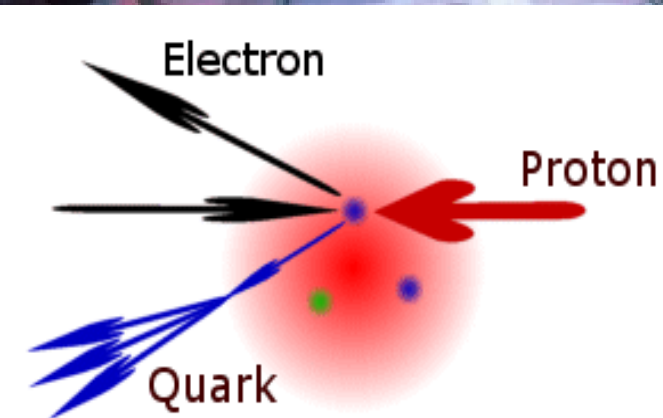




6th Workshop on QCD and Diffraction
joint with

VARIOUS
FACES of

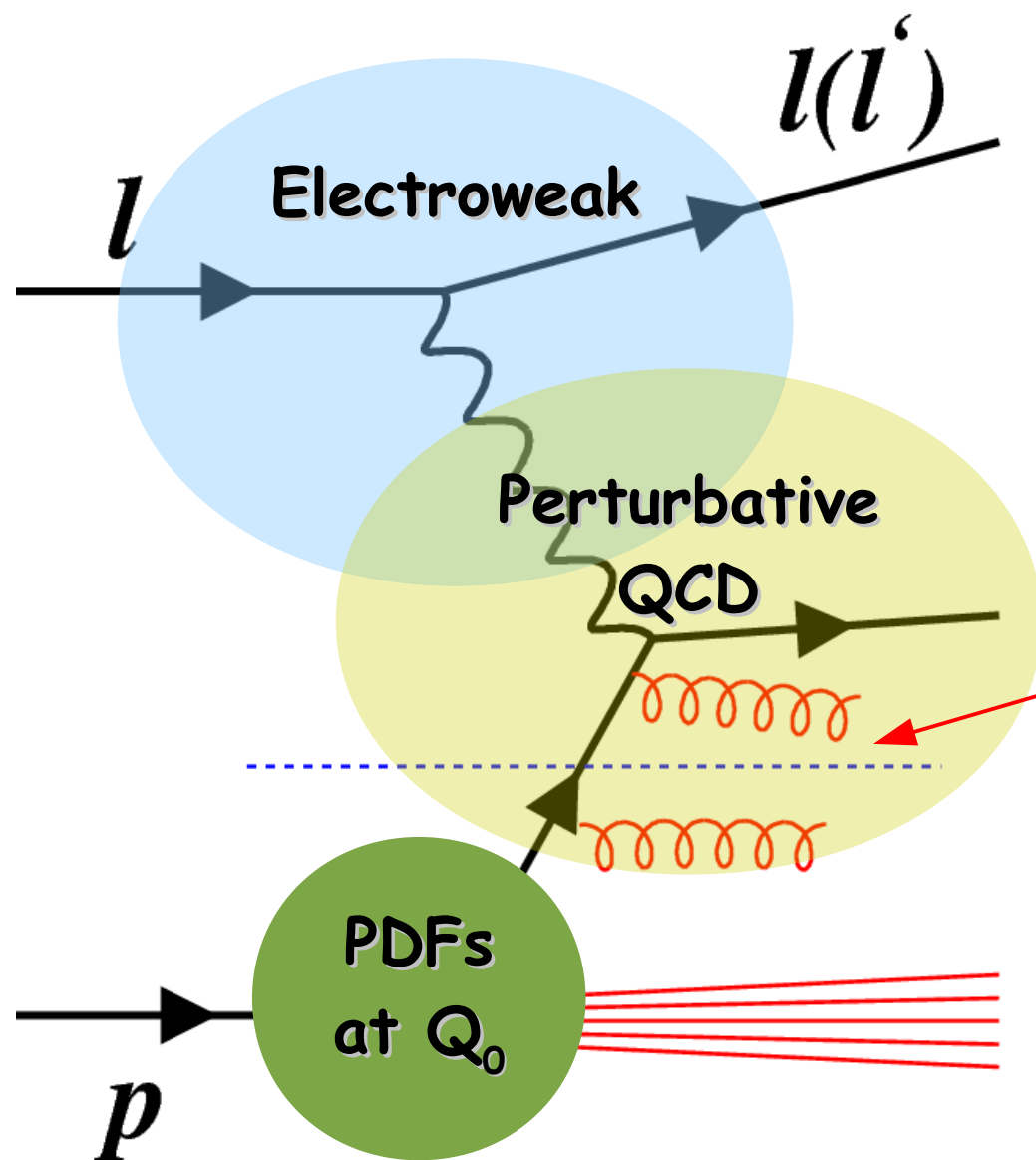
4th Symposium of the Division for Physics of
Fundamental Interactions of the Polish Physical Society



@HERA



ep Scattering @ HERA



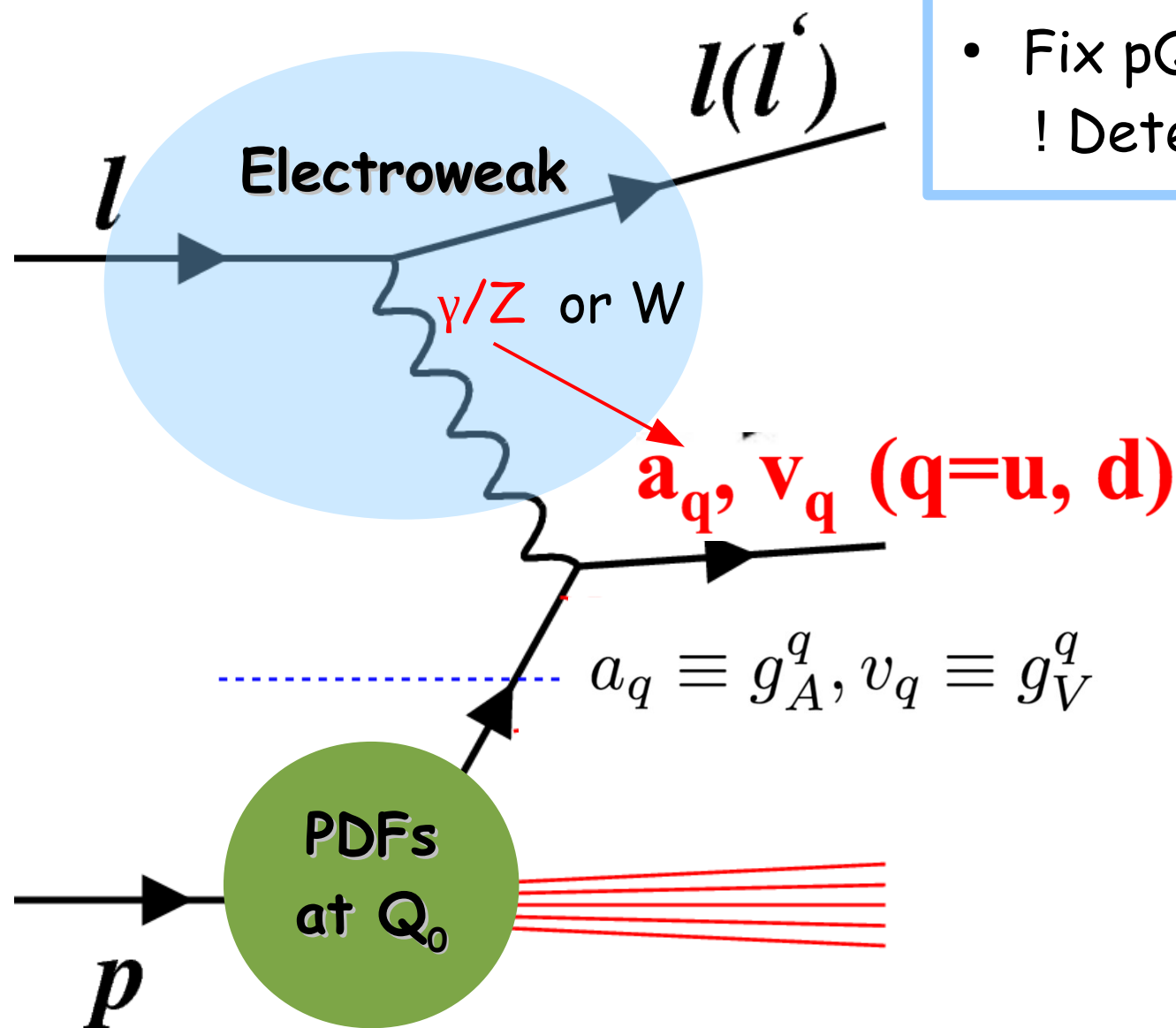
- Fix pQCD & PDFs
! Test Electroweak
- Fix Electroweak
! Test pQCD & PDFs

- Fix Electroweak & pQCD
! Determine PDFs

We can actually fix only one and determine the rest!



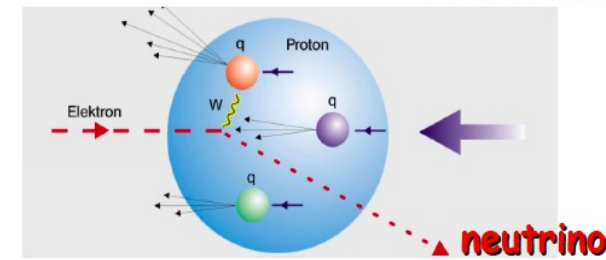
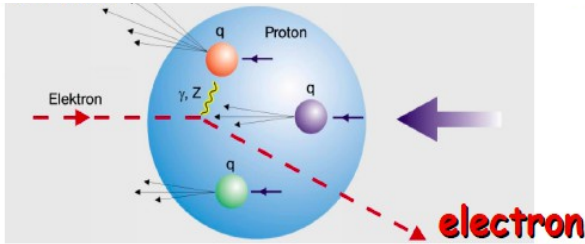
Electroweak Physics @ HERA



- Fix pQCD + polarised DIS
! Determine PDFs & EW

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

Polarised H1 data



• Neutral current

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

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

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

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

$$x F_3^Z = 2x \sum_q g_V^q g_A^q \{q - \bar{q}\}$$

degree of longitudinal polarisation

• Charge current

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

$$W_2^- = x (\rho_{\text{CC},eq}^2 U + \rho_{\text{CC},e\bar{q}}^2 \bar{D})$$

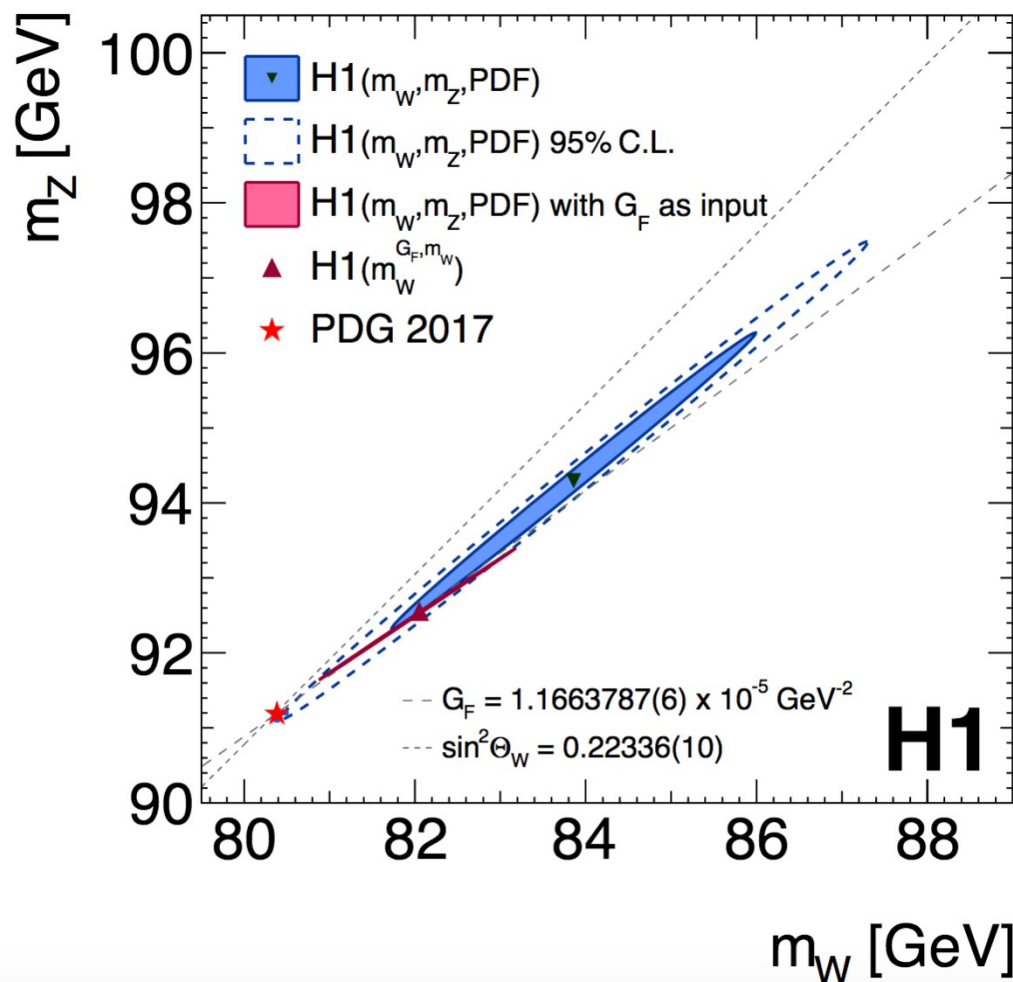
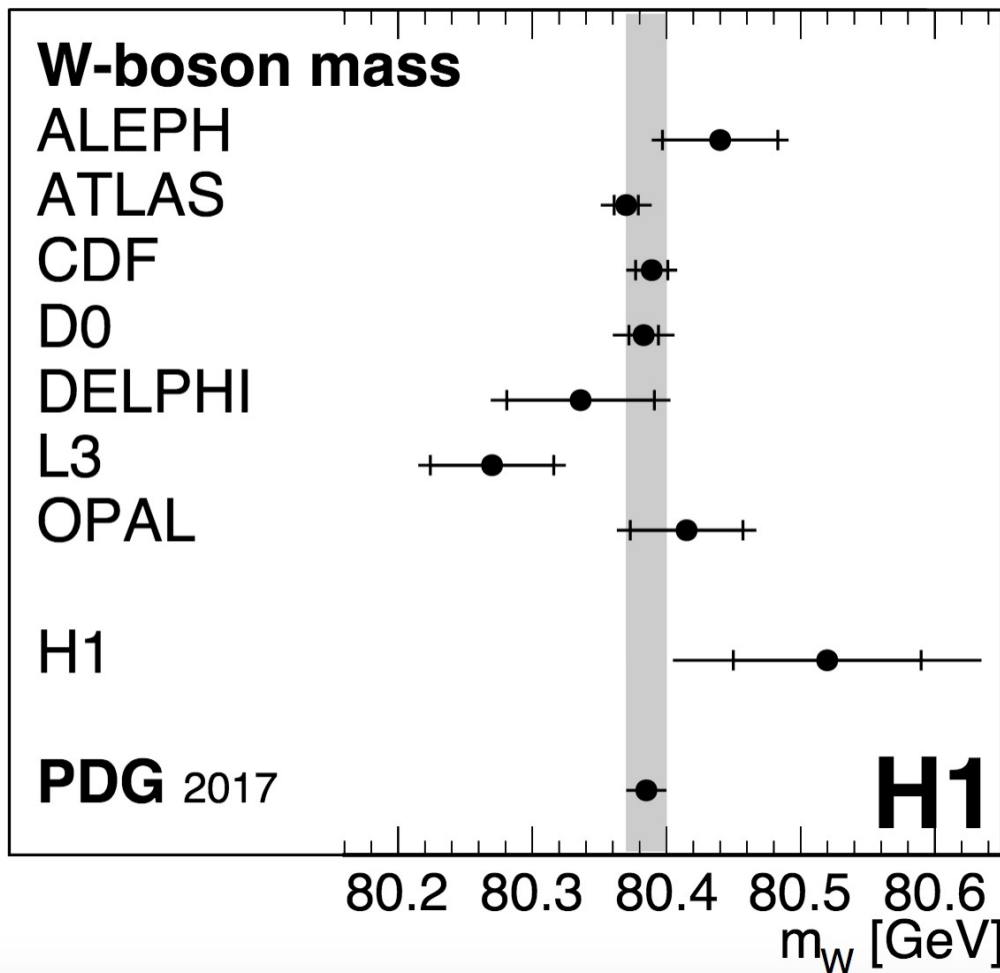
$$x W_3^- = x (\rho_{\text{CC},eq}^2 U - \rho_{\text{CC},e\bar{q}}^2 \bar{D})$$

$$U = u + c$$

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

Perform simultaneous
QCD + EW fit
NNLO for QCD
NLO for EW

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



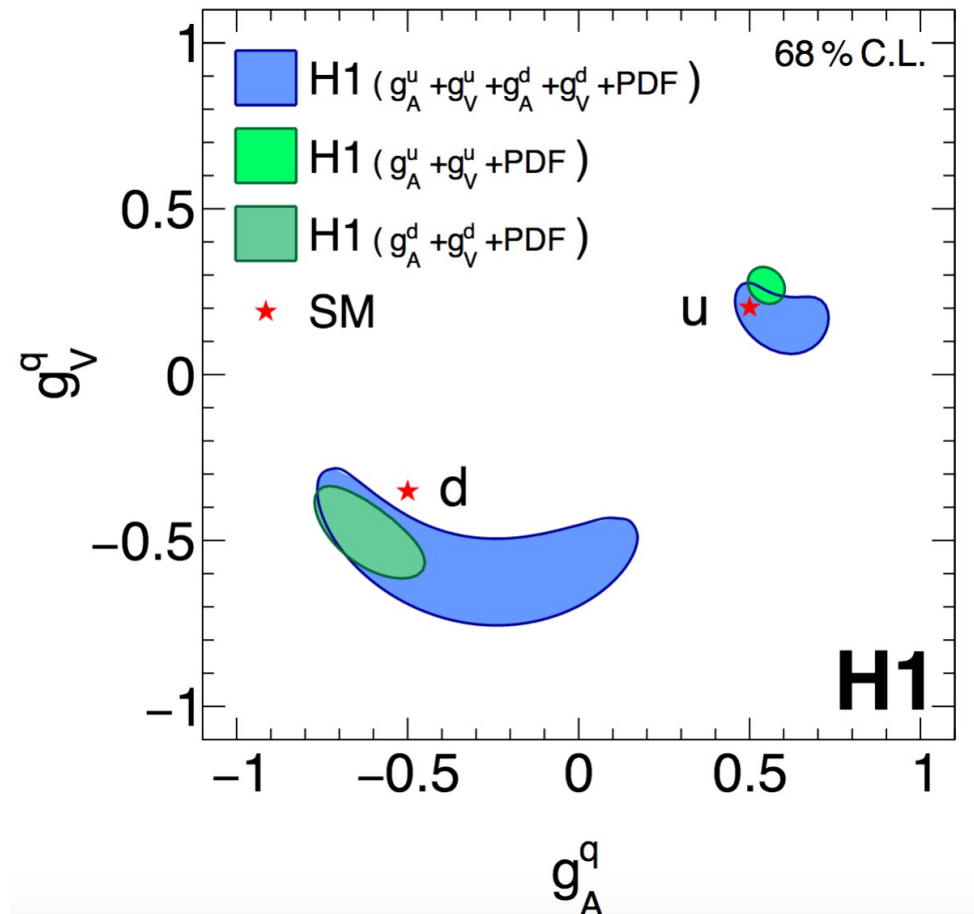
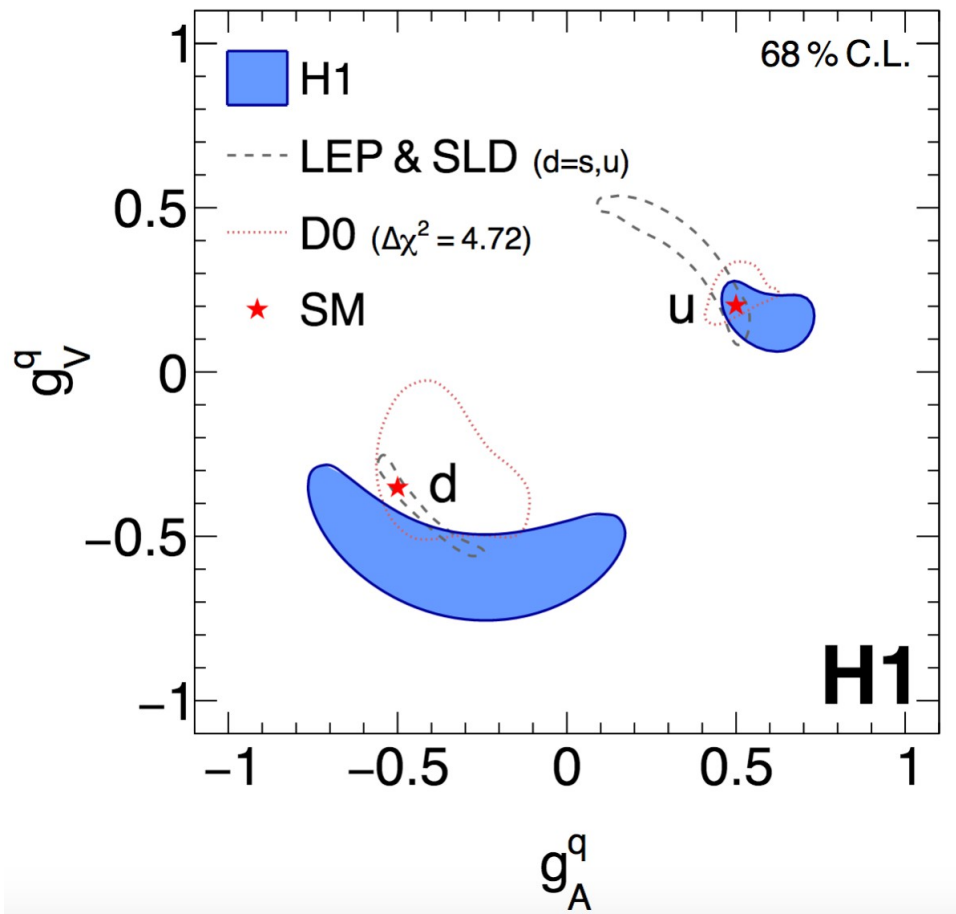
Determination performed in on-shell scheme:

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

to be compared with HERA-I result:

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

Light Quark Couplings to Z Boson

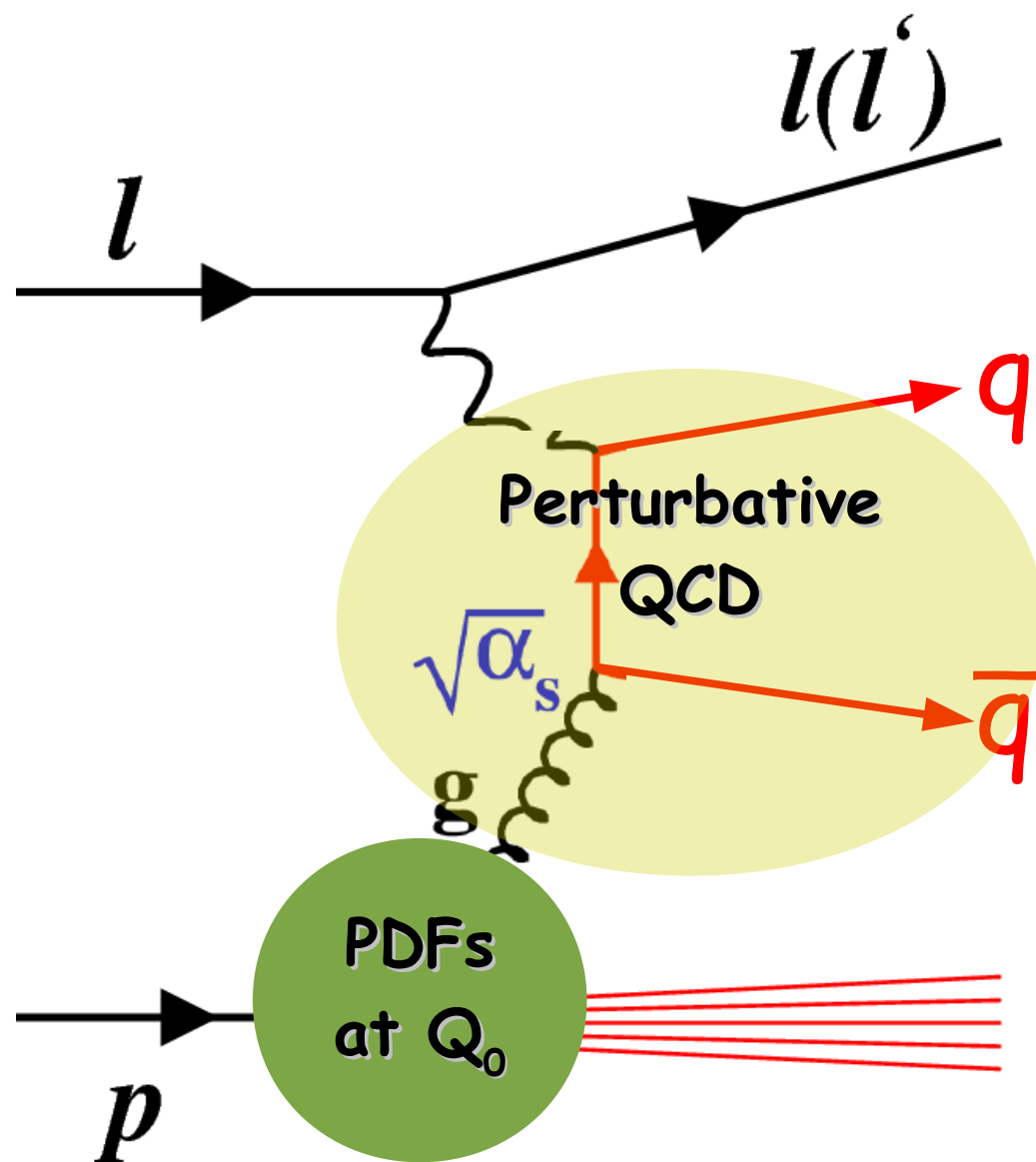


- results are competitive with other determinations, especially for u quarks

- 2-coupling fit is more precise due to the reduced correlation



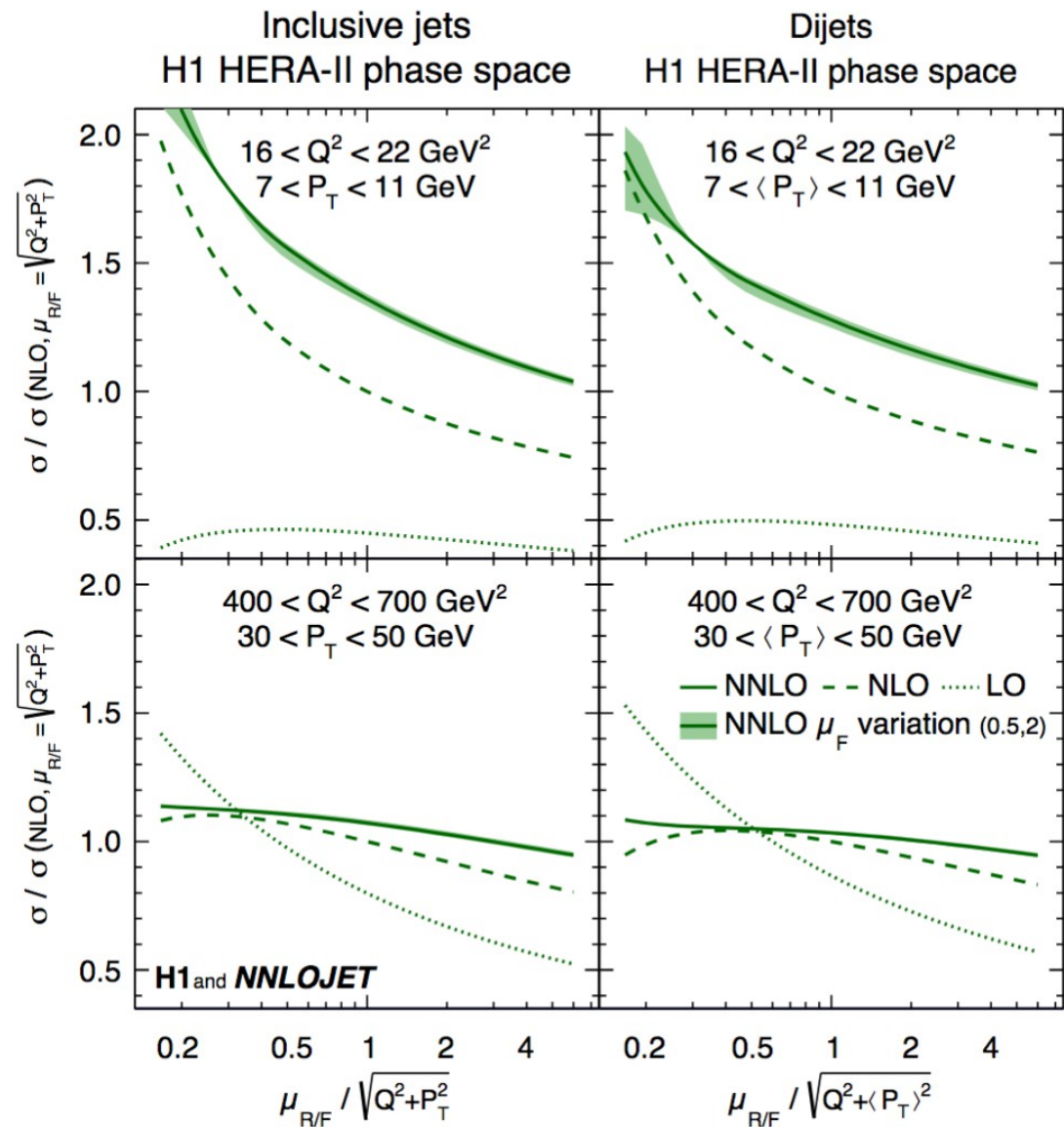
Jet Production @ HERA



- 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**

- Simultaneous variation of μ_R and μ_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
 - μ_F dependence very small



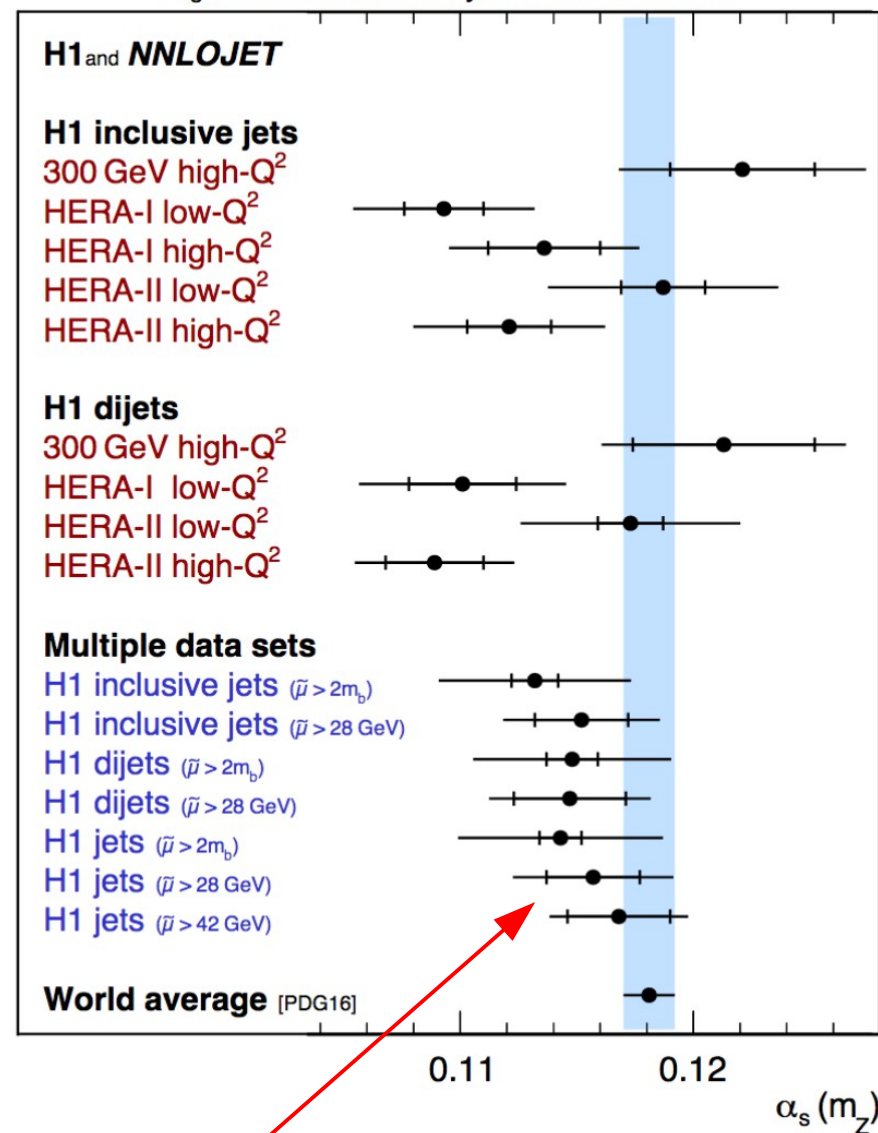
Strong coupling in NNLO from jets

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

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

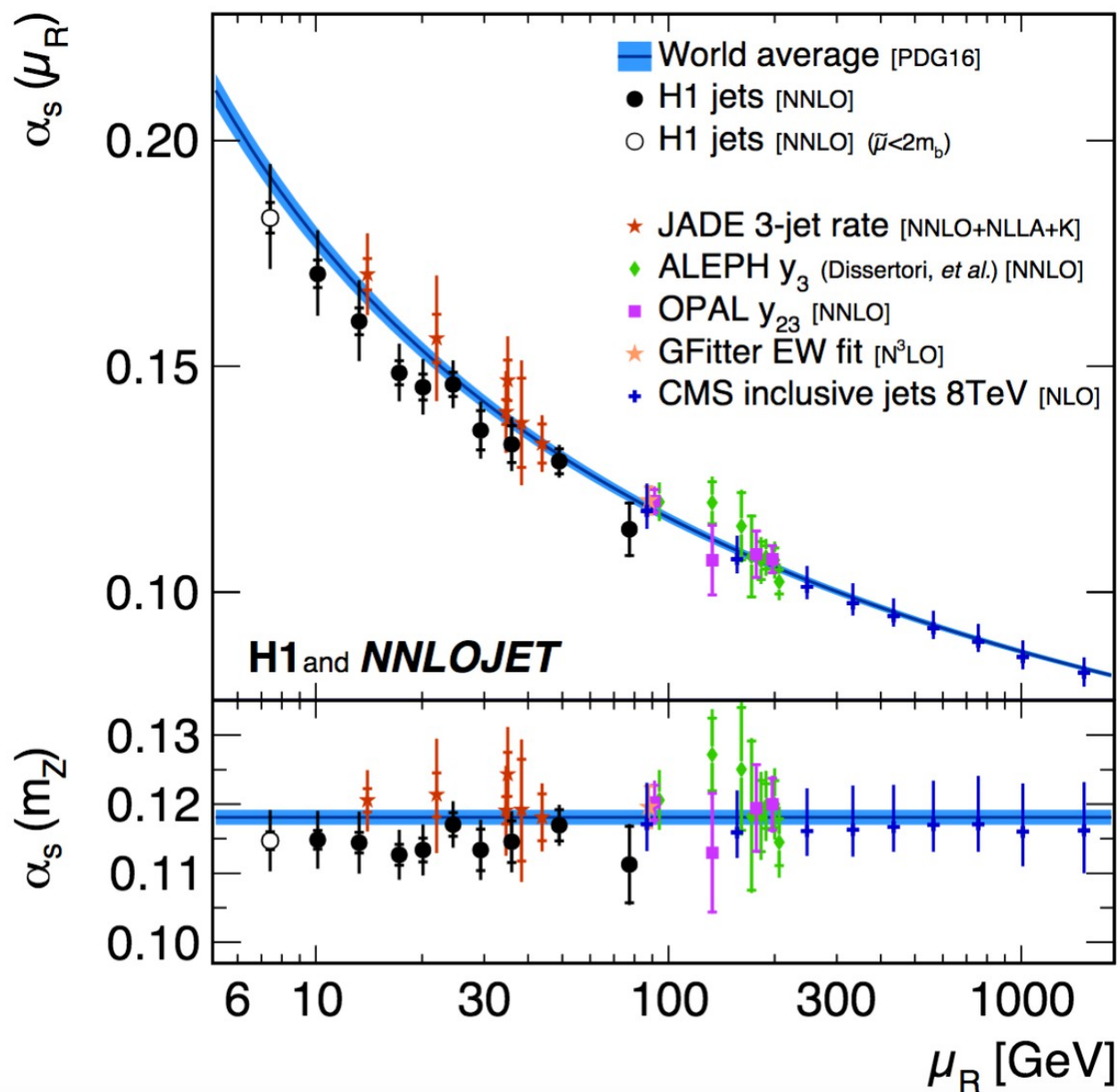
- $\alpha_s(m_Z)$ from individual data sets
 - High experimental precision
 - Scale uncertainty is largest (theory) error
 - All fits with good $\rightarrow$ consistency of data
- Main result
 - Inclusive jets & dijets $\mu > 28\text{GeV}$
 - Moderate exp. Precision (due to $\mu > 28\text{GeV}$)
 - Scale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

α_s results from H1 jet data in NNLO



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

Running of strong coupling constant ...



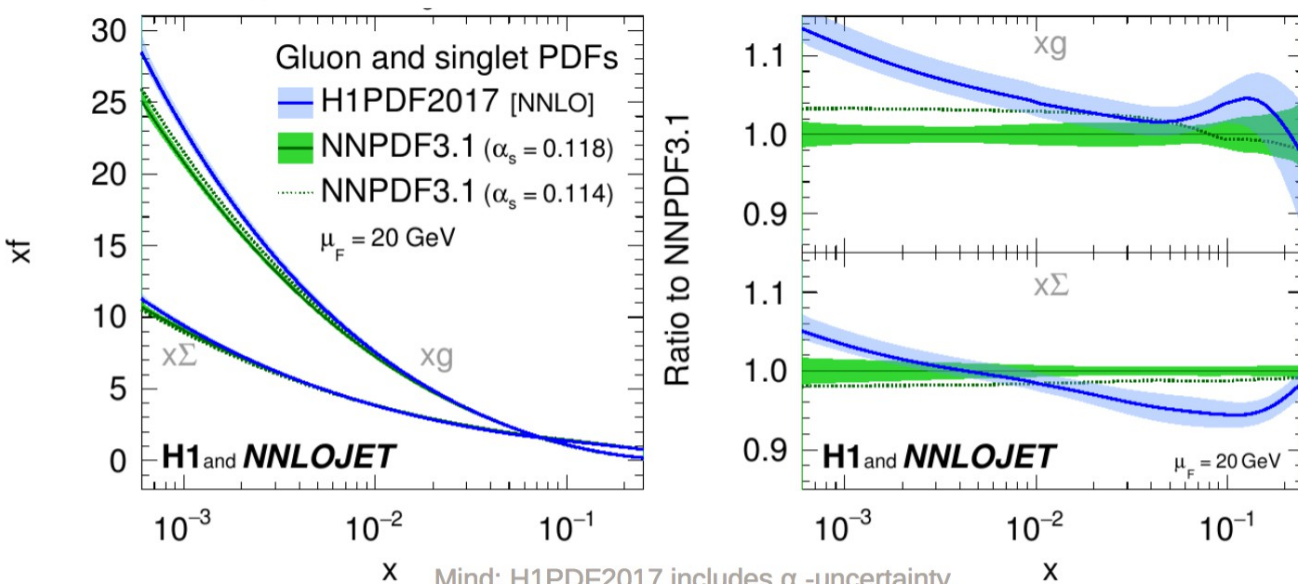
+

Overall good description of
H1 jet data by NNLO

Great success of pQCD

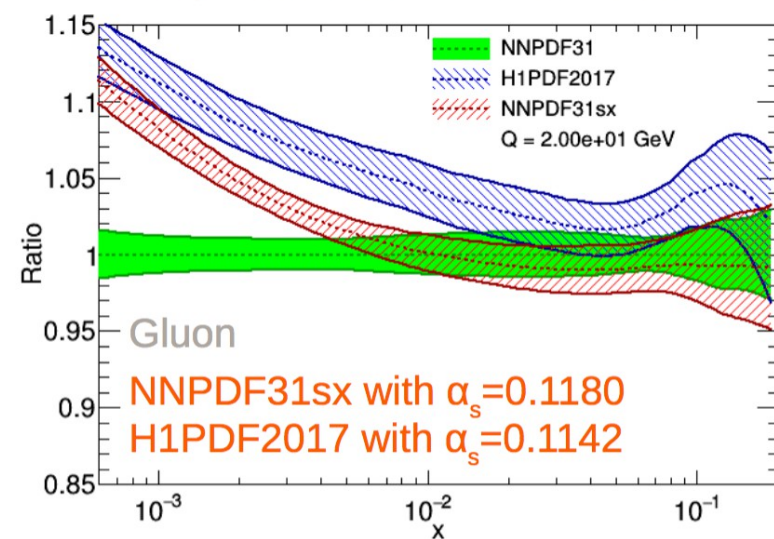
- H1PDF2017
 - High precision, $\chi^2/\text{ndf} \sim 1.01$ (npts=1529)
 - Despite free parameter α_s , precision is competitive with global PDF fit
- Gluon at lower x values tends to be higher (than e.g. NNPDF3.1)
- Gluon very similar to NNPDF3.1sx, which includes low- x resummation

Comparison of H1PDF2017 and NNPDF3.1



Mind: H1PDF2017 includes α_s -uncertainty, whereas NNPDF does not

Comparison with NNPDF3.1sx

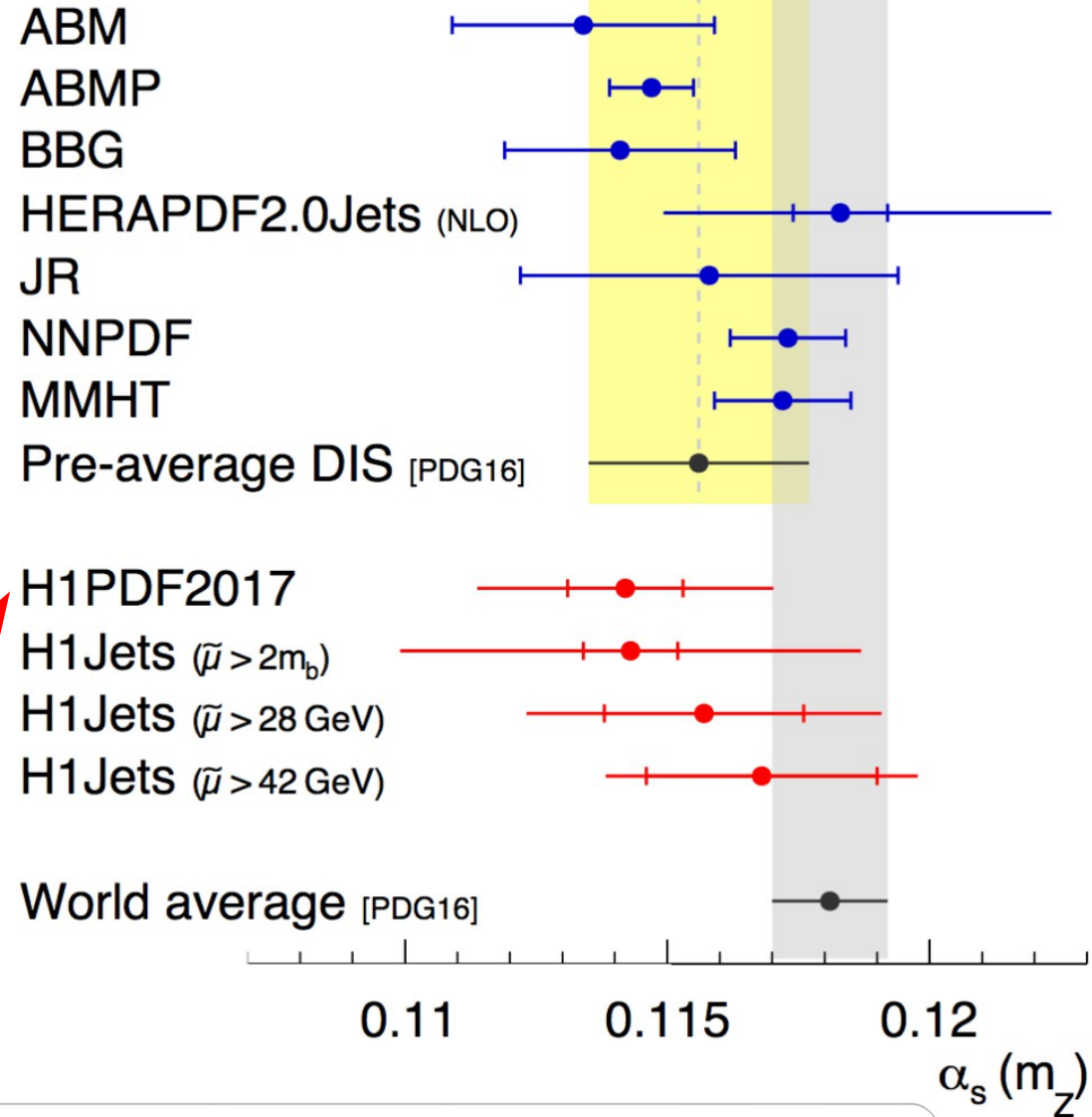


Apfelweb. Thanks to S. Carraza

α_s from simultaneous fit

α_s determinations in NNLO

H1 and NNLOJET

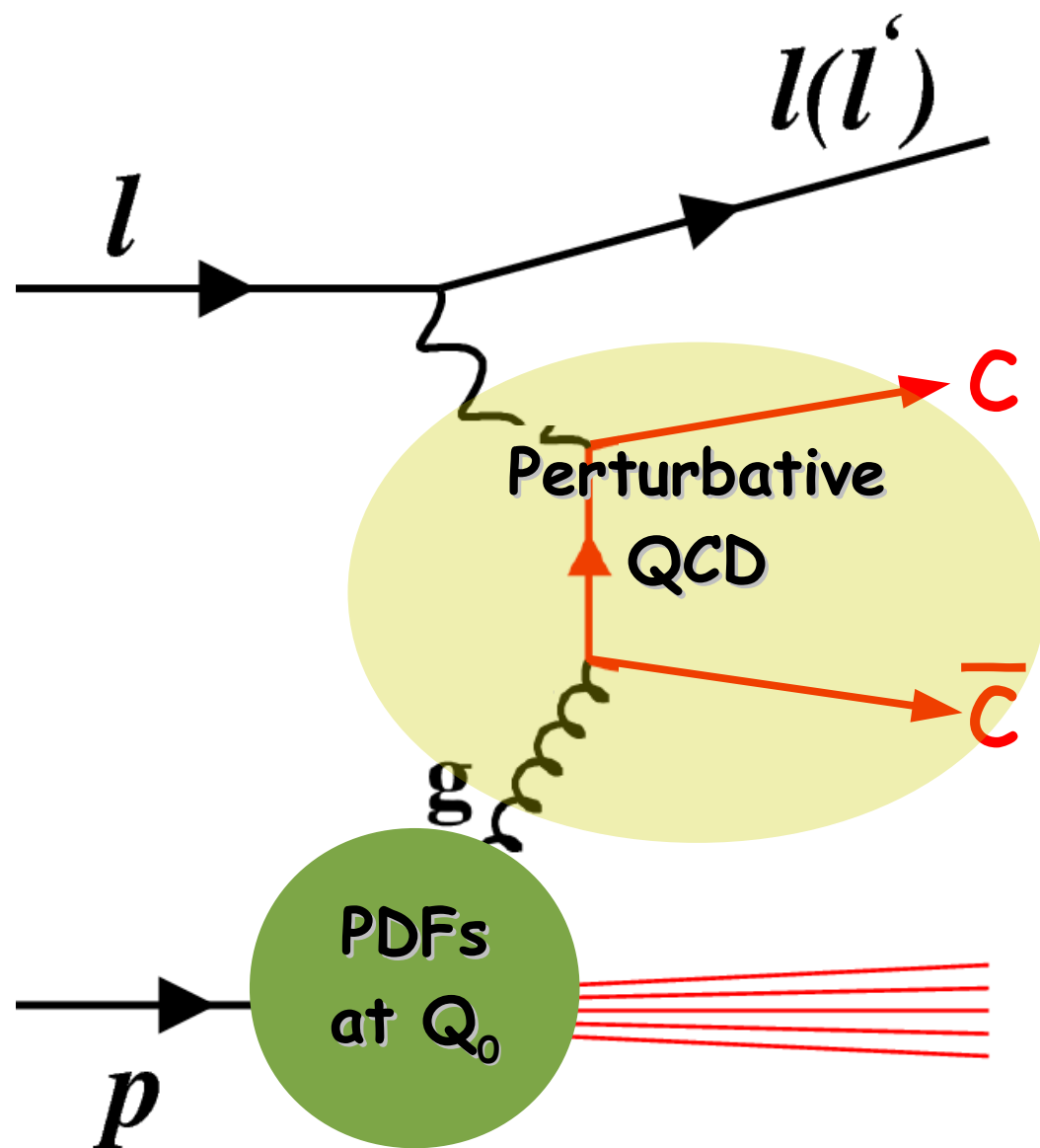


- All results from DIS data tend to be lower than world average value

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



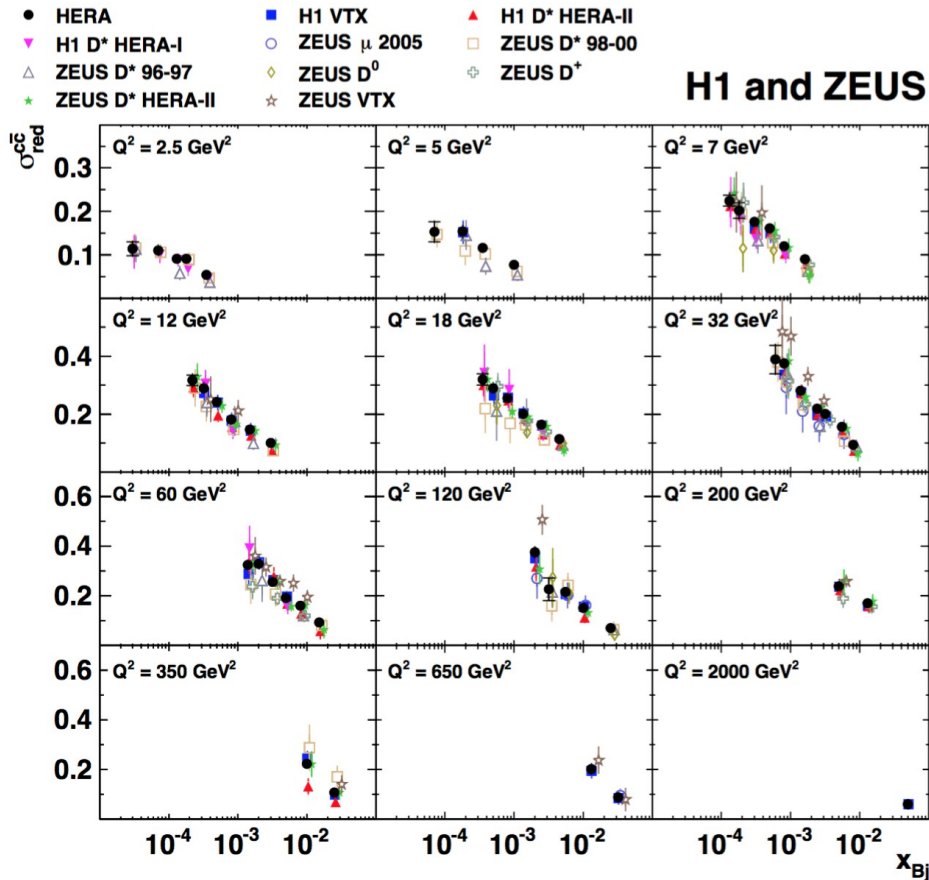
Heavy Quark Production @ HERA



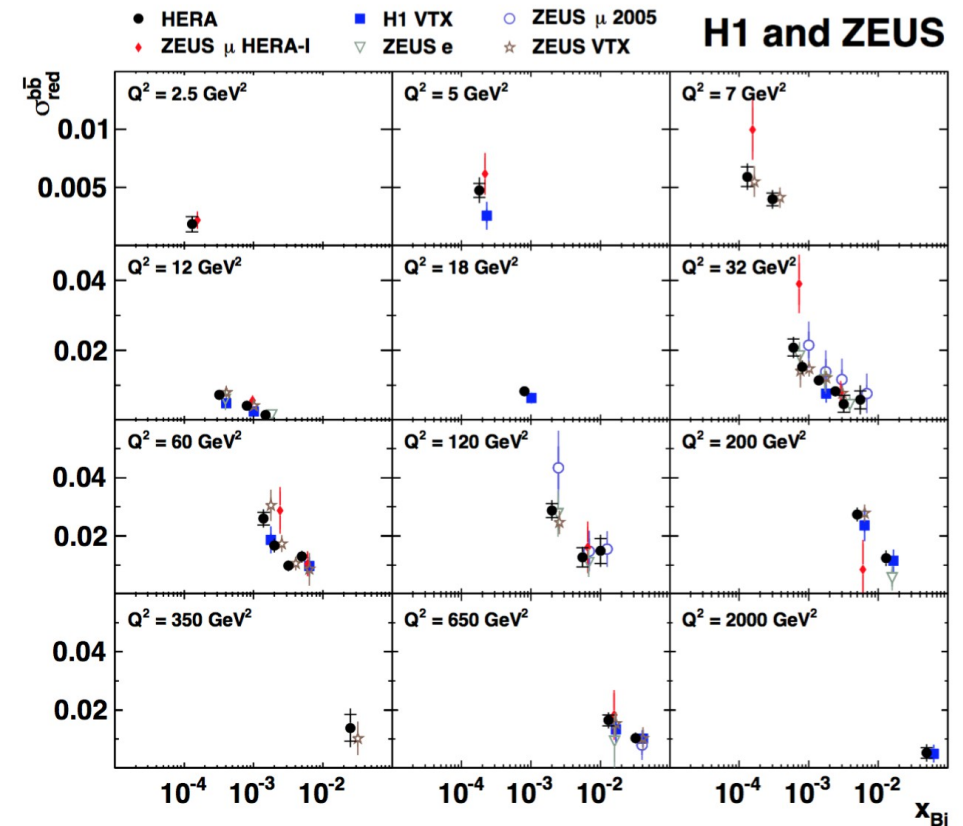
- Final HERA charm and beauty data combined
- QCD global analysis performed
- Simultaneous fit of PDFs and HQ masses



Charm

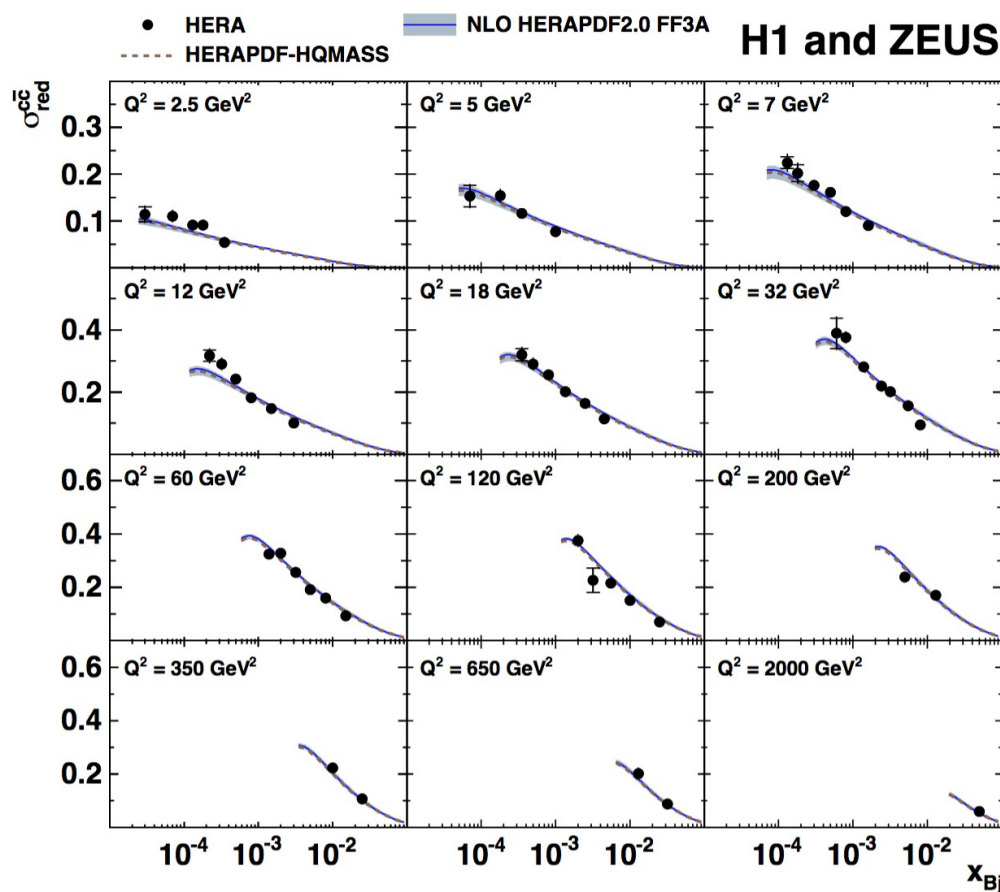
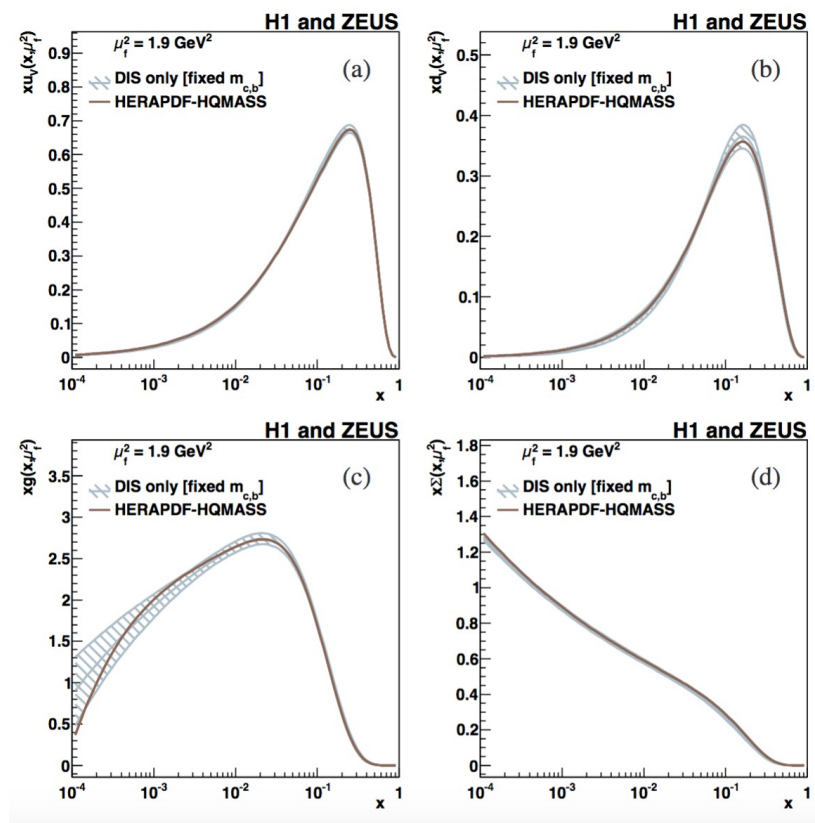


Beauty: first combination



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

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

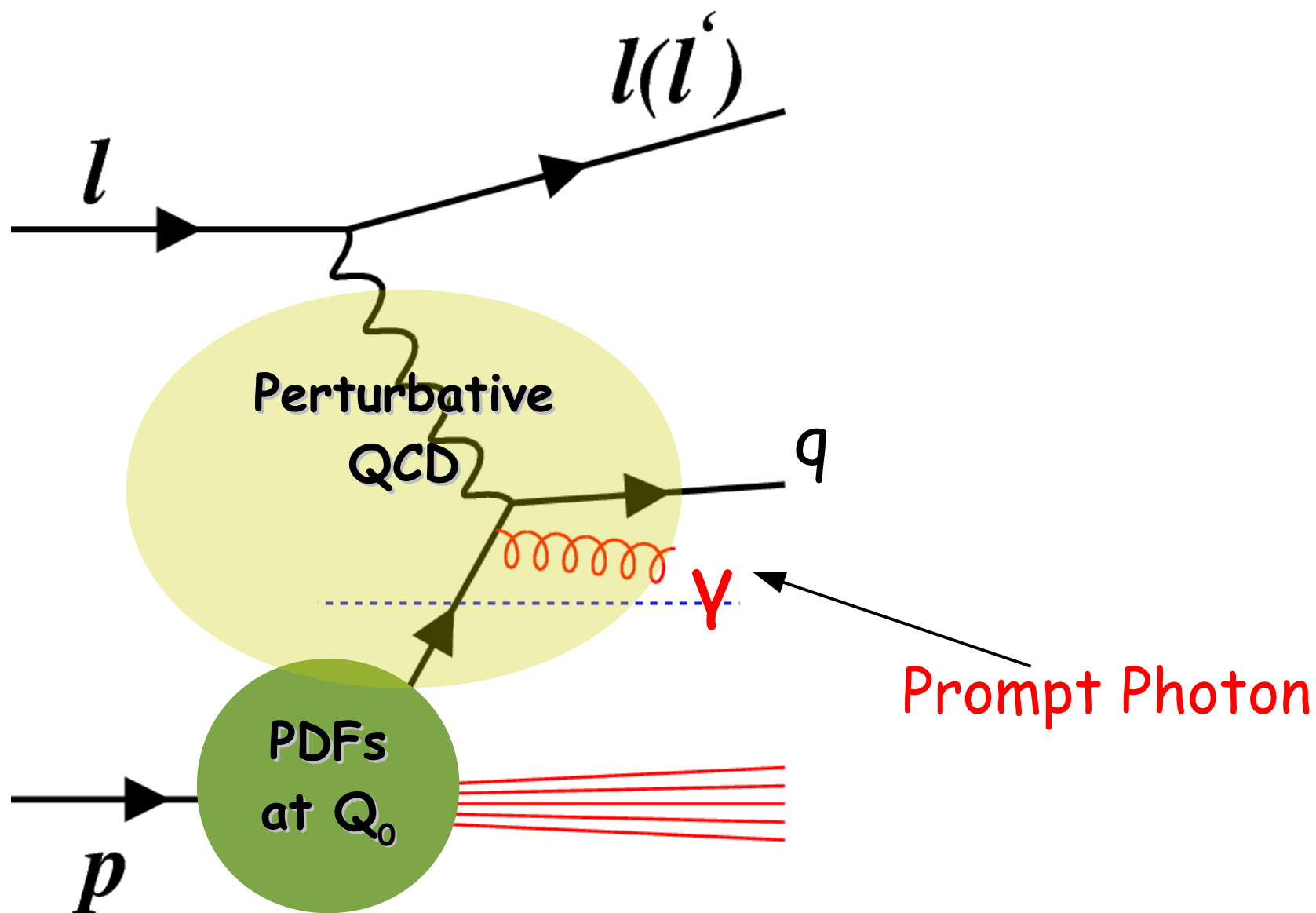


$$m_c(m_c) = 1.290^{+0.046}_{-0.041}(\text{exp/fit})^{+0.062}_{-0.014}(\text{model})^{+0.003}_{-0.031}(\text{parameterisation}) \text{ GeV}$$

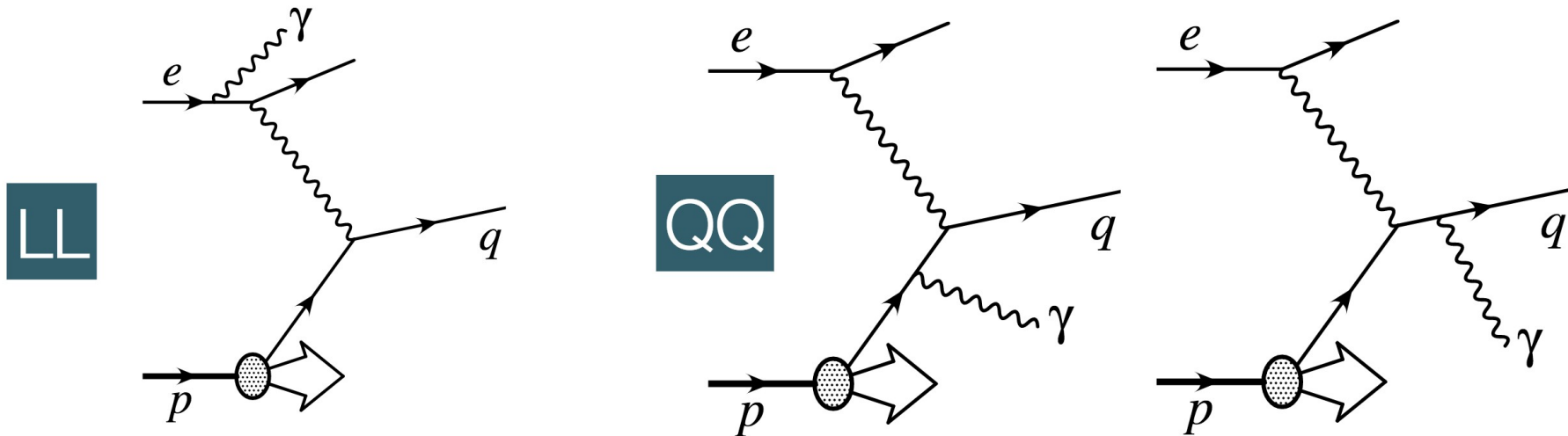
$$m_b(m_b) = 4.049^{+0.104}_{-0.109}(\text{exp/fit})^{+0.090}_{-0.032}(\text{model})^{+0.001}_{-0.031}(\text{parameterisation}) \text{ GeV}$$



Prompt Photons @ HERA



Where do isolated photons come from?



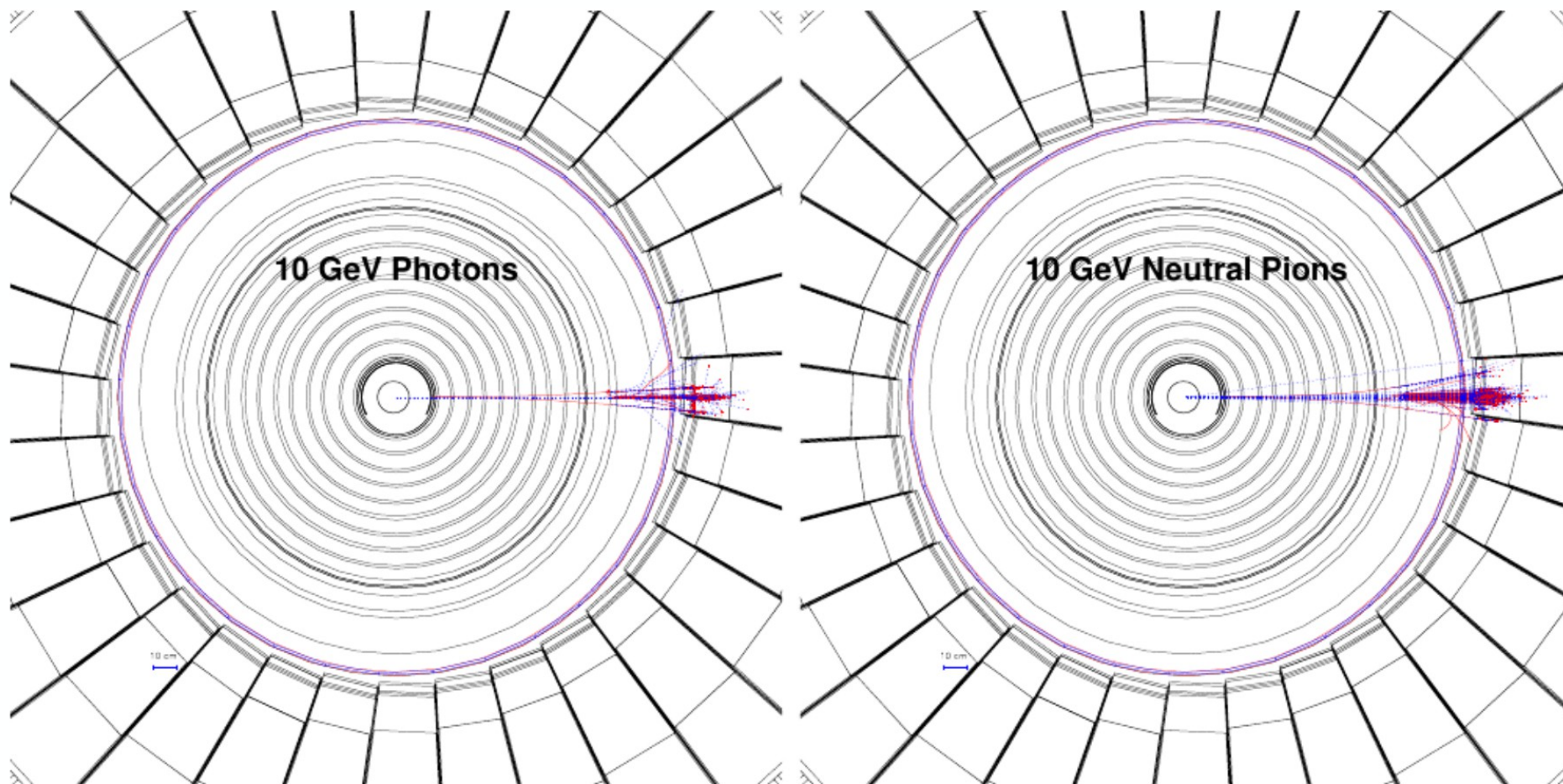
- Can be emitted from lepton (LL) or proton (quark, QQ)
- Emerge directly from hard scattering process
 - Use dynamics to probe modes such as k_+ -factorisation and pQCD approaches
- Assume lepton emission is well known

→ Use photon to probe proton

Trick is to find these photons ...

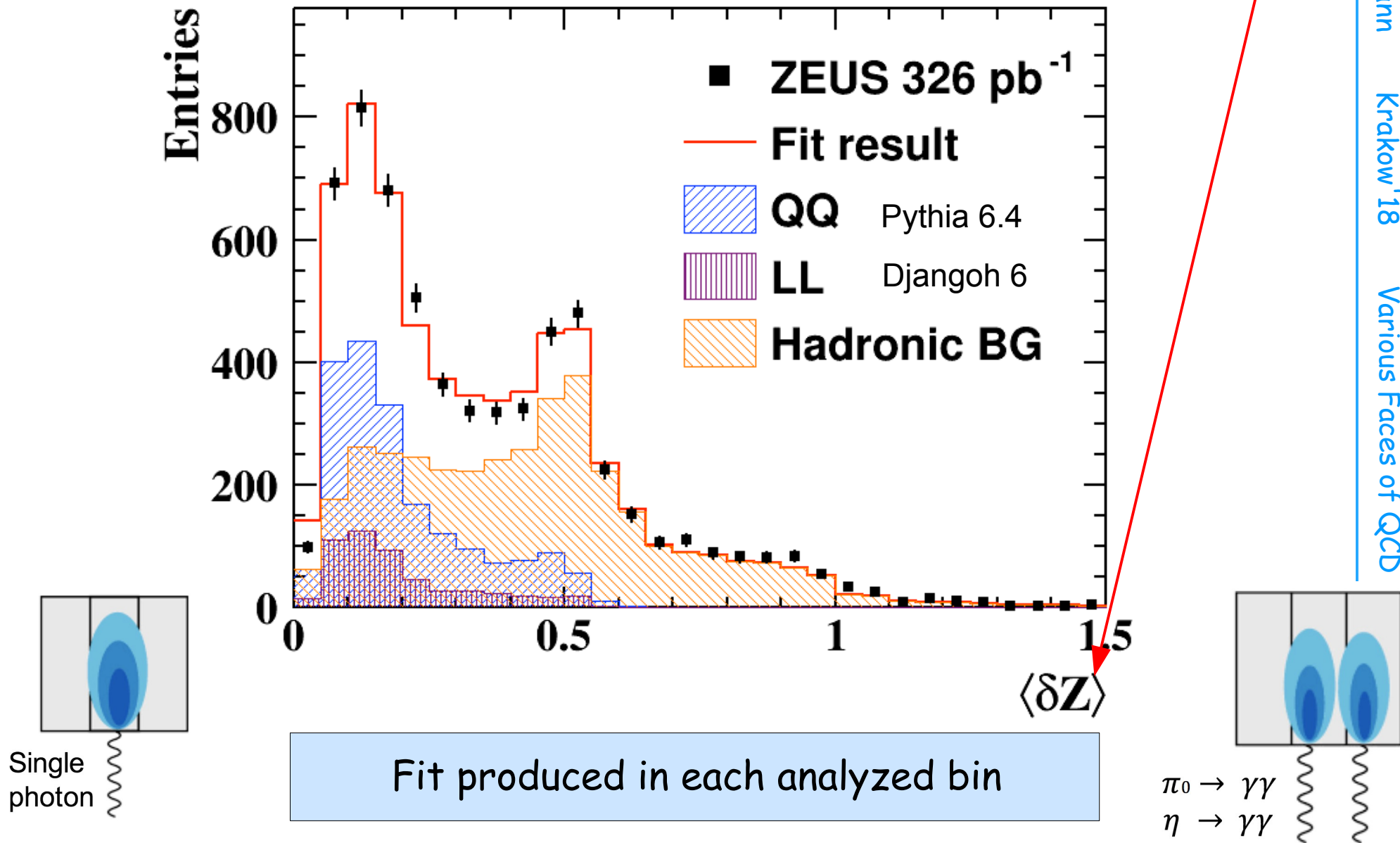
Irreducible background

$$\pi^0 \rightarrow \gamma\gamma \quad \eta \rightarrow \pi^0\pi^0\pi^0(\gamma\gamma)$$



Neutral-meson produce broader energy deposits

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



Comparison with theory



- BLZ

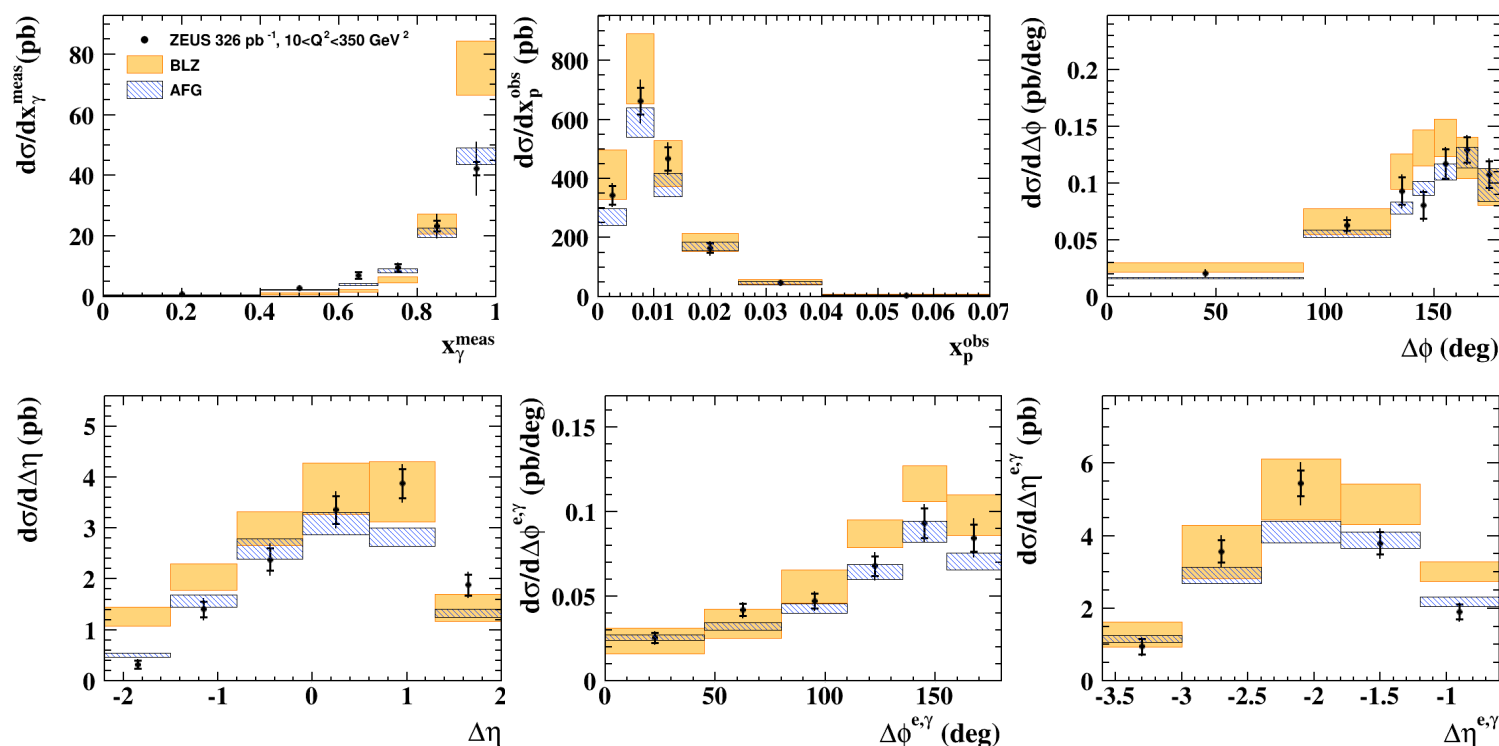
S. Baranov, A. Lipatov and N. Zotov, Phys. Rev. D 81 (2010) 094034.

- $K_{\perp}$ factorisation

- AFG: NLO

P. Aurenche, M. Fontannaz and J.Ph. Guillet, Eur. Phys. J. C 44 (2005) 395.

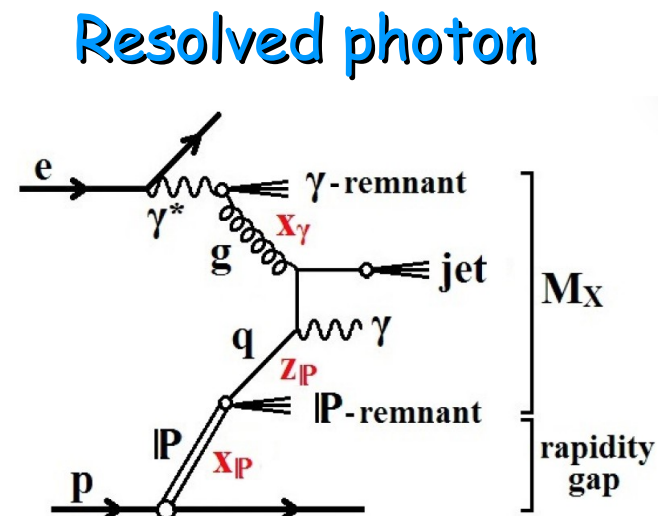
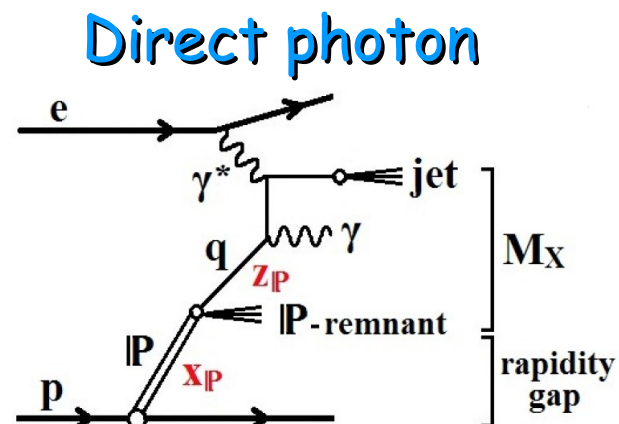
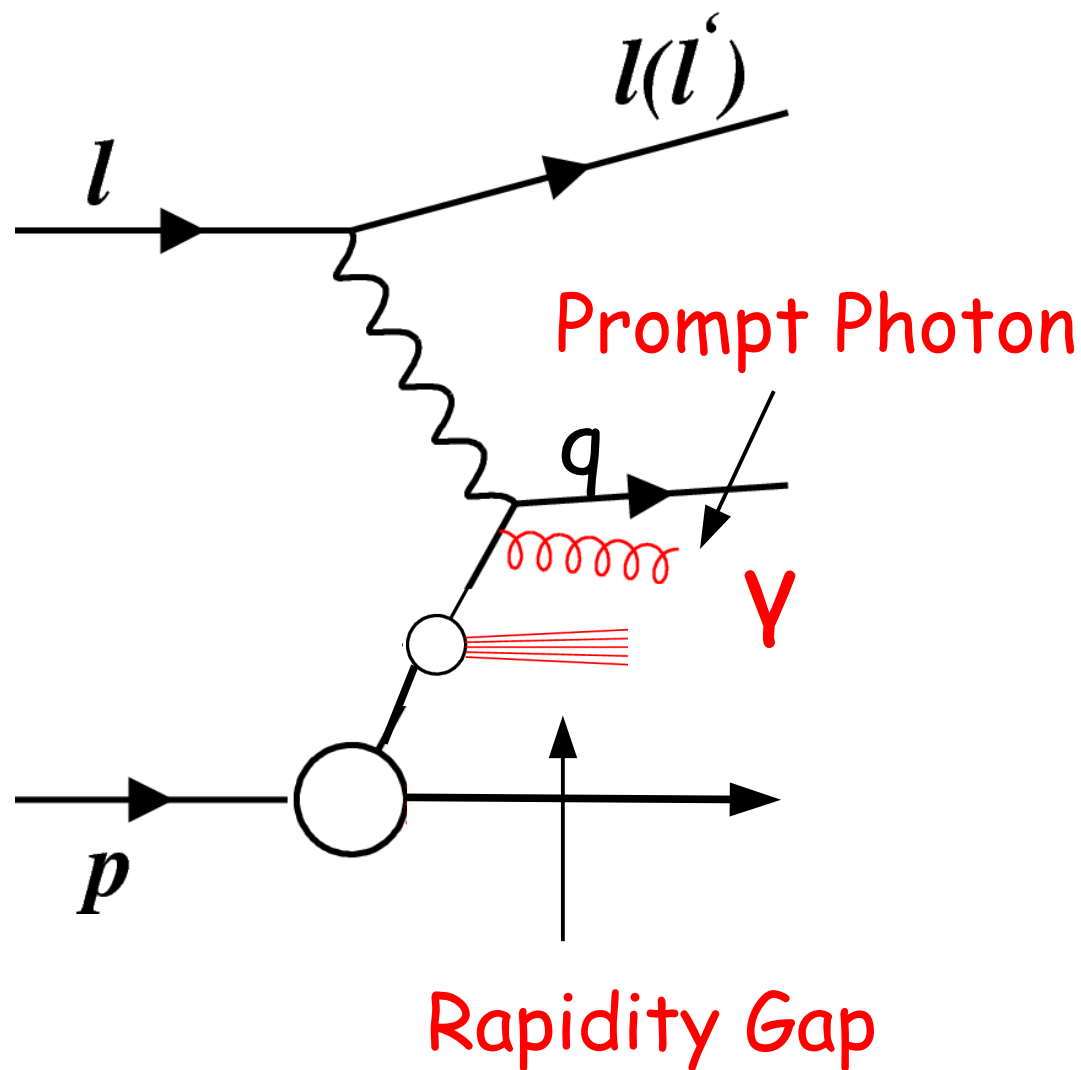
P. Aurenche and M. Fontannaz, Eur. Phys. J. C 77 (2017) 324.



- 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



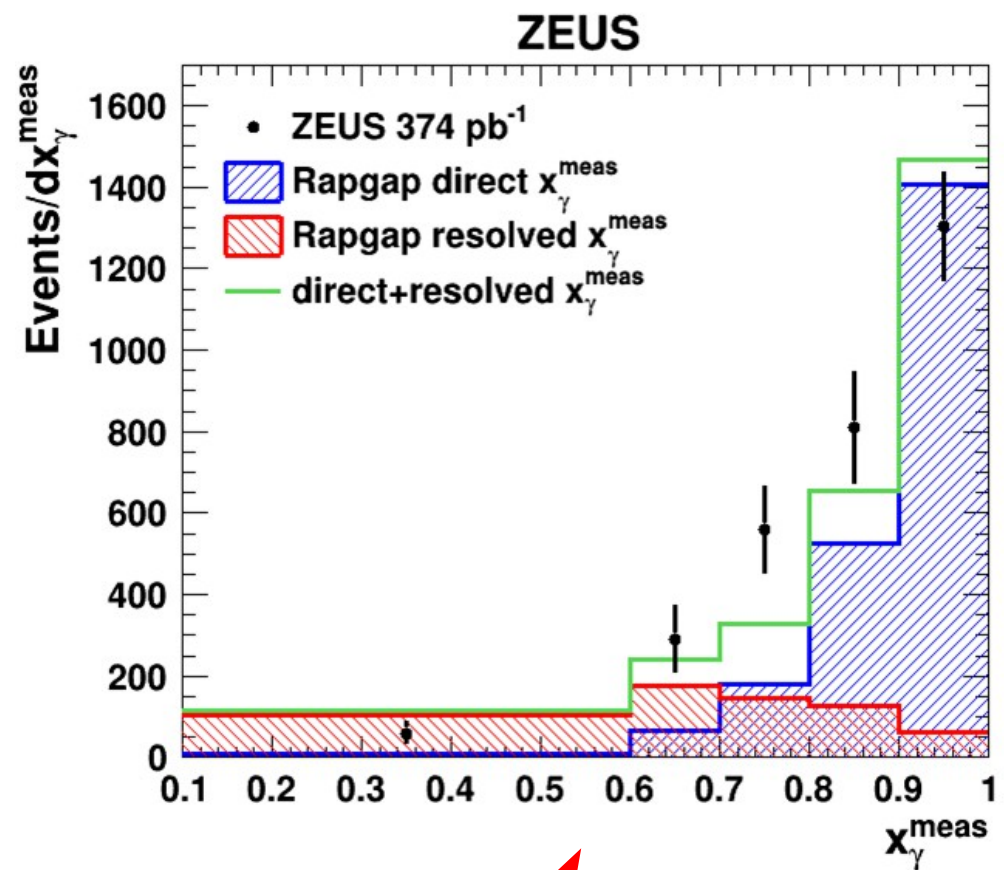
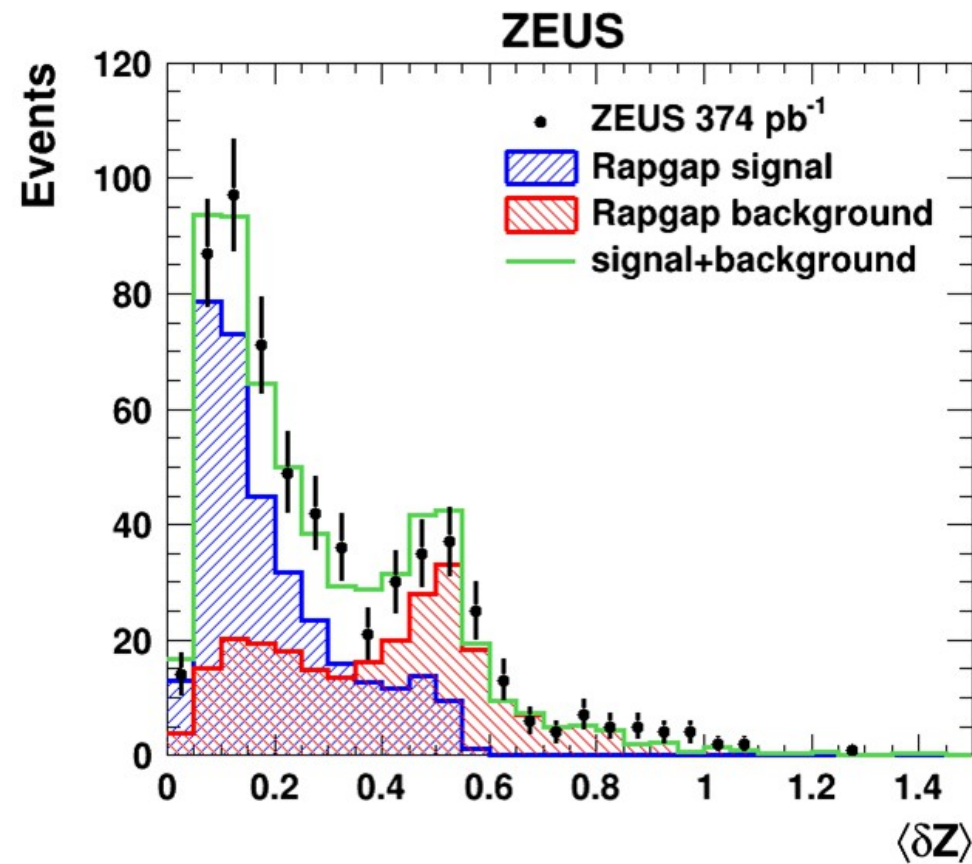
Prompt photons & rapidity GAP



K. Wichmann

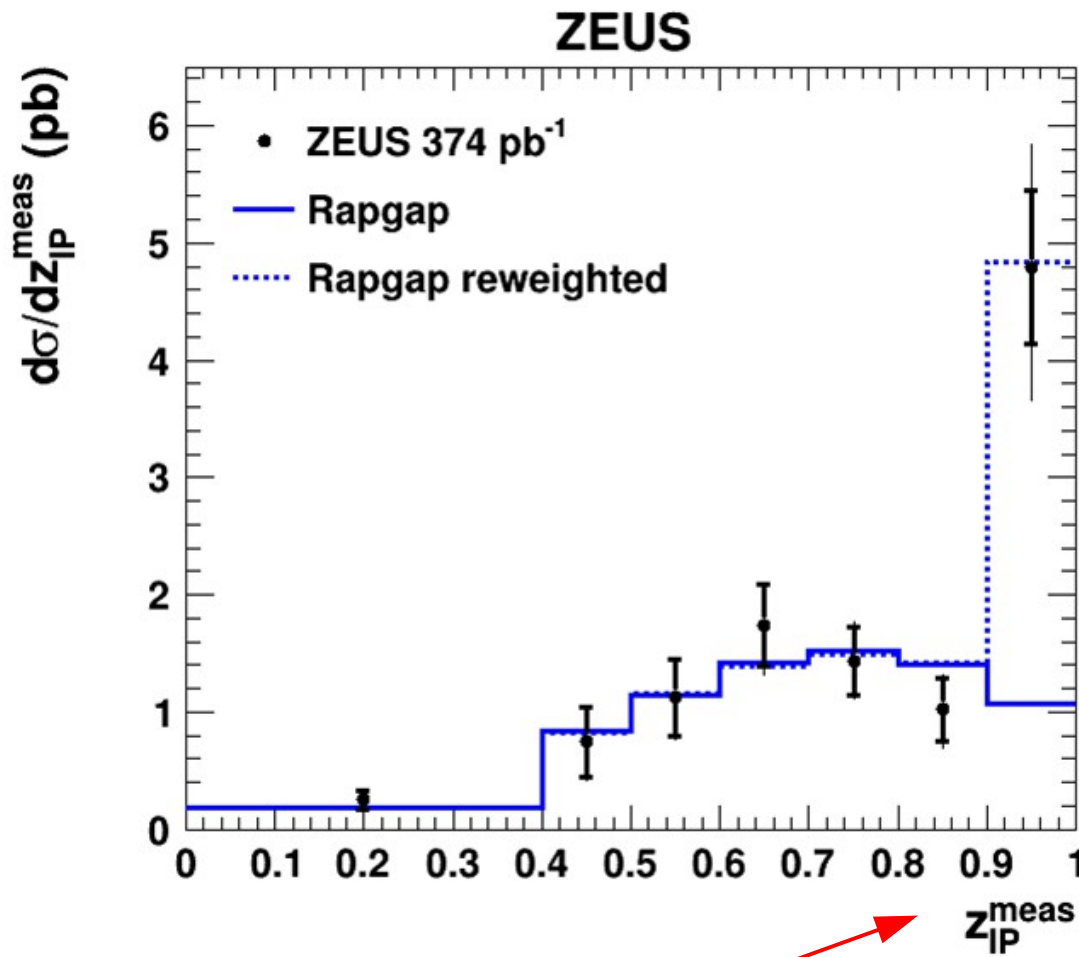
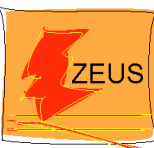
Krakow'18

Various Faces of QCD @ HERA



70:30 mixture of direct:resolved

Diffraction prompt photon + jet

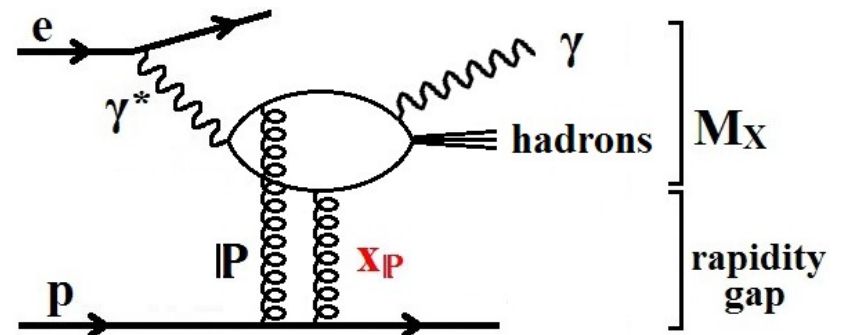


Fraction of Pomeron energy given to prompt photon and jet

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

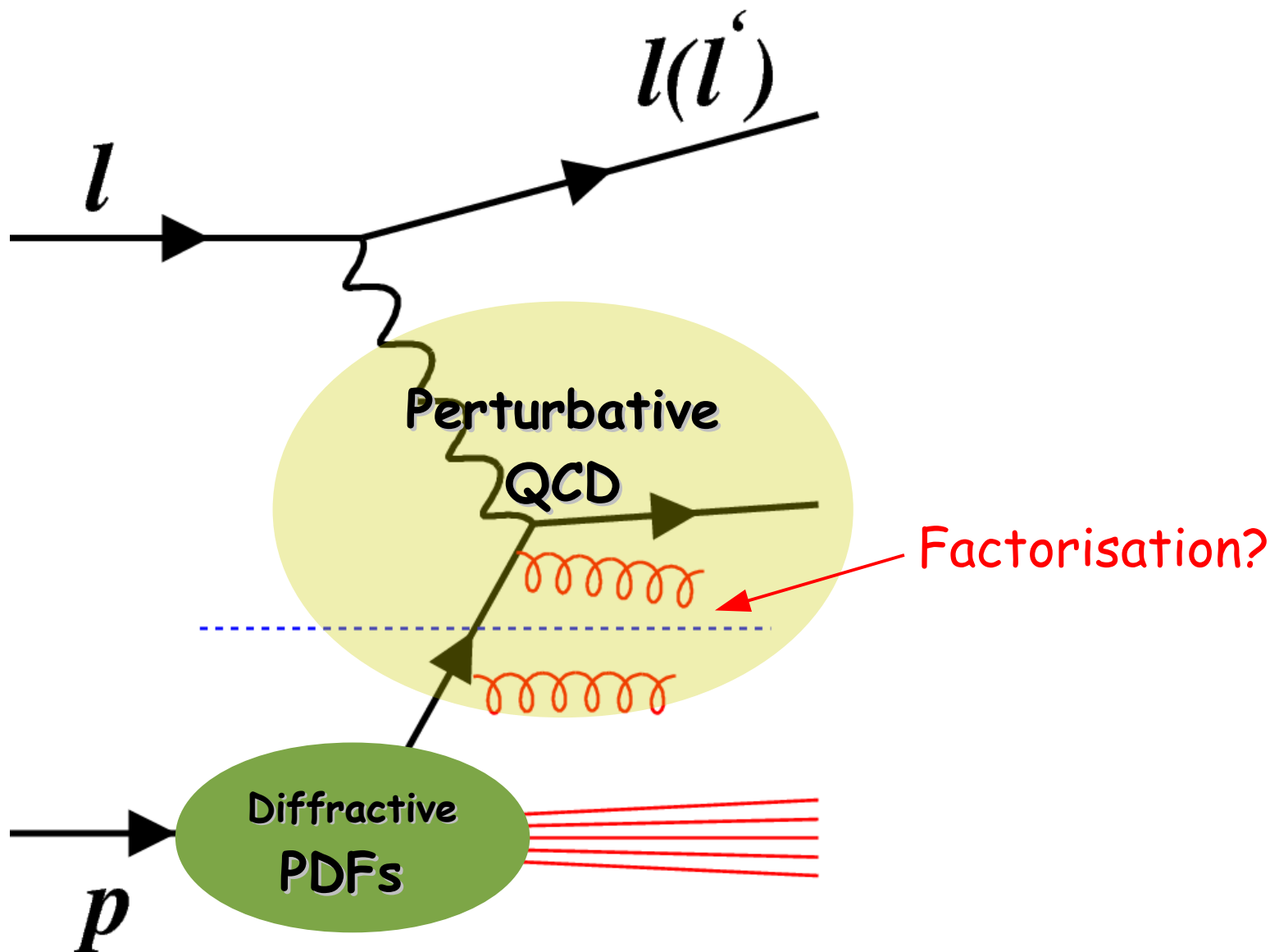
→ indicates presence of direct Pomeron interaction (not present in RAPGAP)

For example





Does factorisation hold in diffractive DIS?

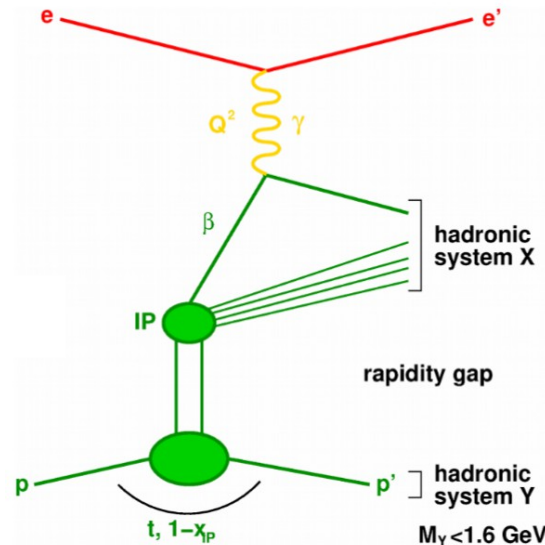


Charm production in diffractive DIS

- ~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

Theory (Collins):

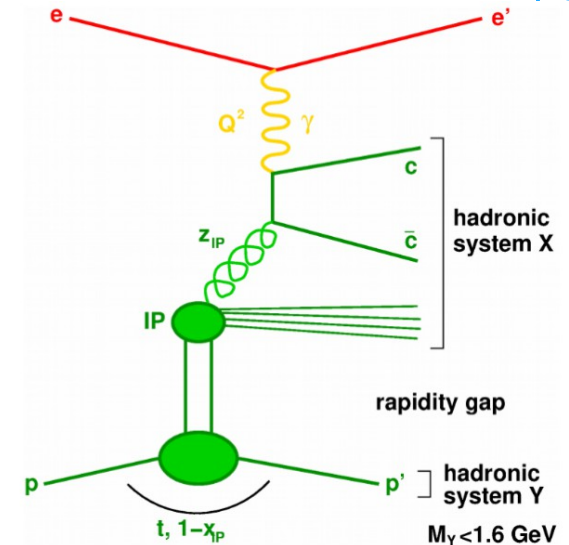
- QCD factorisation holds in diffractive DIS
→ diffractive PDFs (DPDFs)



Inclusive diffraction:
extract DPDFs

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

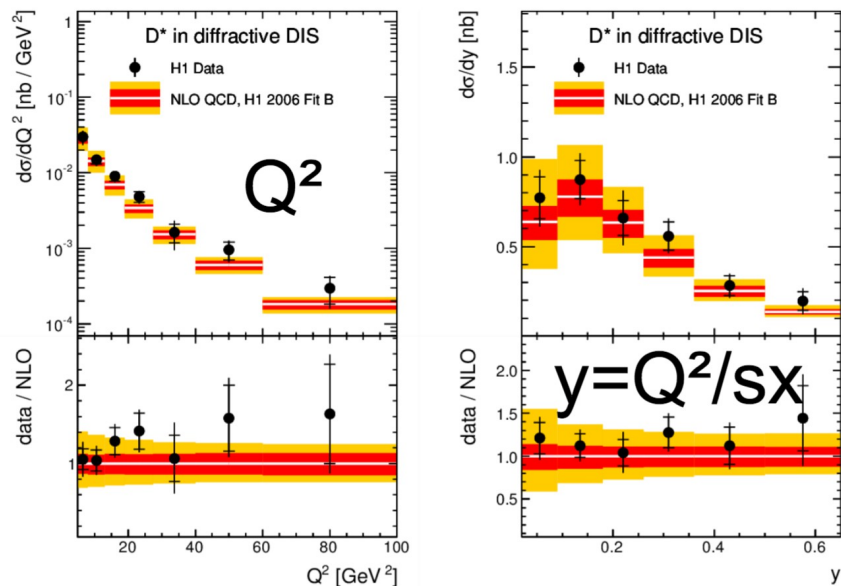
predict



Diffractive charm
production: test
factorisation theorem in
diffraction



Diffractive D^* cross sections



Electron variables

EPJ C77 (2017) 340

[arXiv:1703.09476]

DIS phase space

$$5 < Q^2 < 100 \text{ GeV}^2$$

$$0.02 < y < 0.65$$

D^* kinematics

$$p_{t,D^*} > 1.5 \text{ GeV}$$

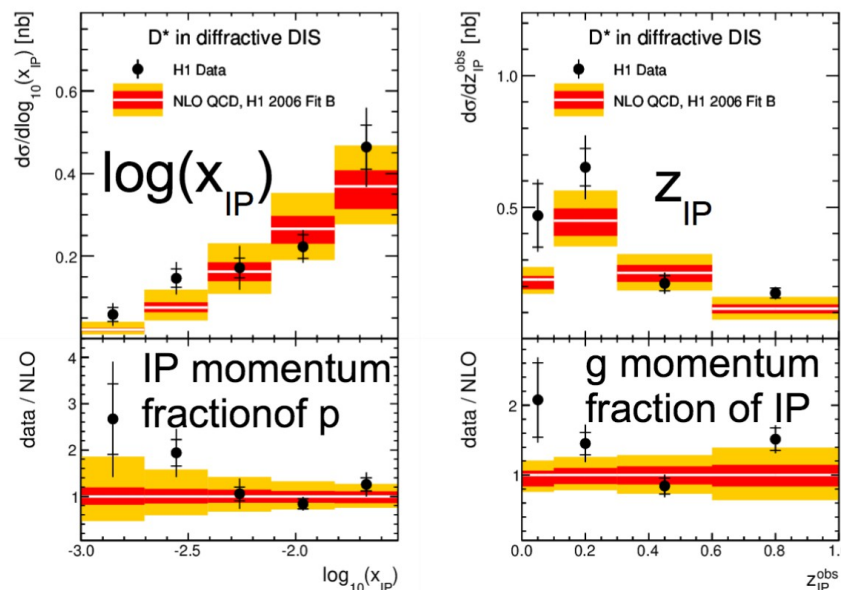
$$-1.5 < \eta_{D^*} < 1.5$$

Diffractive phase space

$$x_{\mathbb{P}} < 0.03$$

$$M_Y < 1.6 \text{ GeV}$$

$$|t| < 1 \text{ GeV}^2$$



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

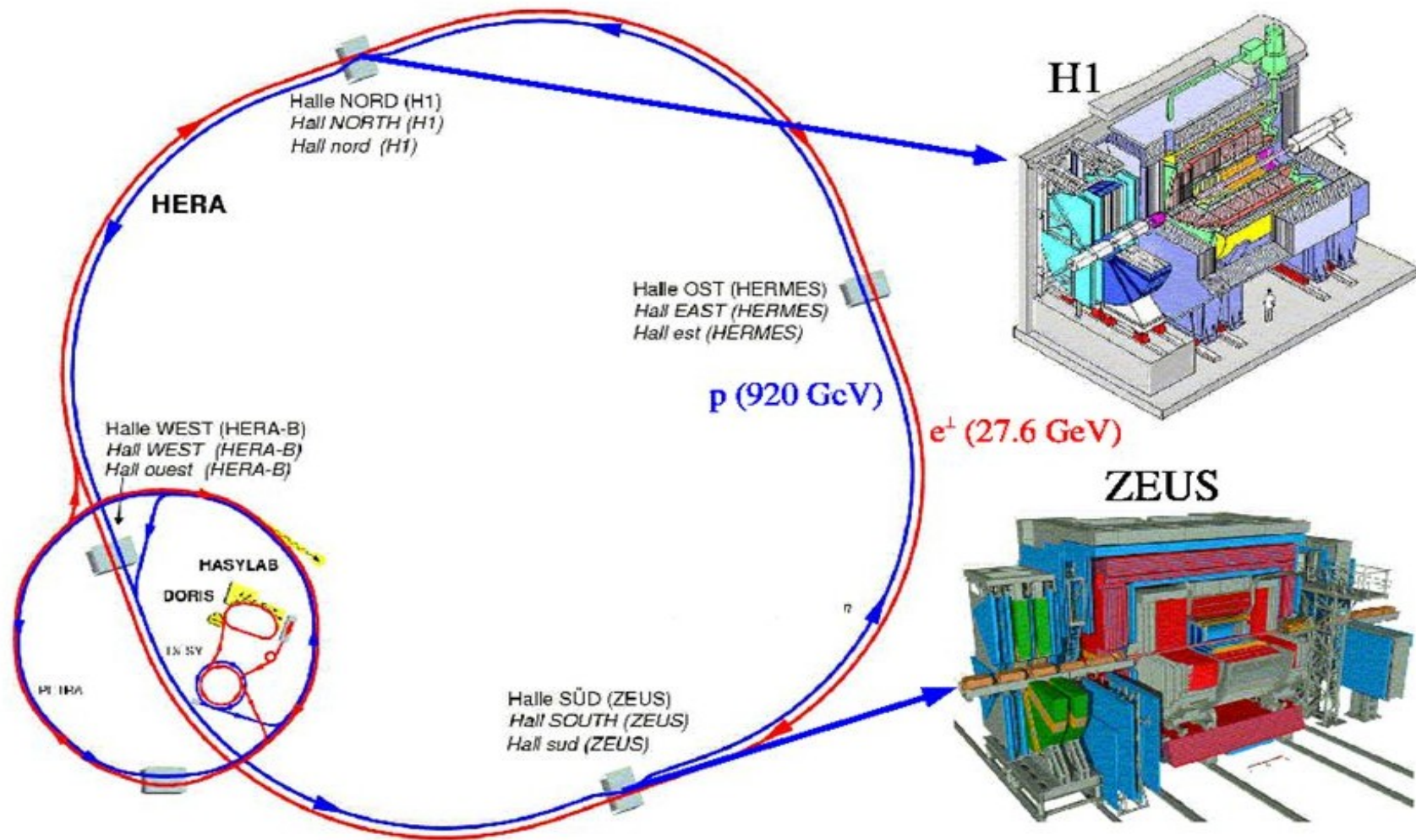
- Good description by NLO QCD
 - large theory scale uncertainties
- DPDF uncertainties similar to data precision
- D^* kinematic distributions also described

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

Instead of summary:
thank you for your patience :)

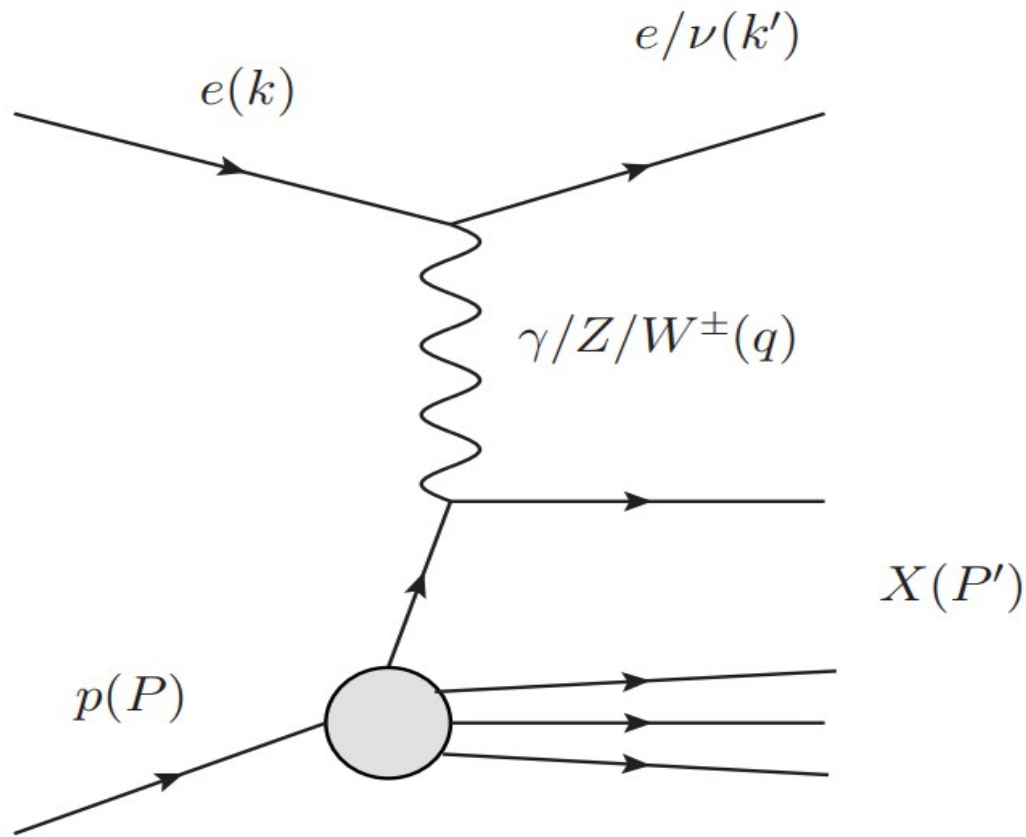


Extra slides



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

ep Scattering at HERA



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

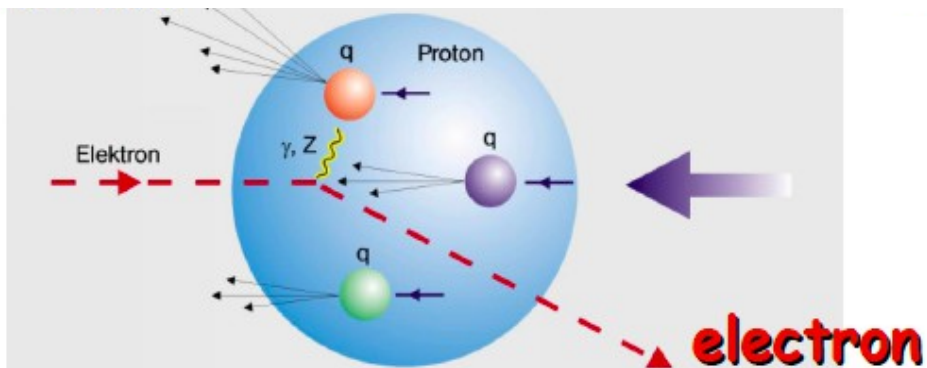
$$x_{Bj} = \frac{Q^2}{2pq} \quad y = \frac{pq}{pk}$$

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

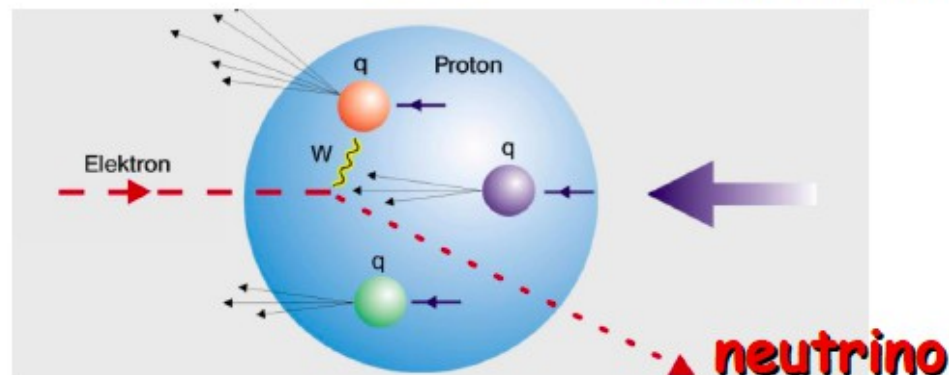
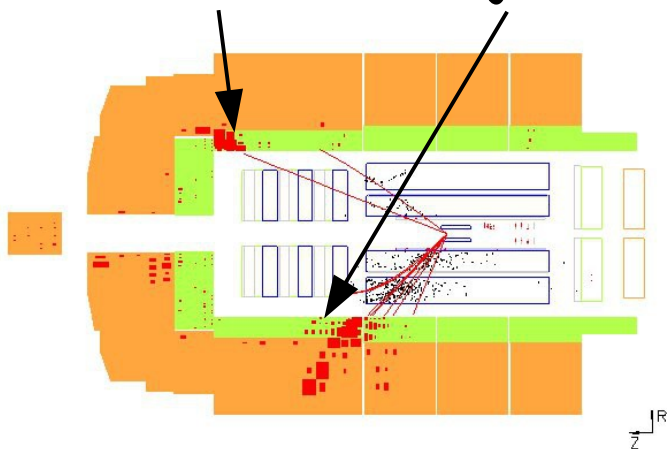
$$W^2 = Q^2(1/x_{Bj} - 1) + m_p^2$$

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

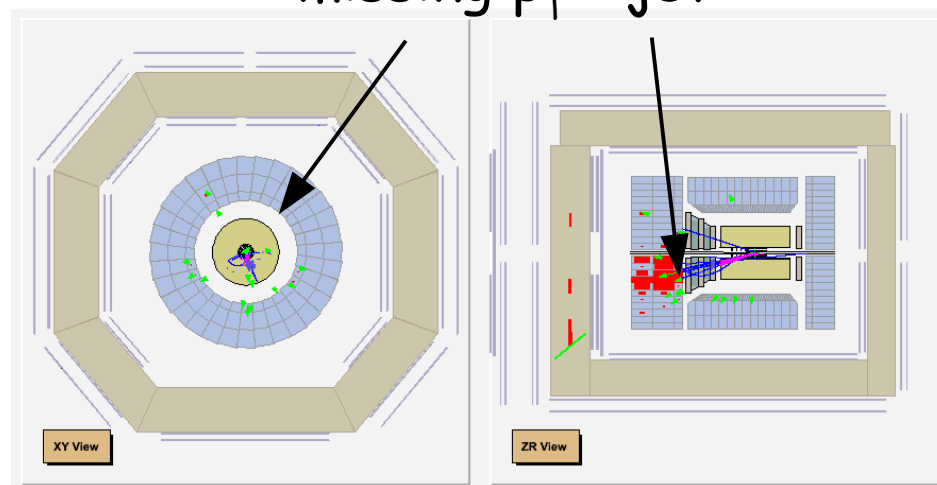
Deep Inelastic Scattering @ HERA



Neutral Current (NC): γ , Z exchange
electron + jet



Charge Current (CC): W exchange
missing p_T + jet



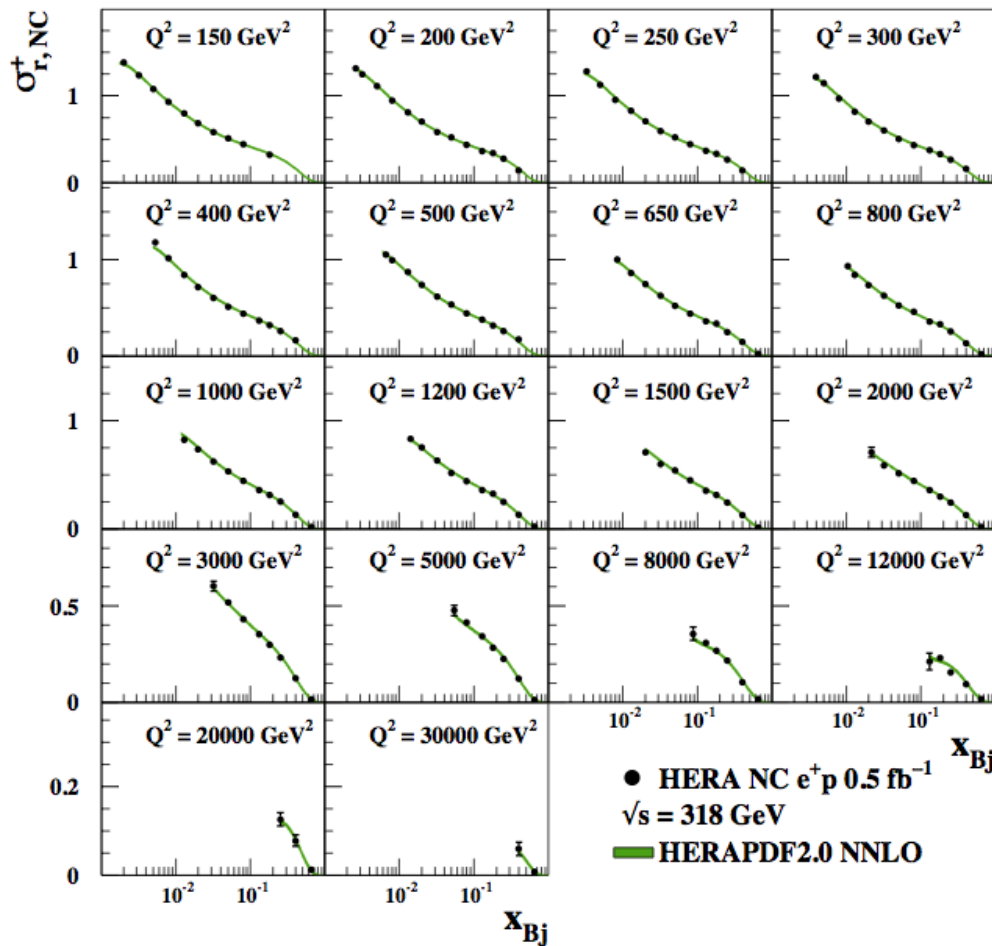
- NC/CC cross section expresses in terms of **structure functions**

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

Neutral Current

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

H1 and ZEUS



Proton structure functions

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

- Sensitive to quarks

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

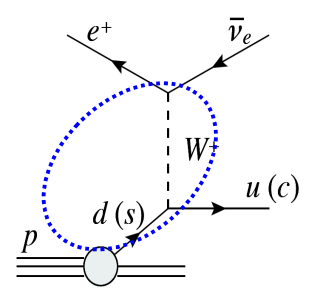
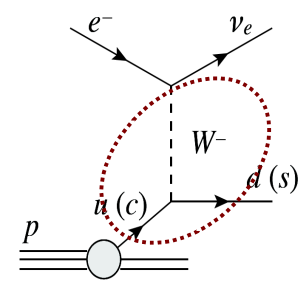
- Sensitive to valence distributions

$$F_L \sim \alpha_s x g$$

- Sensitive to gluon

- Gluon also from scaling violation and charm+jet data

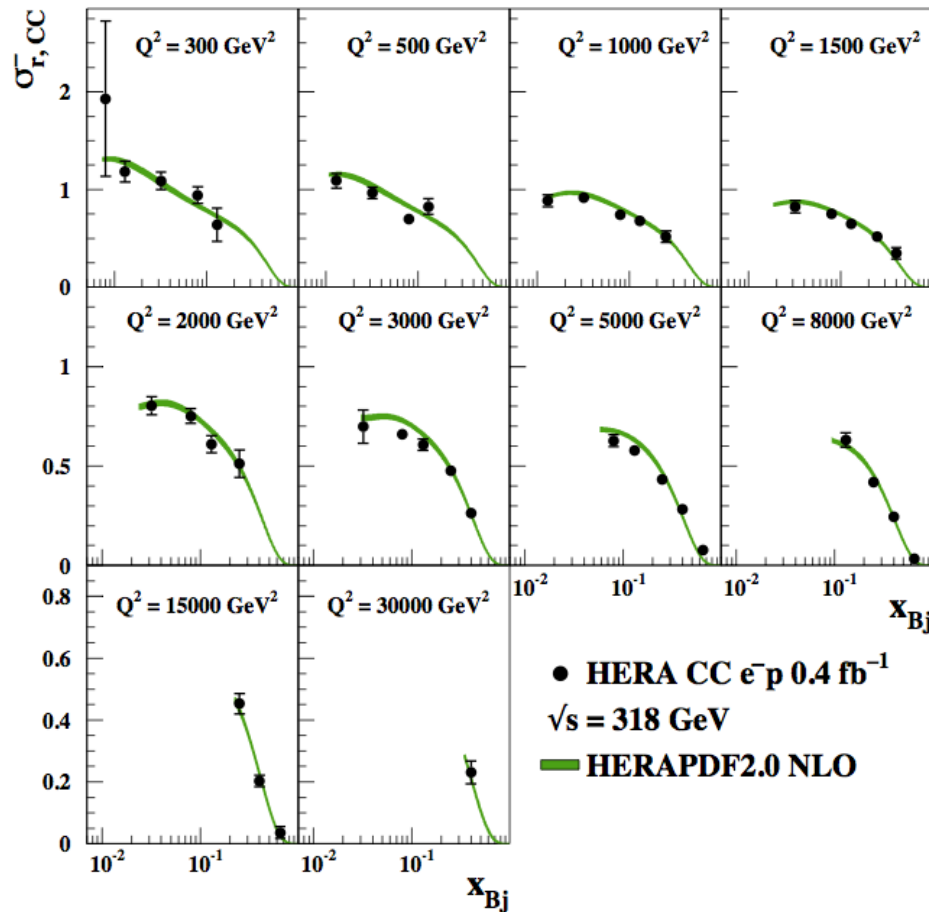
Charge Current: flavor decomposition



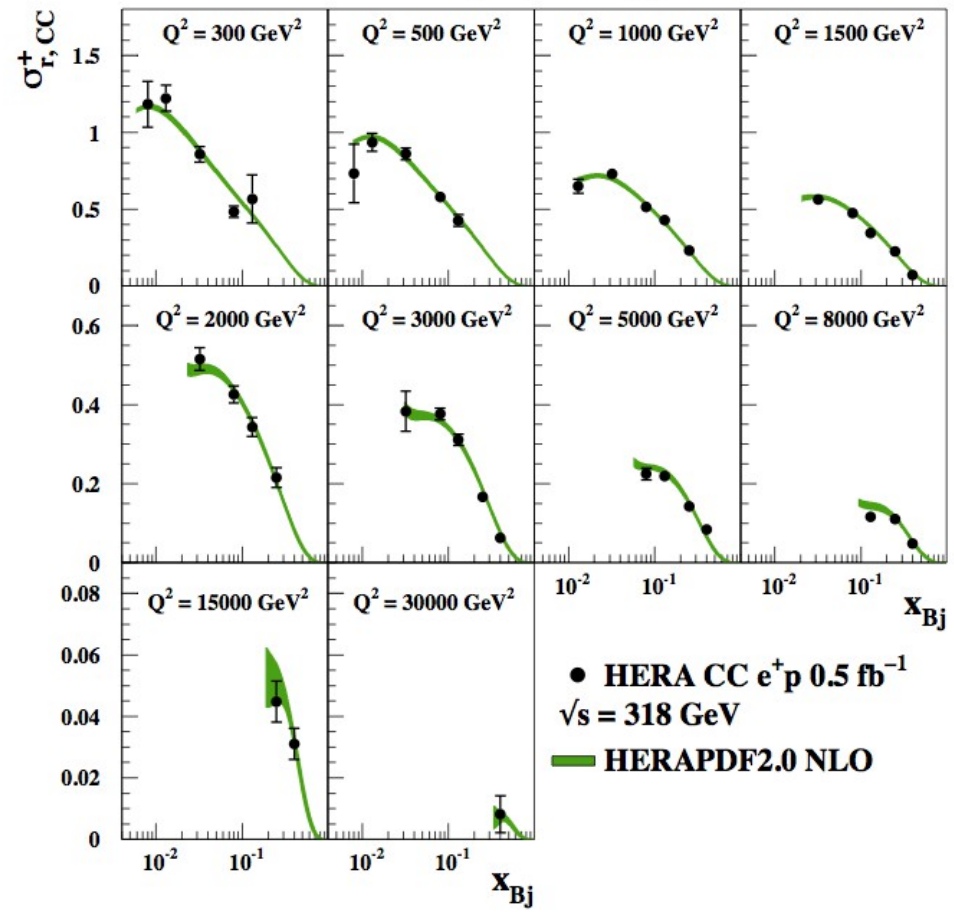
$$\sigma_{CC}^- \sim x[u + c] + x(1 - y)^2[\bar{d} + \bar{s}]$$

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

H1 and ZEUS

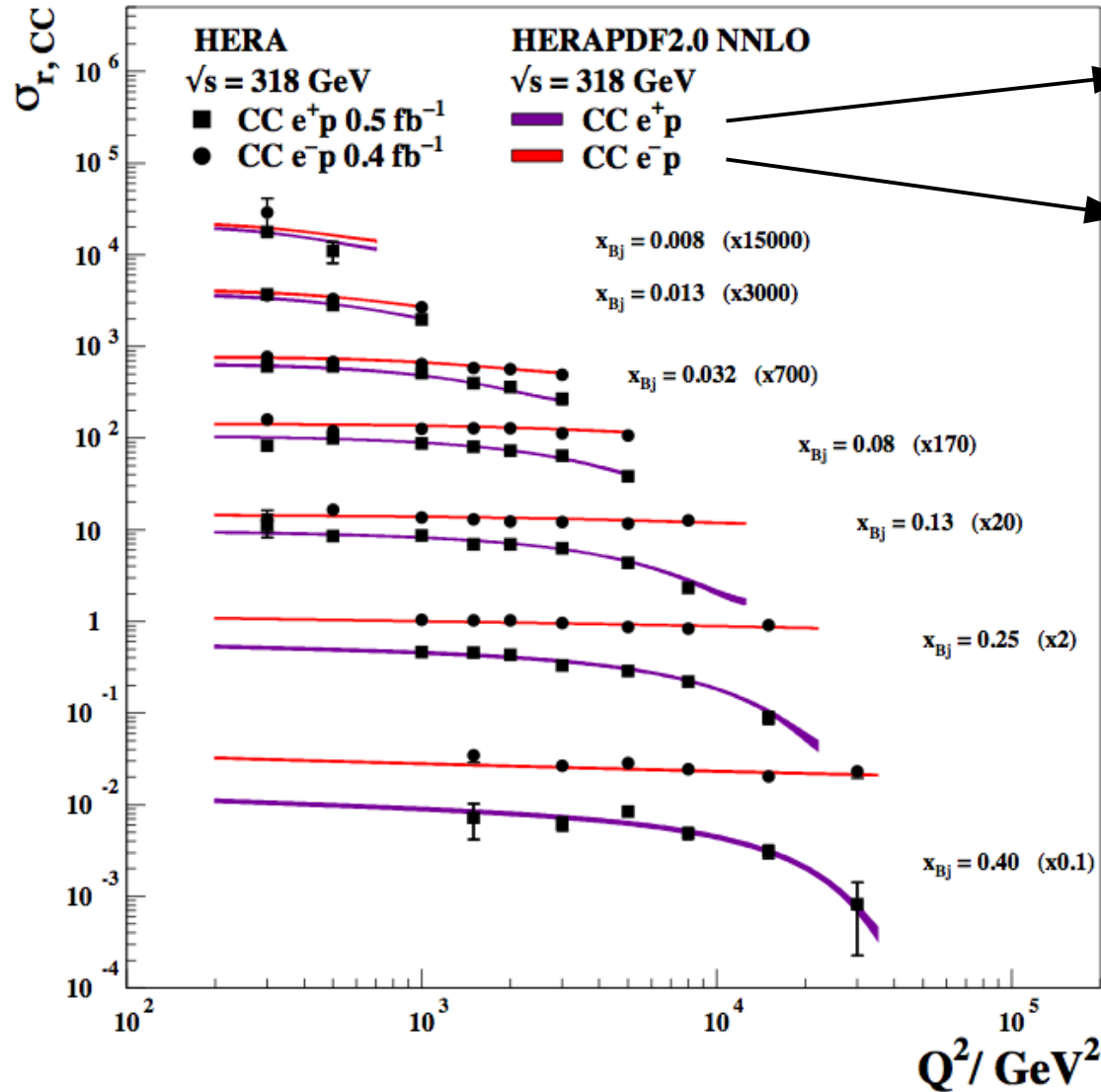


H1 and ZEUS



CC: helicity effects

H1 and ZEUS

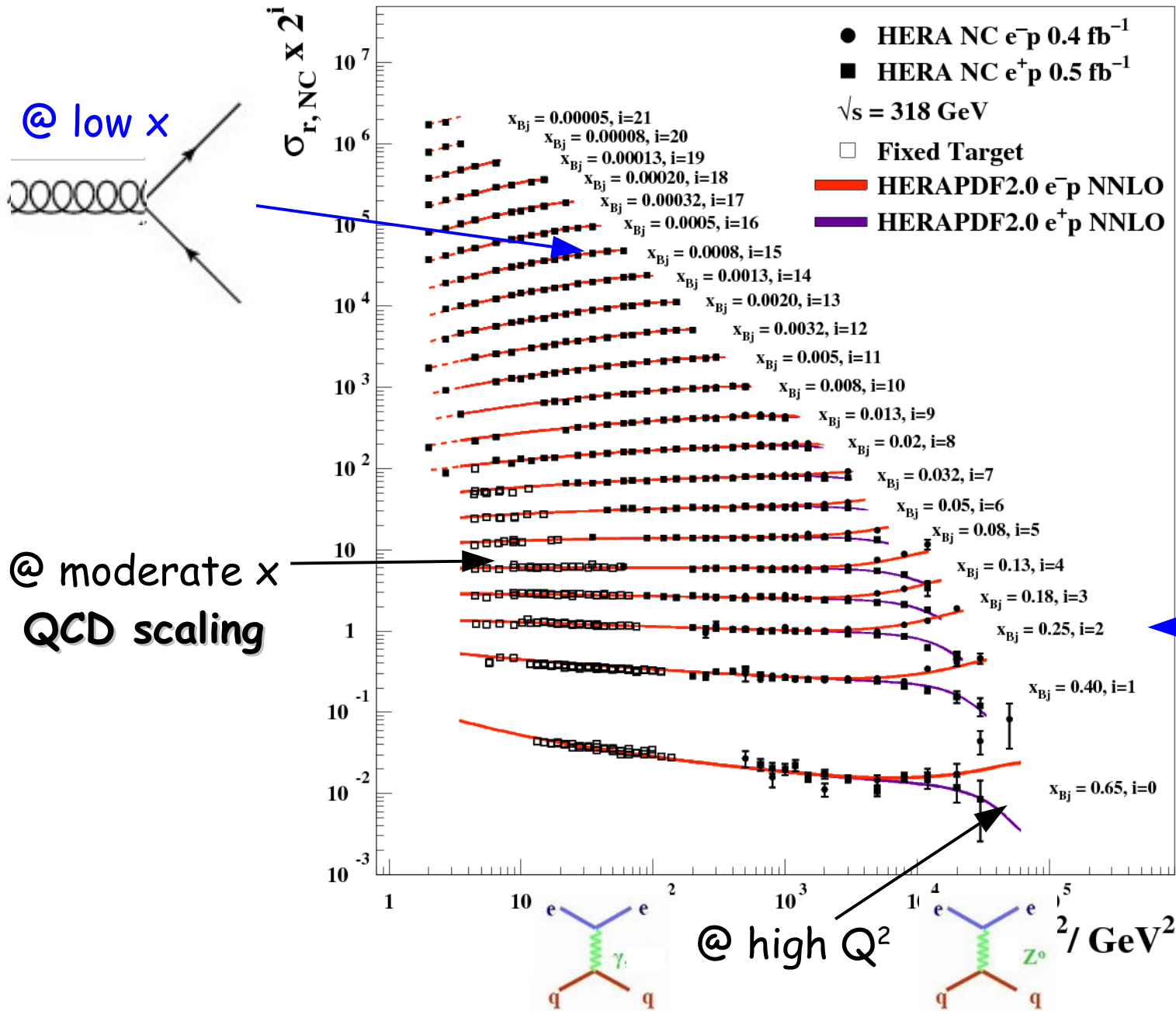


$$\sigma_{CC}^+ \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d + s]$$

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

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

H1 and ZEUS



electron-proton
positron-proton

Text book plots of fundamental properties of particle interactions



Polarised DIS

- Generalised structure functions depend on e-beam polarisation

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

$$\begin{aligned}\tilde{F}_2^\pm &= F_2^\gamma - (v_e \pm P_e a_e) \chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e) \chi_Z^2 F_2^Z, \\ x\tilde{F}_3^\pm &= -(a_e \pm P_e v_e) \chi_Z x F_3^{\gamma Z} + (2v_e a_e \pm P_e (v_e^2 + a_e^2)) \chi_Z^2 x F_3^Z\end{aligned}$$

- Structure functions in QP model

NC

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

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

CC

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

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

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

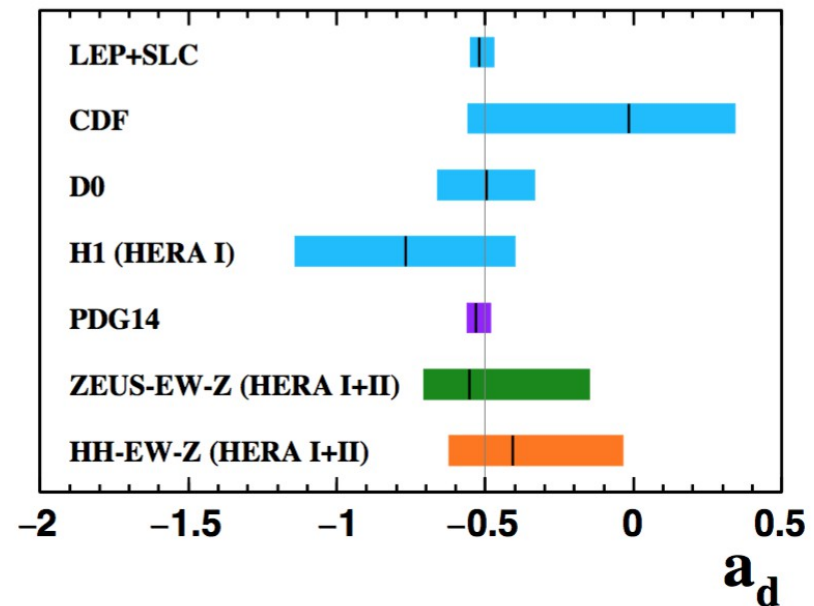
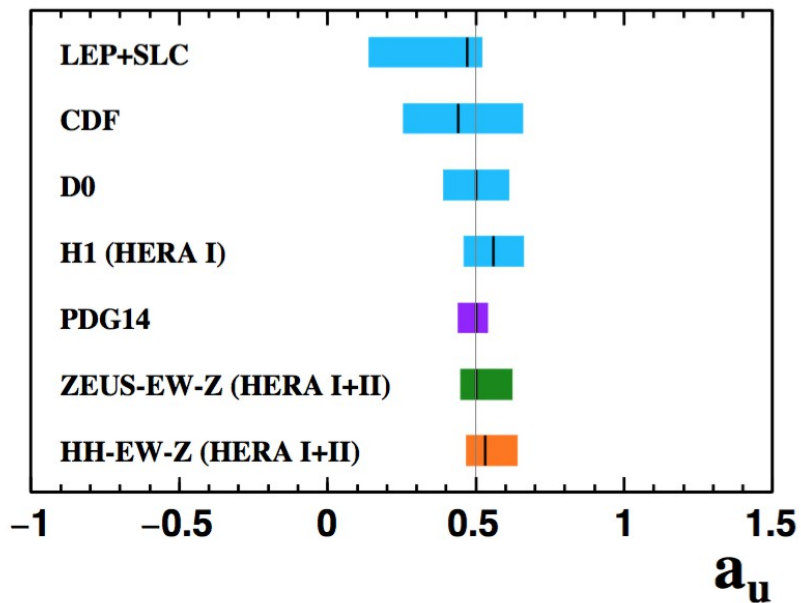
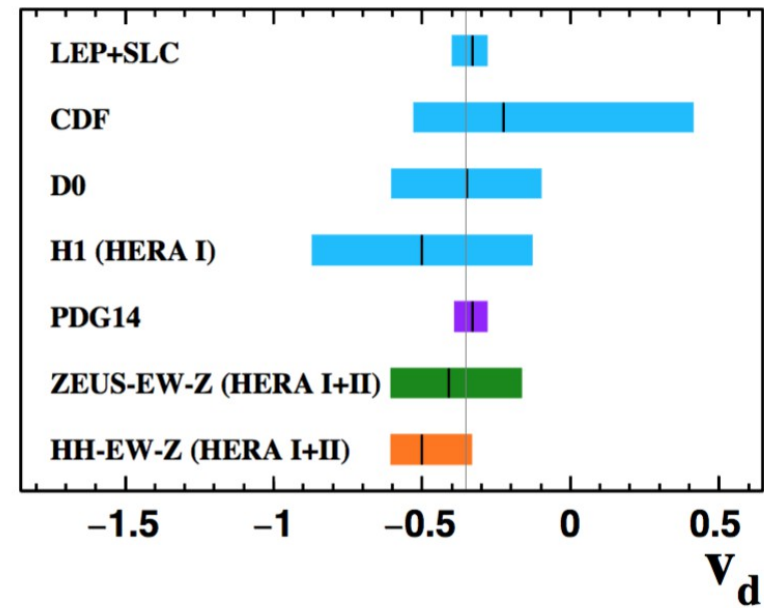
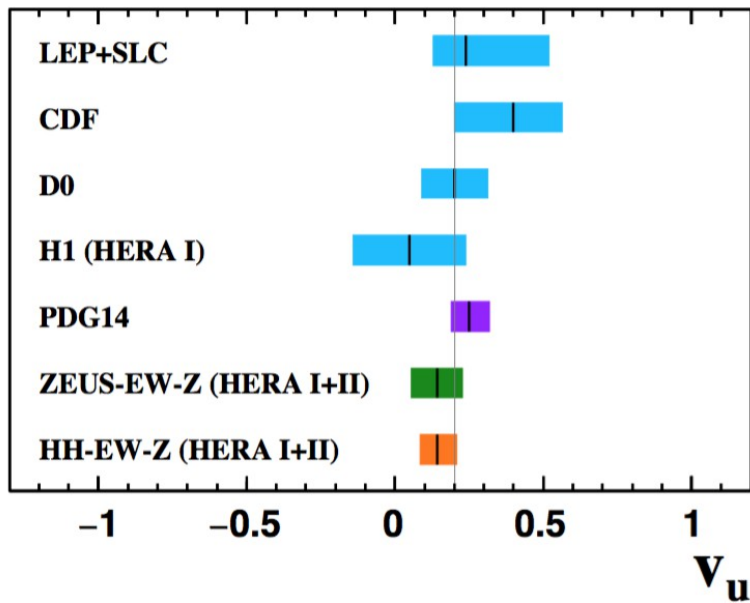
$$\chi_Z = \frac{1}{\sin^2 2\theta_W} \frac{Q^2}{M_Z^2 + Q^2} \frac{1}{1 - \Delta R}$$

- 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 @ $Q^2 = 1.9 \text{ GeV}^2$

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

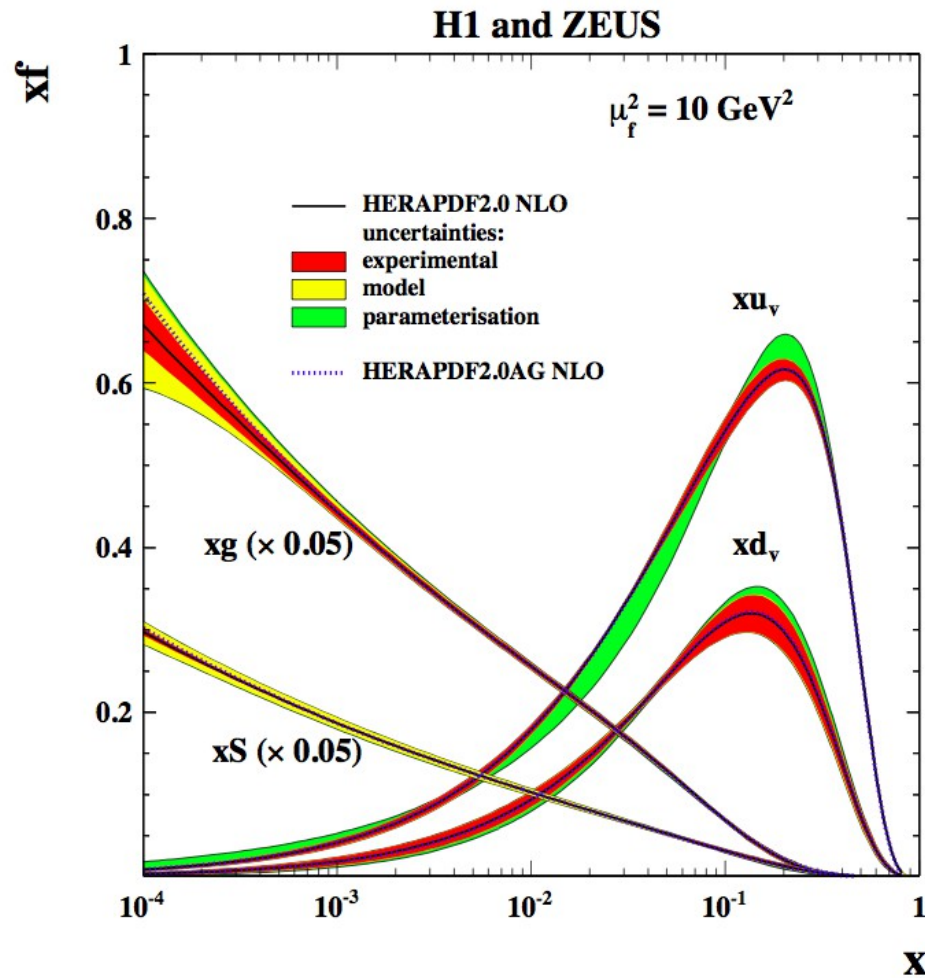
$$xg(x), xu_v(x), xd_v(x), x\bar{U}(x), x\bar{D}(x)$$

- Evolution using DGLAP equations

- 14 parameters determined in parameterisation scan

- Heavy quarks from Roberts-Thorne Variable Flavor Number Scheme

Color decomposition of uncertainties



Experimental uncertainties:

- Hessian method
- Conventional $\Delta\chi^2 = 1 \Rightarrow 68\% \text{ CL}$

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

α_s determined from QCD fit

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

Experimental uncertainty below 1%

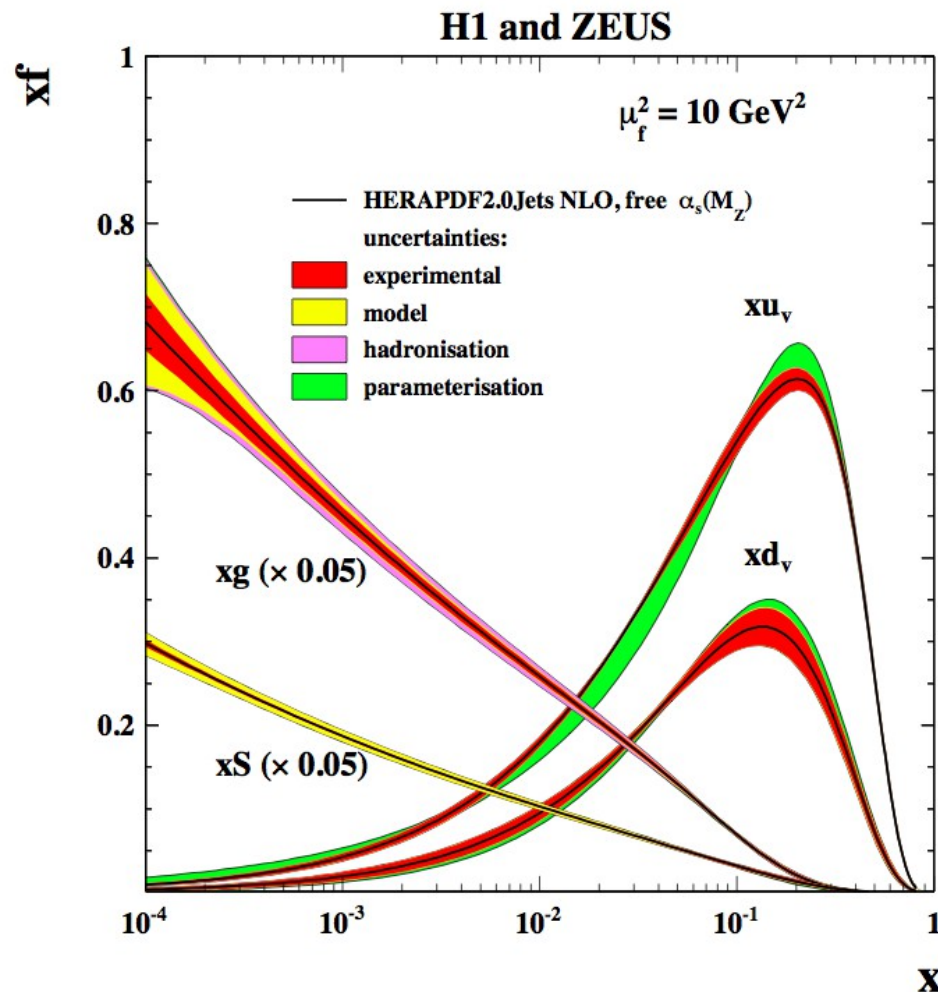
$$\pm 0.0005(\text{model/parameterisation})$$

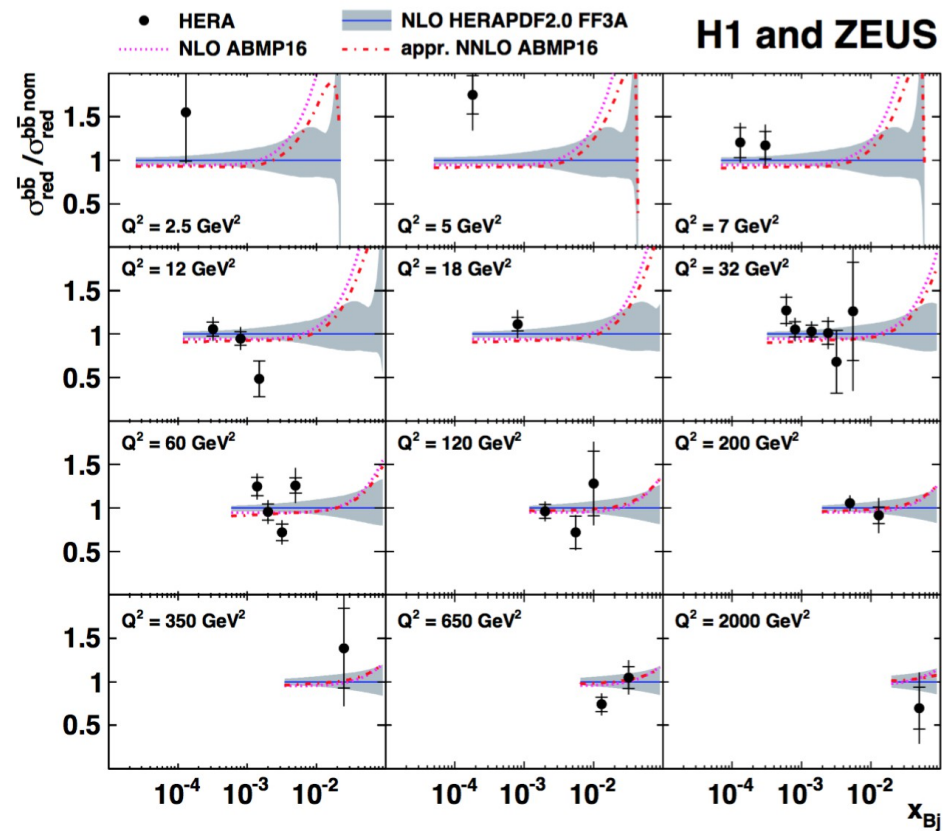
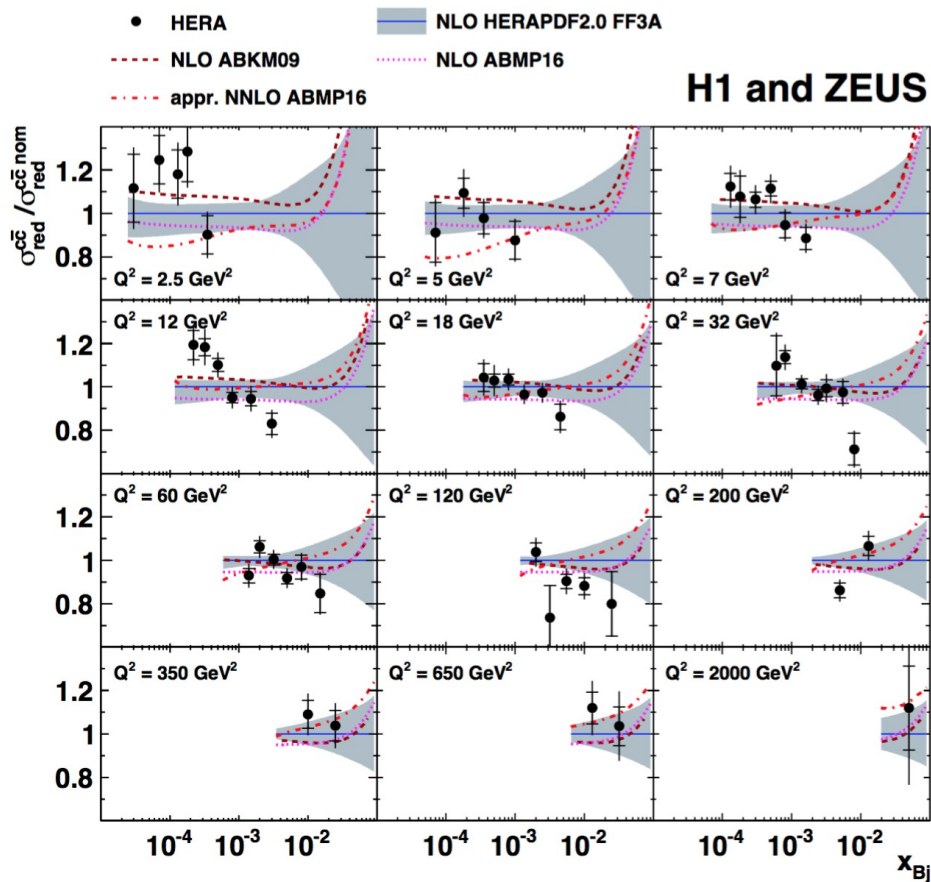
$$\pm 0.0012(\text{hadronisation})$$

$$+0.0037$$

$$-0.0030(\text{scale})$$

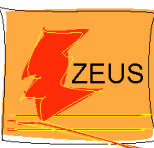
Uncertainty dominated by theory
NNLO ep jet calculations needed





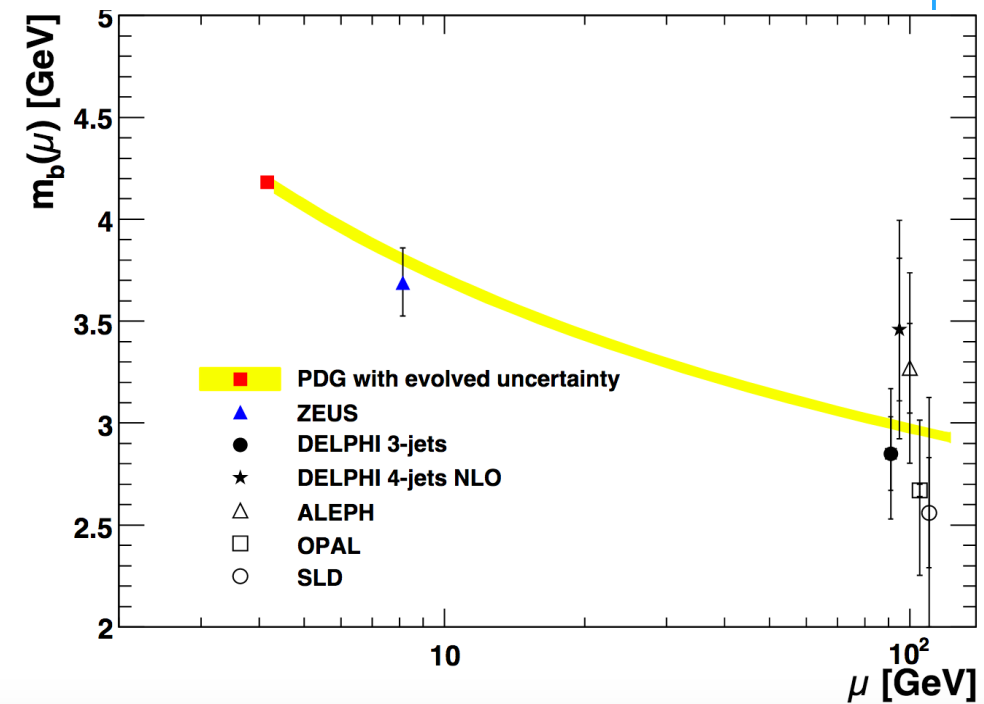
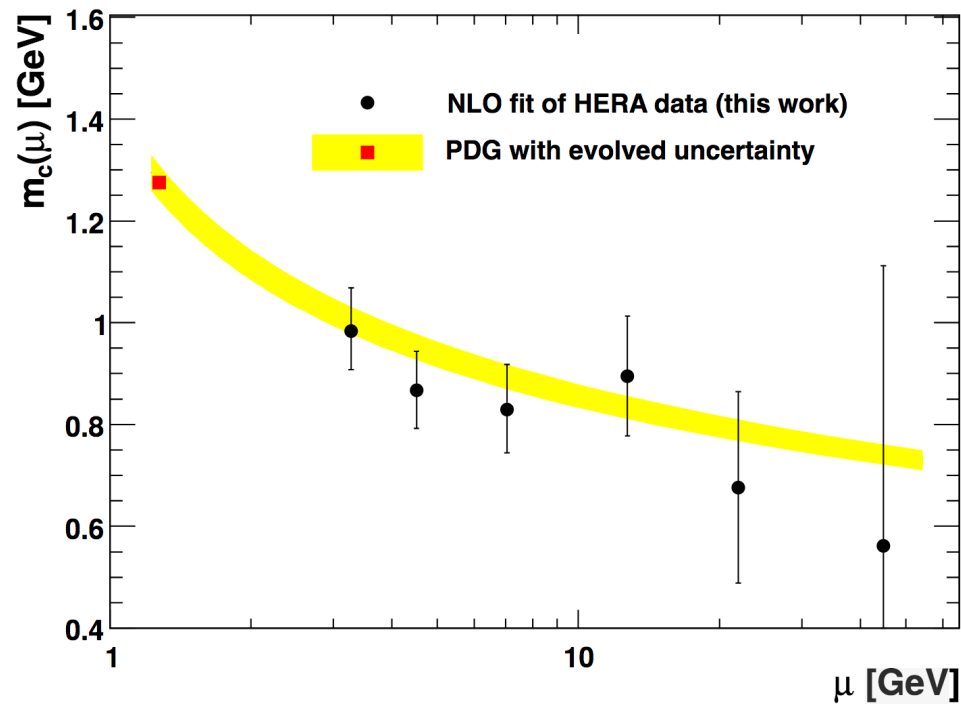
- NLO and approximate NNLO QCD predictions compared to the data
 - fair agreement charm data
 - Best description for NLO in fixed-flavour-number scheme
- beauty data, with larger uncertainties, well described by all predictions

Charm & beauty mass running



K. Wichmann

arXiv:1705.08863

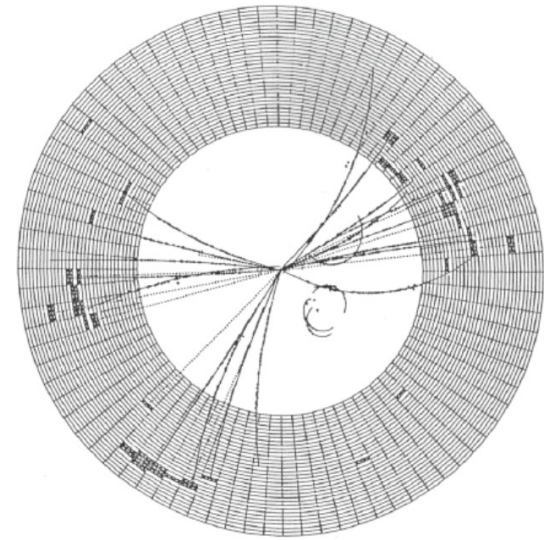


Heavy quark masses run in agreement with pQCD

@ HERA

Jet production @HERA

Jets at PETRA, 1979



*** SUMS (GeV) *** PTOT 35.768 PTRANS 29.904 PLONG 15.788 CHARGE -2
TOTAL CLUSTER ENERGY 15.169 PHOTON ENERGY 4.893 NR OF PHOTONS 11

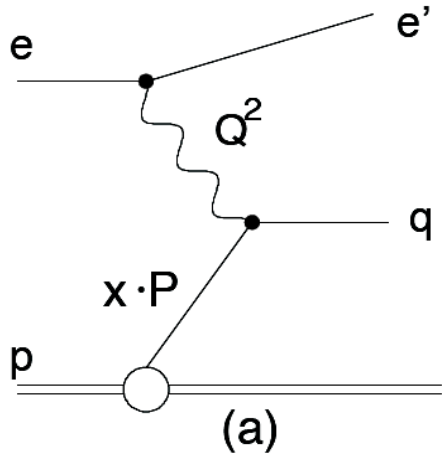
K. Wichmann

Krakow'18

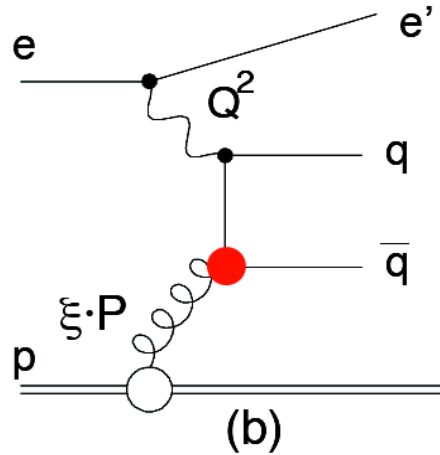
Various Faces of QCD @ HERA

43

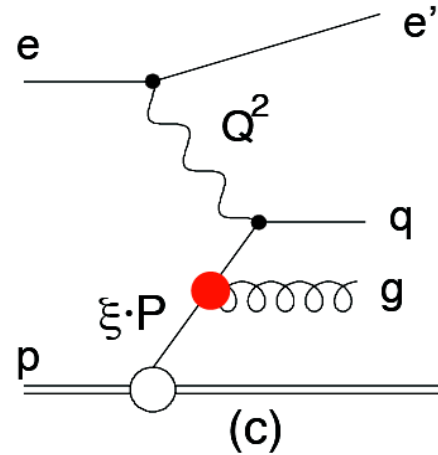
- Direct information on gluon distribution comes from jet production
- Possible simultaneous determination of parton densities and α_s
- Jets at HERA



elweak coupling

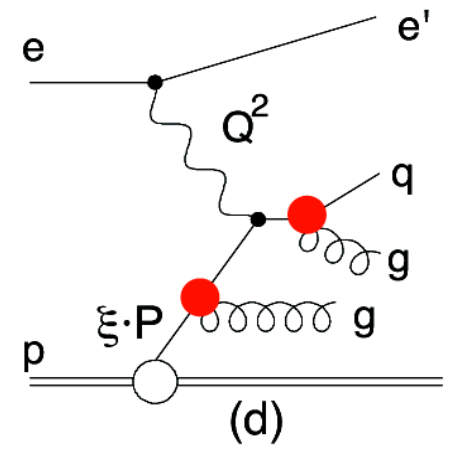


$\propto \alpha_s$



$\propto \alpha_s$

dijets

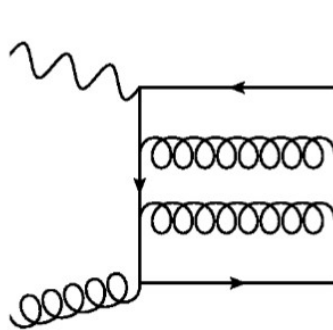


$\propto \alpha_s^2$

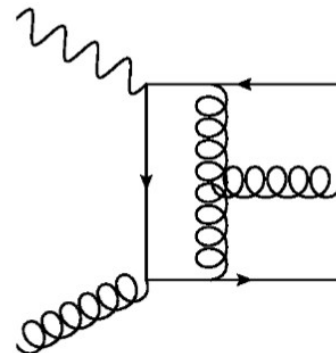
trijets

DIS jet production in NNLO

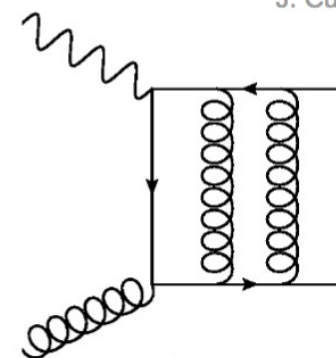
J. Currie, et al. [RPL 117 (2016) 042001]
J. Currie, et al. [JHEP 1707 (2017) 018]



Double-real



Real-virtual



Double-virtual

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

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



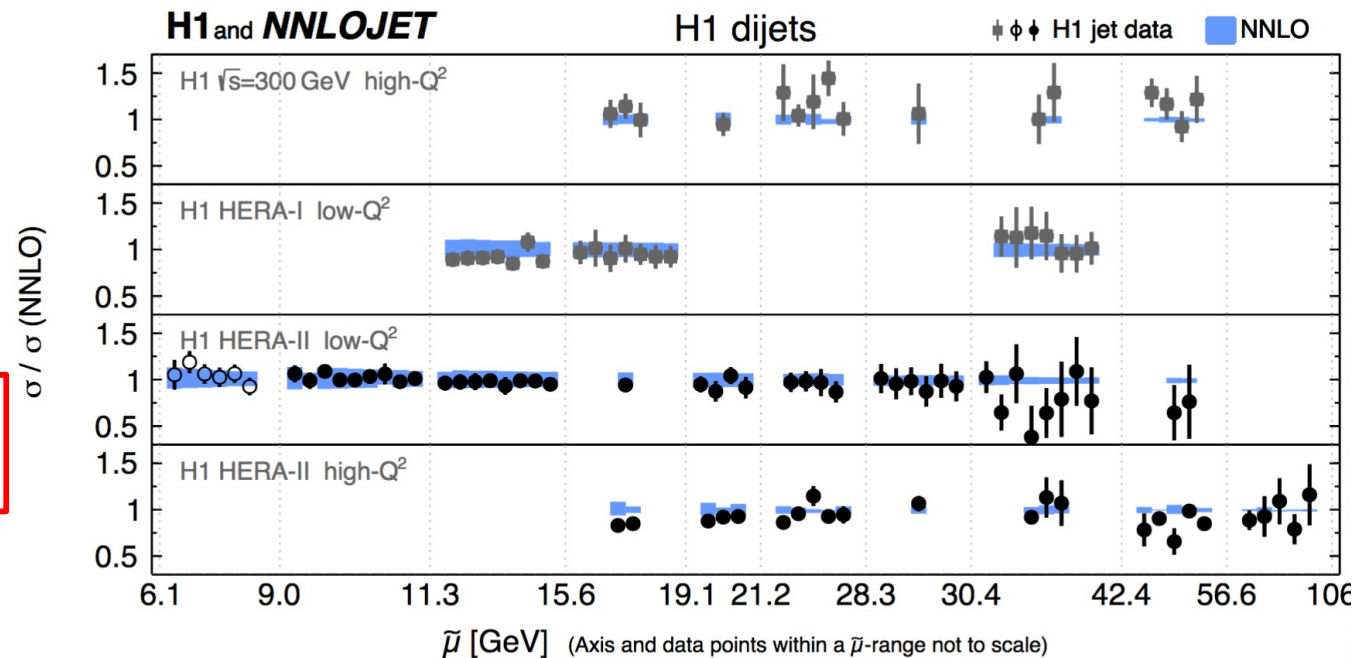
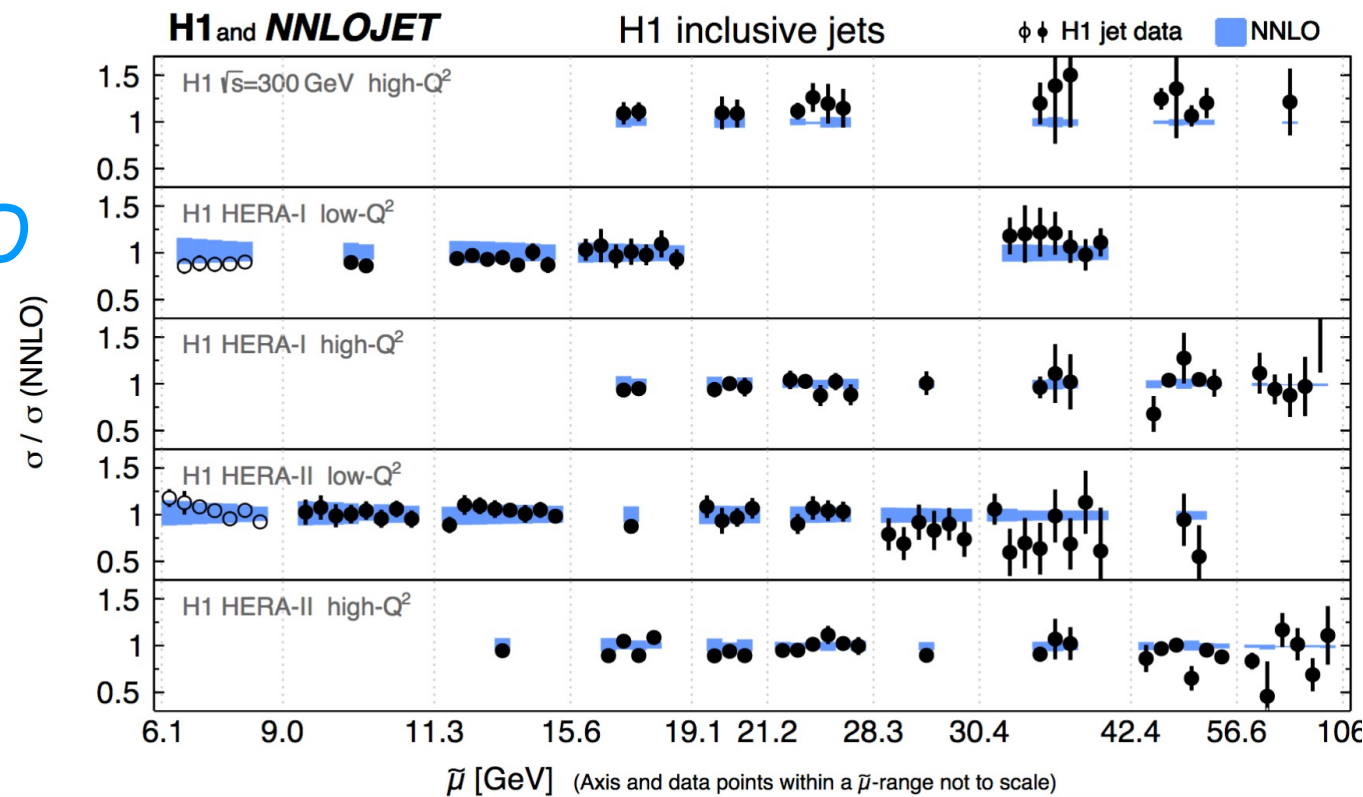
Comparison of NNLO predictions to data



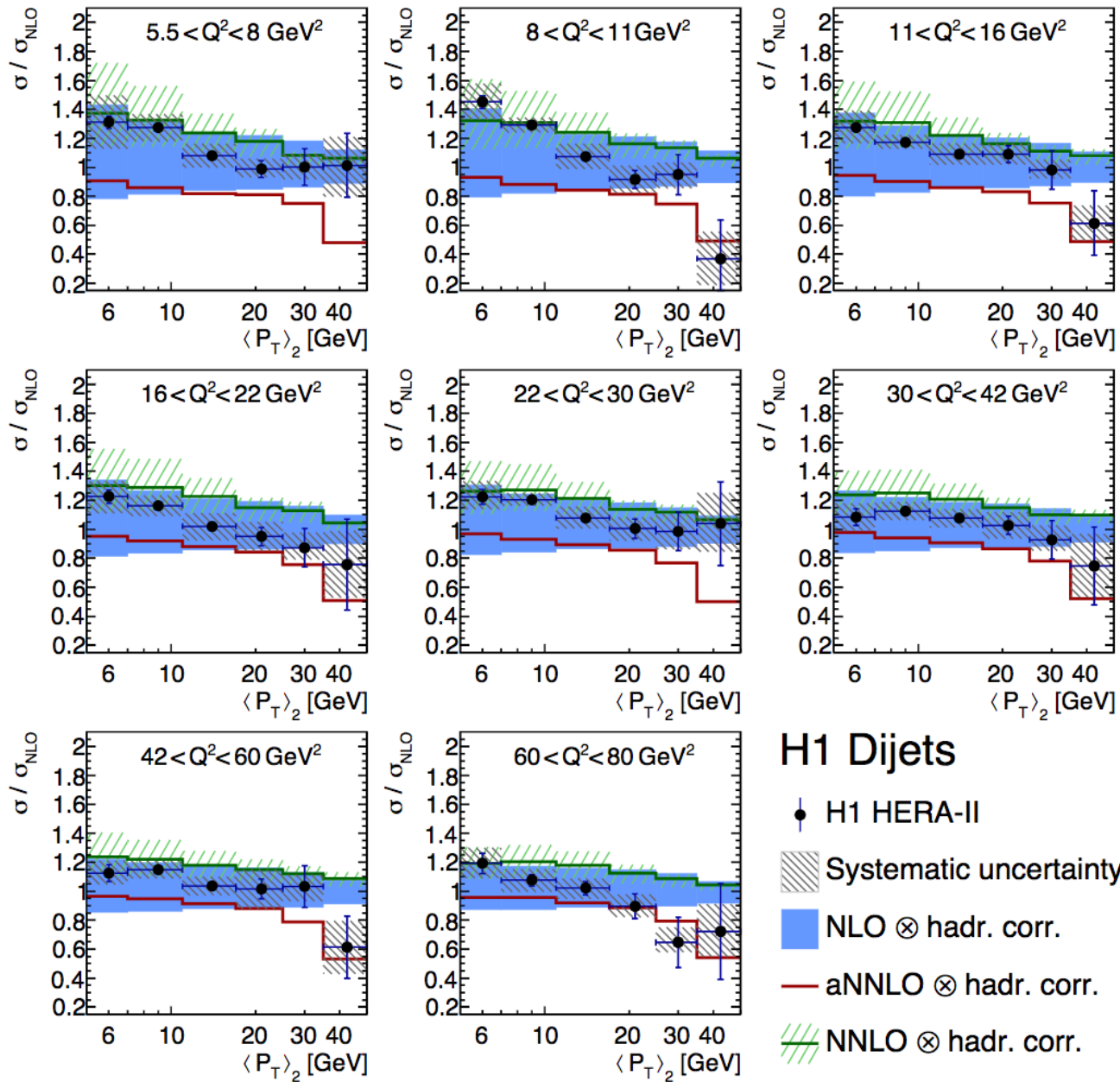
Overall good agreement



Great success of pQCD



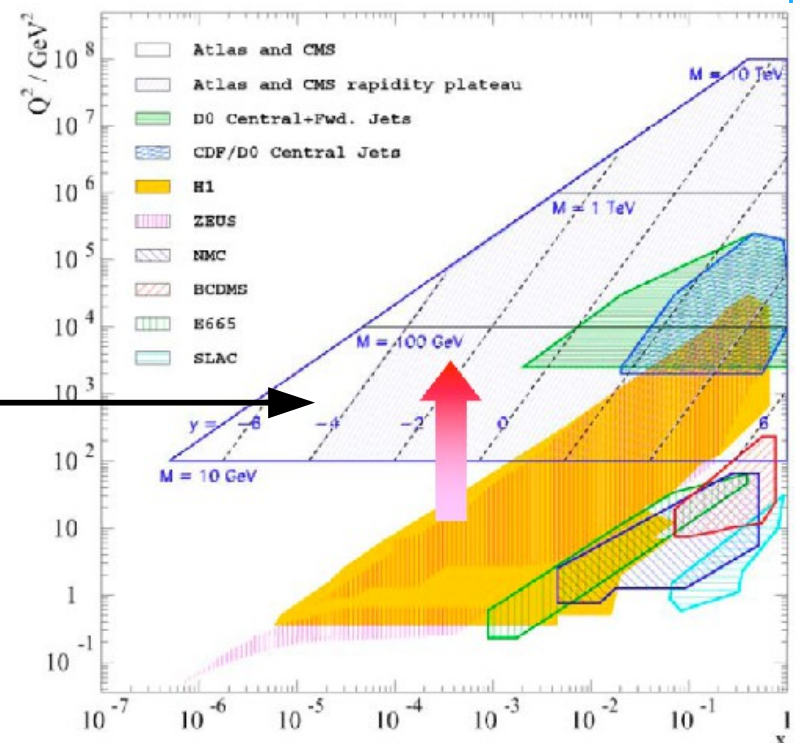
H1 dijets with NNLO predictions



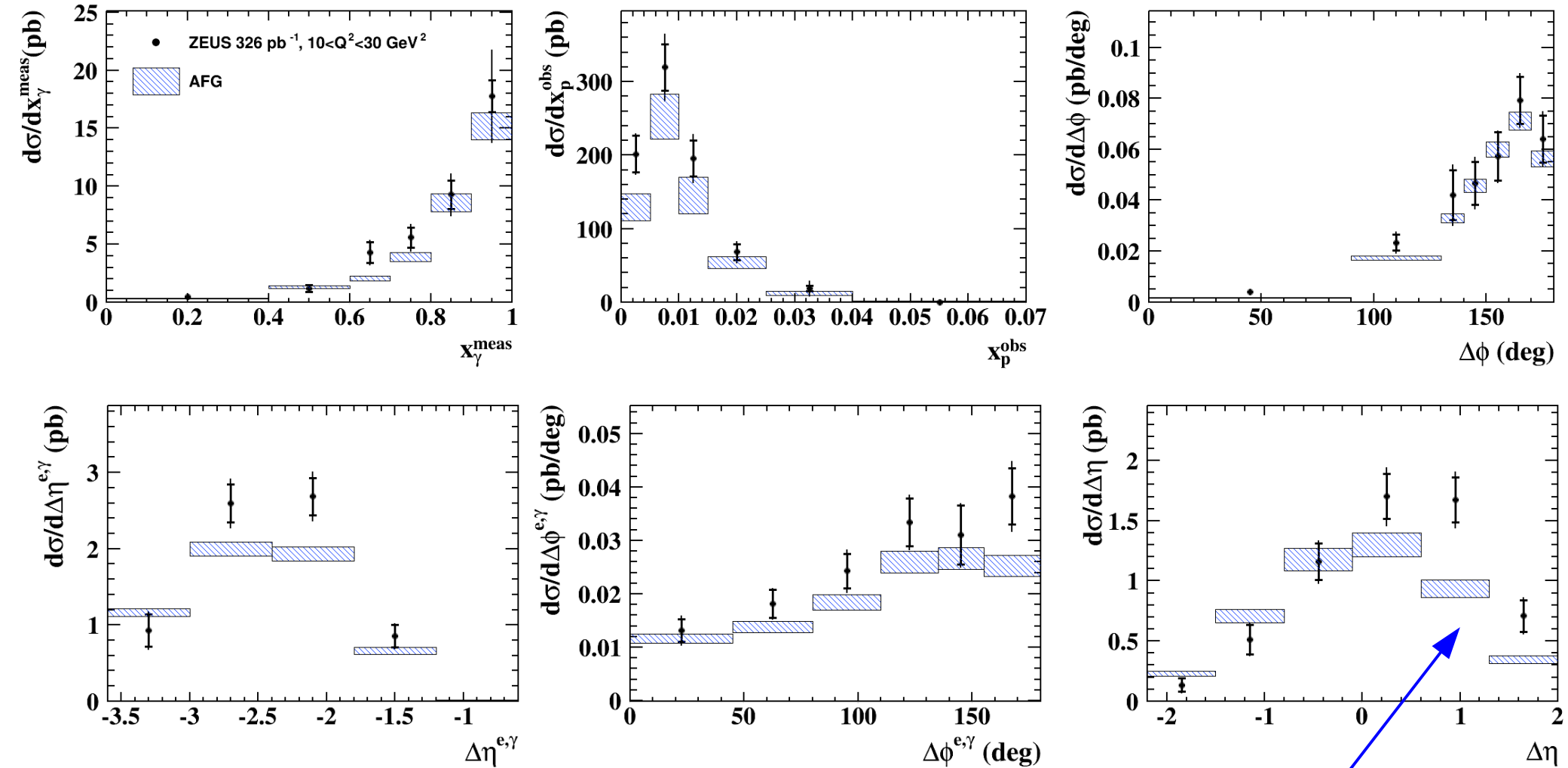
Why study prompt photons?

- Prompt photons emerge directly from the hard scattering process and give a particular view of this
- Use dynamics to probe modes such as $k_{\perp}$ -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

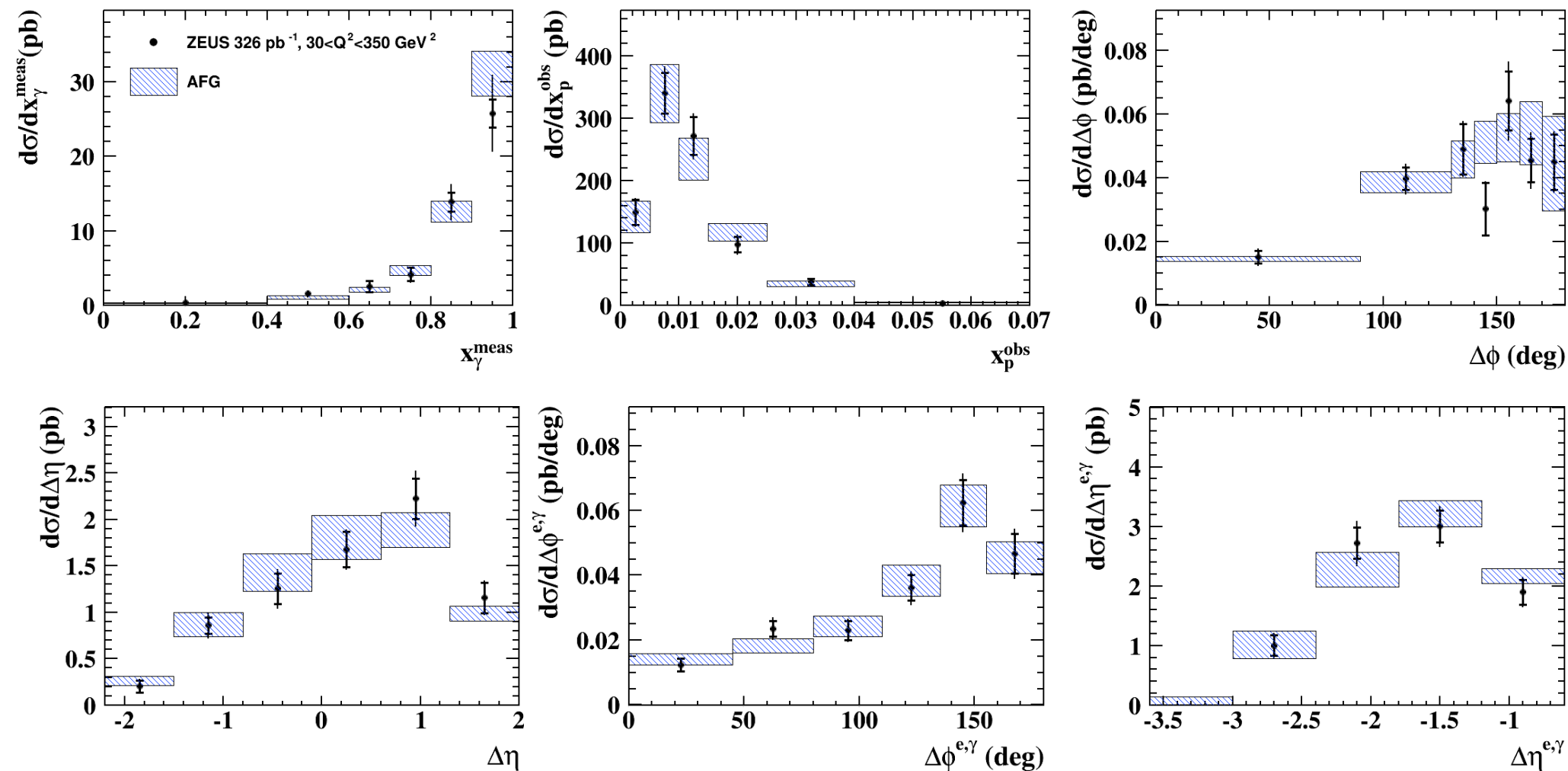
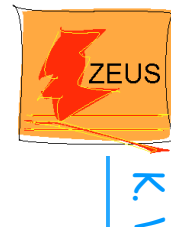


Comparison to AFG: low Q^2



- 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