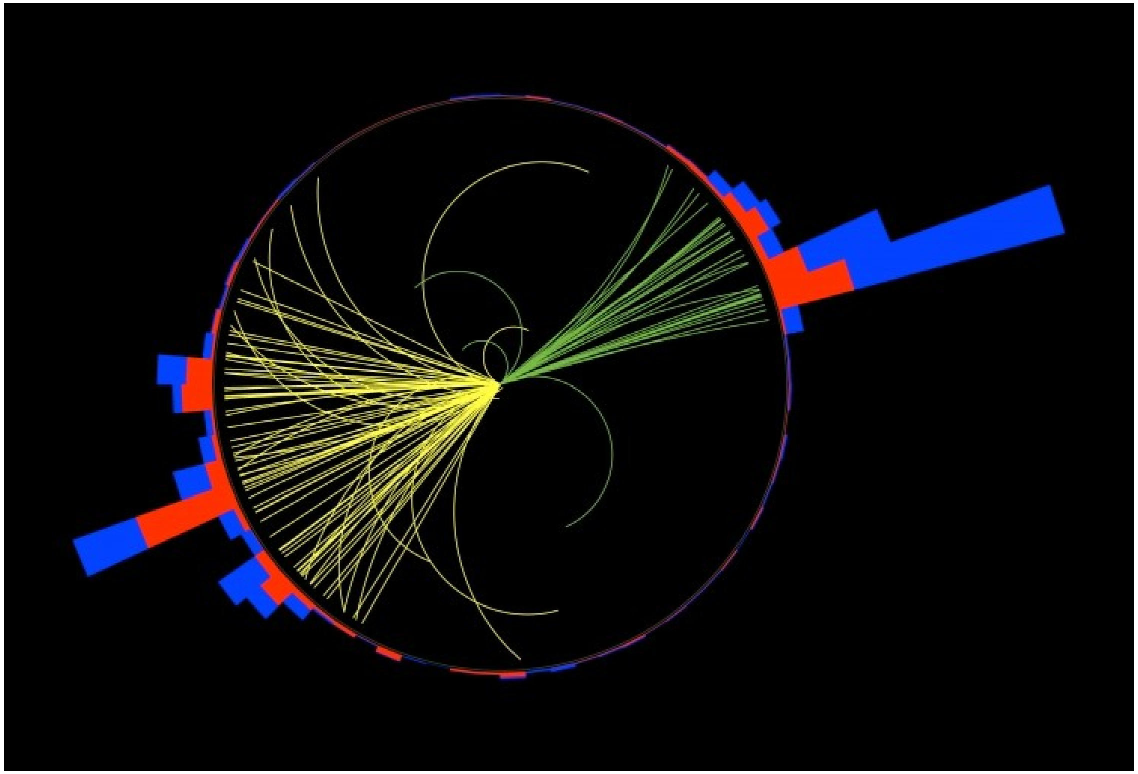
Jet measurements @ LHC

K. Wichmann

Motivation and QCD analysis strategy

- Jets allow extensive tests on (p)QCD

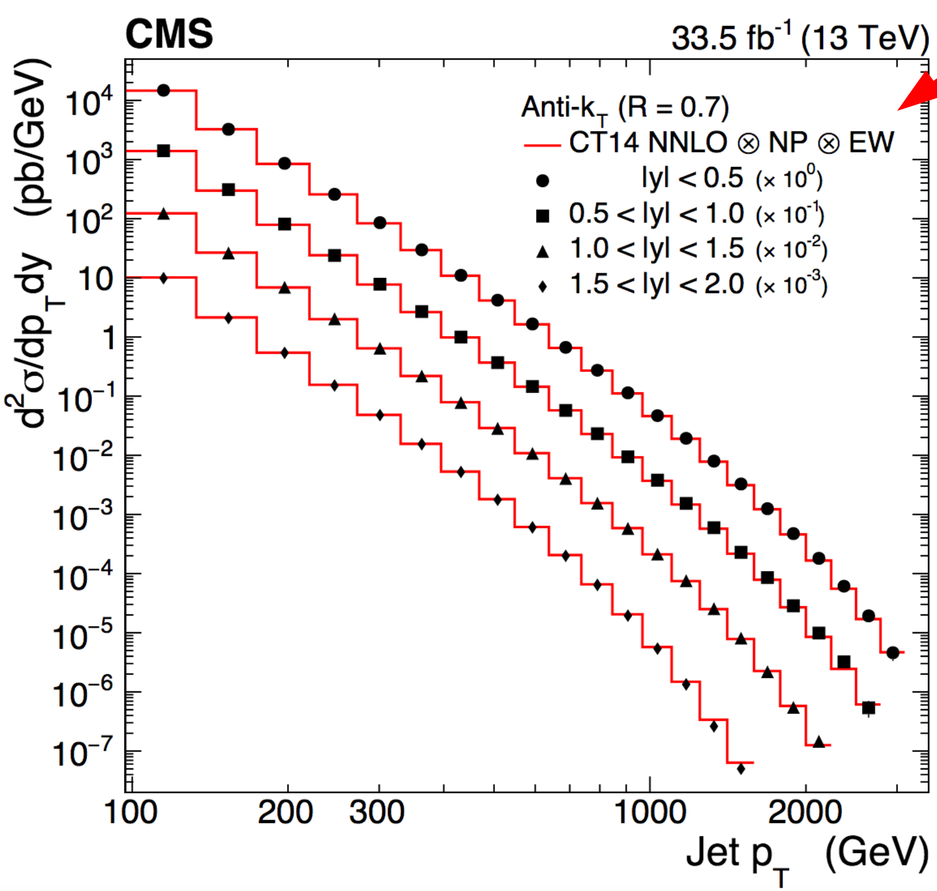
- Together with HERA inclusive data they allow simultaneous fits of parton densities and α_s
  → QCD fits presented here follow HERAPDF strategy
  → QCD fits presented here done using xFitter



Inclusive jets at CMS @ 13 TeV

JHEP 2022 (2022) 35
(Addendum to JHEP 02 (2022) 142)

Inclusive jets @13 TeV



- 13 TeV inclusive jet cross sections already published: JHEP 02 (2022) 142
  → also QCD analysis and α_s measurement <u>@ NNLO using k-factors</u>
- NEW: addendum with NNLO analysis using NNLO interpolation grids: JHEP 12 (2022) 035
  → presented here
- NLOJET calculation to derive grids
  → numerical integration uncertainty ~ 1%
  - In fit increased by a factor of 2
    → impact negligible

The most important impact on uncertainties on α_s determination

Simultaneous determination of PDFs and α_s

NEW

$$\alpha_S(m_Z) = 0.1166 \pm 0.0014\,(\text{fit}) \pm 0.0007\,(\text{model}) \pm 0.0004\,(\text{scale}) \pm 0.0001\,(\text{param.})$$

OLD

$$\alpha_S(m_Z) = 0.1170 \pm 0.0014\,(\text{fit}) \pm 0.0007\,(\text{model}) \pm 0.0008\,(\text{scale}) \pm 0.0001\,(\text{param.})$$

→ Improved precision compared to NNLO result with k-factors

Data sets		HERA+CMS Partial χ^2/N_{dp}
HERA I+II neutral current	e^+p, $E_p = 920$ GeV	376/332
HERA I+II neutral current	e^+p, $E_p = 820$ GeV	60/63
HERA I+II neutral current	e^+p, $E_p = 575$ GeV	202/234
HERA I+II neutral current	e^+p, $E_p = 460$ GeV	209/187
HERA I+II neutral current	e^-p, $E_p = 920$ GeV	227/159
HERA I+II charged current	e^+p, $E_p = 920$ GeV	46/39
HERA I+II charged current	e^-p, $E_p = 920$ GeV	56/42
CMS inclusive jets 13 TeV	$0.0 < \lvert y \rvert < 0.5$	8.6/22
	$0.5 < \lvert y \rvert < 1.0$	23/21
	$1.0 < \lvert y \rvert < 1.5$	13/19
	$1.5 < \lvert y \rvert < 2.0$	14/16
Correlated χ^2		81
Global χ^2/N_{dof}		1302/1118

Good description of data by fit results

These results supersede these obtained using k-factor technique

Dijets

13 TeV CMS data with 36.3 fb^{-1}

CMS PAS SMP-21-008

Cross section measurement

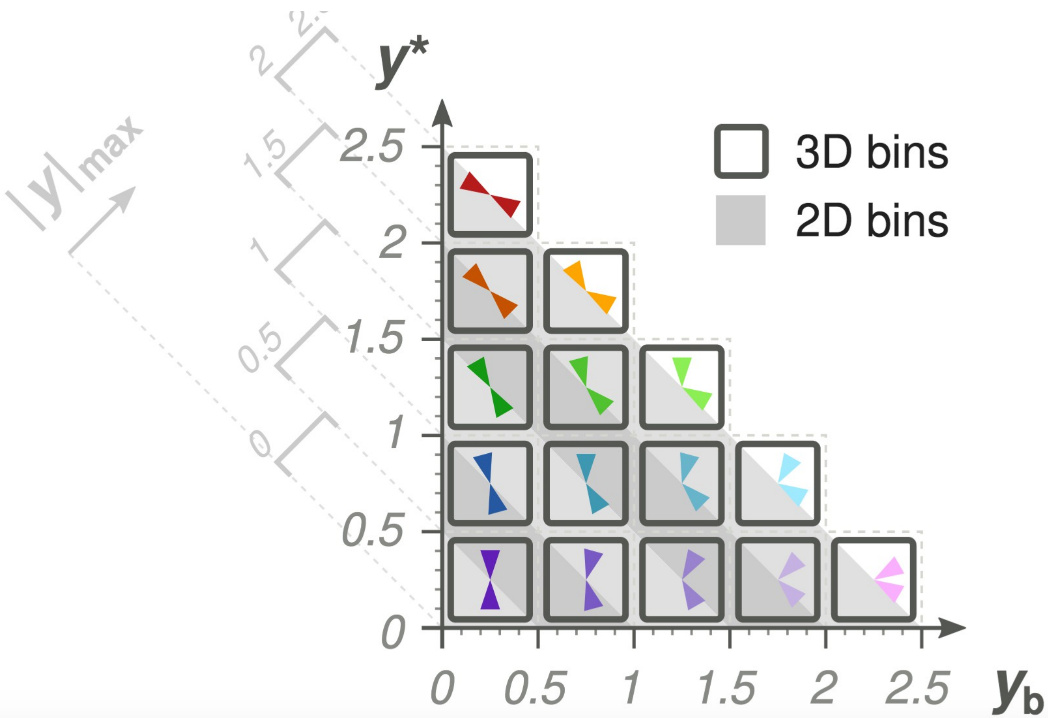
- Dijet cross section measured double- and triple-differentially in terms of properties of system formed by the two p_T-leading jets

  → 2D: as a function of dijet invariant mass $m_{1,2}$ in five rapidity regions $|y_{max}|$

$$y_{\max} = \mathrm{sign}(|\max(y_1, y_2)| - |\min(y_1, y_2)|) \max(|y_1|, |y_2|)$$

  → 3D: $m_{1,2}$ and $\langle p_T \rangle_{1,2}$ in 15 rapidity bins, defined in terms of dijet rapidity separation y^* and total boost y_b of dijet system

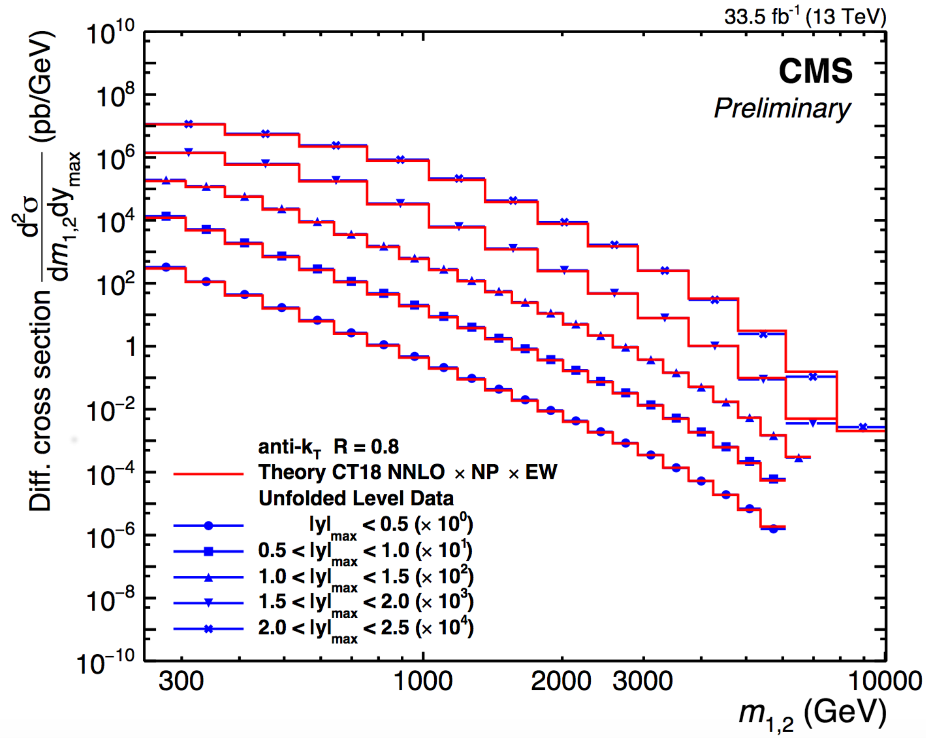
$$y^* = \frac{1}{2}|y_1 - y_2|, \quad y_b = \frac{1}{2}|y_1 + y_2| \quad m_{1,2} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}, \quad \langle p_T \rangle_{1,2} = \frac{1}{2}(p_{T,1} + p_{T,2})$$

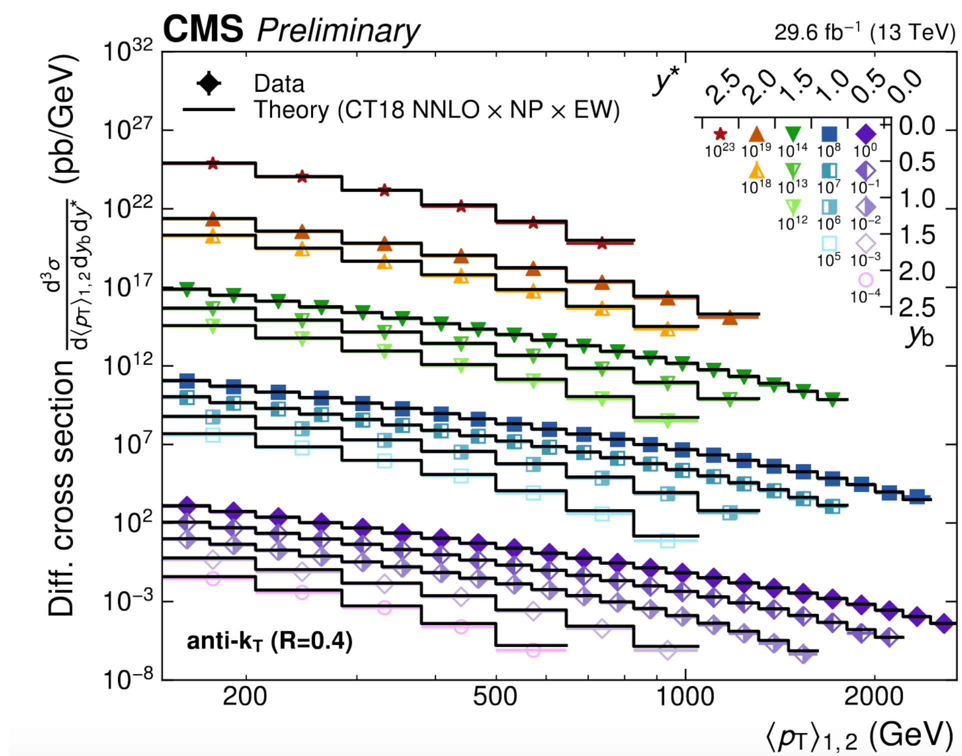


- Illustration of dijet rapidity phase space, highlighting the relationship between variables used for 2D and 3D measurements
- Colored triangles are suggestive of orientation of two jets in different phase space regions in the laboratory frame (beam line runs horizontally)

Measured cross sections

- Unfolded cross sections for 2D and 3D measurements
- → compared with fixed-order theory predictions at NNLO, complemented by NP and electroweak corrections

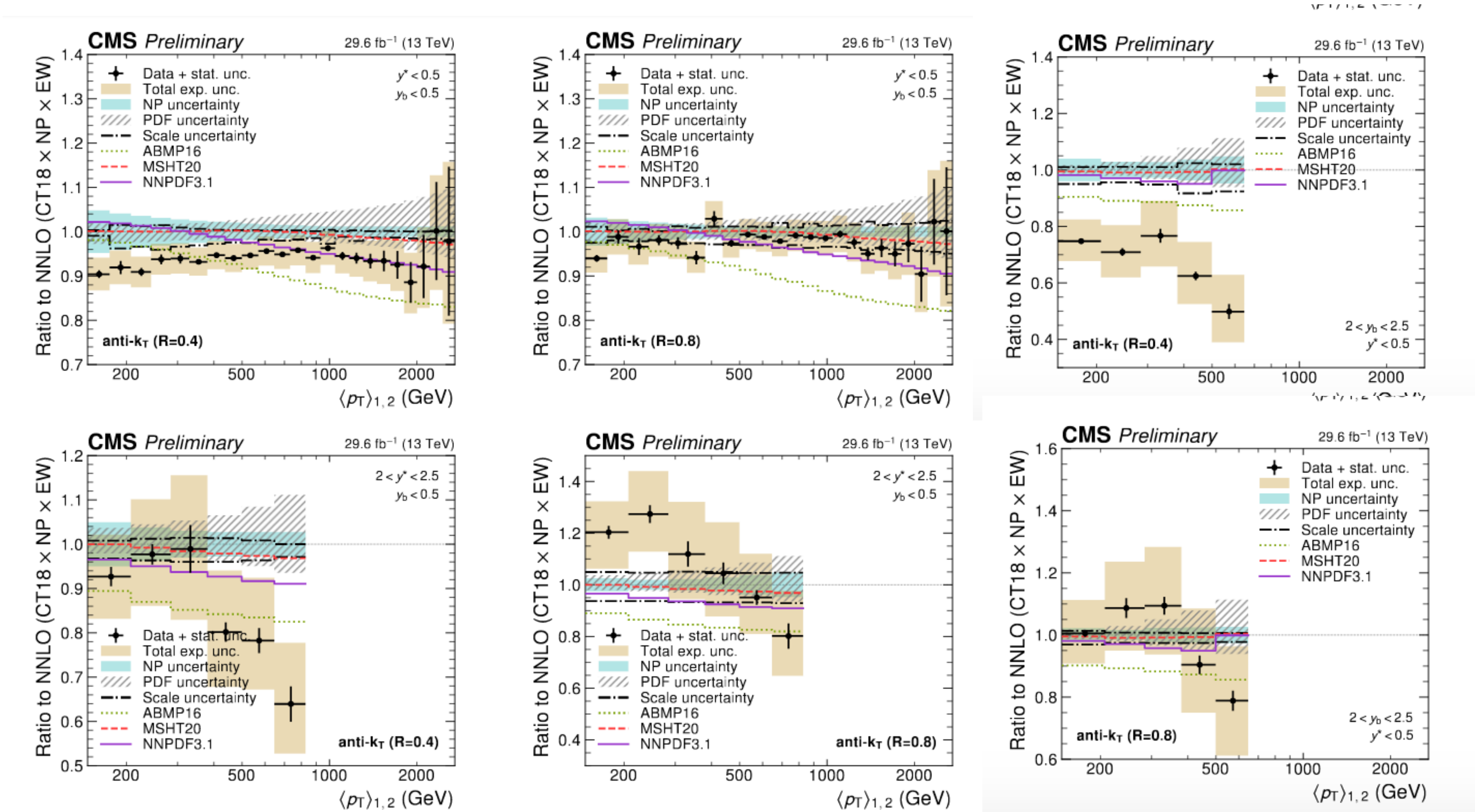




- Predictions for different PDFs generally in agreement
  → except for AMBP16 PDF - predicted cross sections are generally smaller

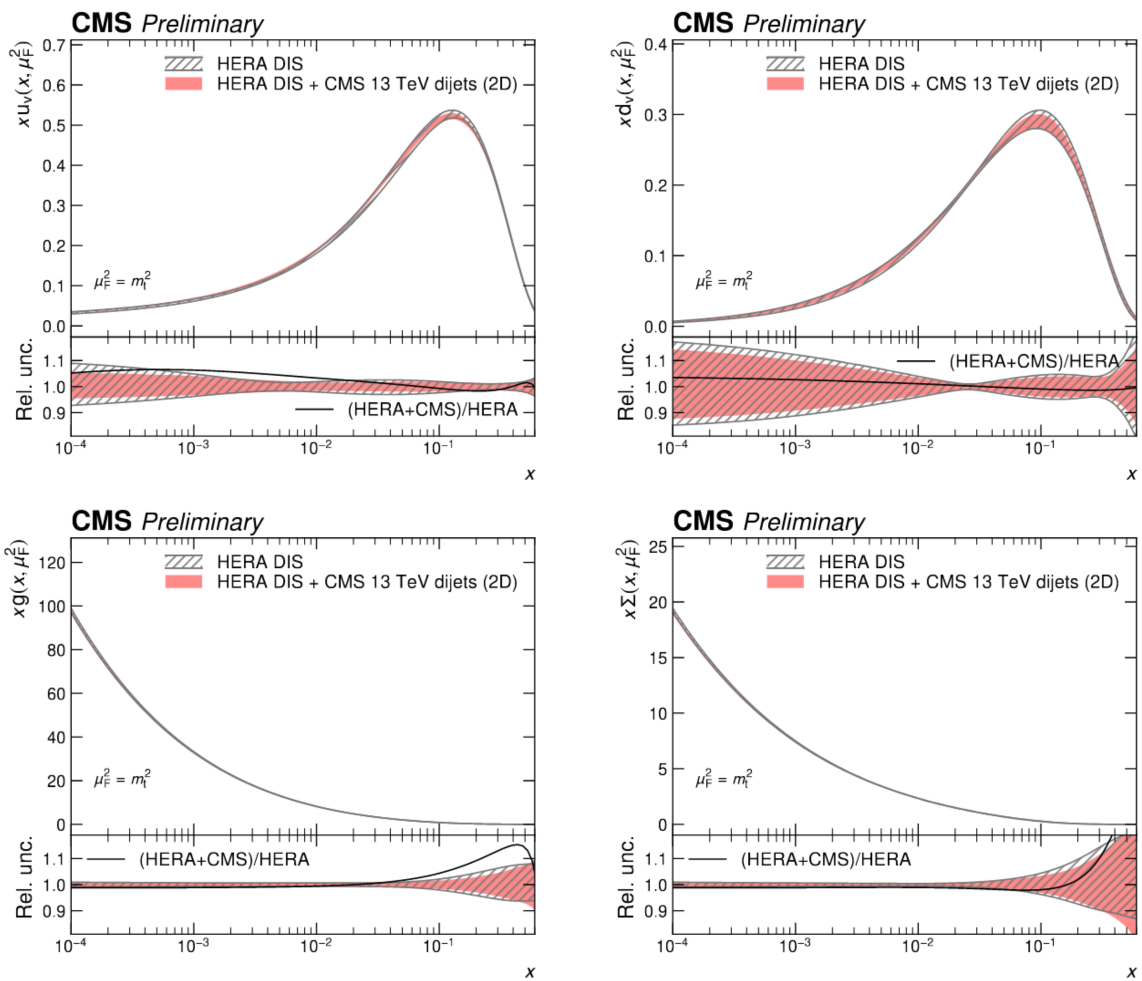
Comparison with NNLO predictions: 3D measurements

- Comparison with fixed-order theory predictions at NNLO, complemented by NP and electroweak corrections



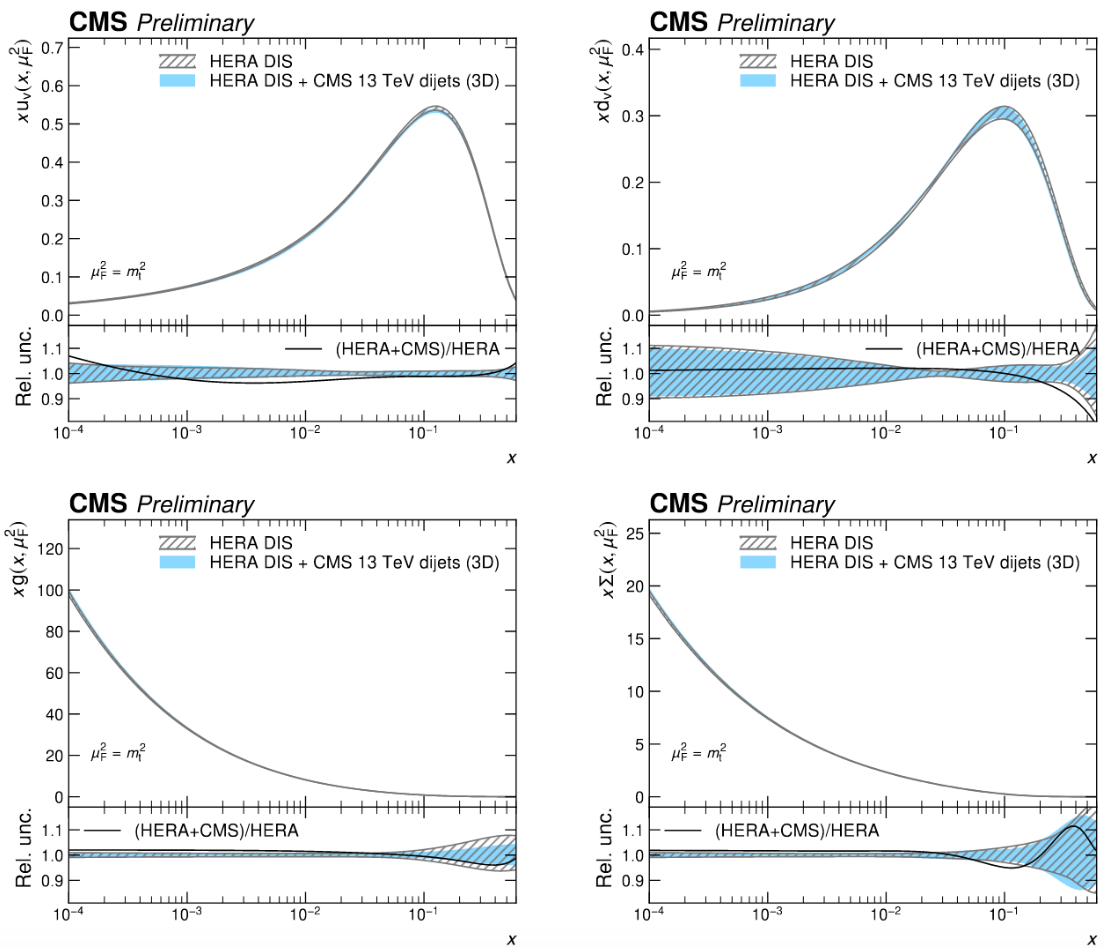
- Predictions for different PDFs generally in agreement
  → except for AMBP16 PDF - predicted cross sections are generally smaller
- The same for 2D distributions (in back-up)

Impact on parton distributions: 2D measurements



- Inclusion of the dijet measurements results in overall reduction of the PDF fit uncertainty
  → In particular precision of gluon PDF is improved for parton momentum fractions x > 0.1
- Distributions obtained with and without the CMS data appear largely compatible within fit uncertainty alone
  → notable exception of gluon at x > 0.1 → increased gluon contribution

Impact on parton distributions: 3D measurements



- Fits including the 3D dijet cross sections result in larger reduction of fit uncertainty
- Distributions obtained with and without the CMS data appear largely compatible even within fit uncertainty alone

QCD analysis @ NNLO and α_s estimation

- Parameterisations used

PDF	Fitted data sets	
	HERA DIS + CMS dijets (2D)	HERA DIS + CMS dijets (3D)
$x\,\mathrm{g}(x,\mu^2_{\mathrm{F},0})$	$A_\mathrm{g}\,x^{B_\mathrm{g}}\,(1-x)^{C_\mathrm{g}}$	$A_\mathrm{g}\,x^{B_\mathrm{g}}\,(1-x)^{C_\mathrm{g}}$
$x\,\mathrm{u_v}(x,\mu^2_{\mathrm{F},0})$	$A_{\mathrm{u_v}}\,x^{B_{\mathrm{u_v}}}\,(1-x)^{C_{\mathrm{u_v}}}\,(1+D_{\mathrm{u_v}}x+E_{\mathrm{u_v}}x^2)$	$A_{\mathrm{u_v}}\,x^{B_{\mathrm{u_v}}}\,(1-x)^{C_{\mathrm{u_v}}}\,(1+D_{\mathrm{u_v}}x)$
$x\,\mathrm{d_v}(x,\mu^2_{\mathrm{F},0})$	$A_{\mathrm{d_v}}\,x^{B_{\mathrm{d_v}}}\,(1-x)^{C_{\mathrm{d_v}}}$	$A_{\mathrm{d_v}}\,x^{B_{\mathrm{d_v}}}\,(1-x)^{C_{\mathrm{d_v}}}$
$x\,\overline{\mathrm{U}}(x,\mu^2_{\mathrm{F},0})$	$A_{\overline{\mathrm{U}}}\,x^{B_{\overline{\mathrm{U}}}}\,(1-x)^{C_{\overline{\mathrm{U}}}}\,(1+D_{\overline{\mathrm{U}}}\,x)$	$A_{\overline{\mathrm{U}}}\,x^{B_{\overline{\mathrm{U}}}}\,(1-x)^{C_{\overline{\mathrm{U}}}}\,(1+D_{\overline{\mathrm{U}}}\,x)$
$x\,\overline{\mathrm{D}}(x,\mu^2_{\mathrm{F},0})$	$A_{\overline{\mathrm{D}}}\,x^{B_{\overline{\mathrm{D}}}}\,(1-x)^{C_{\overline{\mathrm{D}}}}$	$A_{\overline{\mathrm{D}}}\,x^{B_{\overline{\mathrm{D}}}}\,(1-x)^{C_{\overline{\mathrm{D}}}}\,(1+D_{\overline{\mathrm{D}}}\,x)$

- 2D: $\alpha_s(m_Z) = 0.1201 \pm 0.0012\,(\mathrm{fit}) \pm 0.0008\,(\mathrm{scale}) \pm 0.0008\,(\mathrm{model}) \pm 0.0005\,(\mathrm{param.})$
  $= 0.1201 \pm 0.0021\,(\mathrm{total}),$
- 3D: $\alpha_s(m_Z) = 0.1201 \pm 0.0010\,(\mathrm{fit}) \pm 0.0005\,(\mathrm{scale}) \pm 0.0008\,(\mathrm{model}) \pm 0.0006\,(\mathrm{param.})$
  $= 0.1201 \pm 0.0020\,(\mathrm{total}),$
- 2D and 3D estimates agree well
- 3D measurements give slightly more precise value of as

Central values from dijet measurements about 1 standard deviation away from world average of as(mZ) = 0.1179 ± 0.0009 and larger by about 1.6 standard deviations than those for inclusive jets at 13 TeV

Multi-jets

Determination of strong coupling from transverse energy-energy correlations

13 TeV ATLAS data with 139 fb^{-1}
arXiv:2301.09351
JHEP 07 (2023) 85

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

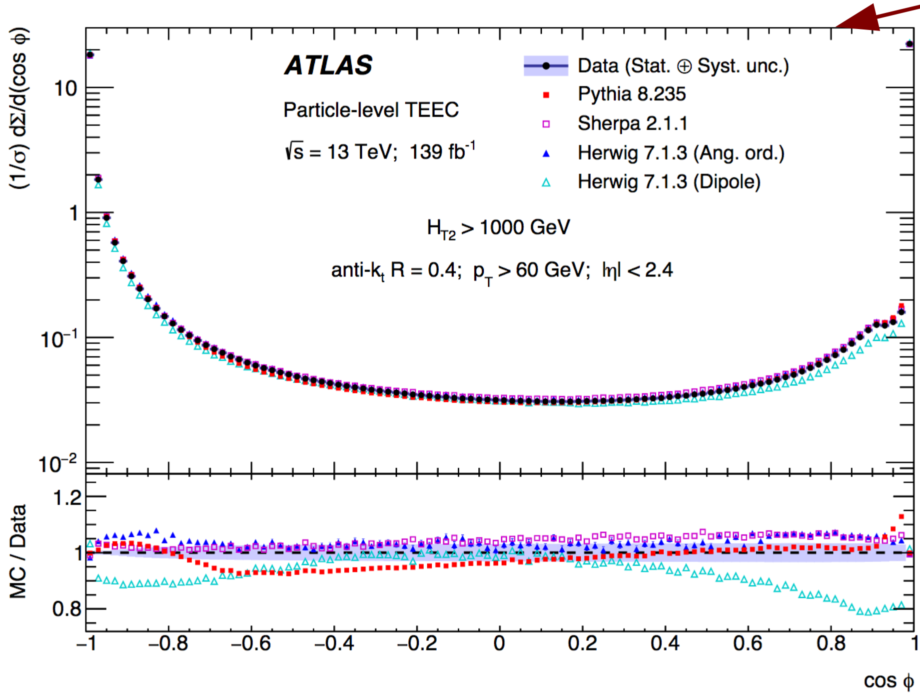
TEEC

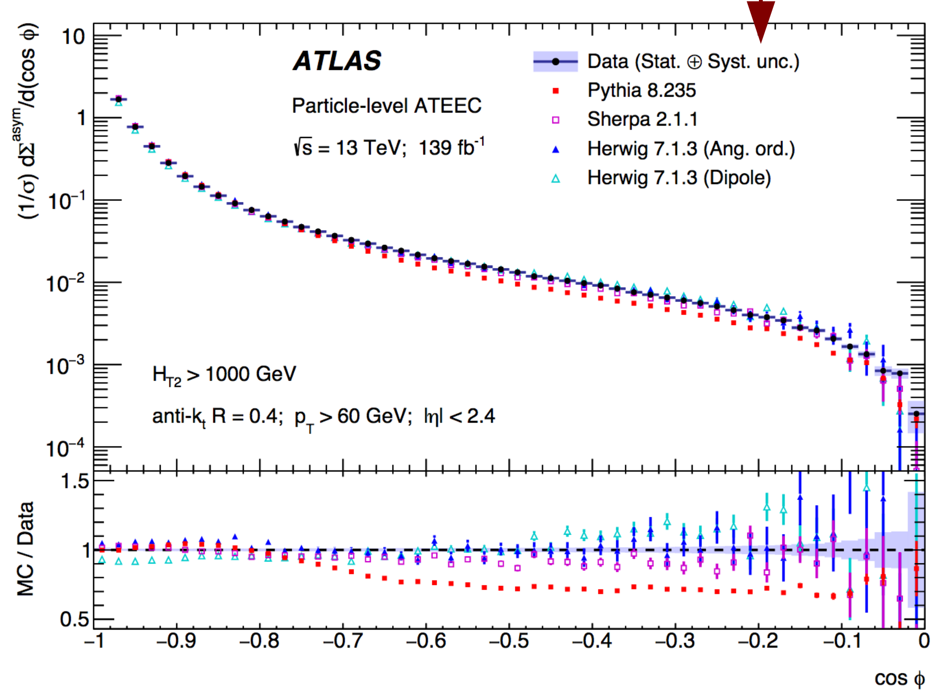
$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma^{\mathrm{asym}}}{\mathrm{d}\cos\phi} = \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\pi-\phi}$$

ATEEC

Measurement

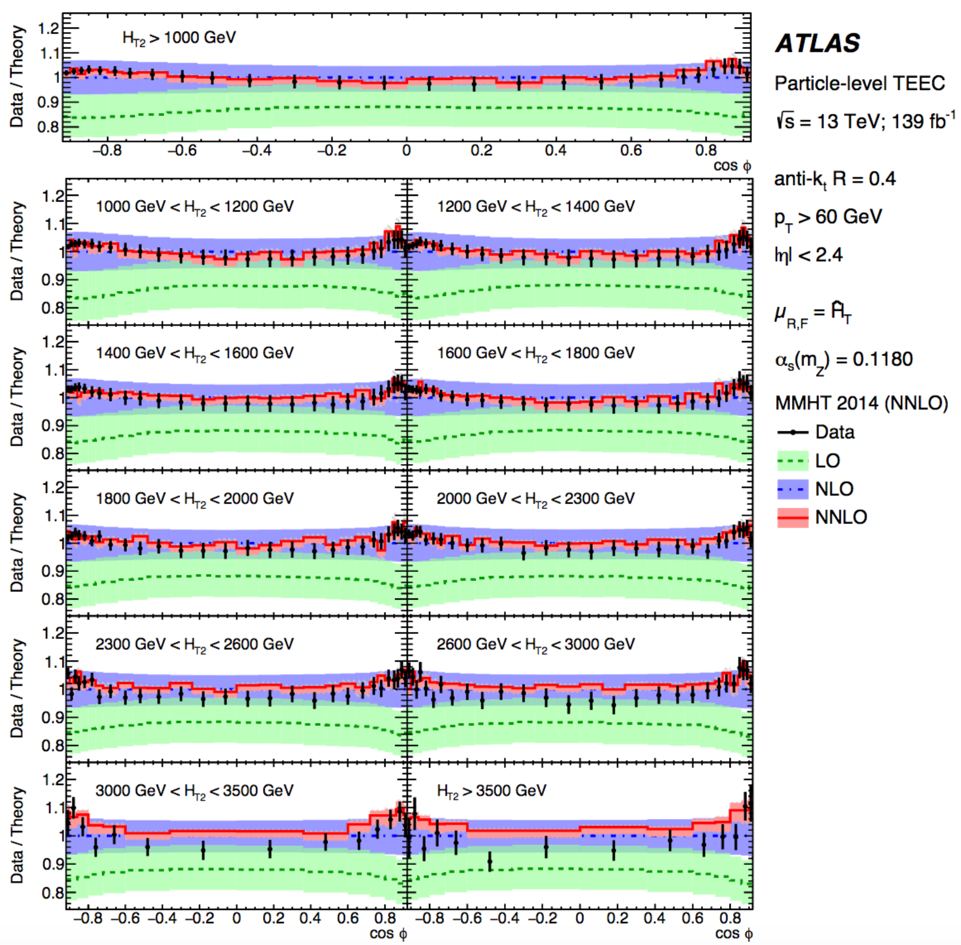
- High-energy multijets selected for scalar sum of p_T of two leading jets H_{T2} > 1TeV (+ binned in H_{T2} to study scale dependence)
  - Jets reconstructed using the anti-kt algorithm with radius R=0.4
  - Data are corrected for detector effects
  - Results are compared with MC predictions
- Total uncertainty of the order of 2% for TEEC and 1% for ATEEC

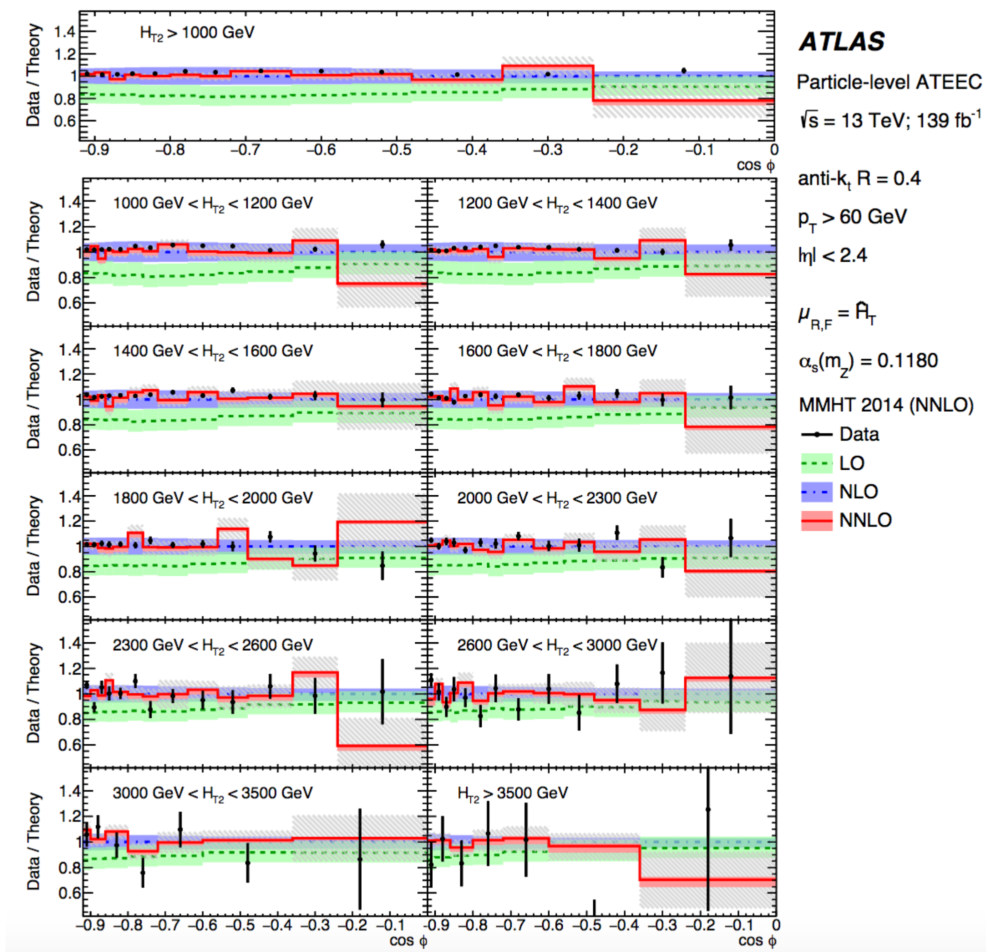




Comparison to theory calculations

- First-time comparison to NNLO pQCD calculations
  - Significant reduction in theoretical uncertainties (scale uncertainty)
  - Good agreement between data and theory → precision test of QCD at large momentum transfers Q

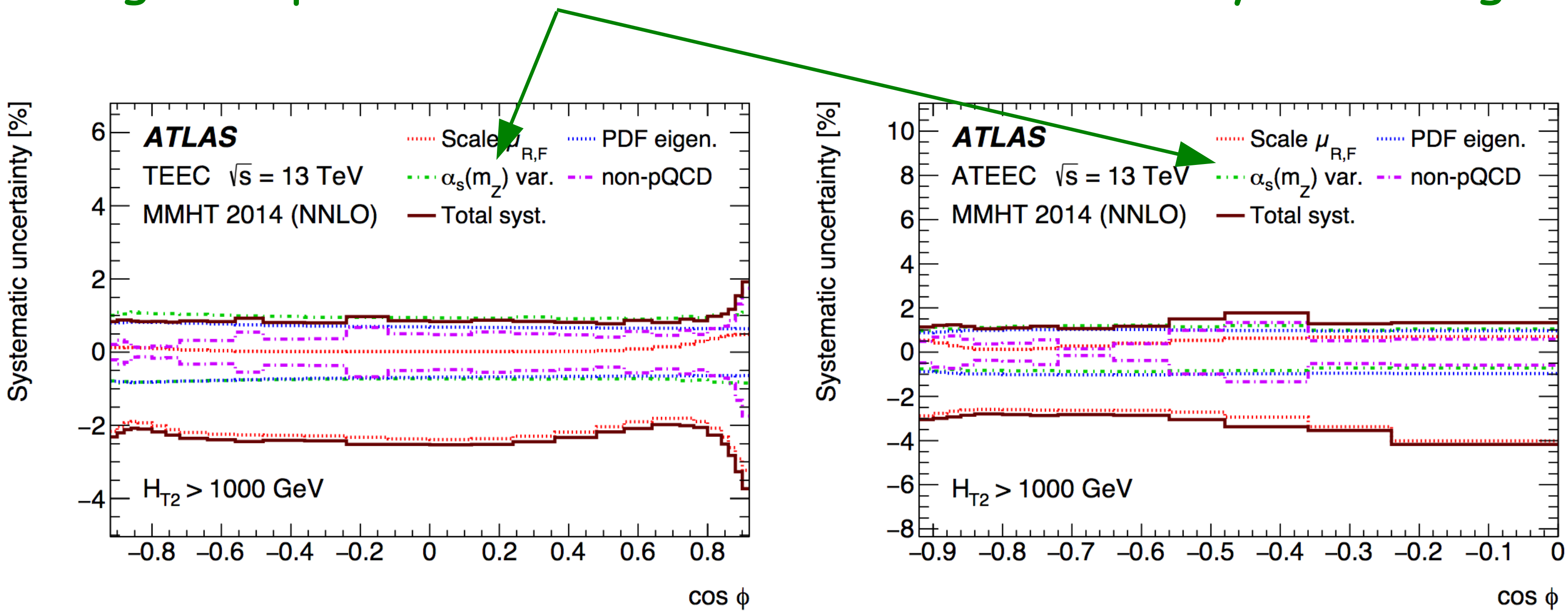




K. Wichm

Determining α_s

- α_s changed in prediction 0.118 +- 0.001 → sensitivity to strong coupling



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

- $\alpha s(mZ)$ obtained from global fits to TEEC and ATEEC distributions using MMHT2014, CT14 and NNPDF 3.0 PDFs
→ state of the art theory calculations included, for the first time with NNLO three-jet corrections

α_s results

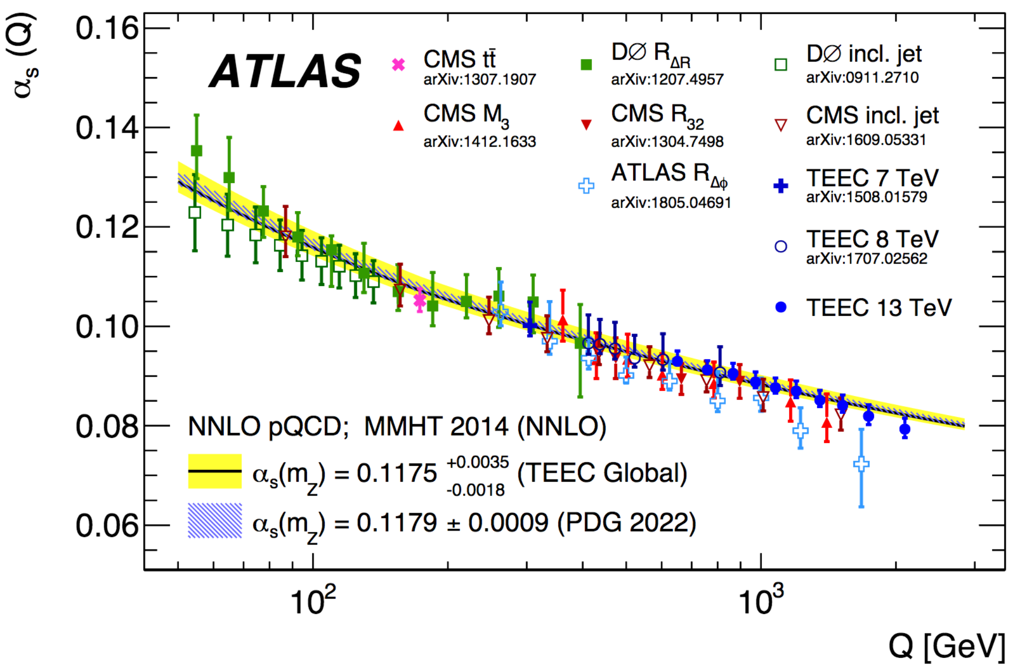
- Final results with MMHT2014 PDF set
- Fits to extract α_s repeated separately for H_{T2} interval → determining α_s for each energy bin → observation of running of α_s possible

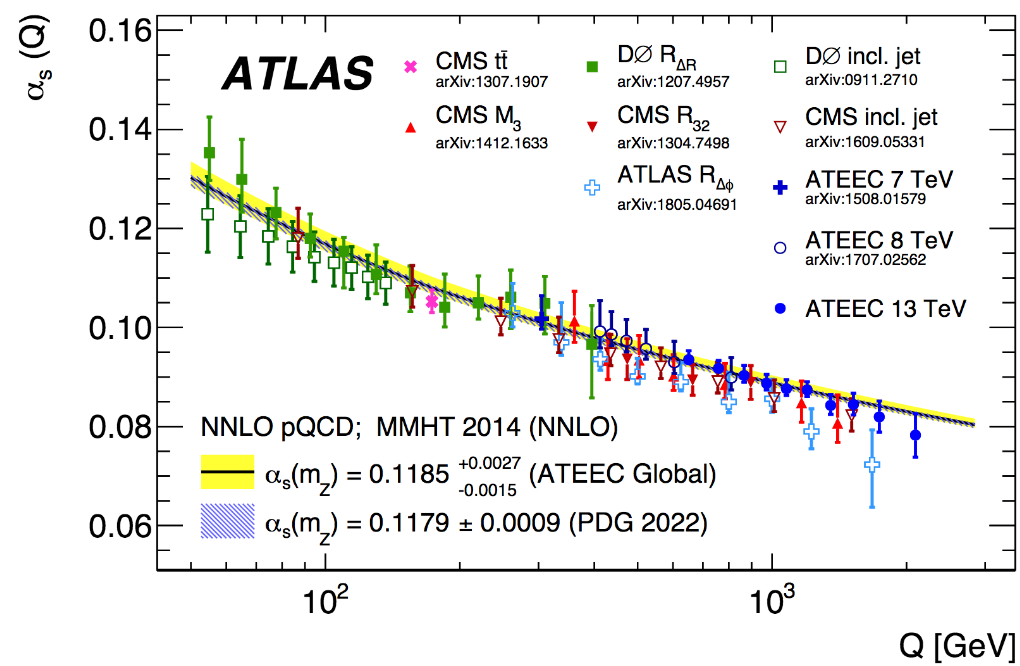
$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\,(\text{exp.})^{+0.0034}_{-0.0017}\,(\text{theo.})$$ TEEC

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

- Drop by a factor of 4 of theoretical uncertainties ← inclusion of NNLO corrections to three-jet production
- TEEC and ATEEC values compatible within uncertainties
  - TEEC value → better experimental precision (smaller stat. uncertainty)
  - ATEEC values → better theoretical precision

α_s running





good agreement between all measurements and prediction

Multi-jets

Beyond collinear PDFs: PB-TMD

13 TeV CMS data with 36.3 fb^{-1}

arXiv:2210.13557

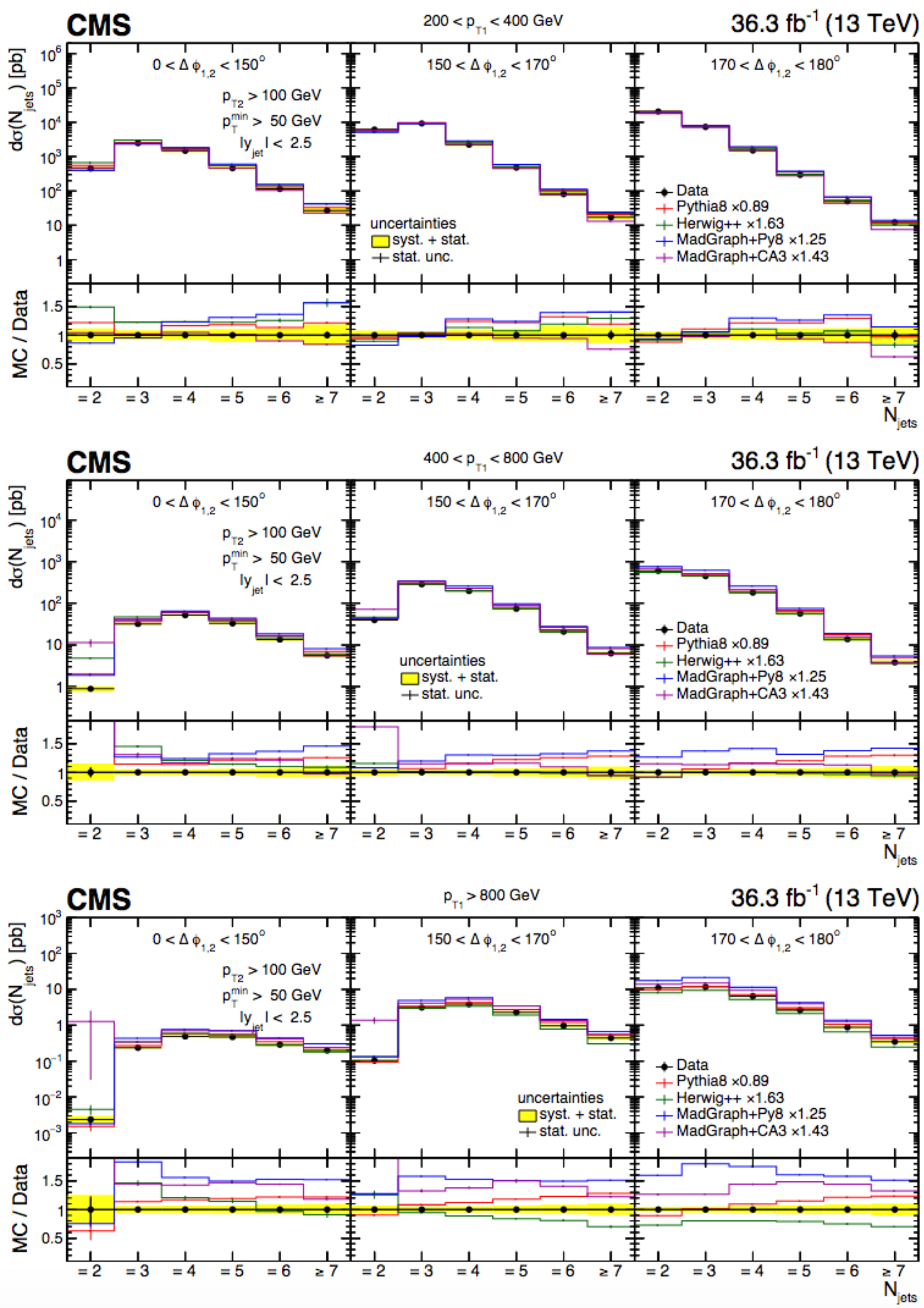
Motivation

- In pp collisions at LO → two colliding partons scatter → production of 2 high p_T partons → jets
- Such jets strongly correlated in transverse plane
  → azimuthal angle difference between them should be close to π
- Higher-order corrections result in decorrelation in azimuthal plane
  → angle significantly deviates from π
- Corrections due to:
  - hard parton radiation, calculated at matrix element level at NLO
  - softer multiple parton radiation described by parton showers

Predictions available with initial-state parton shower is determined by parton-branching PB-TMD densities
→ used in CASCADE → can be confronted with data

Generator	PDF	ME	Tune
PYTHIA 8 [23]	NNPDF 2.3 (LO) [25]	LO $2 \to 2$	CUETP8M1 [24]
MADGRAPH+PY8 [4]	NNPDF 2.3 (LO) [25]	LO $2 \to 2,3,4$	CUETP8M1 [24]
MADGRAPH+CA3 [4]	PB-TMD set 2 (NLO) [1]	LO $2 \to 2,3,4$	—
HERWIG++ [26]	CTEQ6L1 (LO) [27]	LO $2 \to 2$	CUETHppS1 [24]
MG5_aMC+Py8 (jj)	NNPDF 3.0 (NLO) [31]	NLO $2 \to 2$	CUETP8M1 [24]
MG5_aMC+CA3 (jj)	PB-TMD set 2 (NLO) [1]	NLO $2 \to 2$	—
MG5_aMC+CA3 (jjj)	PB-TMD set 2 (NLO) [1]	NLO $2 \to 3$	—

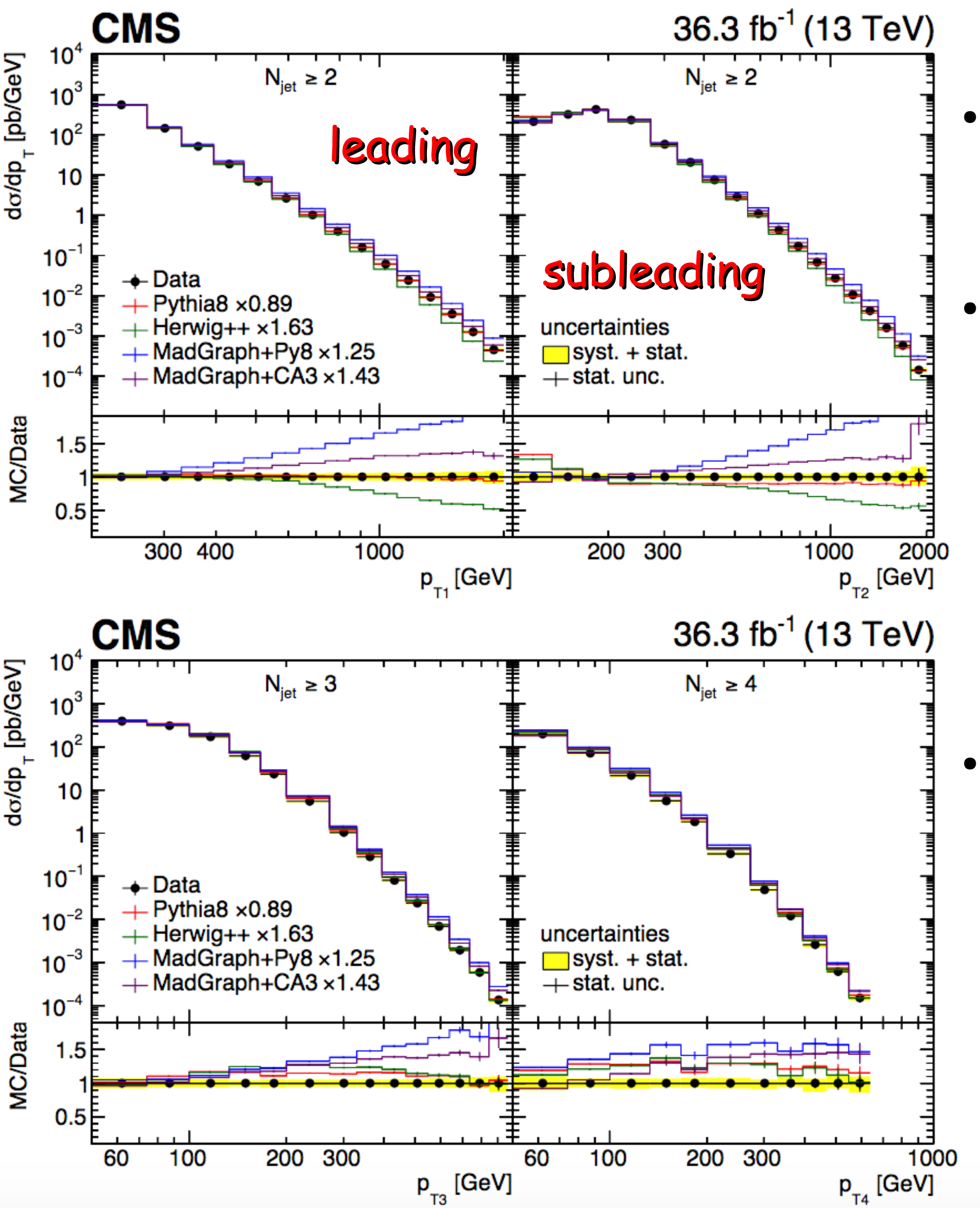
Jet multiplicities



- Jets clustered with anti-k_T algorithm with R=0.4 and $|\eta| < 3.2$ and $p_T > 20$ GeV
- Dijet system with $p_{T,1} > 200$ GeV and $p_{T,2} > 100$ GeV and $|y^{1,2}| < 2.5$
- Additional jets with $p_T > 50$ GeV and $|y| < 2.5$

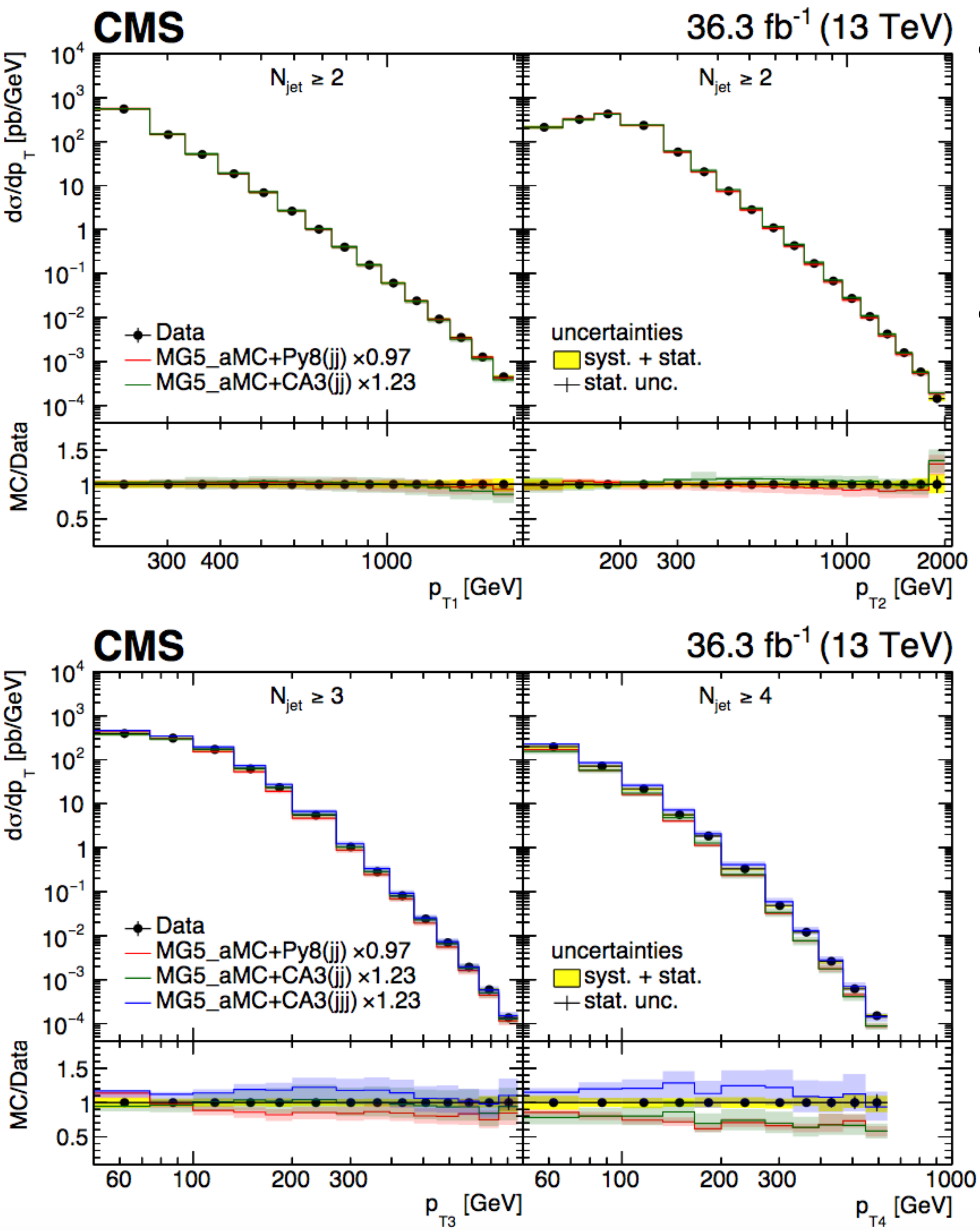
- Differential cross section as a function of exclusive jet multiplicity
  → up to 7 jets
  in bins of p_T of leading jet and azimuthal angle difference between two highest p_T jets in dijet system
- Data compared with LO predictions
  → MADGRAPH+PY8 shape doesn't agree
  → MAD-GRAPH+CA3 and HERWIG++ agree

Transverse momentum distributions



- Transverse momentum distributions of four leading jets
- <u>Data compared with **LO predictions**</u>
  → Only PYTHIA8 describes data reasonably well the shape, except for $p_T^2 < 200$ GeV
  → Shape of 3rd and 4th jet distributions not well described, PYTHIA8 overestimates rate
- Compared to MADGRAPH+PY8, MADGRAPH+CA3 gives significant improvement for shape three leading jets
  - description of 4th jet is similar to MADGRAPH+PY8

Transverse momentum distributions



- Transverse momentum distributions of four leading jets
  → theory bands: scale uncertainties

- <u>Data compared with **NLO predictions**</u>
  → MG5aMC+Py8 (jj) and MG5aMC+CA3 (jj) describe normalization and shape offirst three jets rather well
  → MG5aMC+CA3 (jjj) describes 3rd and 4th jets well within uncertainties

First time calculations using PB-TMDs together with MEs in MC@NLO frame are compared with jet measurements over wide range in transverse momentum and jet multiplicities

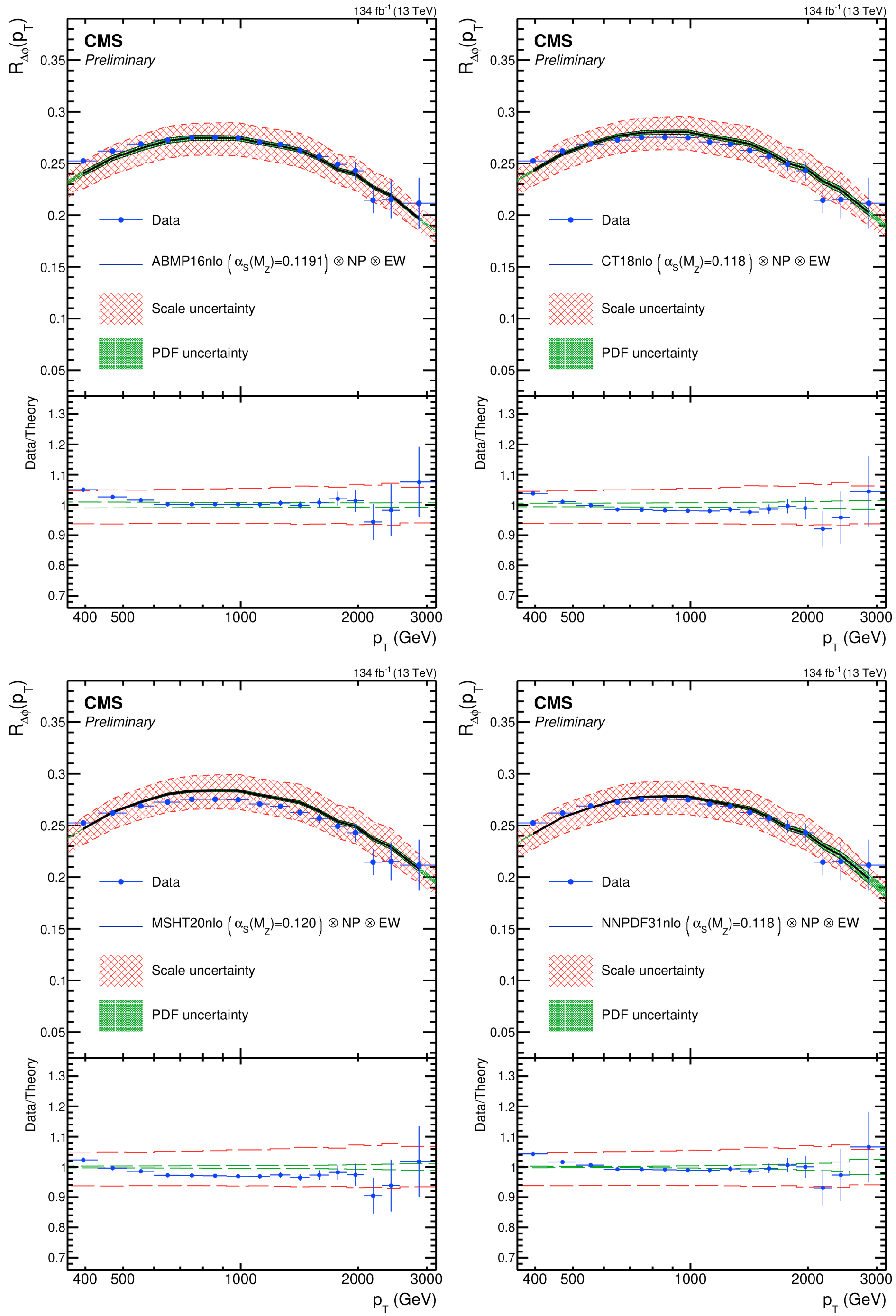
Multi-jets

Azimuthal correlations among jets and determination of strong coupling

13 TeV CMS data with 134 fb^{-1}

CMS-PAS-SMP-22-005

Correlation measurements



- <u>Aim</u>: α_s(**Q**) extraction of from multijet at various energy scale
- <u>Means:</u> ratio observable RΔφ(pT), related to azimuthal correlations among jets measured as a function of jet p_T

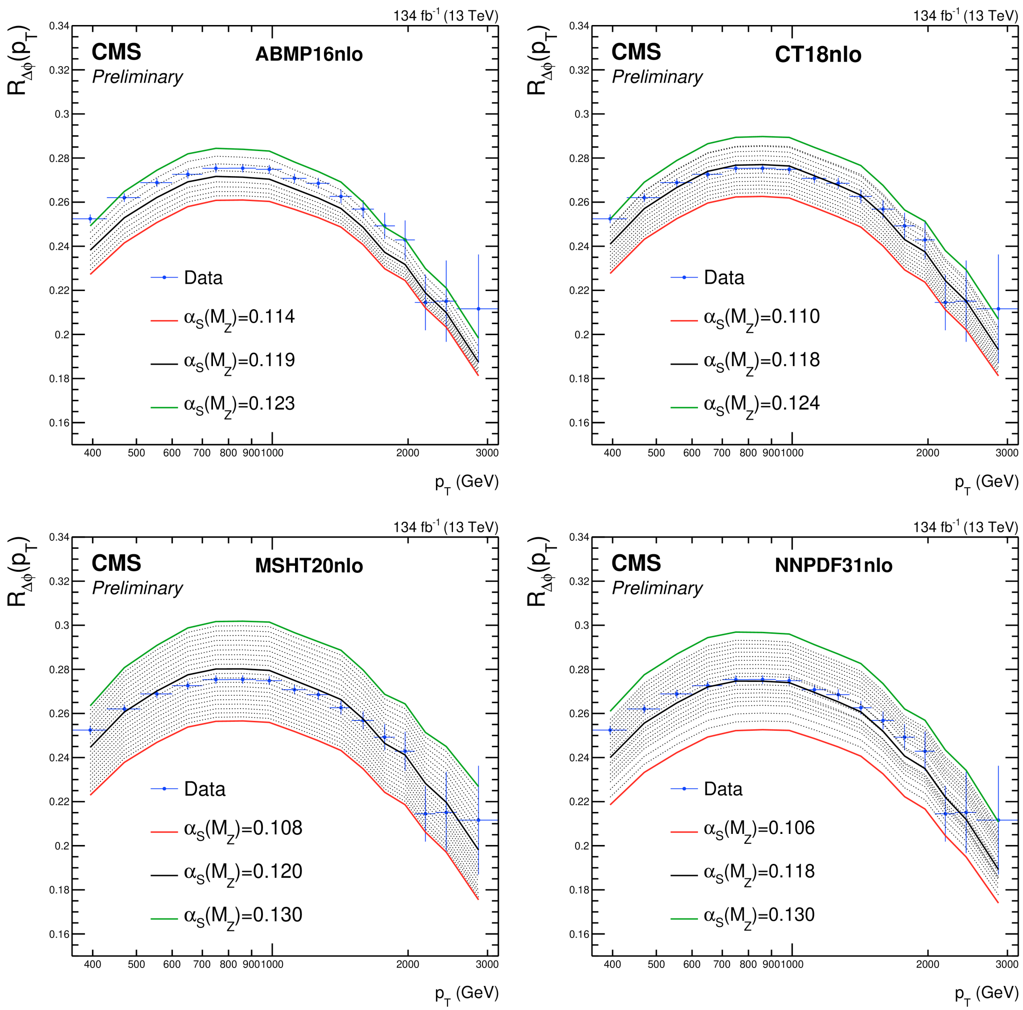
$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{jet}(p_T)} N_{nbr}^{(i)}(\Delta\phi, p_{Tmin}^{nbr})}{N_{jet}(p_T)}$$

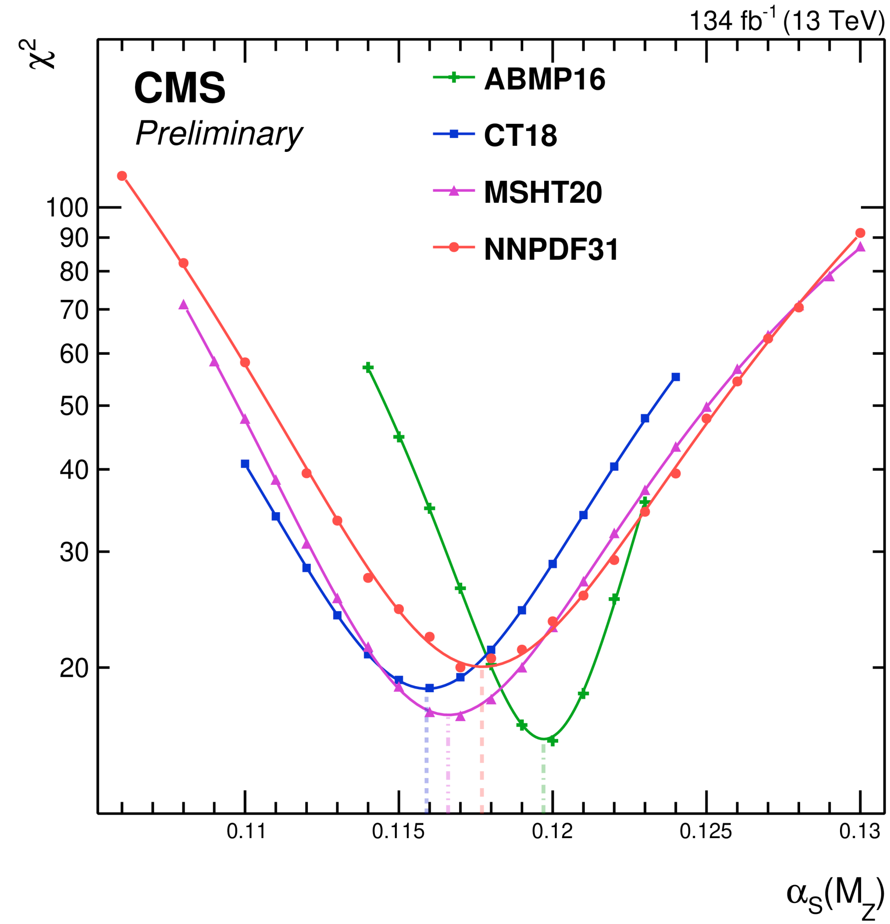
criteria of neighboring jets

- At NLO radiation of a third hard parton allows 3-jet topology
- R directly proportional to α_s at lowest order
  → select 3+jet, reconstructed with anti-k_T and R = 0.7

Determination of strong coupling

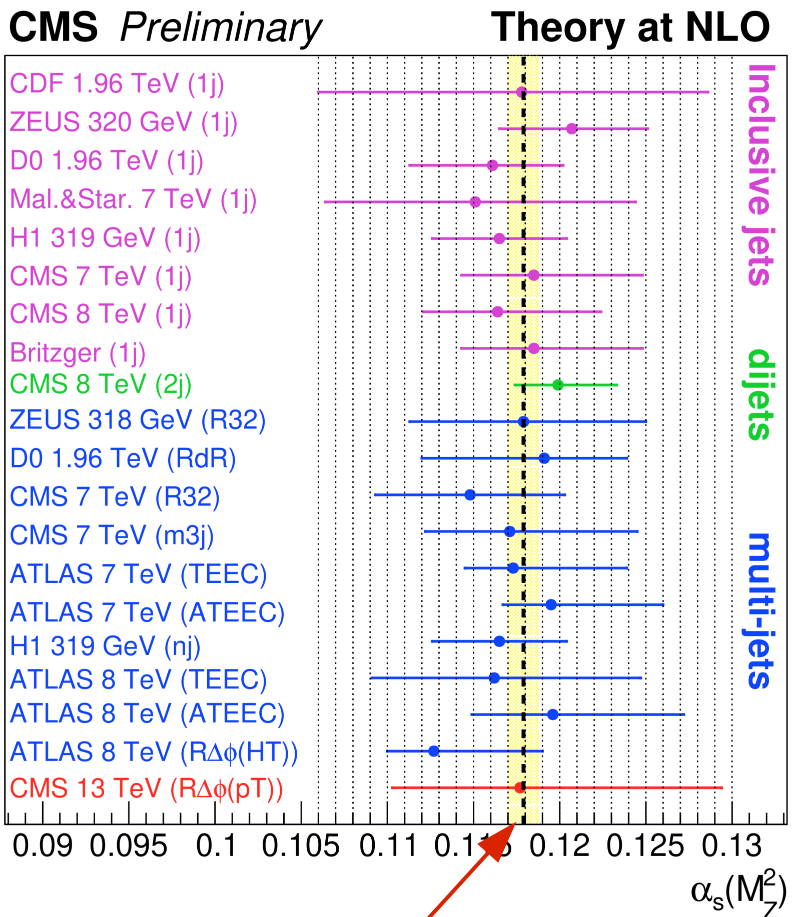
- $R_{\Delta\phi}(p_{\mathrm{T}})$ sensitive to α_s

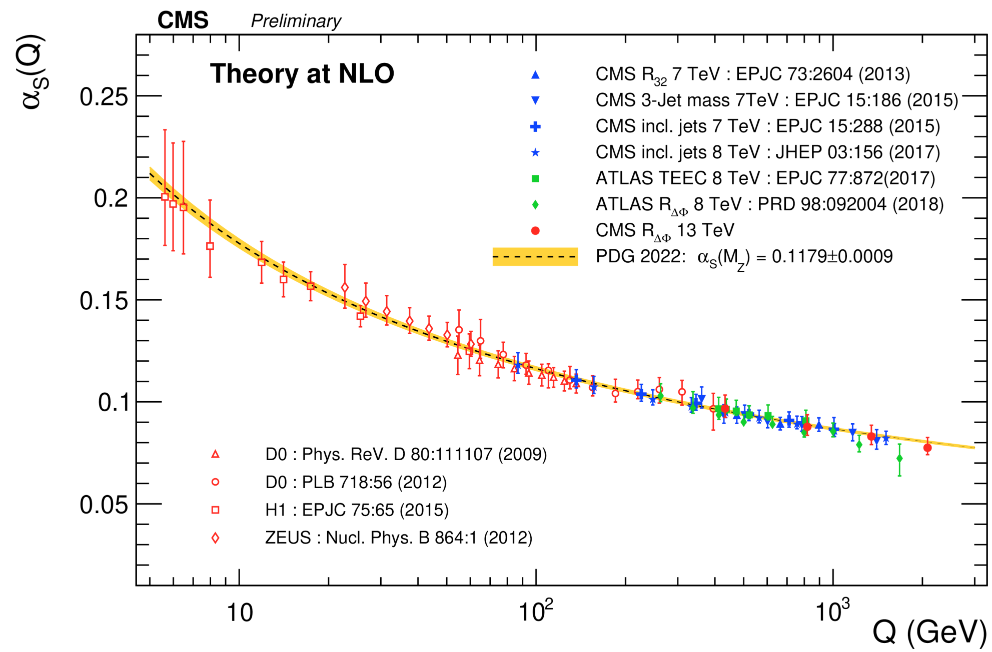




Nominal result with NNPDF3.1 NLO

Strong coupling and strong coupling running





- α_s results using other PDF sets compatible among each other
- central result compatible with world average
- Expected from pQCD running of strong coupling observed

$$\alpha_S(M_Z) = 0.1177 \pm 0.0013\,(\mathrm{exp})^{+0.0116}_{-0.0073}\,(\mathrm{th}) = 0.1177^{+0.0117}_{-0.0074}$$

Multi-jets

Multijet event isotropies with ATLAS detector

13 TeV CMS data with 140 fb^{-1}

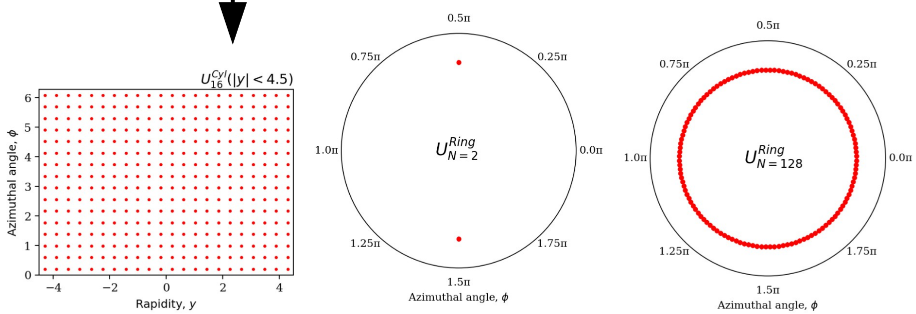
arXiv:2305.16930

Event isotropies

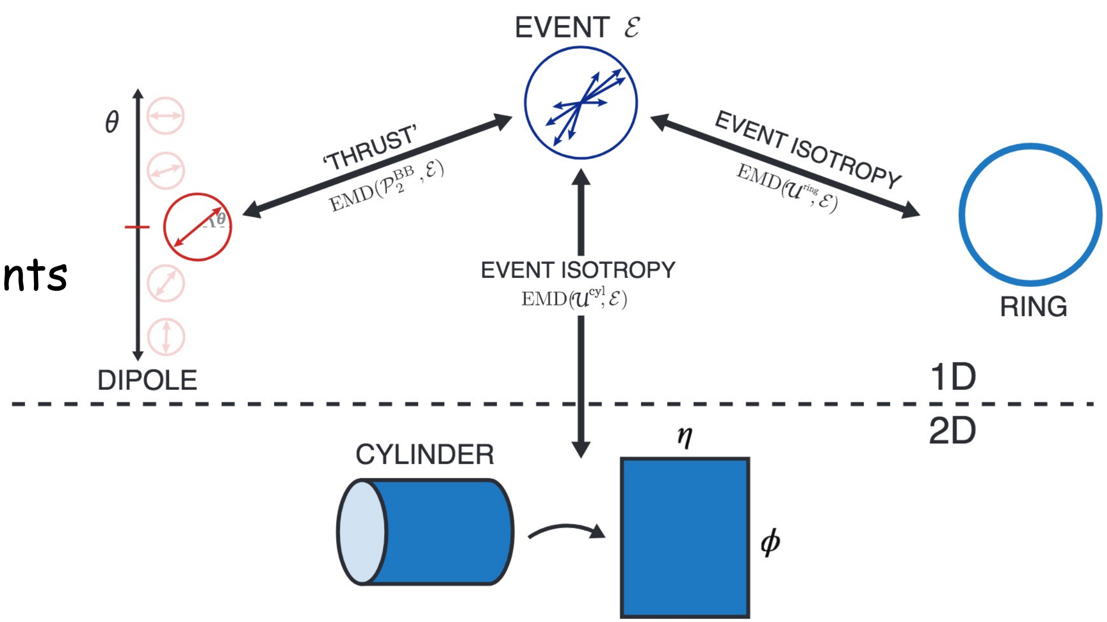
- Novel event shapes constructed to probe different aspects of QCD radiation in collider events
- Used for MC tuning

Event isotropy computed using the Energy-Mover's Distance – application of 'Earth-Mover's Distance' from computer vision to particle physics, using p-Wasserstein metric

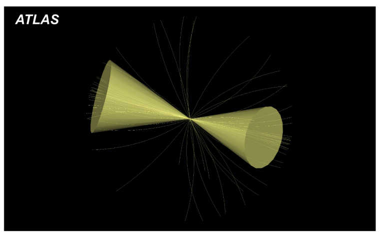
- Reference geometries and observables used in this analysis



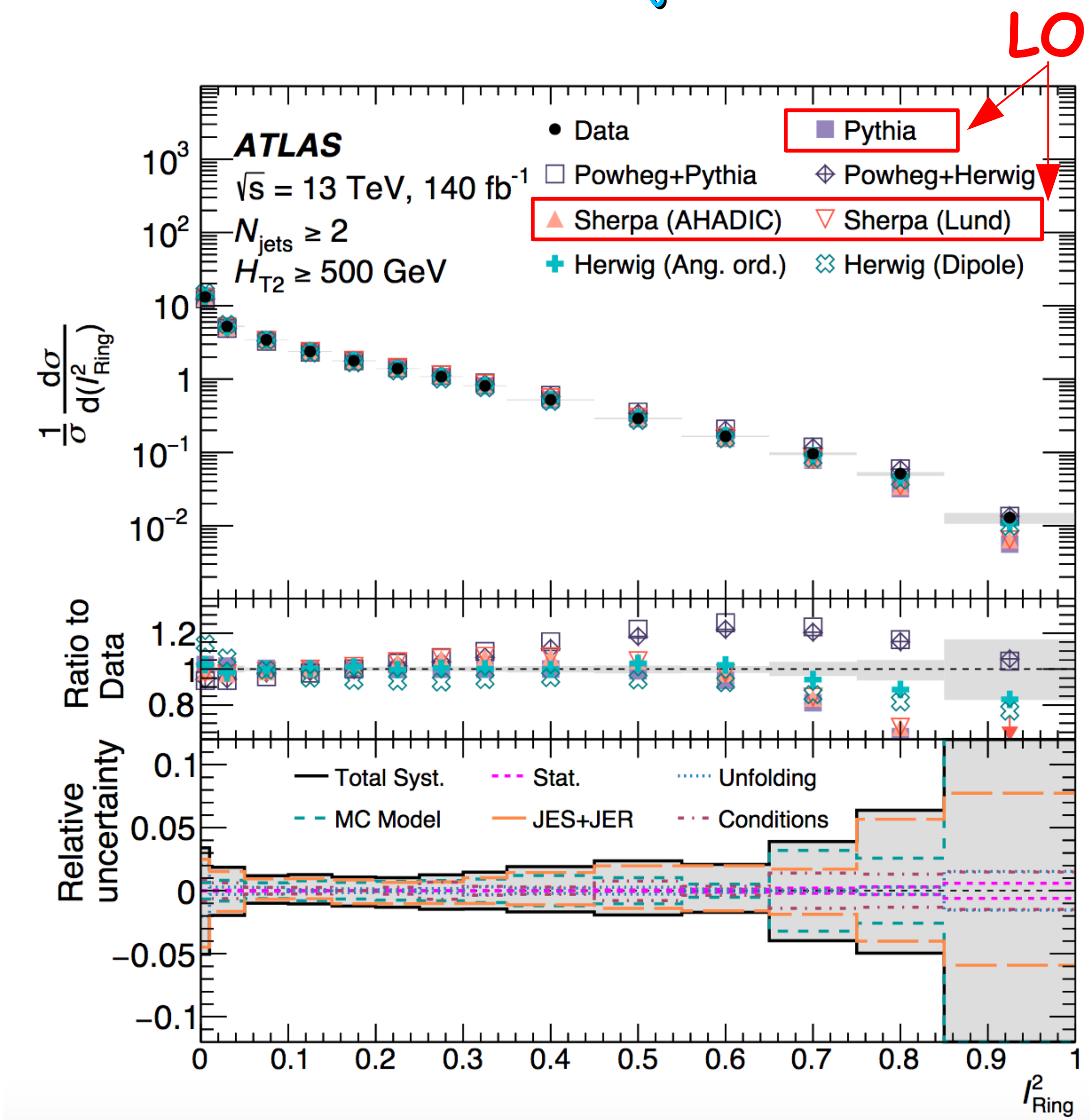
cylindrical ring-like symmetry 128 reference points

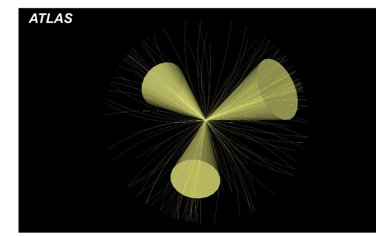


Most inclusive measurement of I^2_{Ring} in events with $N_{jet} \geq 2$ and $H_{T2} \geq 500$ GeV



balanced dijets

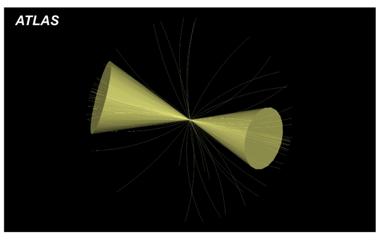




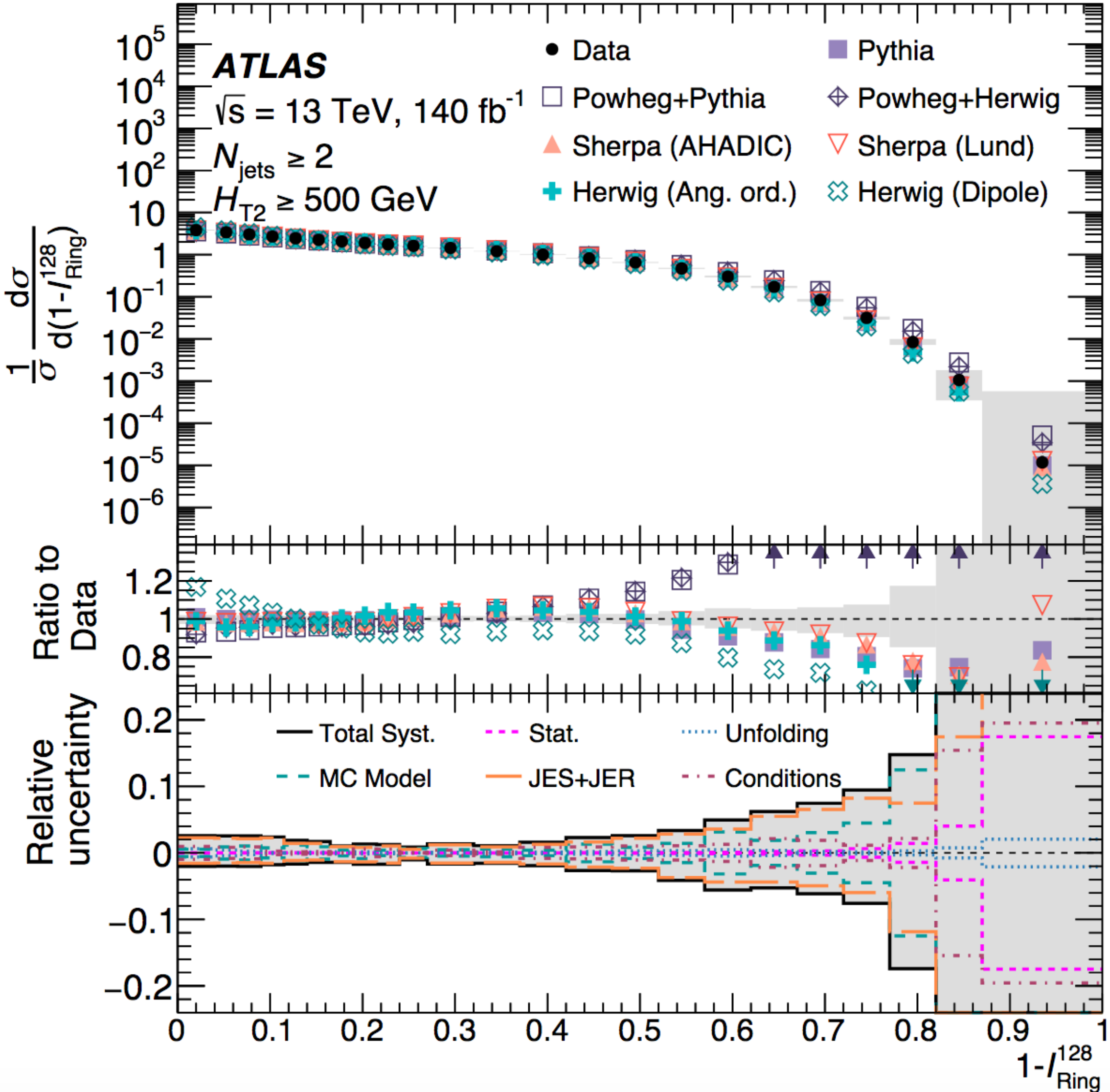
more isotropic

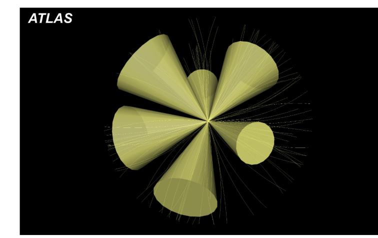
- No perfect description from any model
  → NLO does better than LO

Measurement of 1-I^{128}_{Ring} in events with $N_{jet} \geq 2$ and $H_{T2} \geq 500$ GeV



balanced dijets

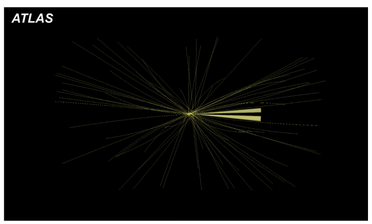




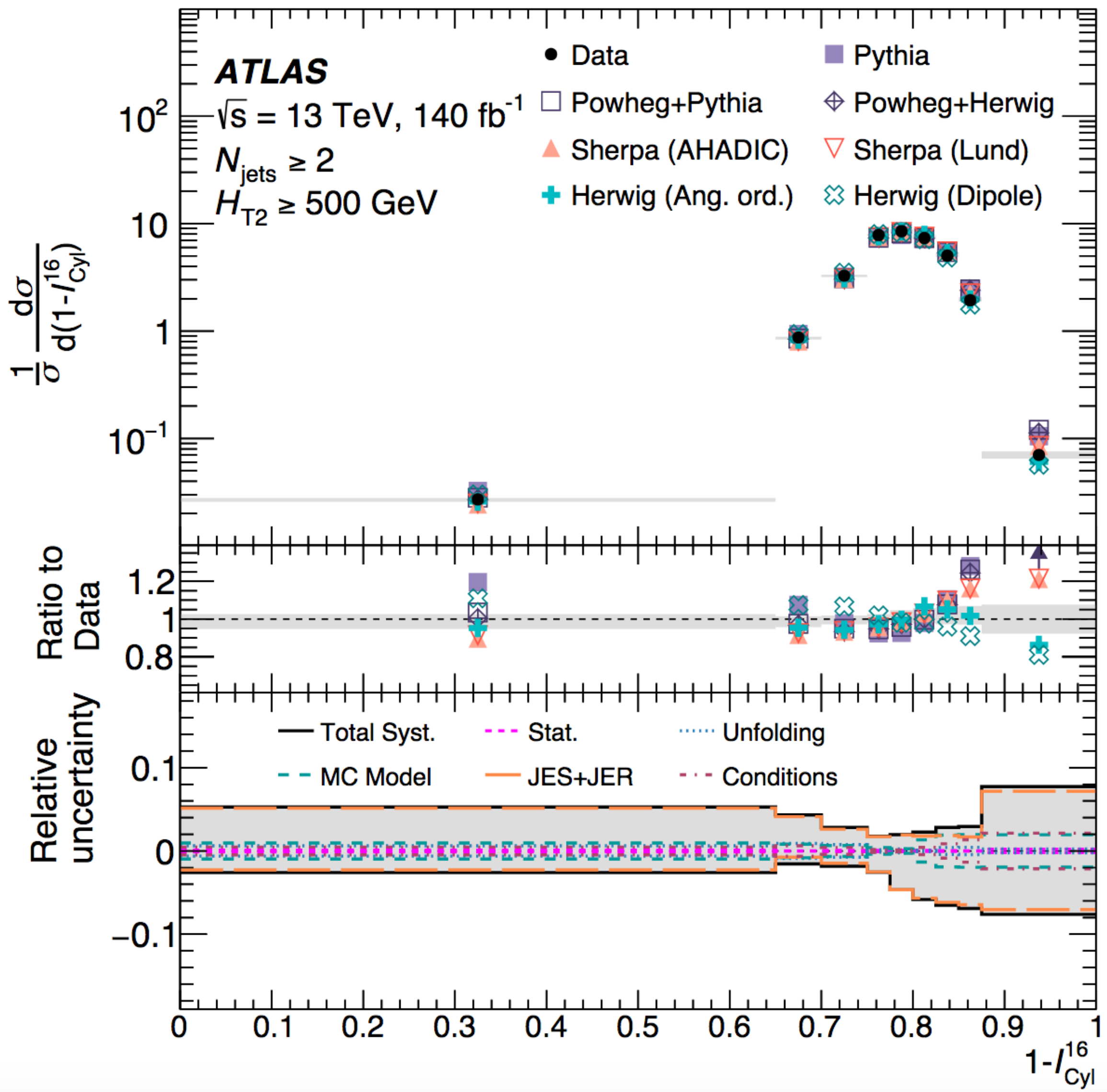
isotropic multijets

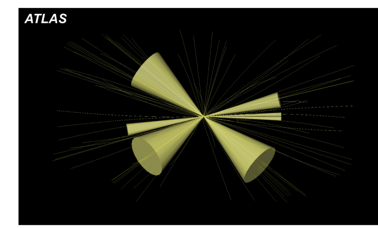
- Powheg+Pythia and Powheg+Herwig strongly disagree with other MCs
  → overestimate measurements for isotropic events, others underestimate it

Most inclusive measurement of 2D 1-I^{16}_{Cyl} for $N_{jet} \geq 2$ and $H_{T2} \geq 500$ GeV



forward dijets





Multijets evenly covering rapidity-azimuth plane (central & forward region)

- None of the MC predictions describe data, except near distribution peak

K. Wichmann @ QCD@LHC23 Jets @ LHC

MC tuning tool

- Available also measurements of event isotropy with
  → increasing N_{jets} requirement
  → inclusive bins of both N_{jets} and H_{T2}

No MC model offers satisfactory description of most variables or most regions → perfect tool for tuning

→ Rivet routine is available for these measurements
→ measured data points have been made publicly available along with other auxiliary information for use in future MC tuning and other QCD studies

Message to take home

- Jets @ LHC provide multiple opportunities for probing fundamental properties of QCD

Beautiful differential and multi-dimensional measurements (up to 3D)

→ improving PDF uncertainties, especially for gluon
→ studies of PB-TMDs and their implementation in MCs
→ high precision α_s measurements and studies (running) using various techniques

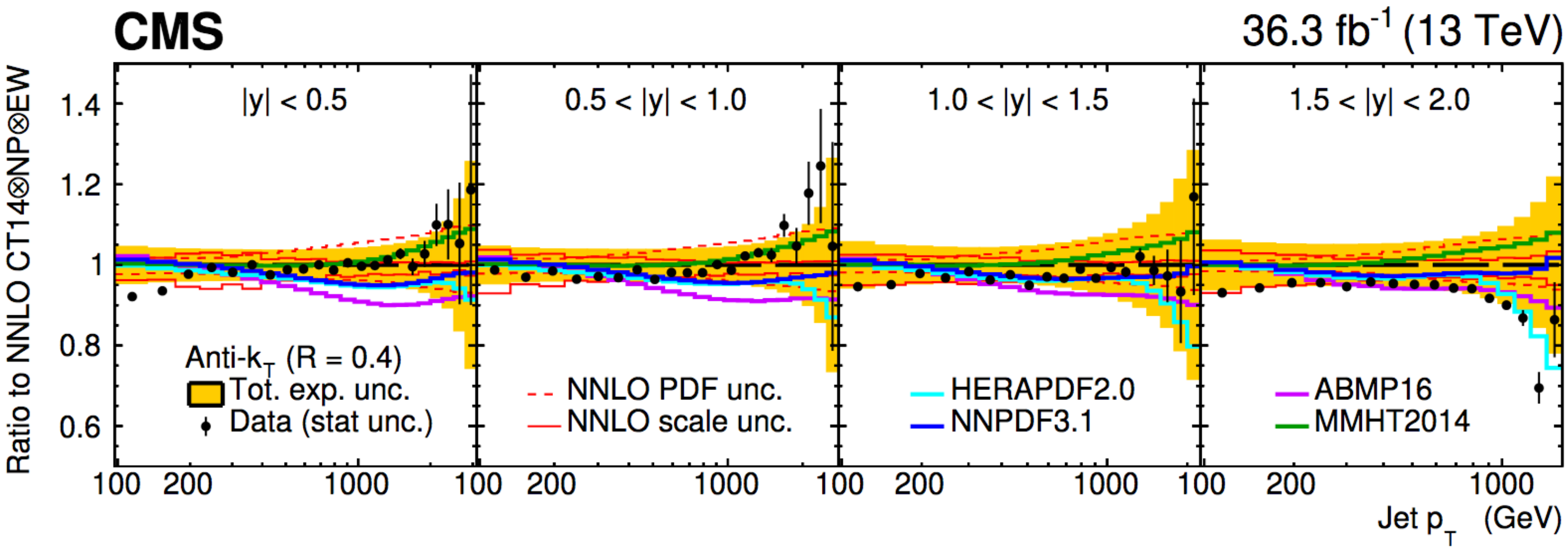
- Global QCD fits
- Transverse energy-energy correlation and asymmetries

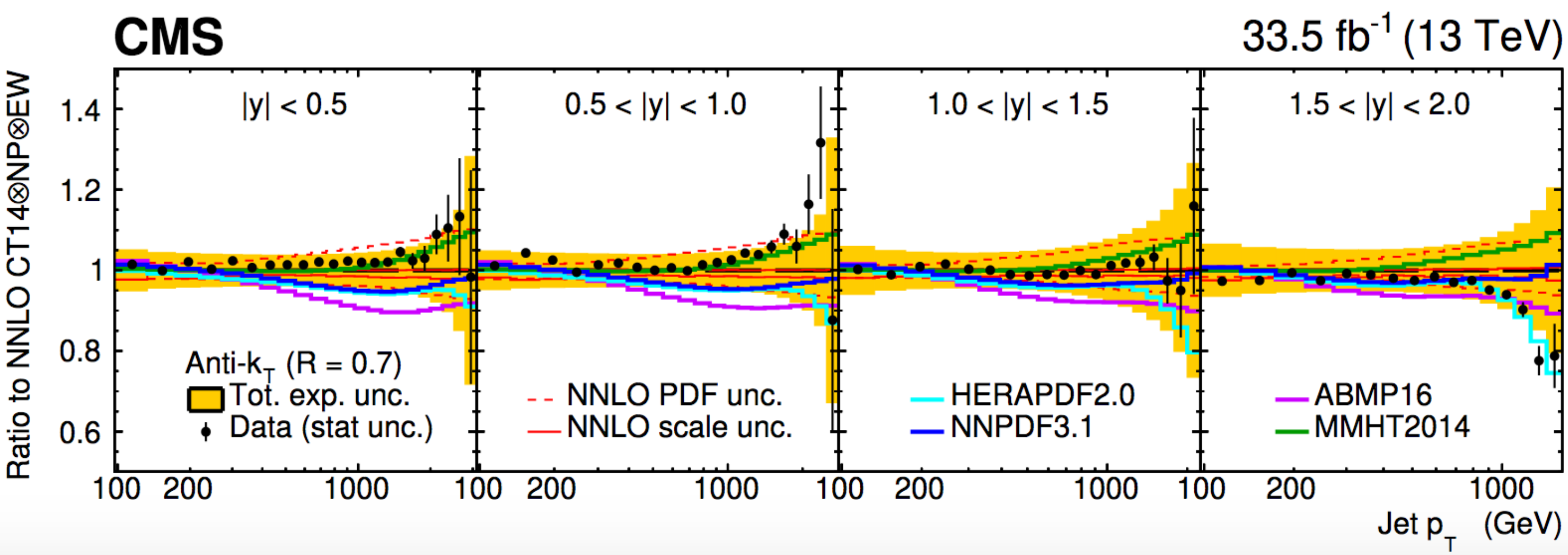
→ probing cylindrical and circular symmetries at hadron colliders using novel event shape variables → input to MC tuning

Some of these done for the very first time

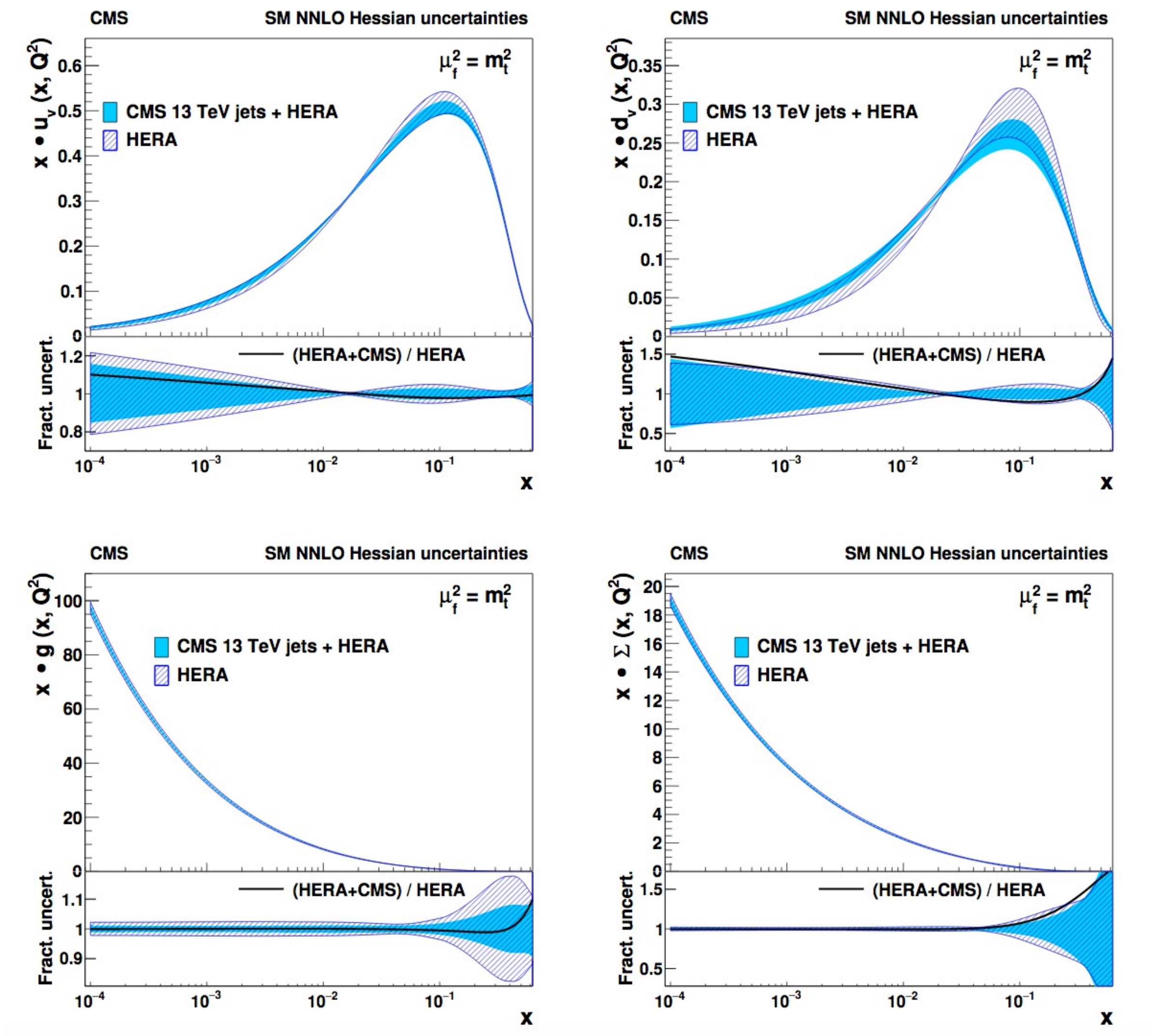
Additional slides

Comparison of measurement with predictions using various PDFs





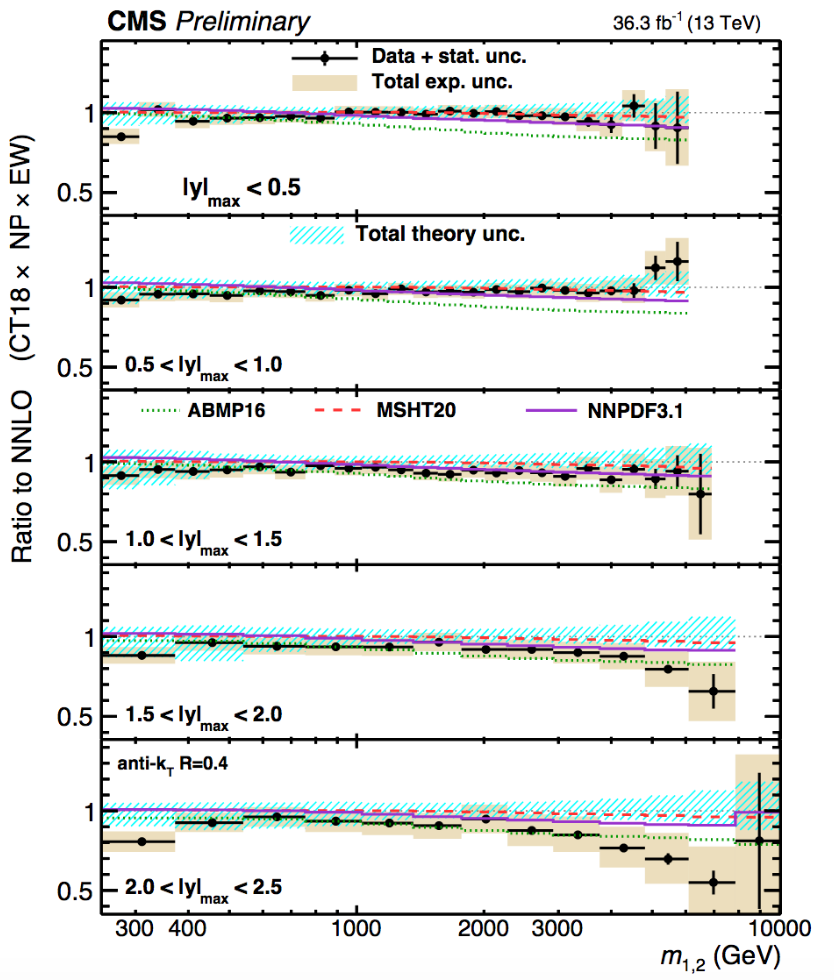
Impact of CMS jet data in QCD analysis

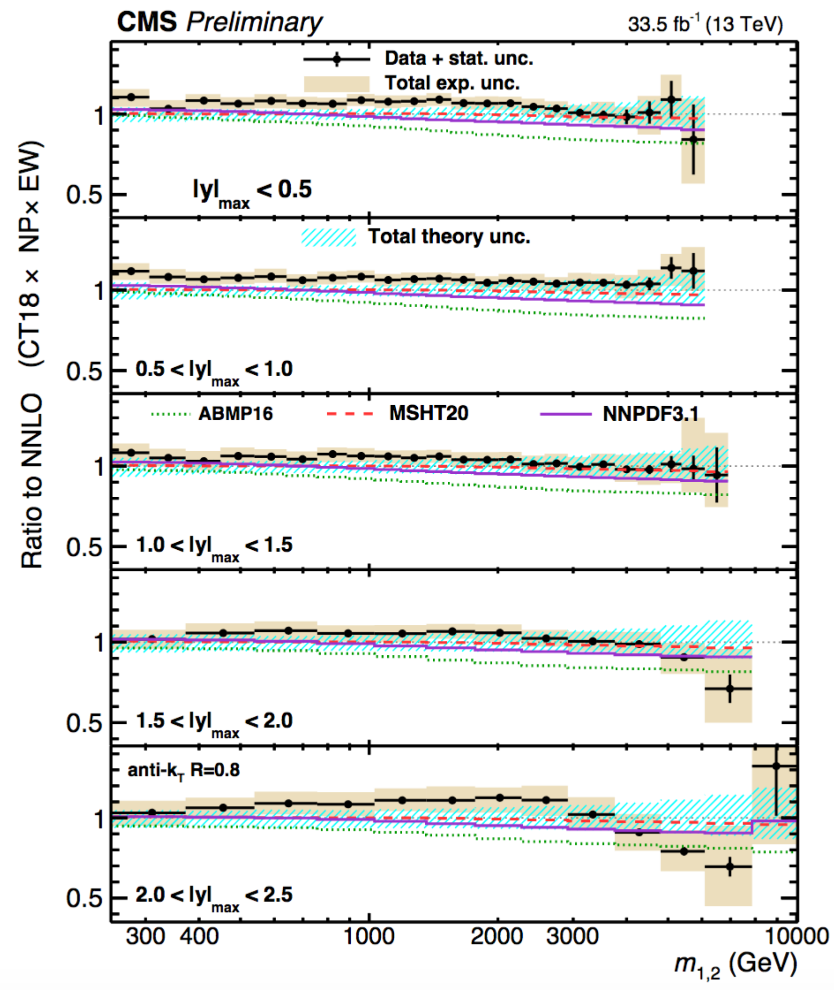


- Precision of PDFs improved, especially for high-x gluon

Comparison with NNLO predictions: 2D measurements

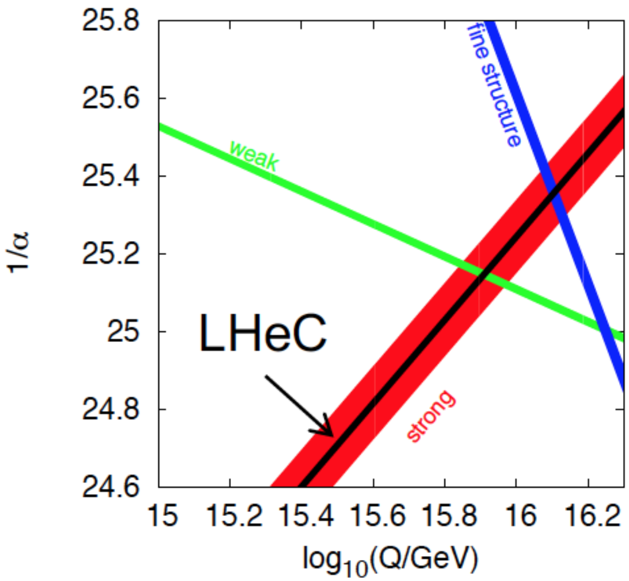
- Comparison with fixed-order theory predictions at NNLO, complemented by NP and electroweak corrections

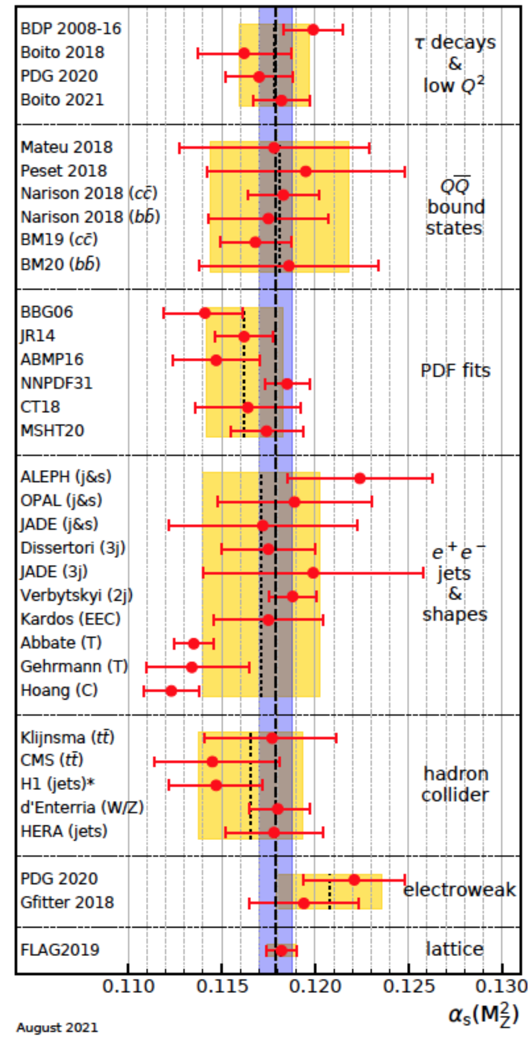


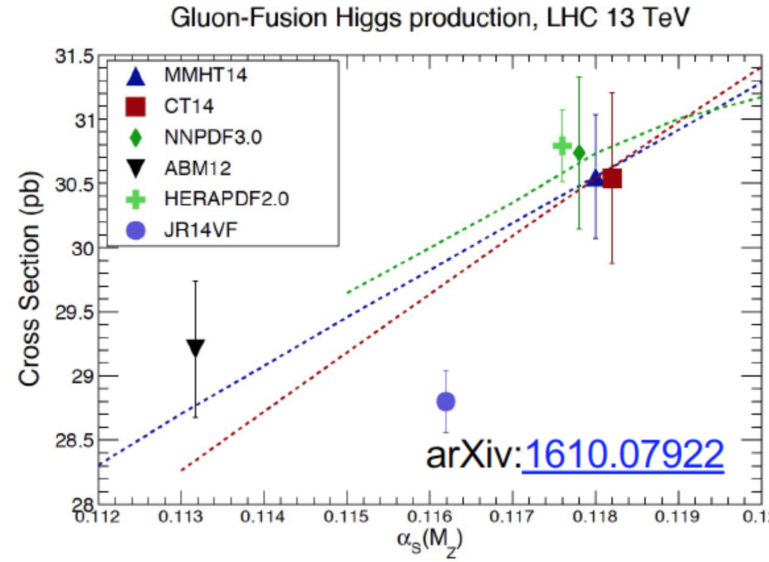


- Predictions for different PDFs generally in agreement
  → except for AMBP16 PDF - predicted cross sections are generally smaller

Why look at α_s?







- **αs** is least known coupling constant;

  needed to constrain GUT scenarios; cross section predictions, including Higgs; …

PDG21: αs = 0.1175 ± 0.0010 (w/o lattice)

- **PDFs** and/or **αs** limit: precision SM and Higgs measurements, BSM searches, …

- **what is true αs central value and uncertainty?**

  new precise determinations have important role to play

HERAPDF2.0 parameterisation

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x),\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}$$

- Additional constrains
  - A_{u_v}, A_{d_v}, A_g: constrained by the quark-number sum rules and momentum sum rule
  - $B_{\bar{U}} = B_{\bar{D}}$;
  - $x\bar{s} = f_s x\bar{D}$ at starting scale, f_s = 0.4

TMDs-what is it? [Phys. Lett. B **772** (2017), 446-451], [JHEP **01** (2018), 070]

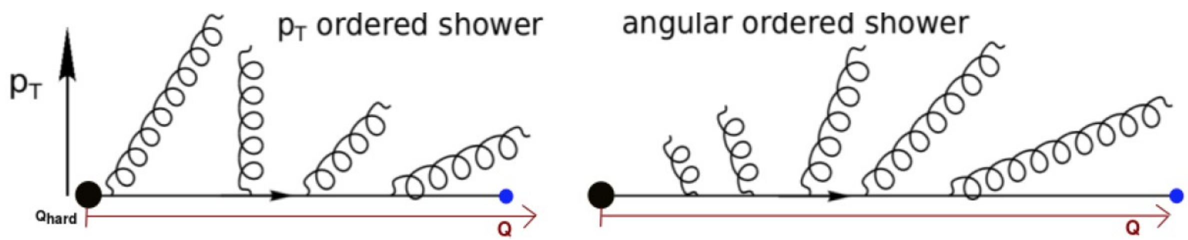
- TMDs : Transverse Momentum Dependent parton distributions
- extended collinear PDFs : transverse momentum effects from intrinsic k_t + evolution

Why TMD?

- fixed order calculations are limited in application
- small transverse momentum & small-x phenomena need TMDs

New approach: Parton Branching (PB) method

- evolution of TMDs and collinear PDFs at LO, NLO & NNLO
- automatically contain soft gluon resummation (at NLL identical to CSS approach)
- unique feature: backward evolution fully determines the TMD shower
- very successful for description of inclusive processes
  [Phys. Rev. D **100** (2019) no.7, 074027], [Eur. Phys. J. C **80** (2020) no.7, 598]



- Two angular ordered sets with different choice of scale in α_s:
  - set1: α_s(evolution scale)
  - **set2**: α_s(transverse momentum): similar quality as the NLO + NNLL prediction in $p_t(z)$ description