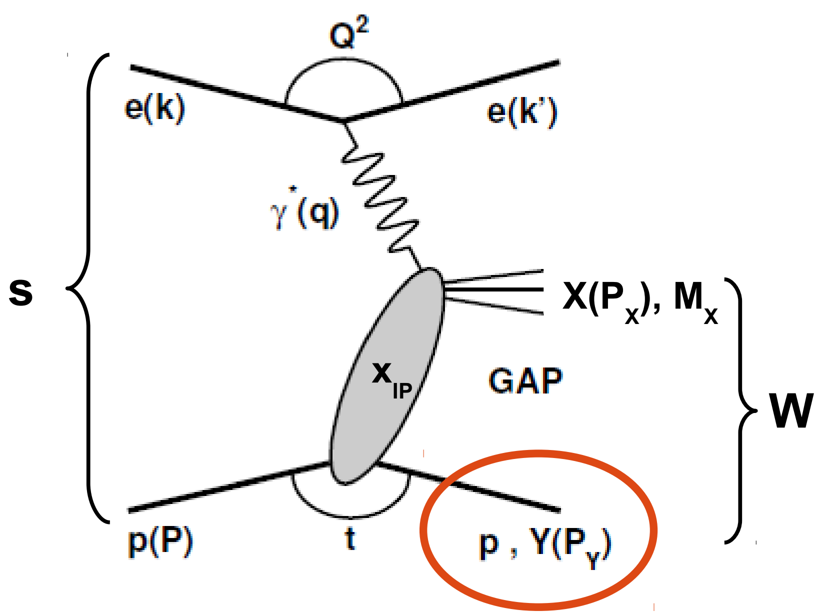
$$s = (k+P)^2$$
$$Q^2 = -q^2 = -(k-k')^2$$
$$y = \frac{q.P}{k.P}$$
$$x = \frac{Q^2}{2q.P}$$
$$W = \sqrt{(q+P)^2}$$
$$t = (P-P_Y)^2$$
$$M_X = P_X^2$$
$$M_Y = P_Y^2$$
$$x_{IP} = \frac{q.(P-P_Y)}{q.P}$$
$$\beta = \frac{x}{x_{IP}}$$

| | | |
|---|---|---|
| $Q^2$,t | … | four-momentum transfers |
| W | … | hadronic CMS energy |
| x | … | Bjorken x |
| X | … | photon dissociative system |
| Y | … | leading proton system |
| $x_{IP}$ | … | fractional proton mom. loss |
| $\beta$ | … | parton mom. frac. w.r.t. $x_{IP}$ |

small momentum transfer to proton, $|t| << W^2$

# Hard diffraction at HERA

**Diffractive** deep inelastic scattering (DDIS) represents ~ 10% of DIS $\sigma$ at low x




ep → eXY

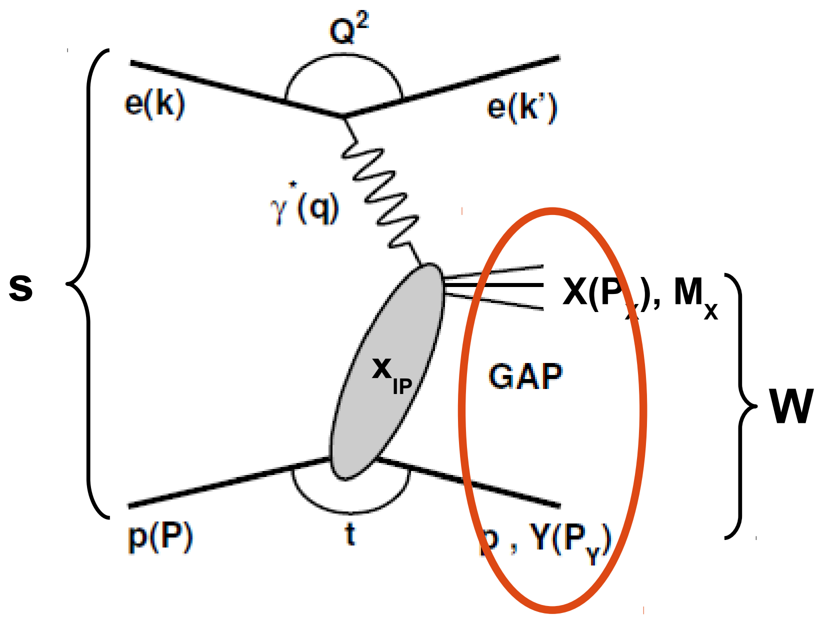
$$s = (k+P)^2$$
$$Q^2 = -q^2 = -(k-k')^2$$
$$y = \frac{q.P}{k.P}$$
$$x = \frac{Q^2}{2q.P}$$
$$W = \sqrt{(q+P)^2}$$
$$t = (P-P_Y)^2$$
$$M_X = P_X^2$$
$$M_Y = P_Y^2$$
$$x_{IP} = \frac{q.(P-P_Y)}{q.P}$$
$$\beta = \frac{x}{x_{IP}}$$

$Q^2$,t … four-momentum transfers
W … hadronic CMS energy
x … Bjorken x
X … photon dissociative system
Y … leading proton system
$x_{IP}$ … fractional proton mom. loss
$\beta$ … parton mom. frac. w.r.t. $x_{IP}$

proton stays intact or dissociates into system Y ($M_Y^2 << W^2$)

# Hard diffraction at HERA

**Diffractive** deep inelastic scattering (DDIS) represents ~ 10% of DIS $\sigma$ at low x




ep → eXY

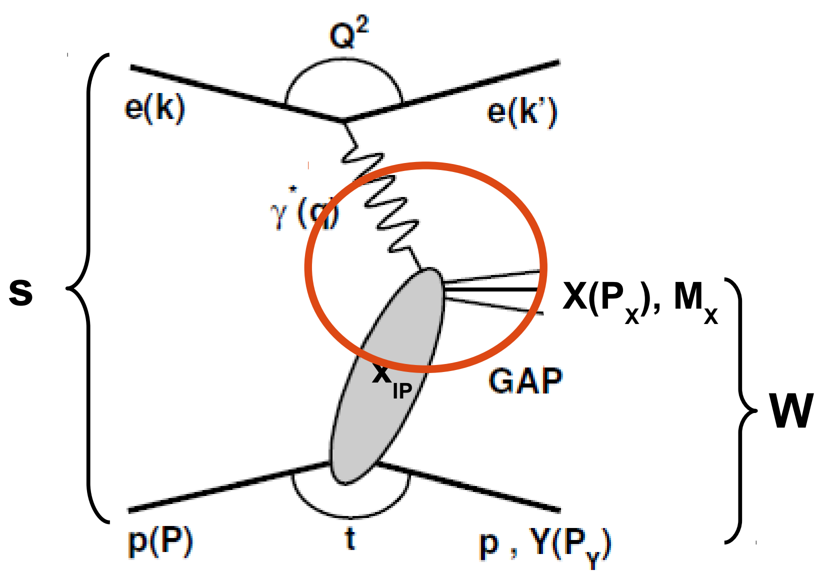
$$s = (k+P)^2$$
$$Q^2 = -q^2 = -(k-k')^2$$
$$y = \frac{q.P}{k.P}$$
$$x = \frac{Q^2}{2q.P}$$
$$W = \sqrt{(q+P)^2}$$
$$t = (P-P_Y)^2$$
$$M_X = P_X^2$$
$$M_Y = P_Y^2$$
$$x_{IP} = \frac{q.(P-P_Y)}{q.P}$$
$$\beta = \frac{x}{x_{IP}}$$

- $Q^2$,t … four-momentum transfers
- W … hadronic CMS energy
- x … Bjorken x
- X … photon dissociative system
- Y … leading proton system
- $x_{IP}$ … fractional proton mom. loss
- $\beta$ … parton mom. frac. w.r.t. $x_{IP}$

large rapidity gap (non-exponentially suppressed) between Y and X

# Hard diffraction at HERA

**Diffractive** deep inelastic scattering (DDIS) represents ~ 10% of DIS σ at low x



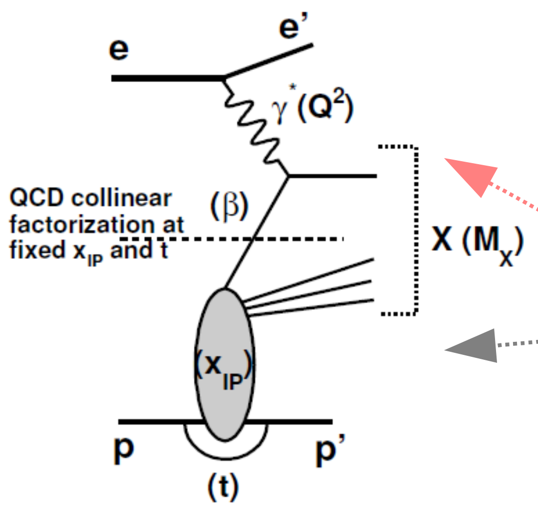

ep → eXY

$$s = (k+P)^2$$
$$Q^2 = -q^2 = -(k-k')^2$$
$$y = \frac{q.P}{k.P}$$
$$x = \frac{Q^2}{2q.P}$$
$$W = \sqrt{(q+P)^2}$$
$$t = (P-P_Y)^2$$
$$M_X = P_X^2$$
$$M_Y = P_Y^2$$
$$x_{IP} = \frac{q.(P-P_Y)}{q.P}$$
$$\beta = \frac{x}{x_{IP}}$$

$Q^2$,t … four-momentum transfers
W … hadronic CMS energy
x … Bjorken x
X … photon dissociative system
Y … leading proton system
$x_{IP}$ … fractional proton mom. loss
β … parton mom. frac. w.r.t. $x_{IP}$

hard scale present ($Q^2$, $p_T^2$, $m_Q^2$) → pQCD applicable

# Factorization in DDIS




**theoretical proof by Collins at. al for DDIS**

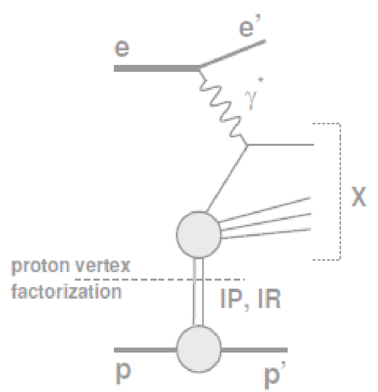
hard cross sections factorize from parton distributions

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \times f_i^D(x, Q^2; x_{IP}, t)$$

hard processes calculable in QCD

→ diffractive parton distribution functions (DPDFs) can be measured by means of fits to the data

**optionally:** Ingelman and Schlein proton vertex factorization (Regge factorization):



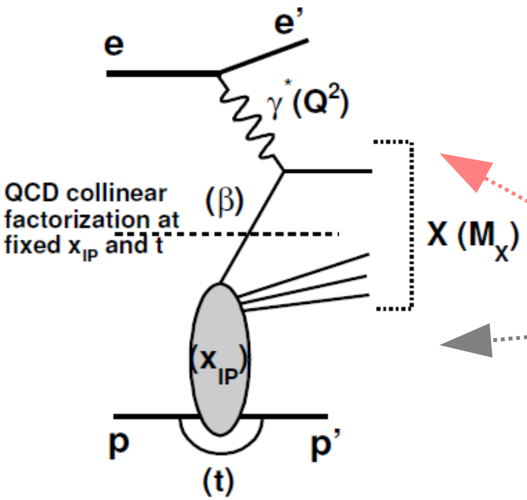

universal *IP* flux in the *IPp* vertex

$f_{IP/p}(x_{IP}, t)$ … flux controls $x_{IP}$, $t$ dependence of σ.

$$F_2^{D(3)}(x_{I\!P}, \beta, Q^2) = f_{I\!P/p} \cdot F_2^{I\!P}(\beta, Q^2)$$

IP with partonic structure is emitted with momentum $x_{IP}$ .$P_{proton}$ and t from the incoming proton and is subject to the hard scattering.

# Factorization in DDIS




**theoretical proof by Collins at. al for DDIS**

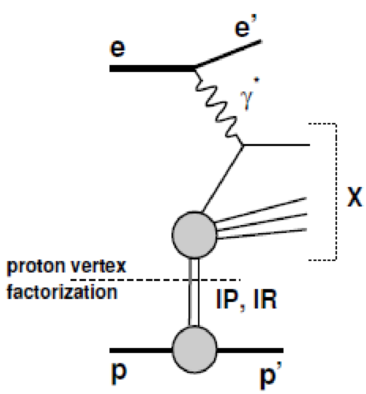
hard cross sections factorize from parton distributions

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \times f_i^D(x, Q^2; x_{IP}, t)$$

hard processes calculable in QCD

→ diffractive parton distribution functions (DPDFs) can be measured by means of fits to the data

**optionally:** Ingelman and Schlein proton vertex factorization (Regge factorization):



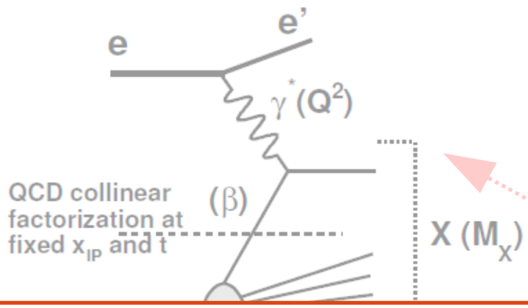

universal *IP* flux in the *IPp* vertex

$f_{IP/p}(x_{IP}, t)$ … flux controls $x_{IP}$, $t$ dependence of σ.

$$F_2^{D(3)}(x_{I\!P}, \beta, Q^2) = f_{I\!P/p} \cdot F_2^{I\!P}(\beta, Q^2)$$

IP with partonic structure is emitted with momentum $x_{IP} . P_{proton}$ and t from the incoming proton and is subject to the hard scattering.

# Factorization in DDIS




theoretical proof by Collins at. al for DDIS

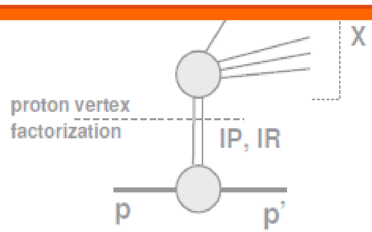
hard cross sections factorize from parton distributions

$$\sigma^{D(4)} \propto \sum \hat{\sigma}^{\gamma^* i}(x, Q^2) \times f_i^D(x, Q^2; x_{IP}, t)$$

**DPDFs obtained from QCD fits of:**

- inclusive data (mainly)
- with inclusion of jet data to provide constraints on gluon DPDF

**using DPDF for QCD predictions of hard final states → factorization is tested**




$f_{IP/p}(x_{IP}, t)$ … flux controls $x_{IP}$, $t$ dependence of σ.

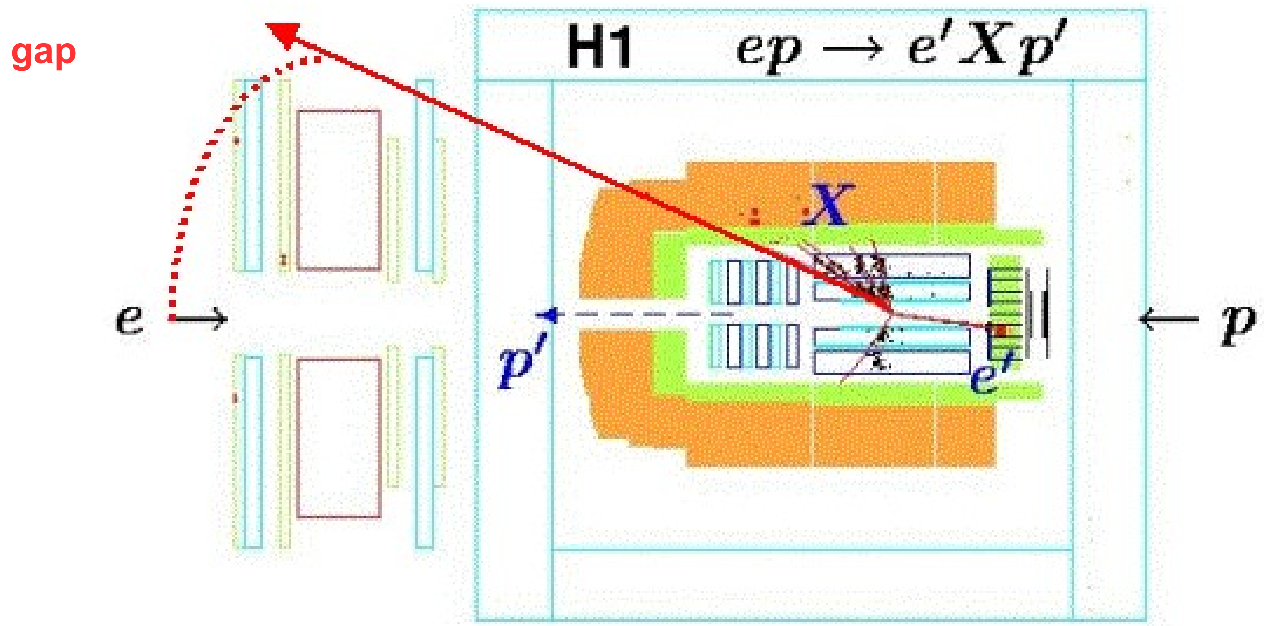
$$F_2^{D(3)}(x_{IP}, \beta, Q^2) = f_{IP/p} \cdot F_2^{IP}(\beta, Q^2)$$

IP with partonic structure is emitted with momentum $x_{IP} \cdot P_{proton}$ and t from the incoming proton and is subject to the hard scattering.

# Selection of diffractive events

**large rapidity gap**

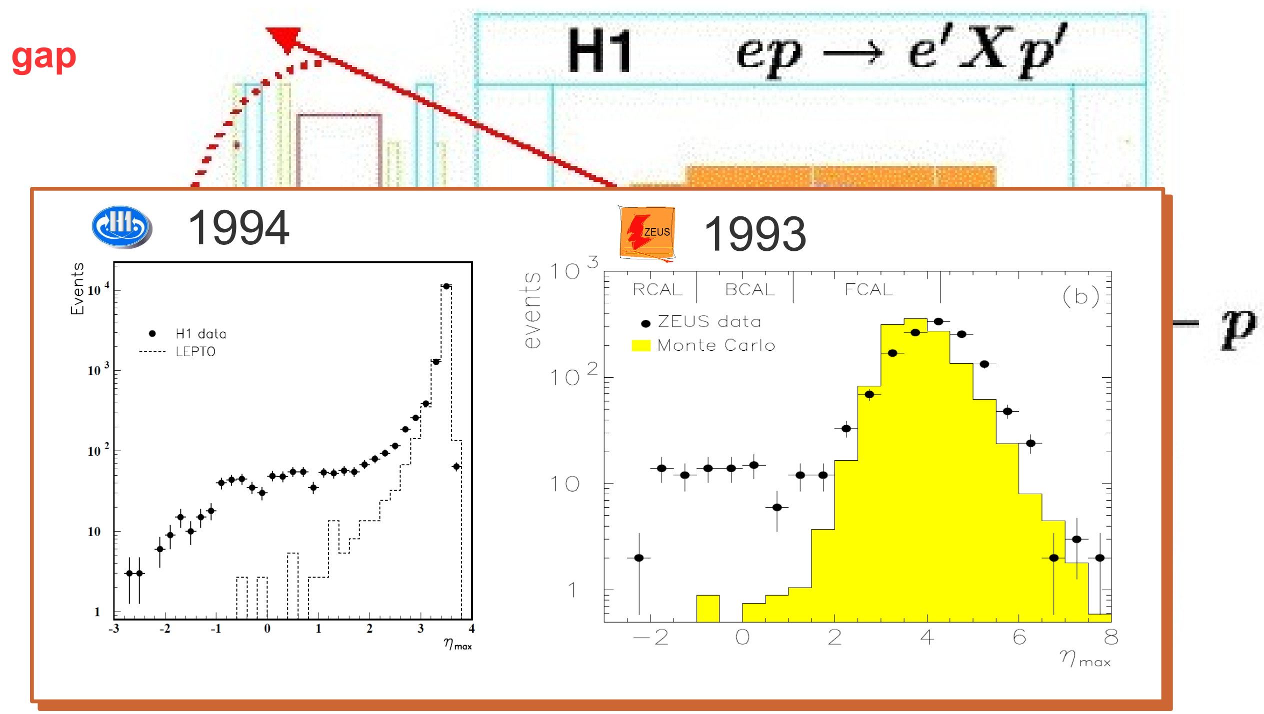
- **high statistics**
- **simple to use**
- proton dissociation contribution



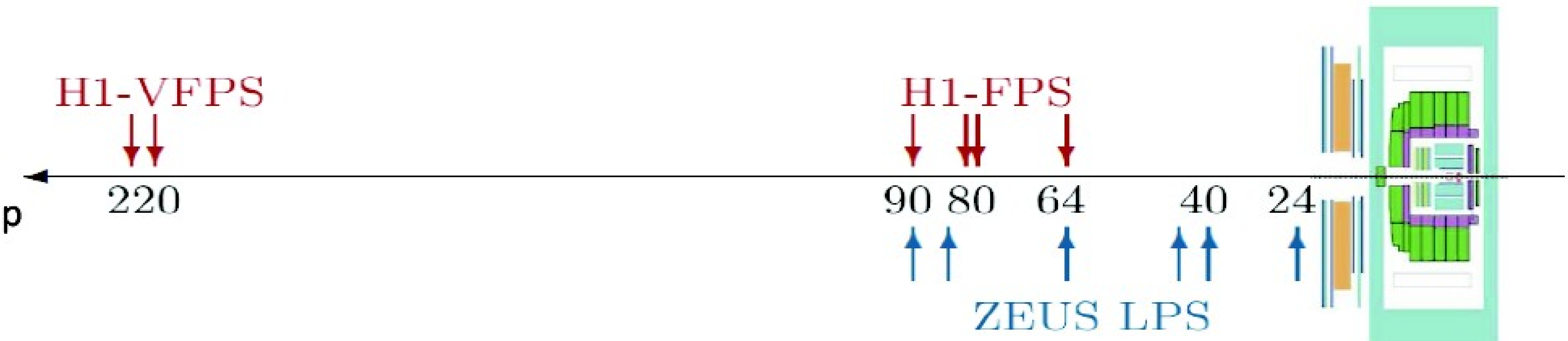
# Selection of diffractive events

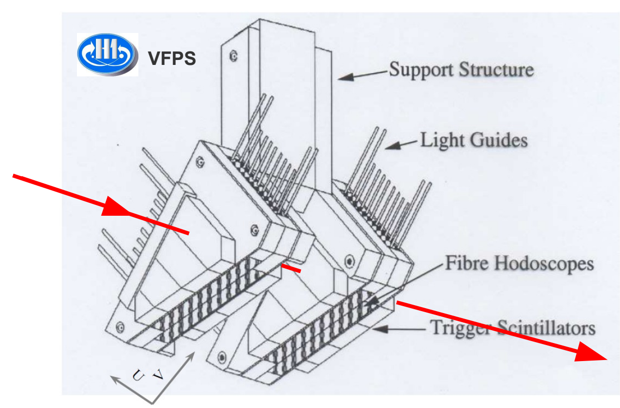
**large rapidity gap**

- **high statistics**
- **simple to use**
- proton dissociation contribution



# Selection of diffractive events

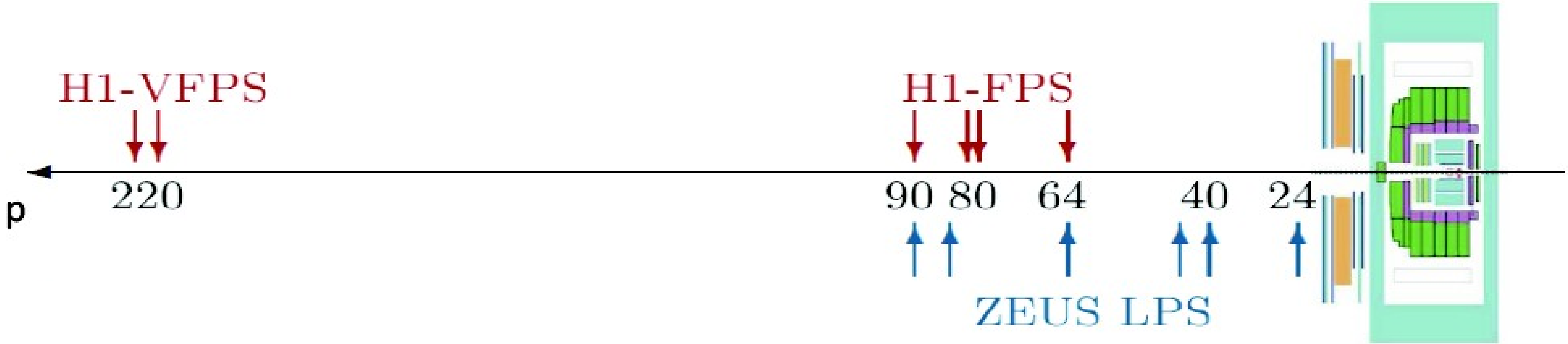



**leading proton tagging**

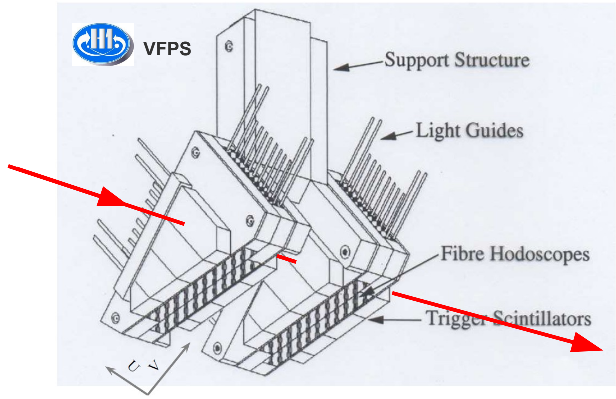
- **free of proton dissociation**
- experimentally demanding
- low acceptance, small statistics

# Selection of diffractive events




**leading proton tagging**

- **free of proton dissociation**
- experimentally demanding
- low acceptance, small statistics



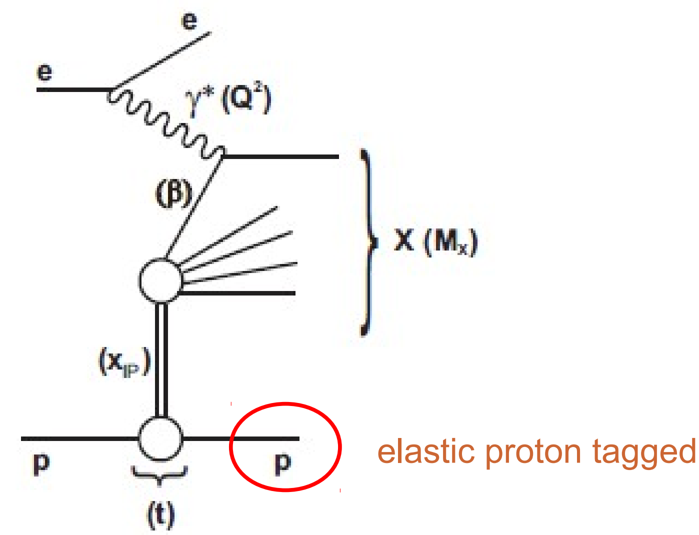

**both methods have been used in H1 and ZEUS**

# Combined inclusive diffractive cross sections measured with forward proton spectrometers in deep inelastic ep scattering at HERA

( published in Eur. Phys. J. C72 (2012) 2175 , 07/12 )

**ep → eXp, selected with leading protons**

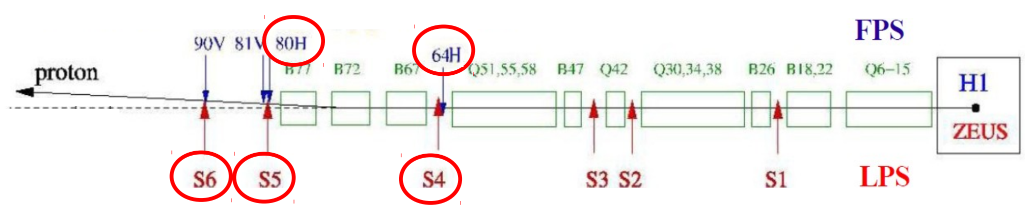
Roman Pots (H1-FPS, ZEUS-LPS)




**common phase space:**

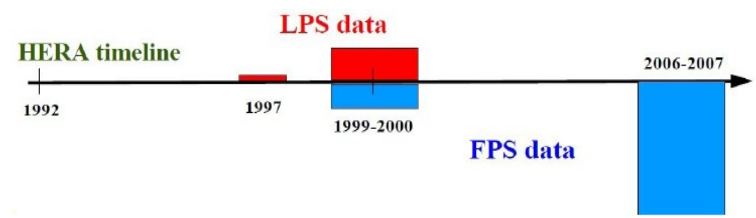
$2.5 < Q^2 < 200\ \mathrm{GeV}^2 \quad 0.00035 < x_{I\!P} < 0.09$

$0.09 < |t| < 0.55\ \mathrm{GeV}^2 \quad 0.0018 < \beta < 0.816 \quad \beta = x/x_{I\!P}$




**combined cross section values**

- measured data points in each dataset translated to a common grid
- optimal values of cross sections and systematic uncertainties of the **combined** result obtained by iterative $\chi^2$ minimization
- full error correlations taken into account



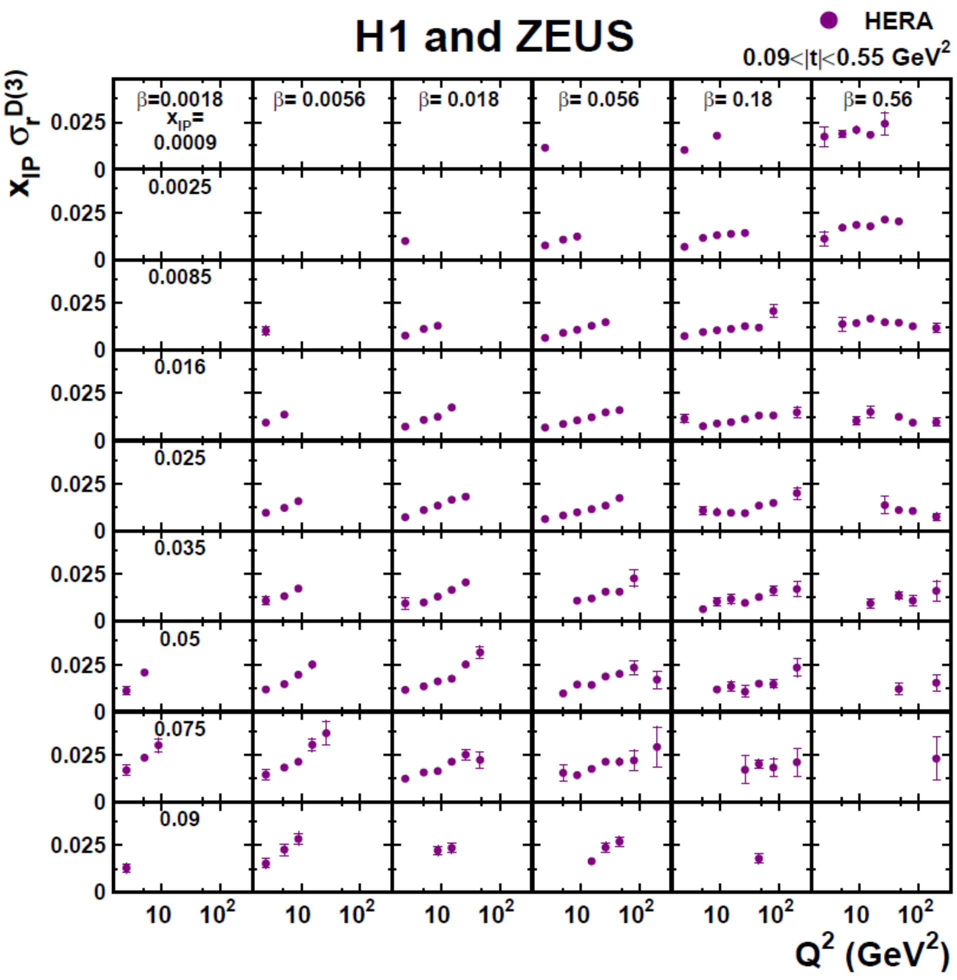

[A. Glazov, AIP Conf. Proc. 792 (2005) 237]

**reduced cross sections**

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

**integrated over t**

$$\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P}) = \int \sigma_r^{D(4)}(\beta, Q^2, x_{I\!P}, t)\,dt$$

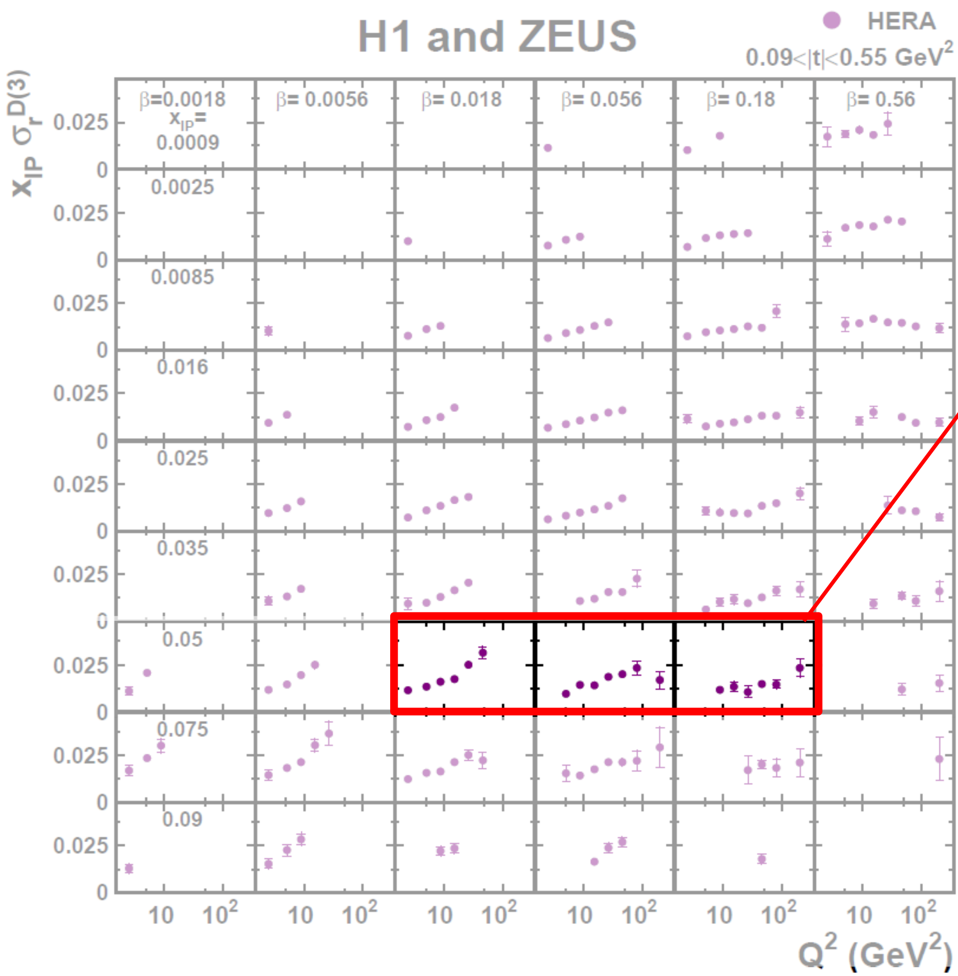


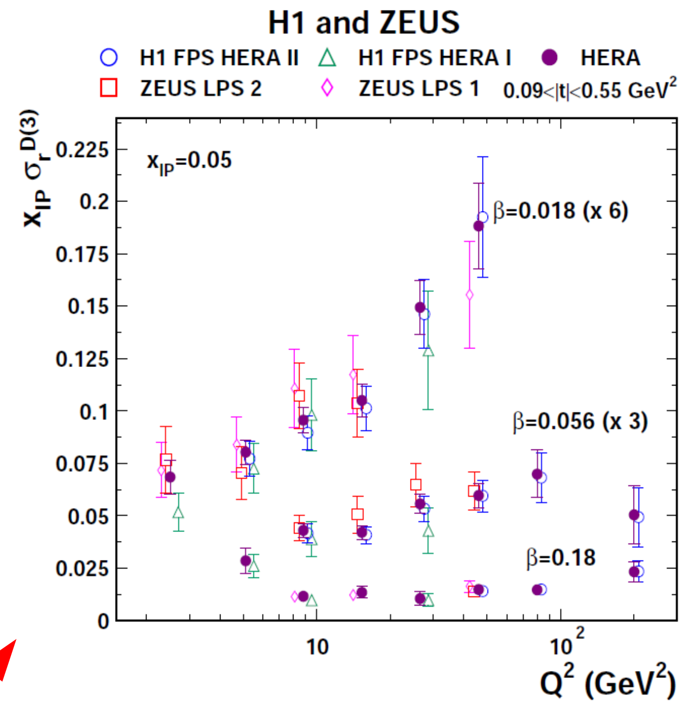
## reduced cross sections

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

## integrated over t

$$\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P}) = \int \sigma_r^{D(4)}(\beta, Q^2, x_{I\!P}, t)\,dt$$




Most precise normalization of σ(ep → eXp)

Some $\delta_{syst}$ get reduced significantly due to cross calibration effects.

Combined data more precise than FPS HERA II by ~27% on average.

Total uncertainty $\delta_{tot}$ ~14%

Most precise point $\delta_{exp}$ ~ 6%

# Diffractive dijet production in photoproduction and DIS with leading proton in VFPS

( preliminary results 2014 )

**diffractive photoproduction ($Q^2$ ~0 $GeV^2$) of dijets in LO QCD**

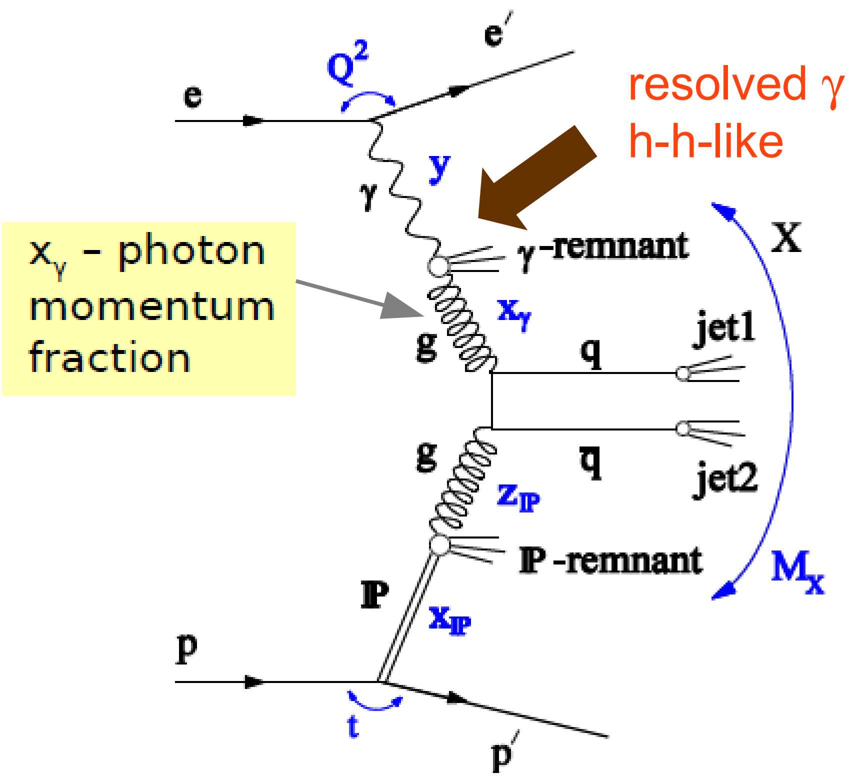
resolved photon, $x_\gamma$ … $\gamma$ momentum fraction in hard process **($x_\gamma$ <1)**

similarity with h-h interactions where factorization does not hold Kaidalov et. al

leading proton detected
→ **independent of LRG analyses** (different technique)

**why independent of LRG?**
LRG analyses by H1 and ZEUS not fully consistent in data/theory comparison

- ZEUS data described with NLO QCD
- H1 data below NLO QCD
- both H1 and ZEUS observe no dependence on $x_\gamma$



# Diffractive dijet production in photoproduction and DIS with leading proton in VFPS

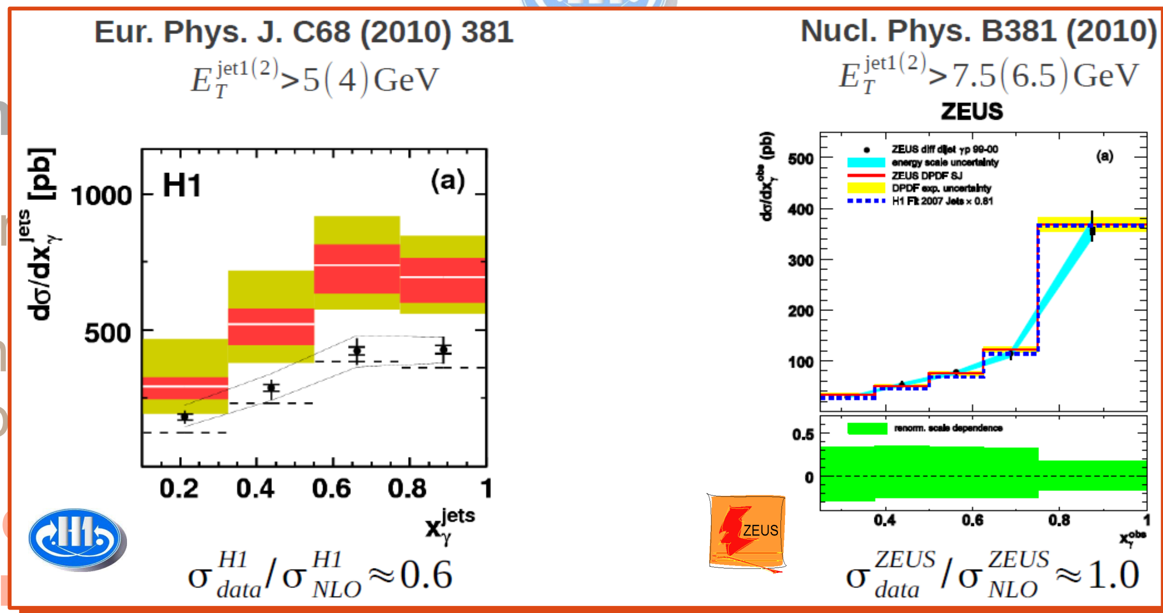
( preliminary results 2014 )

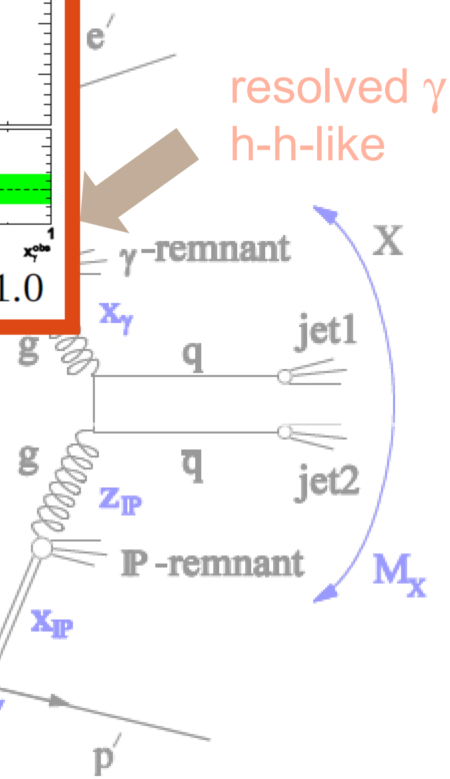
**diffractive ph** ... **LO QCD**

resolved photo ... ($x_\gamma$<1)

similarity with h ...
factorization do ...

leading proton ...
→ **independe** ...
**analyses** (different technique)




**why independent of LRG?**

LRG analyses by H1 and ZEUS not fully consistent in data/theory comparison

- ZEUS data described with NLO QCD
- H1 data below NLO QCD
- both H1 and ZEUS observe no dependence on $x_\gamma$

## **on top of resolved, there is direct γ in DDIS and γp** in LO QCD

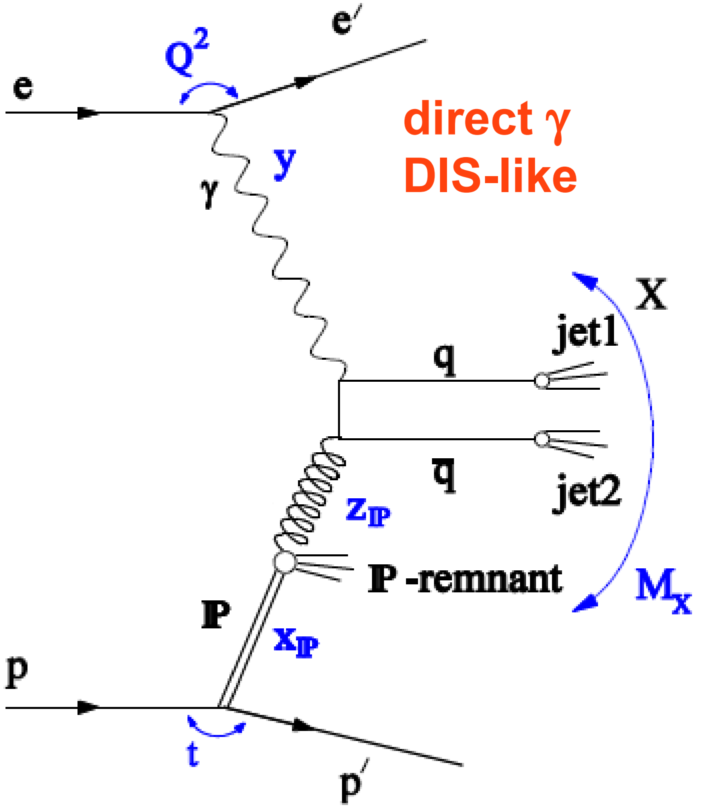
γ directly couples to quarks, $\mathbf{x_\gamma = 1}$

γp events ... mixture of direct and resolved

factorization holds in DDIS

**factorization in γp tested by means of**

- **comparisons with theory**
- **data / theory in γp / DIS double ratios**



## on top of resolved, there is direct γ in DDIS and γp in LO QCD

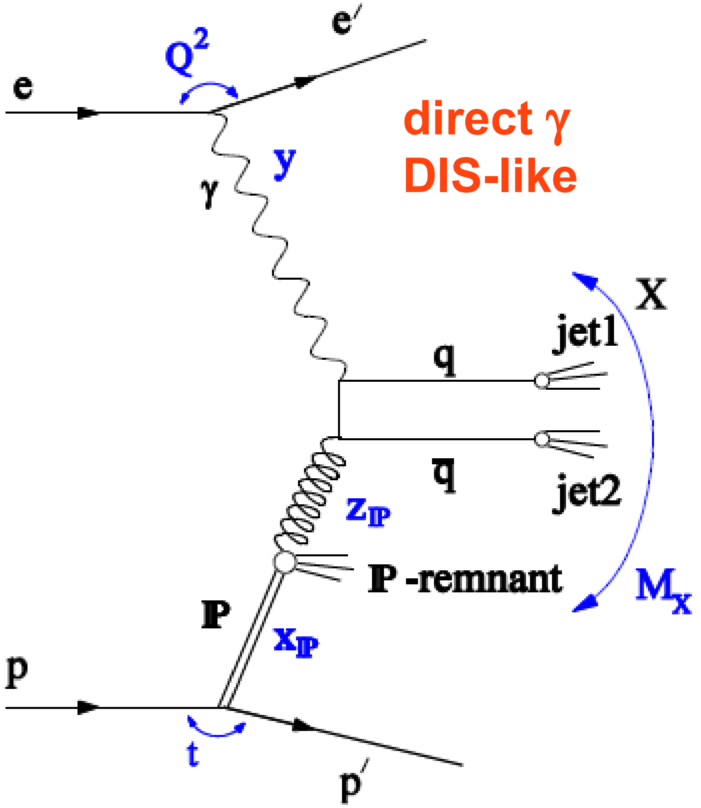
γ directly couples to quarks, $x_\gamma = 1$

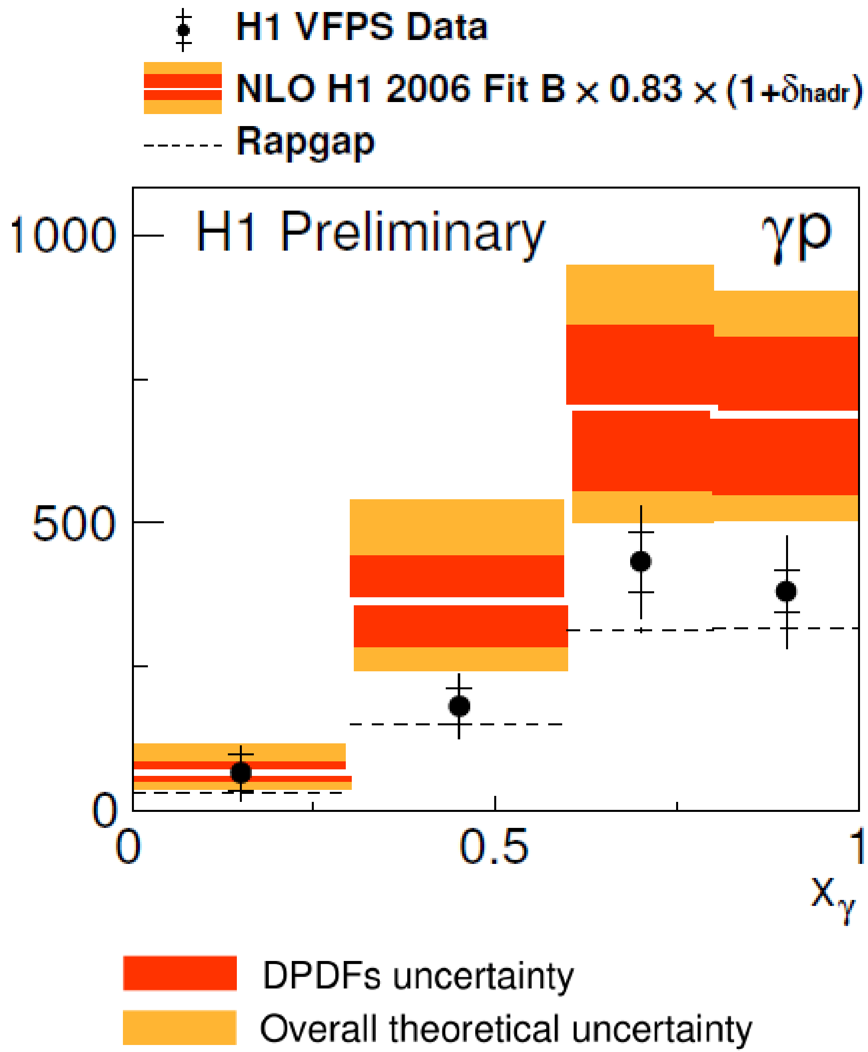
γp events ... mixture of direct and resolved

factorization holds in DDIS

**factorization in γp tested by means of**

- **comparisons with theory**
- **data / theory in γp / DIS double ratios**






$$\text{Data/NLO} = 0.60 \pm 0.08\,(\text{data}) \pm 0.21\,(\text{theor.})$$

# photoproduction

$E_T^{jet1(2)} > 5.5\ (4)$ GeV

$-1 < \eta^{jet1(2)} < 2.5$

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

$0.2 < y < 0.7$

$|t| < 0.6\ \text{GeV}^2$

---

Frixione-Ridolfi NLO QCD

H1 2006 DPDF Fit B

scaled by 0.83 to elastic case

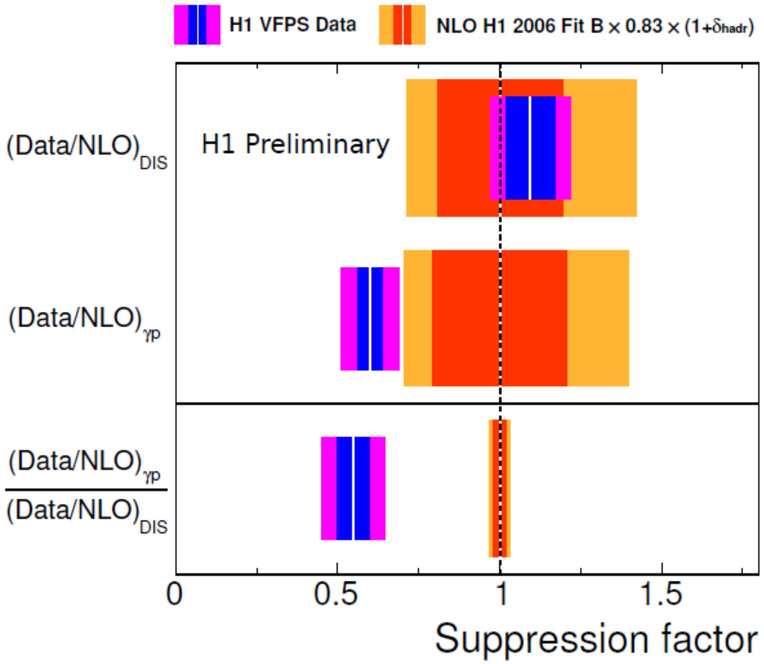
corrected for hadronization

**data/NLO ~ 0.6**

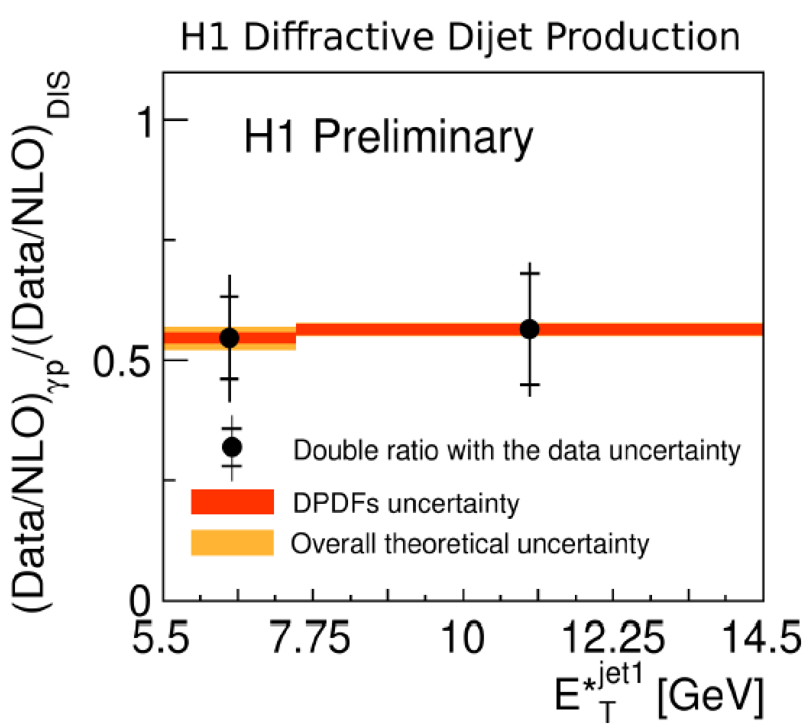
**consistent with previous H1(LRG)**

**does not explain H1/ZEUS difference**

**independent of $x_\gamma$**




$$\frac{(\mathrm{DATA/NLO})_{\gamma p}}{(\mathrm{DATA/NLO})_{\mathrm{DIS}}} = 0.55 \pm 0.10\,(\mathrm{data}) \pm 0.02\,(\mathrm{theor.})$$




# double ratios to DDIS

$E_T^{jet1(2)} > 5.5\ (4)$ GeV

$-1 < \eta^{jet1(2)} < 2.5$

$4 < Q^2 < 80$ GeV$^2$

$0.2 < y < 0.7$

$|t| < 0.6$ GeV$^2$

---

## NLOJET++ used in DDIS

H1 2006 DPDF Fit B

scaled to elastic case again

corrected for hadronization

**double ratio ~ 0.55**

**independent of event variables**

**theory uncertainties significantly reduced**

# Diffractive dijet production with LRG in DIS at HERA

( preliminary results 2014)

## using factorization to predict measured dijet rates in DDIS

results profit from high statistics of HERA II data

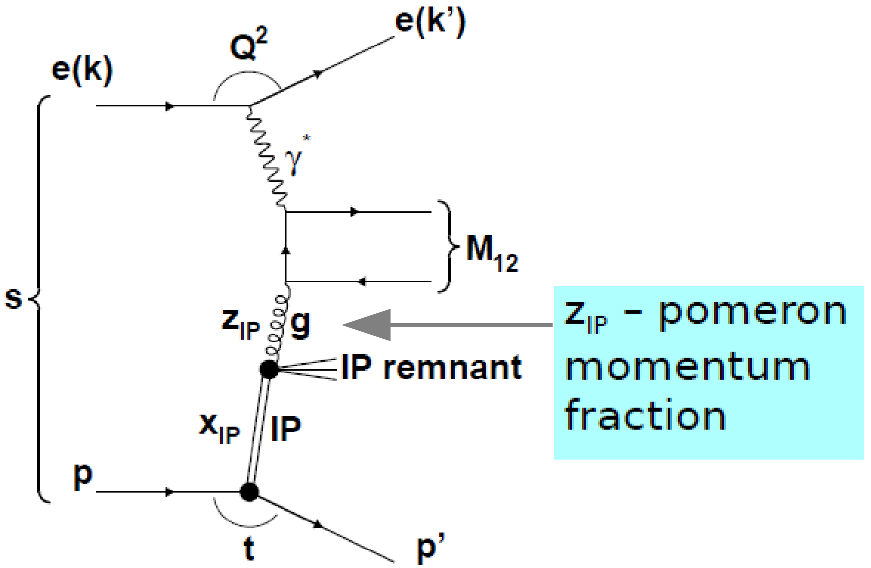
LRG based selection of diffraction

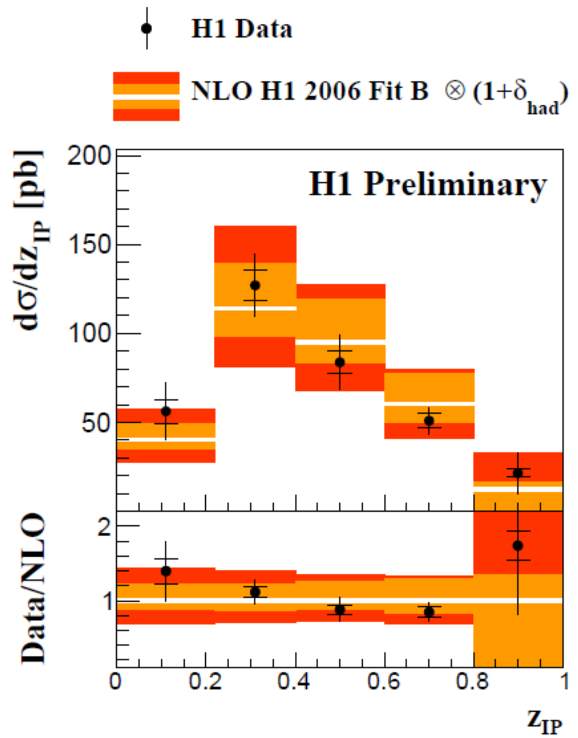
more elaborate correction for detector effects (TUnfold)

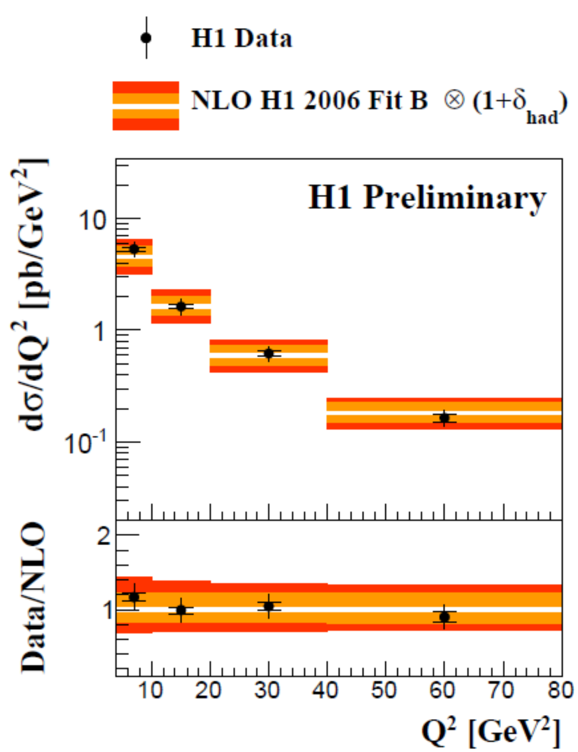
main process photon-gluon fusion - gluon dominates the DPDFs (75%)

| DDIS Dijet Selection |
|---|
| $4 < Q^2 < 80$ GeV$^2$<br>$0.1 < y < 0.7$ |
| $p^*_{T,1} > 5.5$ GeV<br>$p^*_{T,2} > 4.0$ GeV<br>$-1 < \eta_{1,2} < 2$ |
| $x_{I\!P} < 0.03$<br>$\lvert t \rvert < 1$ GeV$^2$<br>$M_Y < 1.6$ GeV |

$\sim$ 14000 events accepted






**in general data described by NLO QCD**

- NLO QCD with NLOJET++
  - based on H1 2006 DPDF Fit B
  - corrected for hadronization

**measurement highest $z_{IP}$**

- data are more precise than theory
  - DPDF and scale uncertainties dominate
- → **new DPDF fits ?**

# Summary

**Combination of H1/ZEUS inclusive DDIS data with leading proton**

- most precise measurement of inclusive DDIS (ep → eXp)

**Diffractive dijet production in γp and DIS with leading proton**

- in agreement with H1(LRG) (H1 data/theory ~0.6, independent of $x_\gamma$)
- not explaining H1/ZEUS results difference (ZEUS data described with NLO QCD)
- new measurement of double ratios data/theory in γp and DIS (~0.55) independent of kinematics

**Diffractive dijets in DIS with LRG**

- confirms factorization in DDIS
- experimental errors small enough to provide constraints at highest $z_{IP}$

**Thank you for your attention!**