Determination of the strong coupling constant $\alpha_s(m_Z)$ from jet cross section measurements

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α_s workshop Trento, Italy

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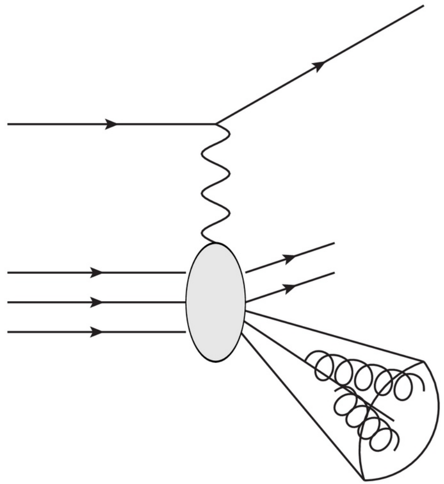
J. Phys. G 48 (2021) 110501
Eur. Phys. J. C79 (2019) 845
Eur. Phys. J. C77 (2017) 791

and some more and work in progress....

MAX-PLANCK-INSTITUT
FÜR PHYSIK

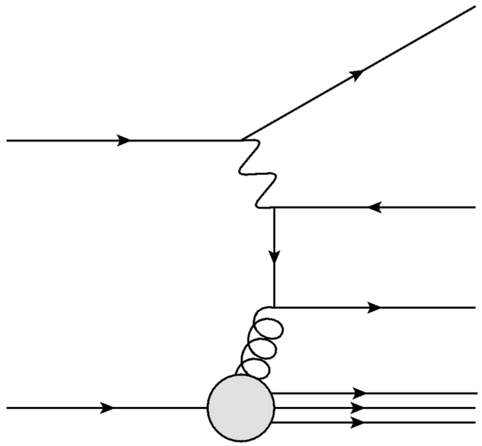
Jet production at hadron colliders

Neutral-current DIS



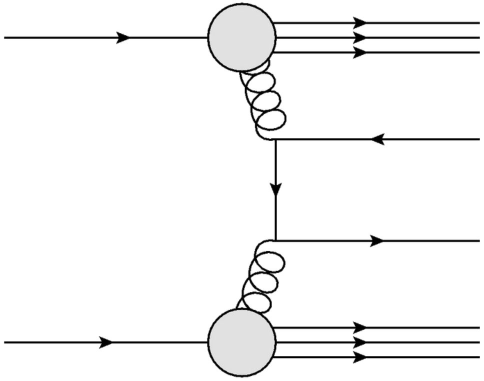
$ep \rightarrow e + \text{jet} + X$

Jet production in DIS



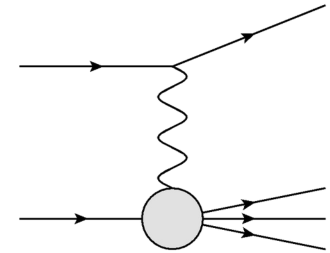
$ep \rightarrow e + 2\text{jets} + X$

Jet production at the LHC



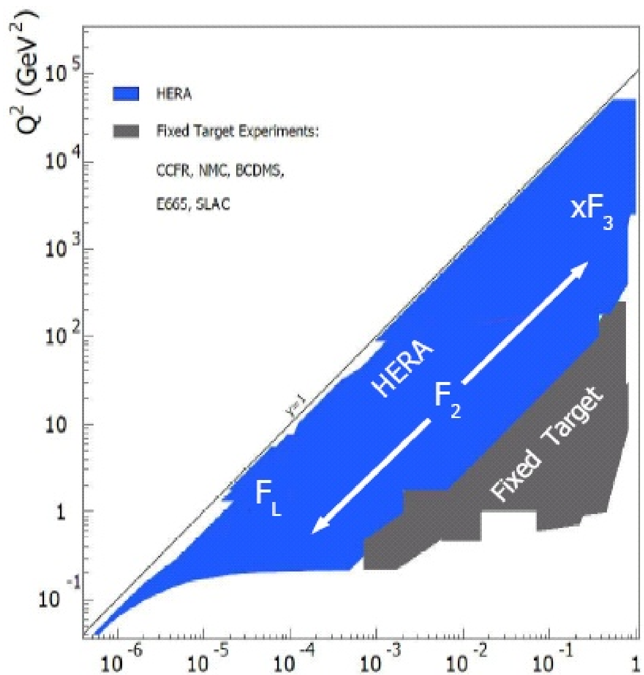
$pp \rightarrow 2\ \text{jets} + X$

Inclusive DIS

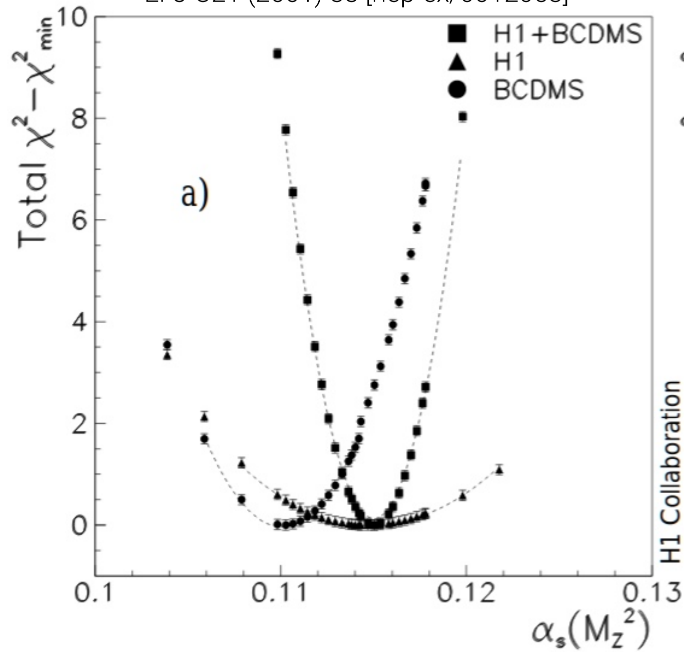


Inclusive DIS is sensitive to α_s through F_2 and F_L

$$\tilde{\sigma}_{NC}(x, Q^2, y) \equiv \frac{d^2\sigma_{NC}}{dx dQ^2} \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y_+} \equiv \left(F_2 - \frac{y^2}{Y_+} F_L - \frac{Y_-}{Y_+} xF_3\right)$$



EPJ C21 (2001) 33 [hep-ex/0012053]



HERA inclusive DIS data has no relevant sensitivity to α_s … but fixed target data has !

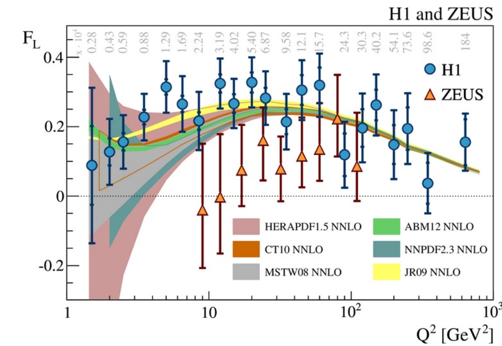
α_s from NC and CC Inclusive DIS

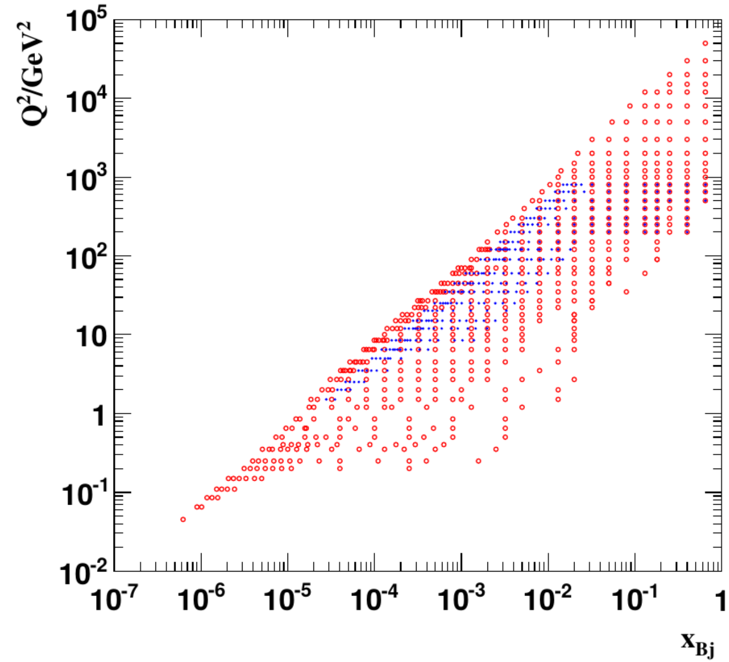
All HERA inclusive NC & CC DIS data

- H1 & ZEUS combined data
- incl. low-E runs → F_L sensitivity
- PDF determination and α_s scan

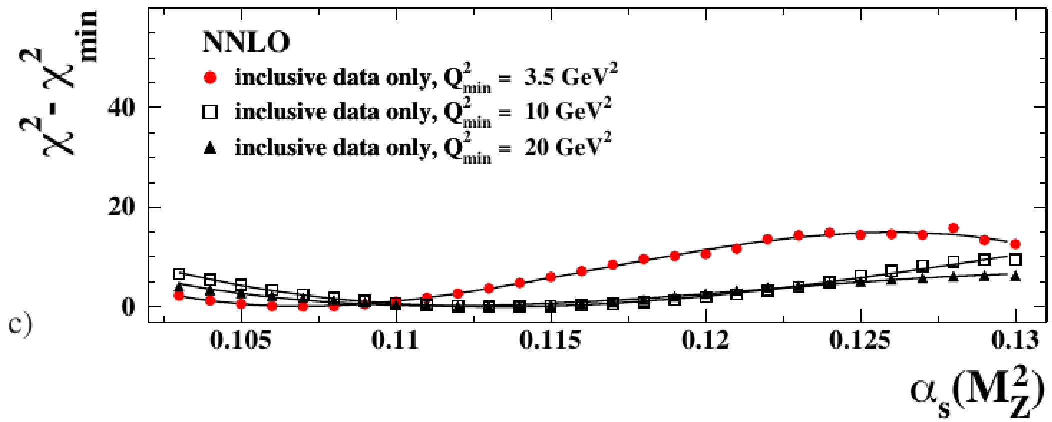
→ No significant sensitivity to α_s from HERA inclusive DIS data

→ … but PDFs are determined with high precision

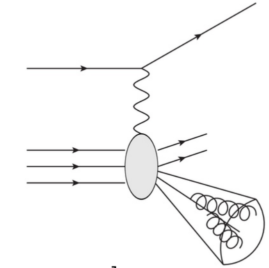




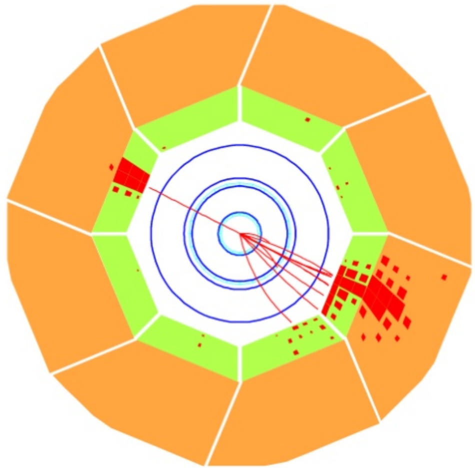
Eur.Phys.J.C75 (2015) 580 [arXiv:1506.06042]



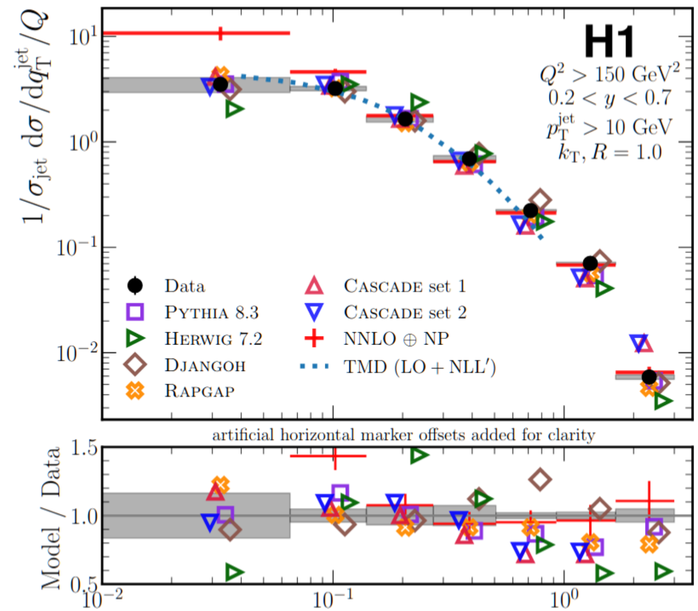
Hadronic final state in NC DIS



More detailed measurements of hadronic final state in NC DIS



H1 Collaboration [arxiv:2108.12376]



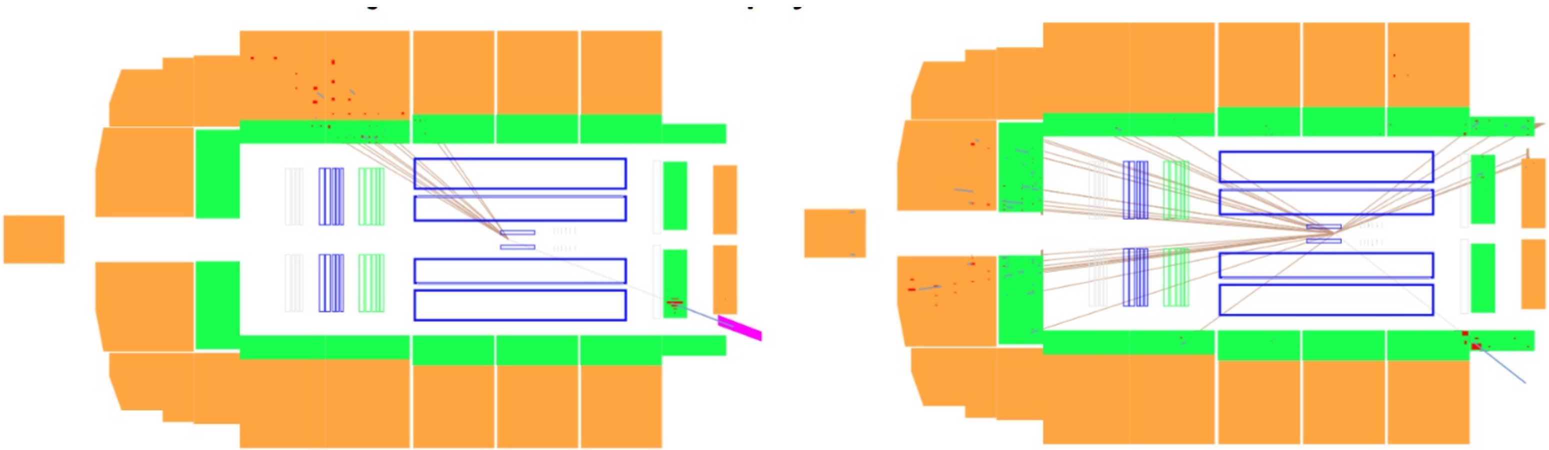
$$q_T^{jet} = |\vec{p}_T^{\,e} + \vec{p}_T^{\,jet}|$$

Measurement of lepton-jet correlations
→ Very clean: no pile-up, no underlying event, ...
→ sensitive to α_s through parton-shower, PDFs, resummation, TMD?, etc...

Very rich physics inside DIS jets with strong α_s sensitivity:
→ Jet substructure & subjets, groomed jets, hadron-in-jets, charge-energy-corrleations, Lund plane, ...
→ measurements still ongoing. Stay tuned ... (DIS22)

Hadronic final state in NC DIS

Event shapes: measurement of hadronic final state w/o jets



α_s from event shapes in HERA-I (EPJ C46 (2006) 343)

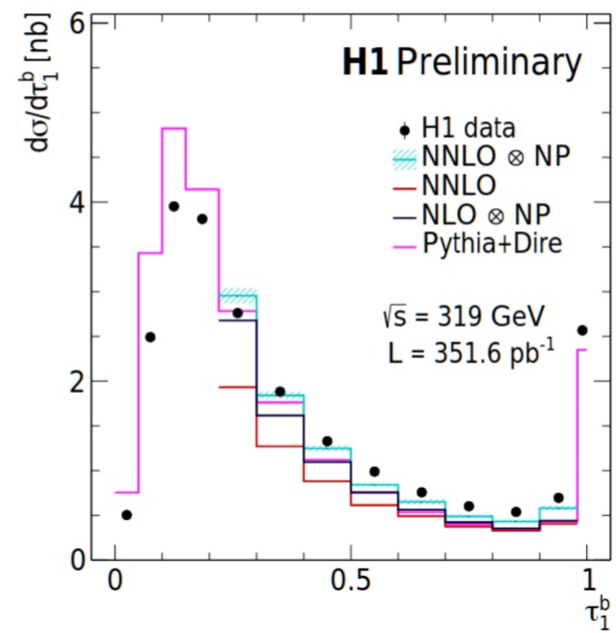
$$\alpha_s(m_Z) = 0.1198 \pm 0.0013\,(\text{exp})\,^{+0.0056}_{-0.0043}\,(\text{theo})$$

→ high experimental precision (while just HERA-I)

→ largely limited by theory

1-jettiness

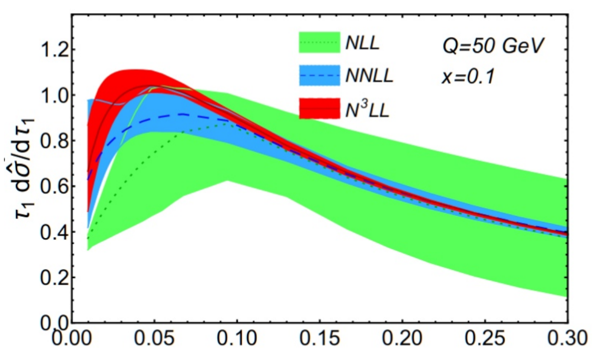
H1prelim-21-032 (also [arXiv:2111.1136])

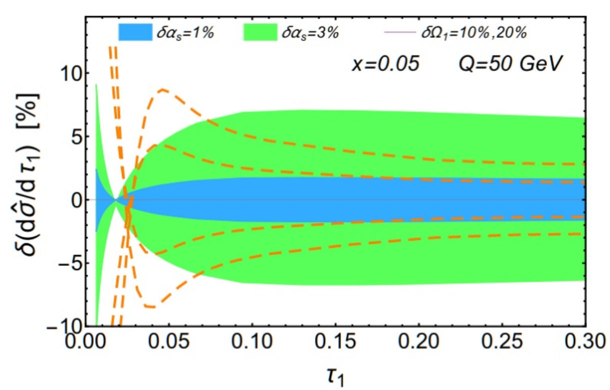


Event shapes free of non-global logs

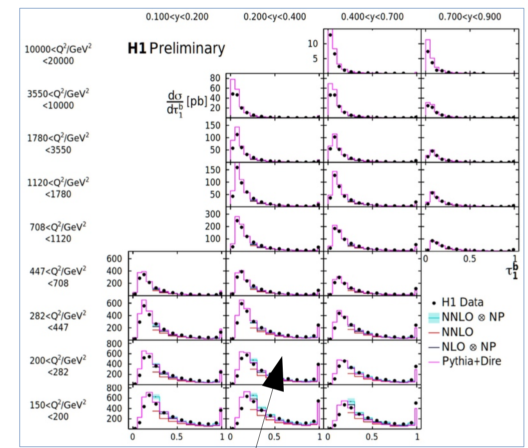
$$\tau_1^b = \frac{2}{Q^2}\sum_{i\in X}\min\{xP\cdot p_i, (q+xP)\cdot p_i\}$$

- Axes of incoming parton (*xP*) and *q+xP*
- Advances in factorization, SCET, fixed-order pQCD and ME+PS matching allow for precise predictions
- Fresh measurement in DIS
  → Exciting α_s sensitivity w/ high theo. and exp. precision





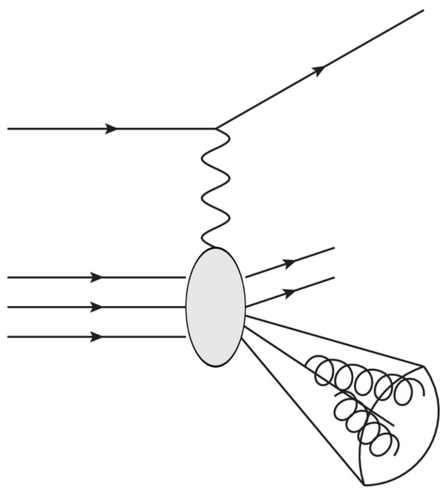
I. Stewart – Future Physics with HERA, Hamb. Nov 2014



Triple-differential NC DIS data !

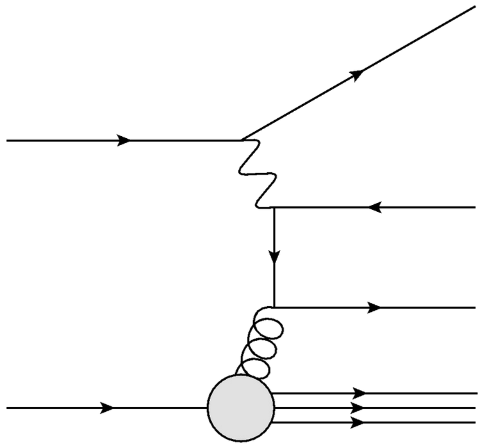
Jet production at hadron colliders

Neutral-current DIS



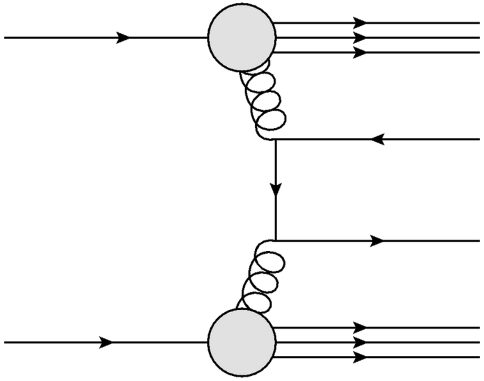
ep → *e* + jet +X

Jet production in DIS



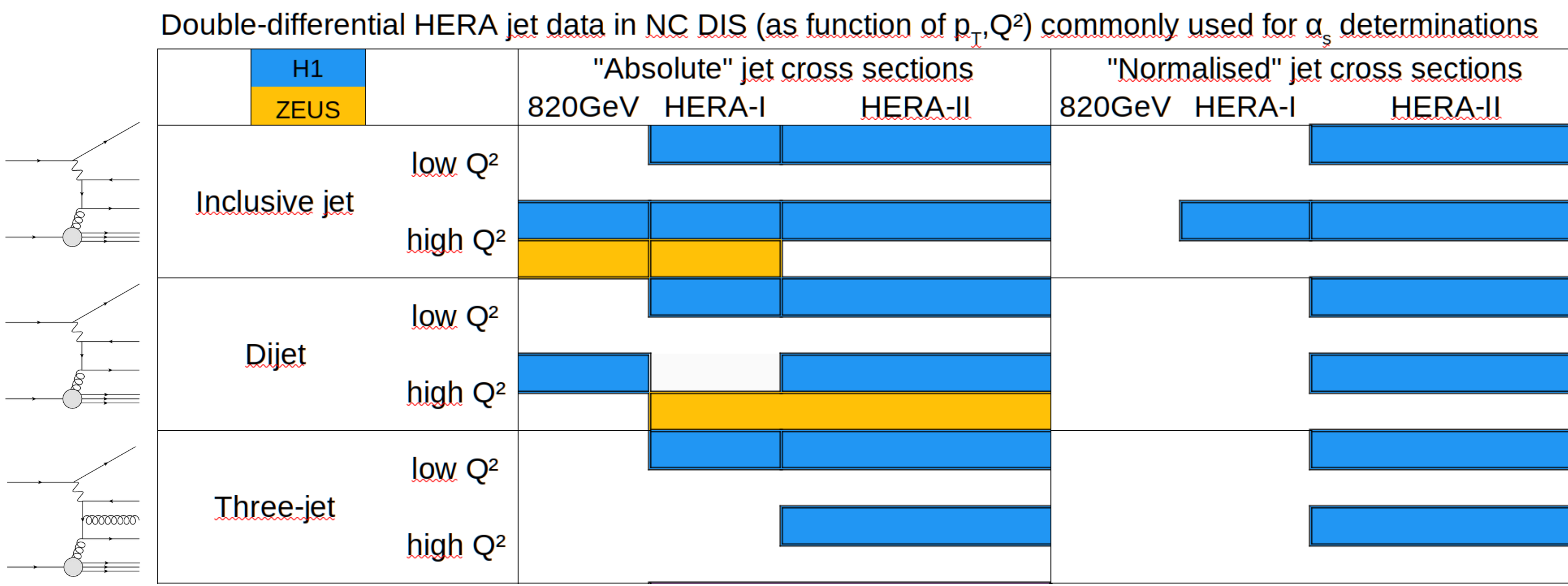
ep → e + 2jets + X

Jet production at the LHC



pp → 2 jets + X

Summary of (most) HERA jet data

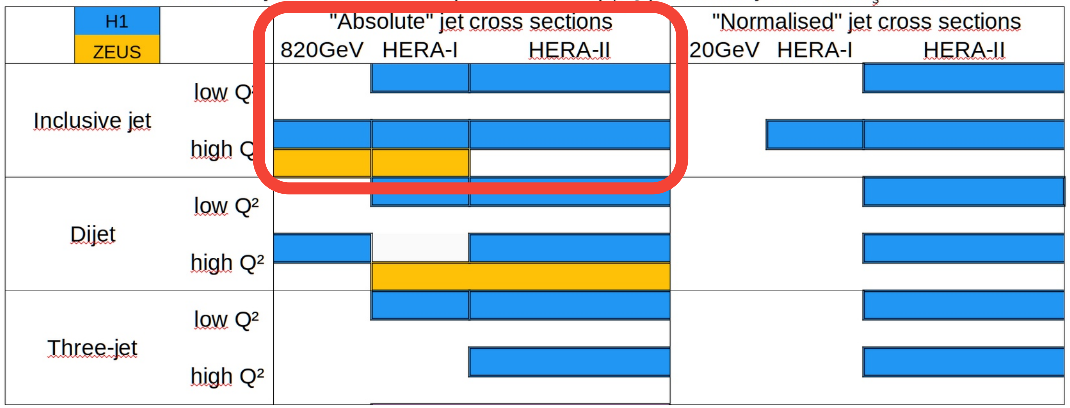


Note: more jet-data are available (H1 and ZEUS) – mainly from HERA-I, but these were not yet analysed in NNLO. Also jets in photoproduction or in charged-current DIS, or heavy flavor production could be considered.

Inclusive jets in NNLO pQCD

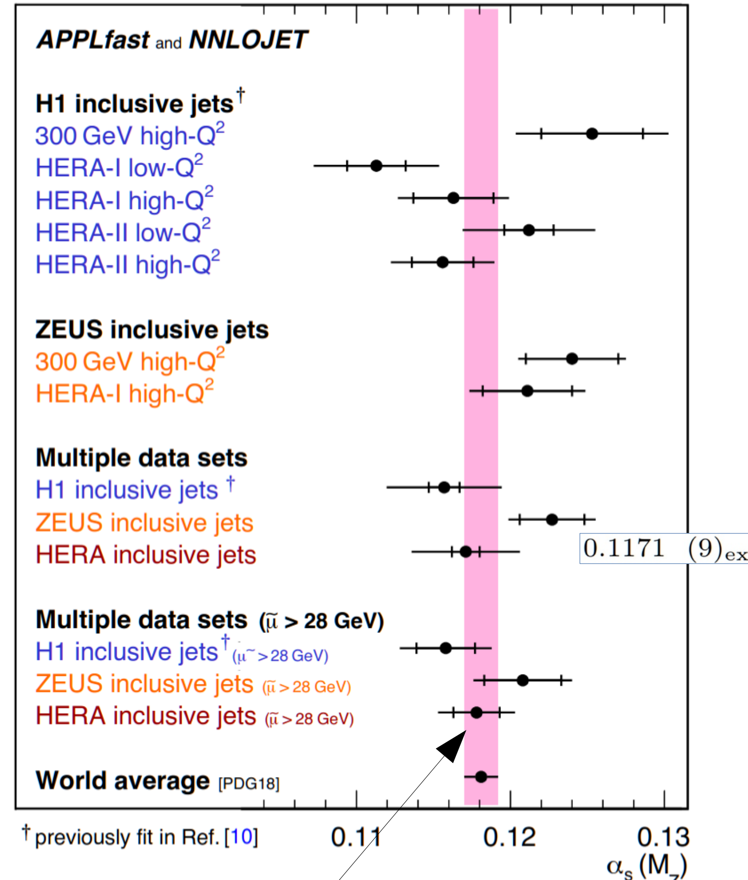
Eur.Phys.J.C 79 (2019) 845
[Erratum EPJ C 81 (2021) 957]
[1906.05303]

Double-differential HERA jet data in NC DIS (as function of p_T,Q^2) commonly used for α_s determinations



- α_s from inclusive jet cross sections in NC DIS
- NNLO pQCD w/ non-pert. hadronisation corrections
- H1 and ZEUS consistent
- Sizeable scale uncertainties (MHOU) since data are at comparably low scales
- Highest precision obtained in fit to data with $\mu > 28$ GeV

α_s results from HERA inclusive jet data in NNLO



$$\alpha_s(M_Z) = 0.1178\,(15)_{\rm exp}\,(21)_{\rm th}$$

Inclusive jets in NNLO pQCD

Eur.Phys.J.C 79 (2019) 845
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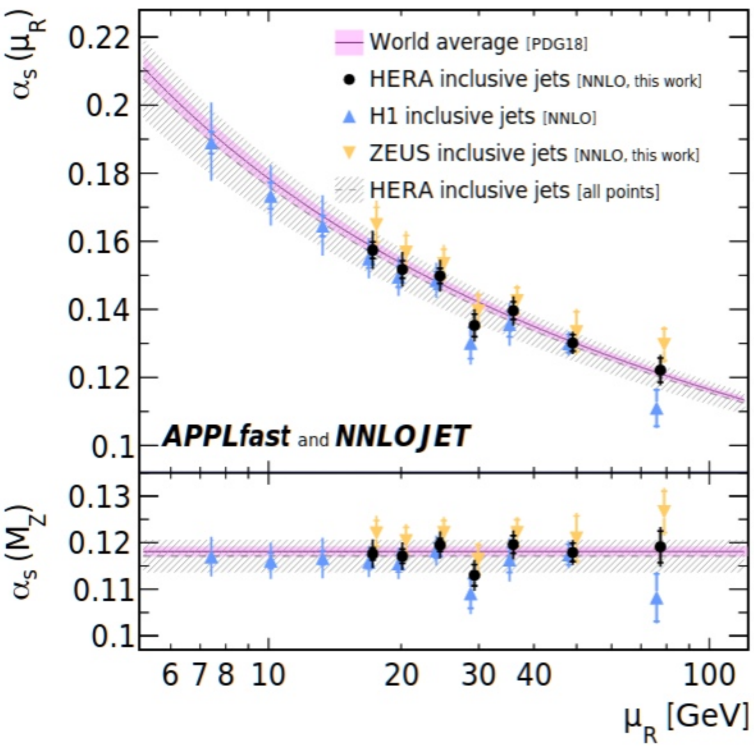
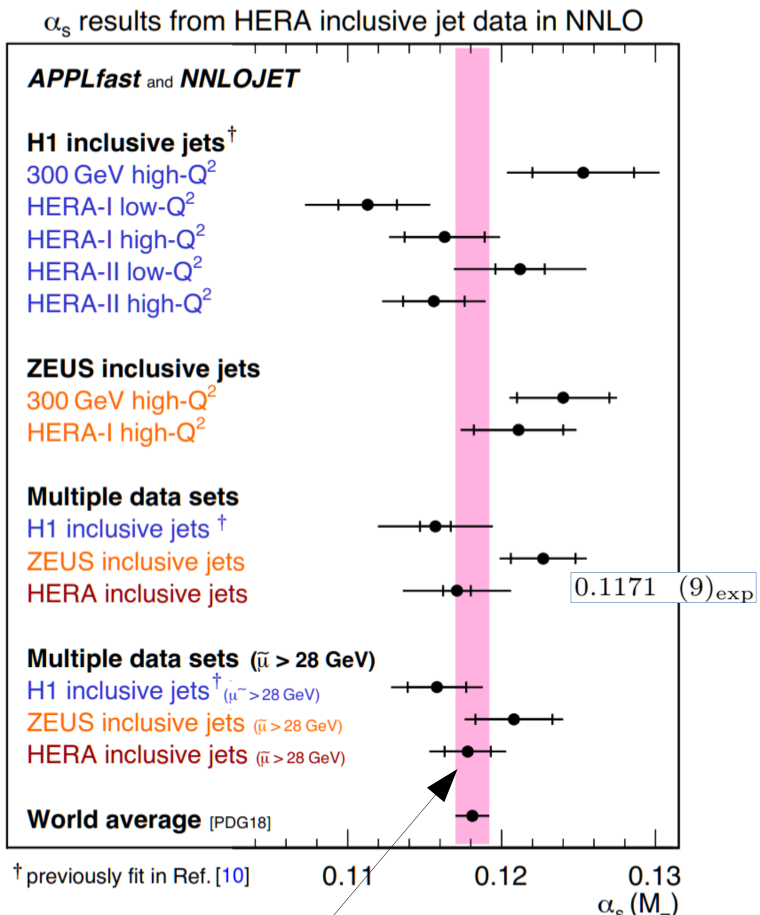




$$\alpha_s(M_Z) = 0.1178\,(15)_{\rm exp}\,(21)_{\rm th}$$

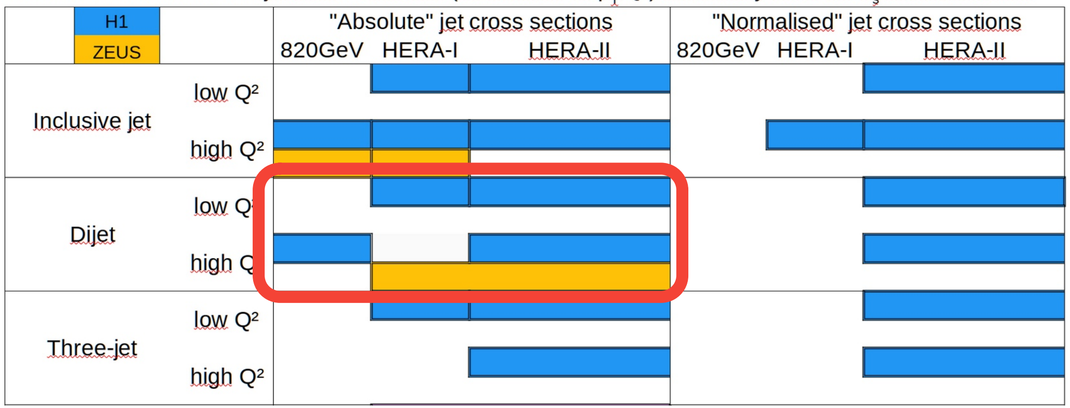
- Running from inclusive jets in range $7 < \mu < 80$GeV

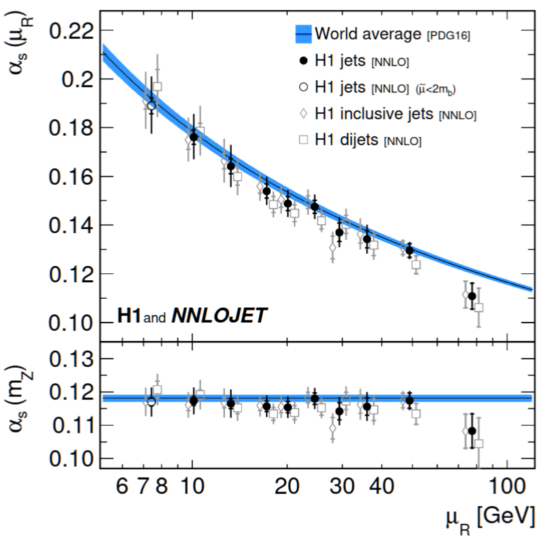
  $\mu^2 = p_T^2 + Q^2$

EPJ .C77 (2017) 791 [Erratum EPJ C81 (2021) 738]

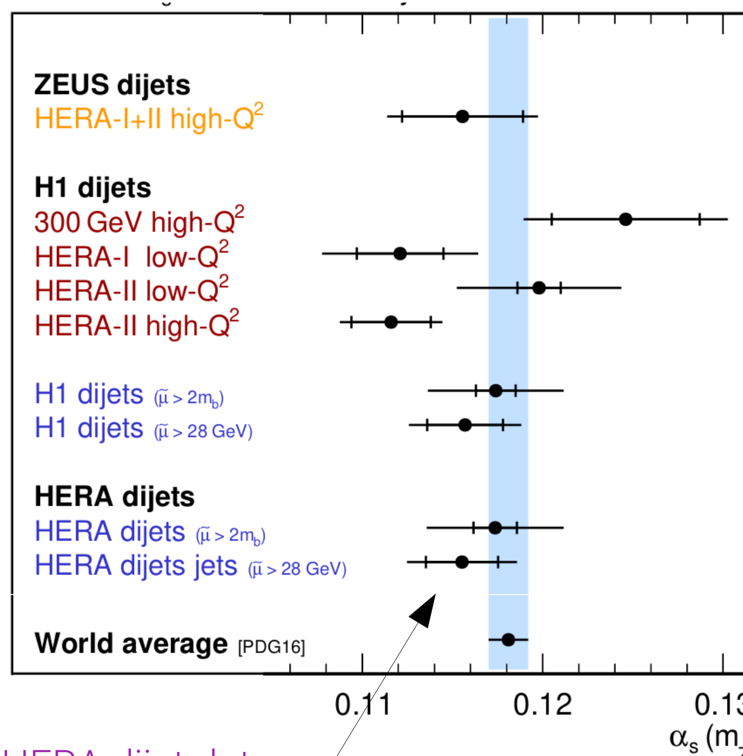
Dijets

Double-differential HERA jet data in NC DIS (as function of p_T,Q^2) commonly used for α_s determinations





- Dijets measured as function of Q^2 and $\langle p_T \rangle$
- Dijets less precise than inclusive jet
- No benefit from H1+ZEUS combination
- Running consistent with incl. jet
- H1 Inclusive jet + dijet → small improvement



HERA dijet data

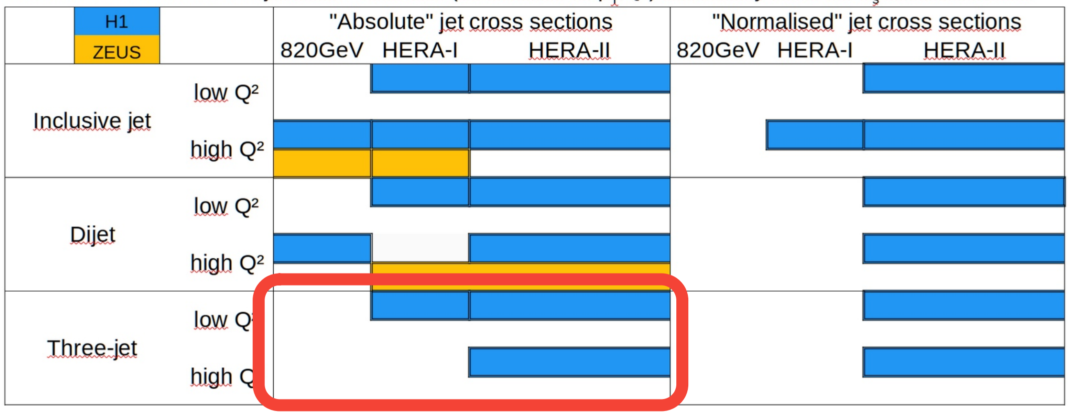
$$\alpha_s(m_Z) = 0.1157\,(22)_{\rm exp}\,(23)_{\rm th}$$

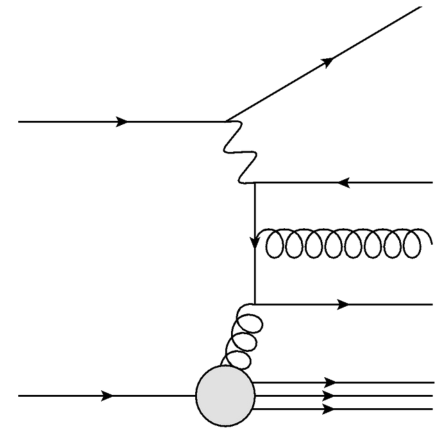
Inclusive jet + dijet data (H1 only)

$$\alpha_s(m_Z) = 0.1166\,(19)_{\rm exp}\,(24)_{\rm th}$$

3-jet – NLO

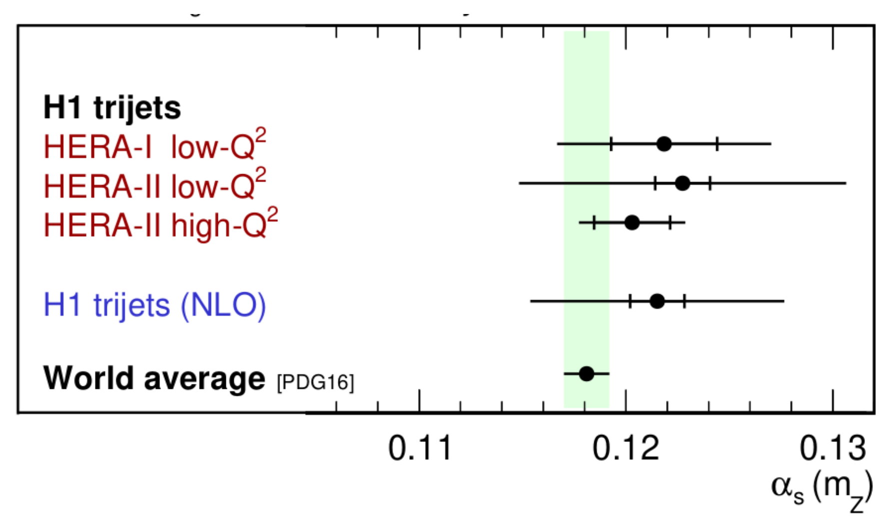
Double-differential HERA jet data in NC DIS (as function of p_T,Q^2) commonly used for α_s determinations





Three-jet cross sections at HERA

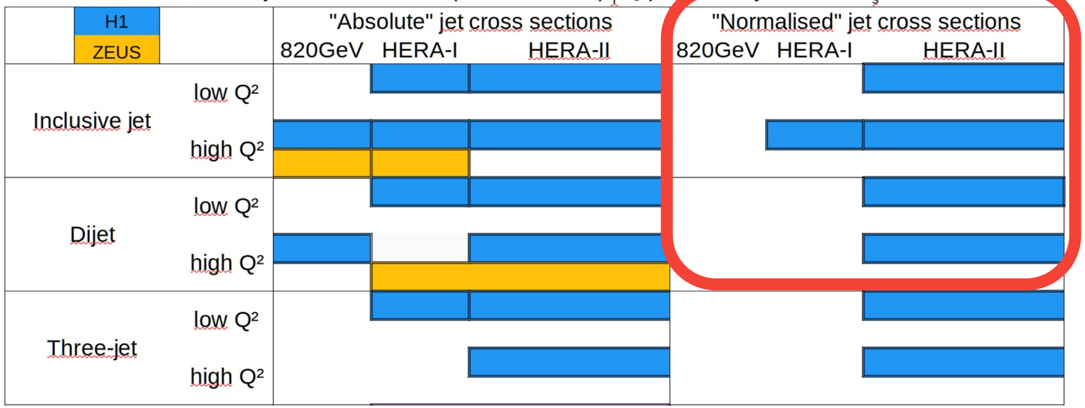
- Enhanced α_s sensitivity $O(\alpha_s^2)$ but limited in statistics
- So far, only NLO calculations available (2→3)
- Reasonable precision from low-Q² data (EPJ C77 (2017) 215) (high stat., low μ_R-scale)
  → but large scale uncertainties in NLO

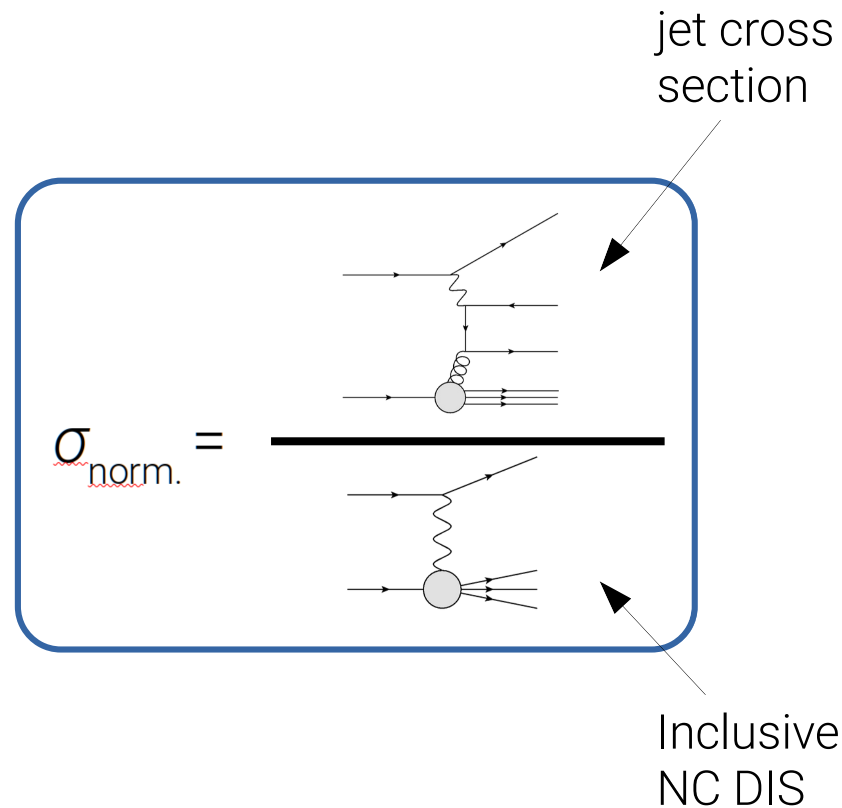


EPJ .C77 (2017) 791 [Erratum EPJ C81 (2021) 738]

Normalised jet cross sections

Double-differential HERA jet data in NC DIS (as function of p_T,Q^2) com





Normalised jets:

→ normalisation w.r.t. inclusive NC DIS

→ preserve α_s sensitivity

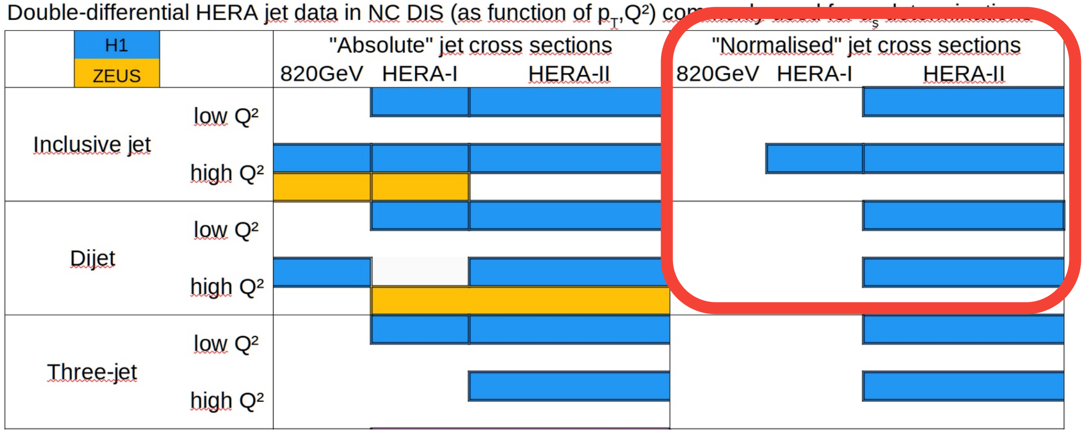
→ Some experimental uncertainties cancel or are reduced

→ Correlations of jet data to inclusive DIS data are correctly treated in common fit

→ Ideal jet-data for combind PDF+α_s determination (together with incl. DIS data)

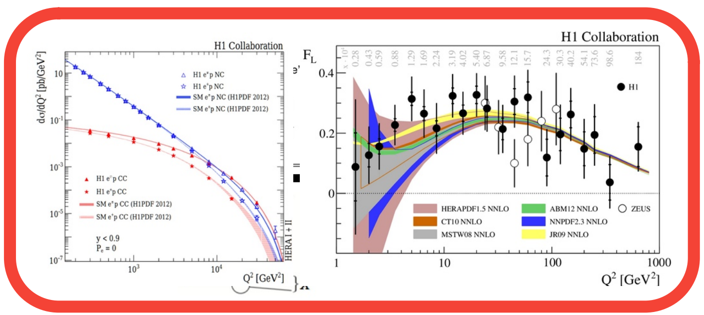
EPJ .C77 (2017) 791 [Erratum EPJ C81 (2021) 738]

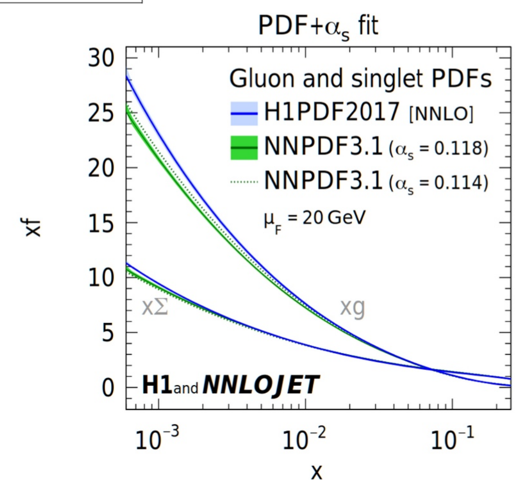
Normalised jets

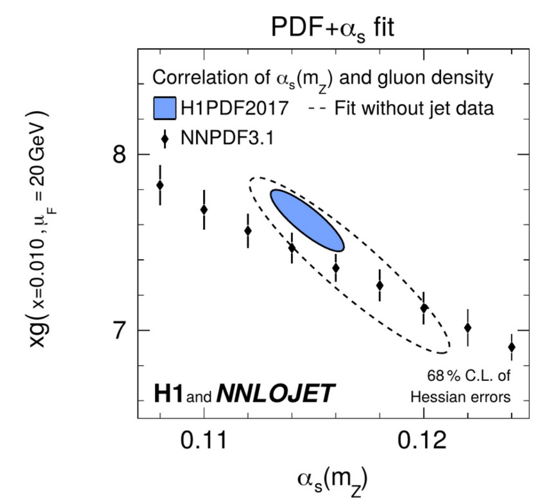


- Normalised jets have highest α_s sensitivity
  → Several exp. uncertainties cancel
  → Correct treatment of correlations in **combined PDF+α_s fit** (H1PDF2017nnlo)

PDF+α_s fit exploits
→ normalised jet cross sections
→H1 inclusive NC & CC DIS data

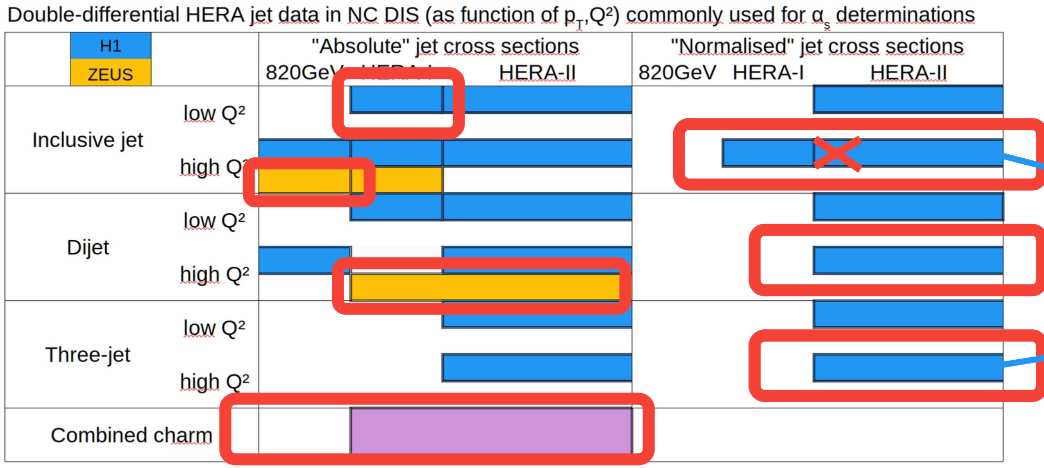




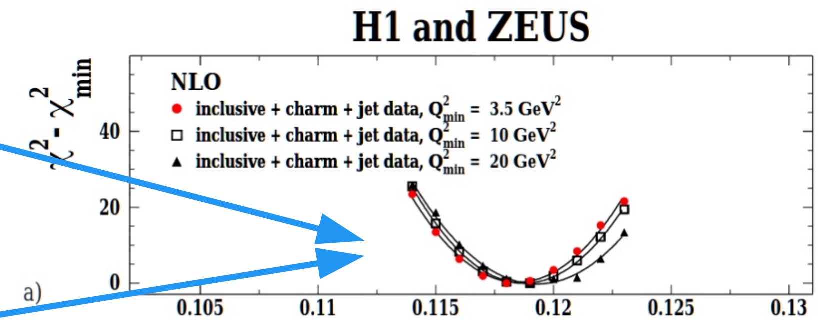


$$\alpha_s(m_Z) = 0.1147\,(11)_{\text{exp,had,PDF}}\,(2)_{\text{mod}}\,(3)_{\text{par}}\,(23)_{\text{scale}}$$

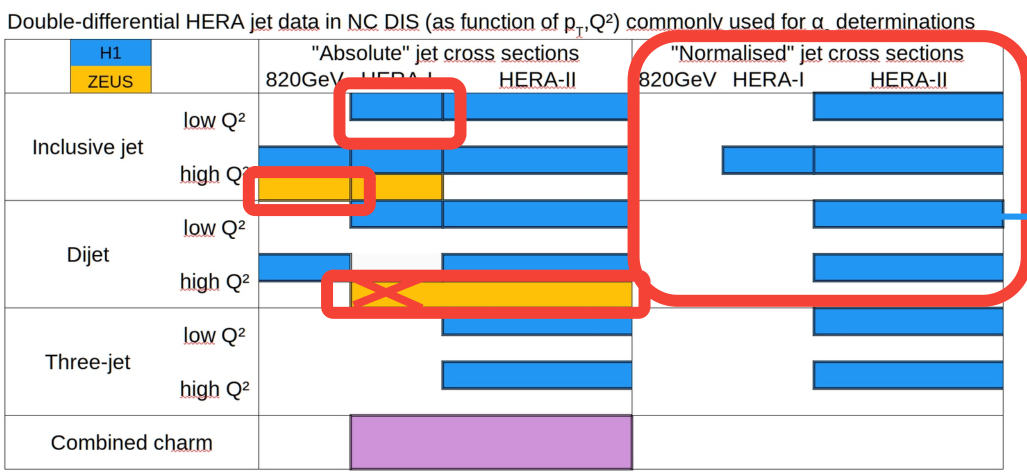
HERAPDF



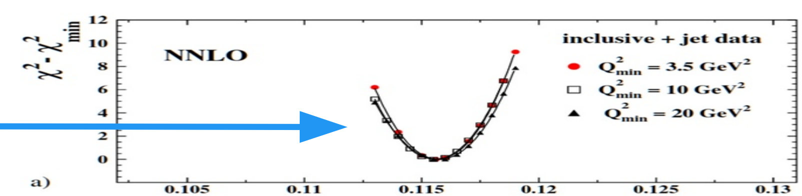
HERAPDF2.0NLO



- Good α_s sensitivity & only small impact on PDFs



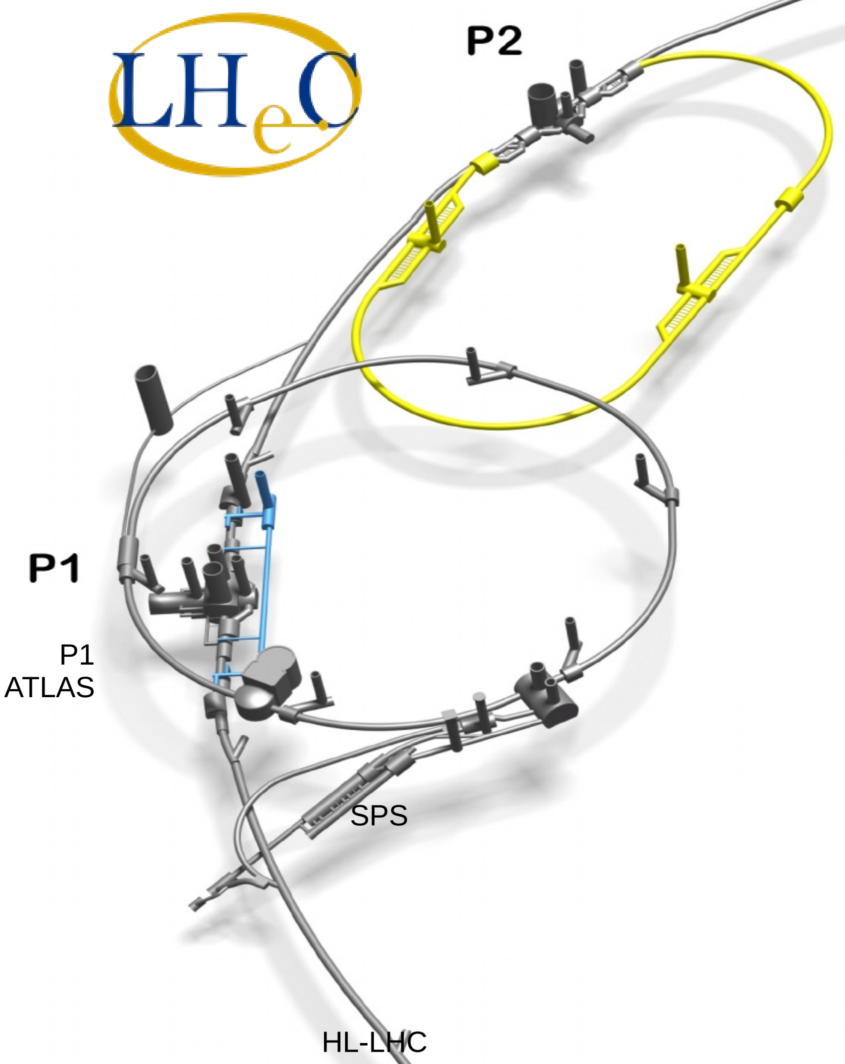
HERAPDF2.0NNLO



- Consistent result as H1 alone

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011\ (\text{exp})$$

Future prospects – the LHeC



LHeC – ep data in 2030s

- ERL electron ring attached to HL-LHC
- E_e = 50 GeV, $L \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$

LHeC

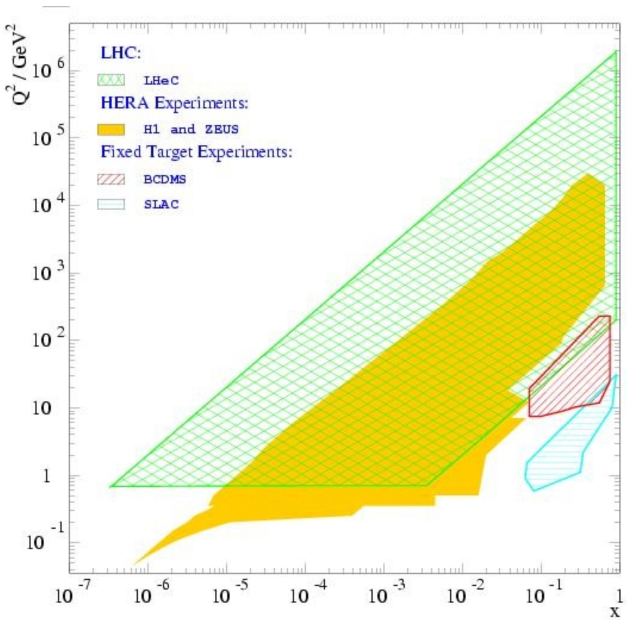
- $\sqrt{s} \sim 1.3$ TeV
- Electron and positron data
- Up to 1 ab^{-1} integrated luminosity
- Detector may possibly be shared with ALICE3/HI
  (Eur.Phys.J.C 82 (2022) 40)
  (J.Phys.G 48 (2021) 110501)

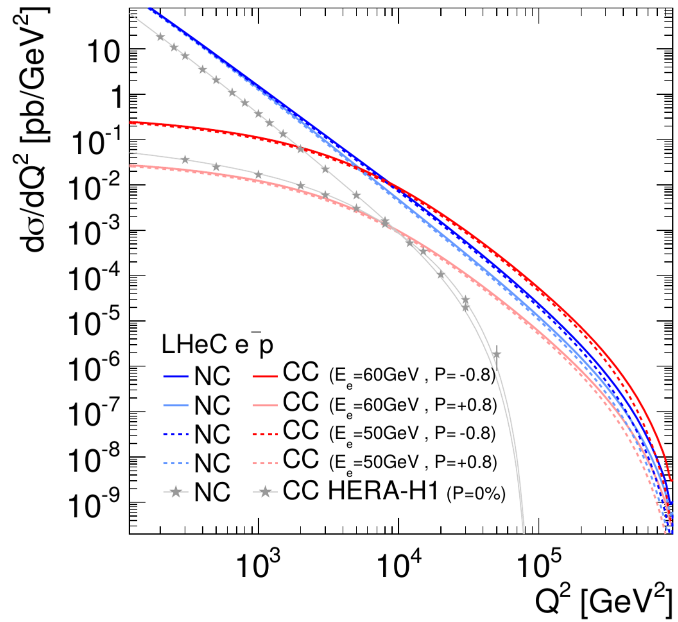
Relocatable

- electron-accelerator components can be relocated from HL-LHC to FCC-hh

Future: Inclusive DIS at LHeC

LHeC vs. HERA: greatly increased kinematic plane, 1000x higher luminosity, almost hermetic 4π detectors (no trigger limitations)



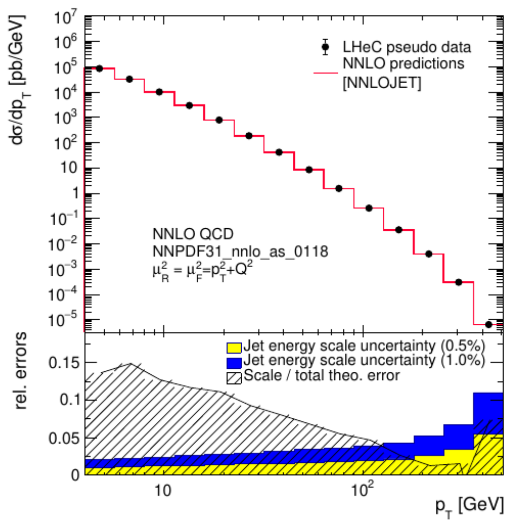


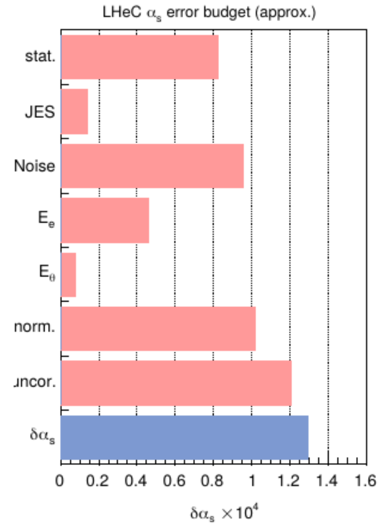
From a PDF+α_s fit to simulated NC & CC DIS data (incl. full set of exp. uncertainties) one expects

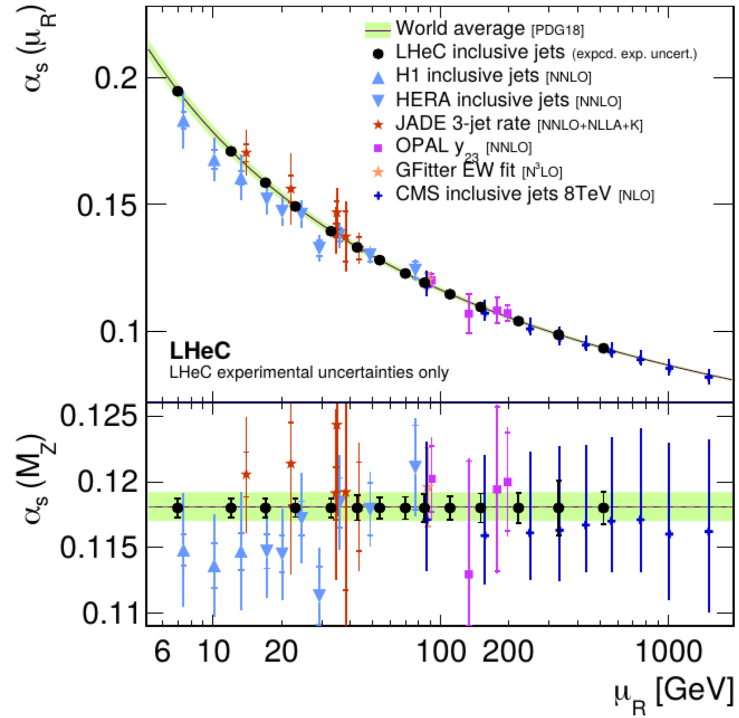
$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$

Future: Jets at LHeC

Simulated inclusive jet cross section data
with full set of uncertainties





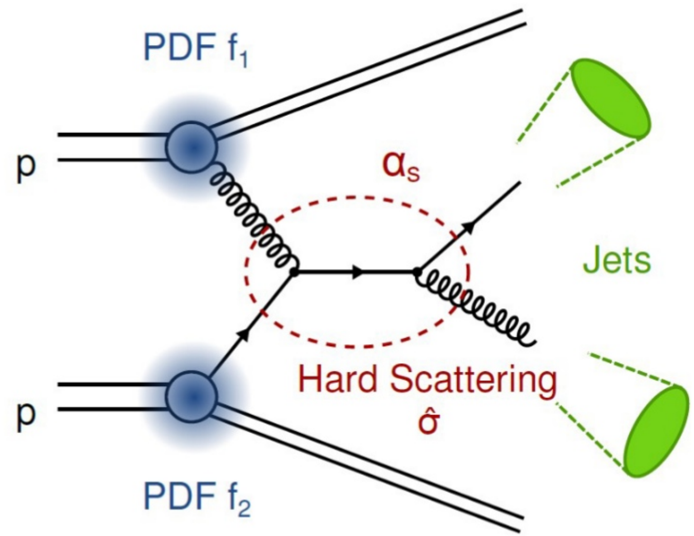


Expected uncertainties from fit with NNLO pQCD

$$\Delta\alpha_s(M_Z)(\text{jets}) = \pm 0.00013_{(\text{exp})} \pm 0.00010_{(\text{PDF})}$$

Running can be tested with permille precision from $5 < \mu_R < 500$GeV

pp → 2 jets



Dijet production is dominant process at LHC → Sensitive to $\alpha_s(m_Z)$ in leading order pQCD

NNLO predictions from NNLOJET (antenna subtraction)

→ interfaced to fastNLO/APPLgrid for repeated calculations

Ongoing work in collaboration with:

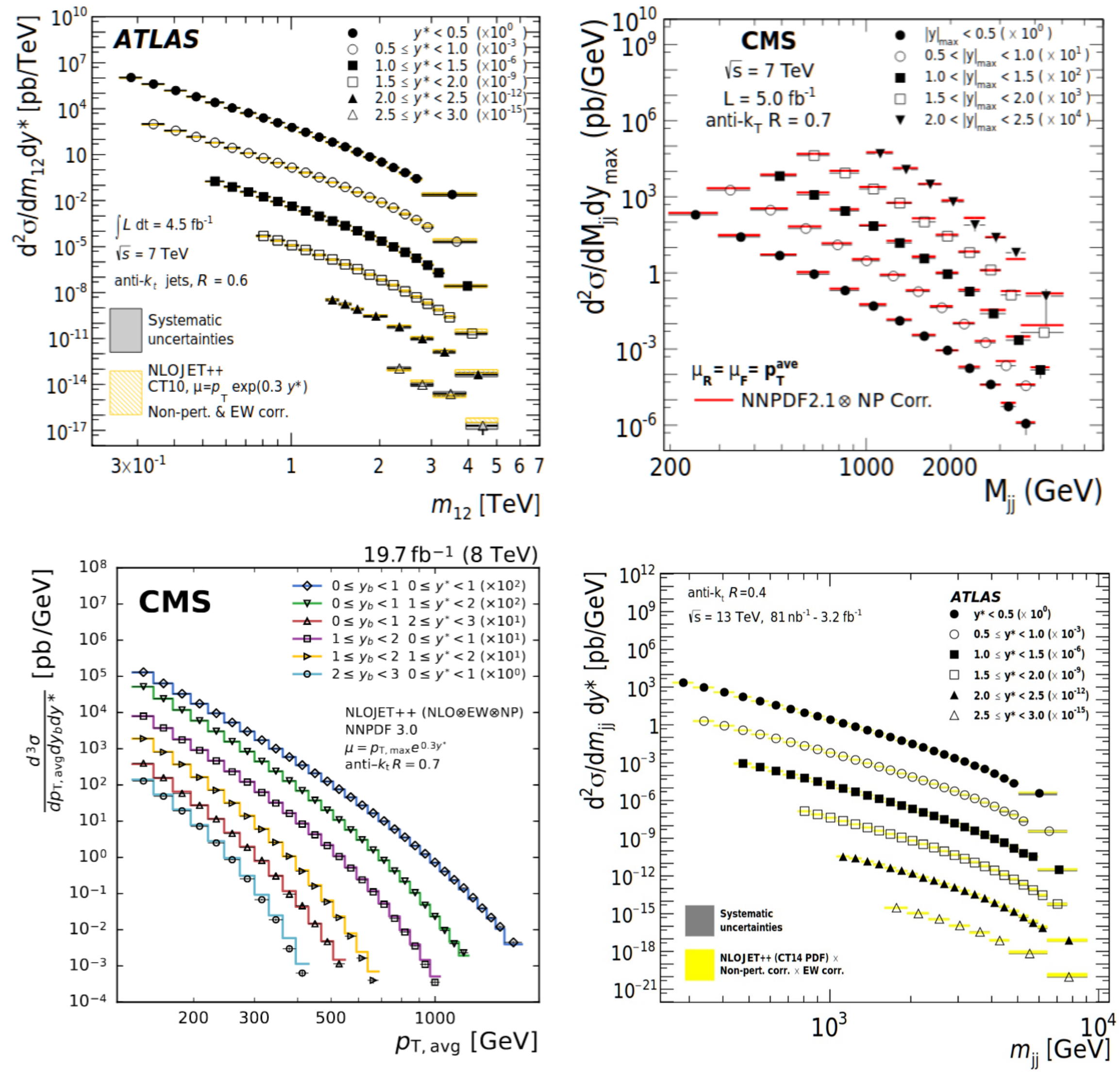
A. Gehrmann-De Ridder, Th. Gehrmann, N. Glover, C. Gwenlan, A. Huss, J. Pires, K. Rabbertz, D. Savoiu and M. Sutton

Dijet cross sections at the LHC

- Dijet production cross sections measured
  - by ATLAS and CMS
  - at $\sqrt{s}$ = 7, 8 and 13 TeV

Data	$\sqrt{s}$ [TeV]	$d\sigma$	R_{jet}	$\mathcal{L}$
ATLAS [7]	7	$\frac{d^2\sigma}{dm_{jj}dy^*}$	0.6	$4.5\,\text{fb}^{-1} \pm 1.8\,\%$
CMS [9]	7	$\frac{d^2\sigma}{dm_{jj}d\|y\|_{\max}}$	0.7	$5.0\,\text{fb}^{-1} \pm 2.2\,\%$
CMS [10]	8	$\frac{d^3\sigma}{dp_{T,\text{avg}}dy^*dy_b}$	0.7	$19.7\,\text{fb}^{-1} \pm 2.6\,\%$
ATLAS [8]	13	$\frac{d^2\sigma}{dm_{jj}dy^*}$	0.4	$3.2\,\text{fb}^{-1} \pm 2.1\,\%$

- We select data with larger jet-R
  → NNLO predictions are more stable
  → smaller relative NP uncertainties
- All: anti-k_T algorithm
- We set $\mu = m_{jj}$



Methodology of α_s determination

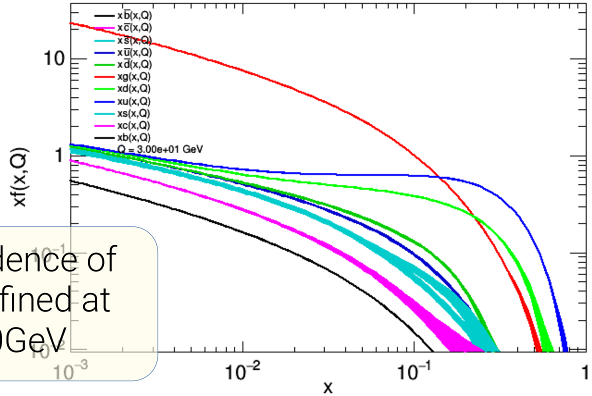
$$\mathrm{d}\sigma = \sum_{a,b} \int \frac{\mathrm{d}\xi_1}{\xi_1} \frac{\mathrm{d}\xi_2}{\xi_2} f_a(\xi_1, \mu) f_b(\xi_2, \mu) \mathrm{d}\hat{\sigma}_{ab}(\mu)$$

PDFs from factorization obey DGLAP
→ Splitting kernel has α_s dependence

$$\mu^2 \frac{\mathrm{d}f}{\mathrm{d}\mu^2} = \mathcal{P}(\alpha_\mathrm{s}) \otimes f\,,$$

$$f_i(\xi, \mu, \alpha_\mathrm{s}) = (\Gamma(\mathcal{P}, \mu, \mu_0, \alpha_\mathrm{s}) \otimes f_{\mu_0})_i$$

→ evolution calculated with Apfel++
→ Evolution starting scale μ_0 can be chosen (set to 30GeV)



x-dependence of PDFs defined at μ_0=30GeV

Hard coefficients → expanded in α_s

$$\mathrm{d}\hat{\sigma}_{ab}(\alpha_\mathrm{s}) = \left(\frac{\alpha_\mathrm{s}(\mu)}{2\pi}\right)^2 \mathrm{d}\hat{\sigma}_{ab,\mathrm{LO}} + \left(\frac{\alpha_\mathrm{s}(\mu)}{2\pi}\right)^3 \mathrm{d}\hat{\sigma}_{ab,\mathrm{NLO}} + \left(\frac{\alpha_\mathrm{s}(\mu)}{2\pi}\right)^4 \mathrm{d}\hat{\sigma}_{ab,\mathrm{NNLO}} + \mathcal{O}(\alpha_\mathrm{s}^5(\mu))\,,$$

→ calculated with NNLOJET and fastNLO/APPLgrid

χ^2 minimization

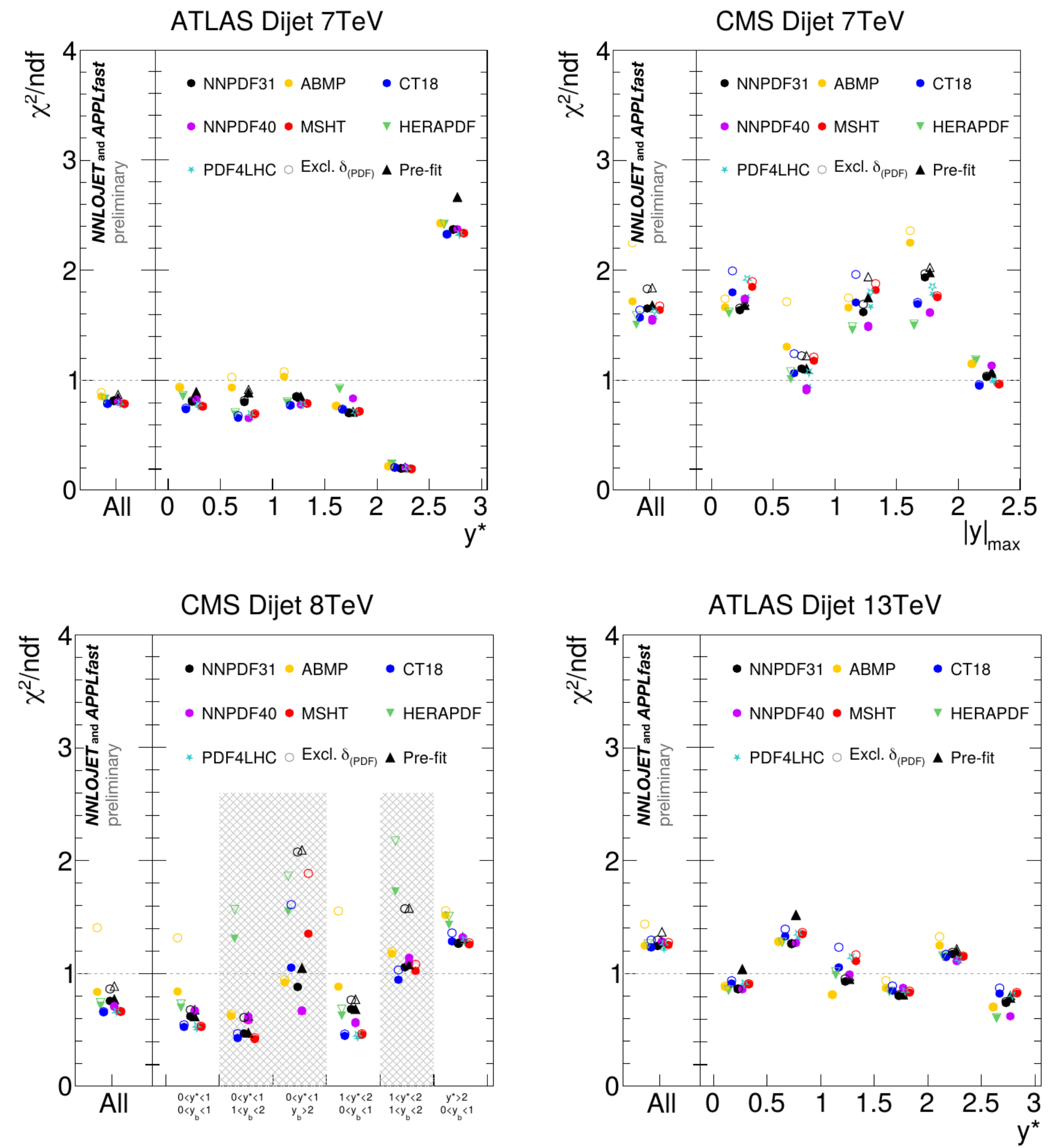
$$\chi^2 = \sum_{i,j} \log\frac{\varsigma_i}{\sigma_i} (V_\mathrm{exp} + V_\mathrm{NP} + V_\mathrm{th.\text{-}stat} + V_\mathrm{PDF})^{-1}_{ij} \log\frac{\varsigma_j}{\sigma_j}$$

Include PDF uncertainty
→ "PDF profiling" (=PDF fit)

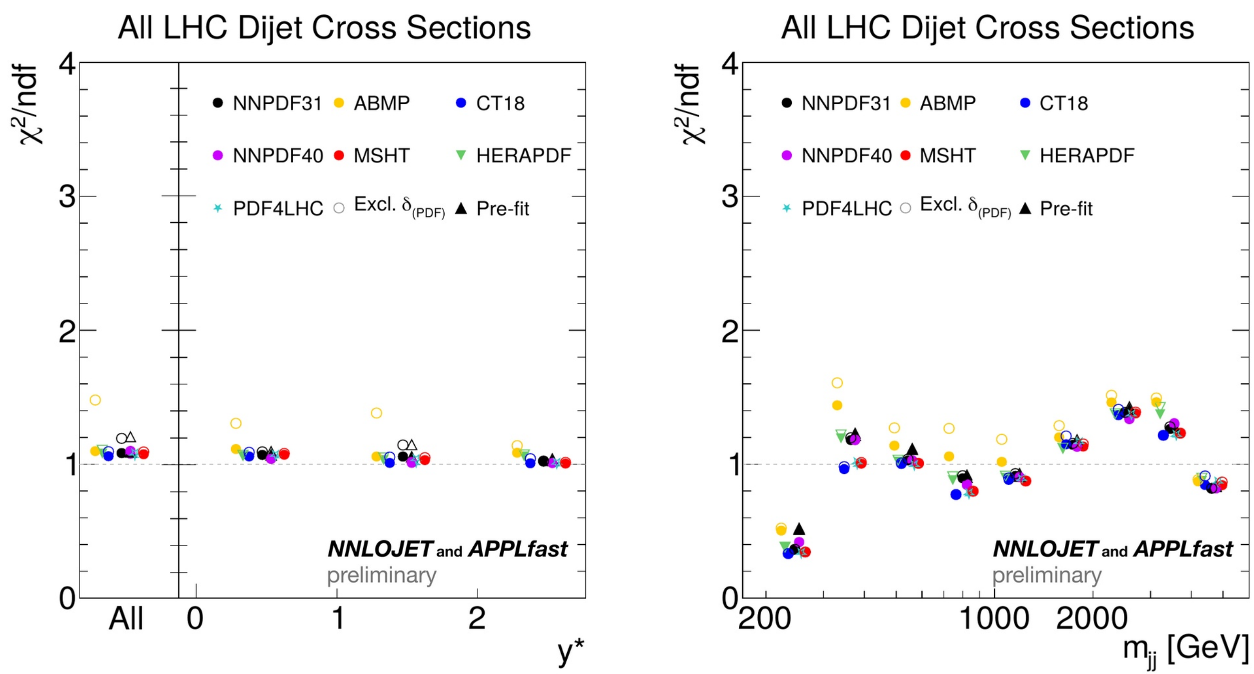
Data consistency

- First: study data consistency and agreement with NNLO pQCD
  → Perform χ^2 fits to individual y-regions (y^*, $|y|_{max}$ or y_s,y_b)

- Overall, excellent post-fit agreement of data and NNLO pQCD
  - Some fluctuations (as expected)
  - CMS 7TeV a bit higher, CMS 8TeV a bit lower (also seen elsewhere)
  - All PDFs provide good description
  - triple-differential CMS 8TeV data has enhanced PDF sensitivity (as expected)
    → exclude bins with $y_b > 1$



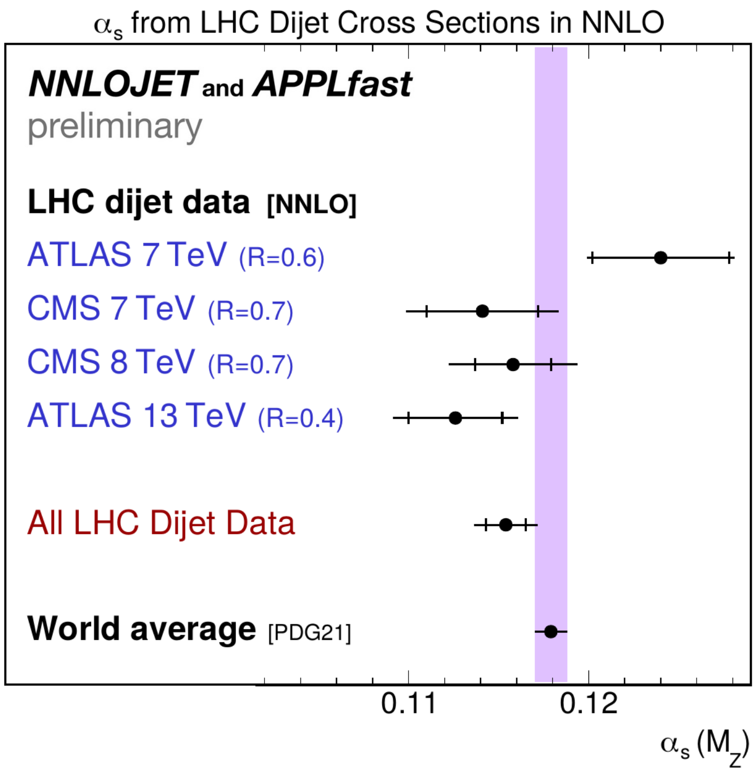
Combined fit to all dijet data



- Fit to all four data sets, but restricted to individual y* ranges, or m_{jj} ranges
  → Very good data-theory agreement → no systematic trend visible in χ^2 values
- Fit to all data close to χ^2/ndf~1.0

$\alpha_s(m_Z)$ from LHC dijet data in NNLO

- $\alpha_s(m_Z)$ from LHC dijet data in NNLO pQCD
  (MSbar, n_f=5, massless, m_Z=91.1876 GeV)
- Fit to all dijet data χ^2/ndf = 379.0/(351-1)
- Reasonable agreement of data sets
- Use NNPDF3.1 as central PDF
  (other PDF result in a bit larger α_s value, but smaller χ^2)
- Uncertainties include
  - experimental
  - non-perturbative corrections
  - PDF (replicas/eigenvectors)
  - PDFset, PDFα_s, PDFμ_0
  - Scale



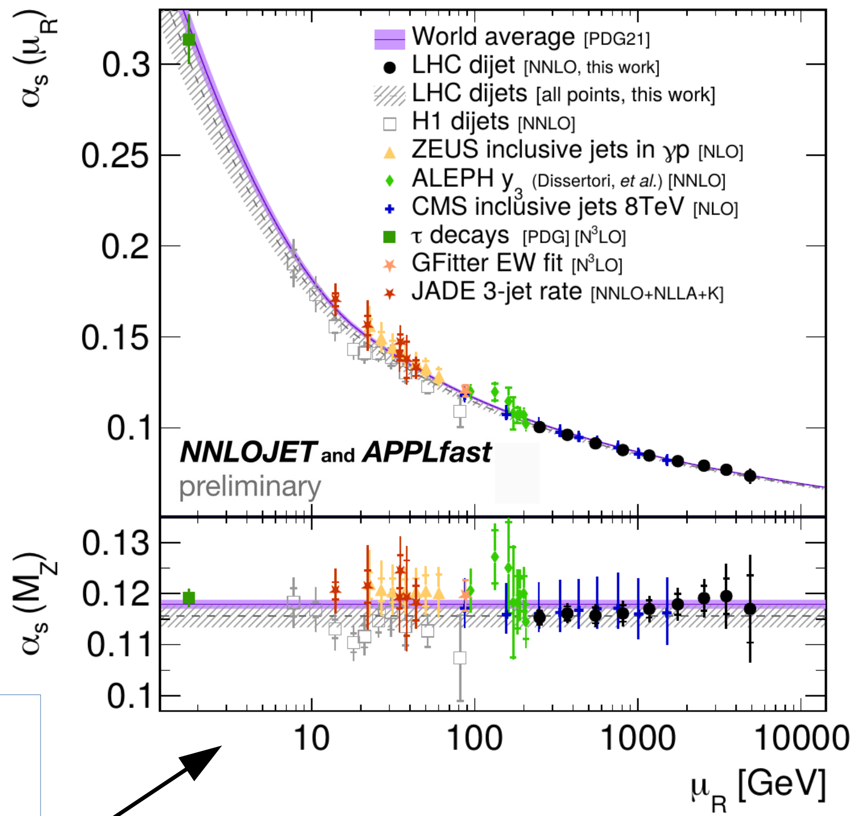
preliminary

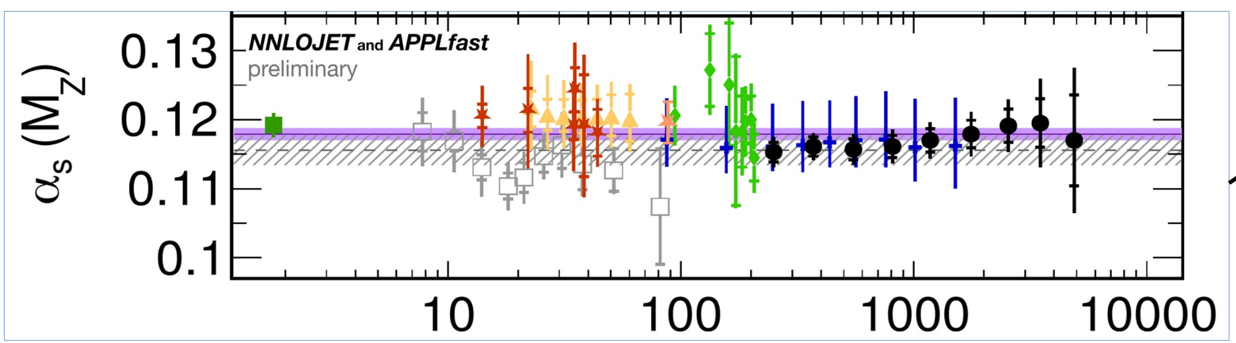
$$\alpha_s(m_Z) = 0.1154\ (14)_{\rm fit}\ (12)_{{\rm PDFset},\alpha_s,\mu_0}\ (8)_{\rm scale}$$

Running

- α_s determinations in adjacent regions of m_{jj}
- Simultaneous fit to all regions:
  9 free parameters and assumption that running is valid within m_{jj}-range

  → Excellent agreement with RGE expectation
  - α_s determined up to μ_R ~ 5TeV
  - 3.3% uncertainty at μ_R ~ 2.5TeV



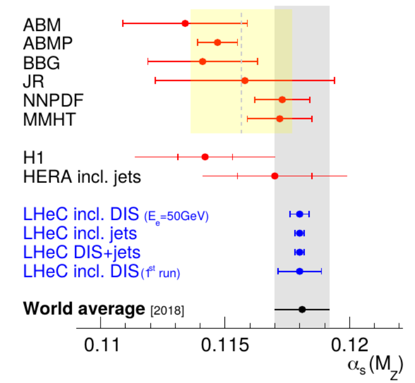


Summary

Inclusive NC &CC DIS

- HERA inclusive DIS without noteworthy sensitivity to α_s
- Fixed target, or future *ep* experiments (LHeC) have high sensitivity
- Precision measurements of hadronic final state in DIS still ongoing at HERA → jet substructure, event shapes, groomed event shapes will provide new data for α_s in the near future, with precise predictions (N3LO, N3LL, NNLO+PS, etc...)

Future DIS prospects (2030+)



Jets in DIS

- α_s determinations dominated by HERA-II jet data Inclusive jets (H1&ZEUS) yield

$$\alpha_s(M_Z) = 0.1178\,(15)_{\mathrm{exp}}\,(21)_{\mathrm{th}}$$

- Fit to incl. jet and dijet with PDFs yields (recent confirmed by HERAPDF assessment)

$$\alpha_s(m_Z) = 0.1147\,(11)_{\mathrm{exp,had,PDF}}\,(2)_{\mathrm{mod}}\,(3)_{\mathrm{par}}\,(23)_{\mathrm{scale}}$$

Dijet production at LHC

- NNLO determination using ATLAS and CMS dijet data at $\sqrt{s}$ = 7, 8 and 13 TeV yields

$$\alpha_s(m_Z) = 0.1154\ (14)_{\mathrm{fit}}\ (12)_{\mathrm{PDFset},\alpha_s,\mu_0}\ (8)_{\mathrm{scale}}$$