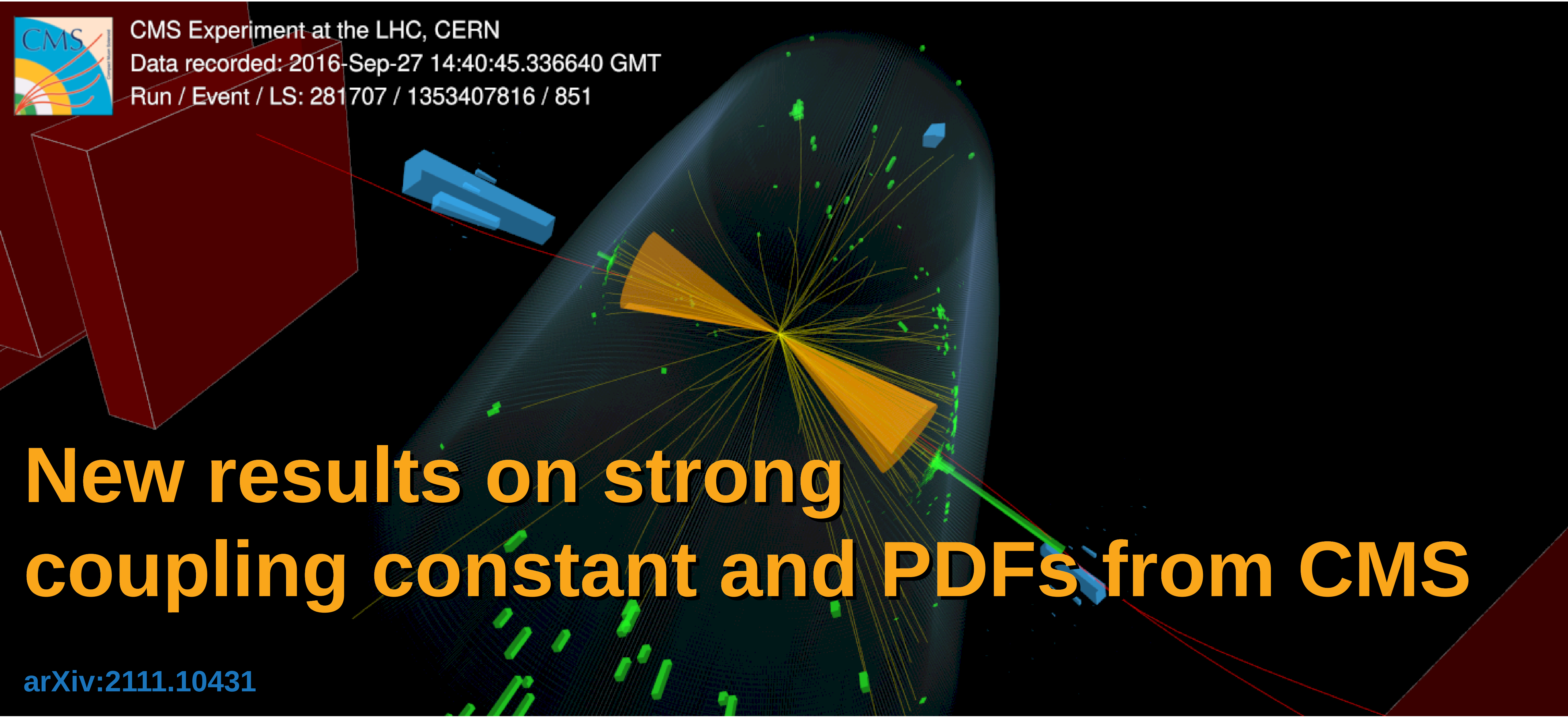


New results on strong coupling constant and PDFs from CMS

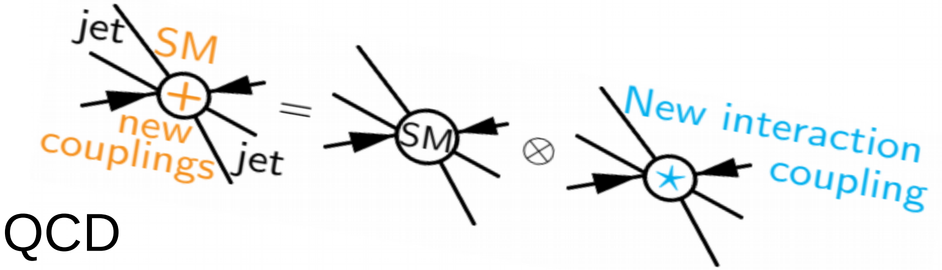
arXiv:2111.10431

Toni Mäkelä*, Katerina Lipka
alphas-2022 Workshop
31. Jan. - 4. Feb. 2022

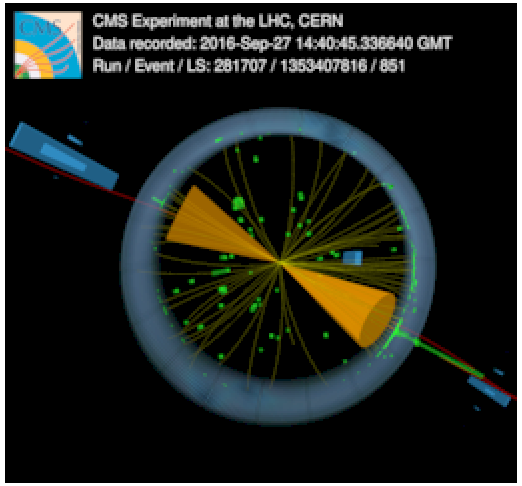
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

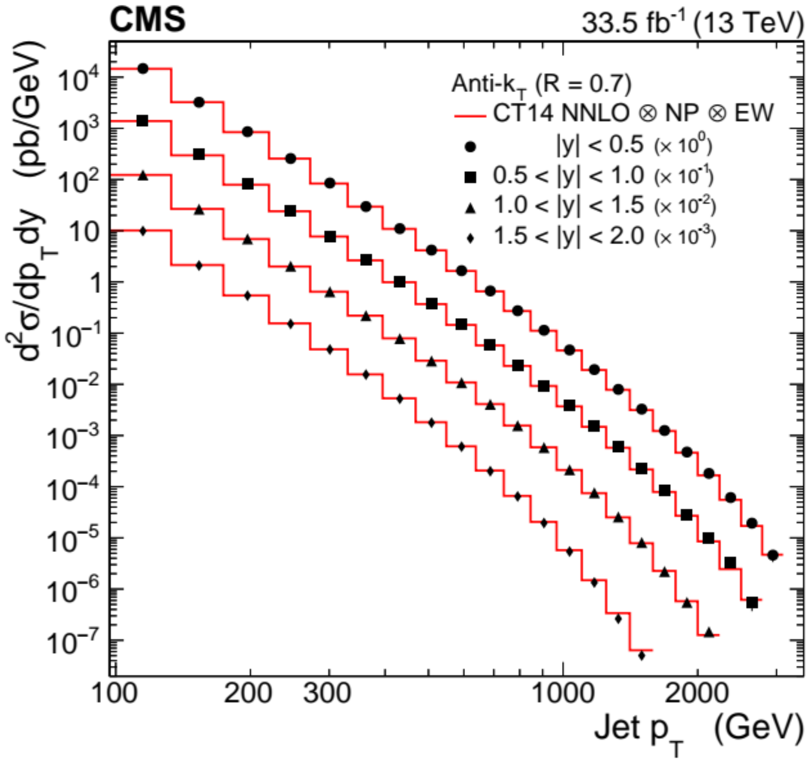
DESY.

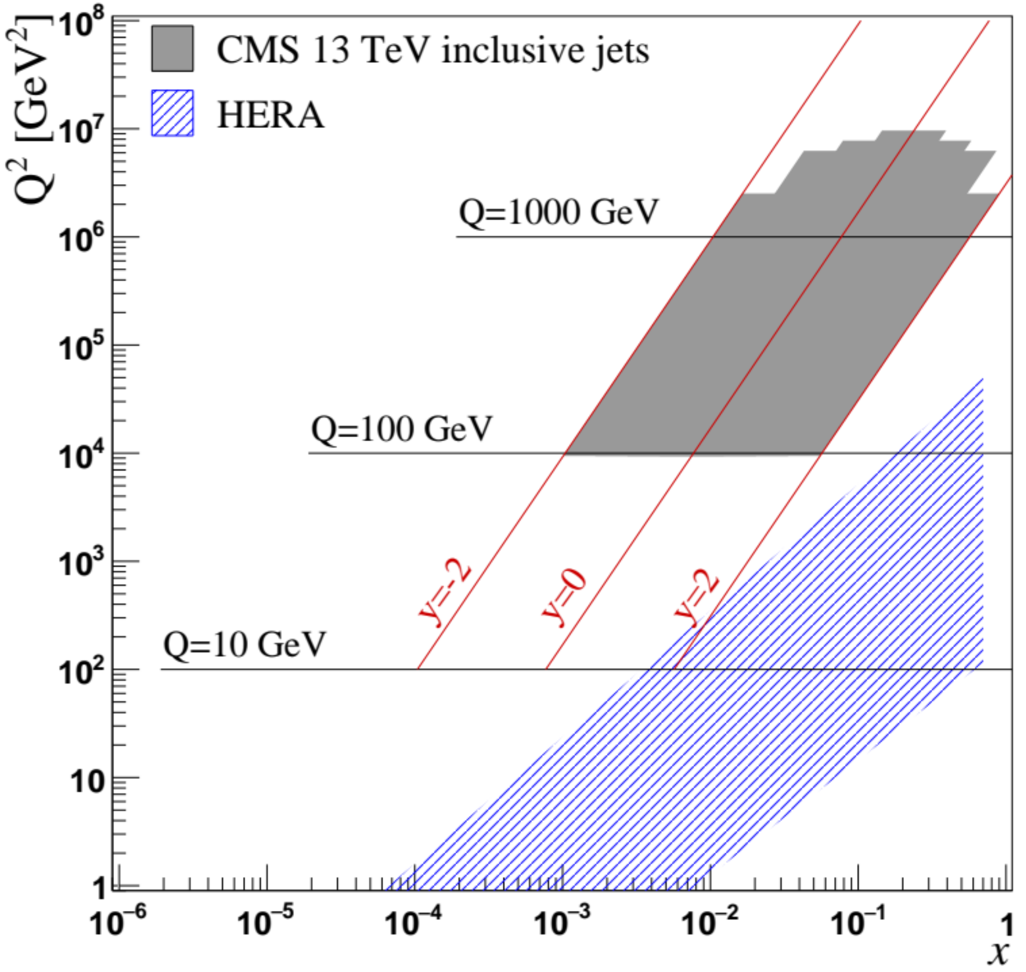
Jets as a probe of QCD & new physics



- Jet production is the most fundamental process for studying QCD
  - *Extract strong coupling constant* and other QCD parameters
  - Improve the precision of proton structure studies
- *Perform indirect BSM searches:* jets at high-p_T







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

(Accepted by 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*

Theoretical predictions

- **13 TeV inclusive jet cross sections (NLO)**
- FastNLO QCD prediction at NLO [1]

  NLO+NLL resummation computed using NLLjet [2] and MEKS [3]

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

  Contact Interactions (CI) for the SMEFT fits computed with CIJET [4, 5]

  By default, QCD scales set to individual jet transverse momentum

- **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 Ref. [6]

[1] arXiv:1208.3641
[2] Comm. w/ the authors of arXiv:1801.07284
[3] arXiv:1207.0513
[4] arXiv:1204.4773
[5] arXiv:1301.7263
[6] 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++ [7,8]
  - NNLOJET (rev5918) [9, 10, 11]
  - NLO implemented in FastNLO

  Obtained with the CT14nnlo PDF

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

  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

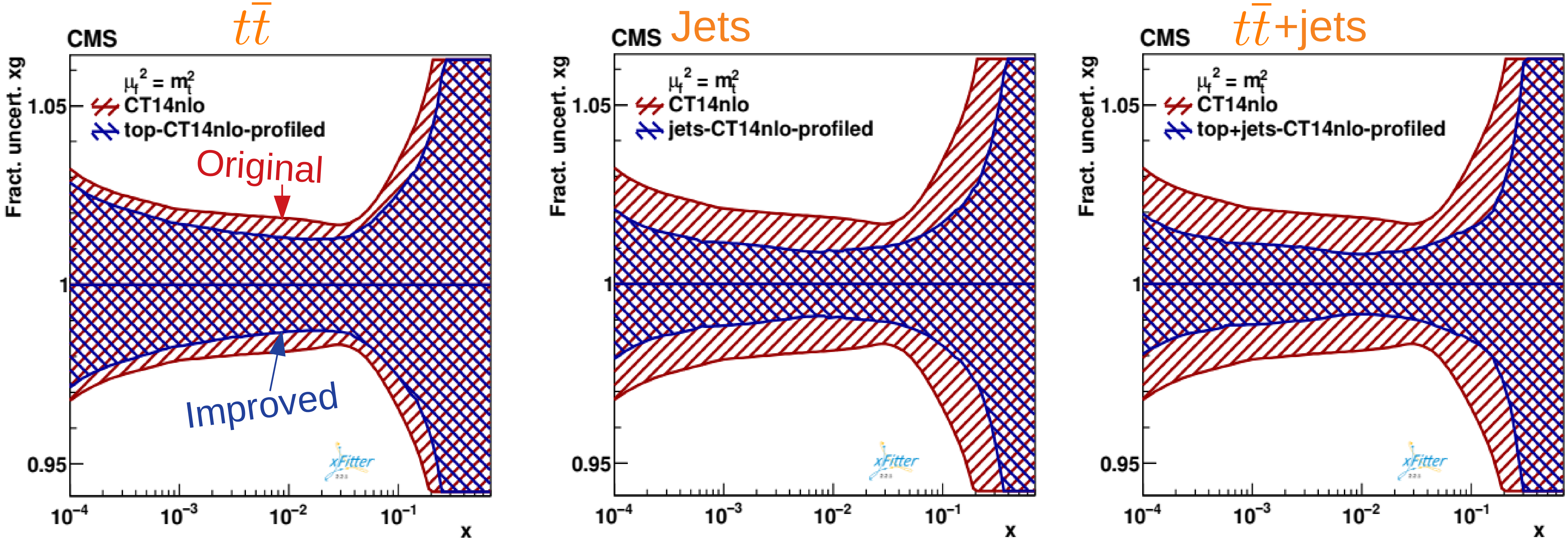
[7] arXiv:hep-ph/0110315
[8] arXiv:hep-ph/0307268
[9] arXiv:1611.01460
[10] arXiv:1807.03692
[11] arXiv:1801.06415

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 in future fits
- 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

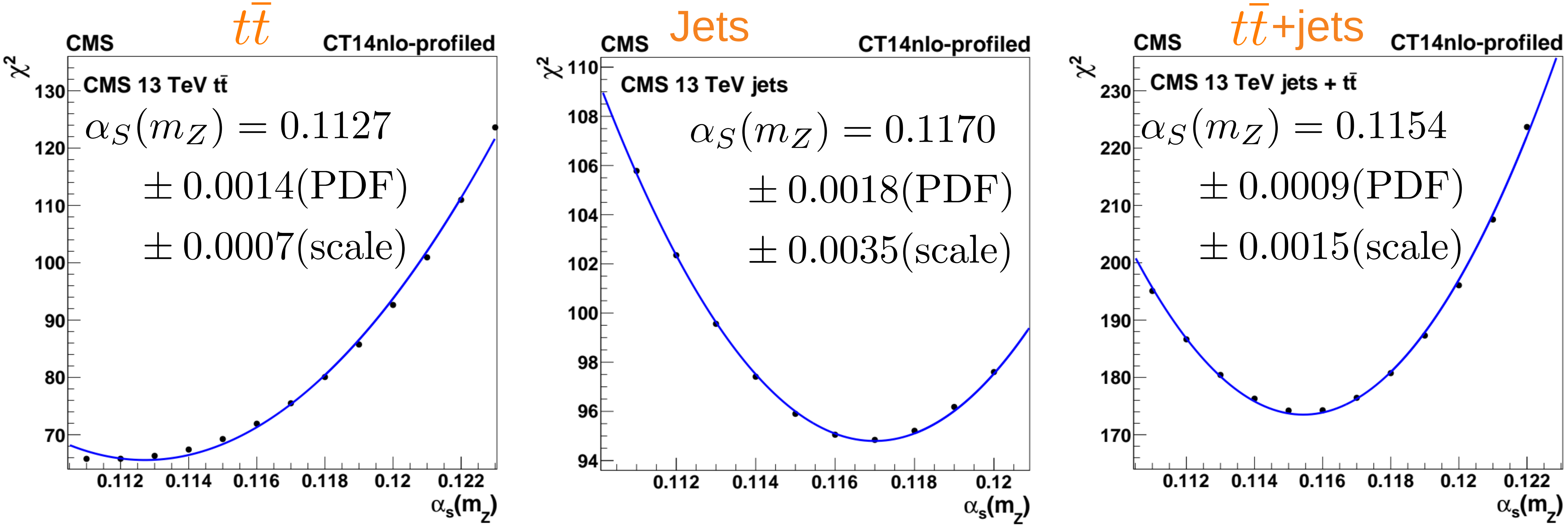
PDF profiling at NLO: gluon PDF & different data combinations



- Both the top and jet data improve gluon PDF precision
- Profiling results in the same top mass in both top data only and top+jet data cases:

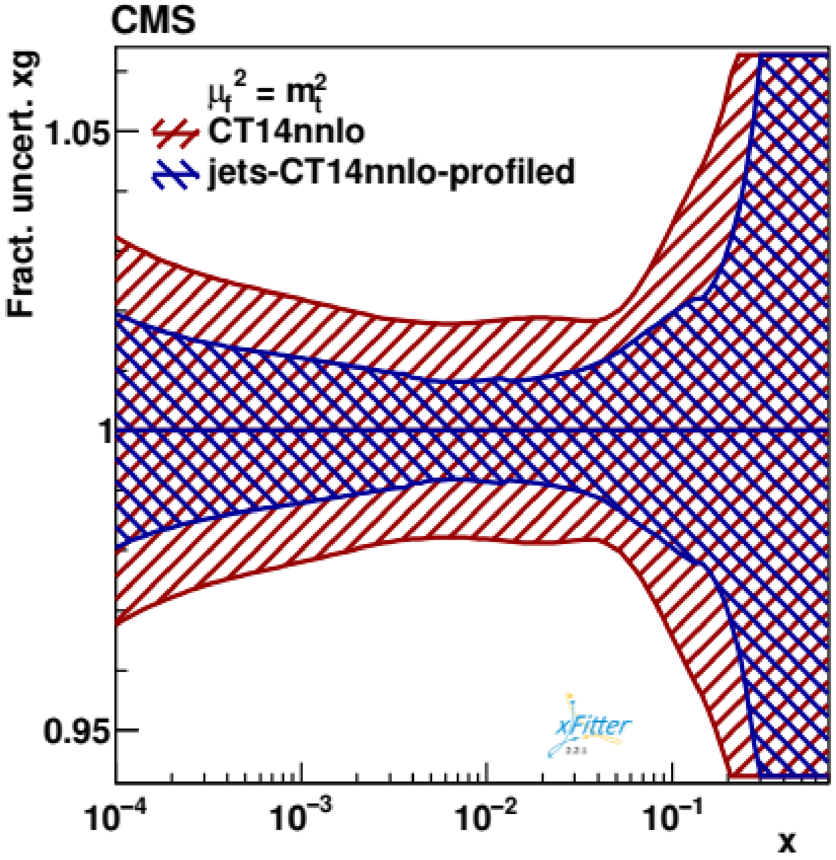
$$m_t = 170.3 \pm 0.5(\text{PDF}) \pm 0.2(\text{scale})\ \text{GeV}$$ → *Consistent with the previous CMS result*

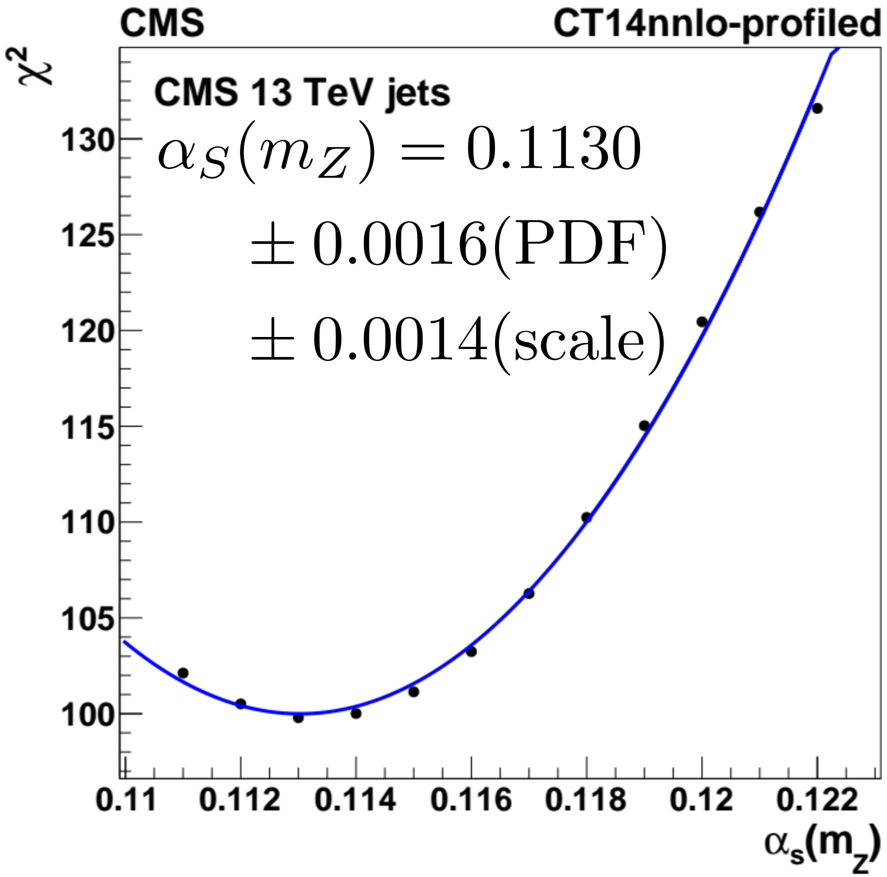
PDF profiling at NLO: scan for $\alpha_S(m_Z)$



- Using only the top data leads to a small $\alpha_S(m_Z)$, as observed in previous fit to $t\bar{t}$ data
- With the jet data, the PDFs become better constrained
- Profiling $\alpha_S(m_Z)$ with jet data only or jet+top data gives compatible results

PDF profiling at NNLO





- Only the jet data are used (no NNLO predictions for top 3-d cross sections)
- Gluon PDF accuracy significantly improved
- The $\alpha_S(m_Z)$ resulting from NNLO profiling is smaller than from NLO

Full PDF fits: parametrizations at the starting scale $Q_0^2 = 1.9\ \mathrm{GeV}^2$

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**, since different data sets used

Assumed relations

$x\overline{U}(x) = x\bar{u}(x)$ and $x\overline{D}(x) = x\bar{d}(x) + x\bar{s}(x)$, with $x\bar{u}(x)$, $x\bar{d}(x)$ and $x\bar{s}(x)$ 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 $f_s = x\bar{s}/(x\bar{d} + x\bar{s}) = 0.4$

NLO

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

NNLO

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

Contributions included in reported total uncertainties

Experimental uncertainties

- Contribute to the Hessian fit uncertainty.

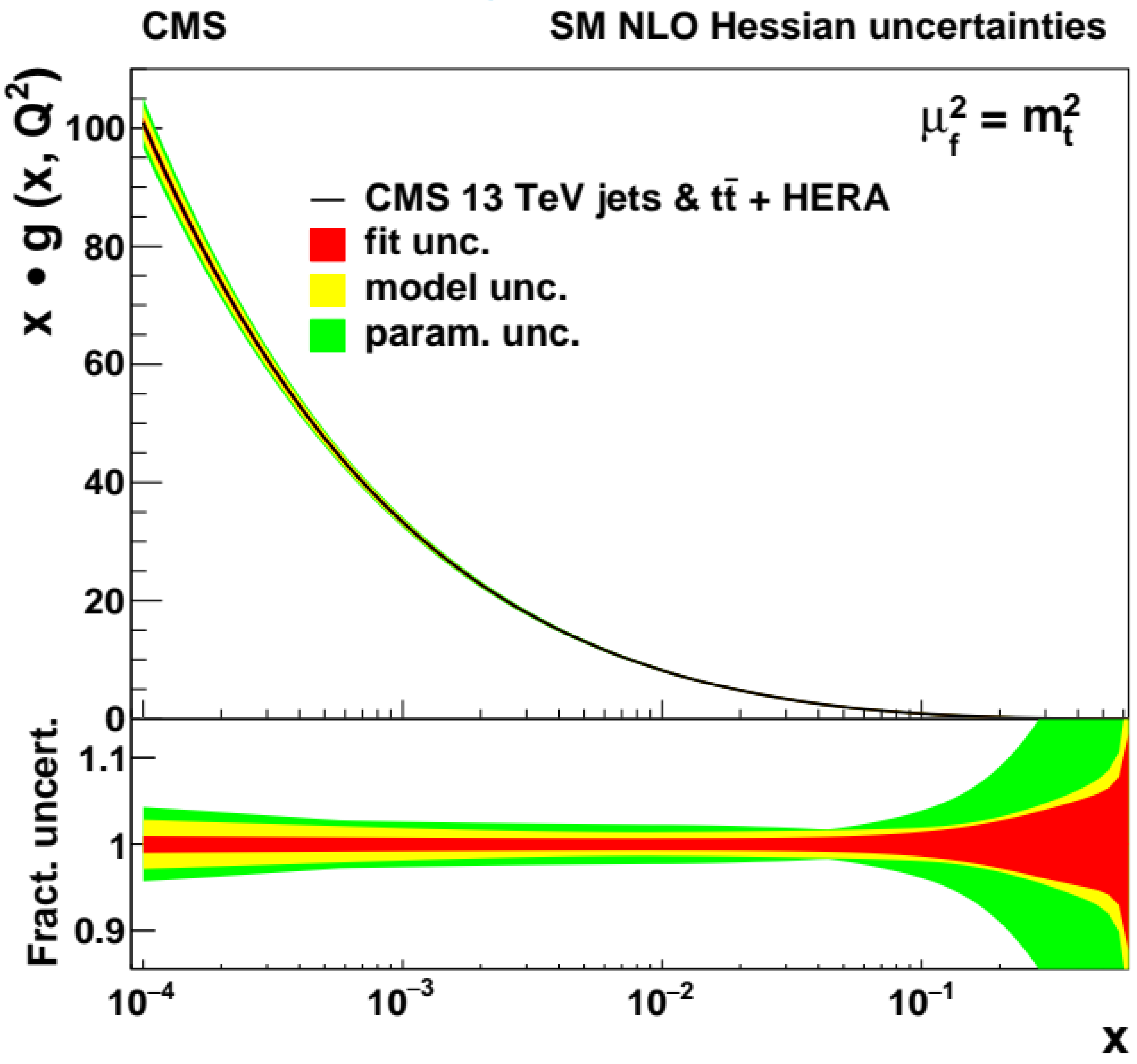
Parameterisation uncertainties

- 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 $1.7 \leq Q_0^2 \leq 2.1$ GeV^2, minimum Q^2 imposed on the HERA data $5.0 \leq Q^2_{\mathrm{min}} \leq 10.0$ GeV^2
- Scale uncertainty is taken as an envelope of 6 variations of the QCD scales.
  The envelope is then treated as a source of model uncertainty

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

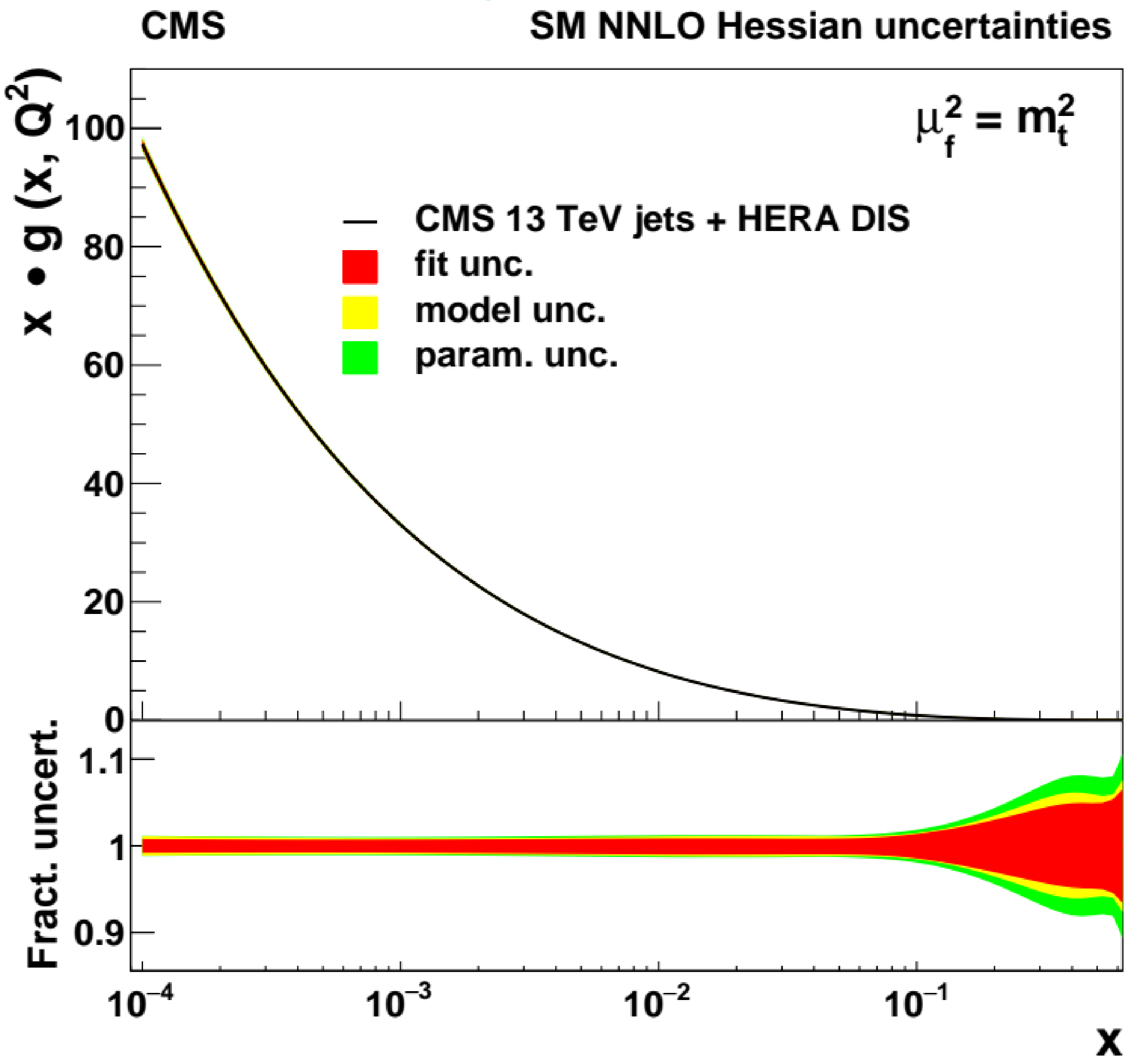
$$m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fit}) \pm 0.1(\text{model}) \pm 0.1(\text{scale}) \pm 0.1(\text{param})\ \text{GeV}$$

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

SM QCD analysis at NNLO



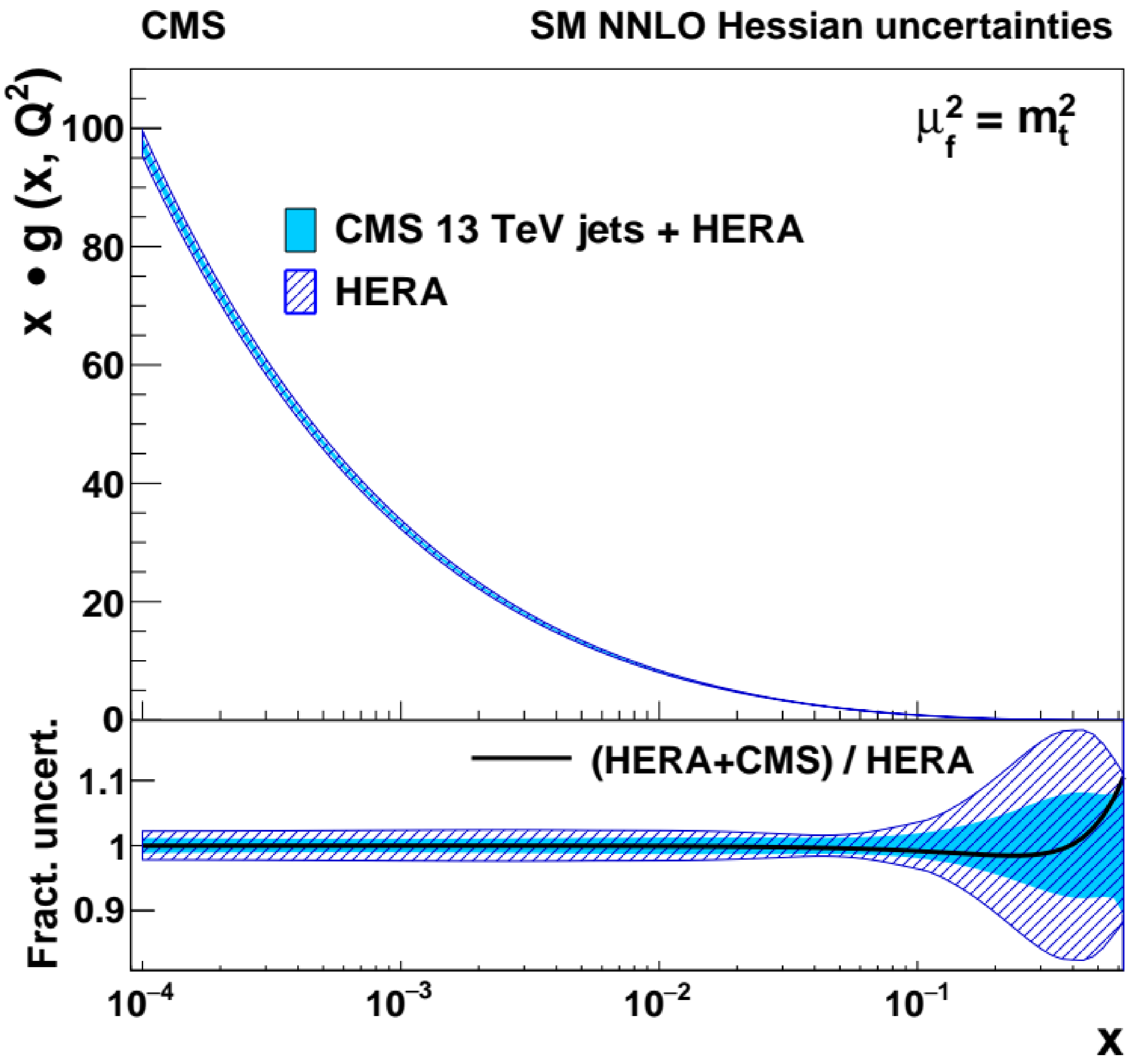
- The triple-differential $t\bar{t}$-production cross-section available only at NLO → No top data in NNLO fit
- Fitted strong coupling result

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

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

SM QCD analysis at NNLO



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

Extending the NLO analysis to SMEFT

Unbiased search for Contact Interactions (CI)

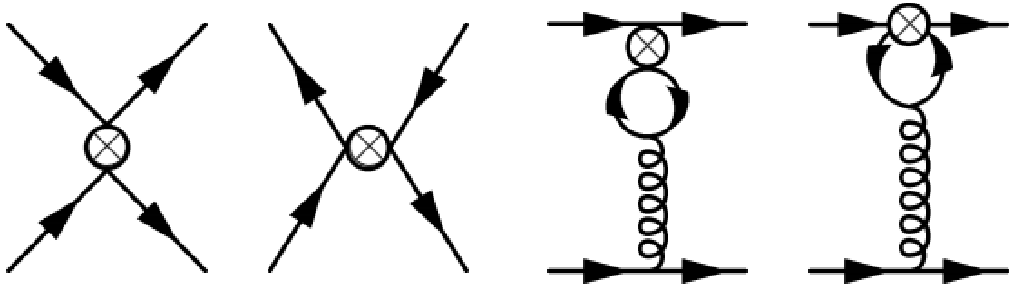
- Expect appearance of CI as deviations from the SM spectrum in jet cross-sections at low rapidity and high transverse momentum

- **The problem**: The SM prediction is based on PDFs obtained from the same process where BSM effects are expected to manifest

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

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



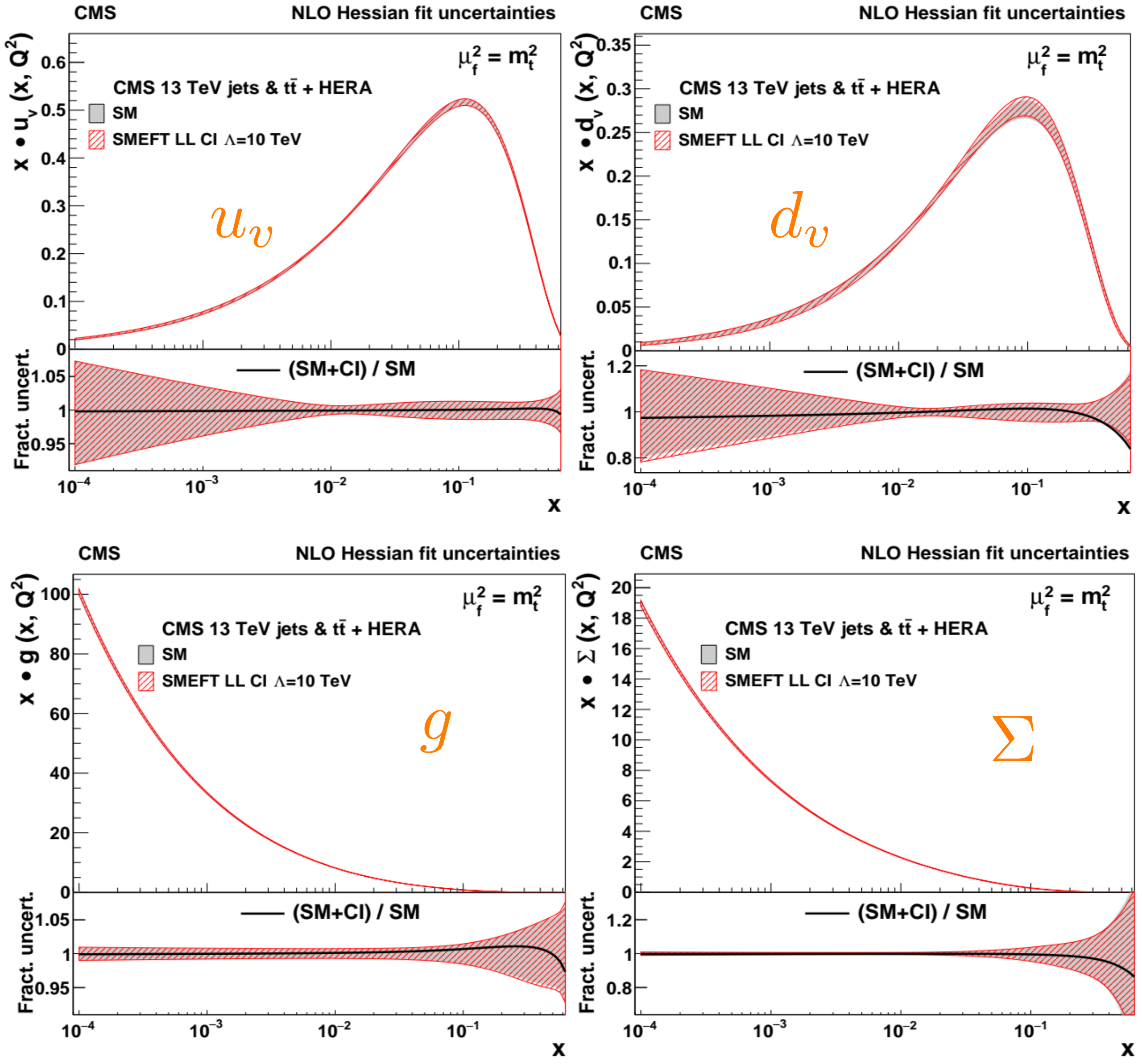
Operators involve products of quark lines with different handedness: *LL, LR, RR*
n= 1 3 5

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

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

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

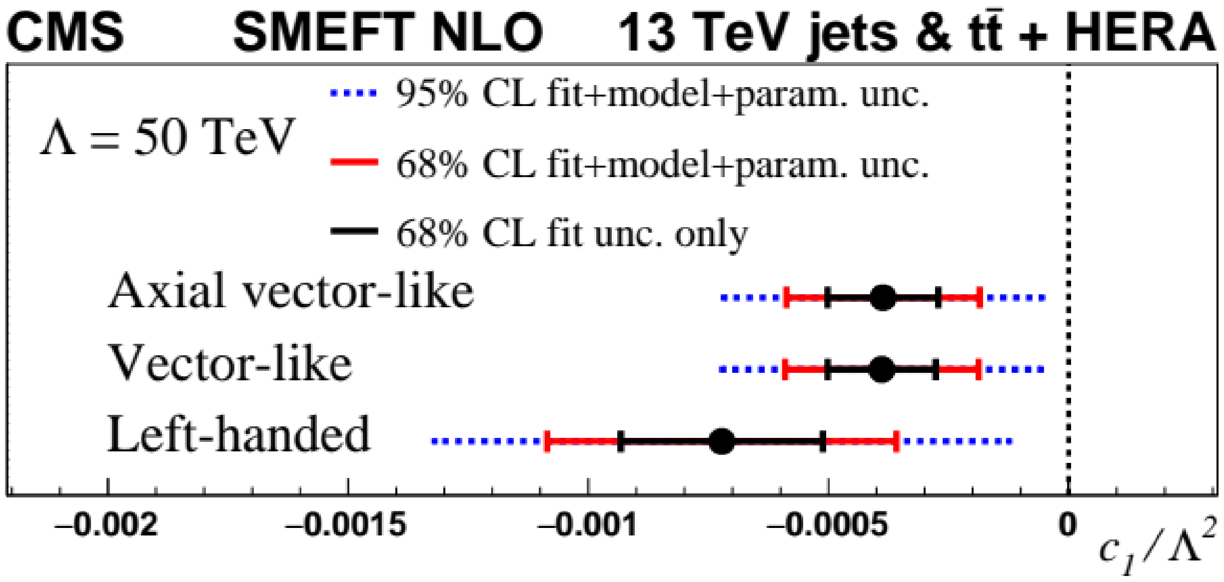


No risk of absorbing BSM effects in the SM PDF fit is observed

No statistically significant deviation from the SM observed

Unbiased exclusion limits for 4-quark CI

- Conventional studies scan for Λ, fix $c_1 = \pm 1$ 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 are translated into ***unbiased*** exclusion limits for constructive interference

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

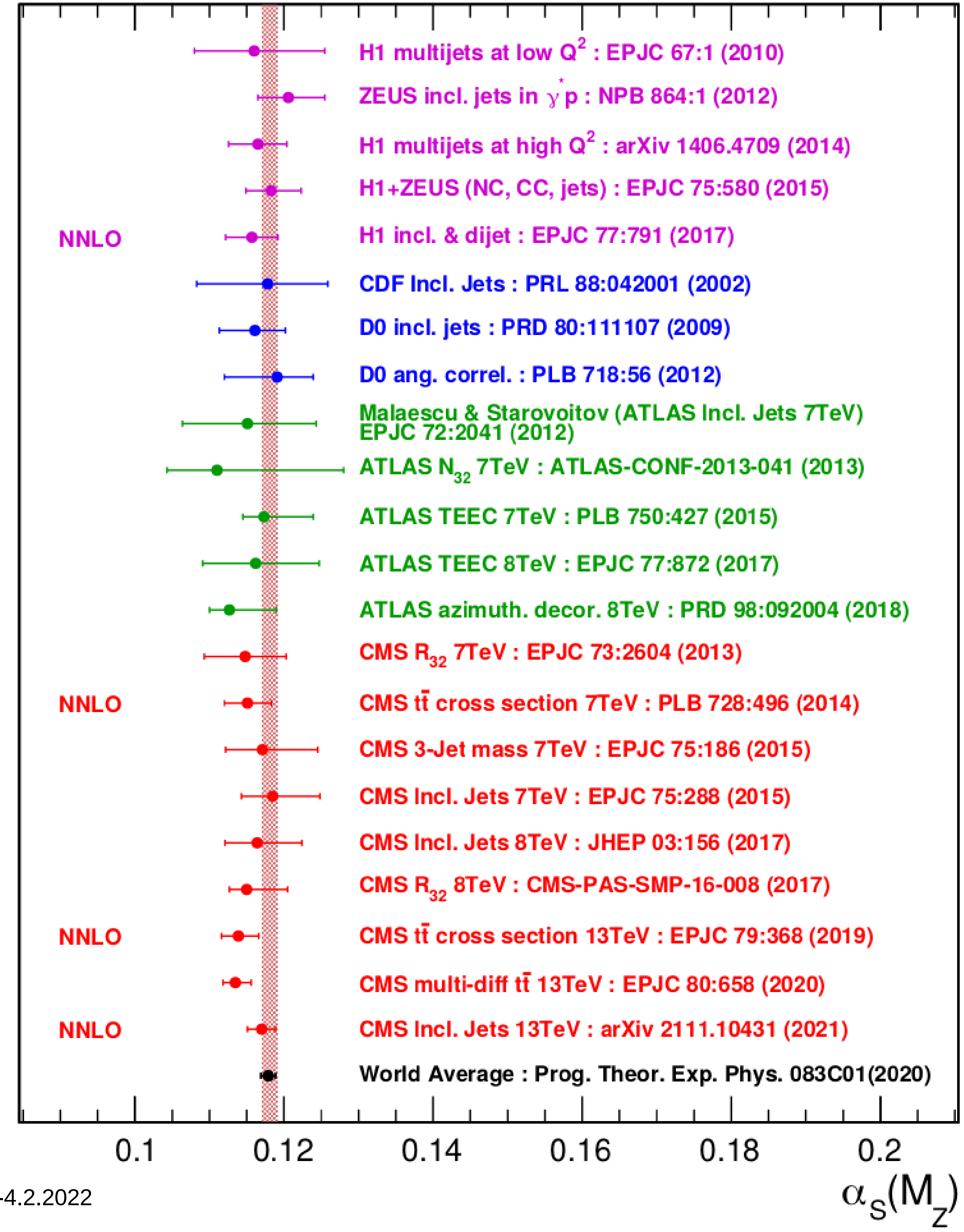
Summary

- 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. Previous 13 TeV fit, using $t\bar{t}$ data only, resulted in a low $\alpha_S(m_Z)$
    - $\alpha_S(m_Z)$ comes closer to world average when jet data included
  - SMEFT fit performed at NLO with simultaneous extraction of PDFs, α_S, m_t and CI Wilson coefficient c_1, ensuring an unbiased CI search
    - Data are well described by the SM, no significant deviation observed
- Overall, good agreement with previous results and world averages

Summary

The NNLO analysis has resulted in the most precise measurement of the strong coupling constant to date:

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



Thanks for listening!

Backup: CI contribution illustration