

Strong coupling from Z-boson and multijet production: Two complementary ATLAS determinations of α_s



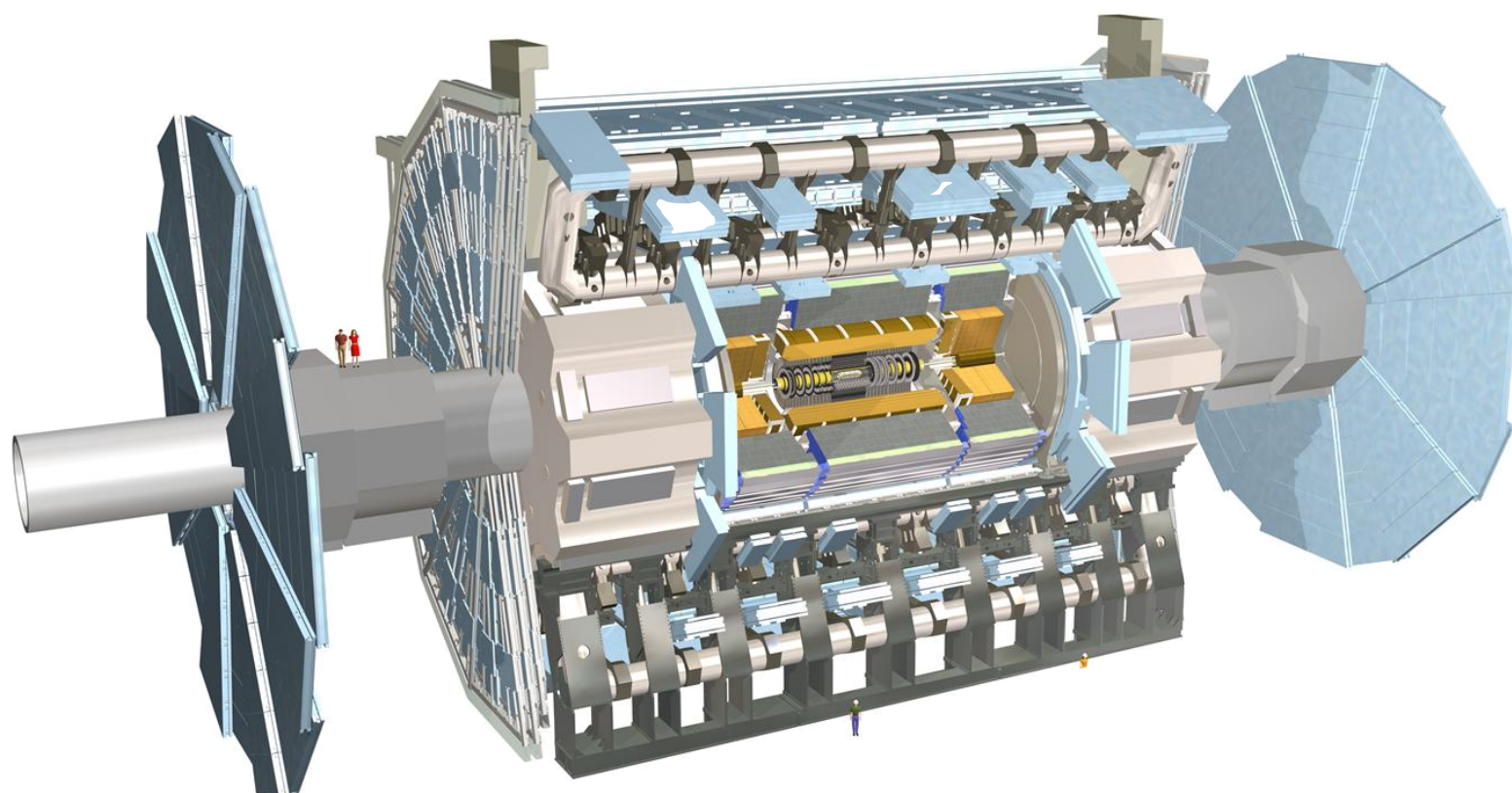
QCD@LHC - Oxford 2026



Laura Fabbri

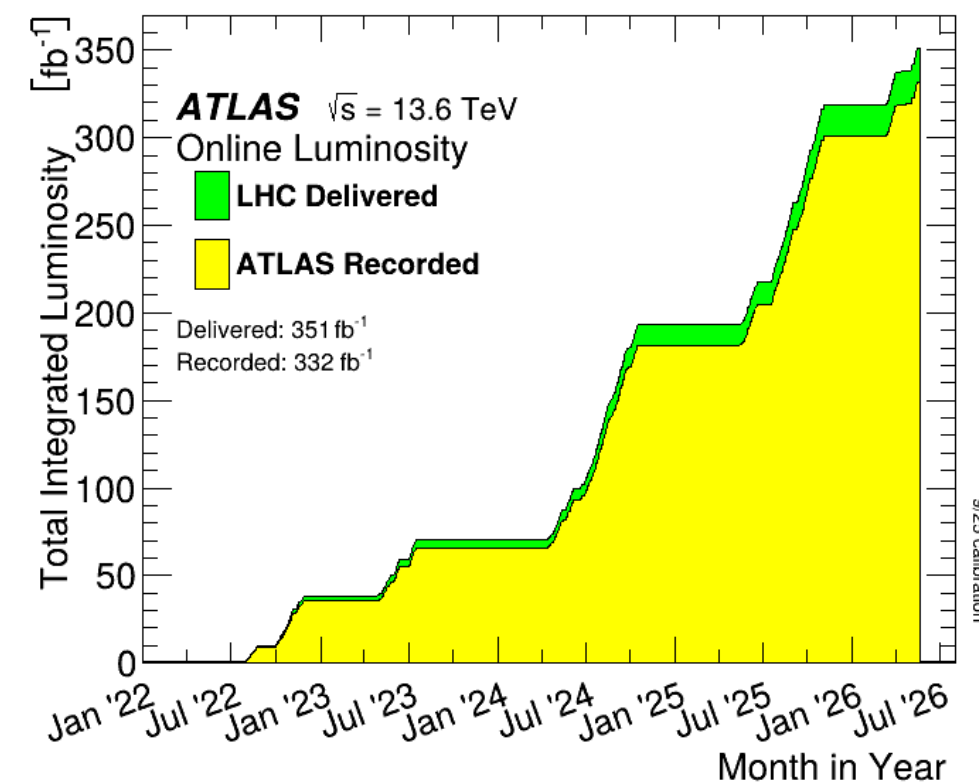
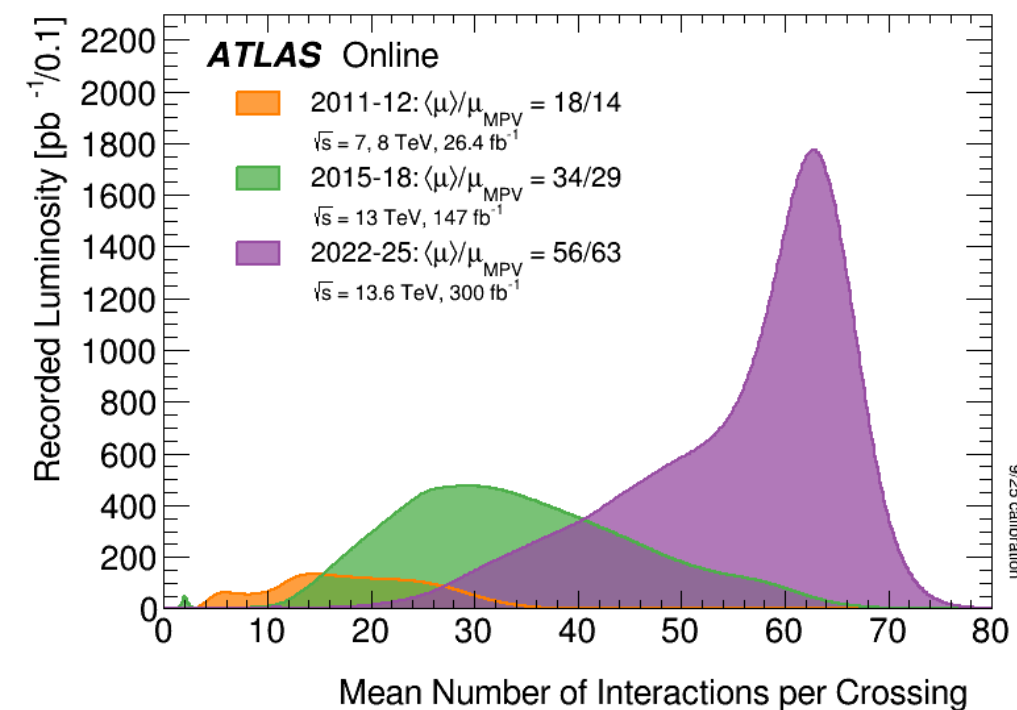
INFN and University of Bologna
on behalf of the ATLAS Collaboration

ATLAS Experimental Status



Record Run 3 luminosity

- unprecedented dataset for precision measurements and discoveries
- ATLAS outstanding data-taking efficiency



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3>

The vast physics program

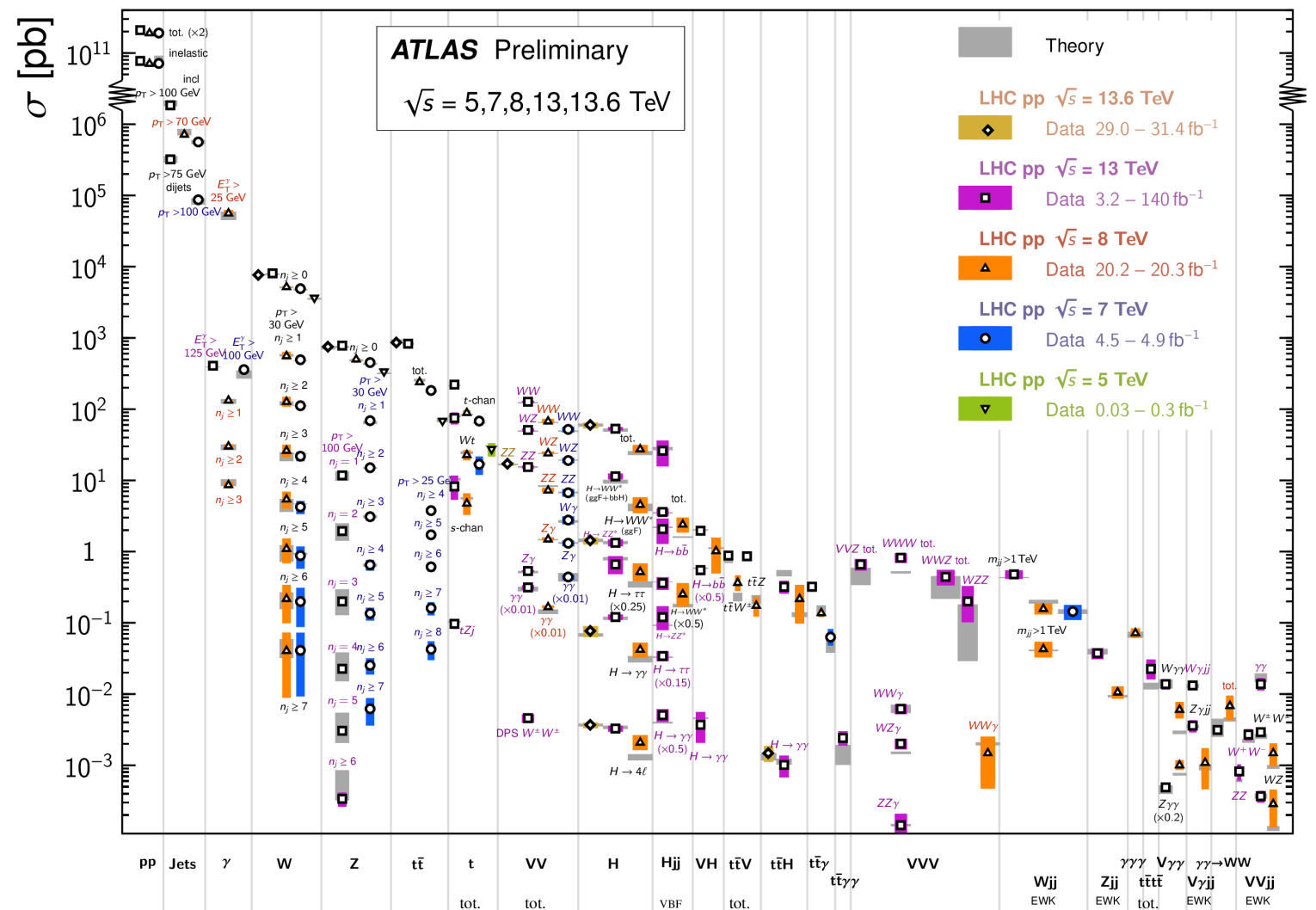
Is the most ambitious and successful physics program

The huge dataset available and the well understood detector performance allow:

- precision measurements
- access to rare processes
- wide search program at/ beyond the TeV scale
- study of new states of matter

Standard Model Production Cross Section Measurements

Status: July 2026



Precision QCD with Z-boson and multijet production:
measuring α_s and testing its running up to the TeV scale

Motivation

α_s underpins precision across LHC physics

$$\mu^2 \frac{d\alpha_s}{d\mu^2} = \beta(Q) < 0$$

asymptotic freedom

The running is predicted by the renormalisation-group equation.

Its value at one reference scale (Q) must be determined experimentally.

The uncertainty propagates into essentially all perturbative LHC cross sections.

PDG 2025

$$\alpha_s(m_Z) = 0.1180 \pm 0.0009$$

The value is measured; its evolution is a QCD prediction

Two observables probe complementary regimes

Z recoil

initial-state radiation

colour-neutral final state

low- p_t Sudakov region

scale fixed near m_Z

precision

Multijet TEEC / ATEEC

final-state energy flow

infrared- and collinear-safe

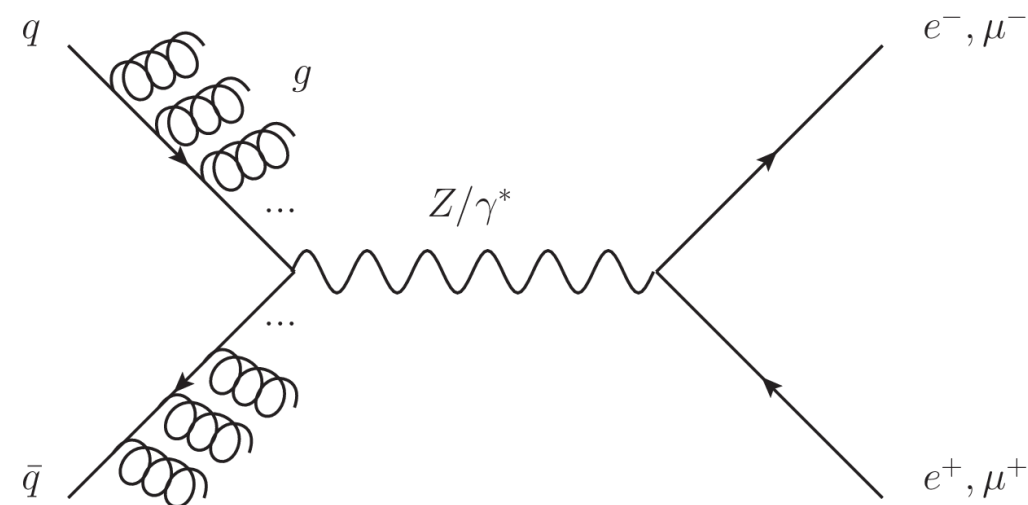
NNLO three-jet predictions

$Q \approx 0.5\text{--}2$ TeV

running

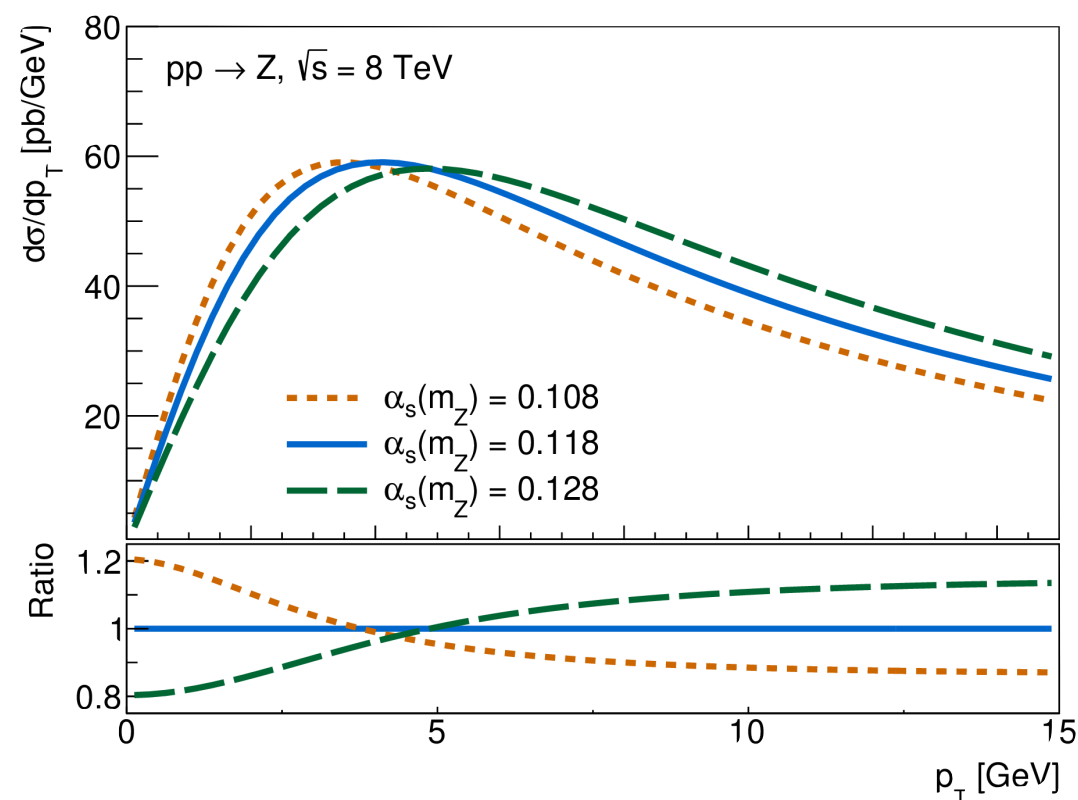
Z recoil turns soft initial-state radiation into an α_s analyser

The leptons do not carry colour.
Soft gluon emission gives the Z
boson transverse recoil.
The hardness of the p_T spectrum
tracks the strength of α_s .



QCD radiation is inferred from a clean electroweak final state.

The low- p_t spectrum is directly sensitive to α_s



$\Delta \pm 0.010$ variation

visibly changes both the peak position and the tail

Fit region

$0 < p_t^Z < 29$ GeV

15.3 million e^+e^- and $\mu^+\mu^-$ pairs

[arXiv:2309.12986](https://arxiv.org/abs/2309.12986)

Z Recoil: analysis strategy

MEASUREMENT

$d^2\sigma / dp_t dy$
8 rapidity regions
full lepton phase
space

PREDICTIONS

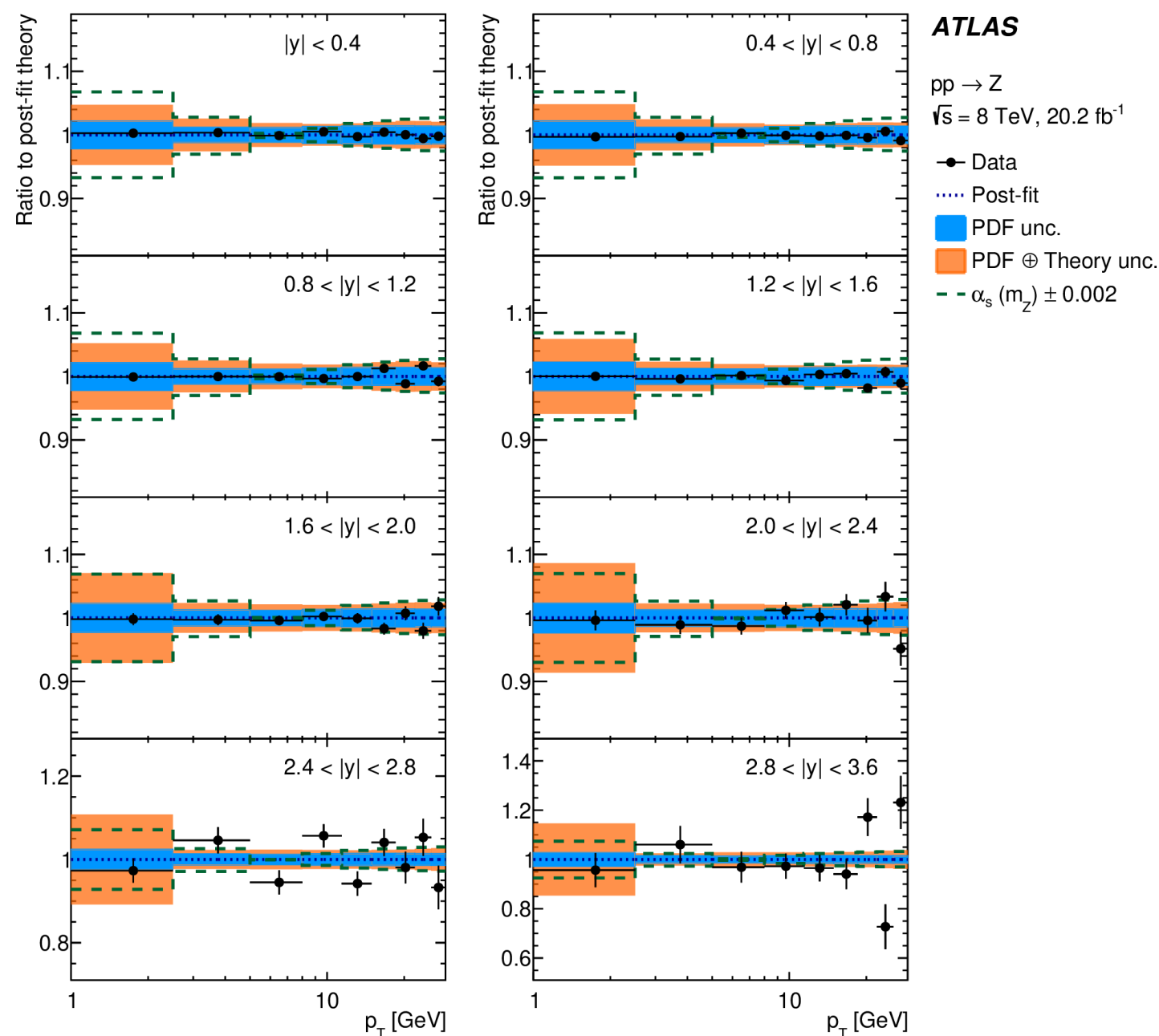
$N^4LL + N^3LO$
approx. N^3LO PDFs
non-perturbative
form factor

PROFILE FIT

experimental
systematics
PDF nuisance
parameters
non-perturbative
parameters

One coherent fit extracts α_s while propagating experimental and theory correlations

Post-fit theory agrees across rapidity bins



82 / 72

$\chi^2 / \text{data points}$

p-value = 0.20

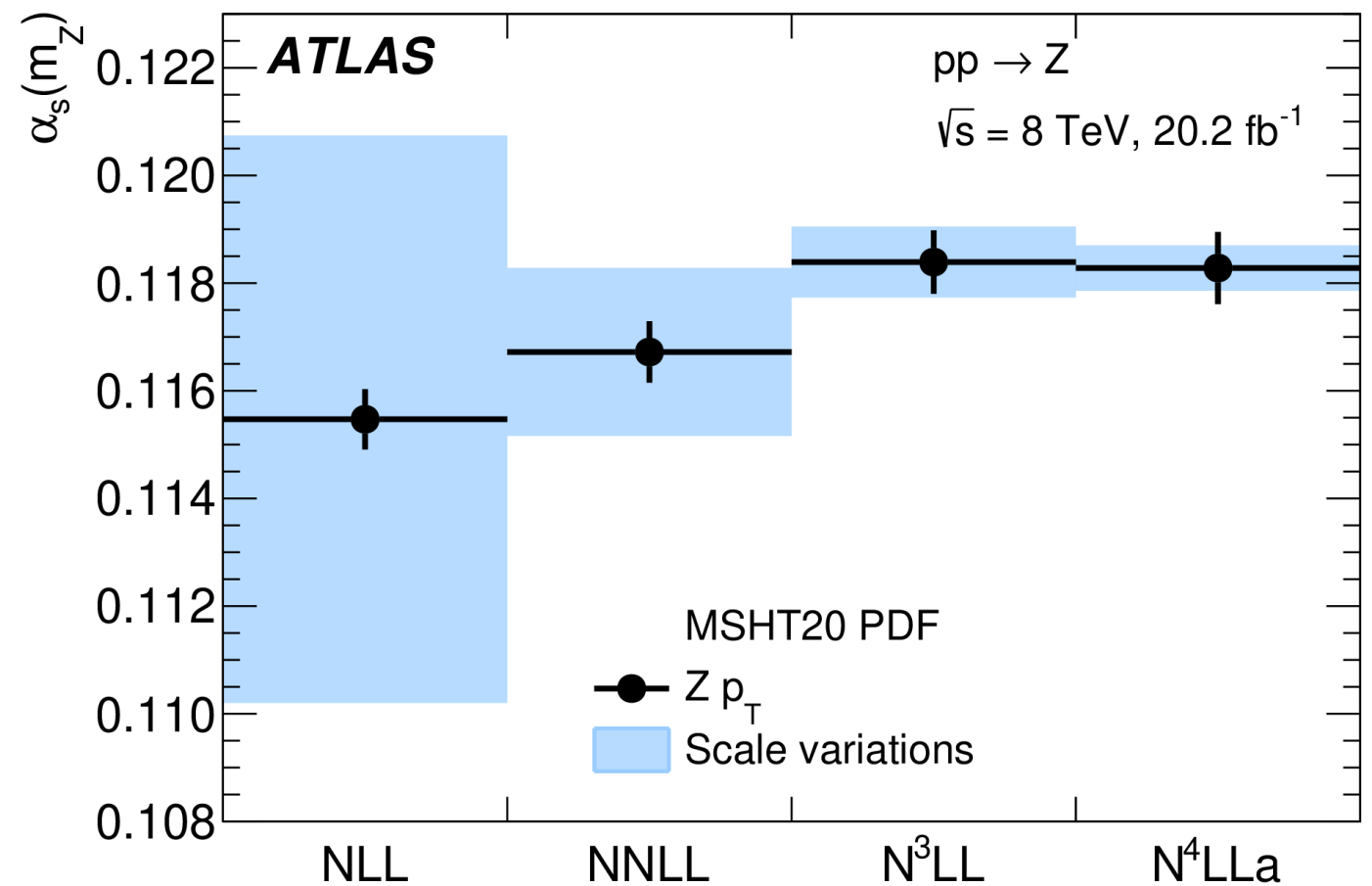
No significant rapidity-dependent tension in the fitted region

Higher orders stabilise the extracted coupling

NLL $\rightarrow$ N⁴LL

central values converge
scale-variation bands shrink
successive estimates
remain compatible

**This is the perturbative control
needed for a sub-percent extraction**



[arXiv:2309.12986](https://arxiv.org/abs/2309.12986)

Z Recoil: results 1/2

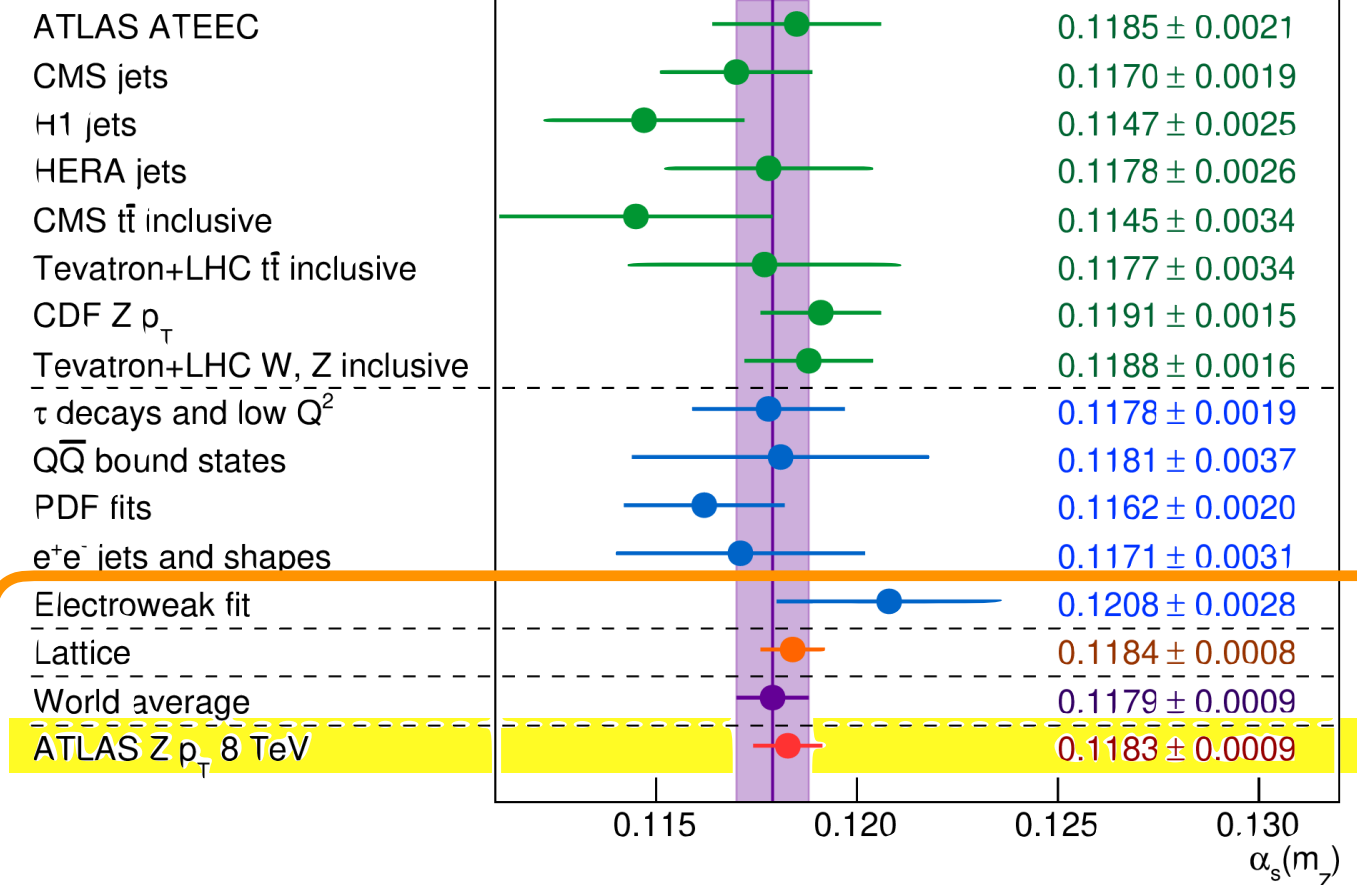
$\alpha_s(m_Z)$

0.1183 ± 0.0009

0.8% relative precision

[arXiv:2309.12986](https://arxiv.org/abs/2309.12986)

Dominant contributions [$\times 10^{-3}$]



Energy–energy correlations map multijet radiation

TEEC

$$\sum_{i,j} xT_i xT_j \delta(\cos\varphi - \cos\varphi_{ij})$$

transverse-energy-weighted angular correlations between jet pairs

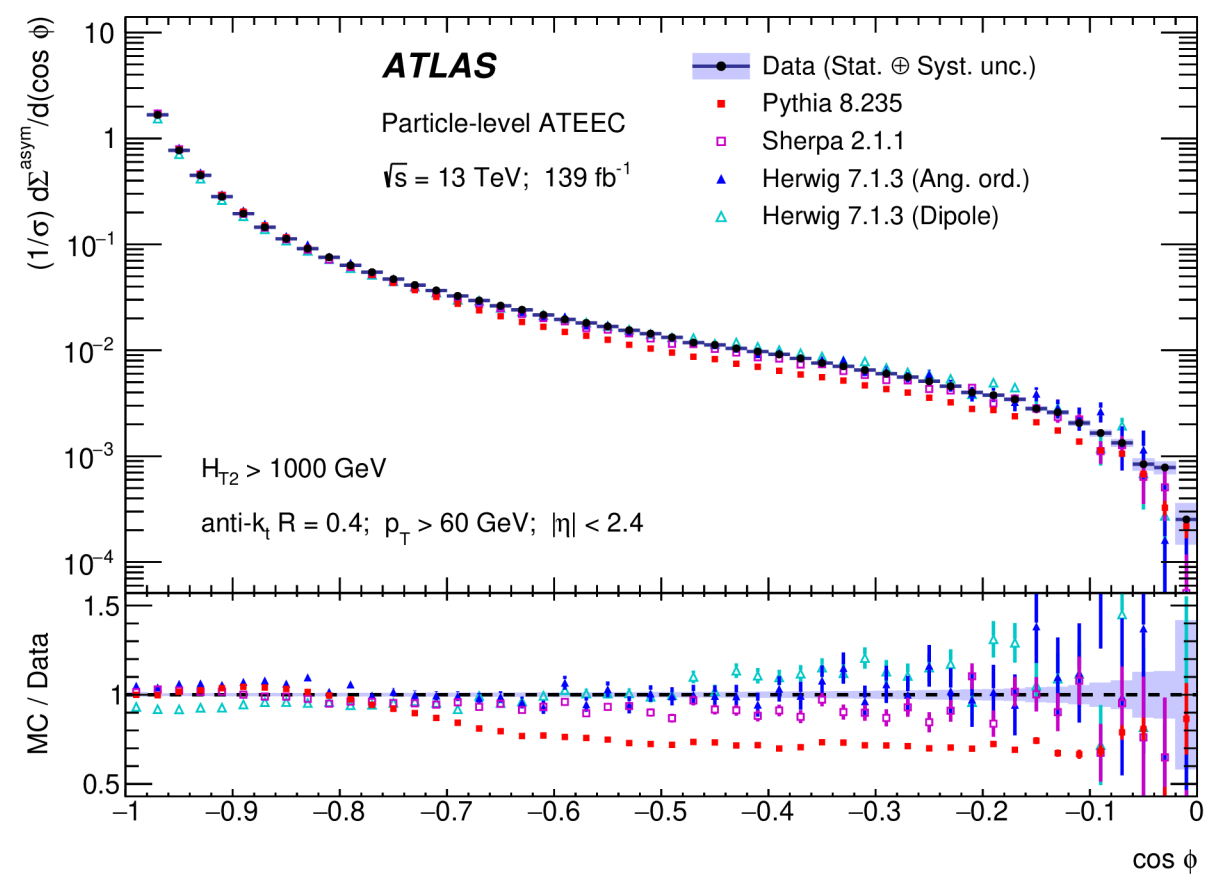
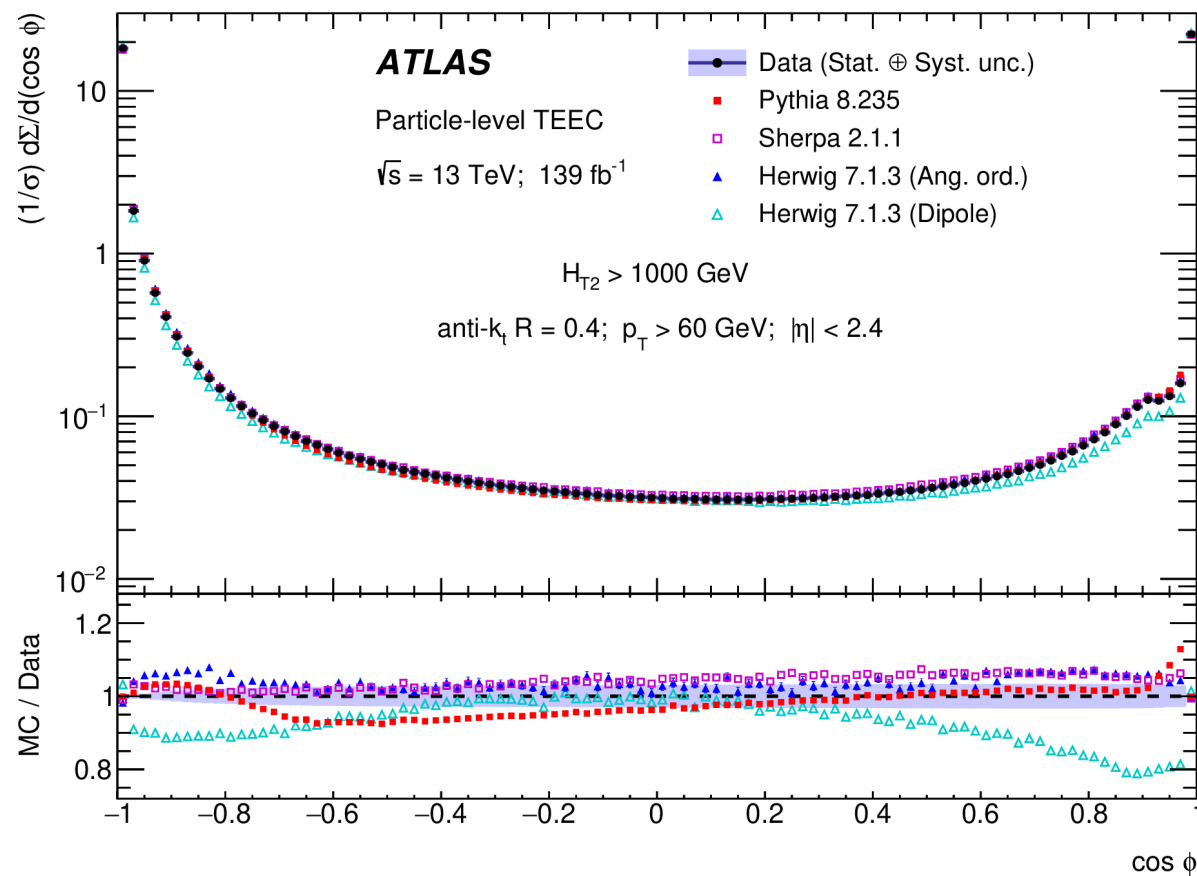
ATEEC

$$\text{TEEC}(\cos\varphi) - \text{TEEC}(-\cos\varphi)$$

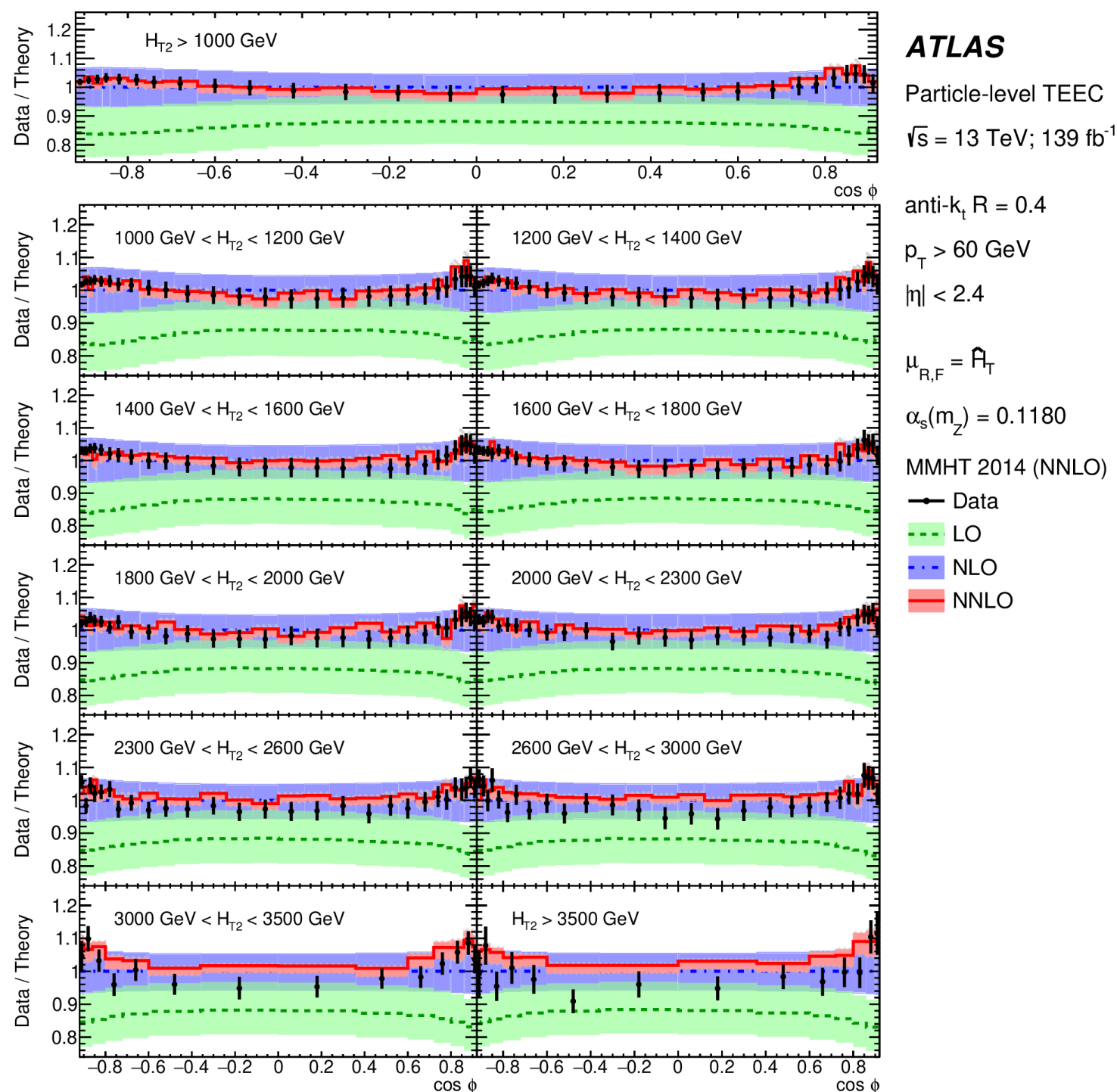
cancels contributions symmetric in $\cos\varphi$ and reduces correlated uncertainties

Scale handle: $H_{T2} = p_t(\text{jet 1}) + p_t(\text{jet 2}) > 1 \text{ TeV}$

MC: PYTHIA8, SHERPA, HERWIG7(angular order or dipole radiation PS)



NNLO brings the multijet prediction onto the data



LO

large normalisation offset

NLO

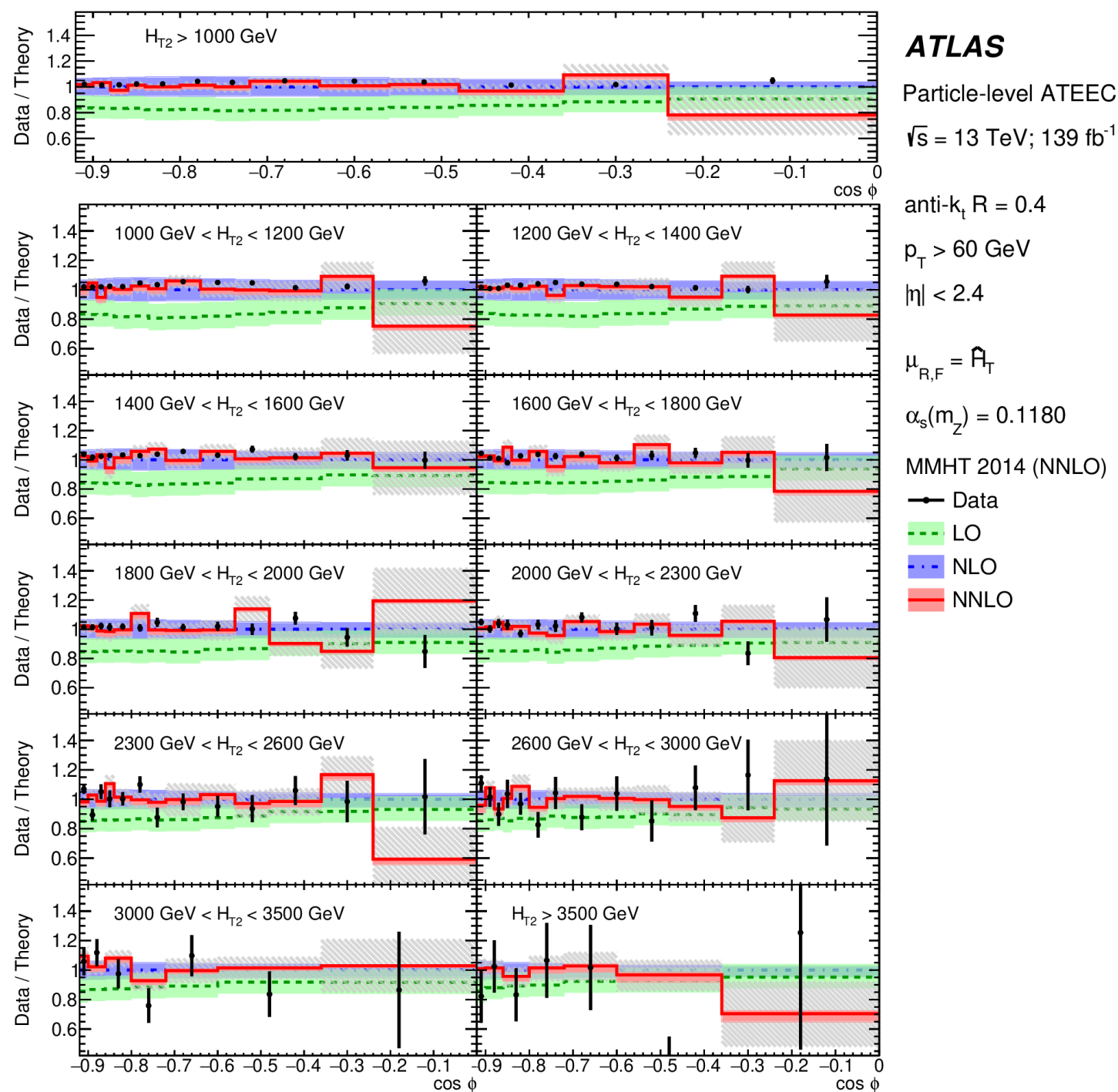
closer, but broad scale bands

NNLO

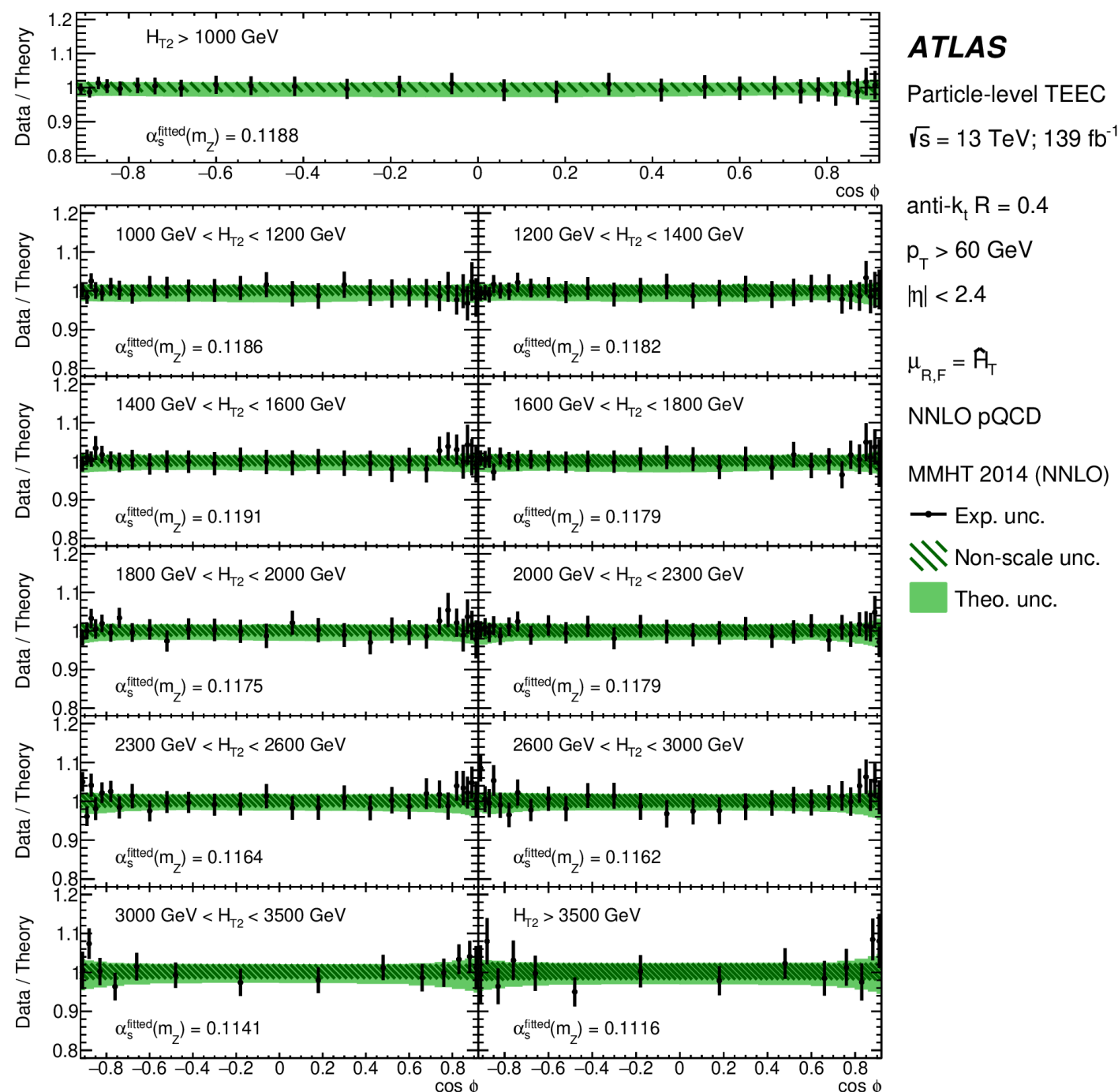
excellent agreement;
theory uncertainty
reduced by a factor 3

$$\sigma^{exp} < \sigma^{th}$$

NNLO brings the multijet prediction onto the data



Fits remain consistent across H_{T2} intervals



11 kinematic regions

one inclusive bin

ten exclusive H_{T2} bins

full covariance retained

scale uncertainty remains dominant

Each bin becomes a measurement of $\alpha_s(Q)$

TEEC and ATEEC global fits agree

TEEC

0.1175

± 0.0006 (exp.)
 $+0.0034 / -0.0017$ (theo.)

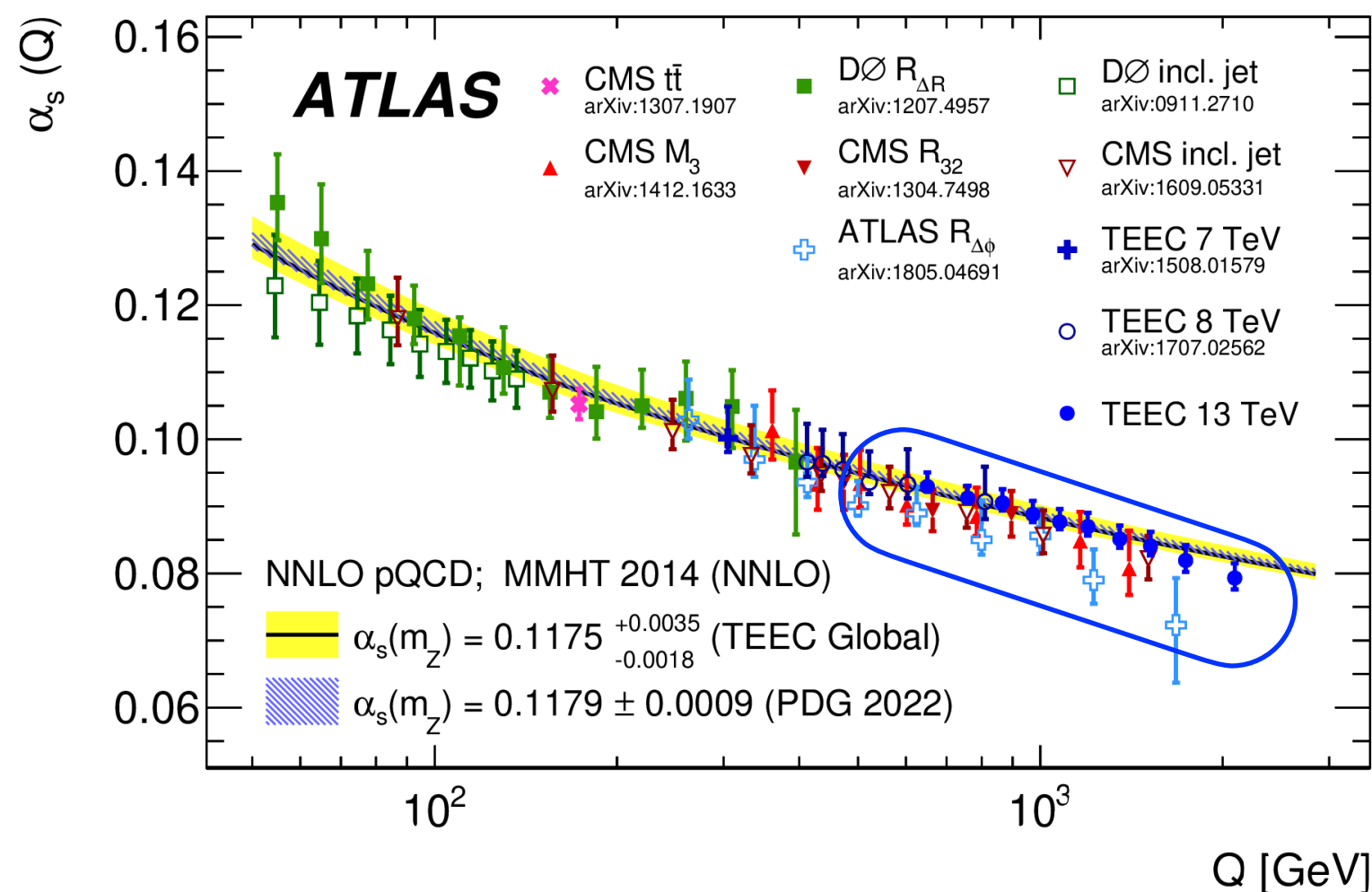
ATEEC

0.1185

± 0.0009 (exp.)
 $+0.0025 / -0.0012$ (theo.)

Experimental precision is already high; missing higher orders set the total uncertainty.

The running follows the RGE beyond 1 TeV



$Q \gtrsim 1$ TeV

directly tested with
the 13 TeV TEEC data

No deviation from the
NNLO RGE evolution
is observed.

At m_Z and TeV scales, QCD remains consistent

Z recoil

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

clean initial-state probe
sub-percent precision

Multijet TEEC / ATEEC

$\alpha_s(Q)$ tested to the TeV scale

NNLO precision
direct test of the running

Different observables. Different systematics. Mutually consistent results.

At m_Z and TeV scales, QCD remains consistent

Z recoil

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

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Multijet TEEC / ATEEC

$\alpha_s(Q)$ tested to the TeV scale

NNLO precision
direct test of the running

Different observables. Different systematics. Mutually consistent results.

Thanks for your attention

BACKUP

Precise determination of $\alpha_s(m_Z)$

BACKSTORY:

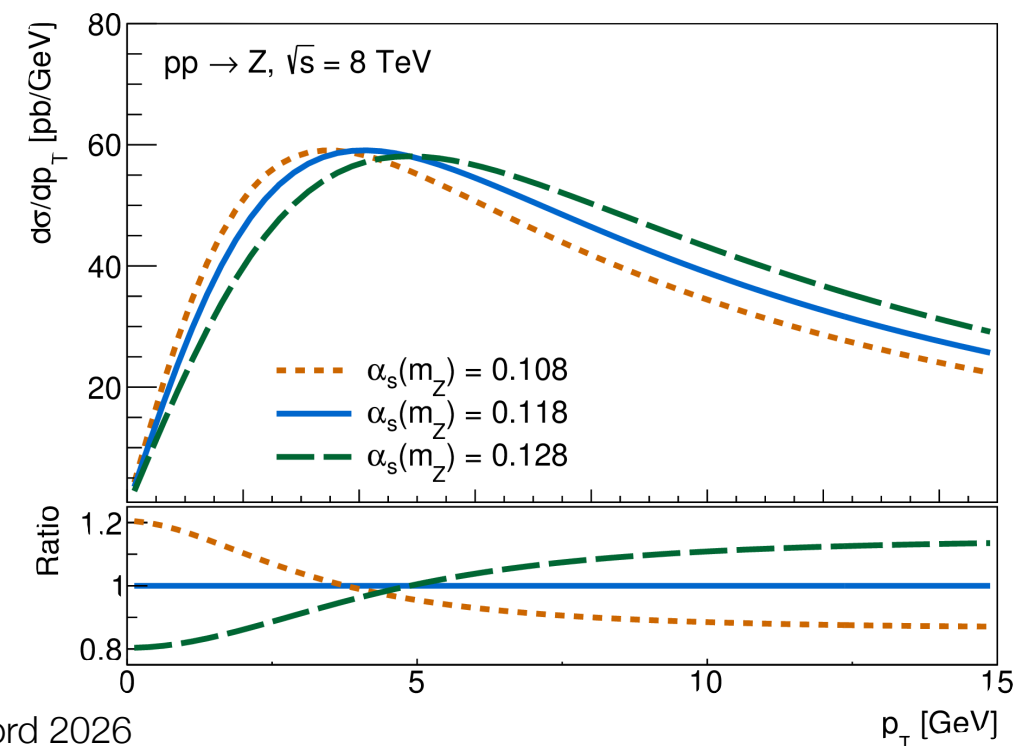
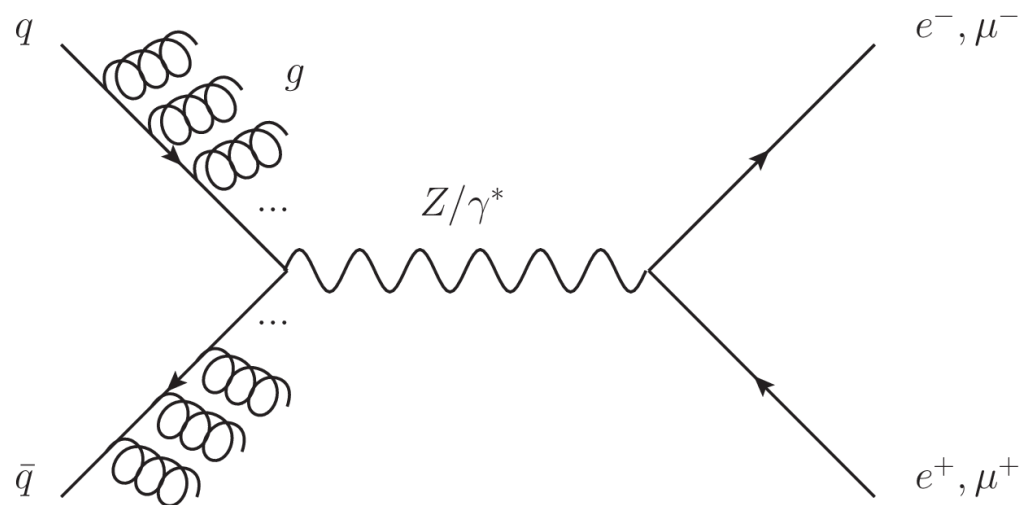
- ▶ $\alpha_s(Q)$ uncertainty is orders of magnitude larger than $\alpha_{EM}(Q), \alpha_W(Q) \dots$
- ▶ The most precise determinations are based on lattice QCD analysis

IMPROVEMENTS: determination performed at N3LO in QCD limited by exp unc.; simultaneously determination of PDFs

ANALYSIS: Drell-Yan process measured in the low-momentum Sudakov region

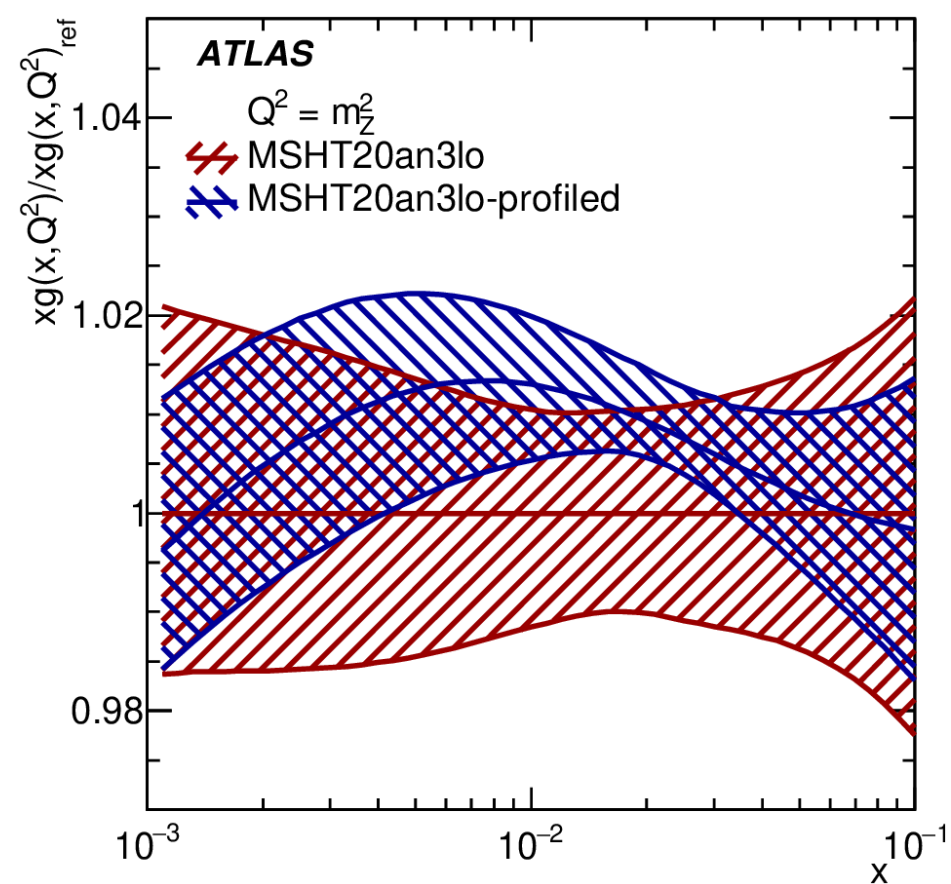
➡ high probability of ISR

➡ Z recoil, $p_{T,Z} \neq 0$

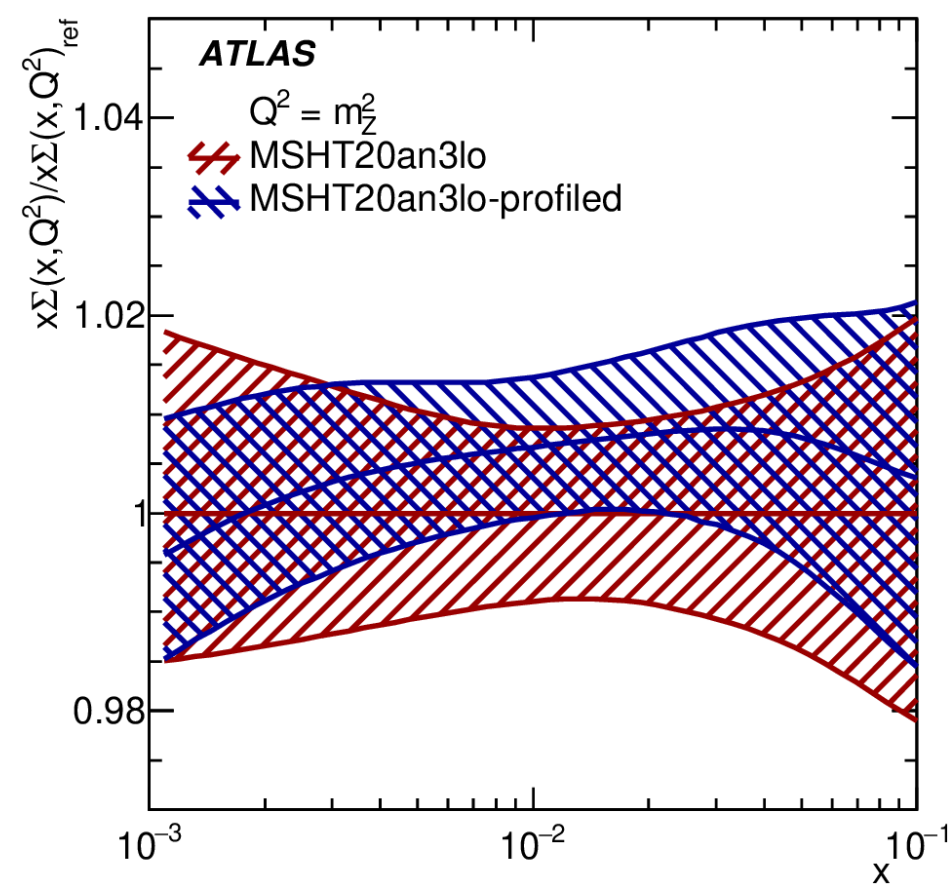


arXiv:2309.12986

GLUON



SEA-Q



[arXiv:2309.12986](https://arxiv.org/abs/2309.12986)

Multijet energy-energy correlation

GOALS: extraction of $\alpha_s(Q) \rightarrow$ precision test of QCD at large Q and sensitivity to gluon radiation

IMPROVEMENTS: $\sqrt{s}=13\text{TeV}$, first comparison with NNLO pQCD predictions

ANALYSIS: dataset: $139 \text{ fb}^{-1} \sqrt{s}=13 \text{ TeV}$

all details

[JHEP07 \(2023\) 085](#)

- ▶ trigger 1 jet with $p_T > 460 \text{ GeV}$;
 - ▶ ≥ 2 jets anti-kt algorithm with $R = 0.4$ with $p_T > 60 \text{ GeV}$ and $|\eta| < 2.4$
 - ▶ $H_{T2} = p_{T1} + p_{T2} > 1 \text{ TeV}$
- ➔ $Y = 57.5 \text{ M events}$

MEASUREMENTS:

- Transverse energy-energy correlations (TEEC): inclusive and vs H_{T2} bins
- Azimutal TEEC asymmetries (ATEEC): inclusive and vs H_{T2} bins
- $\alpha_s(m_Z)$ obtained by fitting TEEC and ATEEC

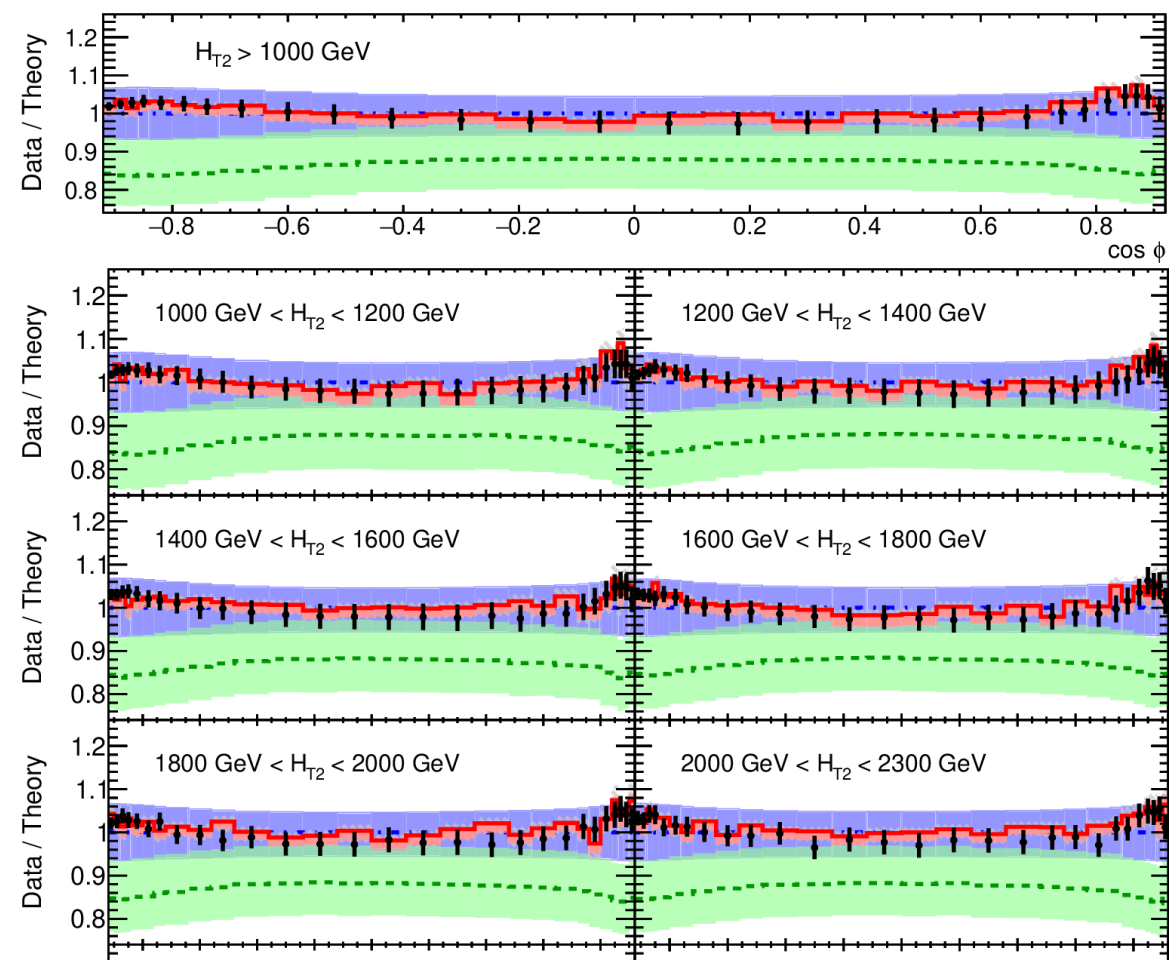
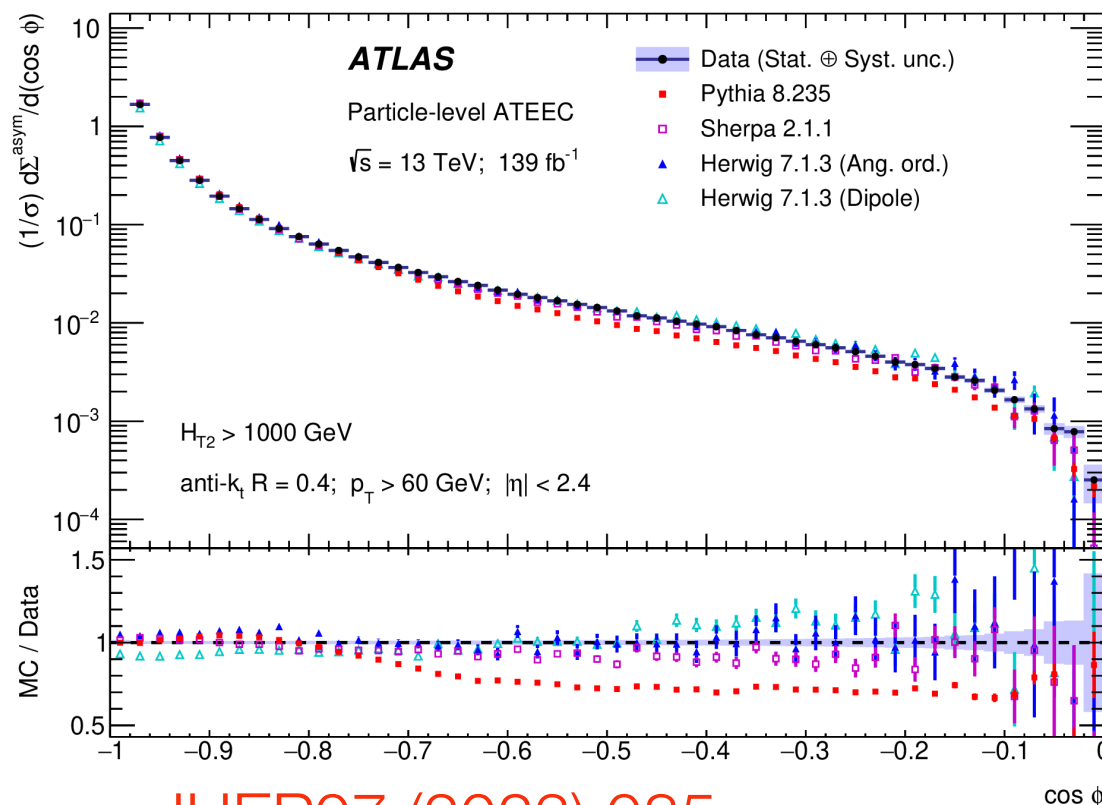
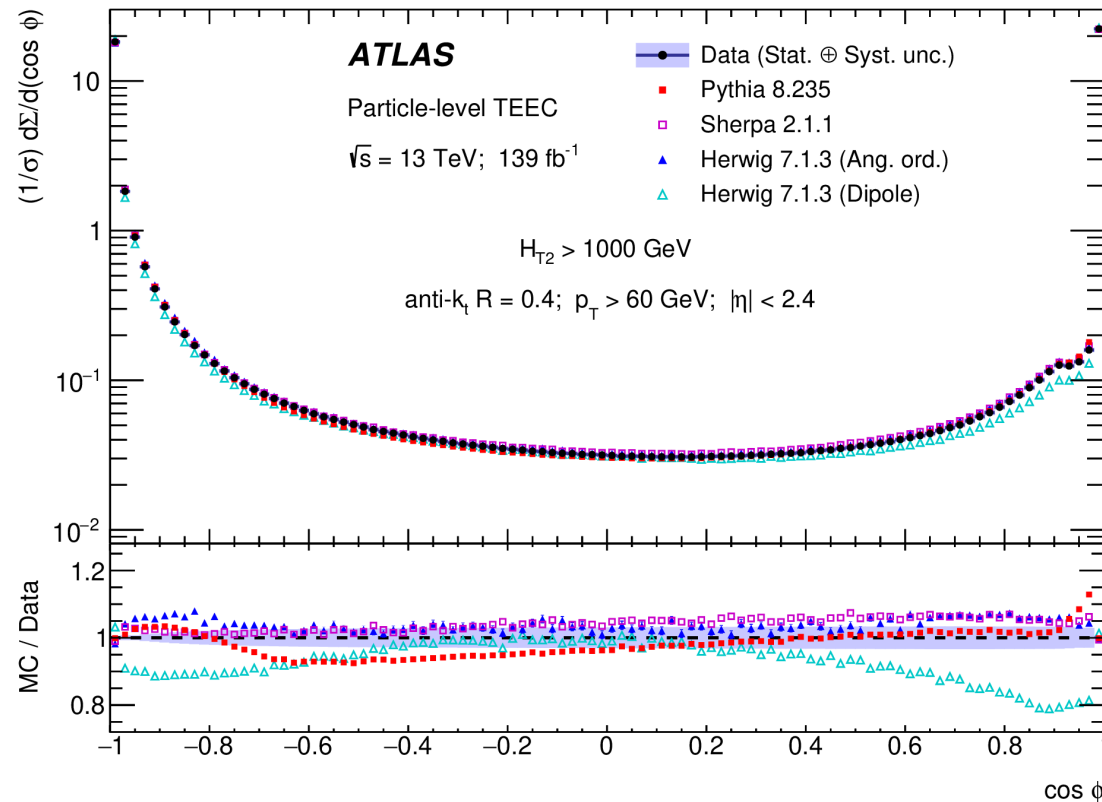


Multijet energy-energy correlation: Results

- MC: PYTHIA8, SHERPA, HERWIG7(angular order or dipole radiation PS)
- NNLO corrected for non-perturbative effects such as hadronisation and multiple parton interactions

$$\sigma^{exp} < \sigma^{th}$$

EXCELLENT AGREEMENT



ATLAS
Particle-level TEEC
 $\sqrt{s} = 13 \text{ TeV}; 139 \text{ fb}^{-1}$
anti- k_t $R = 0.4$
 $p_T > 60 \text{ GeV}$
 $|\eta| < 2.4$
 $\mu_{R,F} = \hat{P}_T$
 $\alpha_s(m_Z) = 0.1180$
MMHT 2014 (NNLO)

The strong coupling constant

$\alpha_s(m_Z)$ obtained by fitting (χ^2) TEEC and ATEEC in each $(H_{T2}, \cos \phi)$ bin

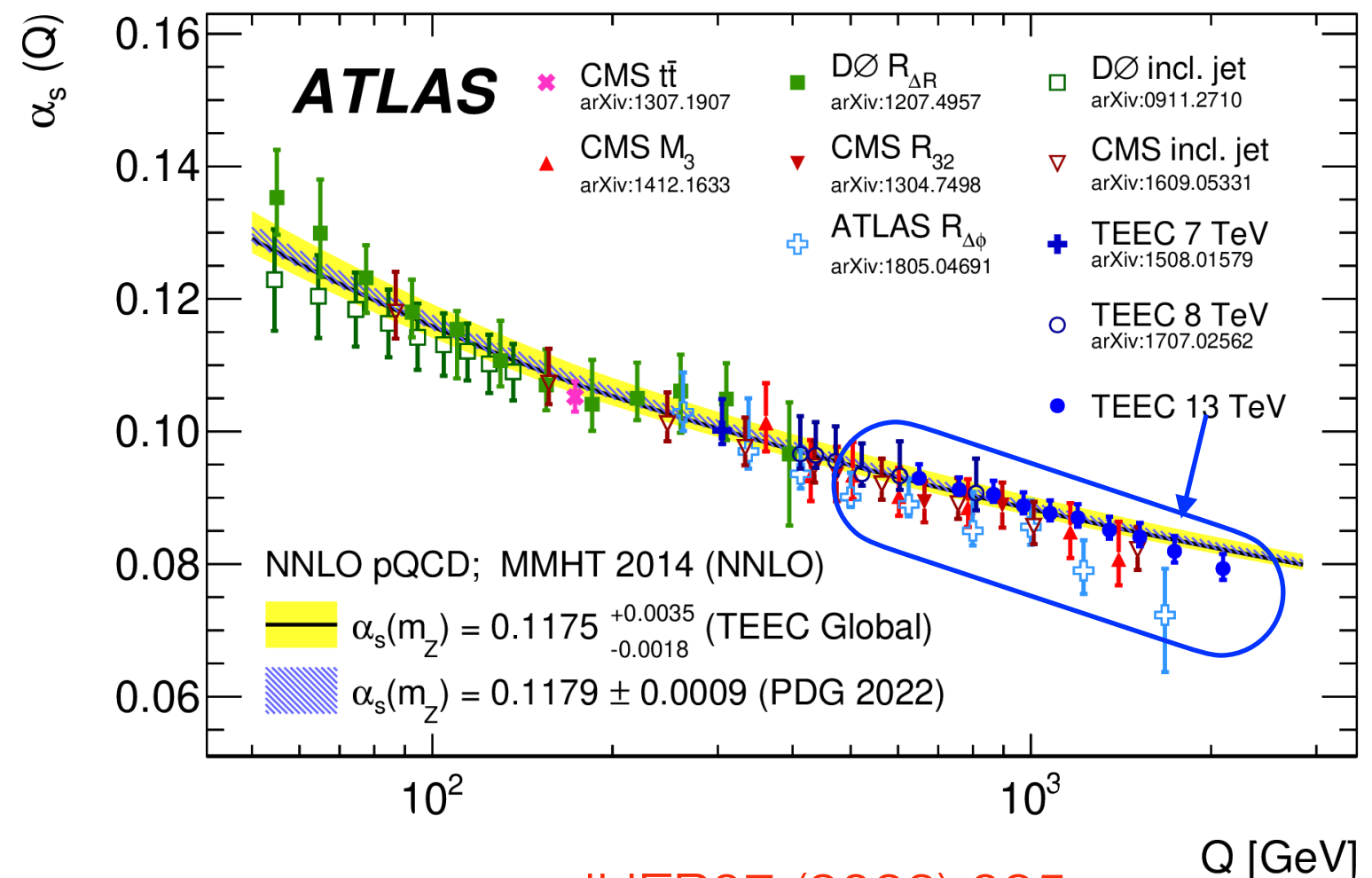
TEEC $\alpha_s(m_Z) = 0.1175 \pm 0.0006 \text{ (exp.)}^{+0.0034}_{-0.0017} \text{ (theo.)}$

ATEEC $\alpha_s(m_Z) = 0.1185 \pm 0.0009 \text{ (exp.)}^{+0.0025}_{-0.0012} \text{ (theo.)}$

NNLO corrections to 3jets

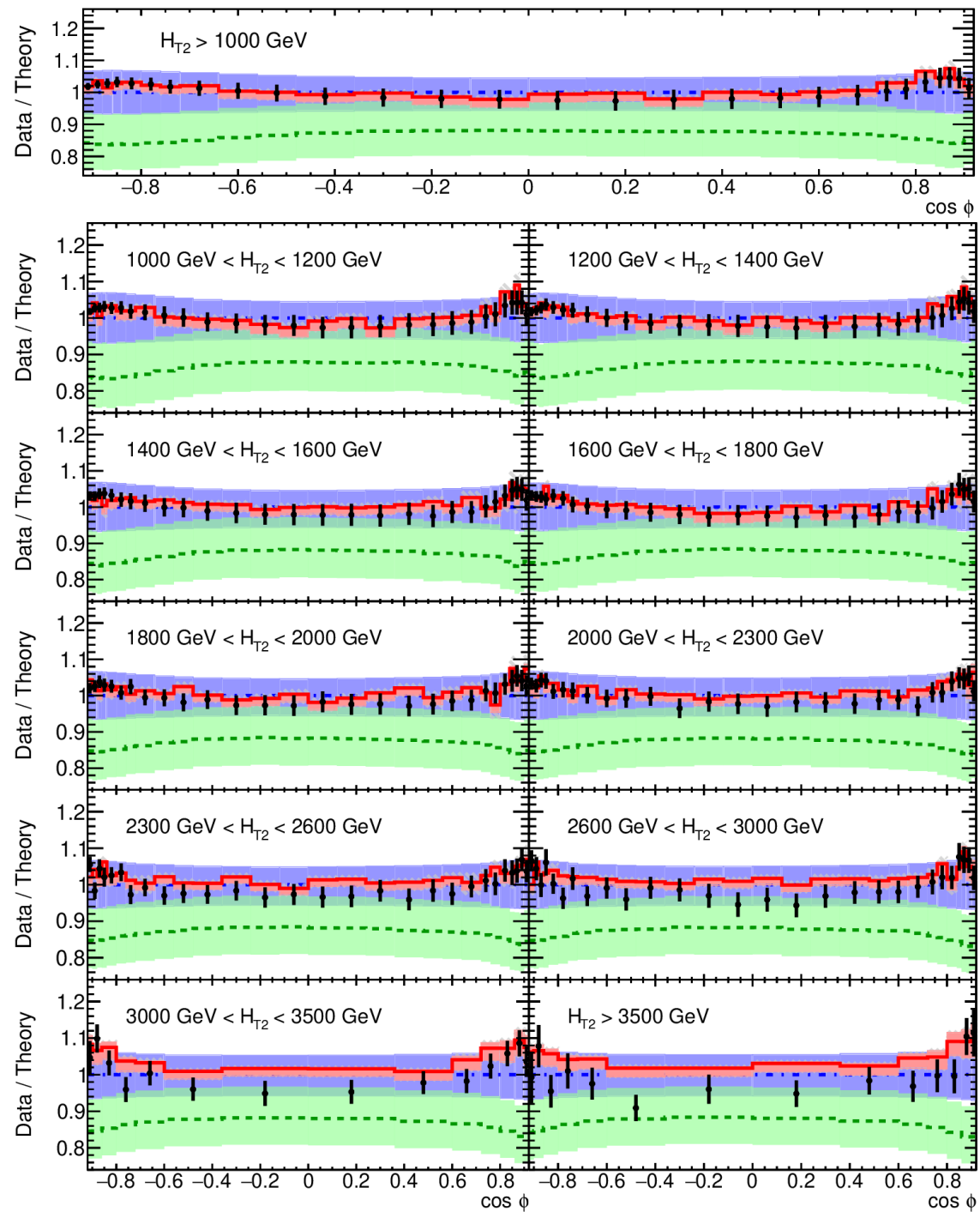
$\Rightarrow \sigma_{\text{theo}}$ reduced by a
factor 3

**Test of the
asymptotic behaviour
of QCD wrt RGE**

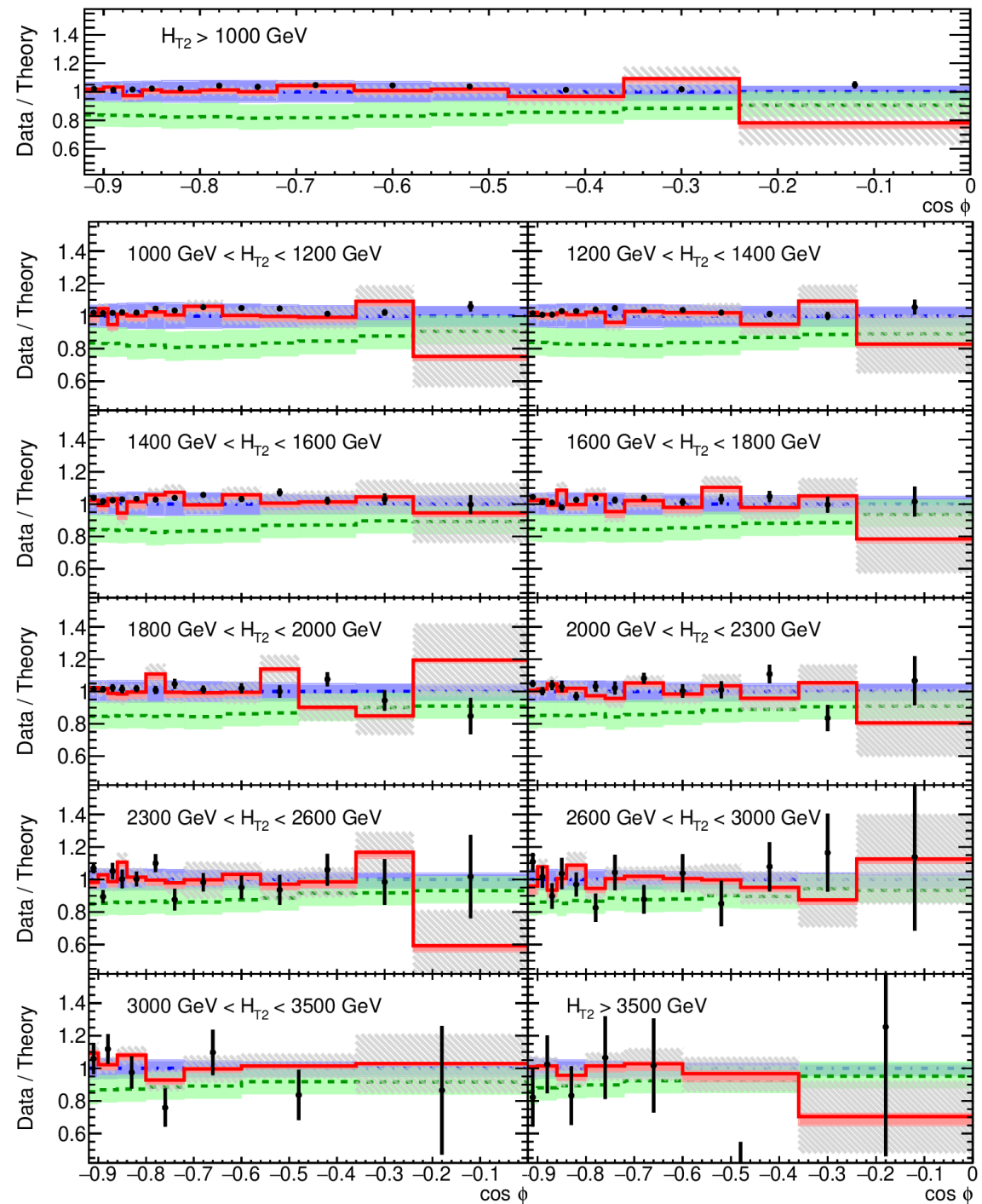


Multijet energy-energy correlation: Results

TEEC



ATEEC



ATLAS

Particle-level ATEEC

$\sqrt{s} = 13 \text{ TeV}; 139 \text{ fb}^{-1}$

anti- k_t $R = 0.4$

$p_T > 60 \text{ GeV}$

$|\eta| < 2.4$

$\mu_{R,F} = \hat{p}_T$

$\alpha_s(m_Z) = 0.1180$

MMHT 2014 (NNLO)

— Data
— LO
— NLO
— NNLO