Multijet and multi-differential dijet measurements with ATLAS and CMS

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On behalf of ATLAS and CMS collaborations

University of Ioannina

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Outline

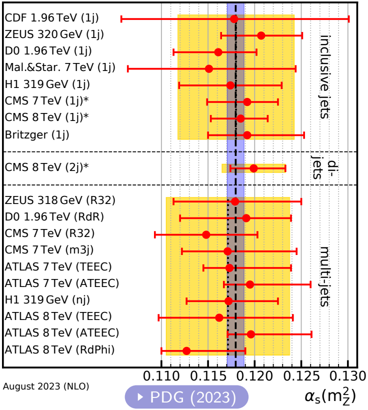
1. Motivation
2. ATLAS measurements
   - (Azimuthal Asymmetry)Transverse Energy-Energy Correlations [1]
   - Jet cross section ratios[2]
3. CMS measurements
   - Azimuthal correlations ($R_{\Delta\phi}$)[3]
   - Multi-differential dijet cross sections[4]
4. Summary & Conclusions

[1] JHEP 07 (2023) 85
[2] arXiv:2405.20206, submitted to PRD
[3] EPJC 84, 842 (2024)
[4] arXiv:2312.16669, submitted to EPJC

Motivation

Jet measurements

- Study of QCD (precision measurements)
- Extraction of $\alpha_S(m_Z)$, running of $\alpha_S(Q)$
- Tune Monte Carlo event generators
- Constrain Parton Distribution Functions



PDG (2023)

In this presentation

Run 2 analyses are discussed

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Multijet cross section ratios

- Determination of the strong coupling constant $\alpha_S(m_Z)$
- Investigation of α_S running in TeV scale

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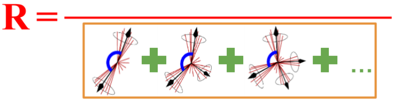

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- Determination of the strong coupling constant $\alpha_S(m_Z)$
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In ratios (R) with

- **Denominator: topologies with at least 2-jets ($\sim \alpha_s^2$ @LO)**

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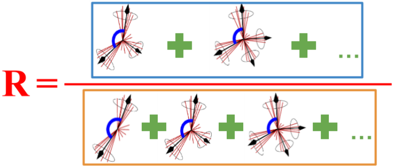

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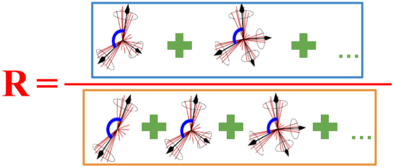

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- **Numerator: topologies with at least 3-jets ($\sim \alpha_s^3$ @LO)**

Benefits

✔ Cancellation of systematic effects e.g. luminosity
✔ Reduction of theoretical uncertainties *e.g.* non-perturbative

ATLAS - TEEC: Observable (1/2)

- Transverse Energy-Energy Correlations (TEEC)

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{T_i}^{A}E_{T_j}^{A}}{(\sum_k E_{T_k}^{A})^2}\delta(\cos\phi - \cos\phi_{ij})$$

- Normalised to σ
- Weighted by $E_T = \frac{E}{\cosh y}$
- i, j, k: indices over all jets
- ϕ_{ij}: angle in transverse plane
- N multijet events
- $\delta(x)$: Dirac function $\rightarrow \phi = \phi_{ij}$

ATLAS - TEEC: Samples and event selection

- Associated azimuthal (A)symmetries of (A)TEEC
- Cancel uncertainties symmetric in $\cos\phi$
- Difference between $\cos\phi > 0$ and $\cos\phi < 0$ of TEEC:

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

- TEEC and ATEEC sensitive to gluon radiation and α_S

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Data

Full Run 2 (2015-2018)
$\rightarrow \sqrt{s} = 13\ \mathrm{TeV},\ \mathcal{L}_{int} = 139\ \mathrm{fb}^{-1}$

Jet reconstruction (FastJet)

- **Jet algorithm:** anti-k_T
- **Jet size:** R=0.4

Event selection

- Select high-p_T jets:
  - Single-jet trigger minimum threshold: $p_T = 460$ GeV
- Phase-space selection:
  - $p_T > 60$ GeV
  - $|y| < 2.4$
  - $\boldsymbol{H_{T2} = p_{T1} + p_{T2} > 1}$ **TeV** for 2 leading jets, in bins of H_{T2}

ATLAS - TEEC: Unfolding and Systematic uncertainties

- Unfolding using iterative algorithm based on Baeysian theorem
- Parametrise probability of gen jet in bin $i \rightarrow$ rec in bin j : M_{ij} transfer matrix (from MC)
- Inverse problem: $\mathcal{R}_i = \sum_{j=1}^{N} \frac{\mathcal{E}_j}{\mathcal{P}_i} M_{ij} T_j, \quad \mathcal{E}_j(\mathcal{P}_i)$: efficiency(purity) corrections
- $\mathcal{R}_i(T_j)$: content of detector(particle) level distribution in bin $i(j)$

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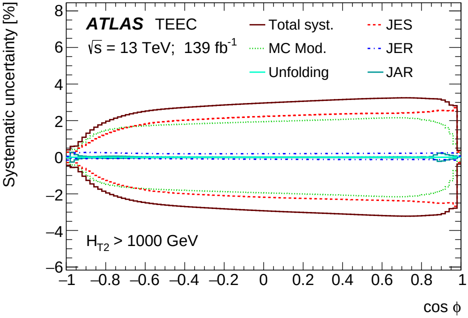
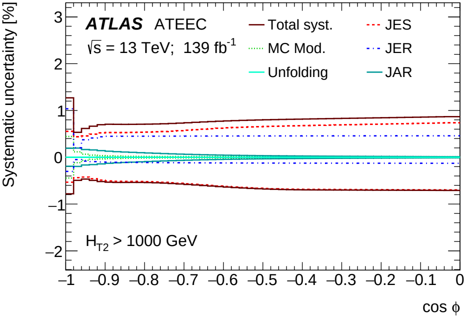
- $\mathcal{R}_i(T_j)$: content of detector(particle) level distribution in bin $i(j)$

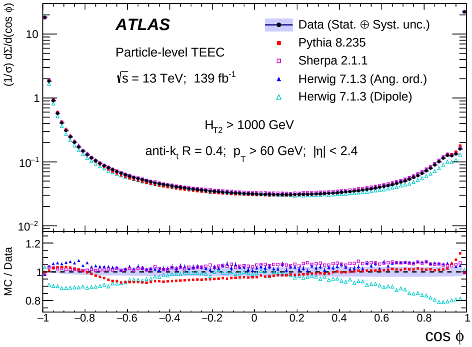
Total: 0.5-3.2% **JES: 0.5-2.5%**
Modelling: 1.5-2% **JER: $\simeq$ 0.25%**
Unfolding:$\simeq$0% **JAR$<$0.5%**



Total: 0.5-1.3% **JES: 0.4-0.7%**
Modelling: $<$0.5% **JER: $<$1%**
Unfolding:$\simeq$0% **JAR$<$0.5%**



ATLAS - (A)TEEC: Experimental results



- Two peaks: $\cos\phi = -1,\ 1$
- Central plateau: wide-angle radiation
- Kink: dependence on R
- Best description: SHERPA and HERWIG7

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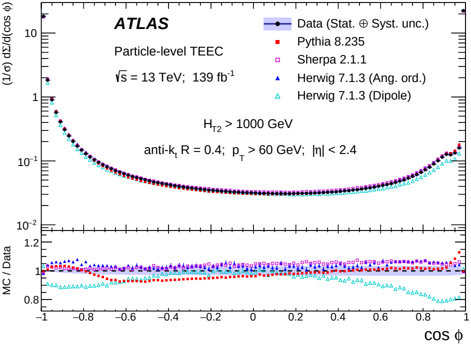

- Two peaks: $\cos\phi = -1,\ 1$
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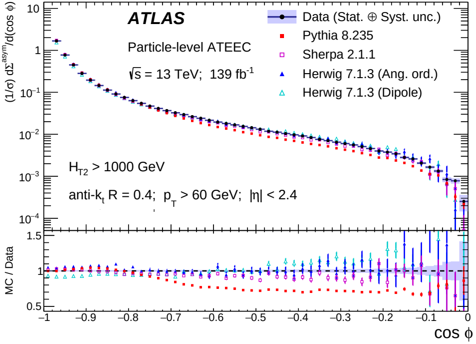
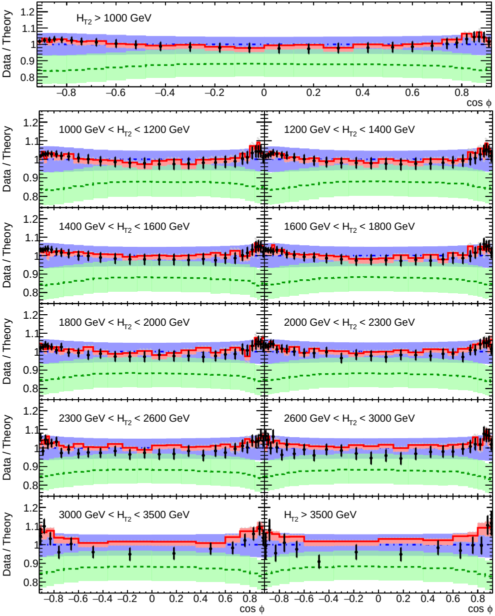
- Steeply falling distributions by several orders of magnitude
- Best description by Sherpa and Herwig7



ATLAS - TEEC: Fixed-order pQCD



ATLAS

Particle-level TEEC

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

anti-k_t R = 0.4

p_T > 60 GeV

|η| < 2.4

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

$\alpha_s(m_Z)$ = 0.1180

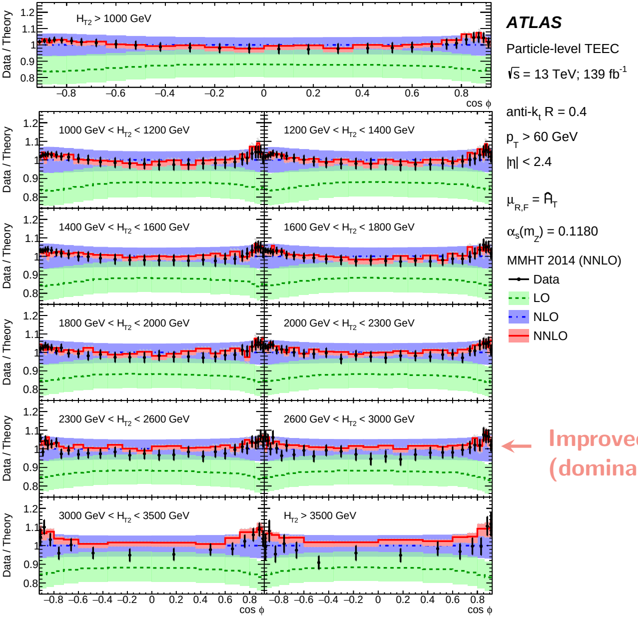
MMHT 2014 (NNLO)

- Data
- LO
- NLO
- NNLO

▸ PRL 127(2021) 152001

Predictions up to NNLO

ATLAS - TEEC: Fixed-order pQCD

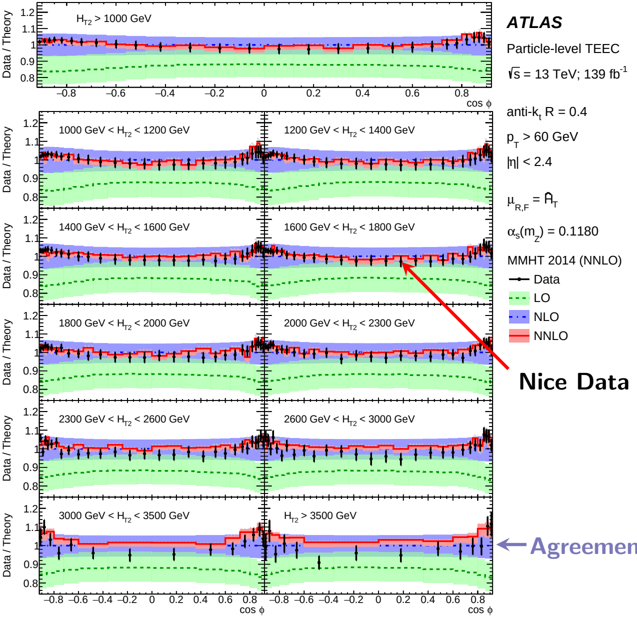


PRL 127(2021) 152001

Predictions up to NNLO

Improved scale uncertainties (dominant)

ATLAS - TEEC: Fixed-order pQCD



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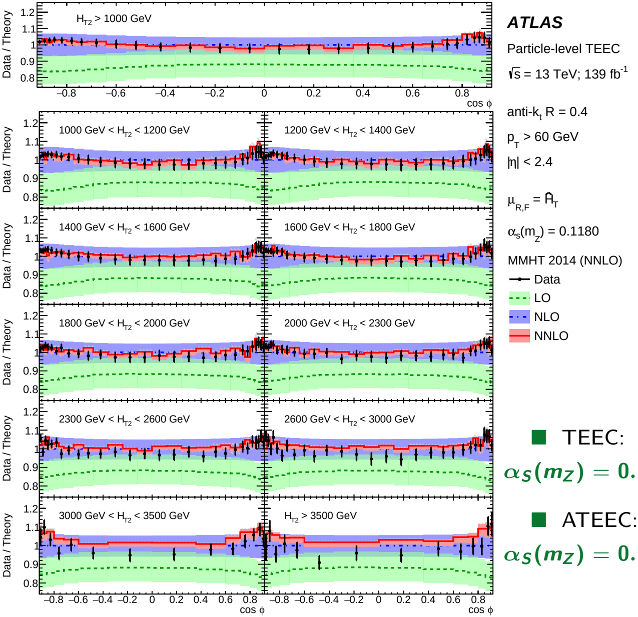
Predictions up to NNLO

Nice Data - Theory agreement

Agreement within uncertainties

ATLAS - TEEC: Fixed-order pQCD



▸ PRL 127(2021) 152001

Predictions up to NNLO

- TEEC:

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

- ATEEC:

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

ATLAS - Cross section ratios: Observable (2/2)

Measurement

- Differential cross sections of multijet events
- Ratios between different inclusive jet-multiplicity bins *e.g.* ($R_{32} = \frac{3-jet}{2-jet}$, $R_{42} = \frac{4-jet}{2-jet}$, $R_{43} = \frac{4-jet}{3-jet}$, $R_{54} = \frac{5-jet}{4-jet}$)

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Variables sensitive to energy scale

- $H_{T2} = p_{T,1} + p_{T,2}$, if 3^{rd} jet exists: varying $p_{T,3}$ thresholds to understand resummation effects
- $p_T^{N_{incl}}$: inclusive jet p_T in bins of multiplicity

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Variables sensitive to topology:

- Leading jets in the event:
  - Δy_{jj}: absolute value of rapidity difference
  - m_{jj}: invariant mass
- All selected jets in the event:
  - $\Delta y_{jj,max}$: absolute value of rapidity difference
  - $m_{jj,max}$: maximum dijet invariant mass

ATLAS - Cross section ratios: Samples and event selection

Data

Full Run 2 (2015-2018)
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Jet reconstruction (FASTJET)

- **Jet algorithm:** anti-k_T
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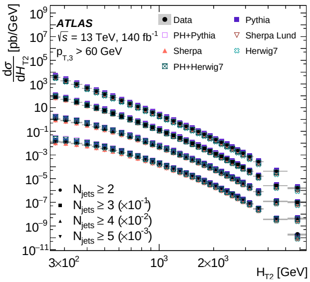
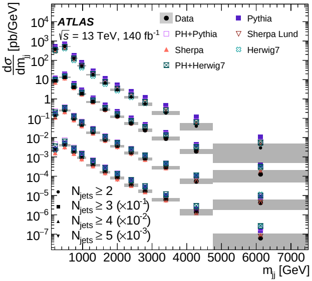
Jet reconstruction (FastJet)

- **Jet algorithm:** anti-k_T
- **Jet size:** R=0.4

Event selection

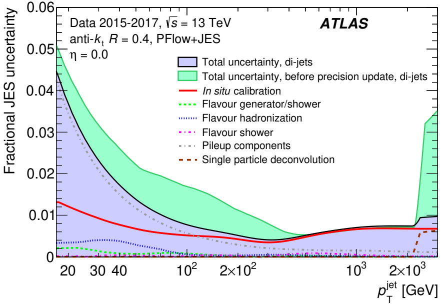
- Kinematic selection criteria to eliminate PU interactions:
  - $p_T > 60$ GeV
  - $|y| < 4.5$
- Phase-space selection:
  - $\boldsymbol{N_{jets} \geq 2}$
  - $\boldsymbol{H_{T2} = p_{T1} + p_{T2} \geq 250}$ **GeV** for leading & sub-leading jets



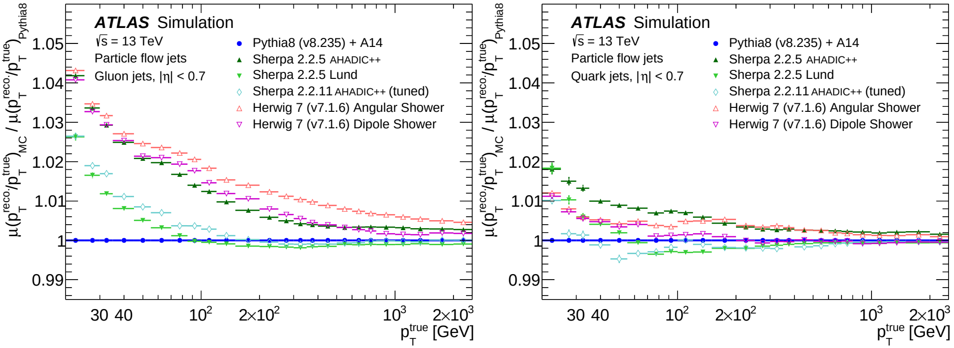


ATLAS - Cross section ratios: Precision study

- Jet energy scale calibration:
  - ➔ Dominant systematic uncertainty source
- Precision improvements:
  - ➔ Jet flavor response dependence
  - ➔ Single hadron response extrapolation to jets
- Significant reduction of JES

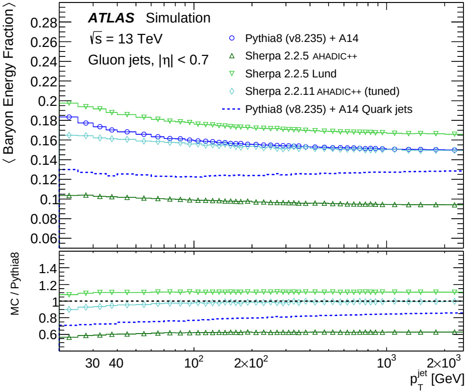


ATLAS - Cross section ratios: Jet flavor response



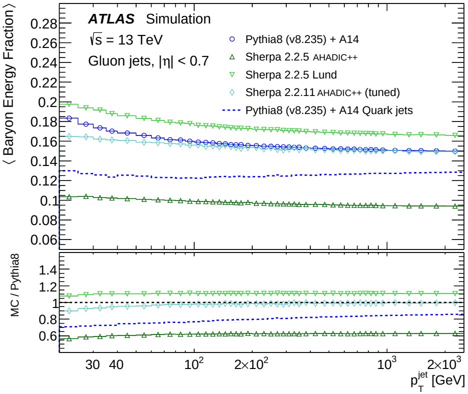
- Parton that initiated jet determines its internal dynamics
- Jet flavor response: uncertainty of actual spectra from data and relationship with JES
- Gluon-initiated jets (left): differences up to 4% with Pythia
- Quark-initiated jets (right): differences up to 1.8% with Pythia

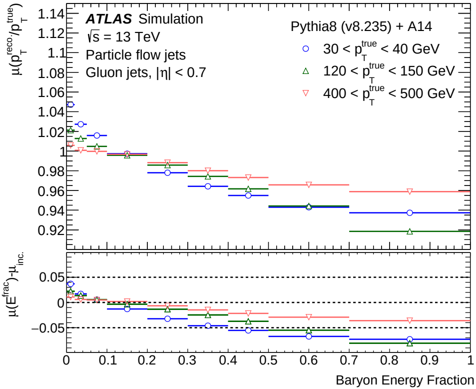
ATLAS - Cross section ratios: Jet flavor response



- Baryon energy fraction for PYTHIA: shown to illustrate the size of possible differences due to jet flavor
- For SHERPA with cluster hadronisation: lower energy fraction by baryons than PYTHIA

ATLAS - Cross section ratios: Jet flavor response





- Baryon energy fraction for PYTHIA: shown to illustrate the size of possible differences due to jet flavor
- For SHERPA with cluster hadronisation: lower energy fraction by baryons than PYTHIA

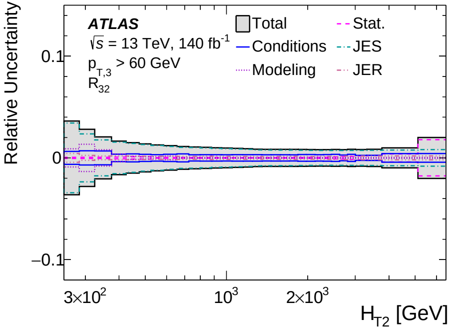
- Larger baryon energy fractions →lower response
- Most baryons: (anti-)protons and (anti-)neutrons

ATLAS - Cross section ratios: Jet flavor response

- Jet flavor response previously taken by plain comparison between PYTHIA8 and HERWIG++
- Split into three separate uncertainty components by comparing different aspects of MC generator setups:
  - **Flavor generator/shower:** PYTHIA8 vs. SHERPA 2.2.5 w/ Lund string hadronisation
  - **Flavor hadronisation:** SHERPA 2.2.11 w/ AHADIC cluster-based hadronization vs. SHERPA 2.2.5 w/ Lund string hadronisation
  - **Flavor shower:** HERWIG 7.1 w/ angle-ordered PS vs. HERWIG 7.1 w/ dipole PS
- Uncertainties derived separately for five different jet flavors (u or d, and s, c, b and g) and applied according to jet label in simulated event samples
- **Subdominant effect of final uncertainty compared to the initial leading contribution of jet flavor response**

ATLAS - Cross section ratios: Unfolding and Exp. uncert.

- Statistical uncertainties arise from finite MC and Data sample size
- Treated during unfolding:
  1. Replicas of measured spectra are created containing Poisson-distributed fluctuations around nominal distributions
  2. Response Matrix is varied using these pseudo-experiments
  3. Replicas unfolded with varied RM → replicas of unfolded spectra
  4. Statistical uncertainty: standard deviation of replicas



- 2D Unfolding (RooUnfold): observable bins and exclusive N_{jets}
- 3D for varied $p_{T,3}$: H_{T2}, N_{jets}, $p_{T,3}$
- Recombination of exclusive → inclusive N_{jets} distributions

Tot: 1-4.5% **Stat:** $<$ 1%

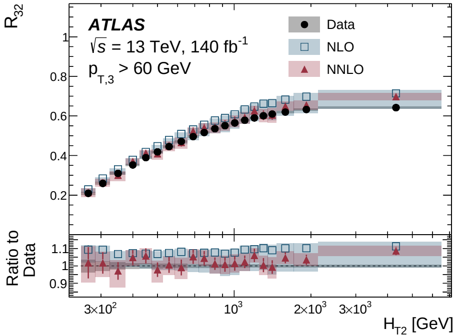
Cond: $<$2% **JES:** 1-3.5%

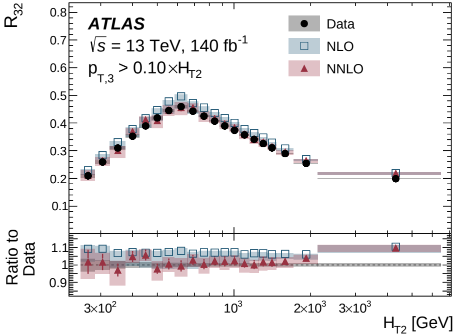
Model: $<$1% **JER** $<$1%

ATLAS - Cross section ratios: Fixed-order pQCD

Theoretical predictions

- 2- and 3-jet cross sections (NLO and NNLO)
- **PDF set:** MSHT20
- $\mu_r = \mu_f = \hat{H}_T = \sum_{i \in partons} p_{T,i}$
- $R_{32}(\mathrm{NNLO}) = \frac{3-\mathrm{jet}\ (\mathrm{NNLO})}{2-\mathrm{jet}\ (\mathrm{NNLO})}$





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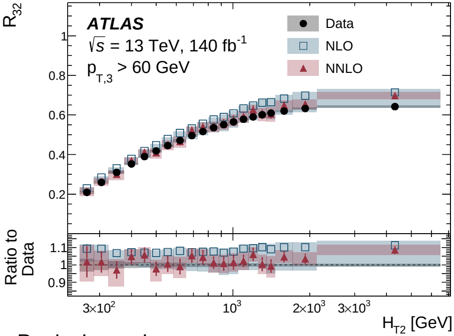

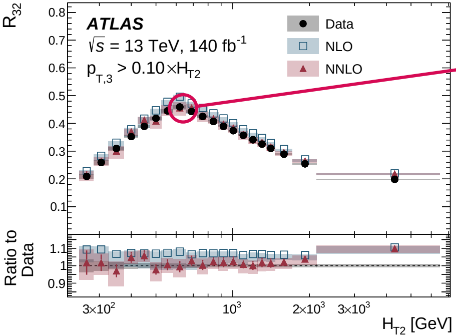

Peak dependent on $p_{T,3}$ cut

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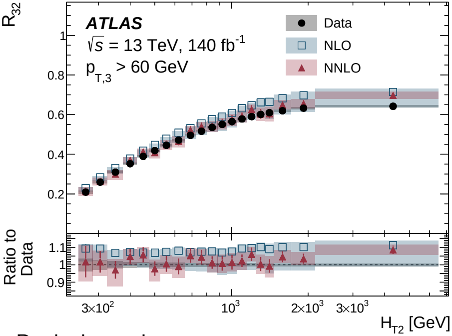
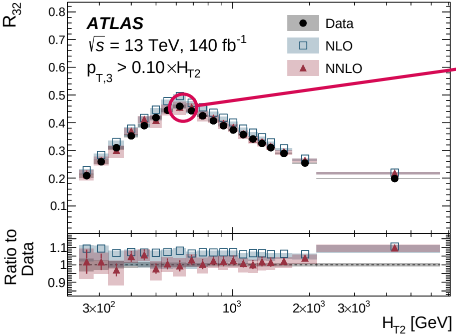




Peak dependent on $p_{T,3}$ cut

NLO prediction: overestimates R_{32}

PRL 127(2021) 152001

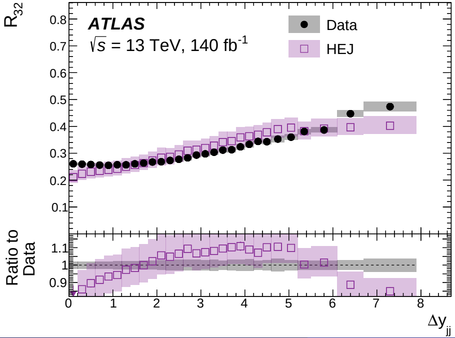
NNLO prediction:

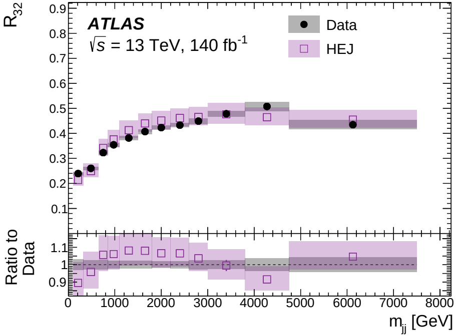
- Reduced scale uncertainty
- Nice agreement between Data and Theory

ATLAS - Cross section ratios: Fixed-order pQCD

JHEP 01(2010) 039

- High Energy Jets (HEJ) framework
  - Leading logarithmic QCD corrections in $\hat{s}/p_T^2$, all orders of α_S and SM processes
  - Resummation of logarithmic correction and matching to fixed-order accuracy: $pp \to 2j,\ 3j,\ 4j,\ 5j,\ 6j$ at tree-level
  - $\mu_r = \mu_f = \hat{H}_T/2$
  - **PDF set:** NNPDF3.1NLO, $\alpha_S(m_Z) = 0.118$

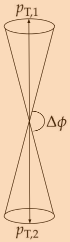




CMS - R_{Δ_ϕ}: Observable (1/2)

$$\mathbf{R}_{\boldsymbol{\Delta\phi}} = \frac{}{N_{\text{jet}}(\mathrm{p_T})}$$

Number of jets in a jet $\mathrm{p_T}$ bin ($\sim \alpha_s^2$ @LO)

2-jet topology	
	
$R_{\Delta\phi}(p_T)$ entries $\Delta\phi \approx \pi$ Numerator: 0 Denominator: 2	

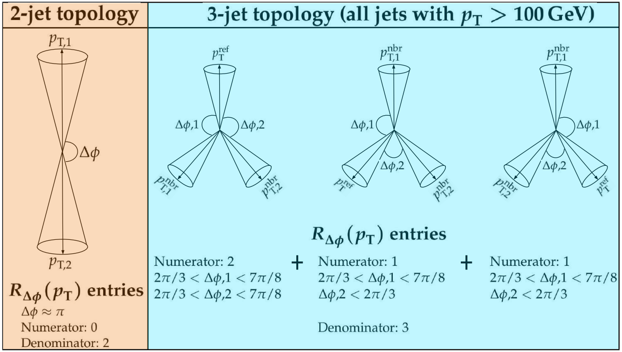
Definition inspired by D0's R_{Δ_R} observable

CMS - R_{Δ_ϕ}: Observable (1/2)

Jets with neighbours within azimuthal separation:
$2\pi/3 < \Delta\phi < 7\pi/8$ and $p_T > 100$ GeV ($\sim \alpha_s^3$ @LO)

$$\mathbf{R}_{\Delta\phi} = \frac{\sum_{i=1}^{N_{\mathrm{jet}}(p_T)} N_{\mathrm{nbr}}^{(i)}(\Delta\phi, p_{\mathrm{Tmin}}^{\mathrm{nbr}})}{N_{\mathrm{jet}}(p_T)}$$

Number of jets in a jet p_T bin ($\sim \alpha_s^2$ @LO)



Definition inspired by D0's R_{Δ_R} observable

CMS -$R_{\Delta\phi}$: Samples and event selection

Data

Full Run 2 (2016-2018) $\rightarrow$ $\sqrt{s} = 13$ TeV, $\mathcal{L}_{int} = 134$ fb^{-1}

Jet reconstruction (FastJet)

- **Jet algorithm:** anti-k_T
- **Jet size:** R=0.7

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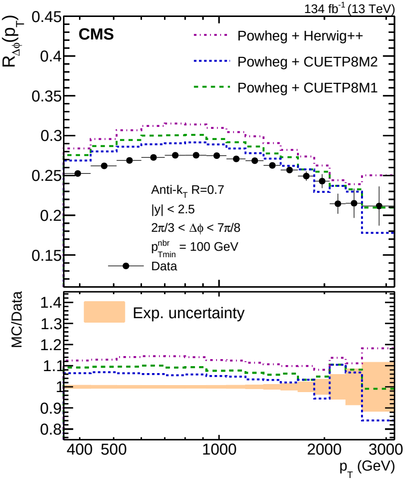
Jet reconstruction (FastJet)

- **Jet algorithm:** anti-k_T
- **Jet size:** R=0.7

Event selection

- Phase space:
  - $p_T > 50$ GeV
  - $|y| < 2.5$
- Numerator criteria:
  - $(\Delta\phi_{\min}, \Delta\phi_{\max}) = (2\pi/3, 7\pi/8)$
  - $p_{T\min}^{nbr} = 100$ GeV



Powheg overestimates the measurement
$\rightarrow$ Fixed-order pQCD needed

CMS - $R_{\Delta\phi}$: Experimental uncertainties

Equivalent observable definition

$$\mathbf{R}_{\Delta\phi} = \frac{\sum_{i=1}^{N_{\mathrm{jet}}(\mathrm{p_T})} N_{\mathrm{nbr}}^{(i)}(\Delta\phi, p_{\mathrm{Tmin}}^{\mathrm{nbr}})}{N_{\mathrm{jet}}(\mathrm{p_T})} = \frac{\sum_n n N(\mathrm{p_T}, n)}{\sum_n N(\mathrm{p_T}, n)}$$

– where n is the number of neighbours and $\mathrm{p_T}$ is jet's transverse momentum.

CMS - $R_{\Delta\phi}$: Experimental uncertainties

Equivalent observable definition

$$\mathbf{R}_{\Delta\phi} = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{T\text{min}}^{\text{nbr}})}{N_{\text{jet}}(p_T)} = \frac{\sum_n nN(p_T, n)}{\sum_n N(p_T, n)}$$

- where n is the number of neighbours and p_T is jet's transverse momentum.

☞ 2D unfolding of $N(p_T, n)$ distribution.

✔ Migrations among p_T **and** among n bins.

✔ Account for non-trivial numerator-denominator correlations.

Stat.: 0.18 – 10.49 %

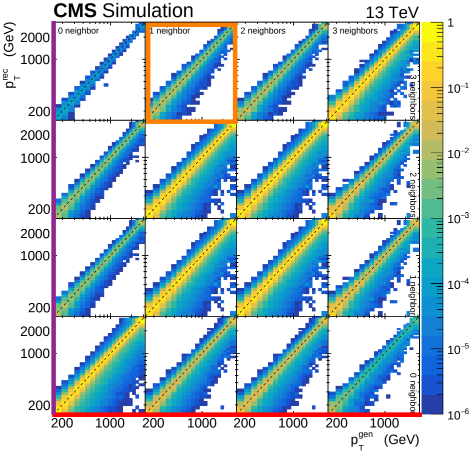
JES: 0.65 – 5.00 %

JER: 0.04 – 0.77 %

Other: $< 1\%$

⚠ **All uncertainties remain below 1% up to 1.5 TeV**

Probability matrix for the 2D $N(p_T, n)$

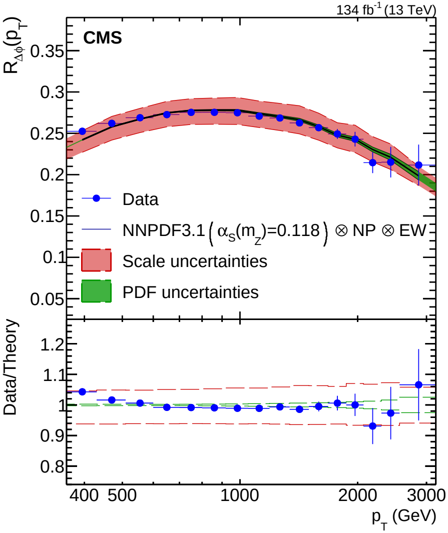


CMS - $R_{\Delta\phi}$: Fixed-order pQCD

Theoretical predictions

- Fixed-order predictions pQCD NLO
- NLOJET++ (up to 3 jets NLO)
- fastNLO framework
- $\mu_R = \mu_F = \hat{H}_T/2$ with $\hat{H}_T = \sum_{i \in \mathrm{partons}} p_{T,i}$
- Separate calculation for numerator and denominator

CMS - $R_{\Delta\phi}$: Fixed-order pQCD



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- Separate calculation for numerator and denominator

Theoretical predictions for $R_{\Delta\phi}$

- Corrected for NP and EW
- Data-Theory agreement (within uncertainties)
- Uncertainties:
  - PDF: 1-2%
  - Scale: 2-8%

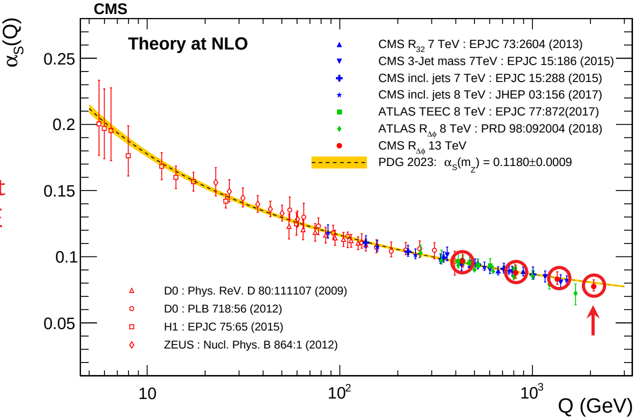
⚠ **NNLO predictions not yet available for $R_{\Delta\phi}$!**

CMS - $R_{\Delta\phi}$: Fixed-order pQCD

$R_{\Delta\phi}$ sensitive to α_S:

$$\alpha_S(m_Z) = 0.117^{+0.0117}_{-0.0074}$$

- $\alpha_S(Q)$ results consistent with predictions by RGE
- Extended range up to $\sim$ 2 TeV



CMS - Dijet cross sections: Observable (2/2)

Double-differential (2D)

- Inclusive double-differential dijet cross-section as function of maximum rapidity and the invariant mass of the two leading jets:

$$\frac{d^2\sigma}{dy_{max}dm_{1,2}} = \frac{1}{\mathcal{L}_{int}} \frac{N_{eff}}{(2\Delta\left|y\right|_{max})\Delta m_{1,2}}$$

- $m_{1,2} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$, $\left|y\right|_{max} = max(\left|y_1\right|, \left|y_2\right|)$

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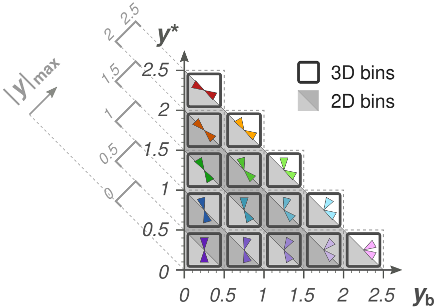
Triple-differential (3D)

- Inclusive triple-differential dijet cross-section as a function of y^*, y_b and the invariant mass **or** average p_T of the two leading jets:

$$\frac{d^3\sigma}{dy^*\,dy_b\,dx} = \frac{1}{\mathcal{L}_{int}} \frac{N_{eff}}{\Delta y^* \Delta y_b \Delta x}$$

- $y^* = \frac{1}{2}|y_1 - y_2|$, $y_b = \frac{1}{2}|y_1 + y_2|$
- $x = m_{1,2}$ or $\langle p_T \rangle_{1,2} = \frac{1}{2}(p_{T,1} + p_{T,2})$



CMS - Dijet cross sections: Samples and event selection

Samples

Data: 2016
$\rightarrow \sqrt{s} = 13$ TeV, $\mathcal{L}_{int} = 36.3$ fb^{-1}

Jet reconstruction (FASTJET)

- **Jet algorithm:** anti-k_T
- **Jet sizes:** R=0.4 and R=0.8

CMS - Dijet cross sections: Samples and event selection

Samples

Data: 2016
$\rightarrow \sqrt{s} = 13$ TeV, $\mathcal{L}_{int} = 36.3$ fb^{-1}

Jet reconstruction (FastJet)

- **Jet algorithm:** anti-k_T
- **Jet sizes:** R=0.4 and R=0.8

Event selection

- Double-differential:
  - $p_{T,1} \geq 100$ GeV , $p_{T,2} \geq 50$ GeV
  - $|y_1| < 2.5$, $|y_2| < 2.5$
- Triple-differential:
  - $p_{T,1} \geq 100$ GeV , $p_{T,2} \geq 50$ GeV
  - $|y_1| < 3.0$, $|y_2| < 3.0$

⚠ **Events from one measurement are not necessarily included in the phase space of the other!**

CMS - Dijet cross sections: Unfolding

- Detector level $\rightarrow$ Particle level spectrum
- Least-square minimisation: $\chi^2 = (Ax + b - y)^T V_y^{-1} (Ax + b - y)$ (same method for $R_{\Delta\phi}$)

CMS - Dijet cross sections: Unfolding

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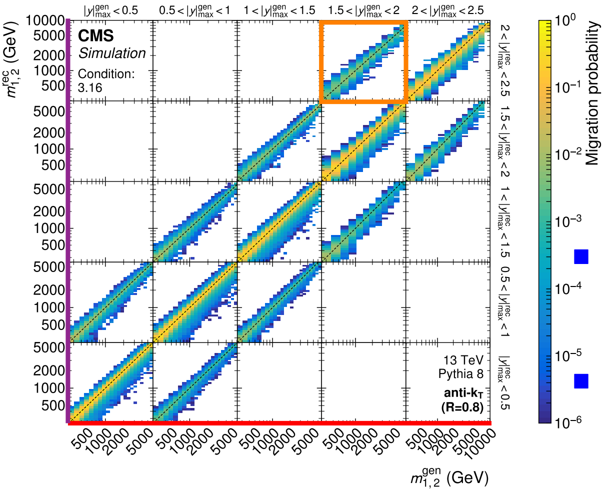
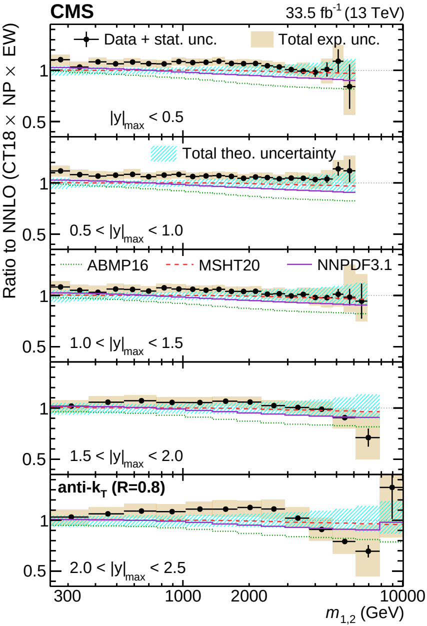


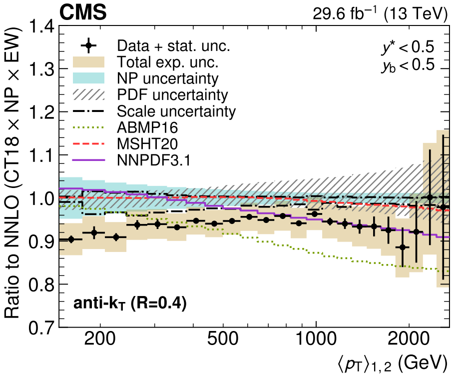
2-D Unfolding with TUnfold
Correct:

- Background (Fake jets)
- Unsmear detector effects
- Inefficiencies (Miss jets)

- Matrix structure
  - x axis: generator-level m_{jj}
  - y axis: reconstructed-level m_{jj}
  - inner cells: different $|y|_{max}$ bins
- Condition Number: $CN = \left|\frac{max\_eig}{min\_eig}\right|$
  CN<10 → Acceptable unfolding performance

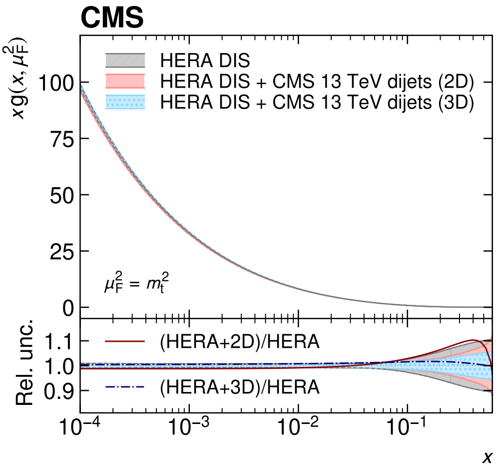
CMS - Dijet cross sections: Fixed order pQCD



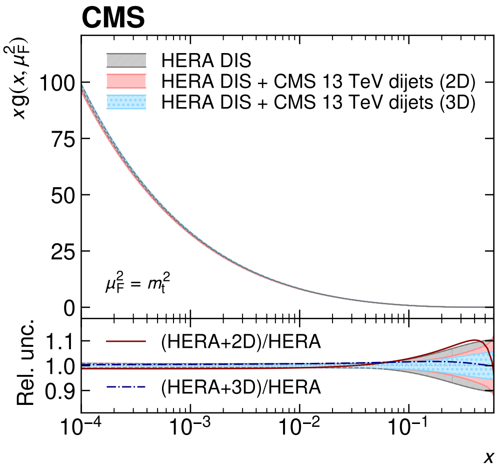


- Theory corrected for NP and EW effects
- Nice description of Data from CT18 (10%)
- Better Data-Theory agreement for AK8
- Comparison with other PDF sets

CMS - Dijet cross sections: Fixed order pQCD



- Impact of measurement on PDFs
- Using HERA parametrisation
- Higher energy range of dijet mass $\rightarrow$ included in fit
- $R = 0.8$ (better Data-Theory agreement)
- Shown here: gluon PDF
- Reduced uncertainties especially in high x region



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- Using HERA parametrisation
- Higher energy range of dijet mass $\rightarrow$ included in fit
- $R = 0.8$ (better Data-Theory agreement)
- Shown here: gluon PDF
- Reduced uncertainties especially in high x region
- Extraction of α_S:

2D: $\alpha_S(m_Z) = 0.1179 \pm 0.0019$ (tot.)

3D: $\alpha_S(m_Z) = 0.1181 \pm 0.0022$ (tot.)

Summary & Conclusions

ATLAS

- (A)TEEC[1]:

  ✔Precise determination of $\alpha_S(m_Z)$ and running of $\alpha_S(Q)$ in TeV scale

- Jet cross section ratios[2]:

  ✔Improvement of JES uncertainty

  ✔Is eligible for determination of $\alpha_S(m_Z)$

[1] JHEP 07 (2023) 85
[2] arXiv:2405.20206, submitted to PRD
[3] EPJC 84, 842 (2024)
[4] arXiv:2312.16669, submitted to EPJC

Summary & Conclusions

ATLAS

- (A)TEEC[1]:

  ✔Precise determination of $\alpha_S(m_Z)$ and running of $\alpha_S(Q)$ in TeV scale

- Jet cross section ratios[2]:

  ✔Improvement of JES uncertainty

  ✔Is eligible for determination of $\alpha_S(m_Z)$

CMS

- Azimuthal correlations ($R_{\Delta\phi}$) [3]:

  ✔ Small experimental uncertainties→appealing for $\alpha_S(m_Z)$ determination using NNLO

  ✔Investigation of $\alpha_S(Q)$ running in the TeV region, expanding the range of the running

- Multi-differential dijet cross sections[4]:

  ✔Improved determination of PDFs compared to fits from HERA data alone

  ✔Precise determination of $\alpha_S(m_Z)$ value

[1] JHEP 07 (2023) 85

[2] arXiv:2405.20206, submitted to PRD

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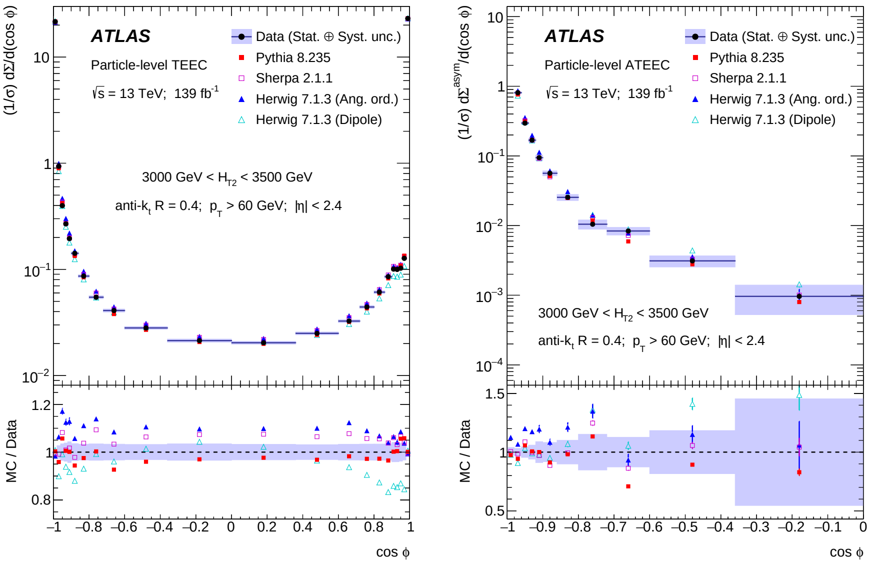
THANK YOU FOR YOUR ATTENTION

BACK UP

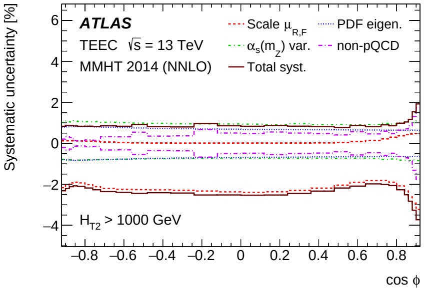
(A)TEEC: Systematic uncertainties

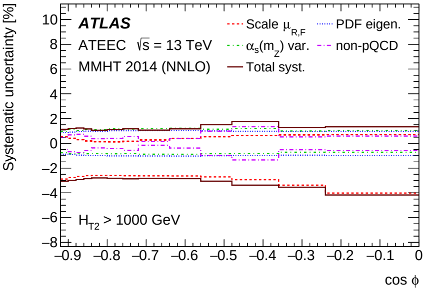
- **Jet Energy Scale(JES):** restores energy of rec. jets by scaling p_T, energy, mass
- **Jet Energy Resolution (JER):** differences in response in Data and MC by imperfect simulation $\rightarrow$ smearing energy of jets in MC: $c = \mathcal{R}^{data}_{in\ situ}/\mathcal{R}^{MC}_{in\ situ}$
- **Jet Angular Resolution (JAR):** smearing ϕ by resolution in MC (p_T constant)
- **Unfolding:** mismodelling of data by simulation, difference between unfolded and generator level MC distribution
- **Modelling:** difference between unfolded cross sections of MC samples

(A)TEEC: Patricle level measurement



(A)TEEC: Theoretical uncertainties



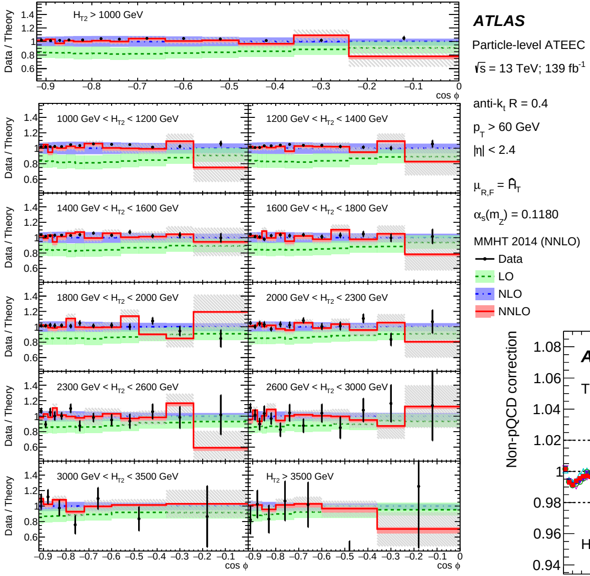


Total: 1.0-3.5% **Scale: 0.5-3.3%**
α_S var.: 0.8-1% **PDF≃0.8%**
NP: 0.3-1.8%

Total: 1.0-4.2% **Scale: 0.5-4%**
α_S var.: 0.5-1% **PDF: ≃1%**
NP: 0.5-1.5%

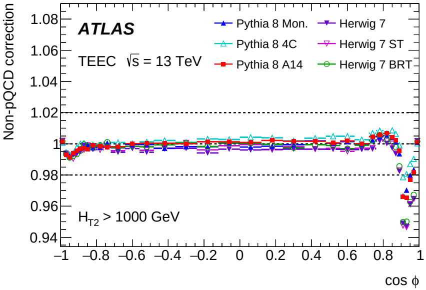
- **Scale:** calculated by considering independent variations of μ_f and μ_r
- **PDF:** obtained by considering the set of eigenvectors/replicas provided by each PDF gtoup
- **Non-perturbative:** extracted from the envelope of the differences from different MC predictions
- **α_S variation:** effect of varying $\alpha_S(m_Z)$=0.117-0.119

(A)TEEC: Fixed-order pQCD

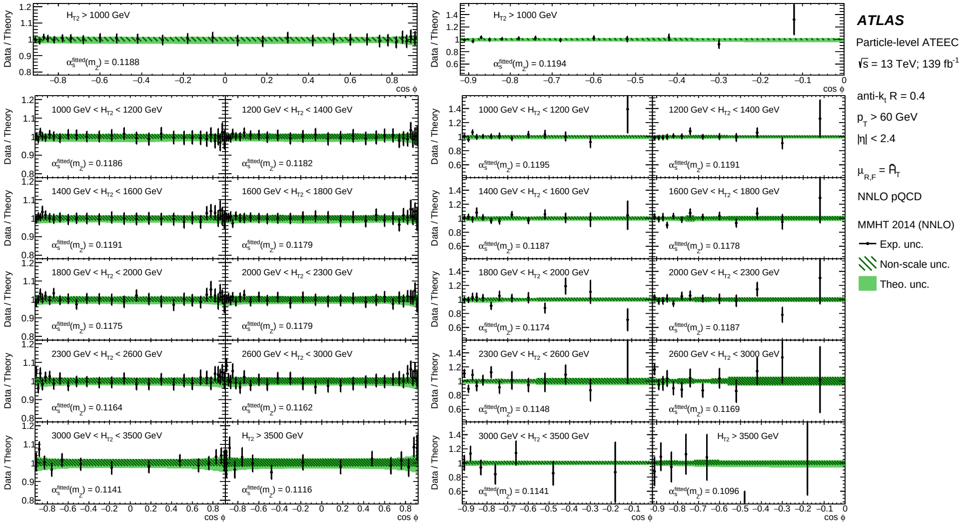


Nice Data - Theory agreement within uncertainties

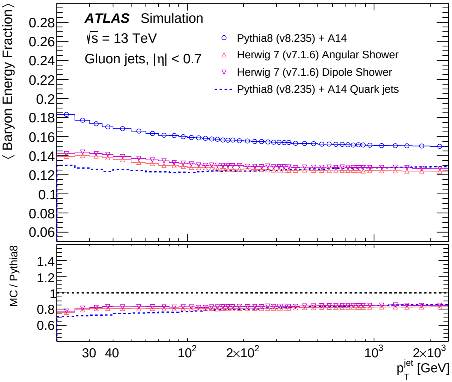
- NP corrections from several MC event generators
- Value of NP factors around unity

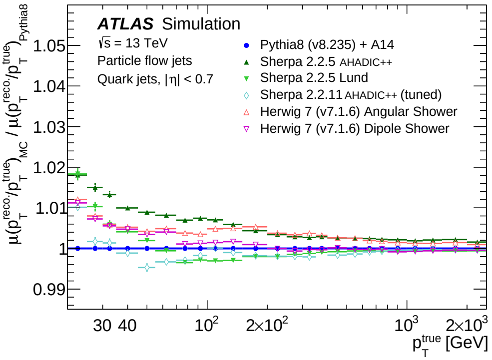


(A)TEEC: Data Ratio to fitted Theory



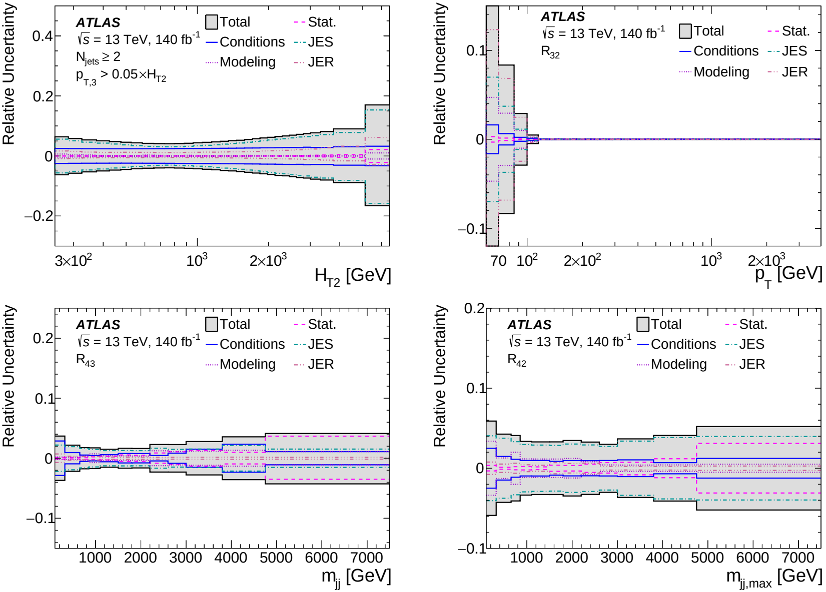
Cross section ratios: Precision study



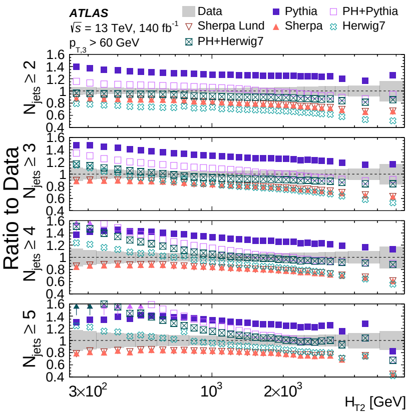


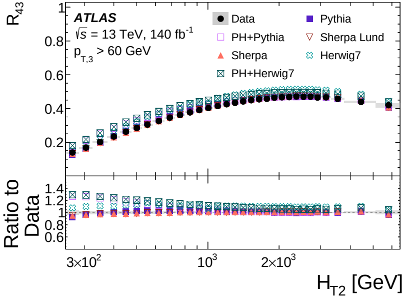
Parton Shower model in HERWIG models does not affect the distribution much

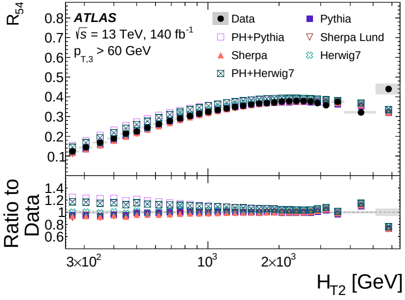
Cross section ratios: JES

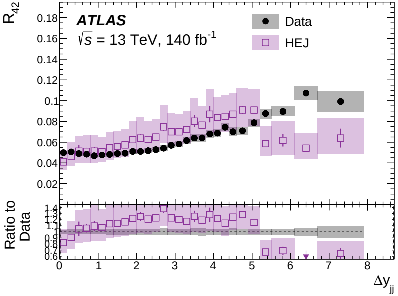


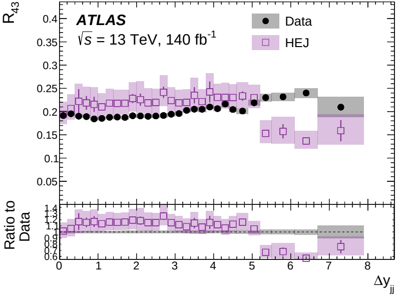
Cross section ratios: Comparison to MC

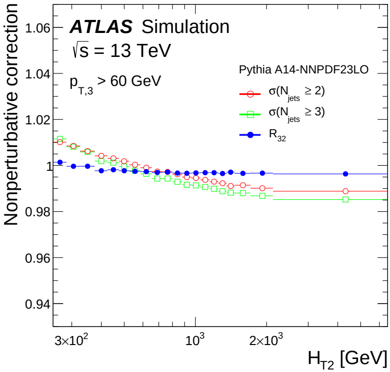












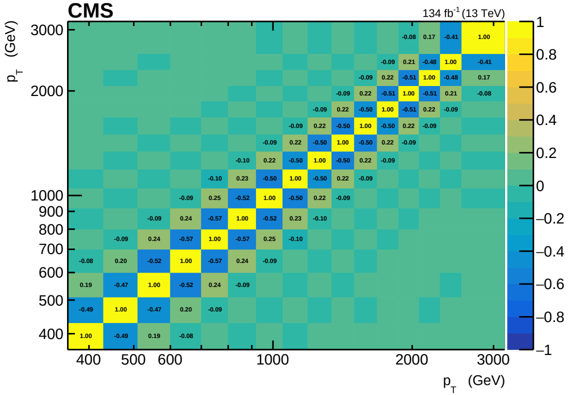
NPs deviate from unity by:

- **2% for 2 and 3 jet cross sections**
- **0.5% for R_{32}**

Uncertainty smaller than 0.5%

$R_{\Delta\phi}$: Experimental uncertainties

Statistical correlation matrix for $\mathrm{R}_{\Delta\phi}$ *after* unfolding



- **Statistical**: from the covariance matrix *after* unfolding
- **JES**: **J**et **E**nergy **S**cale uncertainty sources
  $\rightarrow \mathrm{p_T} = \mathrm{p_T}(1 \pm \text{unc. source})$
- **JER**: **J**et **E**nergy **R**esolution smearing process applied to MC samples
- **Other**: Prefiring corrections, PU profile reweighting, MC modeling

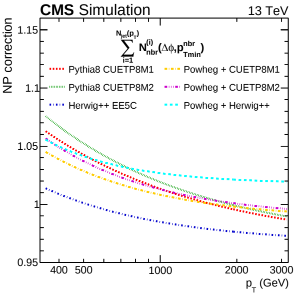
- **Statistical**: from the covariance matrix *after* unfolding
- Correlations are considered in statistical uncertainty
- Diagonal elements: unity by construction (a bin is fully correlated with itself)
- Off-diagonal elements: bin-to-bin (anti-correlations)

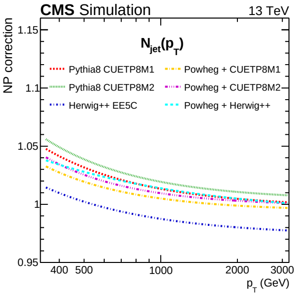
$R_{\Delta\phi}$: NP corrections

- NP correction factors:

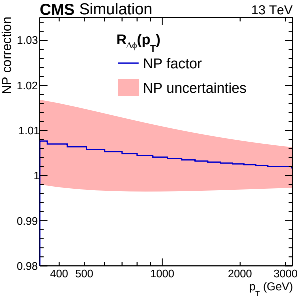
$$C^{NP} = \frac{\sigma^{PS+MPI+HAD}}{\sigma^{PS}}$$

- Parametrisation of C^{NP} with simple polynomial function $a + b \cdot p_T^c$
- Envelope from the predictions of the different MC event generators.





- Corrections of fixed-order pQCD predictions (parton level)for non-perturbative (NP) effects of multiple parton interactions (MPI) and hadronization (HAD)
- Applied on theory to be compatible with particle-level measurement



$R_{\Delta\phi}$: ElectroWeak corrections

Full NLO corrections to 3-jet production and R_{32} at the LHC

M. Reyer, M. Schönherr, S. Schumann arXiv:1902.01763 $\rightarrow \mathcal{O}(\alpha_s^n \alpha^m)$, with $n+m=2$ and $n+m=4$.

Combination of QCD and EW corrections

Pure NLO EW corrections for n-jet:

$$\sigma_{nj}^{\text{NLO EW}} = \sigma_{nj}^{\text{LO}} + \sigma_{nj}^{\Delta\text{NLO}_1}$$

ΔNLO_1: virtual and real EW corrections.

Combination to QCD process:

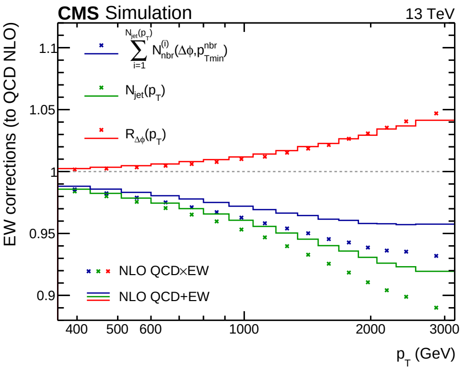
1. **Additive:** $\sigma_{nj}^{\text{NLO QCD+EW}}$

$$\sigma_{nj}^{\text{LO}} + \sigma_{nj}^{\Delta\text{NLO}_0} + \sigma_{nj}^{\Delta\text{NLO}_1}$$

ΔNLO_0: virtual and real QCD corrections.

2. **Multiplicative:** $\sigma_{nj}^{\text{NLO QCD}\times\text{EW}}$

$$\sigma_{nj}^{\text{LO}} \left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_0}}{\sigma_{nj}^{\text{LO}}}\right) \left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_1}}{\sigma_{nj}^{\text{LO}}}\right)$$



EW corrections for $R_{\Delta\phi} < 5\%$ and EW correction uncertainties $< 0.6\%$.

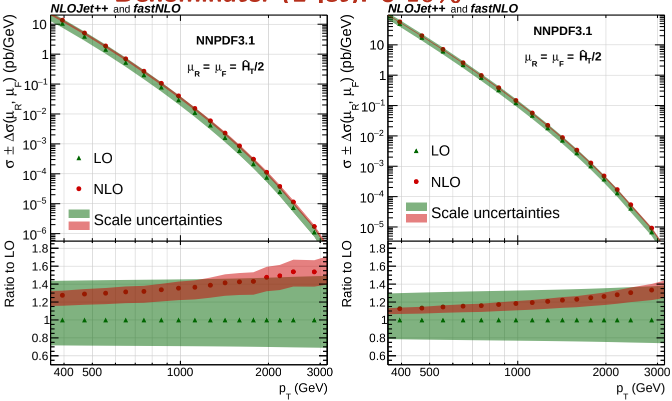
CMS - $R_{\Delta\phi}$: Fixed-order pQCD

- 4 NLO PDF sets (LHAPDF)
- PDF uncertainties: 68% CL Hessian/MC methods
- Scale uncertainties: difference between prediction for varying $\frac{1}{2} \leq \mu_R, \mu_F \leq 2$

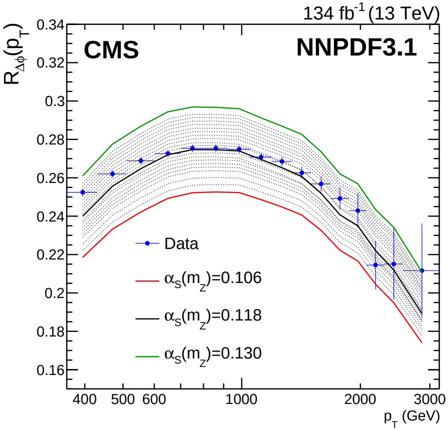
NLO scale uncertainties

Numerator (3-jet): 9-17%

Denominator (2-jet): 5-10%

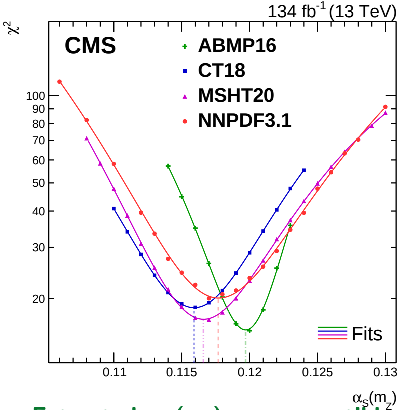


$R_{\Delta\phi}$: Sensitivity of $_{\Delta\phi}$ to $\alpha_s(m_Z)$



- Particle-level Data with Theory corrected for NPs and EW
- Slight change in α_S value from theory $\rightarrow$ significantly different prediction
- Thus, $R_{\Delta\phi}$ sensitive to α_S

$R_{\Delta\phi}$: Determination of $\alpha_s(m_z)$



Least square minimisation

$$\chi^2 = \sum_{ij}^{N}(D_i - T_i)C_{ij}^{-1}(D_j - T_j)$$

N: number of measurements
D_i: experimental data
T_i: theoretical predictions
C_{ij}: covariance matrix

- **Covariance matrix composition:**

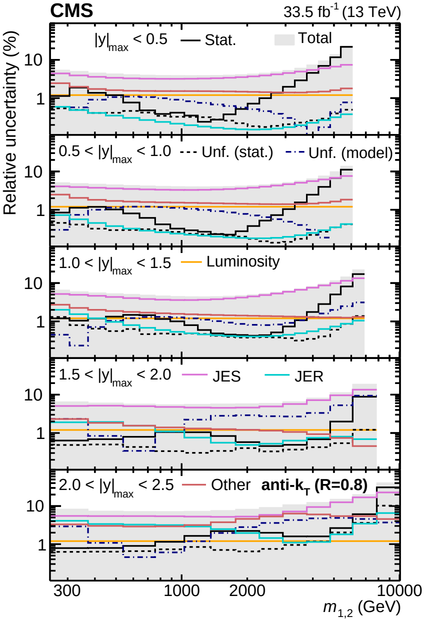
$$C_{ij} = C_{\text{uncor}} + C_{\text{exp}} + C_{\text{theo}}$$

C_{uncor} : numerical precision of FO predictions
C_{exp} : all the experimental uncertainties
C_{theo} : all the theoretical uncertainties

- **Extracted $\alpha_s(m_z)$ are compatible among each other within uncertainties.**
- **Scale uncertainties (theoretical) by far the dominant: $4 - 10$ %.**

PDF set	$\alpha_s(m_z)$	Exp	NP	PDF	EW	Scale	Total	χ^2/n_{dof}
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	$^{+0.0043}_{-0.0042}$	$^{+0.0045}_{-0.0044}$	16/16
CT18	0.1159	0.0013	0.0009	0.0014	0.0002	$^{+0.0099}_{-0.0067}$	$^{+0.0101}_{-0.0070}$	19/16
MSHT20	0.1166	0.0013	0.0008	0.0010	0.0003	$^{+0.0112}_{-0.0063}$	$^{+0.0114}_{-0.0066}$	17/16
NNPDF3.1	0.1177	0.0013	0.0011	0.0010	0.0003	$^{+0.0114}_{-0.0068}$	$^{+0.0116}_{-0.0071}$	20/16

Djet cross sections: Experimental uncertainties



JES: 3→23%

JER: <1 →7%

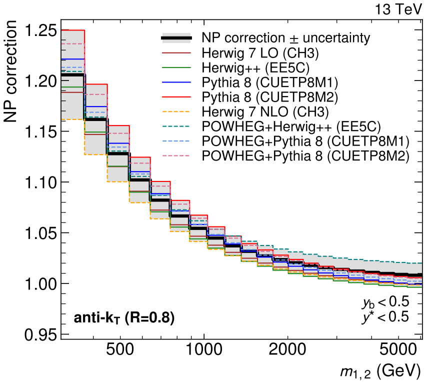
Luminosity: 1.2%

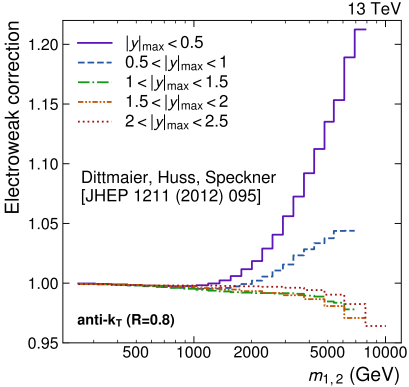
Unfolding: $\sim$ 1%
in forward region: 3-6%

Stat: <1 →31%
(larger in high m_{jj} bins)

Total: 4→41%
(quadratic sum of contribution from all uncertainty sources)

Dijet cross sections: NP and EW corrections





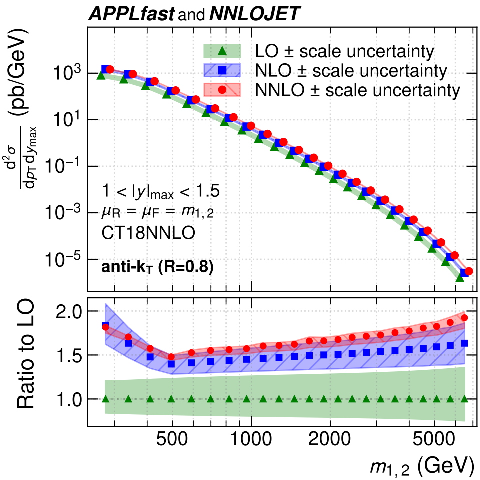
- $C_{NP} = \frac{\sigma^{PS+HAD+MPI}}{\sigma^{PS}}$
- Parametrise following $a/x^b + c$ to mitigate fluctuations
- Large correction values in lowest $m_{1,2}$ bins (up to 20%)

- EW effects become
- Larger EW factors for high $m_{1,2}$ values and central $|y|_{max}$ regions (Up to 15%)
- Forward $|y|_{max}$ regions: negative EW factors

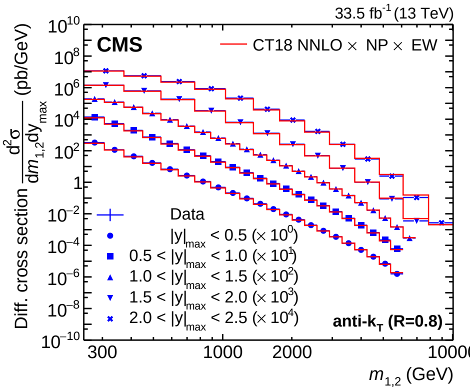
Dijet cross sections: Fixed-order pQCD

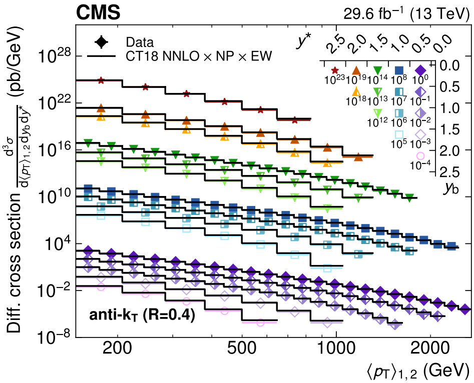
Theoretical predictions

- Up to NNLO in pQCD with NNLOJET (interfaced to FASTNLO via APPLFAST)
- $\mu_R = \mu_F = m_{1,2}$
- **PDF set:** CT18 NNLO
- Band from NNLO corrections mostly lies within the NLO, showing good perturbative convergence.



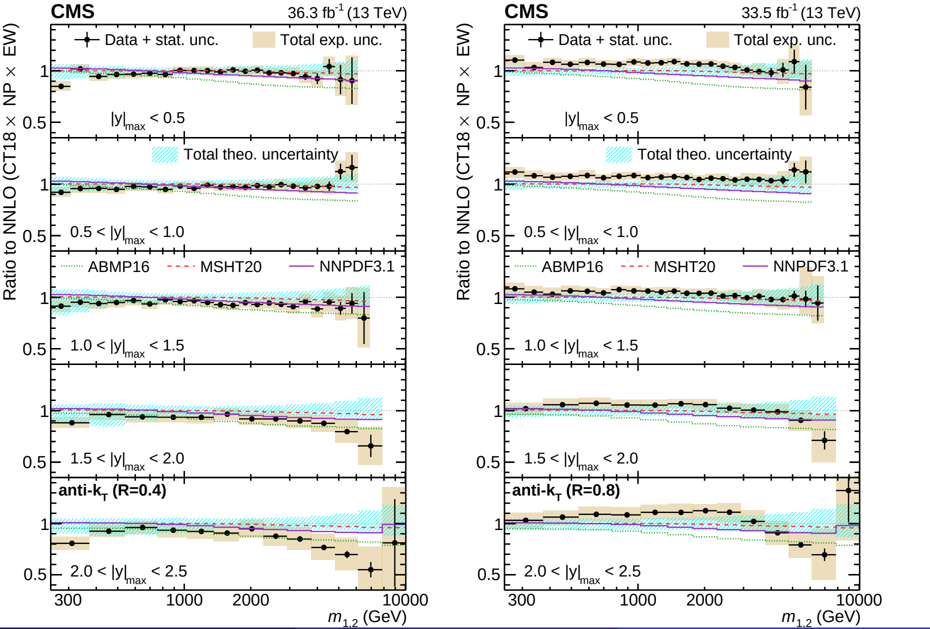
Dijet cross sections: Fixed order pQCD



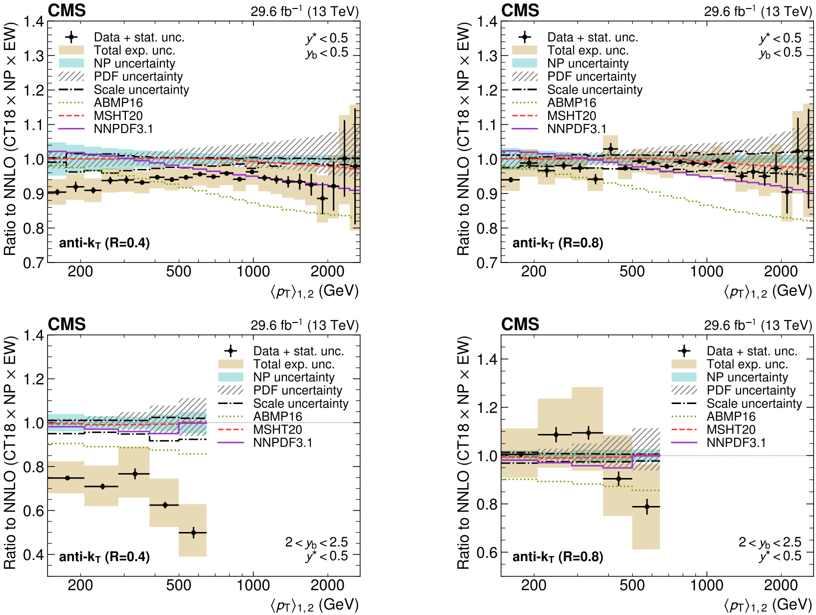


- Fixed-order pQCD predictions at NNLO corrected with NP and EW
- Shown here: Data and CT18

Dijet cross sections: Data - Theory comparison (2D)



Dijet cross sections: Data - Theory comparison (3D)



Dijet cross sections: HERA fits