Jet Correlation Measurements at ATLAS and the determination of the strong coupling constant

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On behalf of the ATLAS Collaboration

Overview

Why multi-jet cross section ratios?

The measured quantity

Measurement results

The strong coupling constant

Extraction procedure

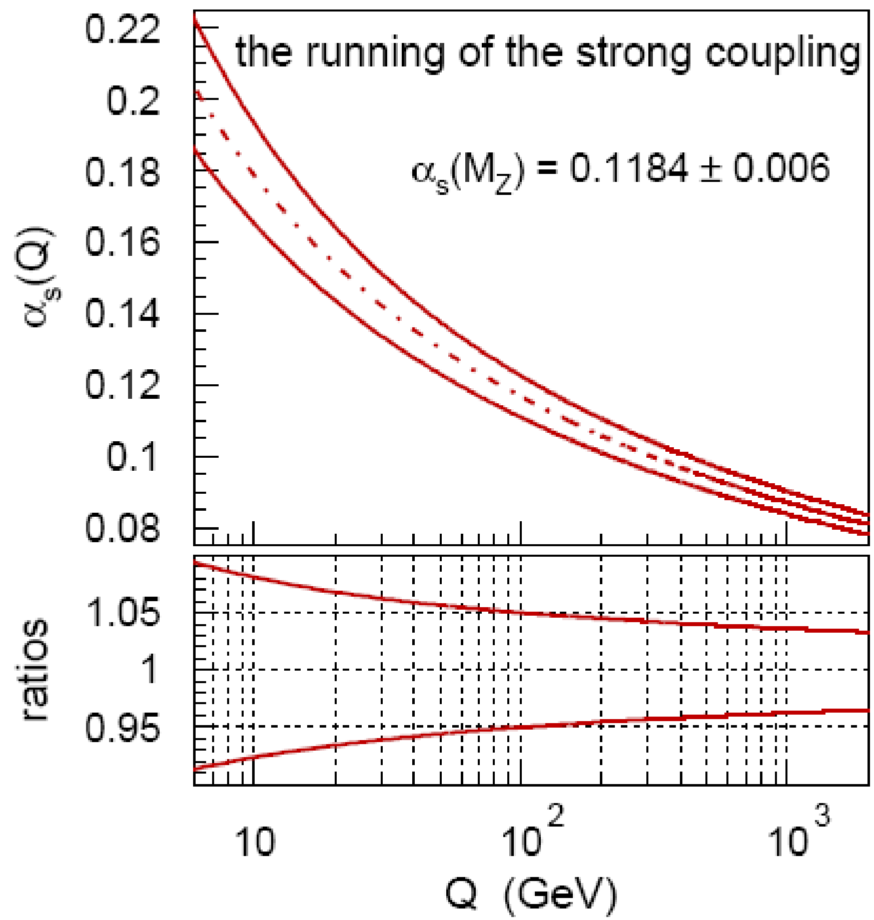
Results

The strong coupling and the RGE

$\alpha_s(\mu_R)$ depends on renormalization scale μ_R

μ_R dependence is predicted by Renormalization Group Equation (RGE)

Values of $\alpha_s(\mu_R)$ are not predicted

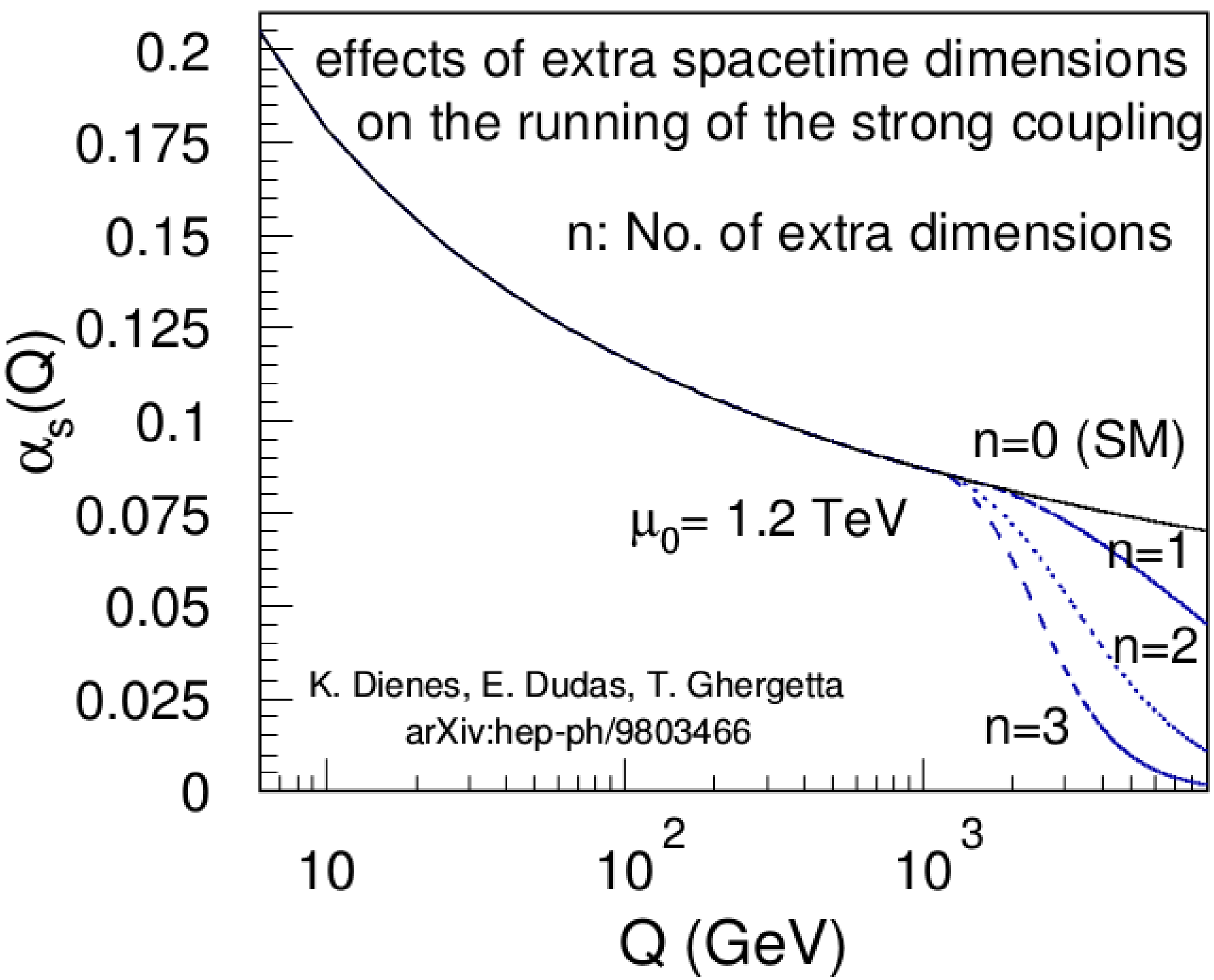


QCD tests → 2 aspects:

- **Determine the value of α_s → $\alpha_s(M_Z)$**
- **test the predictions for its running**

Why we care

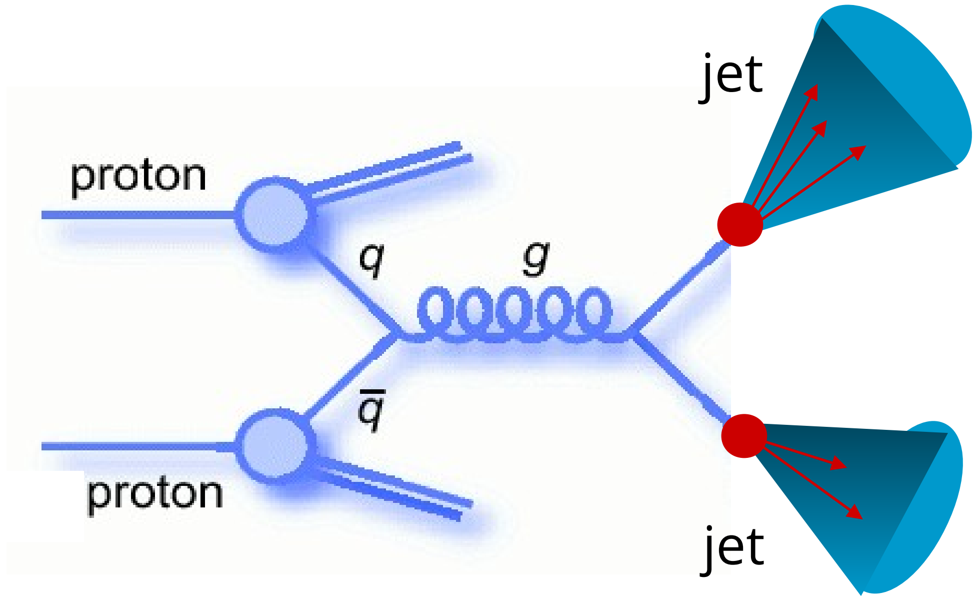
RGE of pQCD may not tell the full story



RGE may be modified by New Physics

e.g. effects from extra spacetime dimensions:
→ Modified running of $\alpha_s(Q)$ at high Q

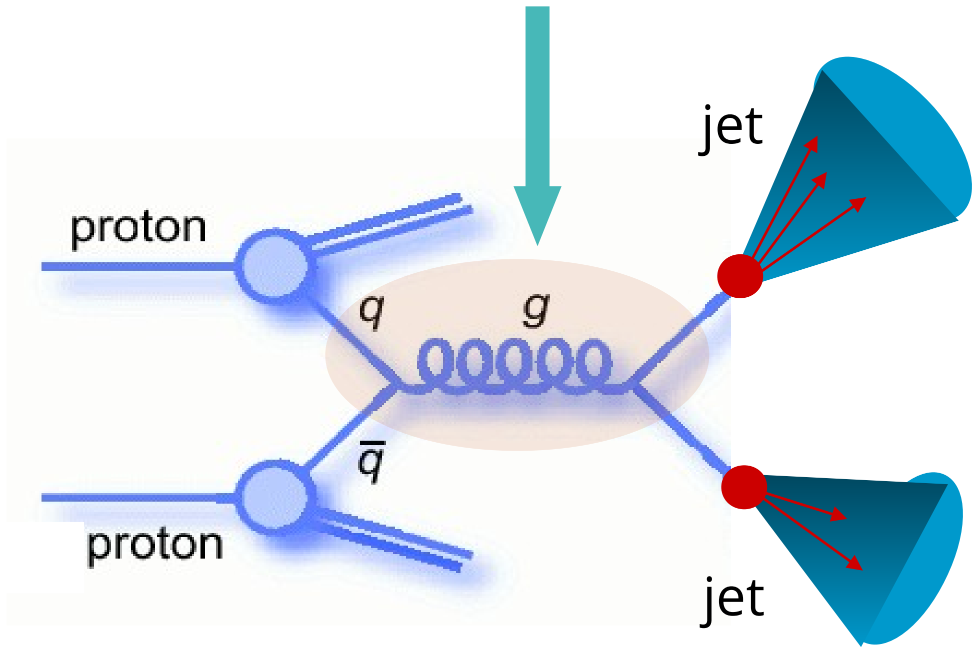
Jet production at a hadron collider



Jet production at a hadron collider

Matrix Elements

Standard Model or New Physics?



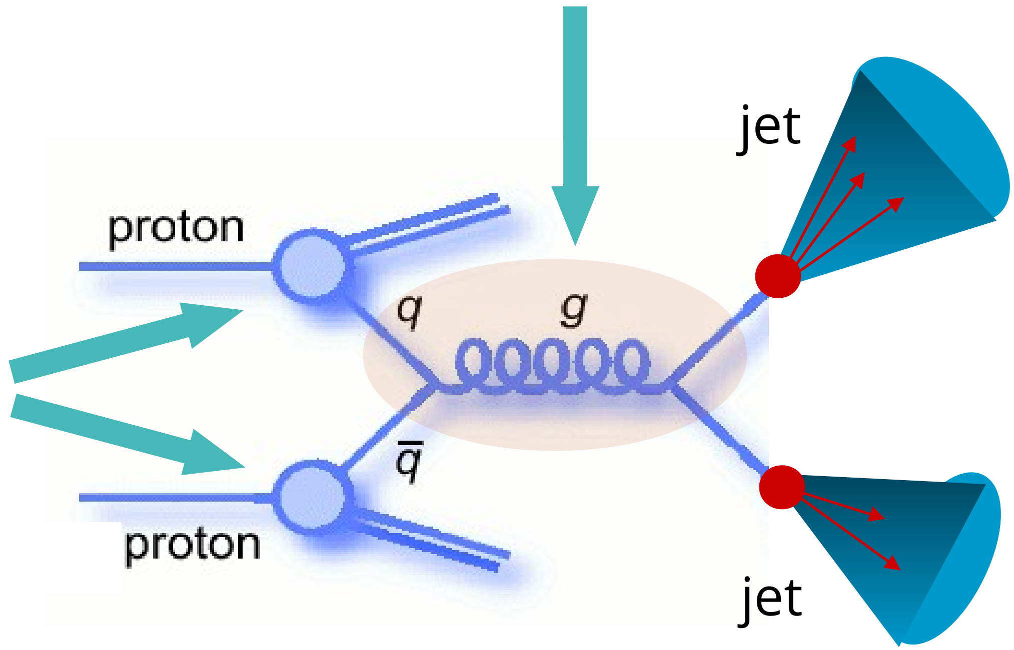
Jet production at a hadron collider

Matrix Elements

Standard Model or New Physics?

Parton distribution functions

Values? Evolution?
Universality?



Jet production at a hadron collider

Matrix Elements

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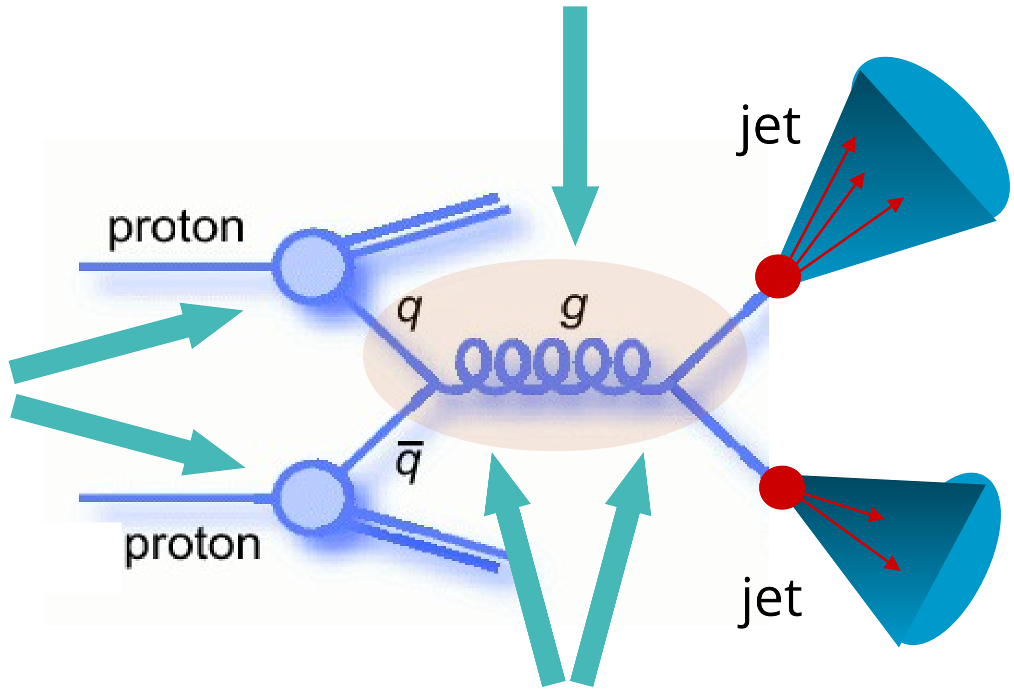


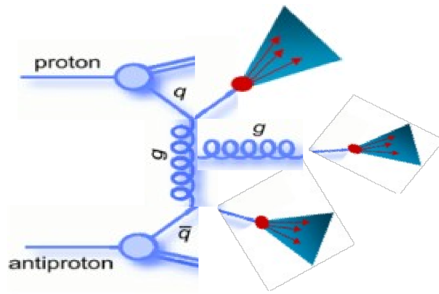
Strong coupling α_s

Value? Evolution? Universality?

Ratios of Multi-Jet Cross Sections

3-jet / 2-jet ratios

$R =$



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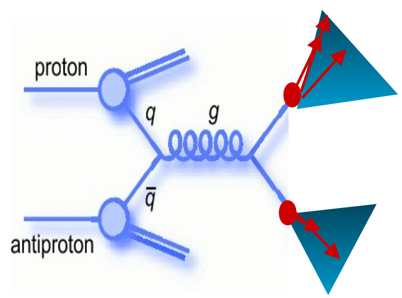

$\Leftrightarrow \alpha_s$

- sensitive to α_s (3-jets: α_s^3 | 2-jets: α_s^2)
- less sensitive to PDFs & exp. uncertainties (cancellations)

Transverse Energy-Energy Correlations

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Transverse enery-energy correlations (TEEC)
Associated asymmetry (ATEEC)

- Energy-Energy Correlations = Energy-weighted angular correlations
- Event shape → independent of thrust axis or sphericity tensor
- Transverse version → use at hadron colliders
- Calculated to NLO pQCD

TEEC:

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

- Sum: over all pairs of jets i,j
- Φ_{ij} : azimuthal angle between i,j

$$x_{\mathrm{T}i} = E_{\mathrm{T}i}/E_{\mathrm{T}} \qquad E_{\mathrm{T}} = \sum_i E_{\mathrm{T}i}$$

ATEEC:

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

TEEC / ATEEC Measurement

Data set

ATLAS data at sqrt(s) = 8 TeV with $L = 20.2\ \text{fb}^{-1}$

Single-jet trigger $E_T > 360$ GeV

Phase space

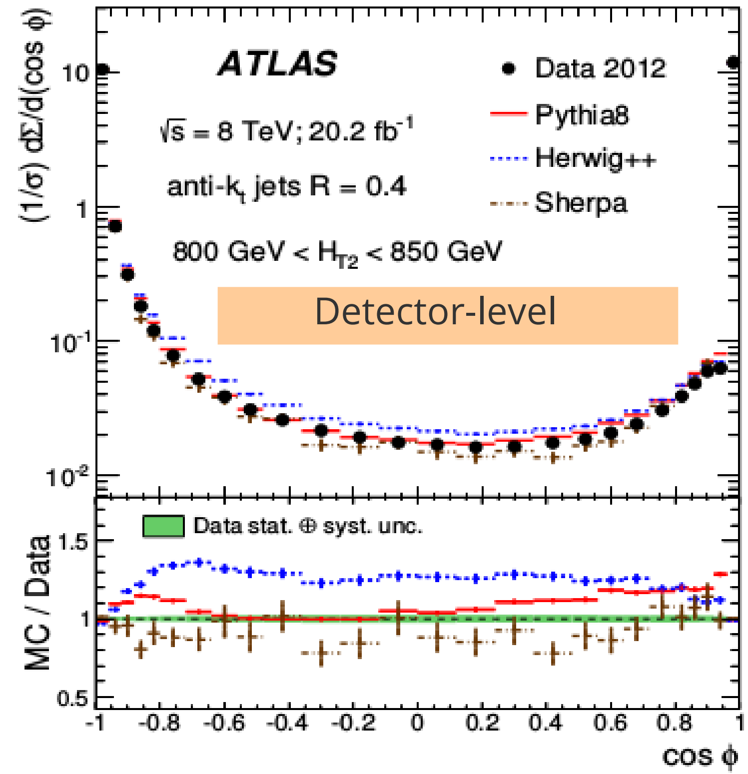
Jets with $p_T > 100$ GeV, $|\eta| < 2.5$

$H_{T2} = (p_{T1} + p_{T2}) > 800$ GeV

Measurement

Normalized distribution in $\cos(\phi)$ and H_{T2}

Distributions unfolded to particle level



Event weights

$$w_{ij} = x_{\mathrm{T}i} x_{\mathrm{T}j} = \frac{E_{\mathrm{T}i} E_{\mathrm{T}j}}{\left(\sum_k E_{\mathrm{T}k}\right)^2}$$

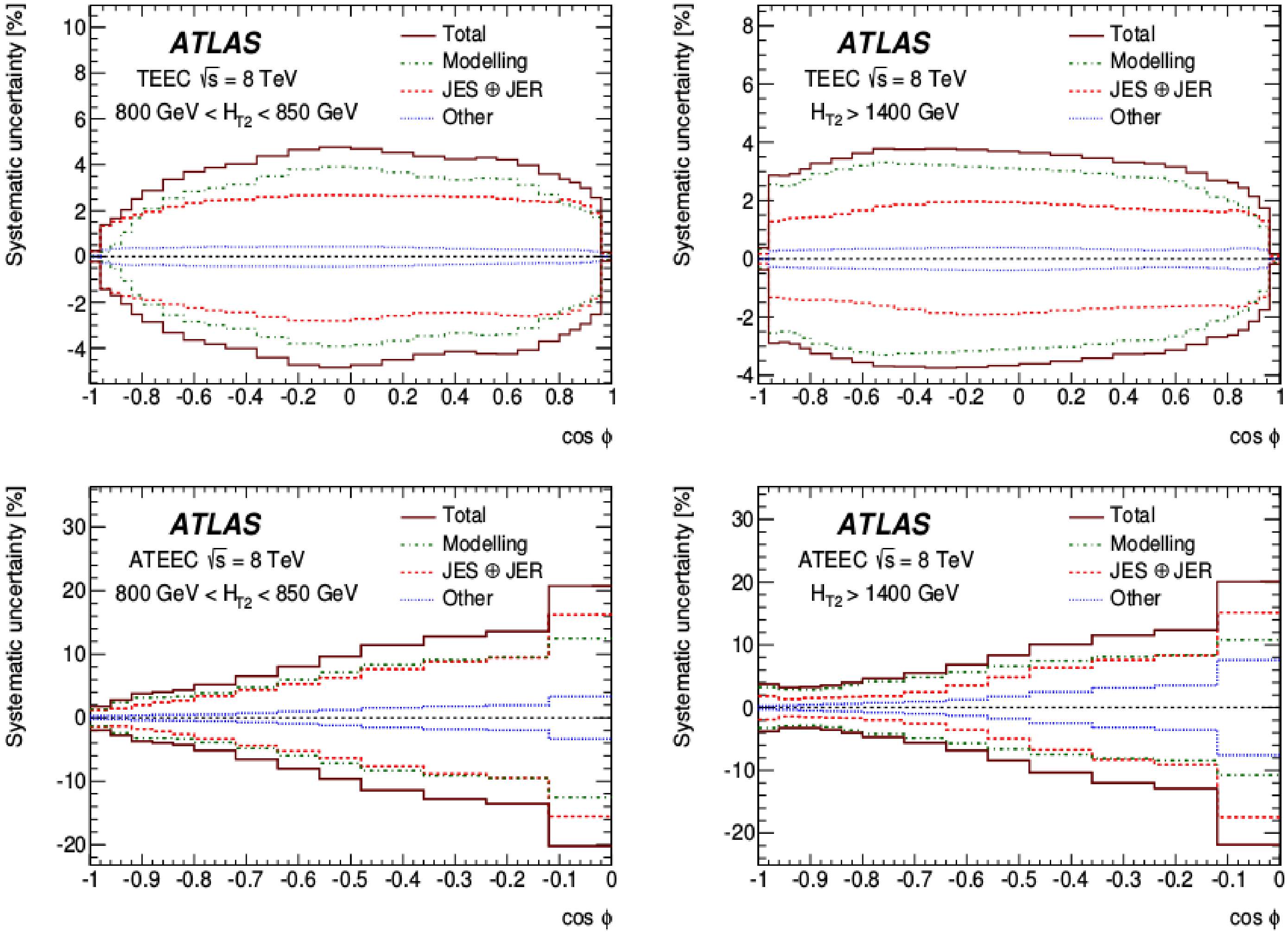
TEEC / ATEEC Syst. Uncertainties

TEEC (top)

ATEEC (bottom)

Lowest H_{T2} (L)

Highest H_{T2} (R)



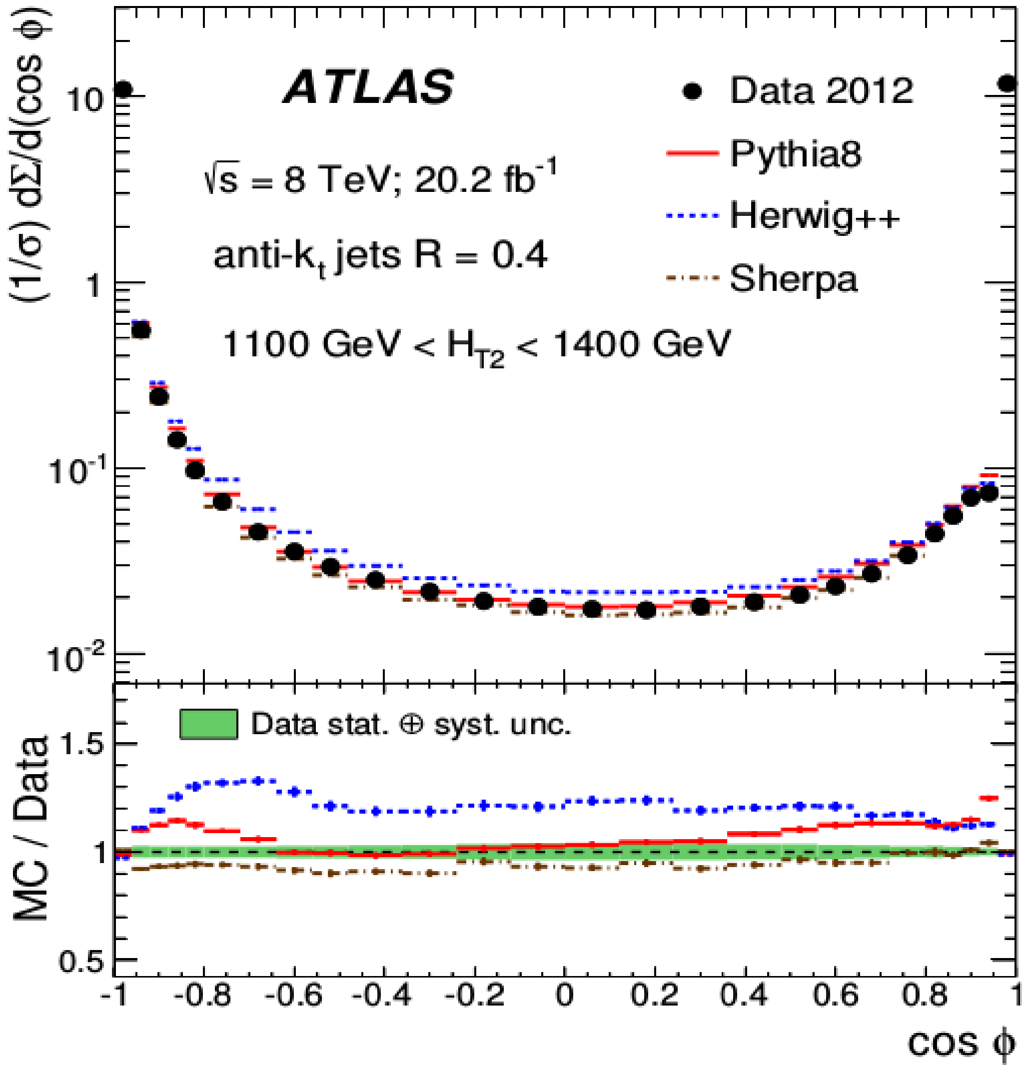
Systematic uncertainties for TEEC are always below 5%

→ Jet energy calibration uncertainties cancel partially in ratio

Measurement Results TEEC

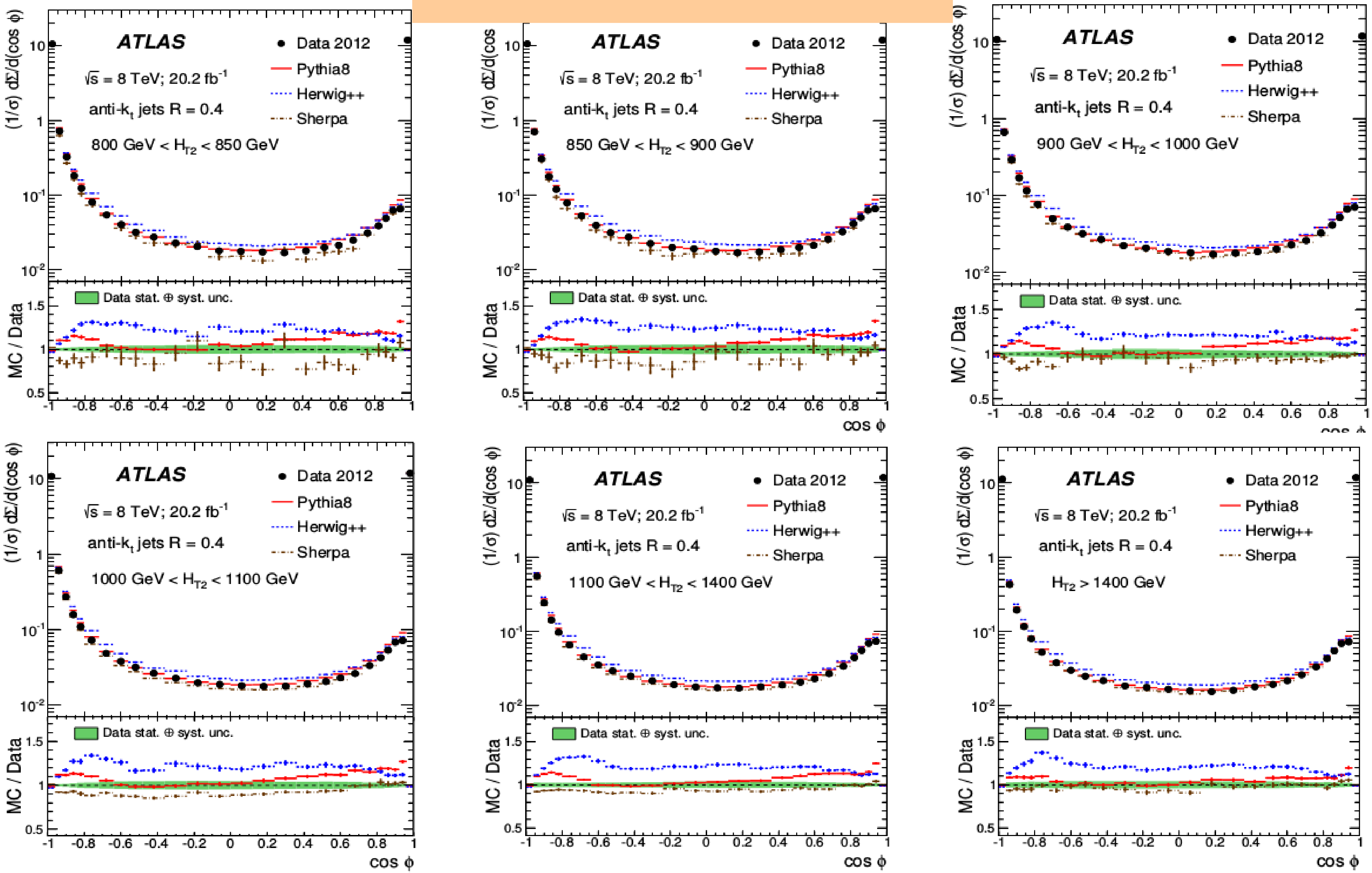
Data vs. Monte Carlo

Well described by PYTHIA8



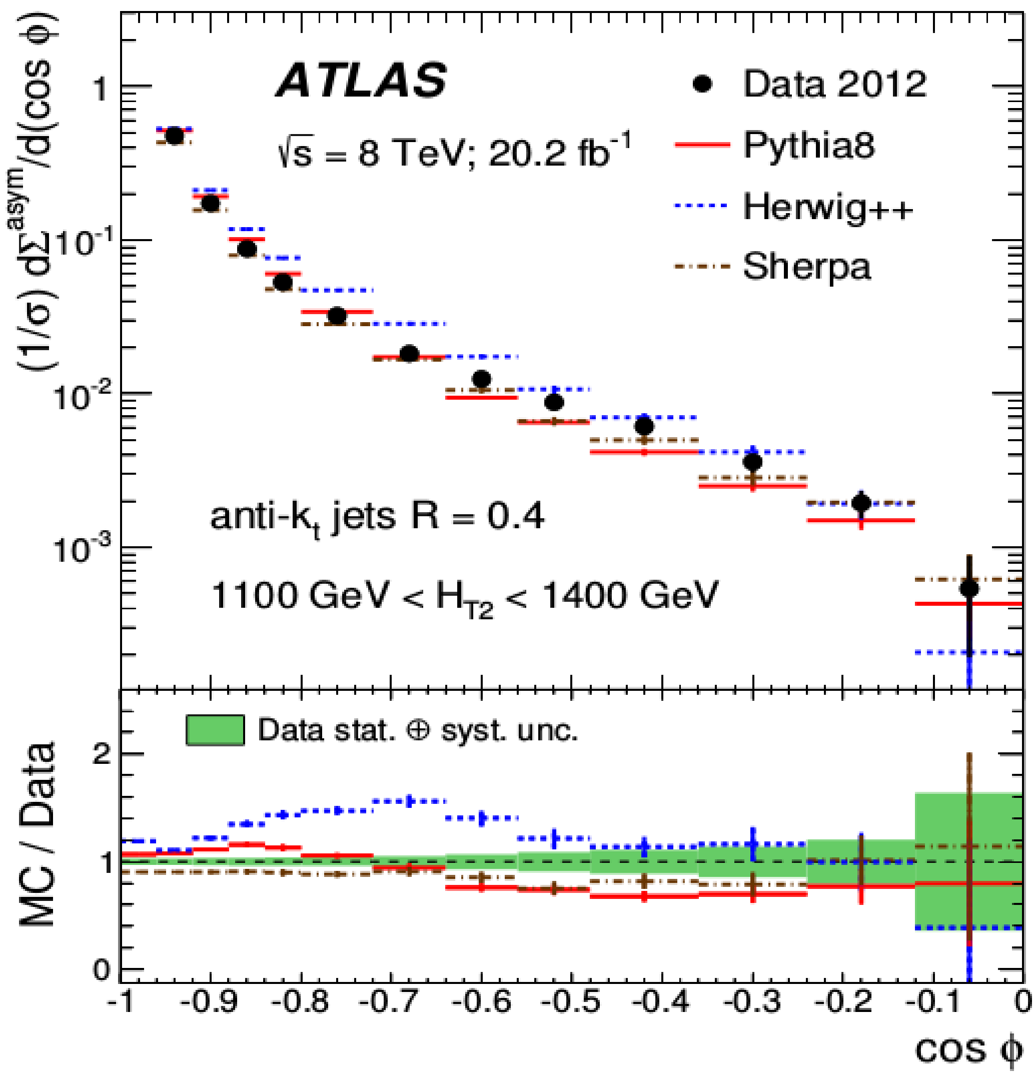
Measurement Results TEEC

Data vs. Monte Carlo



Measurement Results ATEEC

Data vs. Monte Carlo



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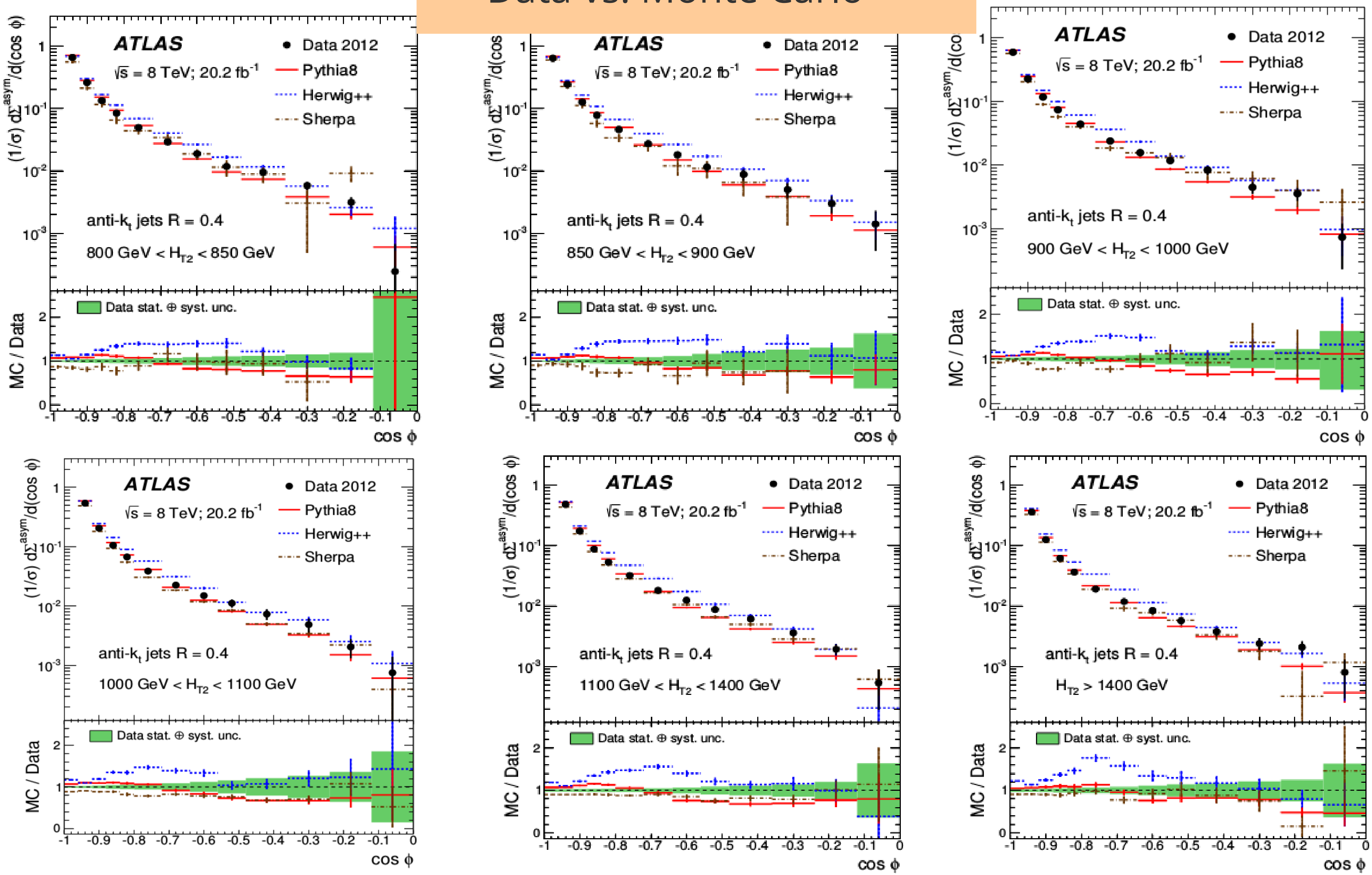
Measurement Results ATEEC

Data vs. Monte Carlo



Theory Predictions

NLO pQCD

NLOjet++ (massless quarks, $n_f = 5$)

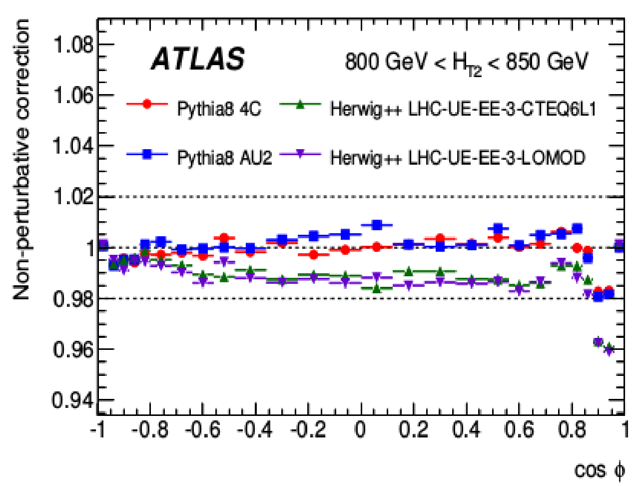
renormalization scale: $H_{T2} / 2$ factorization scale: $H_{T2}/4$

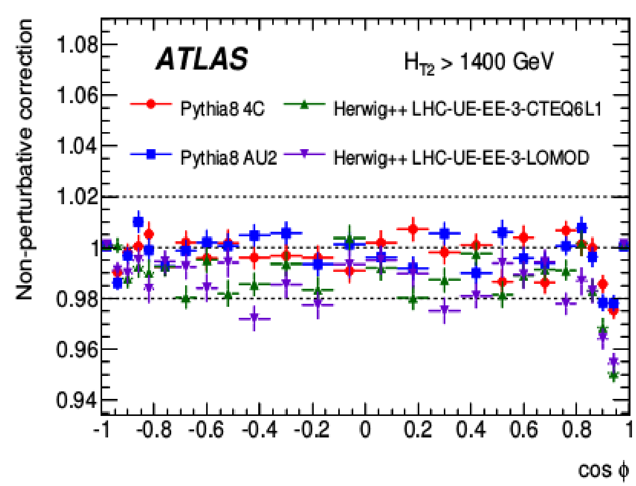
PDFs: MMHT2014, CT14, NNPDF3.0, HERAPDF2.0

Non-perturbative corrections

PYTHIA8 tunes: **AU2** (nominal), 4C

HERWIG++ tunes: LHC-UE-EE-3-CTEQ6L1, LHC-UE-EE-3-LOMOD



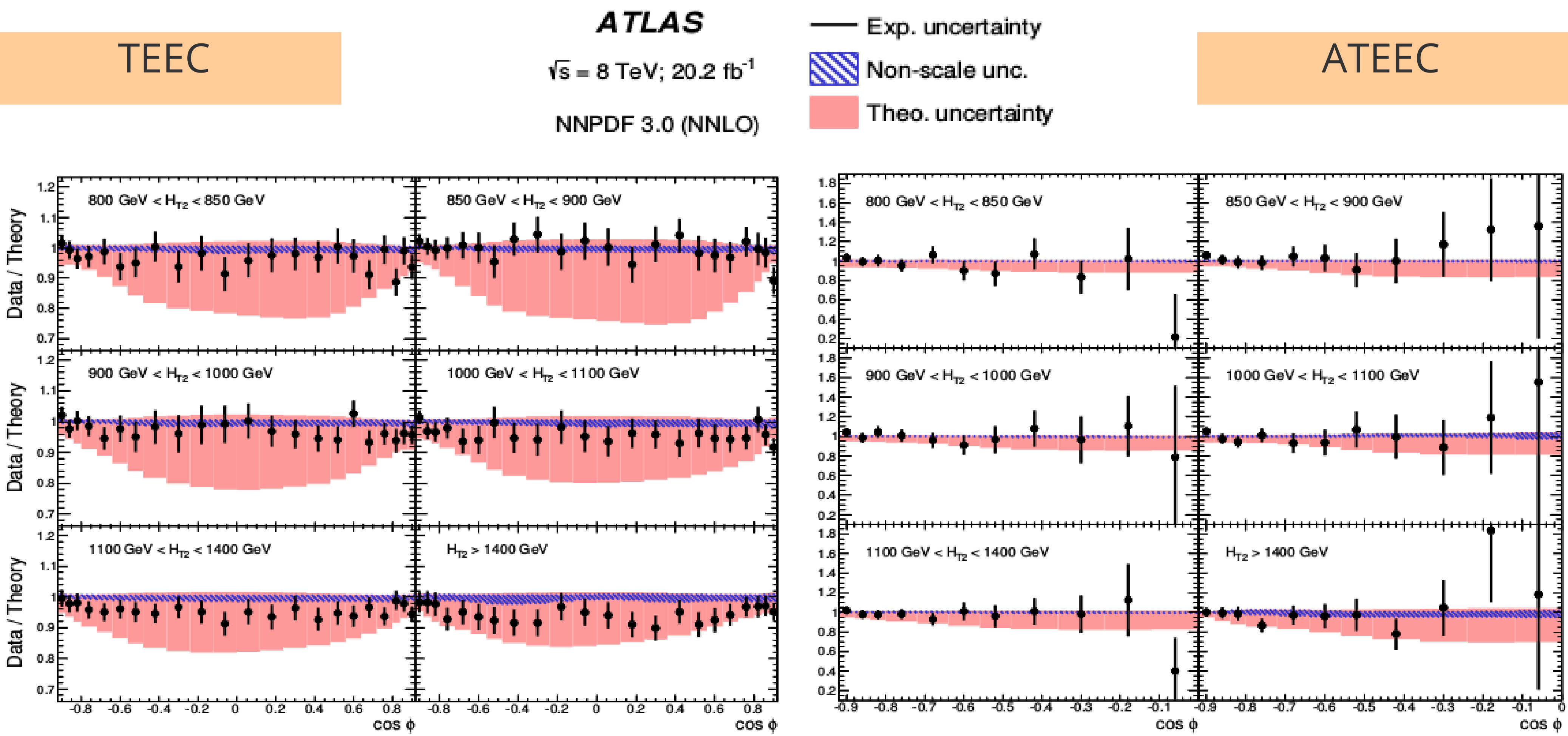


Non-pert corrections for TEEC < 2%

Data / pQCD Theory Comparison

TEEC

ATEEC



Good agreement within theoretical uncertainty from scale dependence

→ <10% for $|\cos\phi| > 0.7$ → up to 20% for $|\cos\phi| < 0.3$

Determination of α_s

Minimize χ^2 function

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

Hessian approach

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

Combine data within each HT2 range → 6 sets → 6 α_s results

TEEC

$\langle Q \rangle$ (GeV)	$\alpha_s(Q^2)$ value (NNPDF 3.0)
412	0.0966 ± 0.0014 (exp.) $^{+0.0054}_{-0.0015}$ (scale) ± 0.0009 (PDF) ± 0.0001 (NP)
437	0.0964 ± 0.0012 (exp.) $^{+0.0048}_{-0.0011}$ (scale) ± 0.0009 (PDF) ± 0.0002 (NP)
472	0.0955 ± 0.0011 (exp.) $^{+0.0051}_{-0.0015}$ (scale) ± 0.0009 (PDF) ± 0.0001 (NP)
522	0.0936 ± 0.0011 (exp.) $^{+0.0043}_{-0.0010}$ (scale) ± 0.0010 (PDF) ± 0.0001 (NP)
604	0.0933 ± 0.0011 (exp.) $^{+0.0050}_{-0.0014}$ (scale) ± 0.0011 (PDF) ± 0.0003 (NP)
810	0.0907 ± 0.0013 (exp.) $^{+0.0049}_{-0.0020}$ (scale) ± 0.0011 (PDF) ± 0.0002 (NP)

$\langle Q \rangle$ (GeV)	$\alpha_s(m_Z)$ value (NNPDF 3.0)	χ^2/N_{dof}
412	0.1171 ± 0.0021 (exp.) $^{+0.0081}_{-0.0022}$ (scale) ± 0.0013 (PDF) ± 0.0001 (NP)	24.3 / 21
437	0.1178 ± 0.0017 (exp.) $^{+0.0073}_{-0.0017}$ (scale) ± 0.0014 (PDF) ± 0.0002 (NP)	28.3 / 21
472	0.1177 ± 0.0017 (exp.) $^{+0.0079}_{-0.0023}$ (scale) ± 0.0015 (PDF) ± 0.0001 (NP)	27.7 / 21
522	0.1163 ± 0.0017 (exp.) $^{+0.0067}_{-0.0016}$ (scale) ± 0.0016 (PDF) ± 0.0001 (NP)	22.8 / 21
604	0.1181 ± 0.0017 (exp.) $^{+0.0082}_{-0.0022}$ (scale) ± 0.0017 (PDF) ± 0.0005 (NP)	24.3 / 21
810	0.1186 ± 0.0023 (exp.) $^{+0.0085}_{-0.0035}$ (scale) ± 0.0020 (PDF) ± 0.0004 (NP)	23.7 / 21

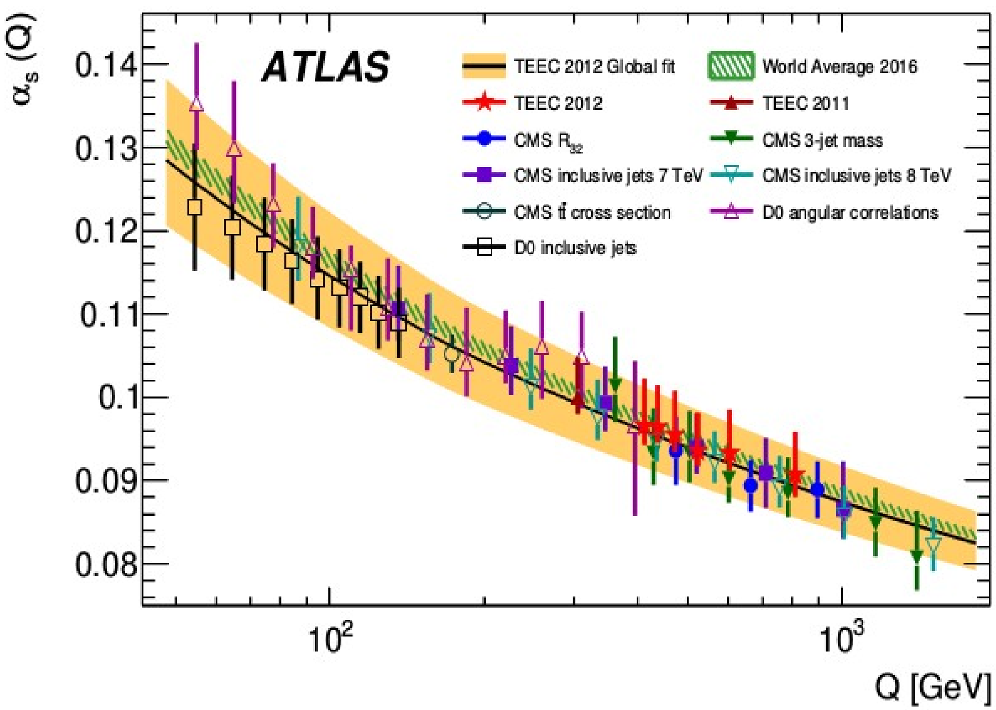
ATEEC

$\langle Q \rangle$ (GeV)	$\alpha_s(Q^2)$ value (NNPDF 3.0)
412	0.0992 ± 0.0024 (exp.) $^{+0.0056}_{-0.0020}$ (scale) ± 0.0009 (PDF) ± 0.0002 (NP)
437	0.0986 ± 0.0017 (exp.) $^{+0.0041}_{-0.0009}$ (scale) ± 0.0010 (PDF) ± 0.0007 (NP)
472	0.0973 ± 0.0018 (exp.) $^{+0.0038}_{-0.0008}$ (scale) ± 0.0010 (PDF) ± 0.0001 (NP)
522	0.0957 ± 0.0016 (exp.) $^{+0.0034}_{-0.0006}$ (scale) ± 0.0011 (PDF) ± 0.0003 (NP)
604	0.0930 ± 0.0019 (exp.) $^{+0.0035}_{-0.0005}$ (scale) ± 0.0012 (PDF) ± 0.0003 (NP)
810	0.0899 ± 0.0021 (exp.) $^{+0.0031}_{-0.0005}$ (scale) ± 0.0013 (PDF) ± 0.0001 (NP)

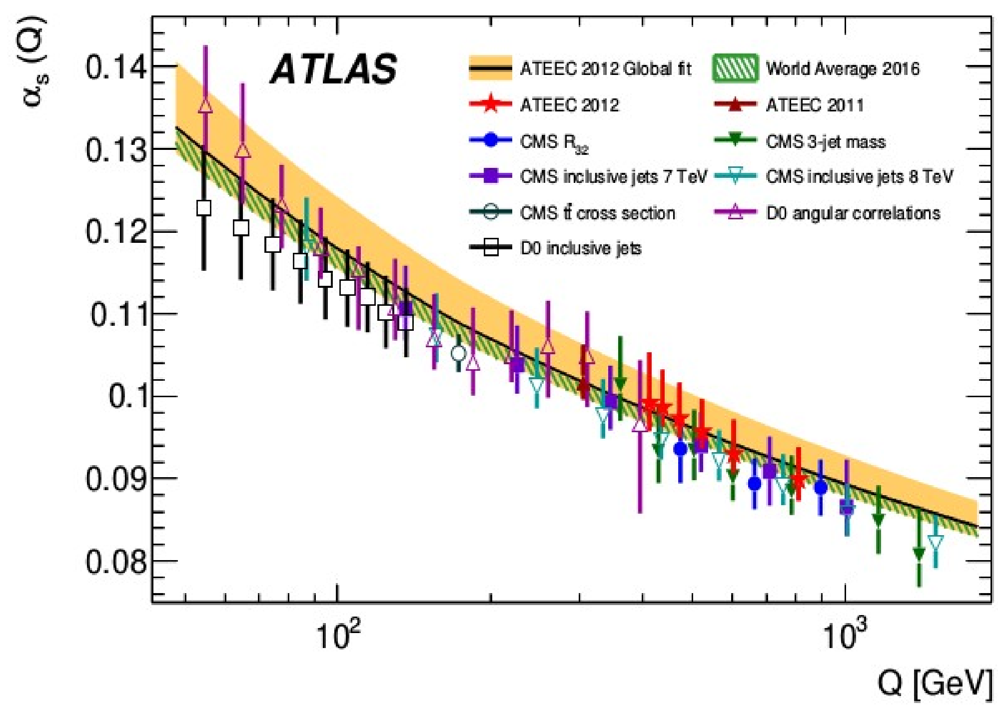
$\langle Q \rangle$ (GeV)	$\alpha_s(m_Z)$ value (NNPDF 3.0)	χ^2/N_{dof}
412	0.1209 ± 0.0036 (exp.) $^{+0.0085}_{-0.0031}$ (scale) ± 0.0013 (PDF) ± 0.0004 (NP)	10.6 / 10
437	0.1211 ± 0.0026 (exp.) $^{+0.0064}_{-0.0014}$ (scale) ± 0.0015 (PDF) ± 0.0010 (NP)	6.8 / 10
472	0.1203 ± 0.0028 (exp.) $^{+0.0060}_{-0.0013}$ (scale) ± 0.0016 (PDF) ± 0.0002 (NP)	8.8 / 10
522	0.1196 ± 0.0025 (exp.) $^{+0.0054}_{-0.0010}$ (scale) ± 0.0017 (PDF) ± 0.0004 (NP)	10.9 / 10
604	0.1176 ± 0.0031 (exp.) $^{+0.0058}_{-0.0008}$ (scale) ± 0.0020 (PDF) ± 0.0005 (NP)	6.4 / 10
810	0.1172 ± 0.0037 (exp.) $^{+0.0053}_{-0.0009}$ (scale) ± 0.0022 (PDF) ± 0.0001 (NP)	9.8 / 10

Determination of $\alpha_s(Q)$

TEEC



ATEEC



Consistency with RGE predictions
& with results from other experiments

Determination of $\alpha_s(m_Z)$

ATLAS

TEEC

PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}
MMHT 2014	$0.1151 \pm 0.0008\ (\text{exp.})\ ^{+0.0064}_{-0.0047}\ (\text{scale}) \pm 0.0012\ (\text{PDF}) \pm 0.0002\ (\text{NP})$	173 / 131
CT14	$0.1165 \pm 0.0010\ (\text{exp.})\ ^{+0.0067}_{-0.0061}\ (\text{scale}) \pm 0.0016\ (\text{PDF}) \pm 0.0003\ (\text{NP})$	161 / 131
NNPDF 3.0	$0.1162 \pm 0.0011\ (\text{exp.})\ ^{+0.0076}_{-0.0061}\ (\text{scale}) \pm 0.0018\ (\text{PDF}) \pm 0.0003\ (\text{NP})$	174 / 131
HERAPDF 2.0	$0.1177 \pm 0.0008\ (\text{exp.})\ ^{+0.0064}_{-0.0040}\ (\text{scale}) \pm 0.0005\ (\text{PDF}) \pm 0.0002\ (\text{NP})\ ^{+0.0008}_{-0.0007}\ (\text{mod})$	169 / 131

$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\ (\text{exp.})\ ^{+0.0076}_{-0.0061}\ (\text{scale}) \pm 0.0018\ (\text{PDF}) \pm 0.0003\ (\text{NP}).$$

ATEEC

PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}
MMHT 2014	$0.1185 \pm 0.0012\ (\text{exp.})\ ^{+0.0047}_{-0.0010}\ (\text{scale}) \pm 0.0010\ (\text{PDF}) \pm 0.0004\ (\text{NP})$	57.0 / 65
CT14	$0.1203 \pm 0.0013\ (\text{exp.})\ ^{+0.0053}_{-0.0014}\ (\text{scale}) \pm 0.0015\ (\text{PDF}) \pm 0.0004\ (\text{NP})$	55.4 / 65
NNPDF 3.0	$0.1196 \pm 0.0013\ (\text{exp.})\ ^{+0.0061}_{-0.0013}\ (\text{scale}) \pm 0.0017\ (\text{PDF}) \pm 0.0004\ (\text{NP})$	60.3 / 65
HERAPDF 2.0	$0.1206 \pm 0.0012\ (\text{exp.})\ ^{+0.0050}_{-0.0014}\ (\text{scale}) \pm 0.0005\ (\text{PDF}) \pm 0.0002\ (\text{NP}) \pm 0.0007\ (\text{mod})$	54.2 / 65

$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\ (\text{exp.})\ ^{+0.0061}_{-0.0013}\ (\text{scale}) \pm 0.0017\ (\text{PDF}) \pm 0.0004\ (\text{NP})$$

Consistent with each other & with world average (0.1181 +- 0.0011)

Summary

ATLAS, Eur.Phys.J. C77 (2017) 12, 872

Measurement of transverse energy-energy correlations & asymmetry

- 2012 ATLAS data, sqrt(s) = 8 TeV, L = 20.2 fb^{-1}
- Small experimental uncertainties for TEEC
- Reasonably well described by different MCs & NLO pQCD + non-pert.
- Determinations of $\alpha_s(Q)$ and $\alpha_s(m_Z)$
- Fits, combining all different H_{T2} regions:

$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\ (\text{exp.})\ ^{+0.0076}_{-0.0061}\ (\text{scale}) \pm 0.0018\ (\text{PDF}) \pm 0.0003\ (\text{NP}),$$
$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\ (\text{exp.})\ ^{+0.0061}_{-0.0013}\ (\text{scale}) \pm 0.0017\ (\text{PDF}) \pm 0.0004\ (\text{NP}),$$

Good agreement with previous results, world average and RGE predictions