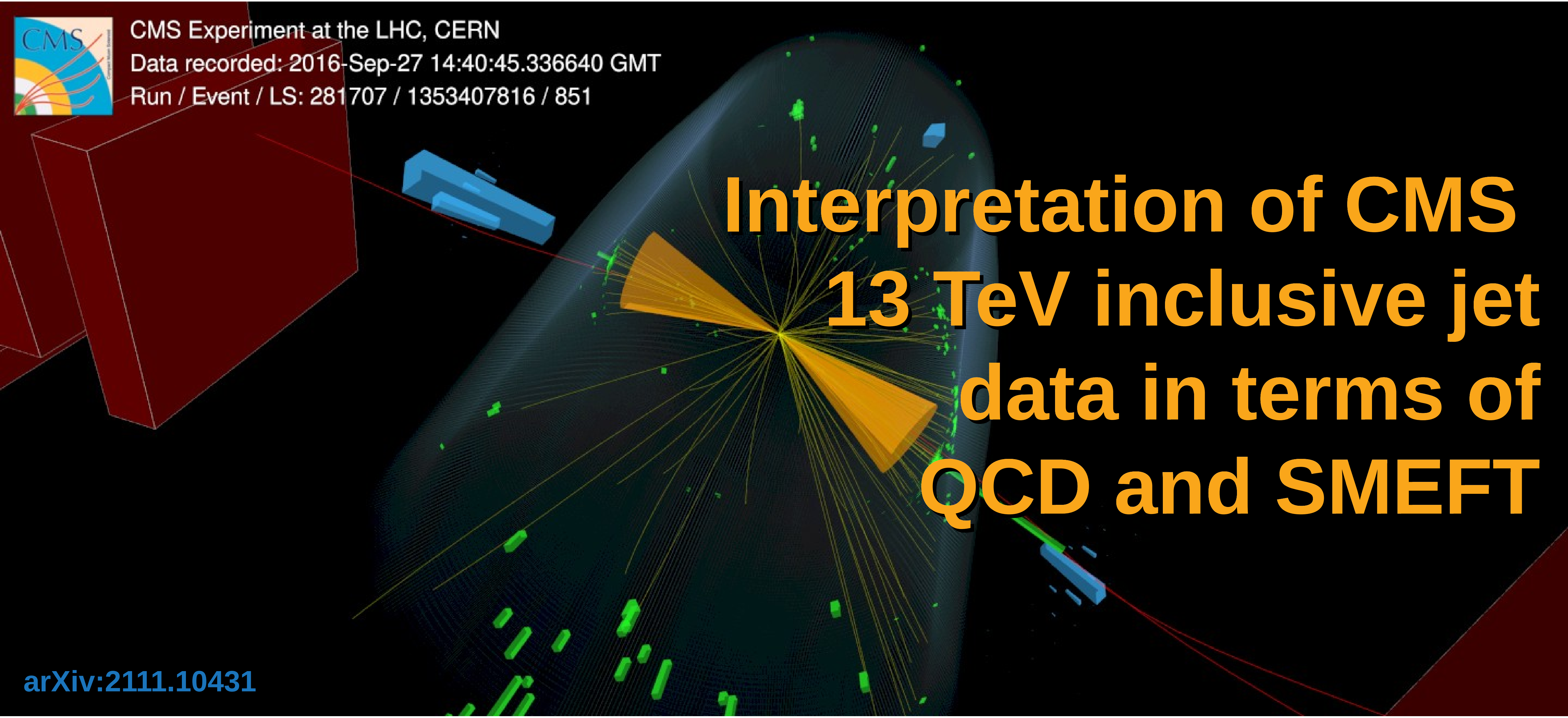

Interpretation of CMS 13 TeV inclusive jet data in terms of QCD and SMEFT

arXiv:2111.10431

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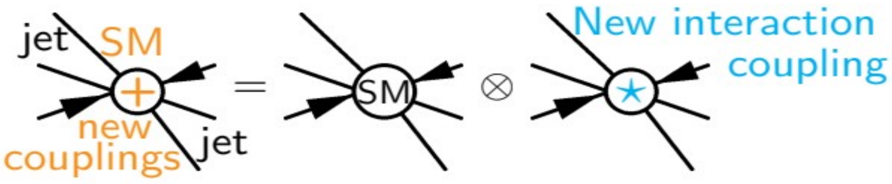
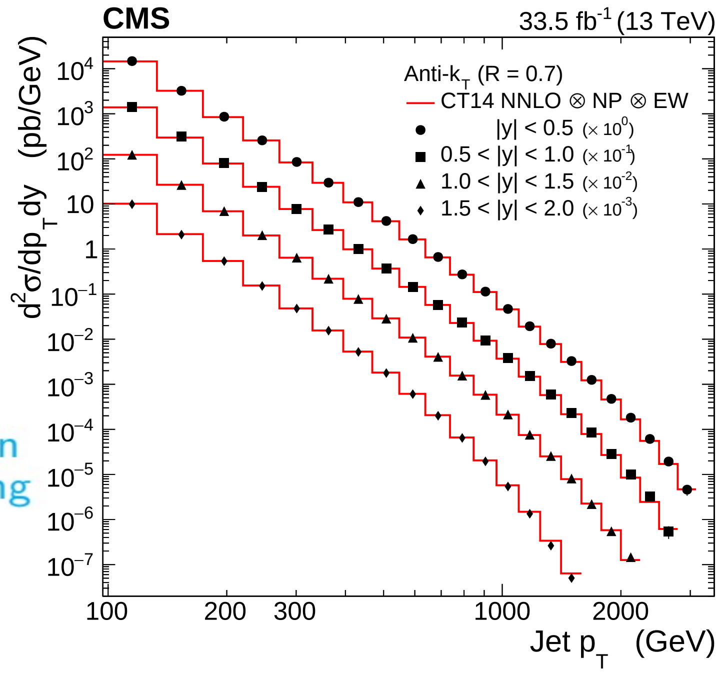
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

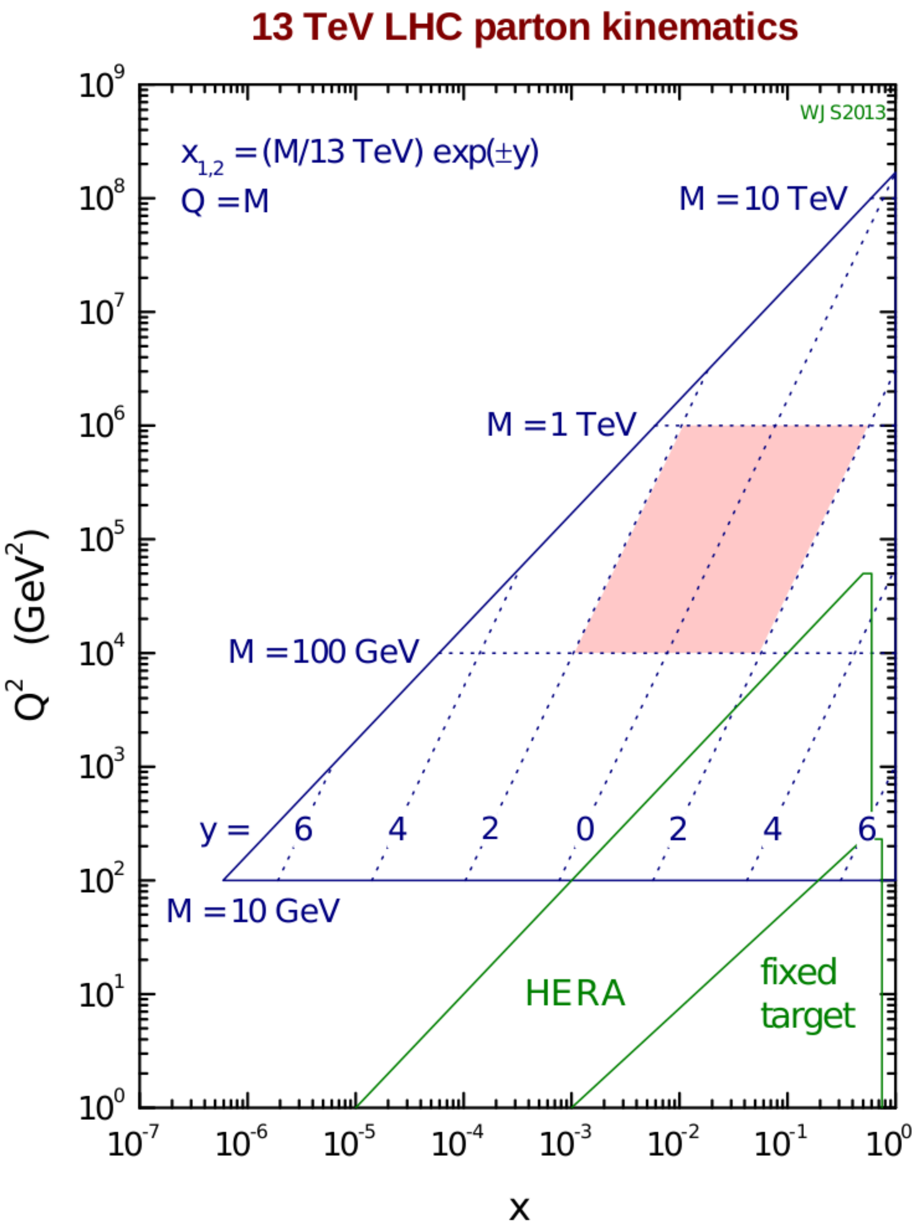
DESY.

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







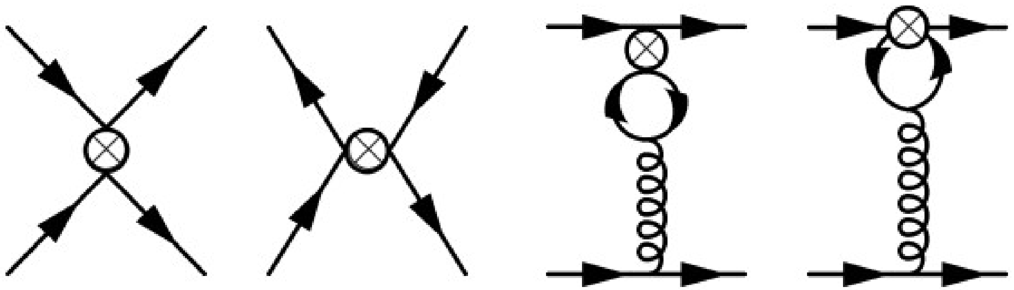
Motivation: unbiased search for Contact Interactions (CI)

- 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

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

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

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

  (Submitted to JHEP, arXiv:2111.10431)

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

  Major constraints on the quark distributions in the proton

  (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**

  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.

  (Eur. Phys. J. C 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

Theory predictions

- **13 TeV inclusive jet cross sections**

  FastNLO QCD prediction at NLO

  NLO+NLL resummation computed using NLLjet and MEKS

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

  Contact Interactions (CI) for the SMEFT fits computed with CIJET

  By default, QCD scales set to individual jet p_T

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

  Predictions available at NLO

  The QCD scales are set to $\frac{1}{2}\sum_i \sqrt{m_i^2 + p_{T,i}^2}$ (Over final state partons)

  Described in detail in Eur. Phys. J. C 80 (2020), no. 7, 658, doi:10.1140/epjc/s10052-020-7917-7, arXiv:1904.05237

Contributions included in reported total uncertainties

- **Experimental uncertainties**
  - Contribute to the Hessian fit uncertainty.
- **Parameterisation uncertainties**
  - Add and remove new parameters to the PDF parameterisation scan result one at a time.
- **Model uncertainties**
  - Fixed parameters varied within their uncertainties: $1.41 \leq m_c \leq 1.53$ GeV, $4.25 \leq m_b \leq 4.75$ 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

PDF parameterisation at starting scale Q_0^2 = 1.9 GeV^2

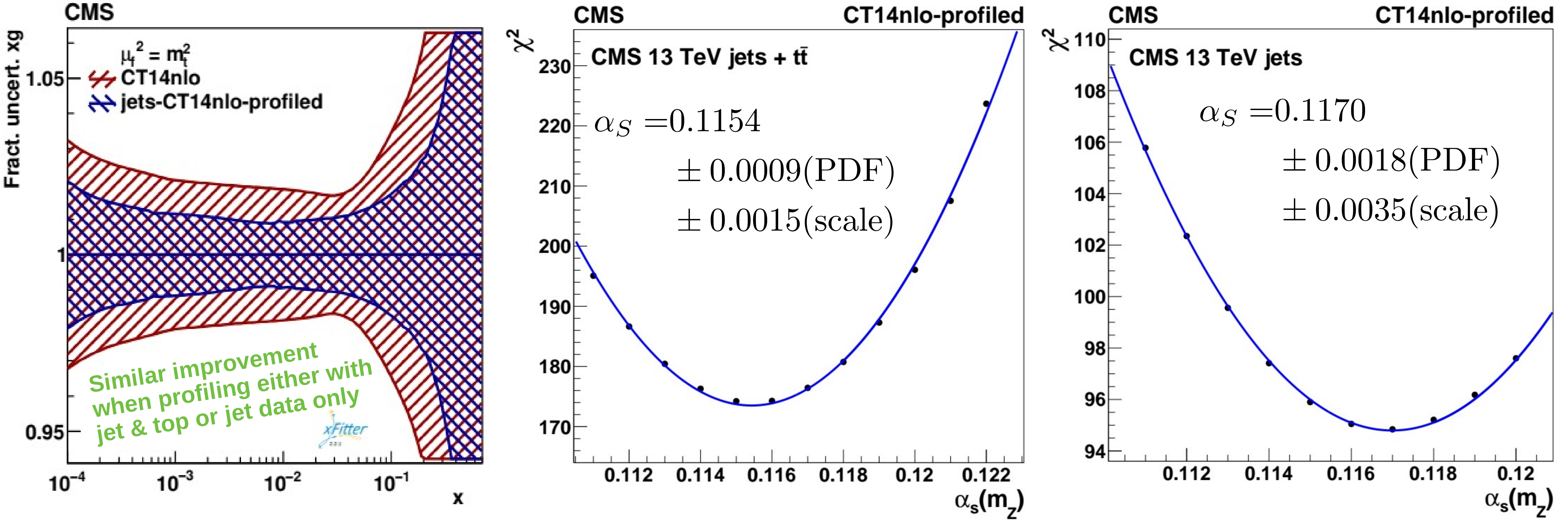
- PDF determination follows the approach of HERAPDF2.0
- Parameters are introduced one-by-one in a parameterisation scan
- The parameterised PDFs are:
  - gluon distribution $xg(x)$
  - valence quark distributions $xu_v(x)$ and $xd_v(x)$
  - $x\overline{U}(x)$ and $x\overline{D}(x)$ for antiquark distributions.

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

- Here $x\overline{U}(x) = x\overline{u}(x)$ and $x\overline{D}(x) = x\overline{d}(x) + x\overline{s}(x)$, with $x\overline{u}(x)$, $x\overline{d}(x)$ and $x\overline{s}(x)$

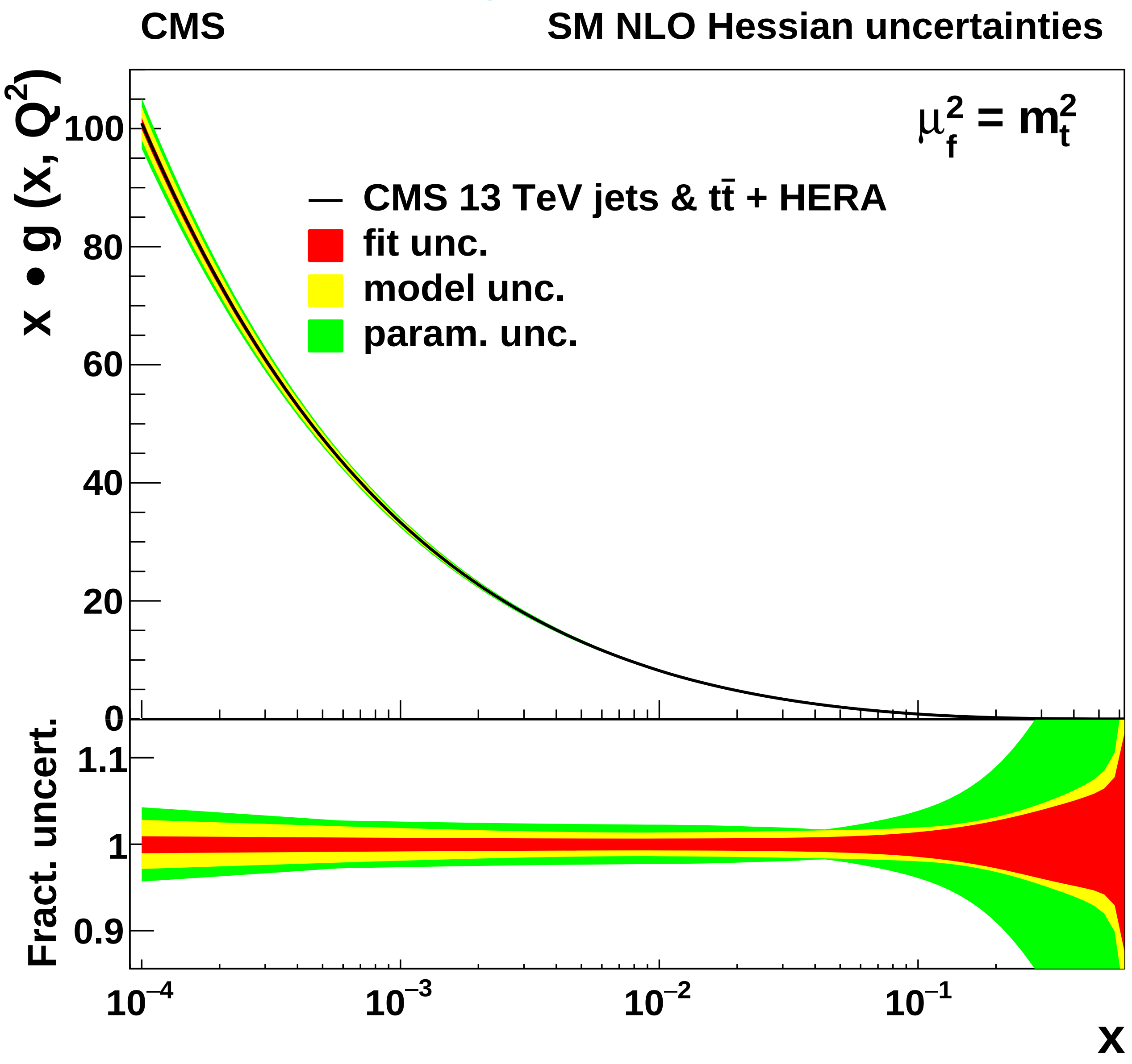
  for up, down and strange antiquarks.
- $B_{\overline{U}} = B_{\overline{D}}$ and $A_{\overline{U}} = A_{\overline{D}}(1-f_s)$ with $f_s = x\overline{s}/(x\overline{d}+x\overline{s}) = 0.4$ the strangeness fraction.

PDF profiling: the data's impact on global PDFs



- 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]
  (PDF) (scale)
- Profiled Wilson coefficients statistically compatible with zero, and hence with the SM

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

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

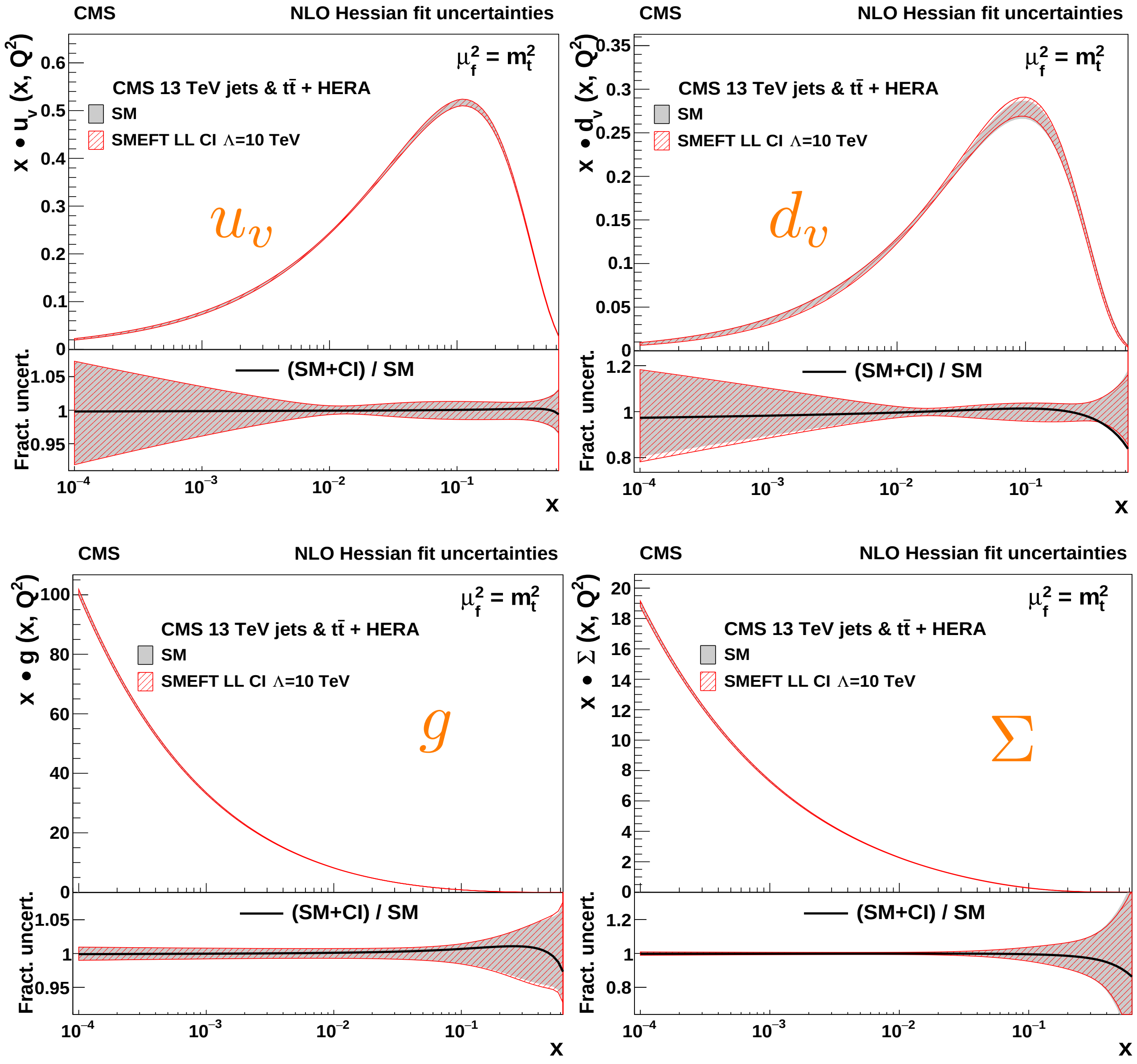
Agrees with CMS 13 TeV ttbar 3D result

$$m_t = 170.5 \pm 0.8\ \text{GeV}.$$

- The QCD scale uncertainties dominate
  - Contribute to model uncertainty

SMEFT QCD analysis at NLO

- 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 as the SM fit



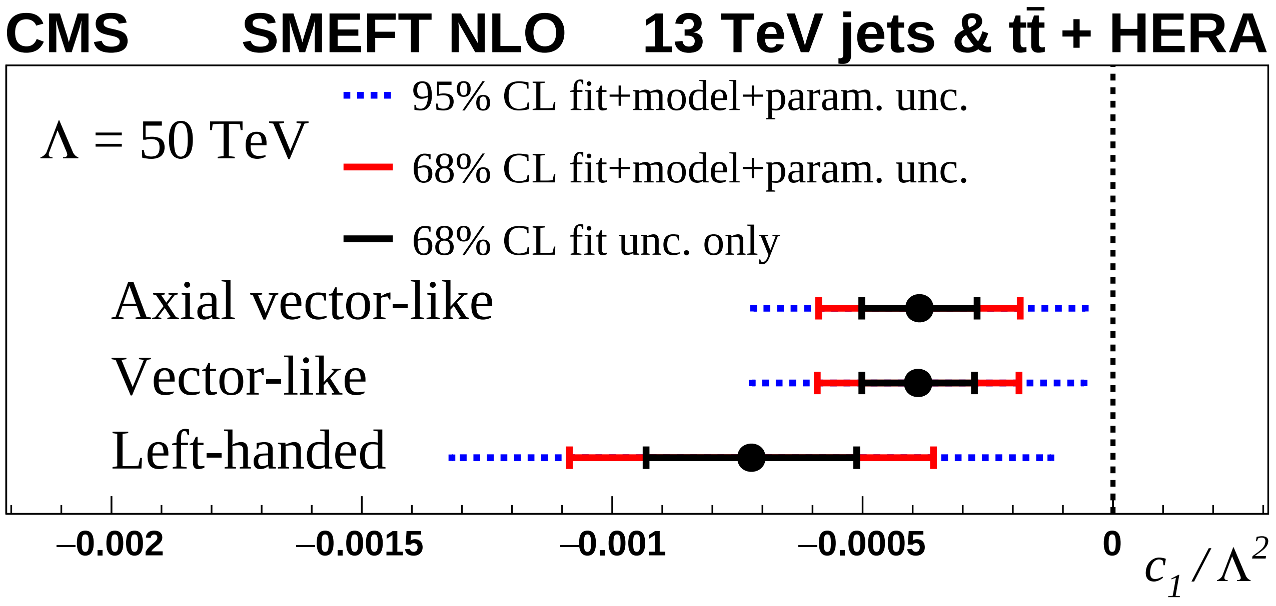
No risk of absorbing BSM effects in the SM PDF fit is observed

No statistically significant deviation from the SM observed

Translating the results into exclusion limits

- 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)



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

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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]

SM QCD analysis at NNLO

- Fixed-order pQCD predictions used for computing *k*-factors:
  - NLOJet++ [1, 2]
  - NNLOJET (rev5918) [3, 4, 5]
  - NLO implemented in FastNLO [6]

$$k = \frac{\sigma^{\mathrm{NNLO}}}{\sigma^{\mathrm{NLO}}}$$

- Obtained with the CT14nnlo PDF
  - PDF uncertainty is small,

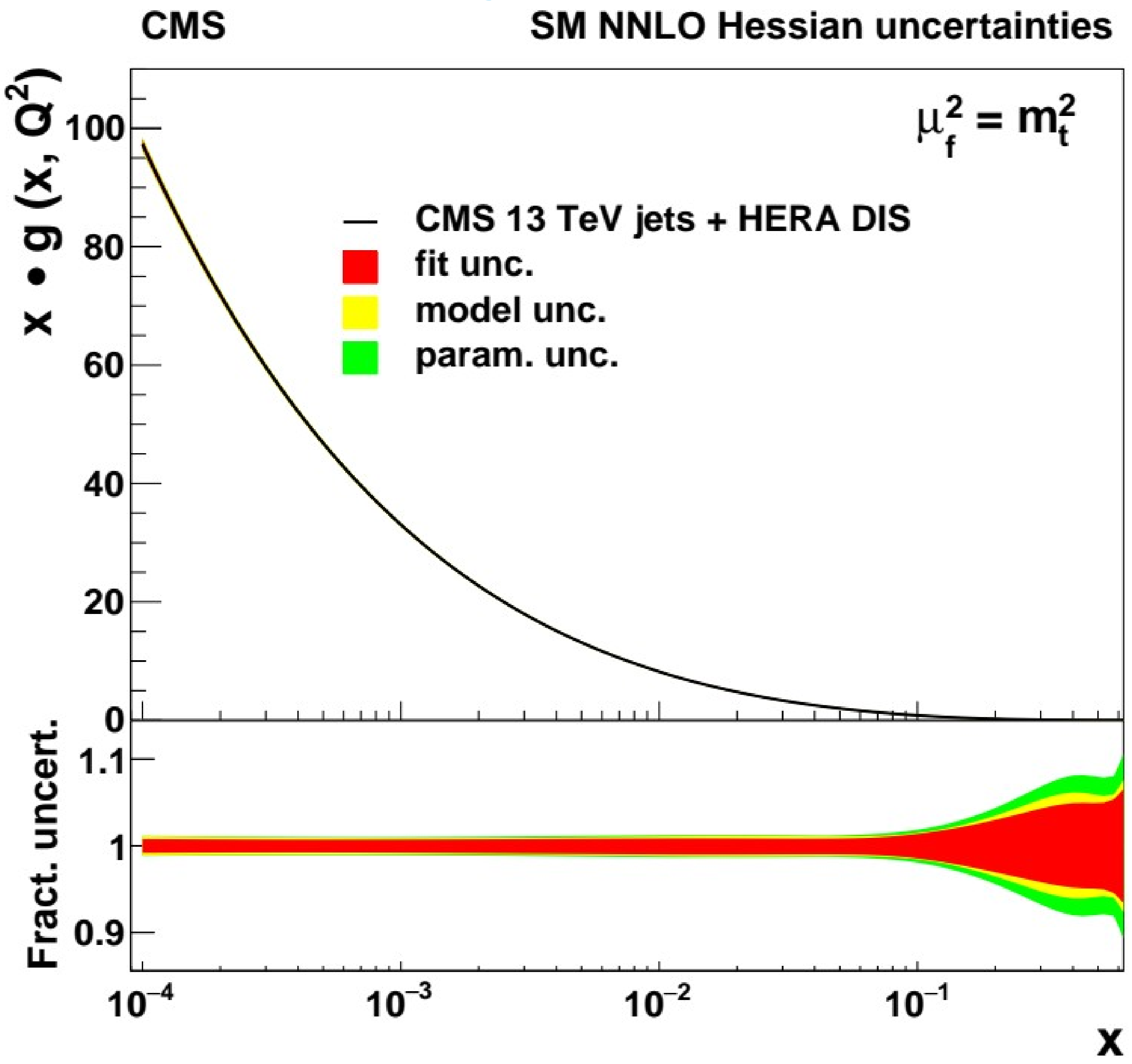
    accounted for as a systematic uncertainty

Reinvestigated starting scale parameterisation for NNLO fits

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

- Factors also obtained with scale variations (μ_r, μ_f multiplied by 2 or ½, excluding $\mu_r/\mu_f = 4^{\pm 1}$)
  - Central factor ranges from 0.96 to 1.06, rising with p_T
  - Lowest variation $(2\mu_r, 2\mu_f)$ from 0.92 to 0.98 and highest $(\mu_r/2, \mu_f/2)$ from 1.04 to 1.17

SM QCD analysis at NNLO



- The triple-differential $t\bar{t}$-production cross-section available only at NLO → No top data in NNLO fit
- Fitted strong coupling result

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

Most precise NNLO value from hadron collisions to date!

- Experimental (Hessian fit) uncertainties dominate
- No large *scale uncertainty* contributions in model uncertainty, as opposed to previous NLO studies
- No SMEFT fit performed, predictions for contact interactions available at NLO only.

Summary

- QCD analysis performed using $R = 0.7$ jet and $t\bar{t}$ cross section measurements at $\sqrt{s} = 13~\mathrm{TeV}$, 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
- The results are in agreement with previous results and world averages
- Data are well described by the SM, no significant deviation observed
- The NNLO analysis has resulted in the most precise measurement of the strong coupling constant to date:

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

Thanks for your attention!

References

[1] Z. Nagy, “Three jet cross-sections in hadron hadron collisions at next-to-leading order”, Phys. Rev. Lett. 88 (2002) 122003, doi:10.1103/PhysRevLett.88.122003, arXiv:hep-ph/0110315.

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