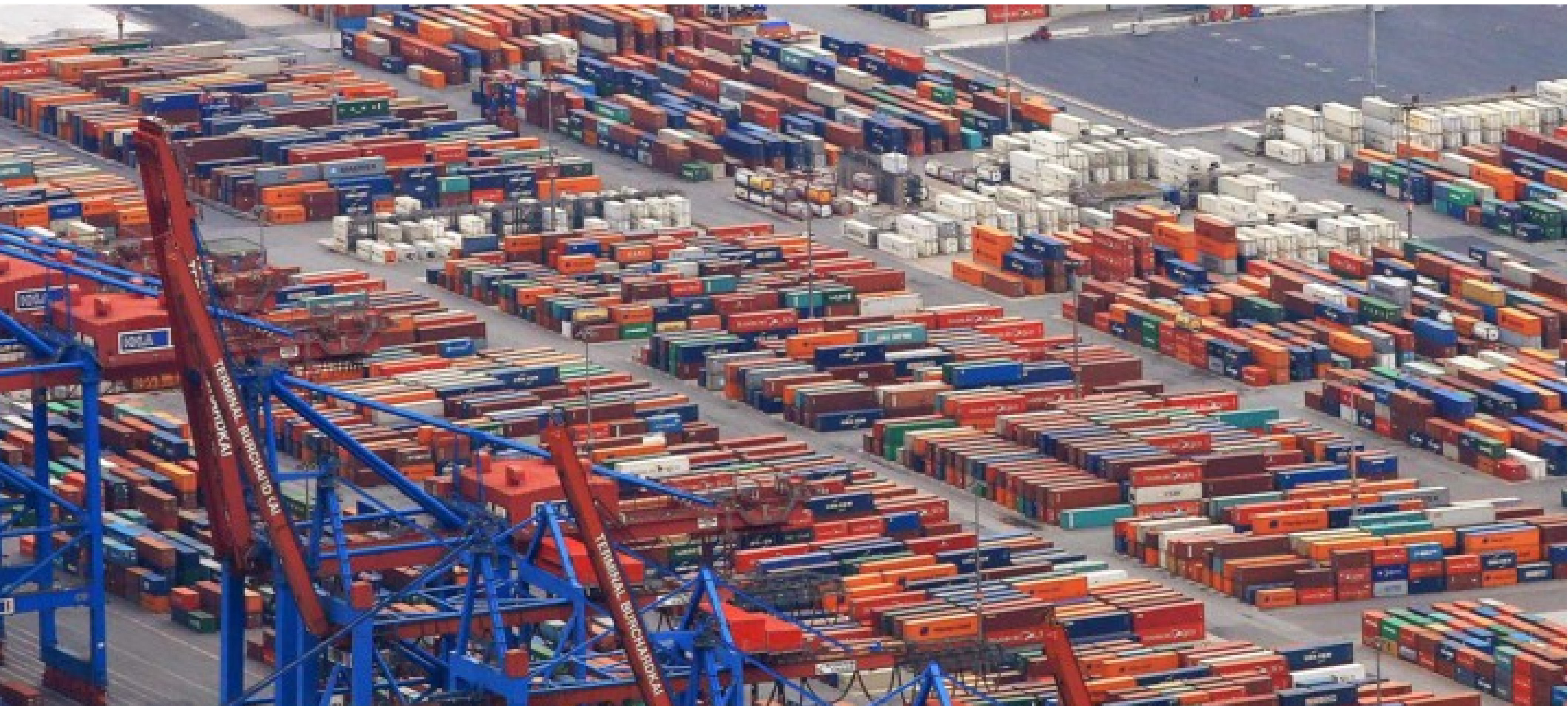
ZEUS-prel-19-001

H1prelim-19-041

H1prelim-19-013

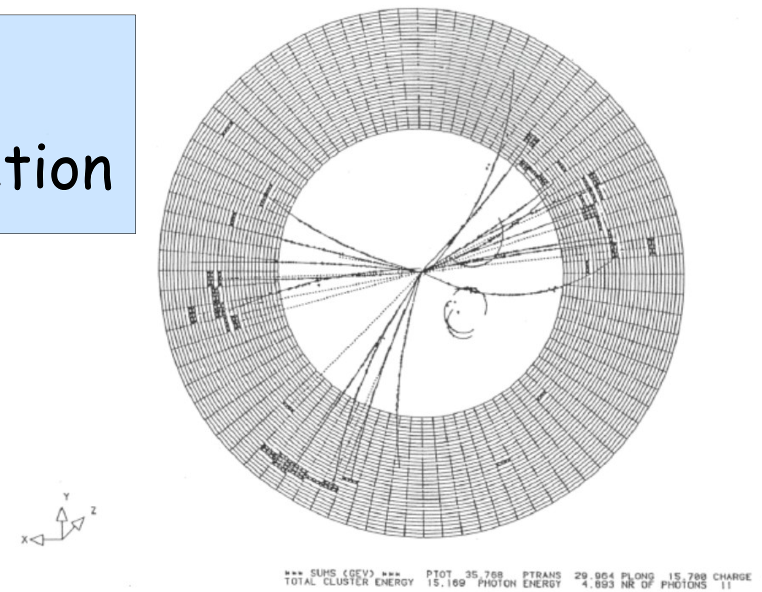
Back to the future:
NNLO QCD fits to HERA jets

K. Wichmann on behalf of H1 and ZEUS Collaborations



40 years of jet production @ DESY

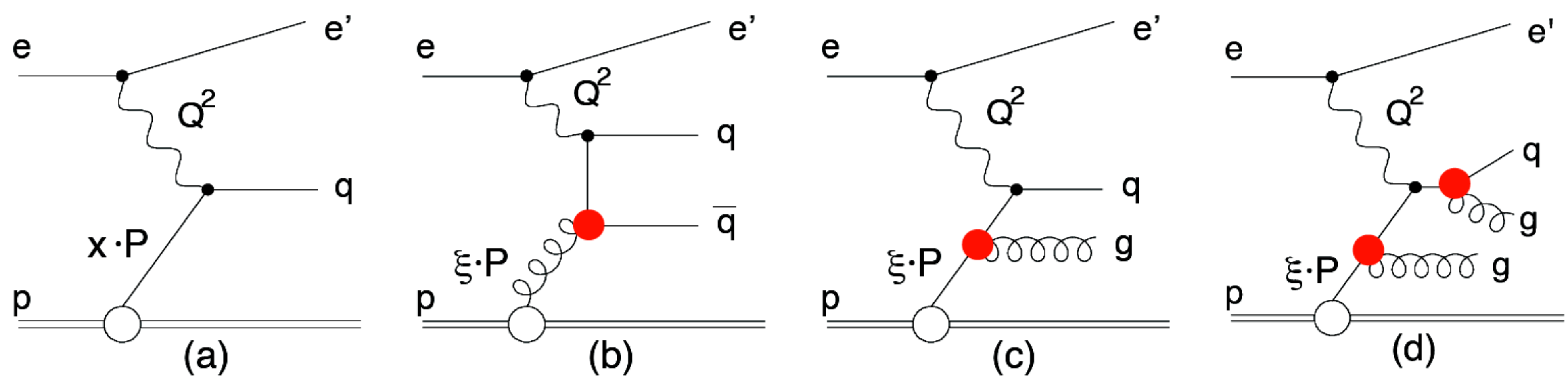
Jets at PETRA, 1979



At HERA direct information on gluon distribution and α_s comes from jet production

→ Possible simultaneous determination of parton densities and α_s

Jets at HERA



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

dijets $\quad$ trijets

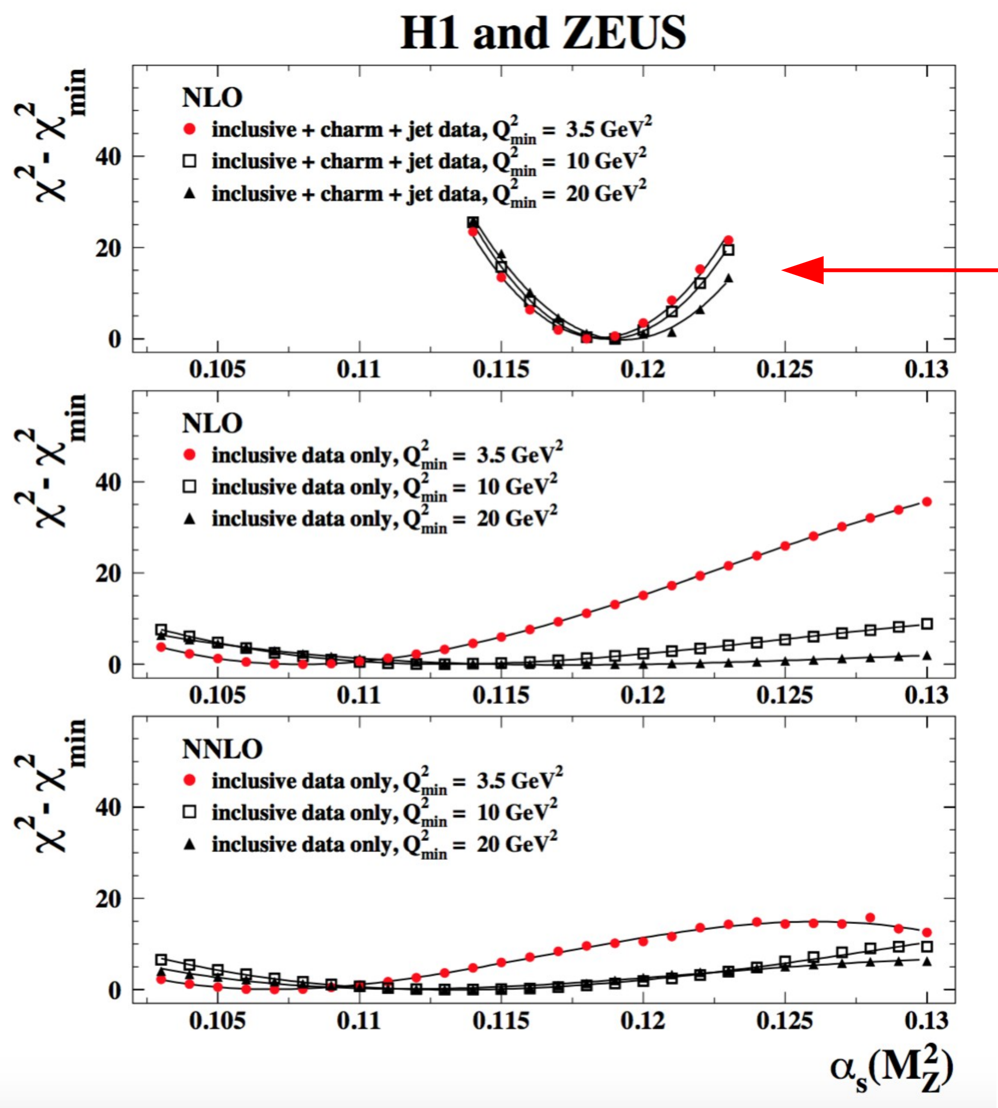
New NNLO calculations for HERA jet production available now

→ Possible simultaneous determination of parton densities and α_s at NNLO

→ Possible simultaneous fit to diffractive inclusive and dijet data and determination of NNLO diffractive parton densities

Simultaneous determination of parton densities and α_s at NNLO

Why study jets in DIS @ HERA?



- HERA inclusive data carry little information on α_s
- Jet data sensitive to α_s
- So far NLO available

New NNLO calculations for HERA ep jet production available now

- Implemented in FastNLO and APPLEGRID → fast cross section calculation possible

→ Possible simultaneous determination of parton densities and α_s at NNLO

HERA jet data used in PDF fit

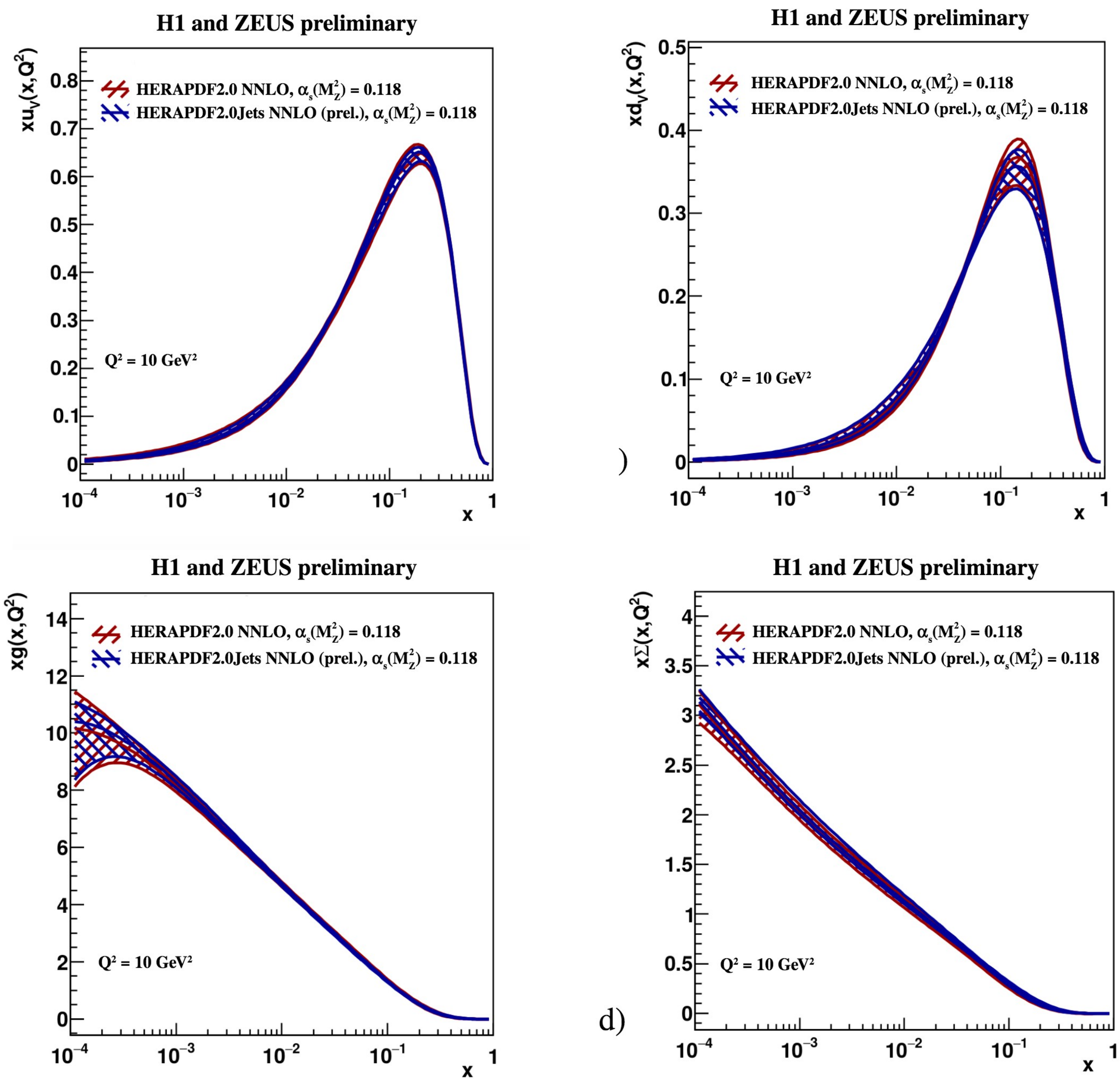
- Inclusive jets and dijets
- Some data points excluded due theory limitations
- Absolute and normalised cross sections
- Low-Q^2 and high-Q^2 production
- HERAI and HERAII

Data Set	taken from – to	Q^2[GeV^2] range from	to	$\mathcal{L}$ pb^{-1}	e^+/e^-	normalised	all points	used points
H1 HERA I normalised jets	1999 – 2000	150	15000	65.4	e^+p	yes	24	24
H1 HERA I jets at low Q^2	1999 – 2000	5	100	43.5	e^+p	no	28	16
H1 normalised inclusive jets at high Q^2	2003 – 2007	150	15000	351	e^+p/e^-p	yes	30	24
H1 normalised dijets at high Q^2	2003 – 2007	150	15000	351	e^+p/e^-p	yes	24	24
H1 normalised inclusive jets at low Q^2	2005 – 2007	5.5	80	290	e^+p/e^-p	yes	48	32
H1 normalised dijets at low Q^2	2005 – 2007	5.5	80	290	e^+p/e^-p	yes	48	32
ZEUS inclusive jets	1996 – 1997	125	10000	38.6	e^+p	no	30	30
ZEUS dijets	1998 –2000 & 2004 – 2007	125	20000	374	e^+p/e^-p	no	22	16

- Possibilities for PDF fit with jet data
  - With fixed α_s
  - With free α_s or doing α_s scan → α_s value

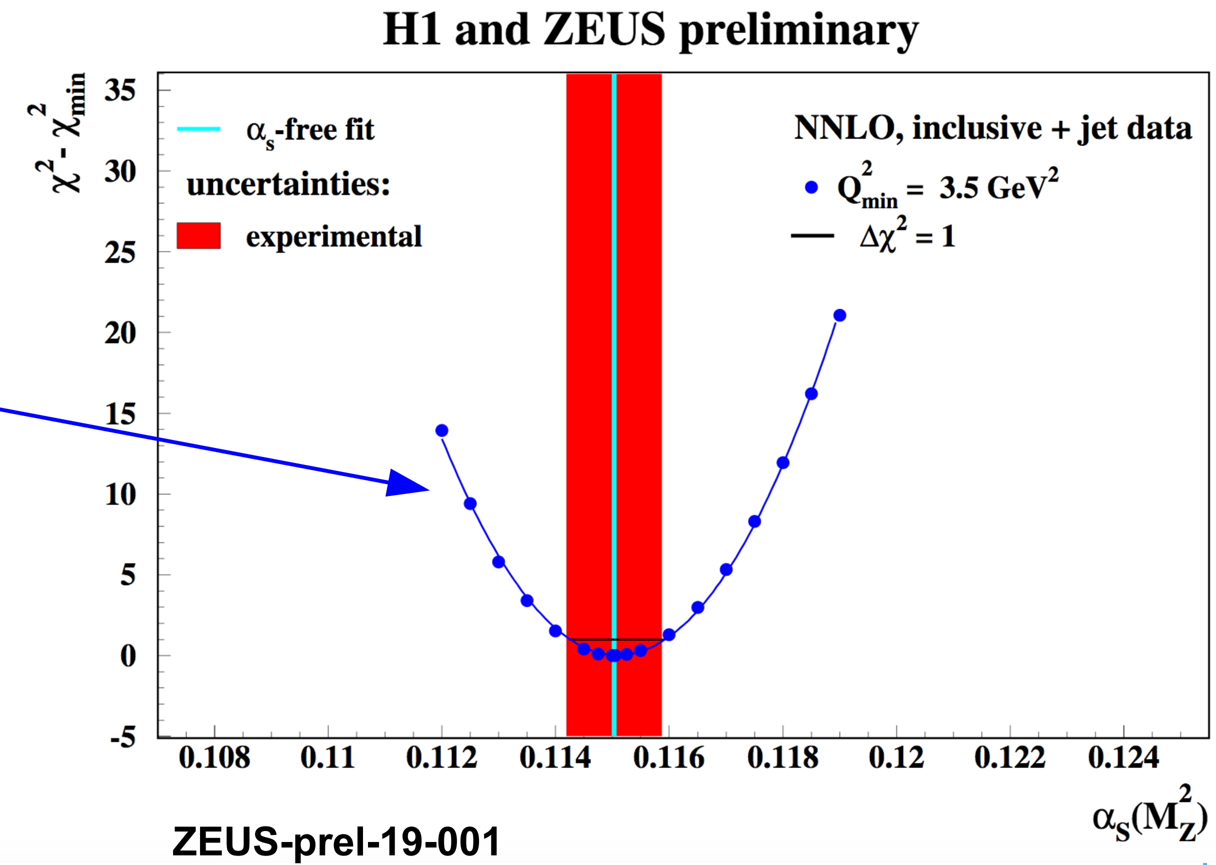
Comparison to HERAPDF2.0

HERAPDF2.0Jets NNLO (prel.), $\alpha_s(M_Z) = 0.118$



α_s @ NNLO from HERA jets

- Two ways of estimating α_s @NNLO using HERA jet data
  - → α_s-scan
  - → simultaneous fit of PDFs and α_s
- Both methods give the same result

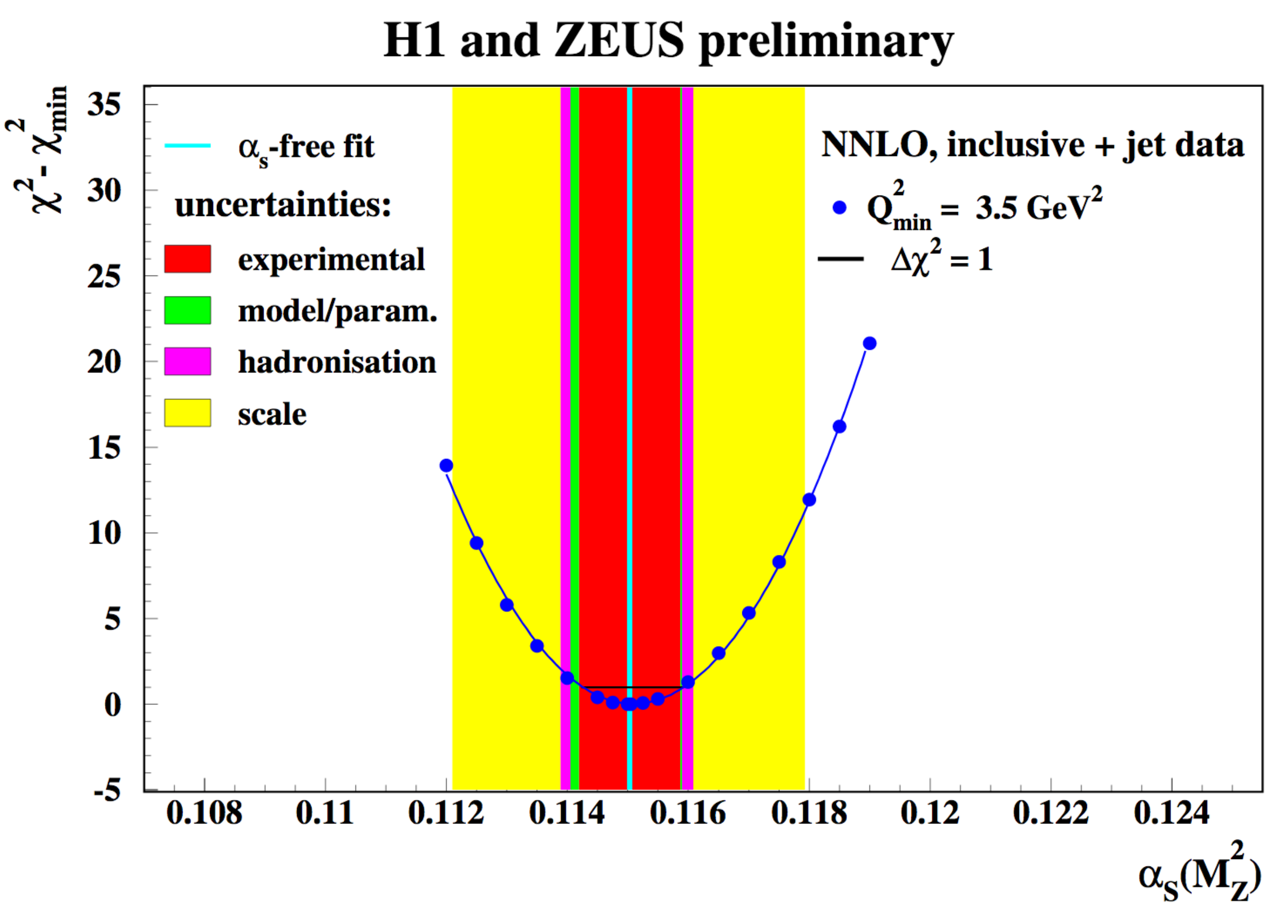


$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008(\text{exp})$$

Full uncertainties

- Experimental, model, parametrisation and hadronisation uncertainties
- In fits with free $\alpha_s(M_Z)$ scale uncertainty important

→ factorisation and renormalisation scales varied both separately and simultaneously by a factor of two and taking maximal positive and negative deviations (assumed to be 50% correlated and 50% uncorrelated)



Comparison to other HERAPDF2.0 fits

- NNLO fits with and without jets of similar quality
  - χ^2/d.o.f = 1.203 for free $\alpha_s(M_Z)$ fit with 1328 degrees of freedom
  - χ^2/d.o.f = 1.205 for HERAPDF2.0NNLO with only 1131 degrees of freedom
- NLO and NNLO results for $\alpha_s(M_Z)$ consistent within experimental uncertainties
  - Scale uncertainties reduced

→ as expected for NNLO calculations

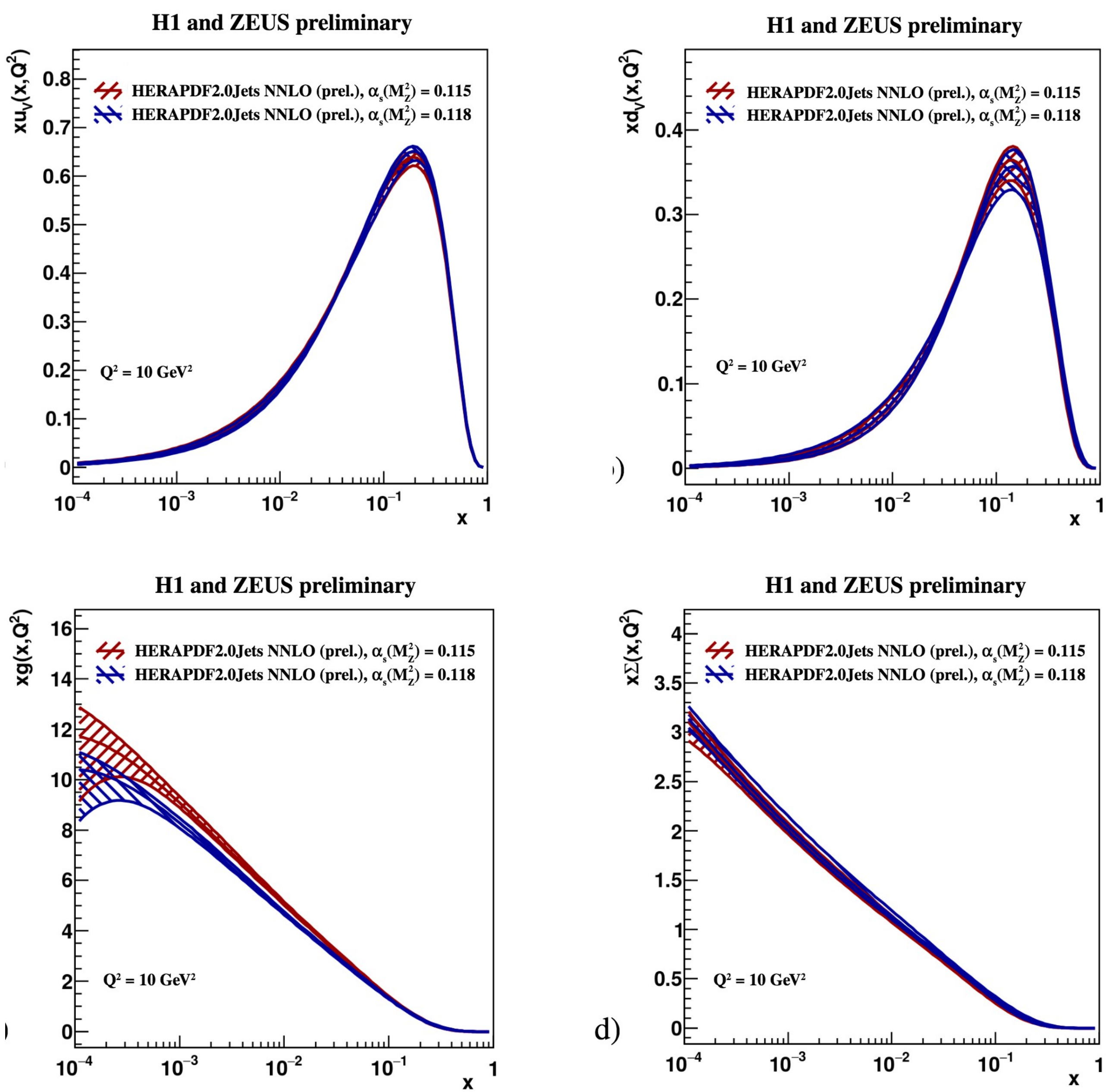
HERAPDF2.0Jets NNLO (prel.), free $\alpha_s(M_Z)$

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008(\mathrm{exp})^{+0.0002}_{-0.0005}(\mathrm{model/parameterisation}) \pm 0.0006(\mathrm{hadronisation}) \pm 0.0027(\mathrm{scale}) .$$

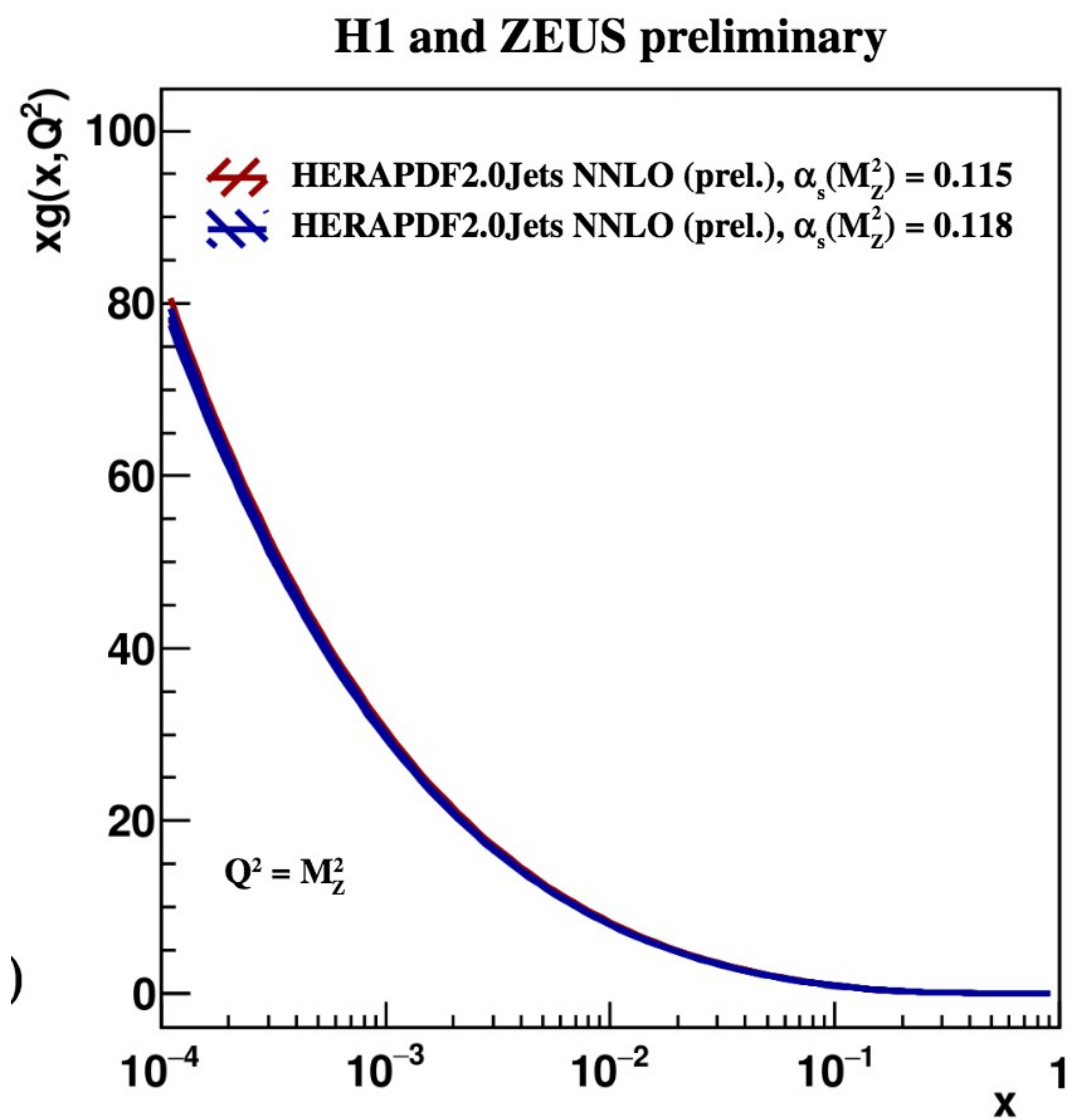
HERAPDF2.0Jets NLO

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\mathrm{exp}) \pm 0.0005(\mathrm{model/parameterisation}) \pm 0.0012(\mathrm{hadronisation}) \, {}^{+0.0037}_{-0.0030}(\mathrm{scale}) .$$

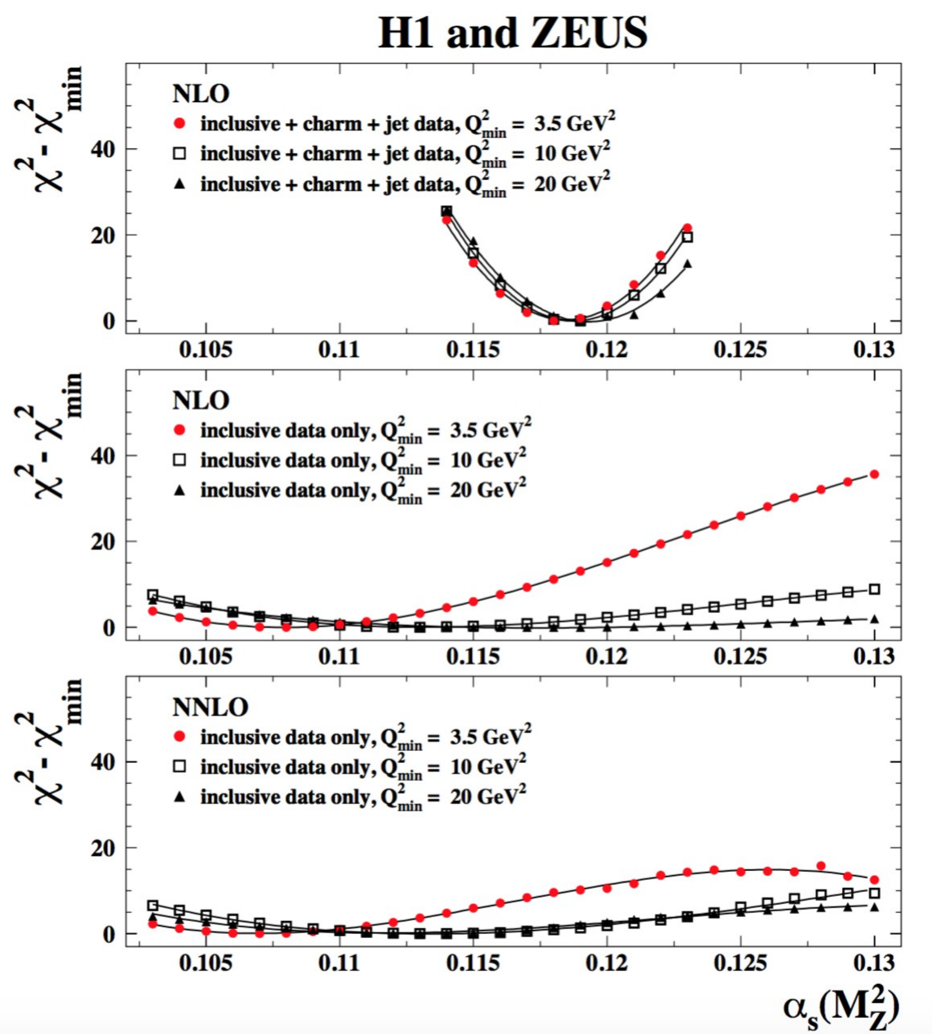
Comparison between α_s = 0.115 and 0.118

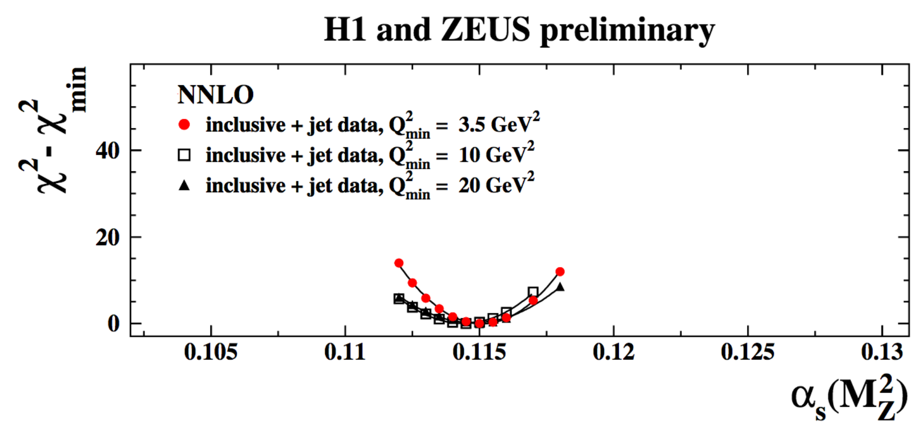


Gluon at scale of M_Z^2 very similar



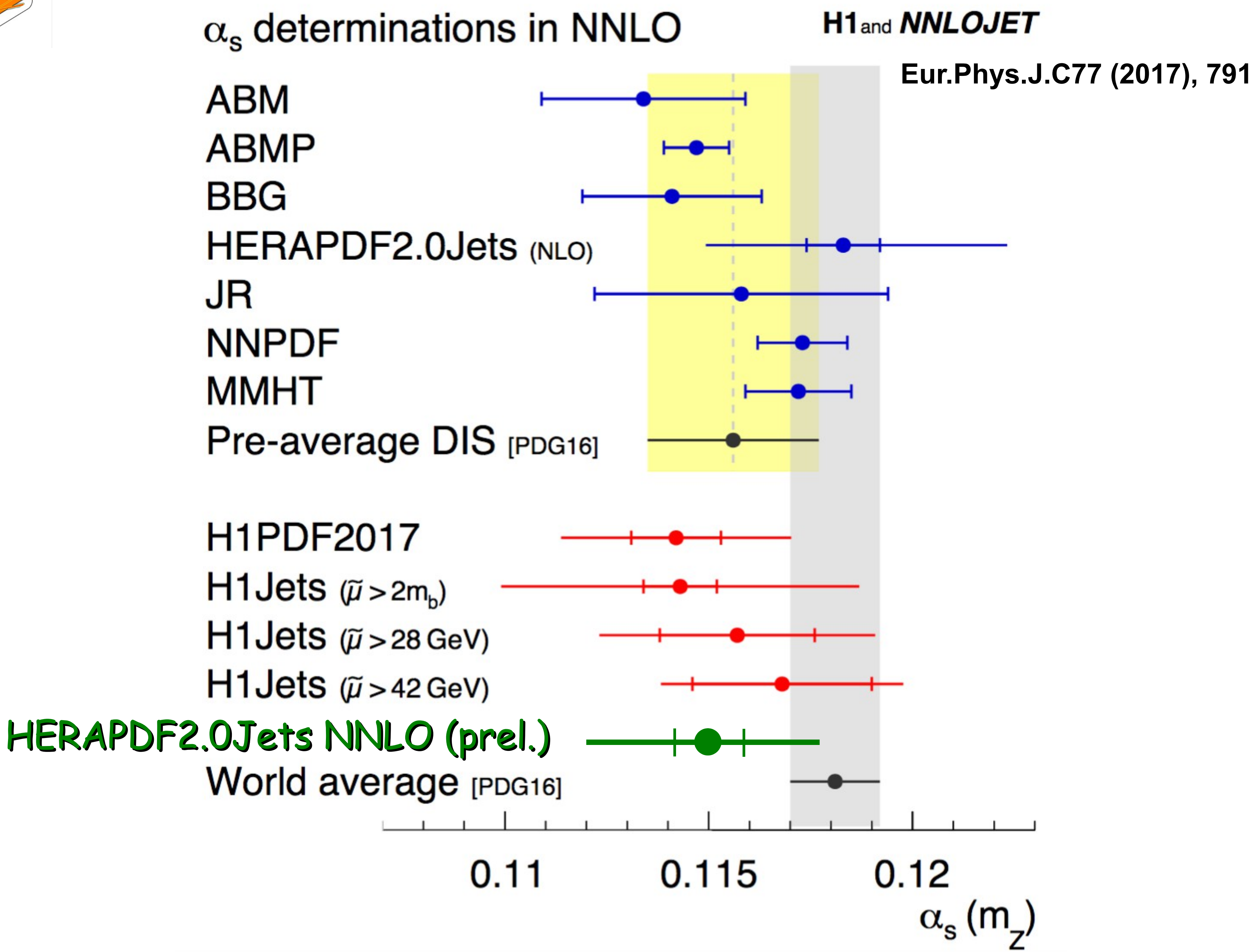
Finally a full picture of jets@HERA



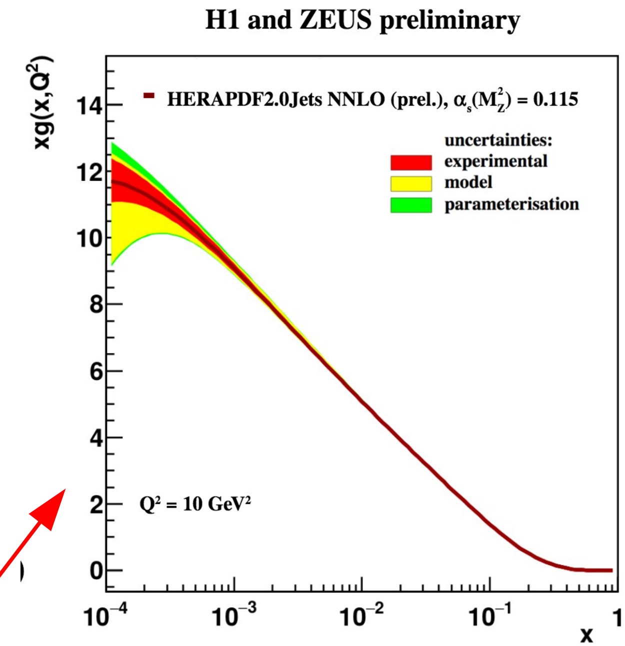


- Just as at NLO the jet data constrain $\alpha_s(M_Z)$
- Similar level of accuracy at NNLO and NLO
- $\alpha_s(M_Z)$ clearly lower at NNLO

Comparison to other NNLO results



Summary & conclusions



- HERAPDF2.0 family completed
  → NNLO fit including jet data performed
- Two new PDF sets
  → HERAPDF2.0Jets NNLO $\alpha_s(M_Z)$ = 0.118 → PDG
  → HERAPDF2.0Jets NNLO (prel.), $\alpha_s(M_Z)$ = 0.115 → value favoured by our fit
- Jet data allow us to constrain $\alpha_s(M_Z)$

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008(\text{exp})^{+0.0002}_{-0.0005}(\text{model/parameterisation}) \pm 0.0006(\text{hadronisation}) \pm 0.0027(\text{scale}) .$$

- Compared to NLO result $\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/parameterisation}) \pm 0.0012(\text{hadronisation}) \; ^{+0.0037}_{-0.0030}(\text{scale}) .$

Systematic shift downwards at NNLO and reduction of scale uncertainty

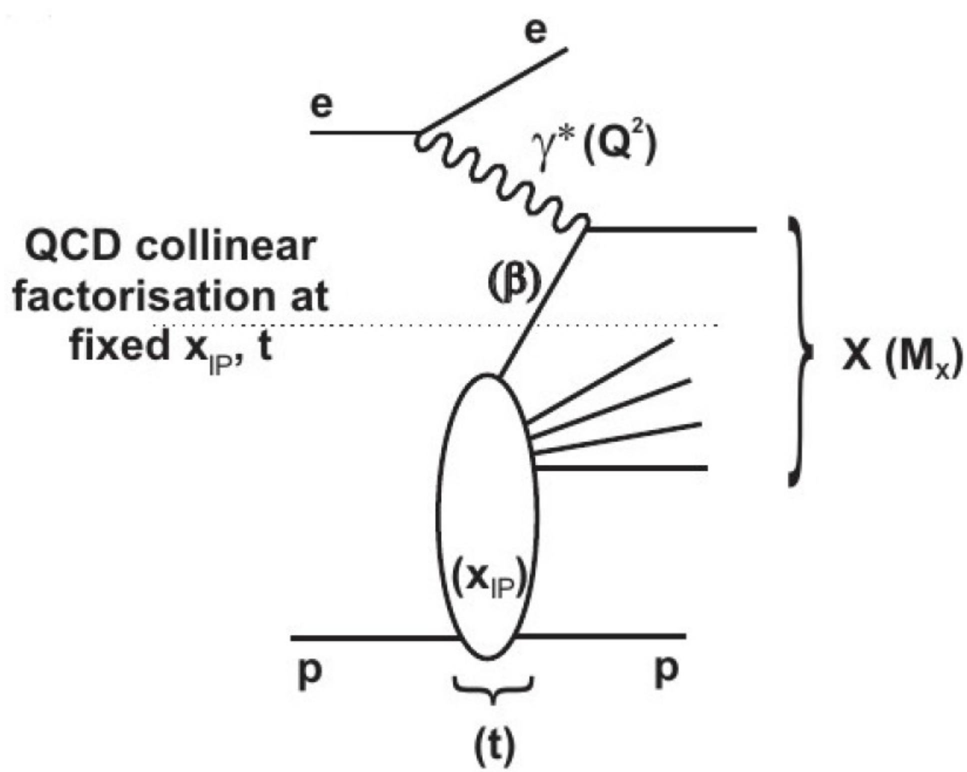
H1prelim-19-013
April 2019

A determination of diffractive parton distribution functions from H1 inclusive diffractive deep-inelastic scattering data and H1 diffractive dijet cross section data in next-to-next-to-leading order QCD

H1 Collaboration

Diffractive production in ep

In diffractive events the beam proton stays intact or dissociates into low mass hadronic system Y



At HERA about 10% of low-x events are diffractive

DIS variables:

$$Q^2 = -(k-k')^2 \qquad y = \frac{p\cdot q}{p\cdot k}$$

Diffractive variables:

$$x_{I\!P} = 1 - \frac{E'_p}{E_p} \qquad t = (p-p')^2$$

Mass: $M_X^2 = Q^2\left(\frac{1}{\beta} - 1\right)$

At LO: The momentum fraction entering the hard subprocess with respect to the diffractive exchange

$$\beta = \frac{x_{Bj}}{x_{I\!P}} = \frac{Q^2}{syx_{I\!P}}$$

DDIS and diffractive jet data in DPDF fit

Inclusive DDIS data:

Data set [ref.]	$\sqrt{s}$ [GeV]	int. $\mathcal{L}$ [pb^{-1}]	DIS kinematic range
H1comb-LRG	319	336.6	$8.5 < Q^2 < 1600\,GeV^2$
H1-LowE-252	252	5.2	$8.5 < Q^2 < 44\,GeV^2$
H1-LowE-225	225	8.5	$8.5 < Q^2 < 44\,GeV^2$

~40 times higher luminosity

Eur.Phys.J. C72 (2012) 2074 [arXiv:1203.4495] + data at lower energies 225, 252 GeV

Used first time in DPDF

The jet data:

New data sample		
2005-2007	920 + 27.6	290 pb^{-1}
Previously published		
1999-2000	920 + 27.5	51.5 pb^{-1}

~6 times higher luminosity

JHEP 1503 (2015) 092 [arXiv:1412.0928]: With proper treatment of correlations between bins

5

Double differential in Q^2 and jet p_T

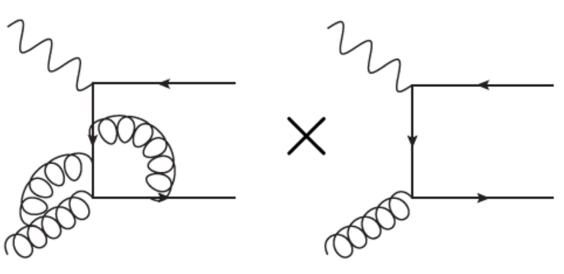
Details of QCD analysis

Theory

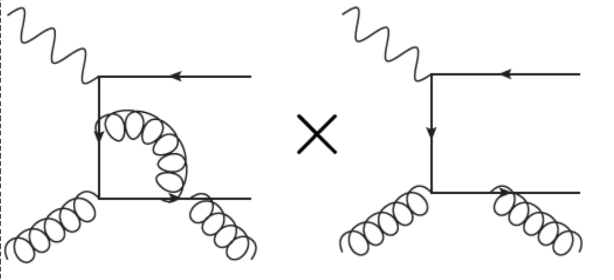
- NNLO accuracy for both inclusive and jet production
- Using FONLL-C GM-VFNS (by APFEL) for inclusive production,
  $\longrightarrow$ default QCD scale for inc. production: $\mu_R^2 = \mu_F^2 = Q^2$
- Using NNLOJET (massles quarks) + fastNLO for dijets,
  $\longrightarrow$ default QCD scale for dijets: $\mu_R^2 = \mu_F^2 = Q^2 + \langle p_T^{*\text{jets}} \rangle^2$
- Scale unc. by simultaneous (for all processes)
  $\mu_F = \mu_R$ x2, x0.5 variation

Examples of α_S^3 diagrams contributing to dijet production

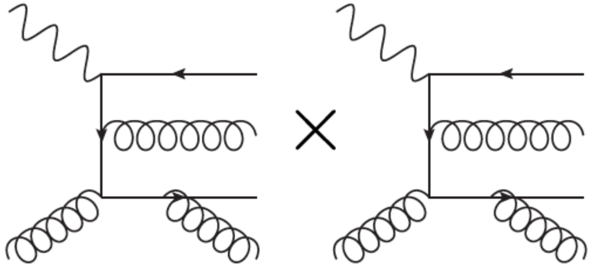
virtual-virtual



real-virtual



real-real



Fit performed using **Alpos** framework https://indico.desy.de/indico/event/22011/session/7/contribution/23

Fitted parameters and model uncertainties

- Fixed params. mostly identical with H1 2006 & 2007 fits

	Parameter	Value	Source
Pomeron slope	$\alpha'_{I\!P}$	$0.04^{+0.08}_{-0.06}$ GeV^{-2}	H1 FPS HII [arXiv:1010.1476]
Pomeron B-slope	$B^0_{I\!P}$	$5.73^{+0.84}_{-0.93}$ GeV^{-2}	H1 FPS HII [arXiv:1010.1476]
Reggeon intercept	$\alpha_{I\!R}(0)$	0.5 ± 0.1	H1 LRG HI [hep-ex/9708016]
Reggeon slope	$\alpha'_{I\!R}$	$0.3^{+0.6}_{-0.3}$ GeV^{-2}	H1 FPS HI [hep-ex/0606003]
Reggeon B-slope	$B^0_{I\!R}$	$1.6^{+0.4}_{-1.6}$ GeV^{-2}	H1 FPS HI [hep-ex/0606003]
charm mass	m_c	1.4 ± 0.2 GeV	PDG2004
bottom mass	m_b	4.5 ± 0.5 GeV	PDG2004
strong coupling	$\alpha_S(M_Z^2)$	0.118 ± 0.002	PDG2004
staring scale of ev.	μ_0	$1.15^{+0.24}_{-0.15}$ GeV	

- Parameters $\alpha'_{I\!P}, B_{I\!P}$ ($\alpha'_{I\!P}, B_{I\!P}$) strongly anti-correlated
  $\longrightarrow$ Varied simultaneously as (up,down) & (down,up)

- The QCD scale varied by a factor of 2
  (dominant unc. together with μ_0 variation)

- **8 parameters fitted:** 6 of pomeron PDF + $\alpha_{I\!P}(0)$ & $n_{I\!R}$

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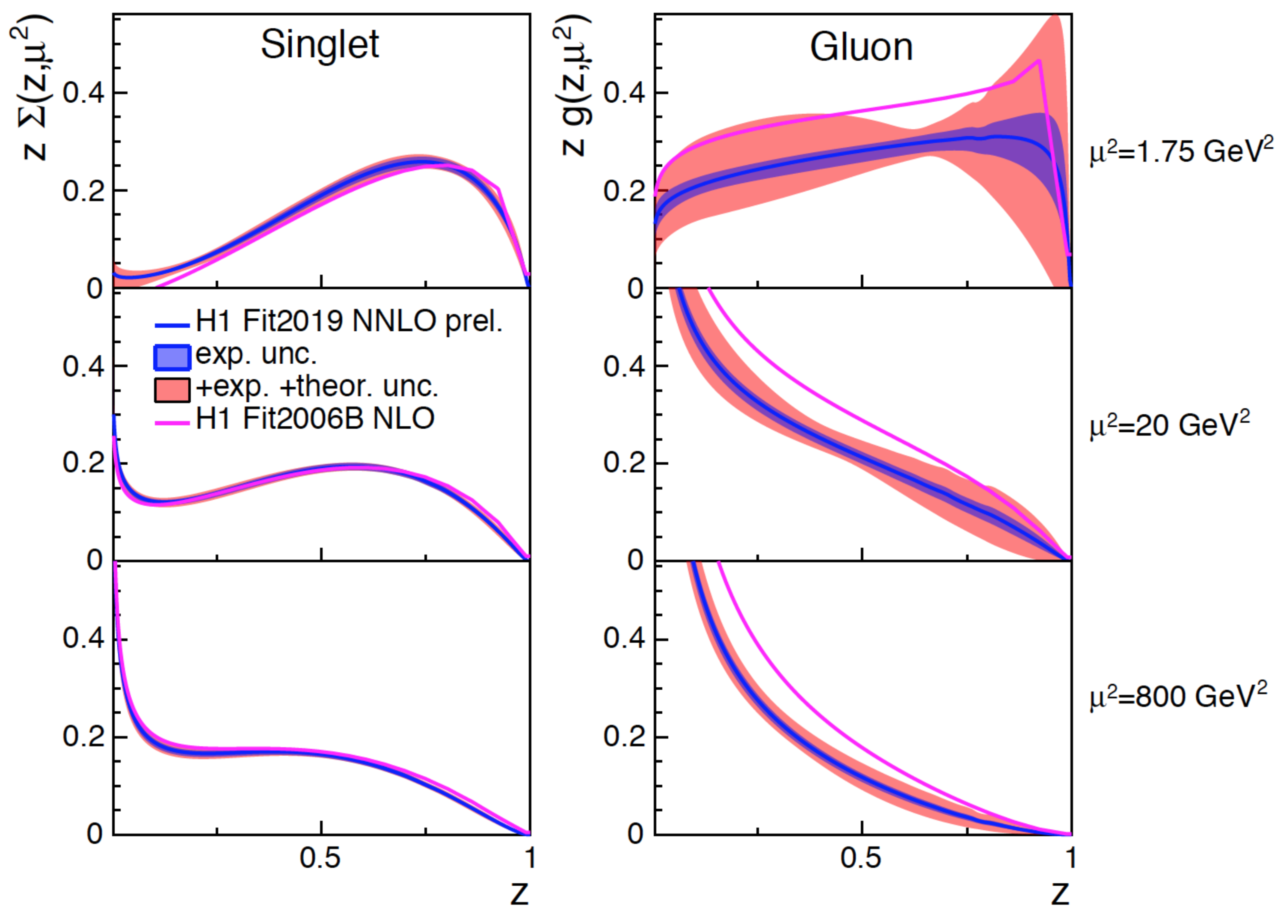
DPDF Comparison
(H1 Fit2019 NNLO vs H1 Fit2006B NLO)

- Old and new DPDFs in different QCD order & flavour scheme

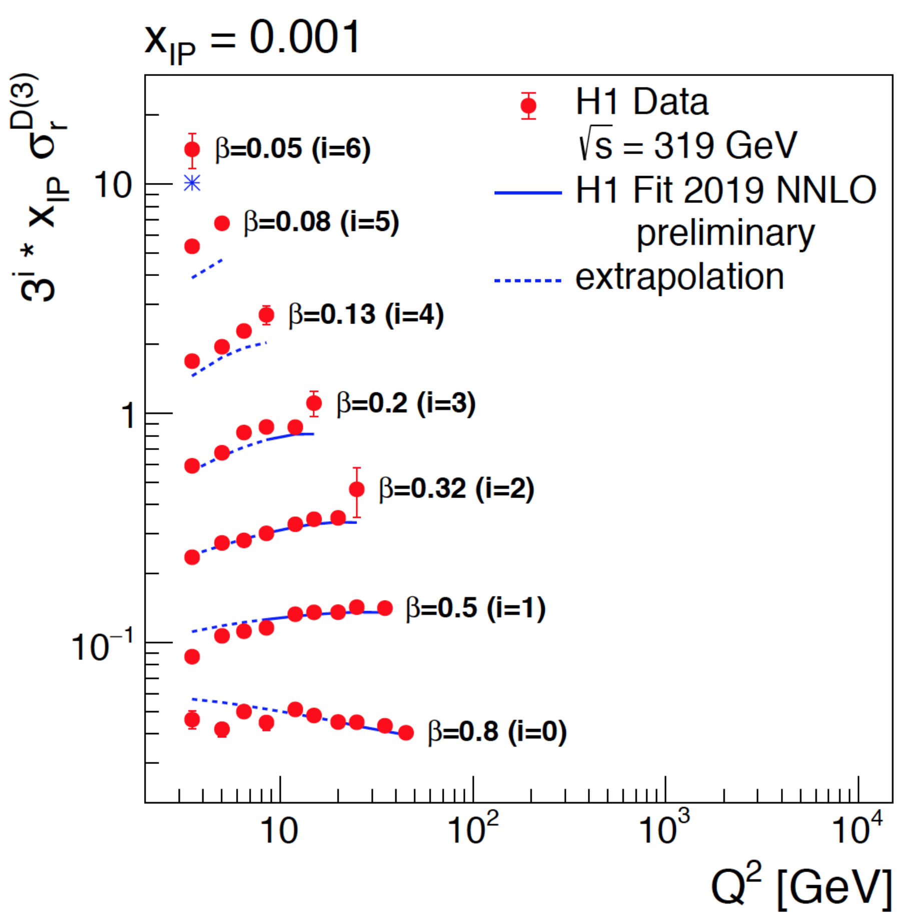
→ comparison problematic

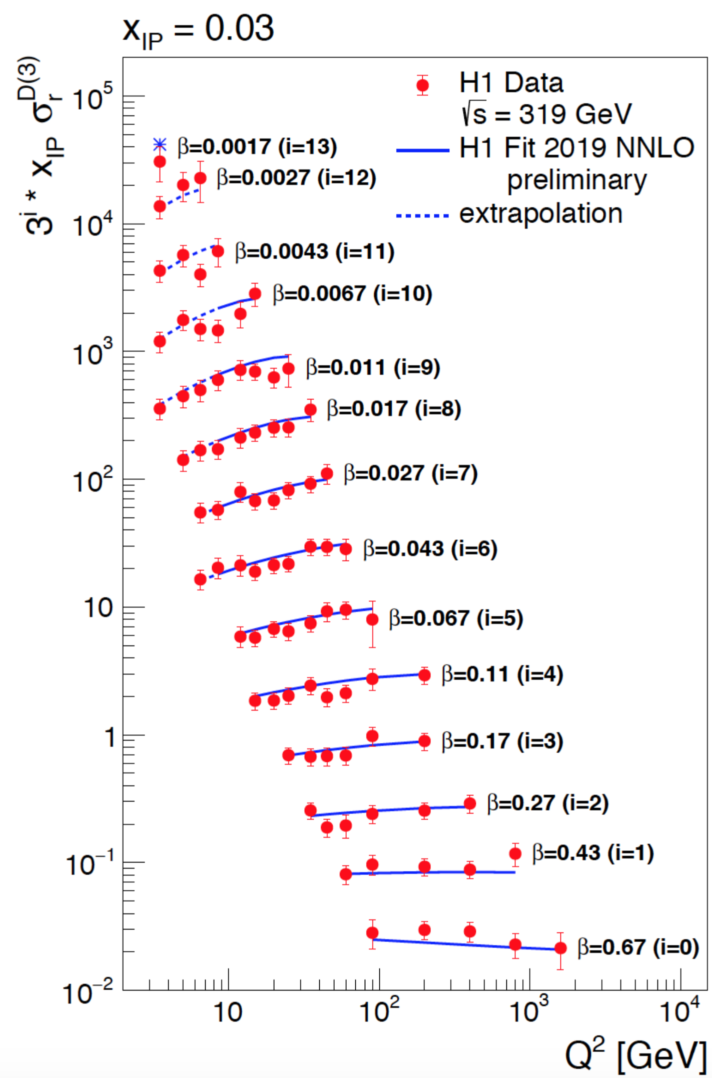
- Quark single component comparable for both fits
- Gluon component of the newer fit ~25% lower



Fitted data - Inclusive Sample - Q^2 dependence

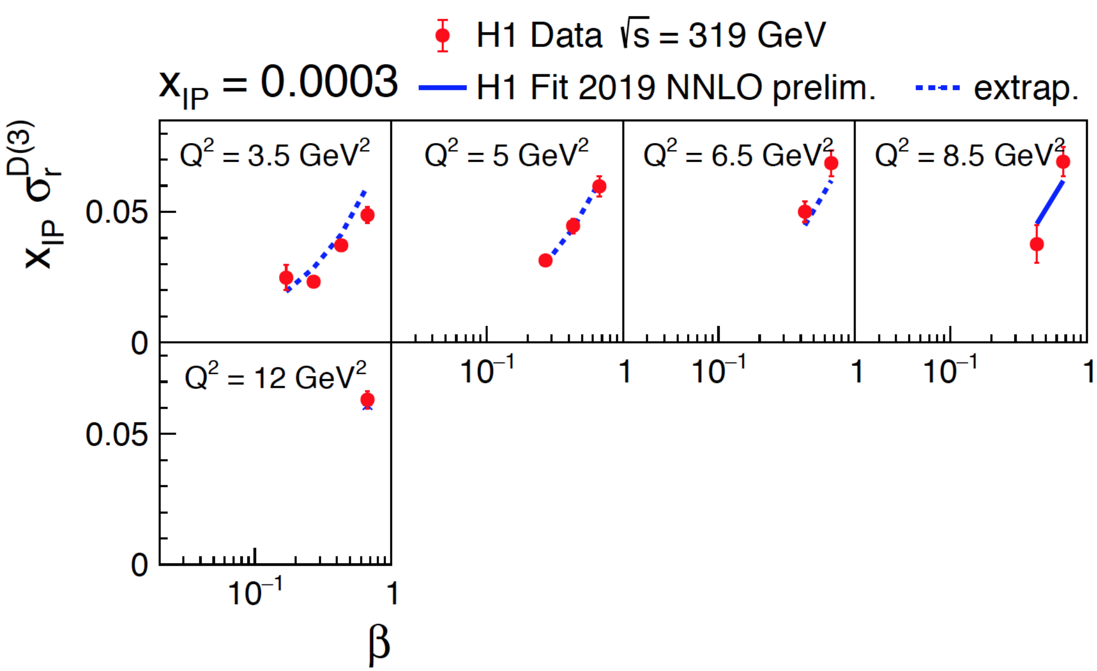
- Good description of fitted combined H1 HERA I+HERA-II data for xIP = 0.0003, 0.001, 0.003, 0.01, 0.03
- Description in "extrapolated" region Q^2 < 8.5 sometimes worse

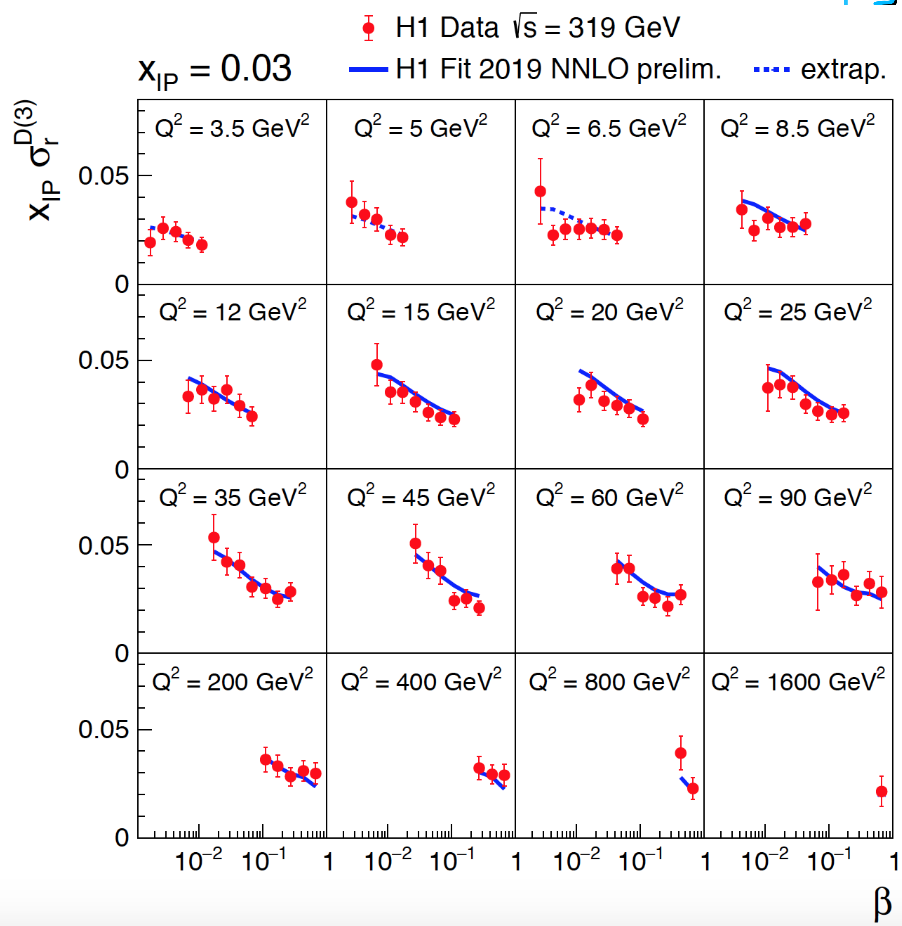




Fitted data - Inclusive Sample - β dependence

- Data well described by NNLO QCD predictions over wide range of xIP and β
  - At LO β is the momentum fraction of parton entering hard process wrt pomeron (argument of DPDF)

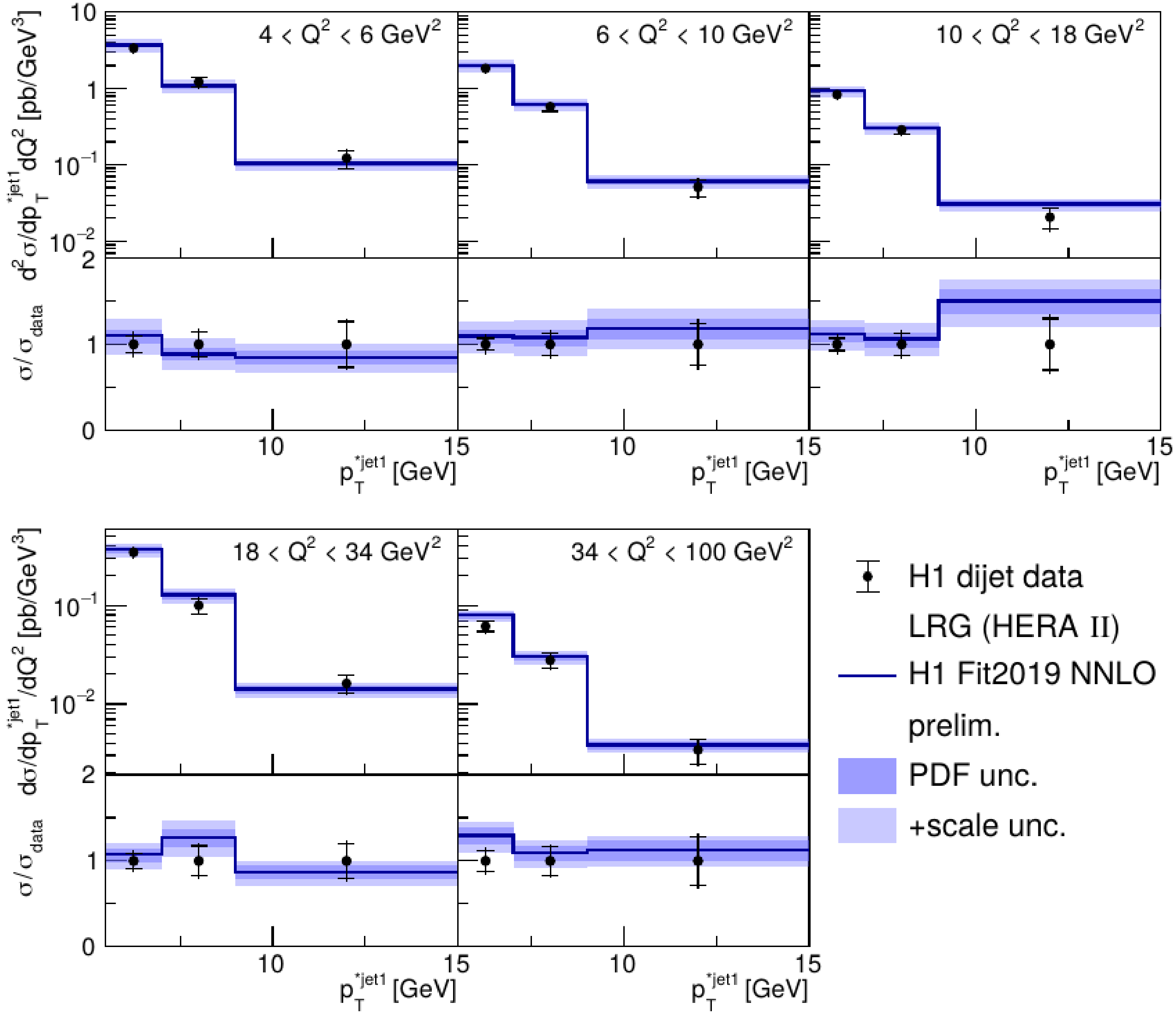




Fitted data - diffractive jets

- Currently only the 2D p_T^{jet1} vs Q^2 H1 HERA-II cross sections fitted
- Shown PDF & scale uncertainty of fit
- Good fit quality

$\chi^2/dof = 12/15$



Testing QCD collinear factorisation

Collinear QCD factorisation theorem in hard diffraction

- For diffractive events with a **hard scale** (e.g Q^2 or jets p_T)
- Factorization of the diffractive cross section into process independent DPDFs and partonic cross sections

$$d\sigma(ep \to epX) = \sum_i f_i^D(x, Q^2, x_{IP}, t) \otimes d\sigma^{ie}(x, Q^2)$$

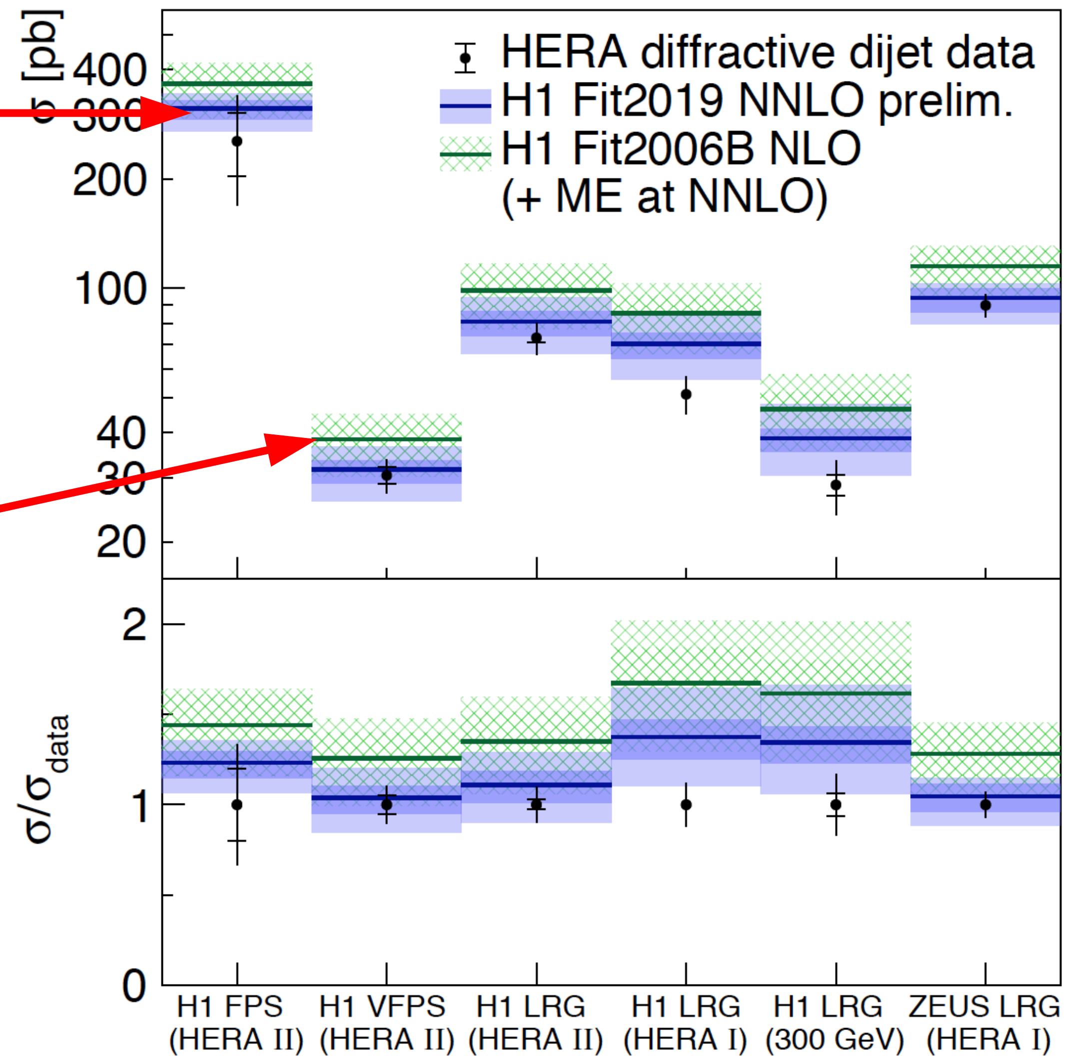
- For diffractive processes (including dijets) with high enough Q^2 factorization proven by Collins within perturbative QCD, for low Q^2 factorization breaking suggested

Factorization of Hard Processes in QCD
John C. Collins (IIT, Chicago & SUNY, Stony Brook), Davison E. Soper (Oregon U.), George F. Sterman (SUNY, Stony Brook). May 30, 1989. 91 pp.
Published in **Adv.Ser.Direct.High Energy Phys. 5 (1989) 1-91**
ITP-SB-89-31
DOI: 10.1142/9789814503266_0001
e-Print: **hep-ph/0409313** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Proof of factorization for diffractive hard scattering
John C. Collins (Penn State U.). Sep 1997. 12 pp.
Published in **Phys.Rev. D57 (1998) 3051-3056**, Erratum: **Phys.Rev. D61 (2000) 019902**
PSU-TH-189
DOI: 10.1103/PhysRevD.57.3051, 10.1103/PhysRevD.61.019902
e-Print: **hep-ph/9709499** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server

NNLO compared to HERA dijets

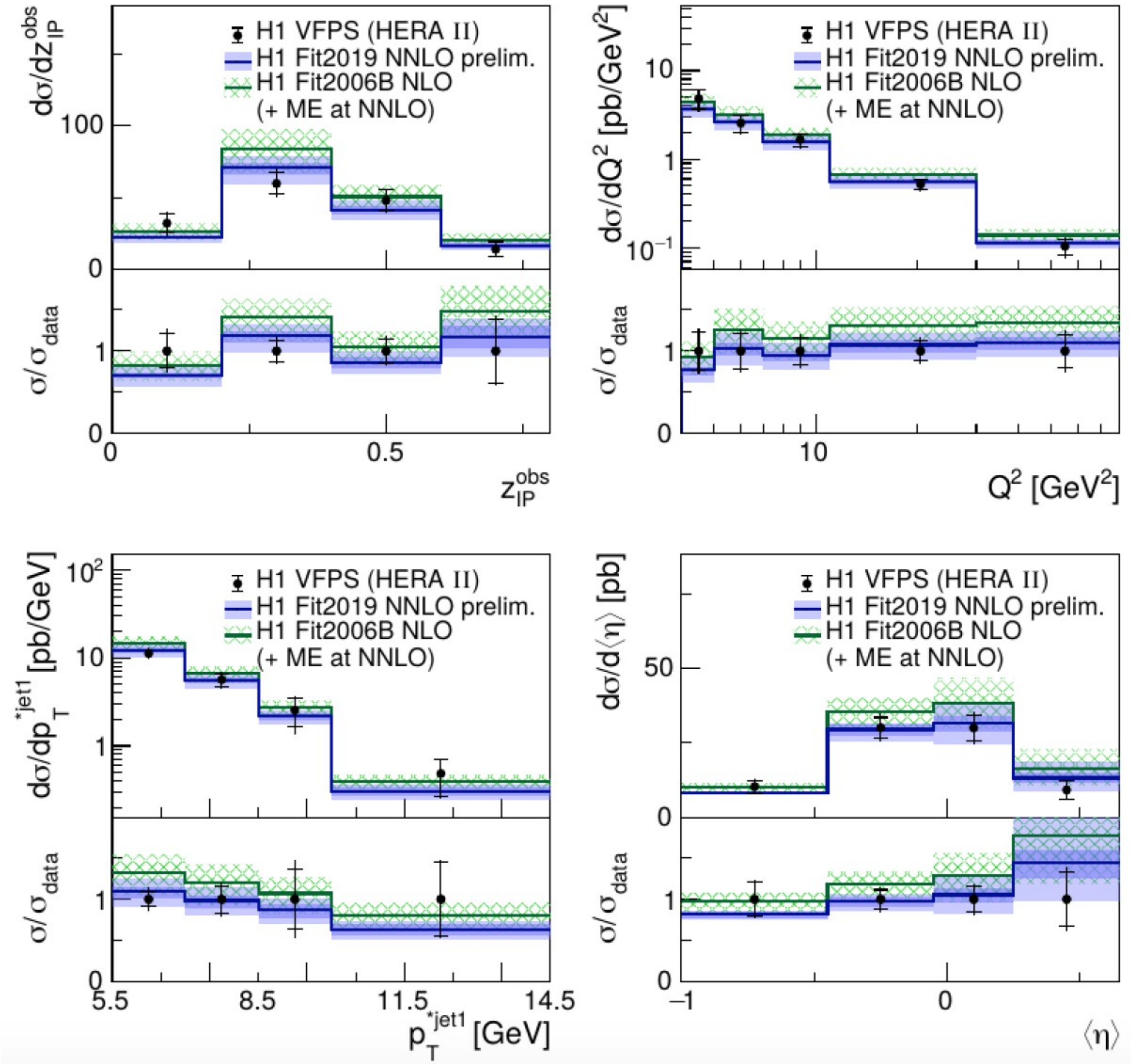
- H1 Fit2019 NNLO
  → describes well the H1 HERA-II data + ZEUS HERA-I
  → H1 HERA-I data slightly below
- H1 Fit2006B NLO with NNLO ME overestimates all cross sections



In addition to total cross sections we analyzed 39 single-differential and 4 double-differential distributions

NNLO compared to H1 jets (VFPS)

- Data based on Very Forward Proton Spectrometer (VFPS) do not contain any proton dissociation and are in many ways systematically independent from LRG-based data
- Good description of kinematic variables zIP, Q^2, p_T^{jet1}, <η>

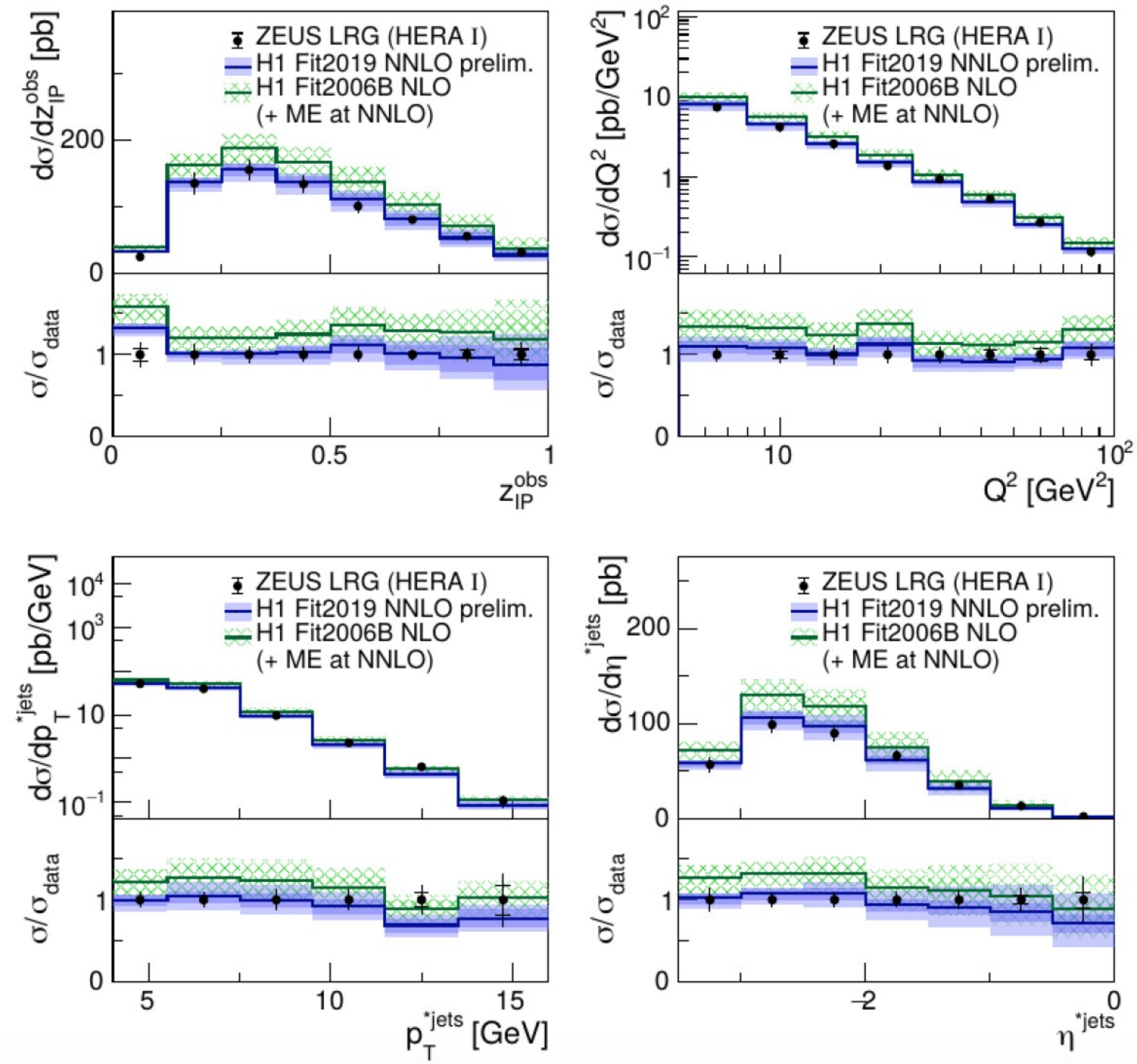


NNLO compared to ZEUS LRG dijets

- Good agreement of H1 Fit2019 NNLO predictions with ZEUS dijet data [arXiv:0708.1415]

At LO the $z_{I\!P}^{obs}$ directly related to the pomeron momentum fraction entering ME

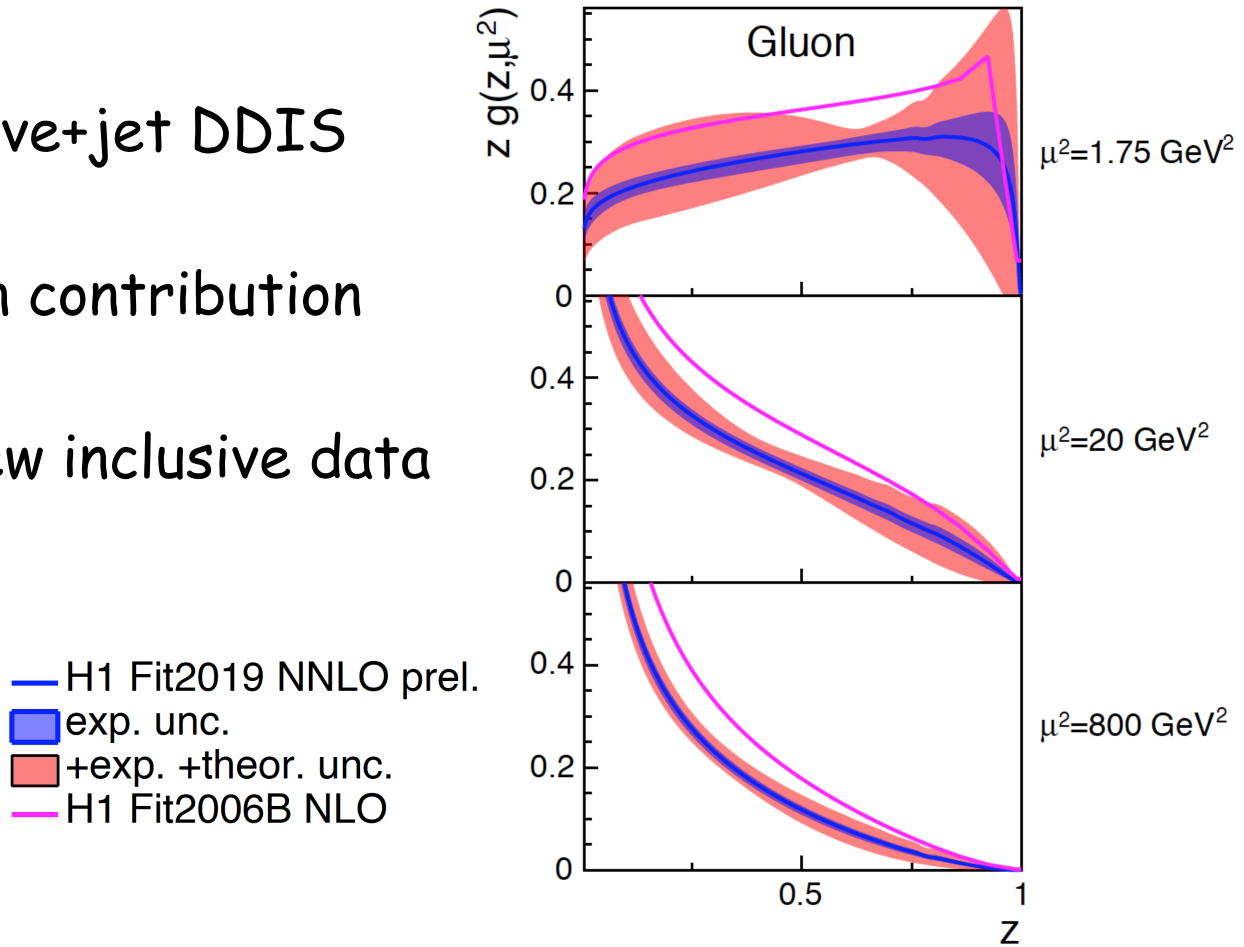
$$z_{I\!P}^{obs} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$



Factorisation in diffractive DDIS up to NNLO established

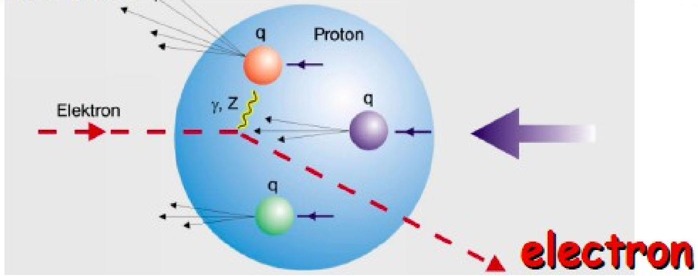
Summary and conclusions

- First combined fit to inclusive+jet DDIS data at NNLO
- NNLO DPDF has lower gluon contribution compared to NLO
- Jet data compatible with new inclusive data (for both NLO and NNLO)

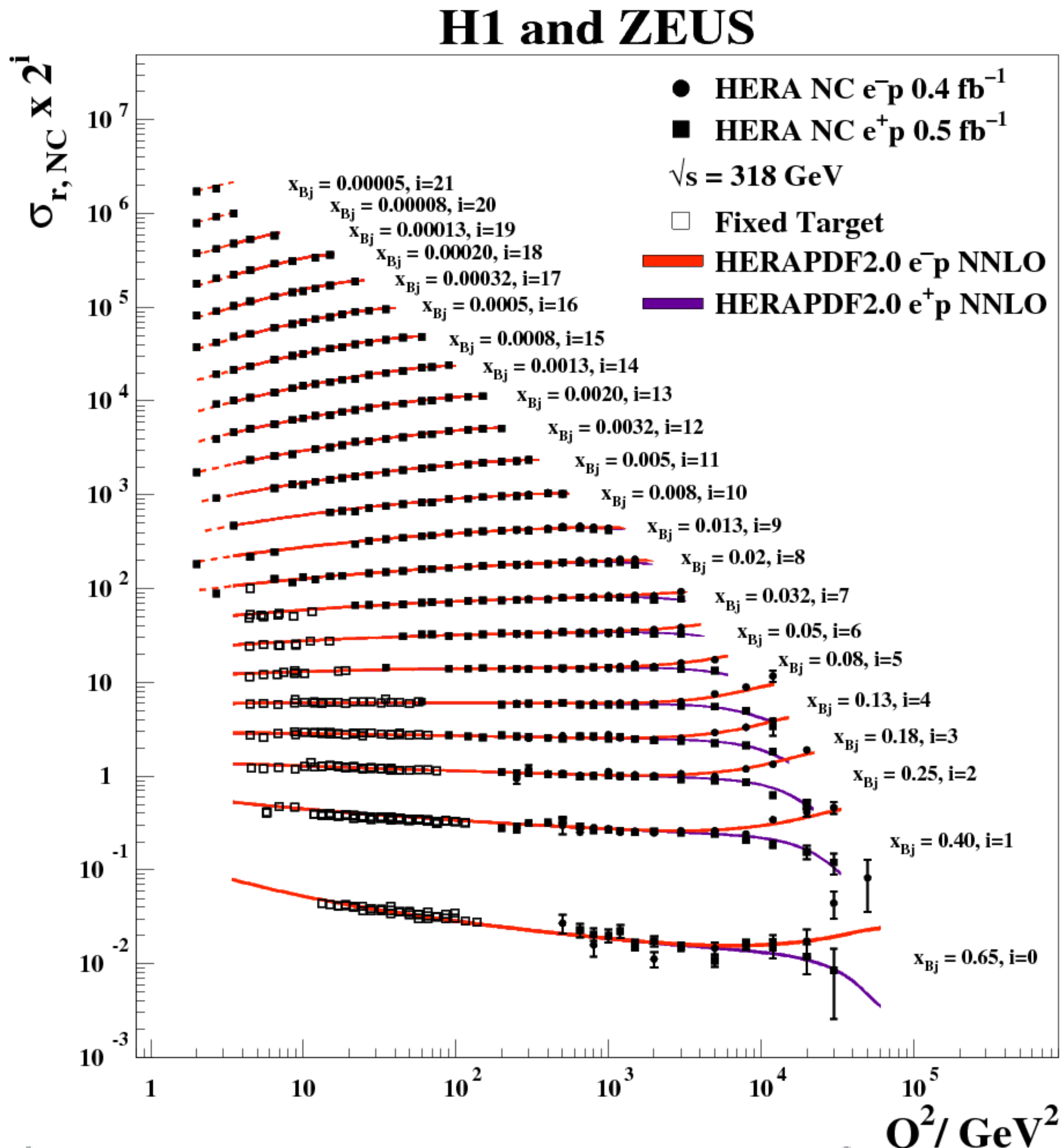


Factorisation in diffractive DDIS up to NNLO established

Additional information



HERA combined inclusive DIS



Eur. Phys. J. **C75** (2015), 12, 580

<u>HERA combined DIS data are core of every modern PDF extraction</u>

- 2927 data points combined to 1307
- impressive precision

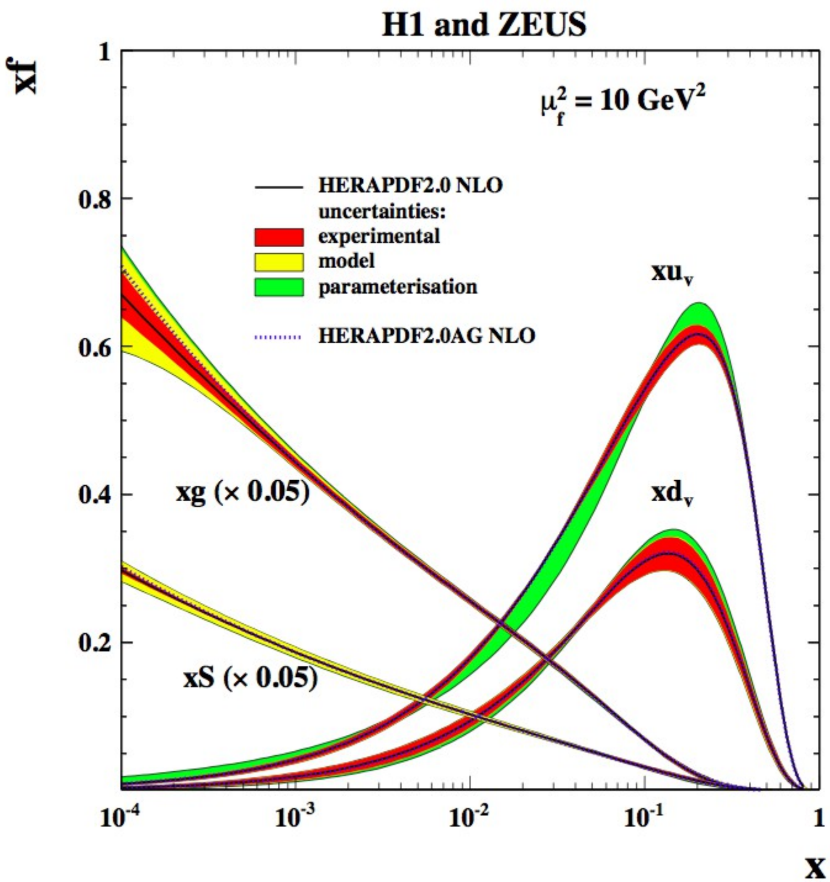
HERAPDF approach uses ONLY HERA data in global QCD fit

HERAPDF2.0 parameterisation

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

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right),\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}$$

- Additional constrains
  - A_{u_v}, A_{d_v}, A_g: constrained by the quark-number sum rules and momentum sum rule
  - $B_{\bar{U}} = B_{\bar{D}}$
  - $x\bar{s} = f_s x\bar{D}$ at starting scale, $f_s = 0.4$



PDF uncertainties

HERAPDF experimental, model and parameterisation uncertainties

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

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV²]	3.5	2.5	5.0
Q^2_{min} [GeV²] 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
μ_{f0} [GeV]	1.9	1.6	2.2

Adding D and E parameters to each PDF

- **Model uncertainties**
  - variations added in quadrature

- **Parametrisation uncertainties**
  - largest deviation

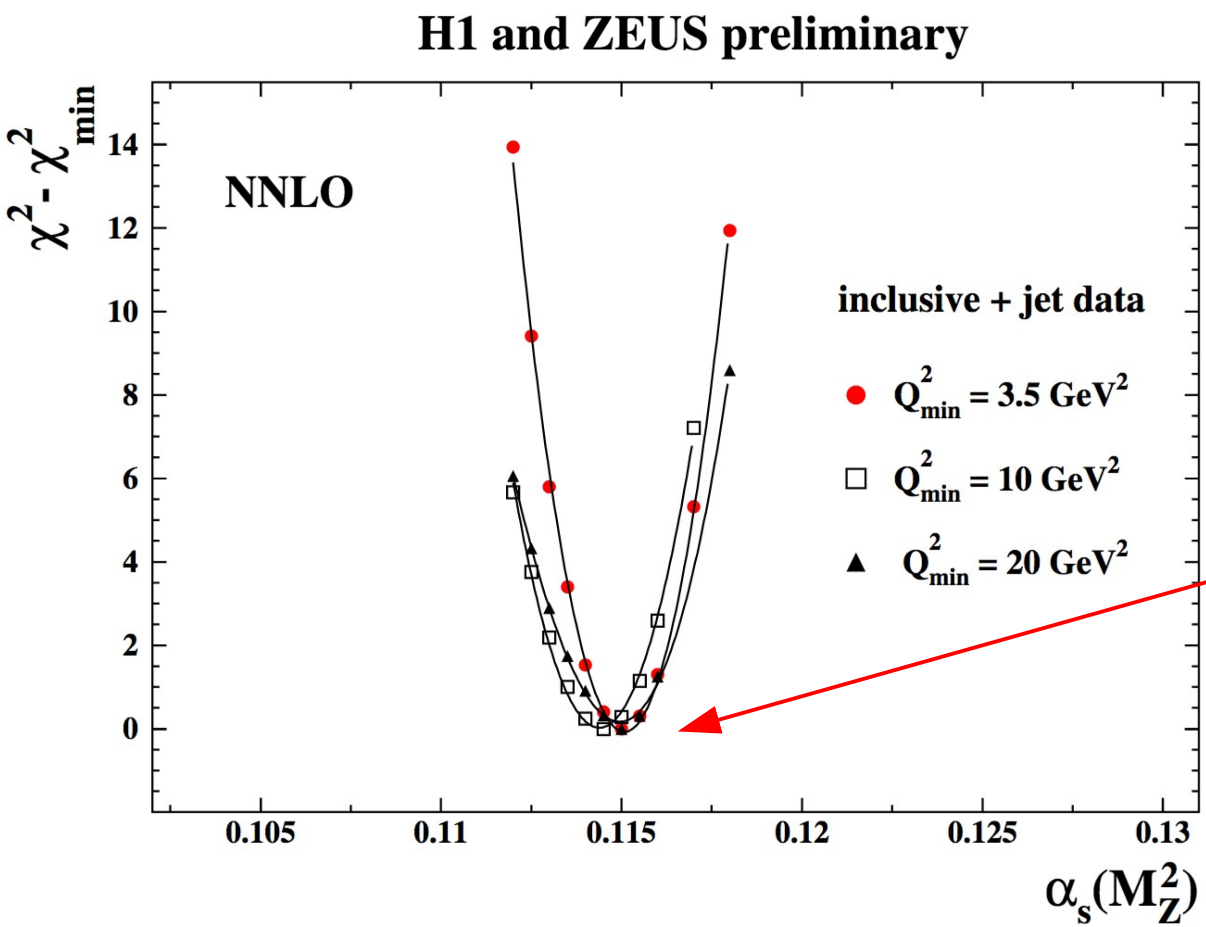
- When jets included – also hadronisation uncertainty

  → offsetting corrections given for each jet data set

Scans with harder Q^2 cuts

• HERA data at low x and Q^2 may be subject to need for ln(1/x) resummation or higher twist effects

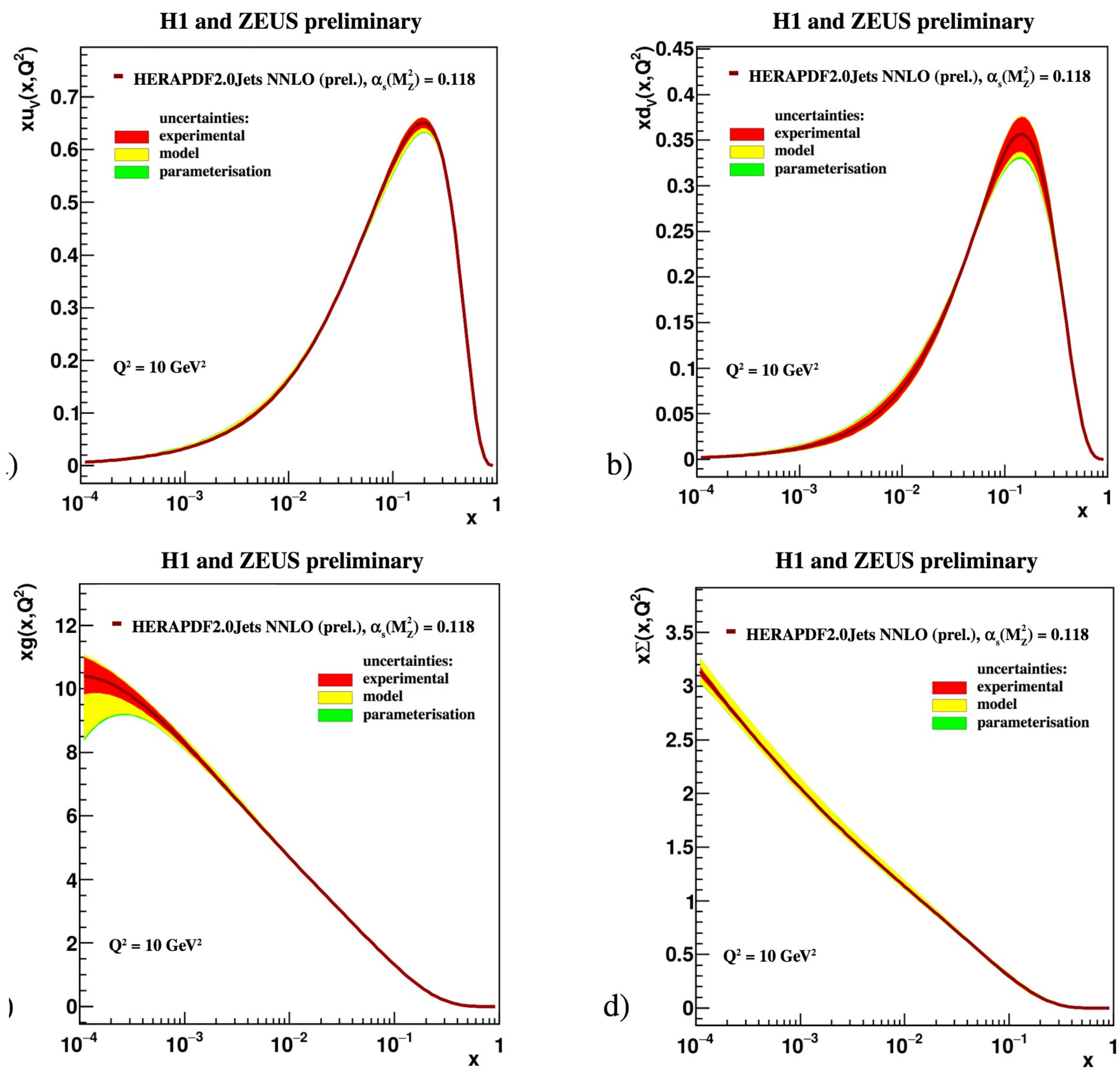
→ χ^2 scans performed with harder Q^2 cuts



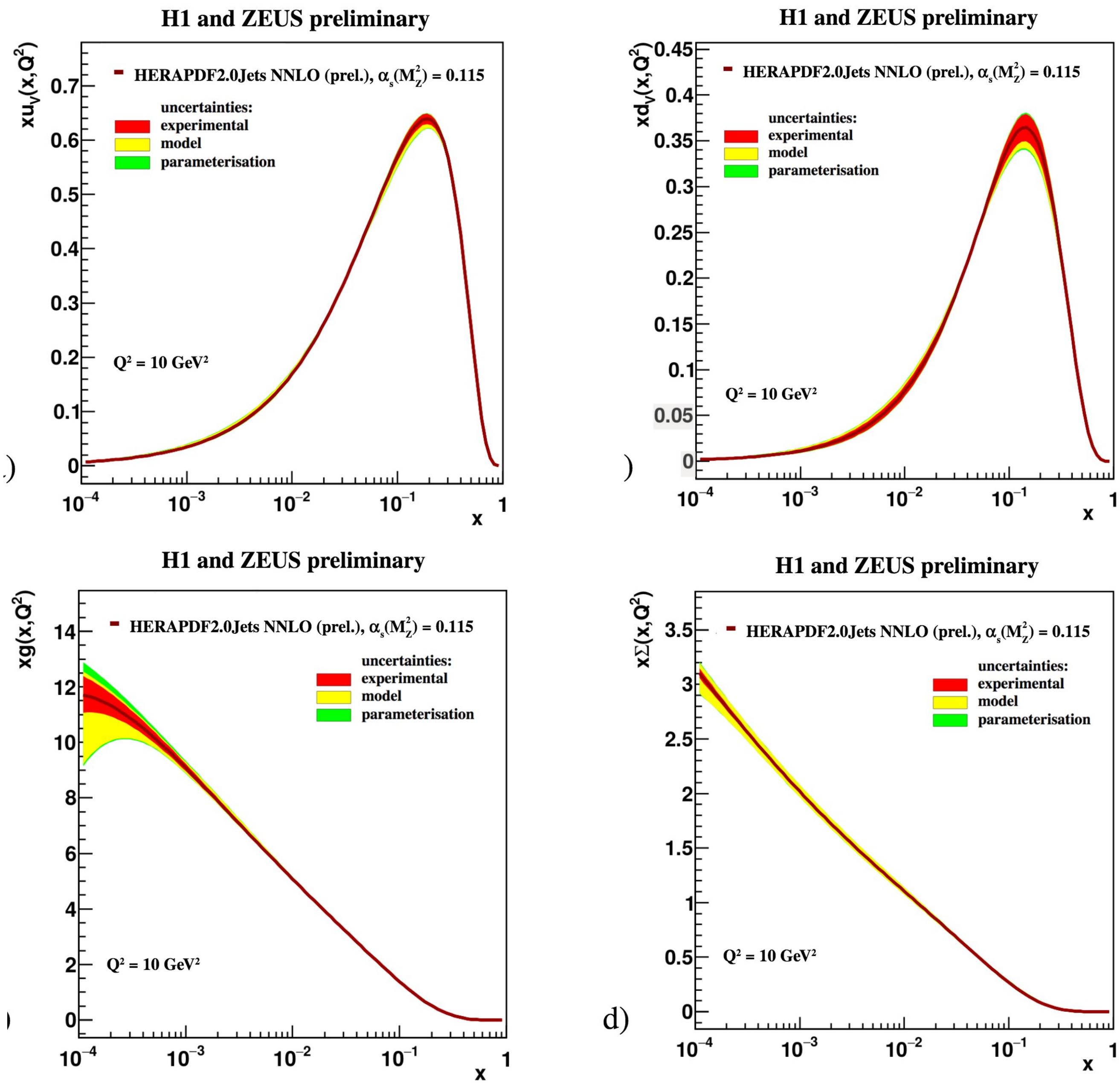
Q^2 cuts do not result in any significant change to the value of $\alpha_s(M_Z)$

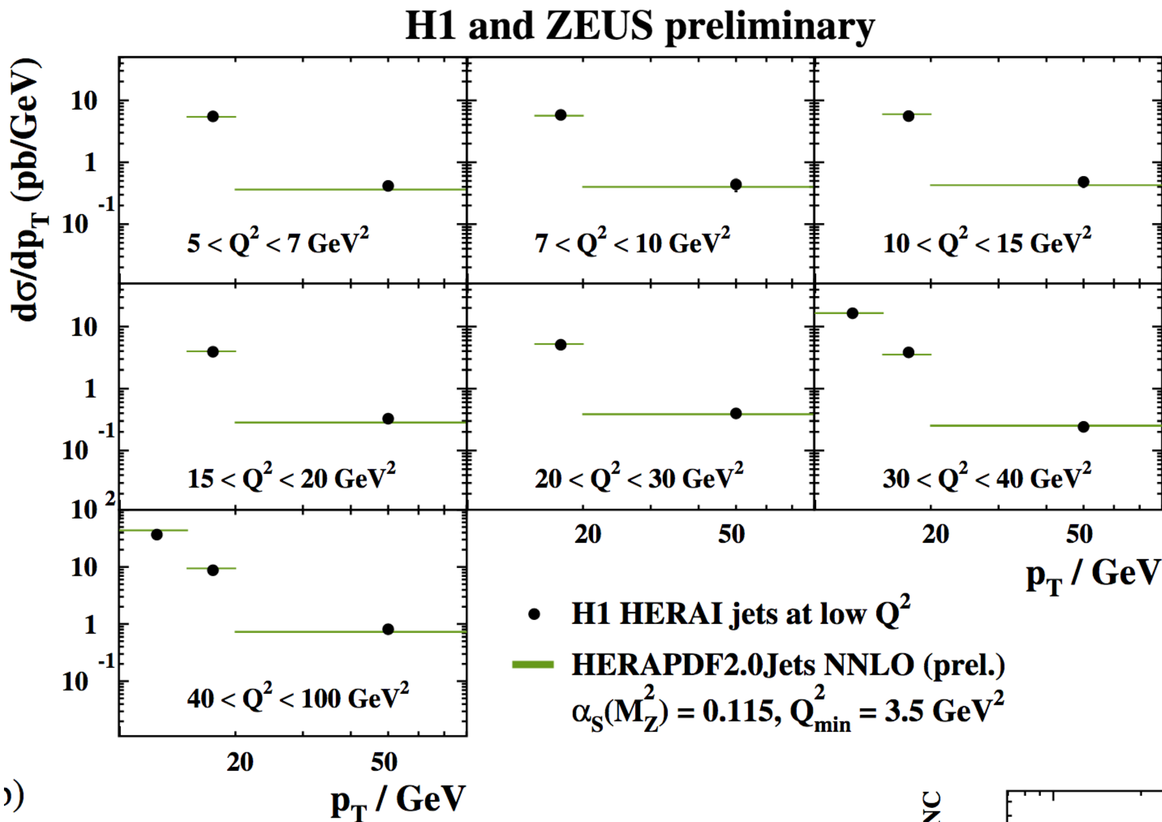
Let's first look at PDFs with α_s = 0.118, as for HERAPDF2.0

HERAPDF2.0Jets NNLO (prel.), $\alpha_s(M_Z)$ = 0.118



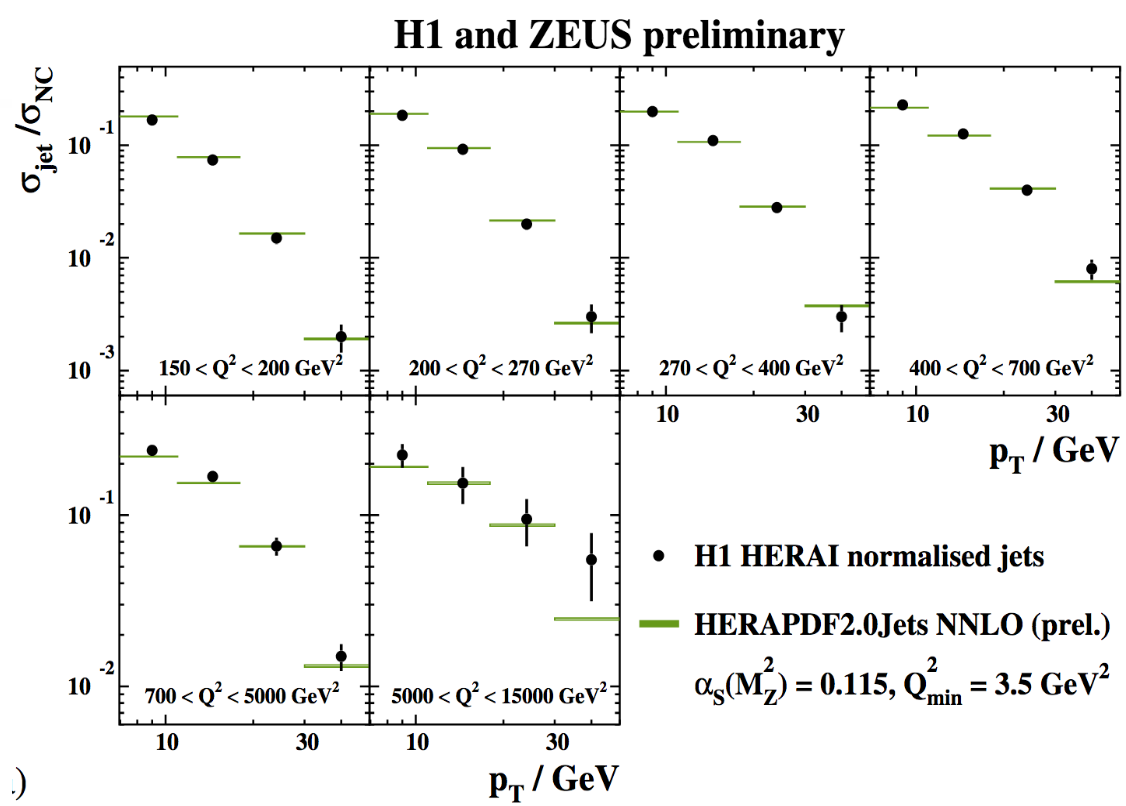
Let's look at PDF with $\alpha_s = 0.118$



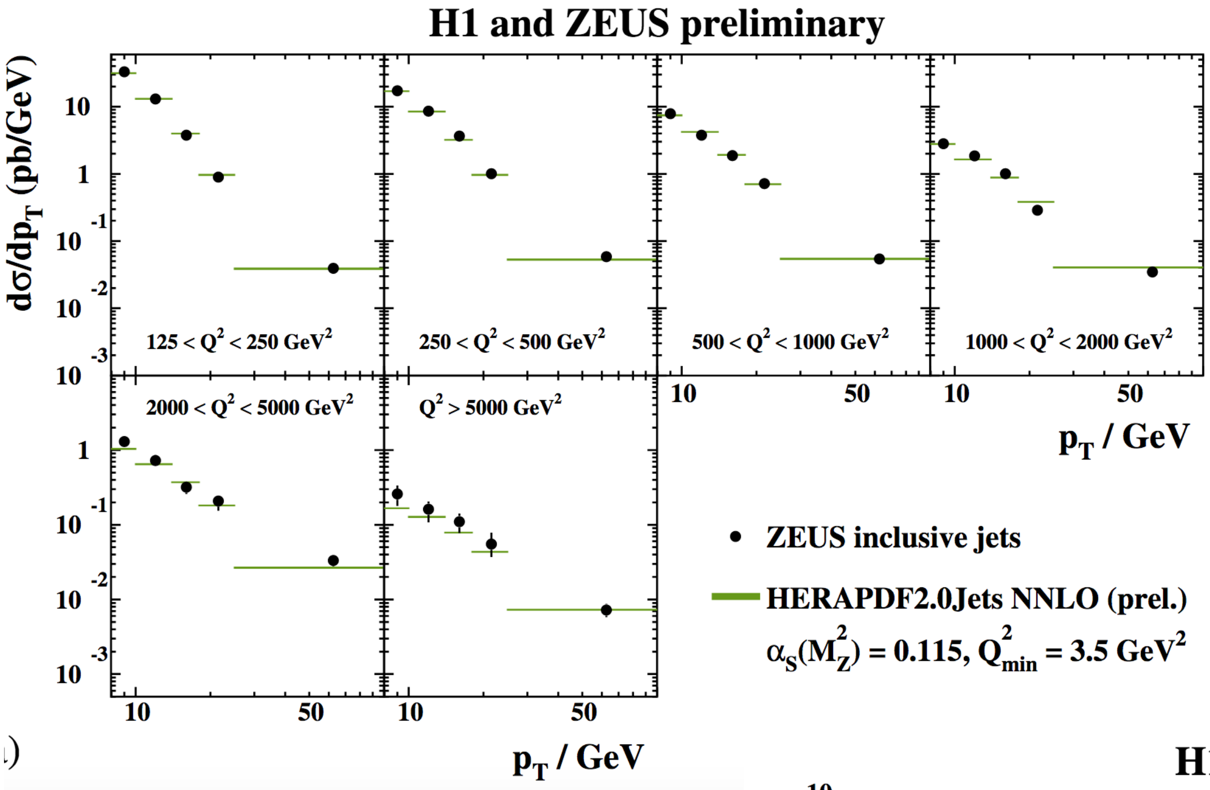


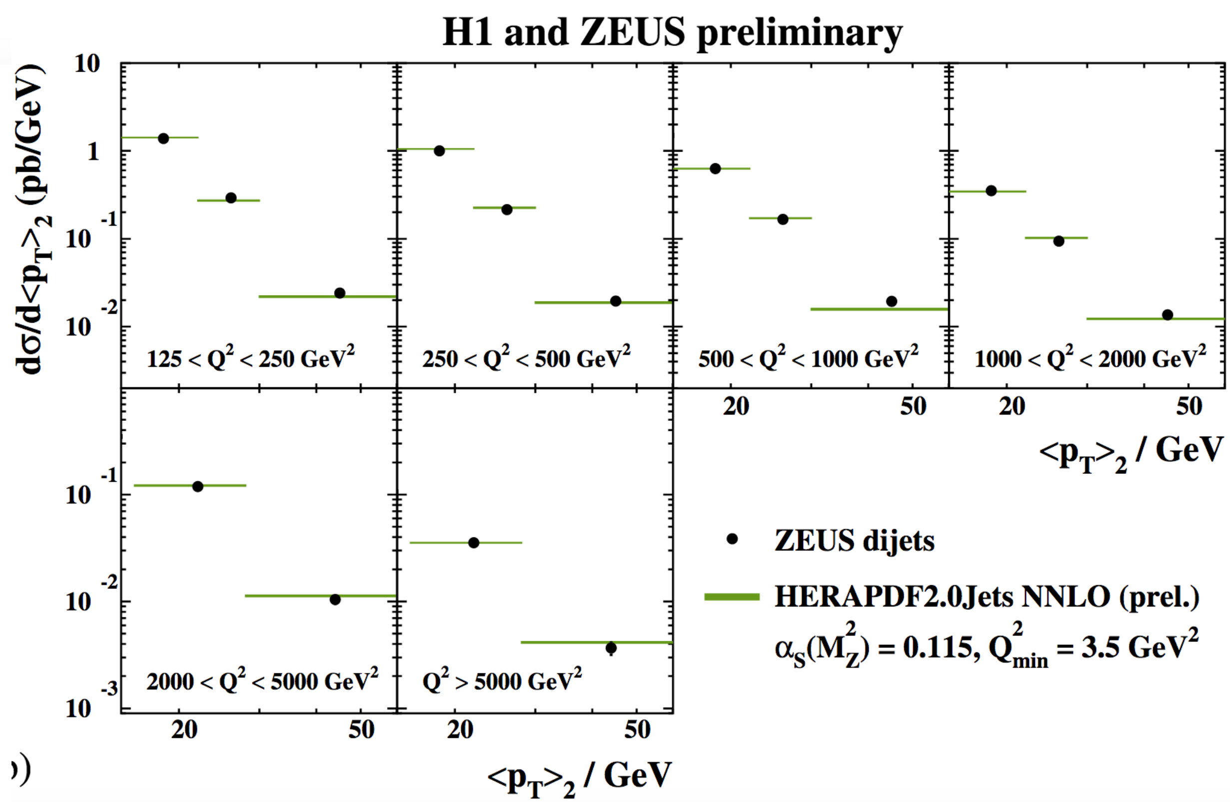
Comparison of theory predictions to H1 HERA I inclusive jets @ low and high Q^2

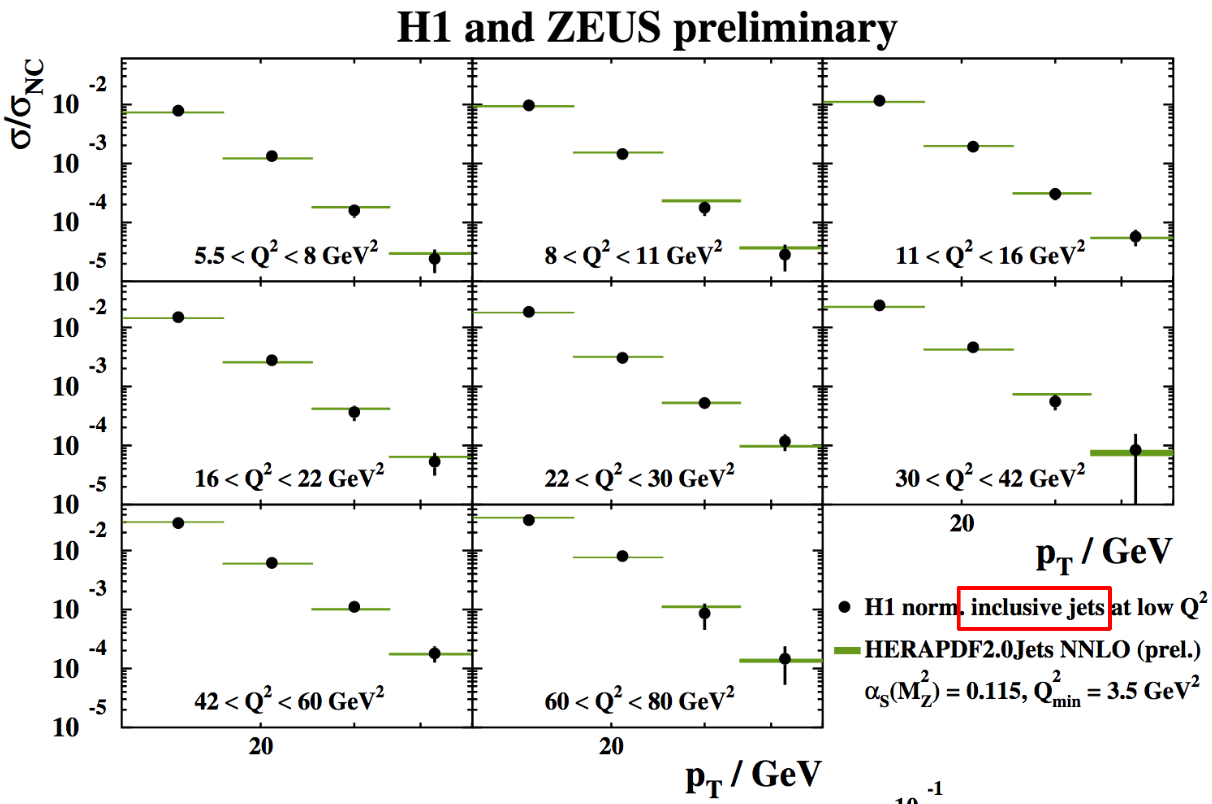
→ good agreement



Comparison of theory predictions to ZEUS HERA I inclusive jets and dijets
→ good agreement

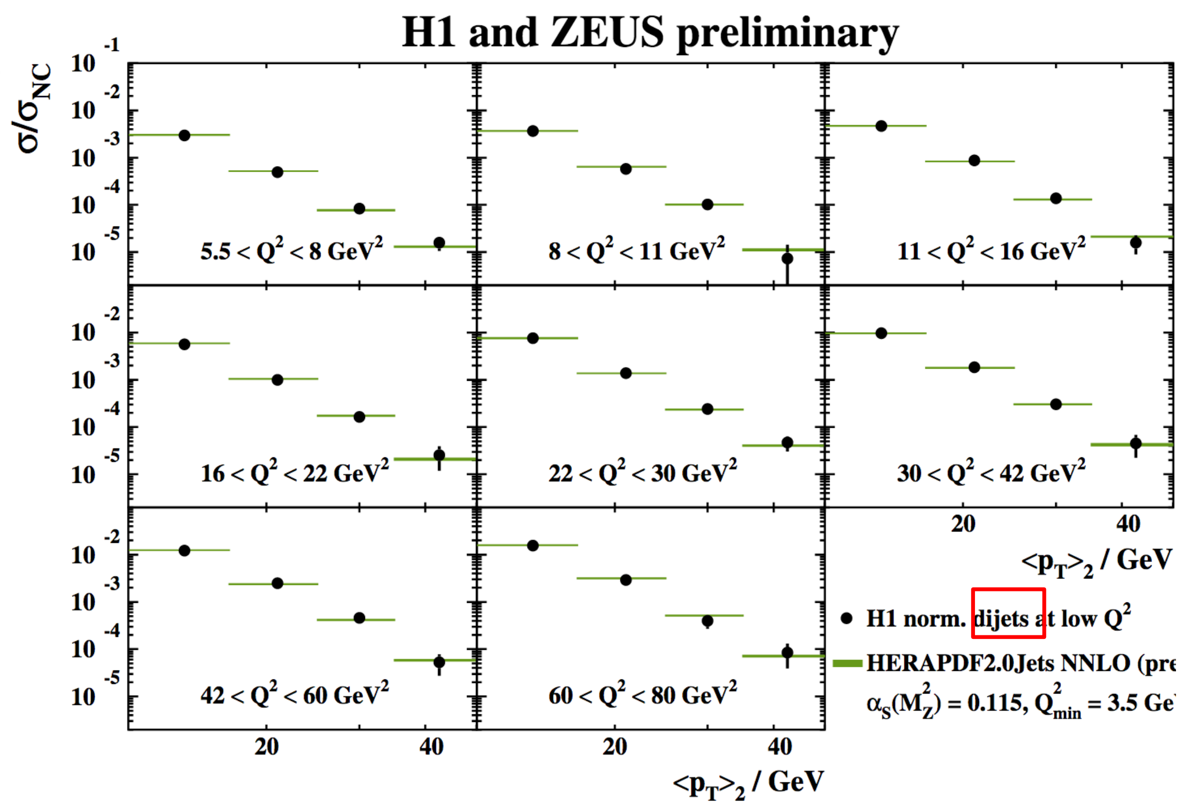


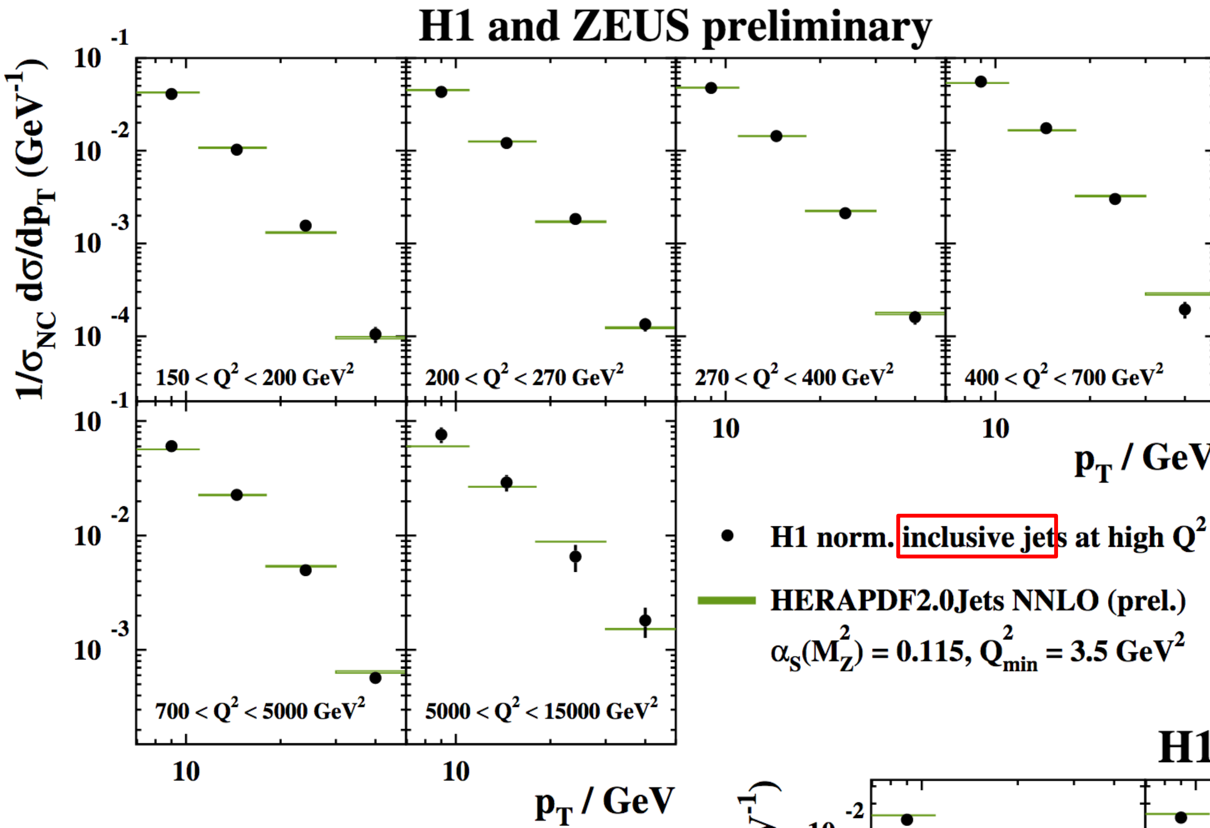




Comparison of theory predictions to H1 HERA II normalised jets @ low Q^2

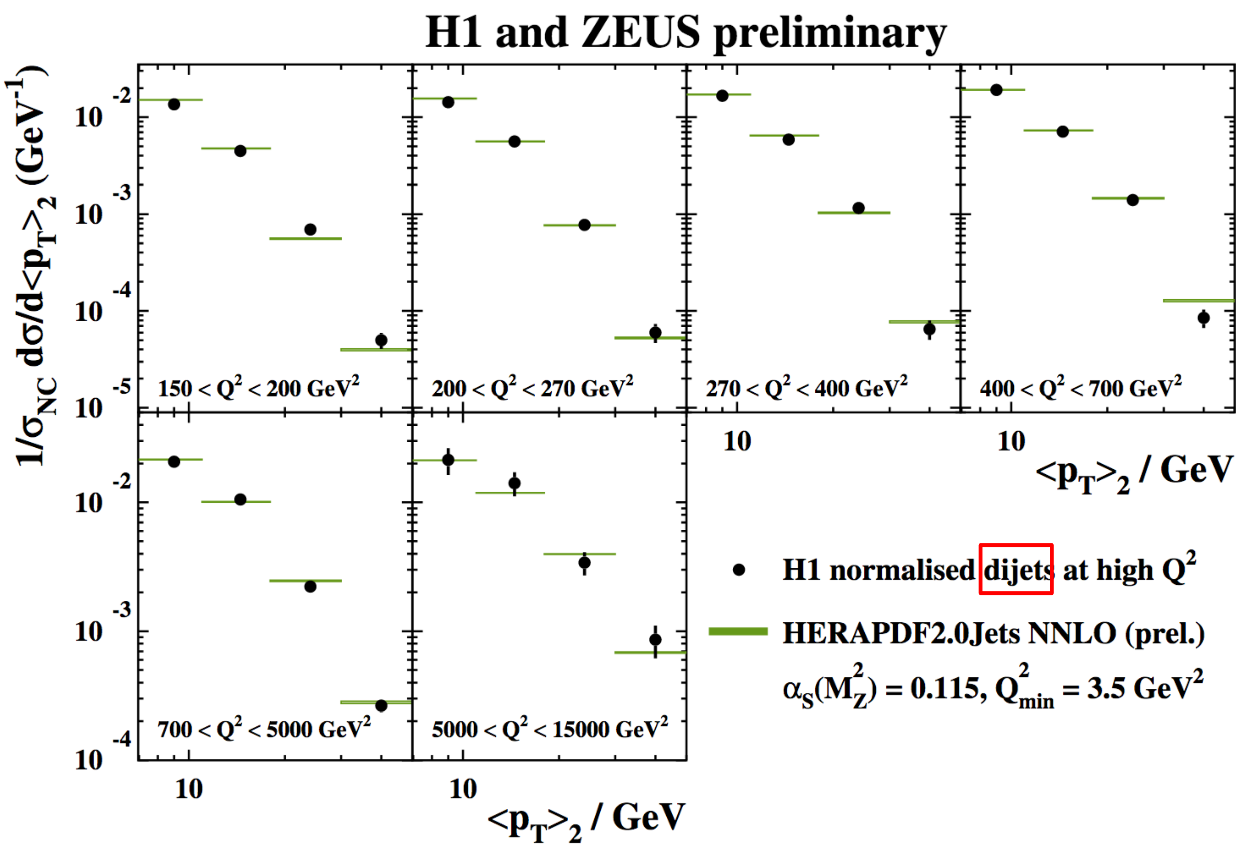
→ good agreement





Comparison of theory predictions to H1 HERA II normalised jets @ high Q^2

→ good agreement



Collinear QCD factorization in inclusive DDIS

$$\alpha_{em} \stackrel{\text{def}}{=} \frac{1}{137}$$

- The reduced diffractive cross section:

$$\frac{d^3\sigma^{ep\to eXY}}{dQ^2 d\beta dx_{I\!P}} = \frac{4\pi\alpha_{em}^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right)\underbrace{\left(F_2 - \frac{y^2}{1+(1-y)^2}F_L\right)}_{\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P})}$$

- Regge factorization ansatz

Fitted — Fixed

$$F_{2/L}^{D(3)}(\beta, Q^2, x_{I\!P}) = f_{I\!P/p}(x_{I\!P})F_{2/L}^{I\!P}(\beta, Q^2) + n_{I\!R} f_{I\!R/p}(x_{I\!P})F_{2/L}^{I\!R}(\beta, Q^2)$$

$$F_{2/L}^{I\!P}(\beta, Q^2) = C_{2/L}^{i}(\beta/z, Q^2, \mu^2) \otimes f_{i/I\!P}(z, \mu^2)$$

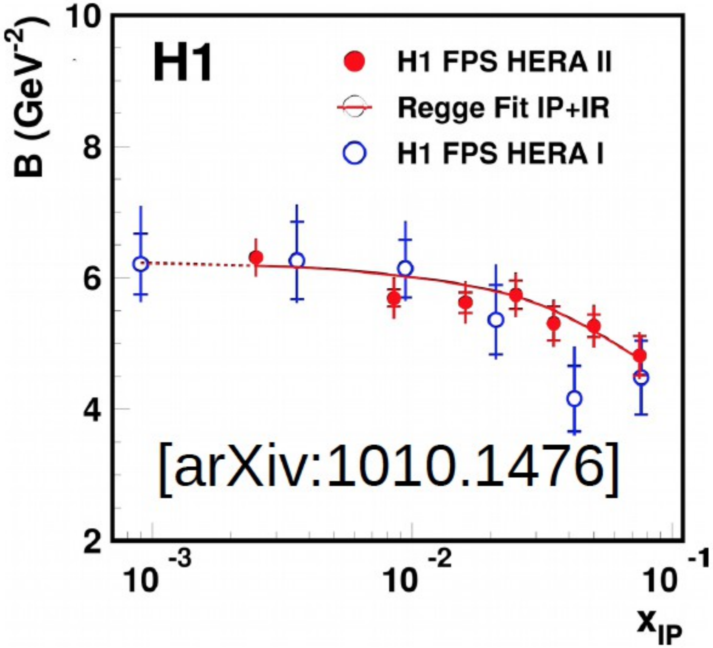
Up to NNLO — Standard DIS coef. functions — Obeys DGLAP

Both coef. functions and DGLAP evolution depend on α_s and m_c, m_b

Flux Parametrization

- Param. inspired by Regge theory (Streng and Berger):

$$f_{I\!P/p}(x_{I\!P},t) \propto \left(\frac{1}{x_{I\!P}}\right)^{2[\alpha_{I\!P}(0)+\alpha'_{I\!P}t]-1} e^{B^0_{I\!P}t} \Rightarrow \frac{d\sigma}{dt} \propto e^{-B|t|}$$



B-slope dependence:

$$B = B^0_{I\!P} + 2\alpha'_{I\!P}\left(\log\frac{1}{x_{I\!P}}\right)$$

$$\Rightarrow \begin{array}{l} \alpha'_{I\!P} = 0.04^{+0.08}_{-0.06}\ \mathrm{GeV}^{-2} \\ B^0_{I\!P} = 5.73^{+0.84}_{-0.93}\ \mathrm{GeV}^{-2} \end{array}$$

Uncertainties anti-correlated

- t-integrated version:

~1.2

~0.01

Fitted

Fixed

$$f_{I\!P/p}(x_{I\!P}) \propto \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(0)-1} \frac{1}{1+2\frac{\alpha'_{I\!P}}{B^0_{I\!P}}\log\frac{1}{x_{I\!P}}} \doteq \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(0)-1-2\frac{\alpha'_{I\!P}}{B^0_{I\!P}}}$$