

Measurement and  
QCD analysis of inclusive jet production  
in deep inelastic scattering  
at ZEUS

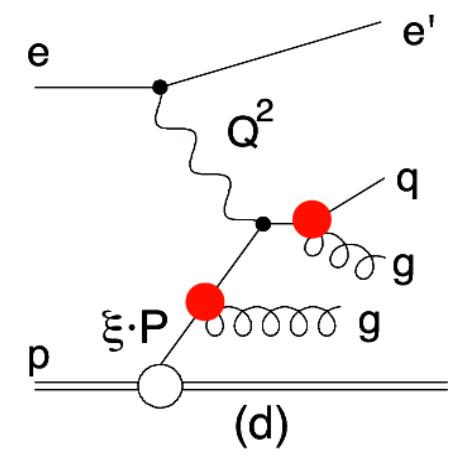
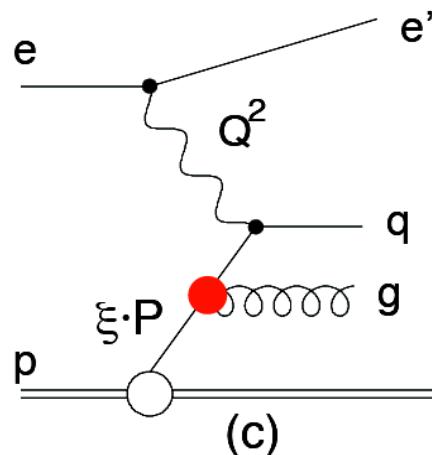
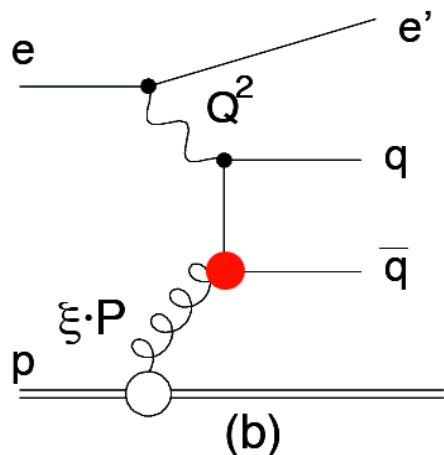
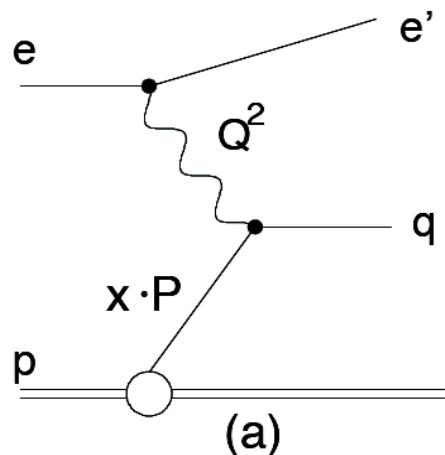


# Jets produced @ DESY for almost 45 years

At HERA direct information on gluon and  $\alpha_s(M_Z)$  comes from jet production

→ Possible simultaneous determination of parton densities and  $\alpha_s(M_Z)$

## Jets at HERA



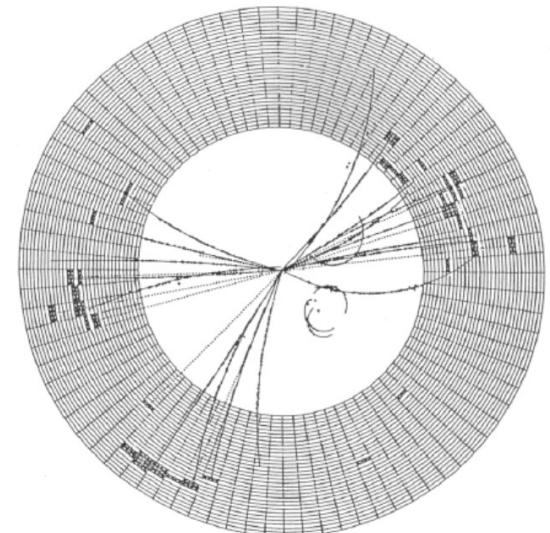
elweak coupling

$\propto \alpha_s$

dijets

$\propto \alpha_s^2$   
trijets

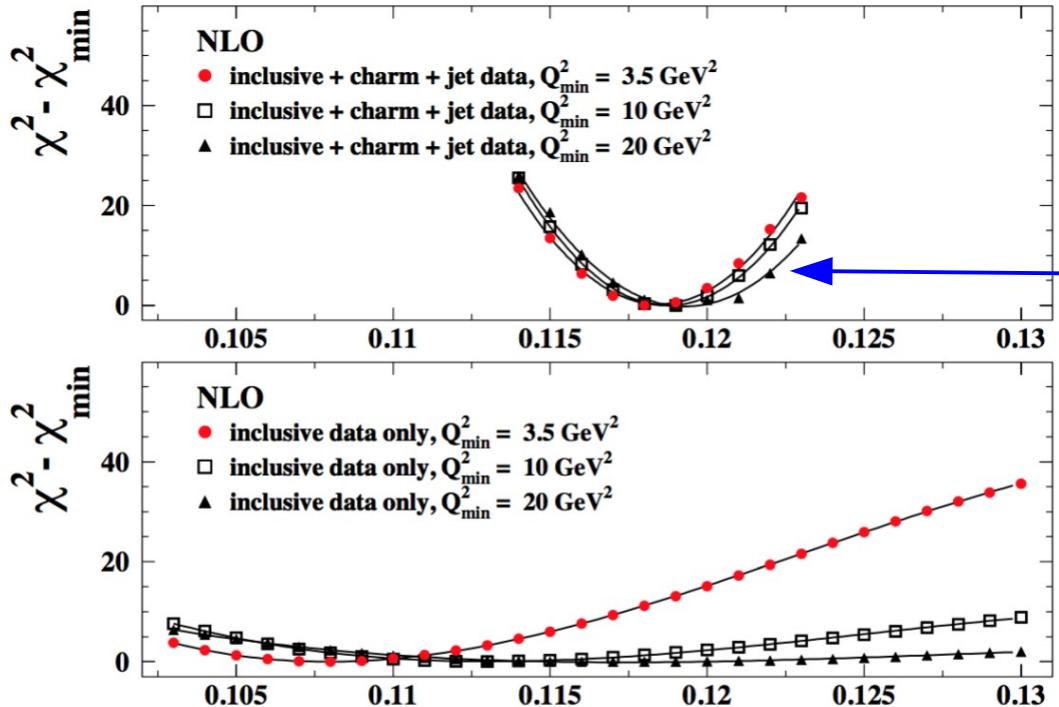
## Jets at PETRA, 1979



\*\*\* SUMS (GeV) \*\*\* PTOT 35.768 PTRANS 29.954 PLONG 15.788 CHARGE -2  
TOTAL CLUSTER ENERGY 15.169 PHOTON ENERGY 4.893 NR OF PHOTONS 11

# Why study jets @ HERA?

## H1 and ZEUS



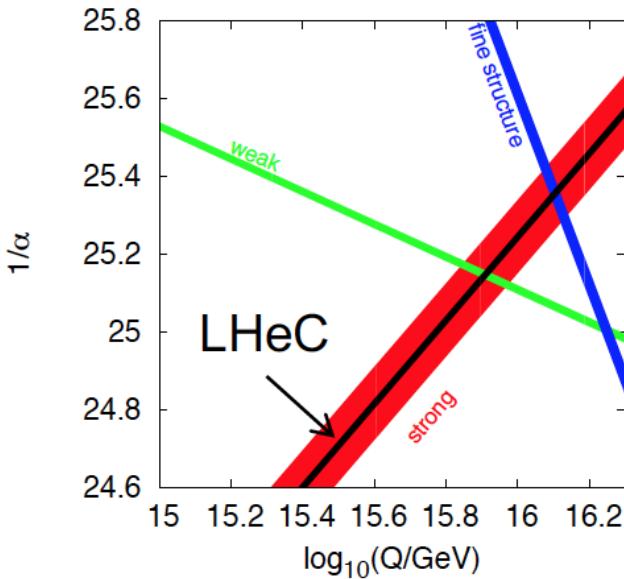
- HERA inclusive data carry little information on  $\alpha_s(M_Z)$
- Jet data sensitive to  $\alpha_s(M_Z)$



New NNLO calculations for HERA ep jet production available now

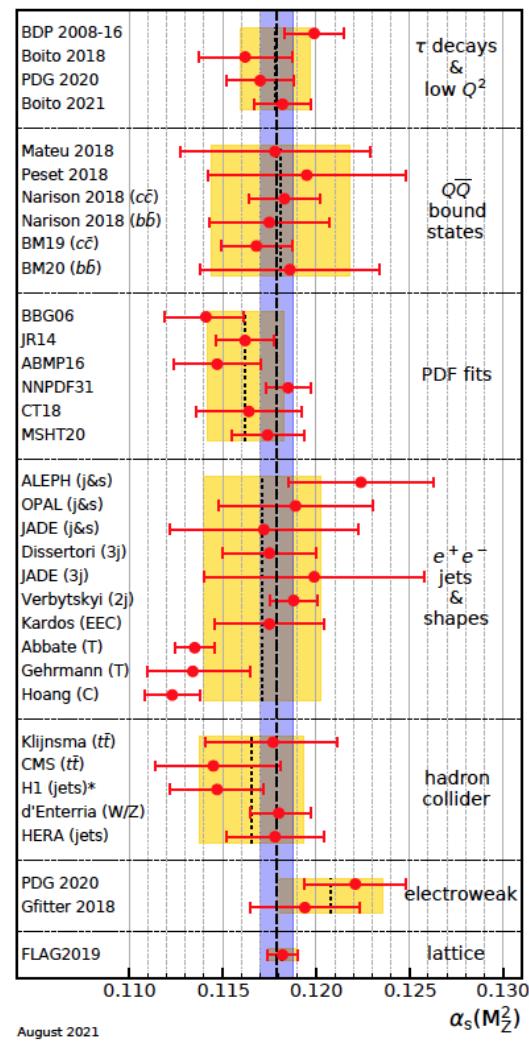
- Implemented in FastNLO and APPLEGRID → fast cross section calculation possible
- EPJ C 82, 243 (2022) arXiv:2112.01120
- Possible simultaneous determination of PDFs and  $\alpha_s(M_Z)$  at NNLO

# Why look at $\alpha_s$ ?



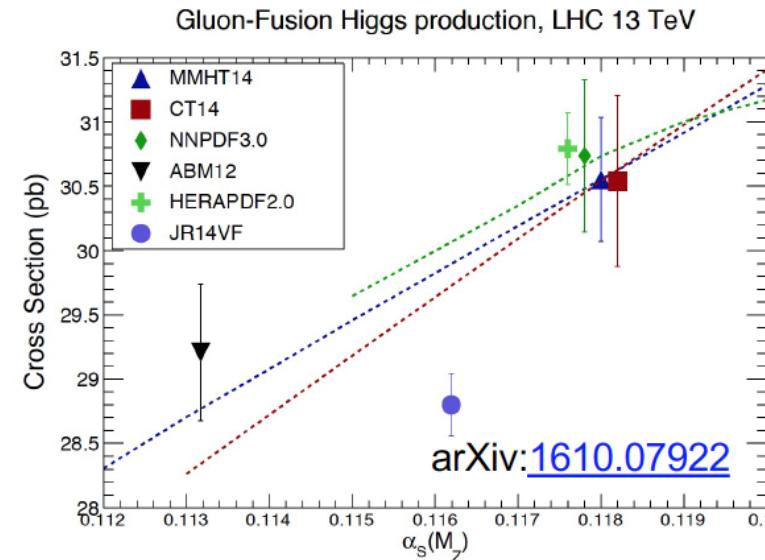
- $\alpha_s$  is least known coupling constant; needed to constrain GUT scenarios; cross section predictions, including Higgs;

...



PDG21:  $\alpha_s = 0.1175 \pm 0.0010$  (w/o lattice)

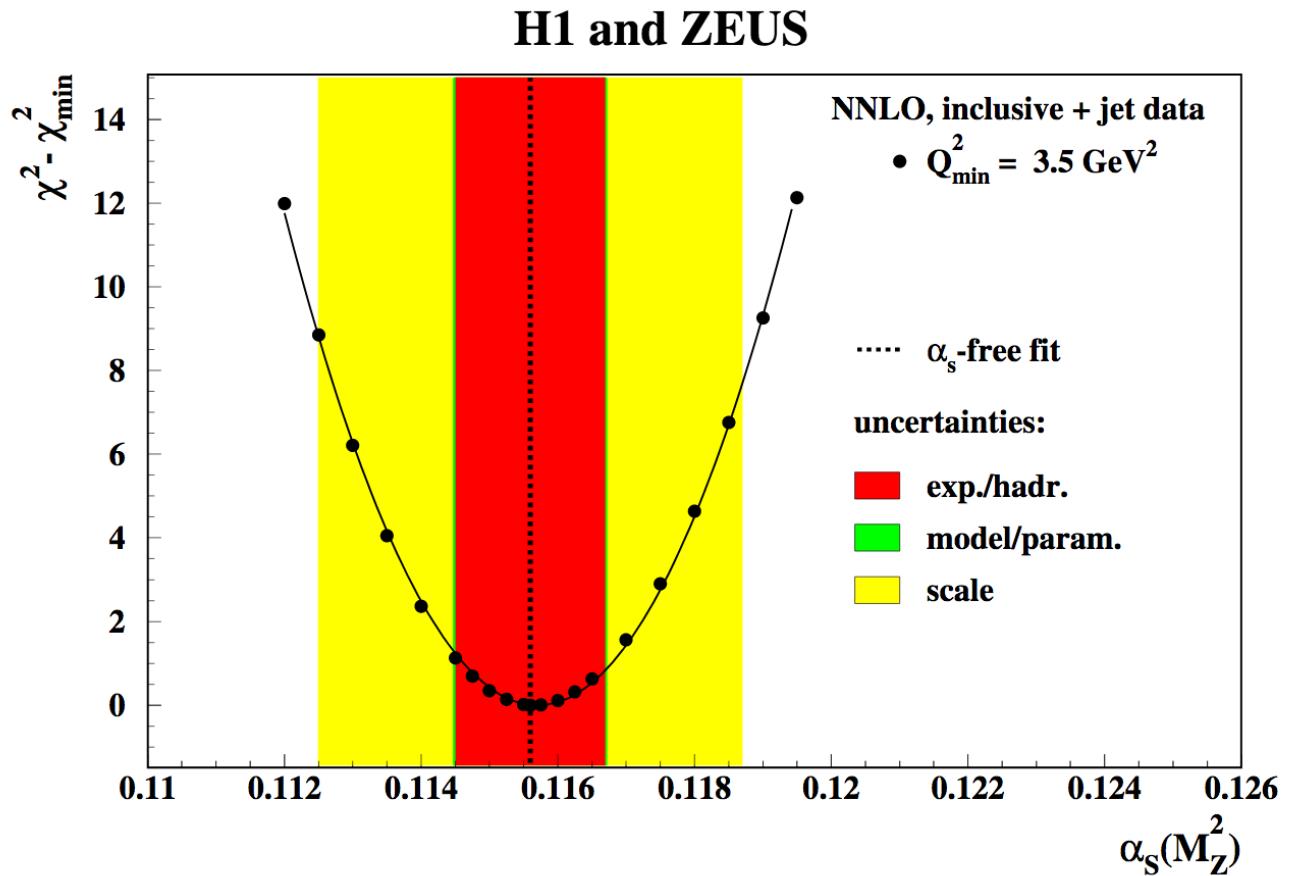
what is true  $\alpha_s$  central value and uncertainty?  
new precise determinations have important role to play



- PDFs and/or  $\alpha_s$  limit: precision SM and Higgs measurements, BSM searches, ...

# New ZEUS jet measurement

→ Recent HERAPDF2.0Jets NNLO PDFs and  $\alpha_s(M_Z)$  determination



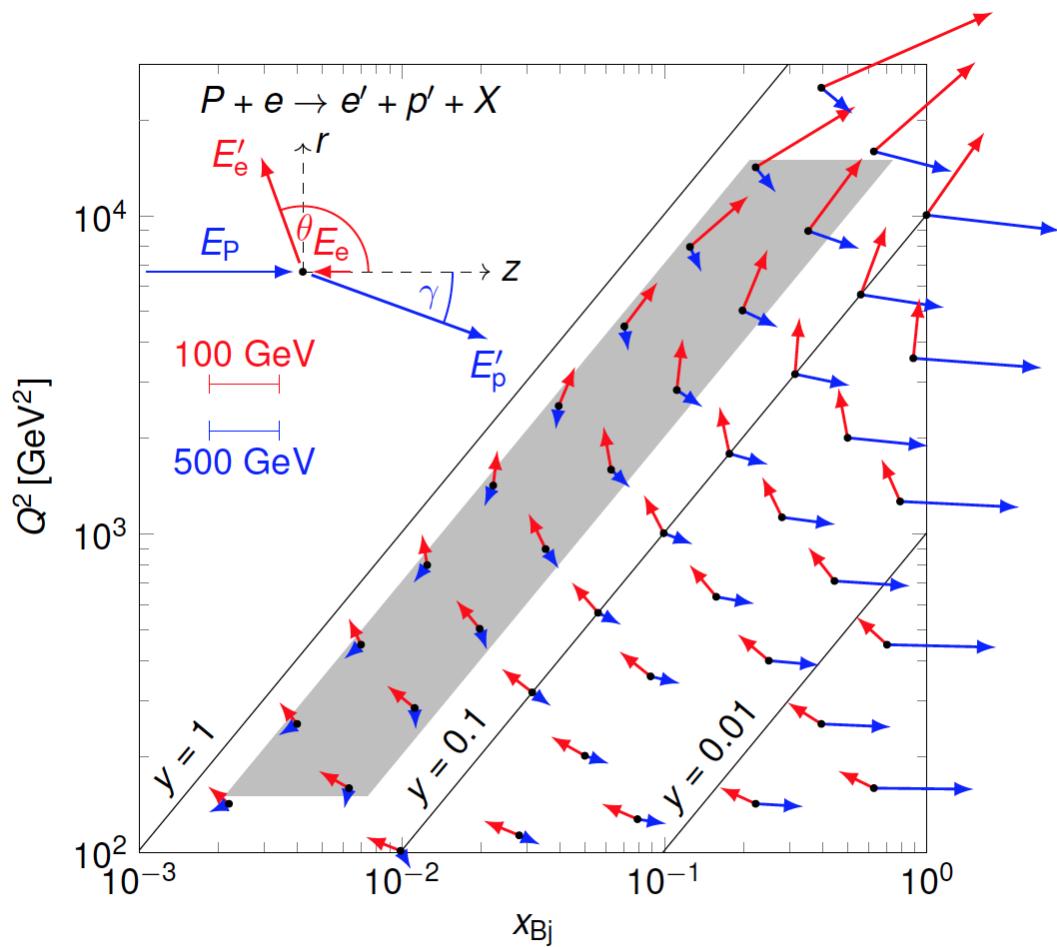
now new ZEUS jet measurement and PDF +  $\alpha_s(M_Z)$  determination



I'm still standing

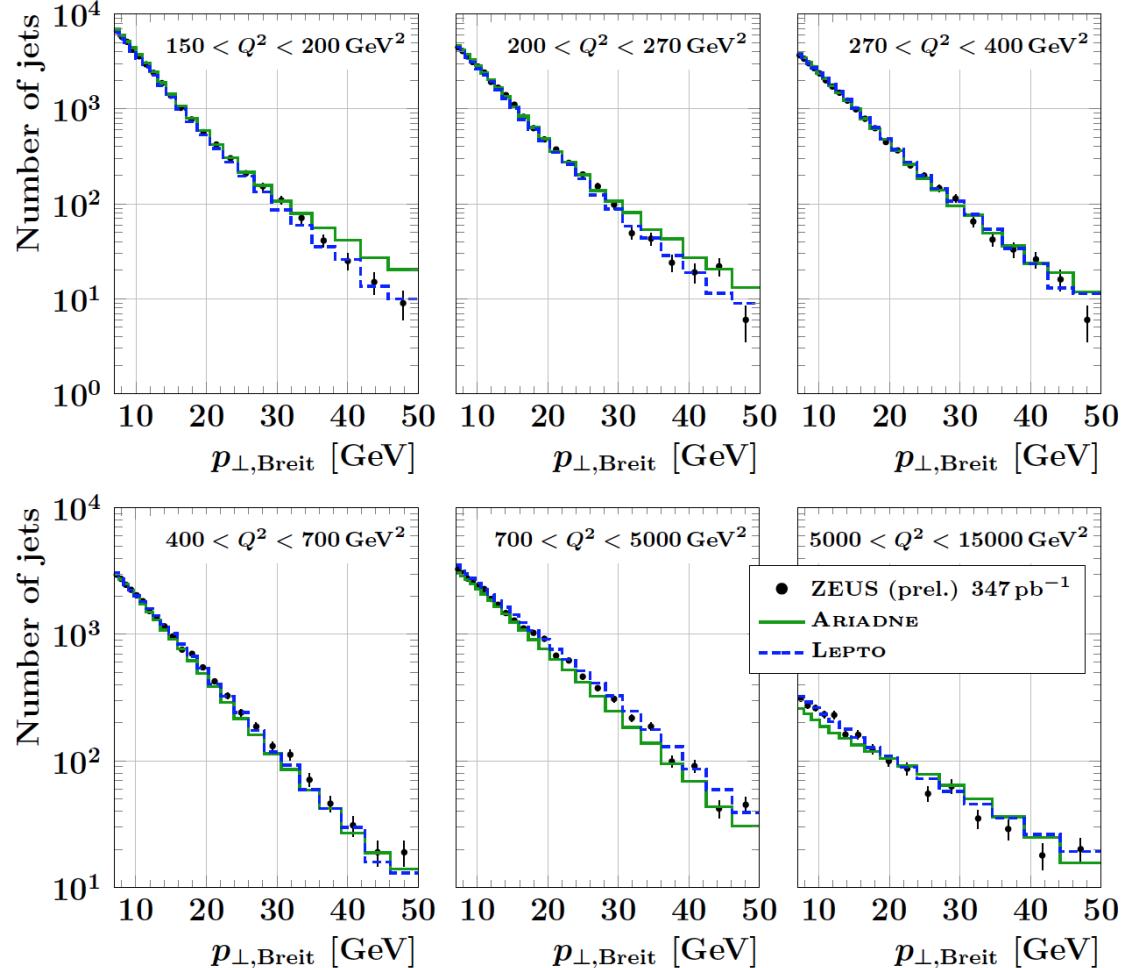
# Cross section definition

- Inclusive jets (count each jet individually, rather than each event)
- Jets clustered using  $k_\perp$  algorithm and  $p_\perp$ -weighted scheme (massless jets) in Breit frame
- Phase space
  - $150 \text{ GeV}^2 < Q^2 < 15000 \text{ GeV}^2$
  - $0.2 < y < 0.7$
  - $7 \text{ GeV} < p_{\perp, \text{Breit}} < 50 \text{ GeV}$
  - $-1 < \eta_{\text{lab}} < 2.5$
- Hadron level jets
- Exchange of  $Z^0$  boson included
- QED Born level (higher order effects removed)



# Monte Carlo models

ZEUS preliminary



- Reconstructed jets corrected to hadron level using bin-by-bin correction  
→ ARIADNE: colour dipole model  
→ LEPTO: leading  $\log(Q^2)$  parton cascade
- After reweighting → good description of data across entire phase space

# Theory predictions

## Theoretical predictions

- ▶ Cross section predictions are calculated at NNLO accuracy
- ▶ Matrix elements calculated using NNLOJET<sup>†</sup>
- ▶ PDFs taken from HERAPDF2.0Jets NNLO<sup>‡</sup>
- ▶  $\alpha_s(M_Z^2) = 0.1155$ ,  $\mu_r^2 = \mu_f^2 = Q^2 + p_\perp^2$
- ▶ Predictions corrected for hadronisation and  $Z^0$ -exchange

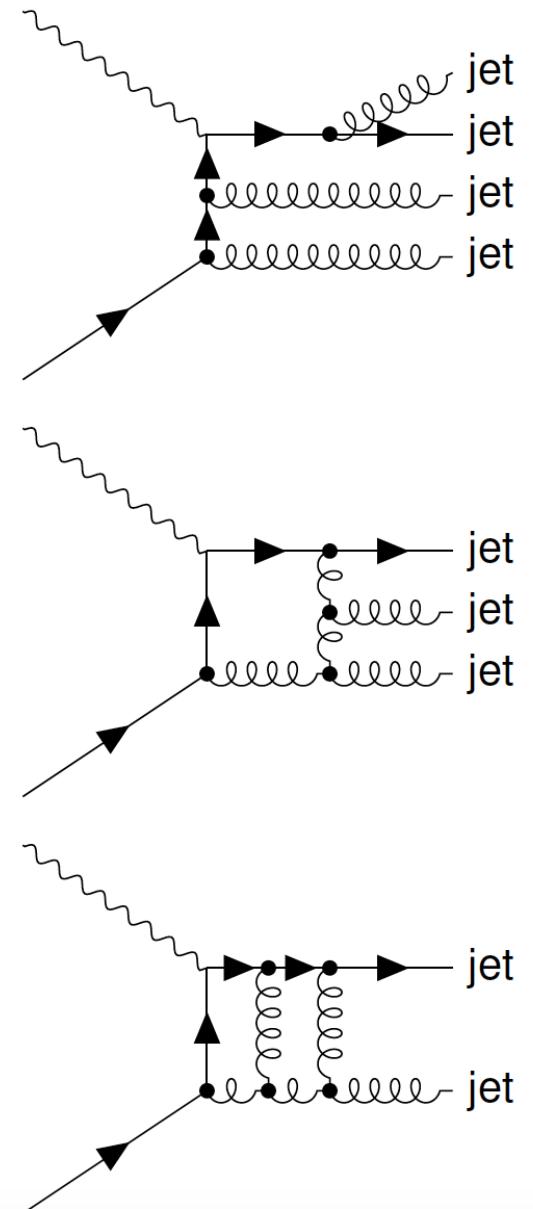
## Theoretical uncertainties

- ▶ Six point scale variation by factor 2
- ▶ Statistical uncertainty of matrix element generation
- ▶ Hadronisation correction uncertainty
- ▶ PDF uncertainty (fit, model, parameterisation)

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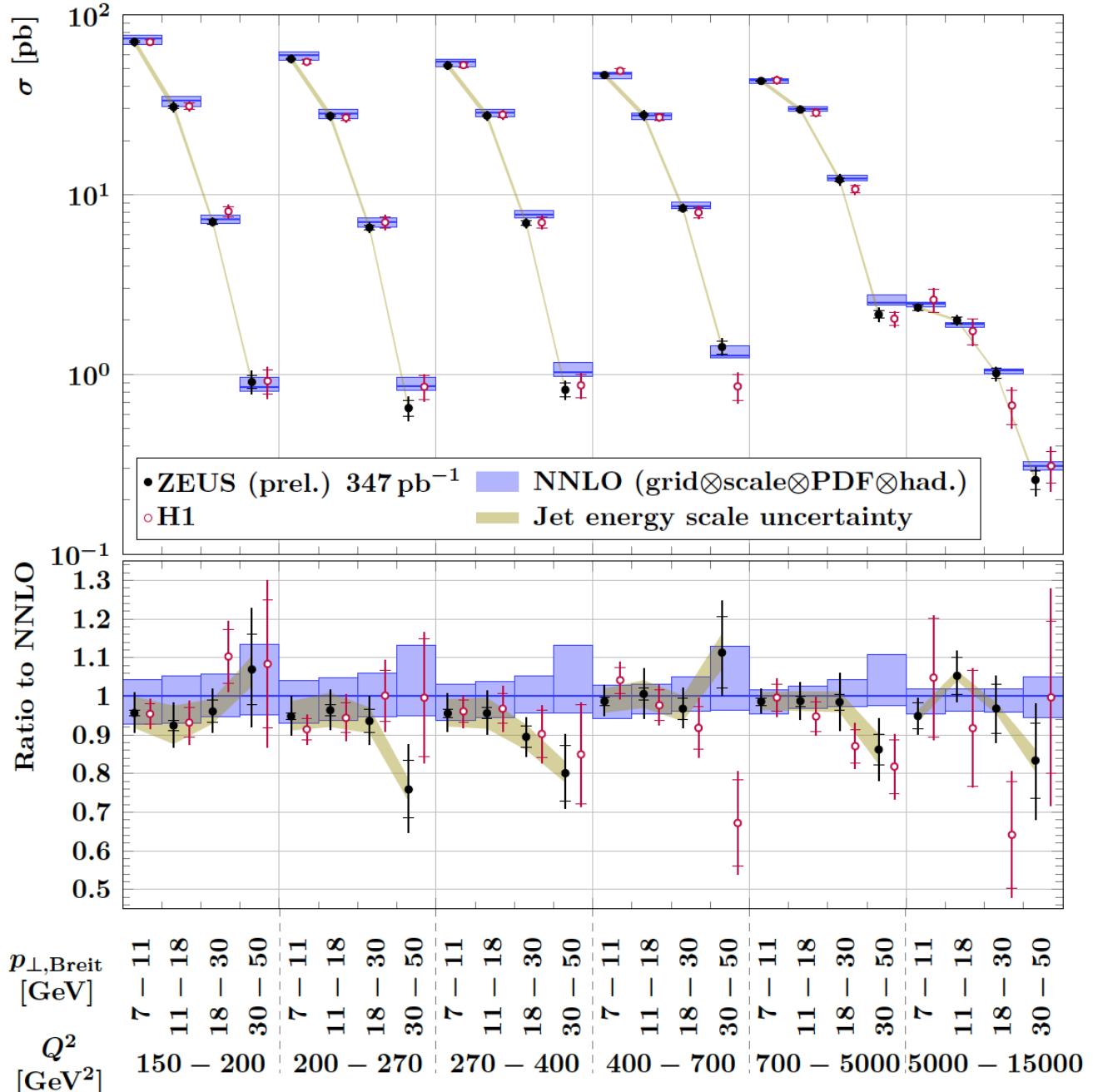
<sup>†</sup>JHEP 2017, 18 (2017). arXiv:1703.05977

<sup>‡</sup>EPJC 82, 243 (2022). arXiv:2112.01120



# New ZEUS jet measurement

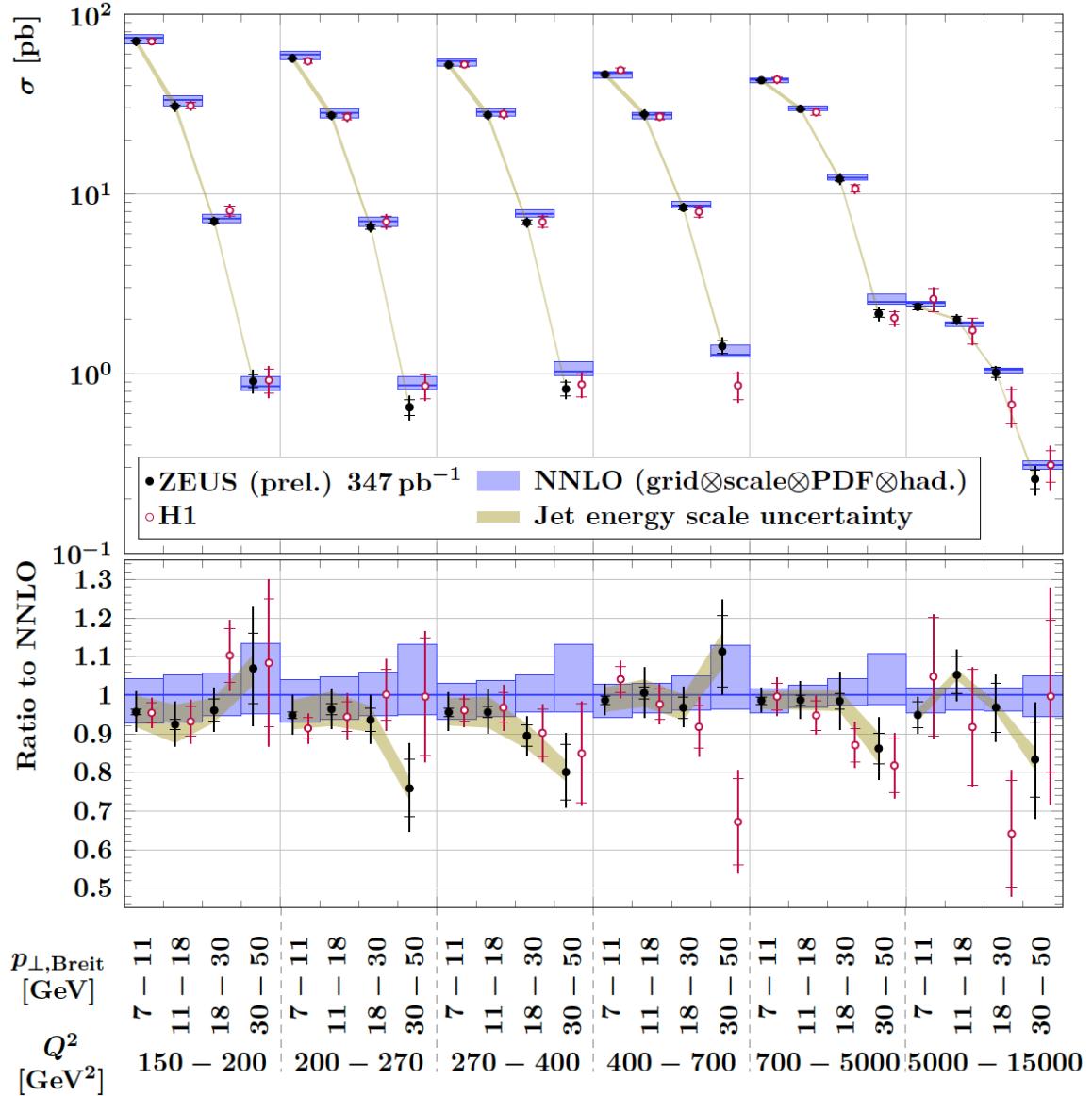
ZEUS preliminary



- New HERAII high- $Q^2$  inclusive jets results from ZEUS (15 years after shutdown)
- Phase-space and cuts identical to H1 high- $Q^2$  result → direct comparison possible
- Good agreement with H1 and with theory predictions → used in simultaneous PDF and  $\alpha_s$  fit

# New ZEUS jet measurement

ZEUS preliminary



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# ZEUS-jets QCD fit @ NNLO

- Used jet data sets
  - HERAI ZEUS inclusive jets at high  $Q^2$
  - HERAI+II ZEUS di-jets at high  $Q^2$
  - *New HERAII ZEUS inclusive jets at high  $Q^2$*
- Statistical correlations between ZEUS HERAII jet data sets taken into account via correlation matrix
- Fit method and settings follow exactly HERAPDF2 strategy

## Results

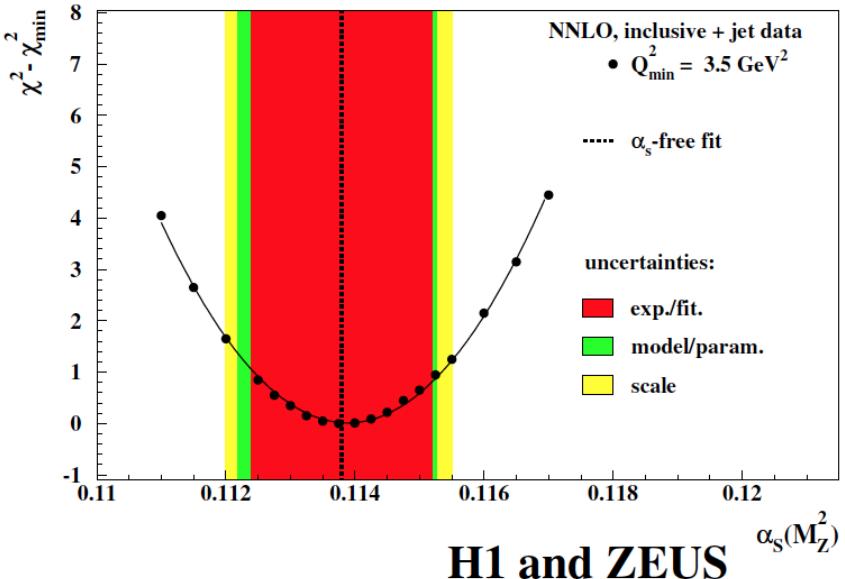
$$\alpha_s(M_Z^2) = 0.1138 \pm 0.0014 \text{ (exp/fit)} \quad {}^{+0.0004}_{-0.0008} \text{ (model/parameterisation)} \quad {}^{+0.0012}_{-0.0005} \text{ (scale)}$$

- *Note scale uncertainty (fully correlated)!*



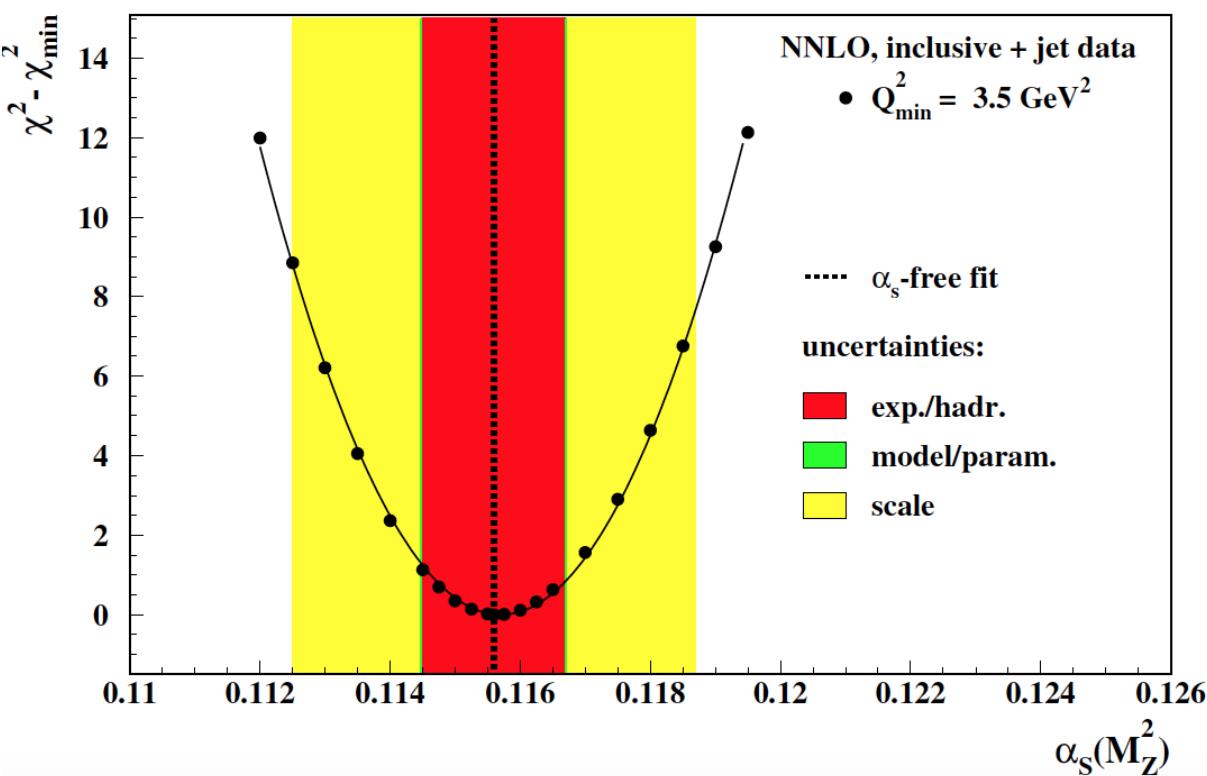
# Comparison to HERAPDF2Jets NNLO

ZEUS preliminary



- Central value compatible with HERAPDF and with PDG world average
- Increased experimental uncertainty  
← fewer jet datasets used

H1 and ZEUS



Significantly decreased  
100% correlated scale  
uncertainty ← absence of low  
 $Q^2$  jet data

# Comparison to NLO

- Scale uncertainties fully correlated

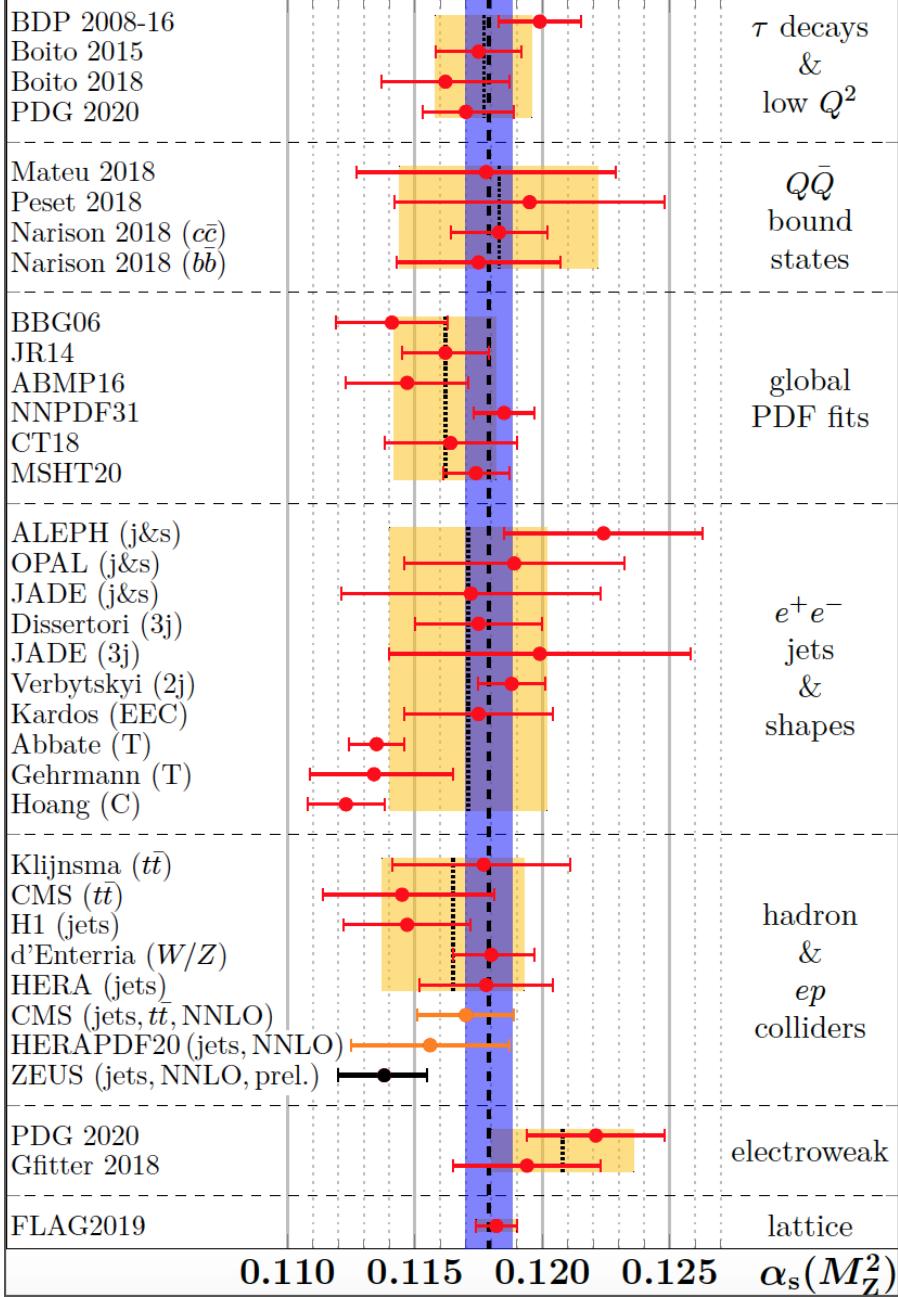
NNLO:  $\alpha_s(M_Z^2) = 0.1138 \pm 0.0014$  (exp/fit)  $^{+0.0004}_{-0.0008}$  (model/parameterisation)  $^{+0.0012}_{-0.0005}$  (scale)  
NLO:  $\alpha_s(M_Z^2) = 0.1170 \pm 0.0015$  (exp/fit)  $^{+0.0005}_{-0.0007}$  (model/parameterisation)  $^{+0.0028}_{-0.0014}$  (scale)

- Scale uncertainties half-correlated, half-uncorrelated

NNLO:  $\alpha_s(M_Z^2) = 0.1138 \pm 0.0014$  (exp/fit)  $^{+0.0004}_{-0.0008}$  (model/parameterisation)  $^{+0.0008}_{-0.0007}$  (scale)  
NLO:  $\alpha_s(M_Z^2) = 0.1170 \pm 0.0015$  (exp/fit)  $^{+0.0005}_{-0.0007}$  (model/parameterisation)  $^{+0.0015}_{-0.0012}$  (scale)

Significant decrease of scale uncertainties in comparison to NLO

# ZEUS preliminary



# Conclusion

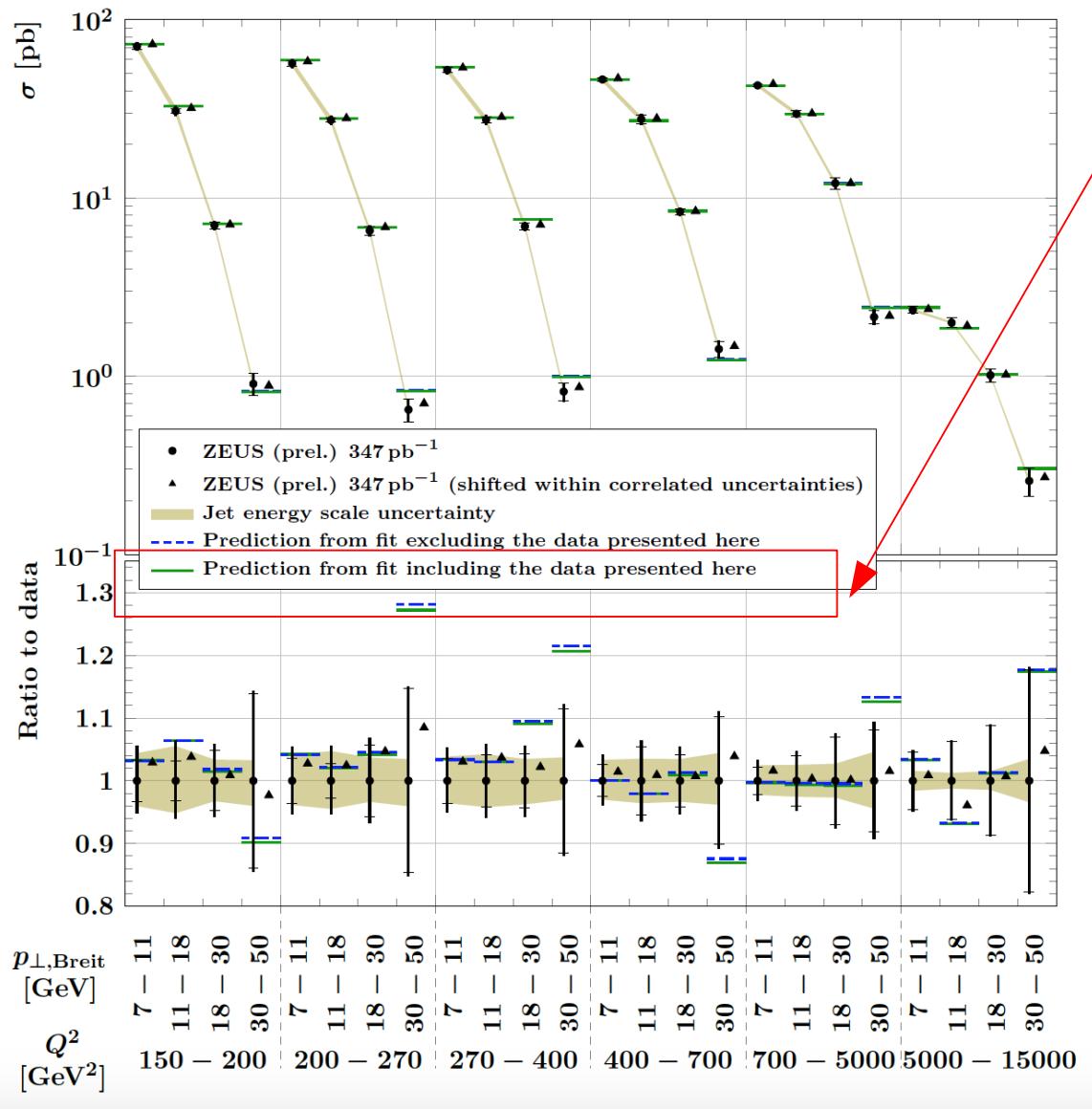
Reduced scale uncertainty →

present analysis is one of the  
most precise measurements of  
 $\alpha_s(M_Z^2)$  at hadron colliders so far<sup>†</sup>

† PTEP 2020, 8, 083C01 (2020)

# Impact of new data on predictions

ZEUS preliminary



- Theoretical cross section before and after including ZEUS inclusive jet dataset in fit  
→ slight change  
→ slightly larger at large  $p_{\perp,\text{Breit}}$
- Largest contribution from updated  $\alpha_s(M_Z^2)$  and gluon PDF
- Quark PDFs not changed significantly

# Message to take away

- New ZEUS new jet measurement +  $\alpha_s(M_Z)$  fit

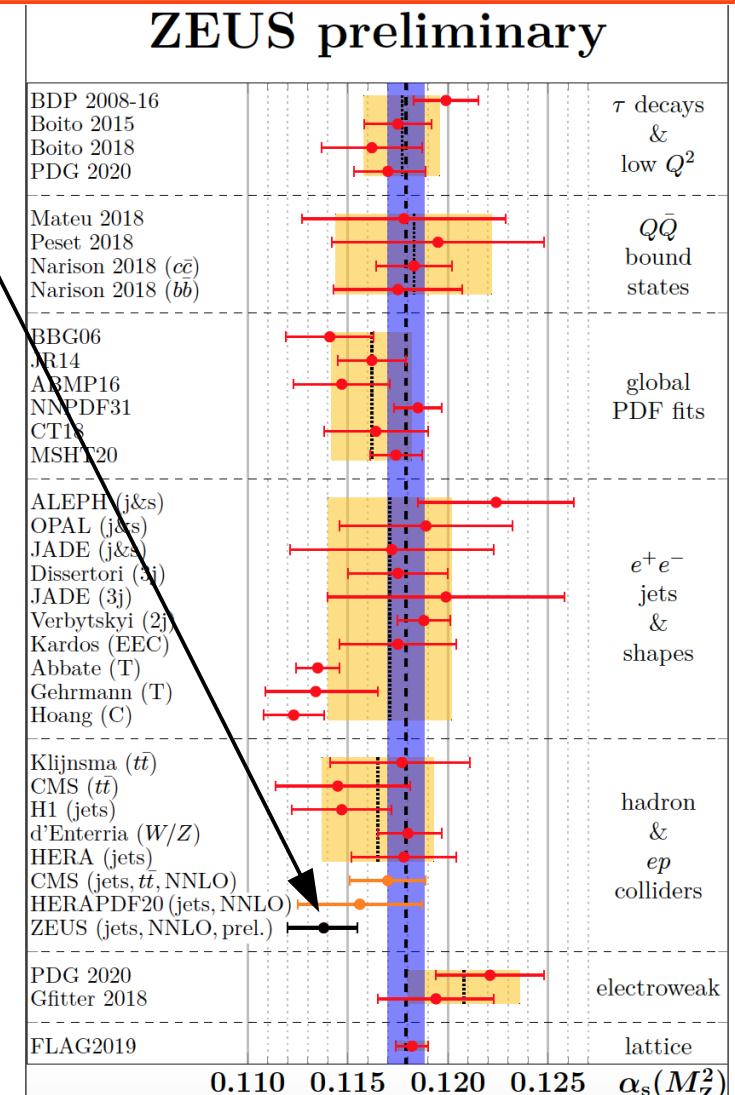
$$\alpha_s(M_Z^2) = 0.1138 \pm 0.0014 \text{ (exp/fit)} \quad {}^{+0.0004}_{-0.0008} \text{ (model/parameterisation)} \quad {}^{+0.0012}_{-0.0005} \text{ (scale)}$$

→ one of the most precise measurements of  
 $\alpha_s(M_Z^2)$  at hadron colliders

→ in comparison to recent HERAPDF2.0Jets  
 NNLO

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp/fit)} \\ {}^{+0.0001}_{-0.0002} \text{ (model/parameterisation)} \quad \pm 0.0029 \text{ (scale)}$$

**HERA still has something to say!**

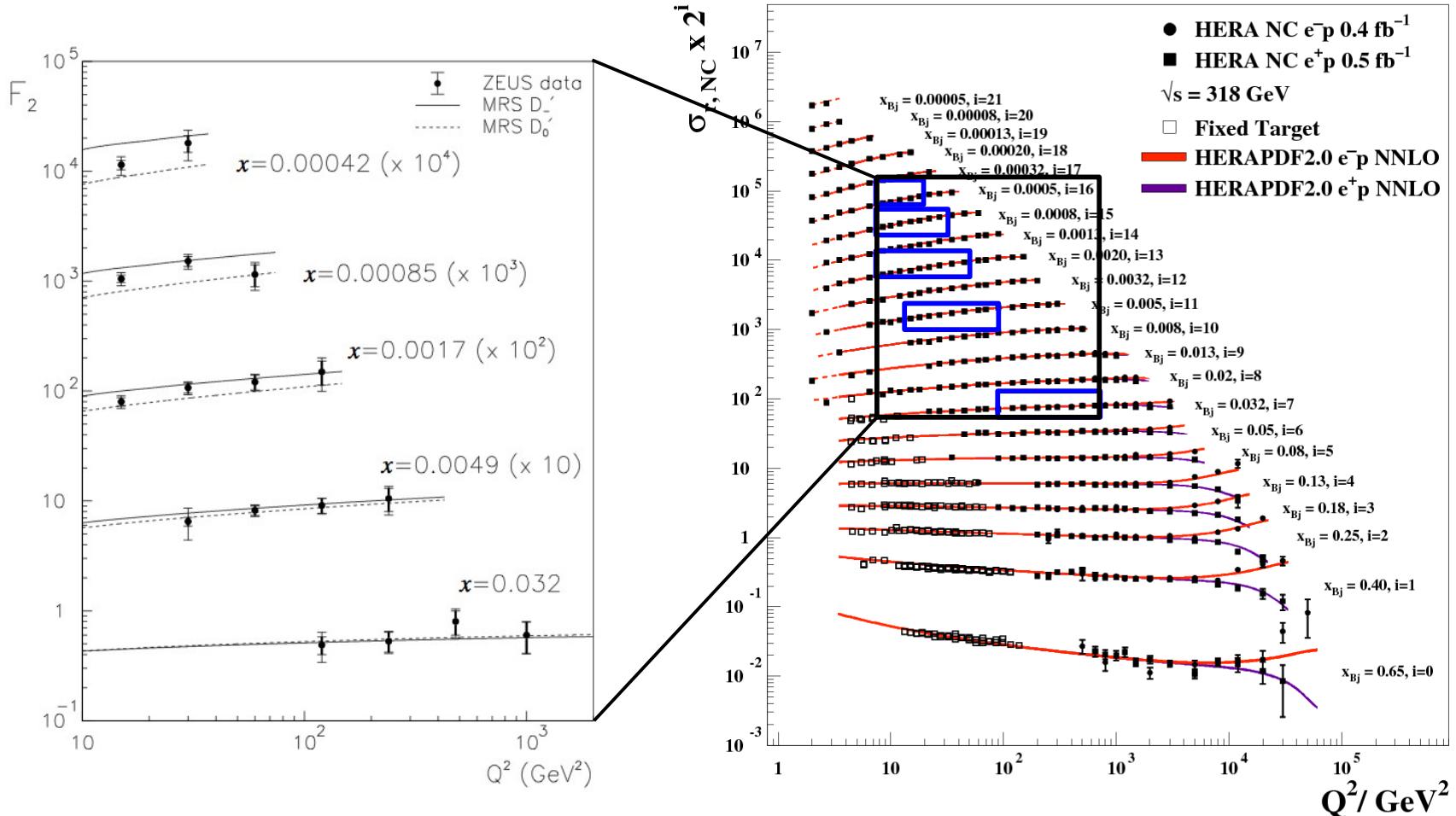


# Additional slides

# DIS @ HERA

First: 1993 → Final: 2015

H1 and ZEUS



2007: HERA shutdown

→ 15<sup>th</sup> anniversary of start, 30<sup>th</sup> anniversary of end

# HERAPDF2.0 parameterisation

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

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} \left( 1 + E_{u_v} x^2 \right),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x),$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}.$$

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



# HERA jet data used in NNLO PDF fit

EPJC C82 (2022) 243

- Inclusive jets and dijets included
- Trijets from HERAPDF2Jets NLO excluded → no NNLO predictions
- H1 low  $Q^2$  data added - particularly sensitive to  $\alpha_s(M_Z)$
- Some data points excluded due theory limitations
  - Data at low scale  $\mu = (pt_2 + Q_2) < 10 \text{ GeV} \rightarrow$  scale variations are large (~25% NLO and ~10% NNLO)
  - 6 ZEUS dijet data points at low  $pt$  for which predictions are not truly NNLO

K. Wichmann @ EPIPHANY23

PDFs @ HERA

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Data set	taken from      to	$Q^2[\text{GeV}^2]$ range from      to	$\mathcal{L}$ $\text{pb}^{-1}$	$e^+ / e^-$	$\sqrt{s}$ $\text{GeV}$	Norma- lised	All points	Used points
H1 HERA I normalised jets	1999 – 2000	150      15000	65.4	$e^+ p$	319	yes	24	24
H1 HERA I jets at low $Q^2$	1999 – 2000	5      100	43.5	$e^+ p$	319	no	28	20
H1 normalised inclusive jets at high $Q^2$	2003 – 2007	150      15000	351	$e^+ p / e^- p$	319	yes	30	30
H1 normalised dijets at high $Q^2$	2003 – 2007	150      15000	351	$e^+ p / e^- p$	319	yes	24	24
H1 normalised inclusive jets at low $Q^2$	2005 – 2007	5.5      80	290	$e^+ p / e^- p$	319	yes	48	37
H1 normalised dijets at low $Q^2$	2005 – 2007	5.5      80	290	$e^+ p / e^- p$	319	yes	48	37
ZEUS inclusive jets	1996 – 1997	125      10000	38.6	$e^+ p$	301	no	30	30
ZEUS dijets	1998 – 2000 &	125      20000	374	$e^+ p / e^- p$	318	no	22	16

- QCD PDF fit with jet data
  - With fixed  $\alpha_s(M_Z)$
  - With free  $\alpha_s(M_Z)$  or doing  $\alpha_s(M_Z)$  scan →  $\alpha_s(M_Z)$  value

# Updates in the procedure

- scale choice changes:
- factorisation:  $\mu F^2 = (Q^2 + pt^2)$
- cf.  $\mu F^2 = Q^2$  in previous NLO analysis; updated since not a good choice for low  $Q^2$  jet data; change makes almost no difference for high  $Q^2$  jets
- renormalisation:  $\mu R^2 = (Q^2 + pt^2)$
- cf.  $\mu R^2 = (Q^2 + pt^2)/2$  in previous NLO analysis
- NNLO fit with  $\mu R^2 = (Q^2 + pt^2)$  gives  $\Delta \chi^2 = -15$  cf.  $\mu R^2 = (Q^2 + pt^2)/2$  and vice versa for NLO fit
- scale uncertainties treated as completely correlated between bins and datasets

†  $pt$  denotes  $pt^{\text{jet}}$  in the case of inclusive jet cross sections and  $\langle pt \rangle$  for dijets

- improved treatment of hadronisation uncertainties; NOW included together with exp. systematics; treated as  $\frac{1}{2}$  correlated,  $\frac{1}{2}$  uncorrelated between bins and datasets
- (small) uncertainties on theory predictions included

# Estimation of charm & beauty masses

- new HERA combined charm and beauty data: EPJ C78 (2018), 473  
 → updated estimation of  $M_c$  and  $M_b$   
 → Heavy Quark (HQ) coefficient functions evaluated using Thorne-Roberts Optimised Variable Flavour Number Scheme

