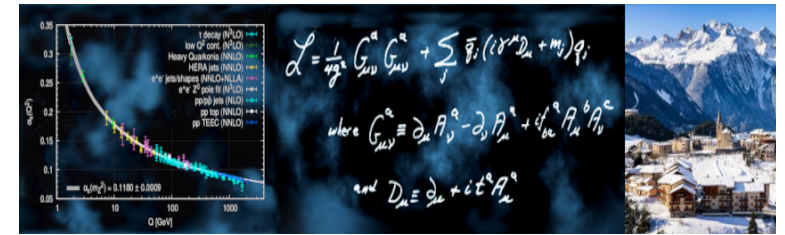


Workshop on precision measurements of α_s
14-19 December, 2025
CNRS Paul Langevin Center in Aussois (Savoie)



**Recent results from the ATLAS
Collaboration on determinations of α_s**



Claudia Glasman
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(on behalf of the ATLAS Collaboration)



The strong coupling constant α_s in pp collisions at LHC

- The strong coupling constant α_s and the PDFs participate in the predictions of any observable in pp collisions at LHC, eg jet cross sections

$$\sigma_{pp \rightarrow \text{jets}} = \sum \int dx_{p_1} f_{a/p_1}(x_{p_1}, \mu_F) \int dx_{p_2} f_{b/p_2}(x_{p_2}, \mu_F) \hat{\sigma}_{ab \rightarrow \text{jets}}(\mu_R, \alpha_s, x_{p_1}, x_{p_2})$$

- ⇒ to determine α_s from a jet observable at LHC, the correlation between
- ↪ explicit dependence on α_s from the matrix elements
 - ↪ implicit dependence on α_s from the pPDFs
- has to be taken into account properly

- Solutions:

- determine α_s from observables with small dependence on the pPDFs (eg, determination from ratios of observables)
- determine α_s by taking properly into account the correlation (eg. using pPDF sets extracted assuming different values of α_s)
- or perform simultaneous determination of α_s and the pPDFs

- More sophisticated observables (TEEC or $Z p_T$) provide determinations of α_s with better precision and improvements in theoretical predictions provide better accuracy

Transverse energy-energy correlations in multijets

Transverse energy-energy correlations in multijets

- **TEEC observable:** transverse energy-weighted azimuthal angular distribution of jet pairs in the final state:

$$\frac{1}{\sigma} \frac{d\Sigma}{d \cos \phi} = \frac{1}{\sigma} \sum_{i,j}^{\text{jets}} \int d\sigma_{pp \rightarrow \text{jets}} \frac{E_{Ti} E_{Tj}}{E_T^2} \delta(\cos \Delta\phi_{ij} - \cos \phi)$$

E_T is the sum of all jets transverse energy and the normalisation to σ ensures that the integral of the function over $\cos \phi$ is unity

- **ATEEC observable:** forward-backward azimuthal angular asymmetry

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

- **These observables provide**

- large sensitivity to QCD radiation and α_s
- smaller sensitivity to IR divergences than other observables in pp collisions
- mild sensitivity to PDFs and high-order QCD corrections

- **TEEC and ATEEC were measured by ATLAS at $\sqrt{s} = 7, 8 \text{ \& } 13 \text{ TeV}$ and $\alpha_s(m_Z)$ extracted and its running tested**

ATLAS Collab, PLB 750 (2015) 427, EPJ C 77 (2017) 872 & JHEP 07 (2023) 085

TEEC and ATEEC normalised cross sections

- The TEEC and ATEEC observables were measured at $\sqrt{s} = 13$ TeV using 139 fb^{-1} of Run 2 pp collisions

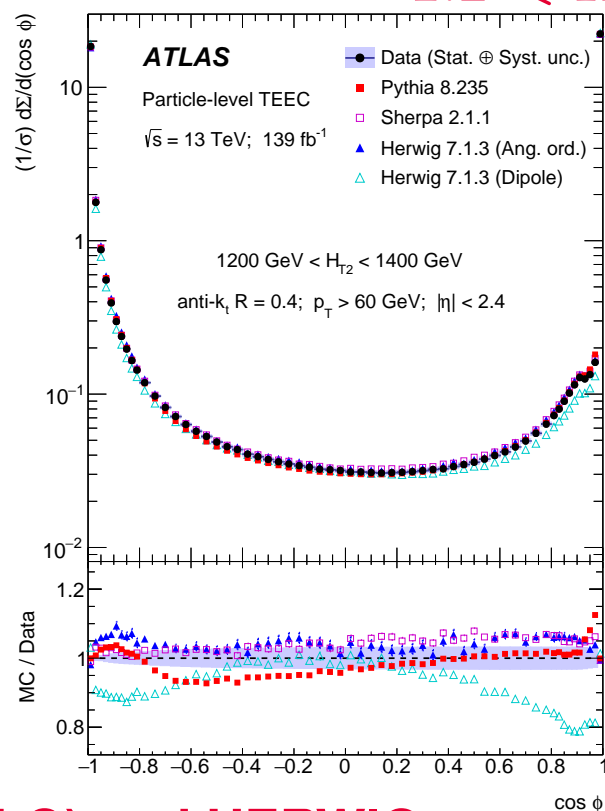
→ anti- k_t jets of $R = 0.4$ with $p_T^{\text{jet}} > 60$ GeV and $|\eta^{\text{jet}}| < 2.4$ were selected

→ events were selected with $H_{T2} = p_T^{\text{jet1}} + p_T^{\text{jet2}} > 1$ TeV

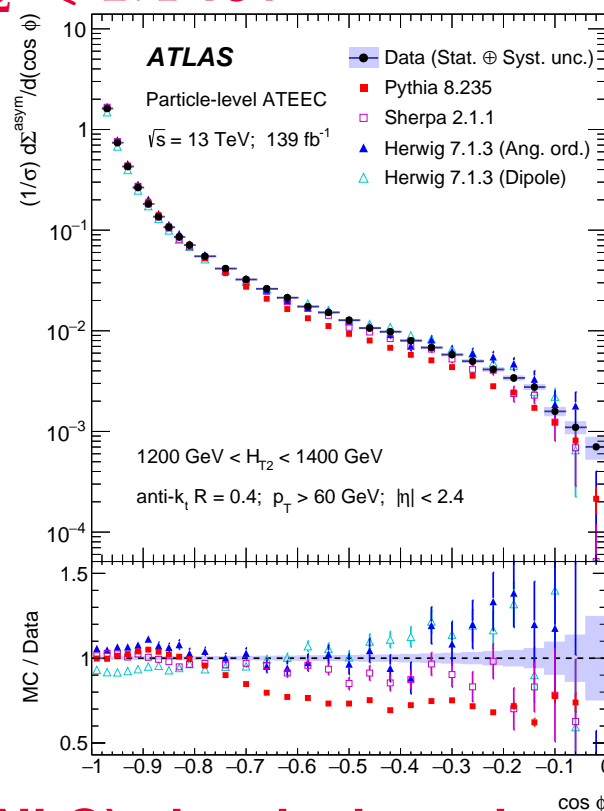
→ the data were separated in 10 intervals of H_{T2} and unfolded to particle level

$1.2 < H_{T2} < 1.4$ TeV

TEEC



ATEEC

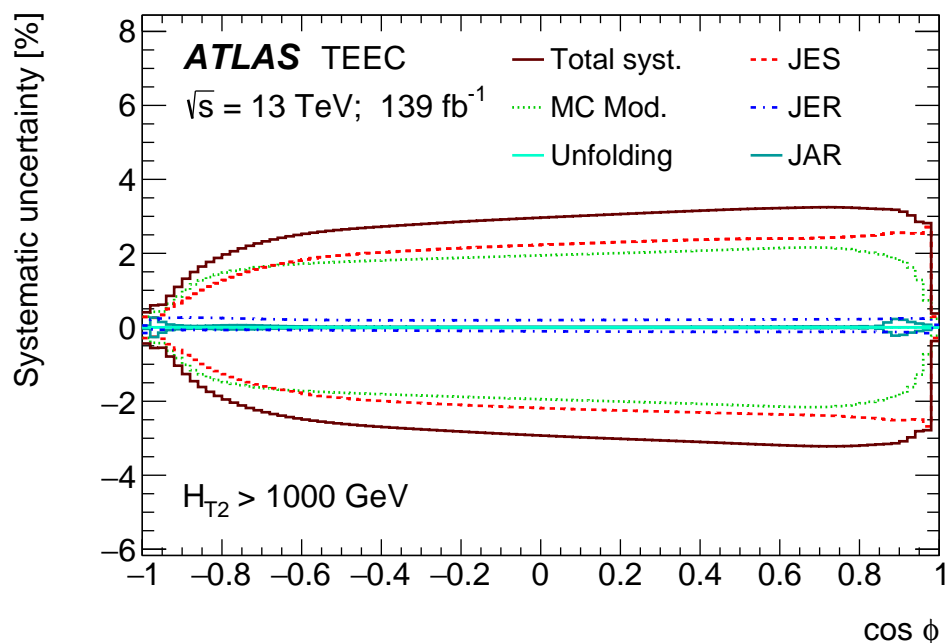


⇒ SHERPA (LO) and HERWIG_ang_ord (NLO) give the best description of the data
 ATLAS Collab, JHEP 07 (2023) 085

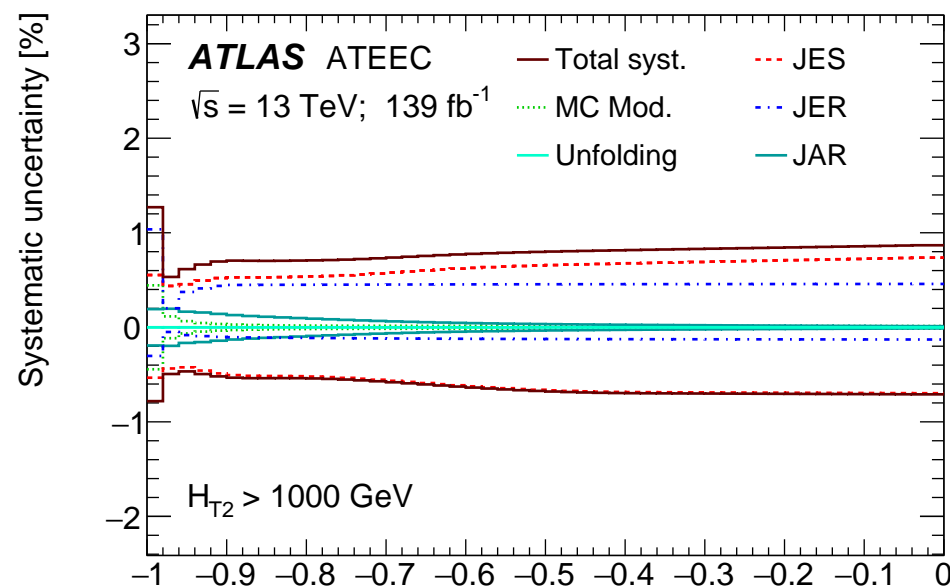
TEEC and ATEEC normalised cross sections

- The data were unfolded to jets of hadrons using the Bayesian unfolding method, which involves transfer matrices that take into account the bin-by-bin migrations in $\cos \phi$ due to the finite detector resolution
- **Experimental uncertainties:** jet energy scale and resolution, jet angular resolution, unfolding procedure & signal modelling
 - the impact of these sources depends on the region of phase space
 - overall, the JES uncertainty dominates, while signal modelling and JER uncertainties also important for TEEC and ATEEC, respectively

TEEC

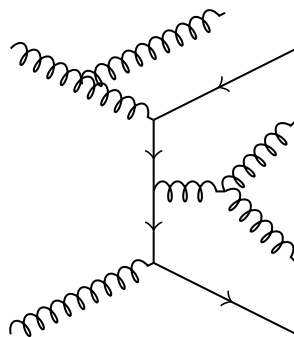


ATEEC

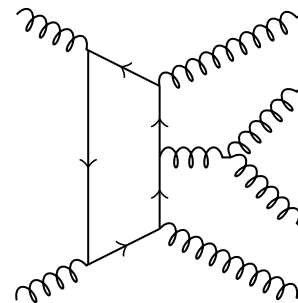


Theoretical predictions @ NNLO

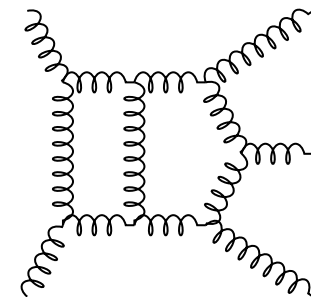
- The theoretical predictions for the TEEC observable were calculated from the NNLO 3-jet cross sections obtained by M Czakon et al. (PRL 127 (2021) 152001) and M Álvarez et al. (JHEP 03 (2023) 129)
- Very difficult and CPU-time-consuming calculations:
 - one million Feynman diagrams contribute to the 3-jet cross section @ NNLO
 - some contributions to $gg \rightarrow jjj$ @ NNLO are:



real-real



real-virtual

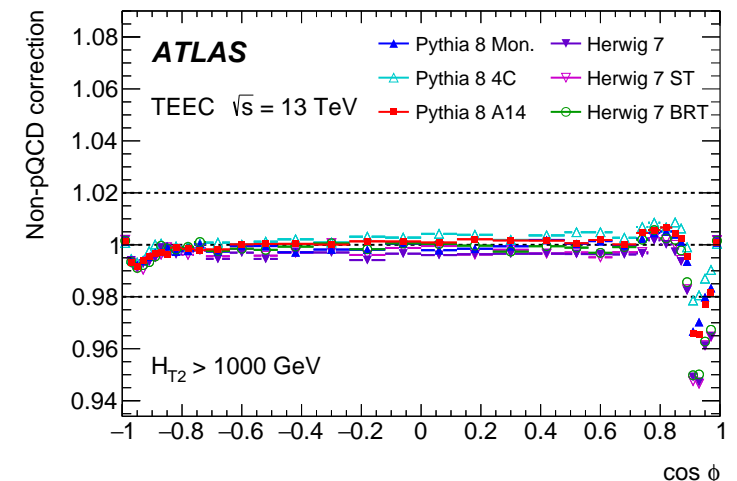


virtual-virtual

- 5×10^{13} events were generated for the full calculation
 - in total, around 200M CPU hours running in the WLCG
- the resulting predictions have very good precision for both TEEC and ATEEC observables

Theoretical predictions @ NNLO

- To evaluate the scattering amplitudes, the calculations use OPENLOOPS2, FIVEPOINTAMPLITUDES and PENTAGONFUNCTIONS++
- At $\mathcal{O}(\alpha_s^5)$, the numerator of TEEC entails the calculation of $2 \rightarrow 3$ @ NNLO, $2 \rightarrow 4$ @ NLO and $2 \rightarrow 5$ @ LO
 - to avoid collinear singularities, $|\cos \phi|$ is restricted to < 0.92
 - this also avoids calculating 3-loop virtual corrections to $2 \rightarrow 2$ subprocesses
- The denominator in TEEC includes $2 \rightarrow 2$, 3 , 4 subprocesses up to and including $\mathcal{O}(\alpha_s^4)$ corrections
- The value of α_s used in the calculations is taken from the NNLO PDF sets:
 - MMHT2014, NNPDF3.0 and CT14
 - and $\mu_R = \mu_F = \hat{H}_T$
 - (at Born level, \hat{H}_T coincides with H_{T2})
- The partonic predictions are corrected for hadronisation, UE and MPI effects to the same particle level as the data using MC models
- These corrections are ≈ 1 within 0.5% for $|\cos \phi| < 0.86$

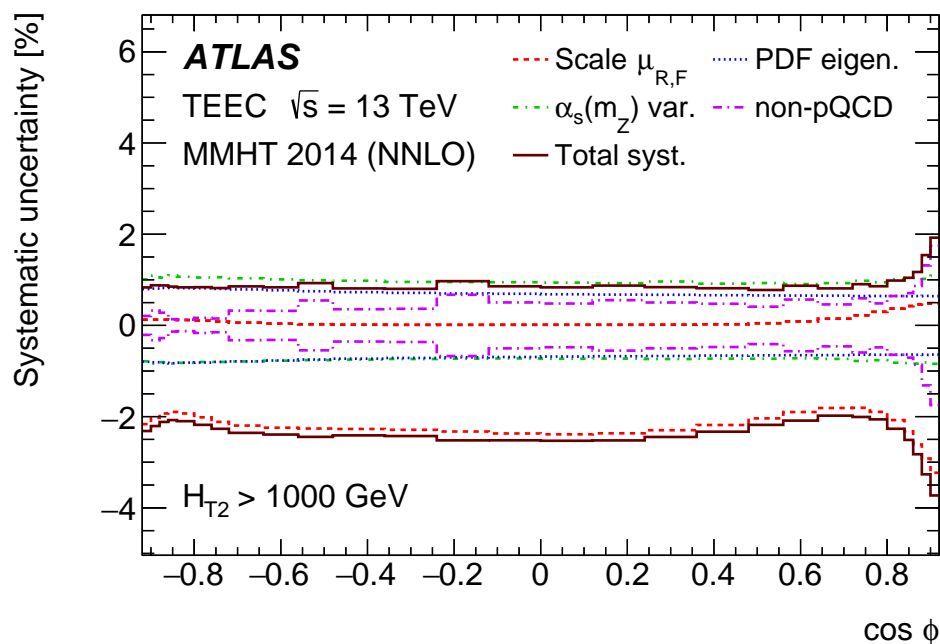


ATLAS Collab, JHEP 07 (2023) 085

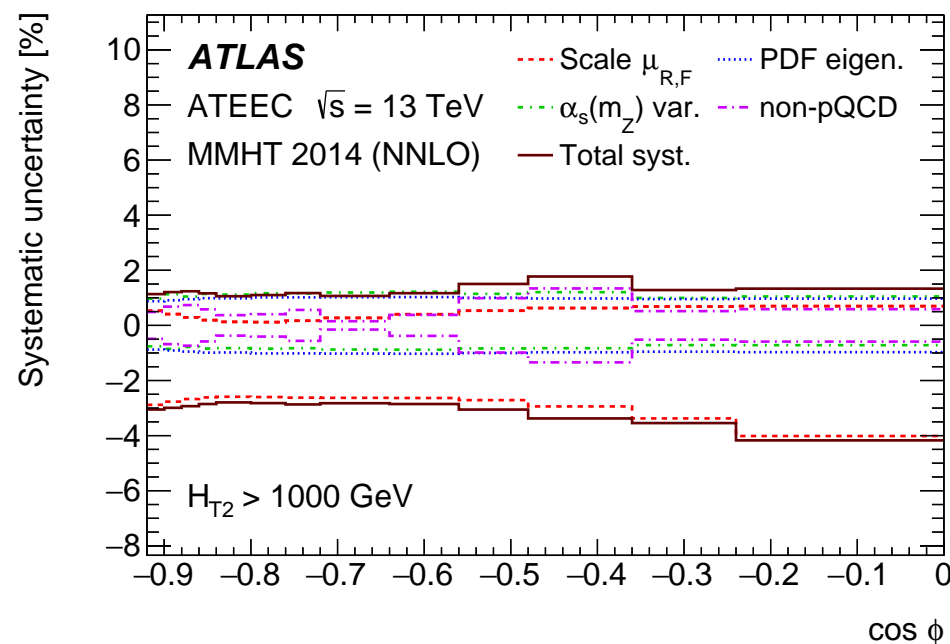
Theoretical predictions @ NNLO uncertainties

- The uncertainties in the theoretical predictions arise from:
 - higher-order corrections (dominant: 6% at NLO and below 2% at NNLO)
 - PDF uncertainties (below 1% for low H_{T2} and up to 2% at high H_{T2} values)
 - non-perturbative corrections (below 1% for $|\cos \phi| < 0.92$)

TEEC



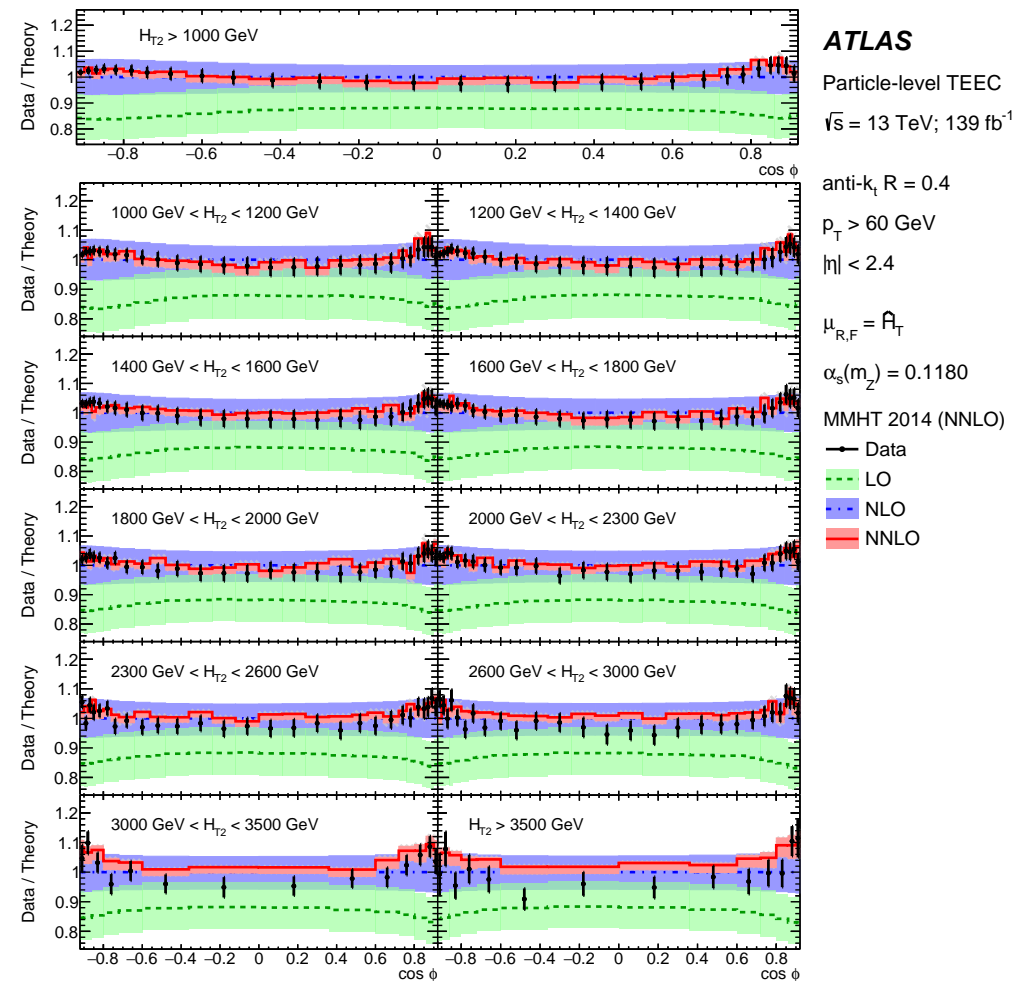
ATEEC



TEEC measurements vs fixed-order QCD predictions

- Ratio of data, LO and NNLO predictions to NLO predictions:

TEEC



⇒ The description of the data is improved by including the NNLO corrections, with reduced theoretical uncertainty

Determination of $\alpha_s(m_Z)$ from TEEC and ATEEC

- $\alpha_s(m_Z)$ was determined from the comparison of data and theoretical predictions using the Hessian method

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

with the theoretical prediction being

$$F_i(\alpha_s, \vec{\lambda}) = \psi_i(\alpha_s) \left(1 + \sum_k \lambda_k \sigma_k^{(i)} \right)$$

where

x_i measured data in bin i and Δx_i its statistical uncertainty

$\Delta \xi_i$ statistical uncertainty of prediction

$\sigma_k^{(i)}$ relative value of k -th correlated source of systematic uncertainty

λ_k are nuisance parameters to take into account correlations

→ the minimum χ^2 is found in a 150-dimensional space (149 NPs and 1 NP for α_s)

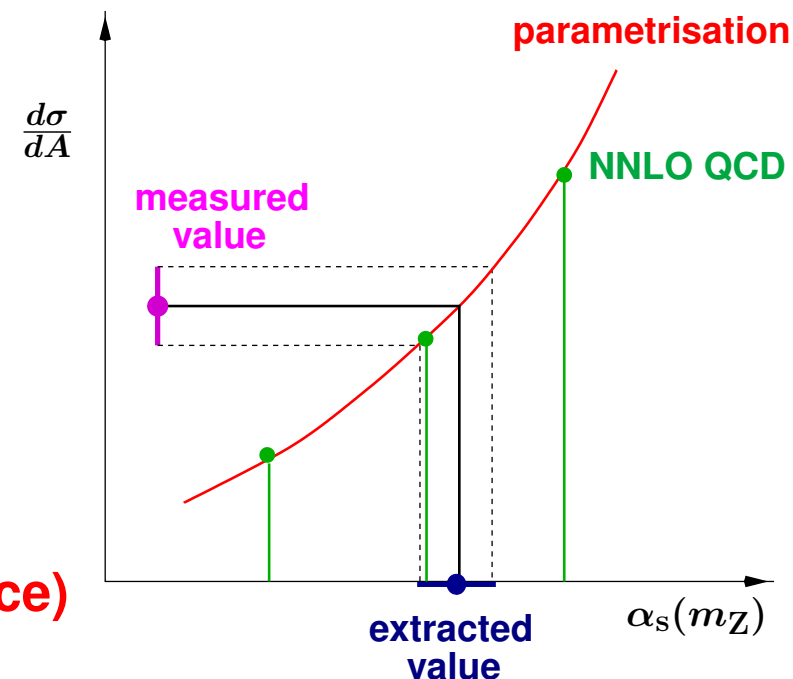
→ for each source of uncorrelated uncertainty, $\alpha_s(m_Z)$ is re-evaluated

ψ_i is the analytical expression for the dependence on $\alpha_s(m_Z)$ of each observable

Determination of $\alpha_s(m_Z)$ from TEEC and ATEEC

- The dependence of the theoretical prediction on $\alpha_s(m_Z)$ for each observable needs also to take into account the correlation with the PDFs:
 - perform **NNLO calculations** using different sets of pPDFs
 - use as input in each calculation the value of $\alpha_s(m_Z)$ assumed in each pPDF set
 - parametrise the α_s dependence of the observable:

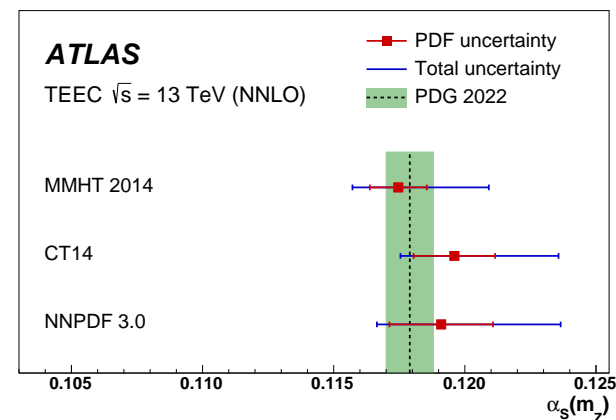
$$\sum_{n=0}^3 p_n(\cos \phi_i) [\alpha_s(m_Z)]^n$$
 - determine $\alpha_s(m_Z)$ from the **measured value** using the **parametrisation (analytical dependence)** in the χ^2 computation
- This procedure handles correctly the complete α_s -dependence of the NNLO calculations (explicit dependence in the partonic cross section and implicit dependence from the pPDFs) in the fit, while preserving the correlation between α_s and the pPDFs



Values of $\alpha_s(m_Z)$ from TEEC and ATEEC

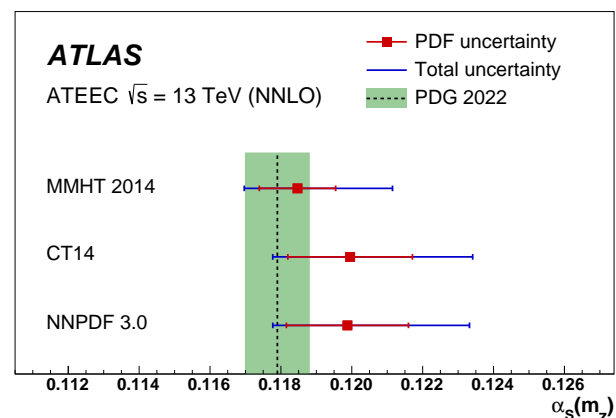
● Values of $\alpha_s(m_Z)$ obtained from TEEC using different PDFs:

PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}
MMHT 2014	0.1175 ± 0.0001 (stat.) ± 0.0006 (sys.) $^{+0.0032}_{-0.0011}$ (μ) ± 0.0011 (PDF) ± 0.0002 (NP) ± 0.0005 (mod.)	318 / 251
CT14	0.1196 ± 0.0001 (stat.) ± 0.0006 (sys.) $^{+0.0035}_{-0.0010}$ (μ) ± 0.0016 (PDF) ± 0.0002 (NP) ± 0.0006 (mod.)	262 / 251
NNPDF 3.0	0.1191 ± 0.0001 (stat.) ± 0.0006 (sys.) $^{+0.0040}_{-0.0011}$ (μ) ± 0.0020 (PDF) ± 0.0003 (NP) ± 0.0007 (mod.)	300 / 251



● Values of $\alpha_s(m_Z)$ obtained from ATEEC using different PDFs:

PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}
MMHT 2014	0.1185 ± 0.0005 (stat.) ± 0.0008 (sys.) $^{+0.0022}_{-0.0002}$ (μ) ± 0.0011 (PDF) ± 0.0004 (NP) ± 0.0001 (mod.)	110 / 117
CT14	0.1200 ± 0.0006 (stat.) ± 0.0009 (sys.) $^{+0.0027}_{-0.0001}$ (μ) ± 0.0016 (PDF) ± 0.0005 (NP) ± 0.0001 (mod.)	110 / 117
NNPDF 3.0	$0.1199 \pm 0.0006 \pm$ (stat.) 0.0009 (sys.) $^{+0.0027}_{-0.0002}$ (μ) ± 0.0017 (PDF) ± 0.0005 (NP) ± 0.0001 (mod.)	108 / 117



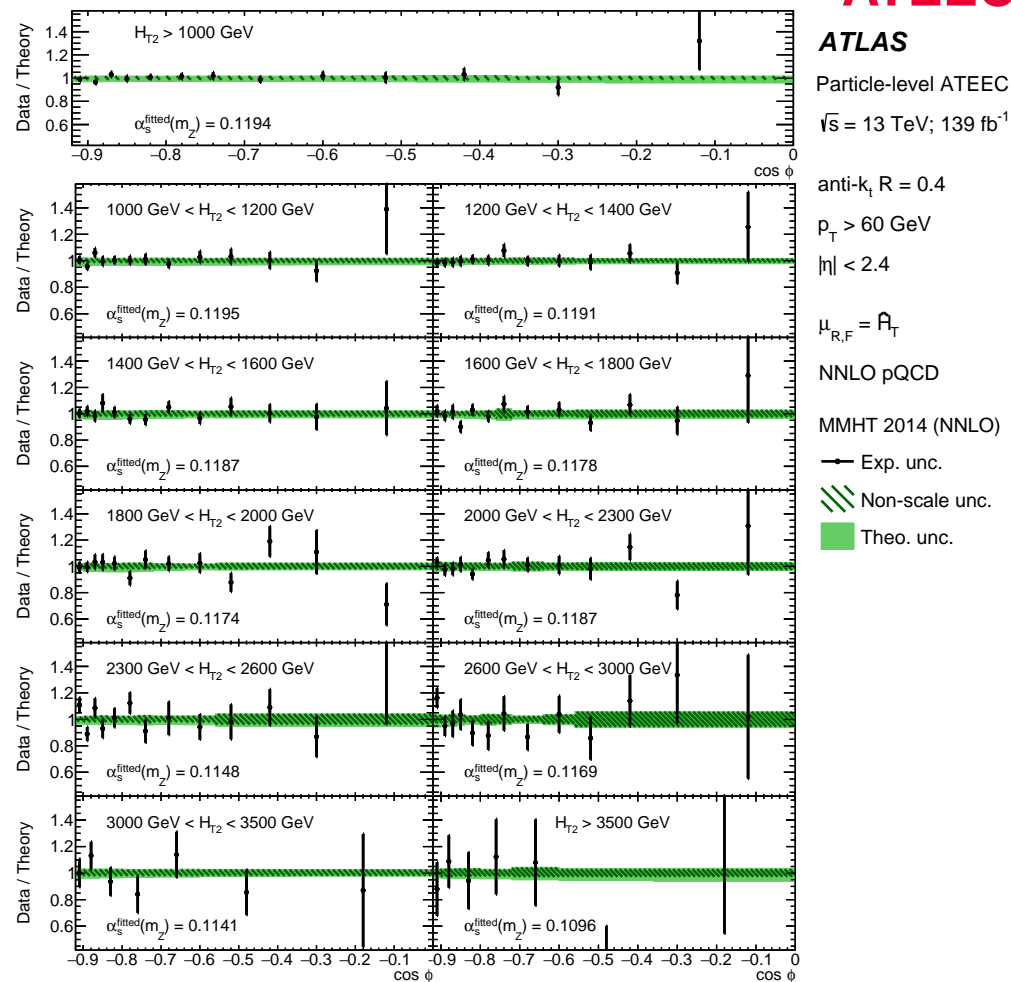
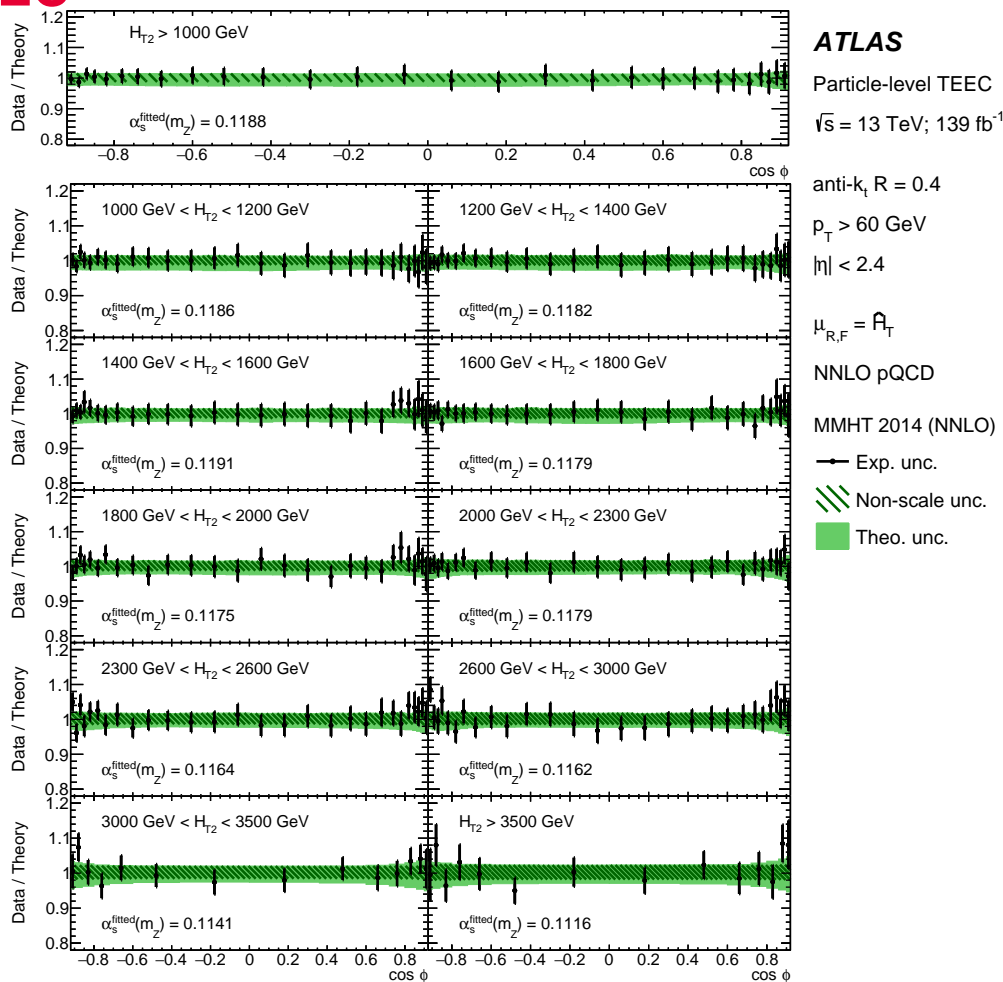
- Since the main purpose of this analysis is to provide a first determination of α_s using NNLO predictions for three-jet cross sections, a combined determination of α_s and the PDF was not attempted (huge challenge for computing resources!)
 \Rightarrow factor 2 reduction in theoretical uncertainty wrt NLO determination

TEEC and ATEEC measurements vs fixed-order QCD predictions

- Ratio of data and NNLO predictions using the extracted $\alpha_s(m_Z)$ values

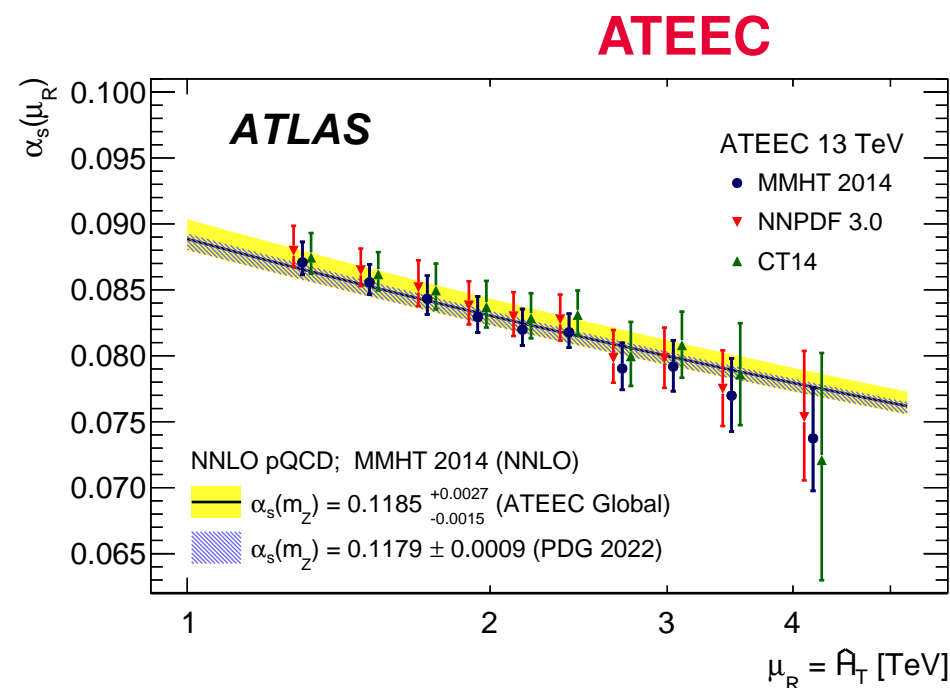
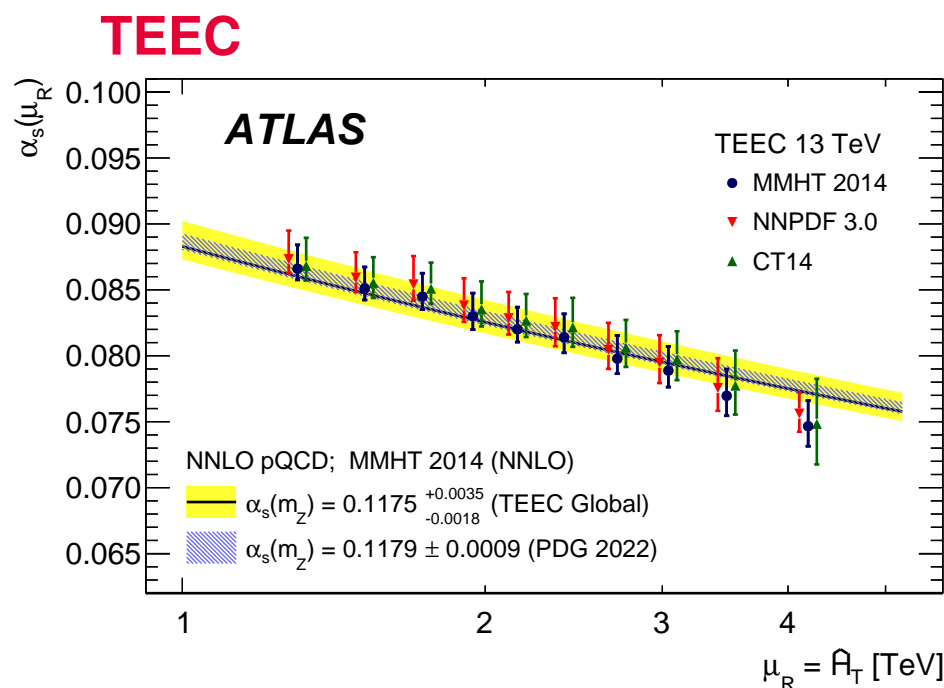
TEEC $\alpha_s(m_Z) = 0.1175^{+0.0035}_{-0.0018}$

ATEEC $\alpha_s(m_Z) = 0.1185^{+0.0027}_{-0.0015}$



Running of α_s from TEEC and ATEEC

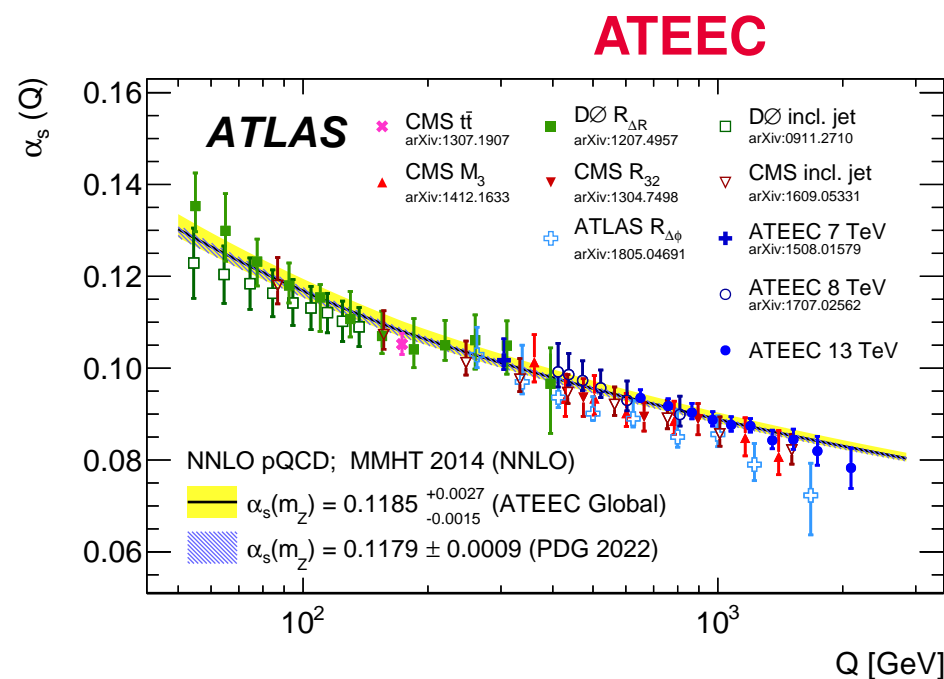
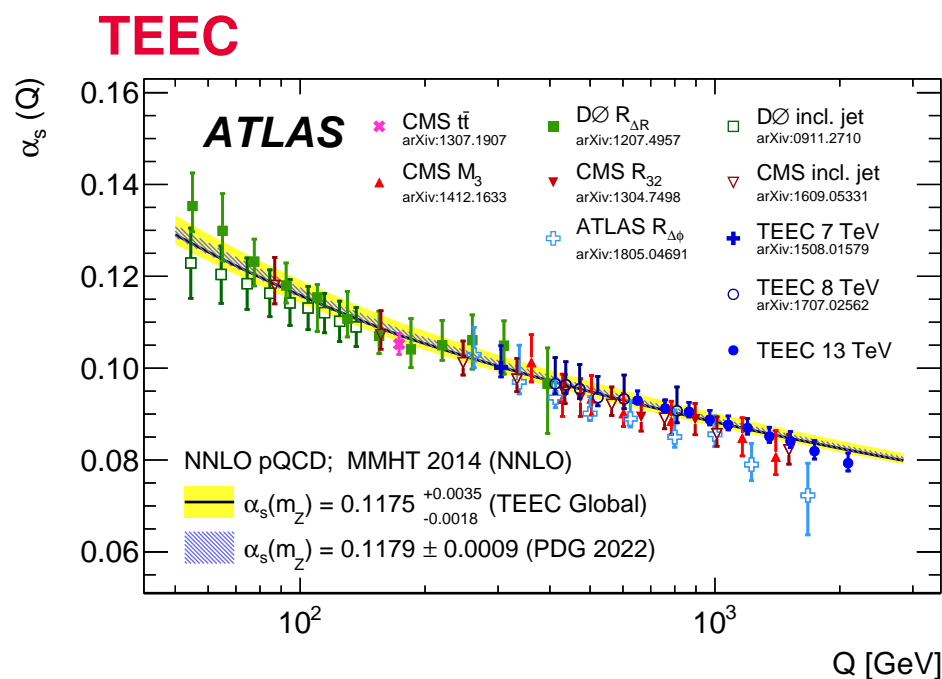
- The energy-scale dependence of the coupling was determined by extracting α_s from the TEEC and ATEEC measured observables in each region of H_{T2}



⇒ The results are in good agreement with the predicted running of α_s with small experimental and theoretical uncertainties in a wide range of the scale

Running of α_s from TEEC and ATEEC

- Comparison of the values of $\alpha_s(Q)$ obtained from TEEC and ATEEC with those from other experiments at lower energies

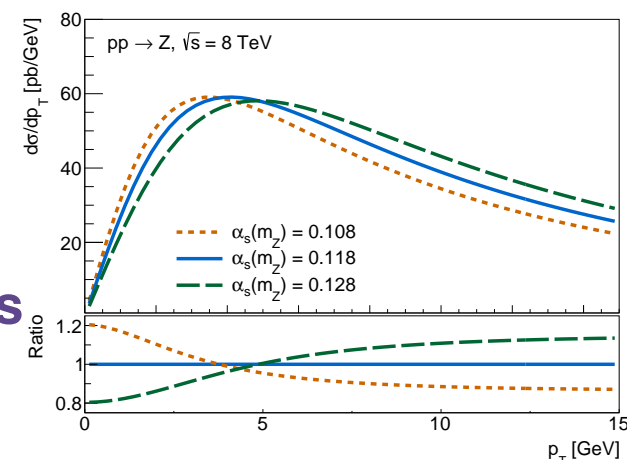
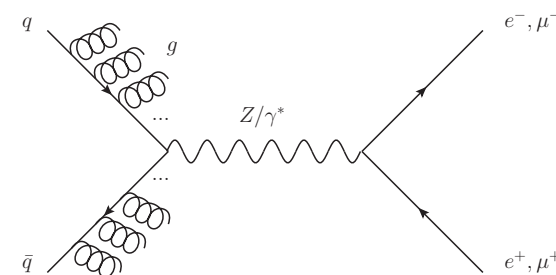


⇒ The results from TEEC and ATEEC extend the phase-space region tested with high precision into a previously unexplored scale

Z p_T distribution

The Z p_T distribution

- As shown in previous results, experimental uncertainties are under control @ LHC
 - improvement in theoretical uncertainties is needed:
 - accuracy of perturbative predictions
 - size of non-perturbative effects
- An alternative to determine α_s from jets is to use semi-inclusive observables
 - Z bosons produced in hadron collisions recoil against QCD initial-state radiation
 - by momentum conservation, ISR gluons will boost the Z in the transverse plane
 - the Sudakov factor is responsible for the existence of a peak in the Z -boson p_T distribution
 - the position of this peak is sensitive to the value of α_s
- In exclusive observables: large sensitivity to α_s
- In inclusive observables: high accuracy of predictions
- Semi-inclusive observables: have benefits from both types of observables



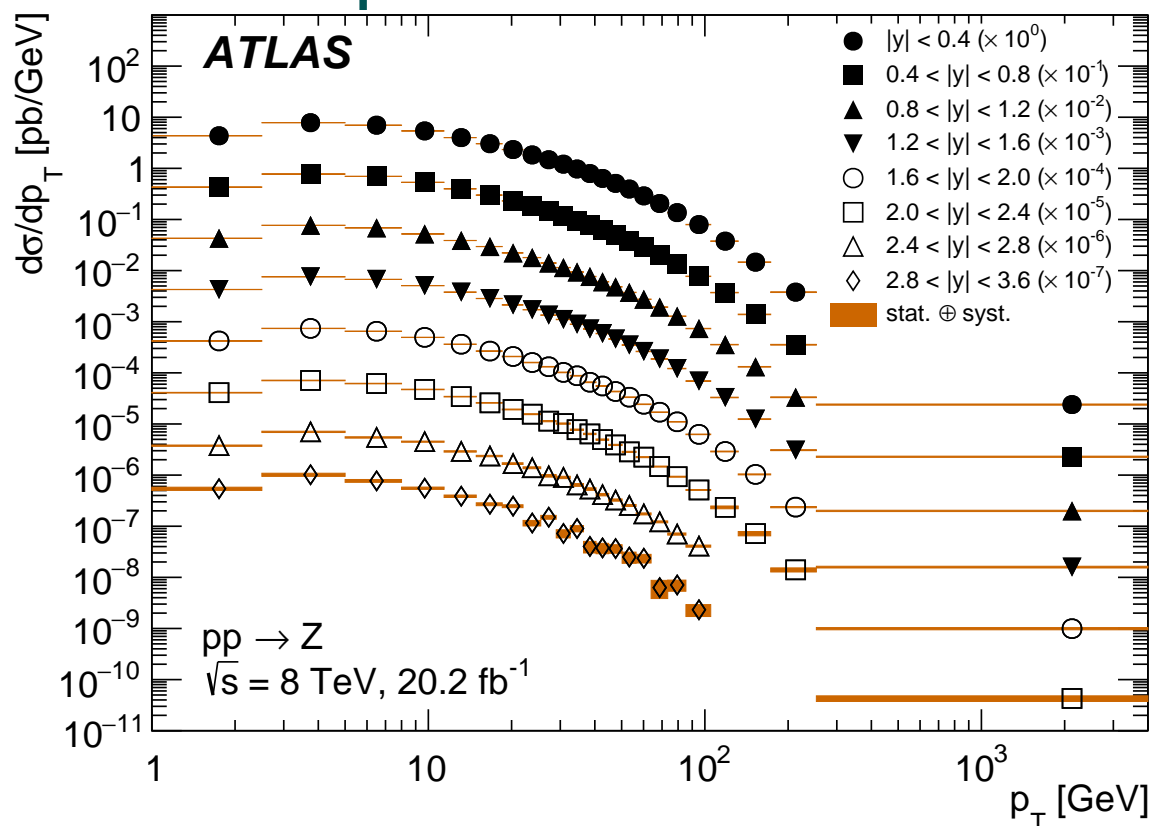
ATLAS Collab, arXiv: 2309.12986

The Z p_T distribution

- The Z p_T distribution was measured in the final state with electron or muon pairs at $\sqrt{s} = 8$ TeV using 20.2 fb^{-1} of Run 1 pp collisions
- Double-differential cross sections as functions of p_T^Z and $|y^Z|$ were measured for $80 < m_{\ell\ell} < 100$ GeV \rightarrow 6.2M electron and 7.8M muon pairs for $|\eta| < 2.4$ (CR) and 1.3M electron pairs with one electron in $2.5 < |\eta| < 4.9$ (FR) and one electron in CR (each lepton with $p_T > 20$ GeV)
- The cross-section measurement relies on the decomposition of the leptons angular distributions in the Collins–Soper frame into 9 spherical harmonic polynomials, multiplied by angular coefficients
- The cross sections in the full lepton phase space are extracted from the data by fitting templates of these polynomials to the measured angular distributions
- **Experimental uncertainties:** below 1% for $|y^Z| < 2$
below 10% for $2 < |y^Z| < 3.6$
dominated by the statistical uncertainties

The Z p_T distribution

- By measuring the cross sections in the full lepton phase space there is no need for the predictions to model the polarisation and decay of the Z boson
 \Rightarrow the determination of α_s is not affected by theoretical uncertainties and ambiguities related to spin correlations



- The phase-space region of $p_T^Z < 29 \text{ GeV}$ and $|y^Z| < 3.6$ was selected for the determination of α_s using 9 bins in p_T^Z for each $|y^Z|$ region

Theoretical predictions for determination of α_s from $Z p_T$

- The theoretical predictions for p_T^Z were calculated using DYTURBO, with resummation of logarithmically enhanced contributions in the low- p_T region at approximate N⁴LLa accuracy, combined with hard-collinear contributions at N³LO, and matched to N³LO, and implementing CDFG QT-resummation (NPB 596 (2001) 299)
→ The resummed cross section is given by the convolution of the LO cross section, the hard-collinear contributions, and the universal (process-independent) Sudakov form factor
S Camarda et al. (EPJ C 80 (2020) 251, PLB 845 (2023) 138125, PRD 104 (2021) L111503)
- The $\mathcal{O}(\alpha_s^3)$ term of the Z +jet cross-section predictions is calculated using MCFM program
- Non-perturbative QCD effects included using a form factor with parameters determined in the fit
- The scales μ_R , μ_F and Q (resummation scale) are set to $\sqrt{m_{\ell\ell}^2 + (p_T^Z)^2}$
- PDF set: N³LO MSHT20 set
- Initial-state photon radiation estimated at LL accuracy using PYTHIA 8 and applied as a multiplicative factor

Determination of $\alpha_s(m_Z)$ from Z p_T distribution

- $\alpha_s(m_Z)$ was determined from the comparison of data and theoretical predictions using the Hessian method

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

where

β_{exp} and β_{th} are NPs corresponding to the correlated experimental and theoretical uncertainties and Γ_{ij}^{exp} and Γ_{ik}^{th} give their correlations
 $\rightarrow \Gamma_{ik}^{\text{th}}$ includes the NPs of the PDF Hessian uncertainties and the parameters of the non-perturbative form factor

$N_{\text{data}} = 72$ data points of the cross sections

σ_i^{exp} are the measurements and Δ_i are the uncorrelated experimental uncertainties; and σ_i^{th} are the theoretical predictions

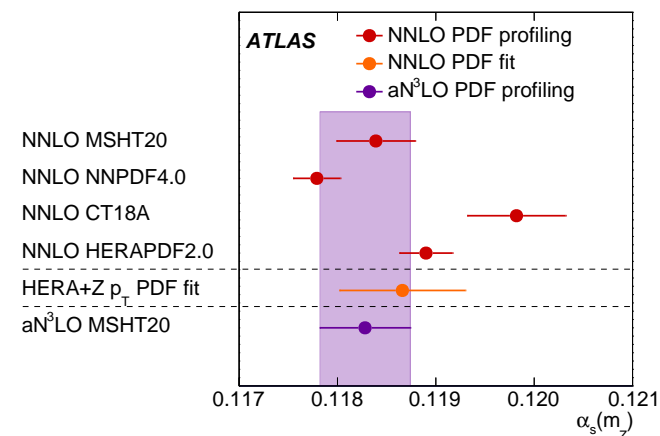
- The same procedure of analytical interpolation as explained before was used in the χ^2 computation (with 7 values in the range $0.114 < \alpha_s(m_Z) < 0.120$) to preserve the correlation between $\alpha_s(m_Z)$ and the PDFs
- In addition, at each value of $\alpha_s(m_Z)$, the PDF uncertainties are Hessian profiled

ATLAS Collab, arXiv: 2309.12986

Values of $\alpha_s(m_Z)$ from $Z p_T$ distribution

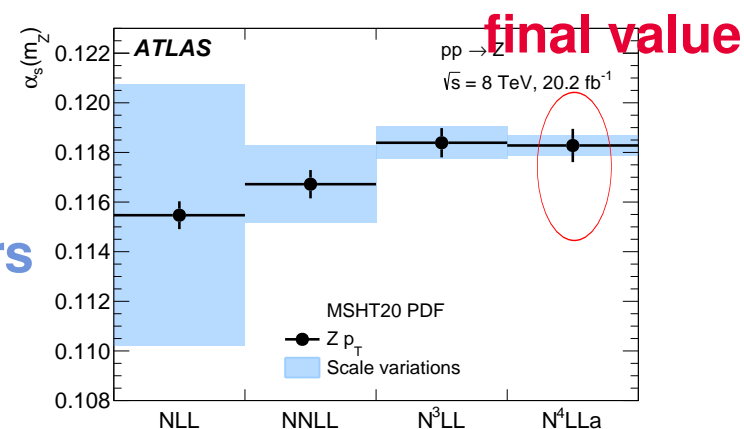
- The final $\alpha_s(m_Z)$ value obtained is: $\alpha_s(m_Z) = 0.1183 \pm 0.0009$
- Values of $\alpha_s(m_Z)$ obtained using different PDF sets (at a lower order):

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]
MSHT20 [37]	0.11839	0.00040	0.44	-0.07
NNPDF4.0 [84]	0.11779	0.00024	0.50	-0.08
CT18A [29]	0.11982	0.00050	0.36	-0.03
HERAPDF2.0 [65]	0.11890	0.00027	0.40	-0.04



- A simultaneous fit of the PDFs, the non-perturbative parameters and $\alpha_s(m_Z)$ using HERA data and the $Z p_T$ distribution gives $\alpha_s(m_Z) = 0.11866 \pm 0.00064$, in agreement with the Hessian profiling result

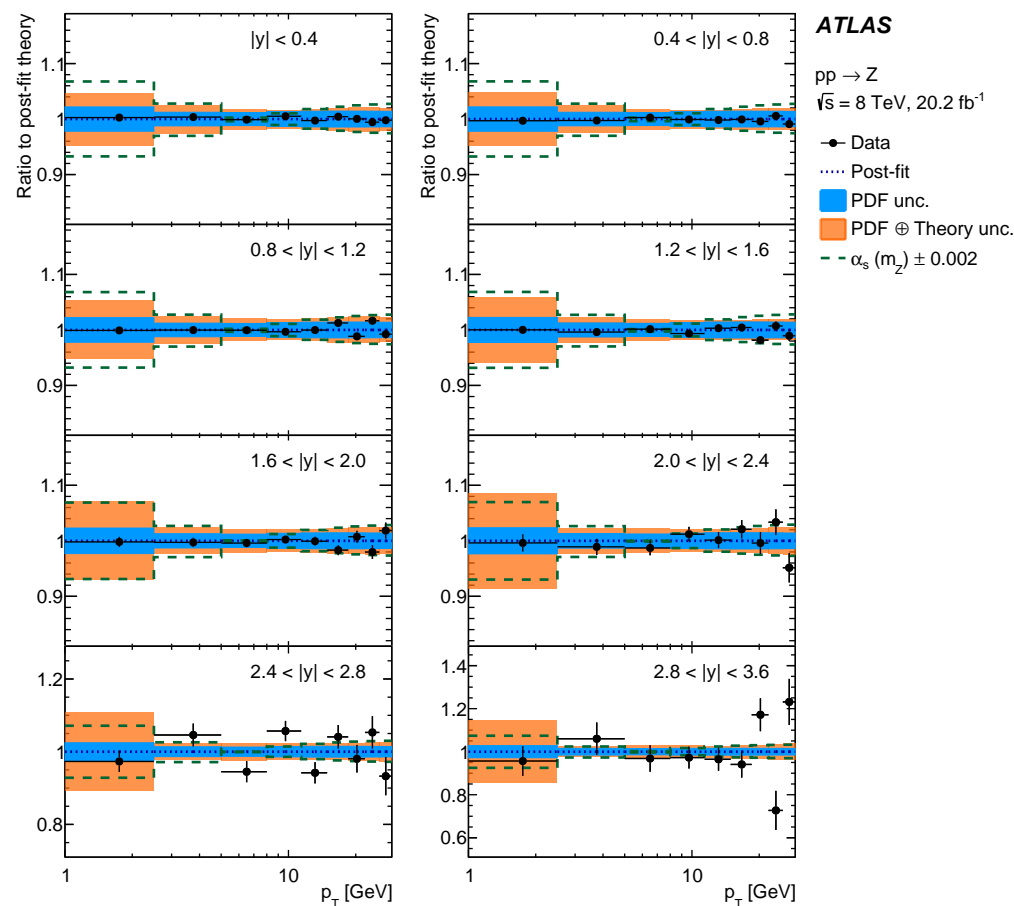
- $\alpha_s(m_Z)$ extracted at different orders:
 \Rightarrow at every order, the uncertainty from higher orders overlaps with the determinations of $\alpha_s(m_Z)$ at the following order



Z p_T measurements vs fixed-order QCD predictions

- Ratio of data and predictions using the extracted $\alpha_s(m_Z)$ value

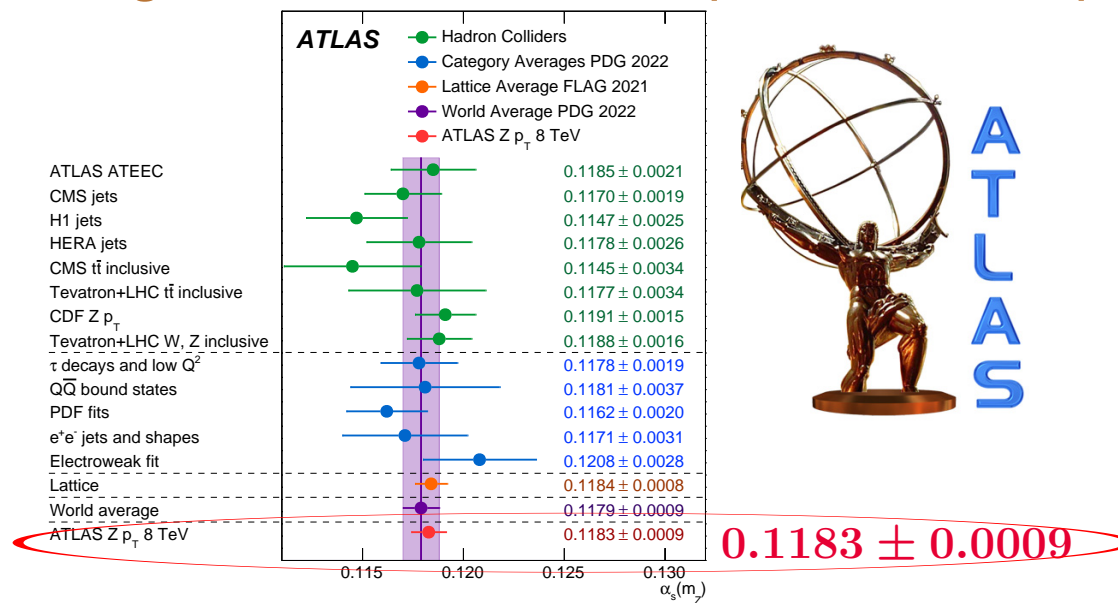
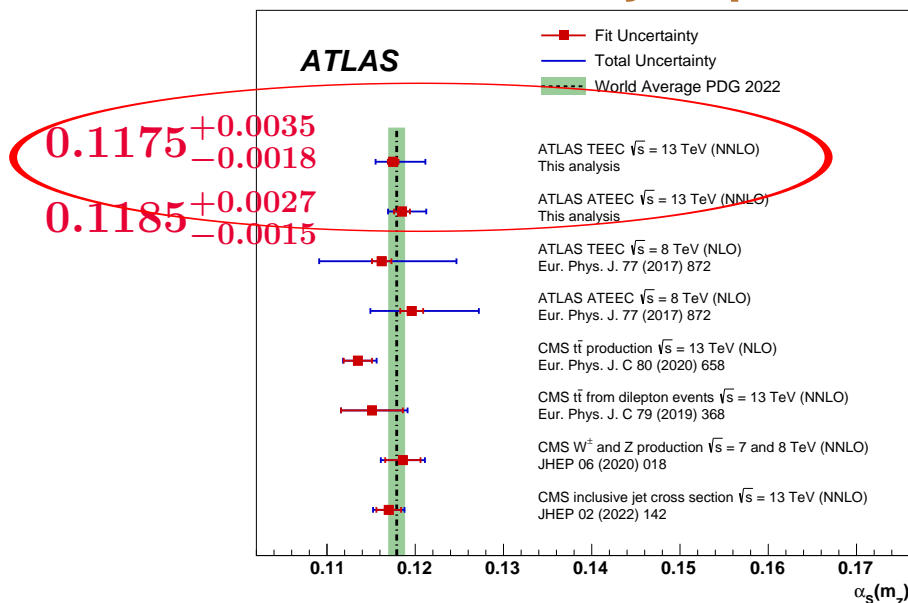
$$\alpha_s(m_Z) = 0.1183 \pm 0.0009$$



Summary

Recent determinations of α_s from ATLAS

- Very precise determinations of $\alpha_s(m_Z)$ are now obtained in hadron colliders
 - very precise measurements of **exclusive** and **semi-inclusive** observables
 - increased accuracy of predictions with higher-order corrections (**N²LO** & **N⁴LLa**)



⇒ The $\alpha_s(m_Z)$ values from these observables are in good agreement and consistent with the current world average

⇒ The test of the energy-scale dependence of α_s is extended to larger scale values

