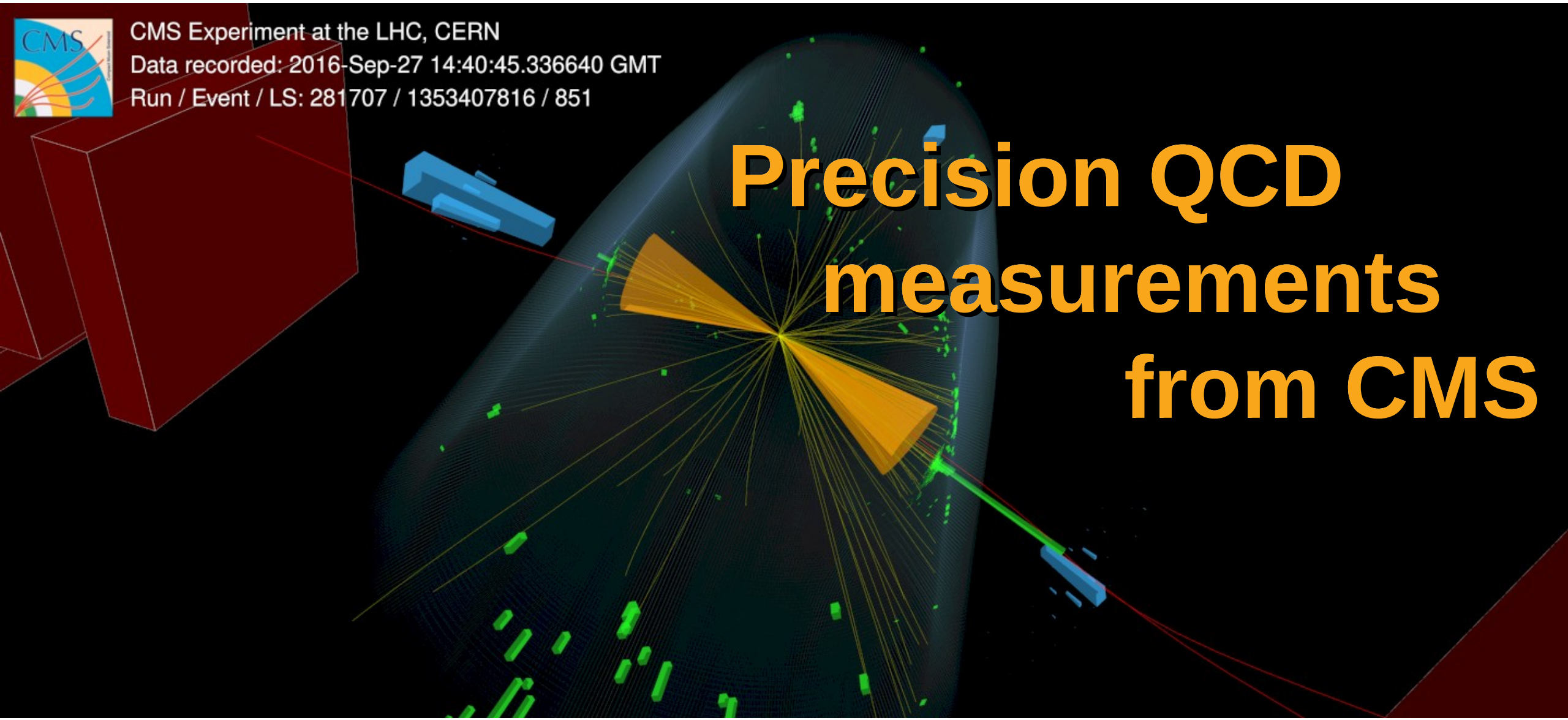


Precision QCD measurements from CMS

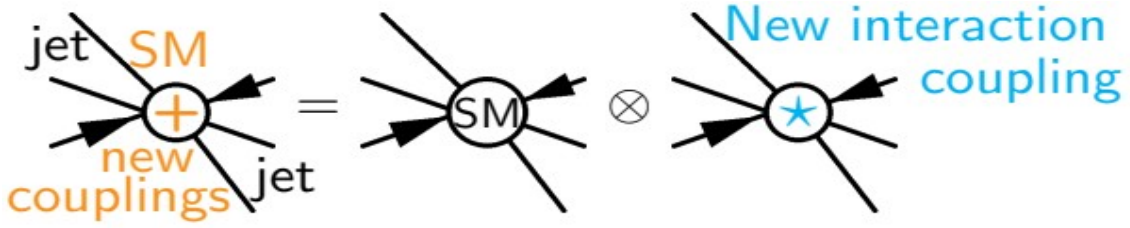
Toni Mäkelä for the CMS collaboration,
Low-x workshop, Elba, Italy
27. Sep. 2021

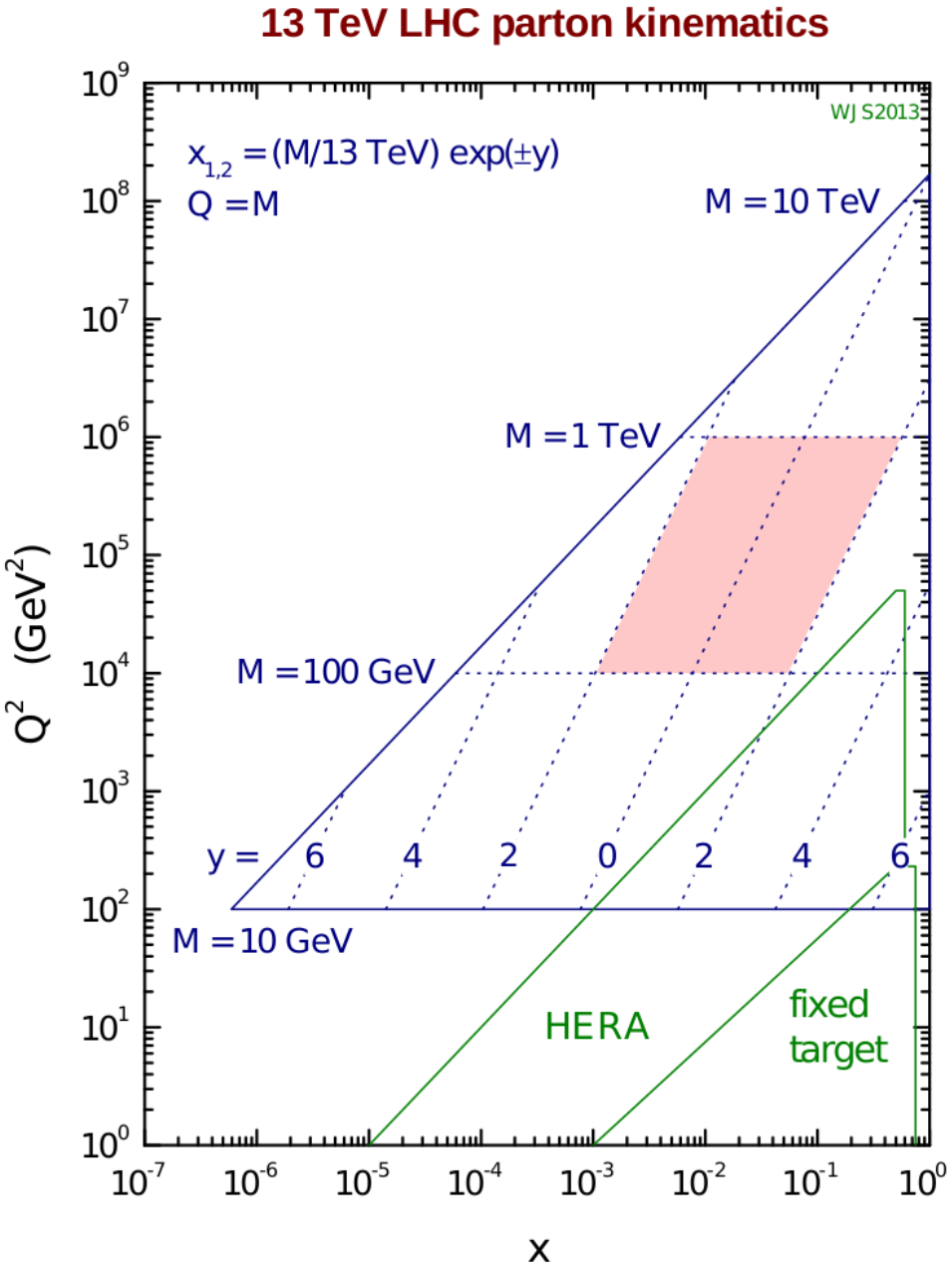
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Jets as a probe of QCD & new physics

- Jet production is the most fundamental process for studying QCD
- Improve the precision of proton structure studies
- Extract QCD parameters, e.g. strong coupling
- Perform indirect searches for physics beyond the standard model: high-p_T jets can probe the scale of new physics





Motivation: unbiased search for Contact Interactions (CI)

- Expect appearance of CI as deviations from the SM spectrum in jet cross-sections at low-y and high-p_T
- **The problem**: The SM prediction is based on PDFs and obtained from the same data

To ensure BSM effects are not absorbed into the PDFs, fit the PDFs simultaneously when using a SMEFT cross-section prediction.

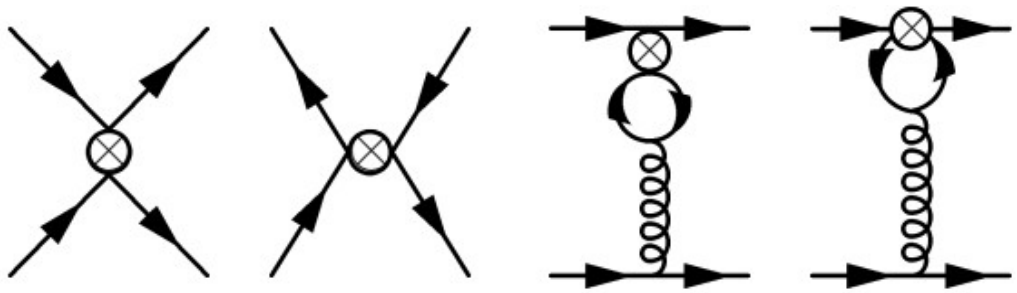
Determined experimentally!

$$\underbrace{\sigma_{pp\to+X}}_{\text{Experimental data}} = \sum_{ij} \underbrace{f_i(x_1,\mu_F)\, f_j(x_2,\mu_F)}_{\text{Proton structure}} \otimes \underbrace{\hat{\sigma}_{ij}\left(x_1, x_2, \alpha_s(\mu), \frac{Q^2}{\mu_R}, \frac{Q^2}{\mu_F}\right)}_{\text{SM or SMEFT}}$$

Operators involve products of quark lines with different handedness: *LL, LR, RR*

n= 1 3 5

- Possible models: quark compositeness, *Z*', extra dimensions



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

Type of CI	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

Analyses covered in this presentation

SMP-18-014 Precision measurement of the Z invisible width

SMP-21-009 Inclusive jet production at 5 TeV

SMP-21-006 13 TeV multijet production

SMP-20-011 Inclusive jet production at 13 TeV

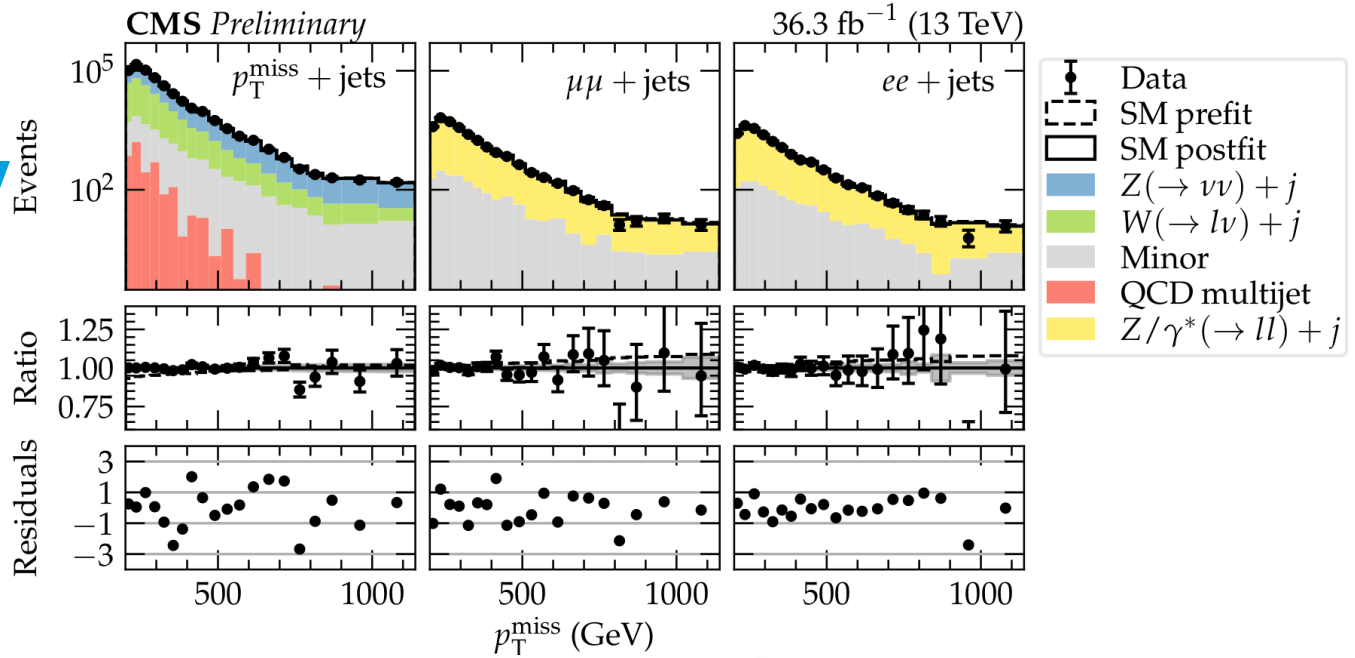
Also featuring 13 TeV triple-differential $t\bar{t}$ cross-section measurement data

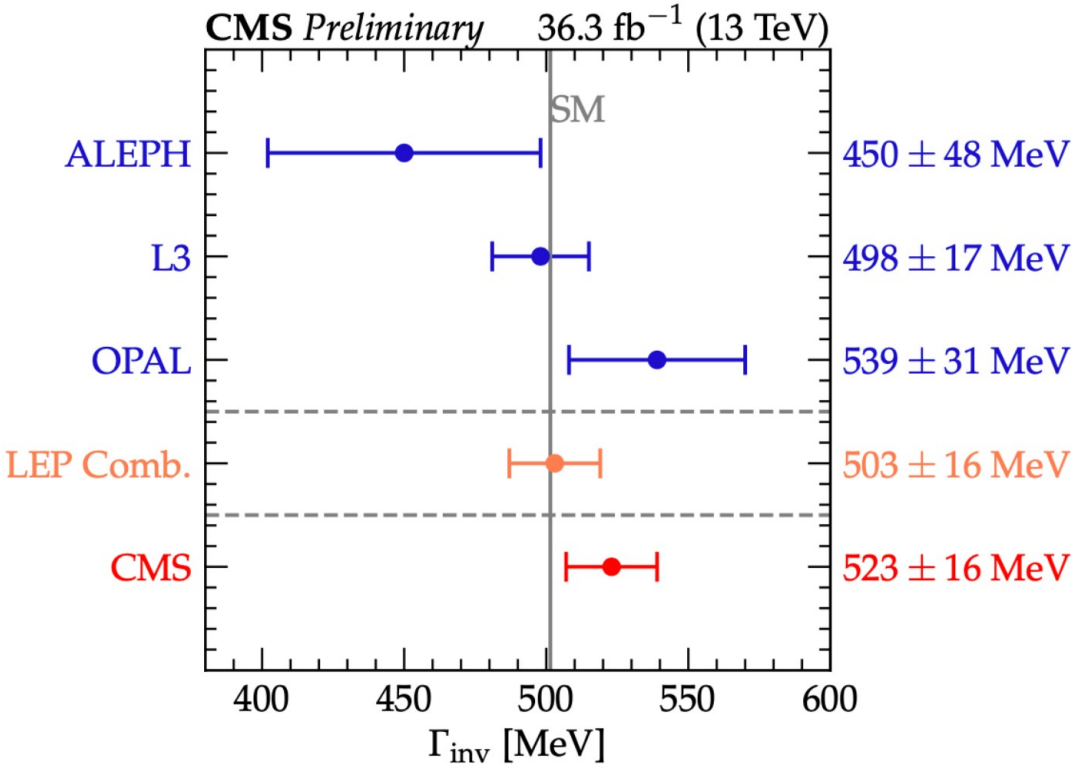
Precision measurement of the Z Invisible width at 13 TeV

SMP-18-014

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z + \text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z + \text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

- Instead of generic jets+MET dark matter search approaches, measure Z invisible measurement precisely
- First direct measurement of Z invisible width with CMS
- Simultaneous fit to jets+MET, $\ell\ell$+jets & ℓ+jets
- Transfer factor estimating W+jets background is an unconstrained parameter in jets+MET and ℓ+jets



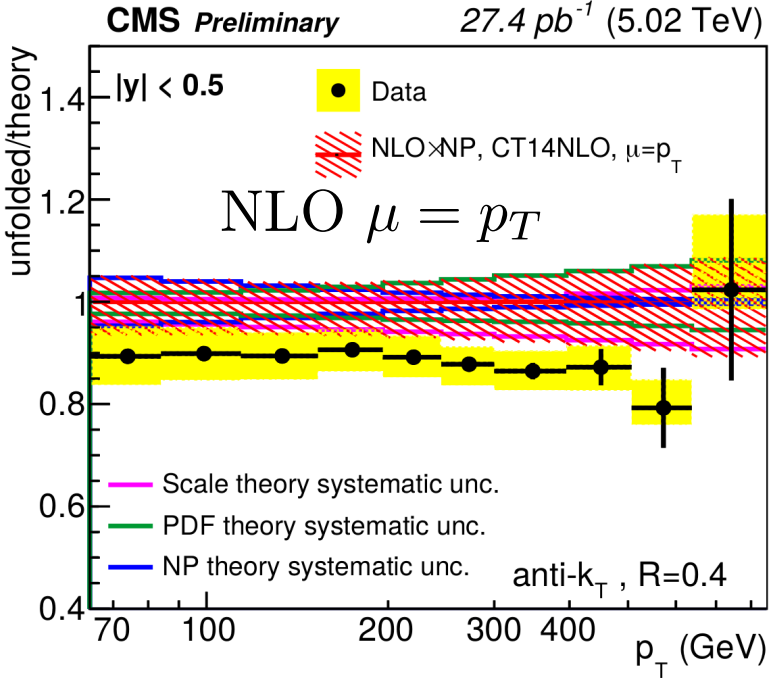


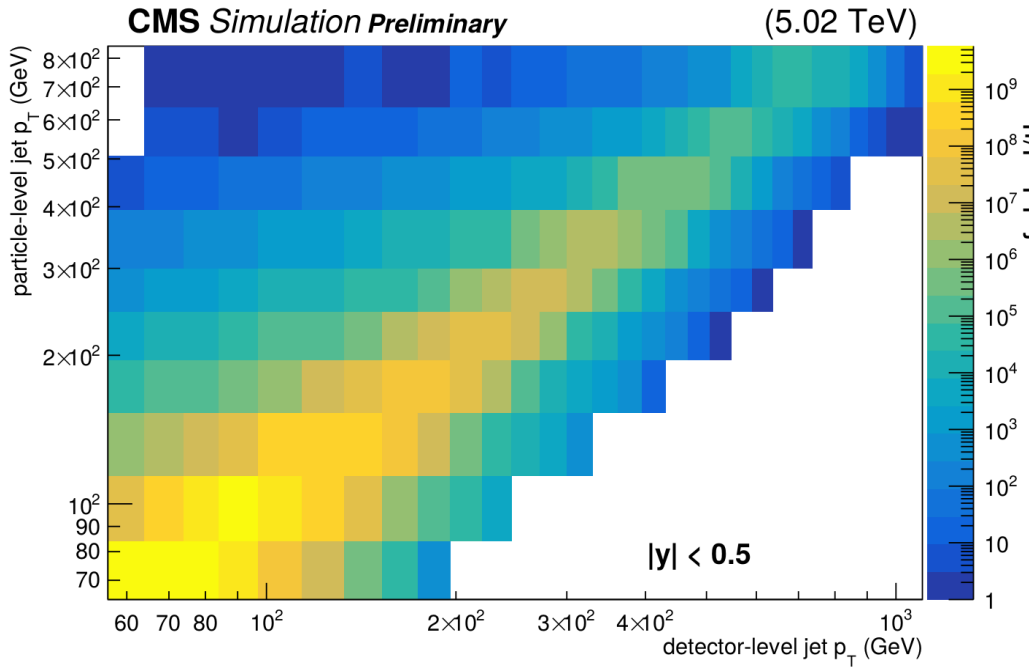
5 TeV inclusive jets

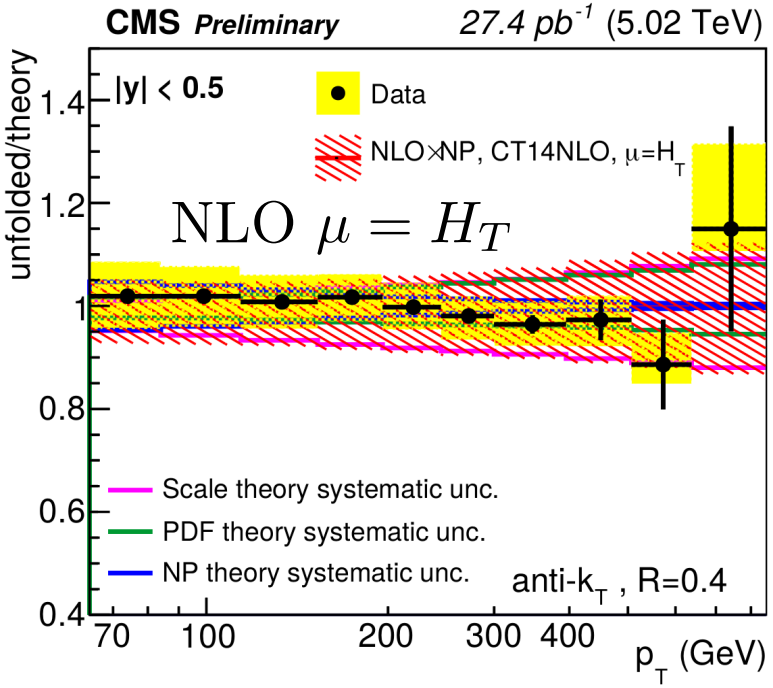
SMP-21-009

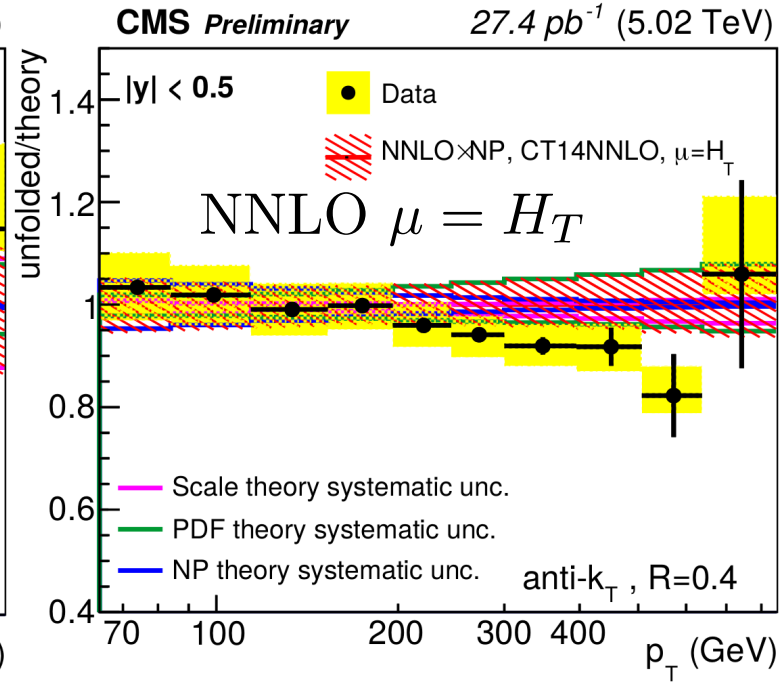
- Low pile-up data, 1D unfolding
- Phase space $p_T > 64\ \mathrm{GeV},\ |y| < 2.0$
- Comparison to (N)NLO with NNLOJET [1, 2, 3]
- Comparison of QCD scale choices
- Various PDF set comparisons also available

Good description of data by NLO with the scale $\mu = H_T$ and NNLO





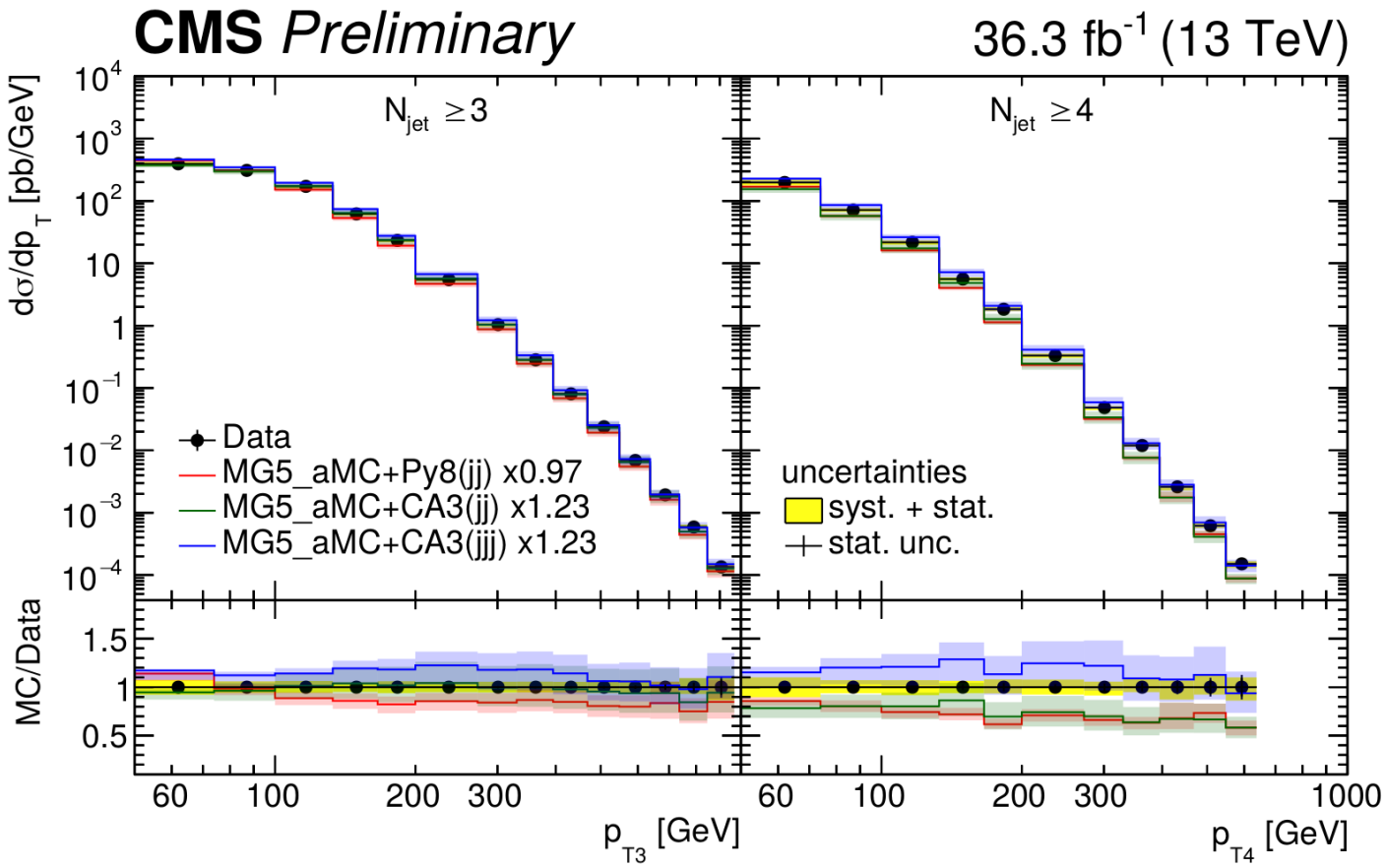


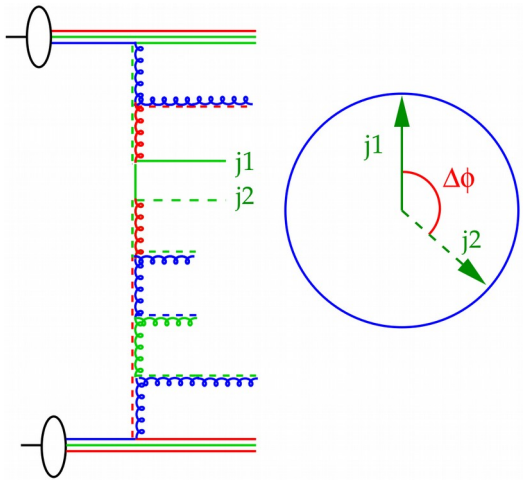


13 TeV multijet production

SMP-21-006

- Single-jet pT spectra in 2-, 3- and 4-jet configurations
- Test of QCD in high pT and high jet multiplicity regions.
- Parton branching transverse momentum dependent parton densities and initial state parton shower are compared to the measurements.





- Good description of data by NLO generators, particularly MadGraph5_aMC@NLO [4] with transverse momentum dependent PDFs [5, 6].

13 TeV inclusive jets

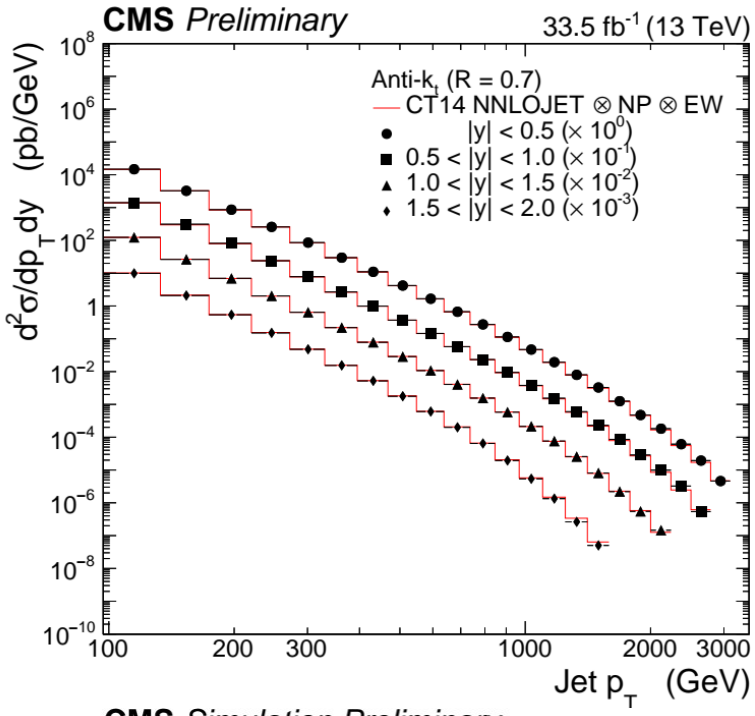
SMP-20-011

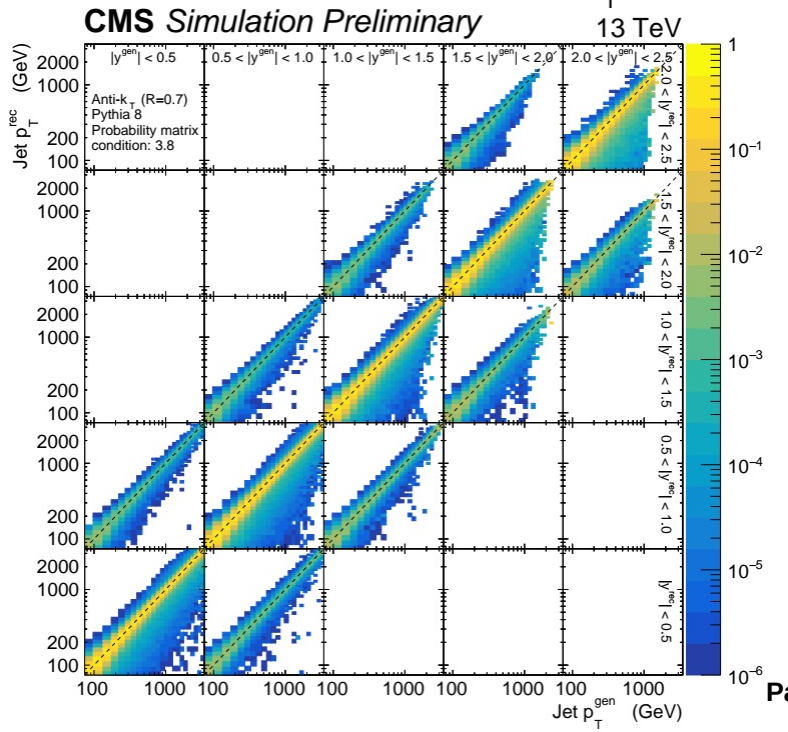
Goal: data interpretation with simultaneous extraction of PDFs, α_s, m_t and contact interaction Wilson coefficient

- 2D unfolding with least-square minimization

  (previously 1D and D'Agostini heavily used)

- Bin-to-bin uncertainties should be smooth
  - Tests of smoothness with Chebyshev polynomials

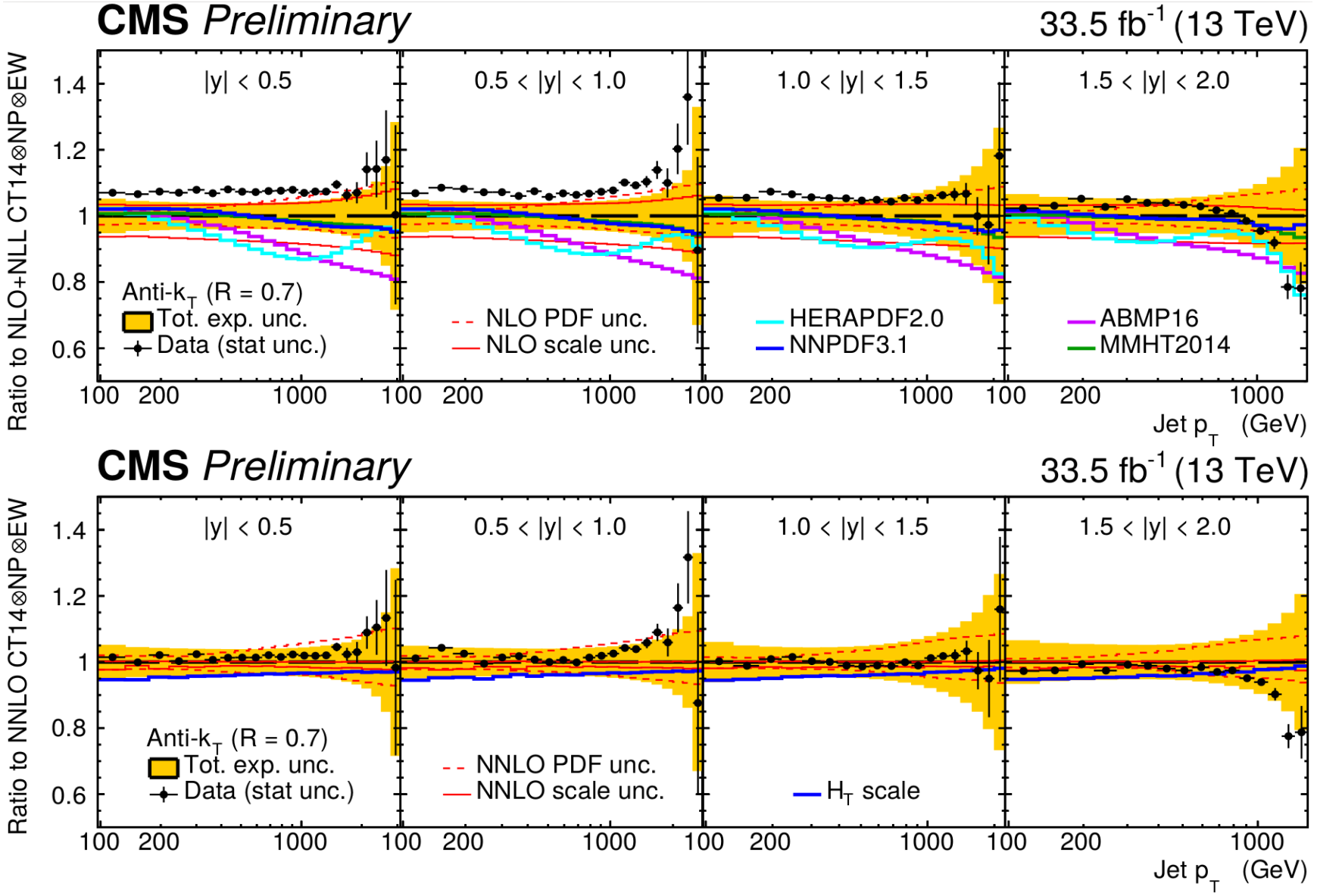




13 TeV inclusive jets: results

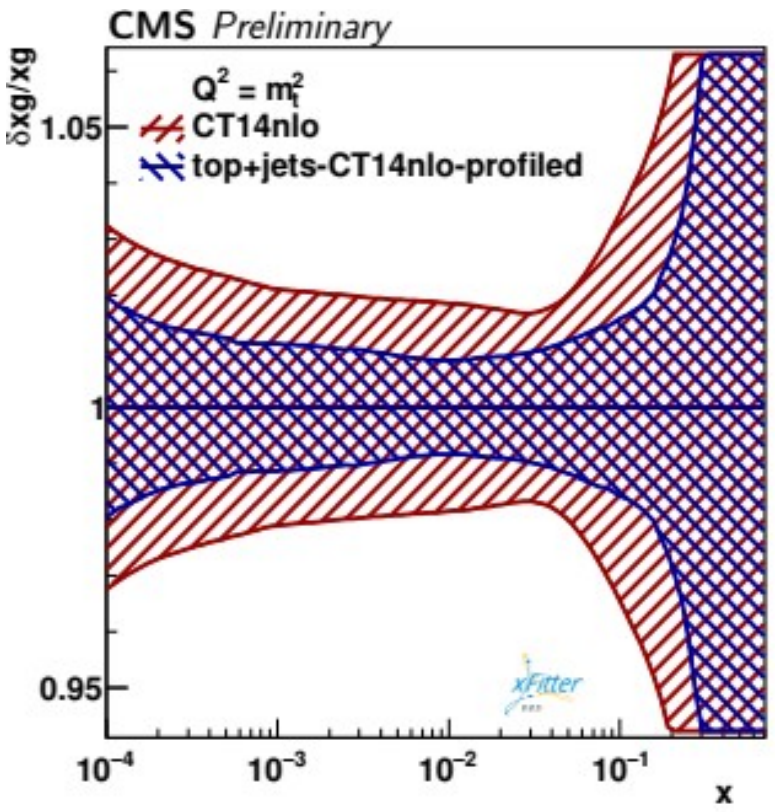
SMP-20-011

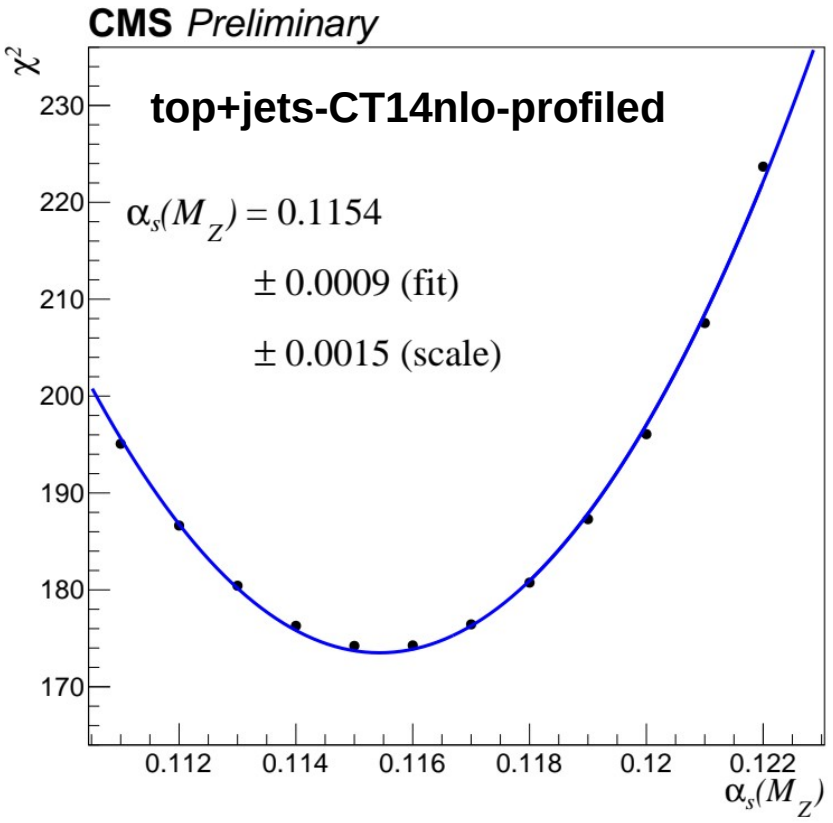
- Cross-section comparison with various global PDFs
- NLO+NLL and NNLO, obtained with *k*-factor technique
- In particular the scale uncertainty is reduced with NNLO



PDF profiling: data's impact on global PDFs

SMP-20-011





Datasets utilized for 13 TeV QCD analysis (SMP-20-011)

CMS 13 TeV inclusive jet cross section SMP-20-011

HERA inclusive Deep Inelastic Scattering
Eur. Phys. J. C75 (2015), no. 12, 580, doi:10.1140/epjc/s10052-015-3710-4

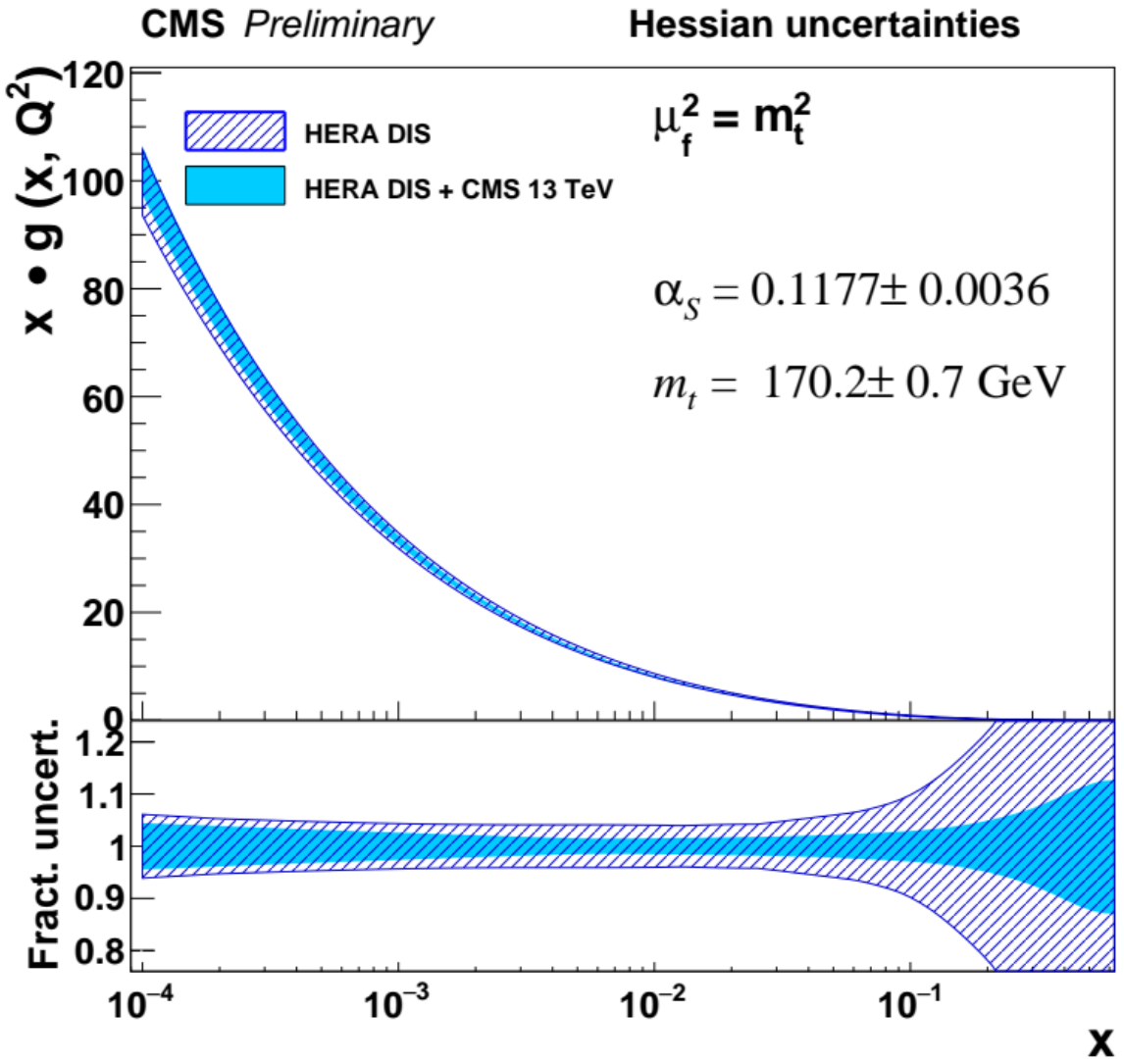
CMS 13 TeV triple-differential $t\bar{t}$ cross-section
Eur. Phys. J. C 80 (2020), no. 7, 658, doi:10.1140/epjc/s10052-020-7917-7

- Significant improvement in gluon PDF precision
- Profiled $m_t = 170.3 \pm 0.5 \pm 0.2$ GeV consistent with previous CMS results [arXiv:1904.05237]

SM QCD analysis at NLO

SMP-20-011

- Comparison of the resulting PDF parameterisation in fits to HERA+CMS and HERA data only indicates the improvement in gluon PDF precision arising from CMS data
- Fitted strong coupling and top mass values are in agreement with world averages and previous results
- Results are obtained using the xFitter QCD analysis framework: *https://www.xfitter.org/xFitter*



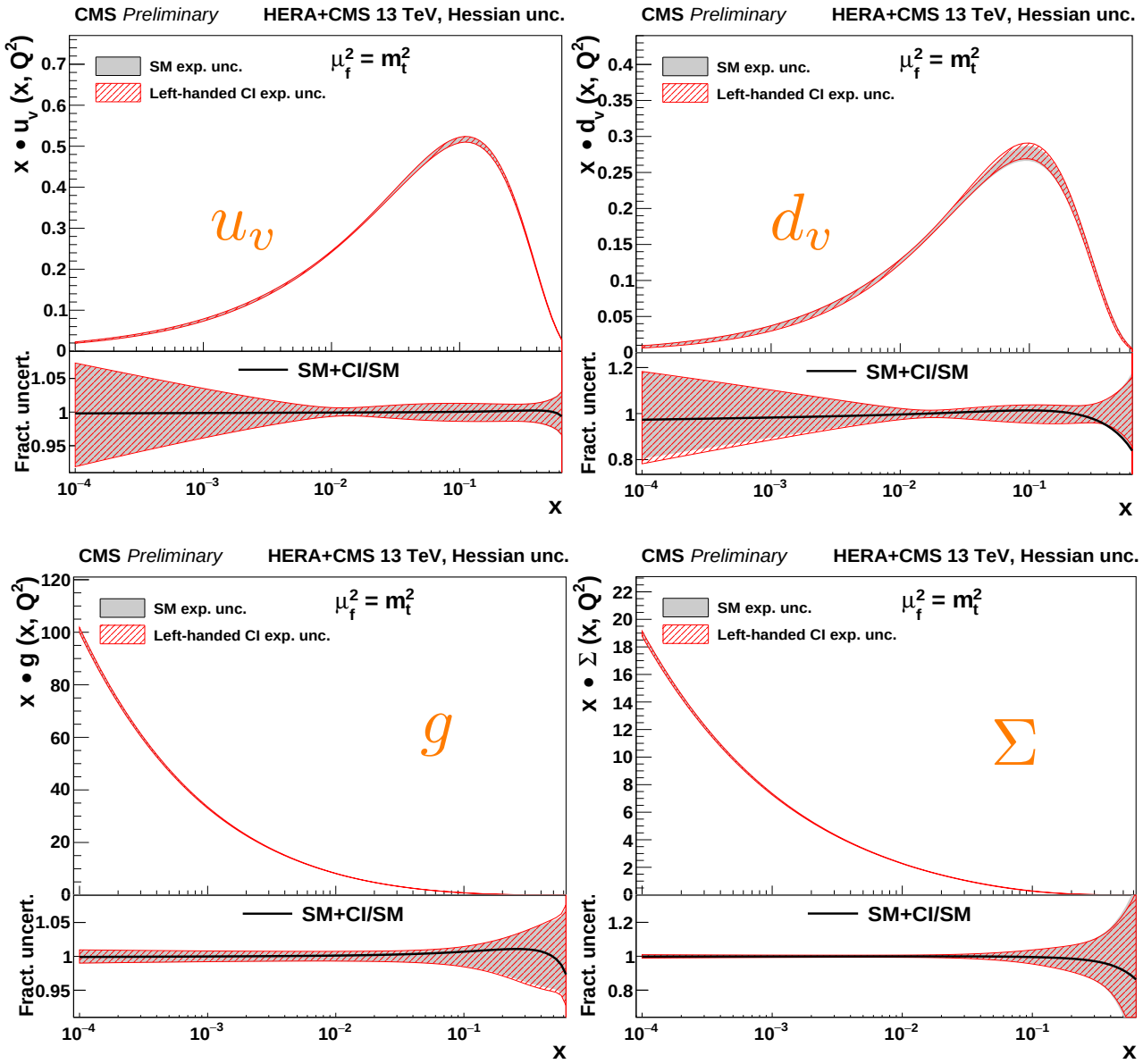
SMEFT QCD analysis at NLO

SMP-20-011

- The fits are performed using SM, or alternatively, SM+CI theory predictions
- The PDFs from SM and SMEFT fits agree, differences within fit uncertainties
- All CI models result in very similar PDFs, strong coupling and top mass values

No risk of absorbing BSM effects in the SM PDF fit is observed

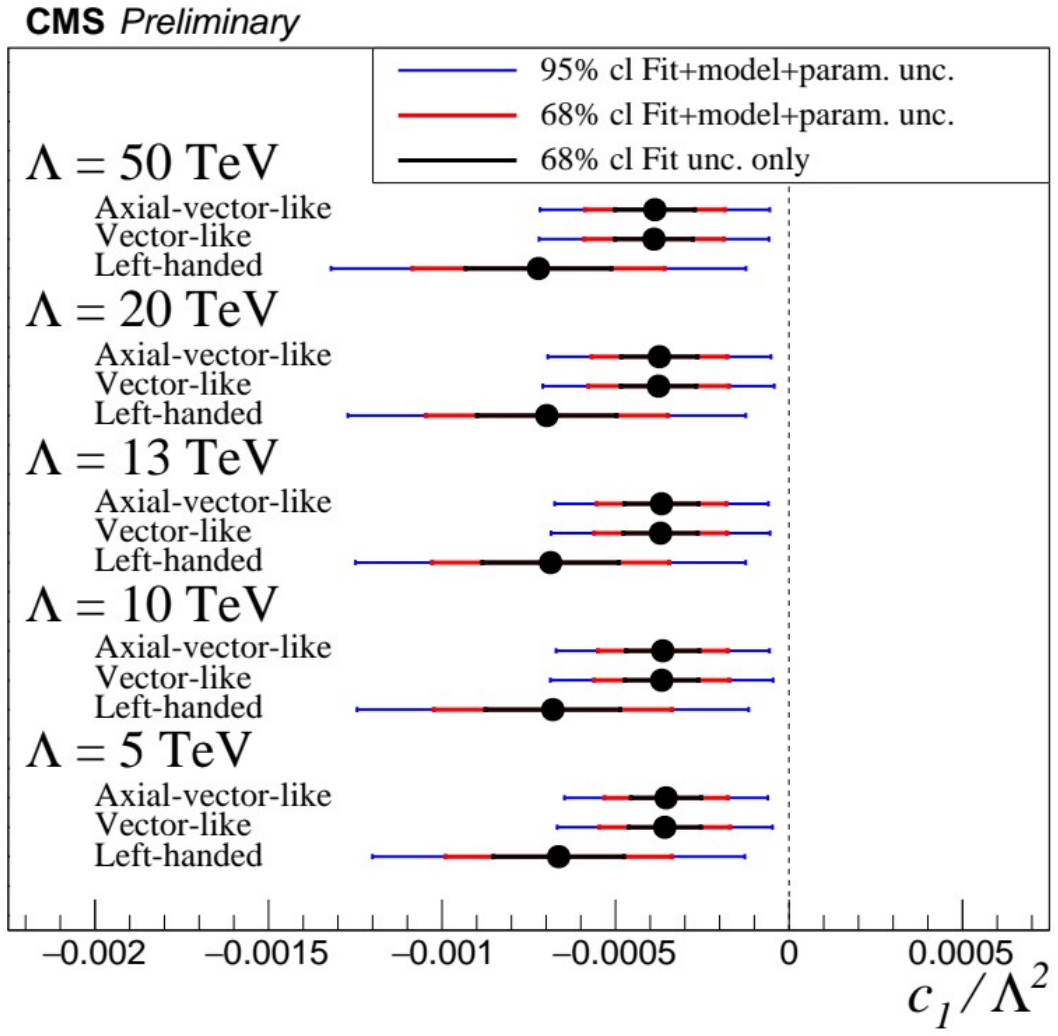
No statistically significant deviation from the SM observed



Translating the results into exclusion limits

SMP-20-011

- Conventional studies scan for Λ with fixed $c_1 = \pm 1$ for constructive (-) or destructive (+) interference with SM gluon exchange
- This is the first time the Wilson coefficient for *4-quark CI* is fitted together with the PDFs using LHC data (previously electron-quark CI at HERA [7])
- All CI fits result in negative c_1. These can be translated into ***unbiased*** exclusion limits for constructive interference for comparison



Translating the results into exclusion limits

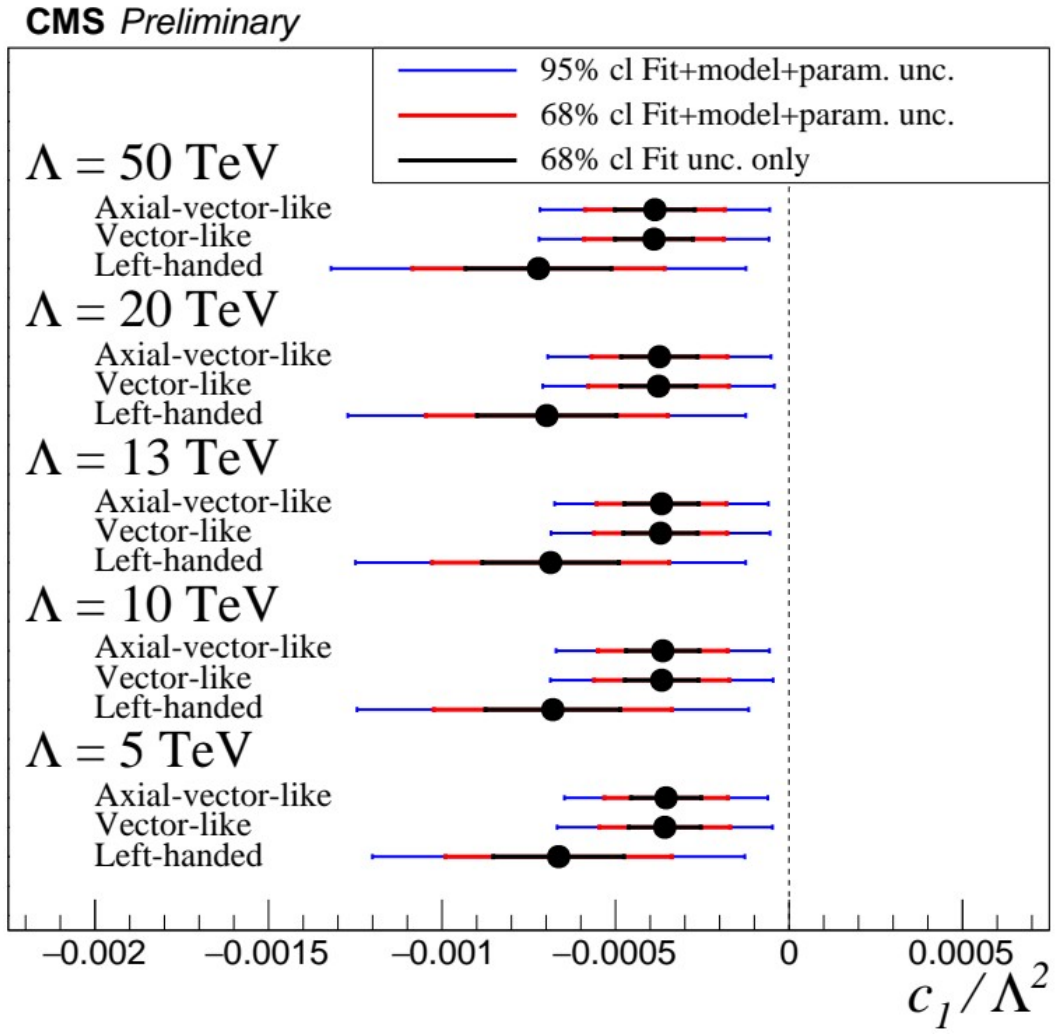
SMP-20-011

95% CL on Λ with $c_1 = -1$

Left-Handed	24 TeV
Vector-like	32 TeV
Axial-vector-like	31 TeV

Most stringent comparable result
from ATLAS 13 TeV dijet cross-sections:
22 TeV for left-handed CI [arXiv:1703.09127]

- All CI fits result in negative c_1. These can be translated into ***unbiased*** exclusion limits for constructive interference for comparison



Summary

- Reported recent precision measurements involving jet production at 13 TeV and 5 TeV
- The results are in agreement with previous results and world averages
- Data are well described by the SM, no significant deviation observed
- QCD analysis performed using $R = 0.7$ jet and $t\bar{t}$ cross section measurements at $\sqrt{s} = 13$ TeV, probing partons at $10^{-3} < x < 0.5$
  - The data's impact on a global PDF set is examined in PDF profiling
  - SMEFT fit performed at NLO with simultaneous extraction of PDFs, α_S, m_t and CI Wilson coefficient c_1, ensuring non-biased CI search

Thanks for your attention!

References

[1] J. Currie et al. “Next-to-Next-to Leading Order QCD Predictions for Single Jet Inclusive Production at the LHC” *Phys. Rev. Lett.* 118 (2017), p. 072002. DOI: 10.1103/PhysRevLett.118.072002

[2] J. Currie et al. “Single Jet Inclusive Production for the Individual Jet pT Scale Choice” *Acta Phys. Polon. B* 48 (2017), p. 955. DOI: 10.5506/AphysPolB.48.955

[3] T. Gehrmann et al. “Jet cross sections and transverse momentum distributions with NNLOJET” *PoS* RADCOR2017 (2018), p. 074. DOI: 10.22323/1.290.0074

[4] J. Alwall et al. “The Automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations” *JHEP* 07 (2014), p. 079. DOI: 10.1007/JHEP07(2014)079

[5] A. Bermudez Martinez et al. “Collinear and TMD parton densities from fits to precision DIS measurements in the parton branching method” *Physical Review D* 99.7 (2019), p. 074008

[6] S. Baranov et al. “CASCADE 3 A Monte Carlo event generator based on TMDs” *Eur. Phys. J.* C 81 (2021), p. 425. DOI: 10.1140/epjc/s10052-021-09203-8

[7] ZEUS collaboration “Limits on contact interactions and leptoquarks at HERA” *Phys. Rev. D* 99, 092006 (2019)