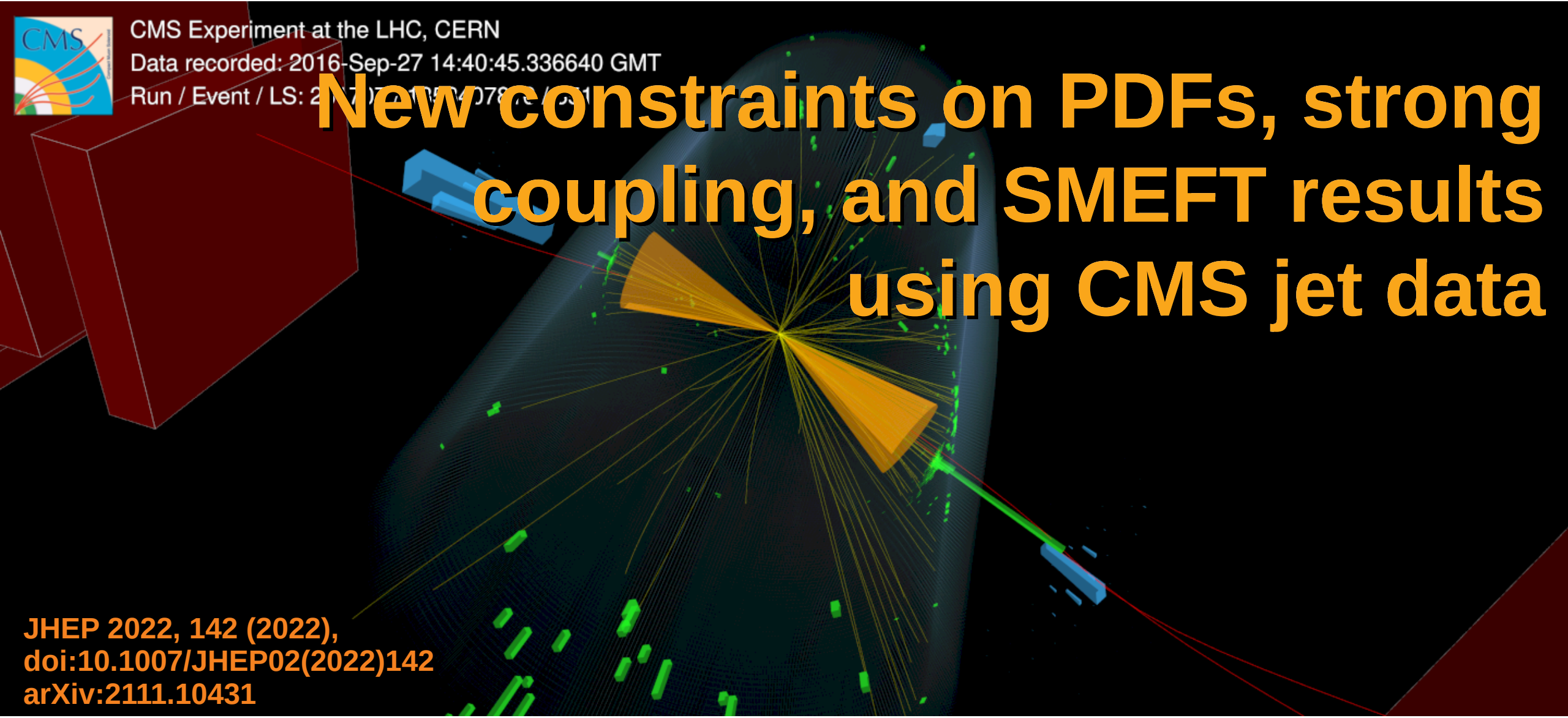


New constraints on PDFs, strong coupling, and SMEFT results using CMS jet data

JHEP 2022, 142 (2022),
doi:10.1007/JHEP02(2022)142
arXiv:2111.10431

Toni Mäkelä, Katerina Lipka for the CMS Collaboration

DIS2022: XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects

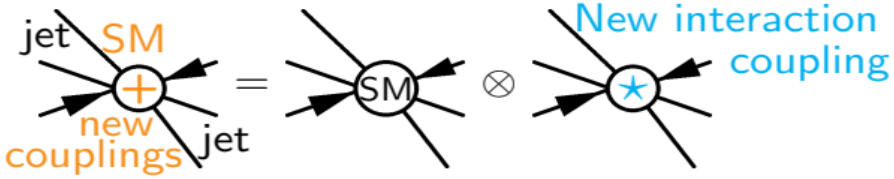
May 4, 2022

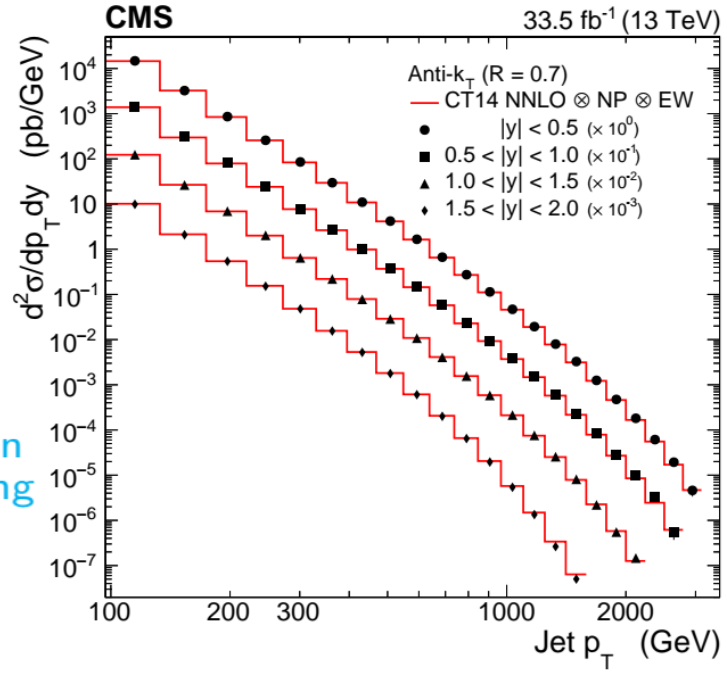
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

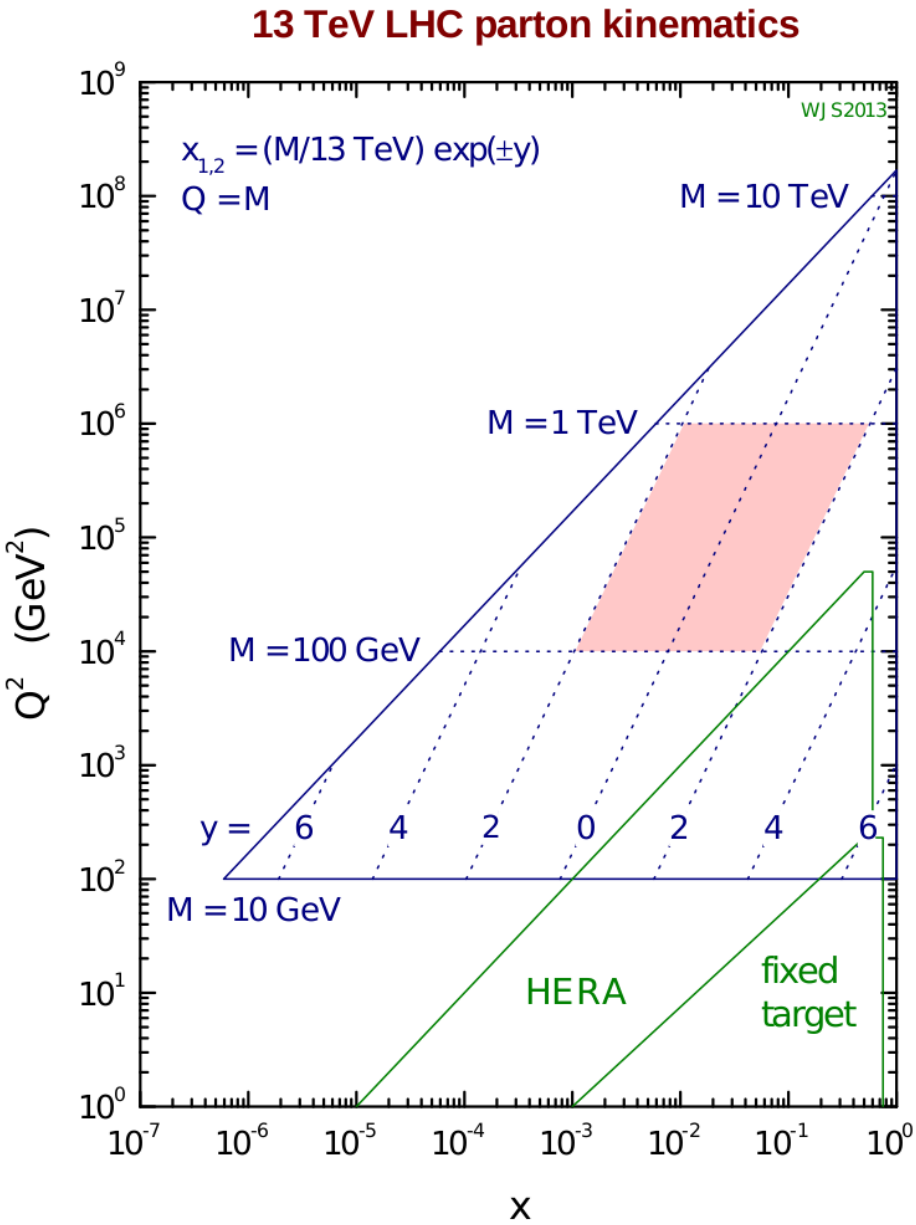
DESY.

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







Datasets utilized in the QCD analysis

CMS 13 TeV inclusive jet cross section, $R = 0.7$

Simultaneously explore the sensitivity to PDFs, α_s and new physics

Improvement of the (gluon) PDF precision at high x

(JHEP 2022, 142 (2022), doi:10.1007/JHEP02(2022)142)

HERA inclusive Deep Inelastic Scattering in $e^{\pm}p$ (Neutral and Charged Current cross-sections)

Major constraints on the quark distributions in the proton

(EPJC 75 (2015), no. 12, 580, doi:10.1140/epjc/s10052-015-3710-4)

CMS 13 TeV triple-differential $t\bar{t}$ cross-section

Examine the compatibility of jet and top data

Additional sensitivity to m_t and constraints on $g(x)$ at high x and α_s, orthogonal to the jet data.

(EPJC 80 (2020), no. 7, 658, doi:10.1140/epjc/s10052-020-7917-7, arXiv:1904.05237)

Results are obtained using the xFitter QCD analysis platform: *https://www.xfitter.org/xFitter*

Theoretical predictions

- **13 TeV inclusive jet cross sections (NLO)**

  FastNLO QCD prediction at NLO [arXiv:1208.3641]

  NLO+NLL resummation computed using NLLjet [arXiv:1801.07284] and MEKS [arXiv:1207.0513]

  Corrections for Electro-Weak and Non-Perturbative effects are included

  Contact Interactions (CI) for the SMEFT fits computed with CIJET [arXiv:1204.4773, arXiv:1301.7263]

  By default, QCD scales set to individual jet transverse momentum

- **13 TeV triple-differential $t\bar{t}$ cross-section**

  Predictions available at NLO

  Over final state partons

  The QCD scales are set to $\frac{1}{2}\sum_i \sqrt{m_i^2 + p_{T,i}^2}$

  Described in detail in [arXiv:1904.05237]

Theoretical predictions

- **13 TeV inclusive jet cross sections (NNLO)**

  Fixed-order pQCD predictions used for computing *k*-factors: $$k = \frac{\sigma^{\mathrm{NNLO}}}{\sigma^{\mathrm{NLO}}}$$

  - NLOJet++ [arXiv:hep-ph/0110315, arXiv:hep-ph/0307268]
  - NNLOJET (rev5918) [arXiv:1611.01460, arXiv:1807.03692, arXiv:1801.06415]
  - NLO implemented in FastNLO [arXiv:1208.3641]

  k-factors obtained with the CT14nnlo PDF

  - PDF uncertainty is small, accounted for as a systematic uncertainty

  k-factors obtained for each combination of the scales: (μ_r, μ_f $\times$ 2 or ½, excluding $\mu_r/\mu_f = 4^{\pm 1}$)

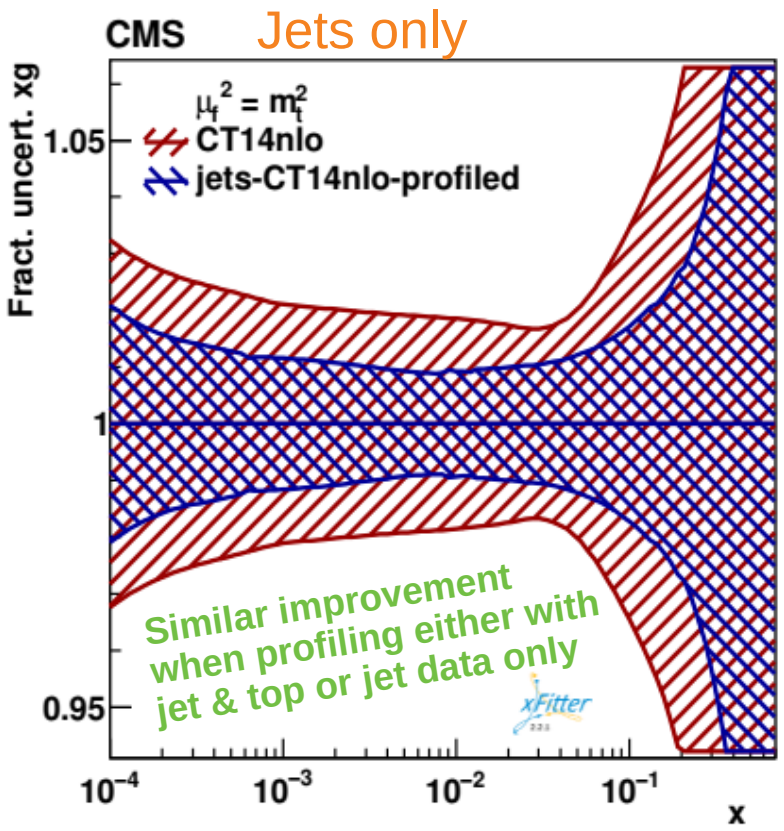
  - the PDF and α_S uncertainty in *k*-factor negligible with respect to the result of scale variations, all taken into account in the fit

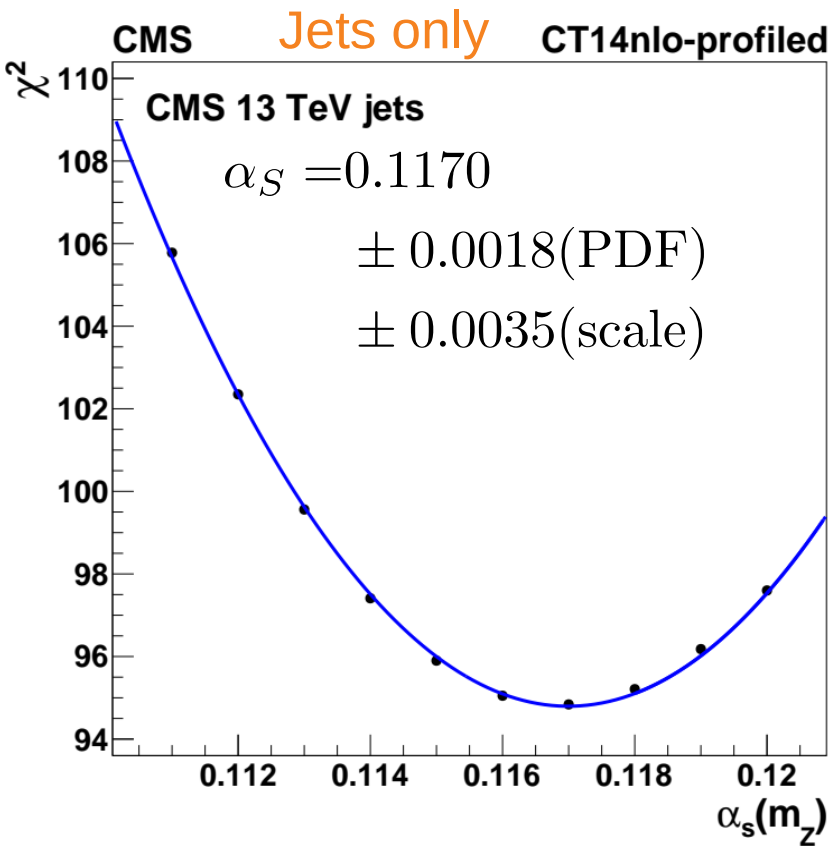
PDF profiling

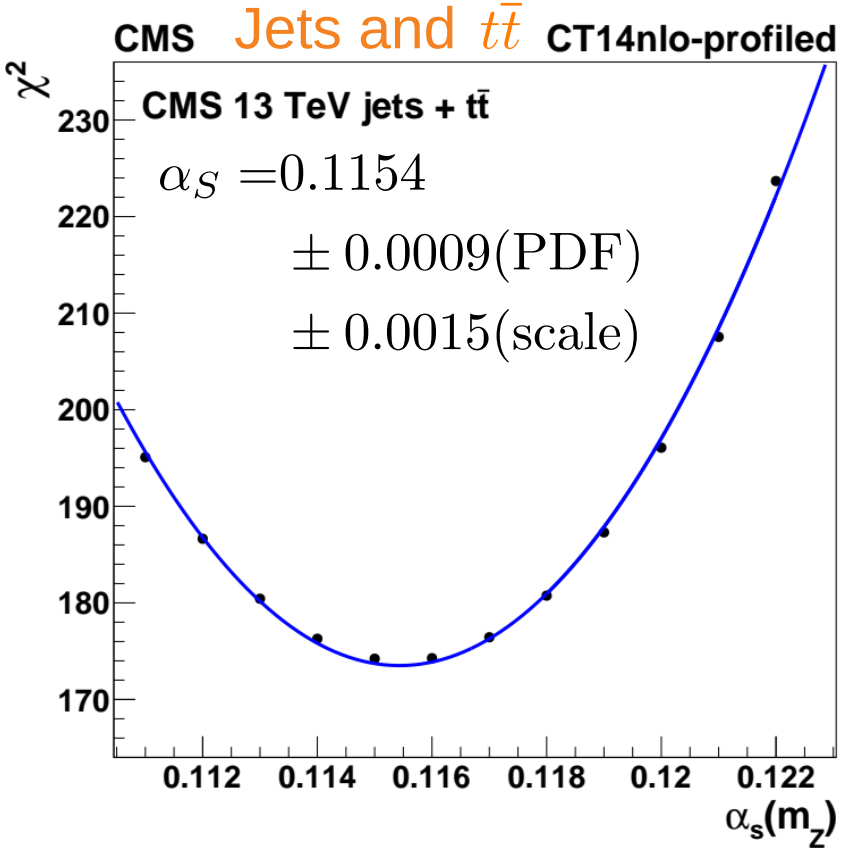
Assessing the impact of new data on a global PDF set

- In the profiling procedure, the correlated theoretical and experimental uncertainties are included via nuisance parameters, allowing slight adjustments to the PDF
  - Not a full PDF fit, but a quick way to estimate the impact of the data using available PDF set
- Both PDF and non-PDF parameters, such as $\alpha_S(m_Z)$ and m_t, can be profiled, but not simultaneously due to technical limitations
  - **Simultaneous extraction requires a full fit**
- The CT14 PDF is used (at NLO and NNLO) since it does not include 13 TeV jet or top quark-antiquark pair production data
- The included uncertainties are the PDF and QCD scale uncertainty, arising from varying the scales independently up and down by factors of 2, excluding the cases with extreme difference, and finding the maximal envelope

PDF profiling: the impact of CMS jet and top data on CT14nlo







- Significant improvement in gluon PDF precision
- Profiled $m_t = 170.3 \pm \underset{\text{(PDF)}}{0.5} \pm \underset{\text{(scale)}}{0.2}\ \mathrm{GeV}$ consistent with previous CMS results [arXiv:1904.05237]

Full QCD/SMEFT fits: parameterisations

Following the HERAPDF2.0 approach

Parameters introduced 1-by-1 in parametrization scan

- NNLO fit includes HERA and CMS 13 TeV jet data, NLO fit also includes CMS 13 TeV ttbar data
  - Dedicated parametrizations for **NLO** and **NNLO** analyses, since different data sets used

Assumed relations

$x\overline{U}(x) = x\overline{u}(x)$ and $x\overline{D}(x) = x\overline{d}(x) + x\overline{s}(x)$, with $x\overline{u}(x)$, $x\overline{d}(x)$ and $x\overline{s}(x)$ for up, down and strange antiquarks.

$B_{\overline{U}} = B_{\overline{D}}$ and $A_{\overline{U}} = A_{\overline{D}}(1 - f_s)$, with the strangeness fraction $f_s = x\overline{s}/(x\overline{d} + x\overline{s}) = 0.4$

NLO $Q_0^2 = 1.9\ \mathrm{GeV}^2$

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

NNLO $Q_0^2 = 1.9\ \mathrm{GeV}^2$

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1 + D_g x + E_g x^2),$$
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$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}(1 + D_{\overline{U}} x),$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}(1 + E_{\overline{D}} x^2).$$

Contributions included in reported total uncertainties

Experimental uncertainties

- Contribute to the Hessian fit uncertainty (cross checked with MC uncertainty)

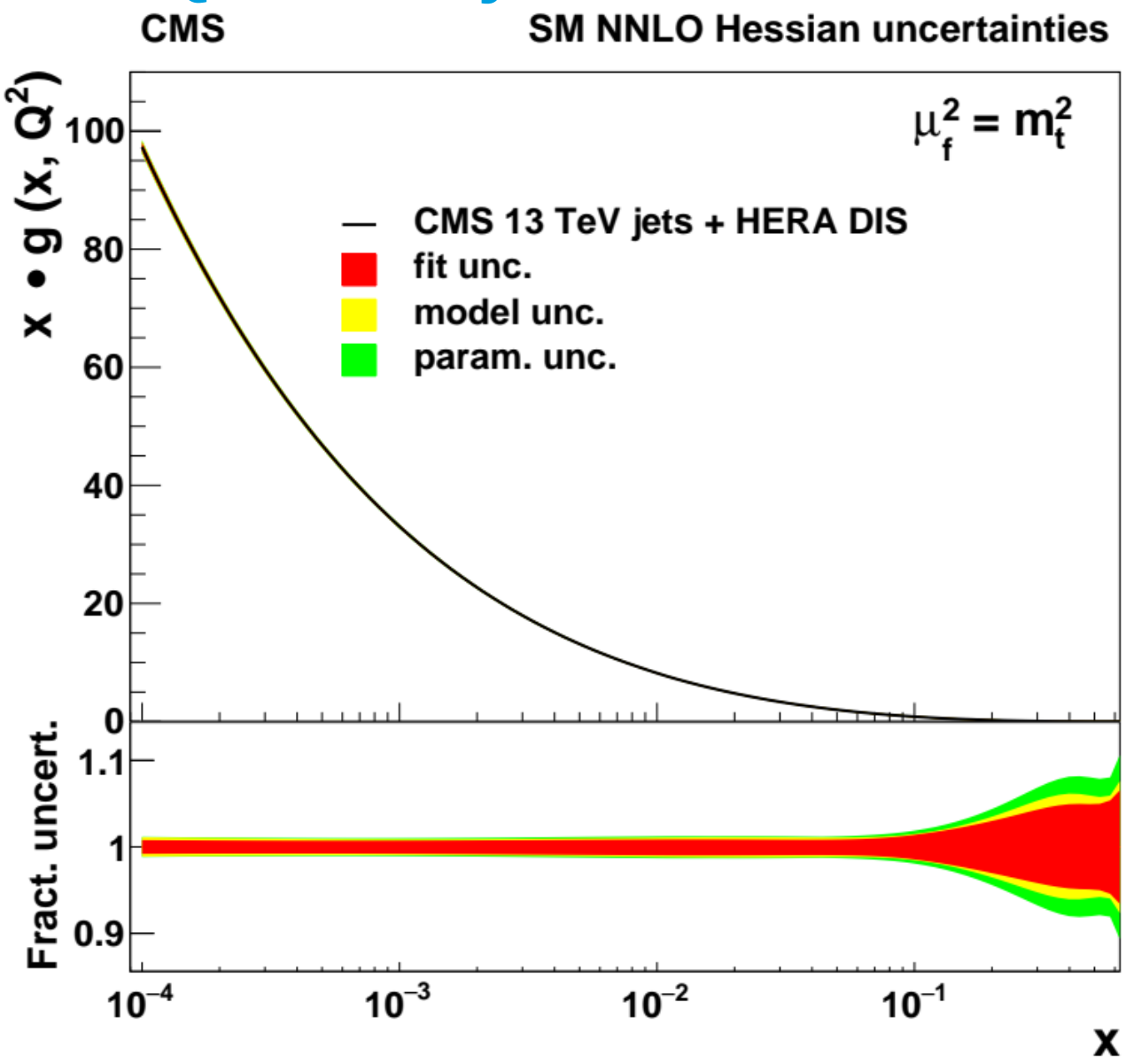
Parameterisation uncertainties

- Add and remove new parameters to the PDF parameterisation one at a time.

Model uncertainties

- Fixed parameters varied within their uncertainties: $1.41 \leq m_c \leq 1.53\ \mathrm{GeV}$, $4.25 \leq m_b \leq 4.75\ \mathrm{GeV}$, strangeness fraction $0.32 \leq f_s \leq 0.48$, evolution starting scale $1.7 \leq Q_0^2 \leq 2.1\ \mathrm{GeV}^2$, minimum Q^2 imposed on the HERA data $5.0 \leq Q^2_{\mathrm{min}} \leq 10.0\ \mathrm{GeV}^2$
- Scale uncertainty is taken as an envelope of 6 variations of the QCD scales. The envelope is then treated as a model uncertainty (if not specified)

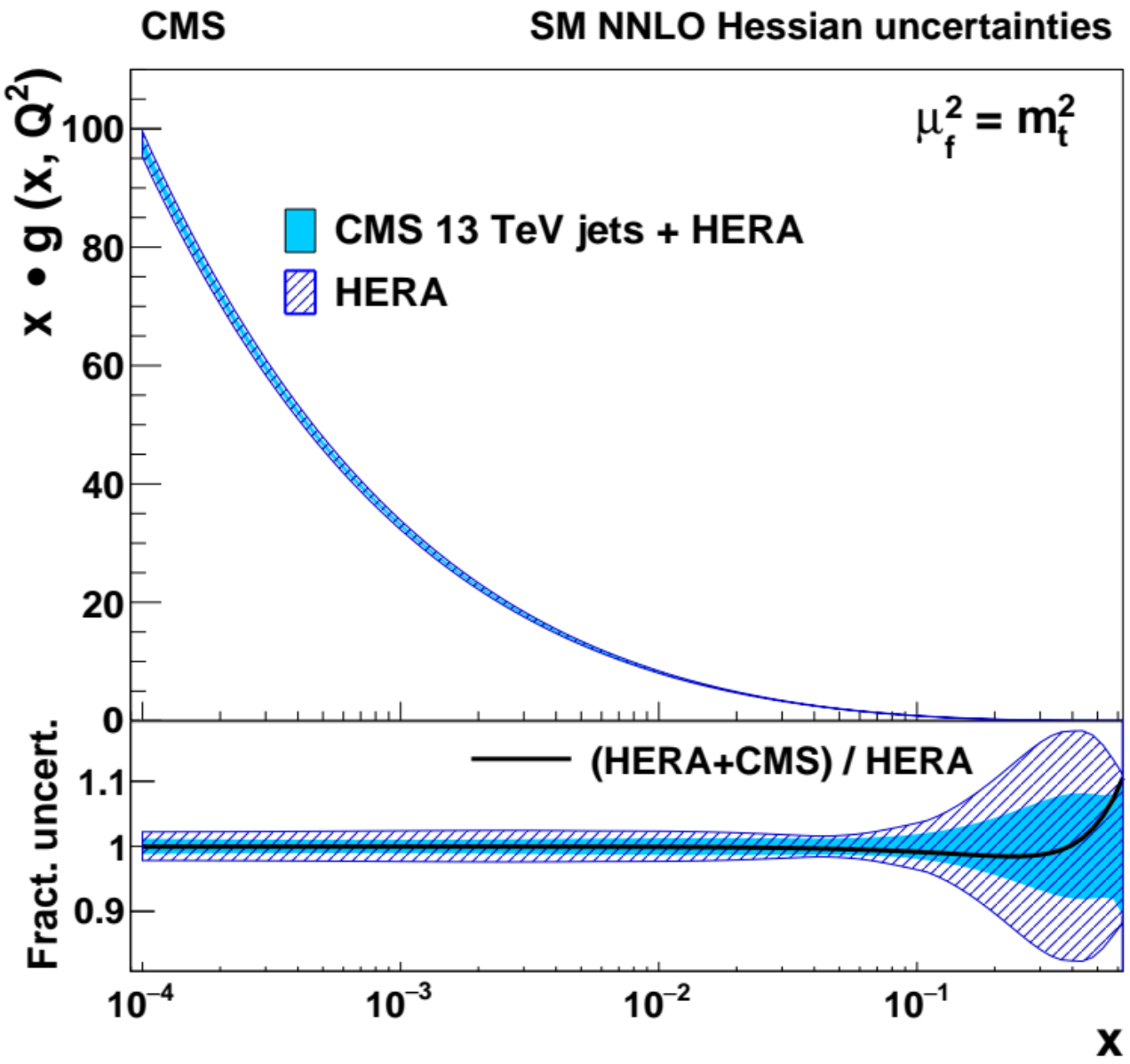
SM QCD analysis at NNLO



- Experimental (Hessian fit) uncertainties dominate
- No large *scale uncertainty* contributions in model uncertainty, as opposed to previous NLO studies

NB: The triple-differential $t\bar{t}$ cross-section prediction available only at NLO ➞ No top data in NNLO fit

SM QCD analysis at NNLO



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- Adding jet data on top of HERA DIS leads to significant improvement in PDF precision

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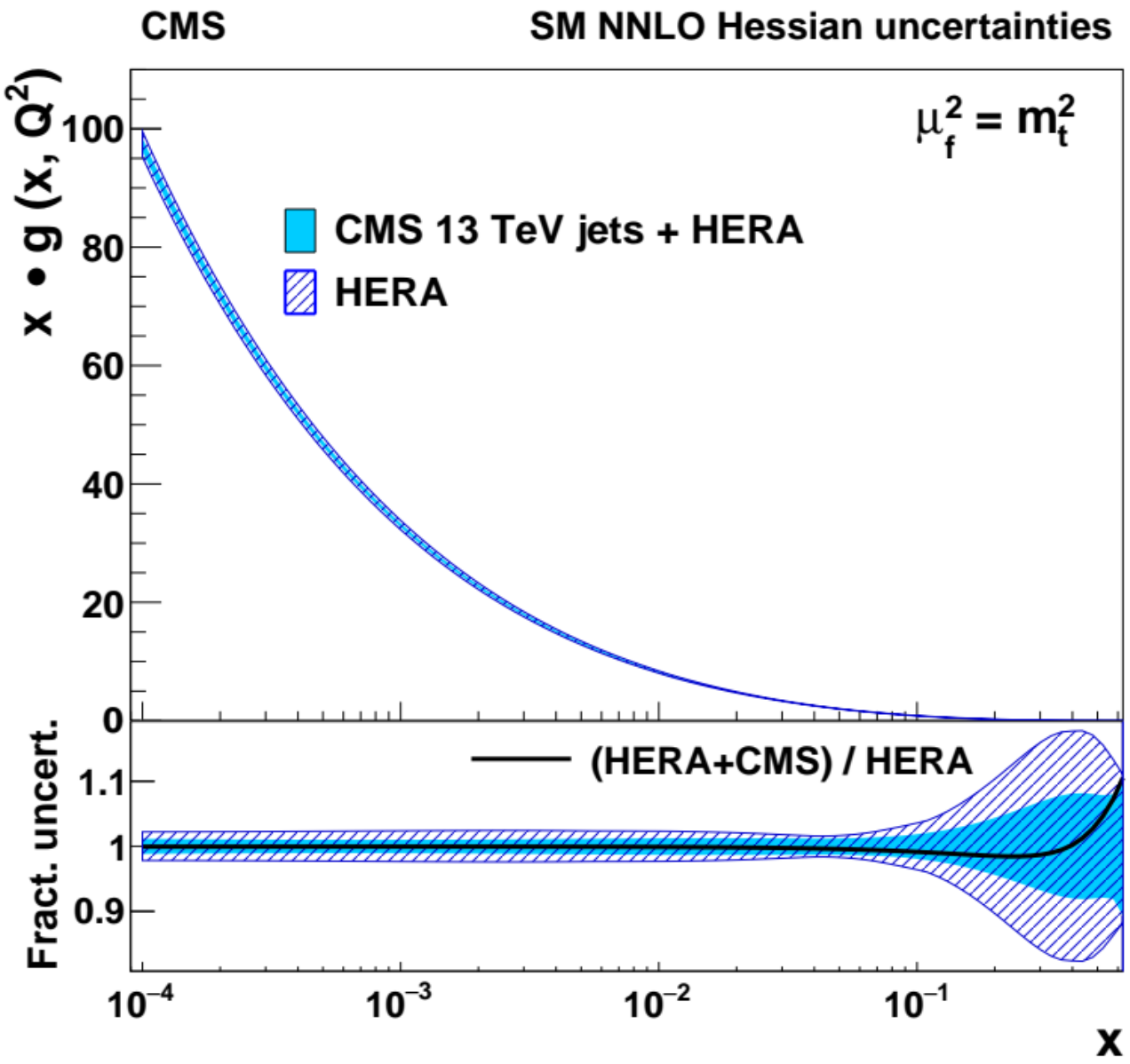
SM QCD analysis at NNLO



- Experimental (Hessian fit) uncertainties dominate
- No large *scale uncertainty* contributions in model uncertainty, as opposed to previous NLO studies
- Adding jet data on top of HERA DIS leads to significant improvement in PDF precision
- α_S extracted simultaneously with the PDFs:

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

Most precise NNLO value from hadron collisions to date!

NB: The triple-differential $t\bar{t}$ cross-section prediction available only at NLO ➞ No top data in NNLO fit

Unbiased search for Contact Interactions (CI)

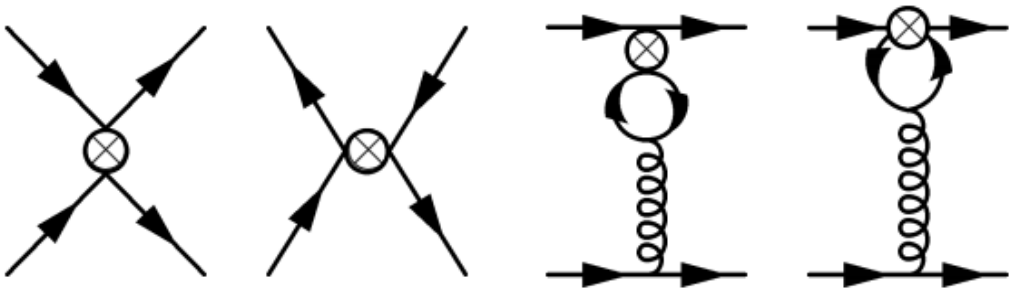
SMEFT analysis at NLO using CMS data

- Expect appearance of CI as deviations from the SM spectrum in jet cross-sections at low rapidity and high transverse momentum
- **The problem**: The SM prediction is based on PDFs obtained from the same process where BSM effects are expected to manifest

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

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

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



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

n= 1 3 5

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

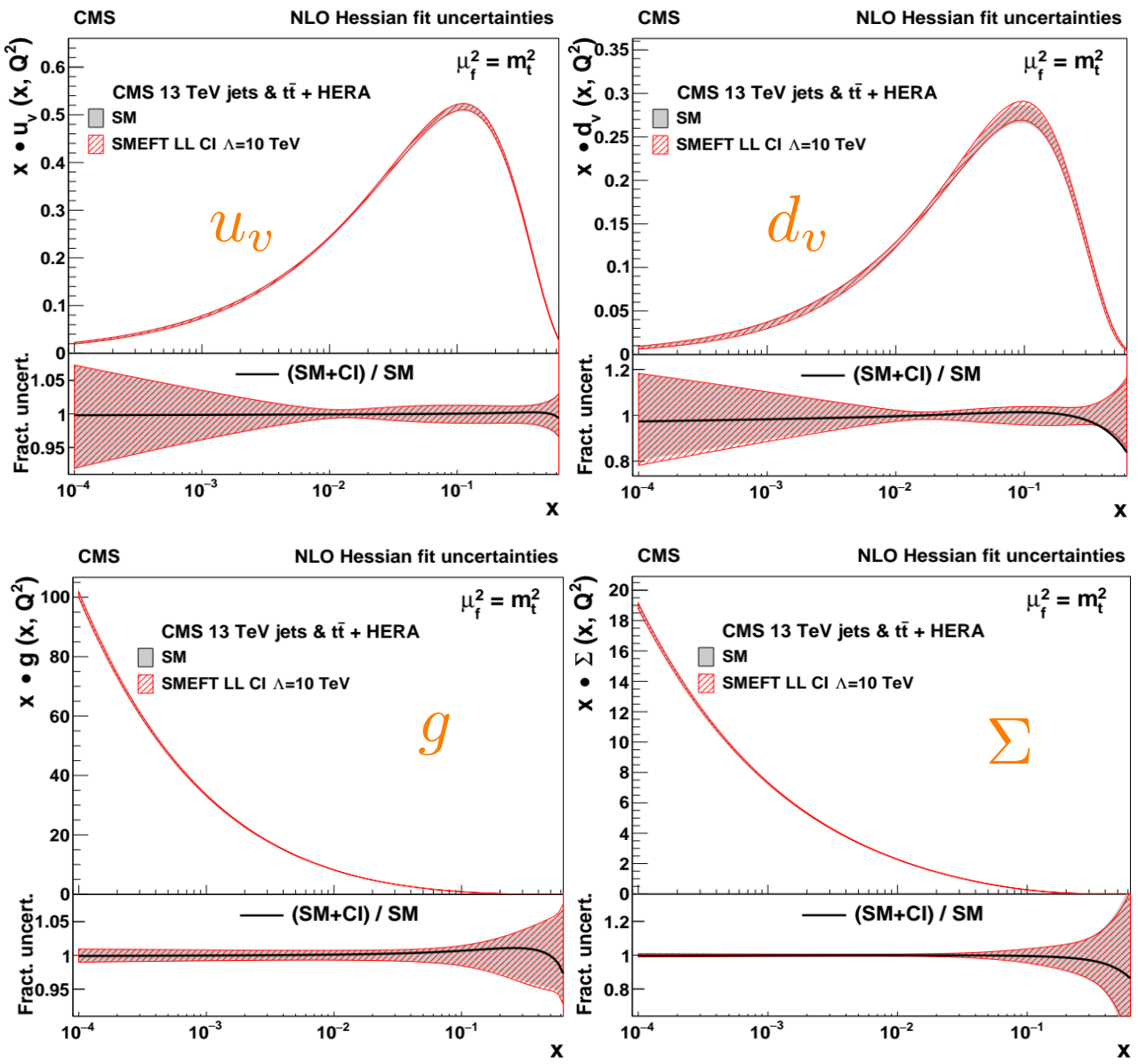
Type of CI	c_1	c_3	c_5
Purely left-handed:	free	0	0
Vector-like:	free	$2c_1$	c_1
Axial-vector-like:	free	$-2c_1$	c_1

SMEFT analysis at NLO

- Using the HERA DIS data together with CMS inclusive jet and $t\bar{t}$ cross section measurements at 13 TeV
- The fits are performed using SM+CI (SMEFT) or, alternatively, SM theory predictions
- The PDFs from SMEFT and SM fits agree, differences within fit uncertainties
- All CI models result in very similar PDFs, strong coupling and top mass values as the SM fit

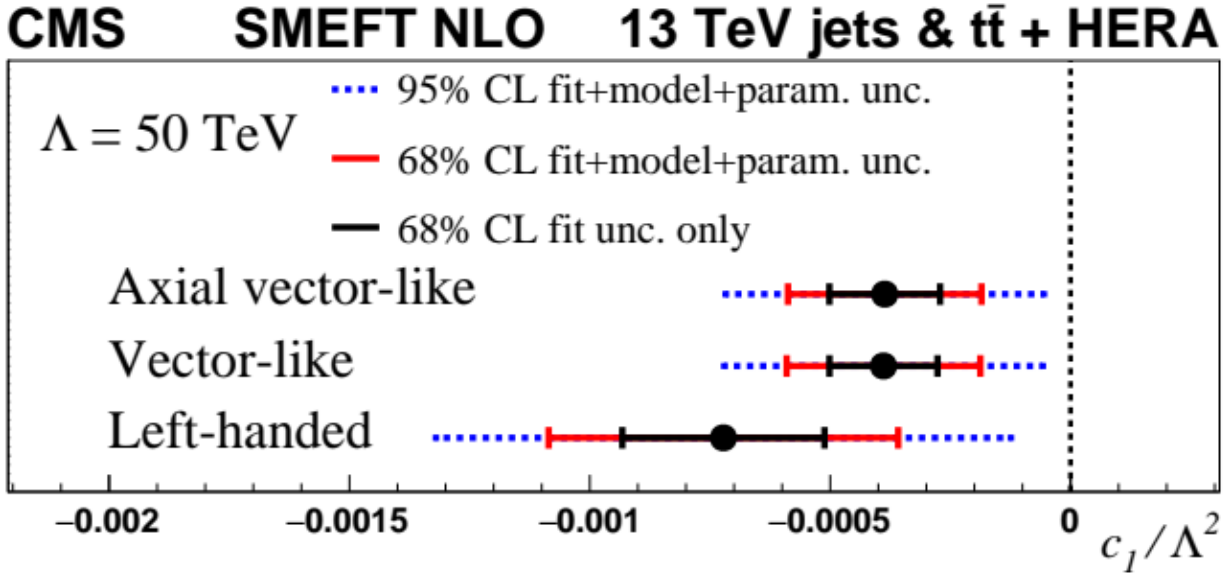
No risk of absorbing BSM effects in the SM PDF fit is observed

No statistically significant deviation from the SM observed



Unbiased exclusion limits for 4-quark CI

- First time at LHC: the Wilson coefficient for 4-quark CI is *fitted together with the PDFs*
- All CI fits result in negative c_1. These are translated into ***unbiased*** 95% CL exclusion limits for CI
- Conventional studies scan for Λ, fix $c_1 = \pm 1$ for constructive (-) or destructive (+) interference with SM gluon exchange

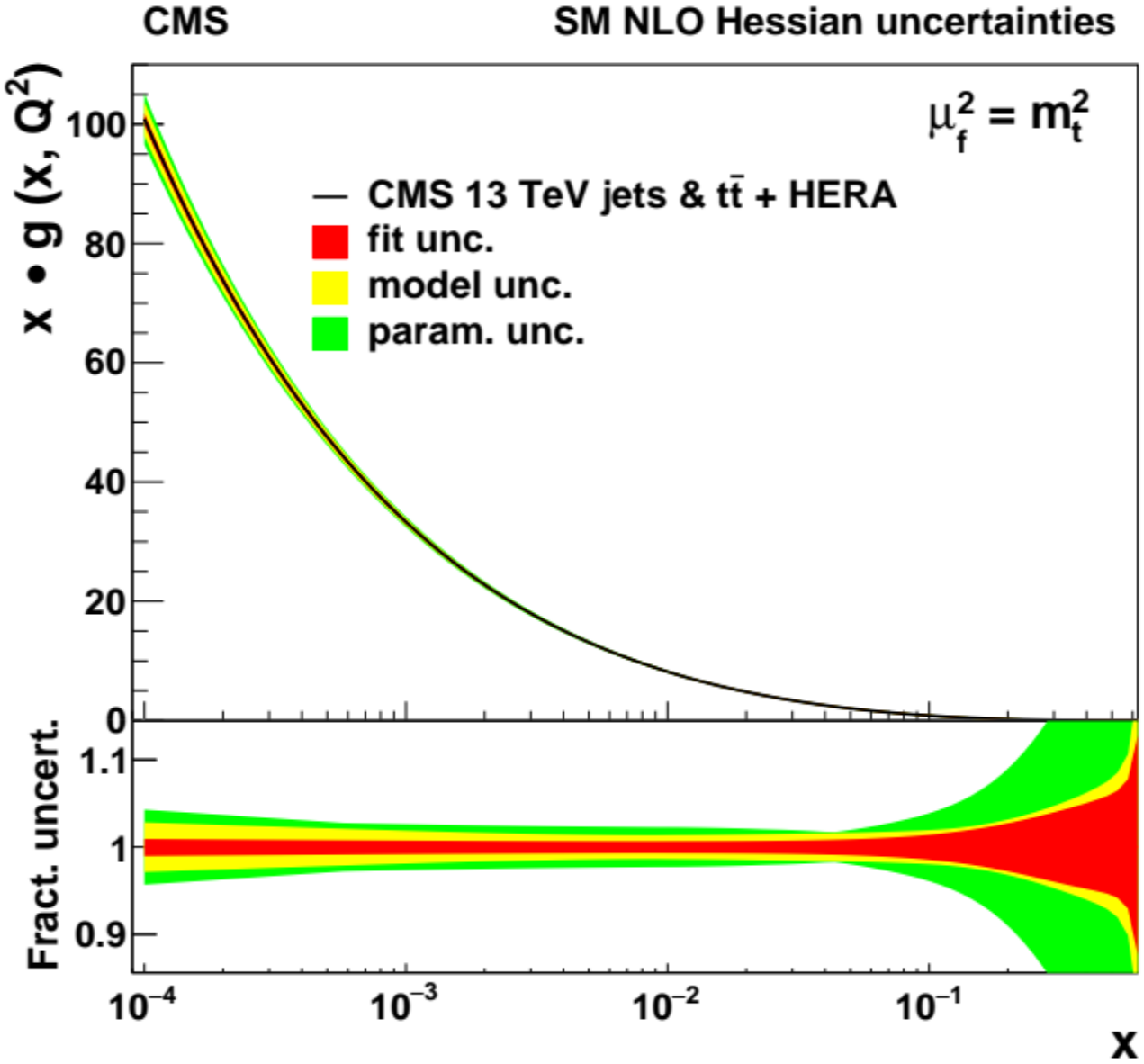


Most stringent comparable result
from ATLAS 13 TeV dijet cross-sections:
22 TeV for left-handed CI [arXiv:1703.09127]

95% CL on Λ with $c_1 = -1$

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

For comparison: SM QCD analysis at NLO



- **Results**

$$\alpha_S(m_Z) = 0.1188 \pm 0.0017(\text{fit}) \pm 0.0004(\text{model}) \pm 0.0025(\text{scale}) \pm 0.0001(\text{param})$$

Agrees with the world average

$$m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fit}) \pm 0.1(\text{model}) \pm 0.1(\text{scale}) \pm 0.1(\text{param})\ \text{GeV}$$

Agrees with previous CMS result [doi:10.1140/epjc/s10052-020-7917-7, arXiv:1904.05237]

- The QCD scale uncertainties dominate
  - Contribute to model uncertainty

Summary

- QCD analysis performed using $R = 0.7$ jet and $t\bar{t}$ cross section measurements at $\sqrt{s} = 13\ \mathrm{TeV}$, probing $10^{-3} < x < 0.5$
  - Profiling study: the data will have significant impact in the global fit
  - QCD analysis at NNLO: sizable improvement in the gluon uncertainty and very precise $\alpha_S(m_\mathrm{Z})$:

$$\alpha_S(m_\mathrm{Z}) = 0.1170 \pm 0.0019$$

- 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

- Data are well described by the SM, no significant deviation observed

Thanks for your attention!