FORTE

α_s from ATLAS

Extracting the Strong Coupling at the EIC and other Future Colliders

Zdenek Hubacek

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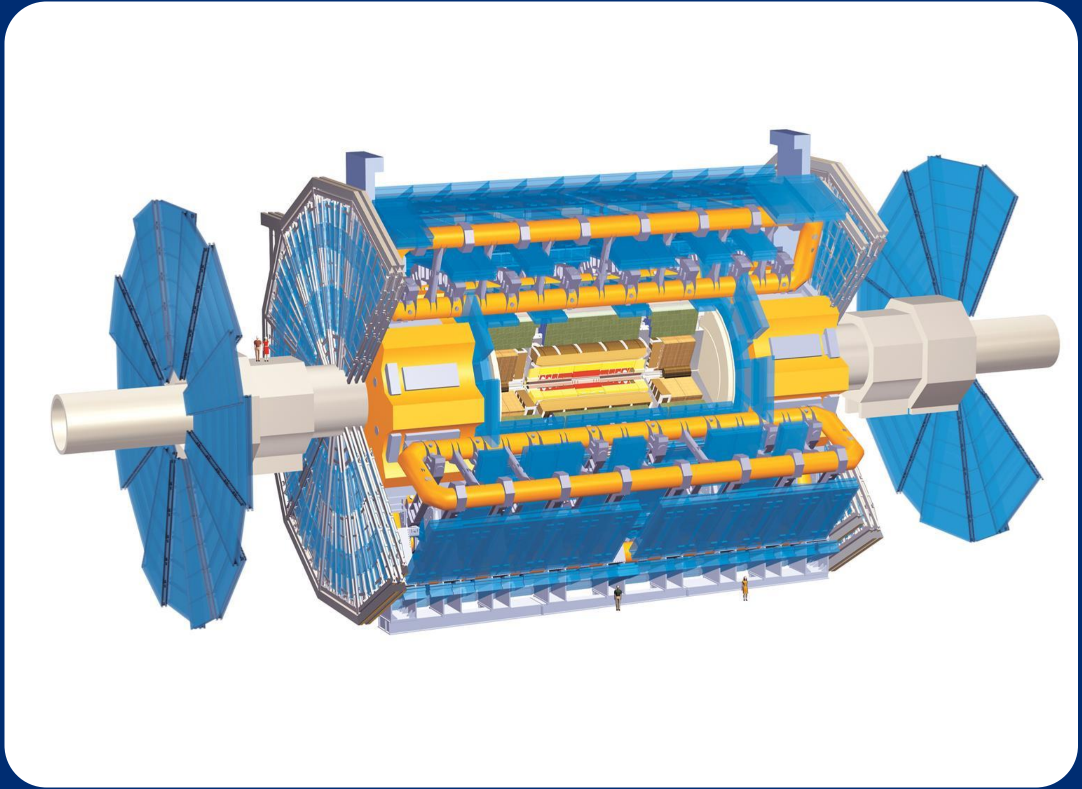
MINISTRY OF EDUCATION, YOUTH AND SPORTS

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Strong coupling constant from ATLAS

- LHC is a QCD powerhouse — a true strong-interaction factory
- ATLAS provides a panoramic view of QCD in action
- QCD isn't background — it's the baseline for discovery
- α_S - small number, big consequences.



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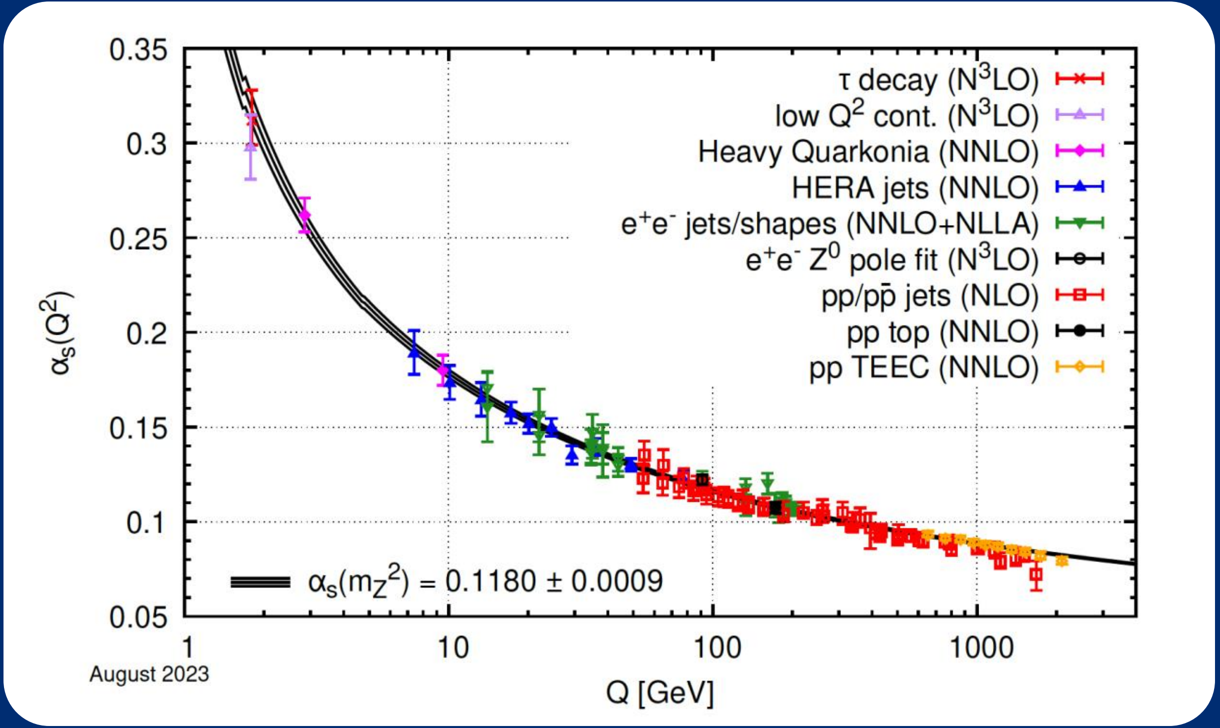
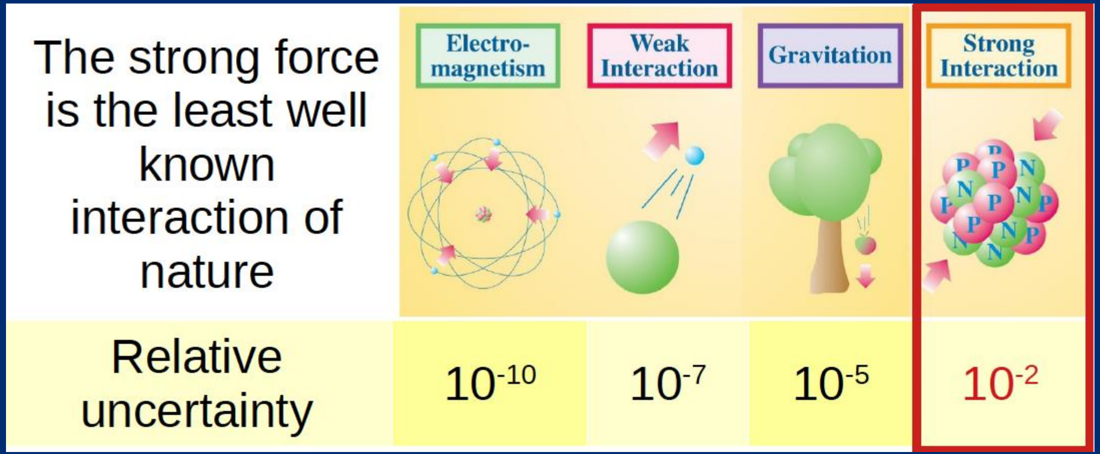
Strong coupling α_S

- One of fundamental constants
- QCD only free parameter in the massless quark limit
- RGE governs how α_S evolves with the energy scale μ.
- Conventionally “measured” at the reference scale $Q=m_Z$
- Is among dominant uncertainties of several precision measurements at colliders (including Higgs coupling for example)





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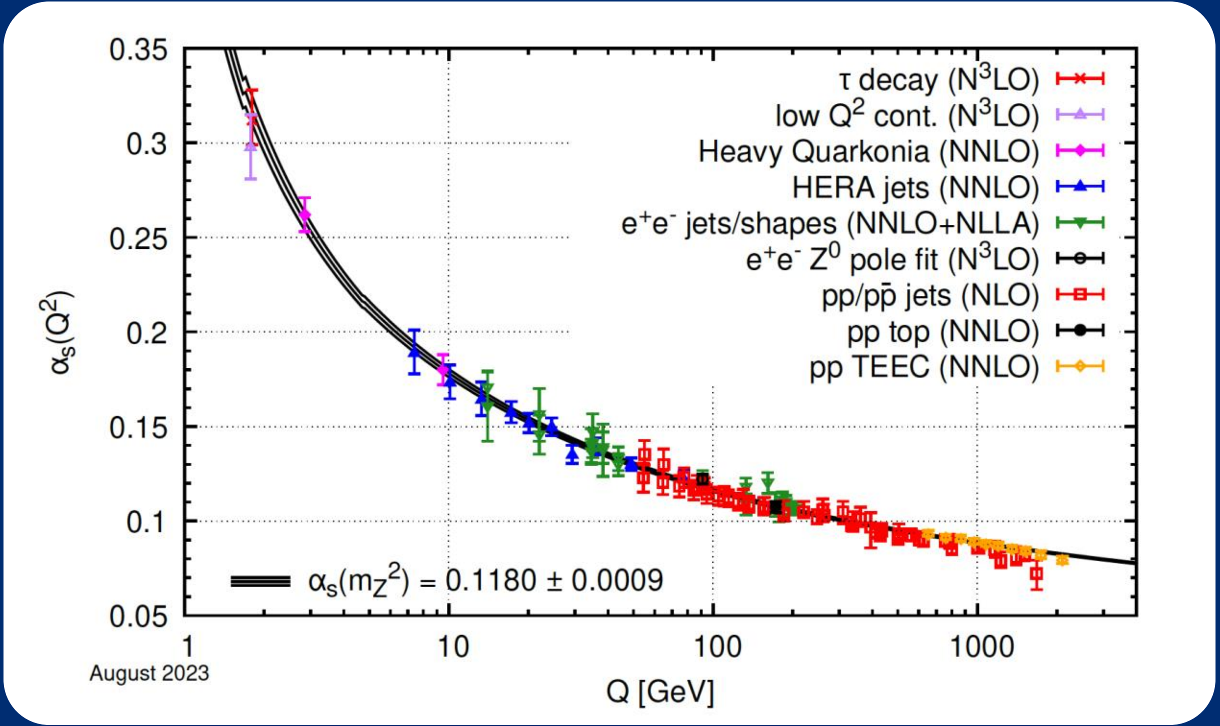

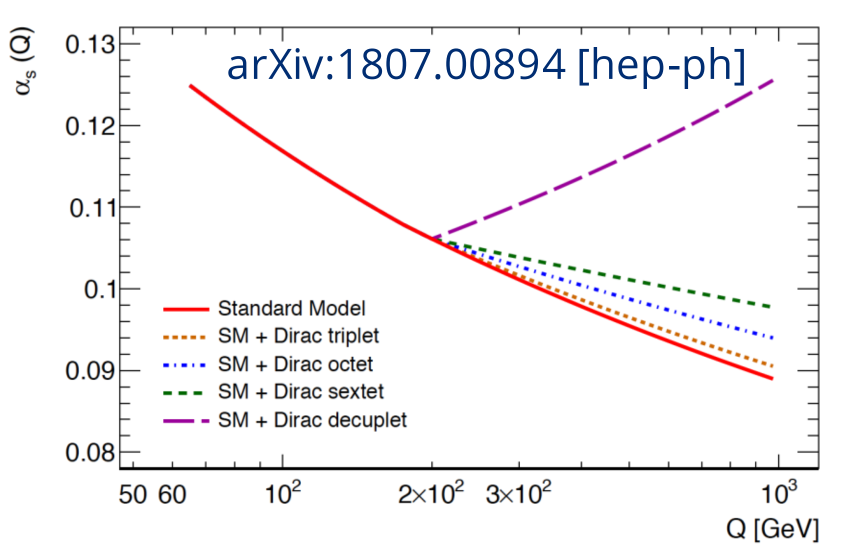

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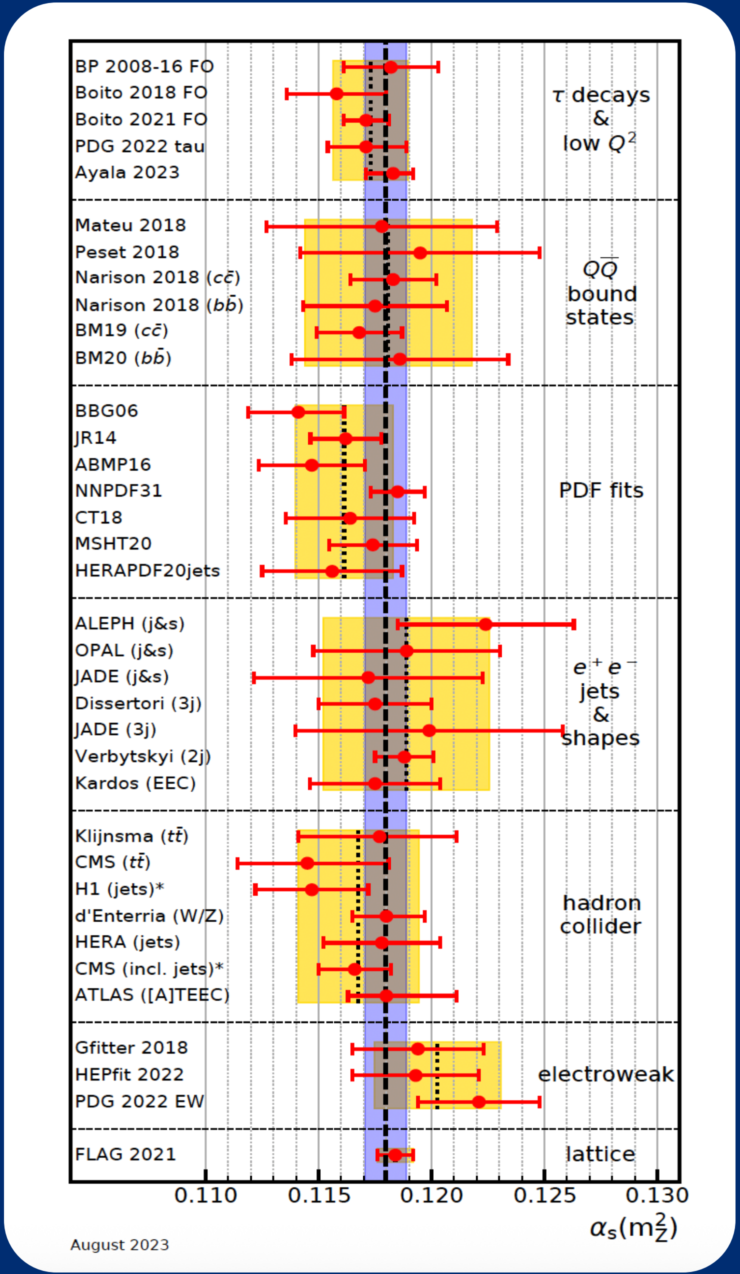
α_S extraction at colliders

Desirable features for the measurement:

- Large observable's sensitivity to α_S compared to the experimental precision
- High accuracy of the theory prediction
- Small size of non-perturbative QCD effects

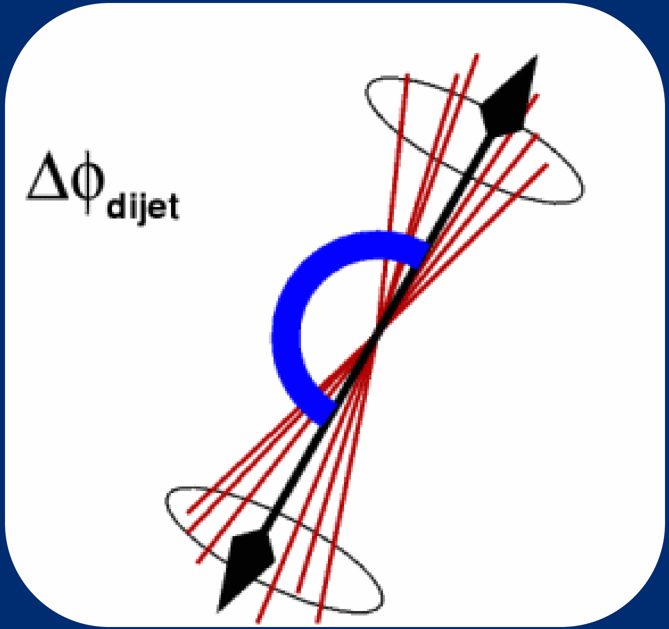
⇒ **Exclusive vs inclusive observables**

- Event shapes, jet ratios, …
- Inclusive observables, differential distributions (jets, top)



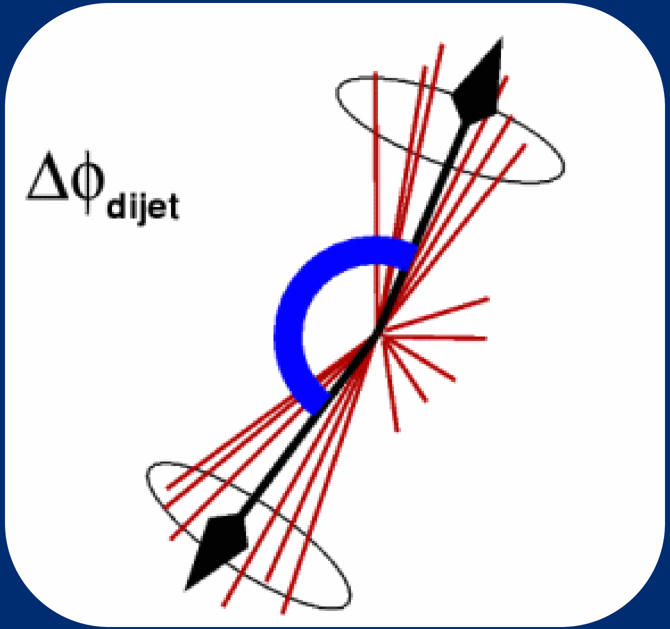
Dijet azimuthal decorrelations

- At leading order (LO), 2 jets are produced back-to-back in the azimuthal angle



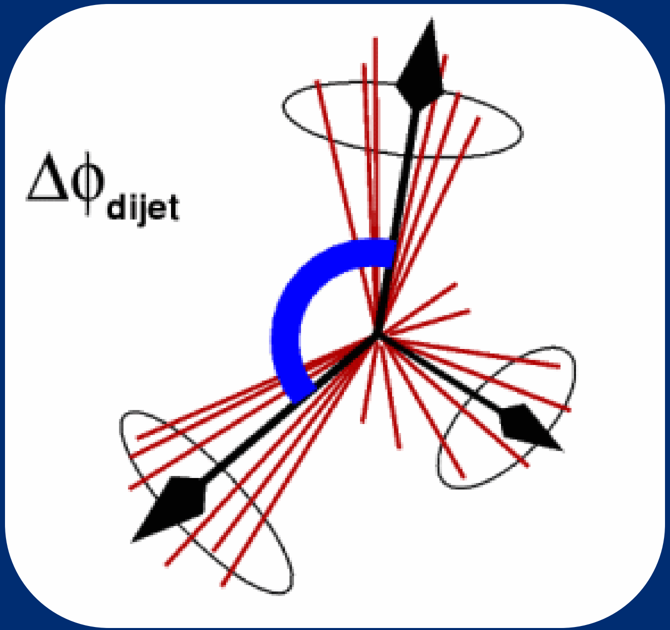
Dijet azimuthal decorrelations

- At leading order (LO), 2 jets are produced back-to-back in the azimuthal angle
- Any additional radiation will cause the decorrelation



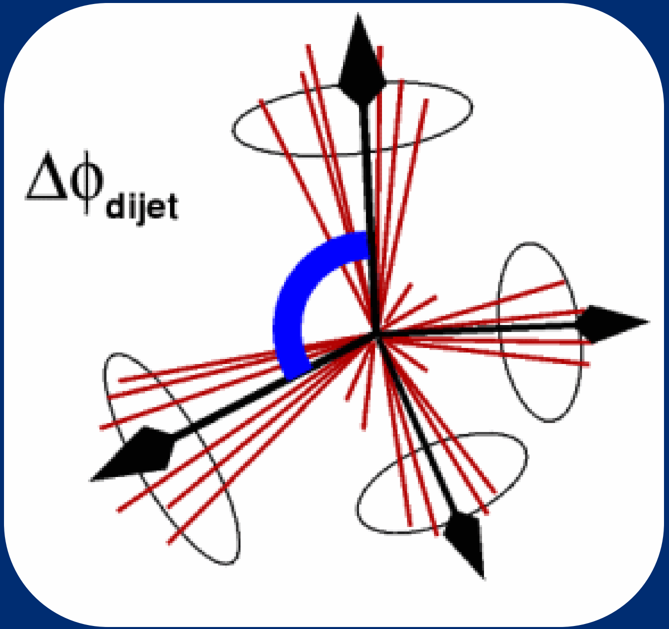
Dijet azimuthal decorrelations

- At leading order (LO), 2 jets are produced back-to-back in the azimuthal angle
- Any additional radiation will cause the decorrelation
- 3rd jet production (2→3 process) restricts the phase space to **$\Delta\phi$**>2**π**/3



Dijet azimuthal decorrelations

- At leading order (LO), 2 jets are produced back-to-back in the azimuthal angle
- Any additional radiation will cause the decorrelation
- 3rd jet production (2→3 process) restricts the phase space to $\Delta\phi > 2\pi/3$
- Lower values accessible only in 2→4 processes



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Observable definition $R_{\Delta\phi}$

- Dijet azimuthal decorrelations have been measured before at hadron colliders (D0, CMS, ATLAS for example)
- Observable based on ratios of cross sections and studies its energy and rapidity dependence

$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{max}) = \frac{\frac{d^2\sigma_{dijet}(\Delta\phi_{dijet} < \Delta\phi_{max})}{dH_T\,dy^*}}{\frac{d^2\sigma\,dijet(inclusive)}{dH_T\,dy^*}}$$

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- Fraction of dijet events where the azimuthal difference between the two leading jets is smaller than some $\Delta\phi_{max}$ value w.r.t. to the inclusive dijet cross section

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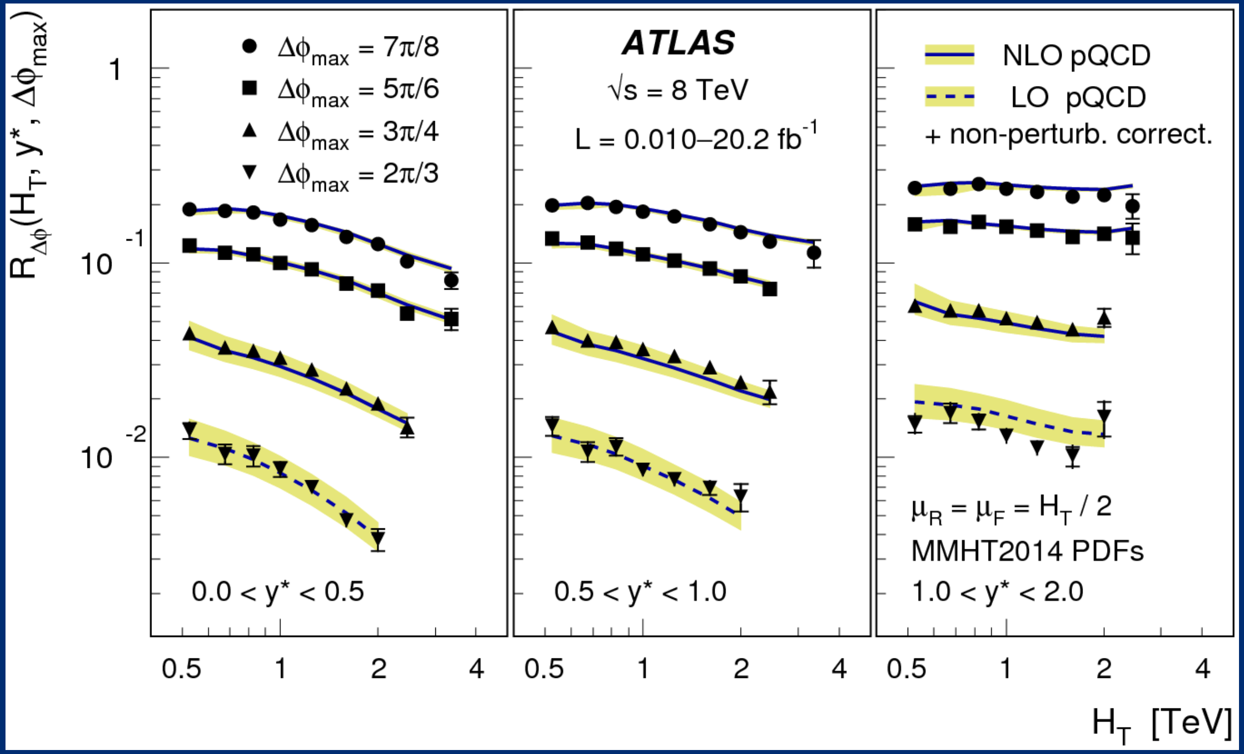
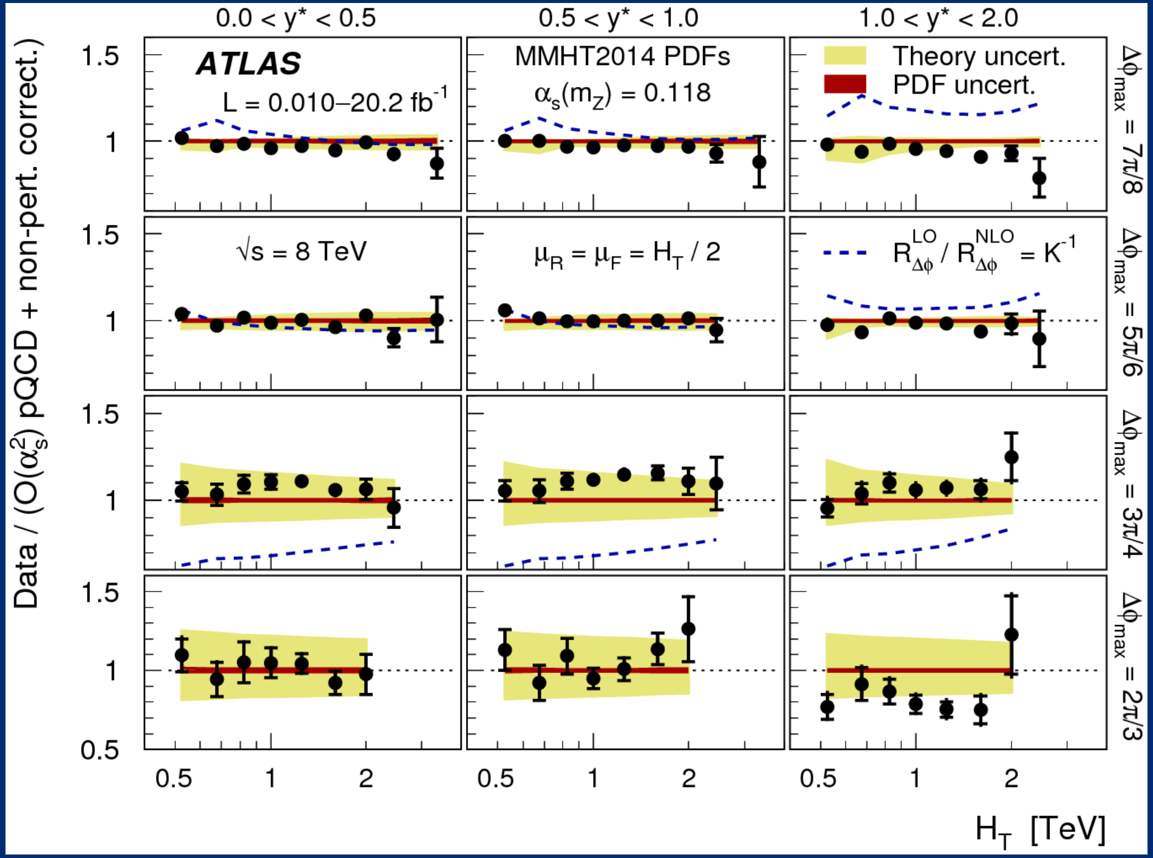
PhysRevD.98.092004

$R_{\Delta\phi}$, $\sqrt{s}$=8TeV, 20.2fb^{-1}





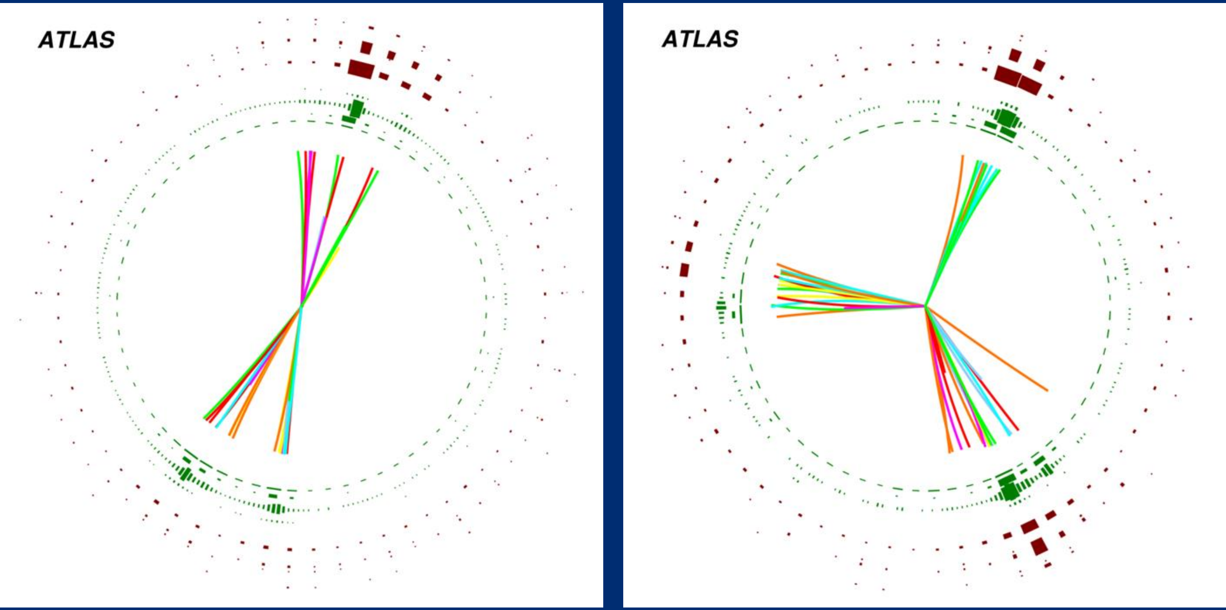
Well described by the pQCD with corrections for nonperturbative effects

Event shape variables

- Family of observables which characterize the event topology and/or energy flow in collider events
- Thrust, thrust minor, sphericity, aplanarity
- Energy-energy correlations, event isotropies

Example: **Transverse thrust** – thrust axis $n_{\perp}$ to which the projections of p_T are maximised, $0 \leq \tau_{\perp} < 1 - 2/\pi$

$$T_{\perp} = \max_{\hat{\boldsymbol{n}}_{\perp}} \frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i} \cdot \hat{\boldsymbol{n}}_{\perp}|}{\sum_i p_{\mathrm{T}i}} \qquad \tau_{\perp} = 1 - T_{\perp}$$



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JHEP07(2023)085

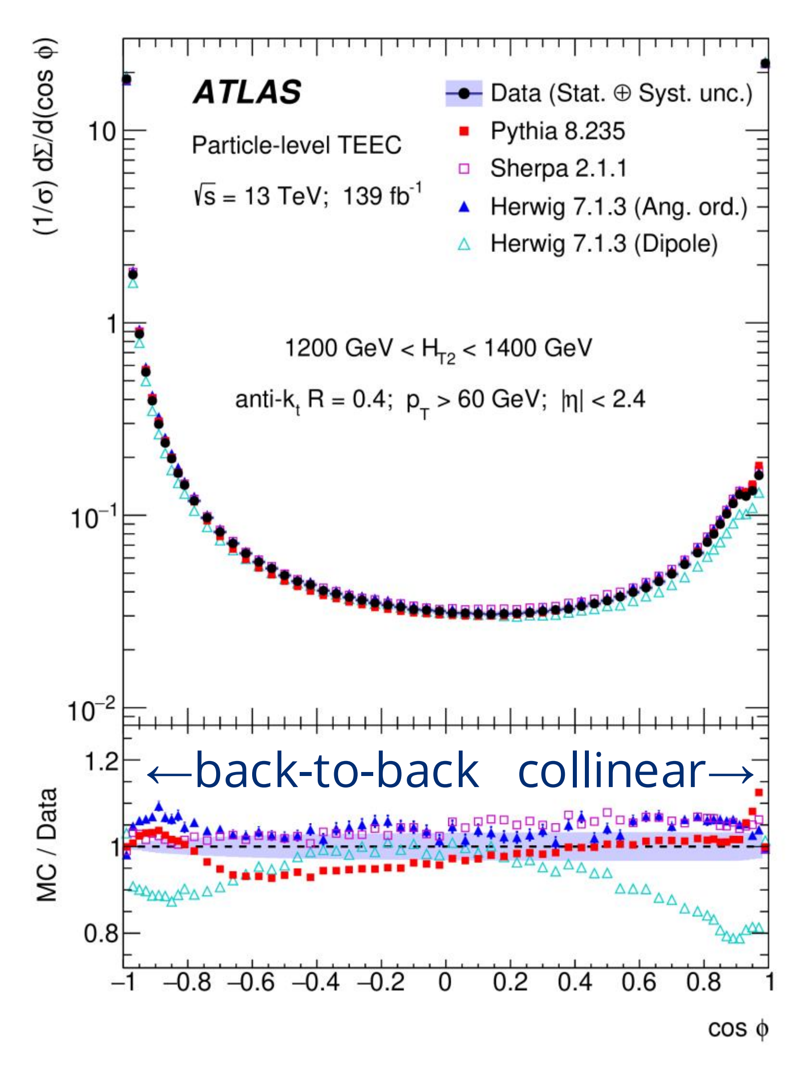
Transverse energy-energy correlations (TEEC)

- Transverse energy-weighted distribution of azimuthal differences between jet pairs

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

- Asymmetry

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



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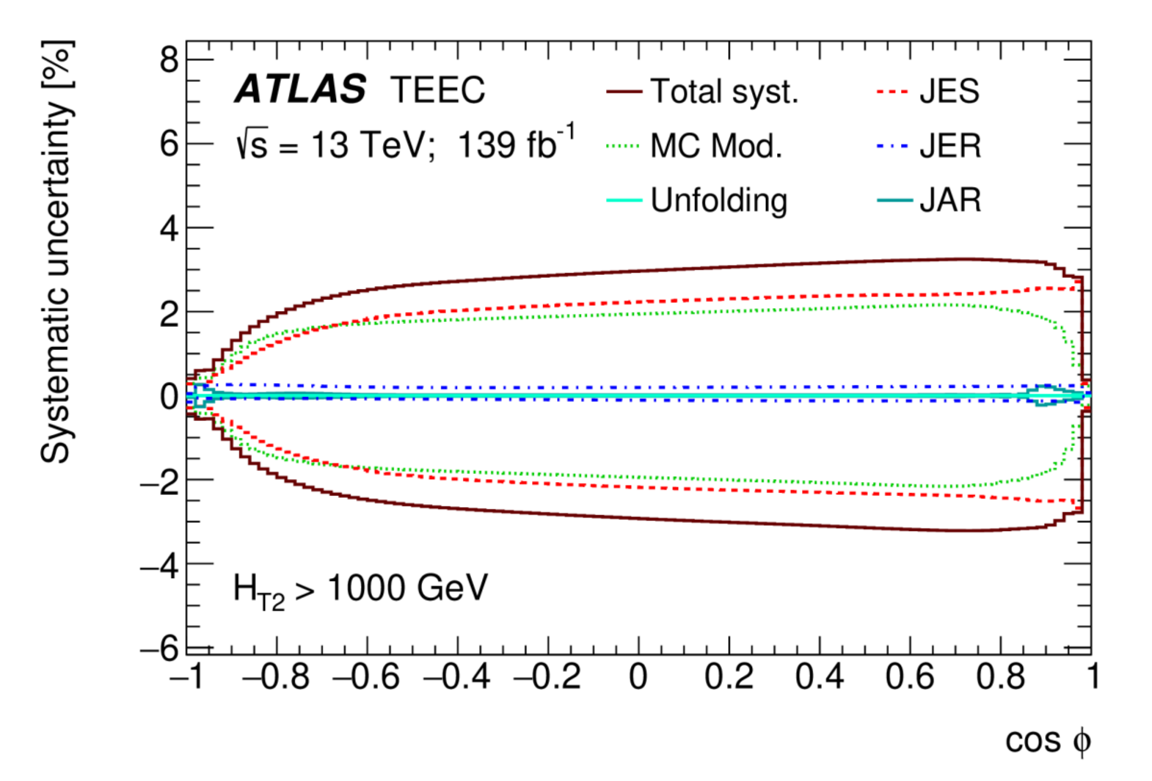
TEEC analysis details, $\sqrt{s}$=13TeV, 139fb^{-1}
Anti-kt R=0.4 jets, p_T>60GeV, $|\eta|$<2.4, $H_{T,2}$>1TeV

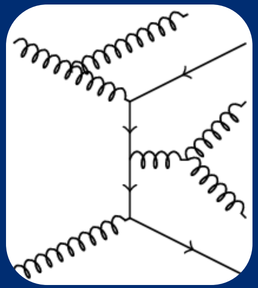
- Experimental uncertainties

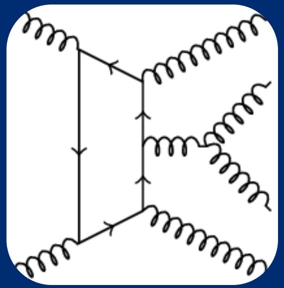


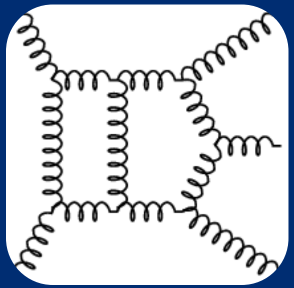
- Theoretical models

Generator	ME order	ME partons	PDF set	Parton shower	Scales μ_R, μ_F	$\alpha_s(m_Z)$
Pythia 8	LO	2	NNPDF 2.3 LO	p_T-ordered	$(m_{T3}^2 \cdot m_{T4}^2)^{\frac{1}{2}}$	0.140
Sherpa	LO	2,3	CT14 NNLO	CSS (dipole)	$H(s,t,u)$ [$2 \to 2$] CMW [$2 \to 3$]	0.118
Herwig 7	NLO	2,3	MMHT2014 NLO	Angular-ordered Dipole	$\max \{p_{Ti}\}_{i=1}^{N}$	0.120

- pQCD calculation (Czakon, Mitov, Poncelet, et al.) – NNLO corrections to three-jet production







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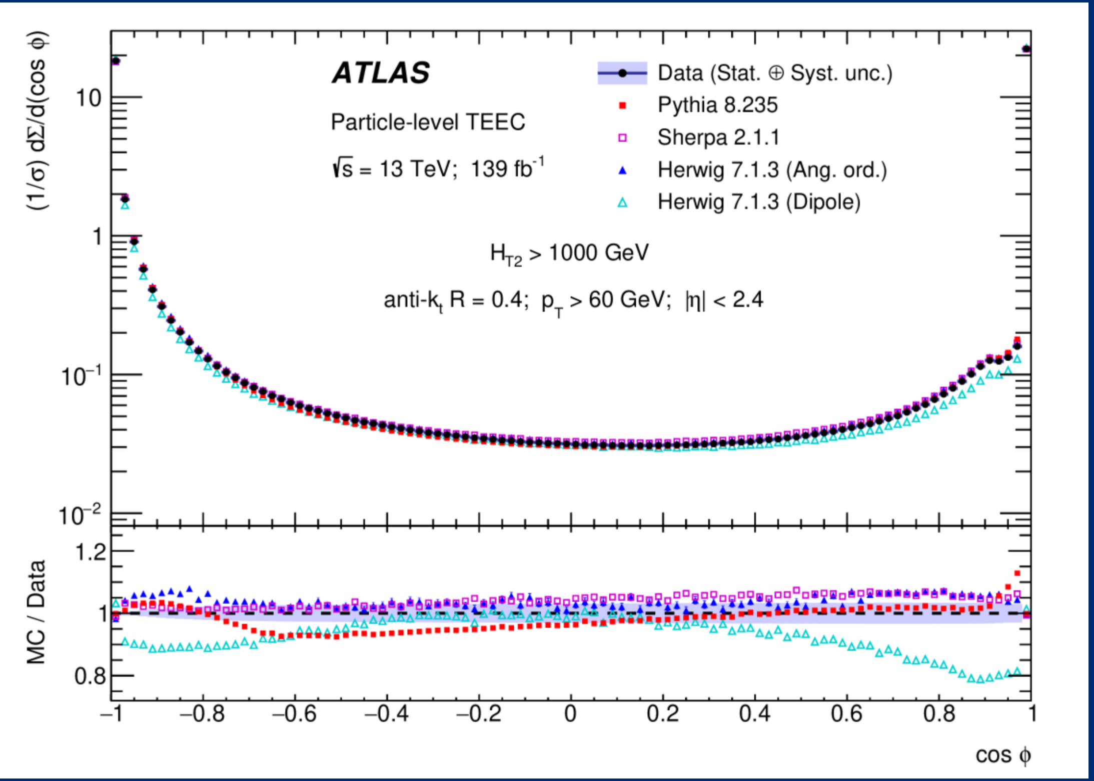
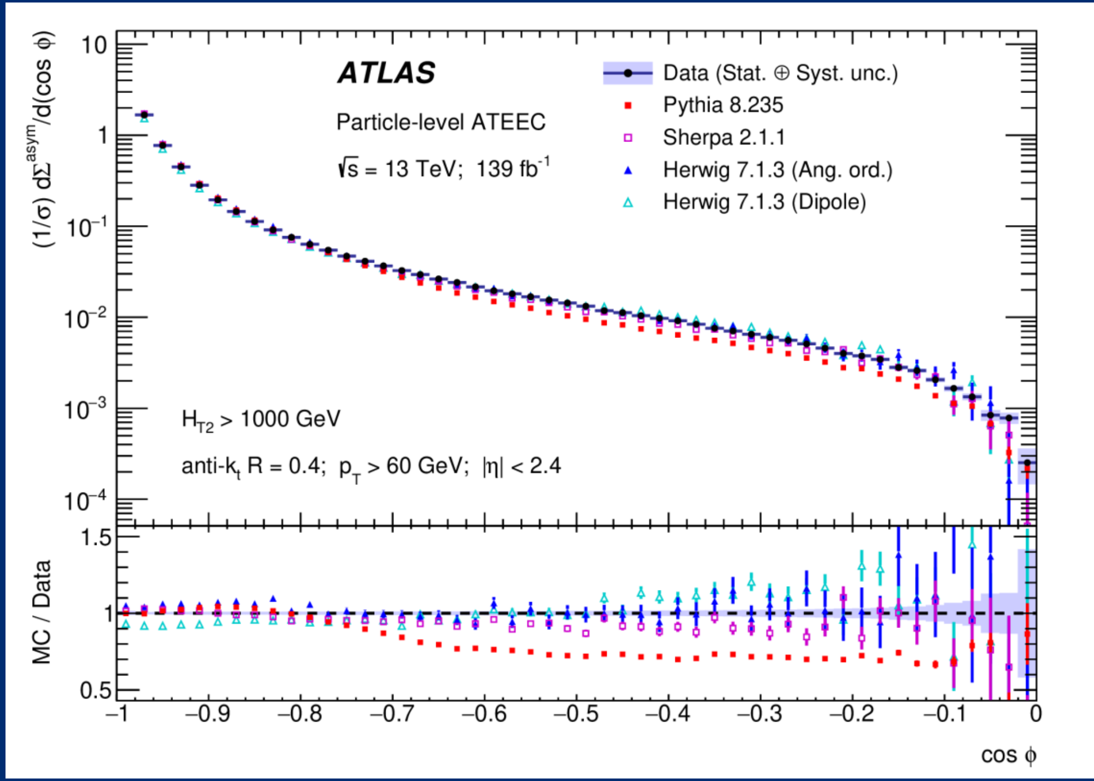
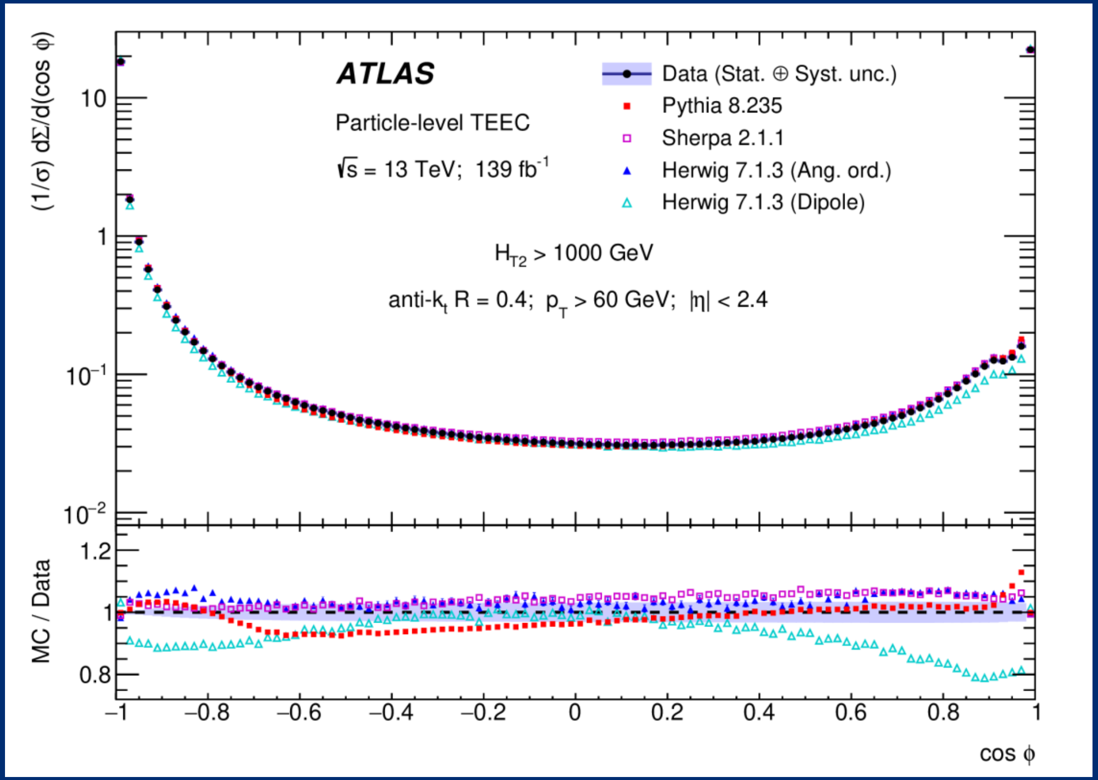
TEEC experimental results



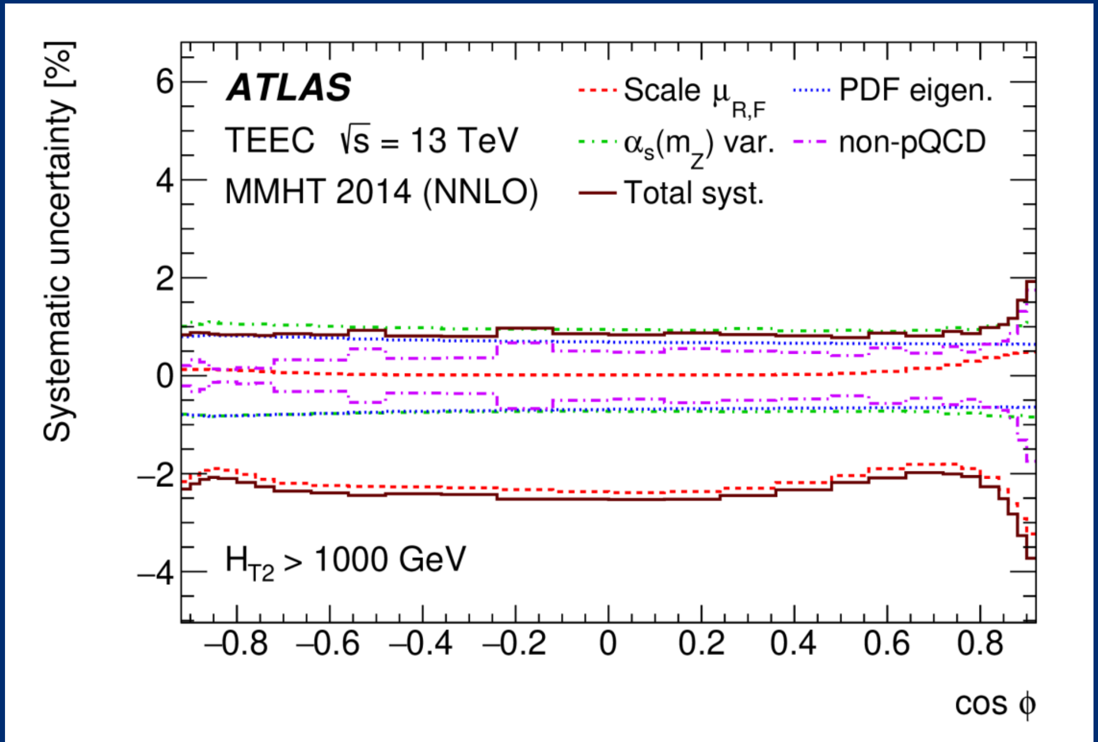


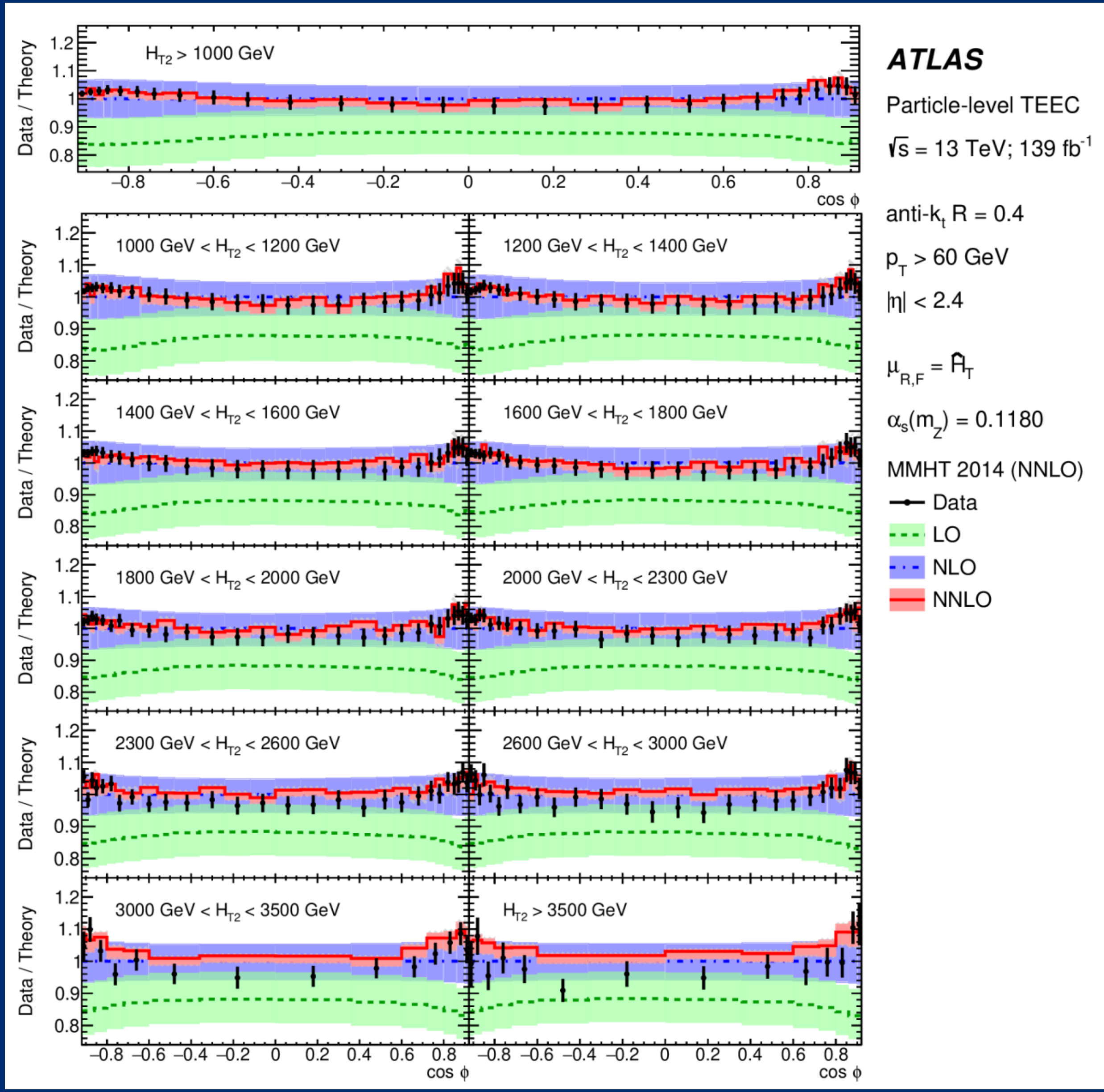
TEEC experimental results



- At low $H_{T,2}$ best description by both Sherpa and Herwig (angle-ordered shower)
- At high $H_{T,2}$ Pythia8 gives the best description while both Sherpa and Herwig overestimate the height of the central plateau

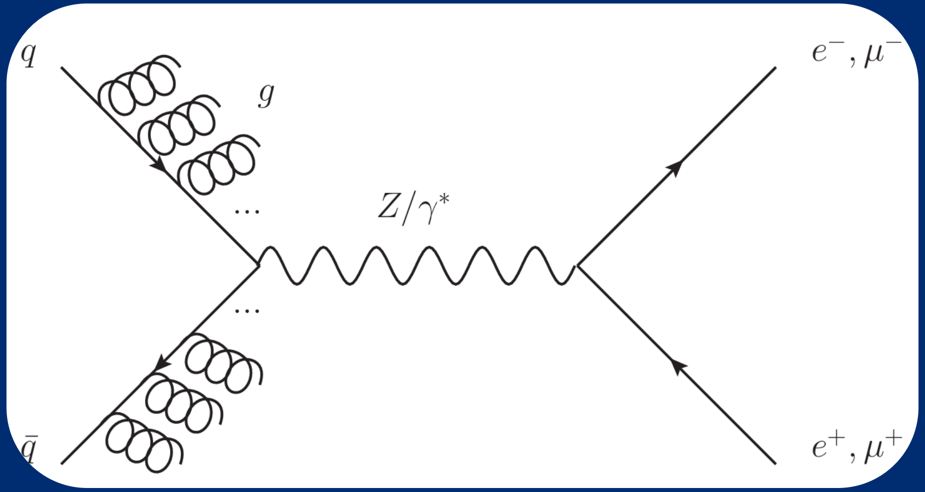
TEEC NNLO prediction

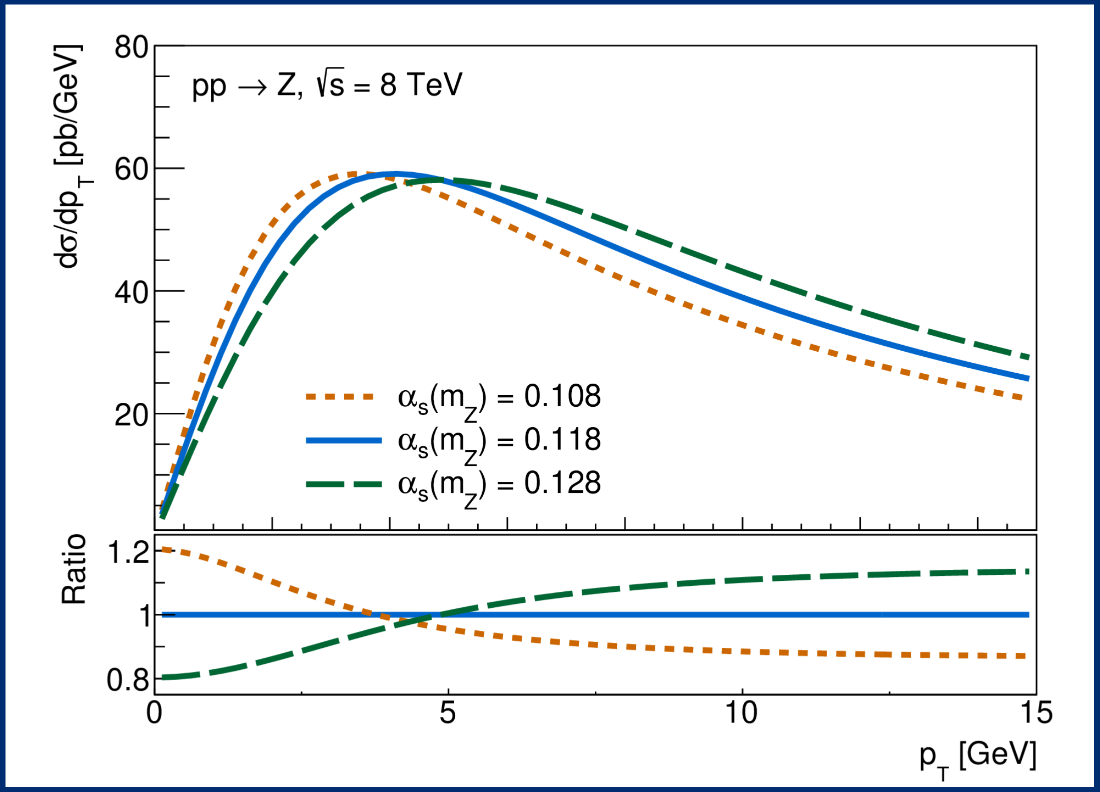




Z transverse momentum p_T

- Z bosons in hadron-hadron collisions recoil against QCD ISR – 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, at values of approximately 4 GeV
- The position of the peak is sensitive to $\alpha_S(m_Z)$





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Precise measurement of Z p_T, $\sqrt{s}$=8TeV, 20.2fb^{-1}

- 15.3M Z dilepton decays (Drell-Yan ee,μμ)
- 80 < m_{ll} < 100 GeV, |y|<3.6
- Double differential pT, y cross section
- Interpretation of fiducial cross sections hampered by breakdown of fixed order perturbation theory ⇒ Full phase space measurement
- Analytical integration over decay angles to correct for fiducial cuts directly at theory level.

$$\frac{d\sigma}{dp_T\, dy\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T\, dy\, dm}$$
$$\times \Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta)$$
$$+ A_1\ \sin 2\theta\ \cos\phi$$
$$+ \frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi$$
$$+ A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$
$$+ A_5\ \sin^2\theta\ \sin 2\phi$$
$$+ A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}.$$

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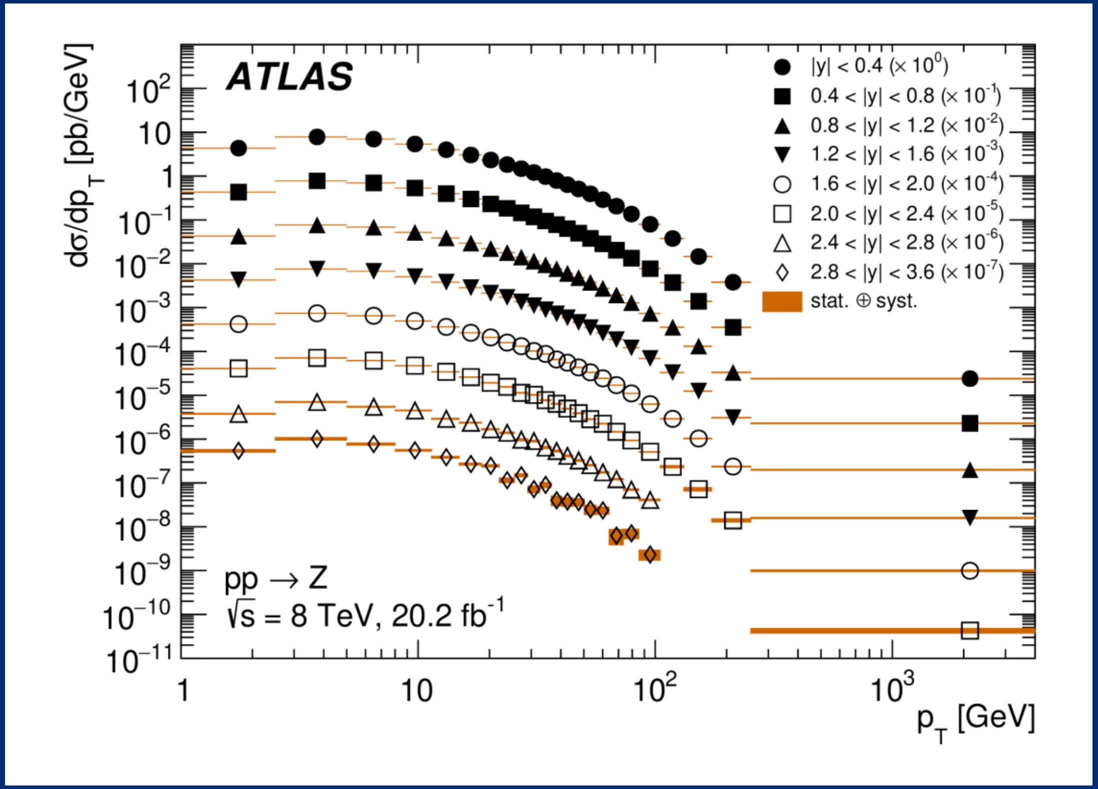
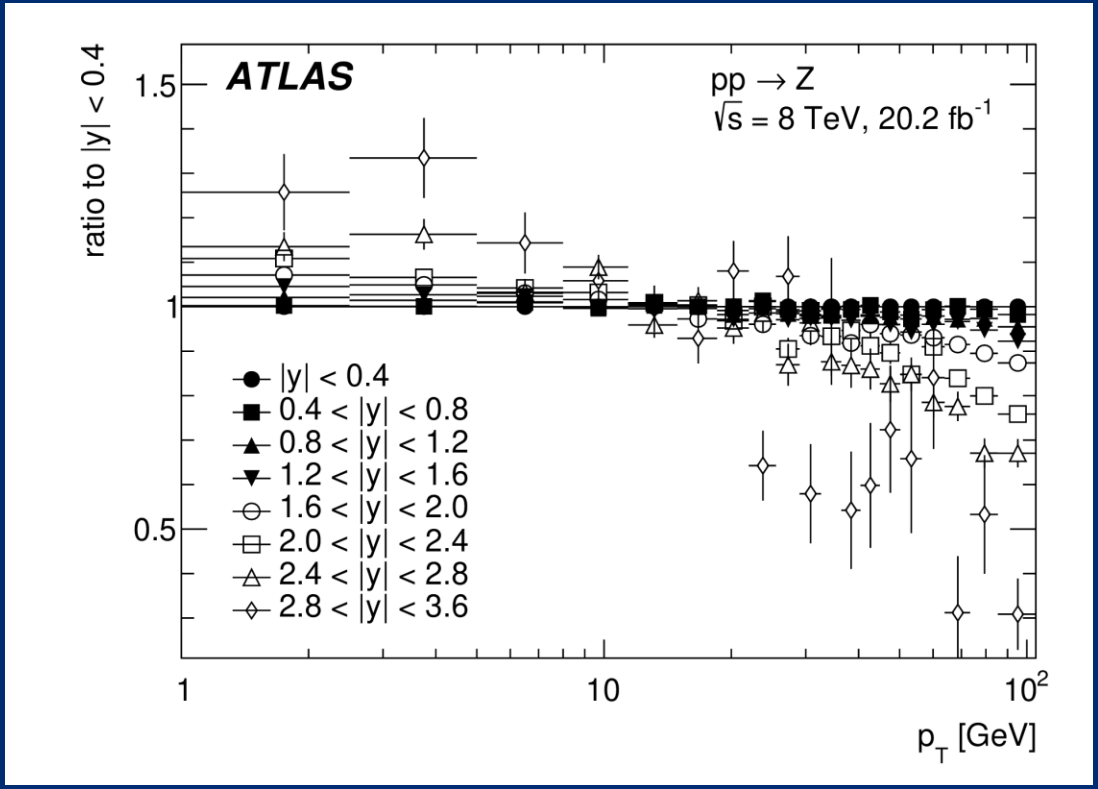
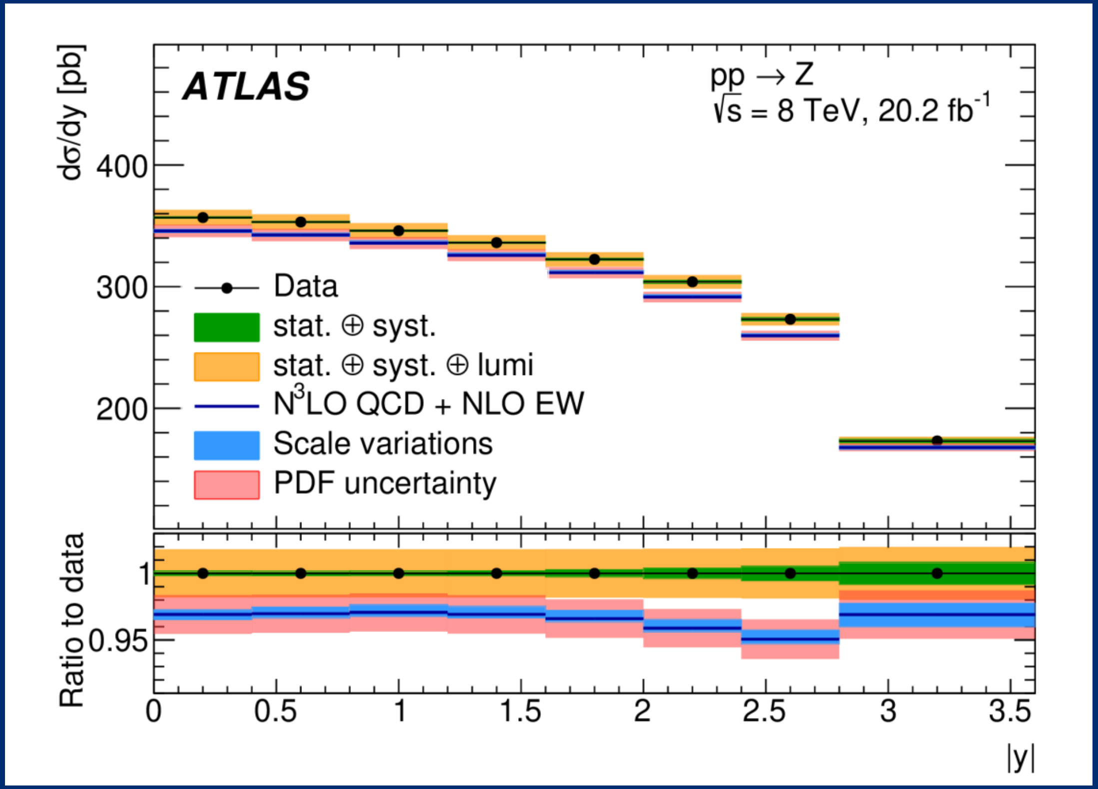
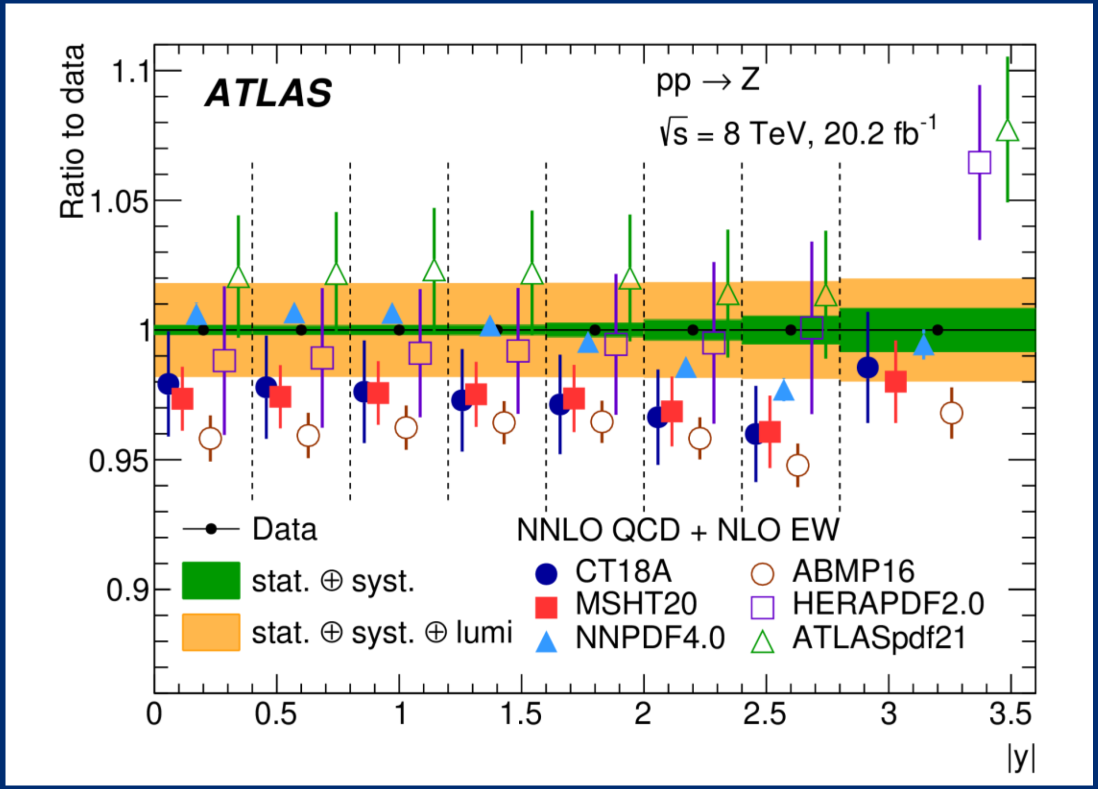
Precise measurement of Z p_T





Precise measurement of Z p_T



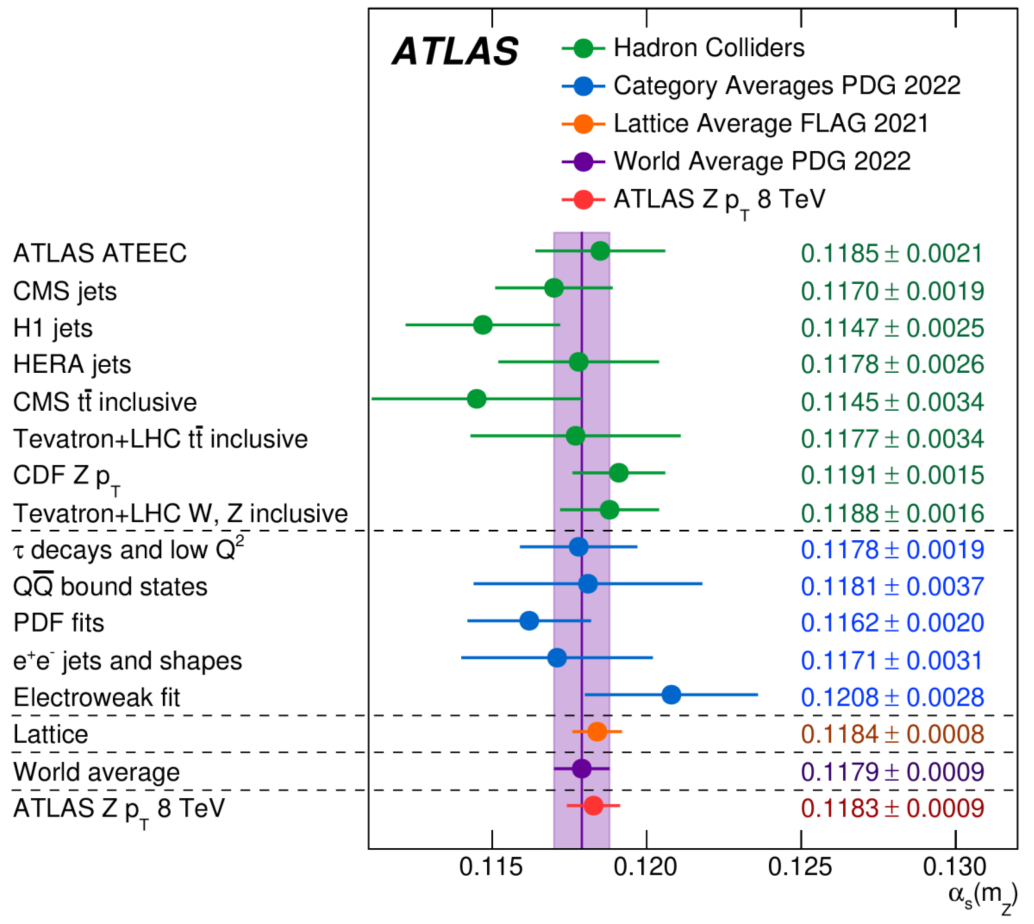


α_S extraction in ATLAS

- Theory–data comparison based on minimizing a $\chi^2(\alpha_S)$ function

$$\chi^2(\alpha_s) = \sum_{i,j} (D_i - T_i(\alpha_s)) (C^{-1})_{ij} (D_j - T_j(\alpha_s))$$

- Sources of uncertainties entering C
  - Experimental: statistical and systematics (luminosity, JES, unfolding, ...)
  - Theoretical: PDF uncertainties, scale variations (μ_r, μ_f), hadronization/UE corrections, PDF-α_S correlation
- Use PDF sets with explicit α_S dependence
- Scale uncertainties estimated by μ_r, μ_f variations and propagated to α_S
- PDF uncertainty propagated either via replicas or eigenvector sets



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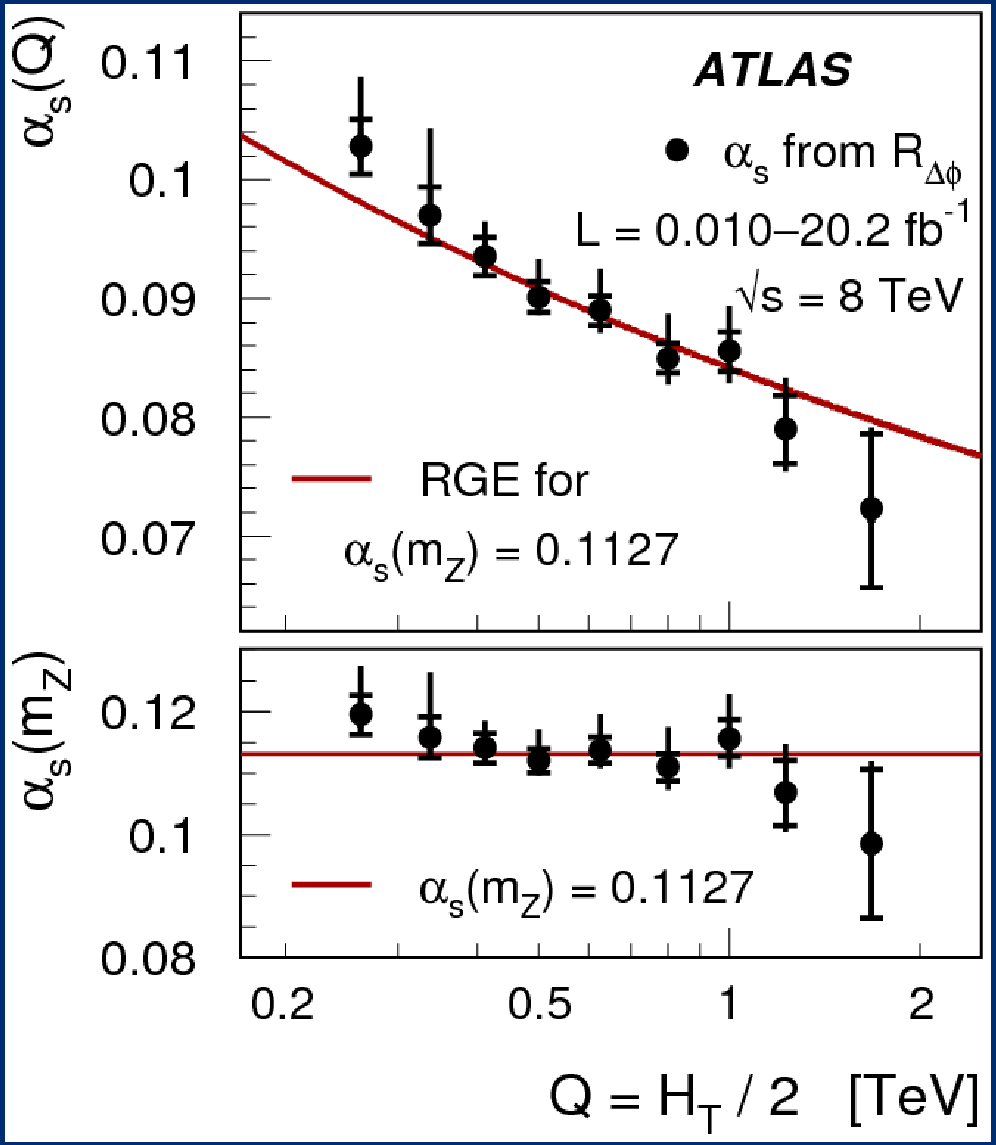
$R_{\Delta\phi}$ α_S extraction

- pQCD calculations carried out using NLOJET++ interfaced to FASTNLO
  - NLO (LO) predictions for 3 (4) jet quantities depending on **Δϕ**max
- $\mu_r = \mu_f = H_T/2$
- Several global PDF (MMHT2014, CT14, NNPDF2.3, ABMP16 (NNLO), HERAPDF2.0)
- Bins 0<y*<0.5 and 0.5<y*<1.0 for **Δϕ**max <7 **π**/8 selected
- α_S (Q) with $Q=H_T/2$ extracted through **χ**2 min. in 9 intervals in the range 262 < Q < 1675 GeV
- Single minimization to obtain the statistical, experimental, non pert. and MMHT2014 PDF uncertainty
- Additional minimization for the PDF set and scale uncertainties



$\alpha_S(m_Z)$	Total uncert.	Statistical	Experimental correlated	Non-perturb. corrections	MMHT2014 uncertainty	PDF set	$\mu_{R,F}$ variation
0.1127	$^{+6.3}_{-2.7}$	±0.5	$^{+1.8}_{-1.7}$	$^{+0.3}_{-0.1}$	$^{+0.6}_{-0.6}$	$^{+2.9}_{-0.0}$	$^{+5.2}_{-1.9}$

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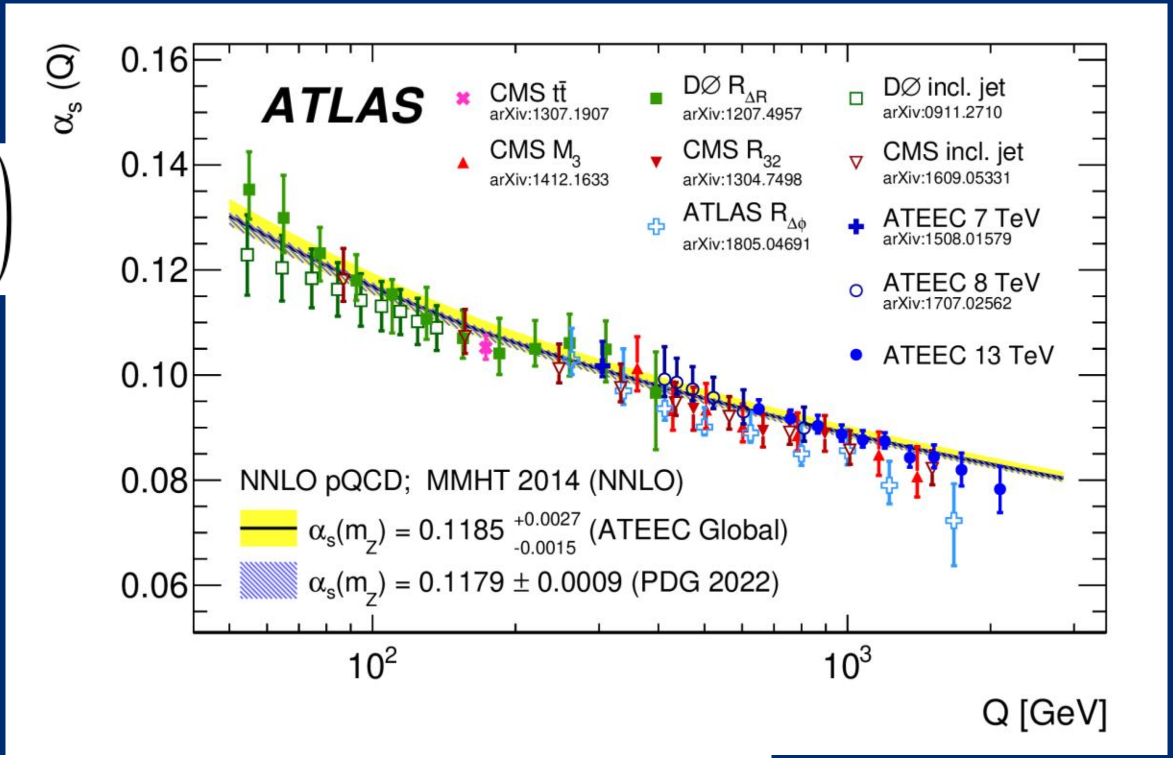
TEEC α_S extraction

Fits in each $H_{T,2}$ interval separately

$$\chi^2(\alpha_s, \vec{\lambda}) = \sum_{\text{bins}} \frac{(x_i - F_i(\alpha_s, \vec{\lambda}))^2}{\Delta x_i^2 + \Delta \xi_i^2} + \sum_k \lambda_k^2, \qquad F_i(\alpha_s, \vec{\lambda}) = \psi_i(\alpha_s)\left(1 + \sum_k \lambda_k \sigma_k^{(i)}\right)$$

TEEC has better exp. precision, but the value determined from ATEEC (shown here) exhibits better precision (TEEC in backup)

Both central values are correlated with ρ = 0.86 ± 0.02 (exp.)



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

arxiv.org/abs/2309.12986

Z p_T α_s extraction

Theory calculation with DYTurbo at **N⁴LLa and N³LO**

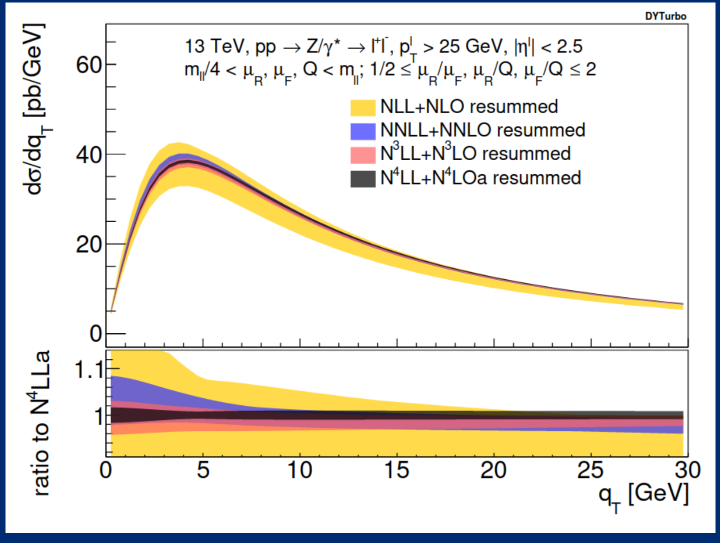
Predictions depend on 3 scales – μ_r, μ_f and Q (resummation scale) – central value set to quadratic sum of m_{ll} and p_T of the Z boson

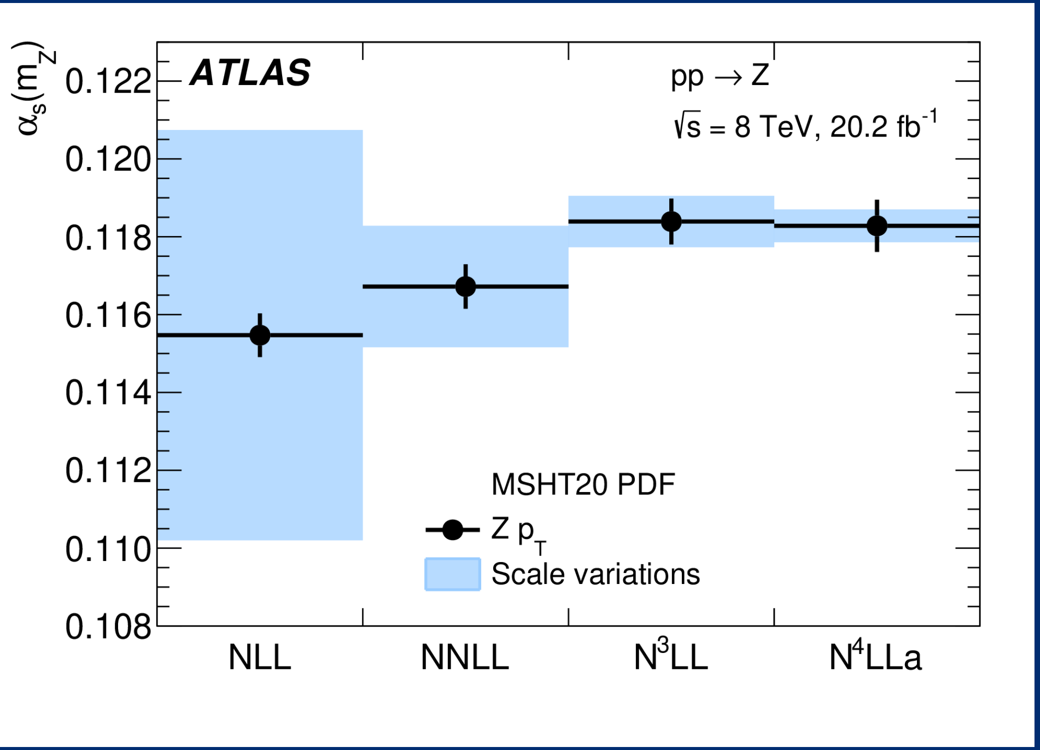
N3LO MSHT20 PDF set - only PDF set at this order

Minimization in xFitter framework

N_{data} = 72 data points in the (pt,y) double differential distribution

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





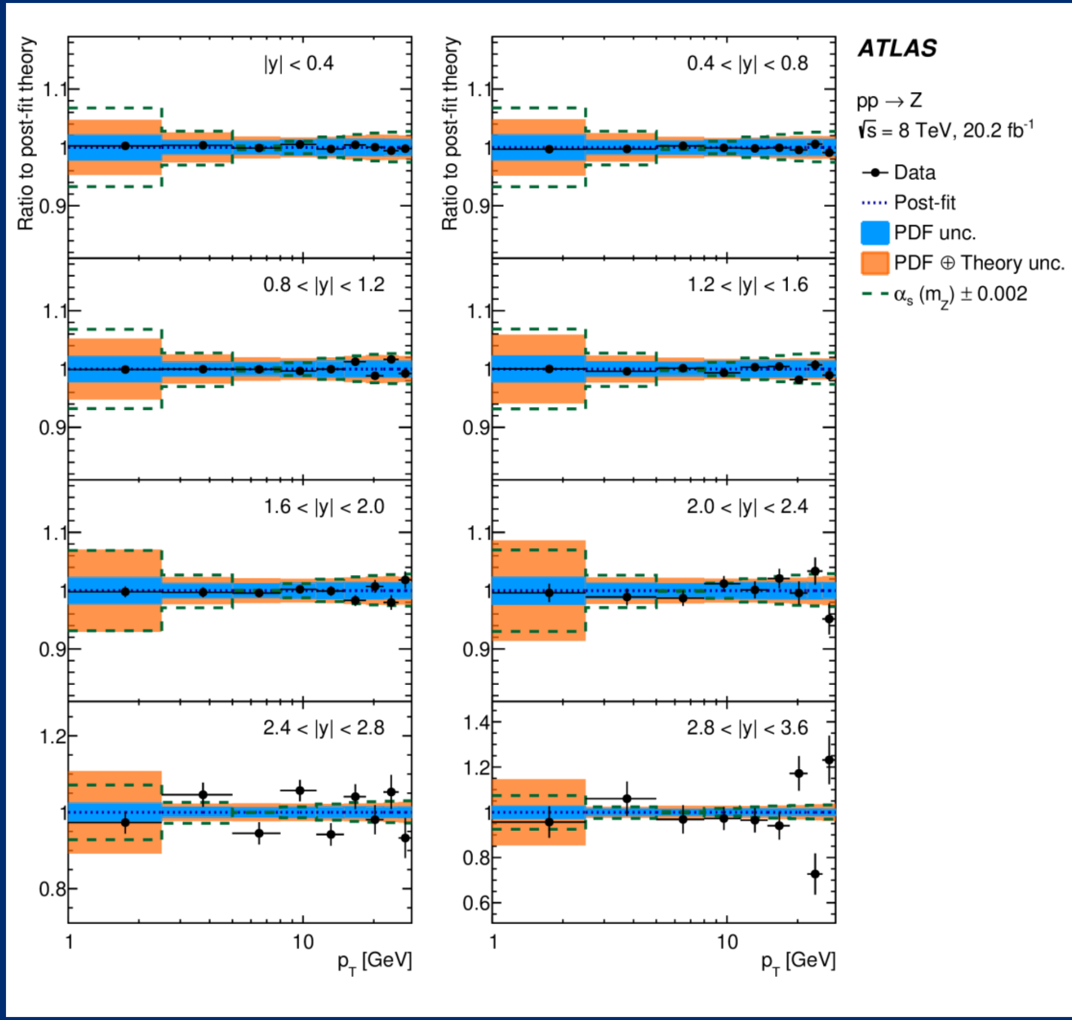
Z p_T α_S extraction

Uncertainties in units of 10^{-3}

Experimental uncertainty	± 0.44	
PDF uncertainty	± 0.51	
Scale variation uncertainties	± 0.42	
Matching to fixed order	0	-0.08
Non-perturbative model	$+0.12$	-0.20
Flavour model	$+0.40$	-0.29
QED ISR	± 0.14	
N^4LL approximation	± 0.04	
Total	$+0.91$	-0.88

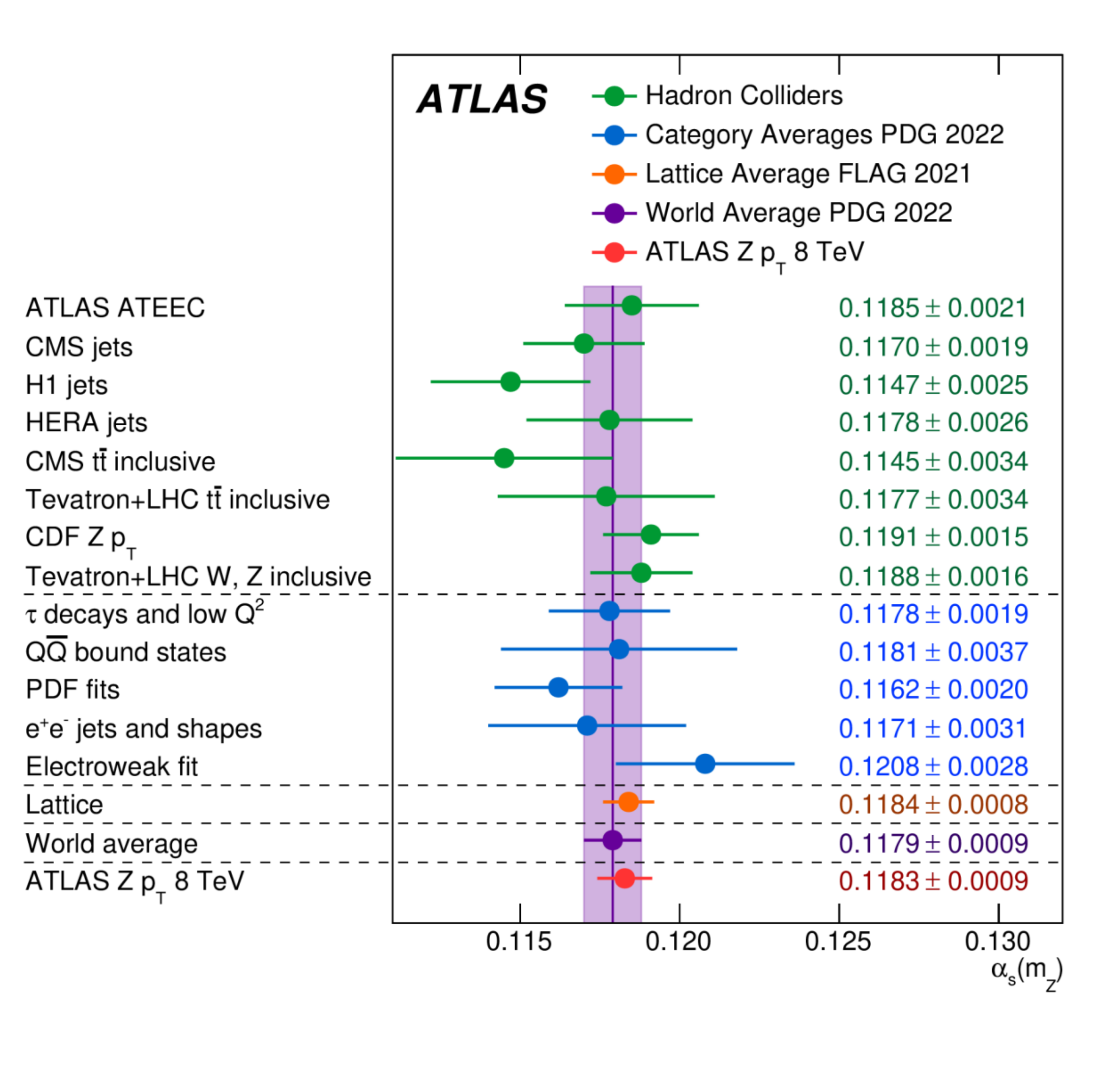
Observable not suitable for inclusion in PDF fits → no correlation with $\alpha_S(m_Z)$ determinations from PDF fits → also tried simultaneous PDF+α_S fit

Ratio to post-fit predictions



Summary

- **α_S is the least precisely known fundamental coupling**, with precision limited compared to electroweak parameters — motivating diverse and independent extractions
- **Hadron collider measurements** achieve competitive precision, thanks to high statistics, sophisticated techniques, and careful observable selection optimizing sensitivity to α_S.
- **Reducing uncertainties requires:**
    - **Experimentally**: choosing observables with minimal non-perturbative and PDF sensitivity;
    - **Theoretically:** improving perturbative predictions (NNLO, resummation) and reducing scale and PDF-related uncertainties.



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Thank you for your attention

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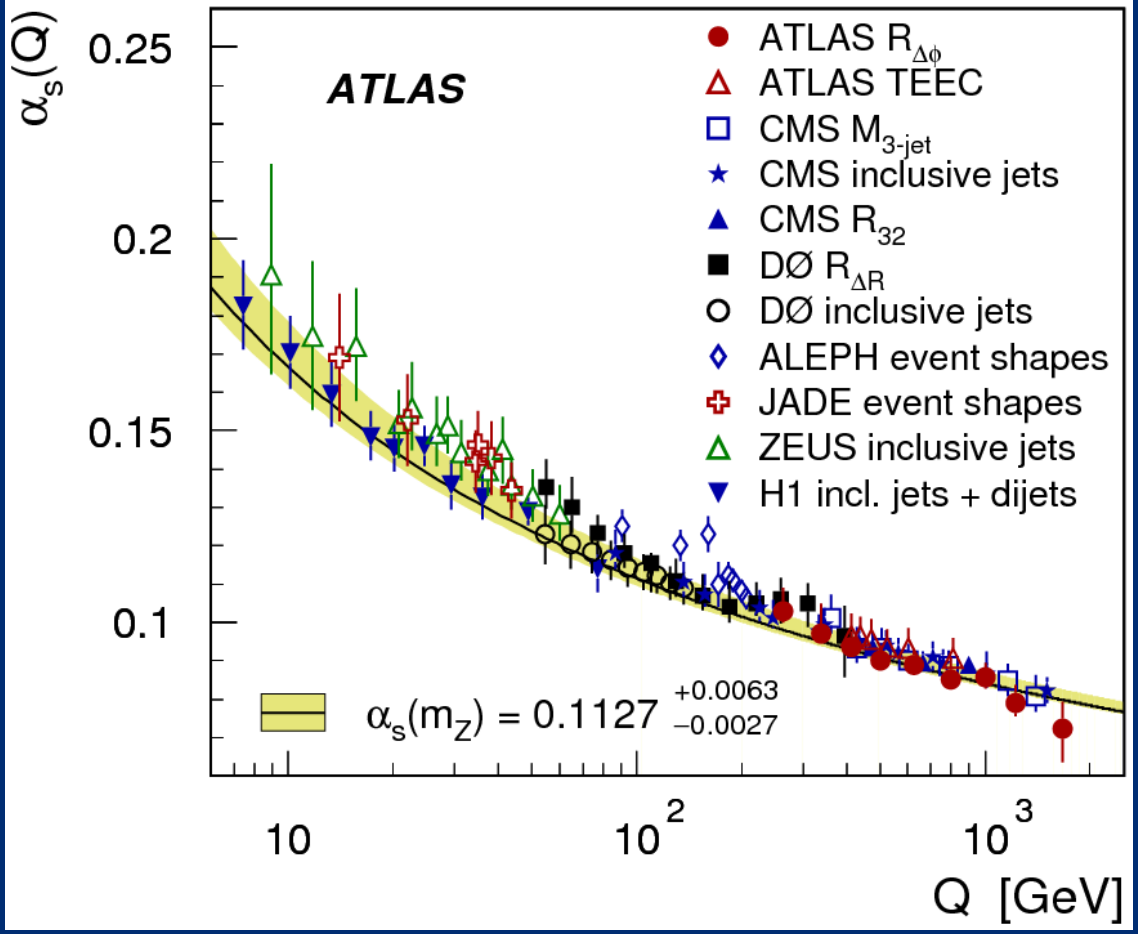
Backup

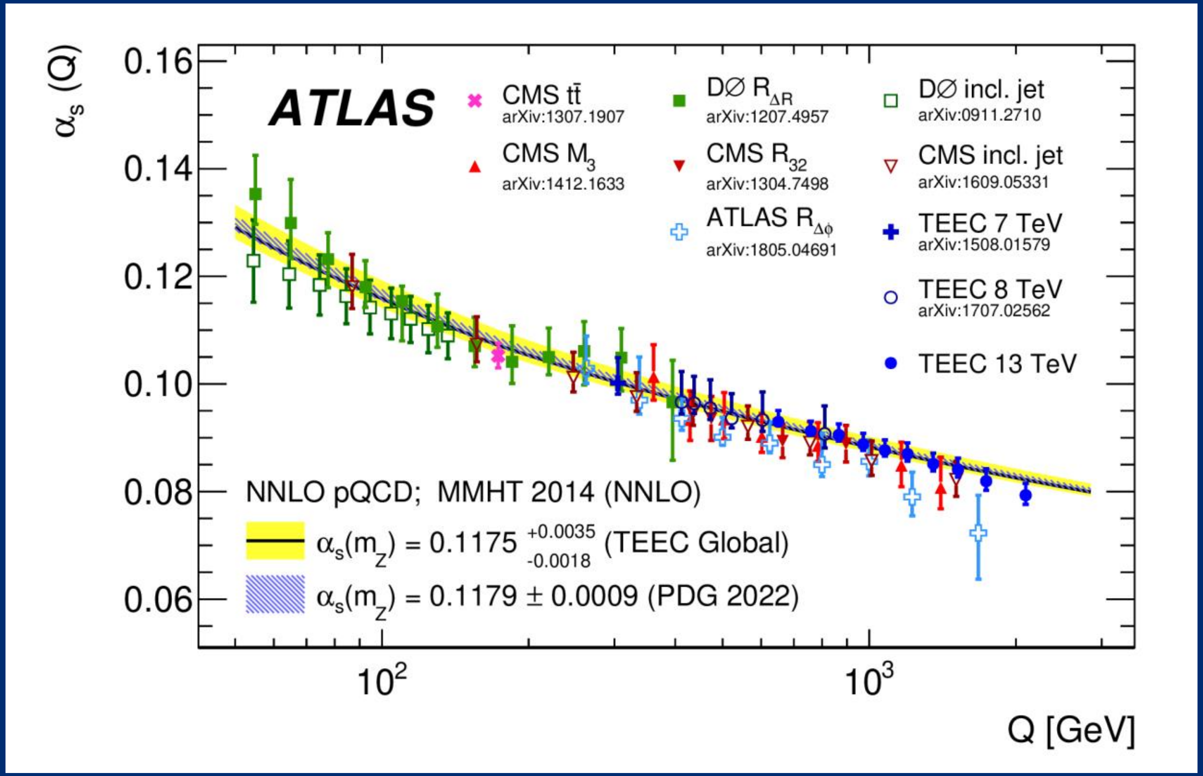
$R_{\Delta\phi}$ α_S extraction

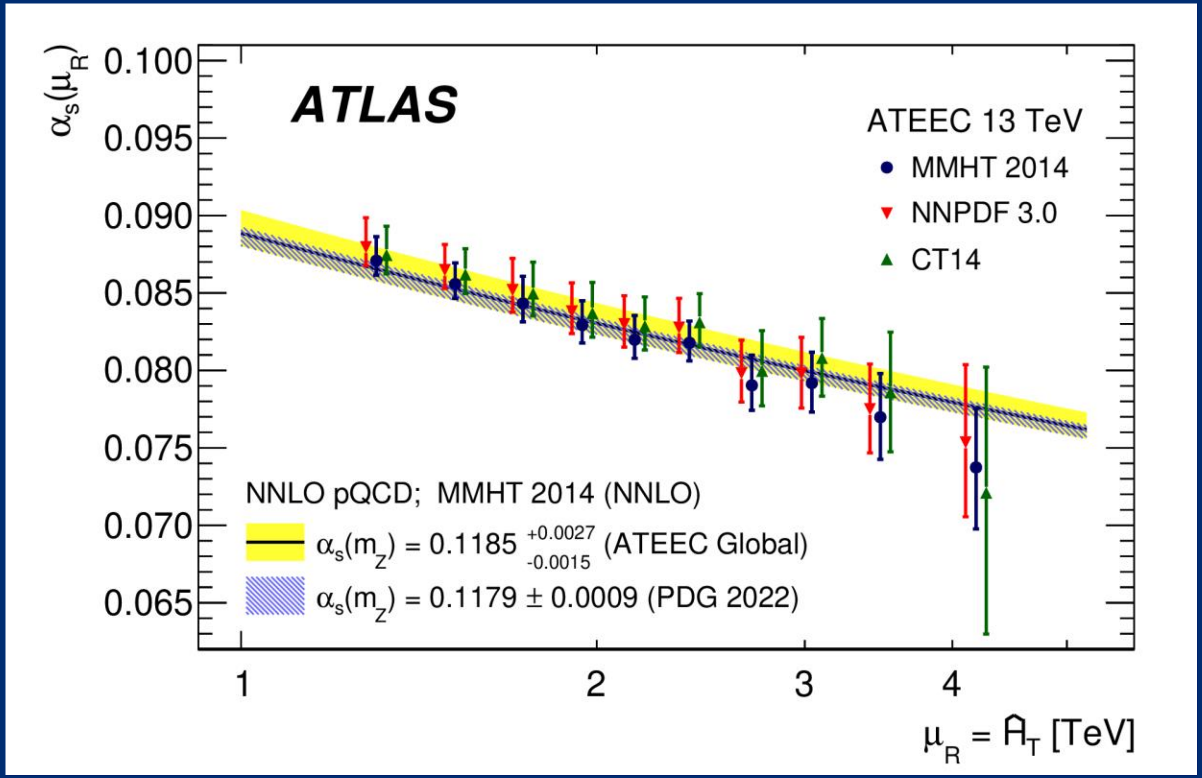
Q [GeV]	$\alpha_S(Q)$	Total uncert.	Stat.	Exp. correlated	Non-perturb. corrections	MMHT2014 uncertainty	PDF set	$\mu_{R,F}$ variation
262.5	0.1029	$^{+6.0}_{-2.8}$	±1.6	$^{+1.6}_{-1.7}$	$^{+0.4}_{-0.4}$	$^{+0.4}_{-0.4}$	$^{+1.4}_{-0.9}$	$^{+5.3}_{-0.2}$
337.5	0.0970	$^{+8.0}_{-2.6}$	±1.8	$^{+1.5}_{-1.5}$	$^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+3.0}_{-0.5}$	$^{+7.0}_{-0.7}$
412.5	0.0936	$^{+4.0}_{-2.2}$	±0.9	$^{+1.3}_{-1.3}$	$^{+0.3}_{-0.3}$	$^{+0.3}_{-0.3}$	$^{+2.6}_{-1.4}$	$^{+2.5}_{-0.2}$
500.0	0.0901	$^{+3.7}_{-1.5}$	±0.6	$^{+1.2}_{-1.2}$	$^{+0.2}_{-0.2}$	$^{+0.3}_{-0.3}$	$^{+1.9}_{-0.3}$	$^{+2.9}_{-0.6}$
625.0	0.0890	$^{+3.9}_{-1.8}$	±0.5	$^{+1.1}_{-1.1}$	$^{+0.1}_{-0.1}$	$^{+0.3}_{-0.4}$	$^{+1.7}_{-0.3}$	$^{+3.3}_{-1.3}$
800.0	0.0850	$^{+5.9}_{-2.2}$	±0.6	$^{+1.0}_{-1.1}$	$^{+0.1}_{-0.1}$	$^{+0.4}_{-0.4}$	$^{+4.6}_{-0.2}$	$^{+3.5}_{-1.8}$
1000	0.0856	$^{+4.0}_{-2.7}$	±1.2	$^{+1.1}_{-1.1}$	$^{+0.1}_{-0.1}$	$^{+0.4}_{-0.4}$	$^{+1.4}_{-0.4}$	$^{+3.4}_{-2.0}$
1225	0.0790	$^{+4.6}_{-3.5}$	±2.5	$^{+1.2}_{-1.2}$	$^{+0.1}_{-0.1}$	$^{+0.5}_{-0.5}$	$^{+1.6}_{-0.4}$	$^{+3.2}_{-1.9}$
1675	0.0723	$^{+7.0}_{-8.6}$	±6.1	$^{+1.3}_{-1.2}$	$< \pm0.1$	$^{+0.5}_{-0.5}$	$^{+1.7}_{-5.1}$	$^{+2.8}_{-1.6}$



FORTE

TEEC α_S extraction





TEEC α_s extraction

TEEC

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