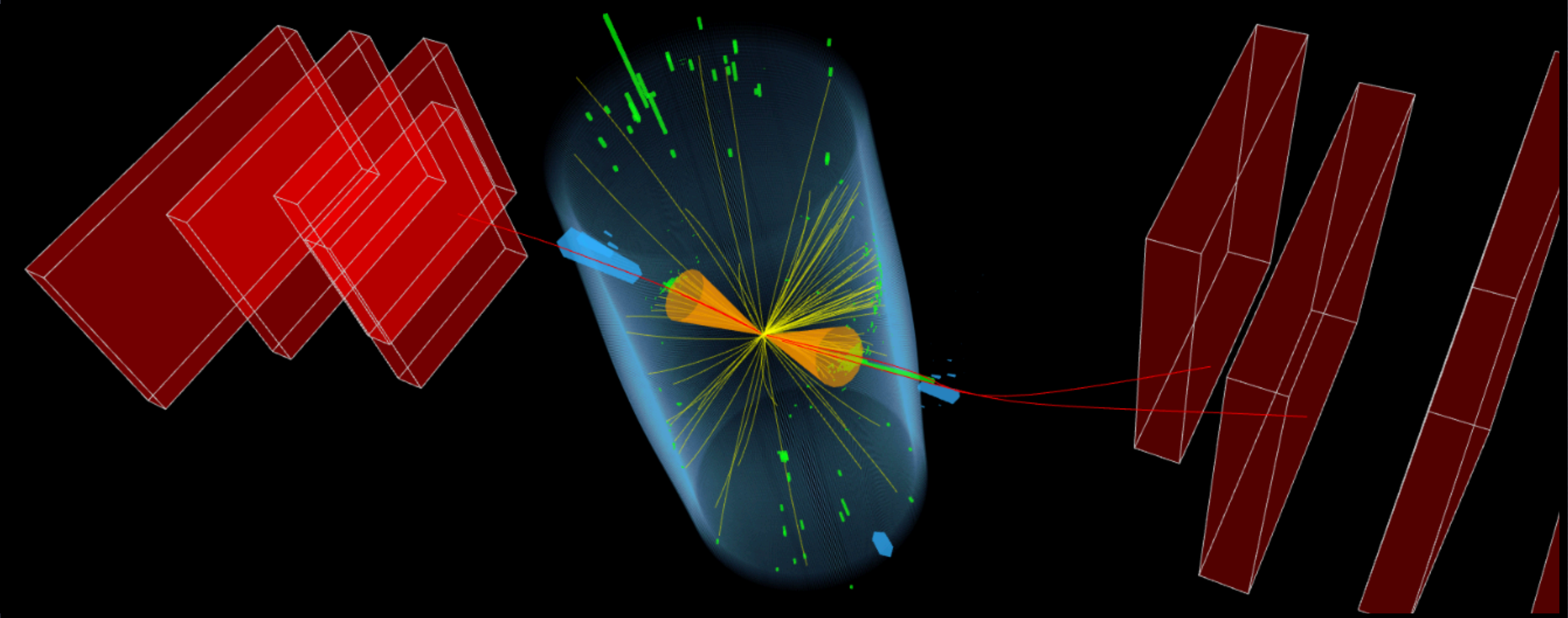
CMS news on $\alpha_S(m_Z)$ and the PDFs using inclusive jets and $t\bar{t}$ cross sections



CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-27 14:40:45

Katerina Lipka

LHC EWK meeting 29. November 2021

HELMHOLTZ
SPITZENFORSCHUNG FÜR
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BERGISCHE
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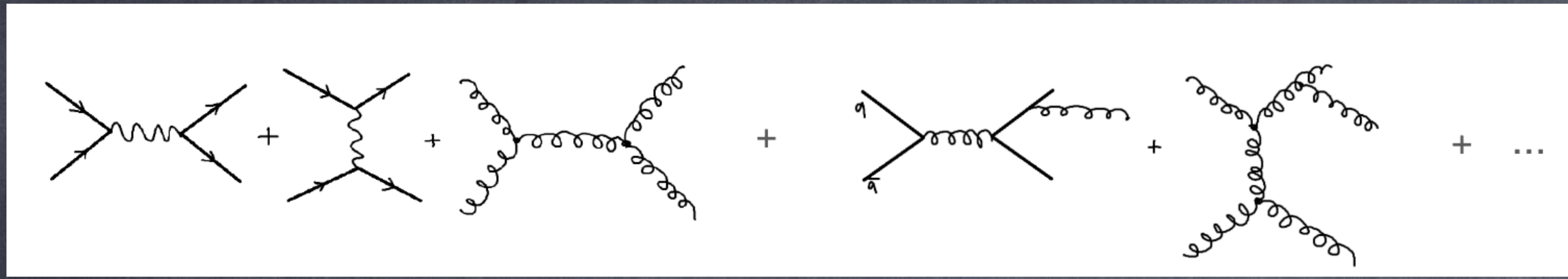
WUPPERTAL

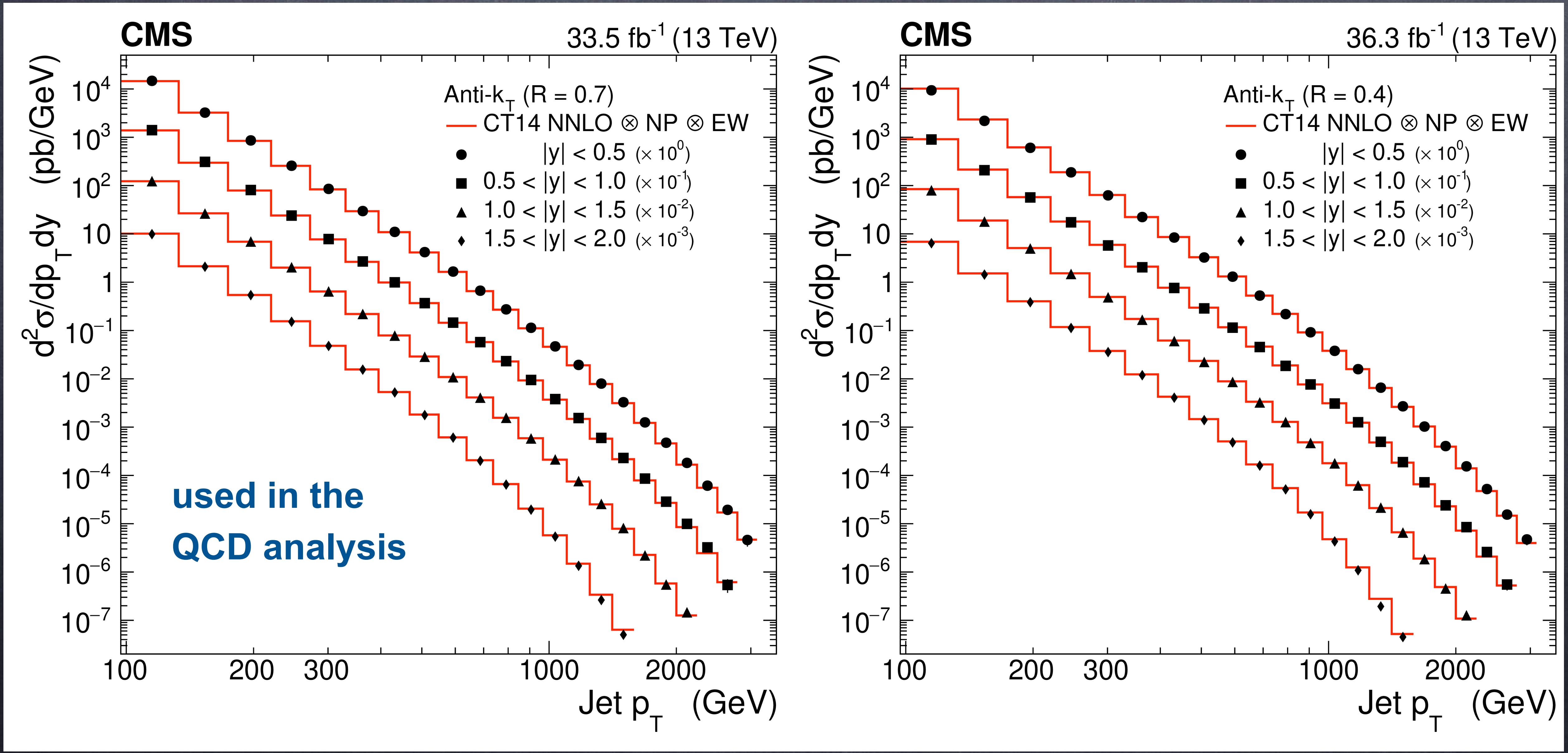
JET PRODUCTION AT LHC: PROBE OF SM



PDFs and $\alpha_S(m_Z)$

New CMS measurement: inclusive jets at 13 TeV: arXiv:2111.10431

2-differential cross sections vs jet p_T and y



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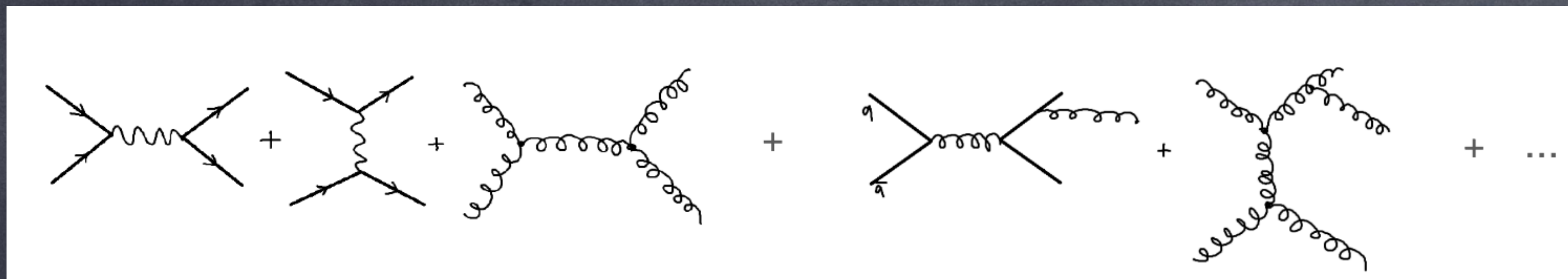

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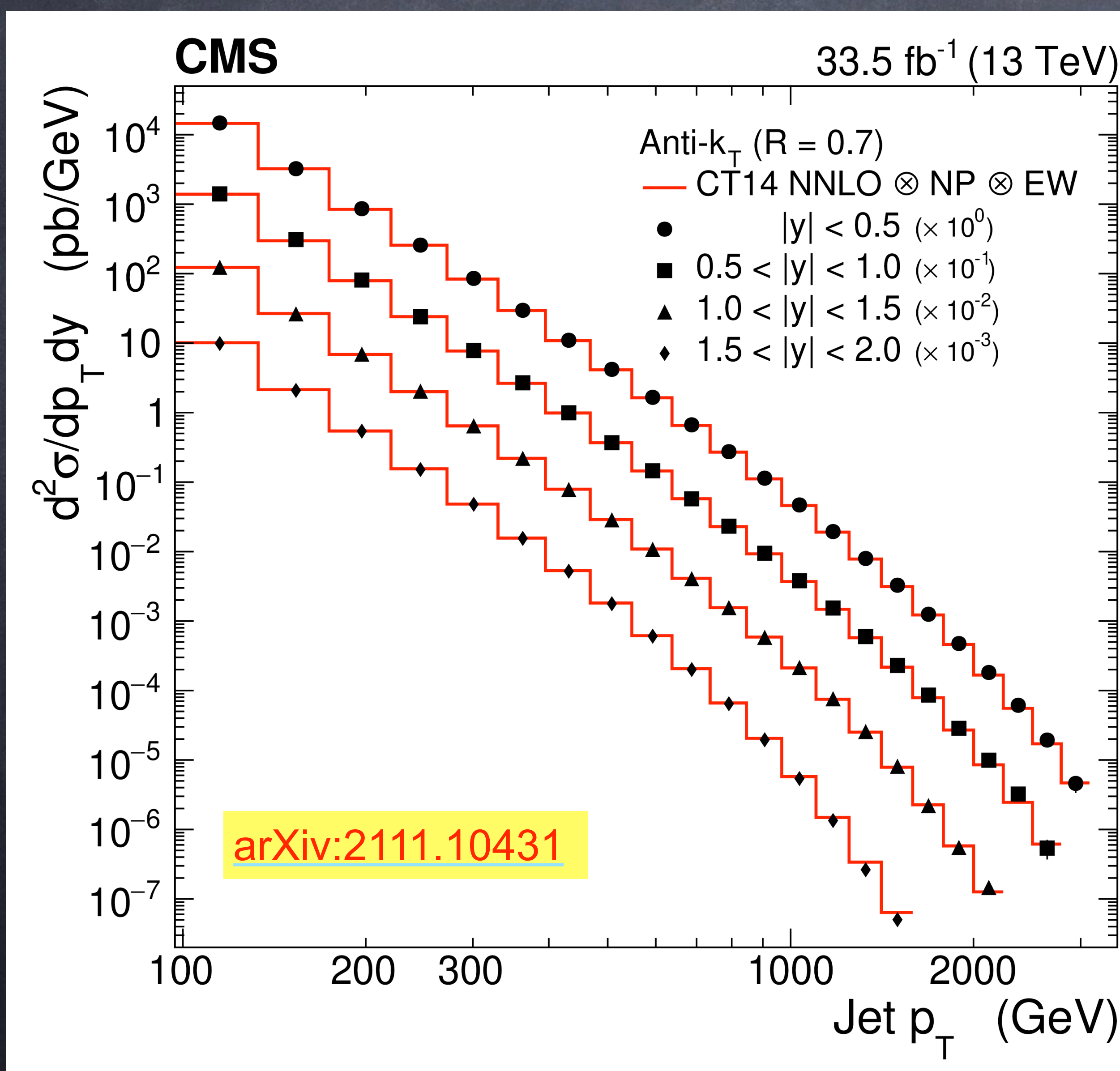
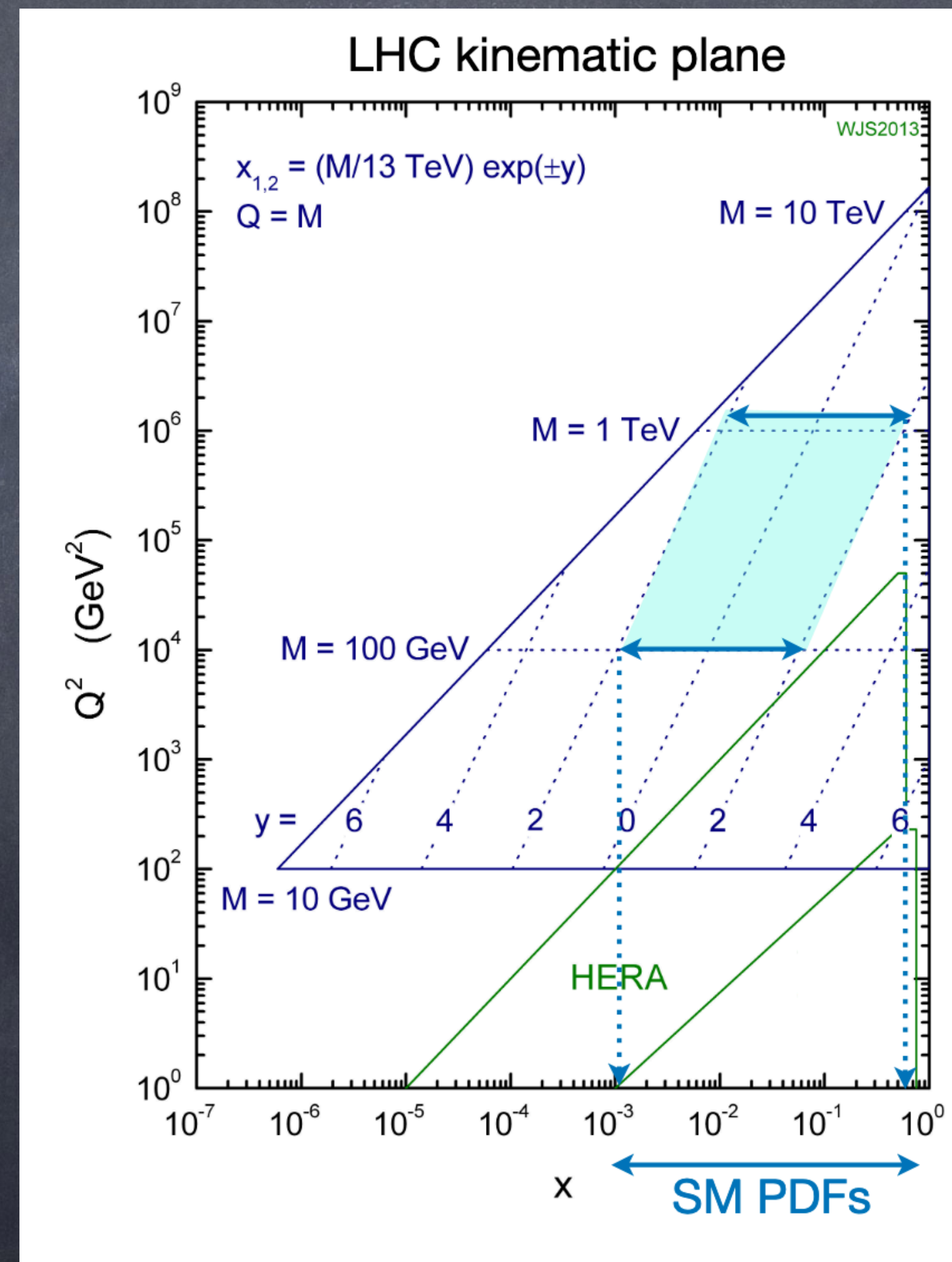
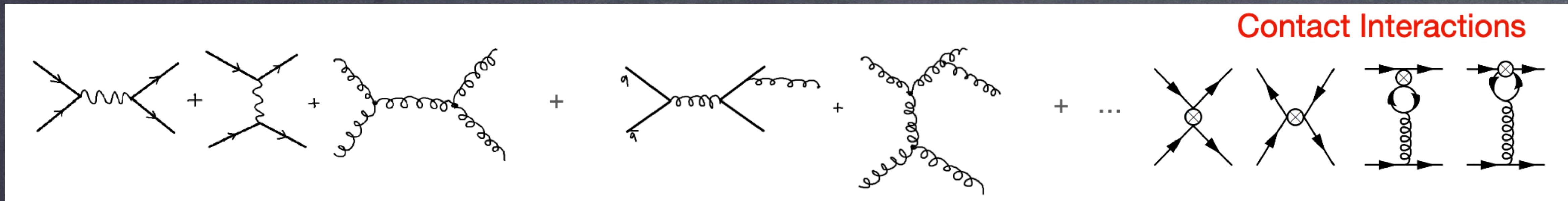
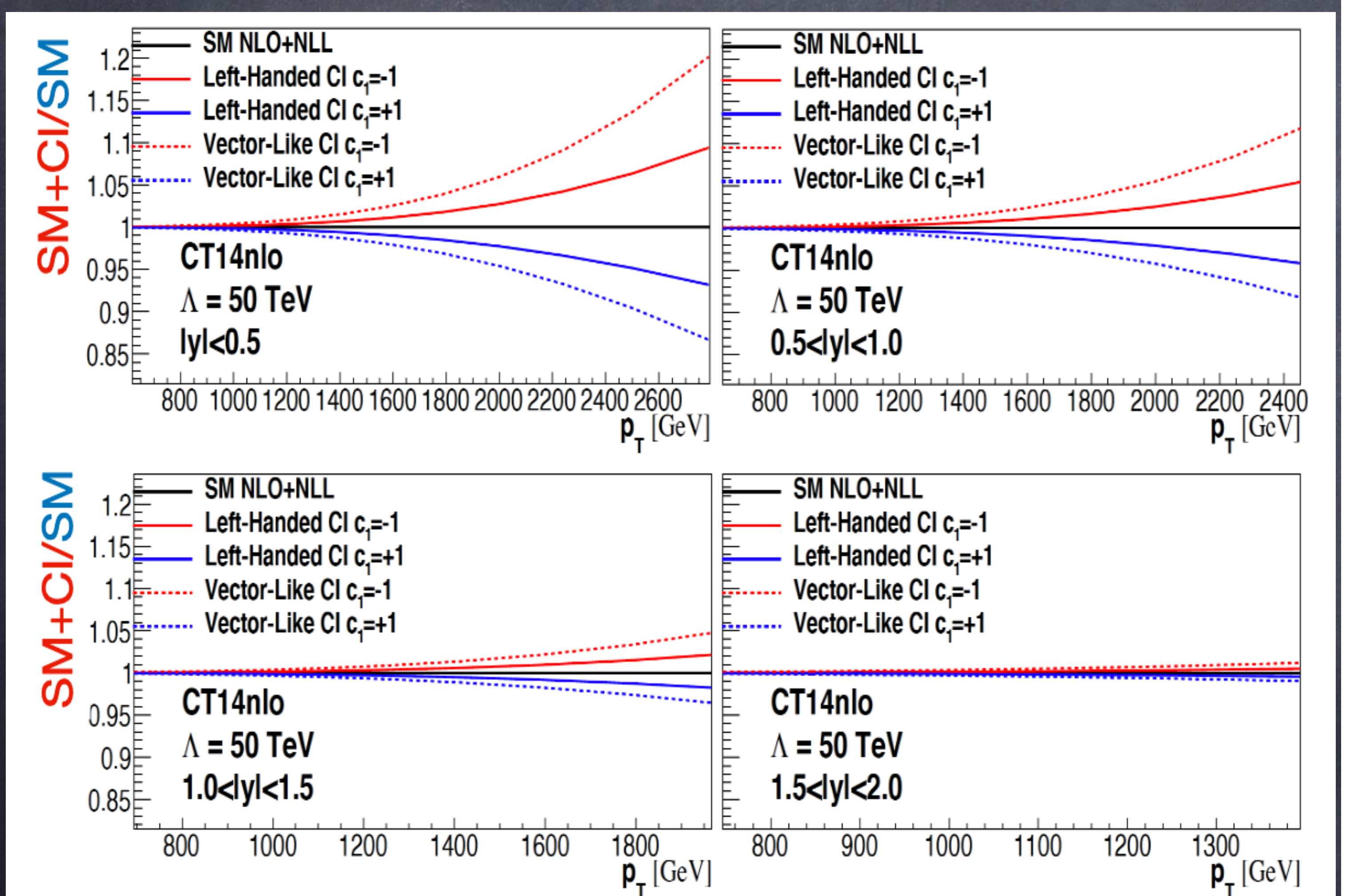




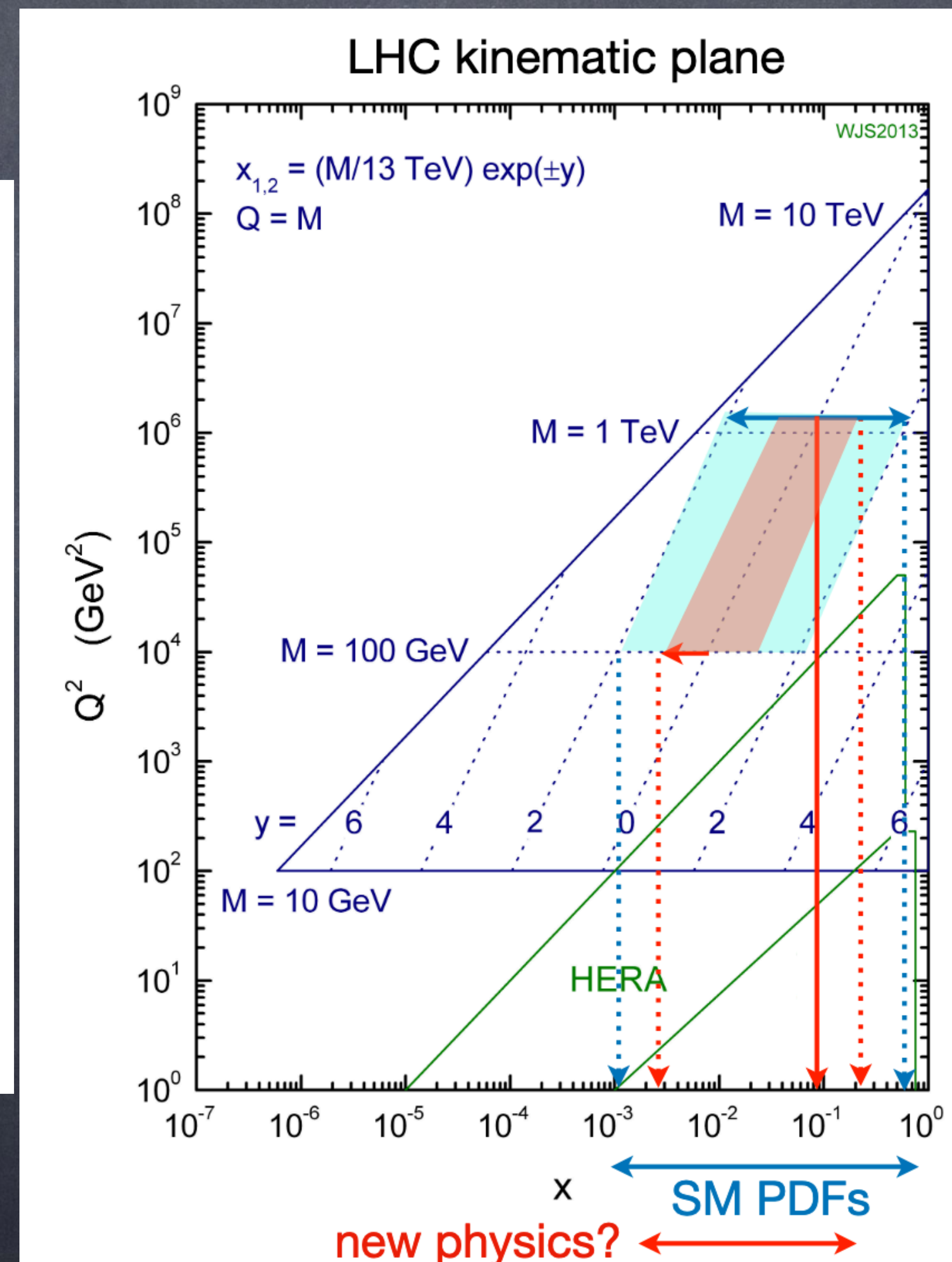
JET PRODUCTION AT LHC: PROBE OF SM + CI



CI expected to show up at high p_T and central y:

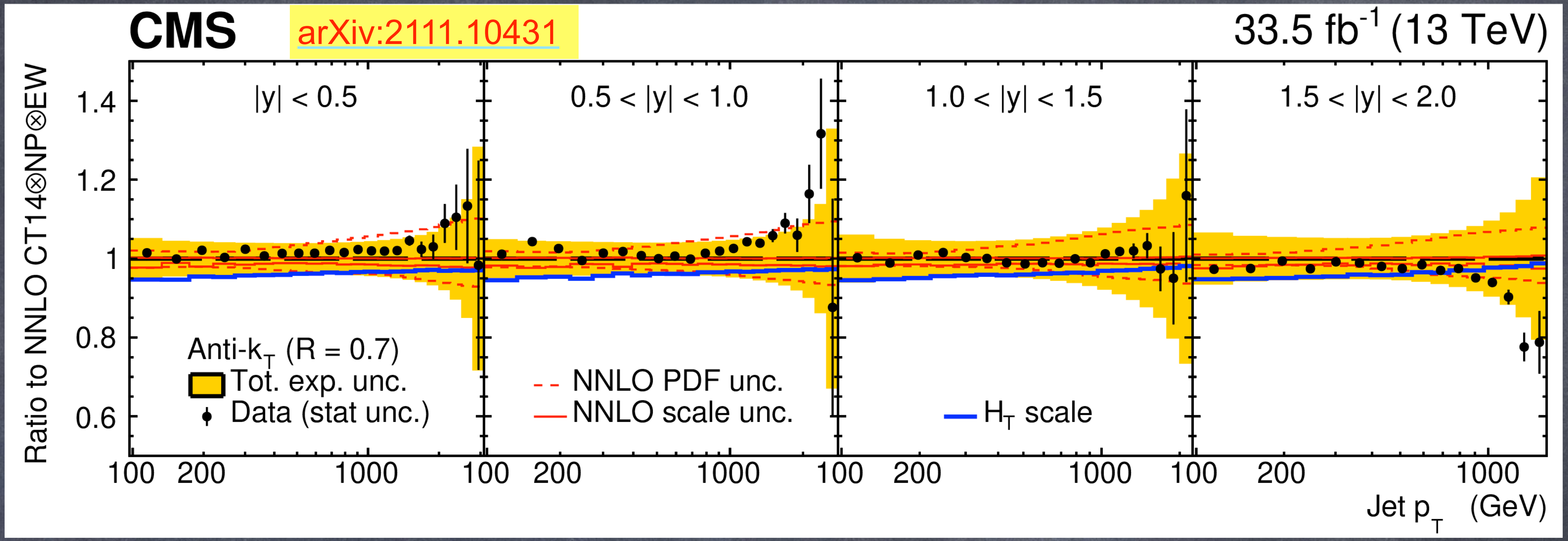


[J. Gao, CIJET arXiv:1301.7263]



JET PRODUCTION AT LHC vs QCD

data vs NNLO

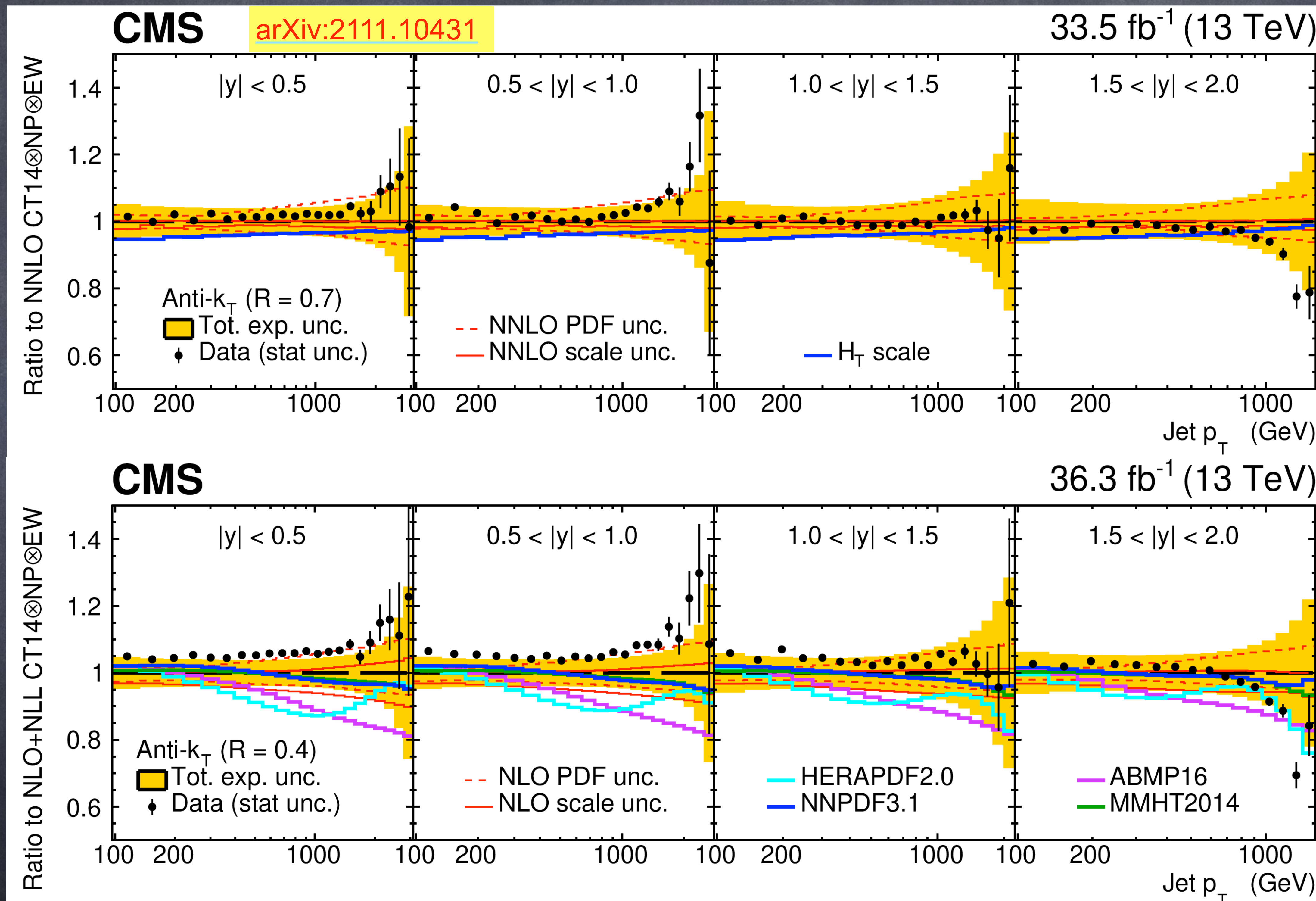


NNLO: [Currie, Glover, Pires, PRL118 (2017) 072002]
[Currie et al. , JHEP 10 (2018) 155]
[T. Gehrmann et al.,PoS RADCOR2017 (2018) 074]
NLOJet++ [Z. Nagy PRL 88 (2002) 122003, PRD 68 (2003) 094002]
fastNLO [D. Britzger, K. Rabbertz, F. Stober, M. Wobisch, arXiv:1208.3641]

JET PRODUCTION AT LHC vs QCD

data vs NNLO

data vs NLO+NLL



NLL resummation [Liu, Moch, Ringer, arXiv:1801.07284]
[J. Gao et al., arXiv:1207.0513]

dominant uncertainty: PDF

EXPLORE SENSITIVITY TO SM / SM+CI

- **Investigate the impact of the measurement on the global PDF**
- **Perform a full QCD fit : extract simultaneously PDF and QCD parameters**
- **Perform a full SMEFT fit : extract simultaneously PDF and QCD parameters + CI coefficients**

General idea of a full QCD analysis:

- parameterise PDFs at a starting scale μ^2_0 : $f(x)=Ax^B(1-x)^C(1+Dx+Ex^2)$

  A: normalisation, **B**: small-x behaviour, **C:** $x \rightarrow 1$ shape
- evolve these PDFs to $\mu^2 > \mu^2_0$
- strong coupling, quark masses, can be added as parameters
- construct cross sections from PDFs and partonic cross sections:

  SM/SMEFT predictions for every data point in (x, μ^2) – plane
- χ^2- fit to the experimental data → determine PDF parameters, $\alpha_S(m_Z)$, m_q, …
- NB: PDFs can not be obtained from LHC data alone, use DIS data as a basis

QCD analysis platform xFitter is used: https://www.xfitter.org/xFitter/

EXPLORE SENSITIVITY TO PDF

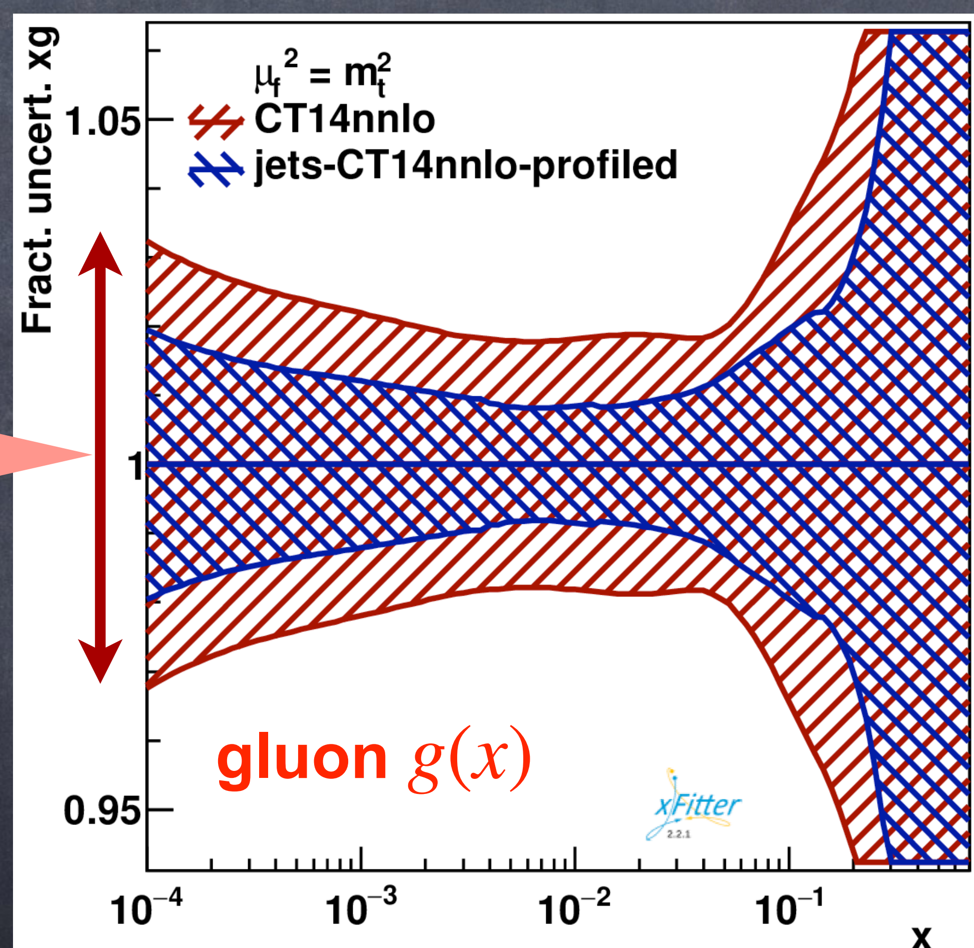
- **Investigate the impact of the measurement on the global PDF (here: CT14)**

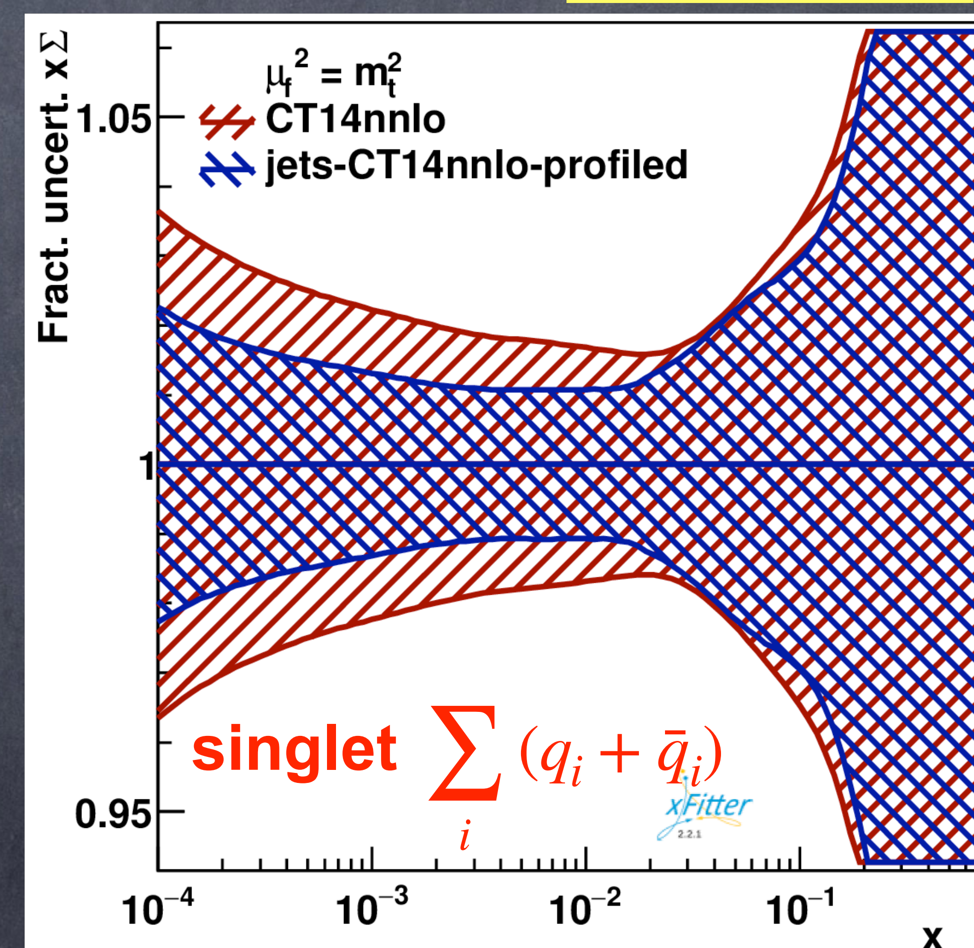
“profiling” analysis [details e.g. J. Pumplin et al arXiv:1806.07950]

- **minimise χ^2 function, based on nuisances of experimental and theory uncertainties**
- **result: profiled PDFs with respect to the original ones**

arXiv:2111.10431

uncertainty in original PDF





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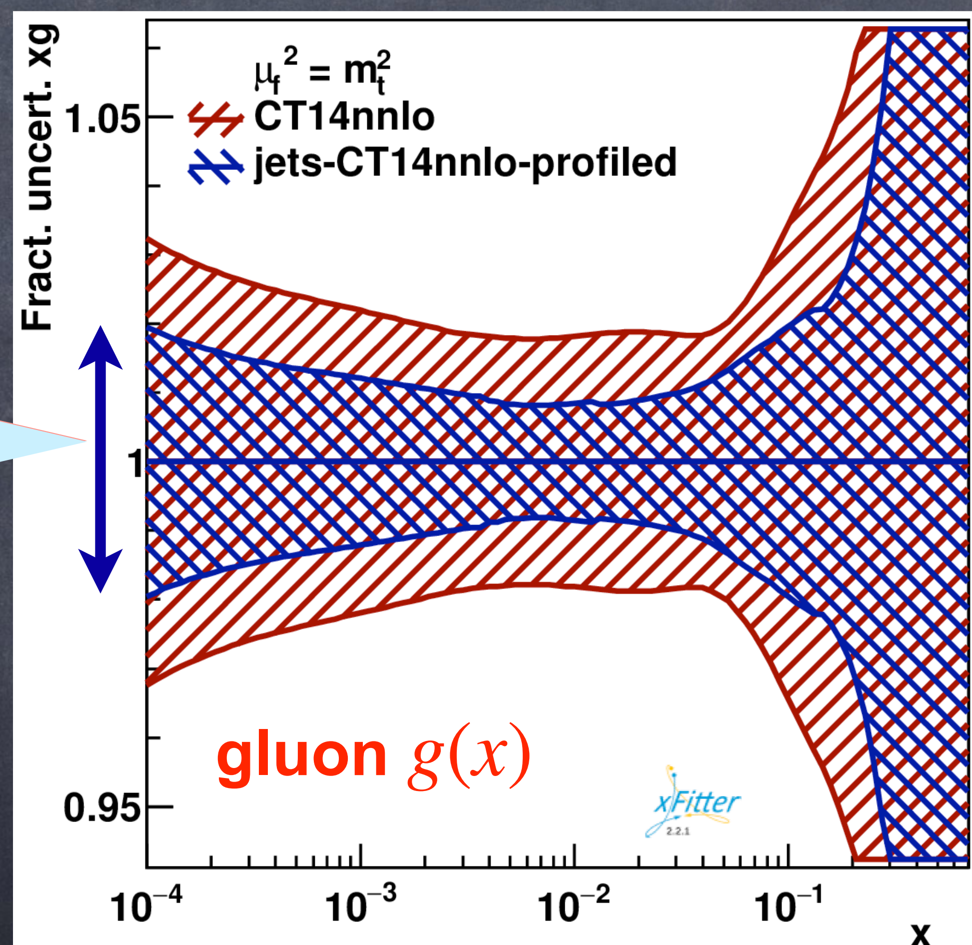
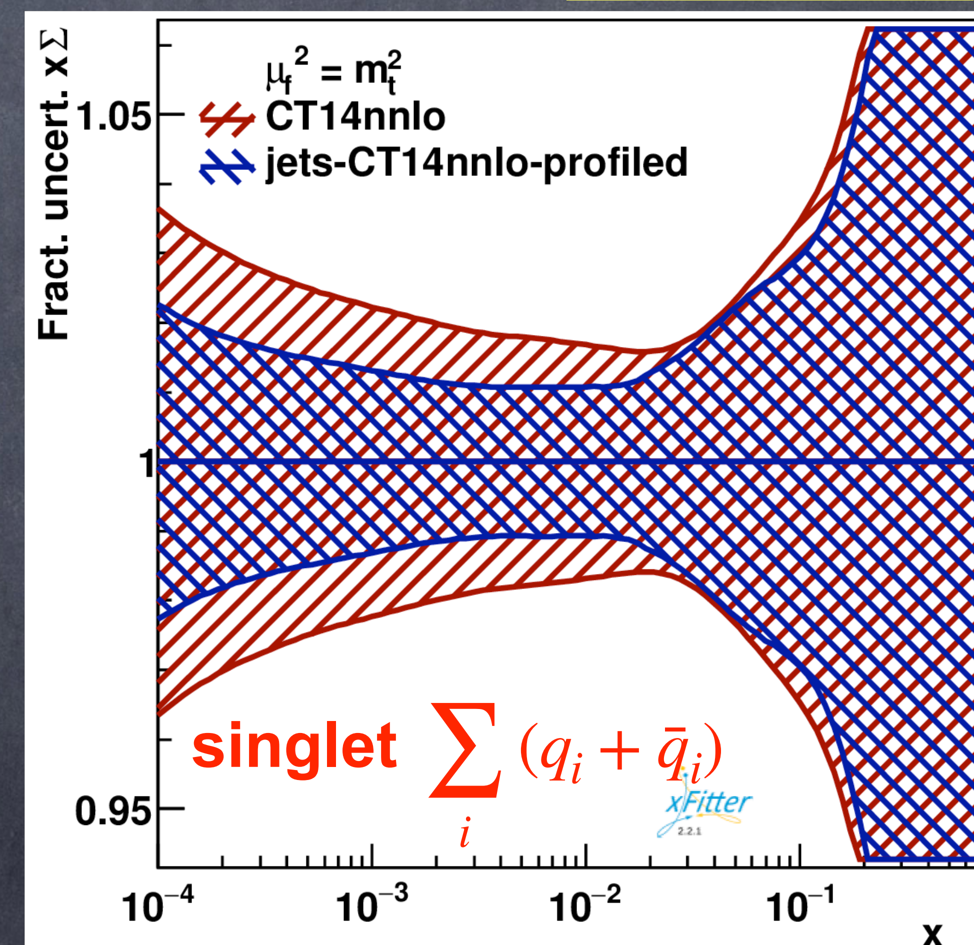
arXiv:2111.10431

improved by jet data

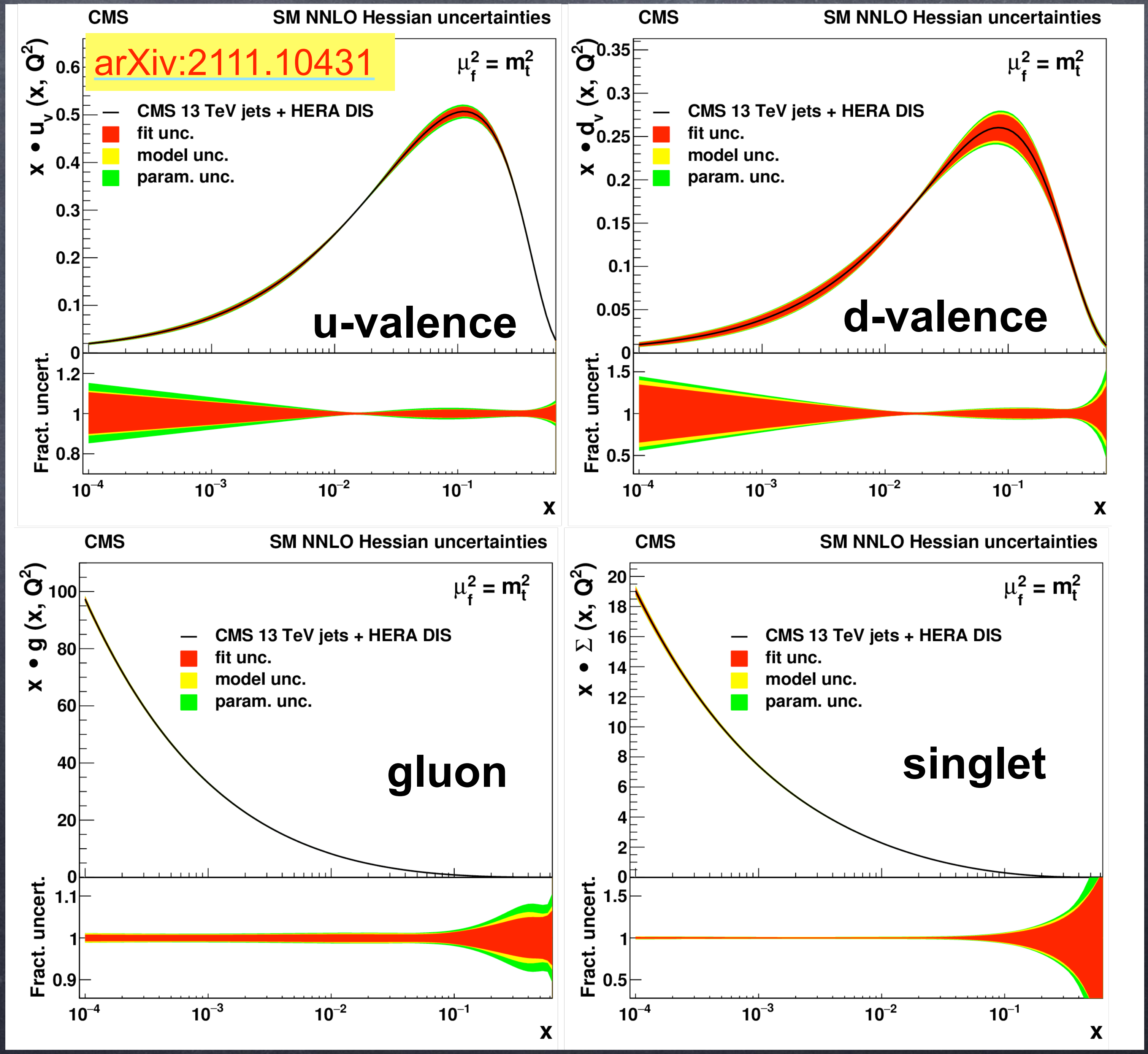




Significant improvements in PDF uncertainties expected for global PDF analyses

EXPLORE SENSITIVITY TO PDF + α_s at NNLO

- **Full QCD fit at NNLO:** basis data - ep inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]: **sensitivity to PDF and α_S**
- **NNLO predictions obtained via fasNLO grids using NNLO k-factors**
  - **PDF + uncertainties from:**
    - uncertainties in exp. data
    - assumed m_c, m_b, f_S, scale variation
    - uncertainties in parametrisation



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- **NNLO predictions obtained via fasNLO grids using NNLO k-factors**

  - **PDF + uncertainties from:**

    uncertainties in exp. data

    assumed m_c, m_b, f_S, scale variation

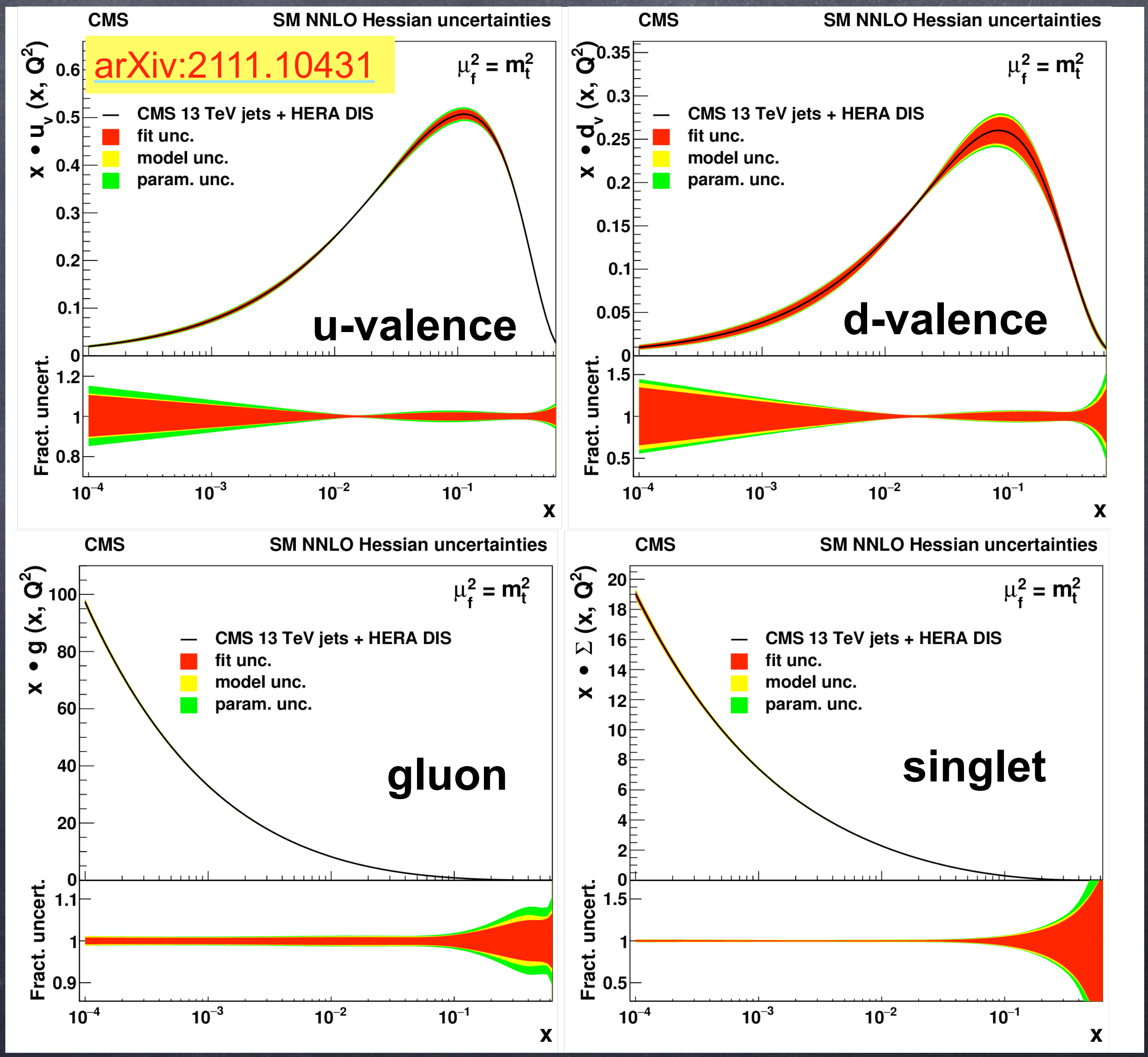
    uncertainties in parametrisation

  - **Strong coupling constant**

$$\alpha_S(m_Z) = 0.1170 \pm 0.0019$$

$$0.0014_{fit} \pm 0.0007_{model} \pm 0.0008_{scale} \pm 0.0001_{param}$$

PDF and $\alpha_s(m_Z)$ obtained simultaneously !



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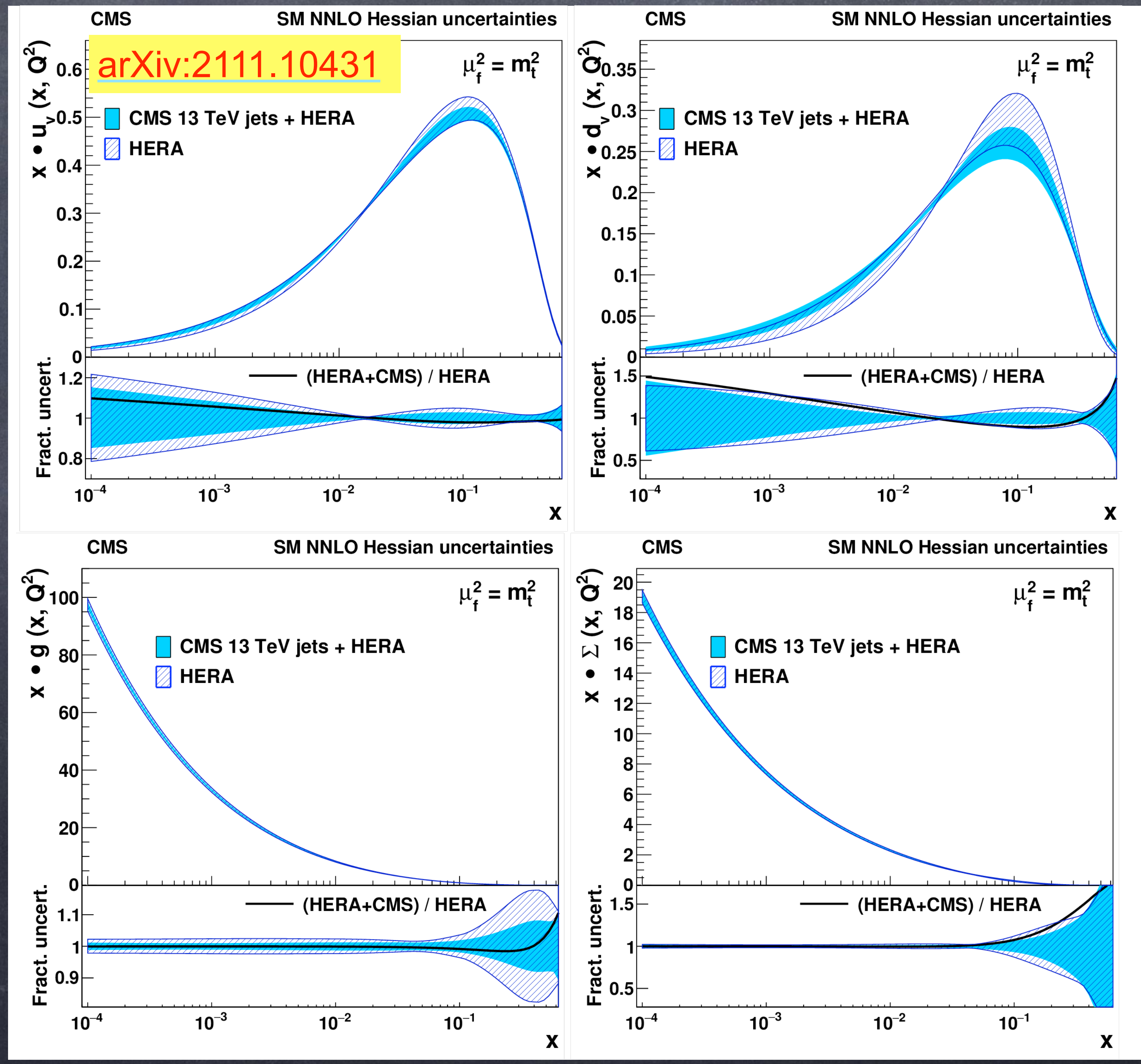
- **NNLO predictions obtained via fasNLO grids using NNLO k-factors**
  - **PDF + uncertainties from:**
    - uncertainties in exp. data
    - assumed m_c, m_b, f_S, scale variation
    - uncertainties in parametrisation
  - **Strong coupling constant**

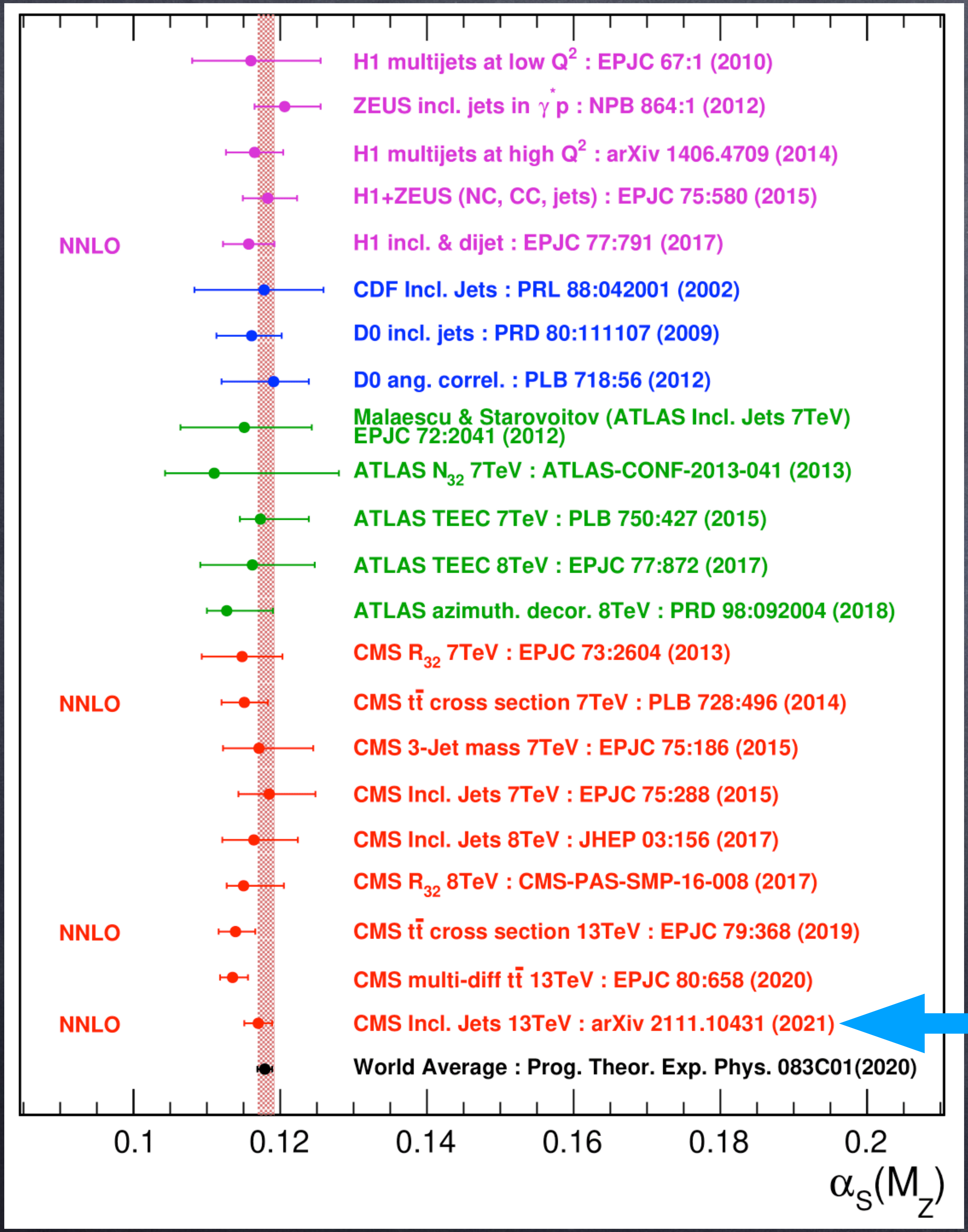
$$\alpha_S(m_Z) = 0.1170 \pm 0.0019$$

  - **compared to HERA-only fit:**

Improved precision of the gluon at high x !



New $\alpha_s(m_Z)$ value on the landscape of earlier results



most precise single measurement
(error 1.6%)
mitigated dependence on PDFs

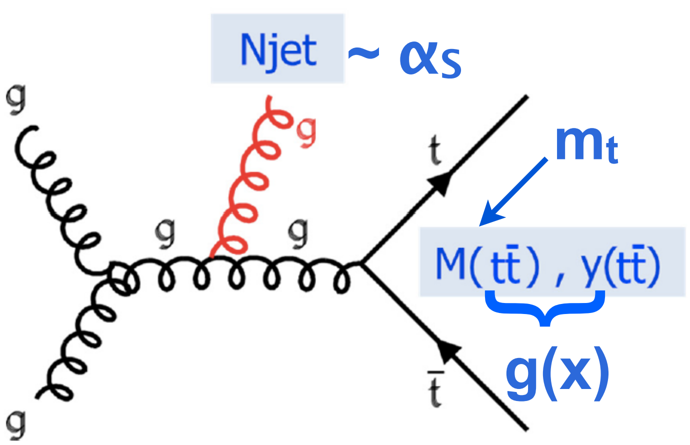
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

EXPLORE SENSITIVITY TO PDF + α_s + m_q at NLO

- **Full QCD fit at NLO:** basis data - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]

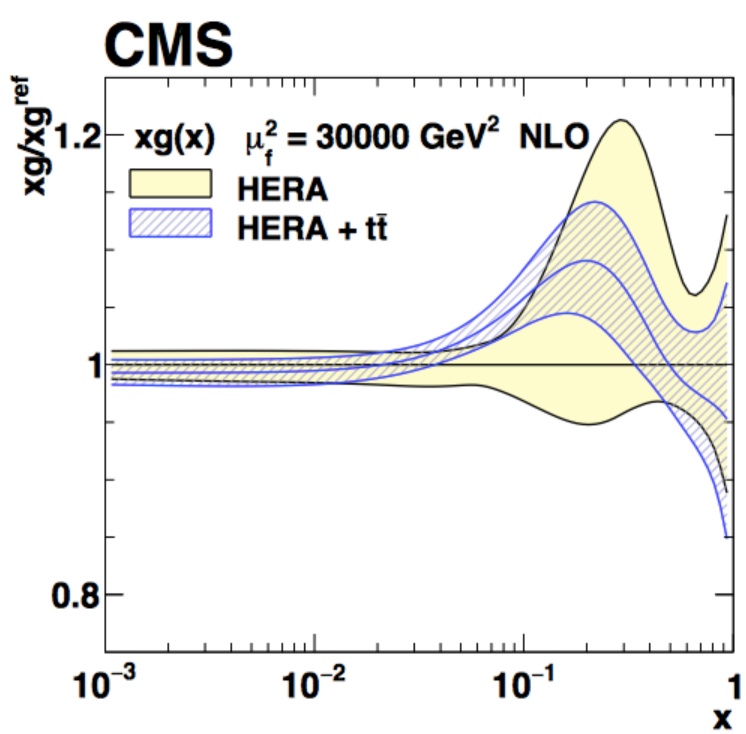
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]: **sensitivity to PDF and α_S**

  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]: **m_t + additional sensitivity to α_S**

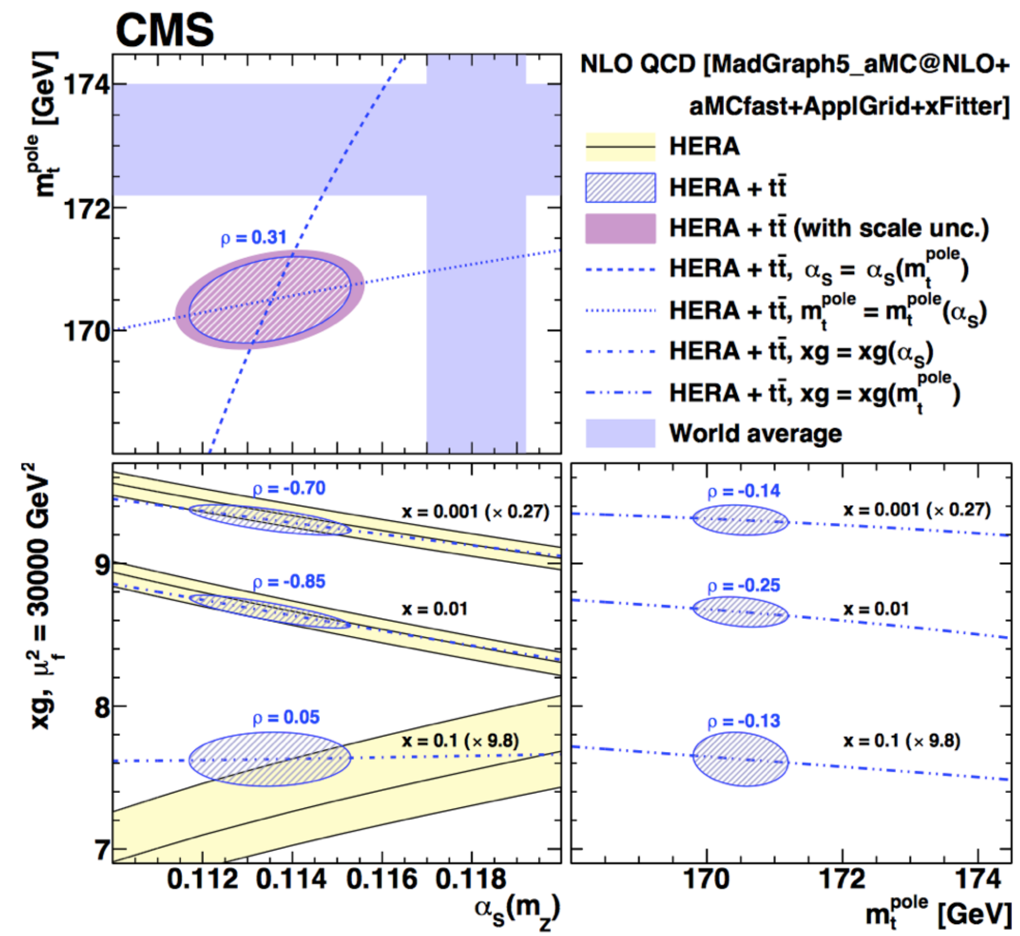


cross section measured in 3-d : $M_{t\bar{t}}, y_{t\bar{t}}, N_{jet}$

gluon precision improved



correlations of g(x) mt, αS reduced



PDFs, $\alpha_S(M_Z)$, m_t^{pole} extracted simultaneously:

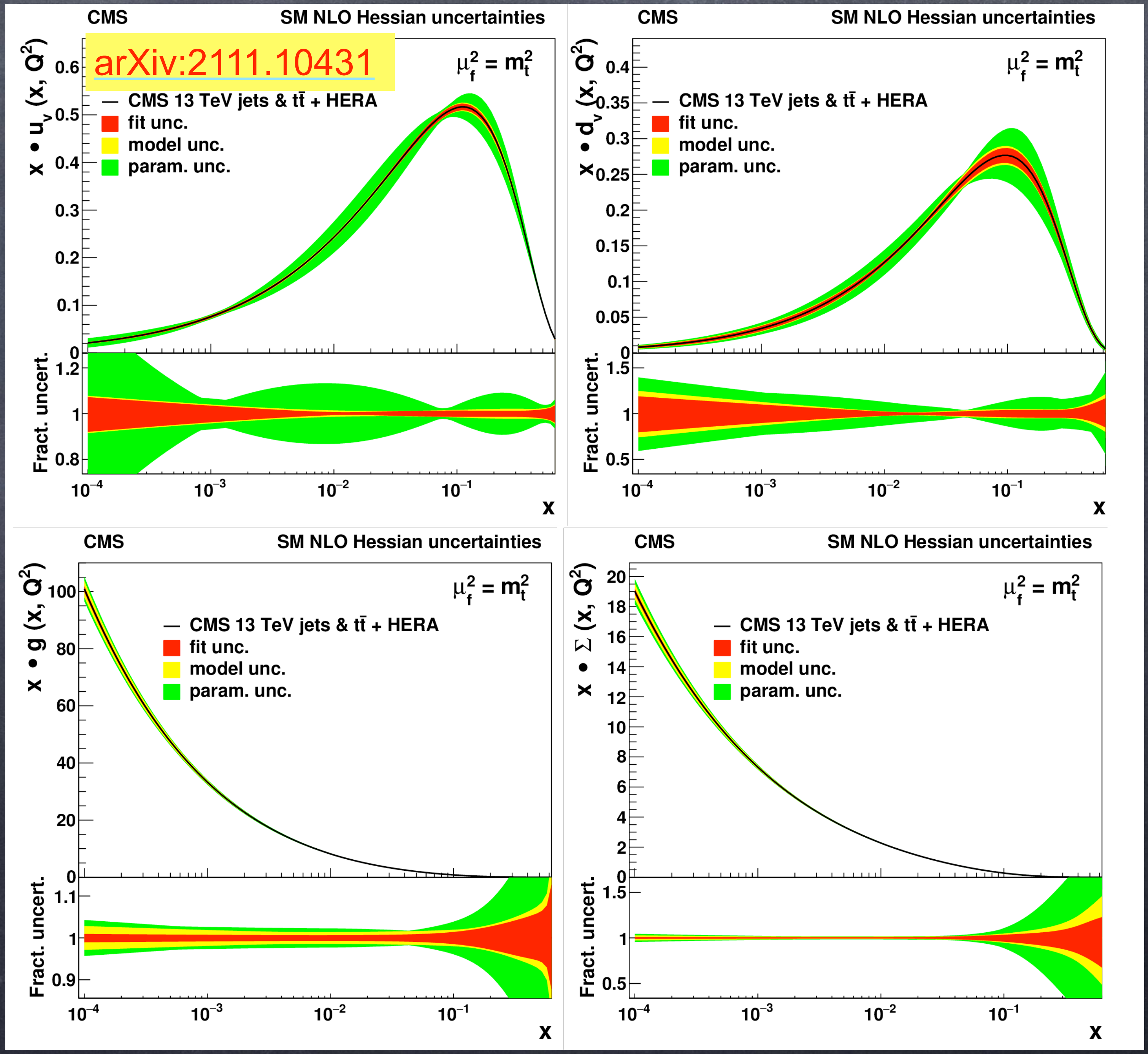
$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{model})^{+0.0008}_{-0.0001}(\text{param})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total}),$$

$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\,\text{GeV} = 170.5 \pm 0.8(\text{total})\,\text{GeV}.$$

EXPLORE SENSITIVITY TO PDF + α_s + m_q at NLO

- **Full QCD fit at NLO:** basis data - ep inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]: **sensitivity to PDF and α_S**
  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]: m_t **+ additional sensitivity to α_S**

- **PDF + uncertainties from:**
  uncertainties in exp. data
  assumed m_c, m_b, f_S, scale variation
  uncertainties in parametrisation



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- **PDF + uncertainties from:**

  uncertainties in exp. data

  assumed m_c, m_b, f_S, scale variation

  uncertainties in parametrisation

- **QCD parameters:**

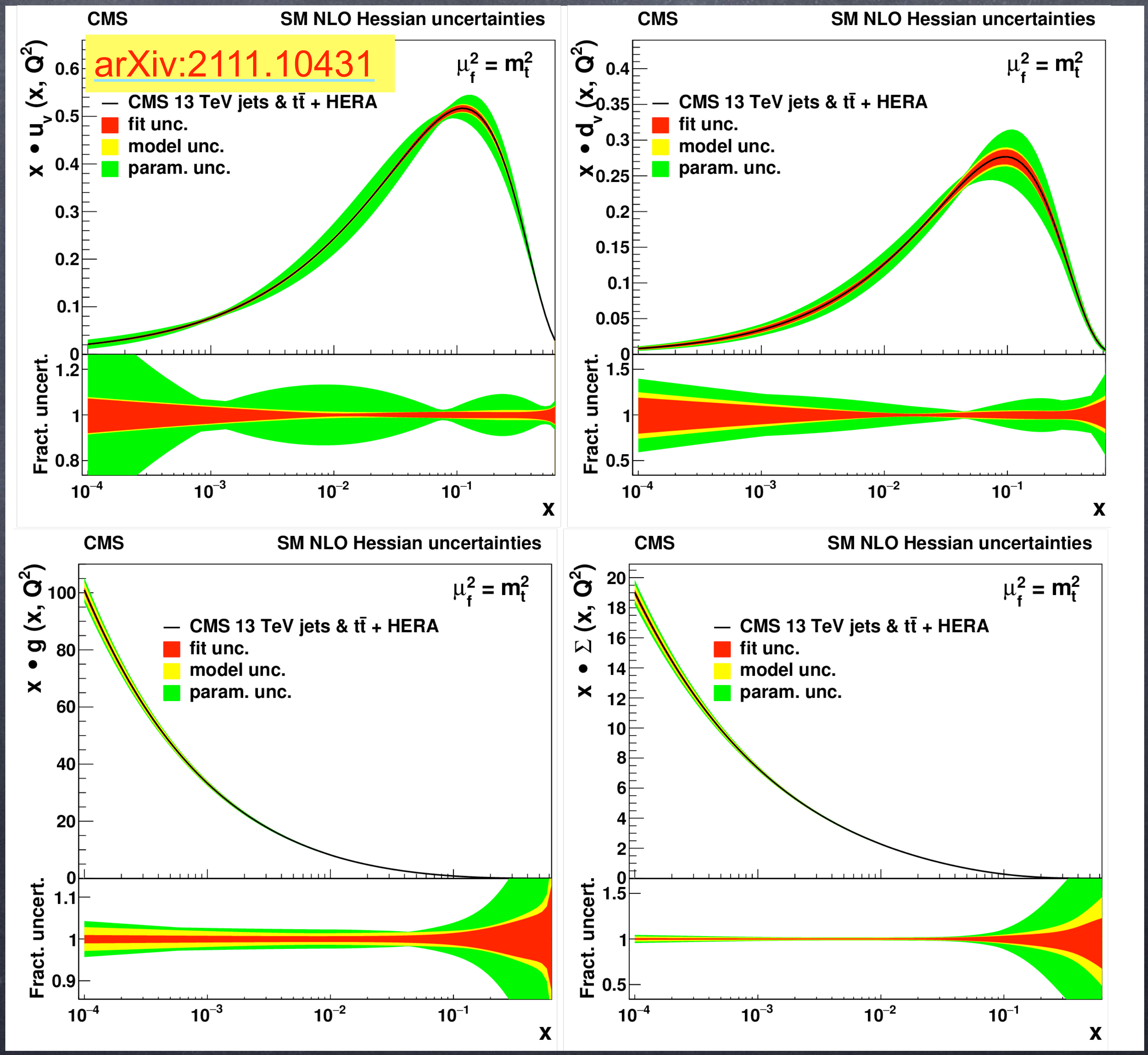
$$\alpha_S(m_Z) = 0.1188 \pm 0.0026$$

$$0.0017_{fit} \pm 0.0025_{scale} \pm 0.0004_{mod} + 0.0001_{param}$$

$$m_t^{pole} = 170.4 \pm 0.7 \text{ GeV}$$

$$0.6_{fit} \pm 0.1_{scale} \pm 0.1_{mod} \pm 0.1_{param}$$

PDF, $\alpha_s(m_Z)$, m_t^{pole} obtained simultaneously !



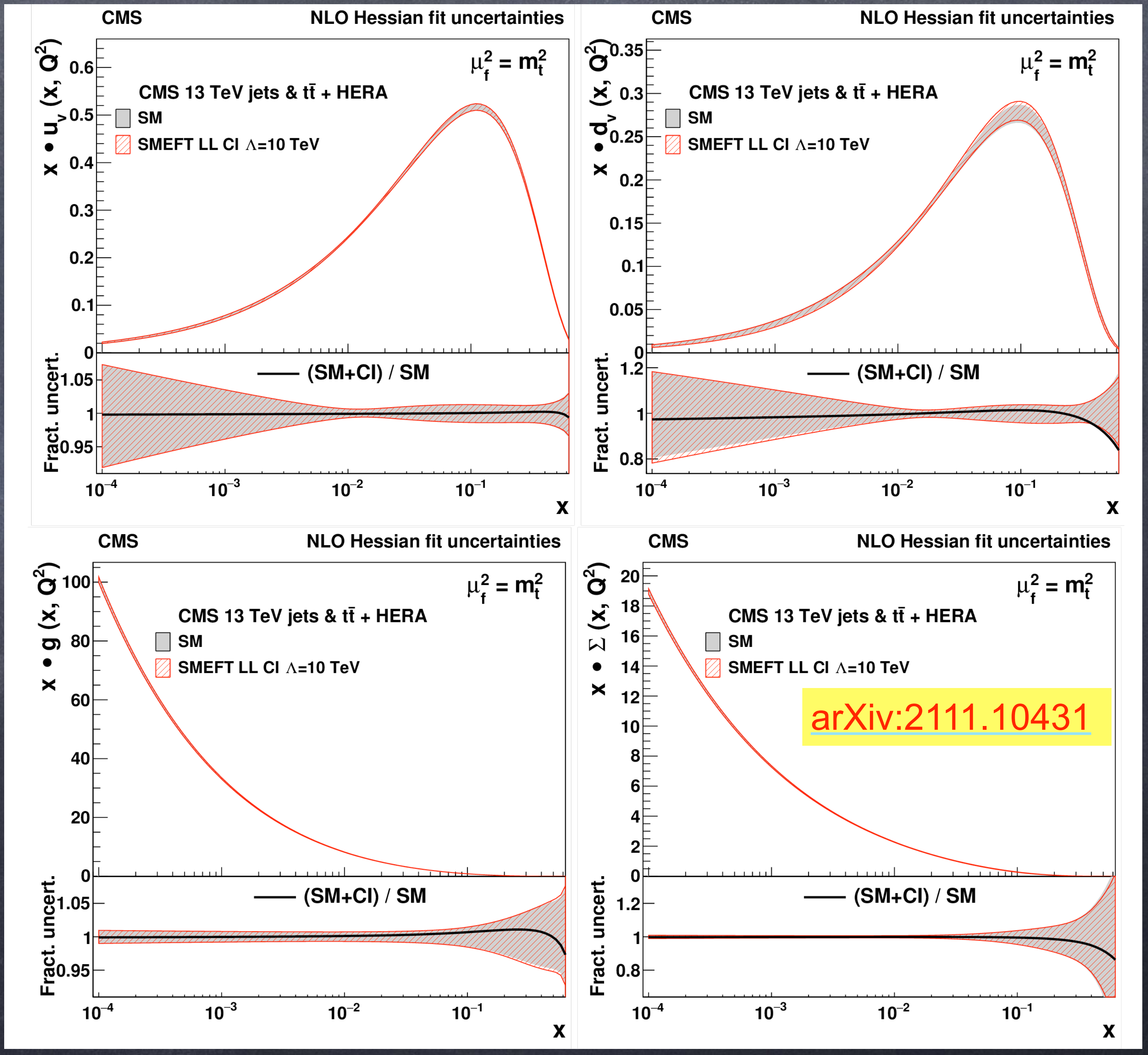
EXPLORE SENSITIVITY TO PDF + α_s + m_q + CI

- **Full QCD fit at NLO:** basis data - ep inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [CMS-SMP-PAS-20-011]: **sensitivity to PDF, α_S + CI**
  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]: **m_t + additional sensitivity to α_S**

SMEFT Solution:

PDFs in SM and SMEFT very similar → no risk of the BSM effects being absorbed in the SM PDF fit

only fit uncertainty shown



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SMEFT Solution:

PDFs in SM and SMEFT very similar → no risk of the BSM effects being absorbed in the SM PDF fit

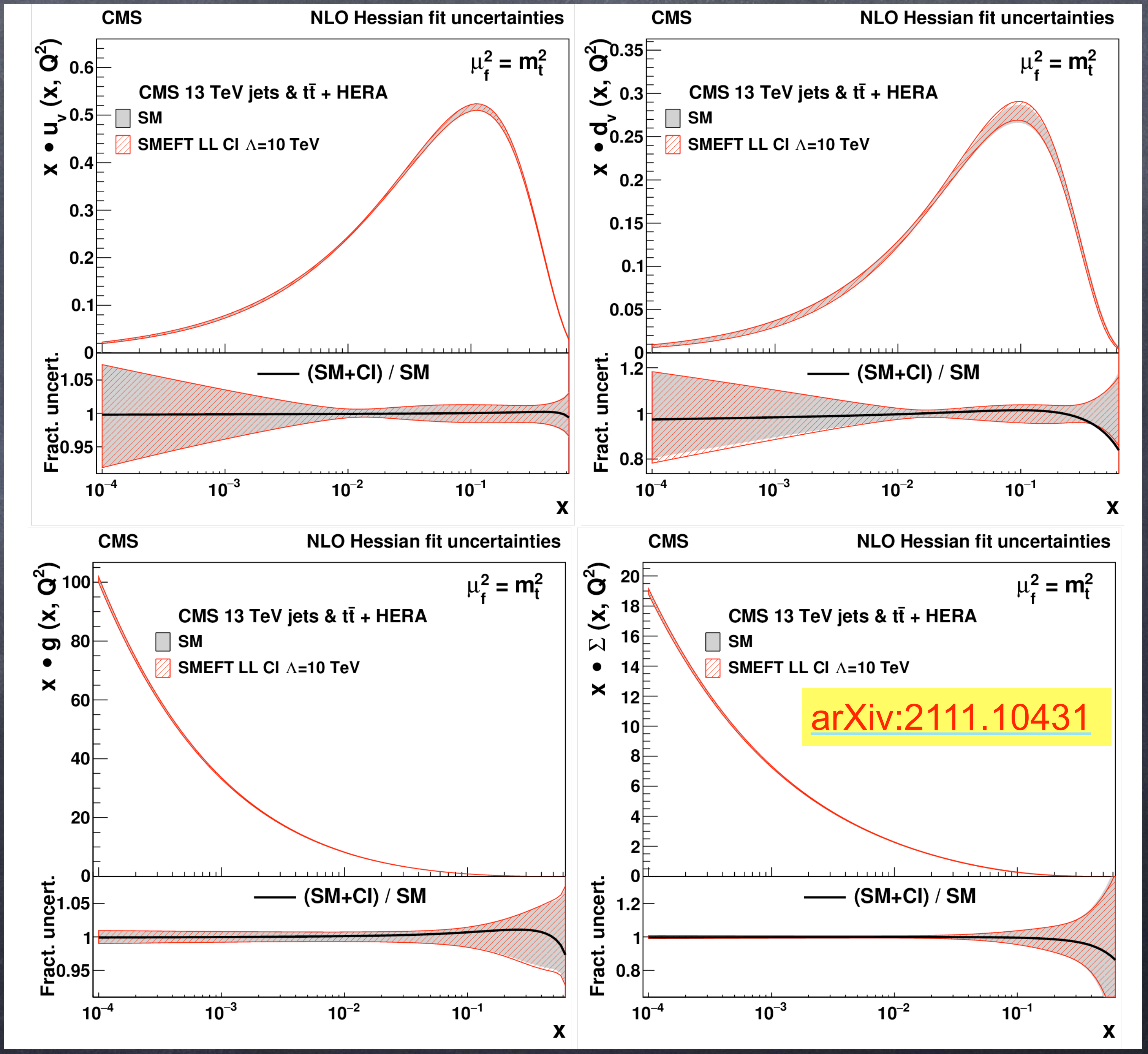
only fit uncertainty shown

- **QCD parameters:**

$$\alpha_S(m_Z) = 0.1187 \pm 0.0033$$

$$m_t^{pole} = 170.4 \pm 0.7 \text{ GeV}$$

very similar to those in SM fit



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- **QCD parameters:**

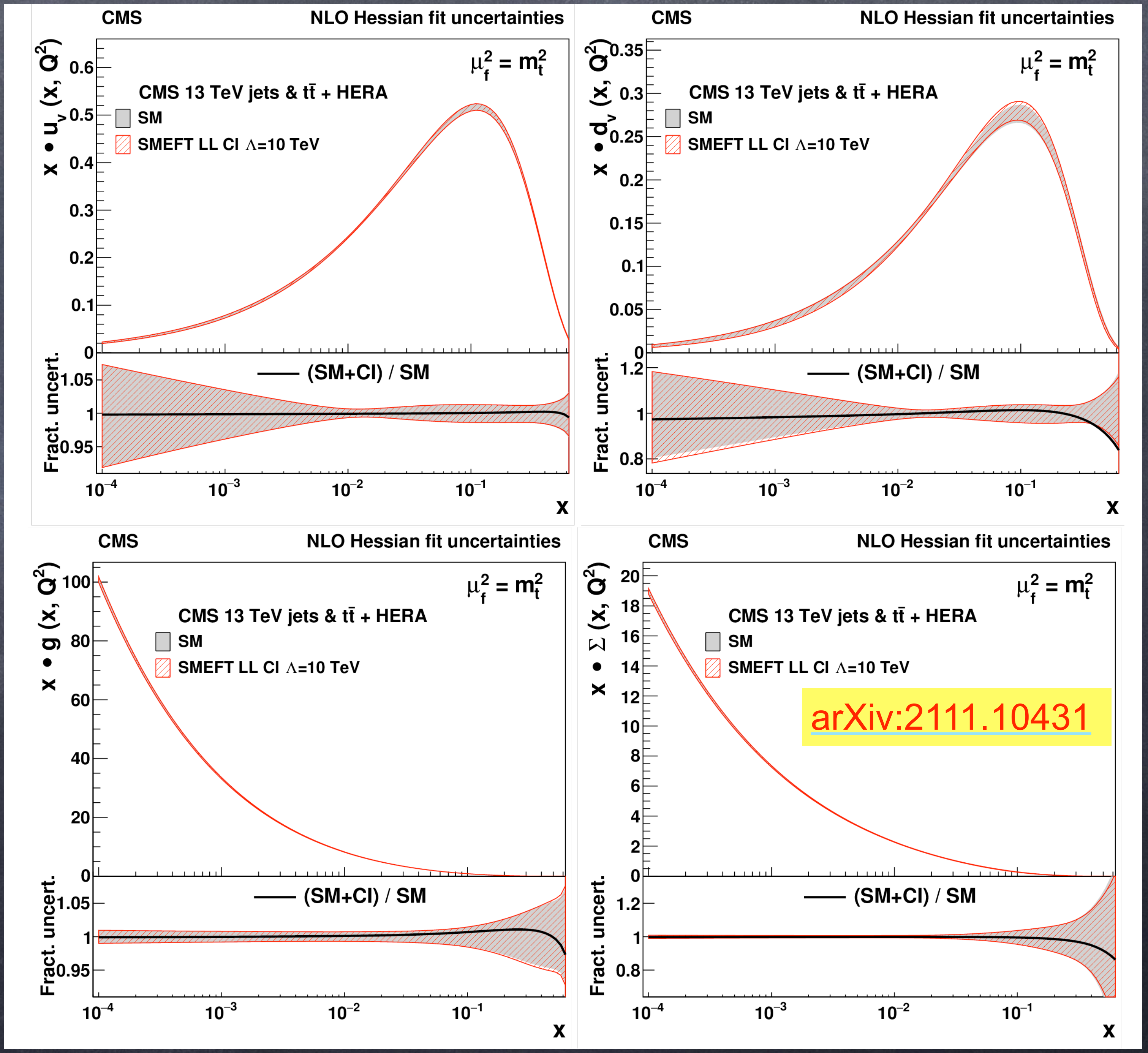
$$\alpha_S(m_Z) = 0.1187 \pm 0.0033$$

$$m_t^{pole} = 170.4 \pm 0.7 \text{ GeV}$$

- **CI parameters (for $\Lambda_{NP} = 10$ TeV):**

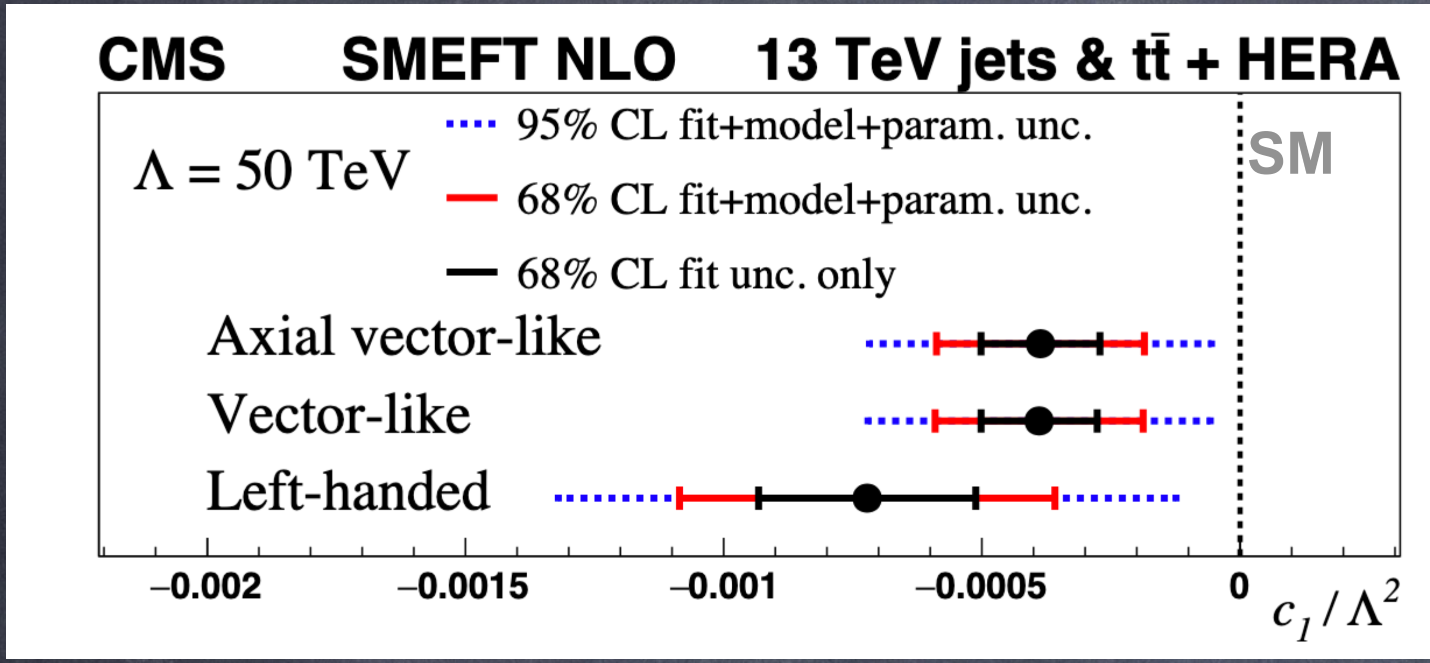
$$c_1^L = -0.07 \pm 0.02_{exp} \pm 0.01_{mod+par}$$

SM +BSM obtained simultaneously !



EXPLORE SENSITIVITY TO PDF + α_s + m_q + CI

SMEFT fit: obtain PDFs, QCD parameters and CI Wilson coefficients simultaneously



Compare to conventional studies:
Λ **scan, fixed** $c_1 = \pm 1$

correspond to 95% exclusion limits for Λ ($c_1 = -1$):

Left-handed : $\Lambda > 24$ TeV

Vector-like: $\Lambda > 32$ TeV

Axial-vector like $\Lambda > 31$ TeV

Agrees well with e.g. ATLAS result [arXiv:1703.09127]
Λ (left-handed CI) > 22 TeV

No significant deviation from SM observed.
BSM constrained in a less QCD-biased way in a SMEFT analysis

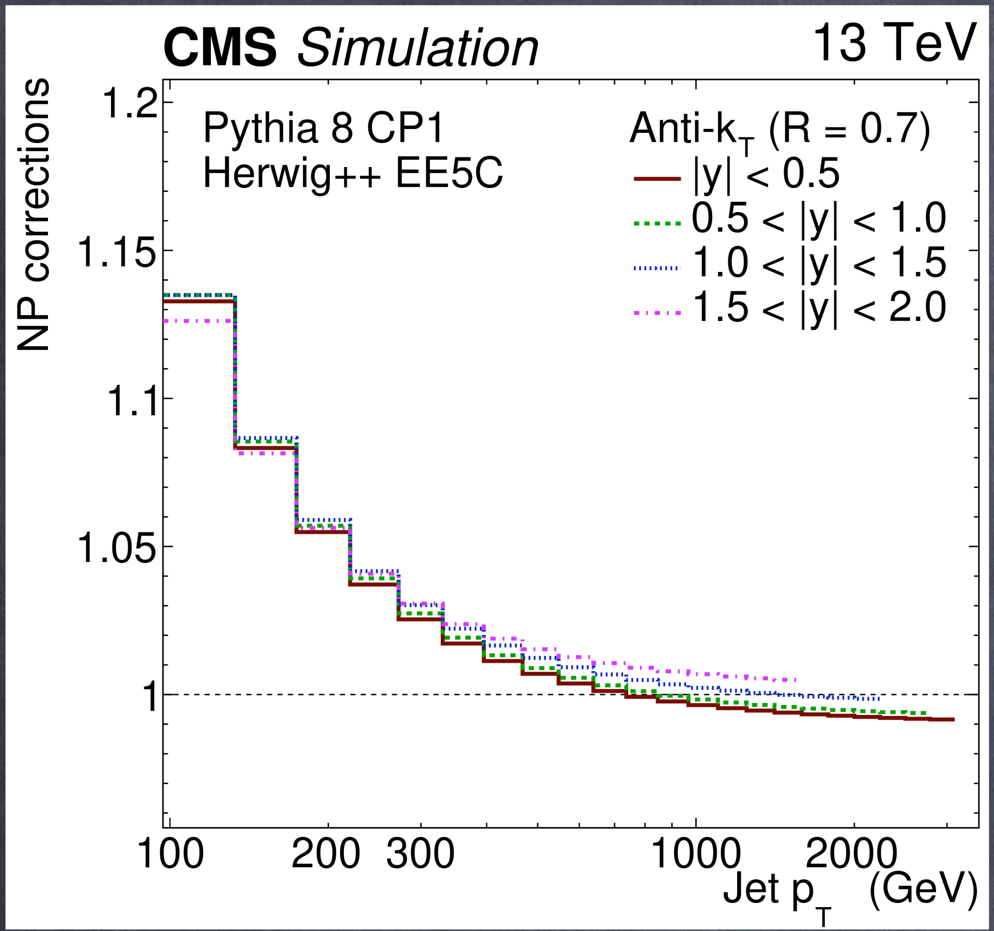
SUMMARY

- New measurement of inclusive jet cross section at 13 TeV (2016 data) available
- NNLO result on strong coupling: most precise single result at a hadron machine
- pave the way towards global SMEFT fit

THANKS FOR LISTENING !

BACKUP

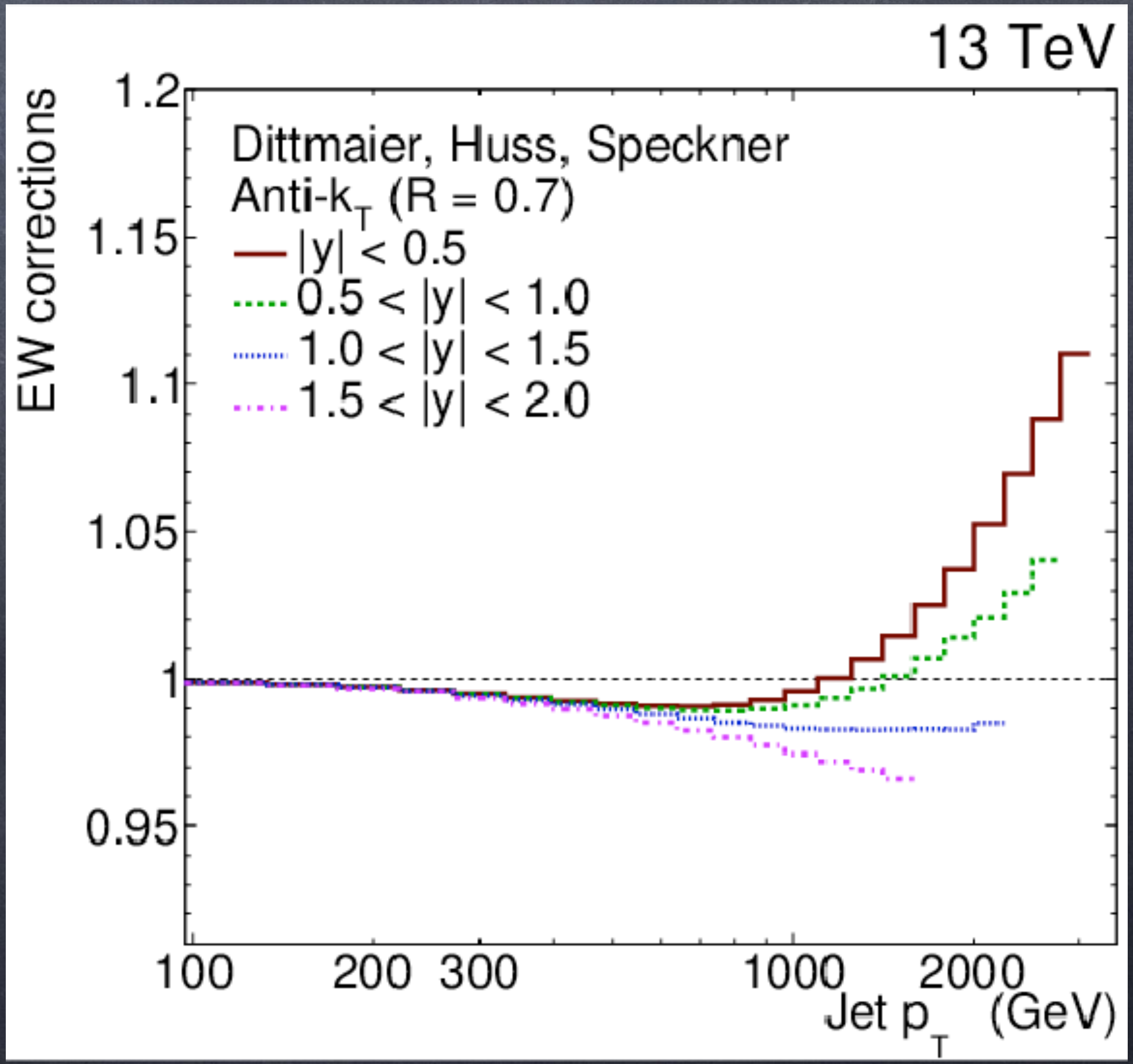
CORRECTIONS TO NLO/NNLO



$$NP_i = \frac{\sigma_i^{MC}(PS \,\&\, MPI \,\&\, HAD)}{\sigma_i^{MC}(PS)},$$

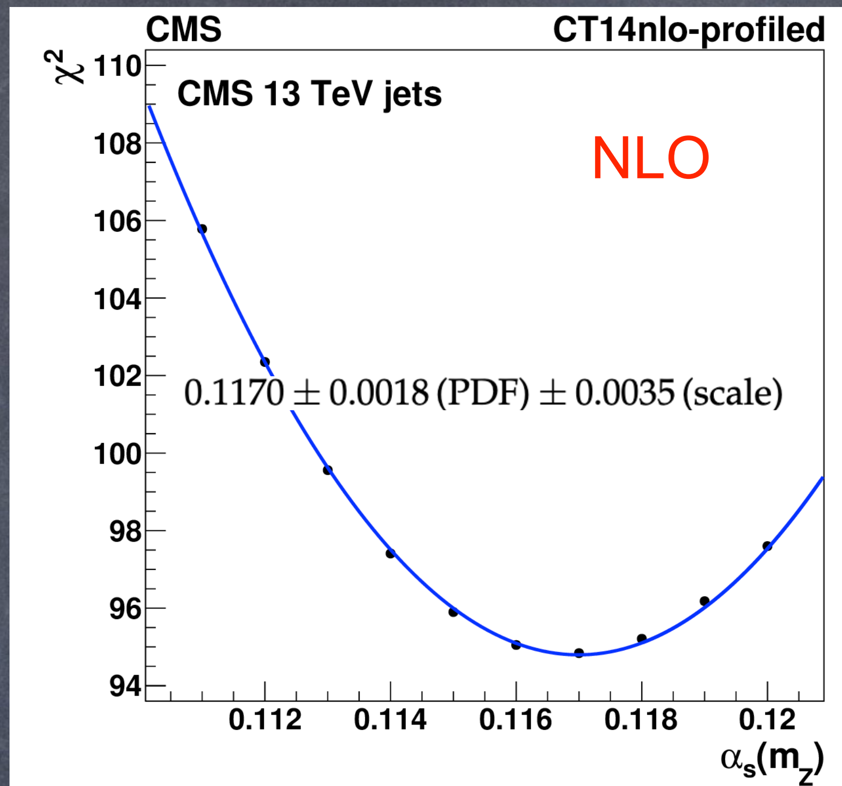
average + envelope of PYTHIA and HERWIG used

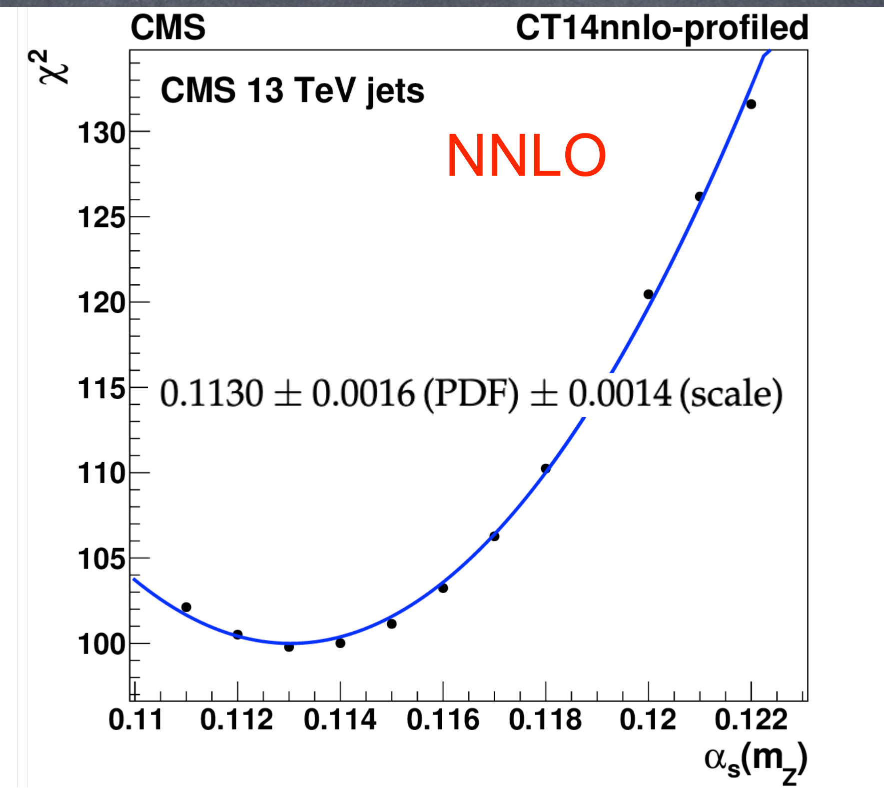
EWK corrections:



PROFILING RESULTS

Jets: profiling strong coupling:

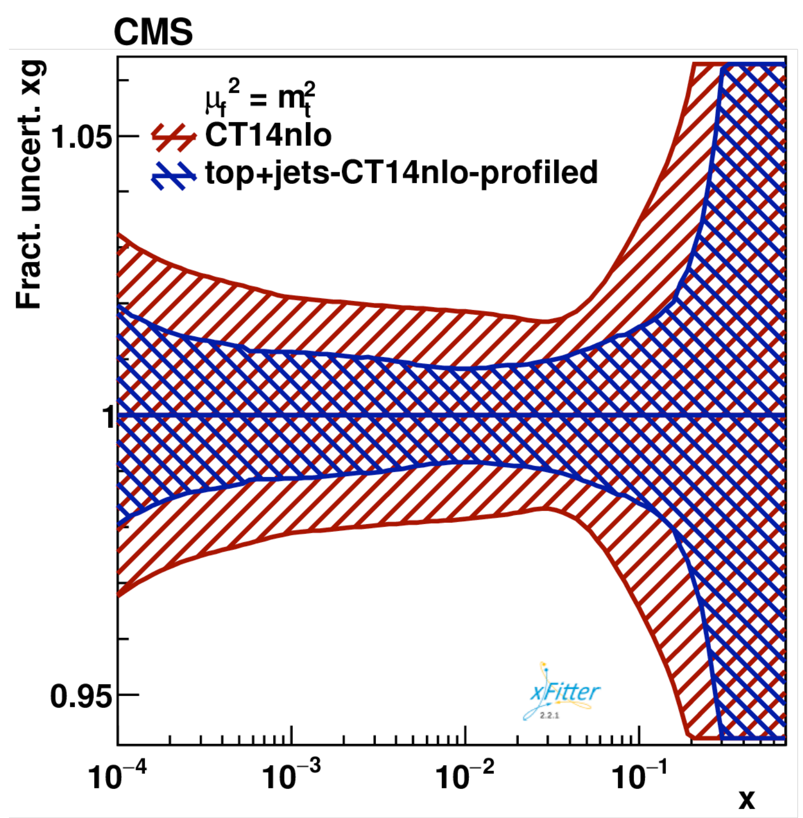


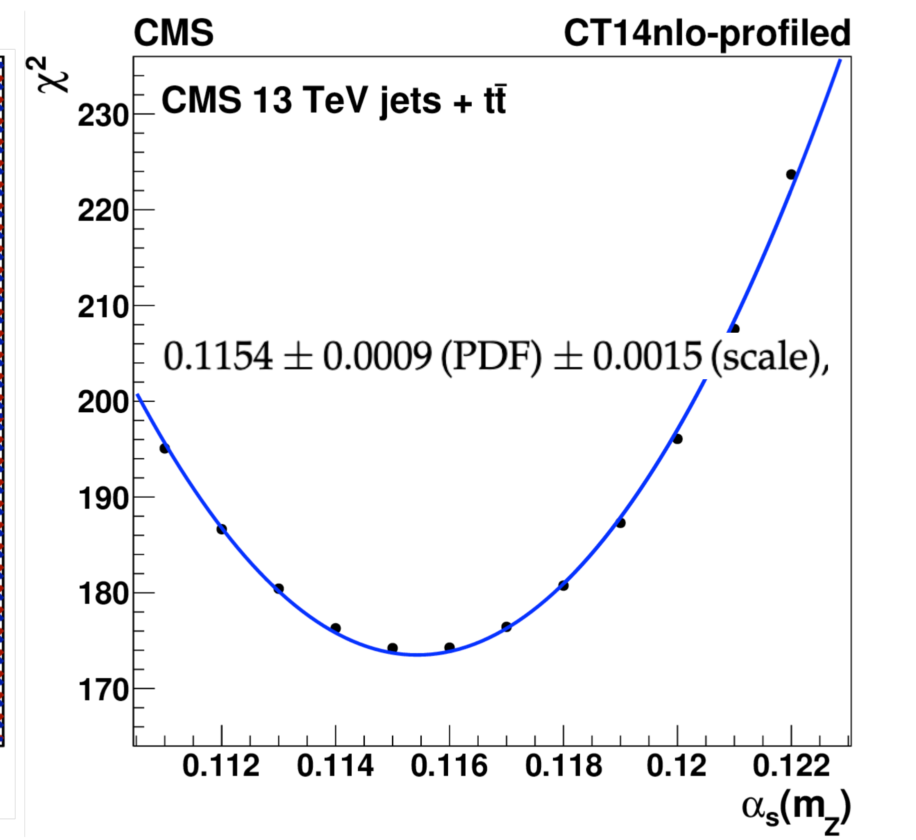


Jets+top: NLO

tension in $\alpha_s(m_Z)$ between jet and top data observed in global PDFs

(no tensions in the data !)





FIT RESULTS NNLO

Parametrisation NNLO (HERA+CMS jets):

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

Goodness of Fit NNLO:

Data sets		HERA-only Partial χ^2/N_{dp}	HERA+CMS Partial χ^2/N_{dp}
HERA I+II neutral current	e^+p, $E_p = 920$ GeV	378/332	375/332
HERA I+II neutral current	e^+p, $E_p = 820$ GeV	60/63	60/63
HERA I+II neutral current	e^+p, $E_p = 575$ GeV	201/234	201/234
HERA I+II neutral current	e^+p, $E_p = 460$ GeV	208/187	209/187
HERA I+II neutral current	e^-p, $E_p = 920$ GeV	223/159	227/159
HERA I+II charged current	e^+p, $E_p = 920$ GeV	46/39	46/39
HERA I+II charged current	e^-p, $E_p = 920$ GeV	55/42	56/42
CMS inclusive jets 13 TeV	$0.0 < \|y\| < 0.5$	—	13/22
	$0.5 < \|y\| < 1.0$	—	31/21
	$1.0 < \|y\| < 1.5$	—	18/19
	$1.5 < \|y\| < 2.0$	—	14/16
Correlated χ^2		66	83
Global χ^2/N_{dof}		1231/1043	1321/1118

FIT RESULTS NLO SM / SMEFT

Parametrisation SMEFT NLO (HERA+CMS jets + $t\bar{t}$):

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

Goodness of Fit NLO:

Data sets		SM fit Partial χ^2/N_{dp}	SMEFT fit Partial χ^2/N_{dp}
HERA I+II neutral current	e^+p, $E_p = 920$ GeV	402/332	404/332
HERA I+II neutral current	e^+p, $E_p = 820$ GeV	60/63	60/63
HERA I+II neutral current	e^+p, $E_p = 575$ GeV	198/234	198/234
HERA I+II neutral current	e^+p, $E_p = 460$ GeV	208/187	208/187
HERA I+II neutral current	e^-p, $E_p = 920$ GeV	223/159	223/159
HERA I+II charged current	e^+p, $E_p = 920$ GeV	46/39	46/39
HERA I+II charged current	e^-p, $E_p = 920$ GeV	55/42	54/42
CMS 13 TeV $t\bar{t}$ 3D		23/23	23/23
CMS inclusive jets 13 TeV	$0.0 < \lvert y\rvert < 0.5$	13/22	20/22
	$0.5 < \lvert y\rvert < 1.0$	28/21	27/21
	$1.0 < \lvert y\rvert < 1.5$	13/19	11/19
	$1.5 < \lvert y\rvert < 2.0$	33/16	28/16
Correlated χ^2		121	115
Global χ^2/N_{dof}		1411/1141	1401/1140

THEORY PREDICTIONS

- **SM Jets:** NNLO computation: NNLOJet, in QCD analysis via K-factors
  NLO: NLOJet++/FastNLO improved by NLL (MEKS) via K-factors
  QCD predictions corrected for NP and EW effects
  Scales: $\mu_r = \mu_f = p_T$ (individual jet), variation up/down by factor 2 independently

- **3-differential $t\bar{t}$ cross section:** NLO MADGRAPH MC@NLO interfaced to APPLGRID
  Scale: $\mu_r = \mu_f = 1/2 \sum_i m_{T,i}\,,\; m_{T,i} \equiv \sqrt{m_i^2 + p_{T,i}^2}\;;$
  $i-$final-state partons $t, \bar{t}$ and max. 3 light partons for $t\bar{t} + jet$

- **CI:** CIJET interfaced to fastNLO / xFitter ; $L_{SMEFT} = L_{SM} + \frac{2\pi}{\Lambda^2} \sum_{n\in\{1,3,5\}} c_n \mathcal{O}_n$

studied non-renormalisable operators $\mathcal{O}_n$:

colour-singlet BSM-exchange between two quark lines integrated out

3 cases studied:
CI left-handed / vector-like / axial-vector-like

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

$$O_1 = \delta_{ij}\delta_{kl}\left(\sum_{c=1}^{3} \bar{q}_{Lci}\gamma_\mu q_{Lcj} \sum_{d=1}^{3} \bar{q}_{Ldk}\gamma^\mu q_{Ldl}\right)$$

$$O_3 = \delta_{ij}\delta_{kl}\left(\sum_{c=1}^{3} \bar{q}_{Lci}\gamma_\mu q_{Lcj} \sum_{d=1}^{3} \bar{q}_{Rdk}\gamma^\mu q_{Rdl}\right)$$

$$O_5 = \delta_{ij}\delta_{kl}\left(\sum_{c=1}^{3} \bar{q}_{Rci}\gamma_\mu q_{Rcj} \sum_{d=1}^{3} \bar{q}_{Rdk}\gamma^\mu q_{Rdl}\right)$$

c, d - generations   i,j,k - colour indices

HESSIAN PROFILING TECHNIQUE

Define a χ^2 with theory uncertainties ($\mathbf{b}_{\mathbf{th}}$ are the PDF uncertainties)

$$\chi^2(\boldsymbol{b}_{\mathbf{exp}}, \boldsymbol{b}_{\mathbf{th}}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_\alpha \Gamma_{i\alpha}^{\rm exp} b_{\alpha,\rm exp} - \sigma_i^{\rm th} - \sum_\beta \Gamma_{i\beta}^{\rm th} b_{\beta,\rm th}\right)^2}{\Delta_i^2} + \sum_\alpha b_{\alpha,\rm exp}^2 + \sum_\beta b_{\beta,\rm th}^2 \,.$$

Correlated experimental and theoretical uncertainties are included using the nuisance parameter vectors $\mathbf{b}_{\mathbf{exp}}$ and $\mathbf{b}_{\mathbf{th}}$, respectively.

Their influence on the data and theory predictions is described by $\Gamma_{i\alpha}^{exp}$ and $\Gamma_{i\alpha}^{th}$ matrices

index α (β) corresponds to the experimental (theoretical) uncertainty nuisance parameters

Minimisation of $\chi^2(\mathbf{b}_{\mathbf{exp}}, \mathbf{b}_{\mathbf{th}})$ leads to a system of linear equations.

The value at the minimum of the χ^2 function provides a compatibility test of the data and theory.

The values at the minimum of the nuisance parameters $\mathbf{b}^{\mathbf{min}}_{\beta_{\mathbf{th}}}$ are interpreted as optimisation ("profiling") of PDFs to describe the data. **The shifted PDFs have reduced uncertainties.**

In xFitter:

- Add the hessian PDF uncertainties as nuisance parameters β in the χ^2
- Minimise χ^2 and profile the PDF shifts β to the data $\chi^2(\beta_{exp}) \rightarrow \chi^2(\beta_{exp}, \beta_{th})$
- Propagate the shifts and the reduction of the uncertainties to the PDFs