CMS jet measurements and constraints on PDFs and α_s

K. Wichmann
of behalf of the CMS Collaboration
@ DIS2023

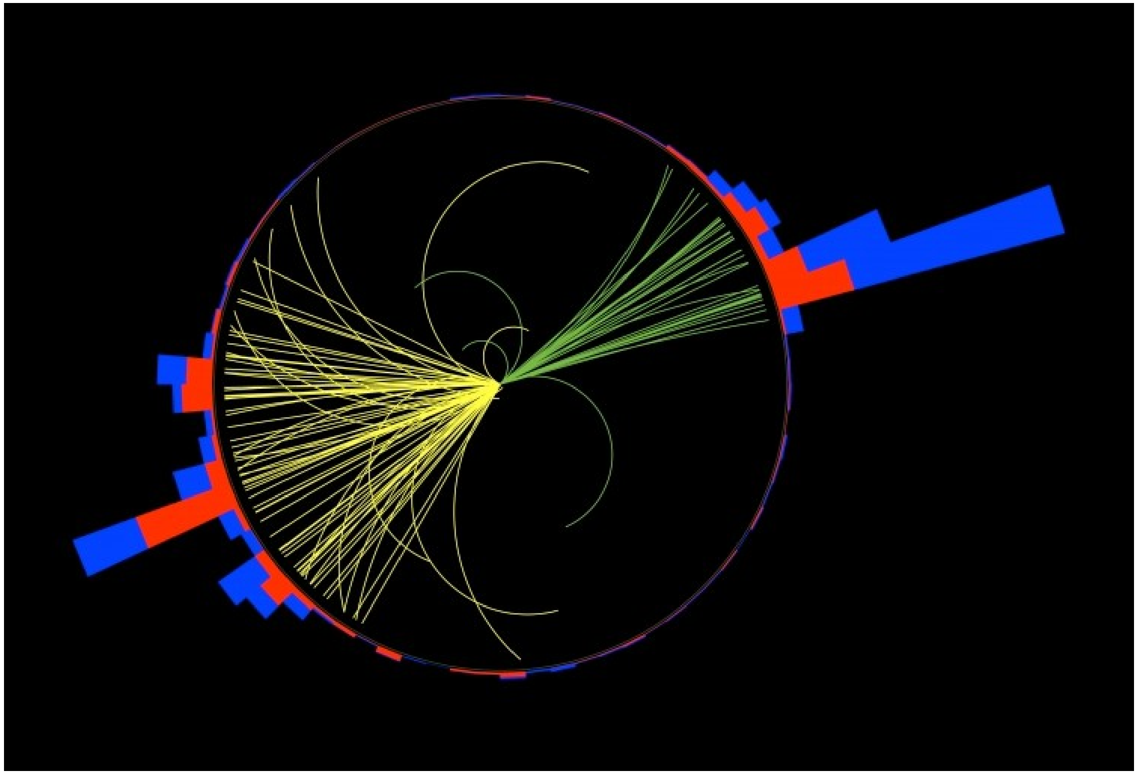
Motivation and QCD analysis strategy

- 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

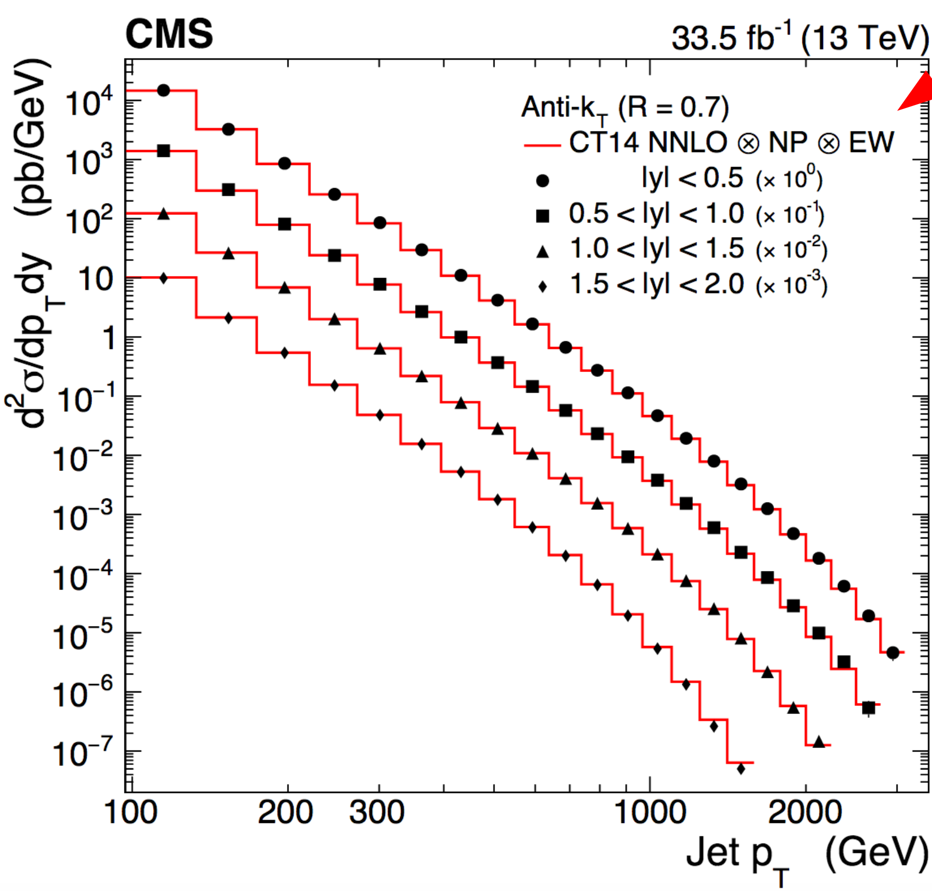


Inclusive jets at CMS @ 13 TeV

JHEP 2022 (2022) 35

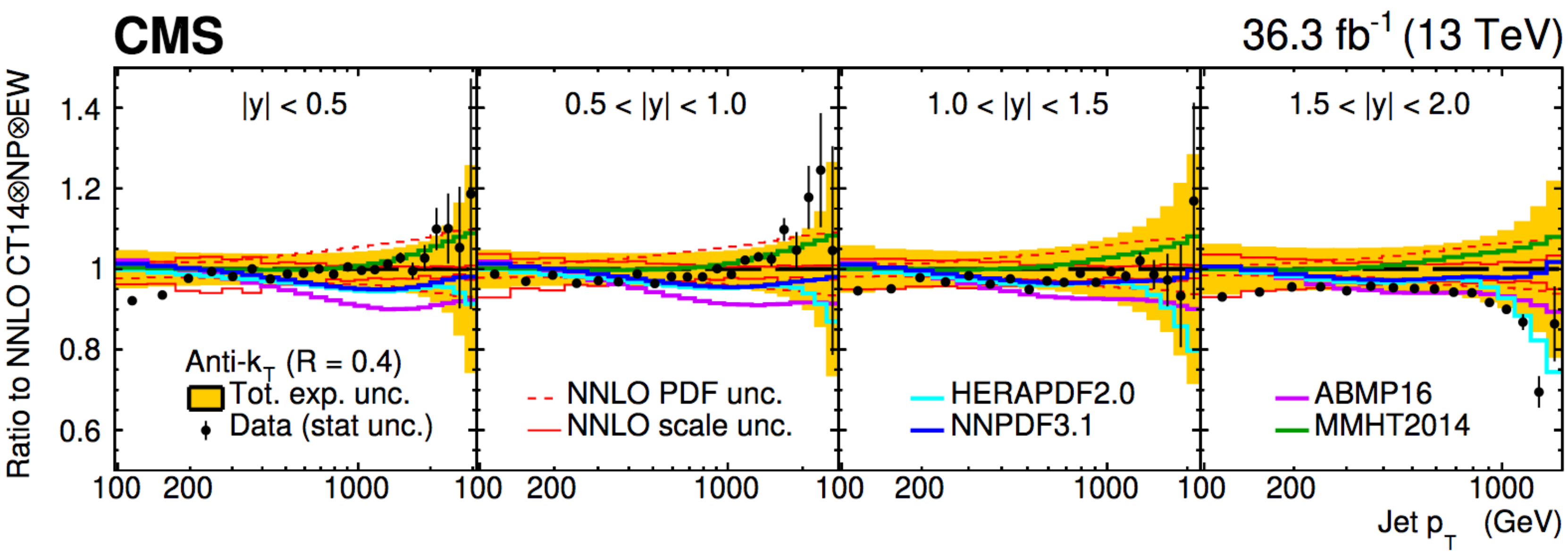
(Addendum to JHEP 02 (2022) 142)

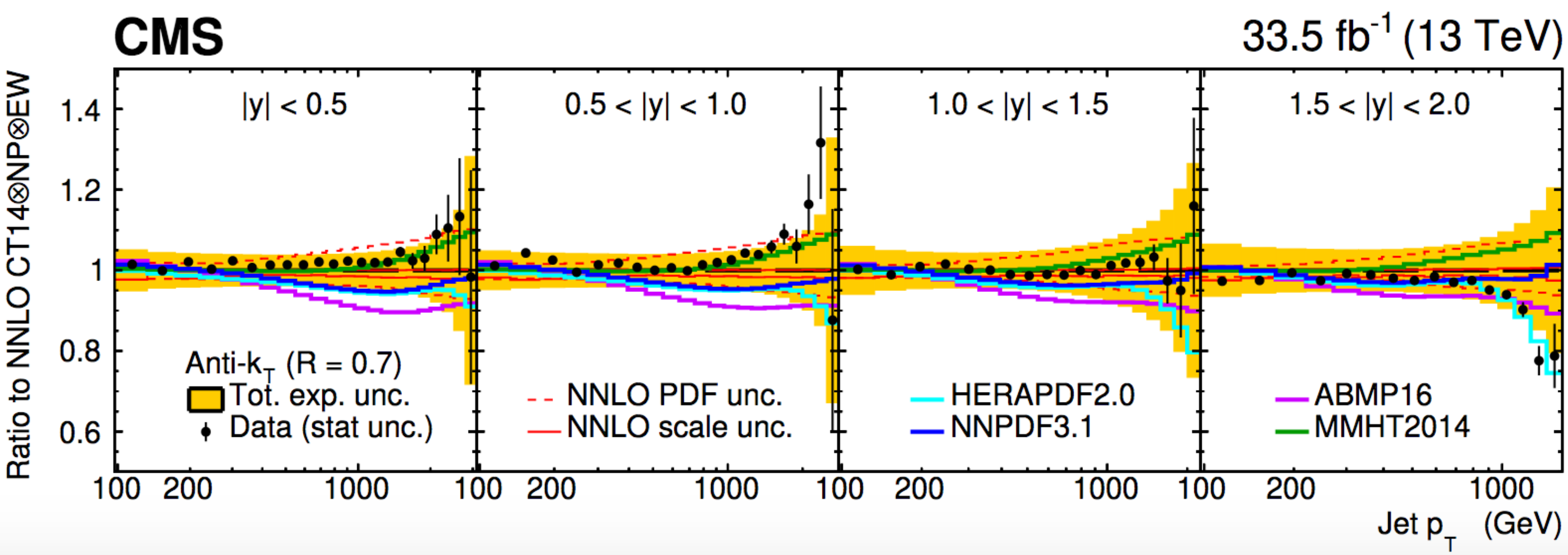
Inclusive jets @13 TeV



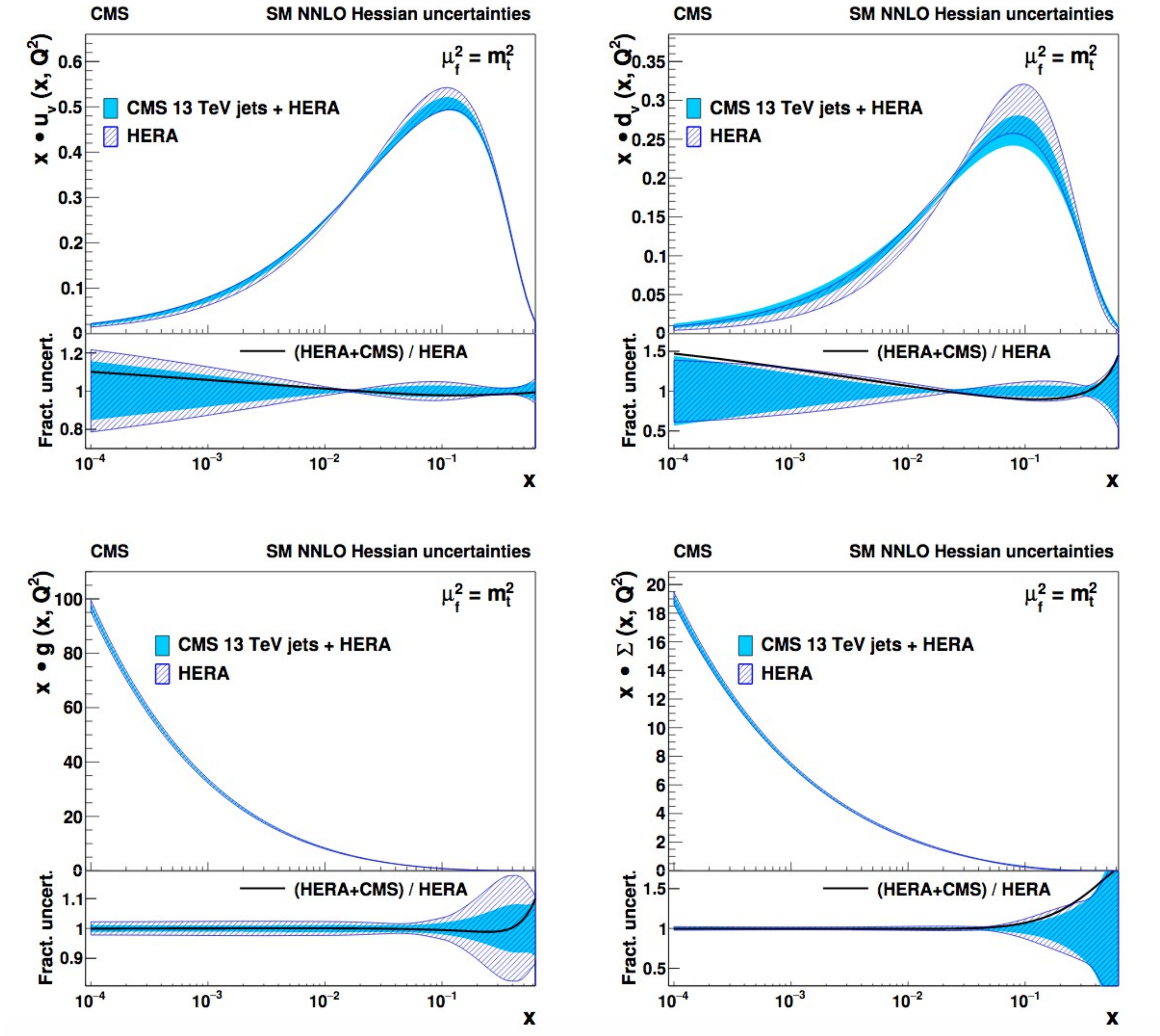
- 13 TeV inclusive jet cross sections already published: JHEP 02 (2022) 142
  → also QCD analysis and as measurement @ NNLO using k-factors
- NEW: addendum with NNLO analysis using NNLO interpolation grids: JHEP 12 (2022) 035
  → presented here
- NLOJET calculation to derive grids
  → numerical integration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

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

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	$0.0 < \|y\| < 0.5$	8.6/22
	$0.5 < \|y\| < 1.0$	23/21
	$1.0 < \|y\| < 1.5$	13/19
	$1.5 < \|y\| < 2.0$	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

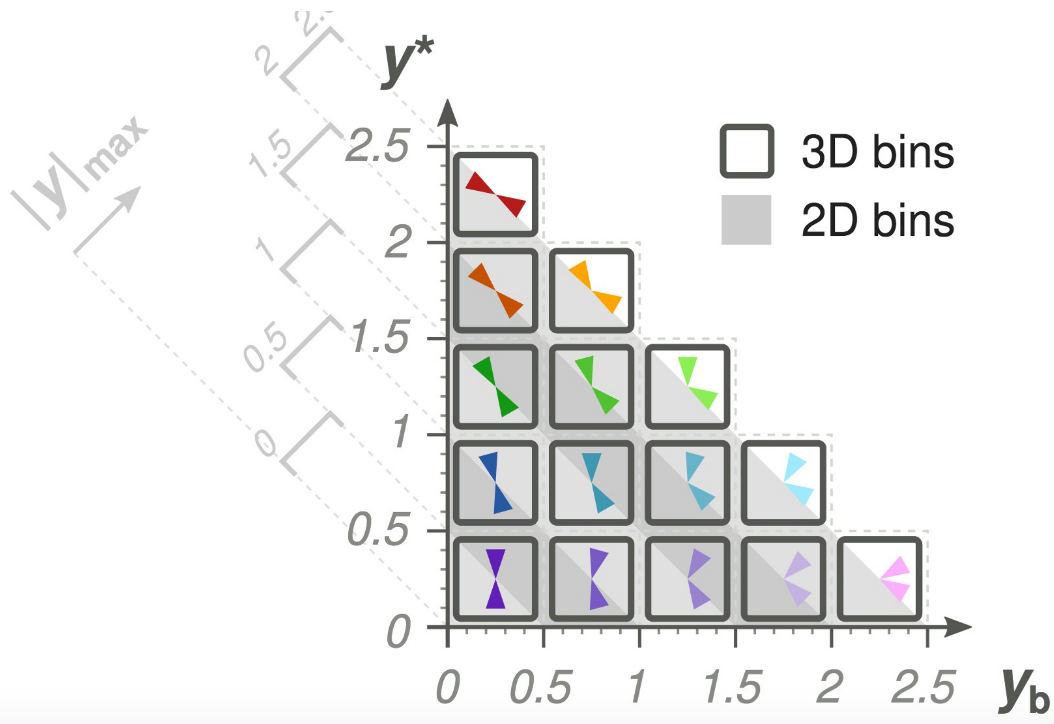
Cross section measurement

- 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)

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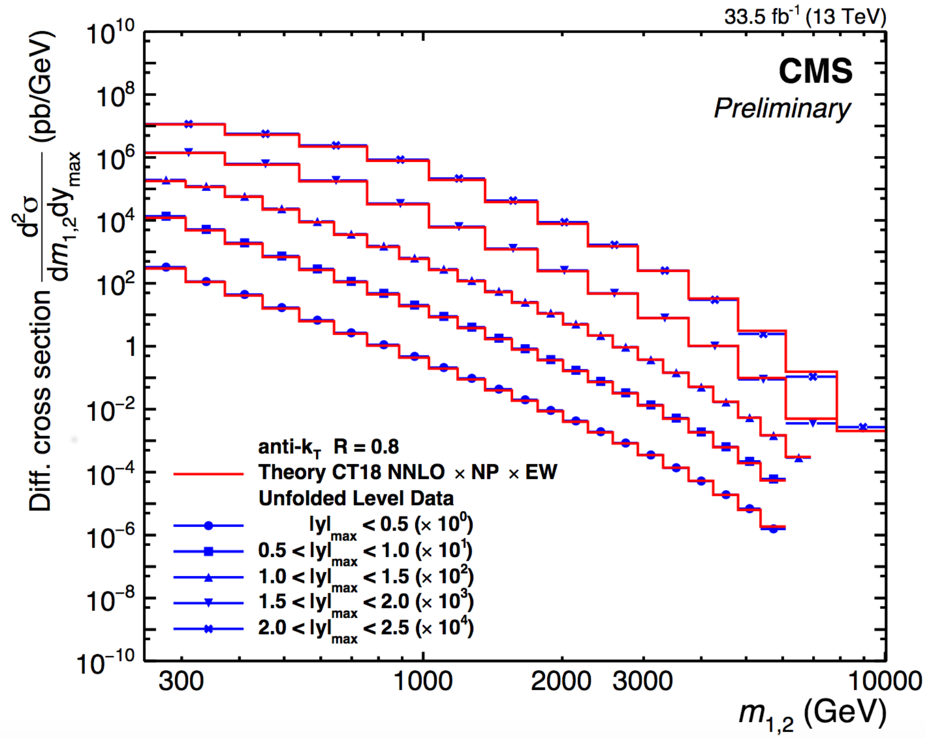
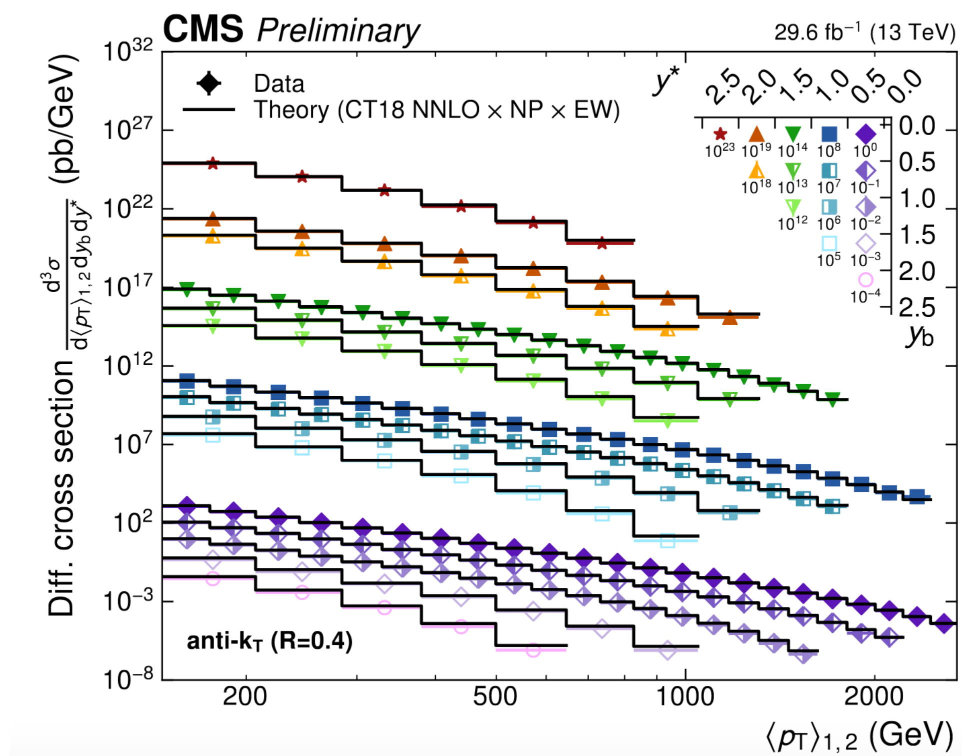
Measured cross sections

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

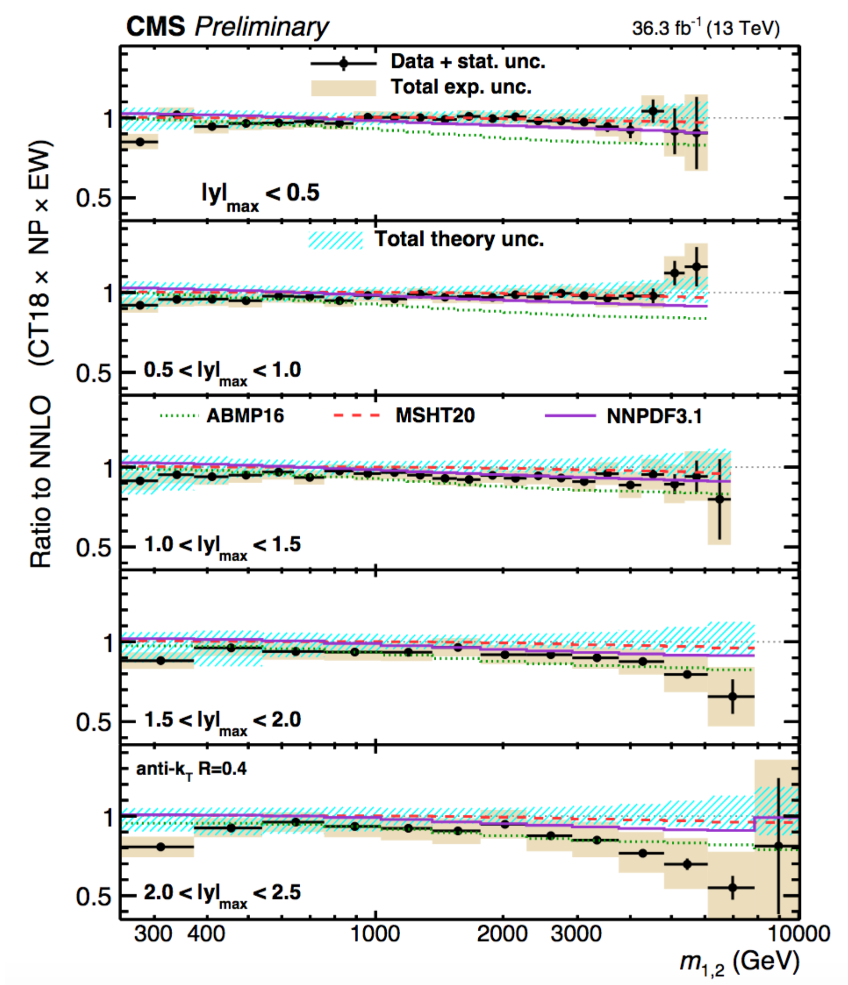


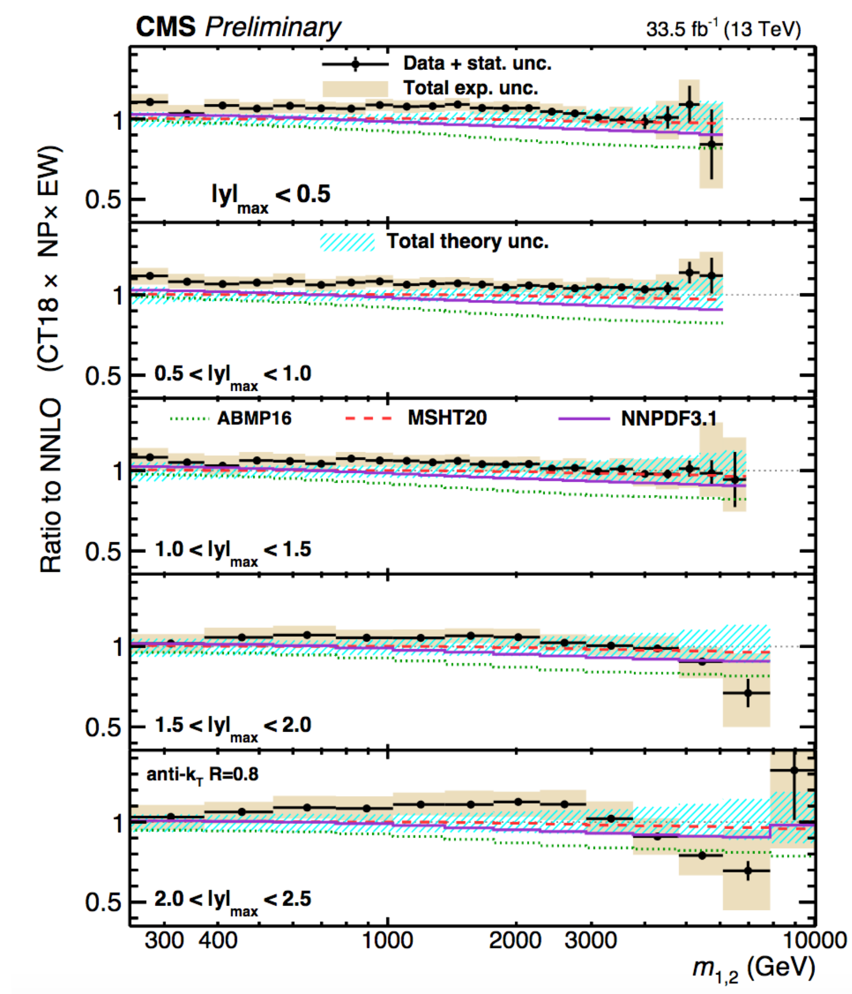


- Predictions for different PDFs generally in agreement
  → except for AMBP16 PDF - predicted cross sections are generally smaller

Comparison with NNLO predictions: 2D measurements

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





- Predictions for different PDFs generally in agreement
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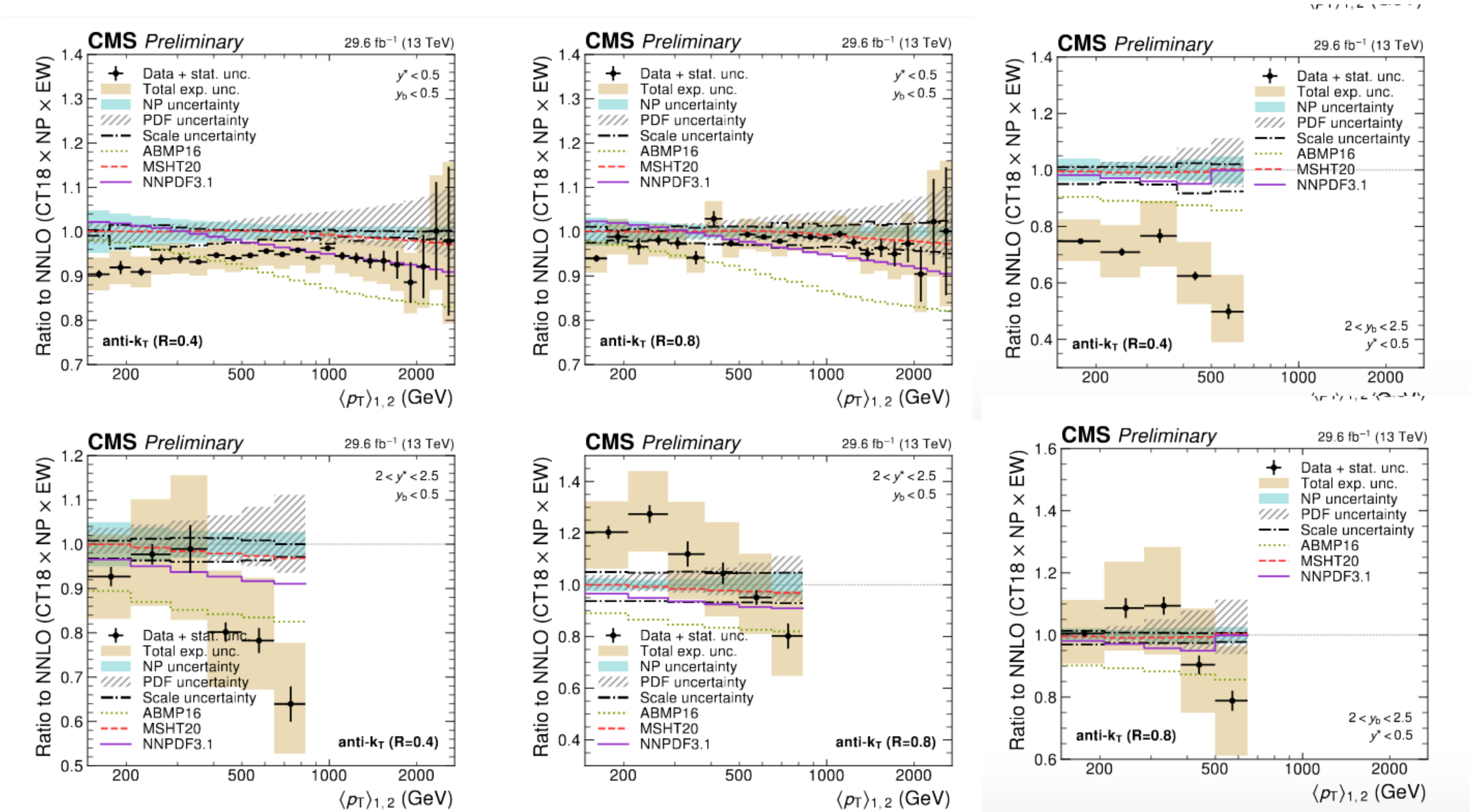
Comparison with NNLO predictions: 3D measurements

- 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

QCD analysis @ NNLO and α_s estimation

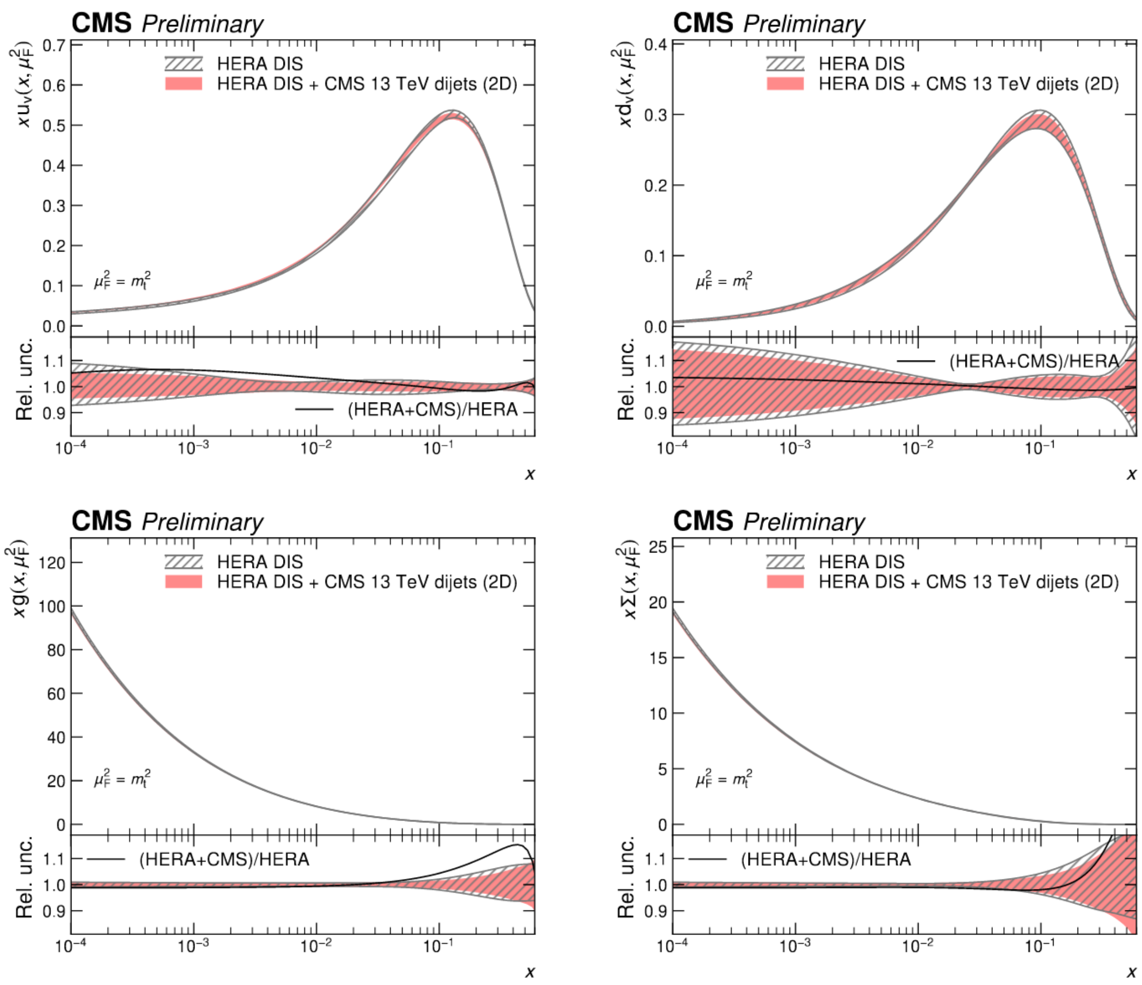
- Parameterisations used

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

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

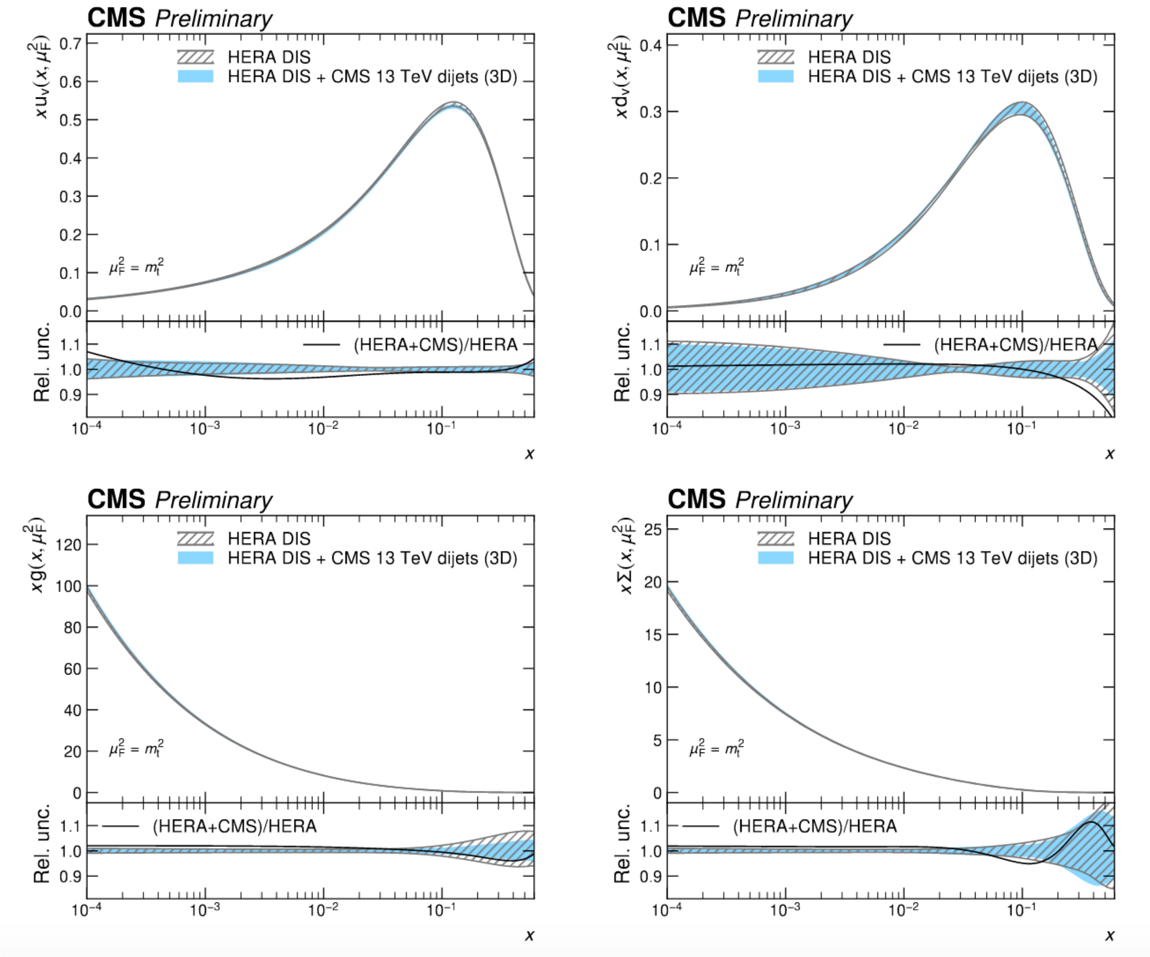
Central values from dijet measurements about 1 standard deviation away from world average of as(mZ) = 0.1179 ± 0.0009 and larger by about 1.6 standard deviations than those for inclusive jets at 13 TeV

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

Multi-jets

Beyond collinear PDFs: PB-TMD

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

arXiv:2210.13557

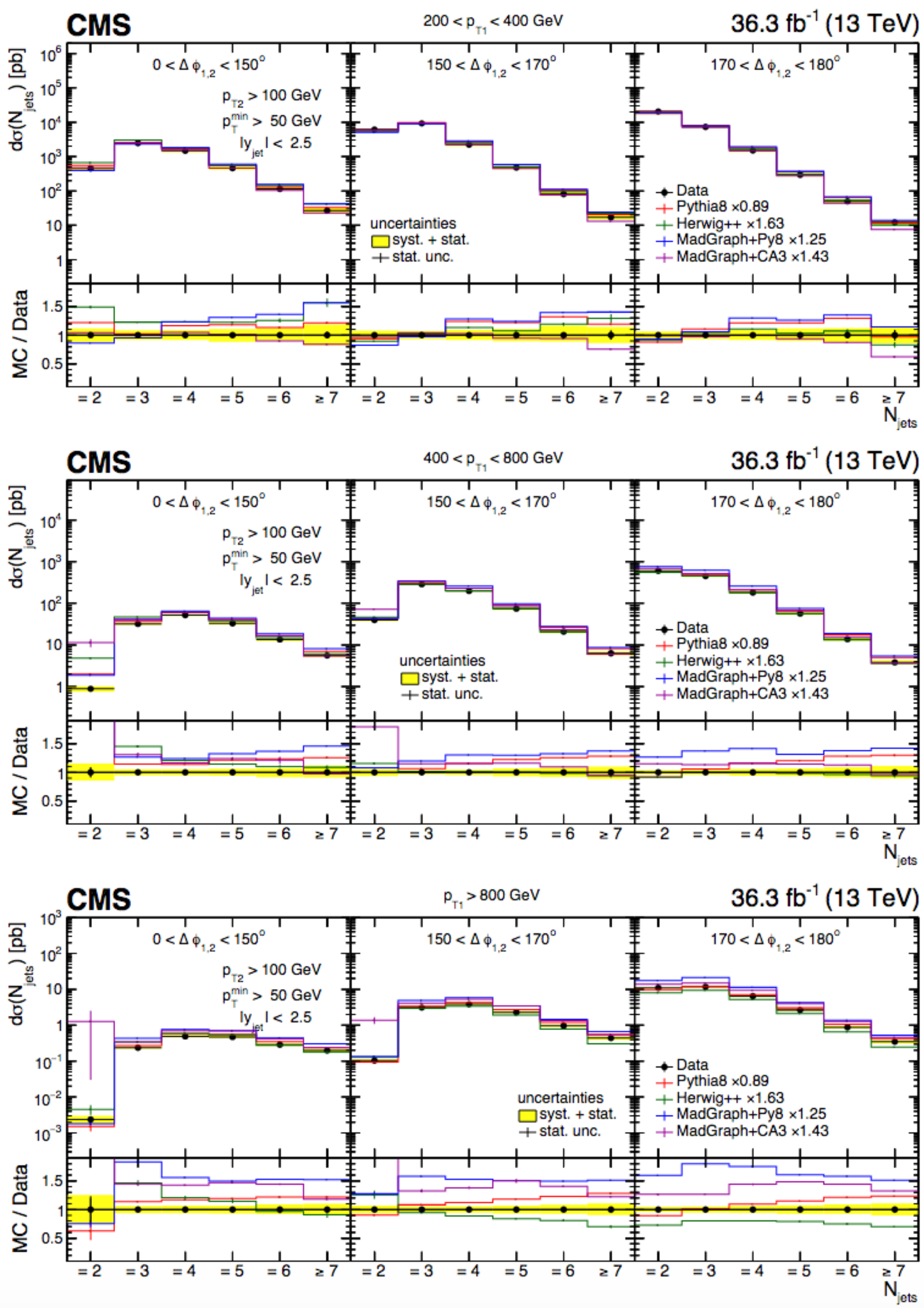
Motivation

- 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
PYTHIA8 [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 $2 \to 3$	—

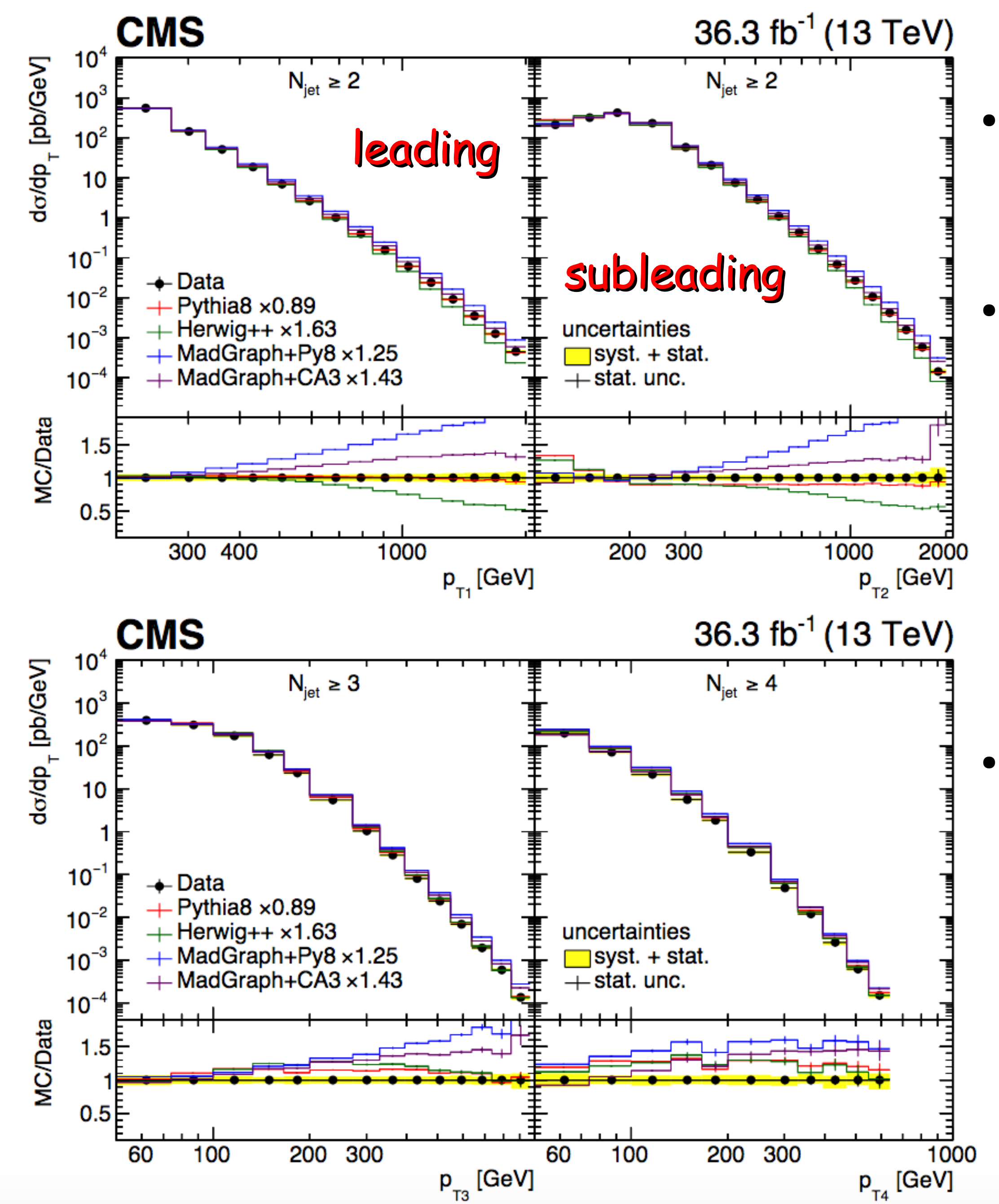
Jet multiplicities



- 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 $|y| < 2.5$

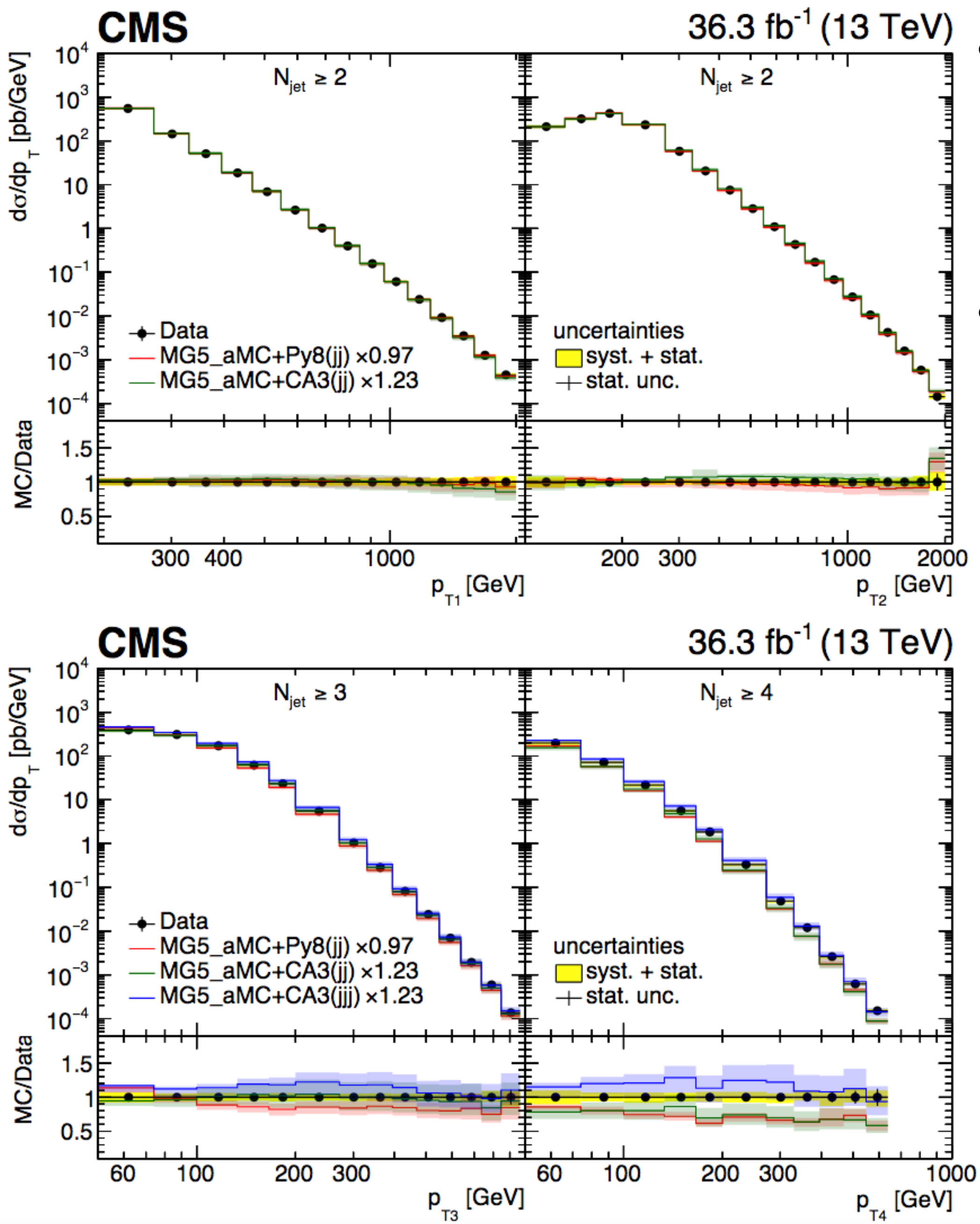
- Differential cross section as a function of exclusive jet multiplicity
  → up to 7 jets
  in bins of p_T of leading jet and azimuthal angle difference between two highest p_T jets in dijet system
- Data compared with LO predictions
  → MADGRAPH+PY8 shape doesn't agree
  → MAD-GRAPH+CA3 and HERWIG++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

Transverse momentum distributions



- Transverse momentum distributions of four leading jets
- Data compared with **LO predictions**
  → 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

Message to take away

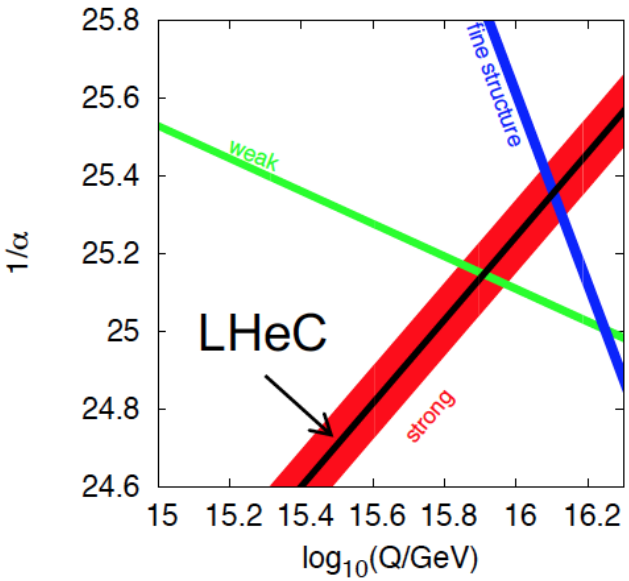
- New QCD analysis and as estimation using NNLO grids for inclusive jests @ 13 TeV
  → Improved precision compared to NNLO result with k-factors
  → New results supersede these obtained using k-factor technique

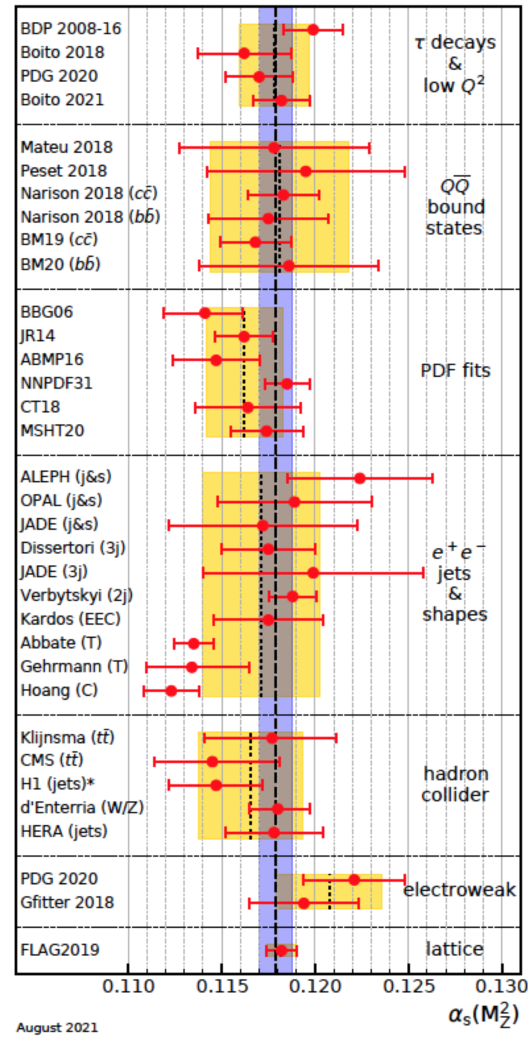
- Double- and triple-differential dijet measurements reduce PDF uncertainties, especially for large values of x
  → as estimated using 2D and 3D measurements
  → central values slightly larger than world average or inclusive CMS estimates, though within 1-1.6 sigma
  → 3D cross sections yield more precise value of as

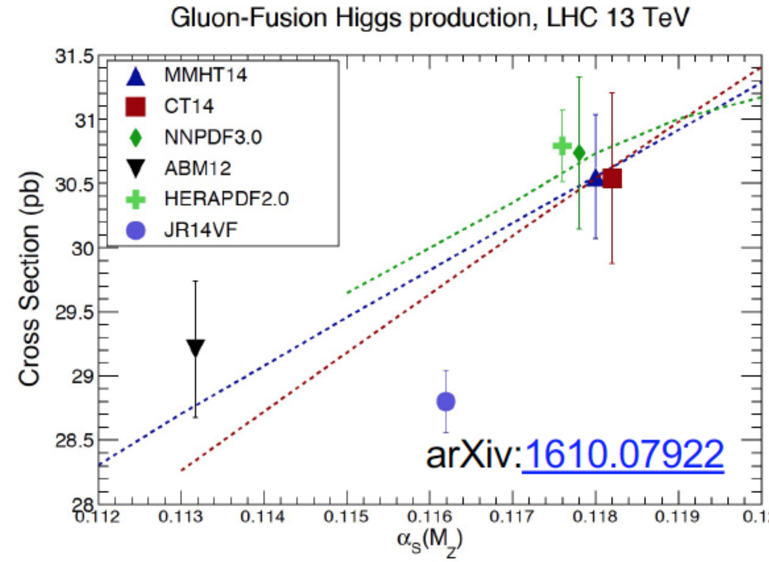
- For the first time calculations using "Parton Branching"-TMDs together with MEs in MC@NLO frame are compared with jet measurements over wide range in transverse momentum and jet multiplicities and describe data well

Additional slides

Why look at α_s ?







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

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

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

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

- 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]

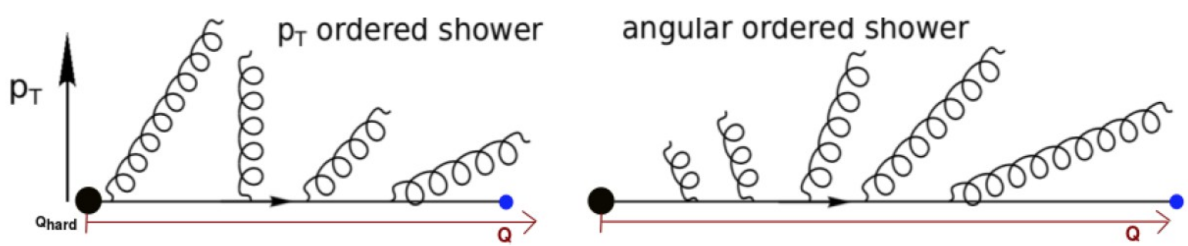
- TMDs : Transverse Momentum Dependent parton distributions
- extended collinear PDFs : transverse momentum effects from intrinsic k_t + evolution

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

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