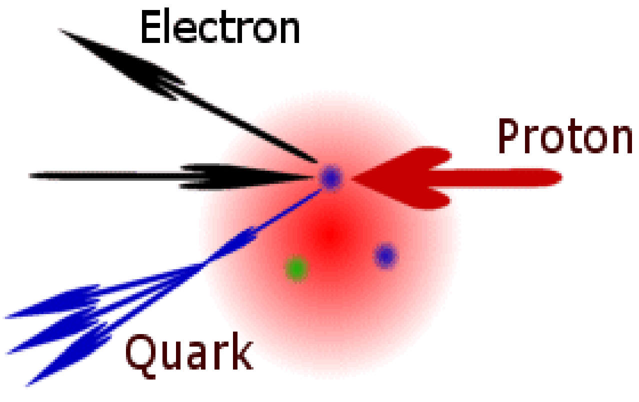
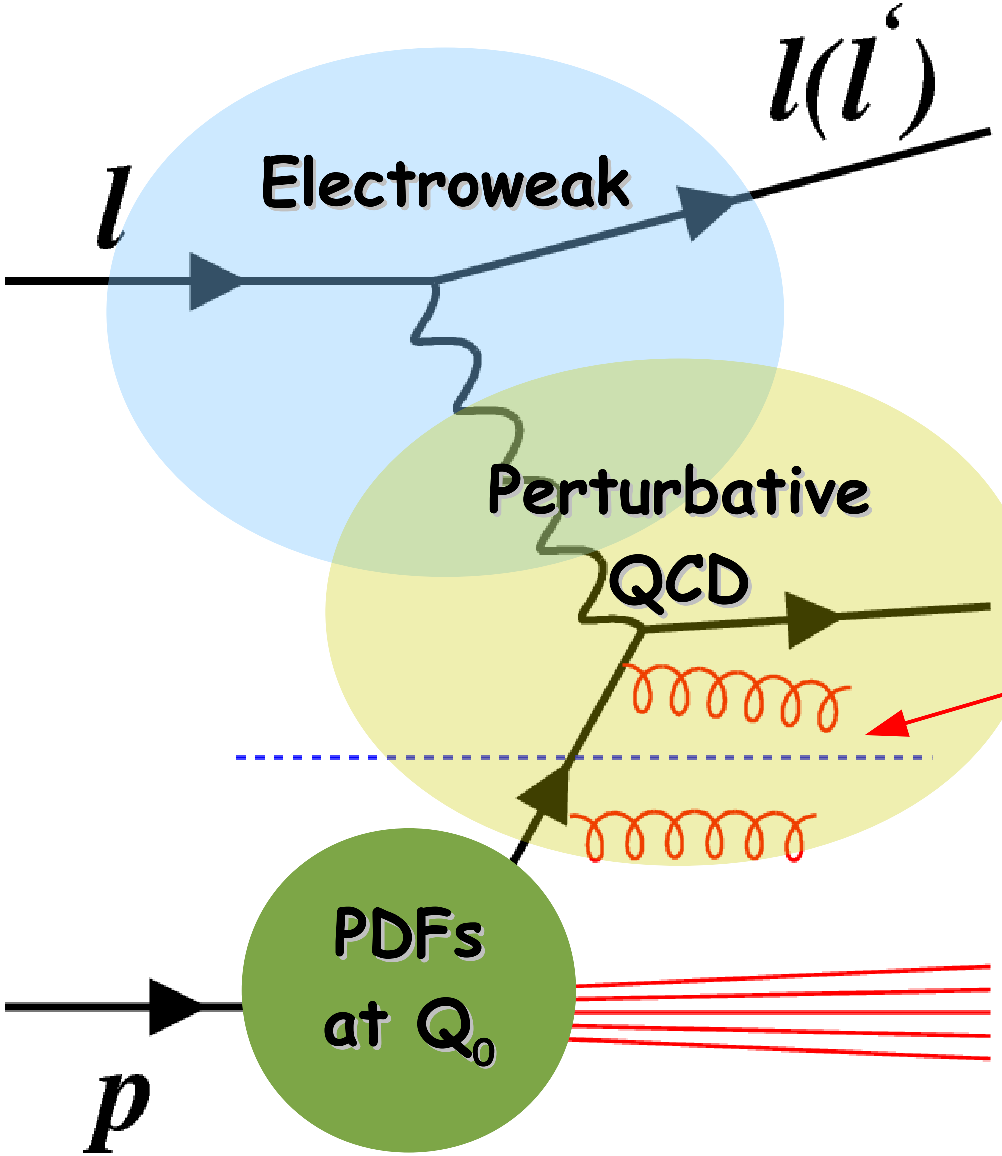



6th Workshop on QCD and Diffraction joint with

# VARIOUS FACES OF QCD @HERA

4th Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society

# ep Scattering @ HERA




- Fix pQCD & PDFs
  ! Test Electroweak
- Fix Electroweak
  ! Test pQCD & PDFs

Factorisation

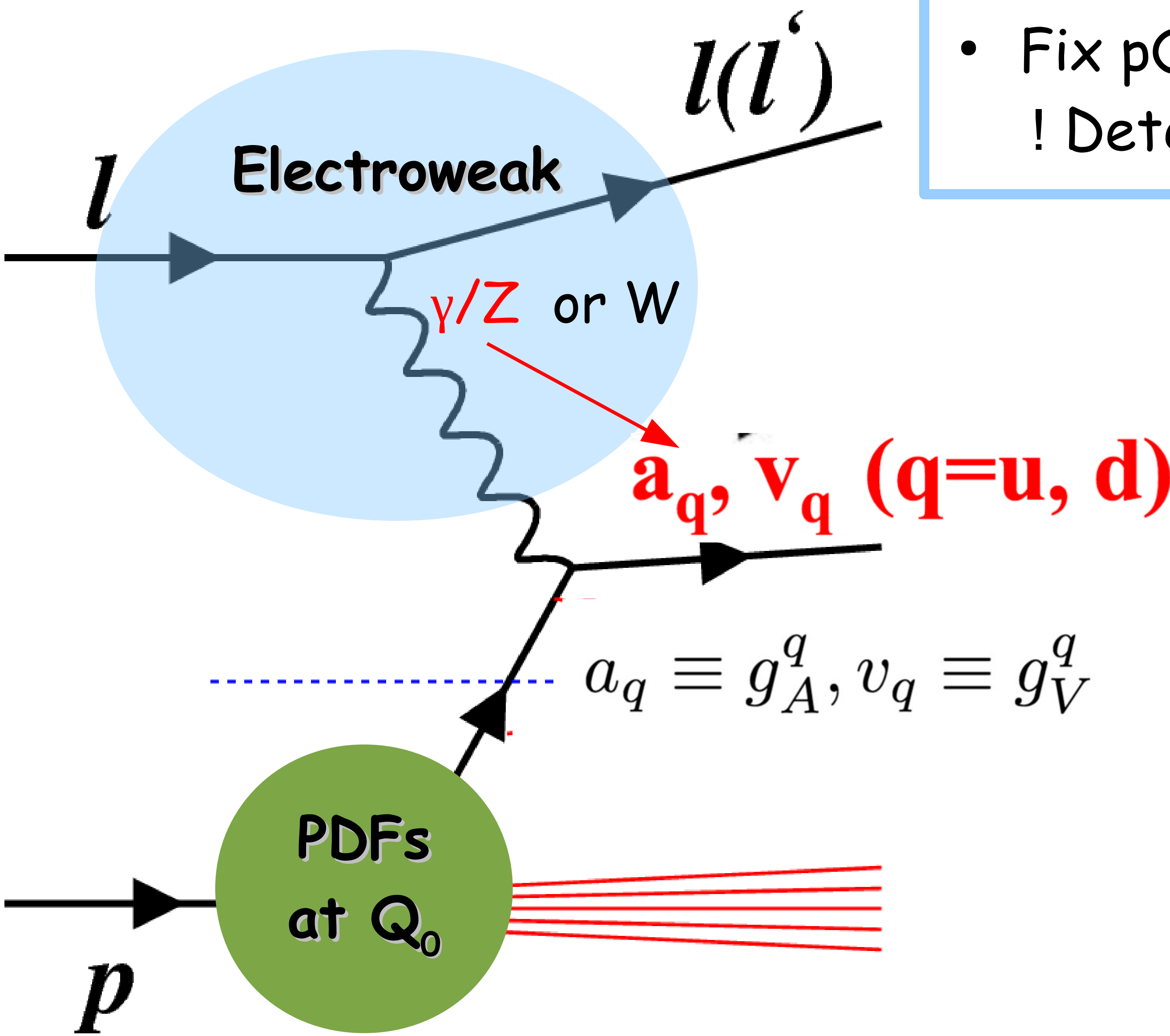
- Fix Electroweak & pQCD
  ! Determine PDFs

We can actually fix only one and determine the rest!

# Electroweak Physics @ HERA



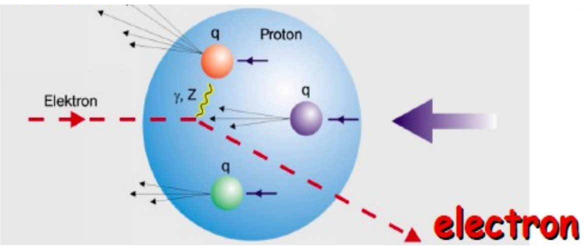
- Fix pQCD + polarised DIS
  ! Determine PDFs & EW

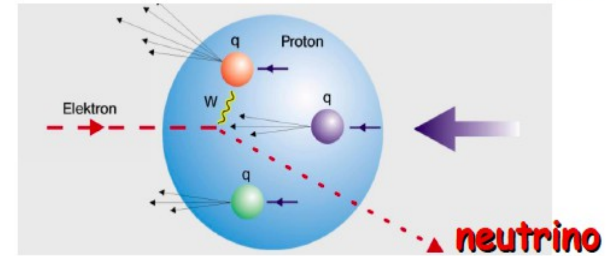



$$a_q \equiv g_A^q, v_q \equiv g_V^q$$

Sensitive to EW parameters (e.g. light quark couplings & W boson mass) in space-like regime

# Polarised H1 data




- Neutral current

$$\frac{d^2\sigma^{\pm}_{\rm NC}}{dx dQ^2} \sim Y_+ \tilde{F}_2 \mp Y_- x\tilde{F}_3$$

$$\tilde{F}_2 \simeq F_2 - P_e g_A^e \kappa_Z F_2^{\gamma Z} + \left(g_V^e g_V^e + g_A^e g_A^e\right) \kappa_Z^2 F_2^Z$$

$$x\tilde{F}_3 \simeq -g_A^e \kappa_Z x F_3^{\gamma Z} + P_e g_A^e g_A^e \kappa_Z^2 x F_3^Z$$

$$F_2^{\gamma Z} = 2x \sum_q Q_q g_V^q \{q + \bar{q}\}$$

$$xF_3^Z = 2x \sum_q g_V^q g_A^q \{q - \bar{q}\}$$

degree of longitudinal polarisation

- Charge current

$$\frac{d^2\sigma^{\pm}_{\rm CC}}{dx dQ^2} \simeq (1 \pm P_e) \frac{G_{\rm F}^2}{4\pi x} \left[\frac{m_W^2}{m_W^2 + Q^2}\right]^2 \left(Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm}\right)$$

$$W_2^- = x\left(\rho^2_{{\rm CC},eq} U + \rho^2_{{\rm CC},e\bar{q}} \overline{D}\right)$$

$$xW_3^- = x\left(\rho^2_{{\rm CC},eq} U - \rho^2_{{\rm CC},e\bar{q}} \overline{D}\right)$$

$$U = u + c$$

$$\overline{D} = \bar{d} + \bar{s}$$

- Longitudinal polarised lepton beams at HERA-II introduce additional terms
- Terms containing $g_V^e$ neglected

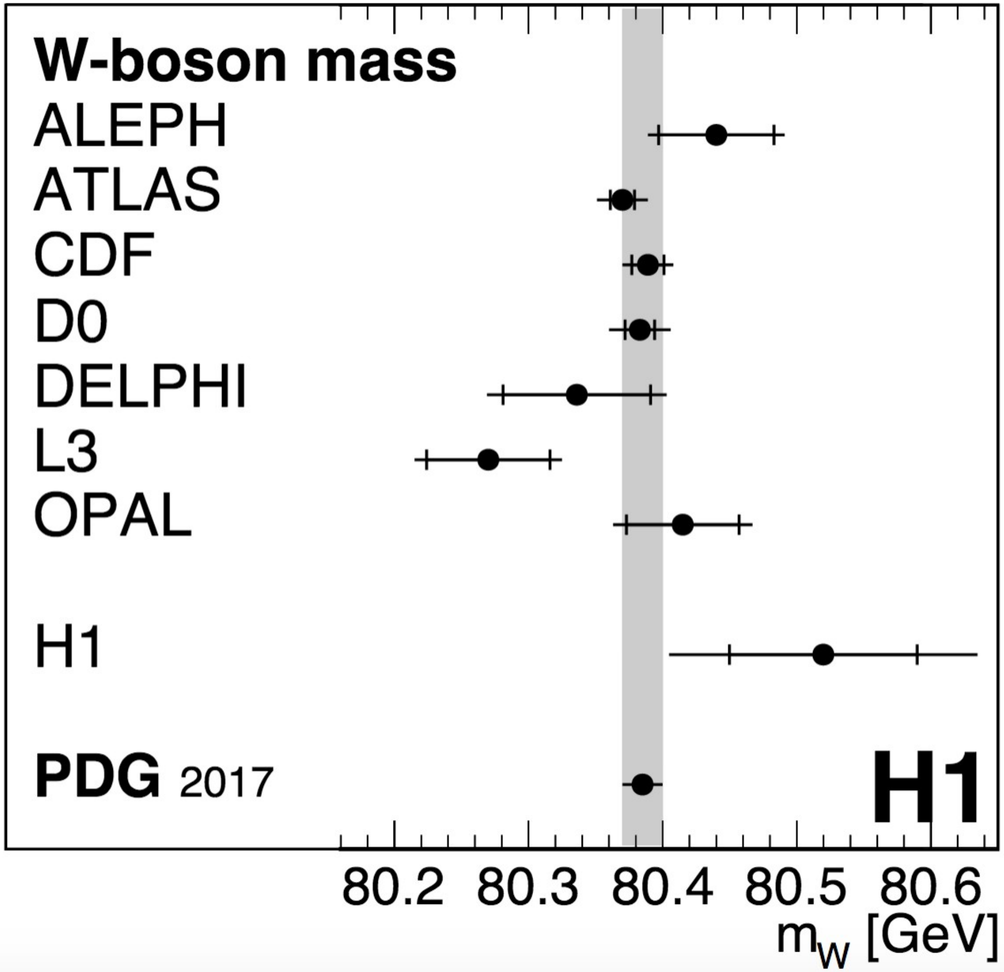
Perform simultaneous QCD + EW fit

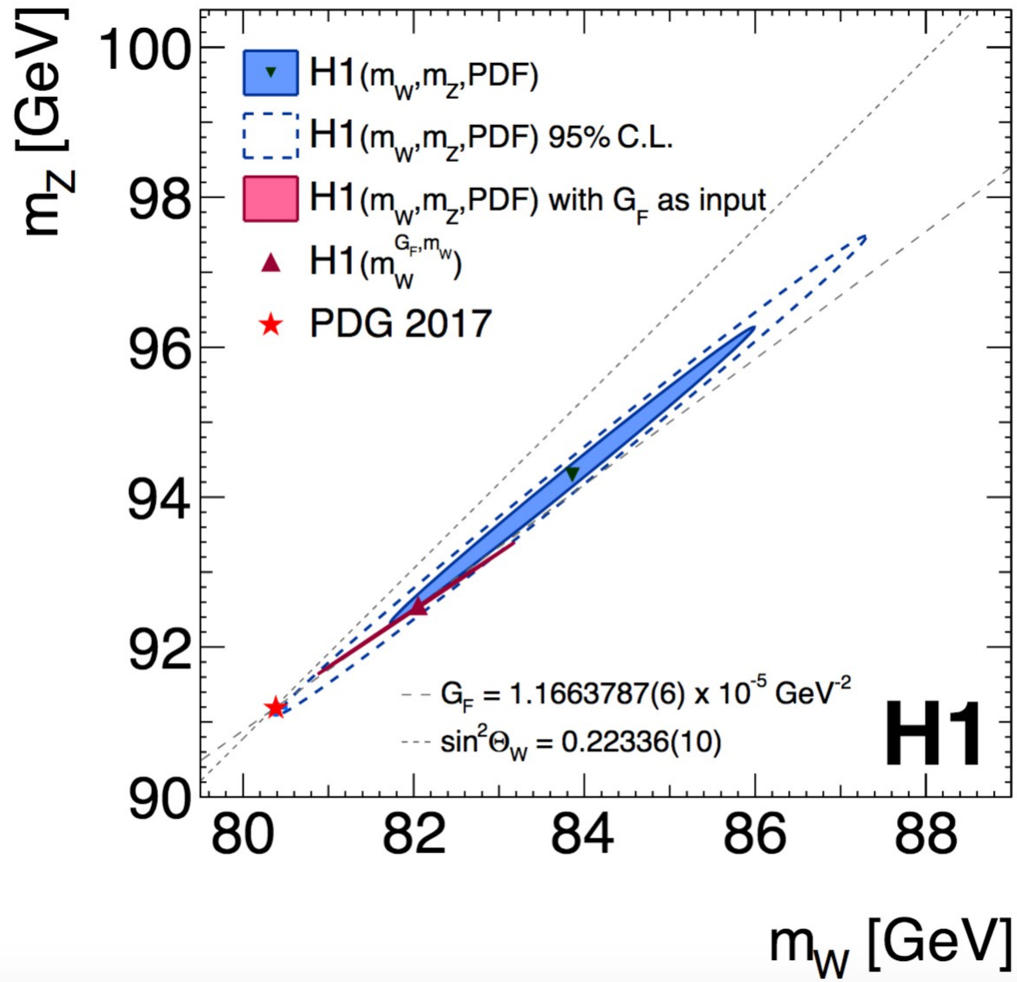
**NNLO for QCD**

**NLO for EW**

# W boson mass

Eur.Phys.J.C78 (2018), 777
[arxiv:1806.01176]



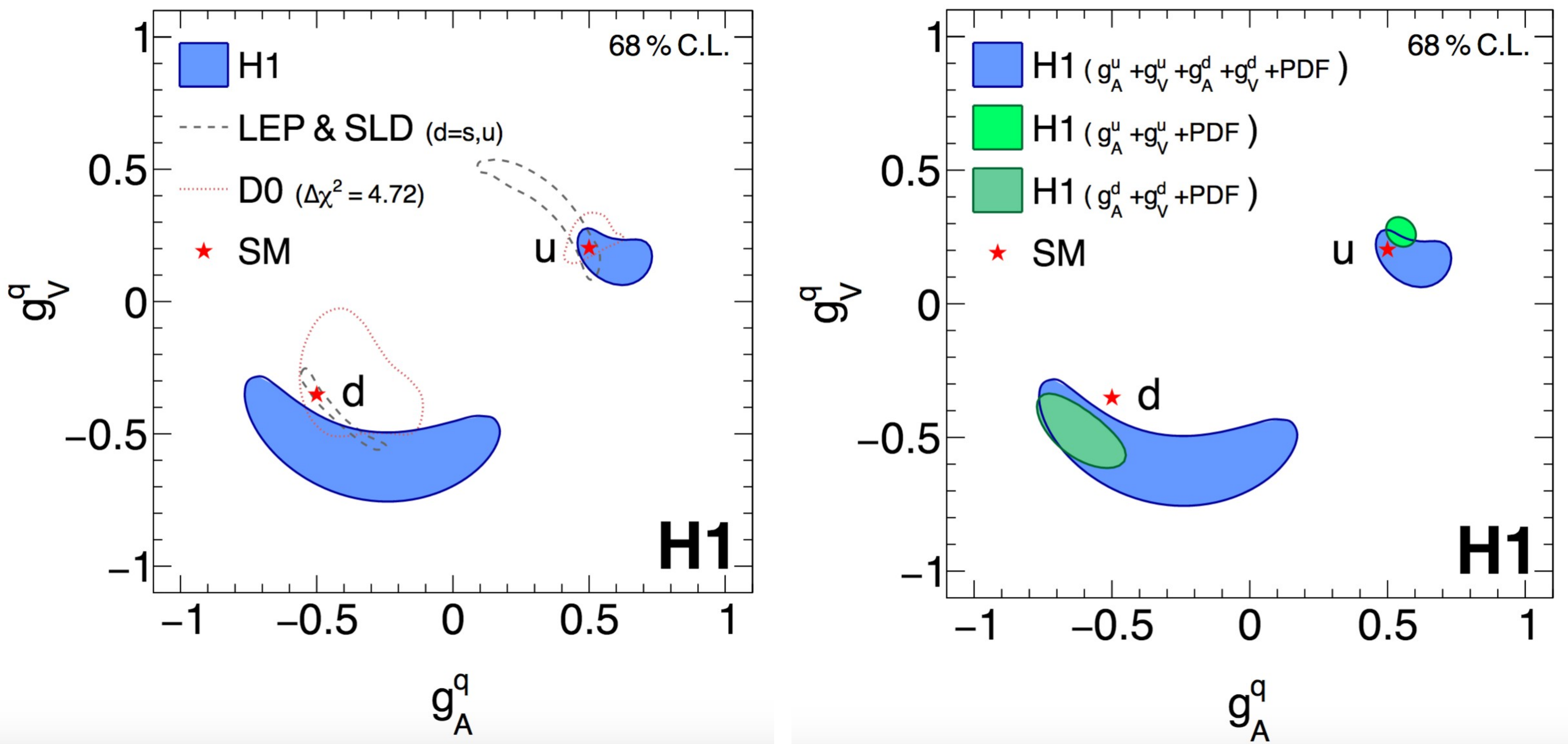

**Determination performed in on-shell scheme:**

$$m_W = 80.520 \pm 0.070_{\text{stat}} \pm 0.055_{\text{syst}} \pm 0.074_{\text{PDF}} [\pm 0.115_{\text{total}}] \text{GeV}$$

to be compared with HERA-I result:

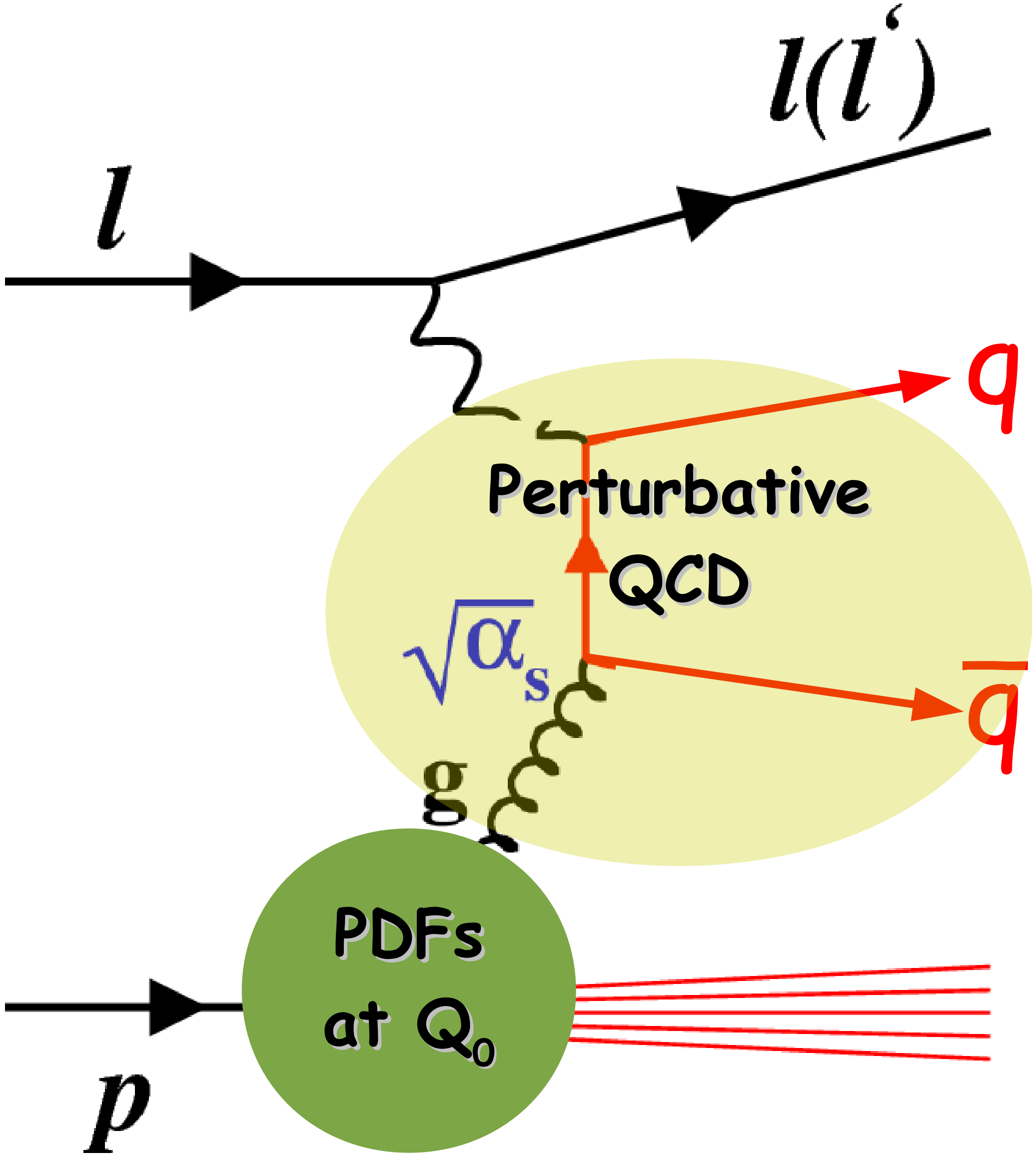
$$m_W = 80.786 \pm 0.205(\text{exp})^{+0.063}_{-0.098}(\text{th}) \text{ GeV}$$

# Light Quark Couplings to Z Boson




- results are competitive with other determinations, especially for u quarks
- 2-coupling fit is more precise due to the reduced correlation

# Jet Production @ HERA




- Direct information on gluon distribution comes from jet production
- Possible determination of $\alpha_s(m_Z)$ and simultaneous determination of parton densities and $\alpha_s(m_Z)$

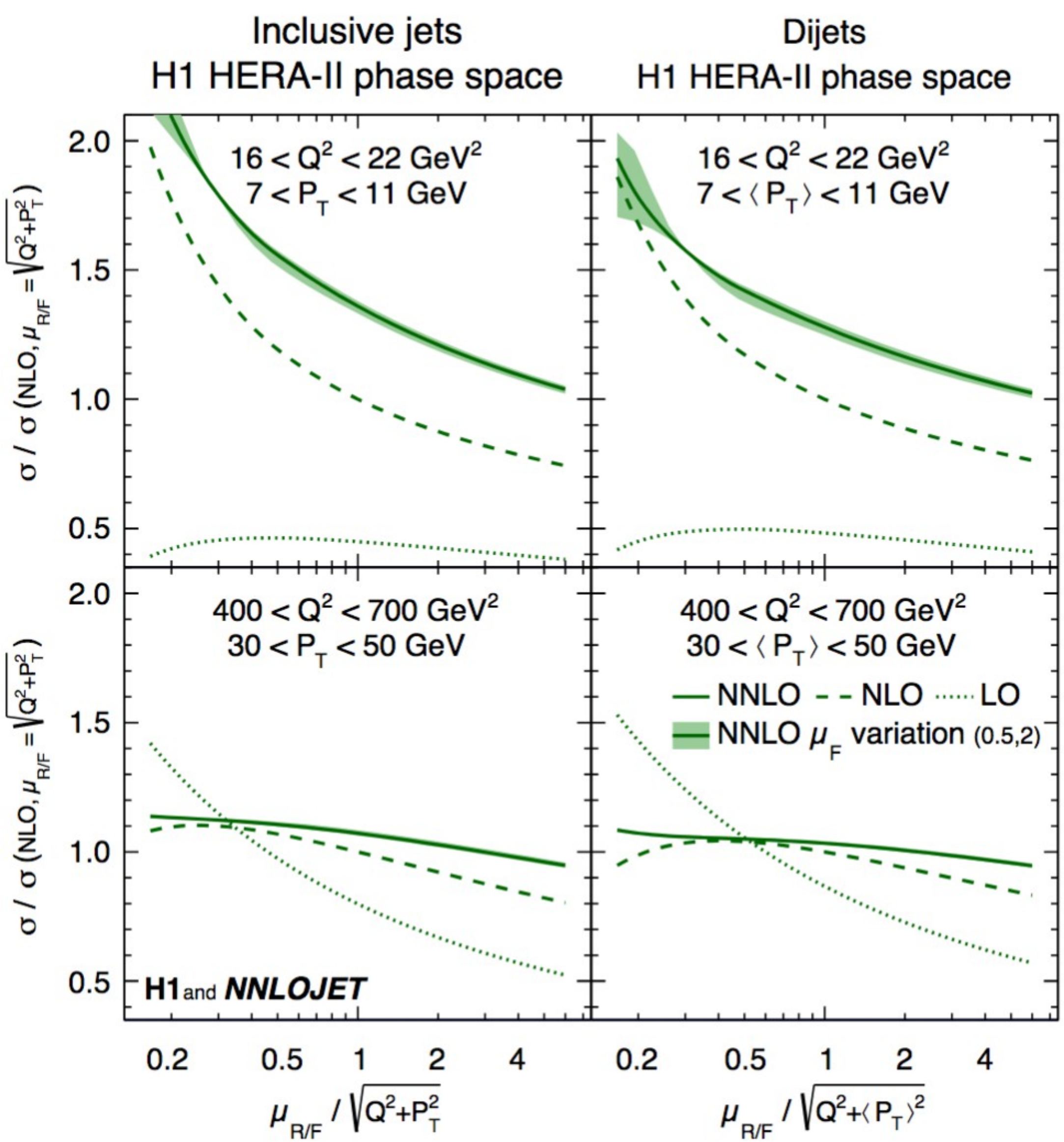
→ ***theory predictions for ep jets available at NNLO***

# Scale dependence of NNLO cross sections

Eur.Phys.J.C77 (2017), 791

[arxiv:1709.07251]

- Simultaneous variation of $\mu_R$ and $\mu_F$
- At lower scales
  - Significant NNLO k-factors
  - NNLO with reduced scale dependence
  - Inclusive jets with higher scale dependence than dijets
- At higher scales
  - NNLO with reduced scale dependence
  - $\mu_F$ dependence very small

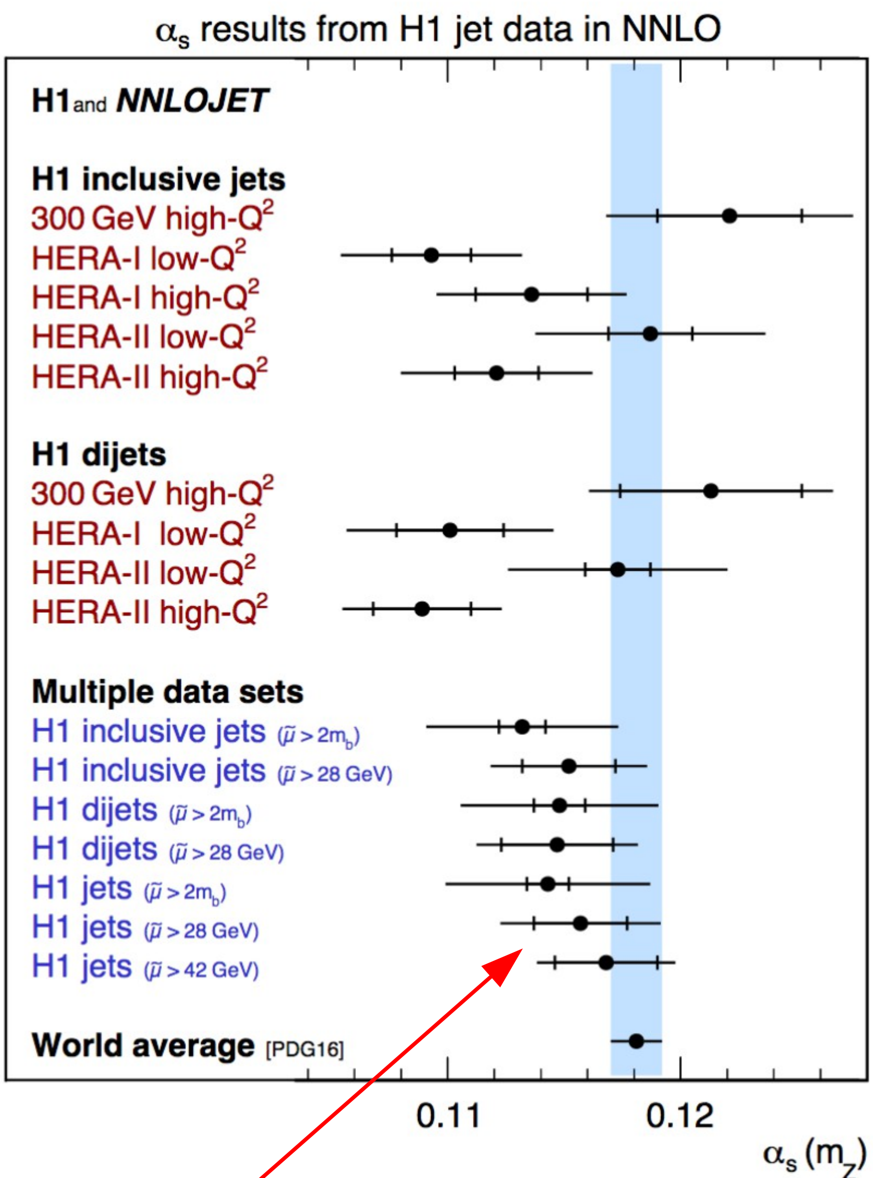


# Strong coupling in NNLO from jets

- $\alpha_s(m_Z)$ determined as free parameter to NNLO theory prediction σ in $\chi^2$ minimisation

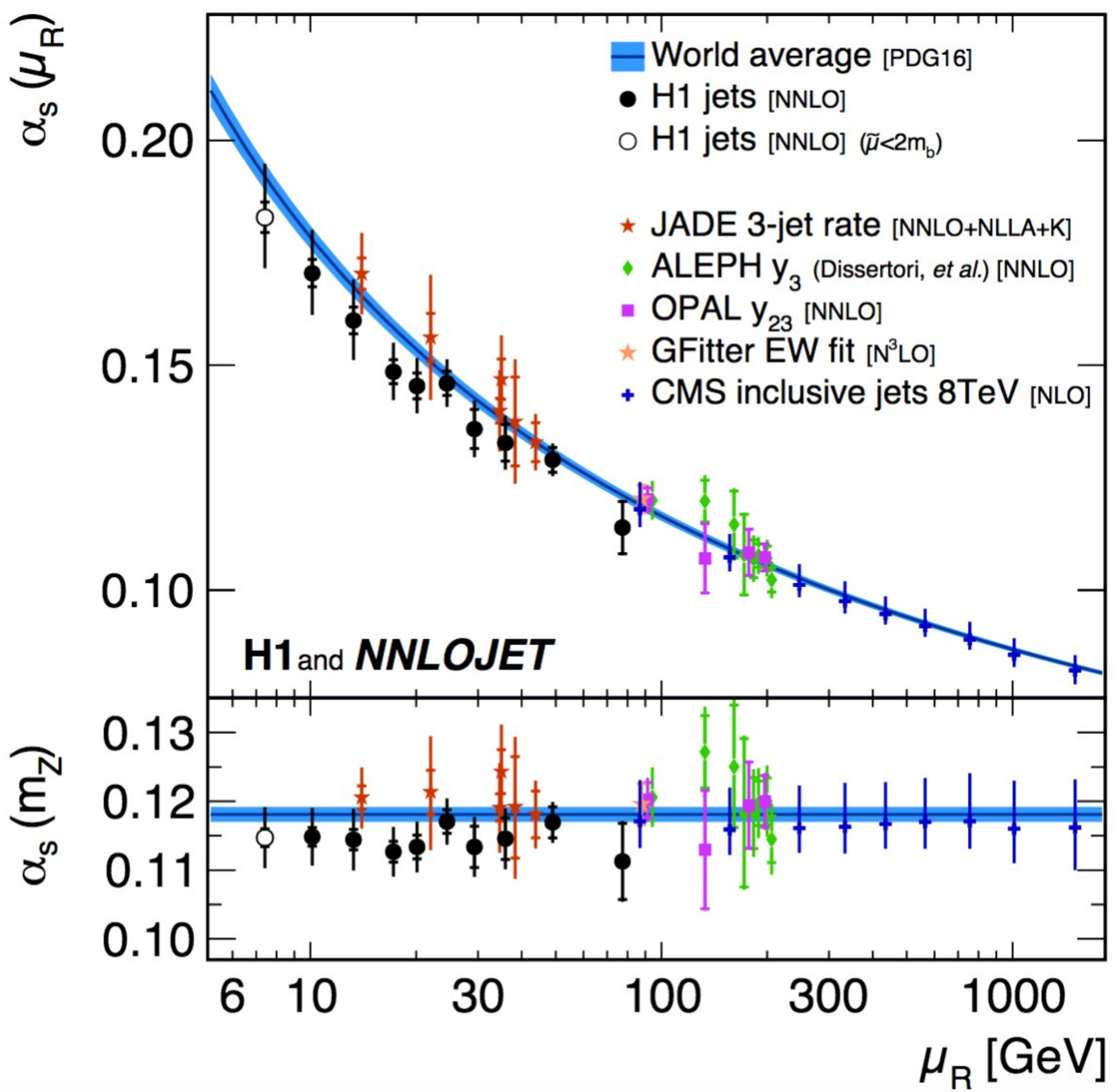
$$\chi^2 = \sum_{i,j} \log \frac{\varsigma_i}{\sigma_i} (V_{\text{exp}} + V_{\text{had}} + V_{\text{PDF}})^{-1}_{ij} \log \frac{\varsigma_j}{\sigma_j}$$

- $\alpha_s(m_Z)$ from individual data sets
  - High experimental precision
  - Scale uncertainty is largest (theory) error
  - All fits with good → consistency of data
- Main result
  - Inclusive jets & dijets μ > 28GeV
  - Moderate exp. Precision (due to μ>28GeV)
  - Scale uncertainty dominates
  - PDF uncertainties negligible




$$\alpha_s(m_Z) = 0.1157\,(20)_{\text{exp}}\,(6)_{\text{had}}\,(3)_{\text{PDF}}\,(2)_{\text{PDF}\alpha_s}\,(3)_{\text{PDFset}}\,(27)_{\text{scale}}$$

# Running of strong coupling constant ...




+

Overall good description of H1 jet data by NNLO

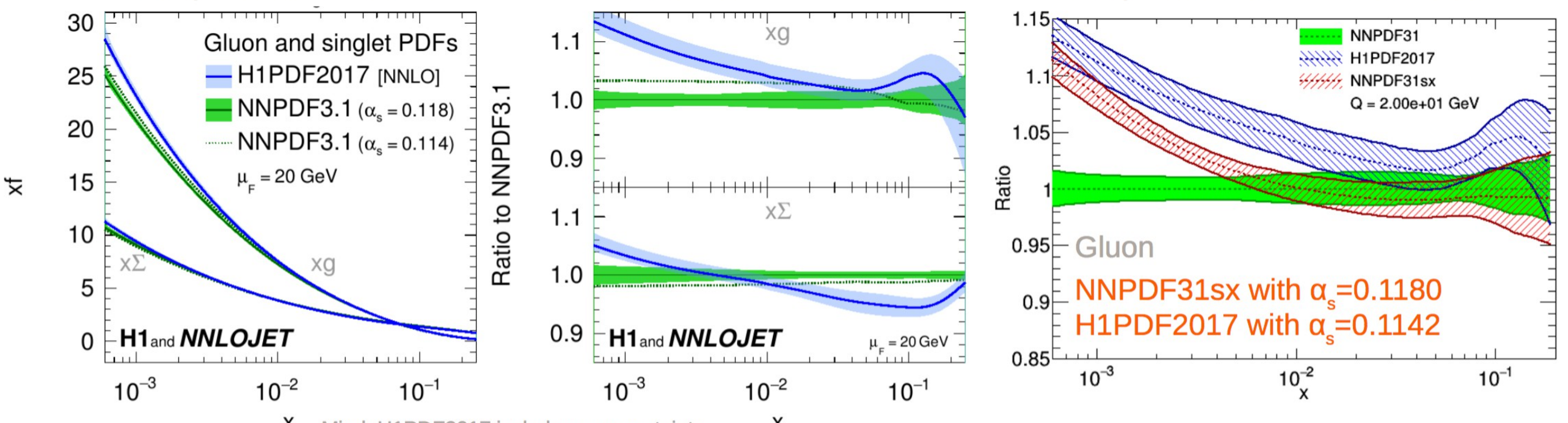
Great success of pQCD

# Simultaneous fit of PDFs and $\alpha_s$

- H1PDF2017
  - High recision, $\chi^2$/ndf ~ 1.01 (npts=1529)
  - Despite free parameter $\alpha_s$, precision is competitive with global PDF fit
- Gluon at lower x values tends to be higher (than e.g. NNPDF3.1)
- Gluon very similar to NNPDF3.1sx, which includes low-x resummation

Comparison of H1PDF2017 and NNPDF3.1

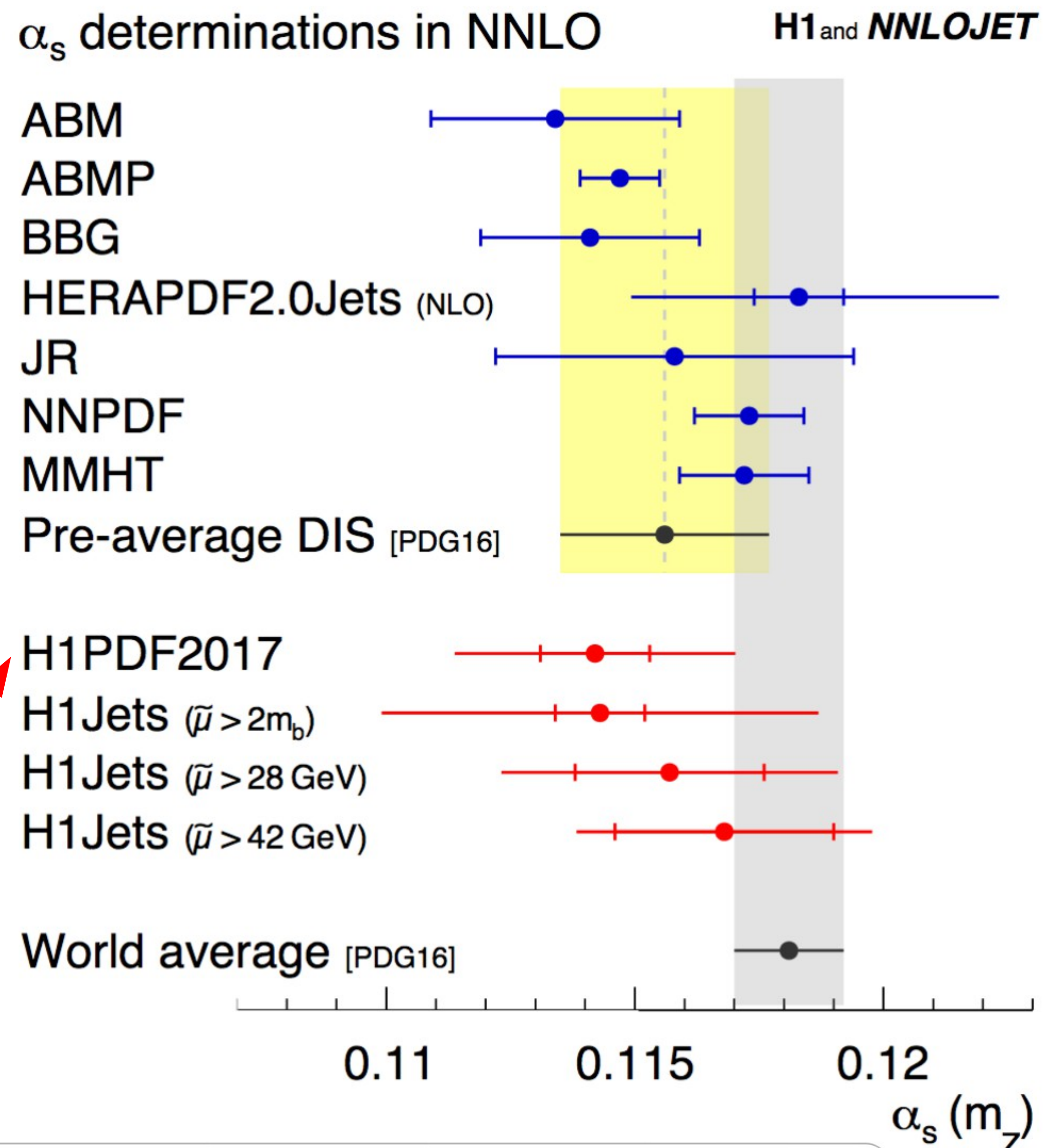
Comparison with NNPDF3.1sx




Mind: H1PDF2017 includes $\alpha_s$-uncertainty, whereas NNPDF does not

Apfelweb. Thanks to S. Carraza

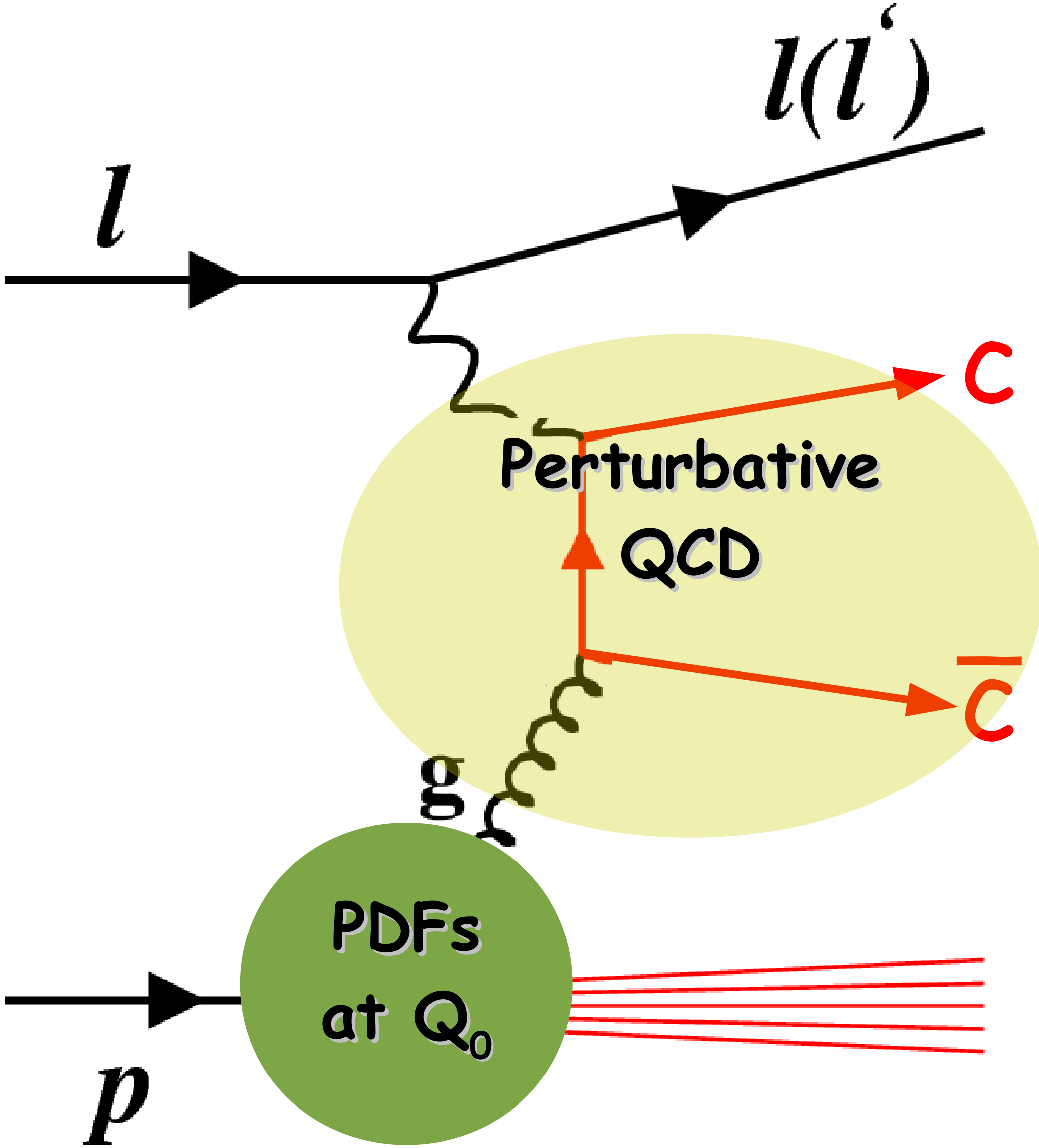
# $\alpha_s$ from simultaneous fit




- All results from DIS data tend to be lower than world average value

$$\alpha_s(m_Z) = 0.1142\,(11)_{\text{exp,had,PDF}}\,(2)_{\text{mod}}\,(2)_{\text{par}}\,(26)_{\text{scale}}$$

# Heavy Quark Production @ HERA




- Final HERA charm and beauty data combined
- QCD global analysis performed
- Simultaneous fit of PDFs and HQ masses

# Combination of charm & beauty

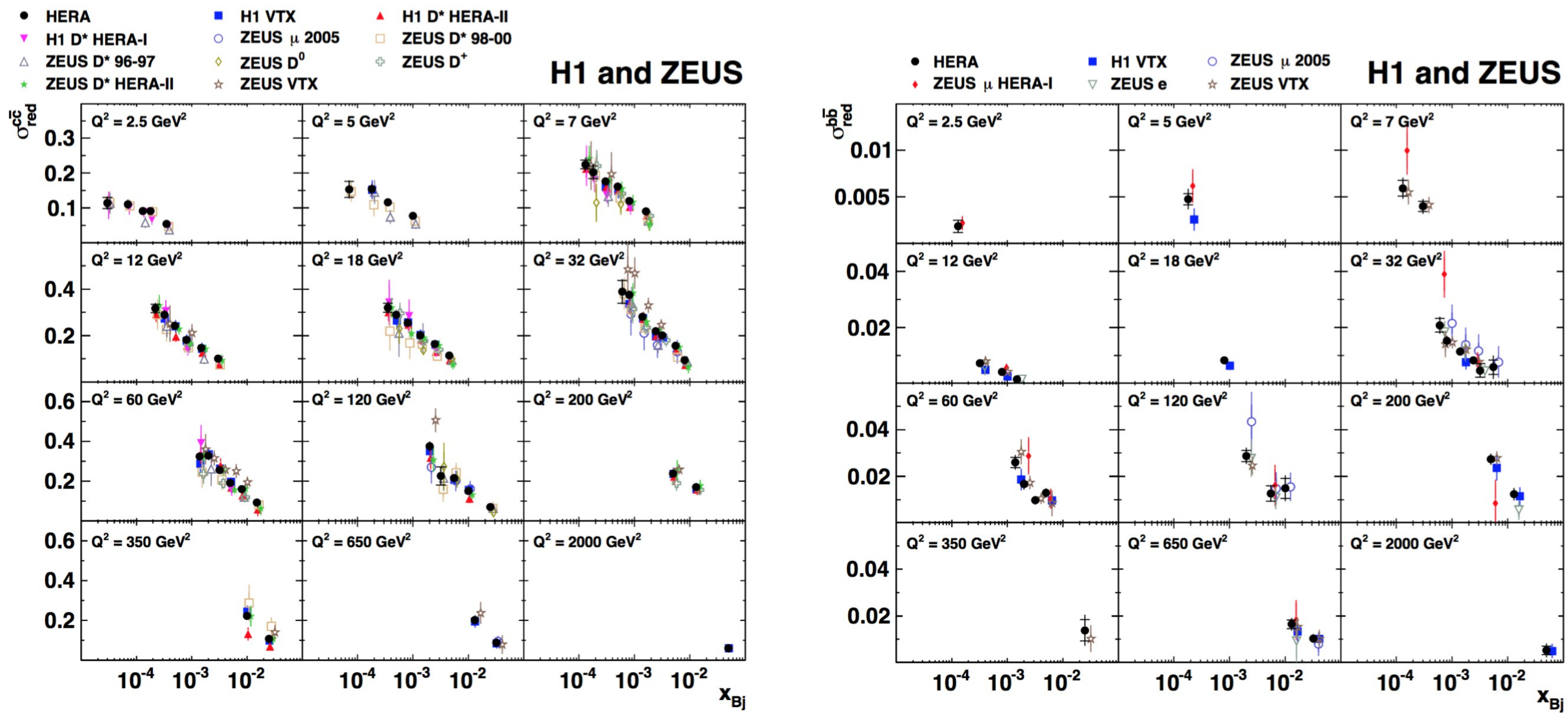
EPJ C78 (2018), 473

[arxiv:1804.01019]



## Charm

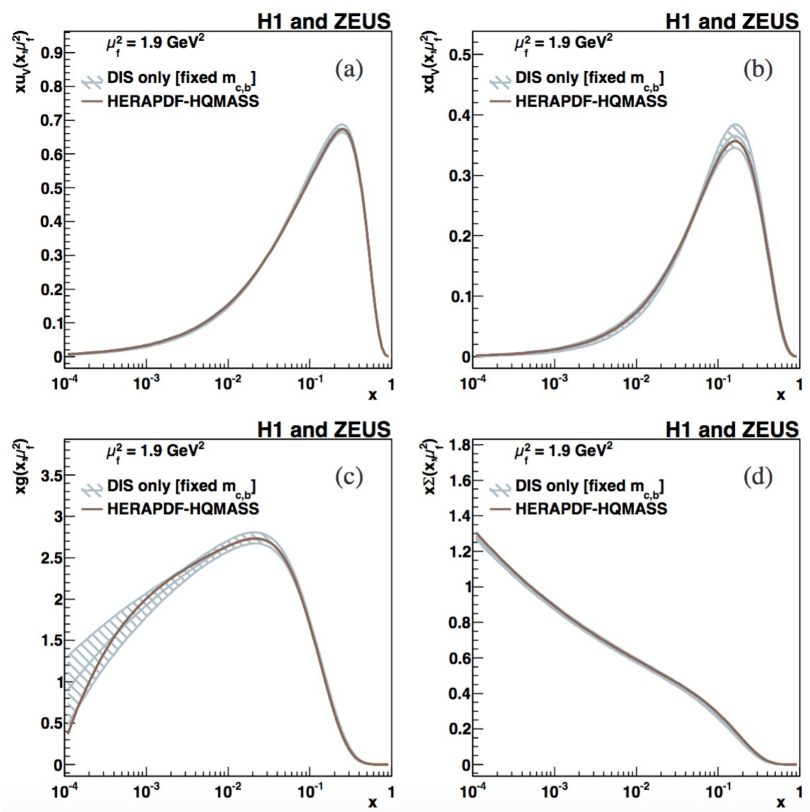
## Beauty: first combination

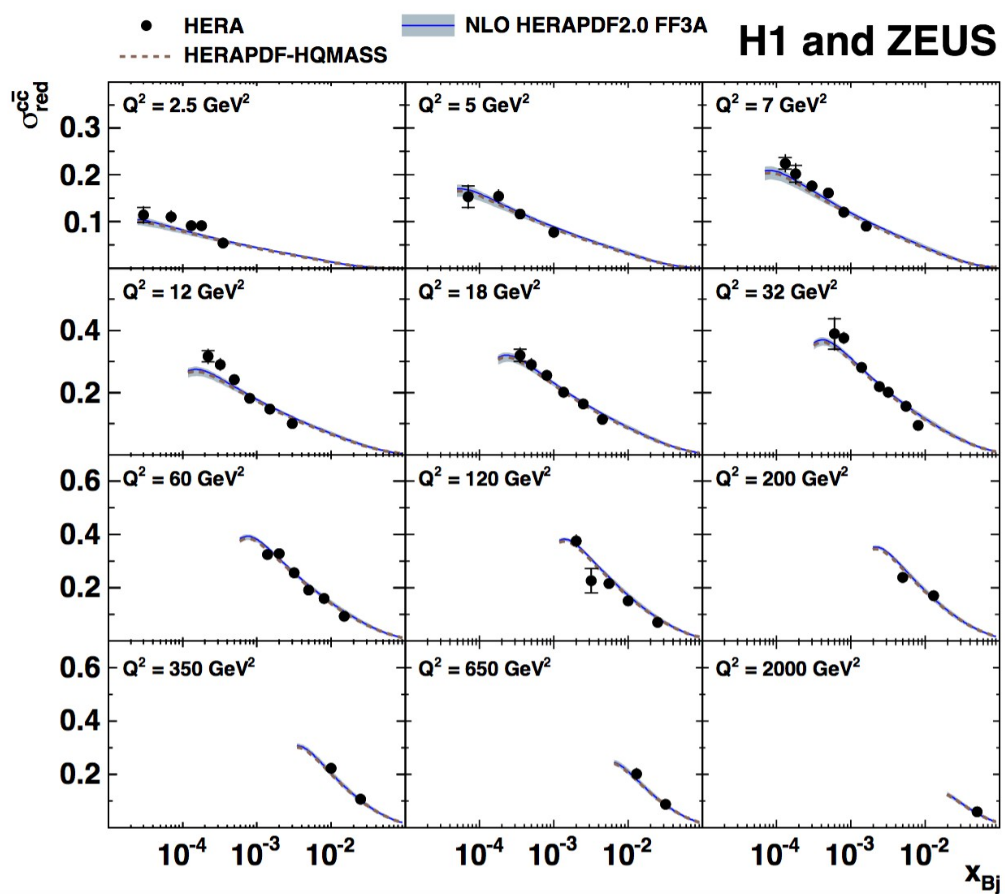



- Datasets consistent and significantly reduced uncertainties
- Combined charm cross sections significantly more precise than those previously published
- Combined data reasonably described by theory predictions

# QCD global analysis & HQ masses

- HERA inclusive + HV data used in NLO QCD analysis in fixed-flavour-number scheme using MS running-mass definition
- Running heavy-quark masses determined → agreement with PDG and previous ones

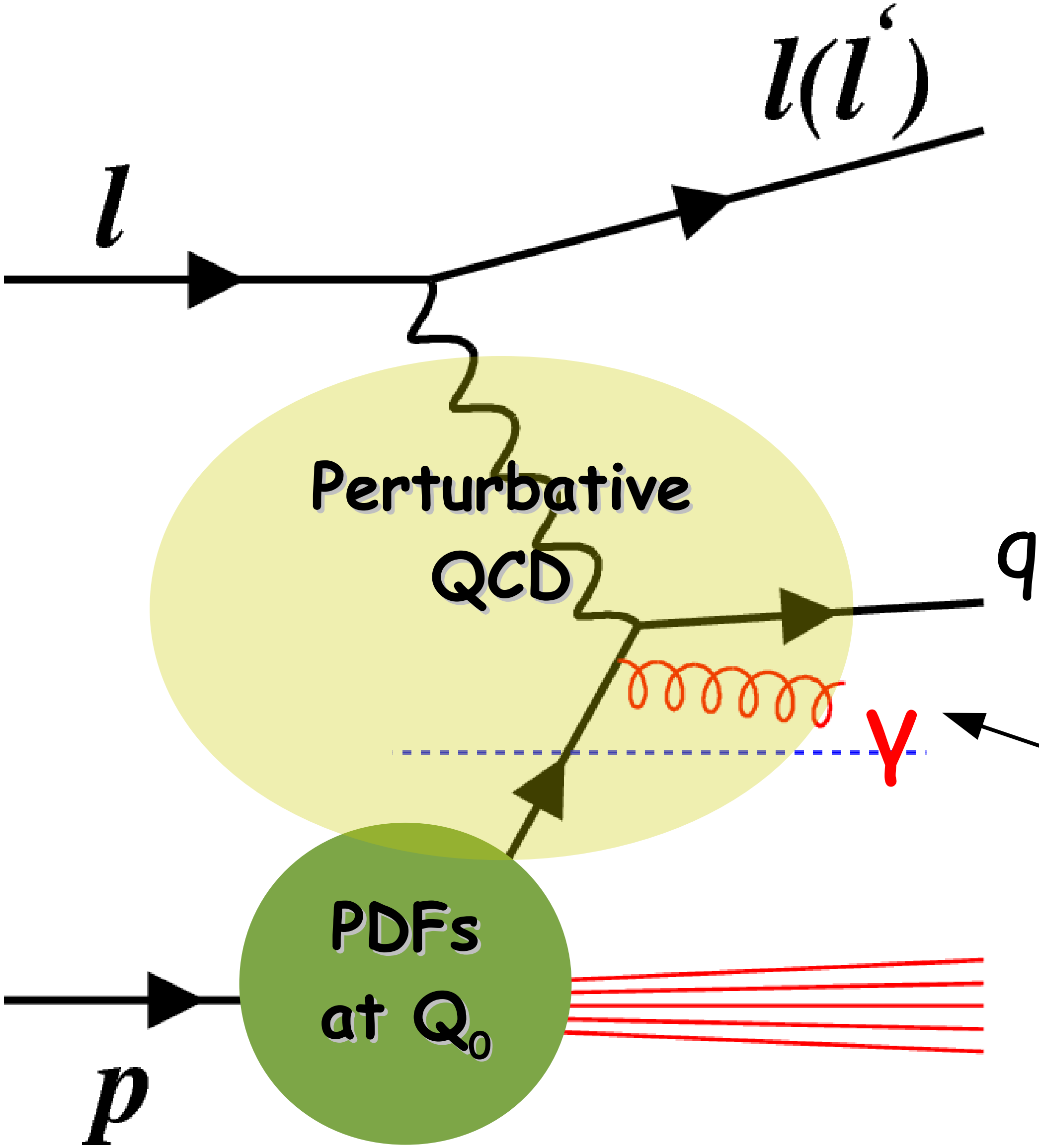



$$m_c(m_c) = 1.290^{+0.046}_{-0.041}(\mathrm{exp/fit})^{+0.062}_{-0.014}(\mathrm{model})^{+0.003}_{-0.031}(\mathrm{parameterisation})\ \mathrm{GeV}$$

$$m_b(m_b) = 4.049^{+0.104}_{-0.109}(\mathrm{exp/fit})^{+0.090}_{-0.032}(\mathrm{model})^{+0.001}_{-0.031}(\mathrm{parameterisation})\ \mathrm{GeV}$$

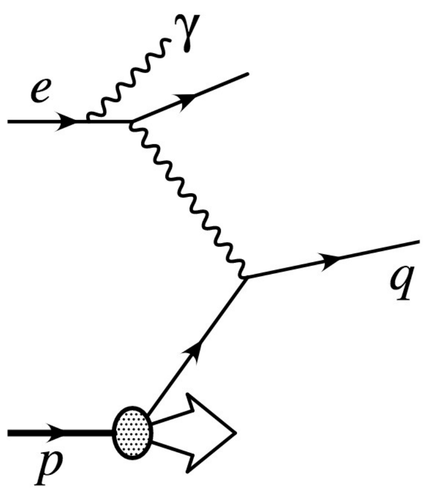
# Prompt Photons @ HERA



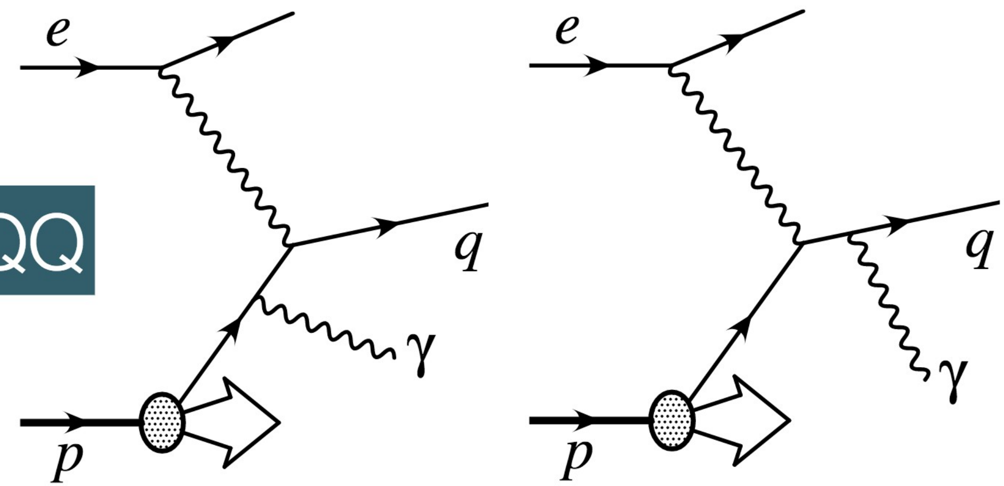

Prompt Photon

# Where do isolated photons come from?

LL




QQ



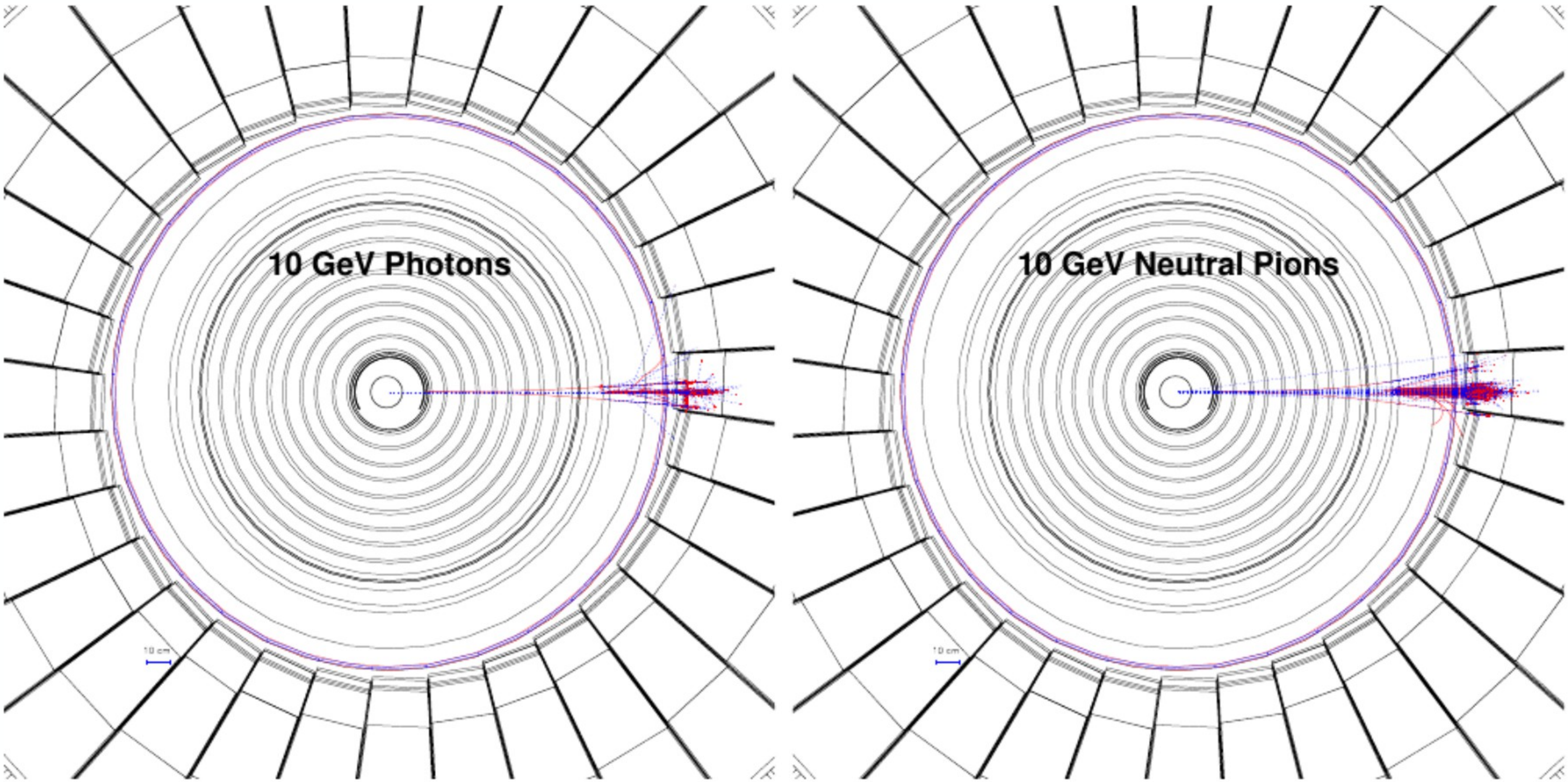

- Can be emitted from lepton (LL) or proton (quark, QQ)
- Emerge directly from hard scattering process
  - Use dynamics to probe modes such as $k_t$-factorisation and pQCD approaches
- Assume lepton emission is well known

$\rightarrow$ Use photon to probe proton

Trick is to find these photons ...

# Irreducible background

$\pi^0 \to \gamma\gamma \qquad \eta \to \pi^0\pi^0\pi^0(\gamma\gamma)$

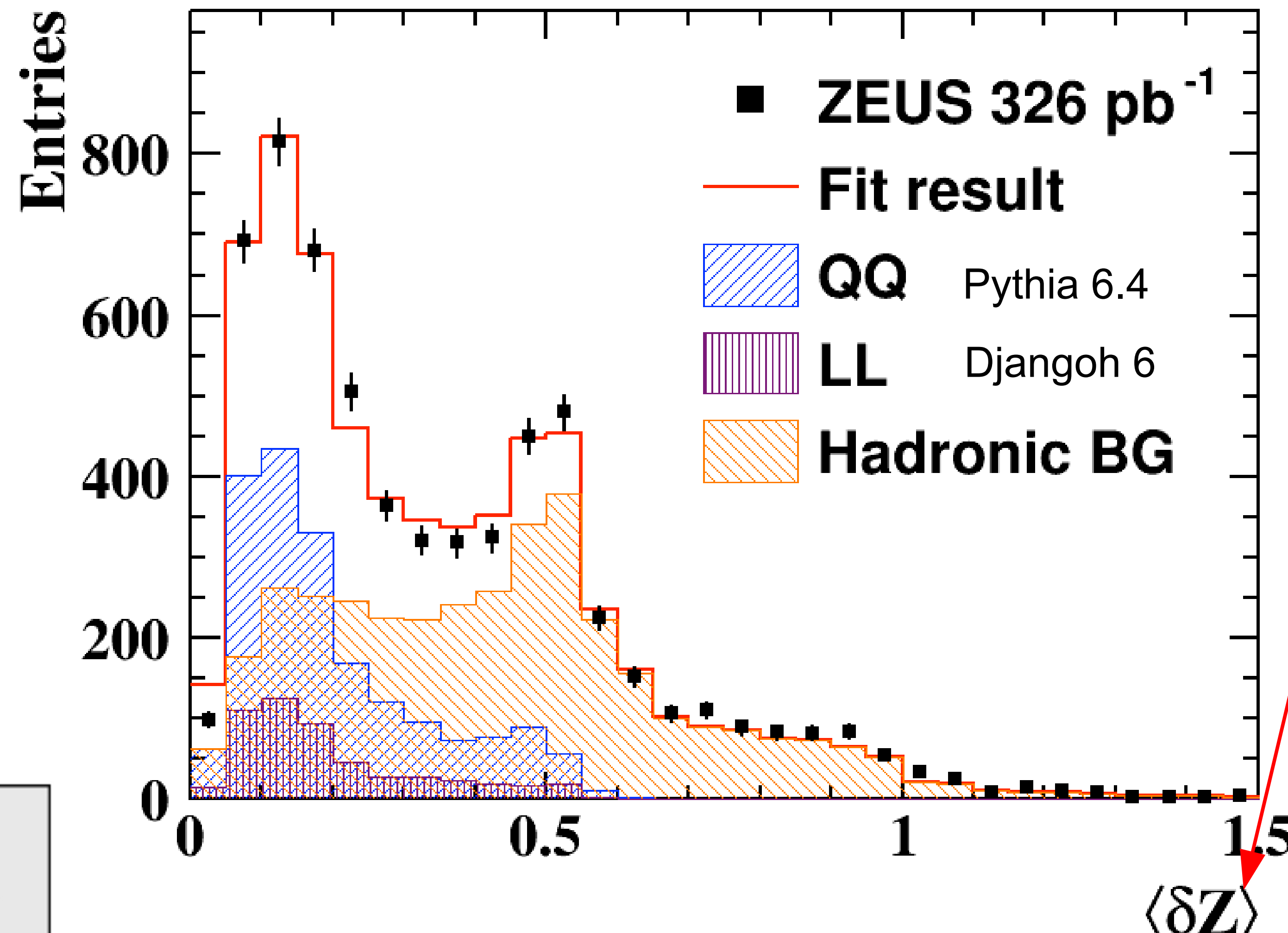


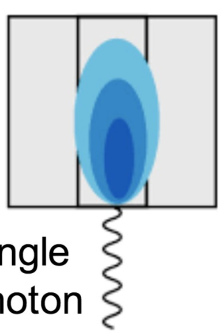

Neutral-meson produce broader energy deposits

JHEP 1801 (2018) 032

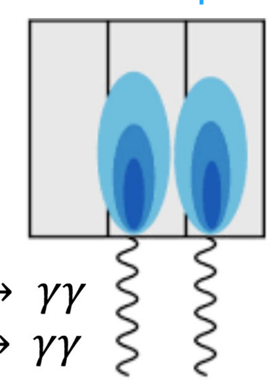
# Dealing with background

- Template fit to energy-weighted mean width of calorimeter EM cluster



Single photon



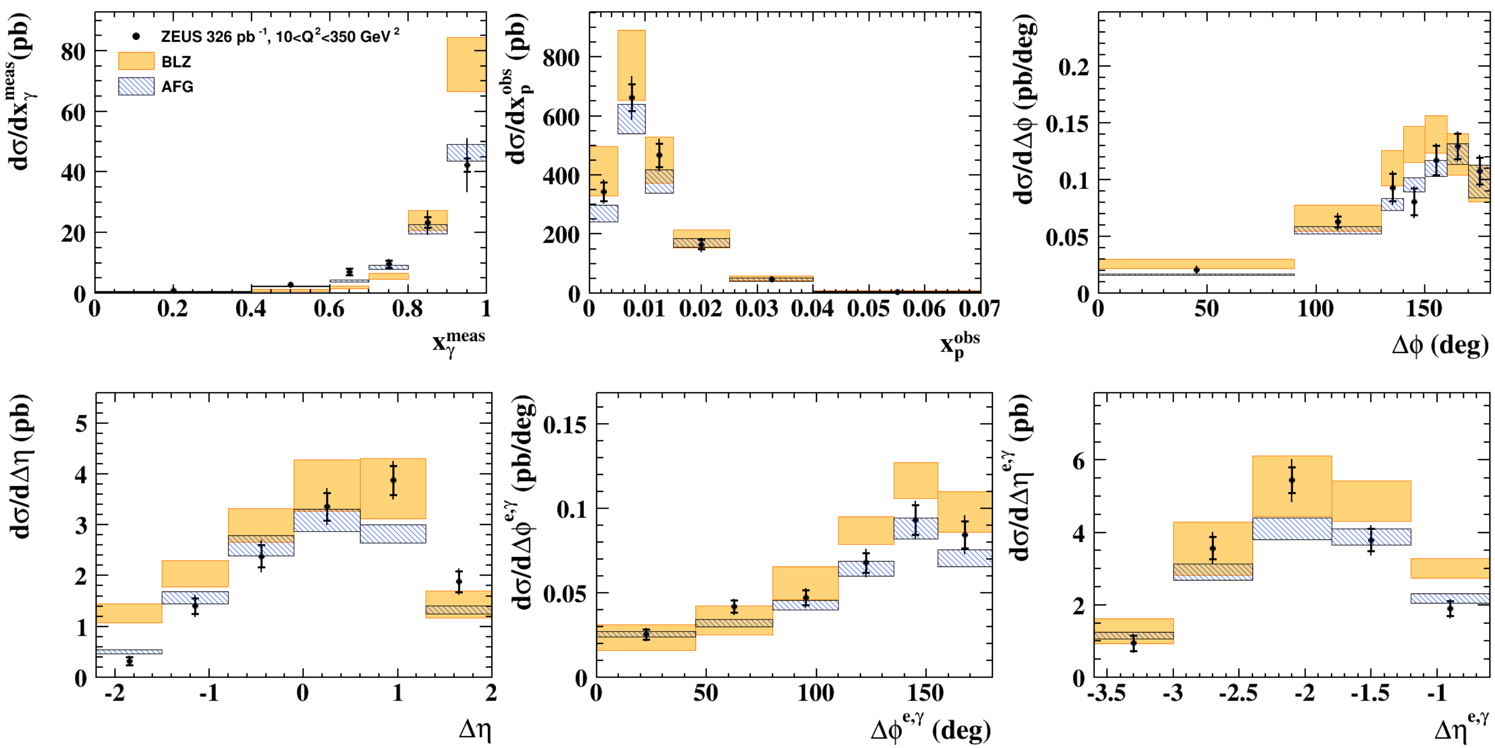
$\pi_0 \rightarrow \gamma\gamma$
$\eta \rightarrow \gamma\gamma$

Fit produced in each analyzed bin

# Comparison with theory

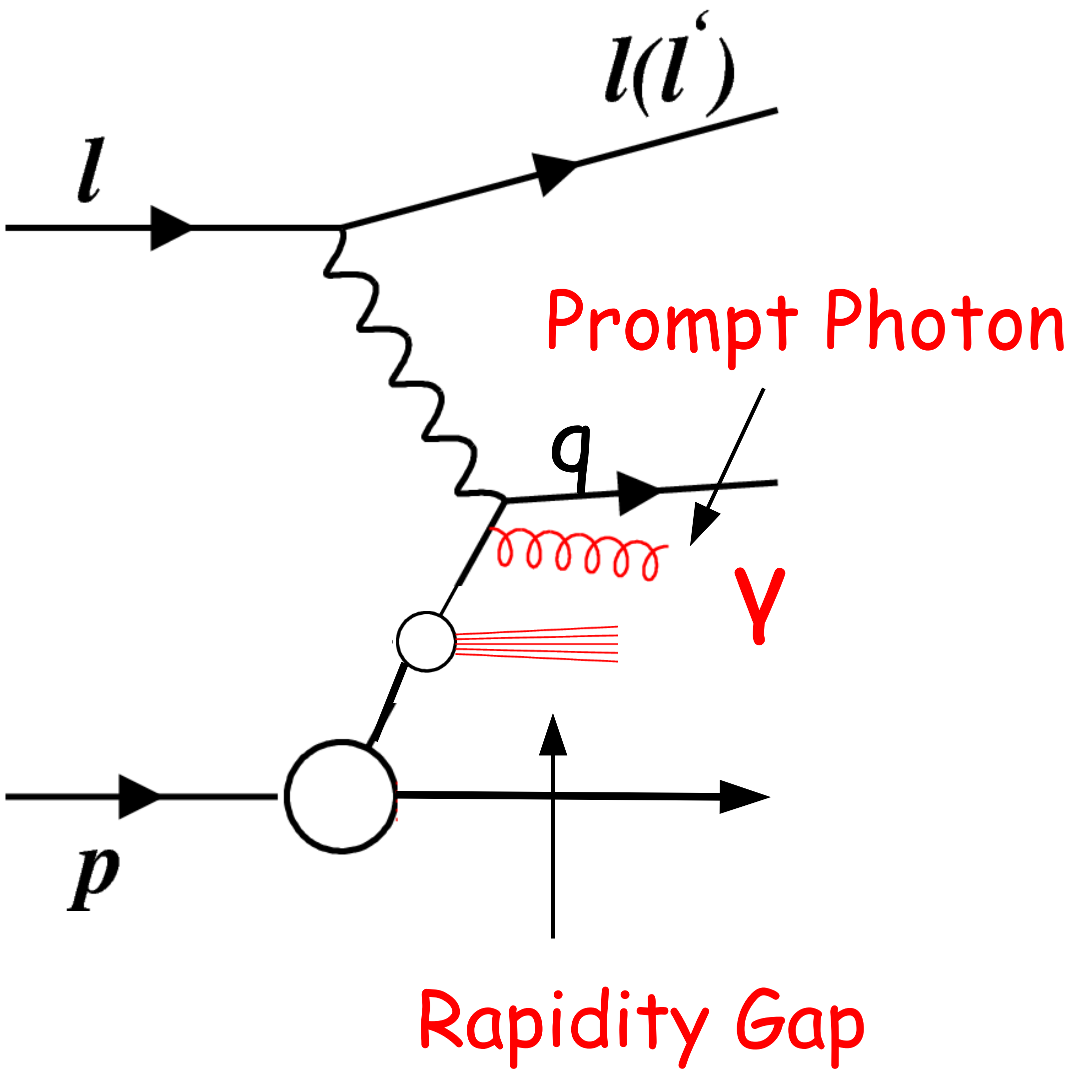
- BLZ — S. Baranov, A. Lipatov and N. Zotov, Phys. Rev. D 81 (2010) 094034.
  - $K_t$ factorisation
- AFG: NLO — P. Aurenche, M. Fontannaz and J.Ph. Guillet, Eur. Phys. J. C 44 (2005) 395.

  P. Aurenche and M. Fontannaz, Eur. Phys. J. C 77 (2017) 324.

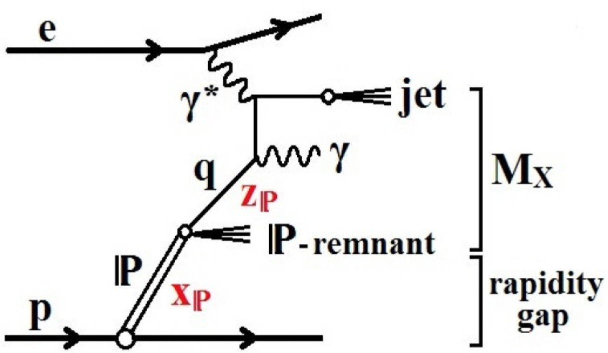



- BLZ: shapes fairly described, some distributions off, ~20% too high normalisation
- AFG: excellent agreement in shape and normalisation for all distributions
  - The same in two $Q^2$ bins, between 10 and 30 $GeV^2$ and 30 to 350 $GeV^2$

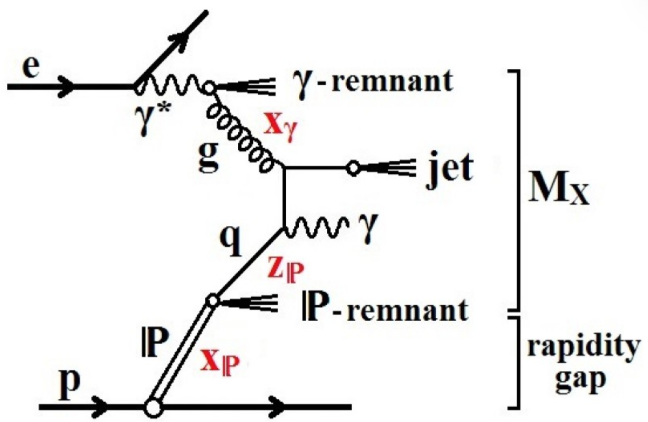
# Diffractive Prompt Photons @ HERA



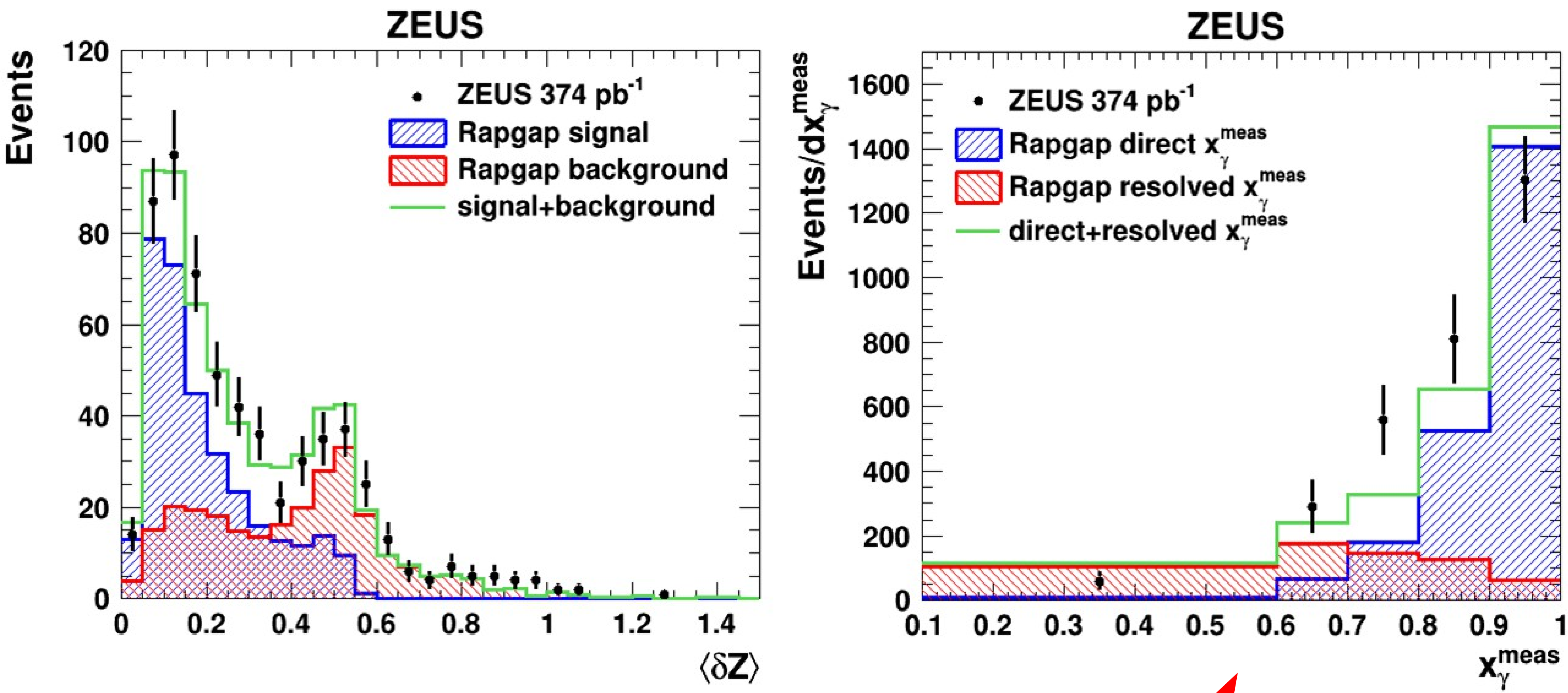

Direct photon




Resolved photon



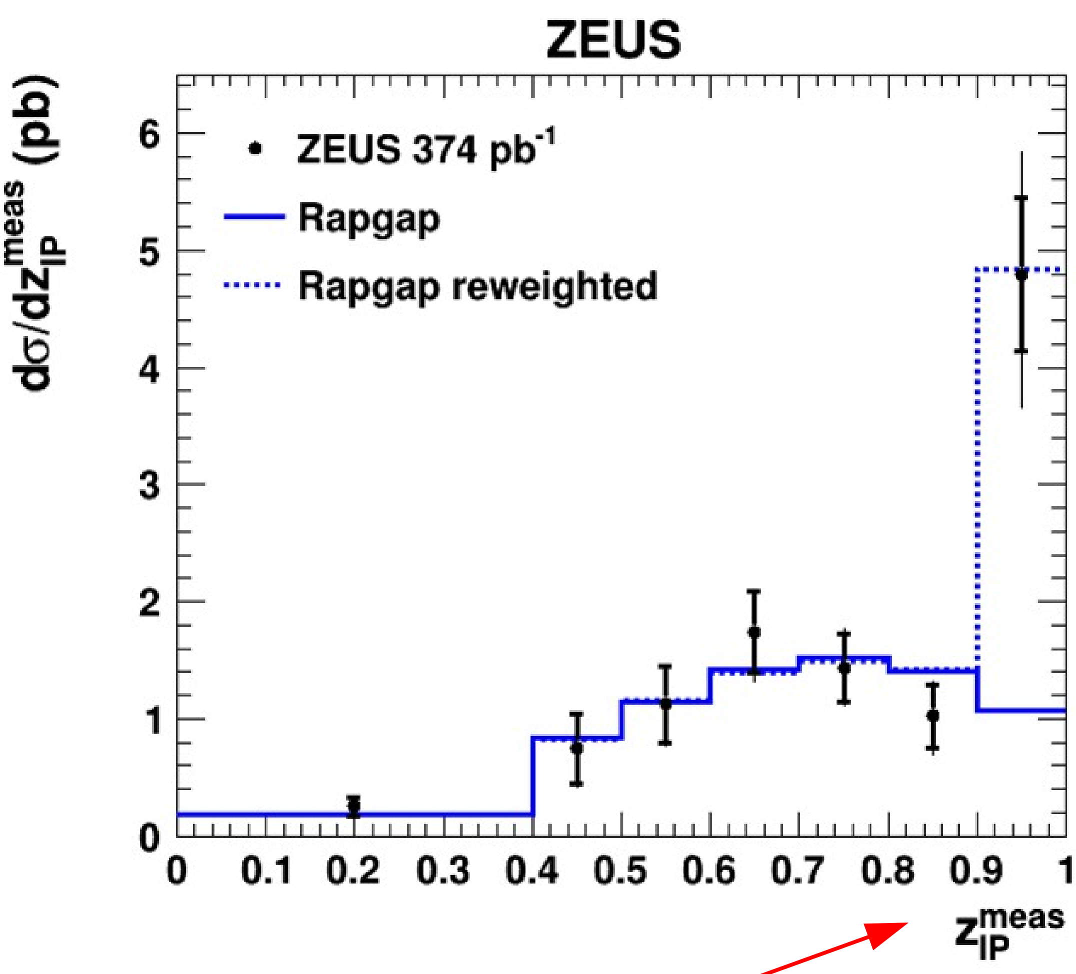
# Prompt photons & rapidity GAP




70:30 mixture of direct:resolved

Phys. Rev. D 96 (2017) 032006

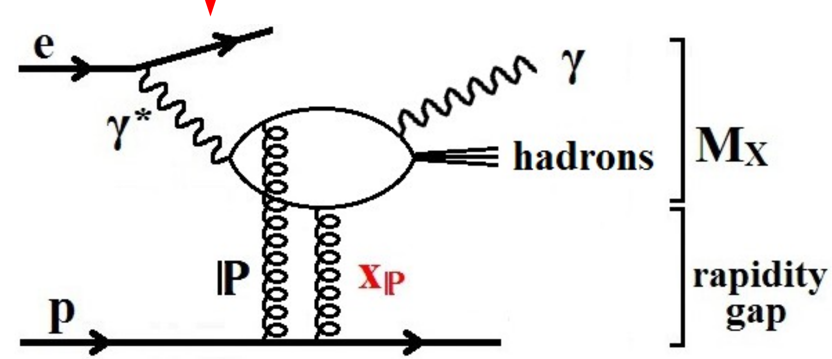
# Diffractive prompt photon + jet




- Excess at low $z_{IP}$
- observed predominantly in direct photon channel
- If RAPGAP reweighted by 7xdirect photon – agreement

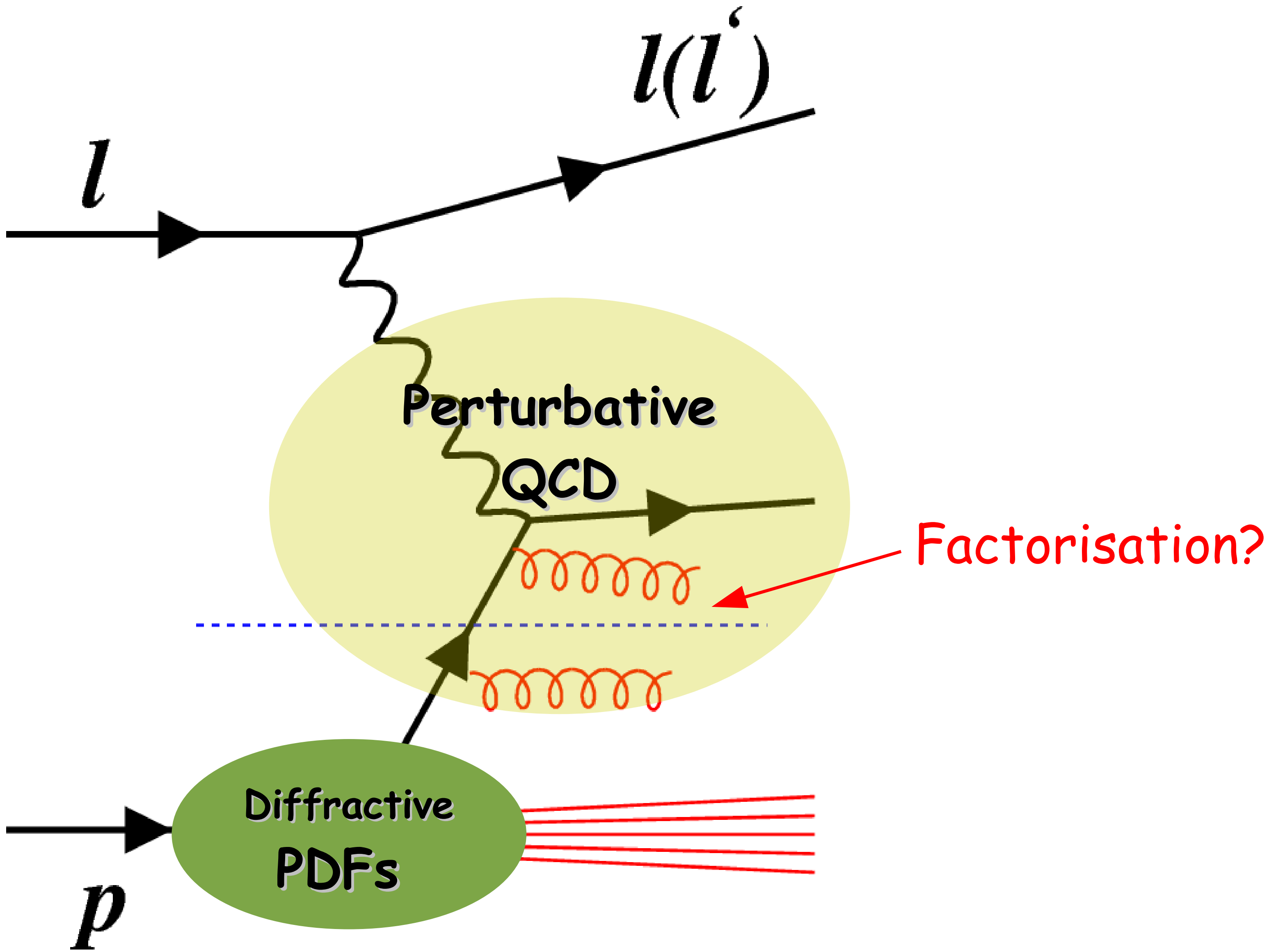
→ indicates presence of direct Pomeron interaction (not present in RAPGAP)

For example




Fraction of Pomeron energy given to prompt photon and jet

# Does factorisation hold in diffractive DIS?

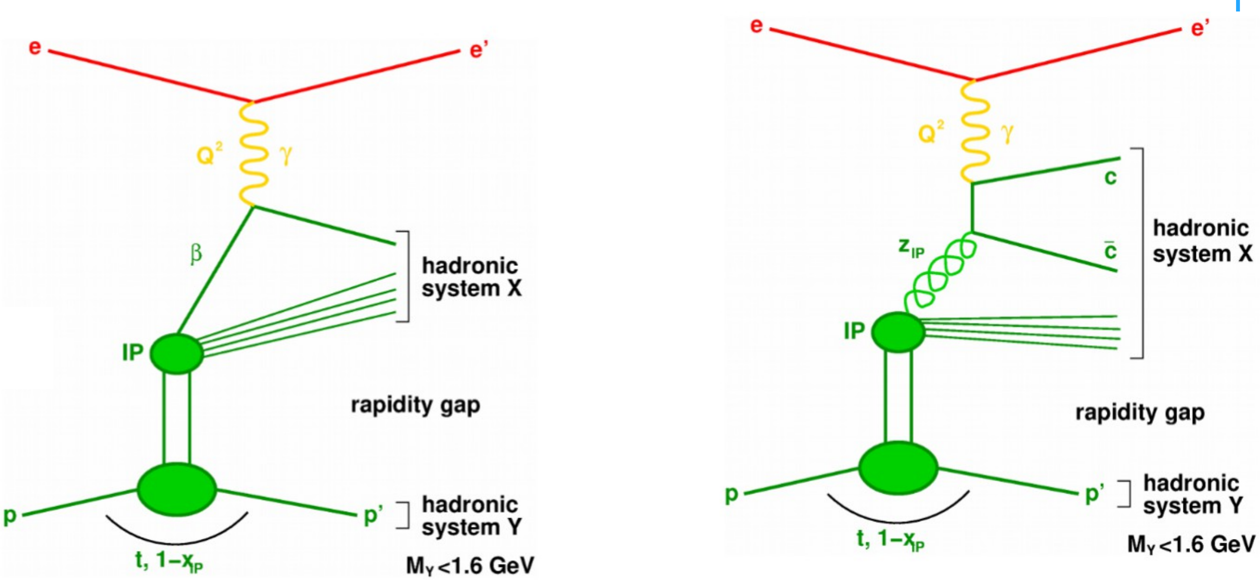


# Charm production in diffractive DIS

- ~10% of inclusive DIS cross section at HERA is diffractive at low x
- Experimental signature:
  - Proton stays intact
  - no activity in forward detectors
  - large rapidity gap

**<u>Theory (Collins):</u>**

- QCD factorisation holds in diffractive DIS
  → diffractive PDFs (DPDFs)



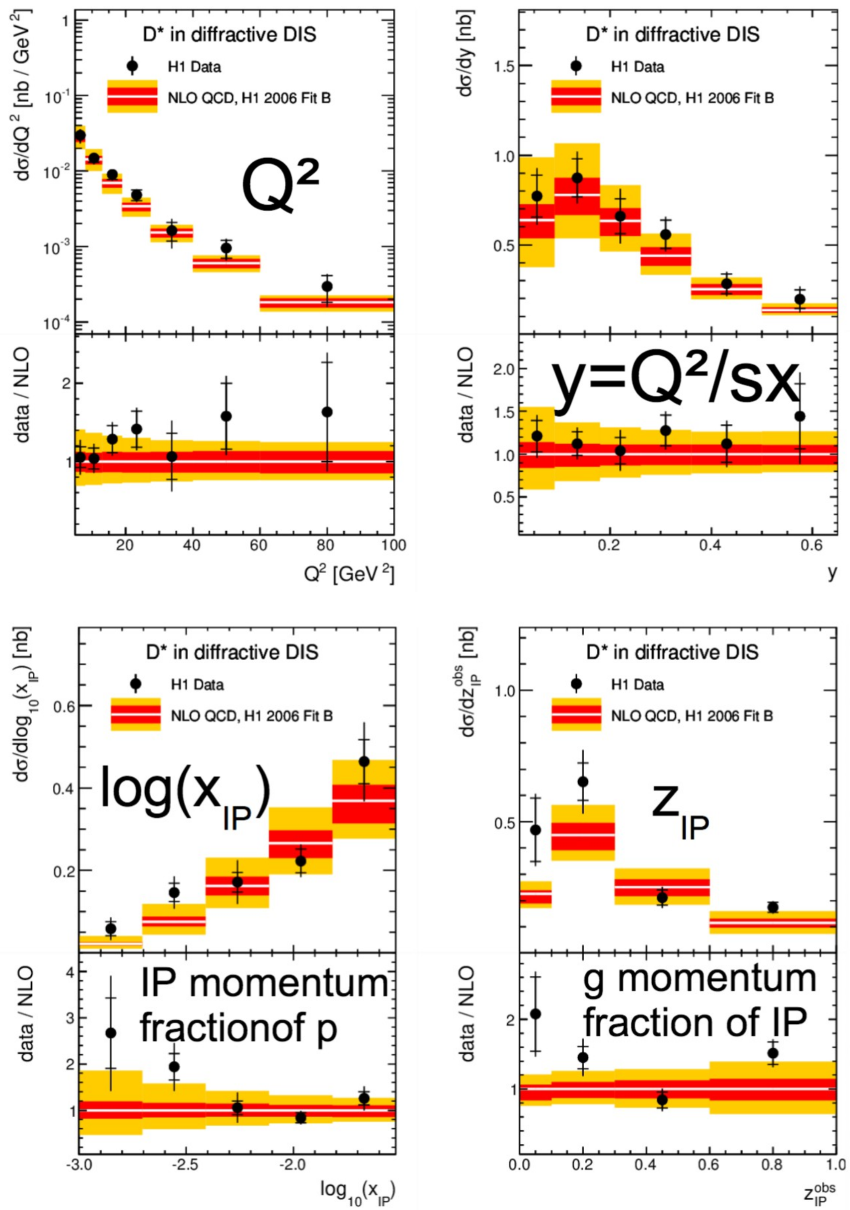

predict →

Inclusive diffraction: extract DPDFs

$$f_i(Q^2, \beta, t, x_{IP})$$

Diffractive charm production: test factorisation theorem in diffraction

# Diffractive D* cross sections




Electron variables

| DIS phase space |
| --- |
| $5 < Q^2 < 100\ \mathrm{GeV}^2$ |
| $0.02 < y < 0.65$ |
| $D^*$ kinematics |
| $p_{t,D^*} > 1.5$ GeV |
| $-1.5 < \eta_{D^*} < 1.5$ |
| Diffractive phase space |
| $x_{I\!P} < 0.03$ |
| $M_Y < 1.6$ GeV |
| $\lvert t \rvert < 1\ \mathrm{GeV}^2$ |

**EPJ C77 (2017) 340**

**[arXiv:1703.09476]**

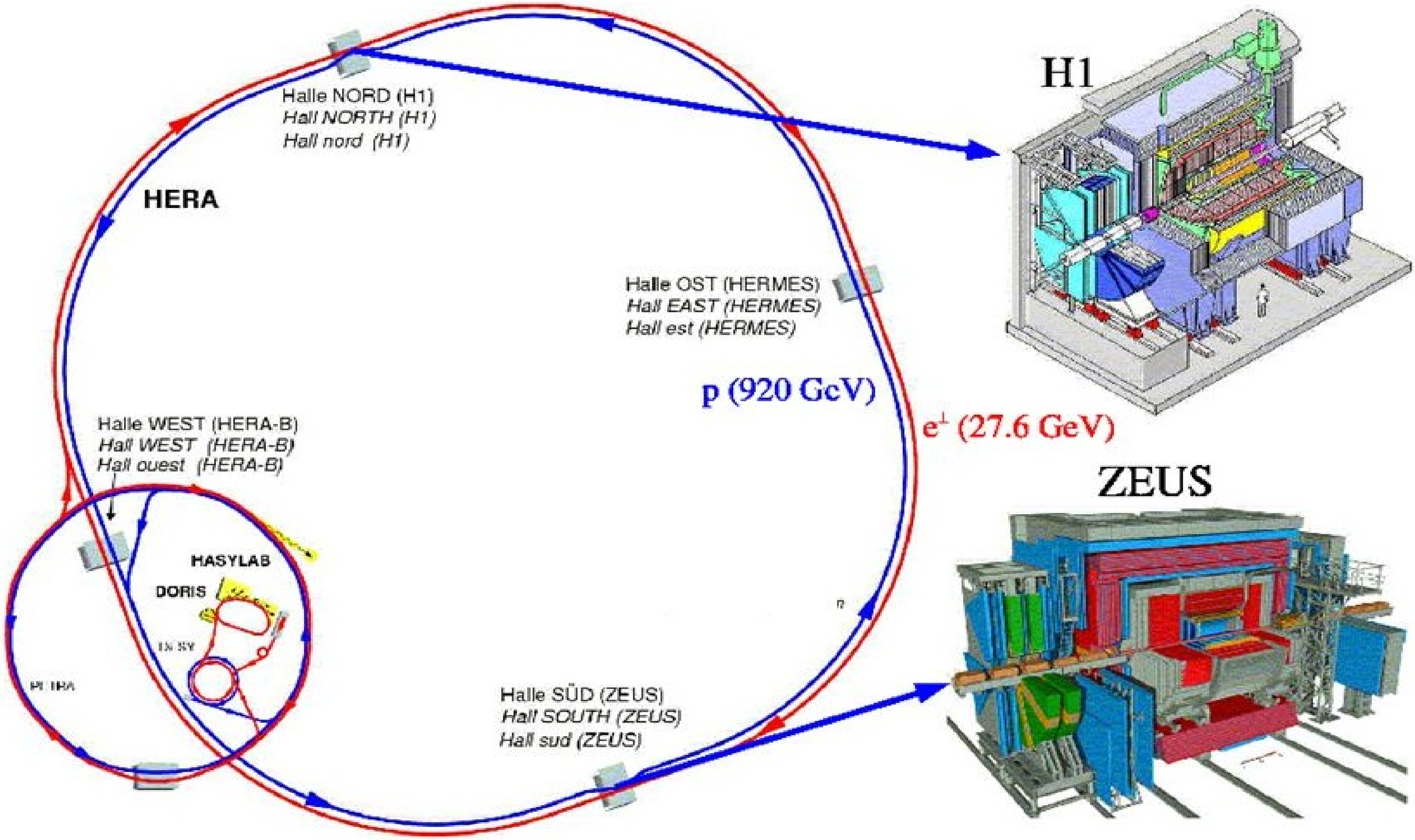
- Good description by NLO QCD
  - large theory scale uncertainties
- DPDF uncertainties similar to data precision
- D* kinematic distributions also described

→ **within large uncertainties factorisation seems to hold in diffractive charm production in DIS**

- Diffractive variables: $\log(x_{IP})$, $z_{IP}$

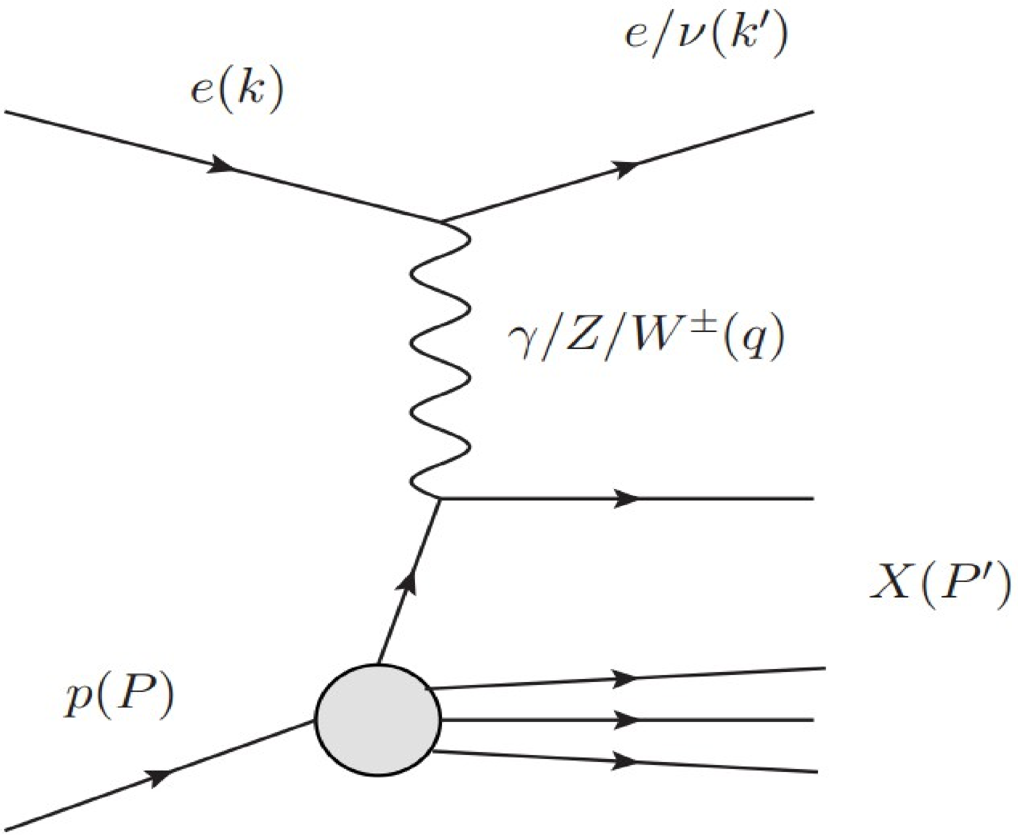
# Instead of summary: thank you for your patience :)

# Extra slides




- HERA: ep collider in Hamburg
- Operation: 1992-2007
- Colliding experiments: H1 and ZEUS
- Collected ~1 $fb^{-1}$ for both experiments together

# ep Scattering at HERA




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

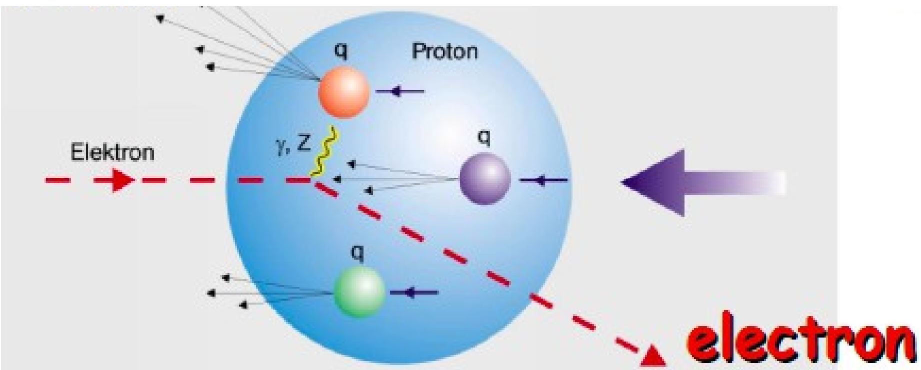
$$x_{Bj} = \frac{Q^2}{2\,pq} \qquad y = \frac{pq}{pk}$$

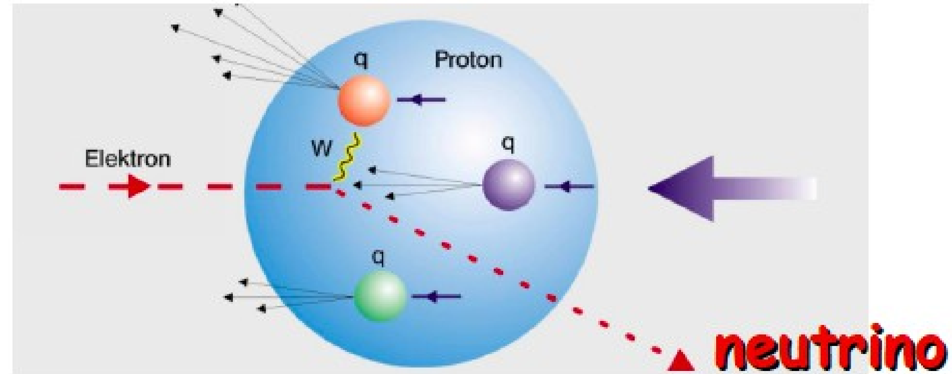
$$s = (p+k)^2 \qquad Q^2 = xys$$

$$W^2 = Q^2(1/x_{\mathrm{Bj}} - 1) + m_p^2$$

two regions: $Q^2 \approx 0$ GeV$^2$ — photoproduction
$Q^2 > 1$ GeV$^2$ — electroproduction (DIS)

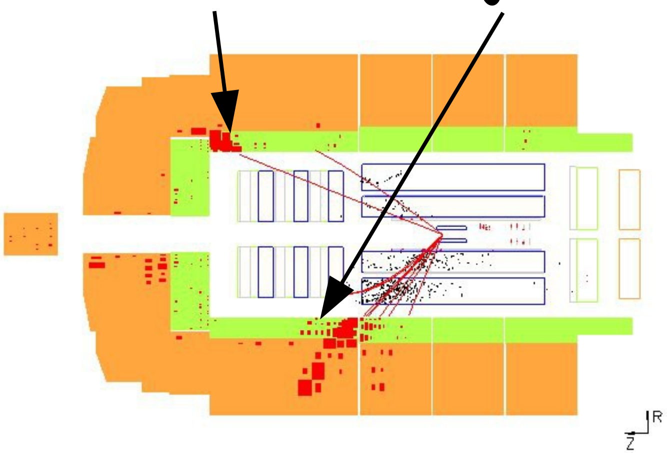
# Deep Inelastic Scattering @ HERA



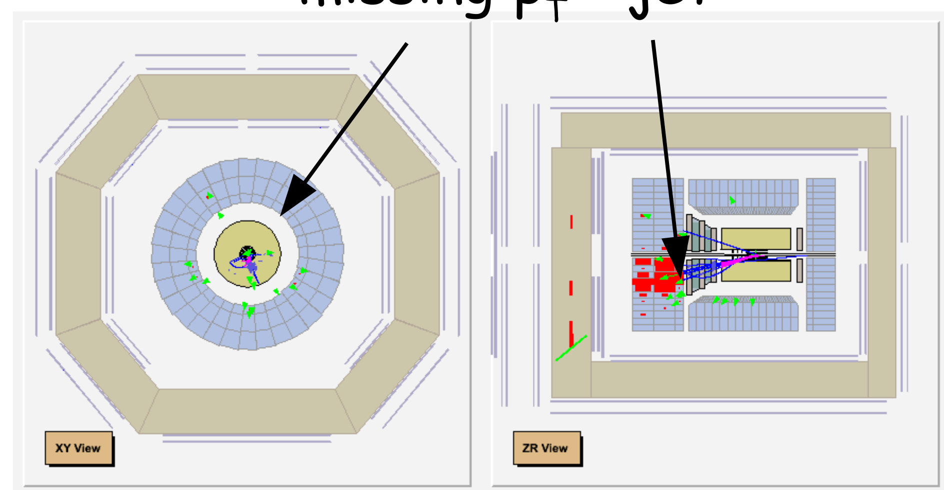

**Neutral Current (NC): γ, Z exchange**

electron + jet




**Charge Current (CC): W exchange**

missing $p_T$ + jet

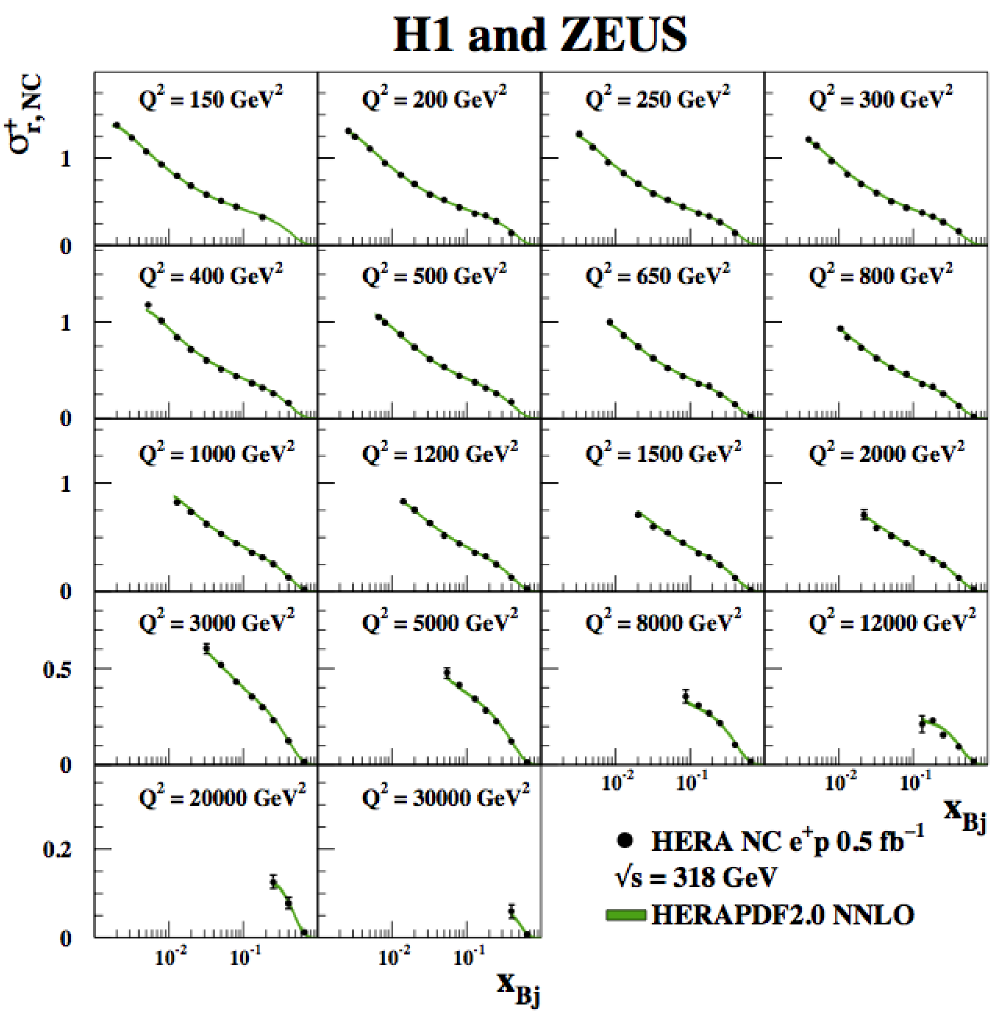



- NC/CC cross section expresses in terms of structure functions

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

# Neutral Current

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$




## Proton structure functions

$$F_2 = x\sum e_q^2[q(x)+\bar{q}(x)]$$

- Sensitive to quarks

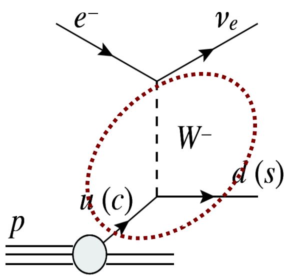
$$xF_3 = x\sum 2e_q a_q[q(x)-\bar{q}(x)]$$

- Sensitive to valence distributions

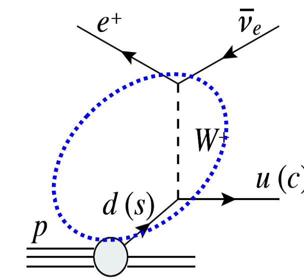
$$F_L \sim \alpha_s\, x\, g$$

- Sensitive to gluon

- Gluon also from scaling violation and charm+jet data

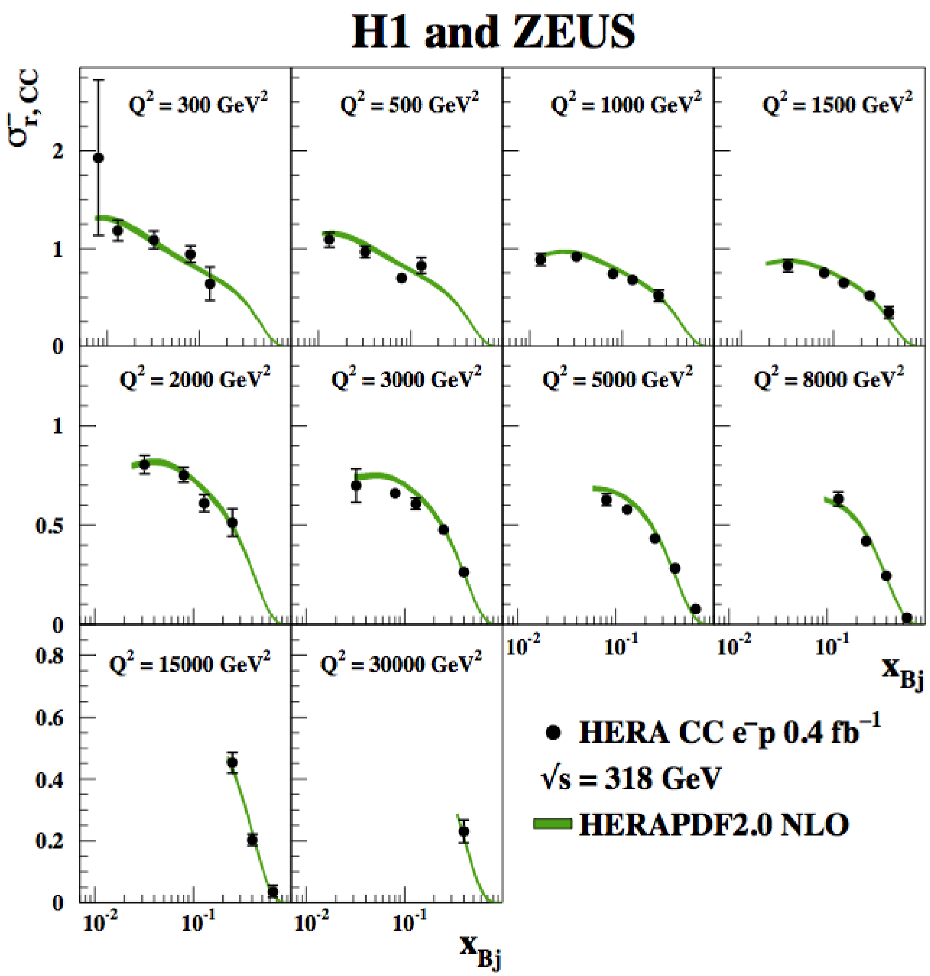


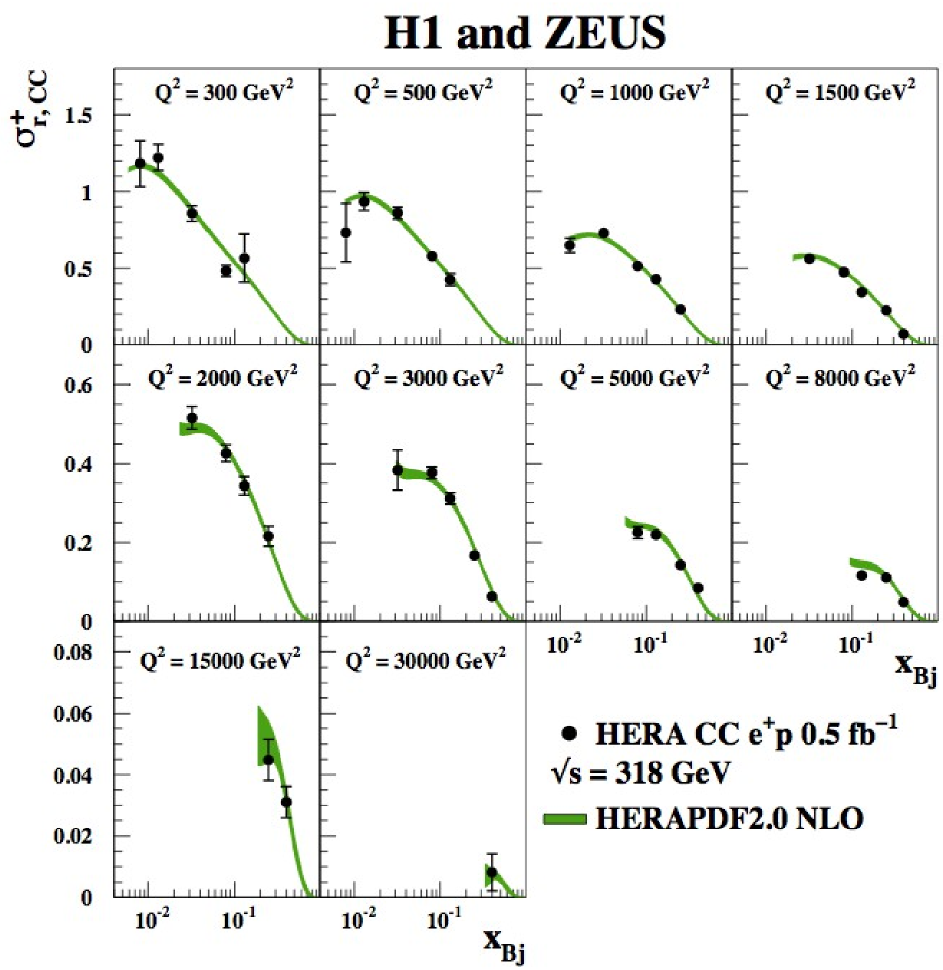

# Charge Current: flavor decomposition



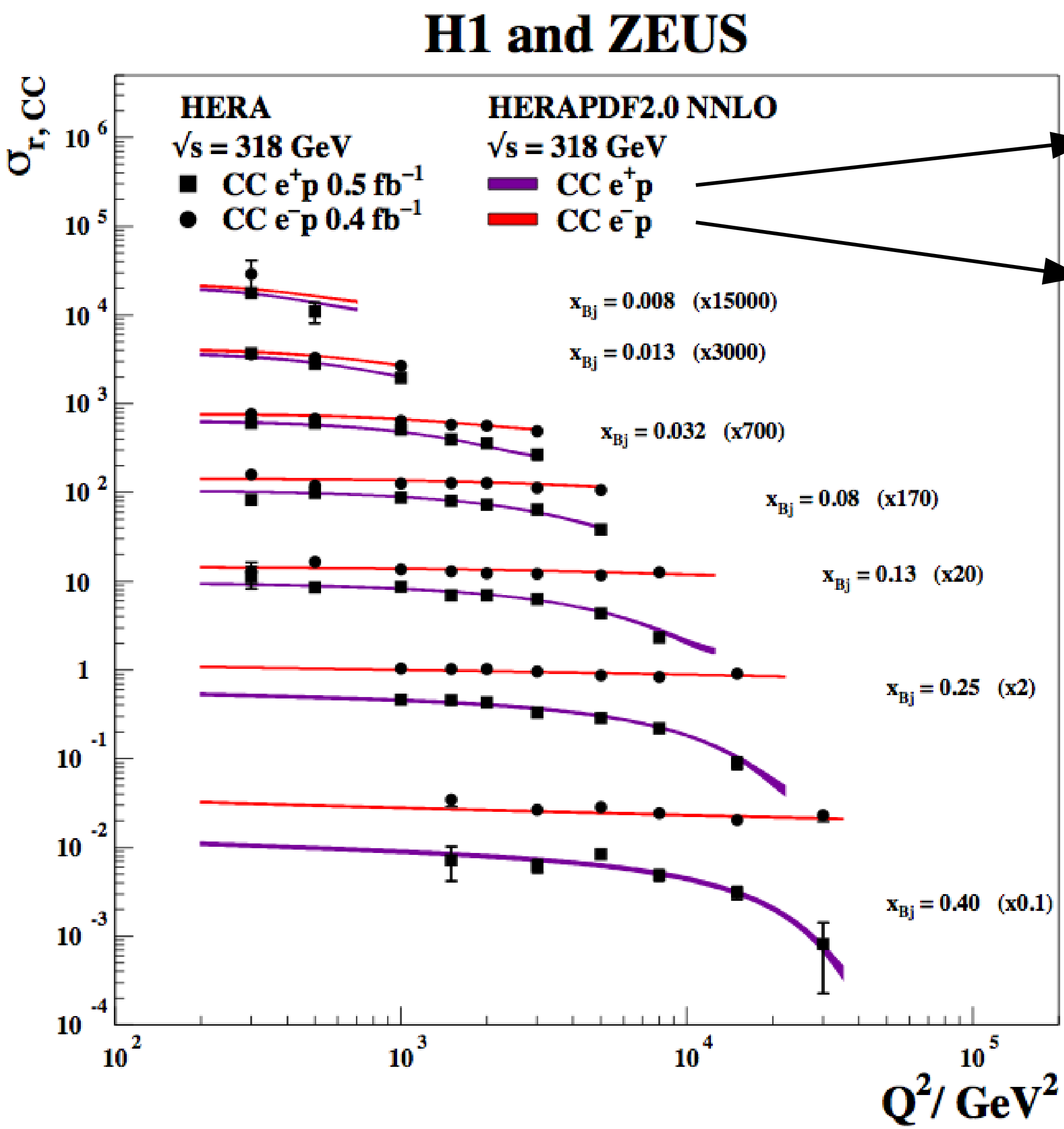

$$\sigma^-_{CC} \sim x[u + c] + x(1-y)^2[\bar{d} + \bar{s}]$$

$$\sigma^+_{CC} \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d + s]$$



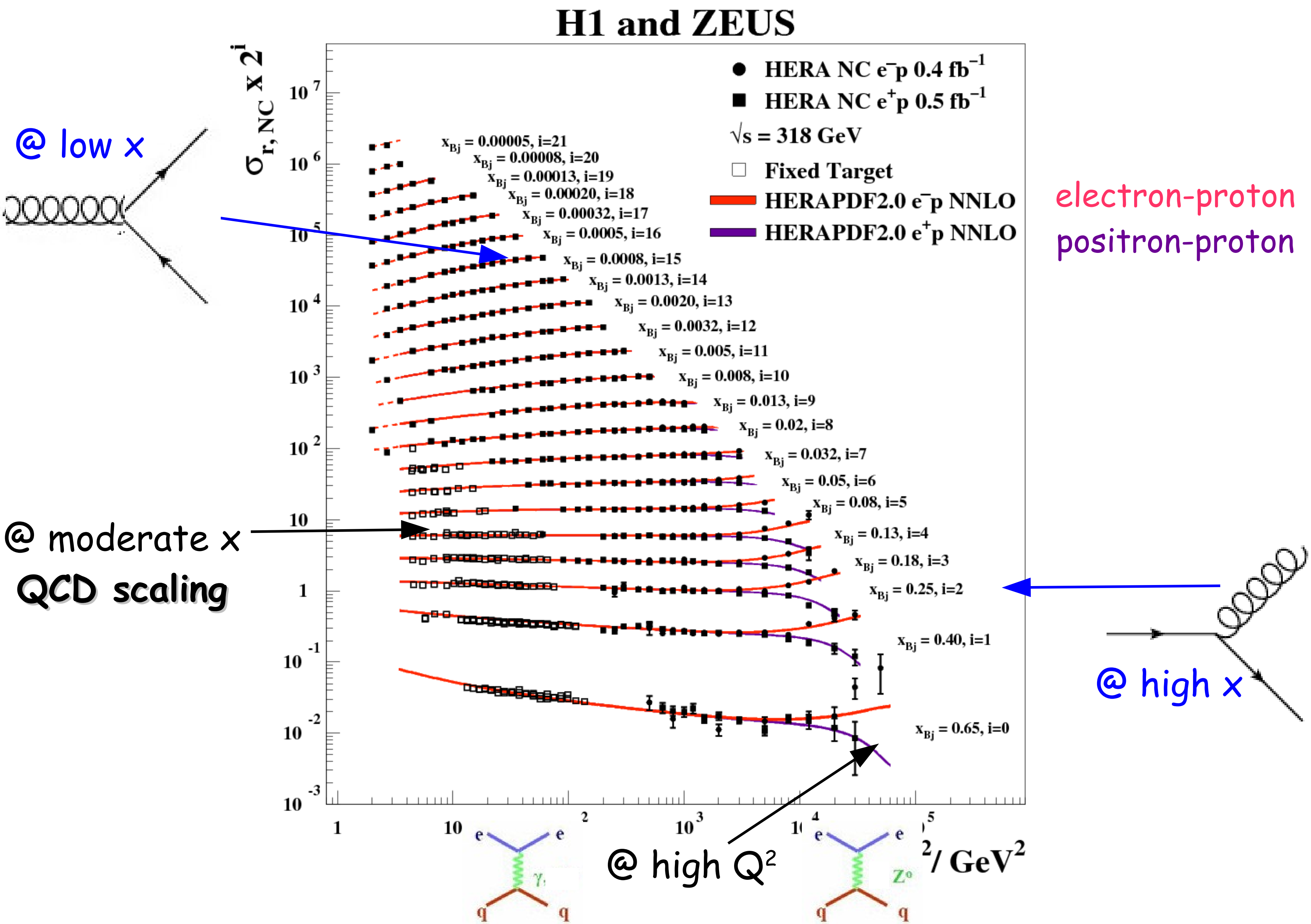
# CC: helicity effects




$\sigma^{+}_{CC} \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d+s]$

$\sigma^{-}_{CC} \sim x[u + c] + x(1-y)^2[\bar{d}+\bar{s}]$

- $e^+p$: $d_v$ quarks are suppressed at high $Q^2$
- $e^-p$: helicity factor applies to sea quarks only




Text book plots of fundamental properties of particle interactions

# Polarised DIS

- Generalised structure functions depend on e-beam polarisation

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

$$\tilde{F}_2^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z,$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z x F_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2 x F_3^Z$$

- Structure functions in QP model

**NC**

$$[F_2^{\gamma}, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q}),$$

$$[xF_3^{\gamma Z}, xF_3^Z] = \sum_q [e_q a_q, v_q a_q] 2x(q - \bar{q}),$$

NC sensitive to $\sin^2\theta_W$ via

$$\chi_Z = \frac{1}{\sin^2 2\theta_W}\frac{Q^2}{M_Z^2 + Q^2}\frac{1}{1 - \Delta R}$$

**CC**

$$\frac{d^2\sigma_{CC}(e^+p)}{dx_{Bj}dQ^2} = (1 + P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2 + M_W^2)^2} x\left[(\bar{u} + \bar{c}) + (1 - y)^2(d + s + b)\right]$$

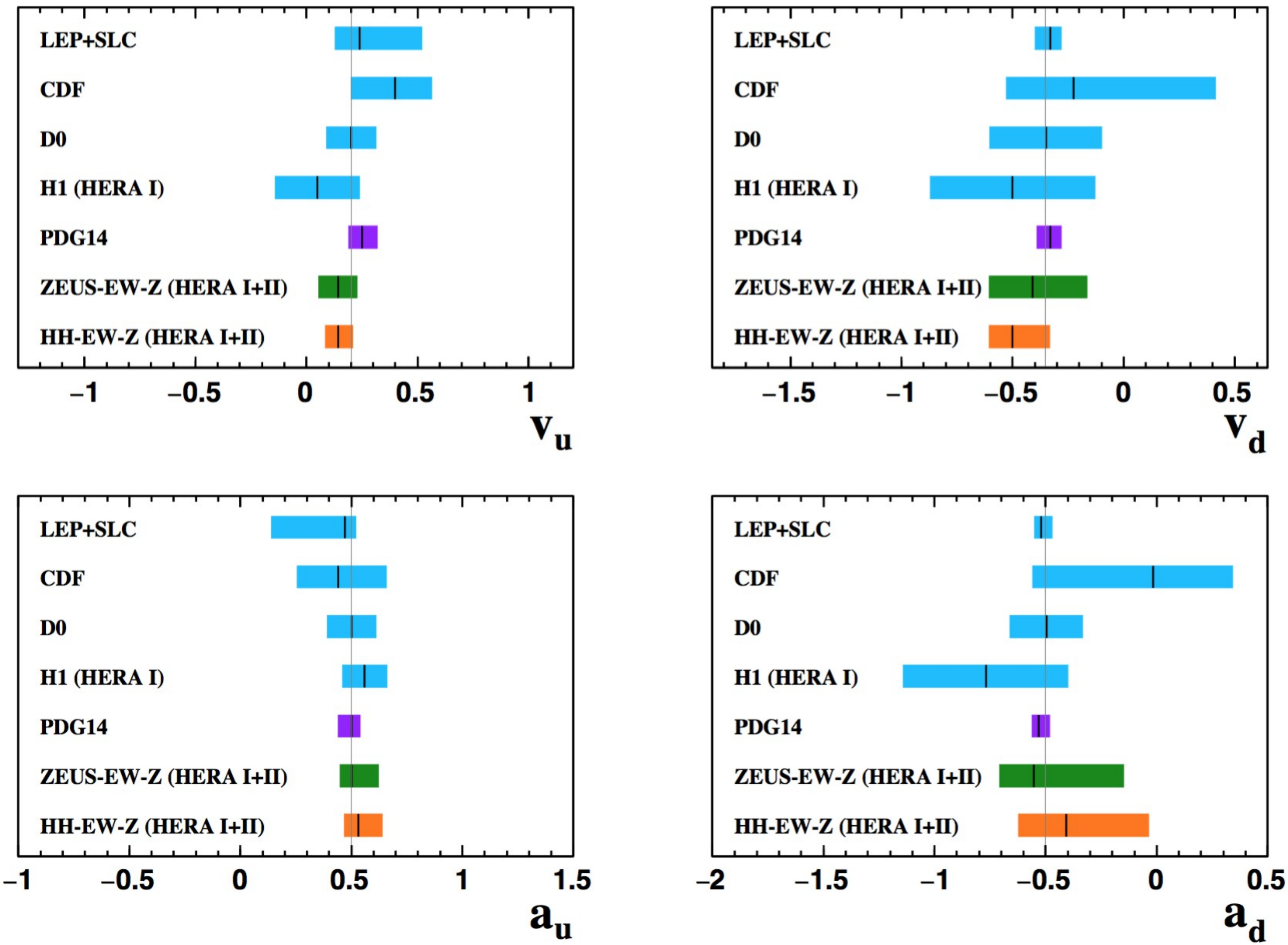
$$\frac{d^2\sigma_{CC}(e^-p)}{dx_{Bj}dQ^2} = (1 - P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2 + M_W^2)^2} x\left[(u + c) + (1 - y)^2(\bar{d} + \bar{s} + \bar{b})\right]$$

- Calculation in on-shell scheme

$$G_F = \frac{\pi\alpha_0}{\sqrt{2}\sin^2\theta_W M_W^2}\frac{1}{1 - \Delta R}$$

CC sensitive to $\sin^2\theta_W$

# HERAI+II determinations so far



# Inclusive measurements from HERA are core of every parton density extraction

Final HERA data – exclusively - used as input to global QCD fit HERAPDF2.0

- Parton densities parametrised @ $Q^2 = 1.9\ GeV^2$

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

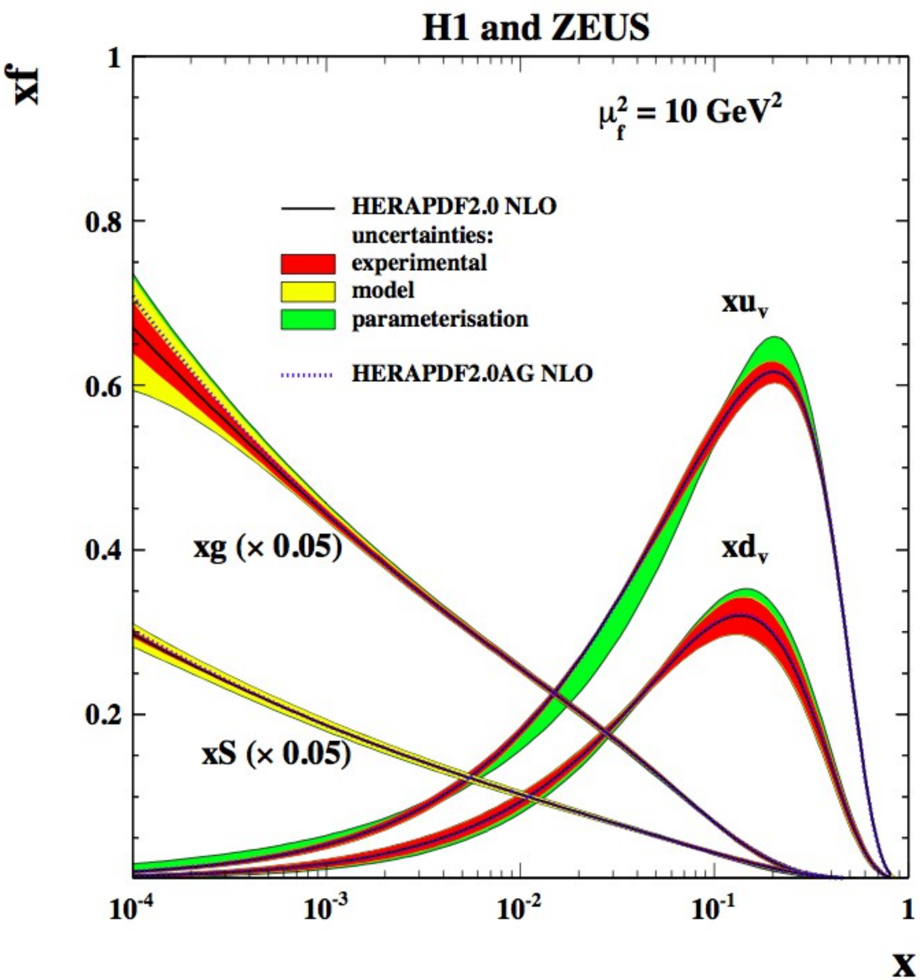
$$xg(x), xu_v(x), xd_v(x), x\bar{U}(x), x\bar{D}(x)$$

- Evolution using DGLAP equations
- 14 parameters determined in paramerisation scan
- Heavy quarks from Roberts-Thorne Variable Flavor Number Scheme

HERAFitter

QCD fits performed using HERAFitter package www.herafitter.org

# Color decomposition of uncertainties



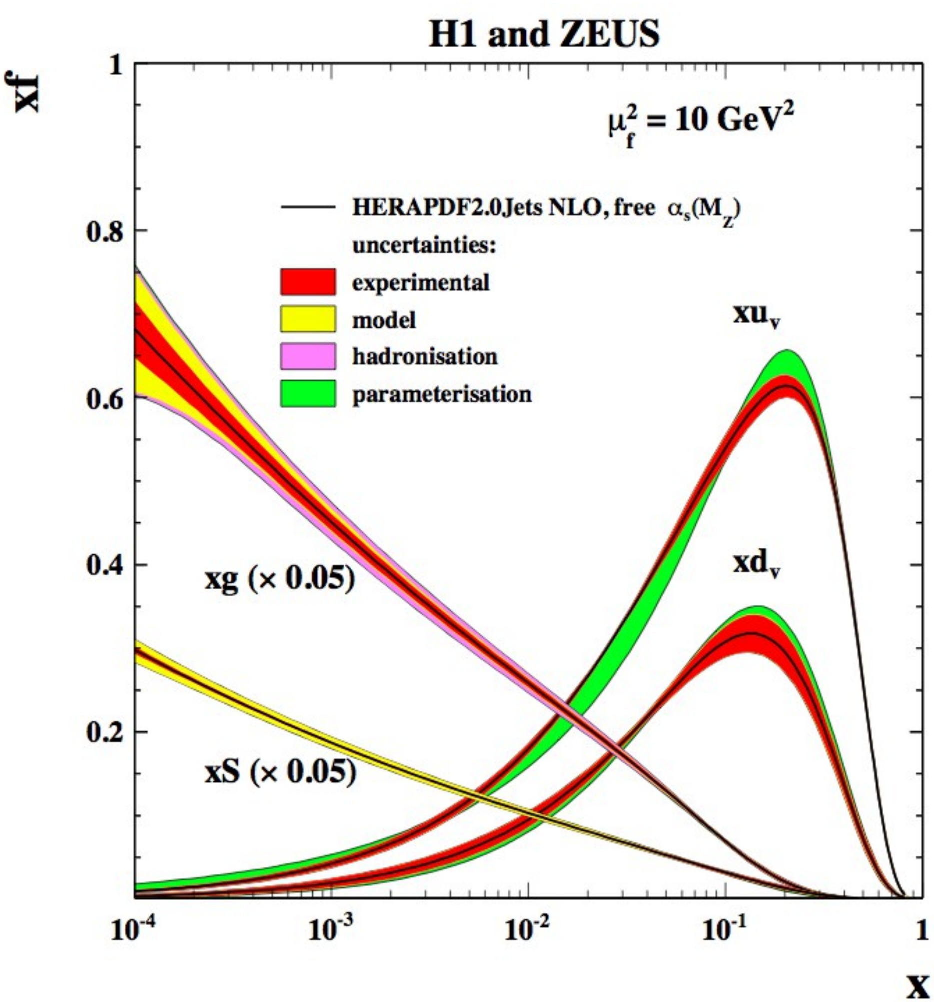

- **Experimental uncertainties:**
  - Hessian method
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

| Variation | Standard Value | Lower Limit | Upper Limit |
|---|---|---|---|
| $Q^2_{min}$ [GeV$^2$] | 3.5 | 2.5 | 5.0 |
| $Q^2_{min}$ [GeV$^2$] HiQ2 | 10.0 | 7.5 | 12.5 |
| $M_c$(NLO) [GeV] | 1.47 | 1.41 | 1.53 |
| $M_c$ (NNLO) [GeV] | 1.43 | 1.37 | 1.49 |
| $M_b$ [GeV] | 4.5 | 4.25 | 4.75 |
| $f_s$ | 0.4 | 0.3 | 0.5 |
| $\mu_{f_0}$ [GeV] | 1.9 | 1.6 | 2.2 |

Adding D and E parameters to each PDF

- **Parametrisation uncertainties**
  - largest deviation
- **Model uncertainties**
  - all variations added in quadrature

# HERAPDF2.0Jets $\alpha_s$ free




<u>$\alpha_s$ determined from QCD fit</u>

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp})$$

Experimental uncertainty below 1%

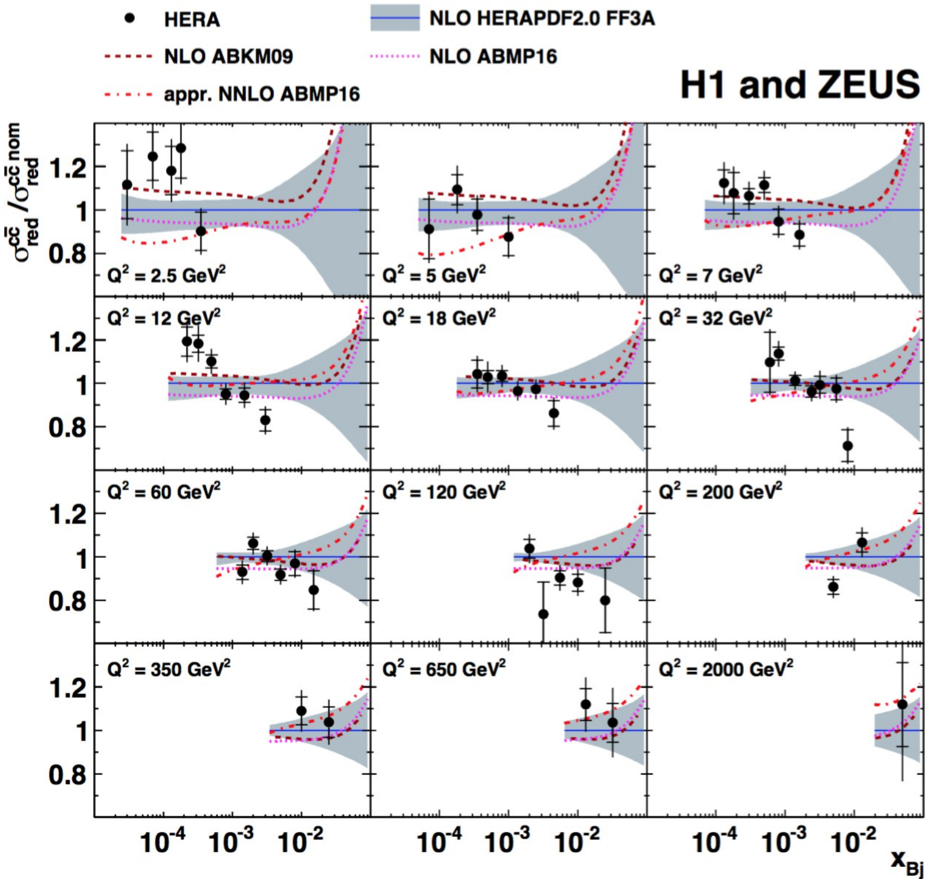
$$\pm 0.0005(\text{model/parameterisation})$$

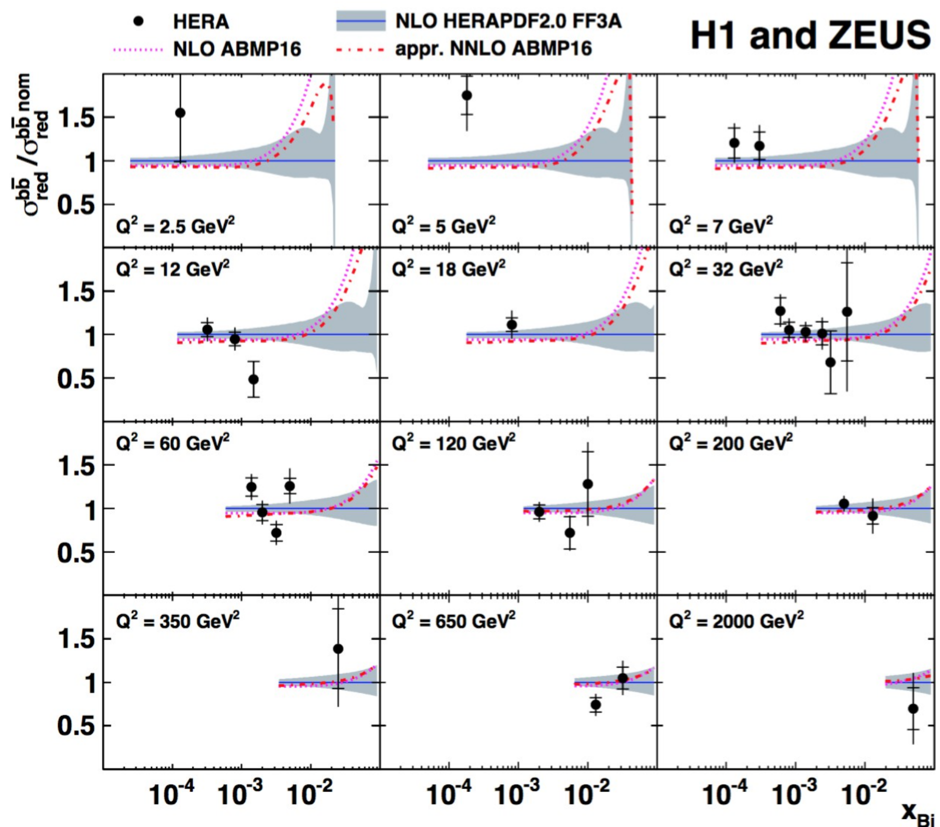
$$\pm 0.0012(\text{hadronisation})$$

$$^{+0.0037}_{-0.0030}(\text{scale})$$

Uncertainty dominated by theory
NNLO ep jet calculations needed

# Comparison to QCD predictions

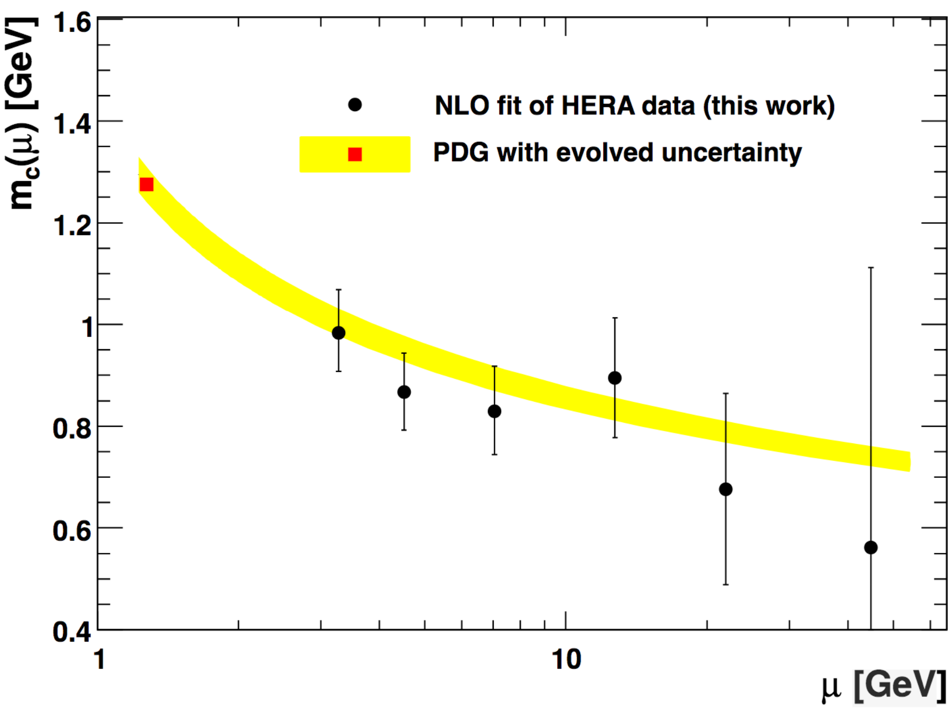


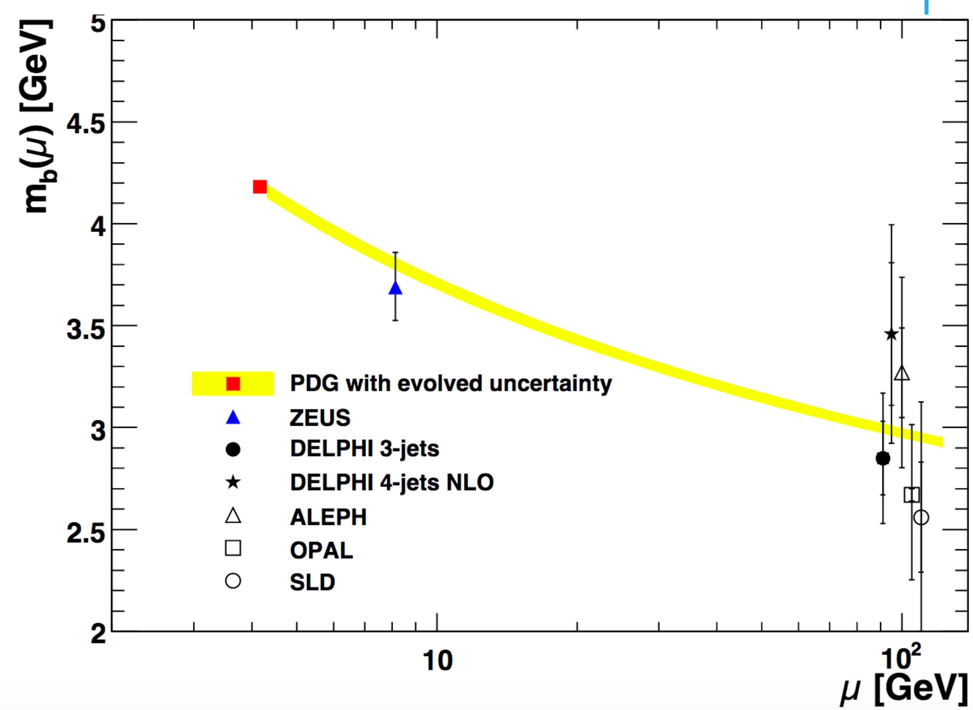




- NLO and approximate NNLO QCD predictions compared to the data
  - fair agreement charm data
  - Best description for NLO in fixed-flavour-number scheme
- beauty data, with larger uncertainties, well described by all predictions

# Charm & beauty mass running

arXiv:1705.08863

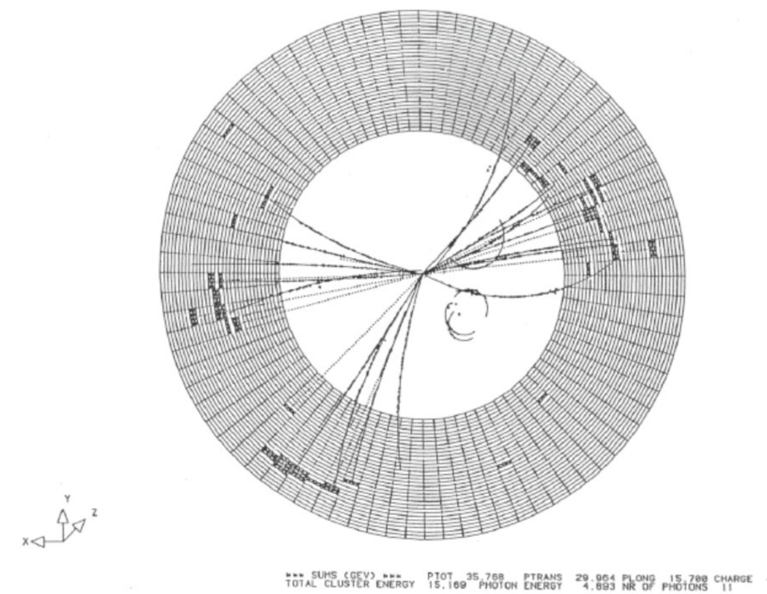


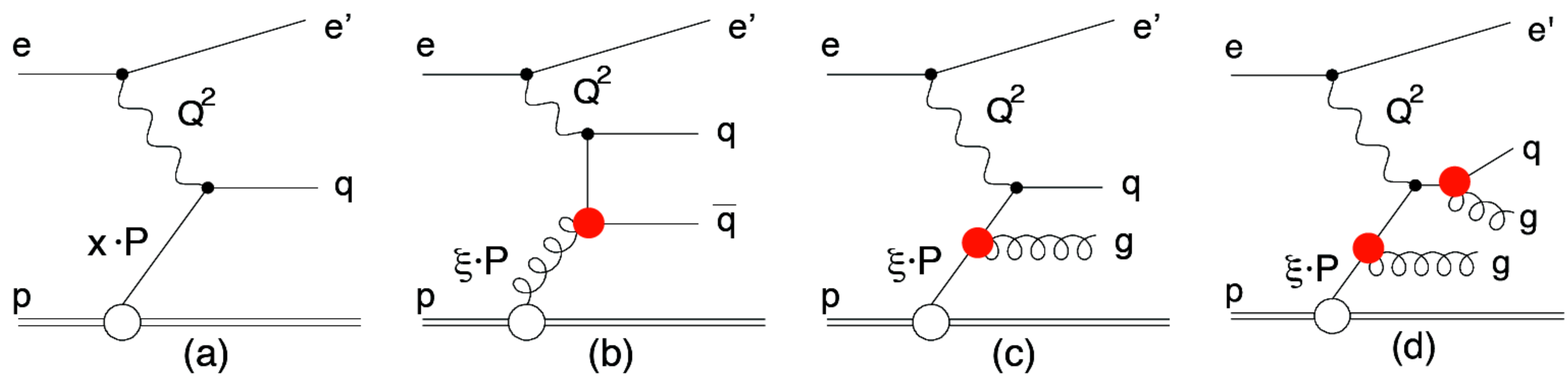

Heavy quark masses run in agreement with pQCD

# Jet production @HERA

Jets at PETRA, 1979



- Direct information on gluon distribution comes from jet production
- Possible simultaneous determination of parton densities and $\alpha_s$
- Jets at HERA

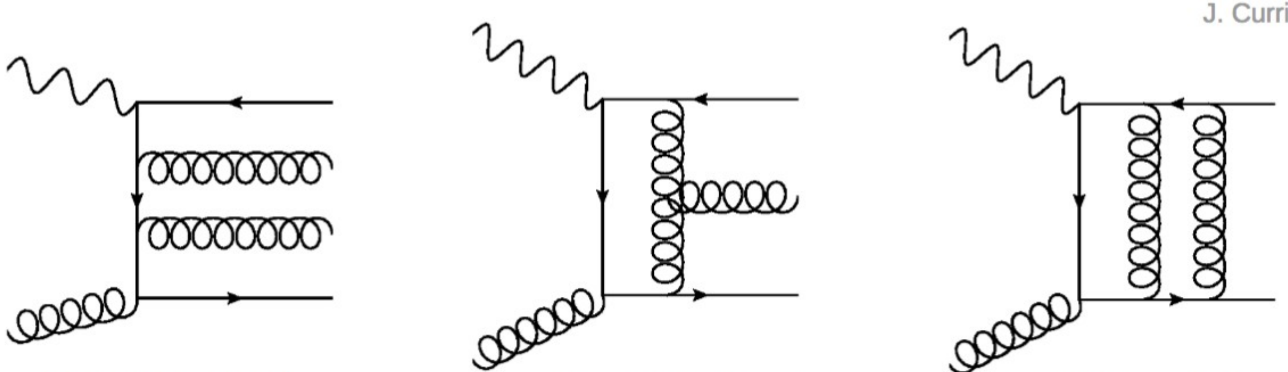



elweak coupling | $\propto \alpha_S$ | $\propto \alpha_S$ | $\propto \alpha_S^2$

dijets | trijets

# DIS jet production in NNLO

J. Currie, et al. [RPL 117 (2016) 042001]
J. Currie, et al. [JHEP 1707 (2017) 018]




$$d\sigma^{RR,S}_{NNLO} \approx \underbrace{X(\{p_X\})}_{\text{antenna}} \overbrace{d\Phi_3(\{p_X\})}^{\text{Antenna PS}} \times \underbrace{|\mathcal{M}(\{\widetilde{p_m}\})|^2}_{\text{reduced ME}} \overbrace{d\Phi_m(\{\widetilde{p_m}\})}^{\text{reduced PS}} \times \underbrace{\mathcal{J}(\{\widetilde{p_m}\})}_{\text{jet function}}$$

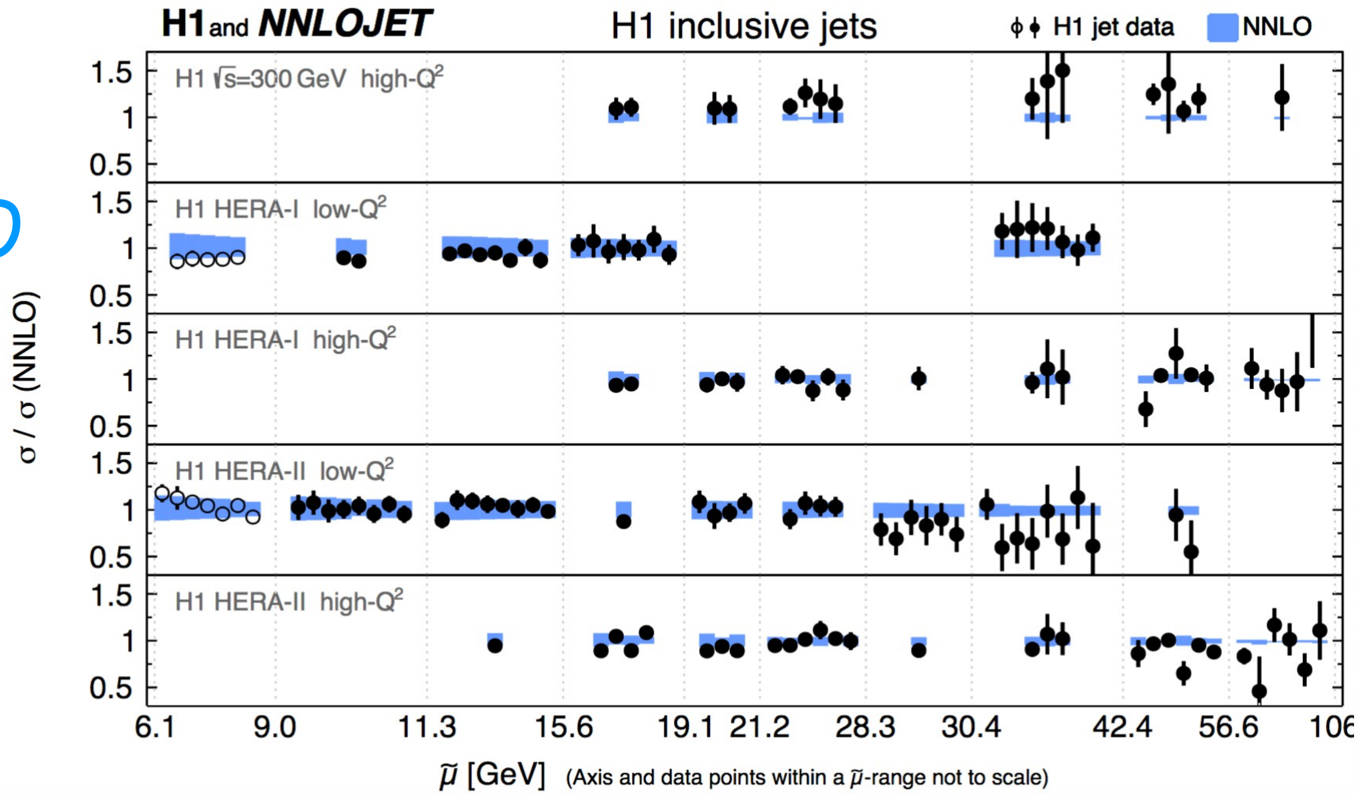
***A bit of history***

- 1973 asymptotic freedom of QCD
  [PRL 30(1973) 1343 & 1346]
- 1993 NLO studies of DIS jet cross sections
  [Phys. Rev. D49 (1994) 3291]
- 2016 NNLO corrections for DIS jets
  [Phys. Rev. Lett. 117 (2016) 042001], [arXiv:1703.05977]

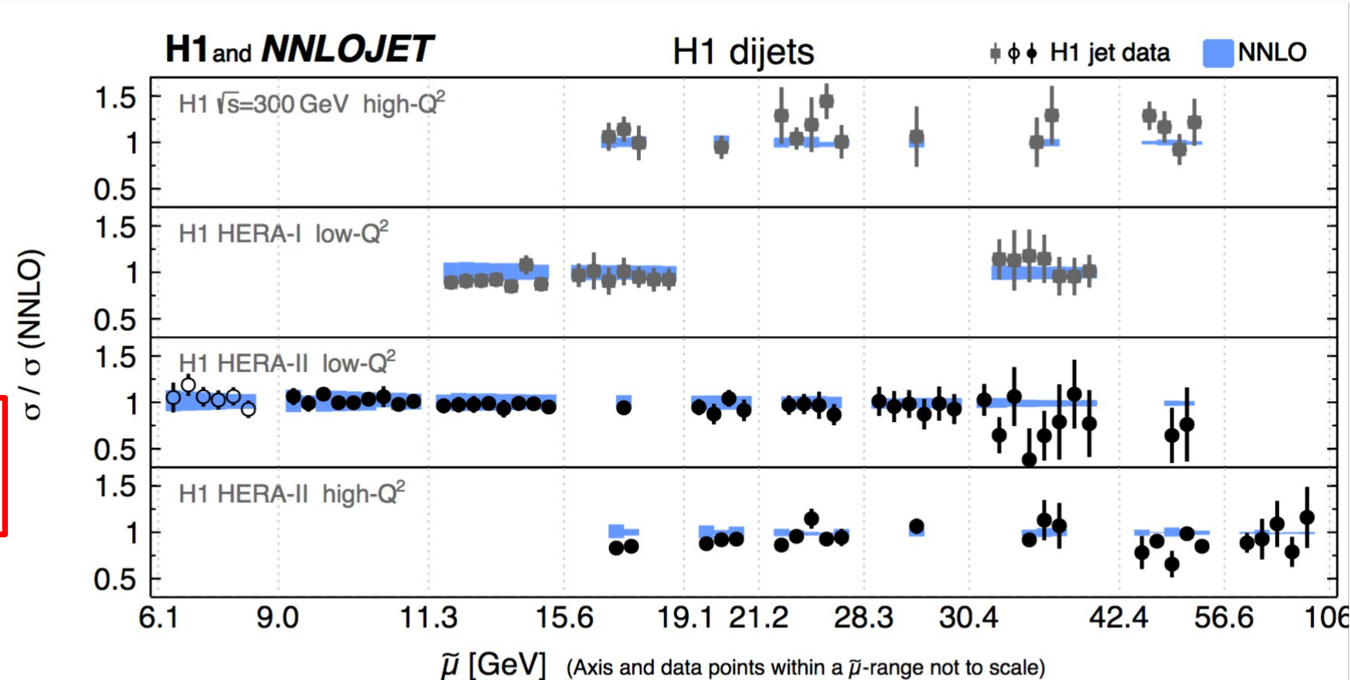
***Antenna subtraction***

- Cancellation of IR divergences with local subtraction terms
- Construction of (local) counter terms
- Move IR divergences across different phase space multiplicities

# Comparison of NNLO predictions to data

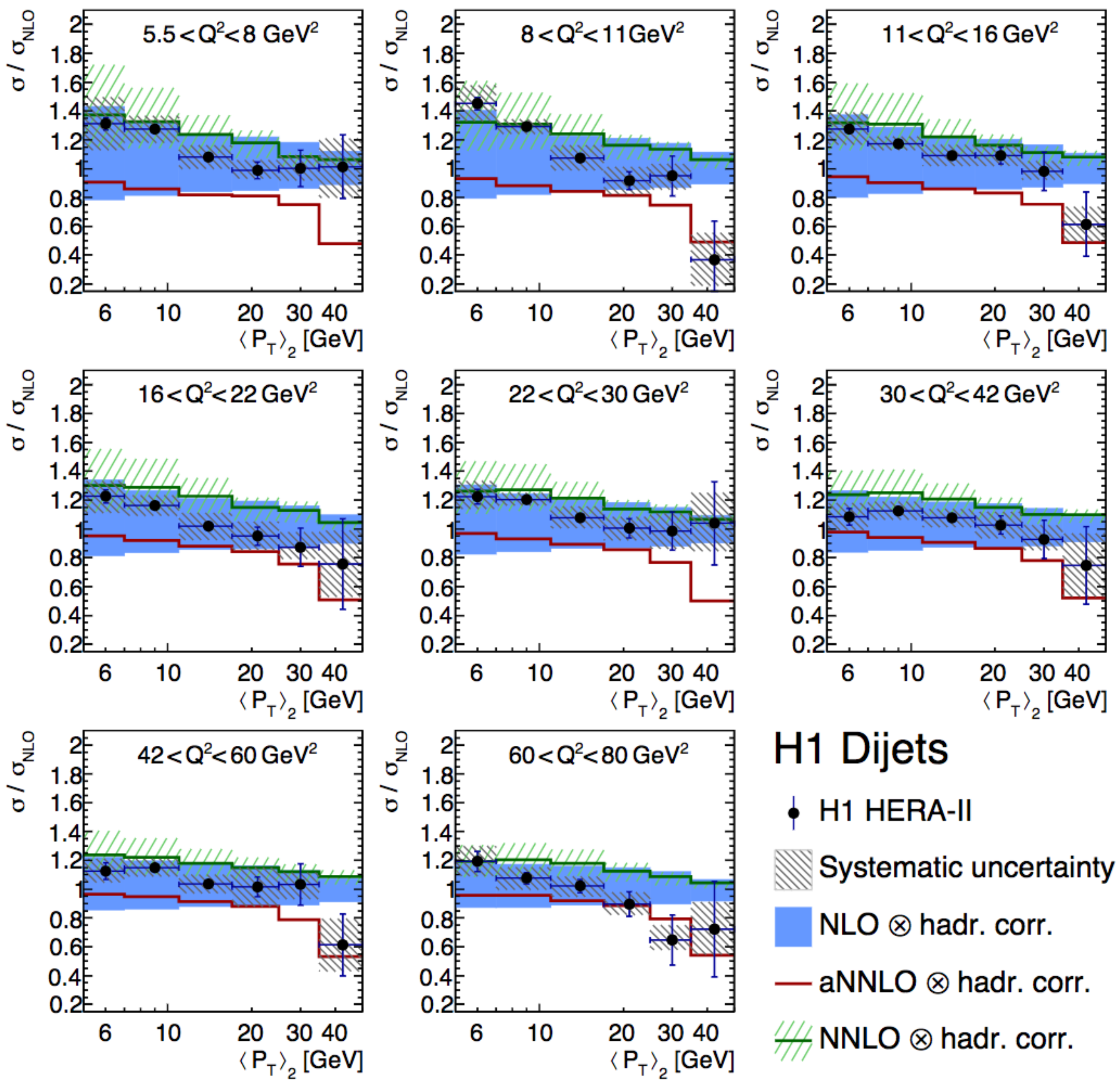



Overall good agreement




Great success of pQCD

# H1 dijets with NNLO predictions



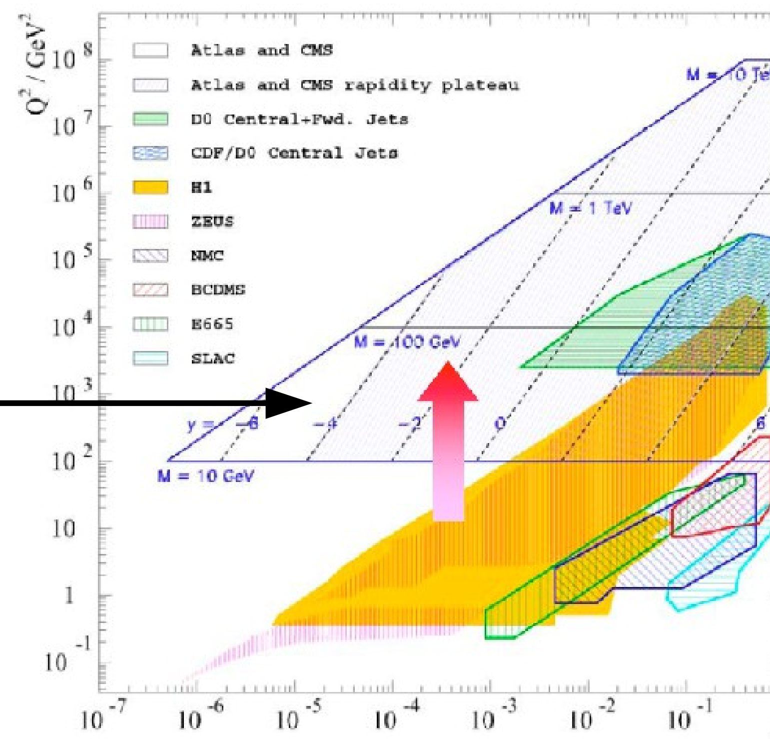

K. Wichmann Krakow'18 Various Faces of QCD @ HERA

# Why study prompt photons?

- Prompt photons emerge directly from the hard scattering process and give a particular view of this
- Use dynamics to probe modes such as $k_t$-factorisation and pQCD approaches
- See if dynamics changes with virtuality
- Combined photon/jet/electron variables give more detailed ways to test the theories than with single particles and jets

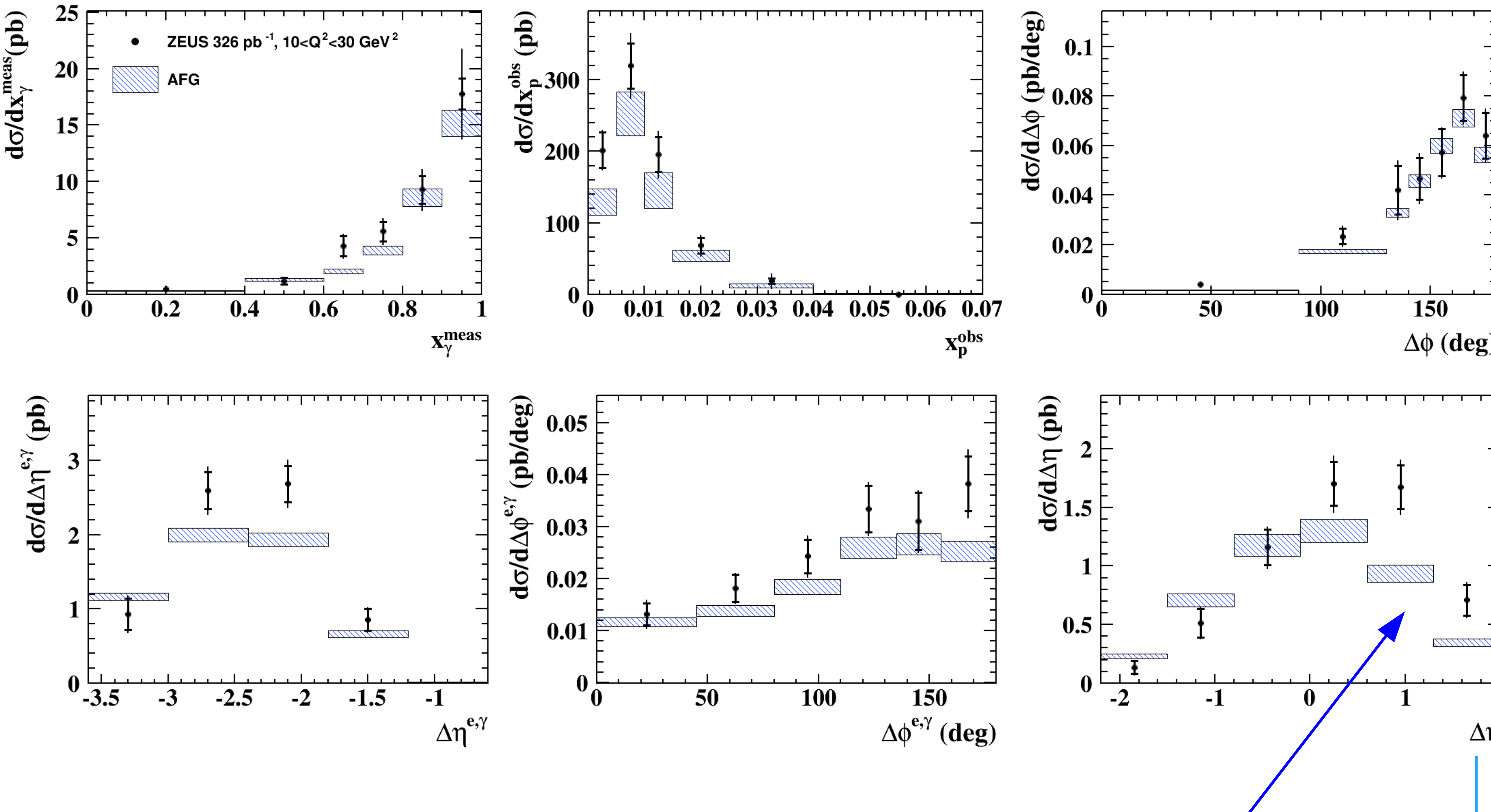
- Check proton PDFs
- Photons can be background to new physics

→ DGLAP evolves HERA scales to LHC scales



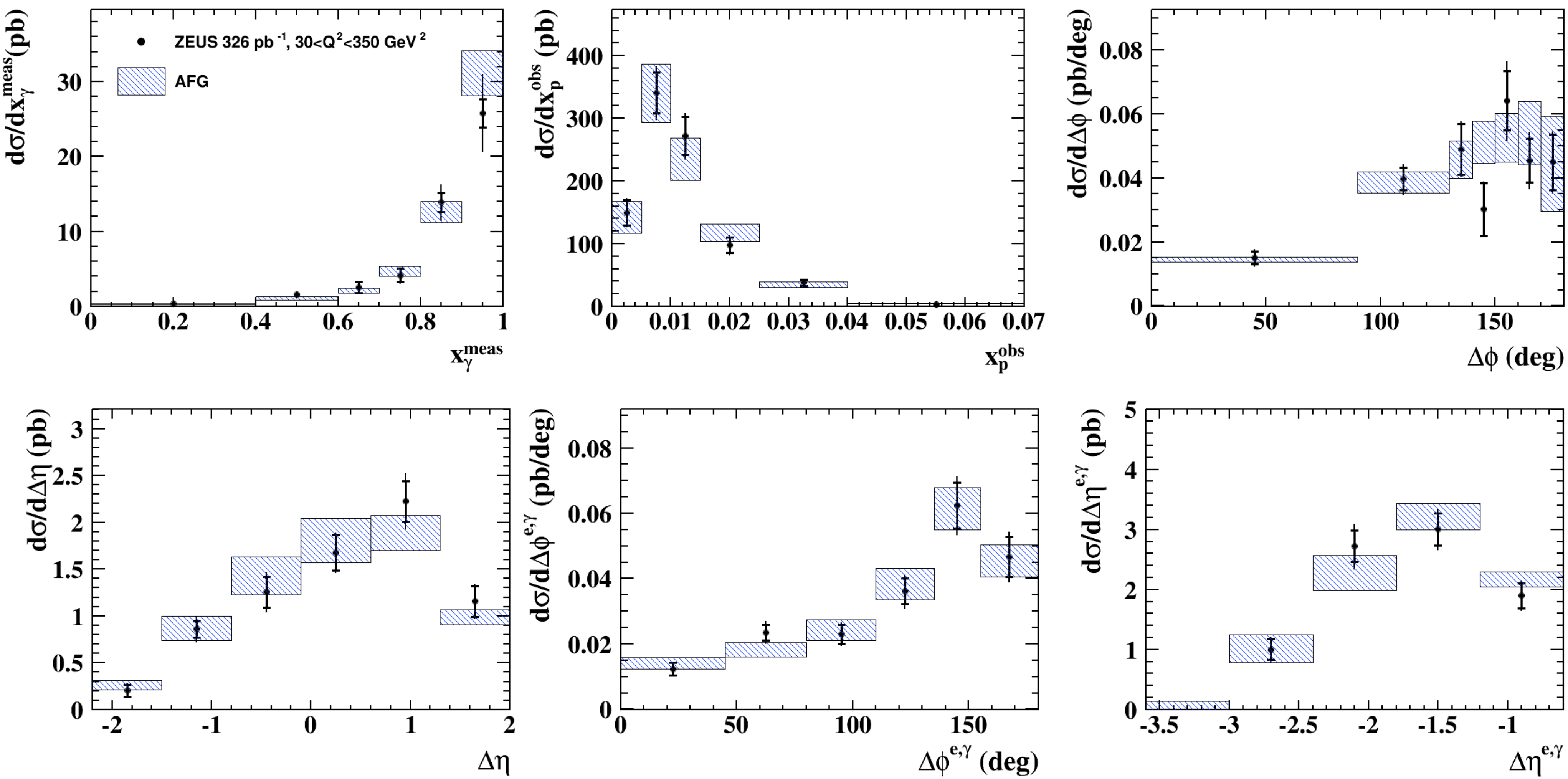

Single prompt variable already measured (Phys. Lett. B 715 (2012) 88-97), this study complements previous analysis

# Comparison to AFG: low $Q^2$




- Excellent agreement in shape and normalisation except for $\Delta\eta$
  - Possibly due to photon $p_T$ cut in calculations

# Comparison to AFG: large $Q^2$




- Excellent agreement in shape and normalisation for all distributions
  - Also in lower $Q^2$ bin in range between 10 and 30 GeV$^2$