Recent jet measurements at CMS

Measurements at 5.02 and 13 TeV
QCD interpretation of inclusive jet production at 13 TeV

Patrick L.S. Connor

(on behalf of the CMS collaboration)

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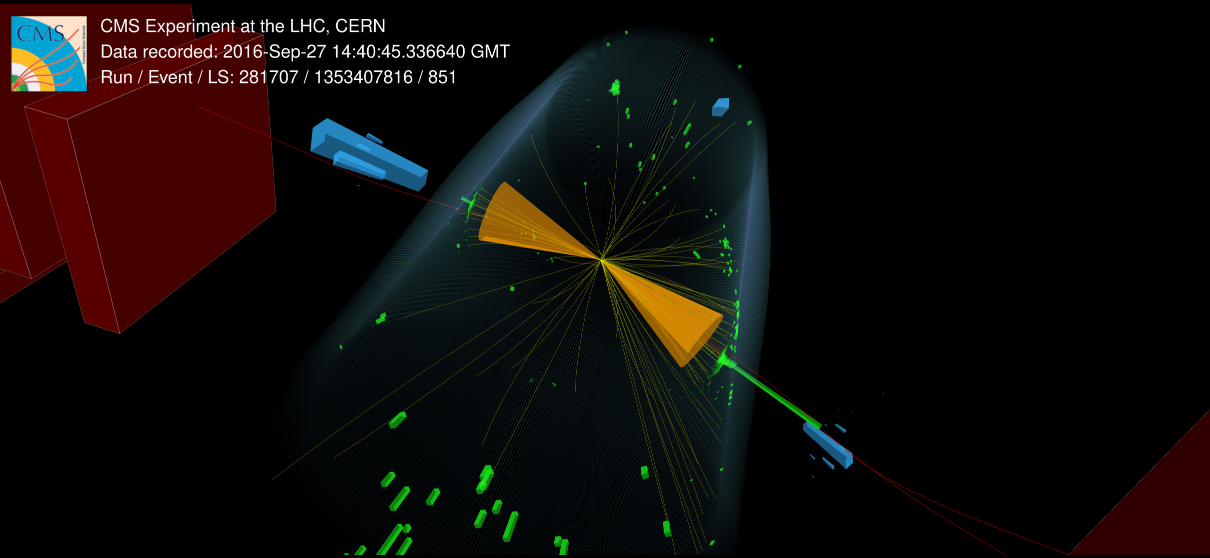
26 July 2021


CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-27 14:40:45.336640 GMT
Run / Event / LS: 281707 / 1353407816 / 851

Ref. [1]

Introduction

Motivation
Inclusive jet
Multijet

Motivation

Factorisation [2]

$$\underbrace{\sigma_{pp\to\text{jet}+X}}_{\text{experimental data}} = \sum_{ij\in gq\bar{q}} \overbrace{f_i(x_i,\mu_F^2)\otimes f_j(x_j,\mu_F^2)}^{\text{PDFs}} \otimes \underbrace{\hat{\sigma}_{ij\to\text{jet}+X}\left(x_i, x_j, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}, \alpha_S(\mu_R^2)\right)}_{\text{SM or ...}}$$

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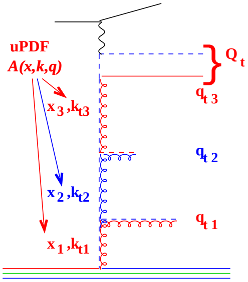
Testing state-of-the art calculations

- NNLO (interpolation tables) or NLO+NLL (resummation) FO predictions.
- NLO MC event generators with Transverse-Momentum-Dependent (TMD) PDFs.



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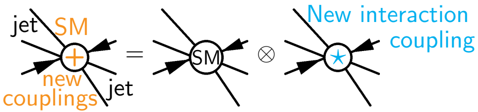
Contact Interaction (CI)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{4\pi}{2\Lambda^2}\sum_n c_n O_n$$

CI model	c_1	c_3	c_5
Purely left-handed	free	0	0
Vector-like	free	$2c_1$	c_1
Axial-vector-like	free	$-2c_1$	c_1

NB: colour-singlet model



Inclusive jet

5.02 TeV

Motivation

Perform **simultaneous fit** of PDFs and α_S.

Phase space

- $p_T > \mathbf{64}$ GeV
- $|y| < 2.0$

Measurement

- **Low-pile-up 2015** data using AK4.
- Syst. effects corrected w. **1D toy** unfolding.

Motivation

Perform **simultaneous fit** of PDFs, α_S, m_t, and **Wilson coefficient** c_1**!**

Phase space [8]

- $p_T >$ **97** GeV
- $|y| < 2.0$

Measurement

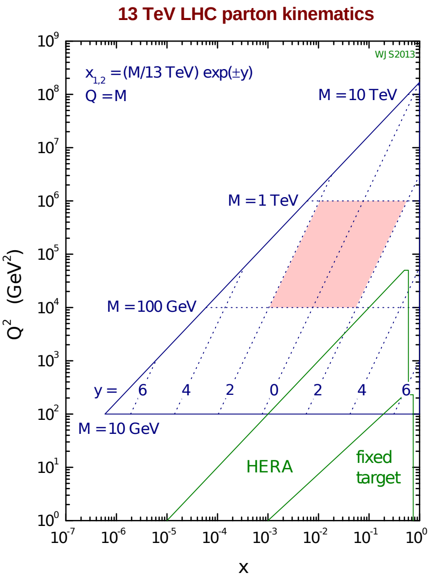
- **High-pile-up 2016** data using AK4 & AK7.
- Syst. effects corrected w. **2D sample** unfolding.

QCD interpretation w. xFitter [3, 4]

- HERA DIS data [5],
- CMS $t\bar{t}$ 3D cross section at 13 TeV [6],
- CMS inclusive jet 2D cross section at 13 TeV [7].

Inclusive jet

13 TeV

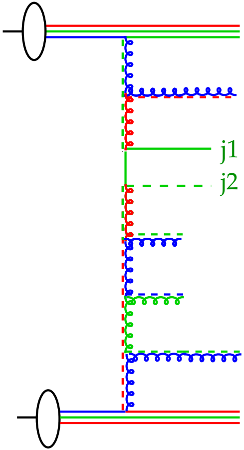


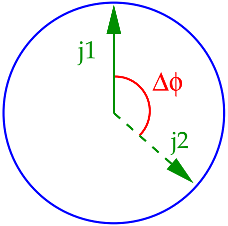
Multijet

13 TeV

Observables

- **Single-jet p_T spectra** in di-, tri- and four-jet configurations.
- **Azimuthal decorrelations** in bins of multiplicity and leading jet p_T.





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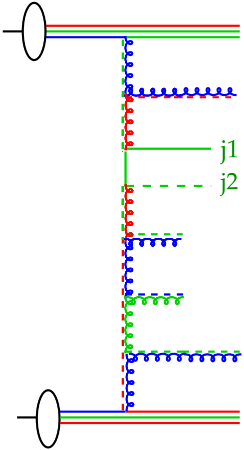
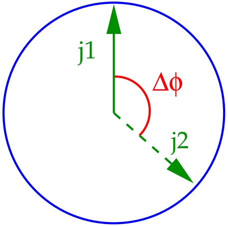
- AK4 jets
- Dijet events
  - $p_T^1 > 200$ GeV
  - $p_T^2 > 100$ GeV
  - $|y^{1,2}| < 2.5$
- Additional jets are considered if
  - $p_T^{3,4} > 50$ GeV
  - $|y^{3,4}| < 2.5$





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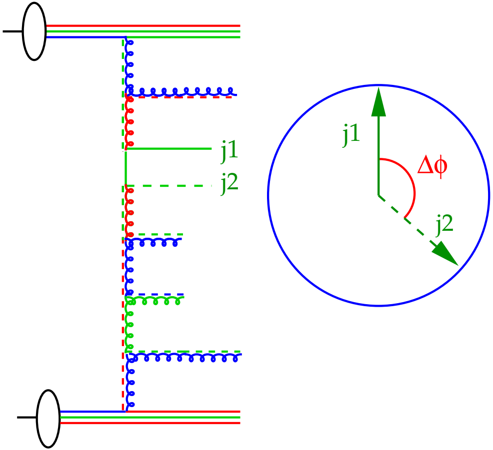


Note

Same analysis strategy as inclusive jet analysis at 13 TeV!

Measurements

Strategy

Results

Data

- $\mathcal{L}_{\text{int}} = 27.4\ \text{pb}^{-1}$.
- Clustering with AK4 .
- Single-jet triggers and normalising each trigger with its respective luminosity.

Corrections

- Jet energy and pile-up
- Detector inefficiencies and artifacts

Unfolding

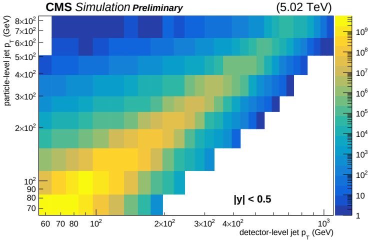
- In the past, most jet measurements were unfolded with D'Agostini [9, 10].
- For the present measurements, we use least-square minimisation [11, 12].

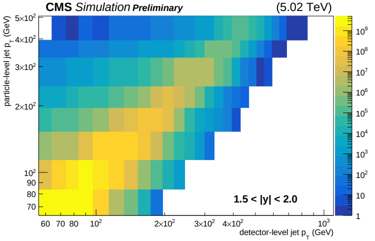
$$\chi^2 = \min_{\mathbf{x}} \left[(\mathbf{A}\mathbf{x} + \mathbf{b} - \mathbf{y})^\intercal \mathbf{V}^{-1} (\mathbf{A}\mathbf{x} + \mathbf{b} - \mathbf{y}) \right]$$

#detector-level bins $= 2 \times$ #particle-level bins
(but **no** Tikhonov regularisation)

Strategy

5.02 TeV





Note

More RMs in back-up.

Strategy

13 TeV

Data

- $\mathcal{L}_{\text{int}} = 36.3(33.5)\ \text{fb}^{-1}$.
- Clustering with AK4 (AK7).
- Single-jet triggers and normalising event by event based on the prescale.

Corrections

- Jet energy and pile-up
- Detector inefficiencies and artifacts

Unfolding

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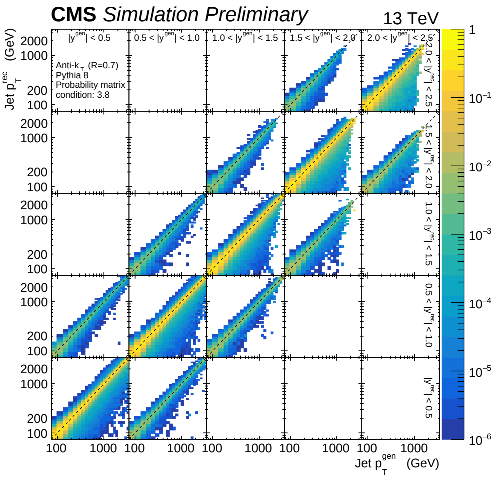

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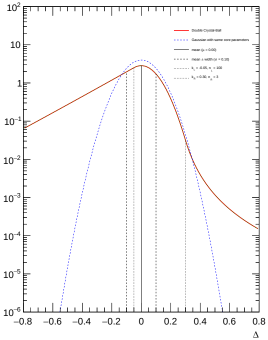


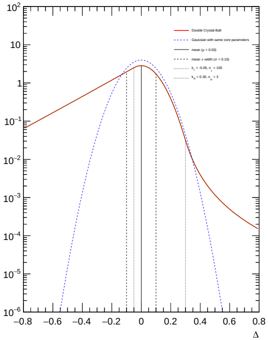
Resolution

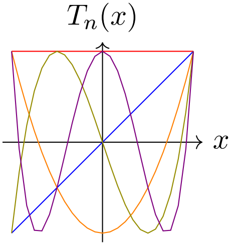
- In former publications, resolution usually assumed to be a perfect, centred Gaussian.
- The present analyses have revisited this ansatz:
  1. residual nonzero means should not be neglected in (un)smearing;
  2. tails should be accounted at least to make a proper fit of the Gaussian core.

⟶ Good description with double-sided Crystal-Ball function [13].

Strategy

Techniques





$T_0(x) = 1$, $T_1(x) = x$,
$T_2(x) = 2x^2 - 1$,
$T_2(x) = 4x^3 - 3x$,
$T_3(x) = 8x^4 - 8x^2 + 1$, etc.

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Smoothness

- Bin-to-bin uncertainties should describe scattering of points around a smooth analytical function.
- Robust smooth fits based on Chebyshev polynomials.

$$f_n(p_T) = \exp\left(\sum_{i=0}^{n} b_i T_i\left(2\frac{\log p_T / \log p_T^{\text{min}}}{\log p_T^{\text{max}} / \log p_T^{\text{min}}} - 1\right)\right)$$

where $T_0(x) = 1, \quad T_1(x) = x$

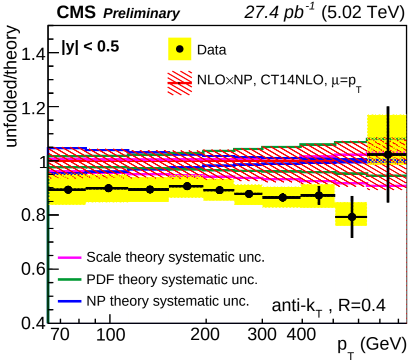
and $T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$

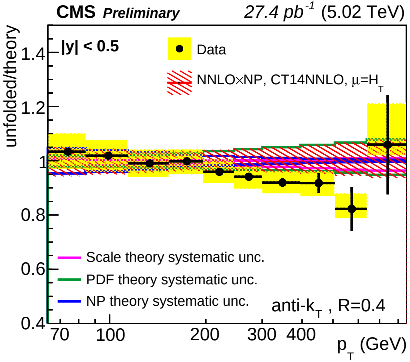
Results

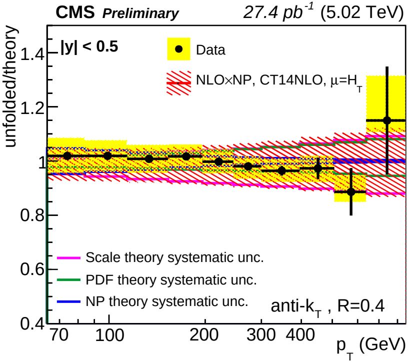
5.02 TeV

Inclusive jet cross section (SMP-21-009 [14])

- Showing here comparison to (N)NLO obtained with NNLOJET [15, 16, 17] from interpolation tables [18, 19, 20, 21].
- Comparison to various global PDF sets also available.

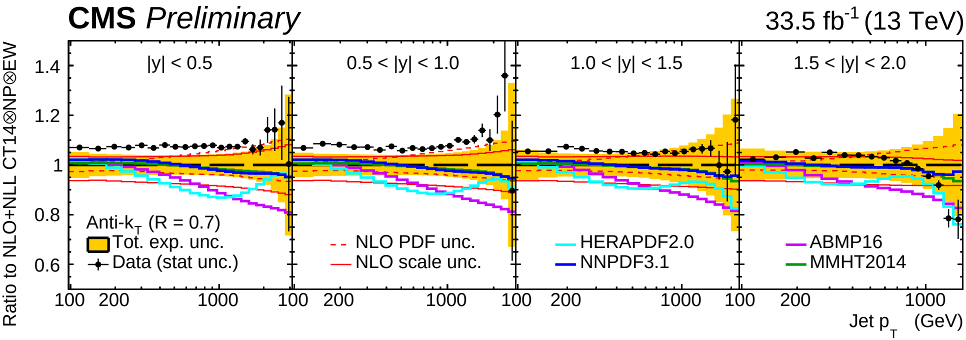






Results

13 TeV

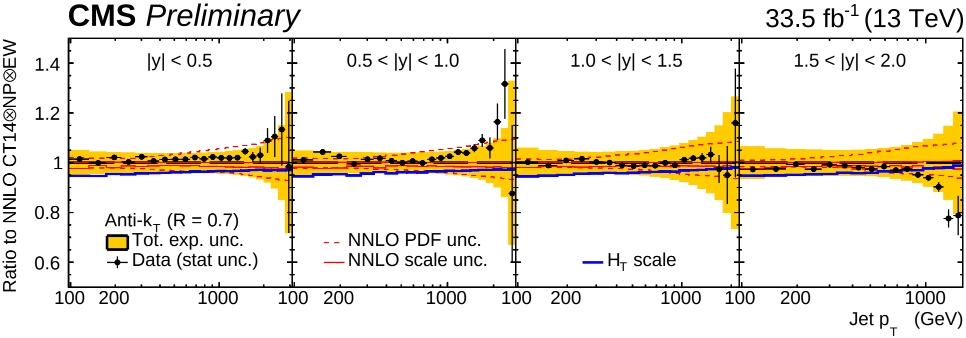


Inclusive jet cross section (SMP-20-011 [7])

- Comparison to various global PDF [5, 22, 23, 24, 25] sets with NLO+NLL [26] obtained via k-factor technique.

Results

13 TeV



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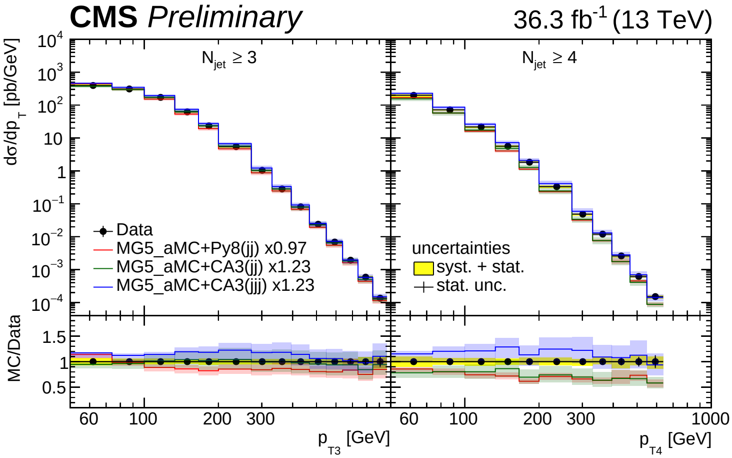
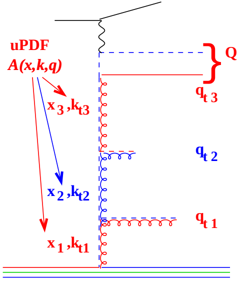
Results

13 TeV



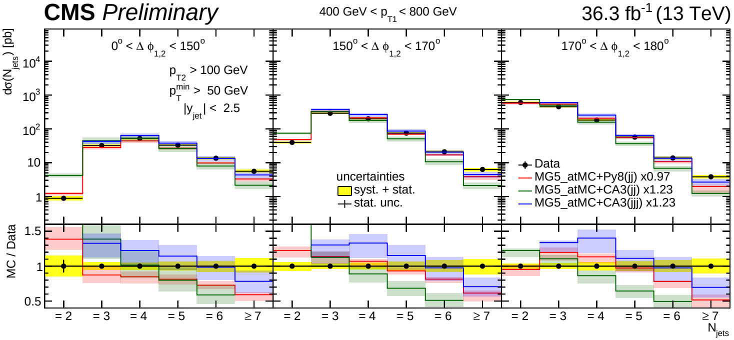


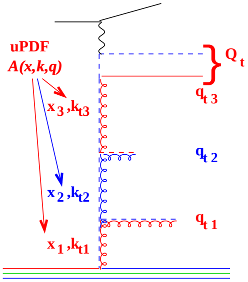
Multijet cross section (SMP-21-006 [27])

- Testing production of extra radiations in the ME or in the PS.
- NLO generators describe better the p_T spectra of the 3rd and 4th jets.
- MC@NLO [28] using PB-TMD calculations [29, 30] rather successful.
- Predictions are normalised to the measured inclusive di-jet cross section.

Results

13 TeV





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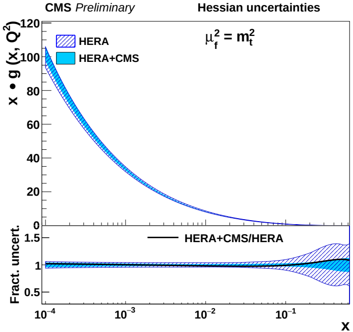
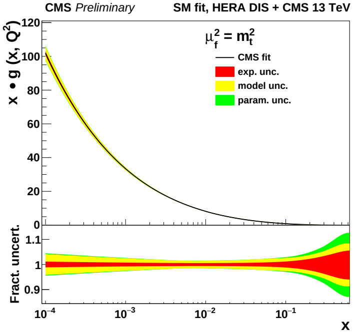
Interpretation

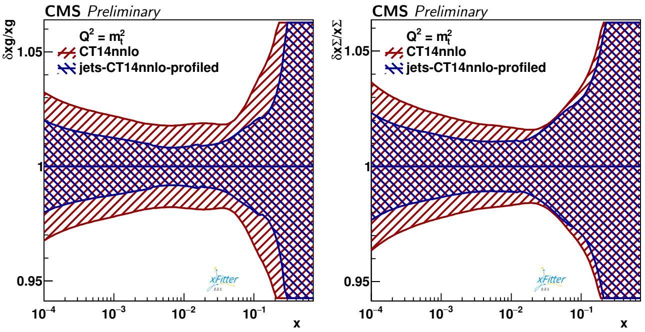
SM

SMEFT





SM



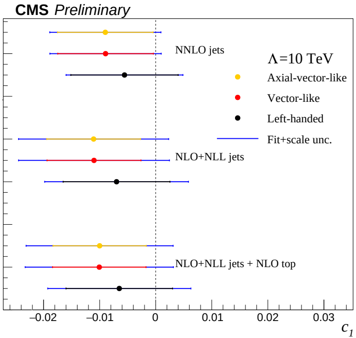
Results

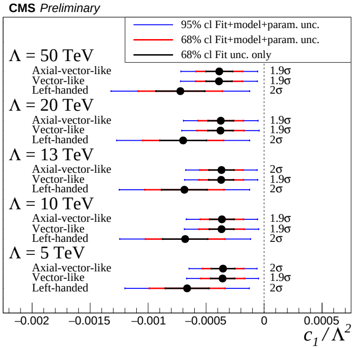
- **Profiling** CT14 at NLO & NNLO.
- **QCD fits** follow the approach of HERAPDF2.0 [5].

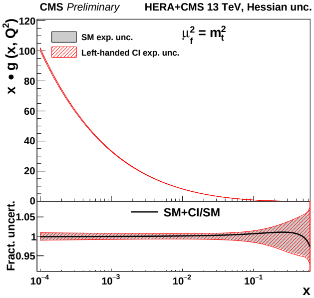
⟶ Strong **reduction of the gluon** PDF uncertainty.

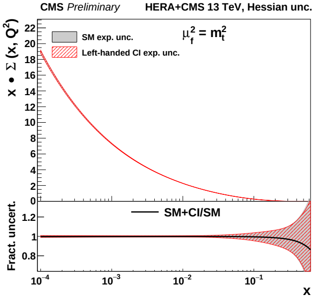
See also **Toni's poster**

SMEFT









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- **QCD fits** follow the approach of HERAPDF2.0 [5].

⟶ SMEFT fits lead to results **compatible w. SM**.

See also **Toni's poster**

Summary & Conclusions

Summary & Conclusions

- The CMS Collaboration is preparing several publications about **inclusive jet** production in pp collisions at 5.02 and 13 TeV, and **multijet** production at 13 TeV.
- Corrections to jet energy resolution **beyond pure Gaussian resolution** are included in the unfolding and **tests of smoothness** have been developed to investigate the quality of the data analysis.
- Data are compared to **FO predictions** at NLO, NLO+NLL, and NNLO, as well as to **MC event generators**.
- A **novel QCD interpretation** including profiling studies and unbiased search for CI has been presented; **no evidence for CI** has been found.

$\longrightarrow$ *The three measurements will be soon submitted for publication.*

Thank you for your attention!

Back-up

Resolution

Double-sided Crystal Ball

$$f(x) = N \cdot \begin{cases} A_2(B_2+z)^{-n_2} & \text{for} \quad z \geq \alpha_2 \\ \exp \frac{-1}{2} z^2 & \text{for} -\alpha_1 < z < \alpha_2 \\ A_1(B_1-z)^{-n_1} & \text{for} \quad z \leq -\alpha_1 \end{cases}$$

where

$$z = \frac{x-\mu}{\sigma}$$

$$A_i = \left(\frac{n_i}{|\alpha_i|}\right)^{n_i} \exp \frac{-1}{2}|\alpha_i|^2$$

$$B_i = \frac{n_i}{|\alpha_i|} - |\alpha_i|$$

$$C_i = \frac{n_i}{\alpha_i} \frac{1}{n_i - 1} \exp \frac{-1}{2}|\alpha_i|^2$$

$$D = \sqrt{\frac{\pi}{2}} \left(\operatorname{erf} \frac{|\alpha_2|}{\sqrt{2}} + \operatorname{erf} \frac{|\alpha_1|}{\sqrt{2}}\right)$$

$$N = \frac{1}{\sigma(C_1 + C_2 + D)}$$

Modified "NSC" function

$$\text{JER} = \sqrt{\left(\frac{p_0}{p_\mathrm{T}}\right)^2 + \frac{p_1^2}{p_\mathrm{T}^{p_3}} + p_2^2}$$

Resolution

Fit procedure

Difficulty: 6 parameters to fit, 2 of them being particularly unstable

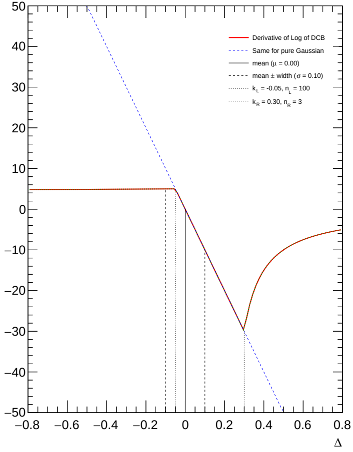
1. Naïve Gaussian fit to get a preliminary value of μ and σ.
2. Trick to find transition points k_L and k_R (see below).
3. Fit each tail separately to get a preliminary value for n_L and n_R.
4. Finally repeat a global fit with 6 free parameters and limited ranges.

Find the transition points

$$\log f(x) = \log N - \frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\Big(\log f(x)\Big) = -\frac{x-\mu}{\sigma^2}$$

$\longrightarrow$ Use numerical derivative to find the transition points



Data treatment

Smoothness

Fit function

$$f_n(p_T) = \exp\left(\sum_{i=0}^{n} b_i T_i\left(2\frac{\log p_T/\log p_T^{\text{min}}}{\log p_T^{\text{max}}/\log p_T^{\text{min}}} - 1\right)\right)$$

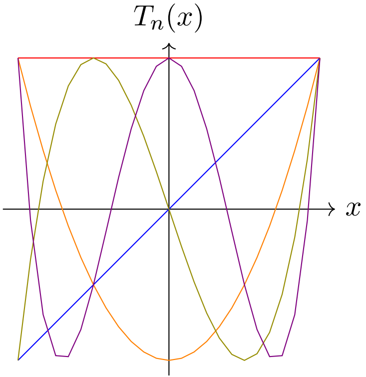
where $T_0(x) = 1, \quad T_1(x) = x$

and $T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$

Tests of smoothness

Robust fit with an **iterative method**:

1. guess the two first parameters from the first and last points of the spectrum;
2. add one more parameter (initialised to zero), and fit all parameters;
3. iterate "until" a satisfactory χ^2 is found.



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Applications

- Combination of triggers
- Effect of each calibration
- Impact of unfolding
- Smoothness of the theory
- Smoothing of the systematic uncertainties
- ...

Unfolding

Matrix inversion for binned data

$$\mathbf{A}\mathbf{x} + \mathbf{b} = \mathbf{y} \tag{1}$$

- $\mathbf{x}$ data spectrum at particle level (what we want);
- $\mathbf{y}$ data spectrum at detector level (measurement);
- $\mathbf{b}$ background spectrum at detector level (from simulated samples);
- $\mathbf{A}$ probability matrix (from simulated samples).

$\longrightarrow$ **possibly ill-conditioned matrix** due to limited statistics of the simulated data used to construct $\mathbf{A}$.

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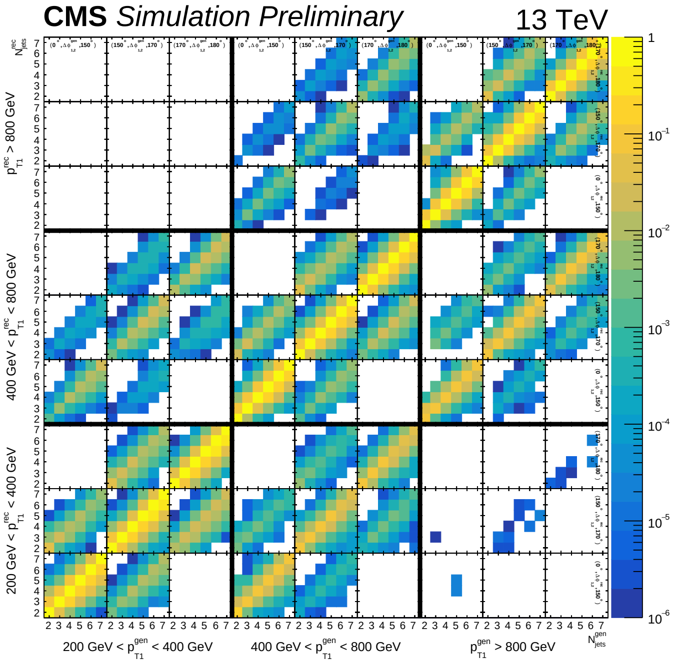
Response matrix



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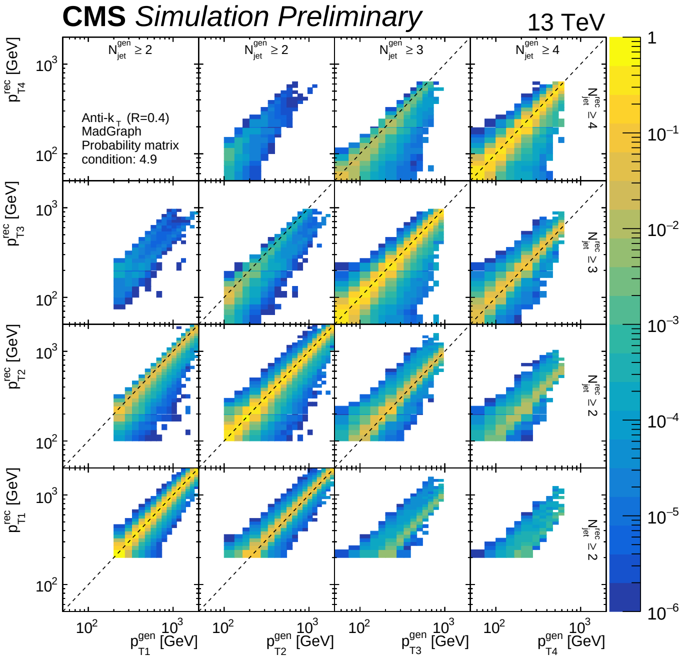
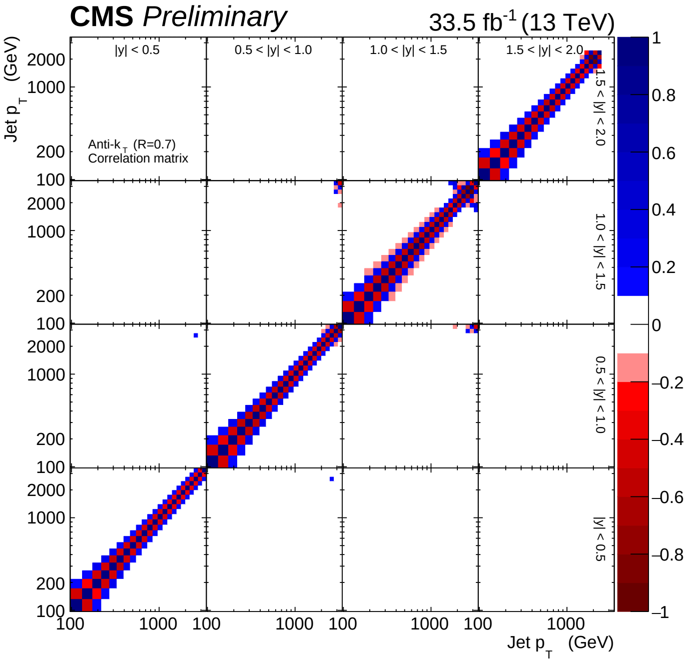
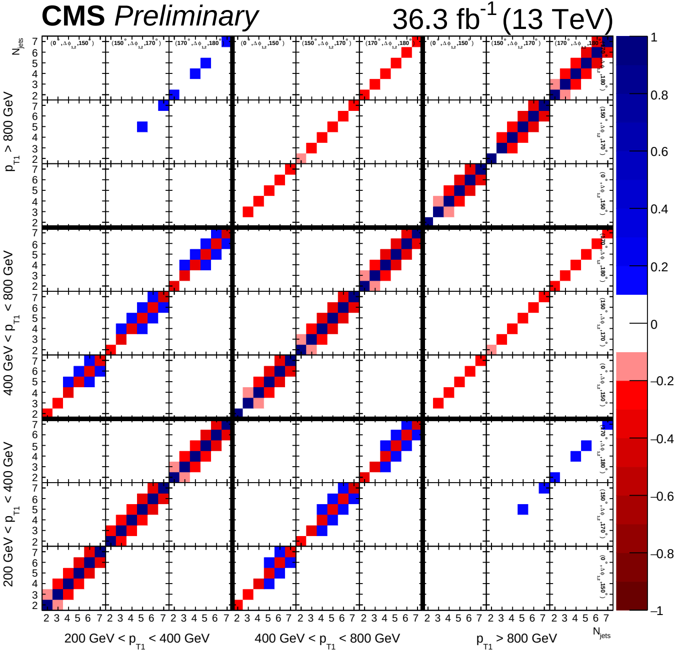


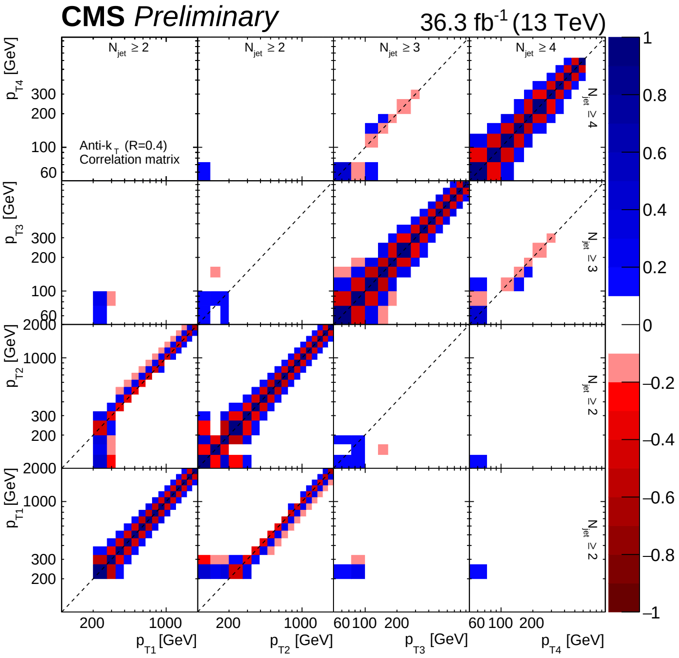
Correlation matrix



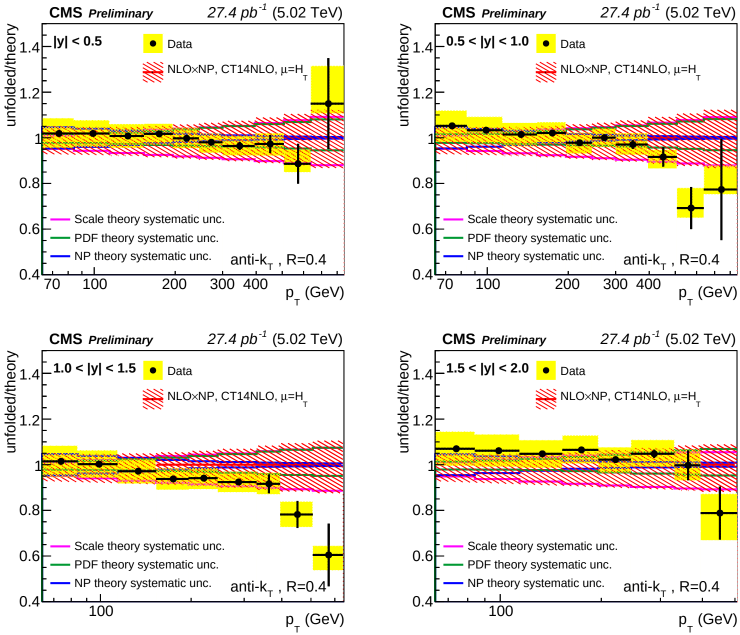
Correlation matrix



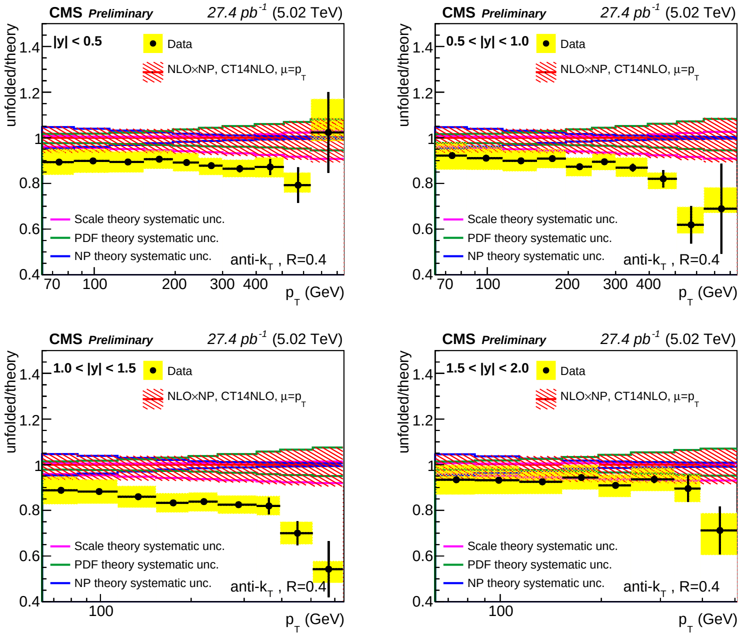
Correlation matrix



Inclusive jet at 5 TeV



Inclusive jet at 5 TeV



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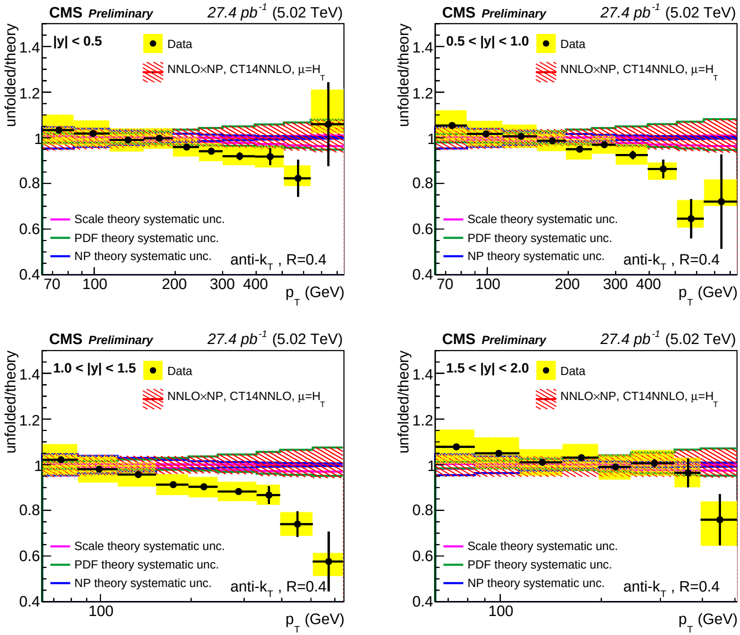
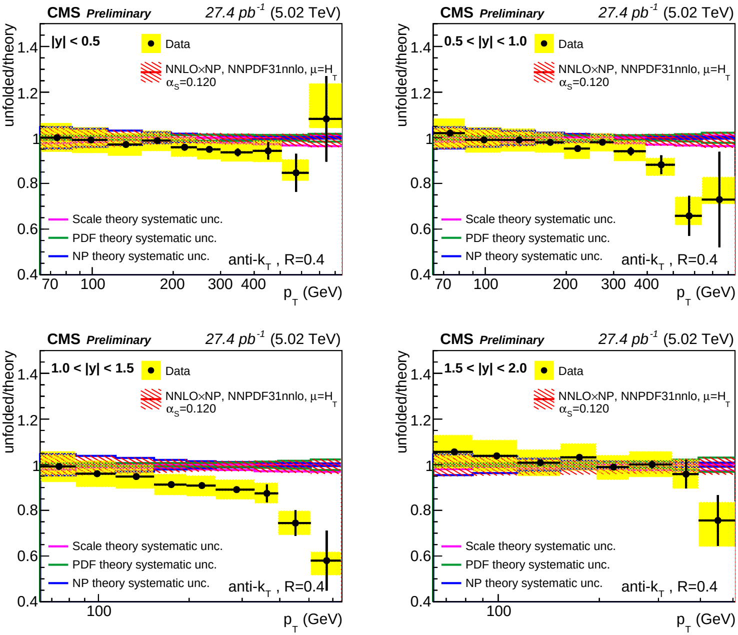
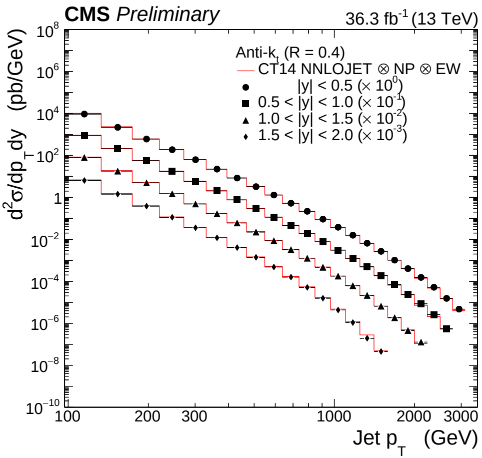
Inclusive jet at 5 TeV

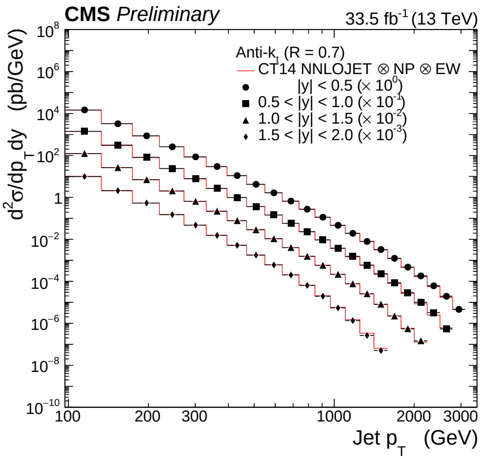


Inclusive jet at 5 TeV

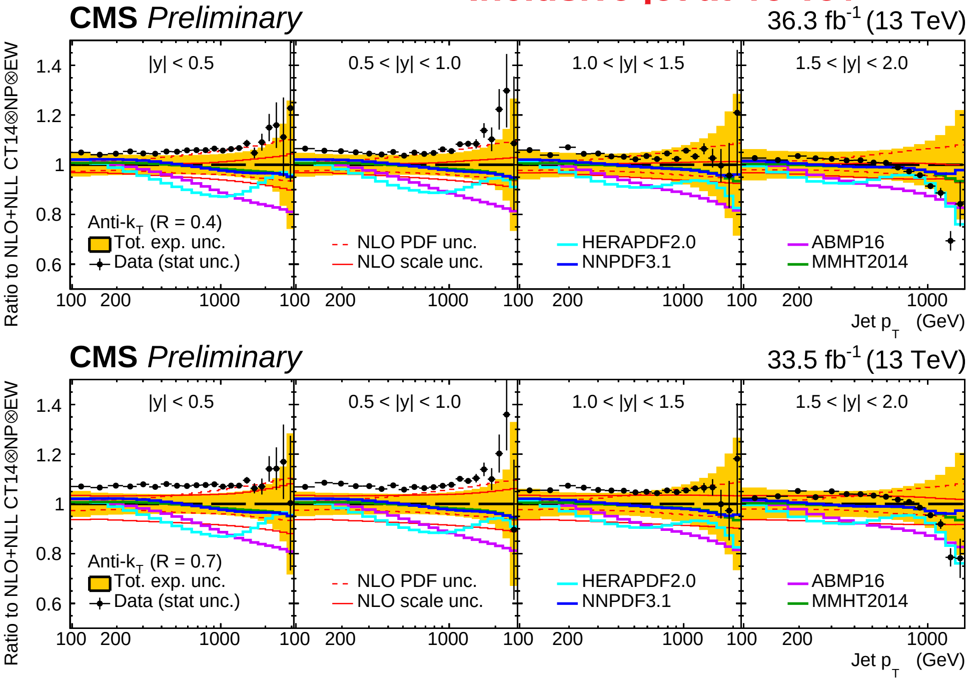


Inclusive jet at 13 TeV

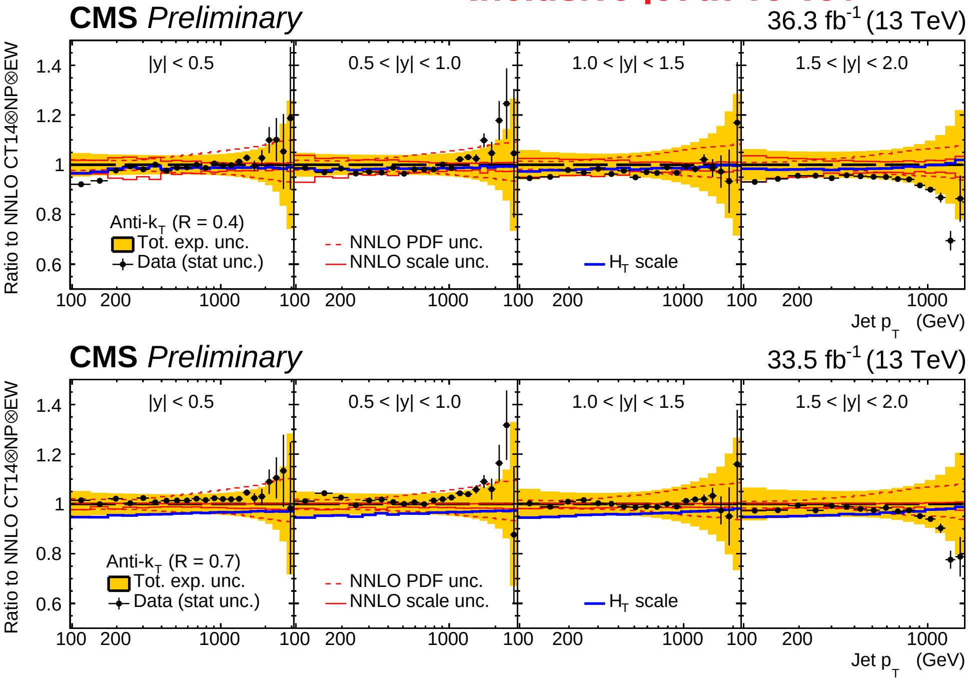




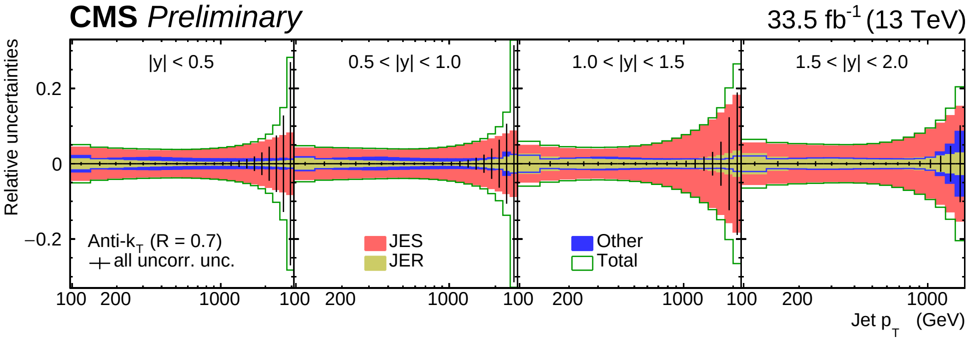
Inclusive jet at 13 TeV



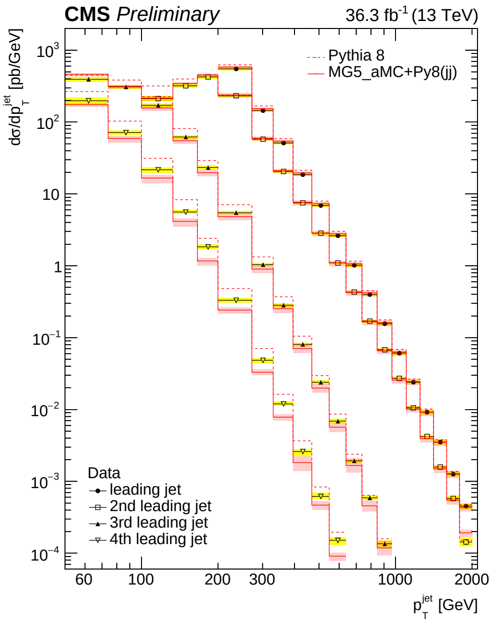
Inclusive jet at 13 TeV



Inclusive jet at 13 TeV

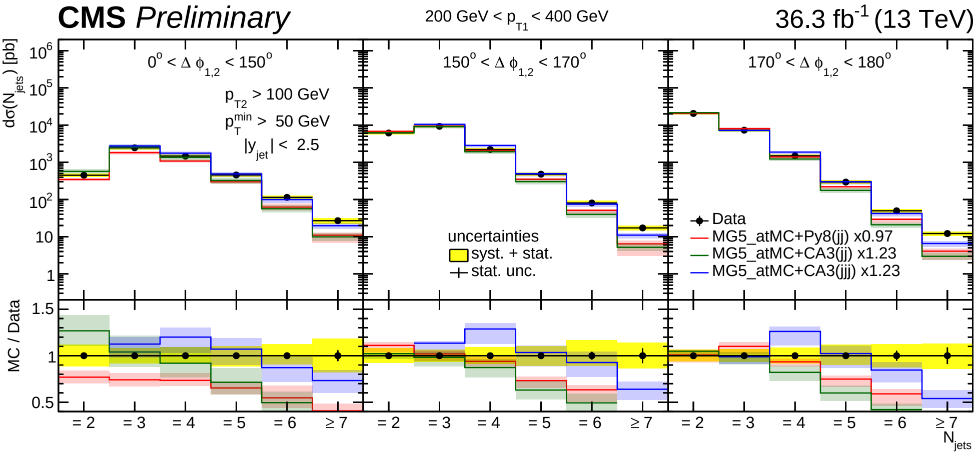


Multijet production at 13 TeV



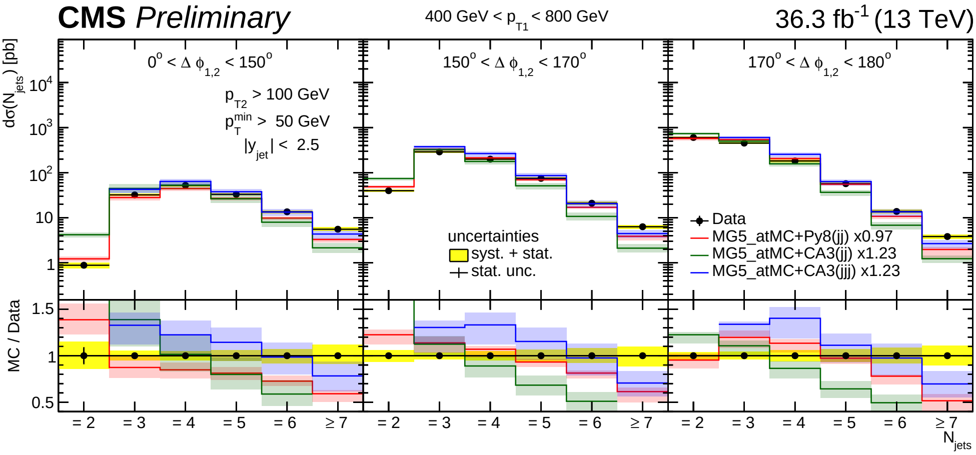
Multijet production at 13 TeV

Multiplicity



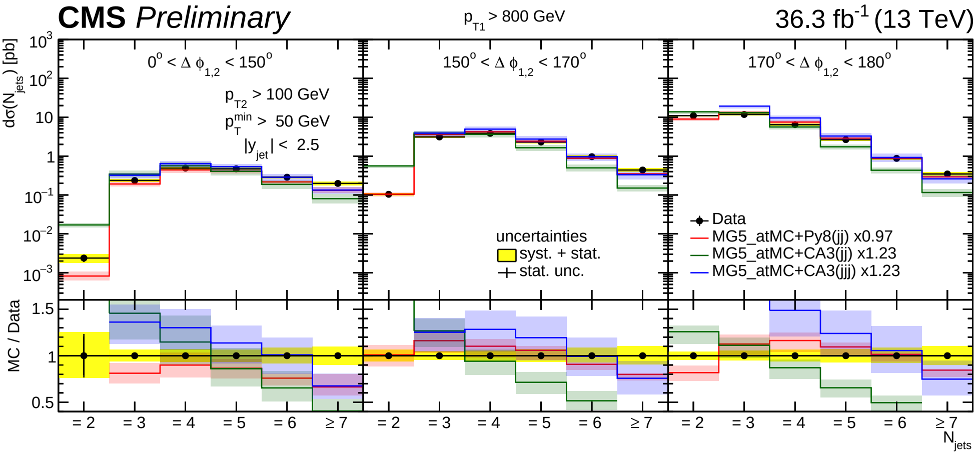
Multijet production at 13 TeV

Multiplicity



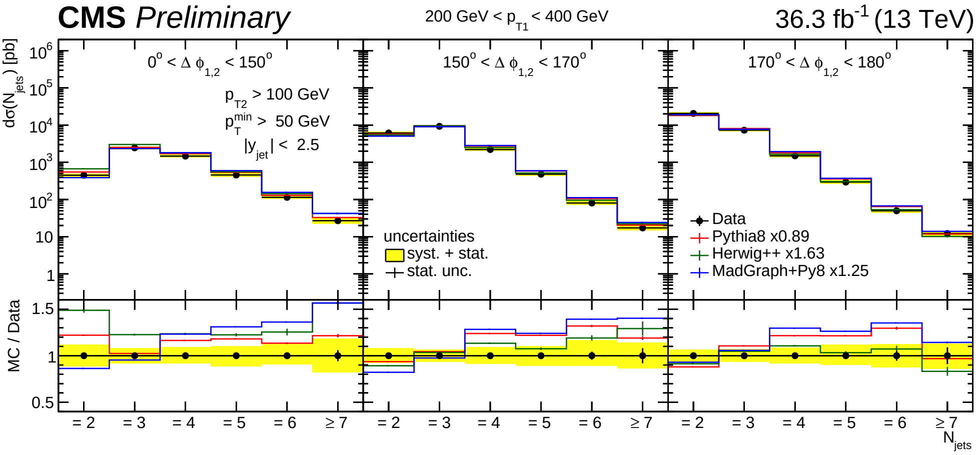
Multijet production at 13 TeV

Multiplicity



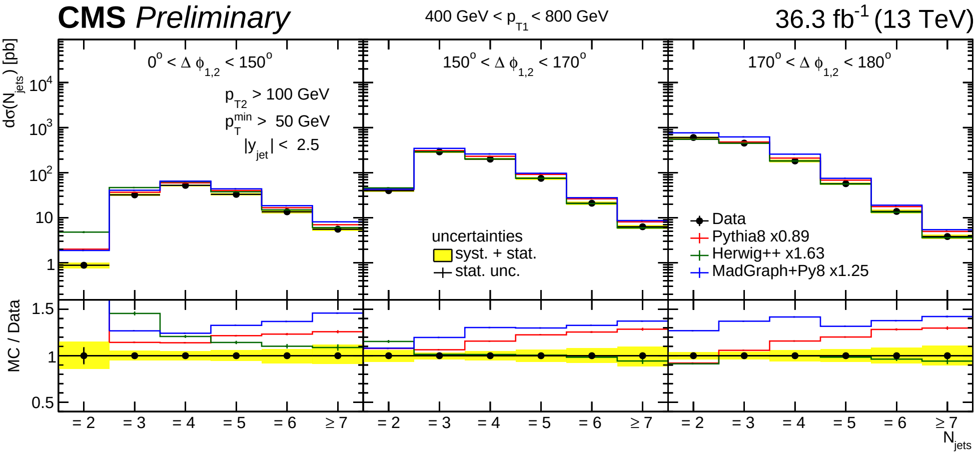
Multijet production at 13 TeV

Multiplicity



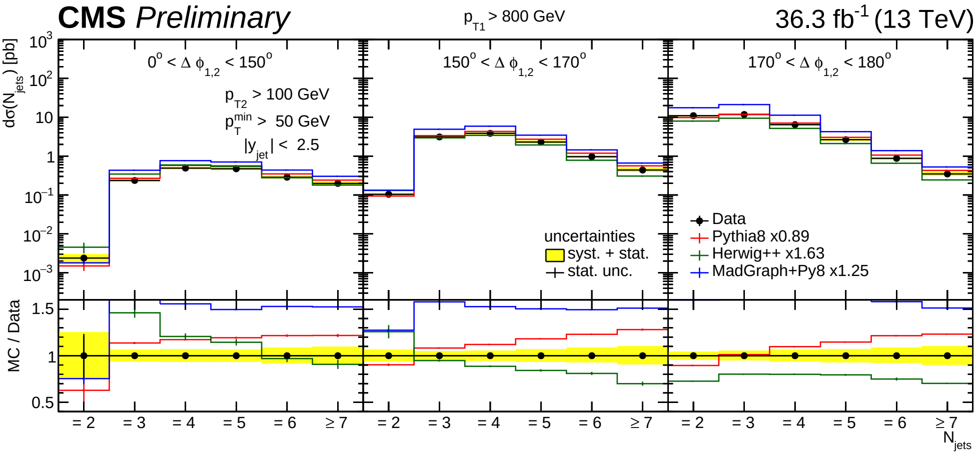
Multijet production at 13 TeV

Multiplicity



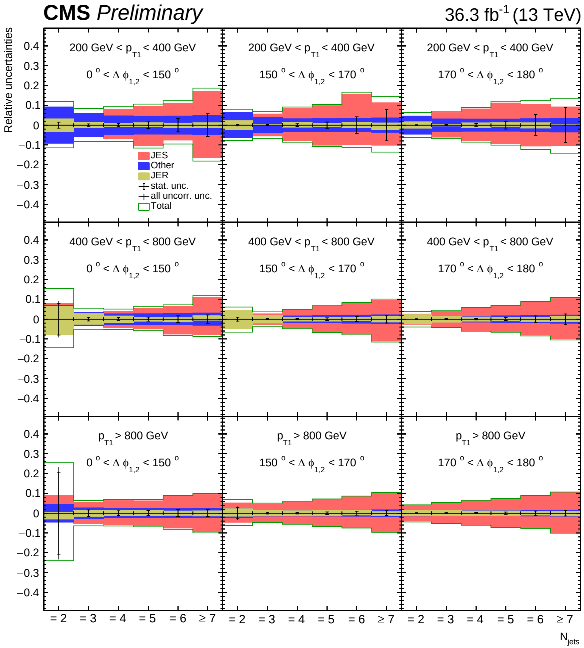
Multijet production at 13 TeV

Multiplicity



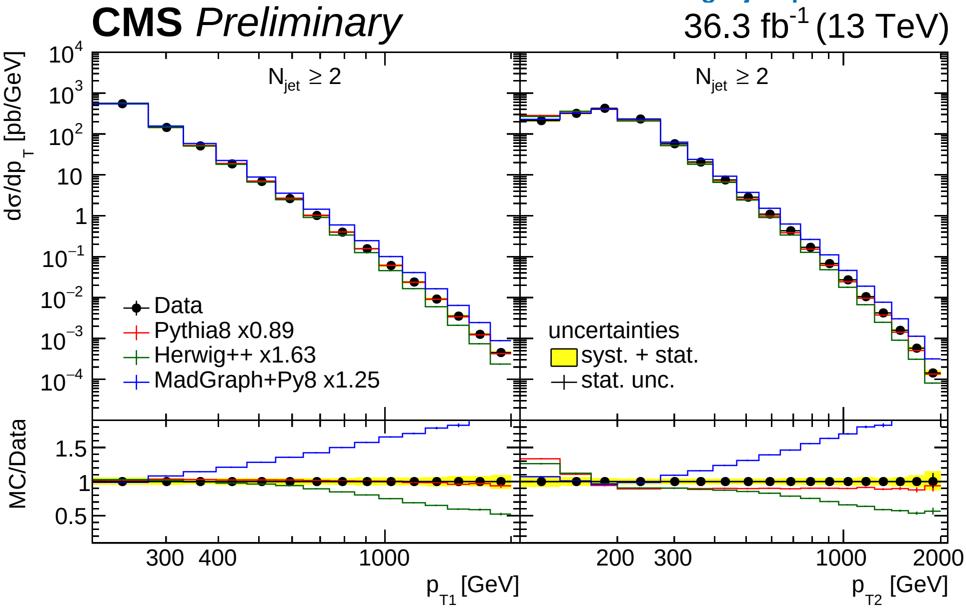
Multijet production at 13 TeV

Multiplicity



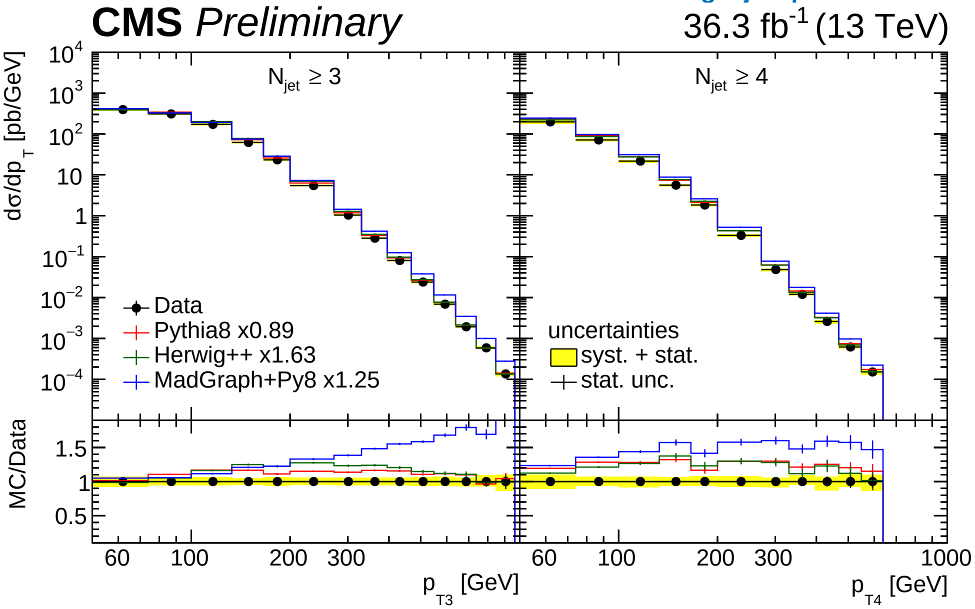
Multijet production at 13 TeV

Single-jet spectra



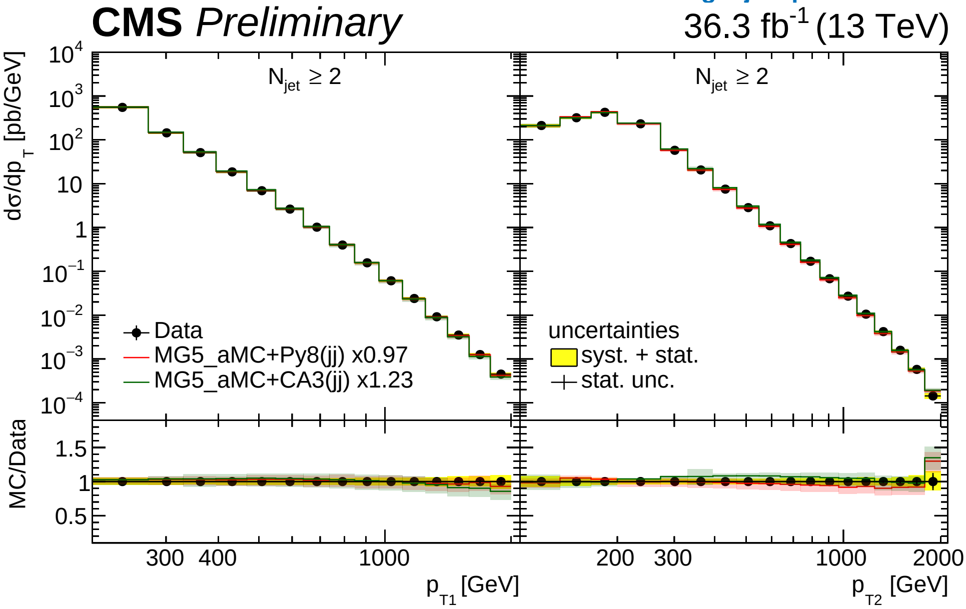
Multijet production at 13 TeV

Single-jet spectra



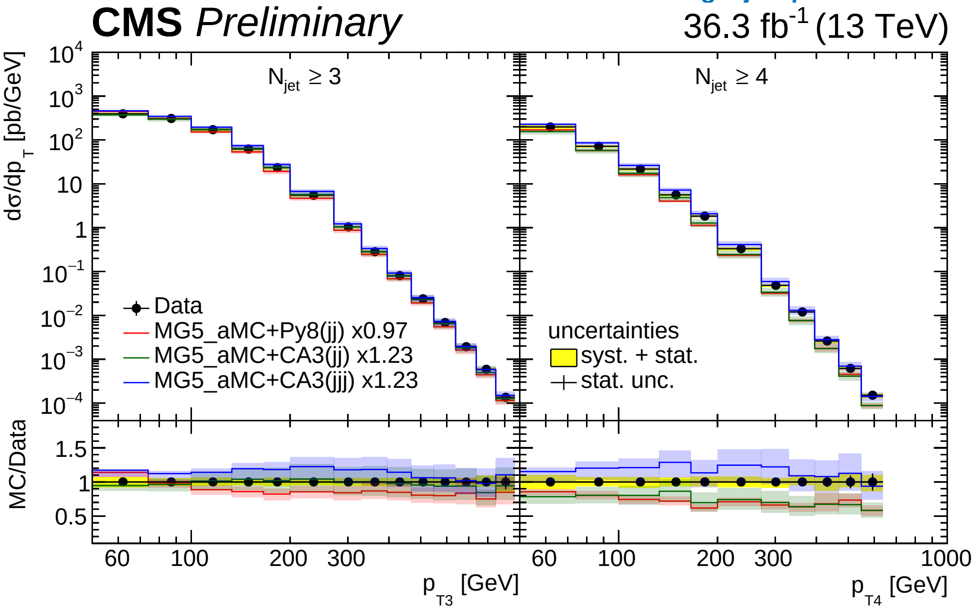
Multijet production at 13 TeV

Single-jet spectra



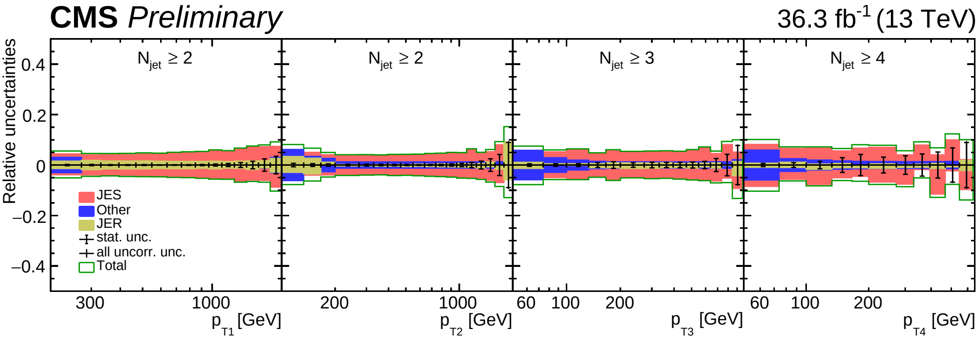
Multijet production at 13 TeV

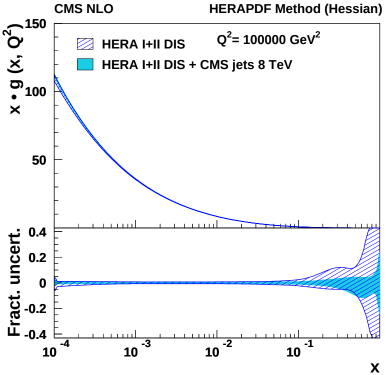
Single-jet spectra



Multijet production at 13 TeV

Single-jet spectra





Motivation

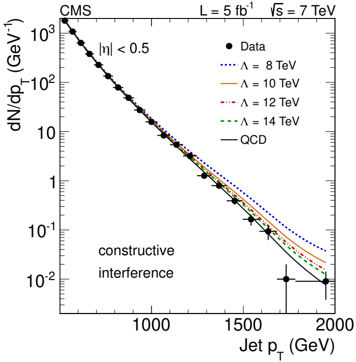
Inclusive jet measurements at LHC

$\sqrt{s}$	ATLAS	CMS
2.76 TeV	0.0002 fb^{-1} [31]	0.0054 fb^{-1} [32]
7 TeV	4.5 fb^{-1} [33]	5.0 fb^{-1} [34, 35]
8 TeV	20 fb^{-1} [36]	20 fb^{-1} [37]
13 TeV	3.2 fb^{-1} [38]	0.071 fb^{-1} [39]

- Unfold data.
- Constrain α_S and PDFs with SM predictions.

Searches for CI at CMS [40, 41]

- Fold SMEFT predictions with existing PDF.
- Constrain CI.

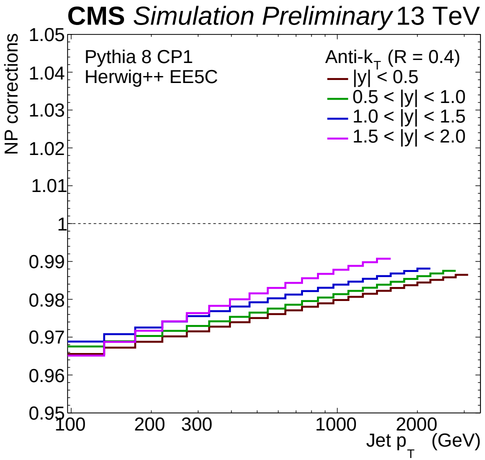


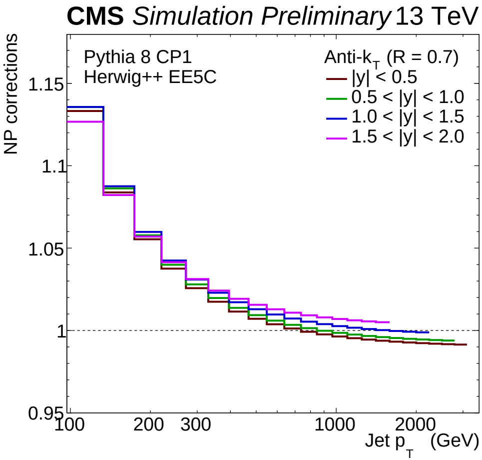
Question

But **what if** the CIs have already been **absorbed** in the PDF**?**

Corrections

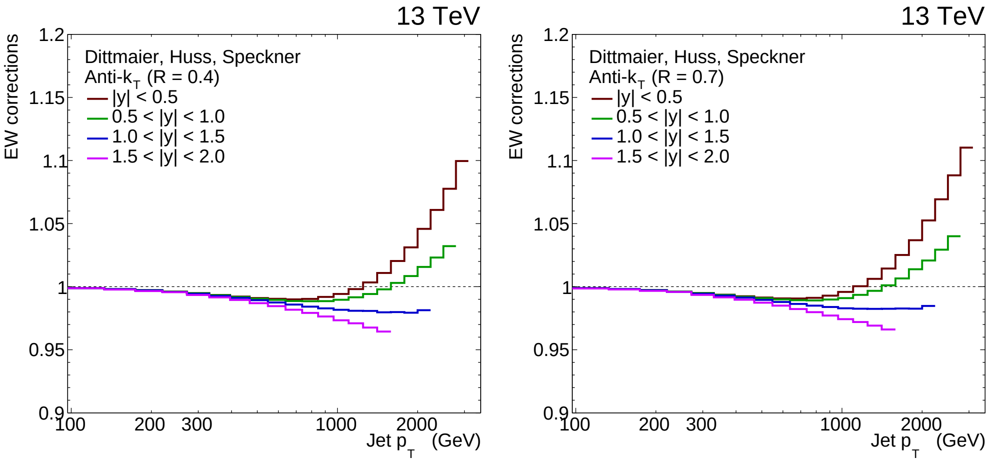
NP corrections





Corrections

EW corrections



Profiling

Method

$$\chi^2 = \sum_{i=1}^{N_{\text{data}}} \frac{\left(\sigma_i^{\text{exp}} + \sum_\alpha \Gamma_{i\alpha}^{\text{exp}} b_\alpha^{\text{exp}} - \sigma_i^{\text{th}} - \sum_\beta \Gamma_{i\beta}^{\text{th}} b_\beta^{\text{th}}\right)^2}{\Delta_i^2} + \sum_\alpha (b_\alpha^{\text{exp}})^2 + \sum_\beta (b_\beta^{\text{th}})^2$$

$$f_0' = f_0 + \sum_\beta b_\beta^{\text{th(min)}} \left(\frac{f_\beta^+ - f_\beta^-}{2} - b_\beta^{\text{th(min)}} \frac{f_\beta^+ + f_\beta^- - 2f_0}{2} \right)$$

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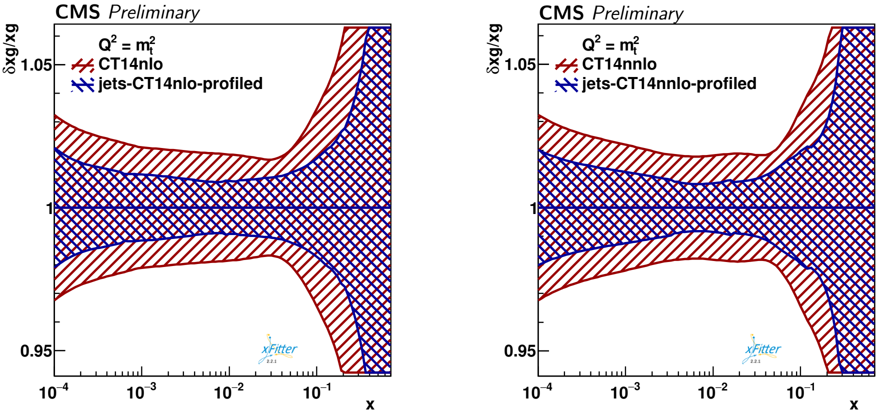
Profiling

PDFs

Goal

Investigate reduction of uncertainties with the present data with existing PDF set.



Impact on PDF, α_S, m_t, and c_1

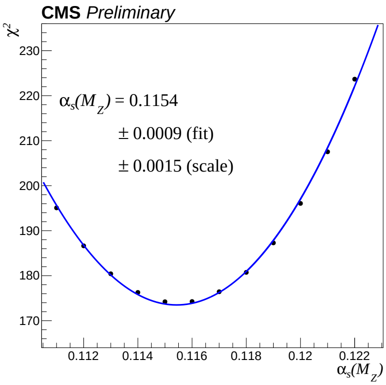
- Using 13-TeV CMS data on top of CT14
- Both NLO & NNLO predictions.

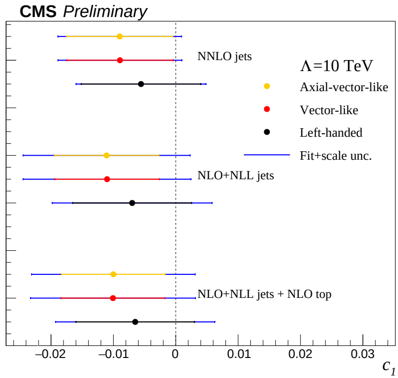
Profiling

SM(EFT)

Goal

Investigate reduction of uncertainties with the present data with existing PDF set.

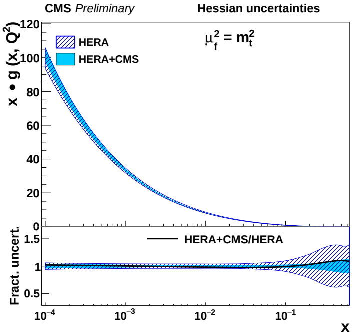


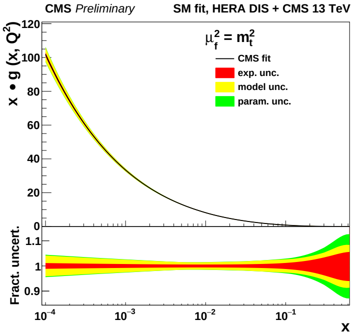


Impact on PDF, α_S, m_t, and c_1

- **Profiling** method is applied on the various parameters separately.

SM Fits





Parameterisation

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+E_g x^2)$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v} x)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}$$

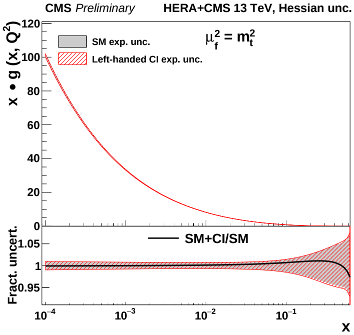
Results

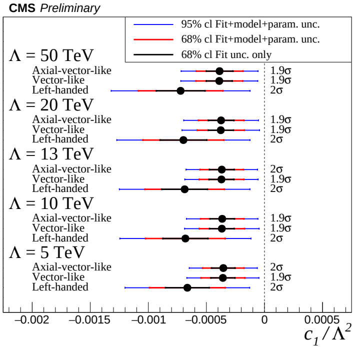
- Strong reduction of the gluon PDF uncertainty.

SM parameters

$$\alpha_S = 0.1188 \pm 0.0017(\text{fit}) \pm 0.0022(\text{model and param.})$$
$$m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fit}) \pm 0.1(\text{model and param.})$$

SMEFT Fits





Parameterisation

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + E_g x^2)$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + D_{u_v} x + E_{u_v} x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} (1 + D_{d_v} x)$$

$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}} (1-x)^{C_{\overline{U}}}$$

$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} (1-x)^{C_{\overline{D}}}$$

Results

- SMEFT fits lead to results compatible w. SM.

SM parameters

$$\alpha_S = 0.1187 \pm 0.0016(\text{fit}) \pm 0.0030(\text{model and param.})$$

$$m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fit}) \pm 0.3(\text{model and param.})$$

Acronyms I

AK4 anti k_T algorithm ($R = 0.4$). 7–11, 13, 14

AK7 anti k_T algorithm ($R = 0.7$). 8, 14

CI Contact Interaction. 4–6, 26, 58

CMS Compact Muon Solenoid. 7, 8, 26, 58, 62

DIS Deeply Inelastic Scattering. 7, 8

FO fixed order. 4–6, 26

HERA *Hadron-Elektron-RingAnlage*. 7, 8

LHC Large Hadron Collider. 58

MC Monte Carlo. 4–6, 26

ME Matrix Element. 20, 21

NLL Next to Leading Logarithm. 4–6, 18, 19, 26

NLO Next to Leading Order. 4–6, 17–21, 23, 24, 26, 62

NNLO Next to Next to Leading Order. 4–6, 18, 19, 23, 24, 26, 62

PB Parton Branching. 20, 21

PDF Parton Distribution Function. 4–8, 18, 19, 23, 58, 62–64

PS Parton Shower. 20, 21

QCD Quantum Chromodynamics. 7, 8, 23, 24, 26

RM Response Matrix. 13, 14

SM Standard Model. 4–6, 24, 58, 64, 65

SMEFT Standard Model Effective Field Theory. 4–6, 24, 58, 65

TMD Transverse-Momentum-Dependent. 4–6, 20, 21

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