# $\alpha_S$ measurements from $p_T^Z$ and 2→3 jet predictions and inclusive jets using NNLO QCD theory input

Francesco Giuli (on behalf of the ATLAS and CMS Collaborations)

SM@LHC2023
Fermilab, USA
12/07/2023

# Introduction

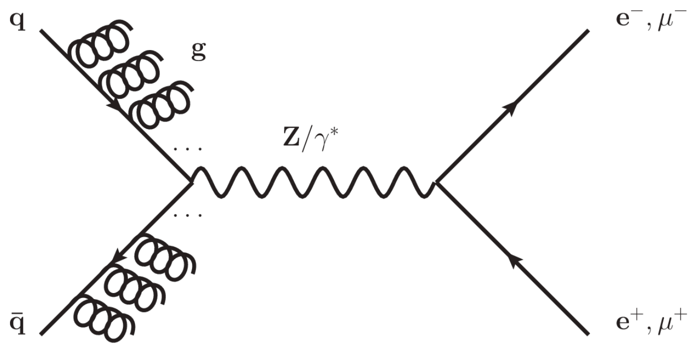
- Processes involving W/Z bosons and jets are standard candle for precision measurements and theory at LHC

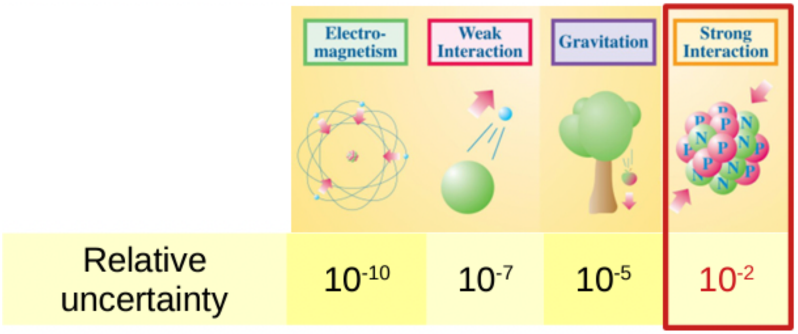
- They allow to:
  - Test precisely perturbative Quantum ChromoDynamics (pQCD)
  - Measure fundamental parameters of the Standard Model (SM)
  - Improve our understanding of Parton Distribution Functions (PDFs)
  - Provide important inputs to simulations

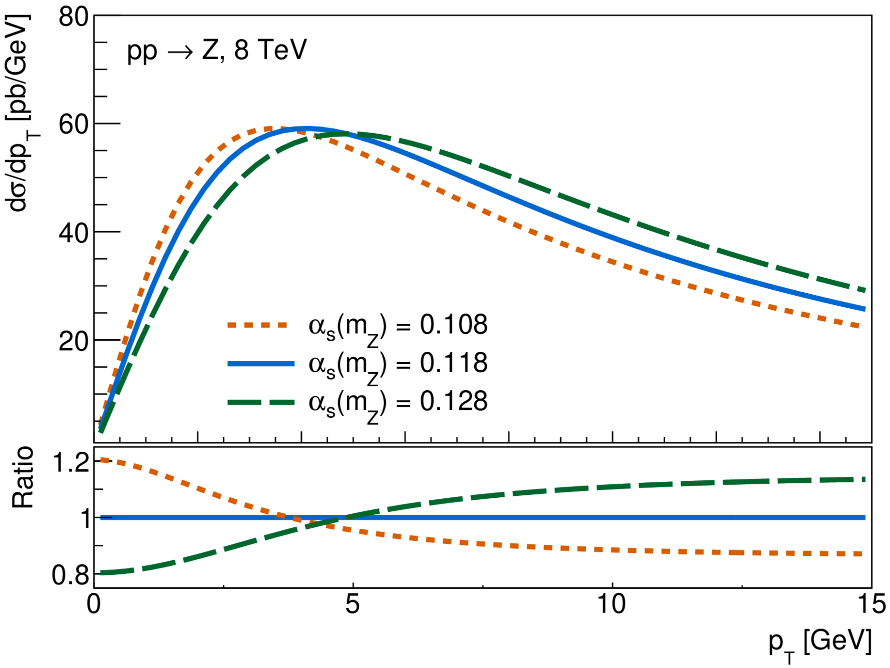
- The following recent results from ATLAS and CMS are presented:
  - $\alpha_S$ extraction at Z pole from Z $p_T$ at $\sqrt{s}$ = 8 TeV - ATLAS-CONF-2023-015
  - Transverse energy-energy correlation (TEEC) and its angular asymmetry (ATEEC) at $\sqrt{s}$ = 13 TeV - 2301.09351
  - Inclusive jet production at $\sqrt{s}$ = 13 TeV - JHEP 02 (2022) 142
  - Dijets production at $\sqrt{s}$ = 13 TeV - CMS-PAS-SMP-21-008

# $\alpha_S$ extraction from Z $p_T$ at 8 TeV

- Strong coupling constant $\alpha_S$ is the **least well known in nature**
- **Dominant uncertainties** to precision measurements of **Higgs coupling** at LHC or **EW precision observables** at $e^+e^-$ colliders
- Non-zero value of Z $p_T$ arises from initial state radiations from incoming partons due to momentum conservation
- The **peak position of Z $p_T$** and above is **sensitive to $\alpha_S(m_Z)$**



# $\alpha_S$ extraction from Z $p_T$ at 8 TeV

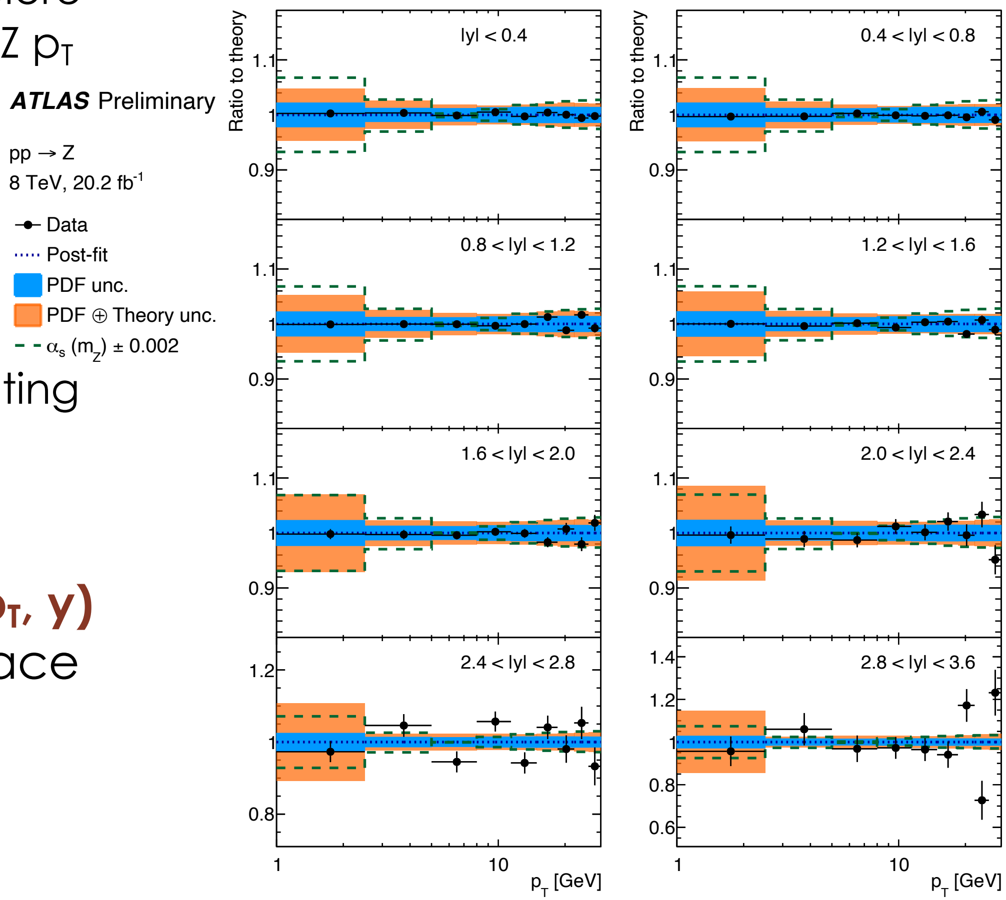
- Evaluate $\chi^2(\alpha_S)$ with $\alpha_S$ variations in LHAPDF
  - Include experimental ($\beta_{j,exp}$) and PDF uncertainties ($\beta_{k,th}$) in the $\chi^2(\alpha_S)$ definition
  - For each value of $\alpha_S$, $\beta_{k,th}$ terms explore the PDF space to find the best fit to Z $p_T$ data
  - aN$^3$LO MSHT20 PDF set is used for the $\alpha_S$ extraction

$$\chi^2(\beta_{\rm exp}, \beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,\rm exp} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,\rm th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\rm exp}^2 + \sum_k \beta_{k,\rm th}^2 .$$

correlated systematic uncertainties

uncorrelated systematic uncertainties

- Fit **Z $p_T$ < 29 GeV region**
  - Non-perturbative form factor (affecting Z $p_T$ < 5 GeV) is added with unconstrained nuisance parameter




- $\alpha_S(m_Z)$ extracted by fitting the **2D ($p_T$, y) cross section** in full lepton phase space

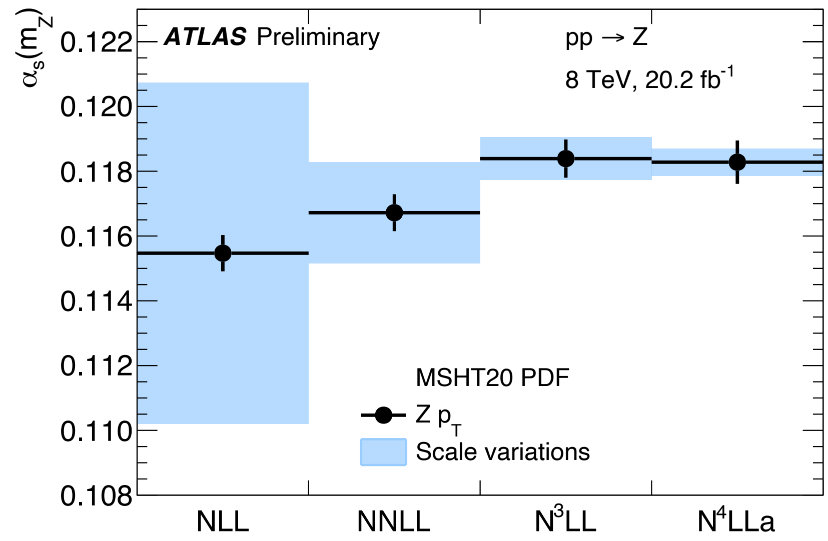
- **$\chi^2$/ndf = 82/72**

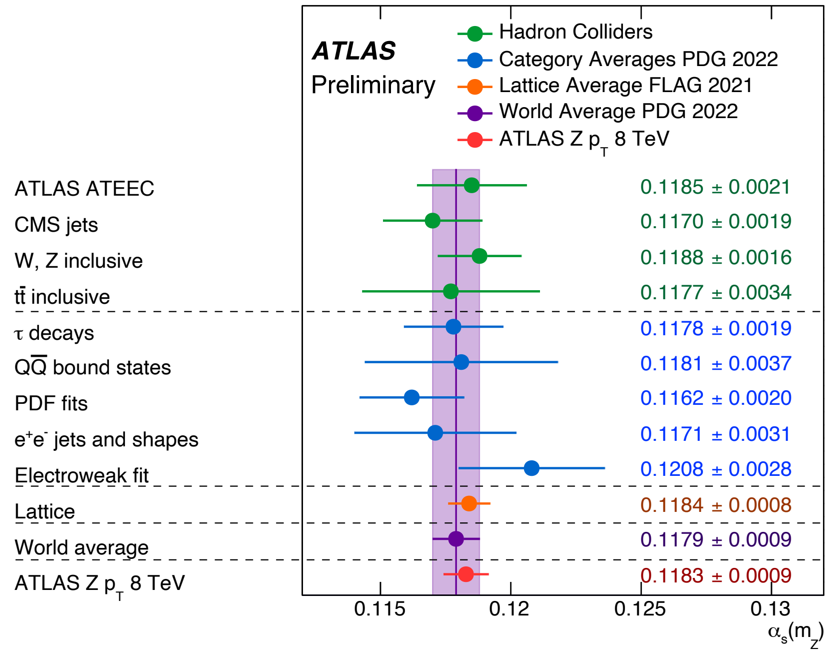
# $\alpha_S$ extraction from Z $p_T$ at 8 TeV

- **First $\alpha_S(m_Z)$ determination based on aN⁴LL+N³LO predictions**
- $\alpha_S(m_Z)$ determined at lower orders → good perturbative series convergence
- **Most precise experimental determination** of $\alpha_S(m_Z)$
- As precise as the PDG and Lattice WA

| | | |
|---|---|---|
| Experimental uncertainty | +0.00044 | -0.00044 |
| PDF uncertainty | +0.00051 | -0.00051 |
| Scale variations uncertainties | +0.00042 | -0.00042 |
| Matching to fixed order | 0 | -0.00008 |
| Non-perturbative model | +0.00012 | -0.00020 |
| Flavour model | +0.00021 | -0.00029 |
| QED ISR | +0.00014 | -0.00014 |
| N4LL approximation | +0.00004 | -0.00004 |
| Total | +0.00084 | -0.00088 |

$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$



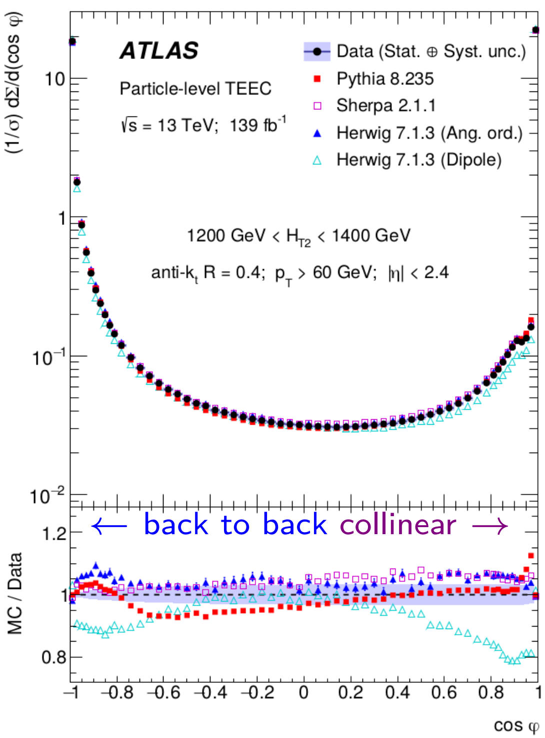
# TEEC and ATEEC measurements

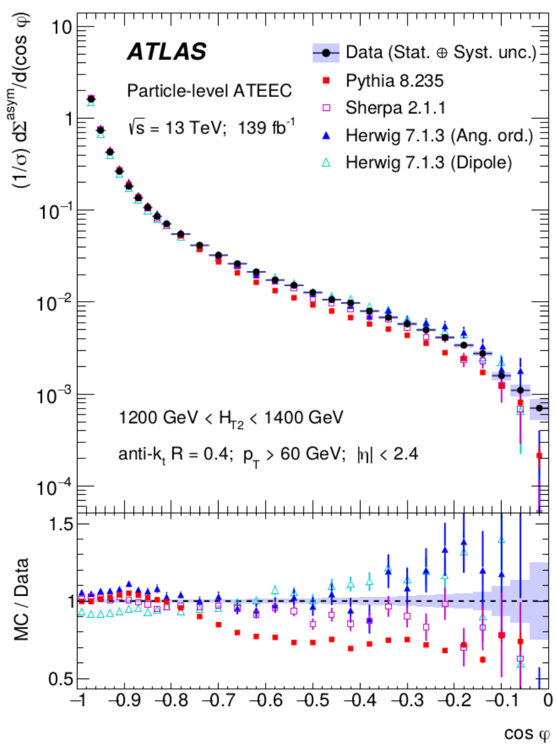
- **TEEC** as transverse-energy-energy-weighted distribution of the azimuthal differences between jet pairs

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j}\mathrm{d}\cos\phi} x_{\mathrm{T}i}x_{\mathrm{T}j}\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

- **ATEEC** as azimuthal asymmetry of forward ($\cos\phi > 0$) and backward ($\cos\phi < 0$) TEEC parts

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma^{\mathrm{asym}}}{\mathrm{d}\cos\phi} = \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\pi-\phi}$$

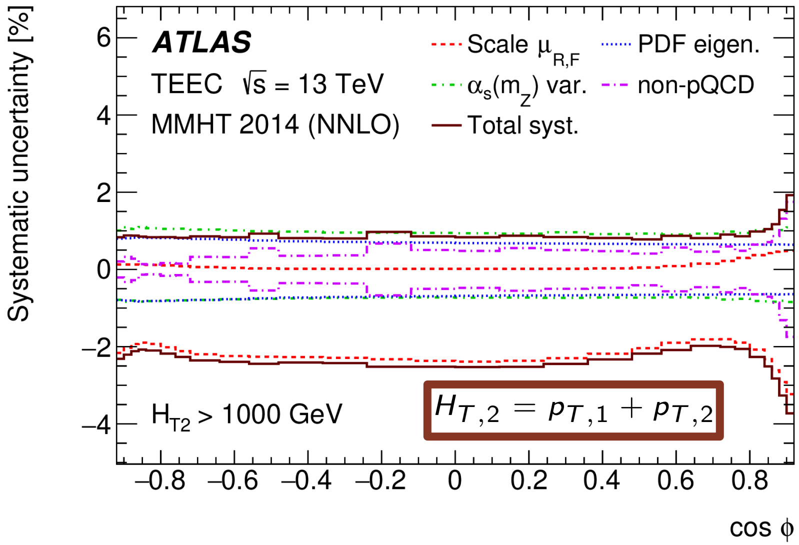


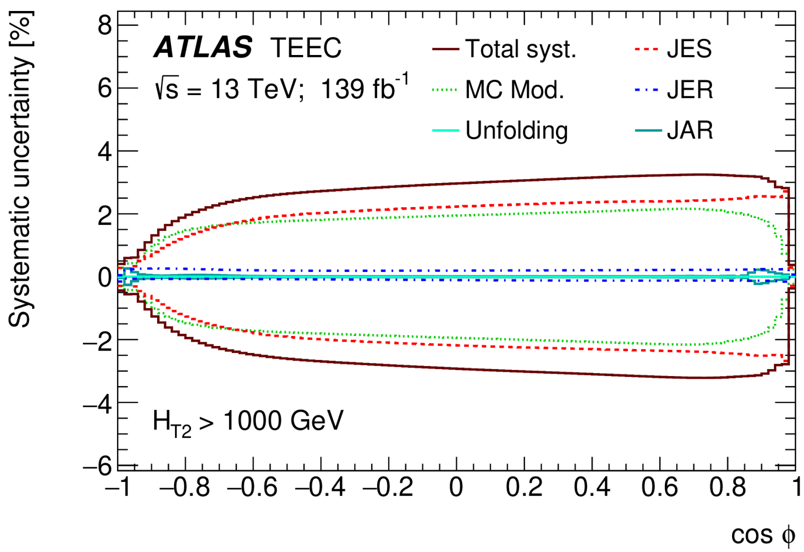

Both TEEC and ATEEC are **sensitive to gluon radiation** and strong coupling constant $\alpha_s(Q)$

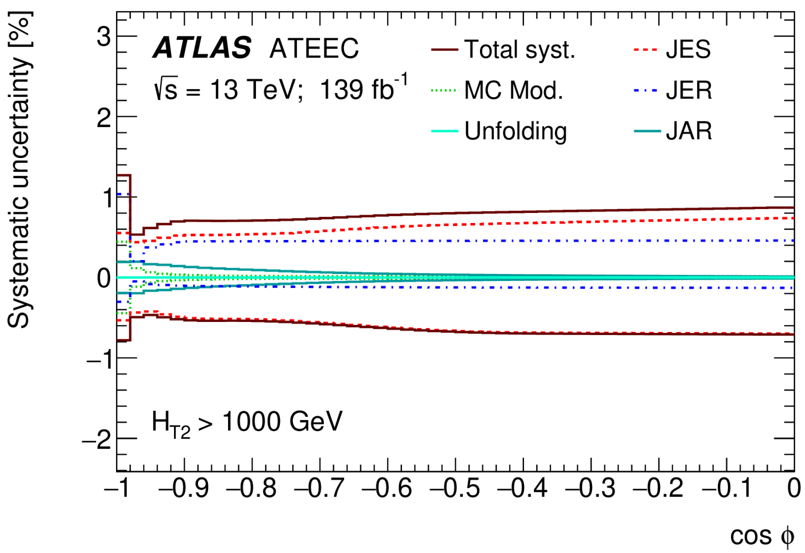
# TEEC and ATEEC measurements

- Full Run2 data set, unfolded data to particle level
  - Anti-$k_T$ R = 0.4 calibrated PF jets with $p_T$ > 60 GeV and $|\eta|$ < 2.4



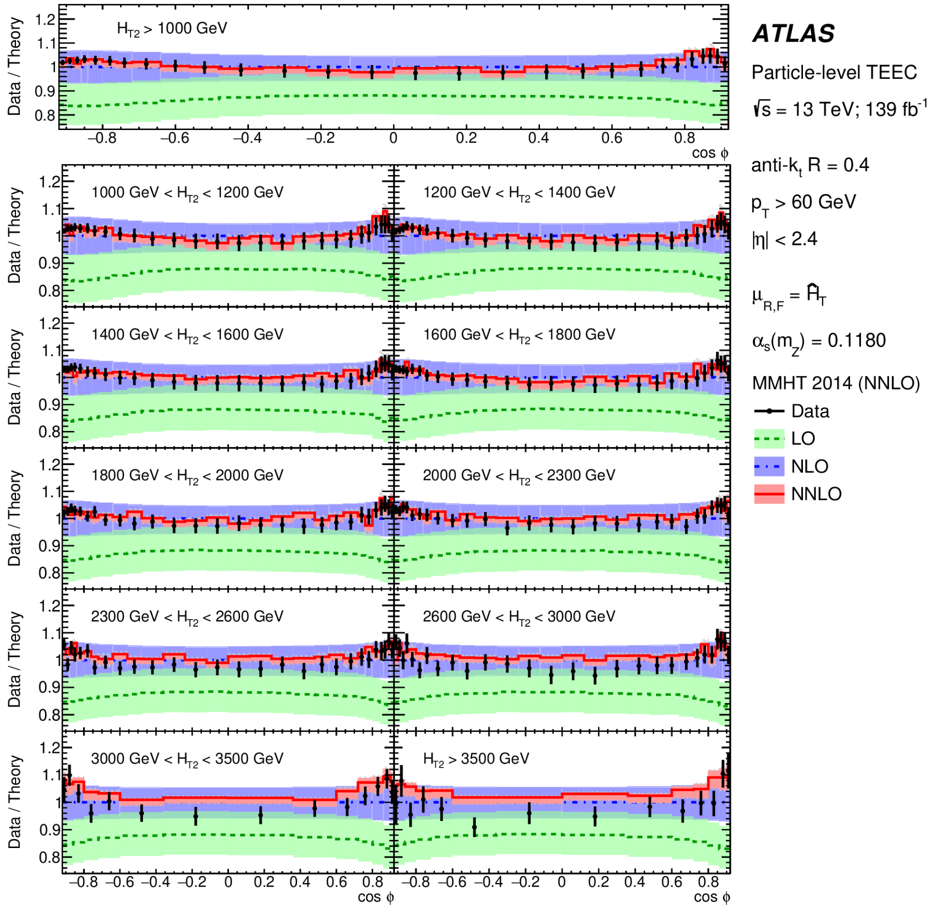

- Extended energy range, improved experimental precision
  - Dominated by JER+JES and MC modelling
- **NNLO pQCD calculations** applied for the first time in 2 → 3 jets process
  - Visible reduction of theory uncertainties
  - Scale uncertainties reduced by 1/3 with new NNLO predictions

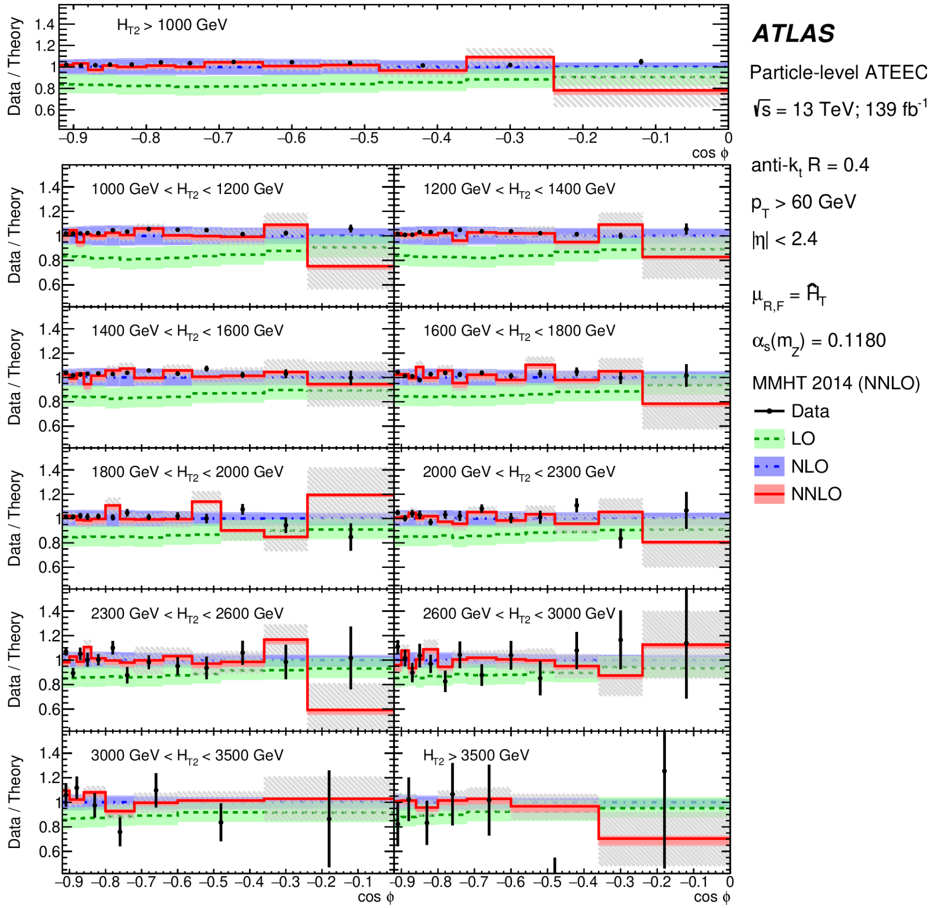


# TEEC and ATEEC measurements

- Measurement done in 1 inclusive $H_{T,2}$ bin and 10 exclusive $H_{T,2}$ bins
- NLO calculations as in previous publication – EPJ C77 (2017) 872
- **NNLO predictions** give a **significant improvement for |** $\cos\phi$ **| > 0.8** and show visible reduction of theoretical uncertainties wrt NLO ones

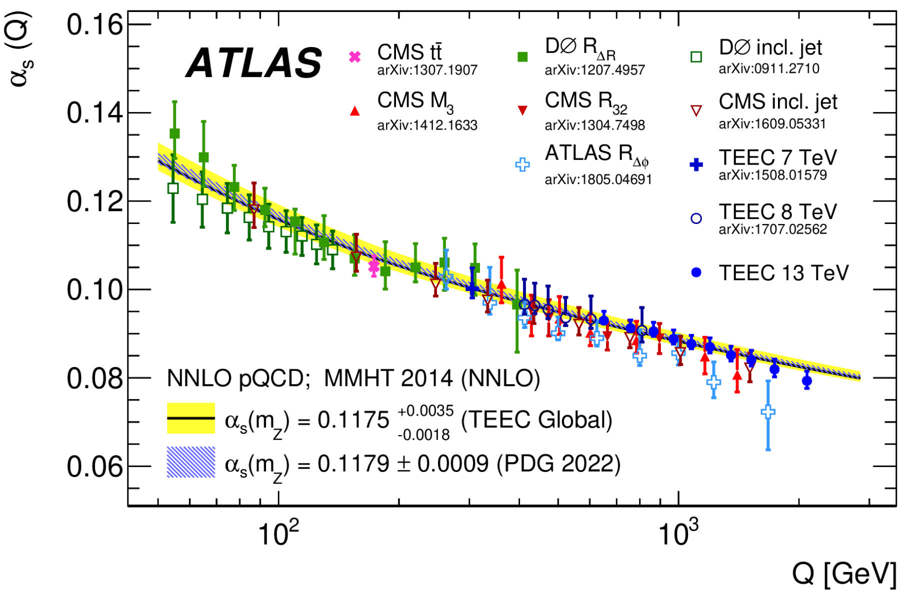


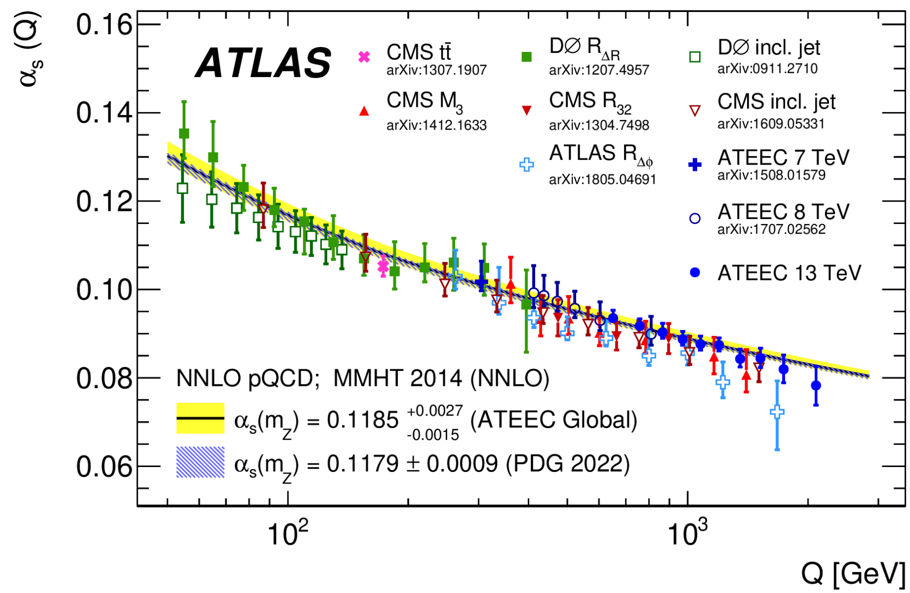



# TEEC and ATEEC measurements

- Running scale $Q$ as half averaged $\widehat{H_T}$ of all final-state partons in each $H_{T,2}$ bin
- $\alpha_S$ determined by comparison with theoretical predictions using this $\chi^2$ formula

$$\chi^2(\alpha_s, \vec{\lambda}) = \sum_{\text{bins}} \frac{(x_i - F_i(\alpha_s, \vec{\lambda}))^2}{\Delta x_i^2 + \Delta \xi_i^2} + \sum_k \lambda_k^2$$



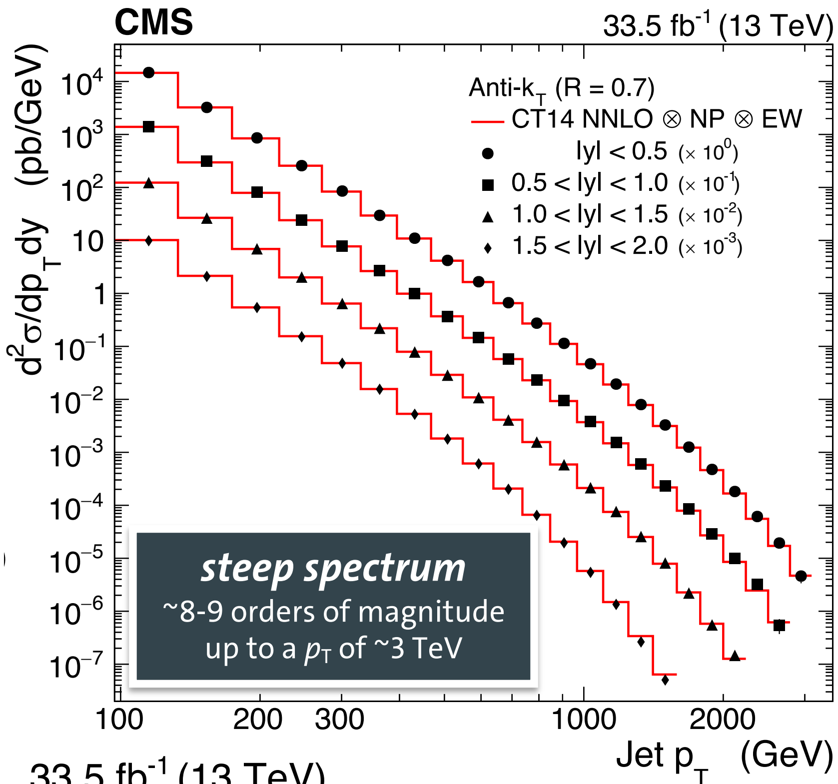

$$\alpha_s(m_Z)^{TEEC} = 0.1175 \pm 0.0006(\text{exp.})^{+0.0034}_{-0.017}(\text{theo.})$$

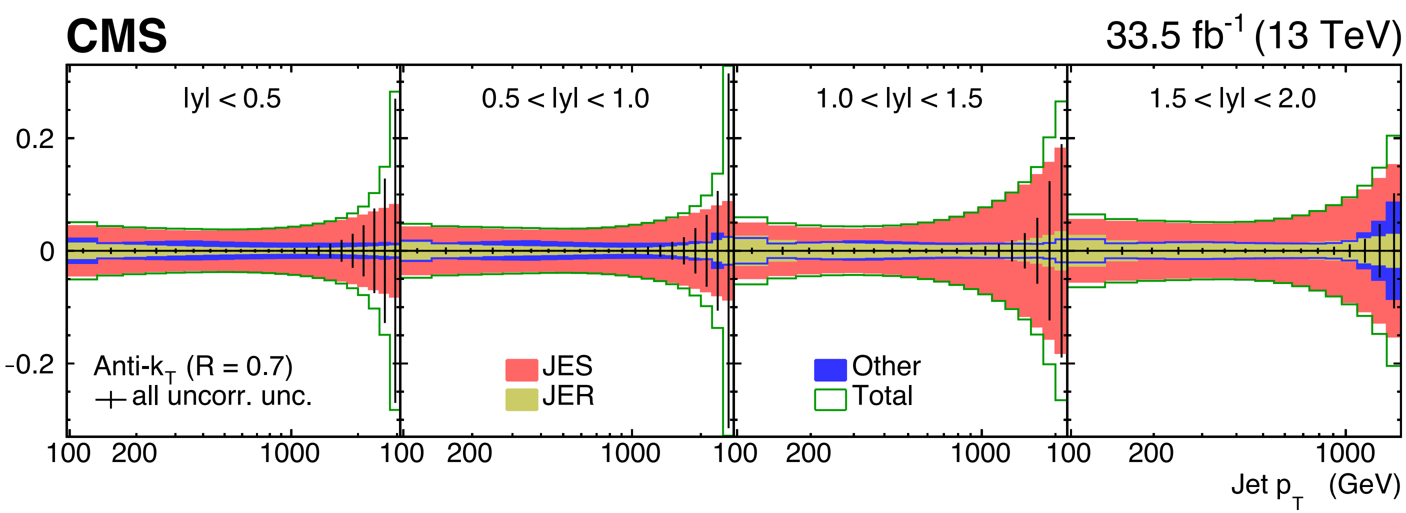
$$\alpha_s(m_Z)^{ATEEC} = 0.1185 \pm 0.0009(\text{exp.})^{+0.0025}_{-0.012}(\text{theo.})$$

- TEEC with better experimental precision, ATEEC with better theoretical one
- Good agreement with other measurements and RGE prediction (i.e. no new coloured fermions)

# Inclusive jet production

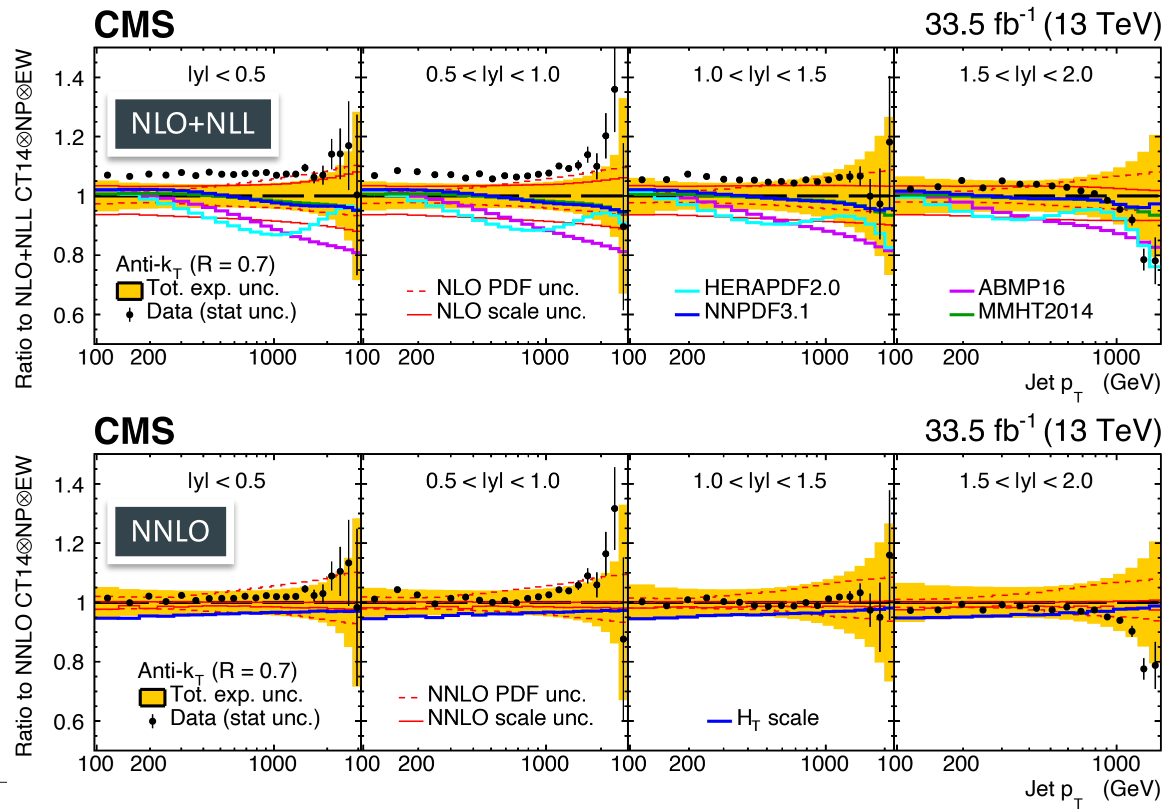
- **Double-differential** cross section measured as a function of **jet $p_T$** and **rapidity** for anti-$k_T$ jets with R = 0.4, 0.7
- Good experimental precision
- **< 5%** uncertainty in main measurement region
- Dominant uncertainty contribution from Jet Energy Scale (**JES**)

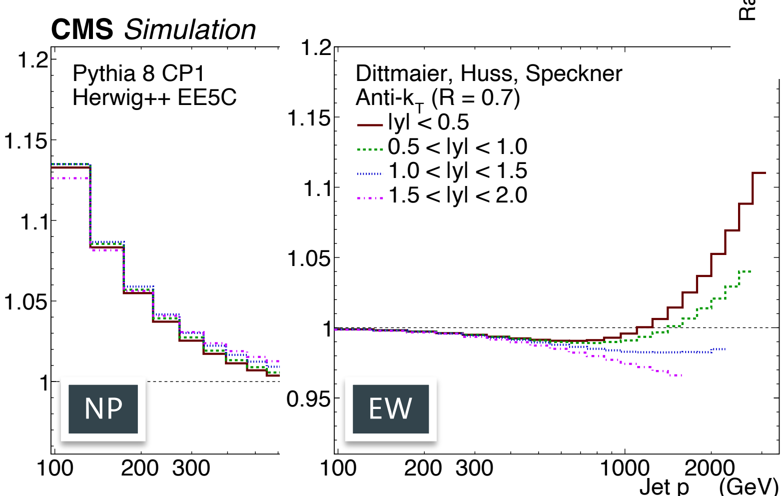


# Inclusive jet production

- Comparison to **FO pQCD** theory at **NNLO** and **NLO+NLL**
- Corrections for NP and EW contributions added as well
- Improved description of data at NNLO and **reduced scale uncertainty**




- NNPDF3.1 and MMHT14 provide a better data description wrt ABMP16 and HERAPDF2.0
- **Some disagreement** between global PDF sets, especially in the **high-$p_T$ region**

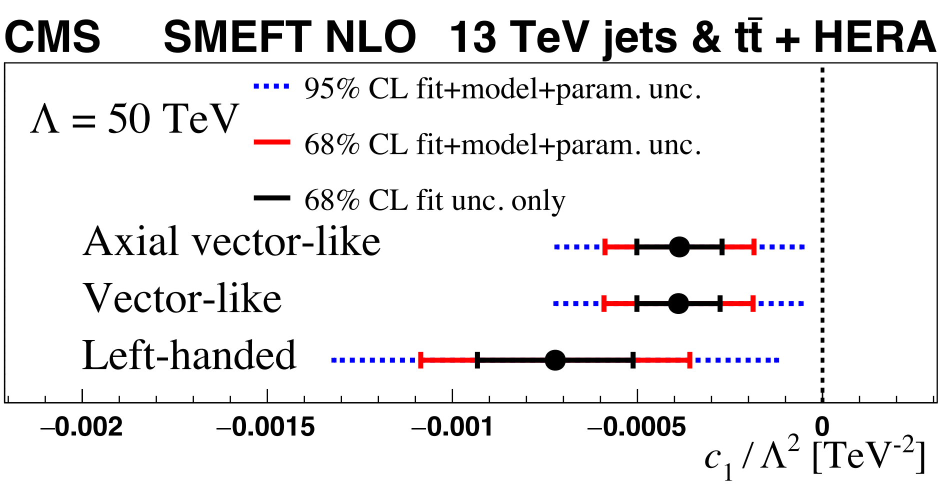
# Inclusive jet production

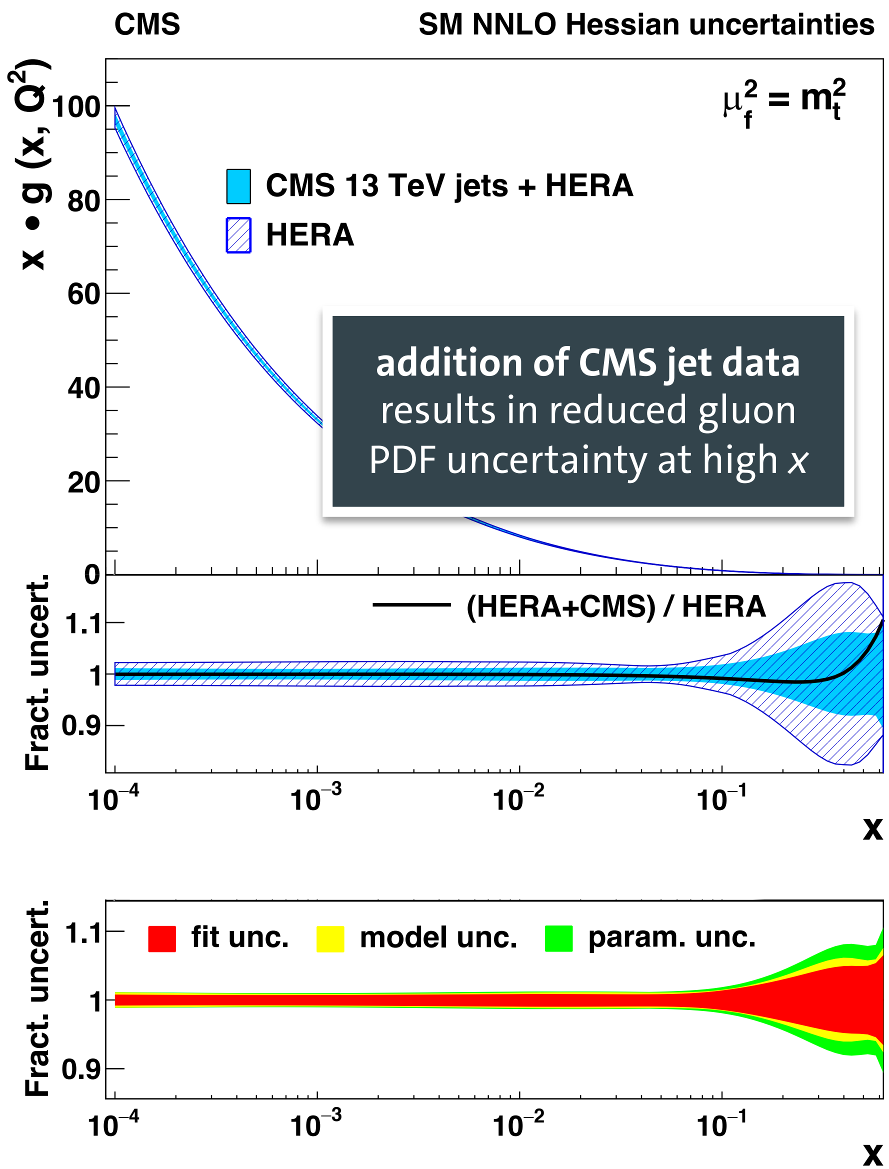
- Determination of **PDFs and $\alpha_s$ at NNLO**

$$\alpha_s(m_Z)_{\text{NNLO}} = 0.1166\ (14)_{\text{fit}}\ (7)_{\text{model}}\ (4)_{\text{scale}}\ (1)_{\text{param.}}$$

↳ $\chi^2 / n_{\text{dof}} = 1302 / 1118$

- **With $t\bar{t}$ data**: limits on Wilson coefficients for four-quark contact interactions
  - Multiple coupling structures probed
  - No significant deviations found

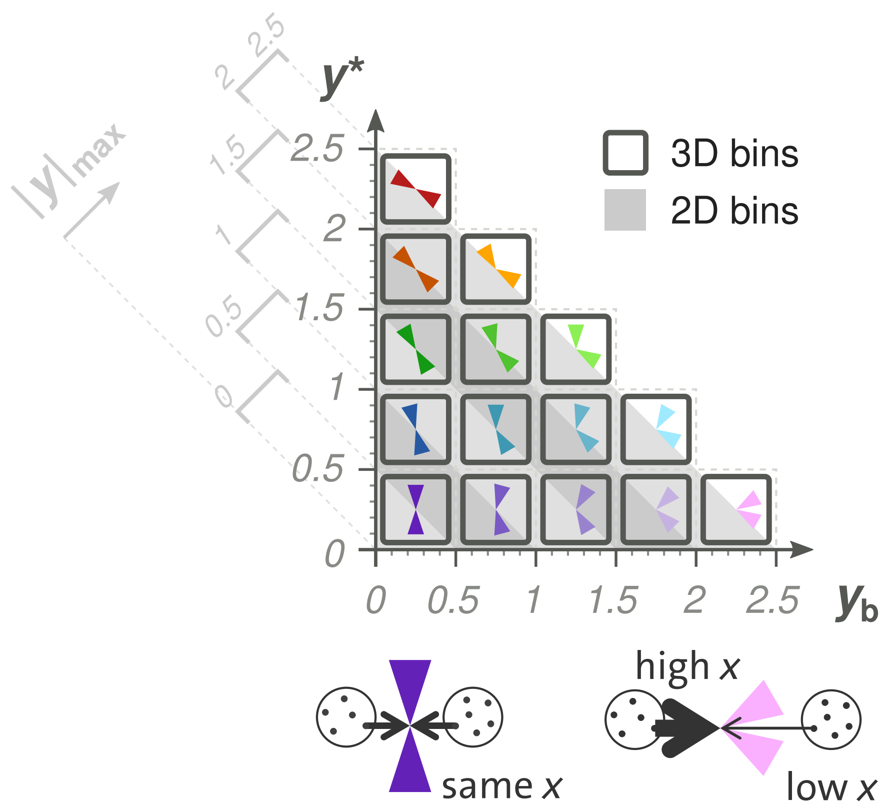


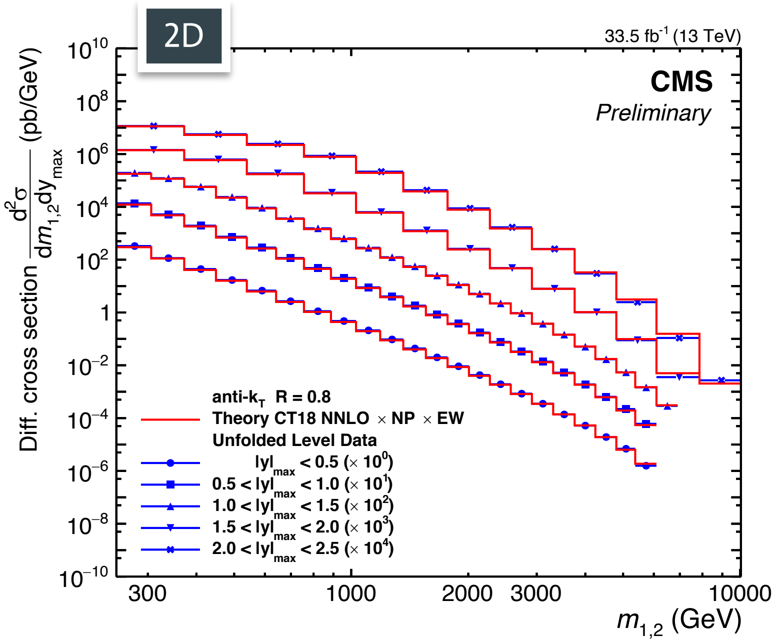



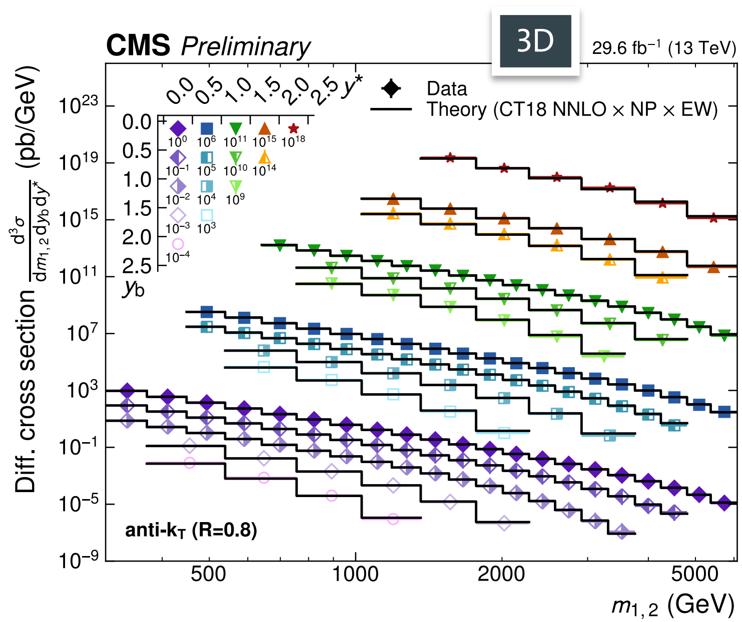

**addition of CMS jet data** results in reduced gluon PDF uncertainty at high *x*

# Dijets production

- **Double- and triple-**differential cross section measured as a function of **dijet invariant mass $m_{1,2}$** and **rapidity** of anti-$k_T$ jets with **R = 0.4, 0.8**
- Disentangle regions of different Bjorken $x$ carried by partons → **PDF fits**

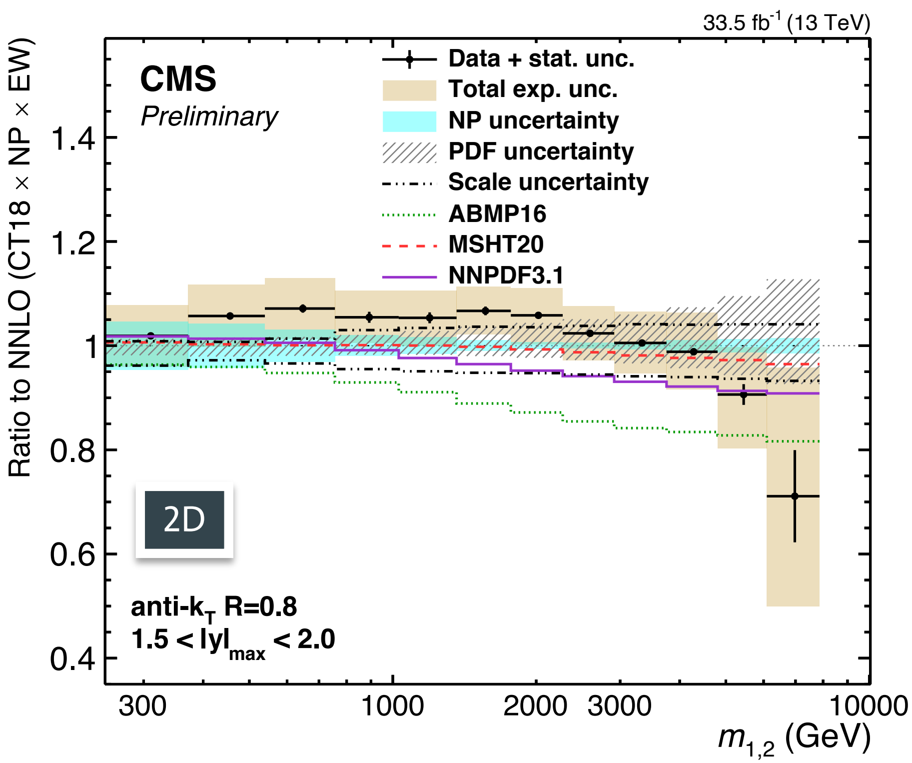


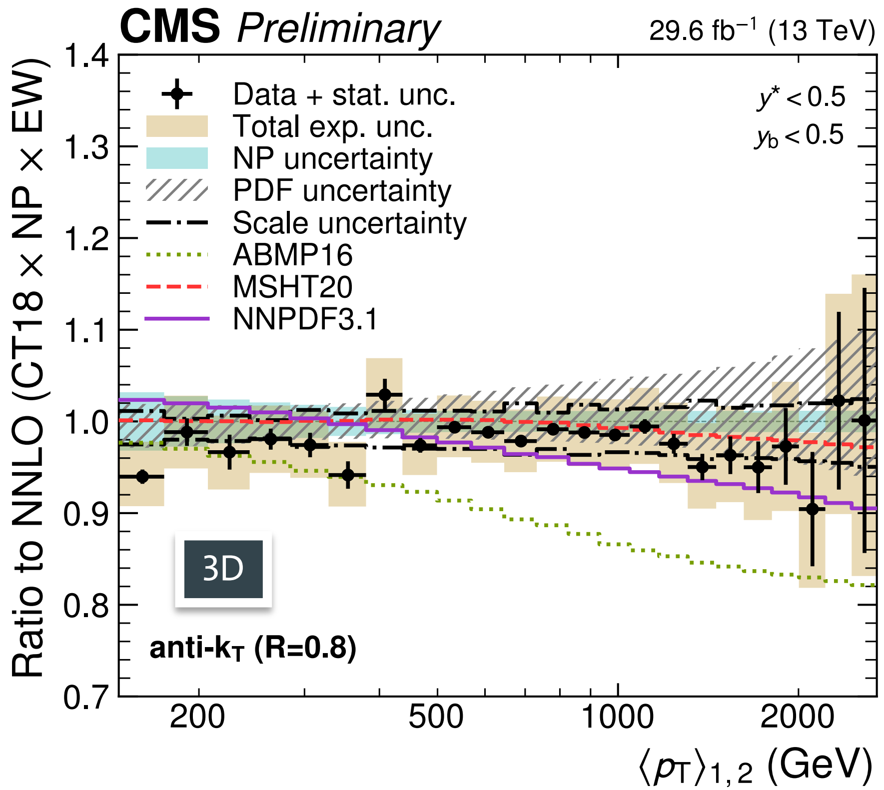



# Dijets production

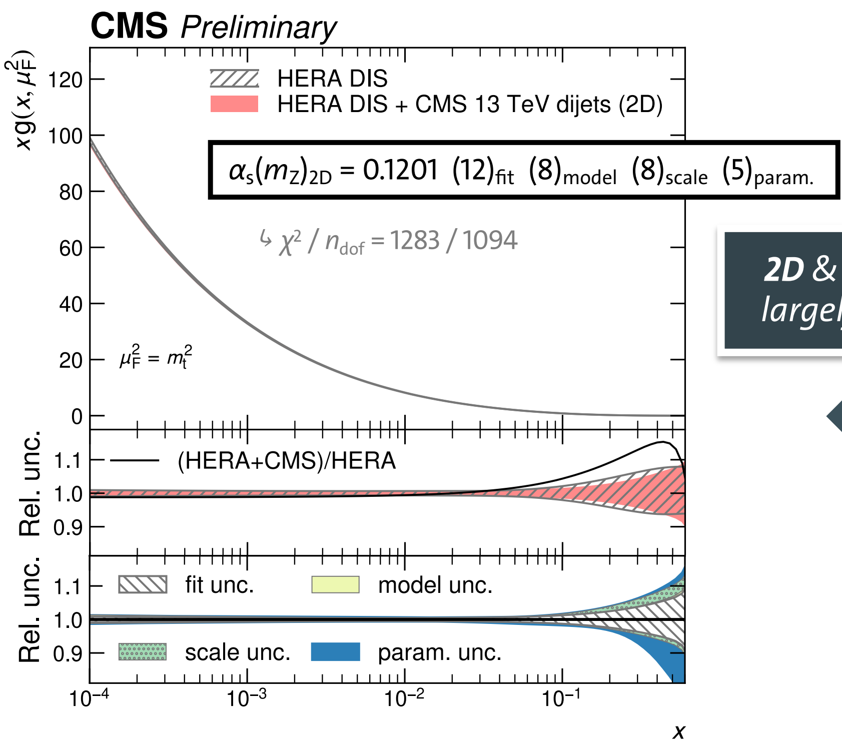
- Comparison to **FO theory** predictions at **NNLO + EW + NP**
- Data generally well described by the theory
- Here **R = 0.8** (similar agreement found for R = 0.4)
- MSHT20 (ABMP16) provides the best (worst) description of the data



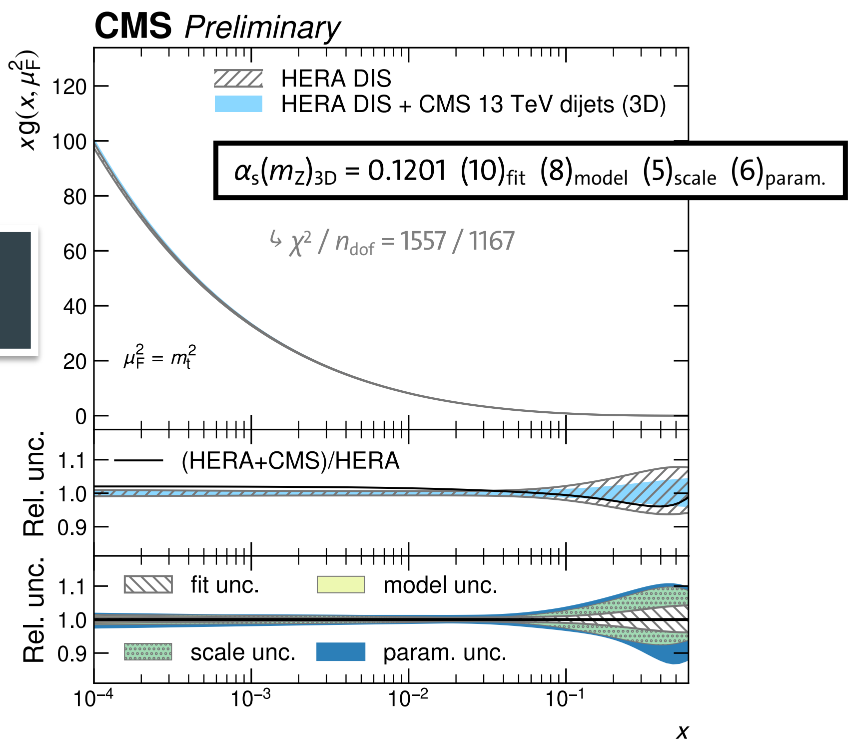



# Dijets production

- Determination of **PDFs and $\alpha_S$ at NNLO**
- Larger $\alpha_S$ value wrt the one obtained when fitting the inclusive jet distributions
- Impact on the gluon PDF (and its uncertainty) mostly for Bjorken x > 0.1
- Pulls in different directions




2D & 3D fit results largely compatible



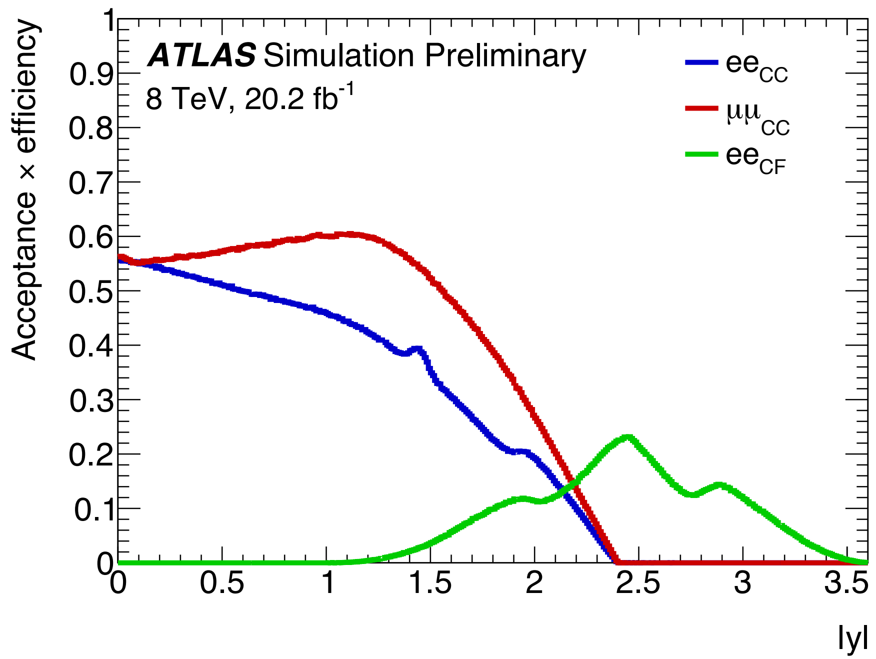
# Conclusion

- SM continues to be a successful theory under immense inspection with unprecedented precision from LHC
- No significant tension from the state of art predictions with aN$^4$LL+N$^3$LO accuracy
- Most precise determination of $\alpha_S$ for Z $p_T$ at 8 TeV in full lepton phase space
- Extracted $\alpha_S(Q)$ from (A)TEEC in good agreement with RGE predictions
- Many measurements from CMS at $\sqrt{s}$ = 13 TeV, targeting wide variety of jet observables
- Improved precision and extended kinematic reach beneficial for:
  - Determination of $\alpha_S(m_Z)$ and PDFs
  - Probes of extensions to the SM in EFT
  - Improvement of MC generator modelling and perturbative and non-perturbative effects
- Really interesting time ahead… STAY TUNED! ☺

# *Backup Slides*

# Z $p_T$ and rapidity at 8 TeV

- Stringent test of the state-of-art pQCD
- Probe large rapidity/small parton momentum fraction $x$ using forward electrons
- Unique full lepton phase space rapidity cross section with per-mille total uncertainties to provide a gateway to a rich field of precise interpretations

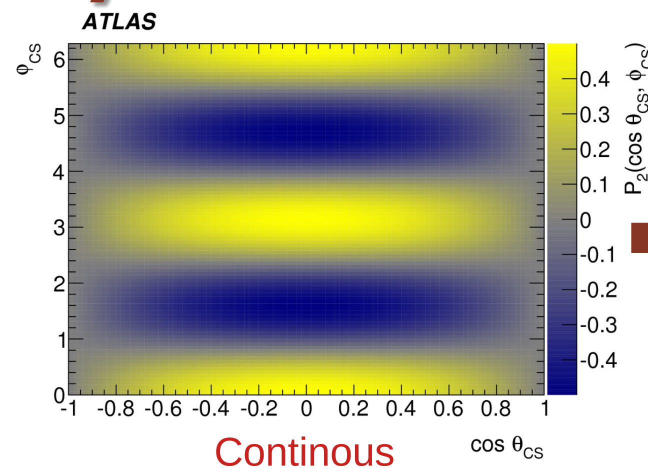



- $ee_{CC}$: two electrons with $p_T > 20$ GeV and $|\eta| < 2.4$
- $\mu\mu_{CC}$: two muons with $p_T > 20$ GeV and $|\eta| < 2.4$
- $ee_{CF}$: central electron with $p_T > 20$ GeV and $|\eta| < 2.4$ forward electron with $p_T > 20$ GeV and $2.5 < |\eta| < 4.9$

# Z $p_T$ and rapidity at 8 TeV

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T\,dy\,dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

- $d\sigma/dp_T$ → Transverse dynamics
- $d\sigma/dy$ → longitudinal dynamics (PDFs)
- Depends on 3 "boson production" variables ($p_T$, y, m) and 2 angular decay variables ($\cos\theta$, $\phi$)
- Decomposition of ($\cos\theta$, $\phi$) into 9 helicity cross sections → basis of spherical harmonics




Continous

$$\begin{pmatrix} H_0 \\ H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \\ H_7 \\ H_8 \end{pmatrix}$$

Quantized

- Measuring the $A_i$ → a quantized representation of the ($\cos\theta$, $\phi$) kinematic space
- **Very powerful**: trade systematics for statistics
- **Very useful**: provide analytic extrapolation of lepton cuts and enables a richer interpretation programme

**Expected Yield**

Reco ($p_T^Z$, $y^Z$, $m^Z$, cosθ, ϕ) bin; Cross section; Background template

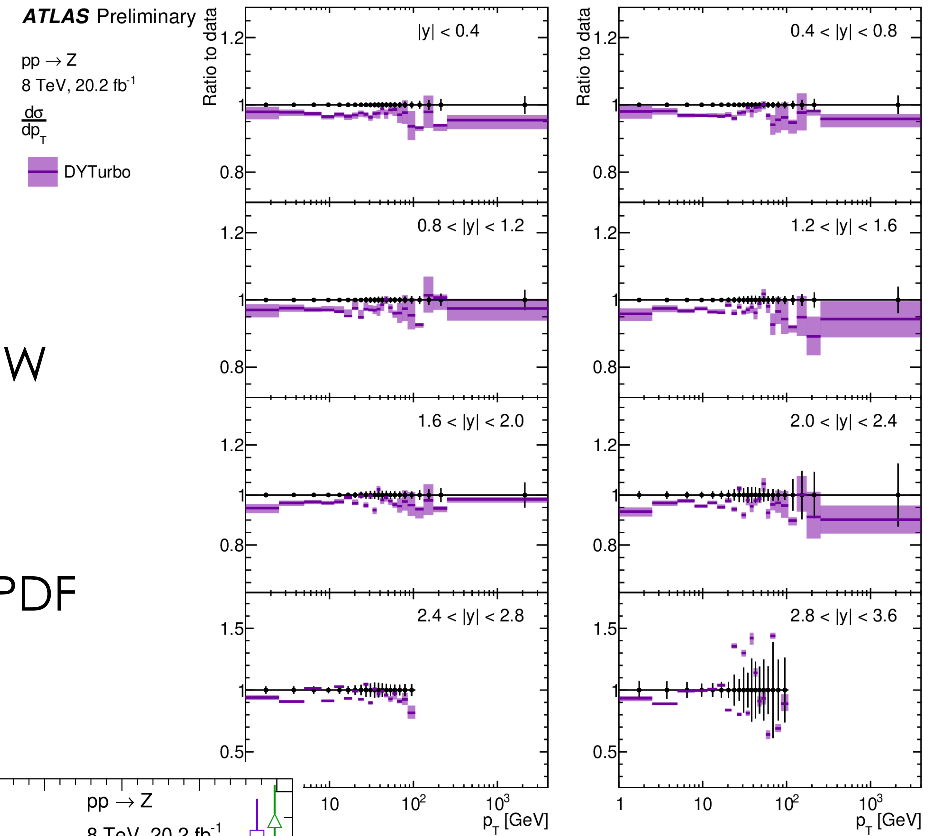
$$N^n_{\mathrm{exp}}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{bins}} \mathcal{L}\sigma_j\left[t^n_{8j}(\beta)+\sum_{i=0}^{7}A_{ij}t^n_{ij}(\beta)\right]\right\}\gamma^n + \sum_{B}^{bkgs} T^n_B(\beta)$$

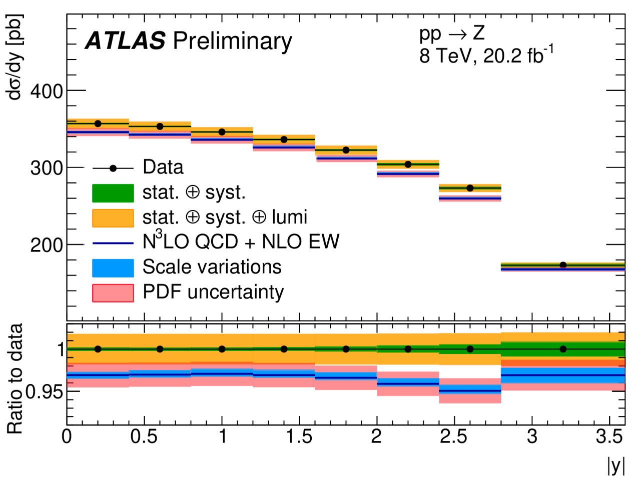
Truth ($p_T^Z$, $y^Z$, $m^Z$) bin; Angular coefficient; Templated polynomial

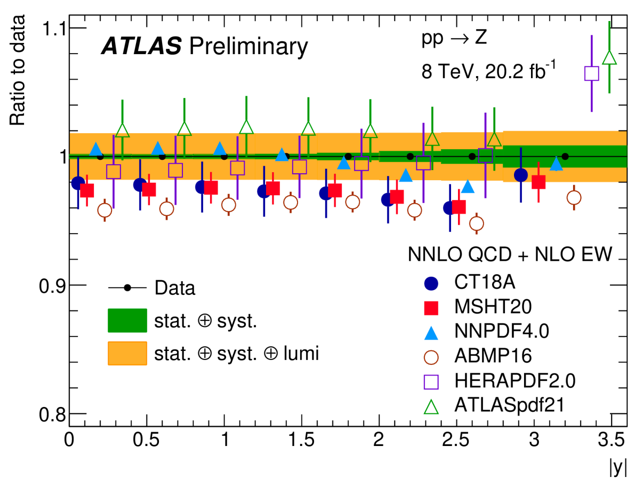
- Likelihood defined in 22528 ($\cos\theta$, $\phi$, $p_T$) bins
- **PoI**: 8 $A_i$ + 1 cross section in 176 ($p_T$, y) bins

# Z $p_T$ and rapidity at 8 TeV

- Per mille level precision in the central region
- Sub-percent precision up to |y| < 3.6
- First comparison to N³LO QCD + NLO EW predictions (DYTurbo + ReneSANCe)
- Allow precise PDF interpretations with QCD scale uncertainties smaller than PDF uncertainties



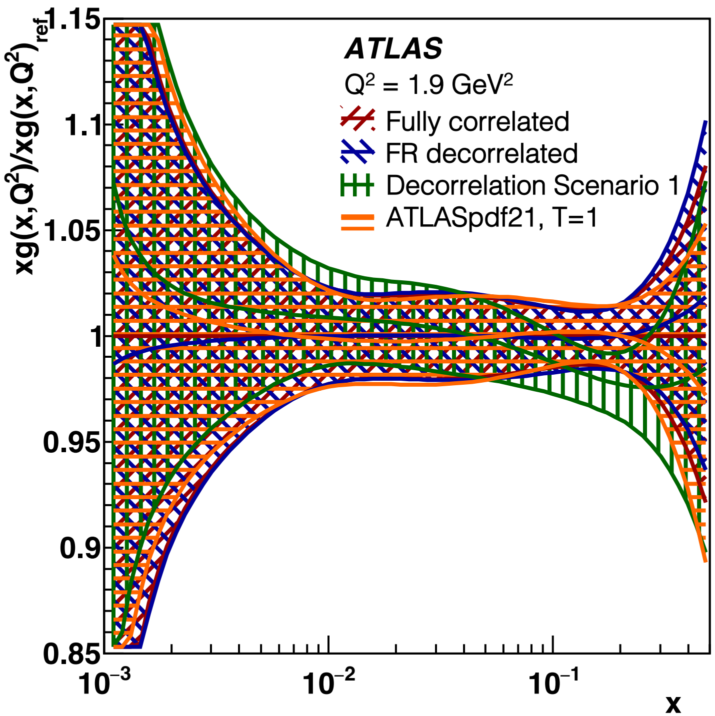



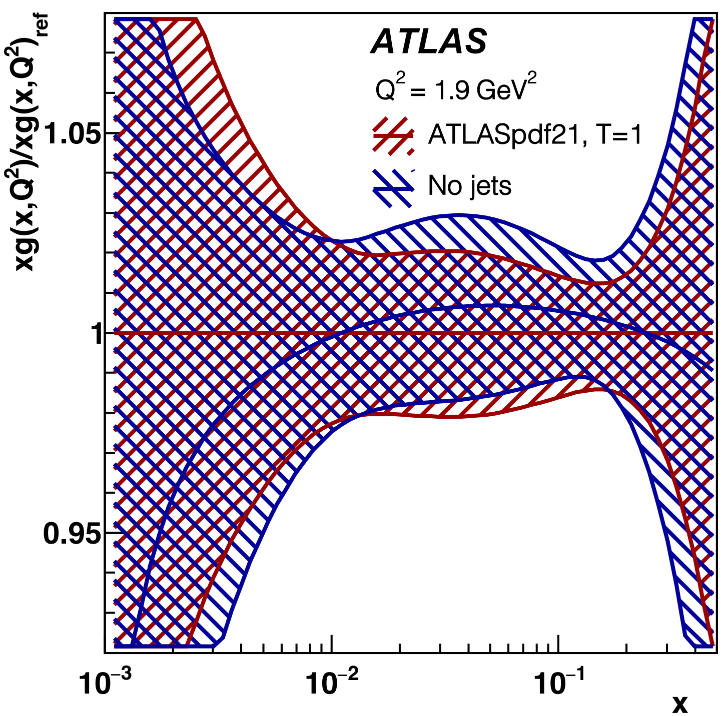

**Good agreement with several high-order qT-resummed predictions**

# Talking about inclusive jets

- Different model to treat correlated systematics: EPJ C82 (2022) 5, 438
  - keeping them fully correlated
  - decorrelating the Jets Flavour Response (FR) between rapidity bins
  - Two decorrelation scenarios as recommended in the 8 TeV jet paper
- This affects the $\chi^2$ but has little effect on the PDFs

| jets 8 TeV R=0.6 | Fully Correlated | FR Decorrelated | Decorrelation Scenario 1 | Decorrelation Scenario 2 |
|---|---|---|---|---|
| $\chi^2$/NDP | 289/171 | 227/171 | 250/171 | 248/171 |




Marginal shape change of the gluon PDF (blue to red) and **very substantial decrease in its high-x uncertainty**