Jet and photon production and extraction of α_S at HERA

Radek Žlebčík[1]
On behalf of H1 and ZEUS collaborations

[1] Deutsches Elektronen-Synchrotron (DESY)

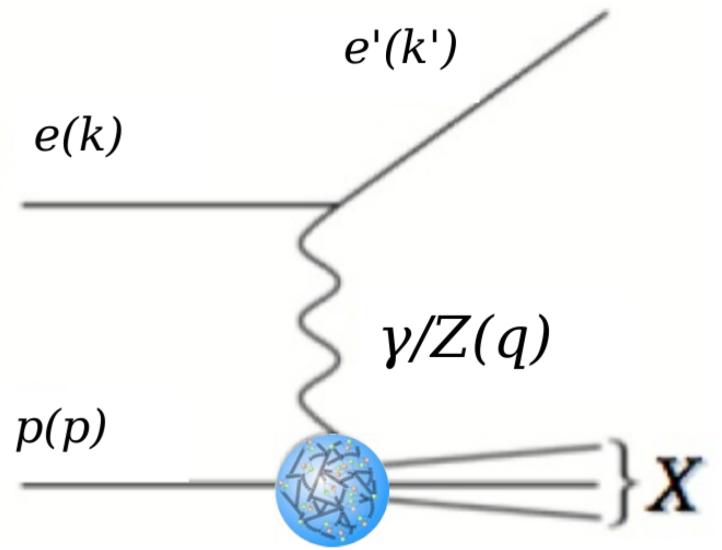
New Frontiers in Physics
Kolymbari, August 24

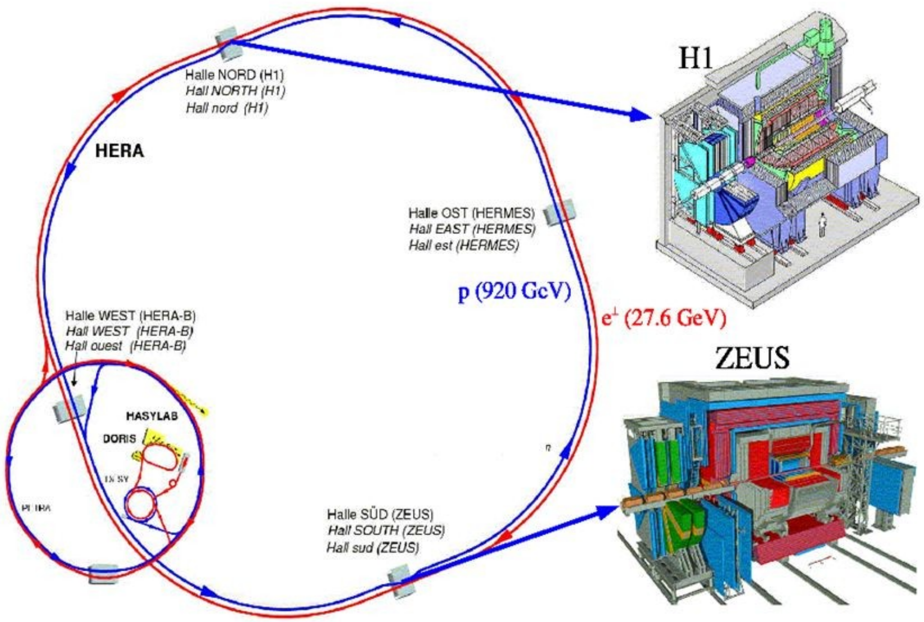
HERA Collider

- The only existing ep collider (1992 - 2007)
- About **0.5 fb^{-1}** of data per experiment
- Two multi-purpose detectors (**H1** + **ZEUS**)

e$^{\pm}$ + p
27.6 GeV + 920 GeV

$$\sqrt{s} = 319\,\mathrm{GeV}$$





Inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

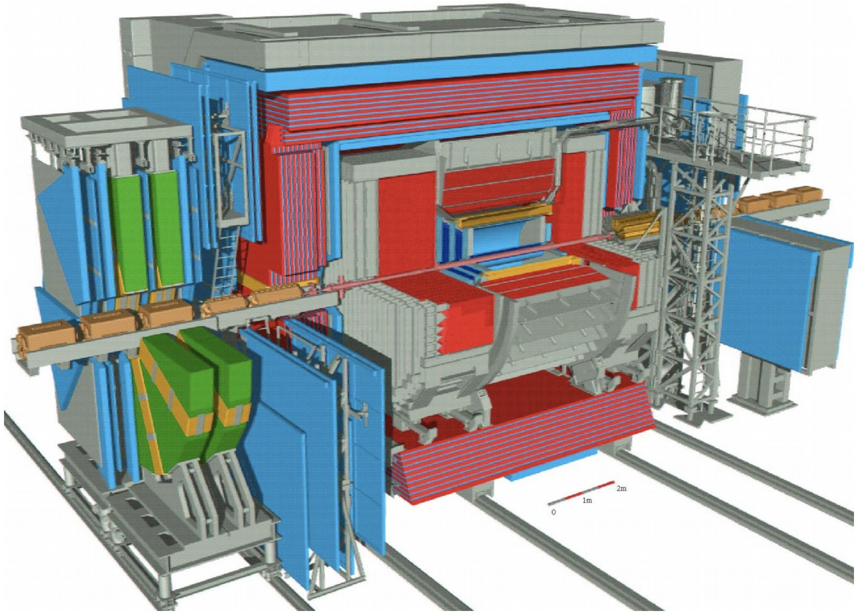
Photon virtuality

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

$Q^2 \approx 0$ Photoproduction

$Q^2 \gg 0$ Deep-inelastic scattering (DIS)

Diffractive photoproduction of the isolated photon (ZEUS)



DESY-17-077 [arXiv:1705.10251]
submitted to Phys. Rev. D

Diffractive **photoproduction** of isolated photon

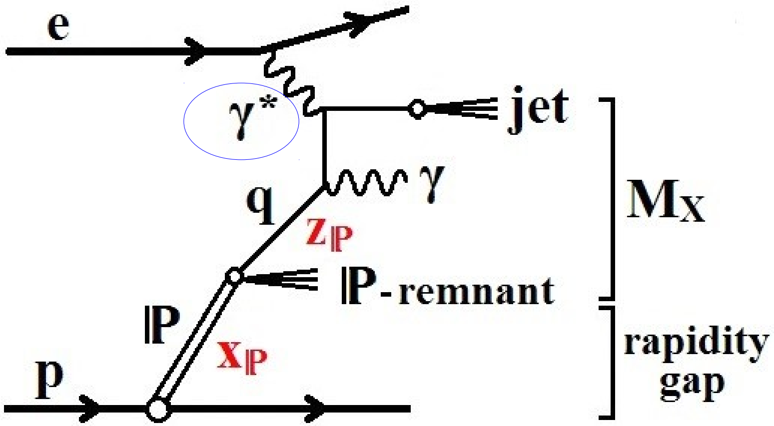
- $Q^2 \approx 0 \rightarrow$ photon may dissociate into low mass hadronic system (structure of such resolved photon described by γPDF)
- $Q^2 \approx 0 \rightarrow \ \theta_e \approx 180^\circ$(electron leaves detector undetected)

Photon momentum fraction entering the hard subprocess:

$$x_\gamma = \frac{\sum_{\gamma+\text{jet}}(E - p_z)}{\sum_{\text{EFO}}(E - p_z)}$$

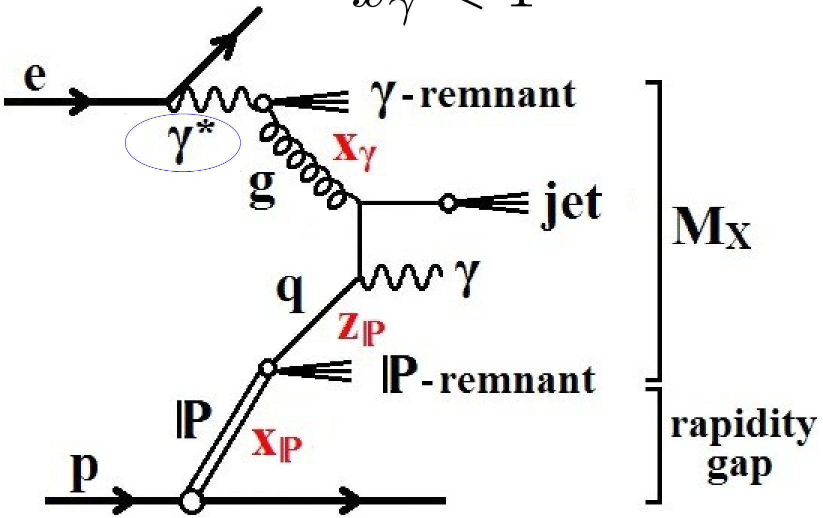
Direct photon interaction

$x_\gamma = 1$



Resolved photon interaction

$x_\gamma < 1$



Diffractive photoproduction of isolated photon

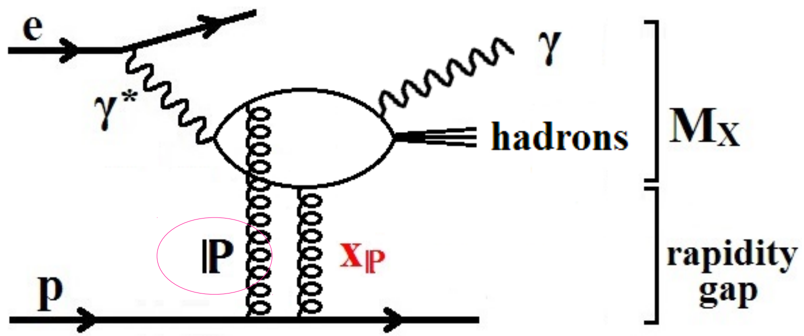
- Diffraction → beam proton stays intact and leaves detector undetected
- Standardly described by exchange of an hadronic object with vacuum quantum numbers (pomeron)

Pomeron momentum fraction entering the hard subprocess:

$$z_{IP} = \frac{\sum_{\gamma+\text{jet}}(E+p_z)}{\sum_{\text{EFO}}(E+p_z)}$$

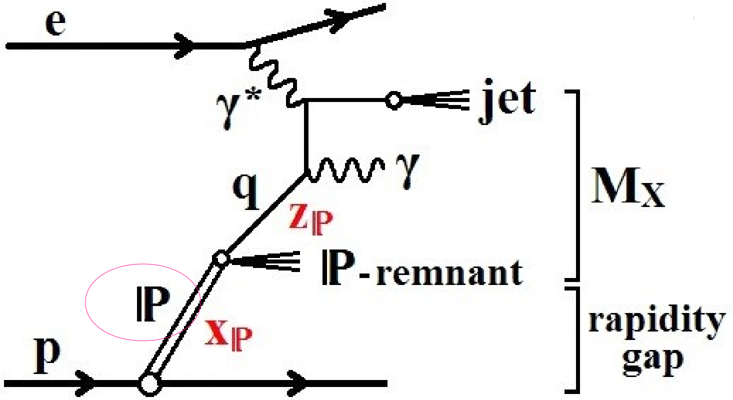
Direct Pomeron

$z_{IP} = 1$



Resolved Pomeron

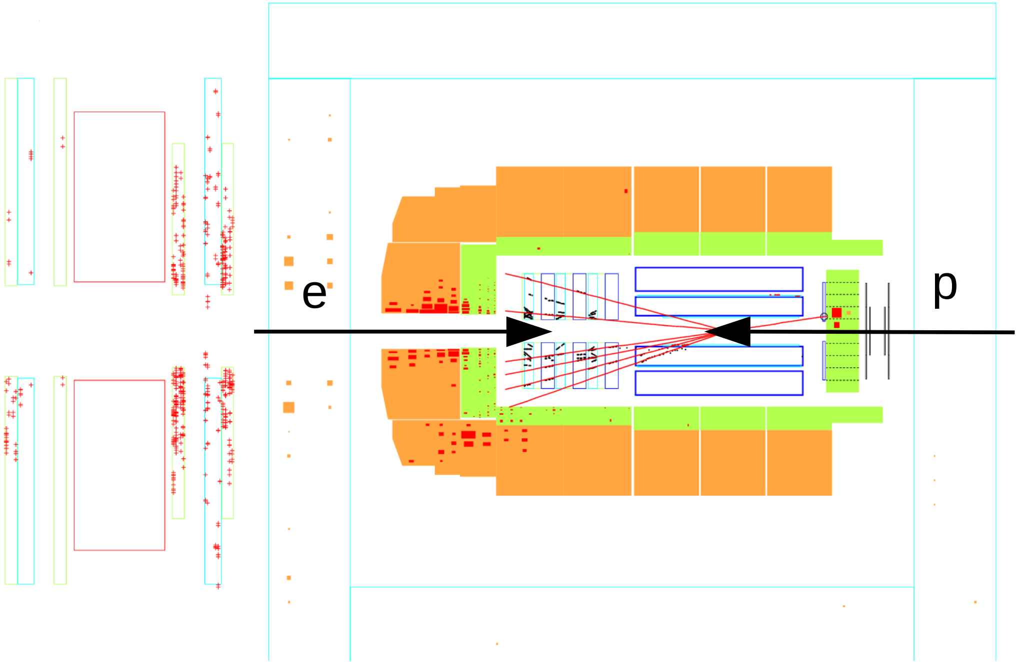
$z_{IP} < 1$



Large Rapidity Gap

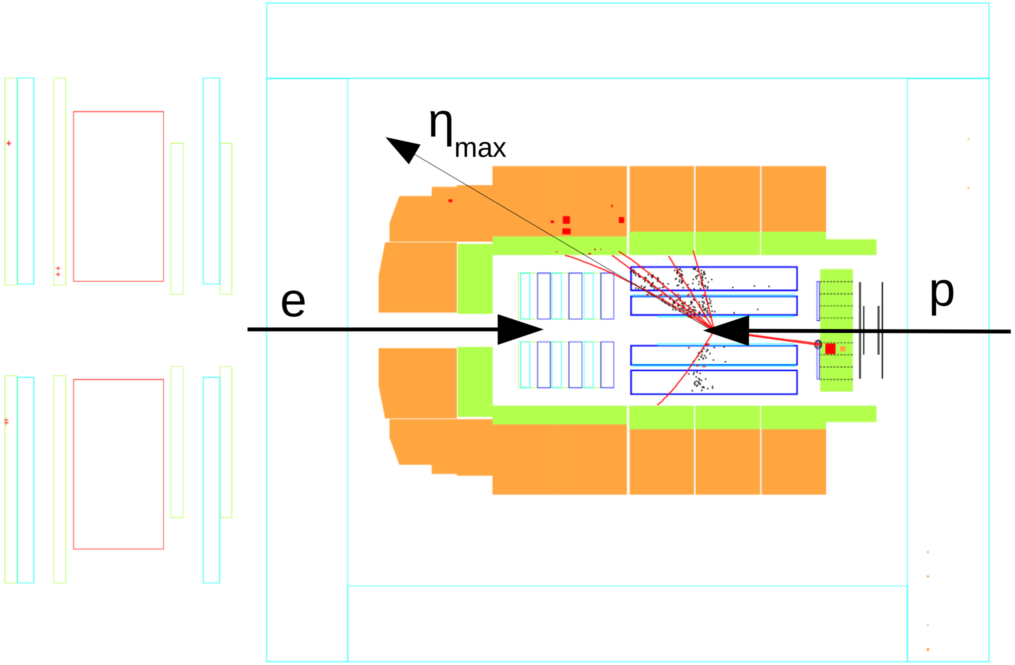
Here H1 detector

Hadronic activity in forward part of detector



Non-diffractive event

Without hadronic activity in forward part of detector



Diffractive event

Theoretical predictions

Diffractive predictions (Resolved pomeron)

- Resolved pomeron model (Ingelman Schlein)
- Implemented in the MC generator **RAPGAP** (LO matrix element + LL parton shower + Lund string fragmentation)
- Contains direct and resolved photon processes

- The partonic structure of the resolved pomeron described by **H1 2006 DPDF Fit B** (from fits of inclusive diffractive DIS)
- The partonic structure of the resolved photon described by **SASGAM-2D γPDF**

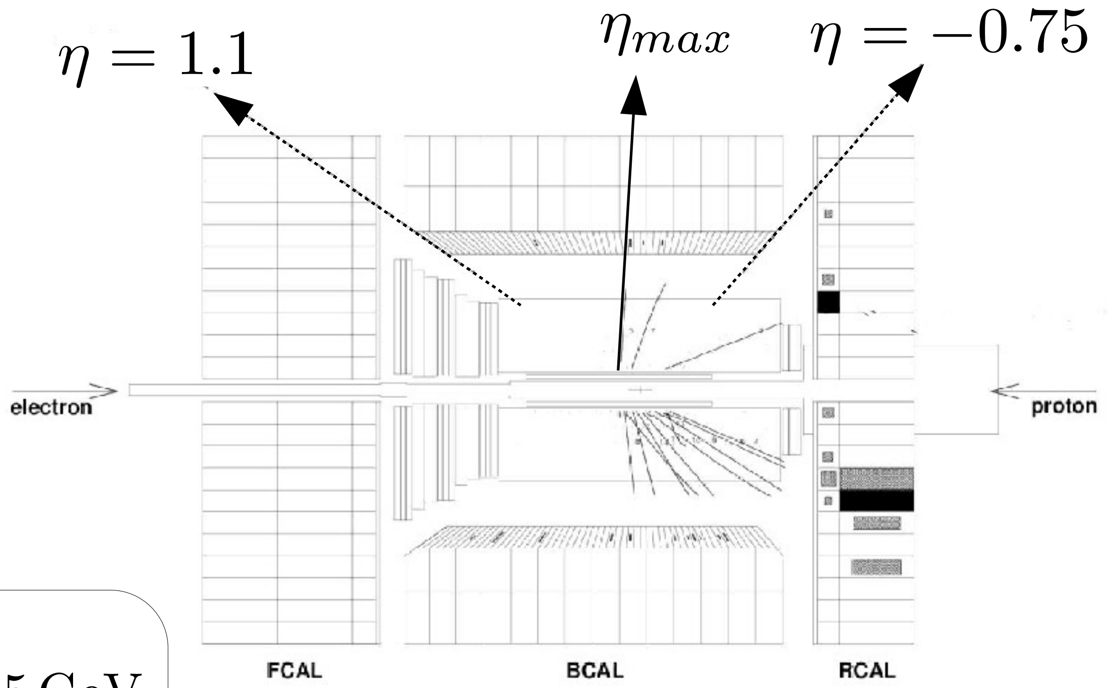
- Non-diffractive background simulated by Pythia 6

No model for the possible direct pomeron interaction available

Event selection

$$e + p \rightarrow e + \gamma + X + p(Y)$$

- Veto on scattered electron
- Diffractive events dominate for small pomeron momentum fraction wrt proton x_{IP}+ **large rapidity gap**



Forward detector's region without hadronic activity

Photon

$$5 < E_T^{\gamma} < 15\,\mathrm{GeV}$$

$$-0.7 < \eta^{\gamma} < 0.9$$

Jet

$$4 < E_T^{jet} < 35\,\mathrm{GeV}$$

$$-1.5 < \eta^{jet} < 1.8$$

Photoproduction

$$Q^2 < 1\,\mathrm{GeV}^2$$

$$0.2 < y < 0.7$$

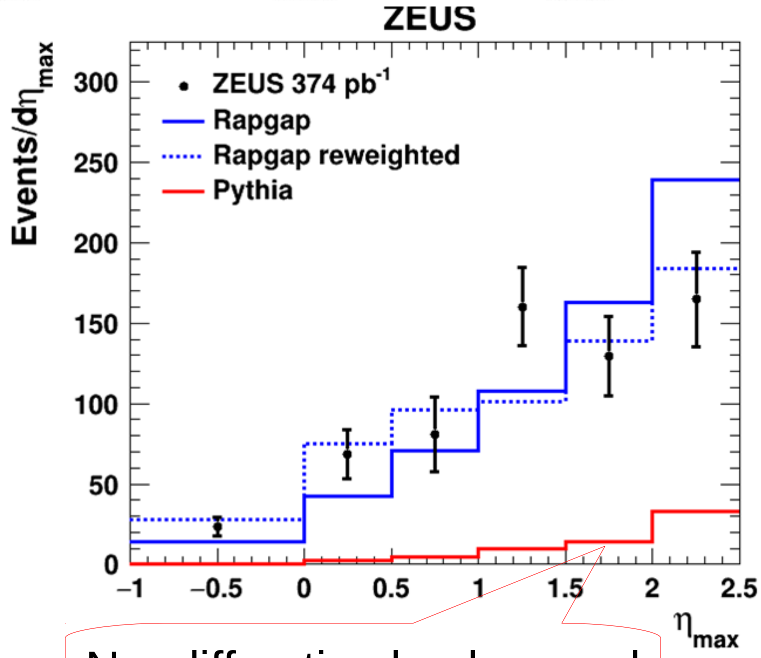
$$y = \frac{\sum_{\mathrm{EFO}} (E - p_z)}{2E_e}$$

Diffraction

$$\eta_{max}^{E>0.4} < 2.5$$

$$x_{IP} < 0.03$$

$$x_{IP} = \frac{\sum_{\mathrm{EFO}} (E + p_z)}{2E_p}$$



Nondiffractive background

Extraction of prompt photons signal

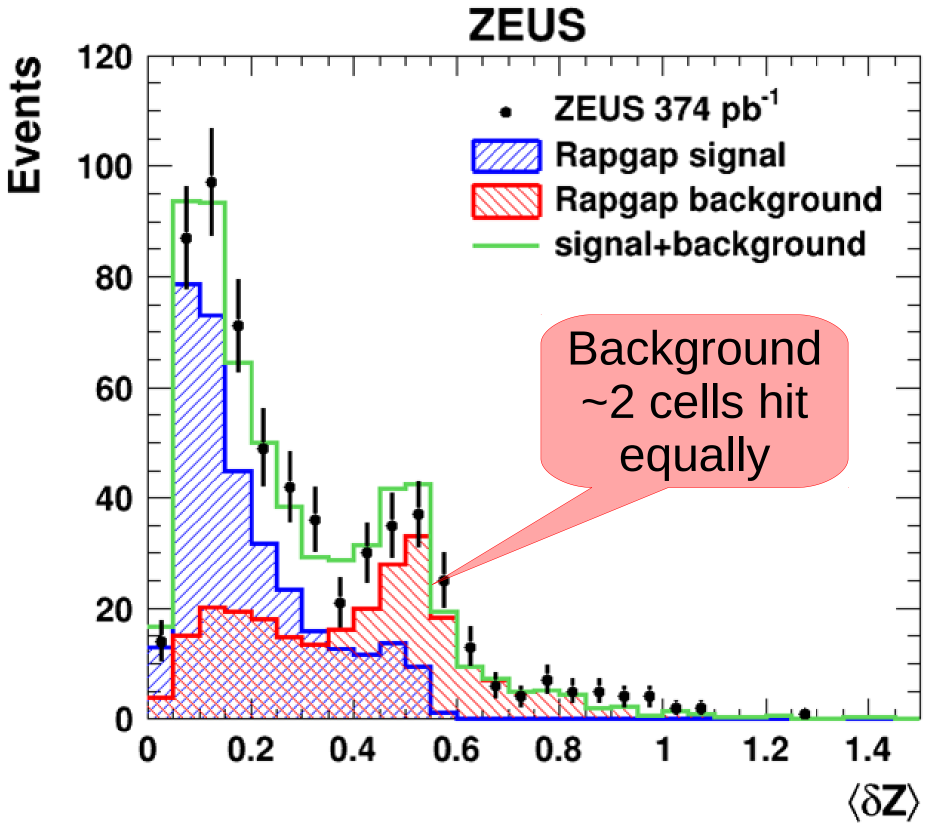
- Template fit to obtain the signal and background contribution
- Background mainly from

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

- Width of the photon candidate cluster in the beam direction in units of cell width δ_{cell}

$$\langle \delta Z \rangle = \frac{\sum_i E_i |Z_i - Z_{cluster}|}{\delta_{cell} \sum_i E_i}$$

- **90%** of photon candidate energy required to be measured in EM calorimeter



Background ~2 cells hit equally

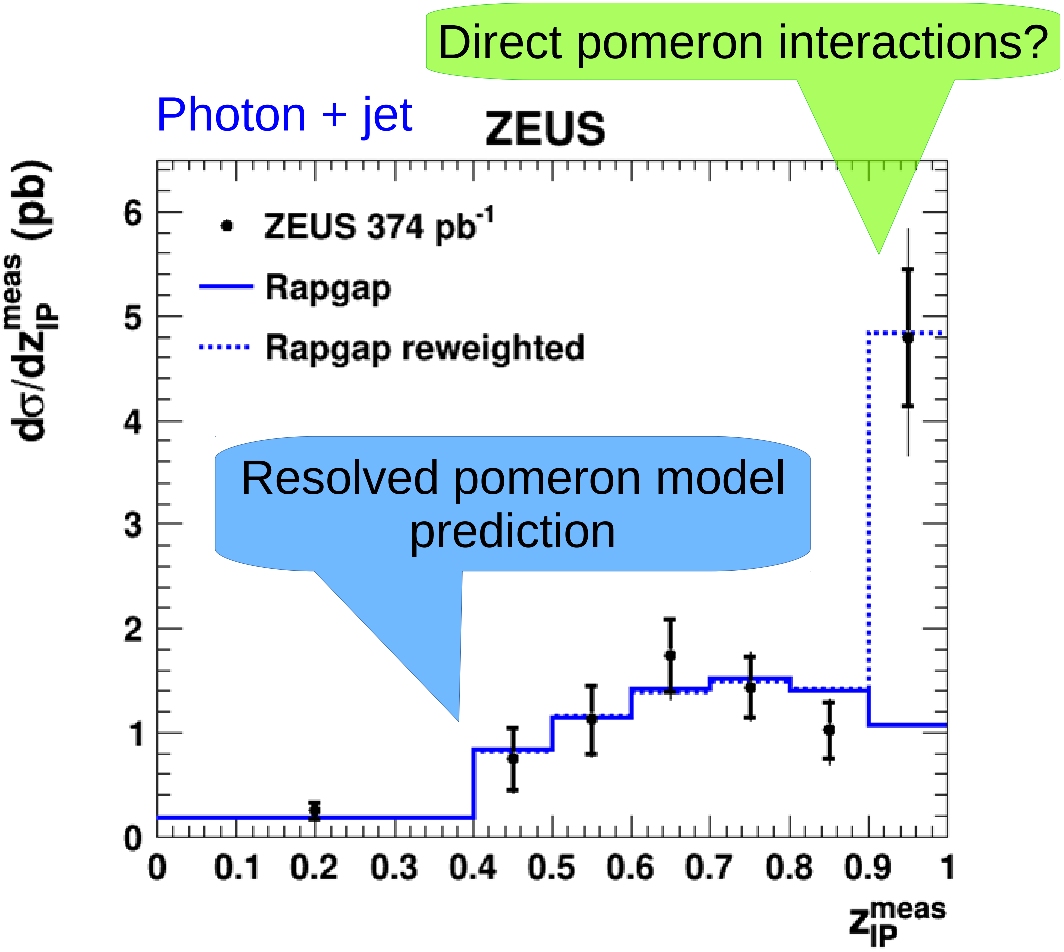
	Gamma events	Gamma+jet events
HERA I (82 pb^{-1})	91	76
HERA II (374 pb^{-1})	366	311

Direct pomeron exchange?

- **The z_{IP} < 0.9 region** well described by MC both in shape and normalization

$$\sigma_{\text{data}}^{z_{IP}<0.9} = 0.57 \pm 0.13\,\text{pb}$$
$$\sigma_{\text{MC}}^{z_{IP}<0.9} = 0.68\,\text{pb}$$

- **The z_{IP} > 0.9 region** overshot in data

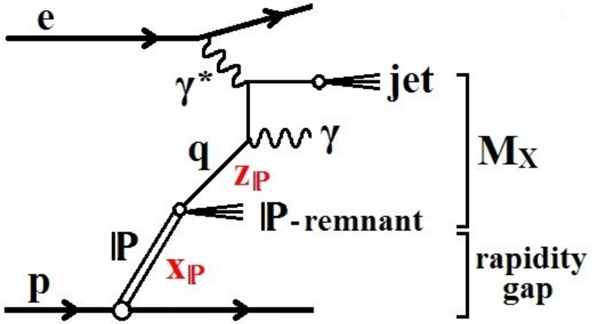


Direct pomeron interactions?

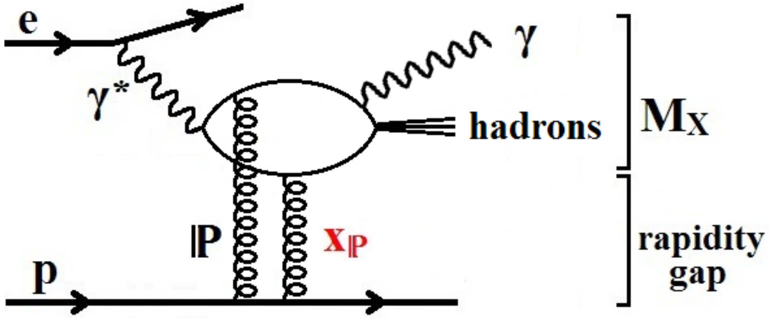
Resolved pomeron model prediction

Rapgap reweighted: MC reweighted separately for z_{IP} < 0.9 and z_{IP} > 0.9 to data

Resolved pom.



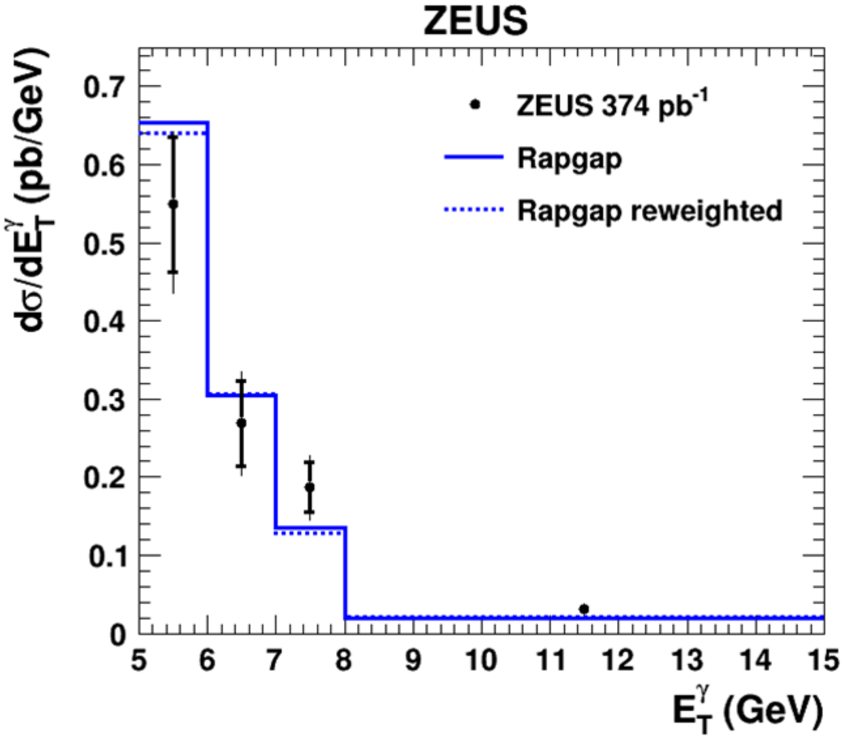
Direct pom.



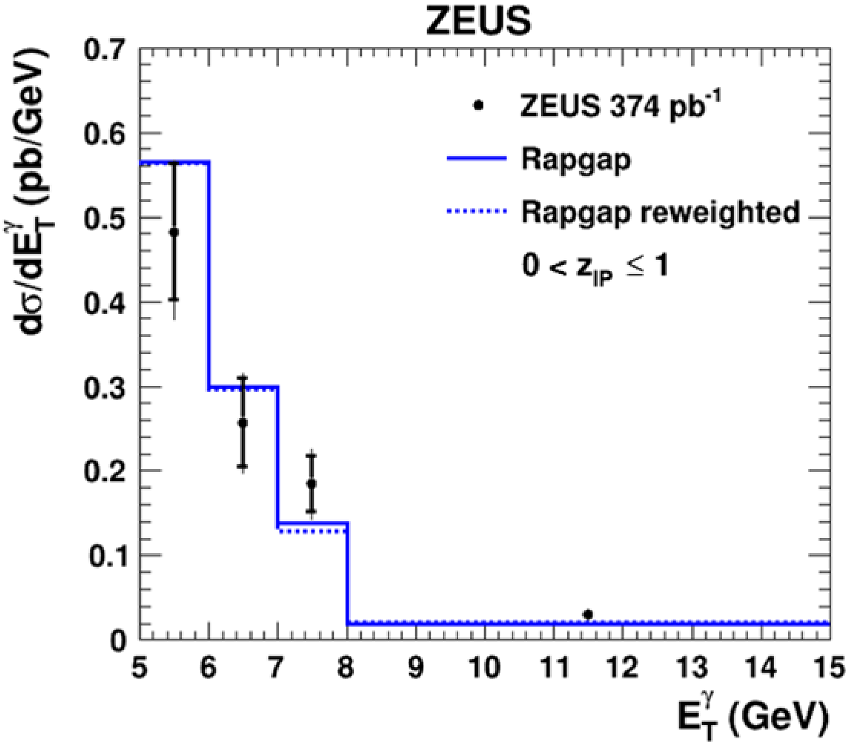
Prompt photon transverse momentum

- Shape of the gamma transverse momentum well described by MC prediction (**MC** always **normalized to data**)
- 85% of events with prompt photon contain jet as well

Prompt photons



Prompt photons with jet



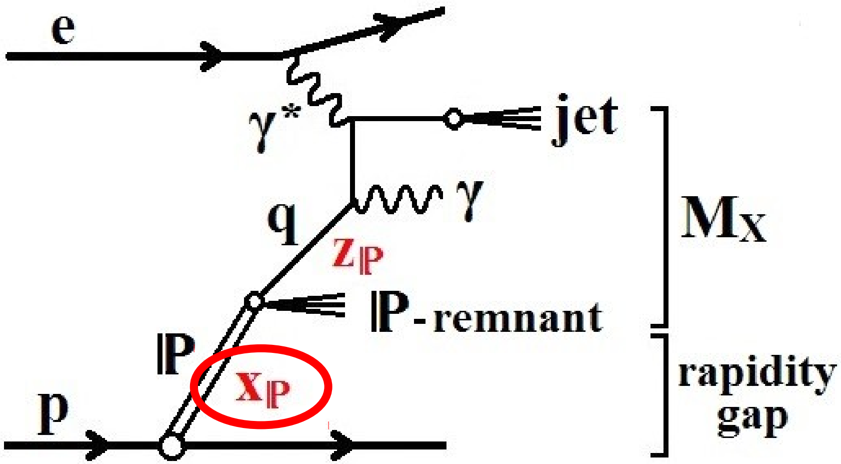
Spectrum of x_{IP}

- The relative energy loss of the leading proton with respect to the incoming beam proton (~1%)
- As leading proton directly not measured, reconstructed from EFO

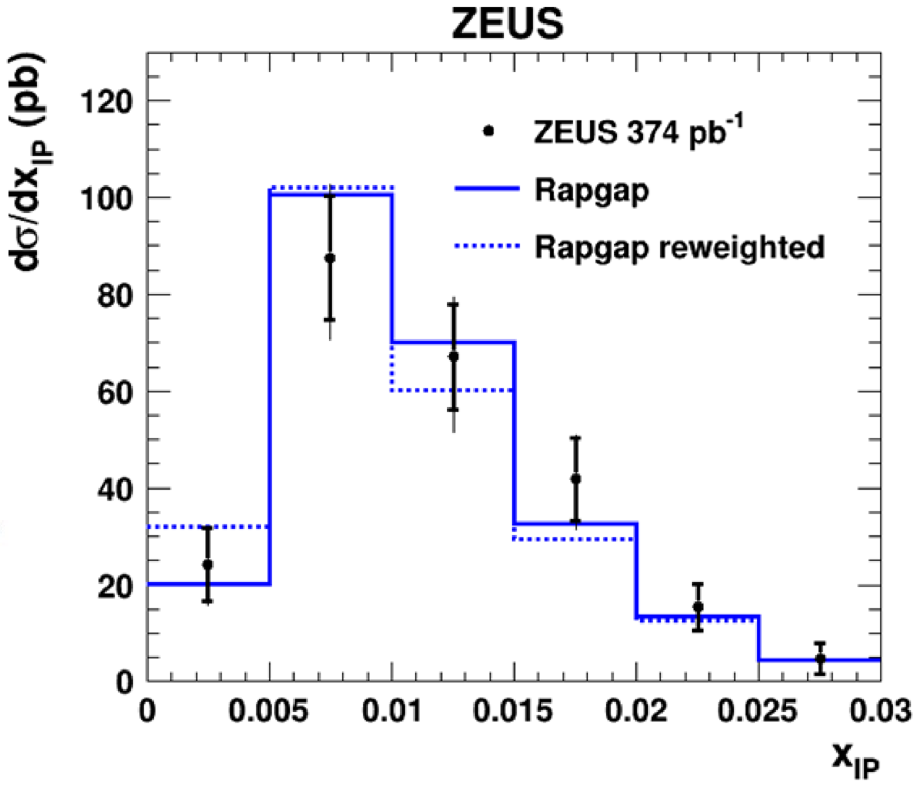
$$x_{IP} = 1 - \frac{E'_p}{E_p}$$

$$\Updownarrow$$

$$x_{IP} = \frac{\sum_{\text{EFO}}(E+p_z)}{2E_p}$$



Prompt photons



Direct vs Resolved pomeron

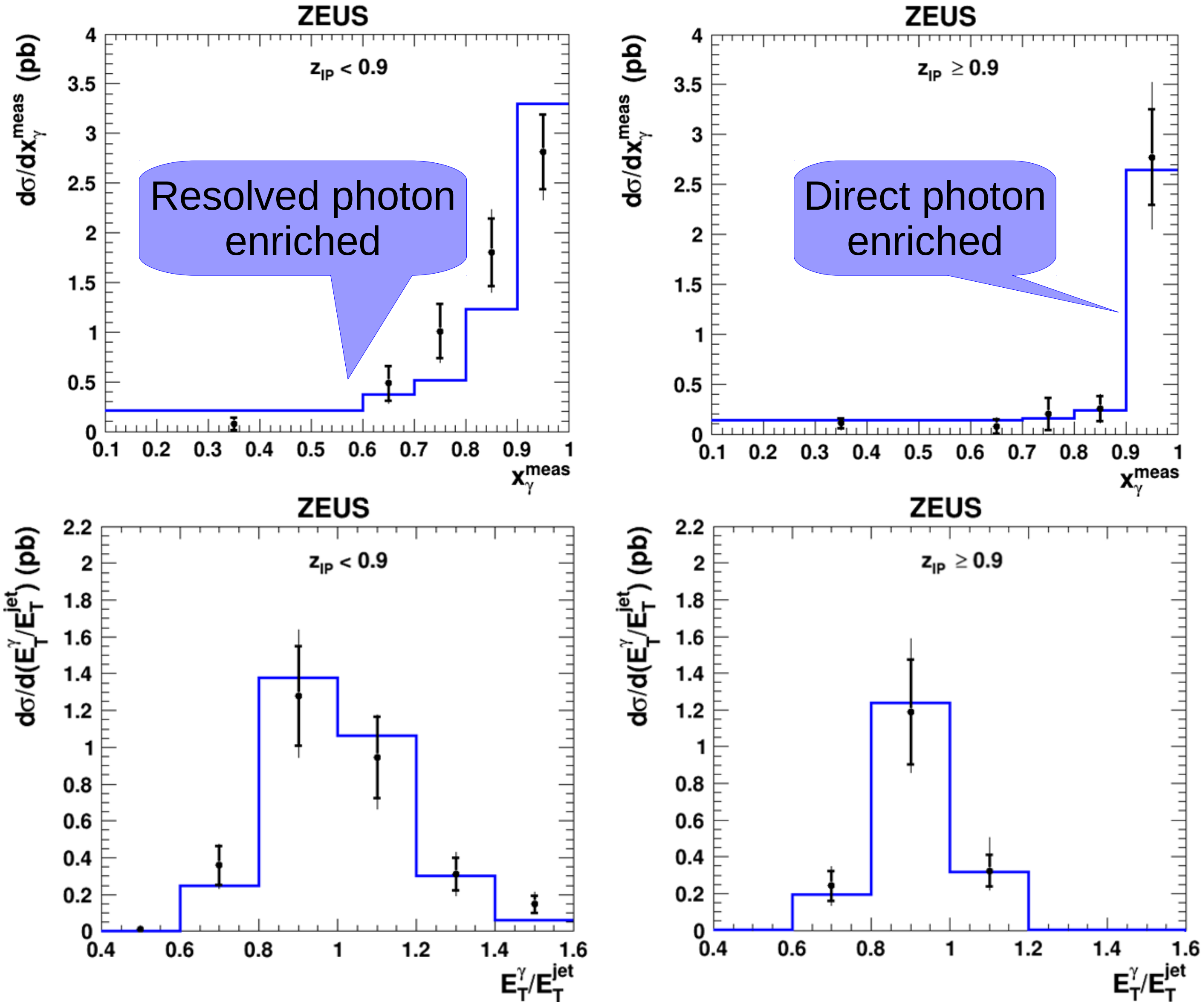
Photon + jet

Resolved pomeron enriched ($z_{IP} < 0.9$)

Direct pomeron enriched ($z_{IP} \geq 0.9$)

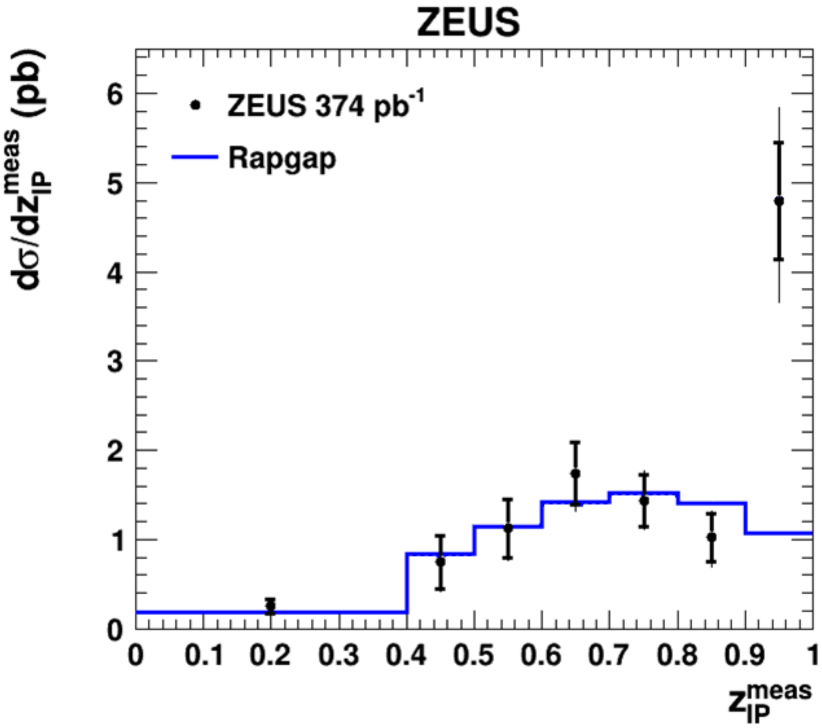
Photon momentum fraction entering hard process

Gamma/jet p_T balance



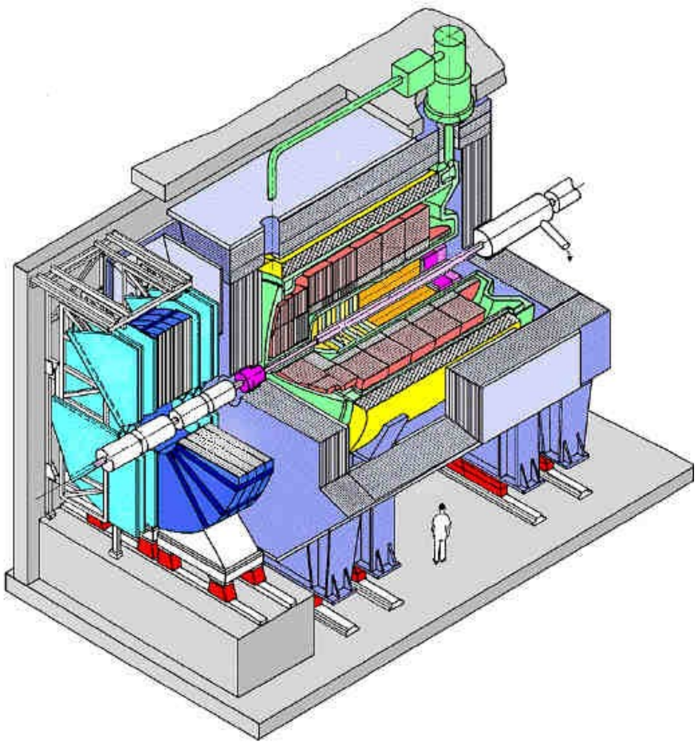
Conclusion 1

- The first measurement of diffractively produced prompt photon
- The peak in z_{IP} distribution suggests direct pomeron interactions (occurring mostly in direct photon interactions)
- Other distributions well described by MC prediction



Extraction of α_S at NNLO from jet cross sections in DIS

(H1)



H1prelim-17-031
[http://www-h1.desy.de/publications/H1preliminary.short_list.html]

DESY-16-200 Eur.Phys.J.C77 (2017) 4, 215 [arxiv:1611.03421]

NNLO α_S fit of H1 jets data in DIS

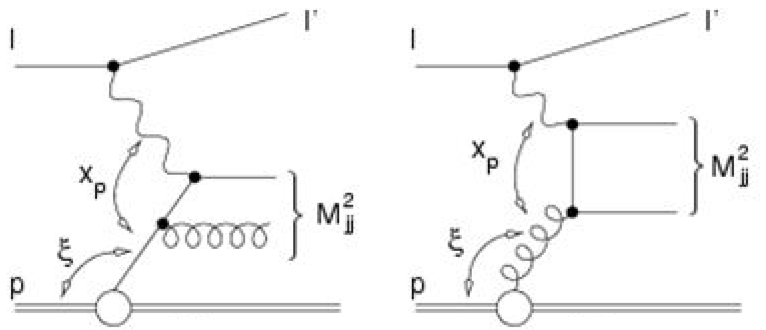
Why α_S ?

- Among the least known SM parameters

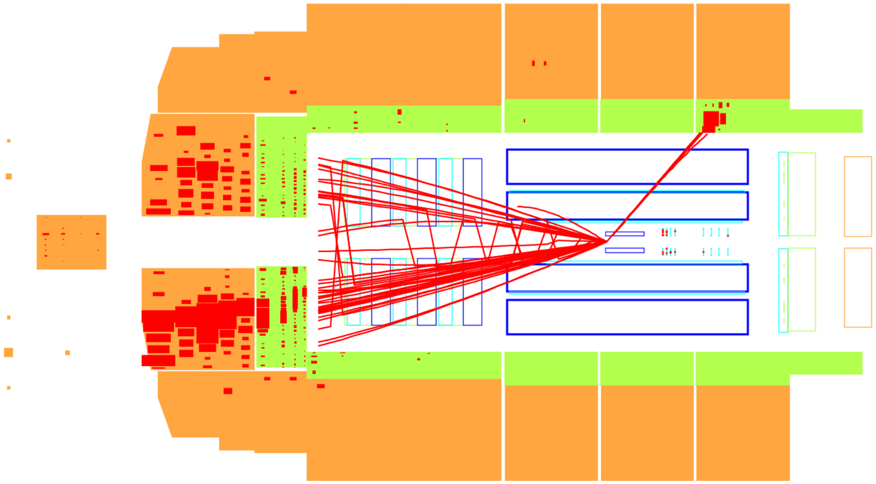
$G_F = 1.1663787(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$

$\alpha_S = 0.1181(11)$ [PDG16]

- Great importance for LHC physics



Dijet DIS production at H1



Why now?

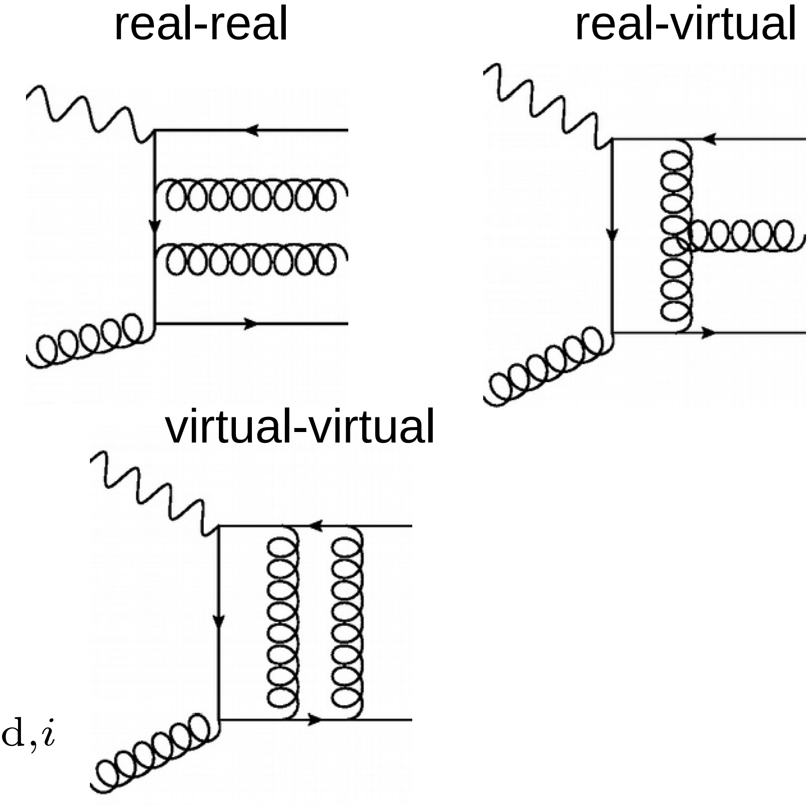
- NNLO revolution in the last years
- NNLO predictions now available for both *pp* and *ep* dijets
- LHC has not fitted their **jet** data with NNLO yet

First NNLO α_S fit of the jet ep data

NNLO calculations

✔ Real-real + real-virtual crosschecked with NLOJET++ & SHERPA

- New NNLO predictions for ep dijets based on **antenna subtraction**
  J. Currie, T. Gehrmann, A. Huss and J. Niehues, JHEP 07 (2017) 018, [1703.05977]
- Matrix element tables precalculated by **NNLOJET** program (~1M CPU hours)
- Then convoluted with PDFs and α_S using **fastNLO** (<1s)



$$\sigma_i = \sum_{k=g,q,\bar{g}} \int dx f_k(x,\mu_F)\, \hat{\sigma}_{i,k}(x,\mu_R,\mu_F) \cdot c_{\mathrm{had},i}$$

$$\hat{\sigma}_{i,k}(x,\mu_R,\mu_F) = \sum_n \alpha_S^n(\mu_R)\, \hat{\sigma}^{(n)}_{i,k}(x,\mu_R,\mu_F)$$

A bit of history

- **1973** Asymptotic freedom of QCD
- **1993** NLO studies of DIS jets
- **2016** NNLO corrections for DIS jets

H1 Data – Dijets

Double-diff.

- Q^2 and $\langle p_T \rangle_2$
- Mean dijet p_T

$$\langle p_T \rangle_2 = \frac{p_T^{\text{jet1}} + p_T^{\text{jet2}}}{2}$$

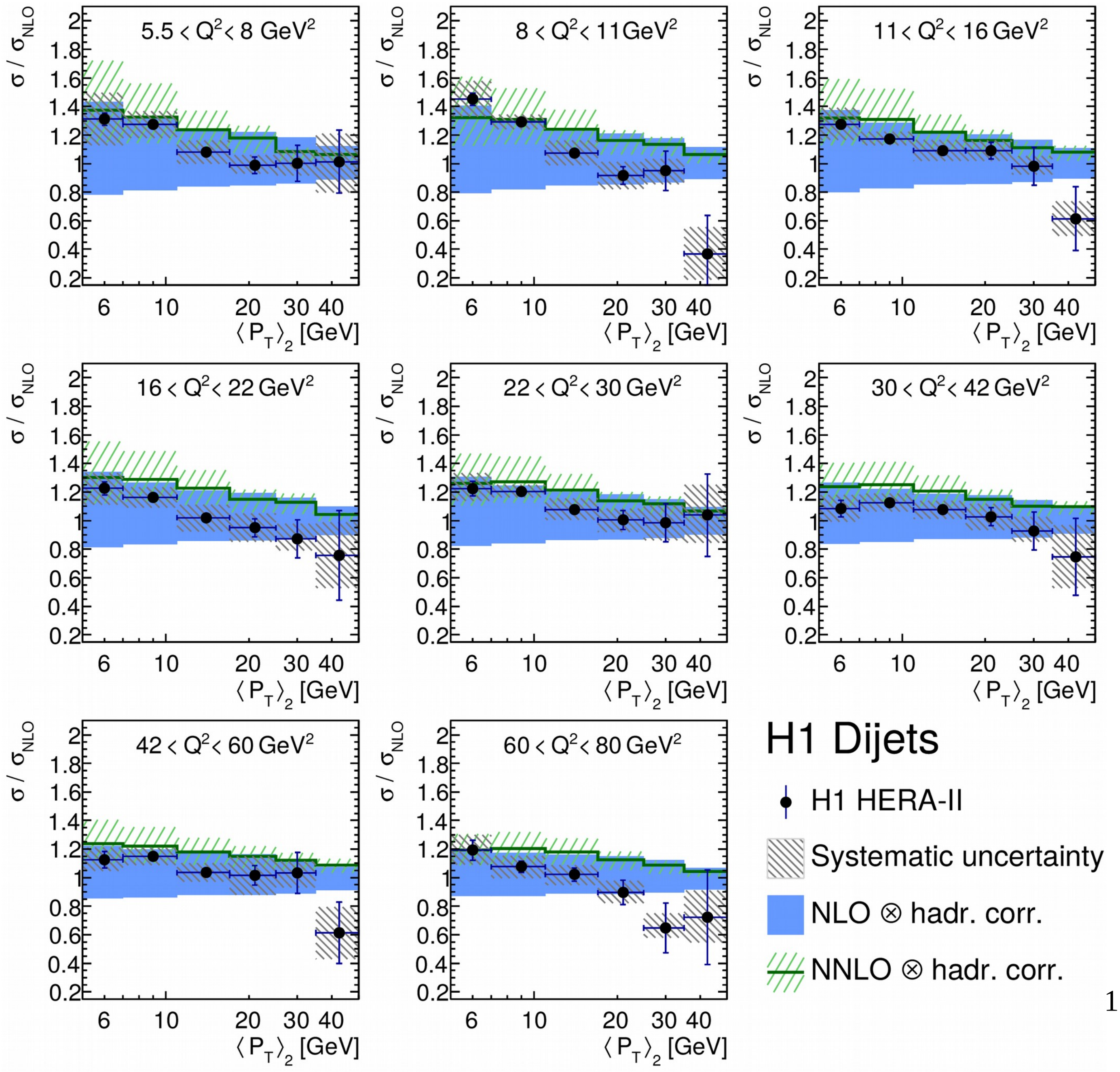
jets found in $\gamma^* p$
with k_T algo (R=1)

NLO predictions

- *NNPDF 3.0 NLO*
- Larger scale unc.
- Chi2/ndf = 1.4

NNLO predictions

- *NNPDF 3.0 NNLO*
- Smaller scale unc.
- Chi2/ndf = 0.6



H1 Data – Inclusive jets

Double-diff.

- Q^2 and p_T^{jet}
- Mean dijet p_T

$0.2 < y < 0.6$

$-1 < \eta_{\text{lab}}^{\text{jet}} < 2.5$

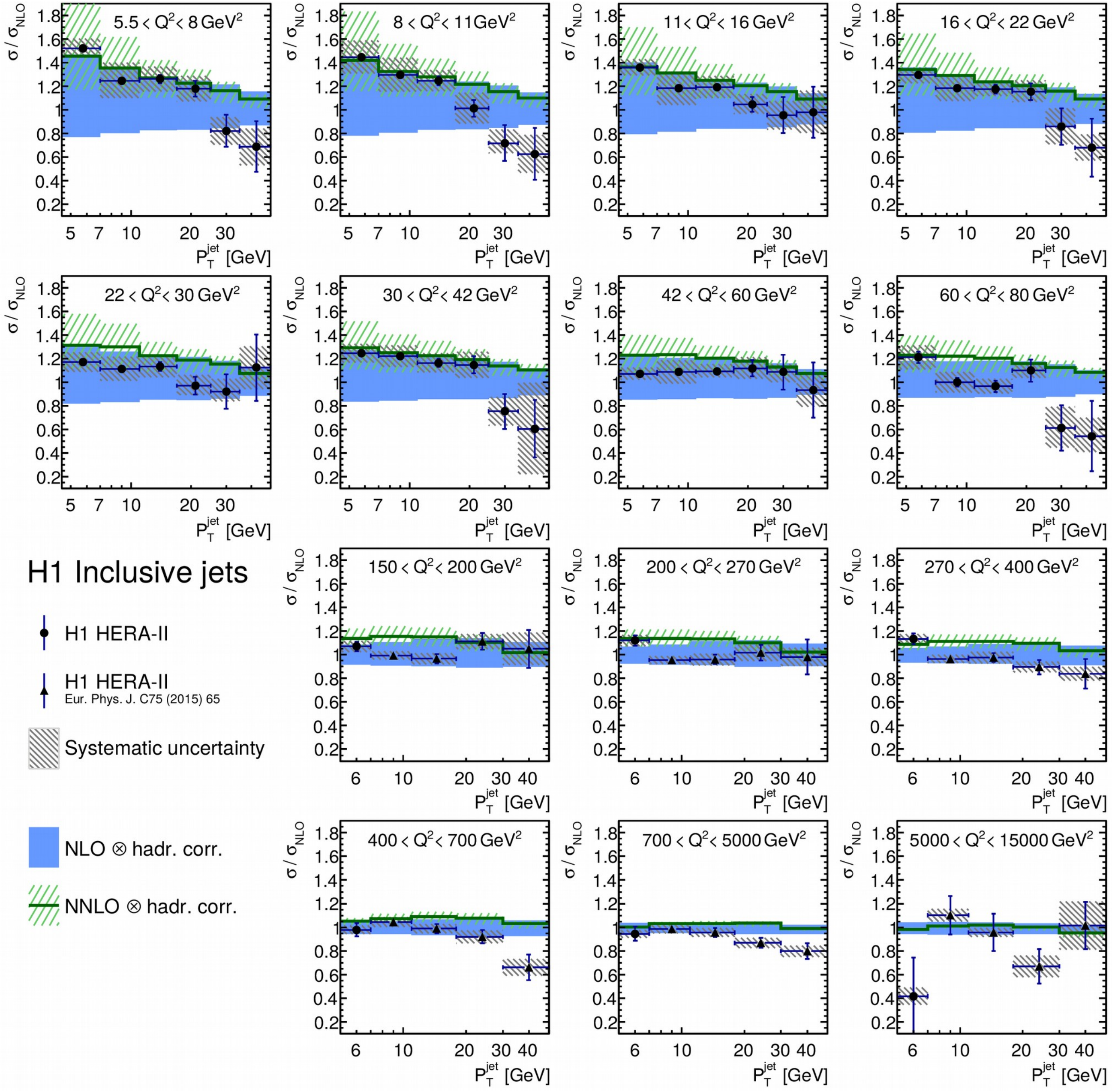
jets found in $\gamma^* p$
with k_T algo (R=1)

NLO predictions

- *NNPDF 3.0 NLO*
- Larger scale unc.
- Chi2/ndf = 1.7

NNLO predictions

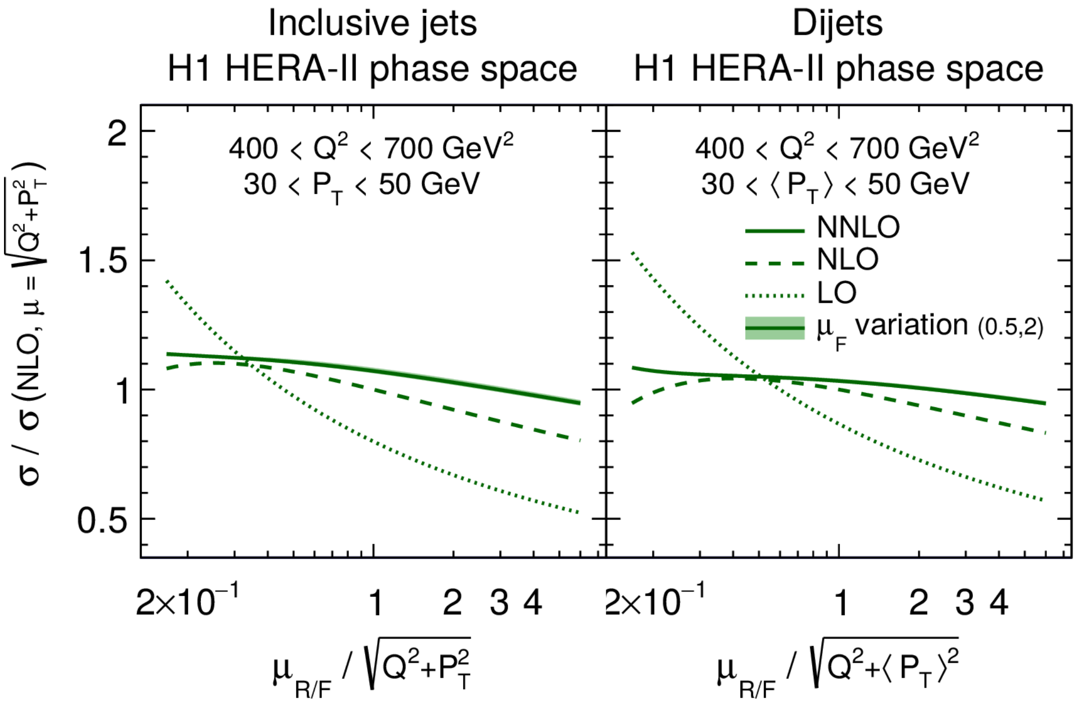
- *NNPDF 3.0 NNLO*
- Smaller scale unc.
- Chi2/ndf = 1.3



Scale dependence

- The NNLO predictions depend **less** on the renormalization scale (=have smaller theor. unc.)
- To estimate the uncertainty the scale varied up and down by the factor of 2
- As a scale we use $\mu_R = \mu_R = \sqrt{Q^2 + p_T^2}$

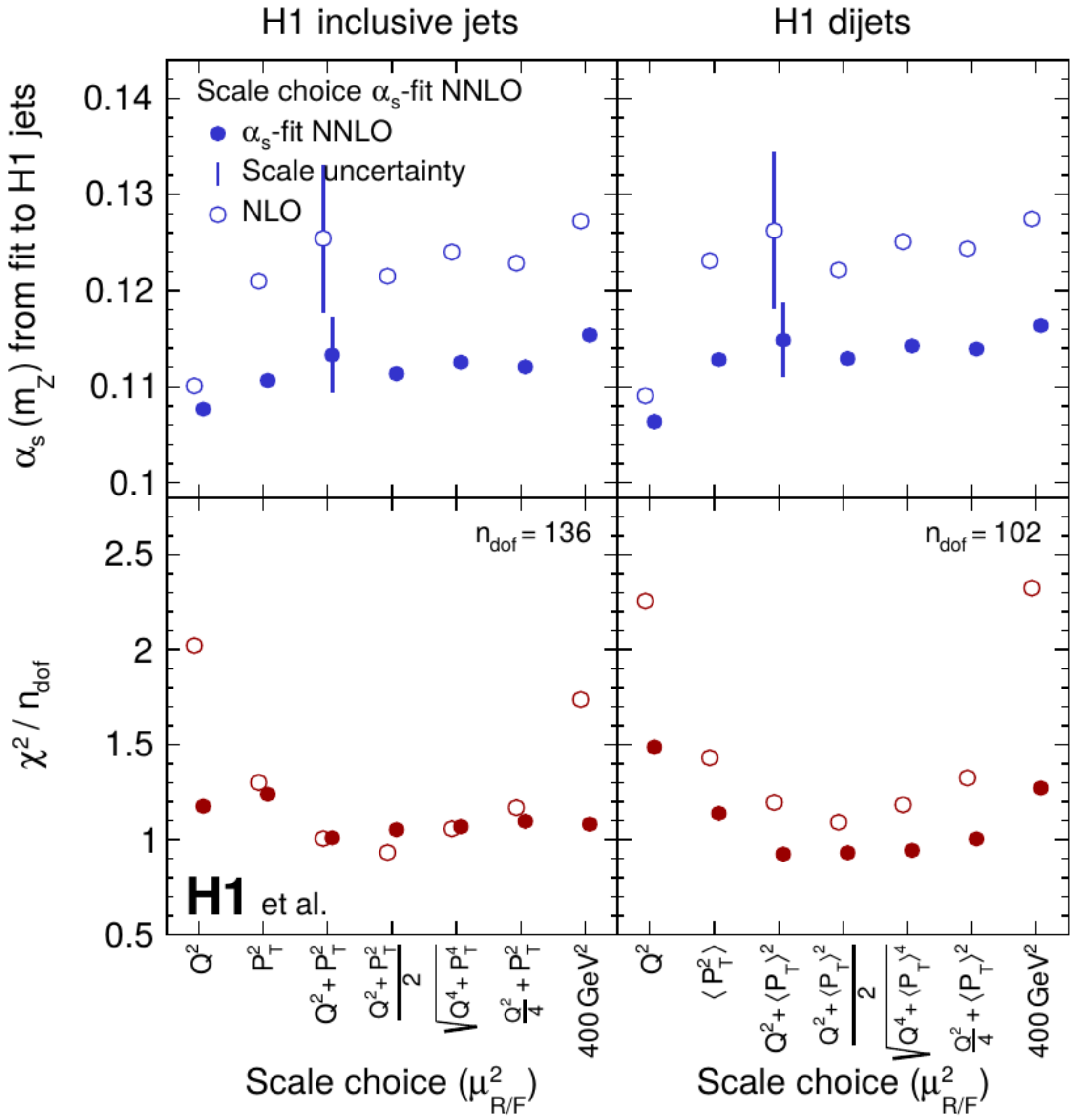
Others functional forms also tested



Functional form of the scale

- 7 possible function studied
- NNLO α_S is usually smaller than the NLO one
- The NNLO chi^2 is usually better
- NNLO scale unc. is smaller

$$
\begin{aligned}
\mu^2 &= Q^2 \\
\mu^2 &= p_T^2 \\
\mu^2 &= Q^2 + p_T^2 \\
\mu^2 &= \frac{Q^2 + p_T^2}{2} \\
\mu^2 &= \sqrt{Q^4 + p_T^4} \\
\mu^2 &= Q^2/4 + p_T^2 \\
\mu^2 &= 400\,\mathrm{GeV}^2
\end{aligned}
$$



All data above m_b threshold used

α_S in PDF and α_S in ME

- Alpha strong affecting both, PDFs and matrix element
- Both effects considered, α_S in ME more prominent

α_S dep.

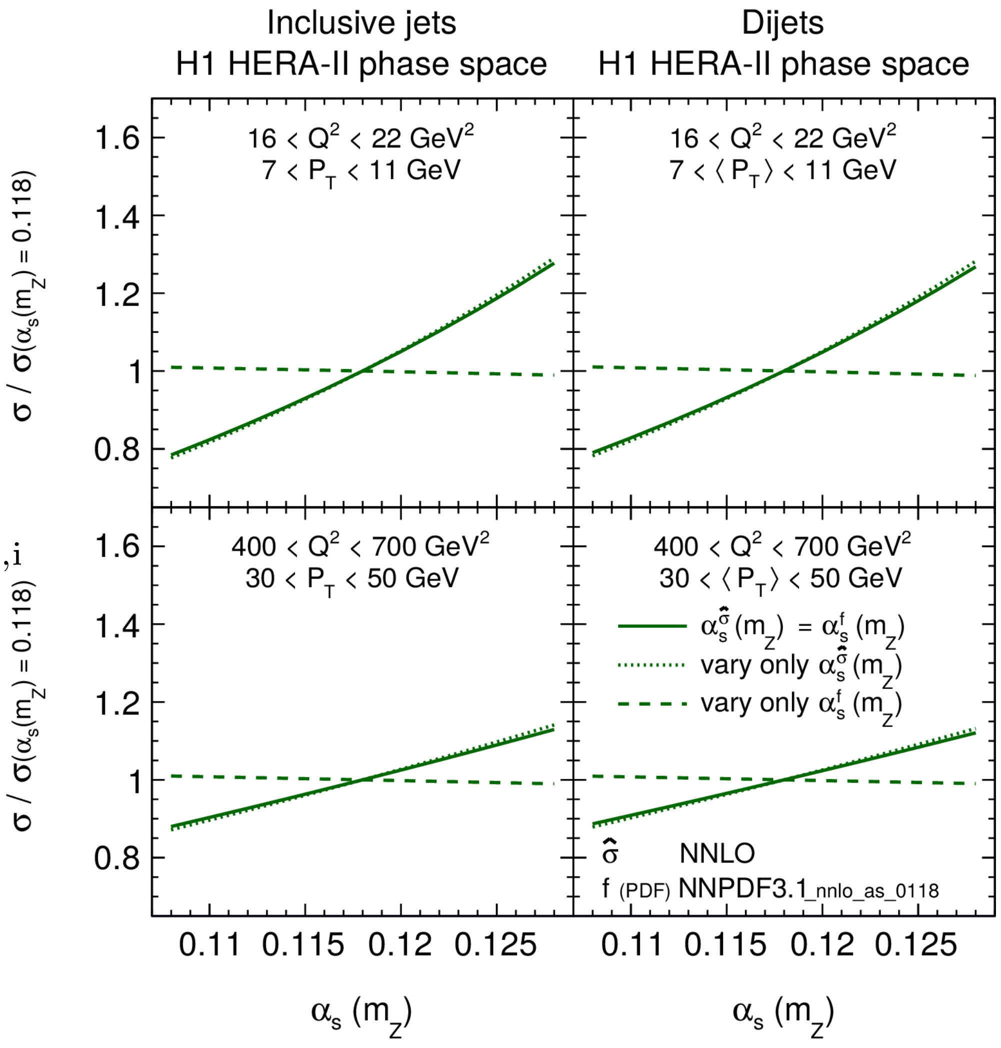
α_S dep.

$$\sigma_i = \sum_{k=g,q,\bar{q}} \int dx\, f_k(x, \mu_F)\, \hat{\sigma}_{i,k}(x, \mu_R, \mu_F) \cdot c_{\mathrm{had,i}}$$

$$\hat{\sigma}_{i,k}(x, \mu_R, \mu_F) = \sum_n \alpha_S^n(\mu_R)\, \hat{\sigma}_{i,k}^{(n)}(x, \mu_R, \mu_F)$$

DGLAP equations

$$\mu_F^2 \frac{df}{d\mu_F^2} = P(z, \alpha_s) \circledast f(x, \mu_F^2)$$



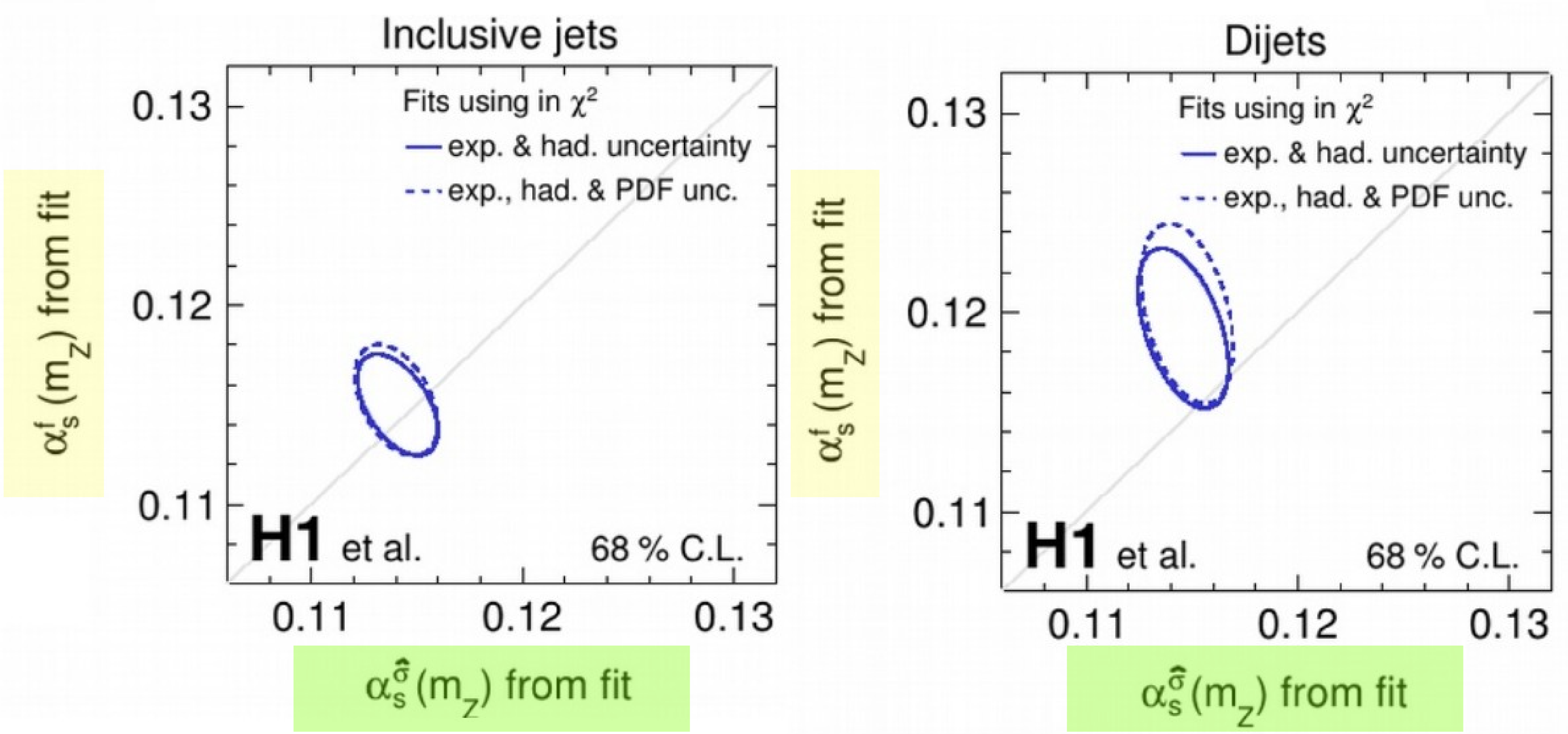
PDFs at scale $\mu_0 = 30\,\mathrm{GeV}$ very well constrained by lot of data $\longrightarrow$ α_S - “independent”

Original PDFs from scale $\mu_0 = 30\,\mathrm{GeV}$ evolved to higher/lower scales by DGLAP with $\alpha_S = \alpha_S(\mathrm{fit\ par.})$

Independent fitting of two α_S

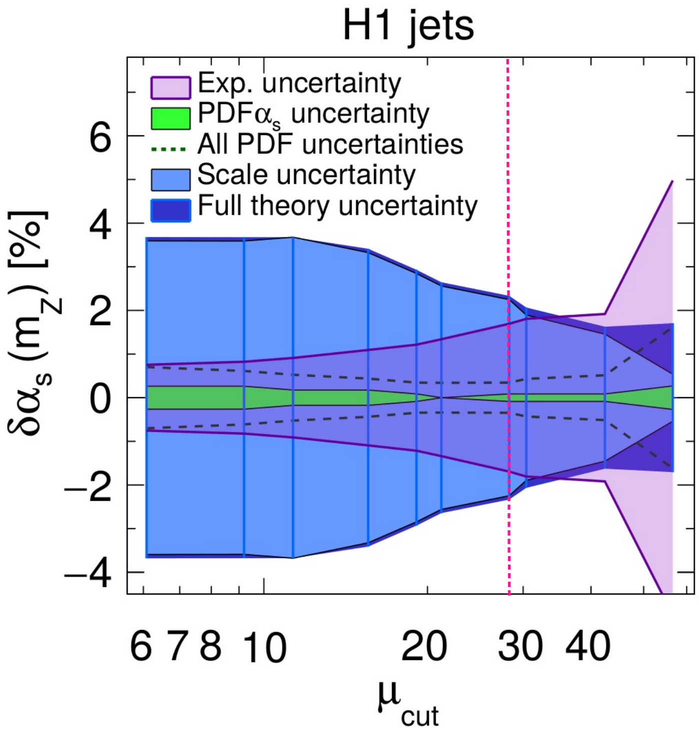
- The alpha strong from PDF and ME consistent

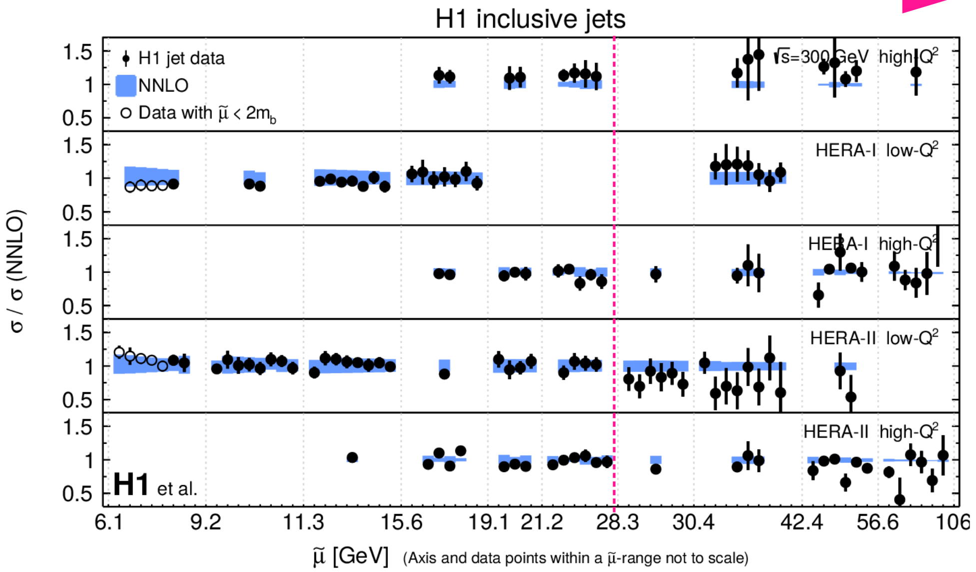
$$\sigma_i = f\left(\alpha_s^f(m_Z)\right) \otimes \hat{\sigma}_i\left(\alpha_s^{\hat{\sigma}}(m_Z)\right) \cdot c_{\mathrm{had},i}$$

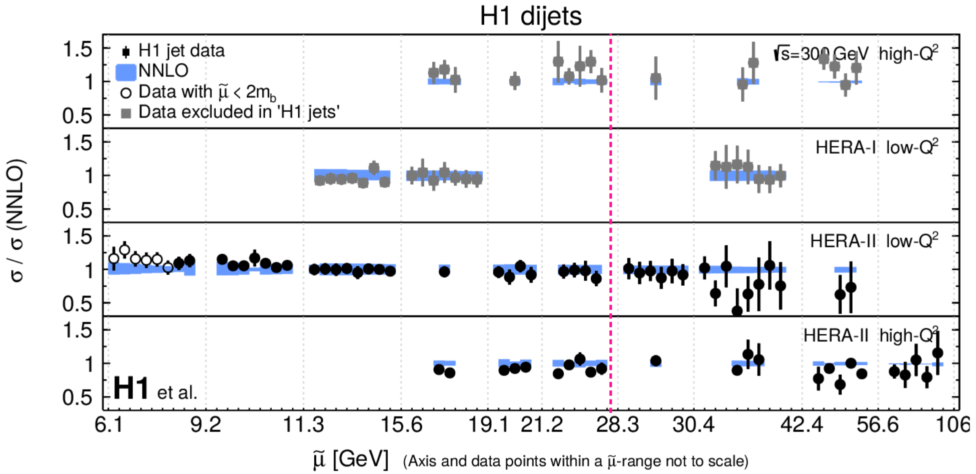


Which data use in the fit?

- The scale uncertainty gets higher with smaller scales ($\mu = \sqrt{p_T^2 + Q^2}$)
- We use only data $\mu > \mu_{\text{cut}}$



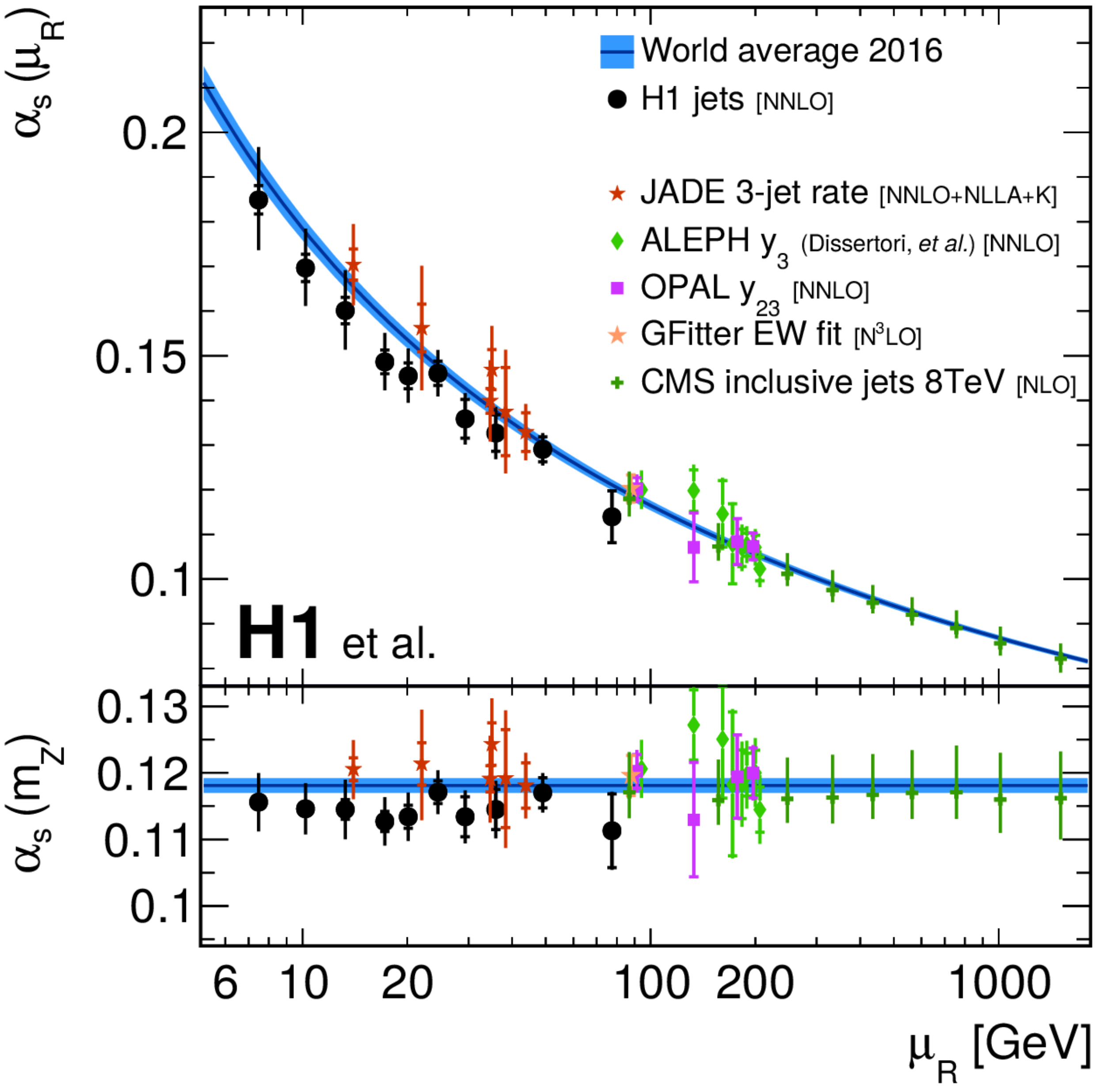




Small $\mu_{\text{cut}} \longrightarrow$ high theor. unc.
Large $\mu_{\text{cut}} \longrightarrow$ high exp. unc.

Compromise $\mu_{\text{cut}} = 28\,\text{GeV}$

Running of alpha strong



← HERA

← PETRA

← LEP

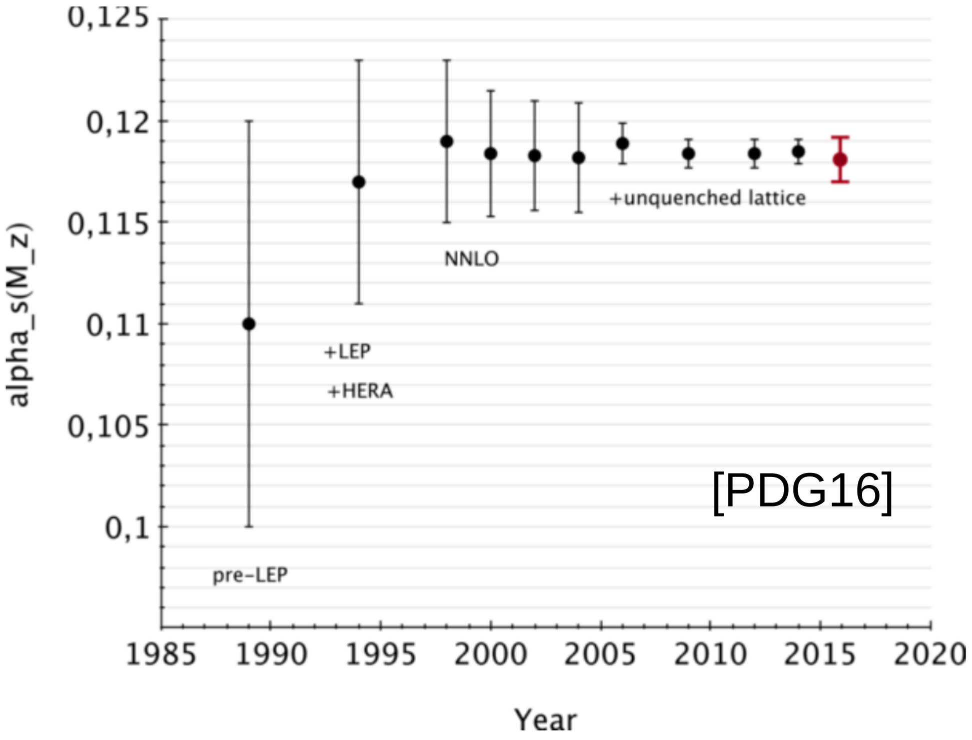
← LEP

← LHC

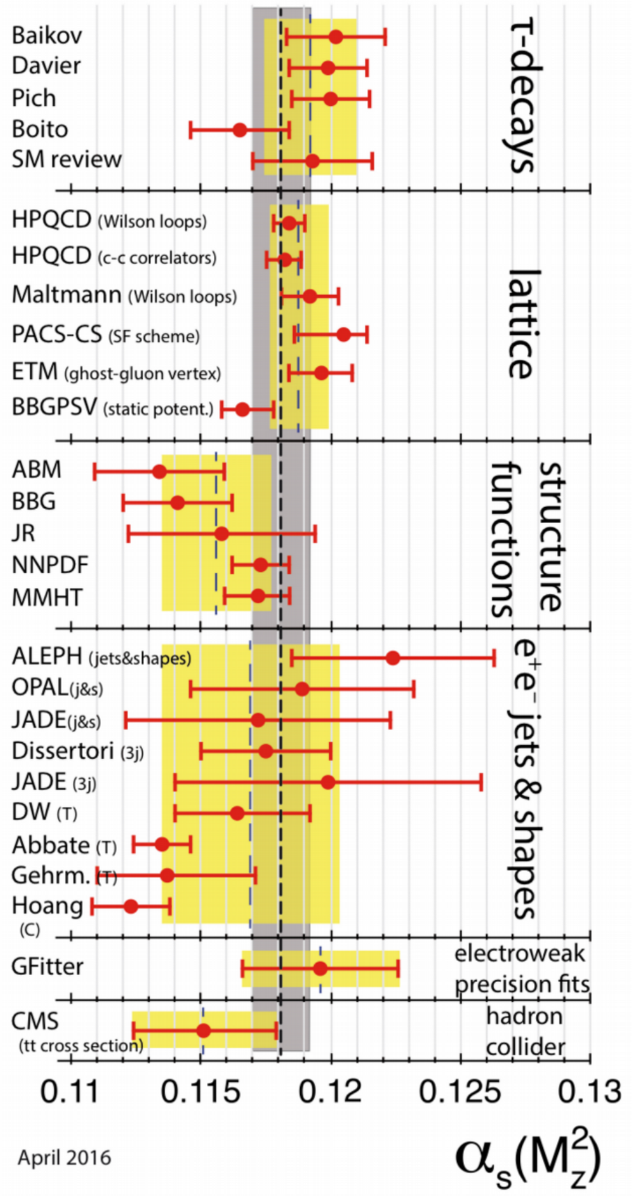
$\alpha_S = 0.1181(11)$

History of Alpha Strong

- The current world average value $\alpha_s(m_Z) = 0.1181(11)$
- Mostly driven by lattice and tau-decays
- From LHC the most precise estimate is from ttbar (NNLO)

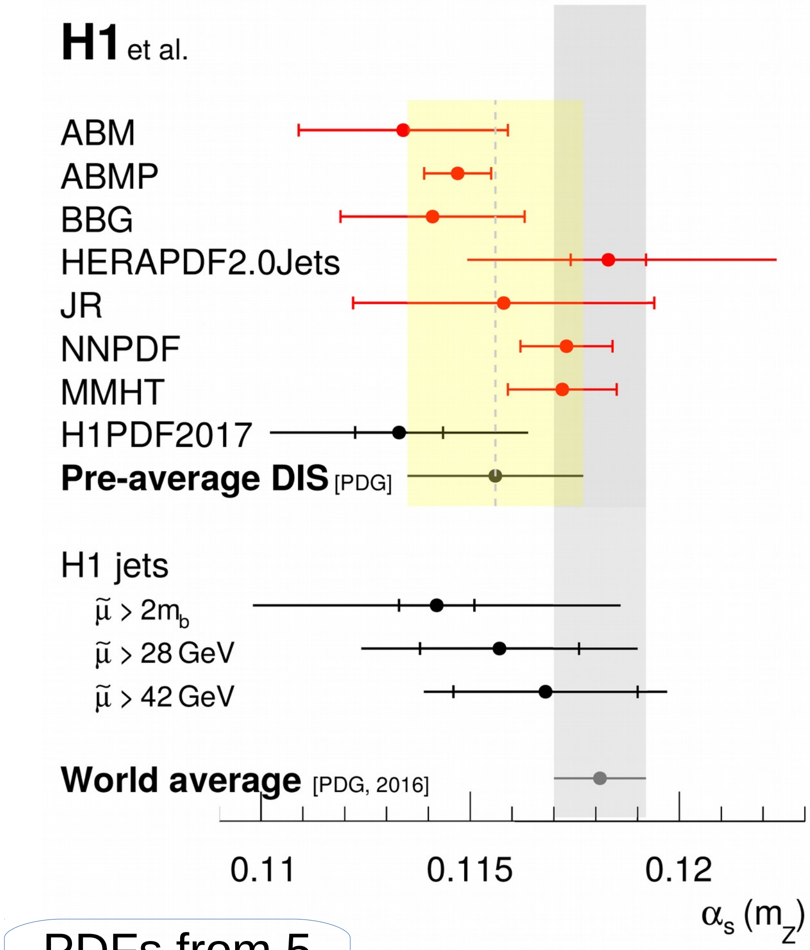


At least NNLO fits [PDG16]



Measured alpha strong value

- Consistent with the "world average value"
- Consistent with α_S from global PDF fits
- The NNLO reduces the scale uncertainty **by half**
- The theoretical scale uncertainty still dominant



Hadronisation

PDFs from 5 collaborations

$$\alpha_S(m_Z) = 0.1156(19)_{\mathrm{exp}}(6)_{\mathrm{had}}(3)_{\mathrm{PDF}}(1)_{\mathrm{PDF}\alpha_S}(3)_{\mathrm{PDFSet}}(25)_{\mathrm{scale}}$$

Data unc.

NNPDF 3.1 unc.

NNPDF 3.1 α_S variants

Scale unc.

Conclusion 2

- The α_S from the jet DIS data estimated with NNLO precision for the first time
- The obtained value competitive with LHC and LEP measurements
- The uncertainty of H1 data even now smaller than the theoretical one ⟶ waiting for N^{3}LO

S. Bethke, Nucl.Part.Phys.Proc. 282-284 (2017) 149-152

Subclass	$\alpha_s(M_Z^2)$
τ-decays	0.1192 ± 0.0018
lattice QCD	0.1188 ± 0.0011
structure functions	0.1156 ± 0.0021
e^+e^- [jets & shps]	0.1169 ± 0.0034
hadron collider	$0.1151 \begin{smallmatrix} +\ 0.0028 \\ -\ 0.0027 \end{smallmatrix}$
ew precision fits	0.1196 ± 0.0030
H1 NNLO jets	0.1156 ± 0.0032