Jet cross section measurements in CMS

Deniz SUNAR CERCI
Adiyaman University
On behalf of the CMS Collaboration
28th September 2021

Low-x 2021

26 September 2021 to 1 October 2021
Europe/Zurich timezone

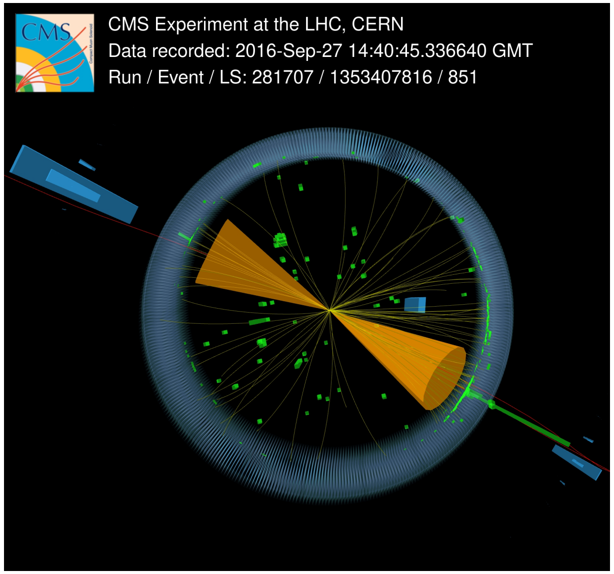
Outline

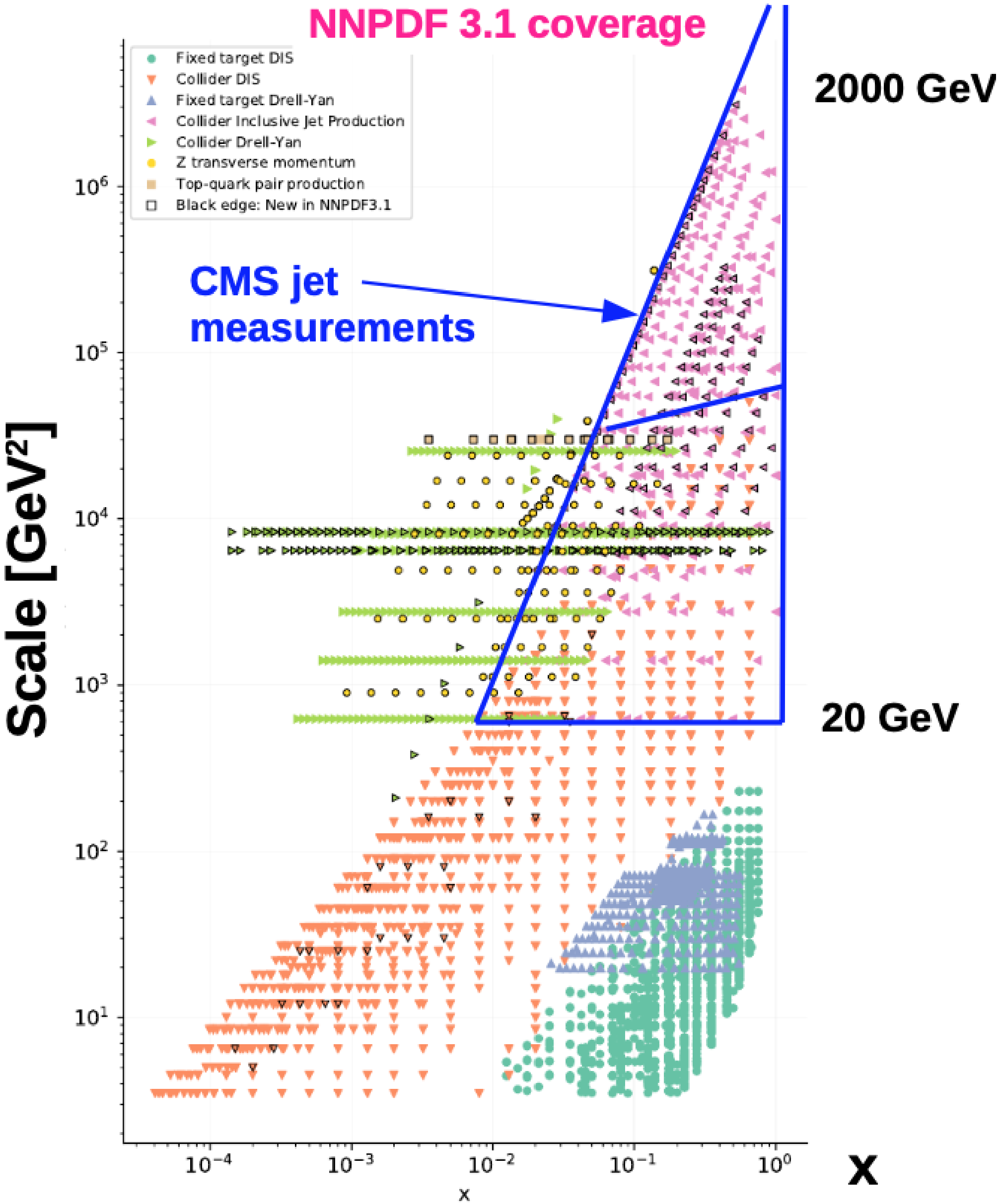
- Introduction
  - Jets and jet reconstruction in CMS
- Measurements
  - Inclusive jet cross section @ 13 TeV (SMP-20-011)
  - Inclusive jet cross section @ 5 TeV (SMP-21-009)
  - Multijet cross section @ 13 TeV (SMP-21-006)
- Summary

Introduction: what are jets?

- Collimated spray of particles
- Experimental signatures of quarks and gluons.
- Invaluable objects to probe QCD
- Abundantly produced in pp collisions:
  - access hard QCD, α_s, PDF...
- Important signature for many physics processes (Higgs, top, SUSY, ...)

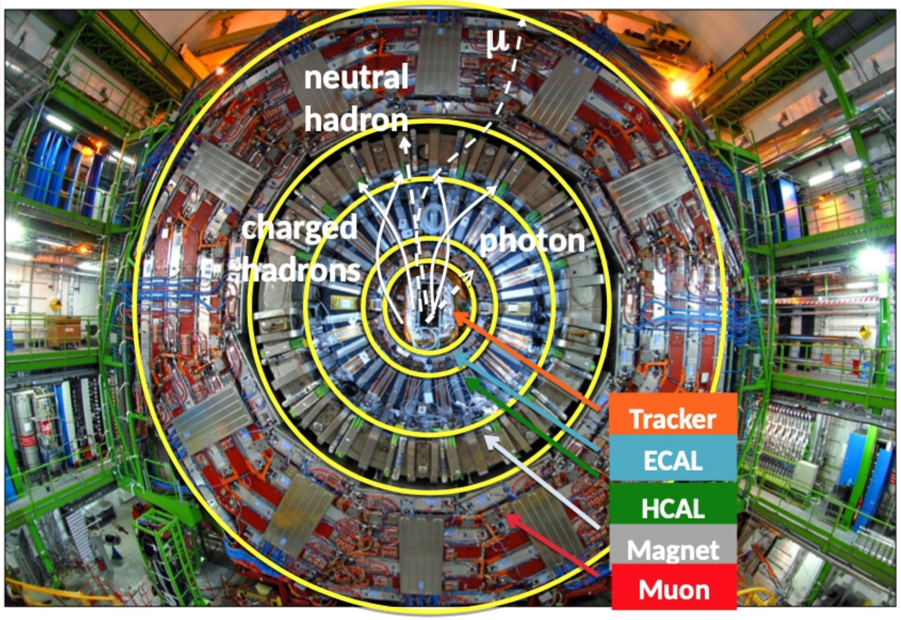
- Jets allow to probe proton structure at the smallest distances (~10^{-19} m)



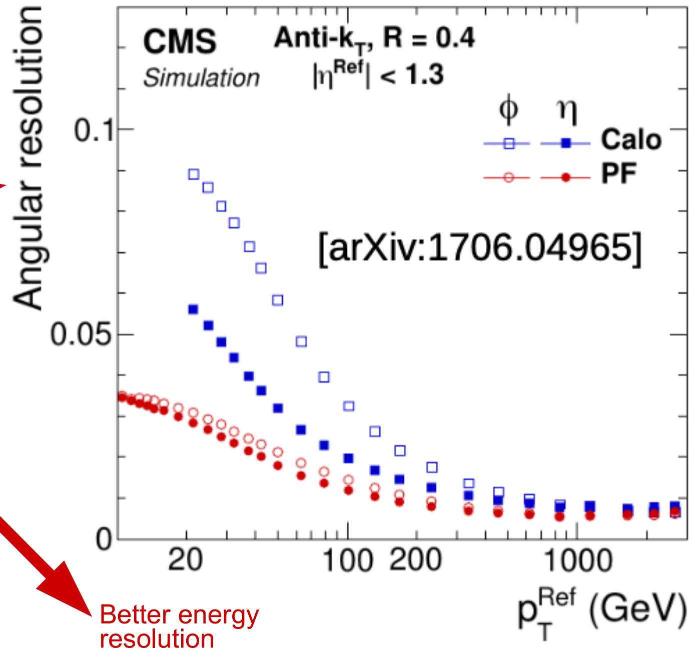


Jet reconstruction in CMS

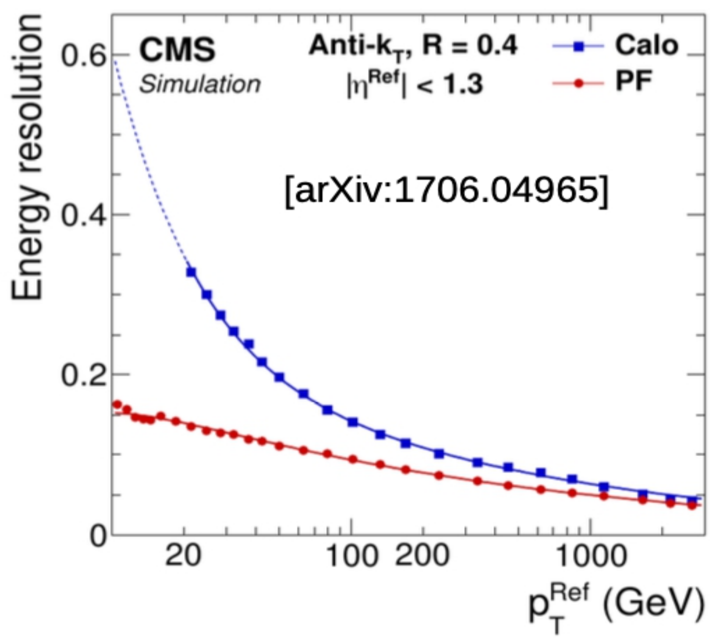
- **“Anti-k_t jet algorithm”** is the default jet reconstruction algorithm
- **Particle Flow (PF)** is an event reconstruction technique which attempts to reconstruct and identify all stable particles in the event, through the optimal combination of all CMS subdetectors.
- **Calorimeter (CALO) jets** are reconstructed from energy deposits in the calorimeter towers.



Better angular resolution

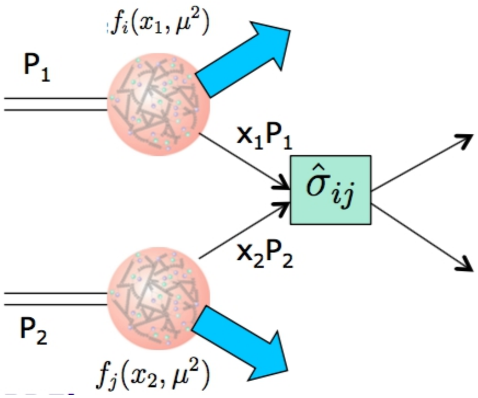


Better energy resolution



Inclusive jets cross section

- Parton density functions (PDFs)
  - evolution with DGLAP equations (Q^2 ordered)
- Hard scattering cross section
  - depend on process
  - valid in short distance
  - small coupling constant
  - calculable with pQCD



$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu^2), Q^2/\mu^2)$$

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \cdot \mathcal{L}_{\text{eff}}} \frac{N_{\text{jets}}}{\Delta p_T (2 \cdot \Delta|y|)} \quad \propto \alpha_s^2$$

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

Inclusive jets at 13 TeV

CMS PAS SMP-20-011

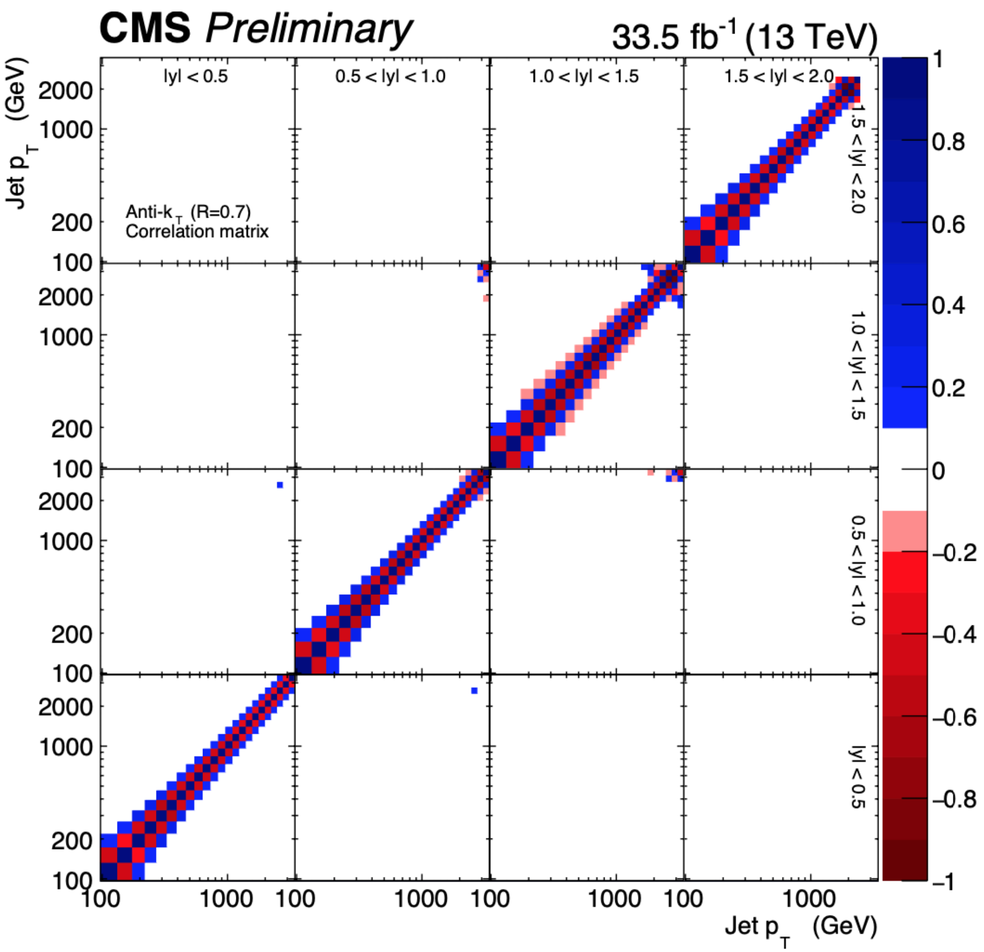
- **Motivation:**
  - Perform simultaneous fit of **PDFs, α_s, m_t and Wilson coefficient c_1**
- **Analysis strategy:**
  - $p_T > 97$ GeV , $|y| < 2.0$
  - High pile up **2016** data with **L_{int} = 36.3** & **33.5 fb^{-1}**
  - Jet clustering with **AK4** & **AK7**
  - Single-jet triggers used
  - In previous measurements mostly D'Agostini unfolding method was used
    - here **least-square minimisation is used for the unfolding**

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

Inclusive jets at 13 TeV

- **Motivation:**
  - Perform simultaneous fit of **PDFs, α_s, m_t and Wilson coefficient c_1**
- **Analysis strategy:**
  - $p_T > 97$ GeV , $|y| < 2.0$
  - High pile up **2016** data with **L_{int} = 36.3** & **33.5 fb^{-1}**
  - Jet clustering with **AK4** & **AK7**
  - Single-jet triggers used
  - In previous measurements mostly D'Agostini unfolding method was used
    - here **least-square minimisation is used for the unfolding**

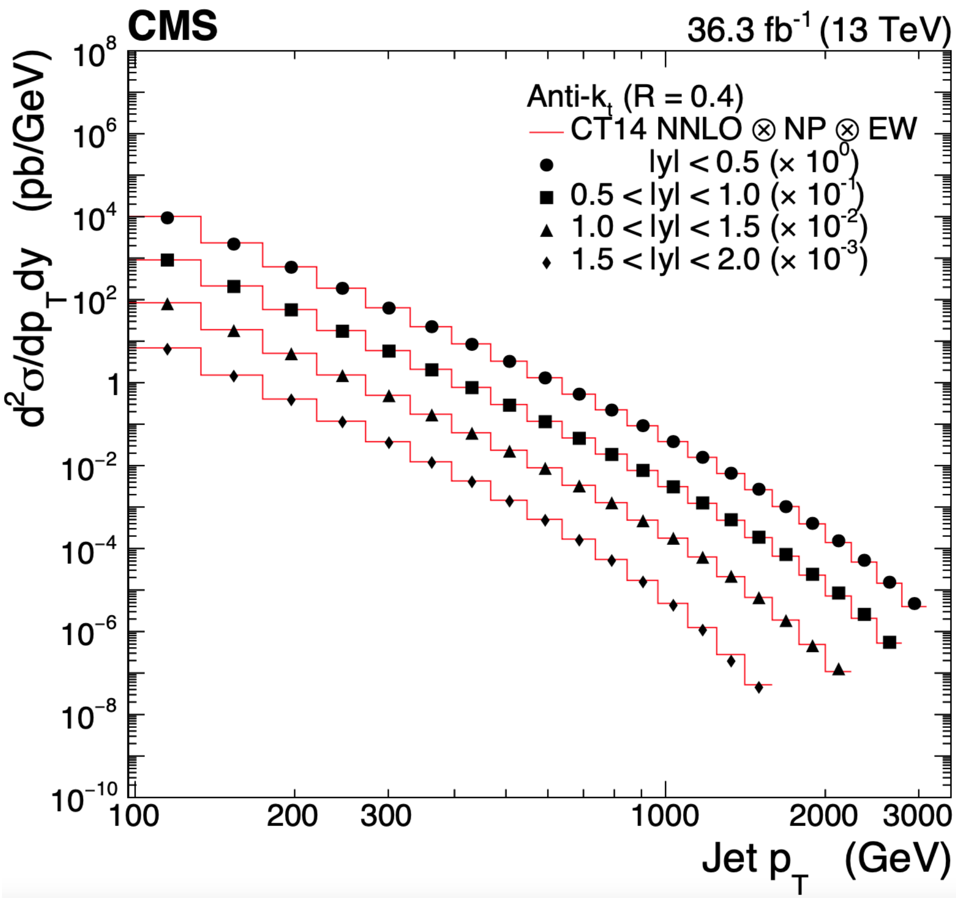
$$\chi^2 = \min_{\mathbf{x}} \left[(\mathbf{Ax} - \mathbf{y} - \mathbf{b})^{\intercal} \mathbf{V}^{-1} (\mathbf{Ax} - \mathbf{y} - \mathbf{b}) \right]$$

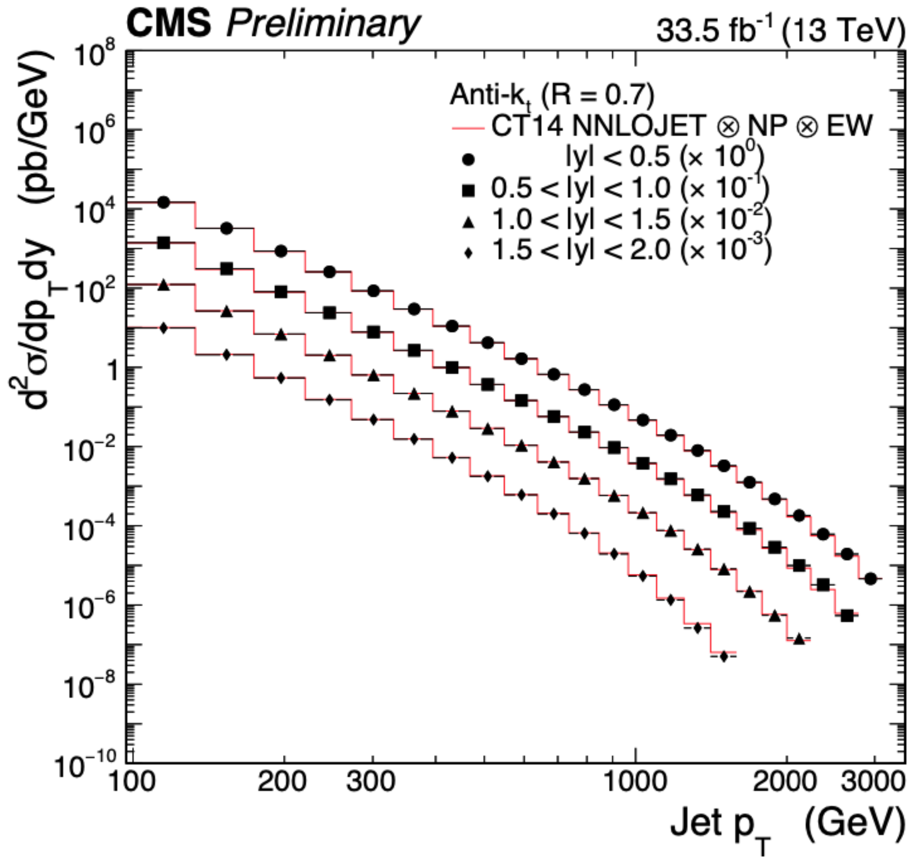


- **Correlation matrix @ particle level (for AK7)**
  - 4 × 4 structure → bins of y_{jets}, indicated by the labels in the uppermost row and rightmost column
  - x and y axes of each cell → p_T of the jets.

Cross sections

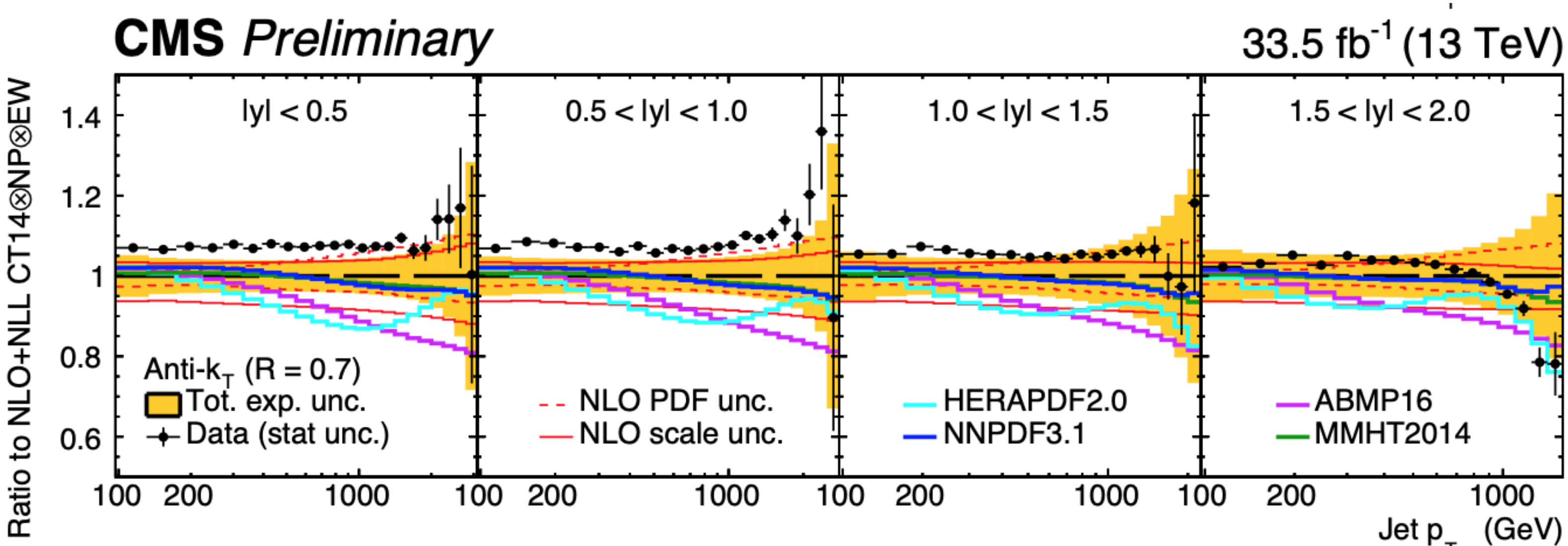
CMS PAS SMP-20-011

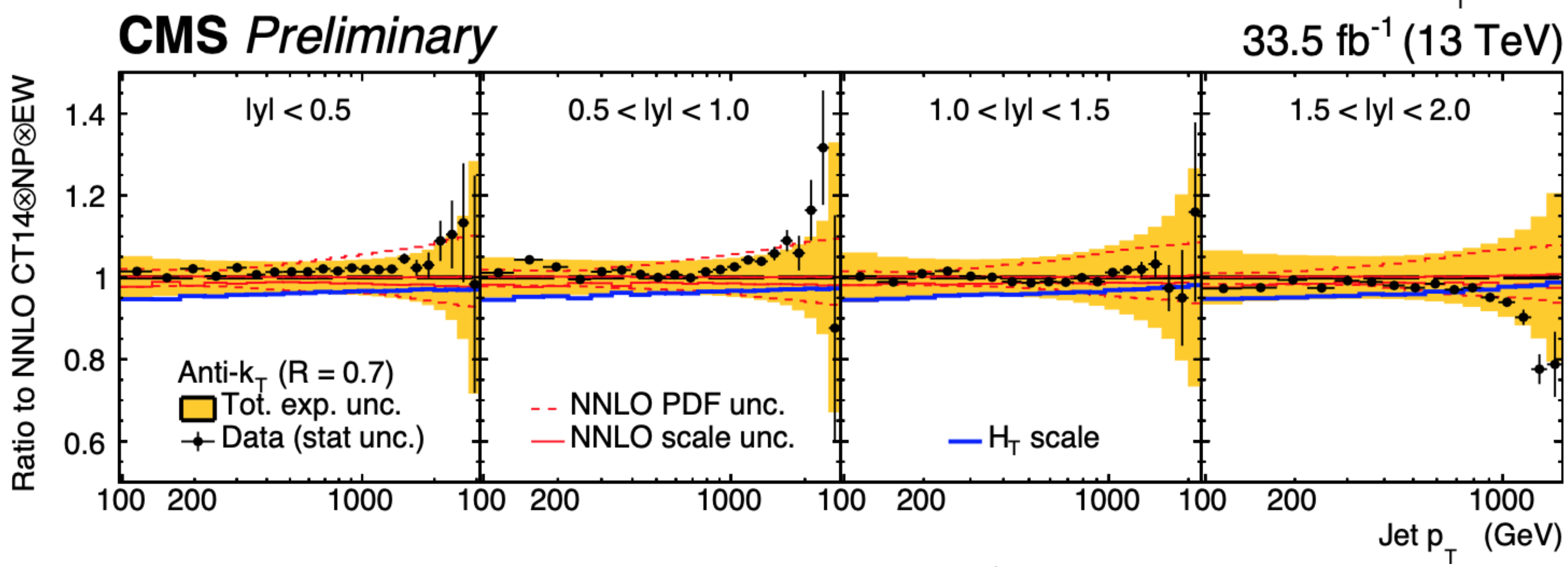




- Cross section obtained for jets clustered using the anti-k_T algorithm with R = 0.4 (R = 0.7).
- Comparison of data with the NLO QCD fixed-order predictions based on CT14 PDF.
- Only the statistical uncertainties of the data are shown.
- The predictions are corrected for EW and NP effects.

Results

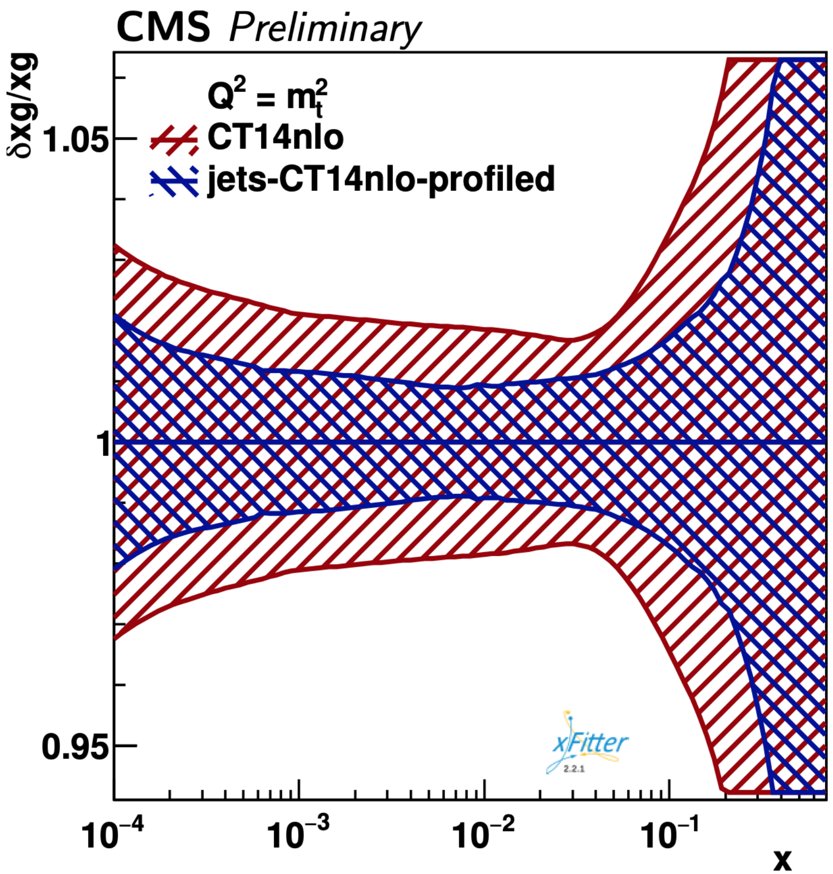


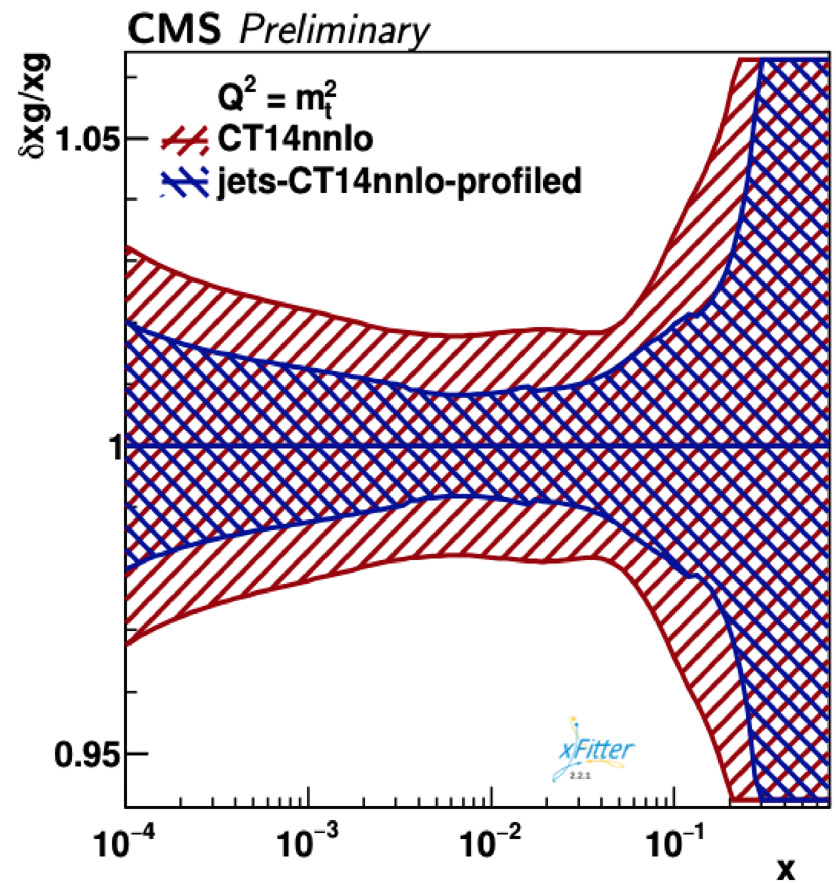


- Comparison to various global PDF sets with NLO+NLL obtained via k-factor technique (top), to NNLO obtained with NNLOJET from interpolation tables (bottom).
- **Predictions @ NNLO & @NLO+NLL: compatible with those @NLO within the scale unc.**
  - **predict a harder p_T and provide a better description of the measurements.**

Impact of the CMS data on the PDFs

CMS PAS SMP-20-011





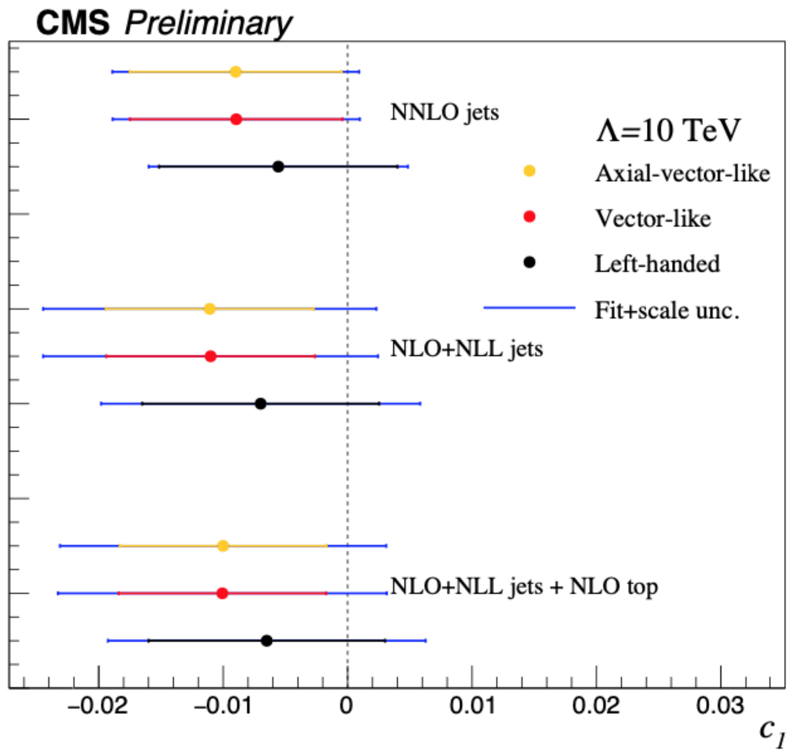
- PDF profiling CT14 at NLO &NNLO
- QCD fits follow the HERAPDF2.0 approach
- Significant improvement on gluon PDF uncs.

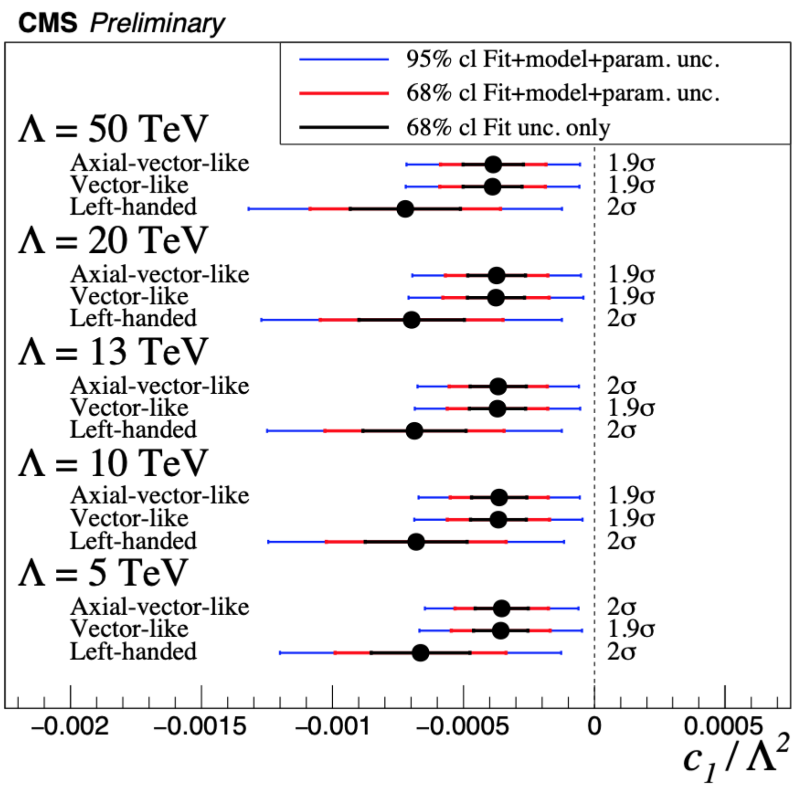
SMEFT fit

- **Profiling analysis is repeated assuming the EFT-modified SM prediction for inc. jet. x-section**

- The Wilson coefficient $\mathbf{c_1}$ is profiled for the value of the scale of the new interaction $\mathbf{\Lambda}$ = 10 TeV

- Values of $\mathbf{c_1}$ are consistent with zero within uncertainties for all models,





- **SMEFT fits sensitive to c_1/Λ^2 ratio**

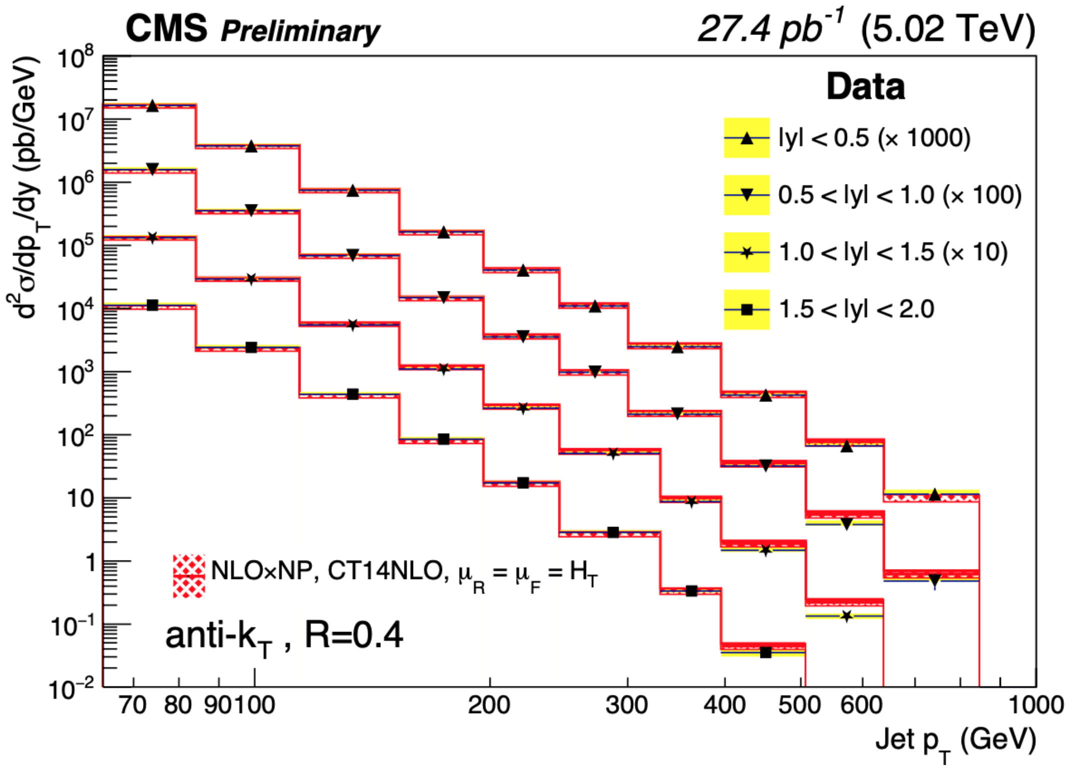
- SMEFT fits lead to results compatible with SM.

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

Inclusive jets at 5 TeV

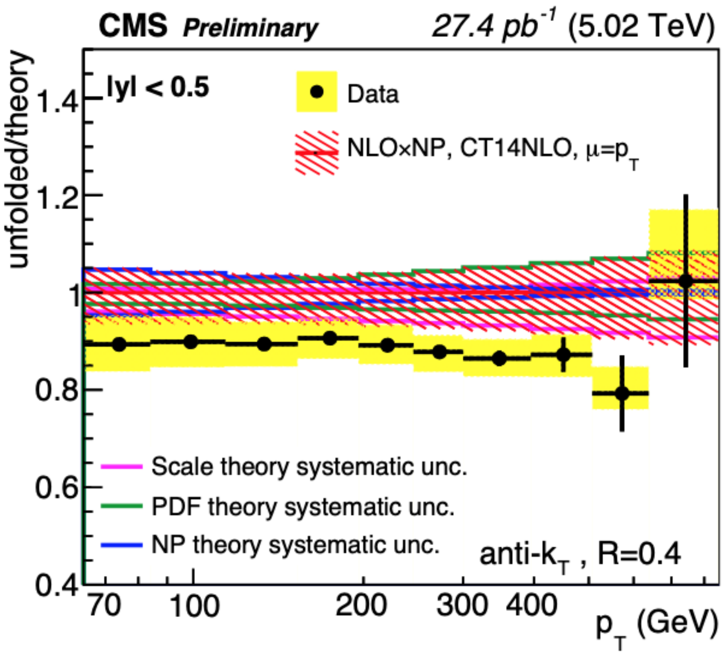
CMS PAS SMP-21-009

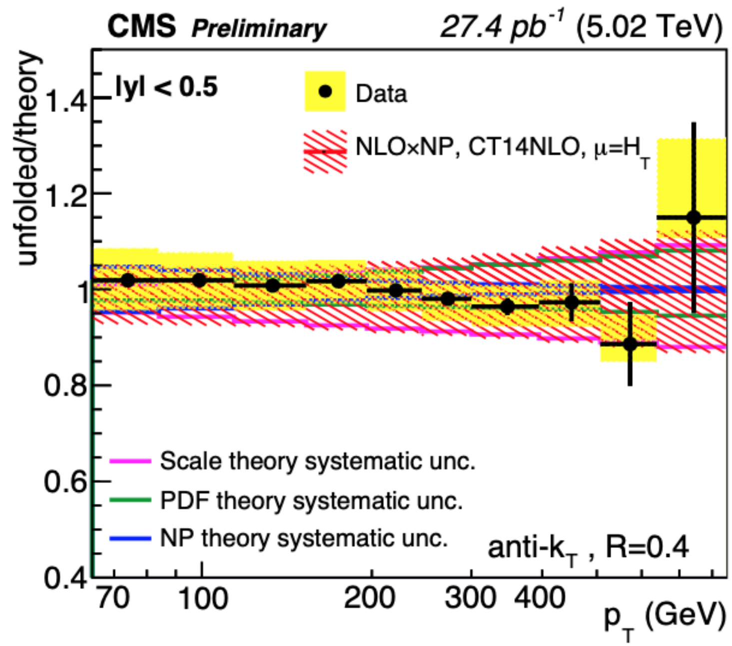
- **Motivation:**
  - Perform simultaneous fit of PDFs and α_s
- **Analysis strategy:**
  - $p_T > 64$ GeV , $|y| < 2.0$
  - Low pile up 2015 data with $L_{int} = 27.4\ pb^{-1}$
  - Jet clustering with AK4
  - Least square minimisation is used for the unfolding



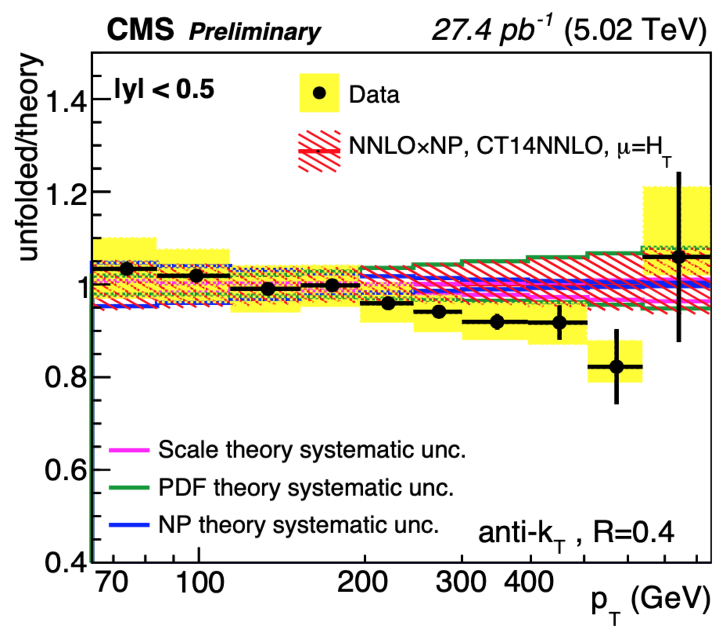
Ratios

CMS PAS SMP-21-009

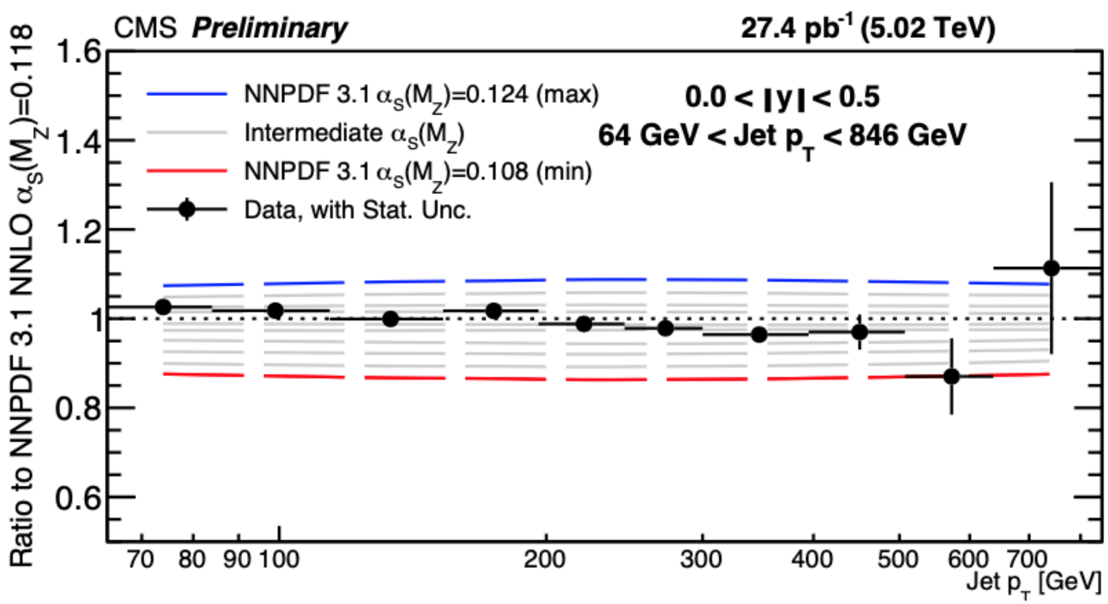


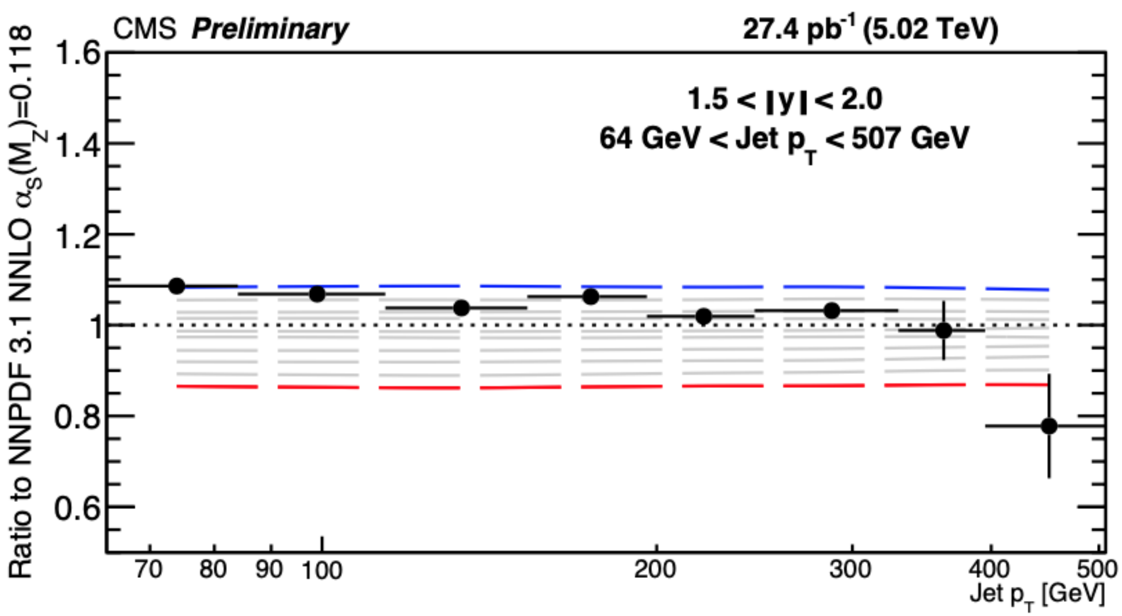


- Comparison to NLO and NNLO obtained with NNLOJET
- Good agreement between theo. & exp.
- NLO calculation with $\mu = H_T$ and the CT14NLO PDF set, agrees better among the NLO calculations.



Effect of α_s variation





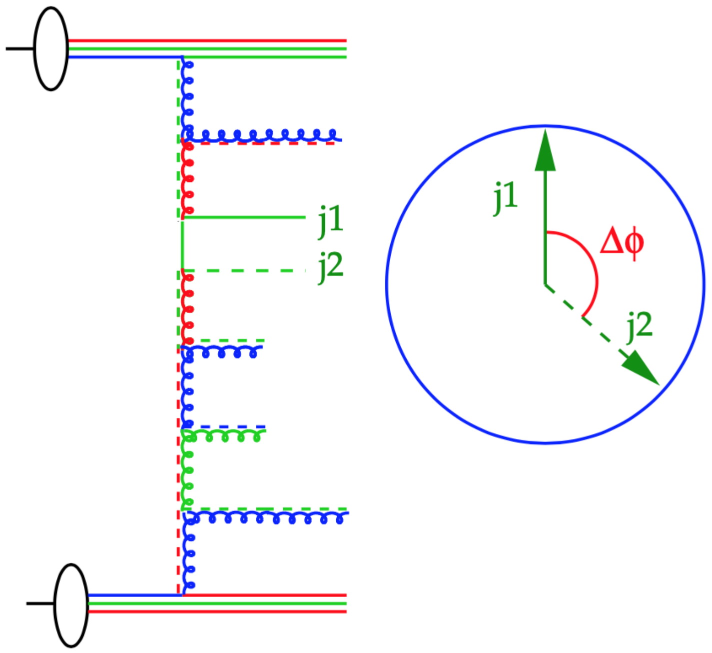
- Comparison to NNPDF3.1 NNLO for $\mu = H_T$
- Sensitivity to the value of α_s, favoring coupling constant values higher than the value $\alpha_s = 0.118$.

Multijets at 13 TeV

- **Motivation:**
  - Azimuthal correlations in high p_T dijet events have been already measured
  - Effects of higher order contributions to the dijet system decorrelation were observed, but still more information on how the decorrelation should be built is missing

Detailed investigations needed:

- Jet multiplicity in bins of $\Delta\phi_{\text{dijet}}$ and p_T^{max}
- p_T spectra of first four leading jets



- **Analysis strategy:**
  - p_{T1} > 200 GeV , p_{T2} > 100 GeV $|y^{1,2}|$ < 2.5
  - Additional jets are considered if
    - p_T > 50 GeV , $|y|$ < 2.5
  - High pile up 2016 data with L_{int} = 36.3 fb^{-1}
  - Jet clustering with AK4

Multijets at 13 TeV

- **Observables:**
  - Jet multiplicity in bins of $\Delta\phi_{\mathrm{dijet}}$ and p_T^{max} $\quad \frac{d^3\sigma}{dp_T^{max}\, d\Delta\phi_{\mathrm{dijet}}\, dN_{\mathrm{jets}}}$

    N_{jets} binning [=2,=3,=4,=5,=6, >=7]

    $\Delta\phi_{\mathrm{dijet}}$ binning [0^o, 150^o, 170^o, 180^o]

    p_T^{max} binning [200,400,800,13000] GeV

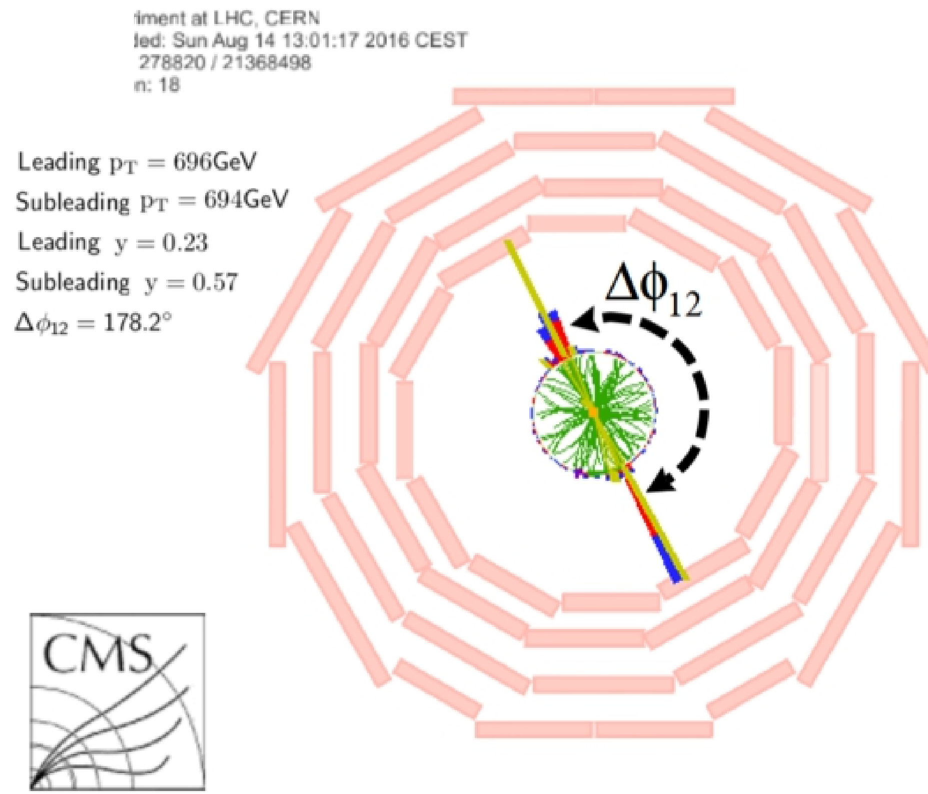
  - p_T spectra of first four leading jets $\quad \frac{d^2\sigma}{dn^i_{\mathrm{jet}}\, dp^i_T}$

    $p_T^{\text{leading jet}}$ ($N_{jets} \geq 2$) [200,.., 2000] GeV

    $p_T^{\text{2nd leading jet}}$ ($N_{jets} \geq 2$) [100,.., 2000] GeV

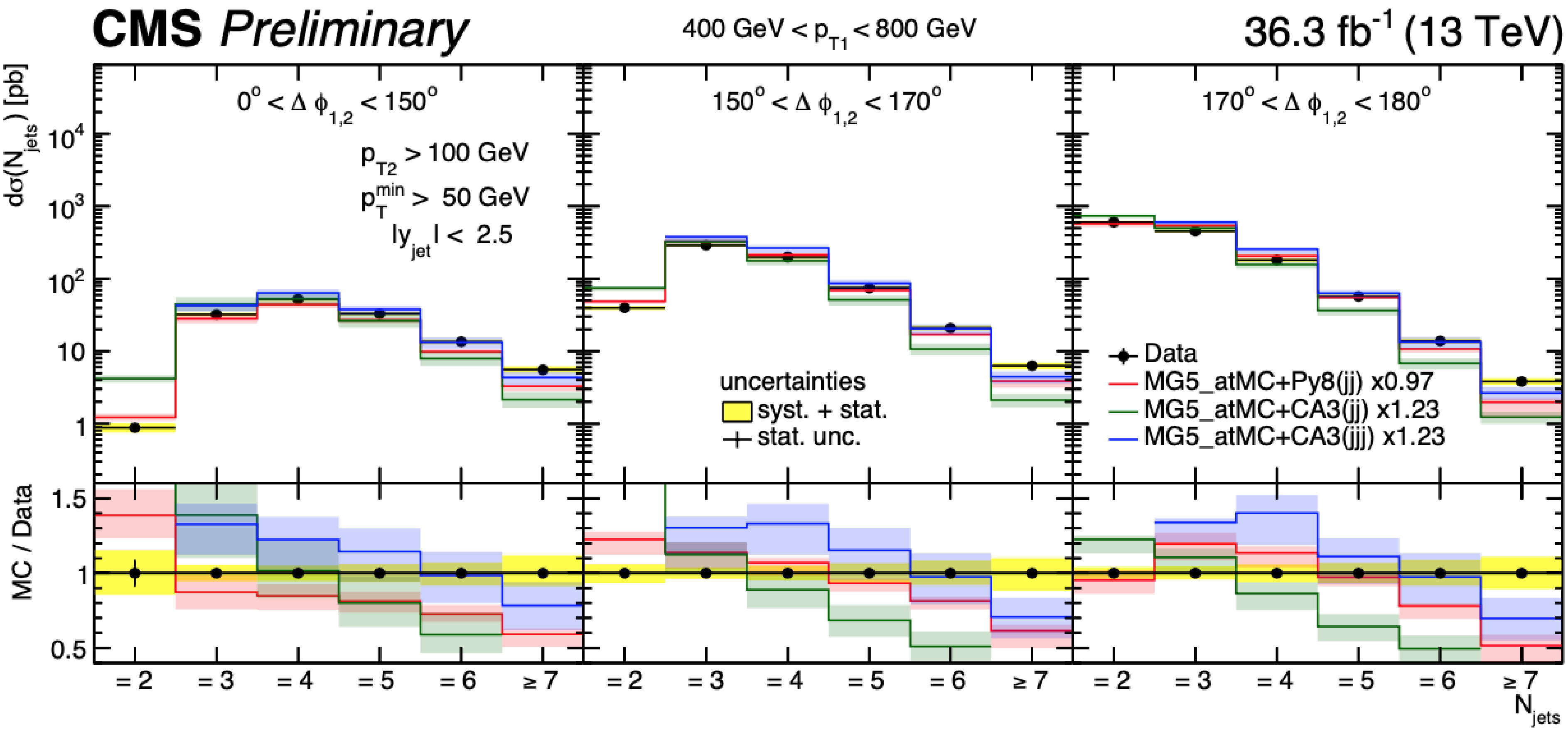
    $p_T^{\text{3rd leading jet}}$ ($N_{jets} \geq 3$) [50,.., 967] GeV

    $p_T^{\text{4th leading jet}}$ ($N_{jets} \geq 4$) [50,..,638] GeV



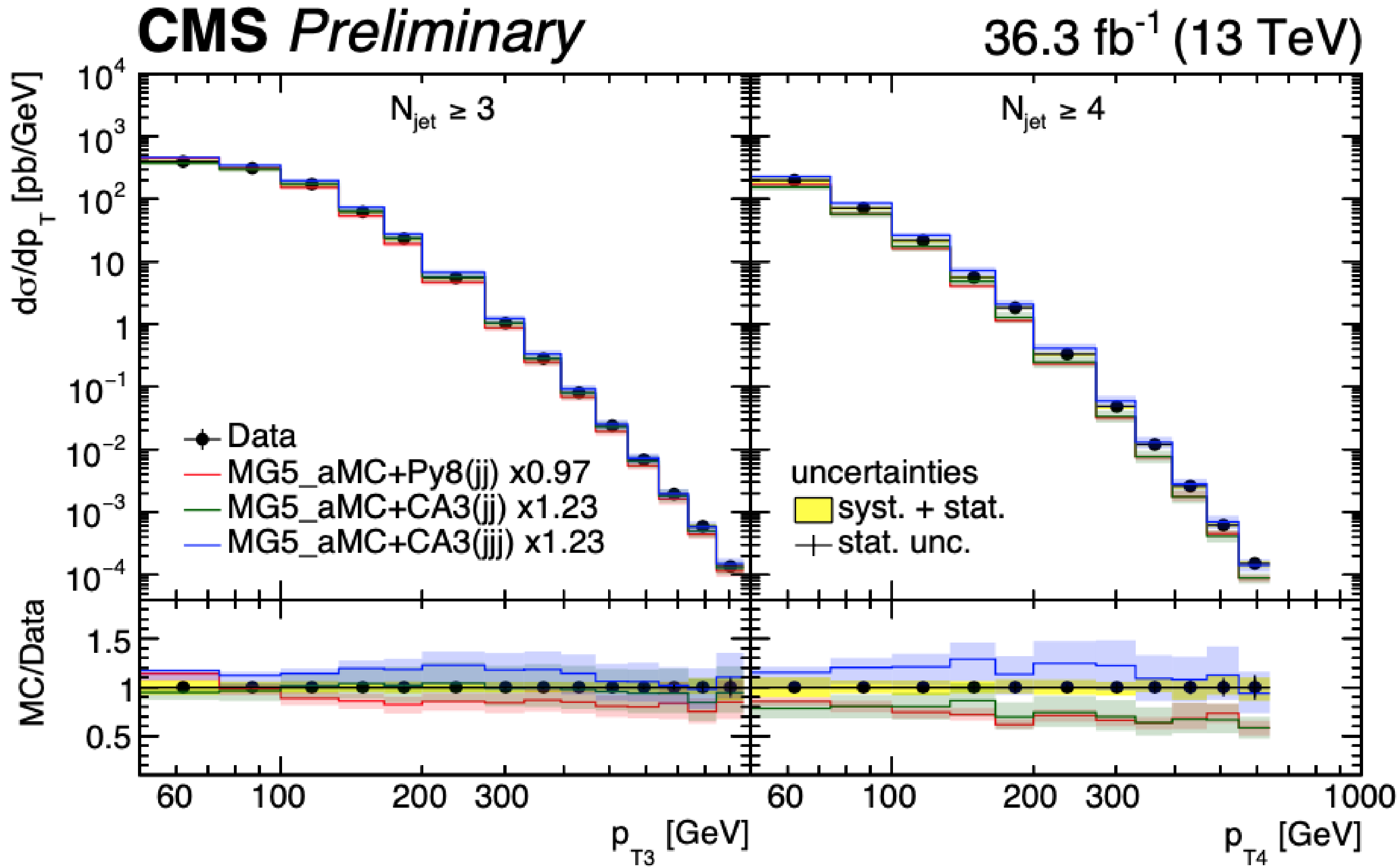
Jet multiplicity

CMS PAS SMP-21-006



- The predictions are normalized to the measured inclusive dijet cross section
- NLO calculation (using the same normalization factor as for MG5 AMC+CA3 (jj)) gives a rather good description of the 3 & 4 jet cross section
- Parton Branching TMD calculations found to be successful!

Transverse momenta of the four leading jets



- First time that calculations using PB-TMD together with ME in MC@NLO frame are compared over a wide range!
- Testing production of extra radiations in the ME or in the PS
- MG5 AMC+PY8 (jj) describes the normalization and the shape of the first 3 jets rather well

Summary

- An overview of recent jet cross section measurements has been presented
- Inclusive jet measurements at 5 and 13 TeV
  - scan of α_s running up to the TeV-scale
  - reduction of PDF unc. at high-x and scales
  - no evidence for contact interaction has been found.
- Multijet production at 13 TeV
  - NLO dijet calculations supplemented with PS or with PB-TMDs and TMD parton shower provide rather good description
  - allow for very stringent tests of theory predictions in the perturbative high p_T and high jet multiplicity regions.

- Still more measurements and efforts as well as LHC run 3 preparation on-going

stay tuned!

Summary

- An overview of recent jet cross section measurements has been presented
- Inclusive jet measurements at 5 and 13 TeV
  - scan of α_s running up to the TeV-scale
  - reduction of PDF unc. at high-x and scales
  - no evidence for contact interaction has been found.
- Multijet production at 13 TeV
  - NLO dijet calculations supplemented with PS or with PB-TMDs and TMD parton shower provide rather good description
  - allow for very stringent tests of theory predictions in the perturbative high p_T and high jet multiplicity regions.

- Still more measurements and efforts as well as LHC run 3 preparation on-going

stay tuned!

Thank you for your attention!

BACKUP