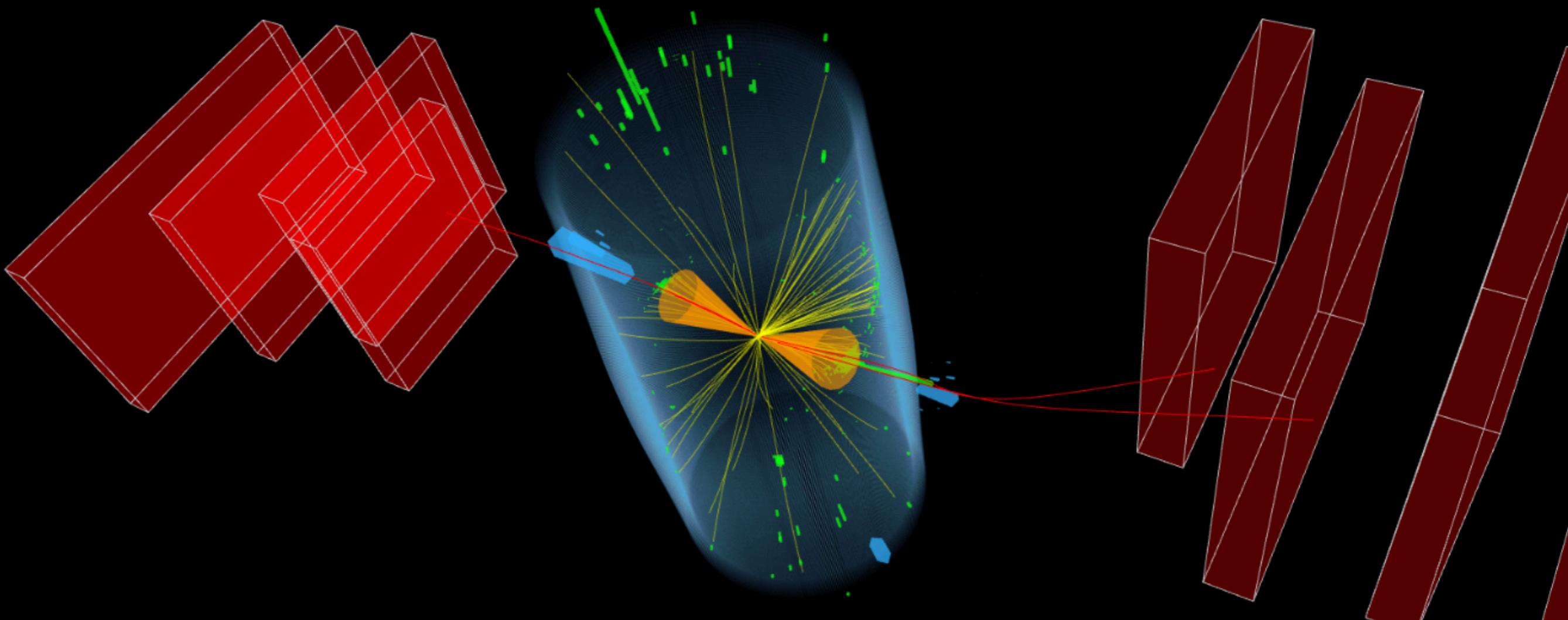




QCD and SMEFT interpretation of double-differential inclusive jet cross sections at 13 TeV

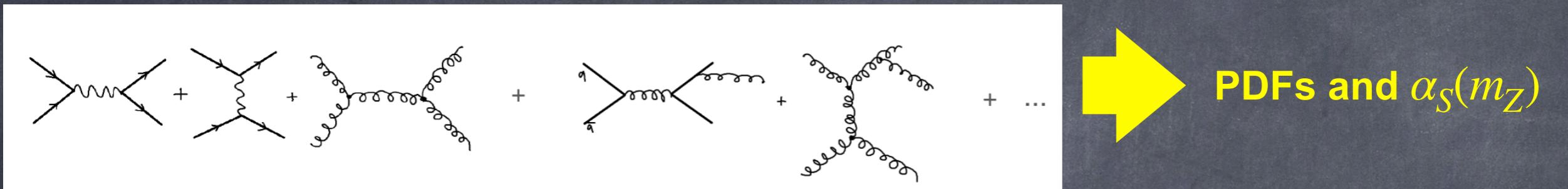


Katerina Lipka for the CMS Collaboration

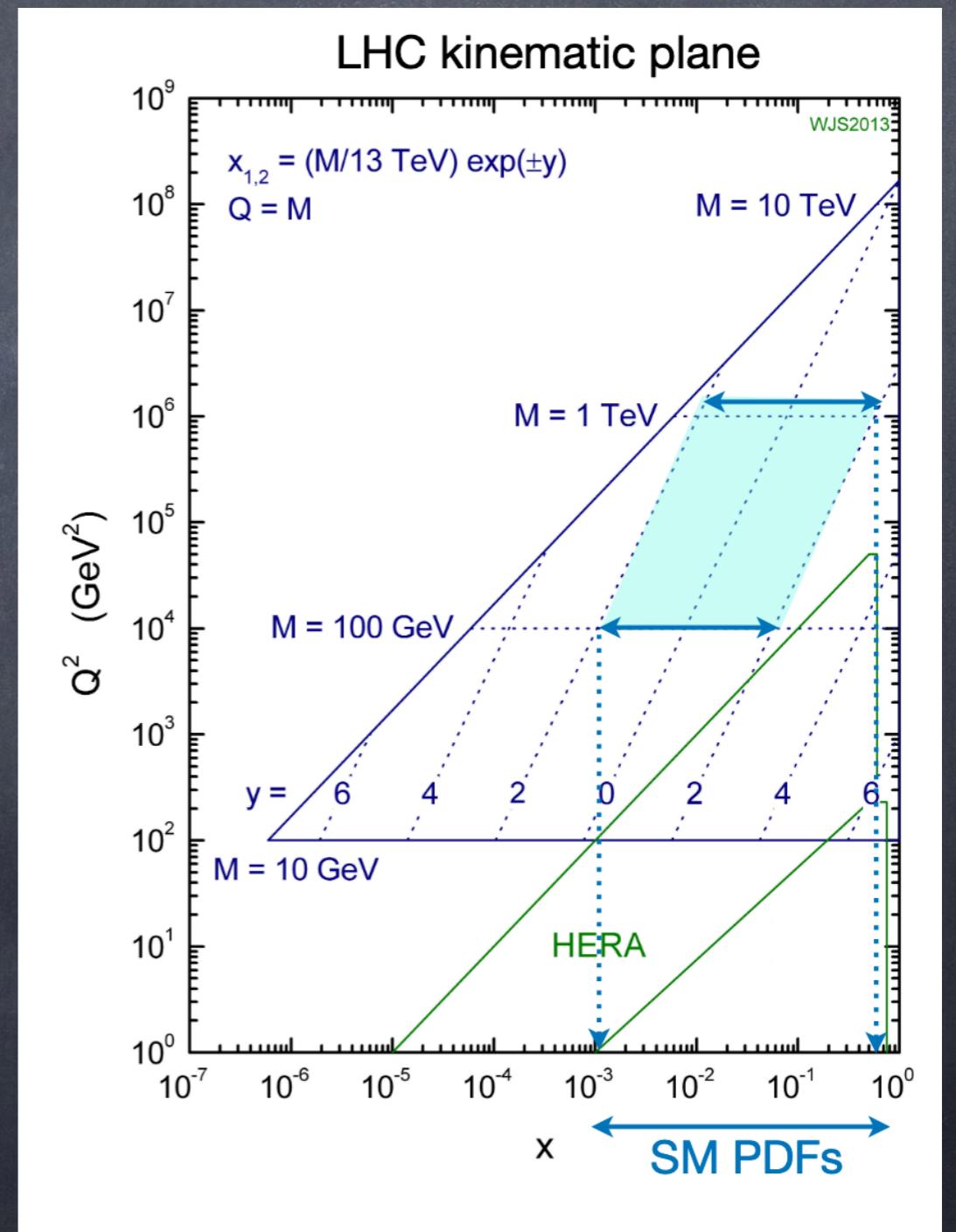
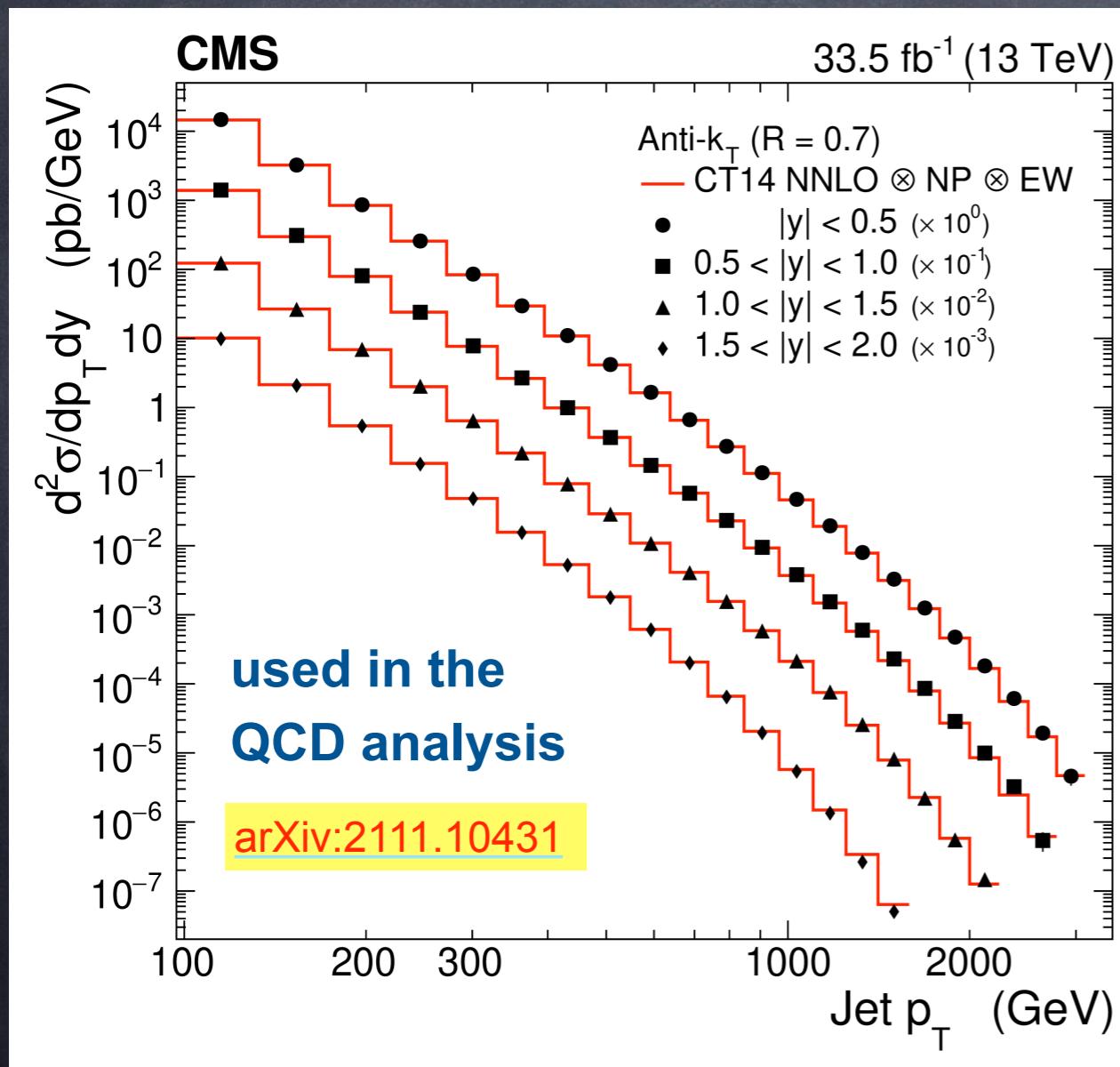
more details in [JHEP 02 \(2022\) 142](#)

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

JET PRODUCTION AT LHC: PROBE OF SM

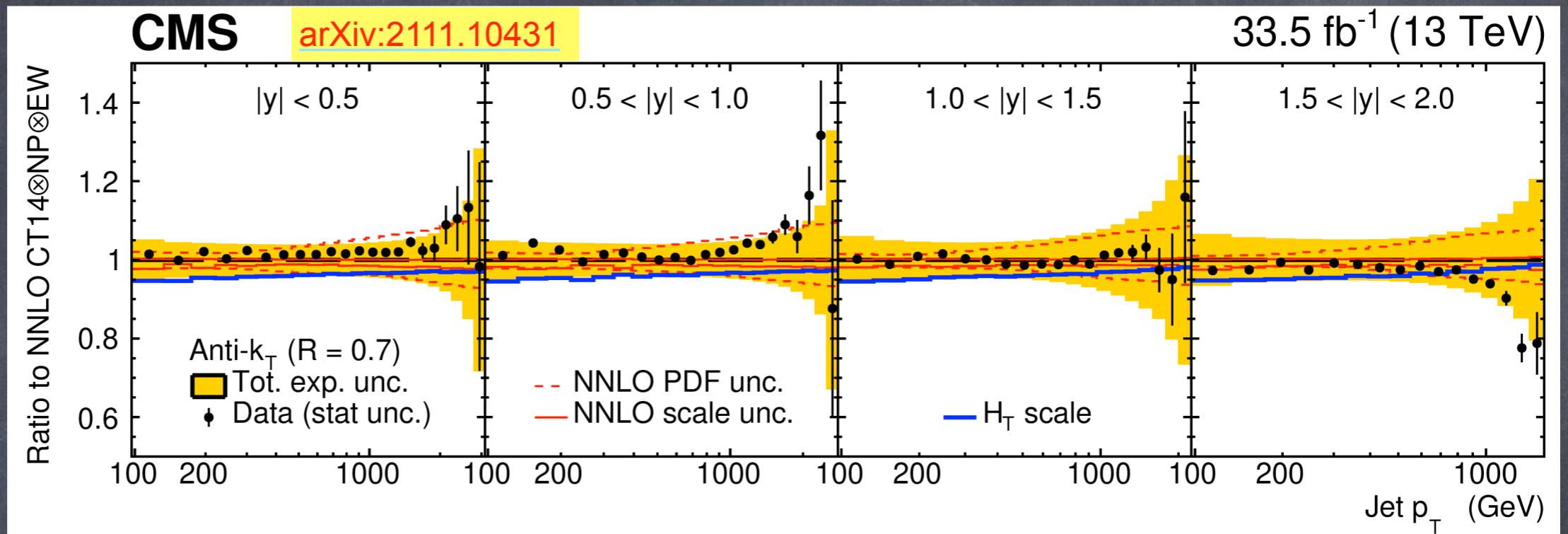


New CMS measurement of inclusive jets at 13 TeV:
2-differential cross sections vs jet p_T and y



JET PRODUCTION AT LHC vs QCD

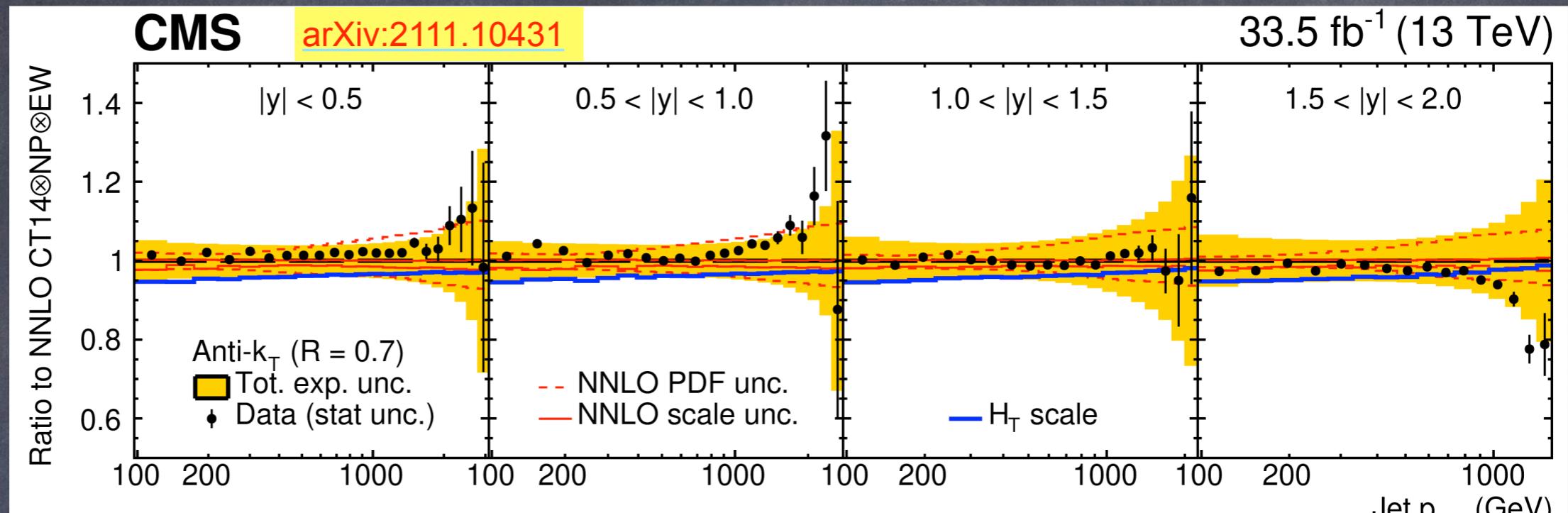
**data vs
NNLO**



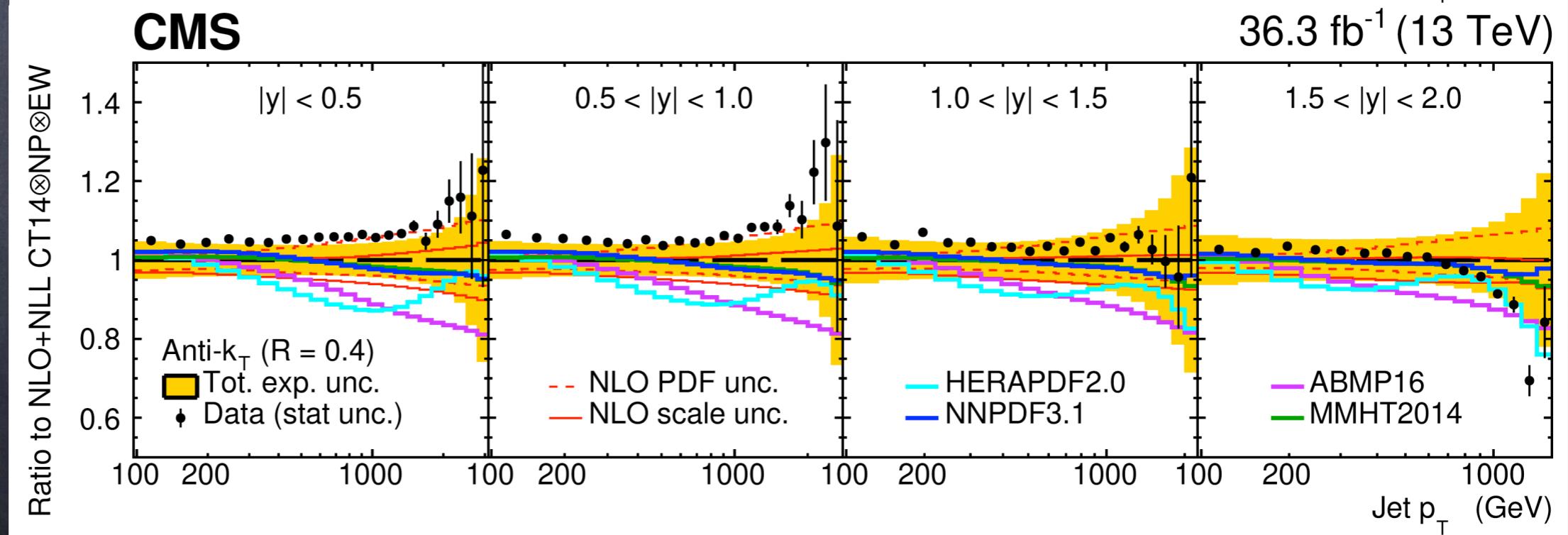
- NNLO: [Currie, Glover, Pires, PRL118 (2017) 072002]
 [Currie et al. , JHEP 10 (2018) 155]
 [T. Gehrmann et al., PoS RADCOR2017 (2018) 074]
- NLOJet++ [Z. Nagy PRL 88 (2002) 122003, PRD 68 (2003) 094002]
- fastNLO [D. Britzger, K. Rabbertz, F. Stober, M. Wobisch, arXiv:1208.3641]

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 PDFs and $\alpha_s(m_Z)$

- Investigate the impact of the measurement on the global PDF: profiling
- Full QCD fit at NNLO : extract simultaneously PDF and QCD parameters

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:
QCD 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/>

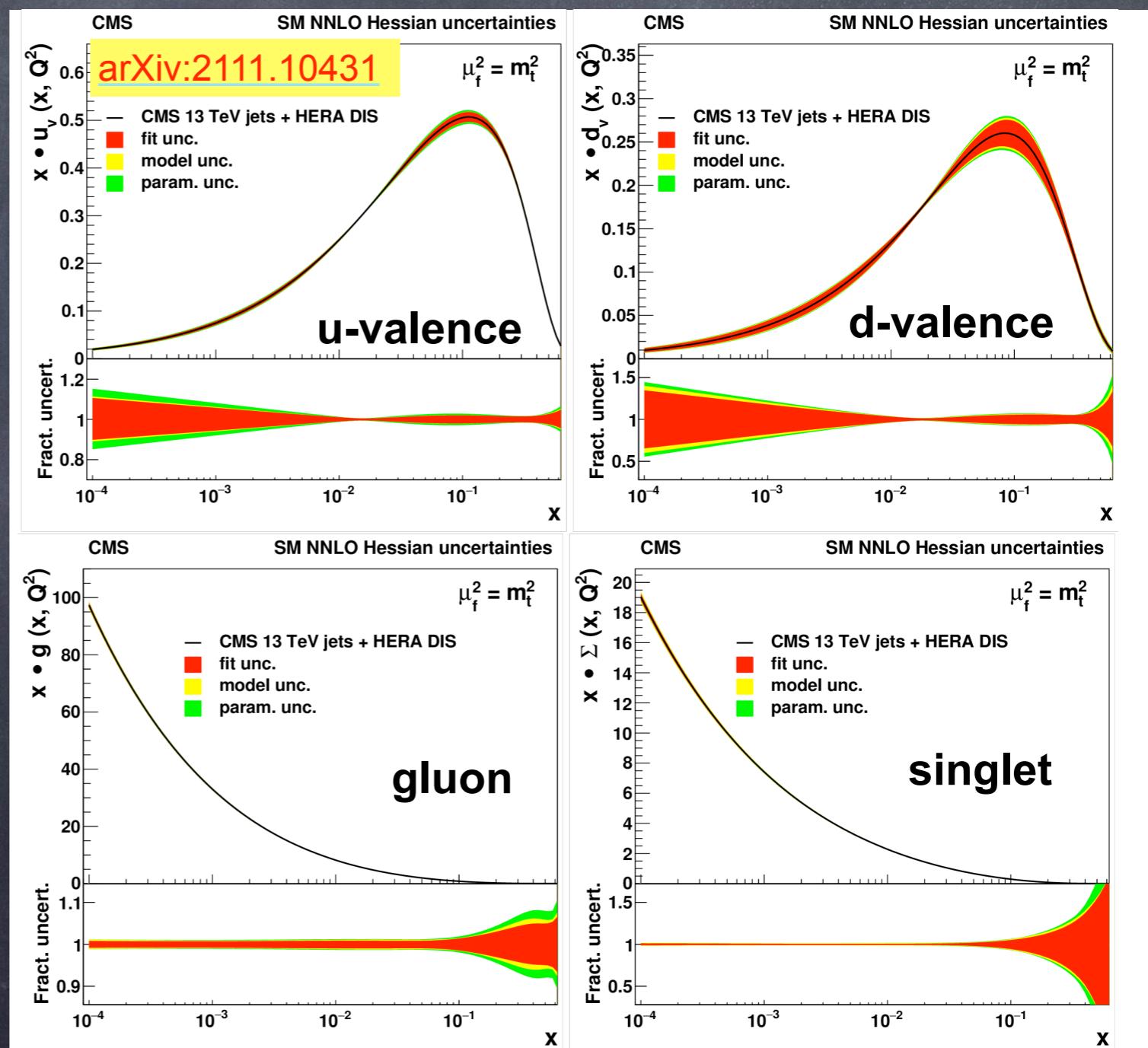
FULL QCD FIT @ NNLO: PDF + $\alpha_s(m_Z)$

- **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](#)]
- **NNLO predictions obtained via fasNLO grids using NNLO k-factors**
 - ✓ individual k-factors are obtained for each variation of the QCD scales
 - ✓ PDF uncertainty in the k-factors is taken into account, negligible wrt scale variation
 - ✓ $\alpha_S(m_Z)$ dependence of the k-factors is negligible wrt PDF uncertainty

FULL QCD FIT @ NNLO: PDF + $\alpha_s(m_Z)$

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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

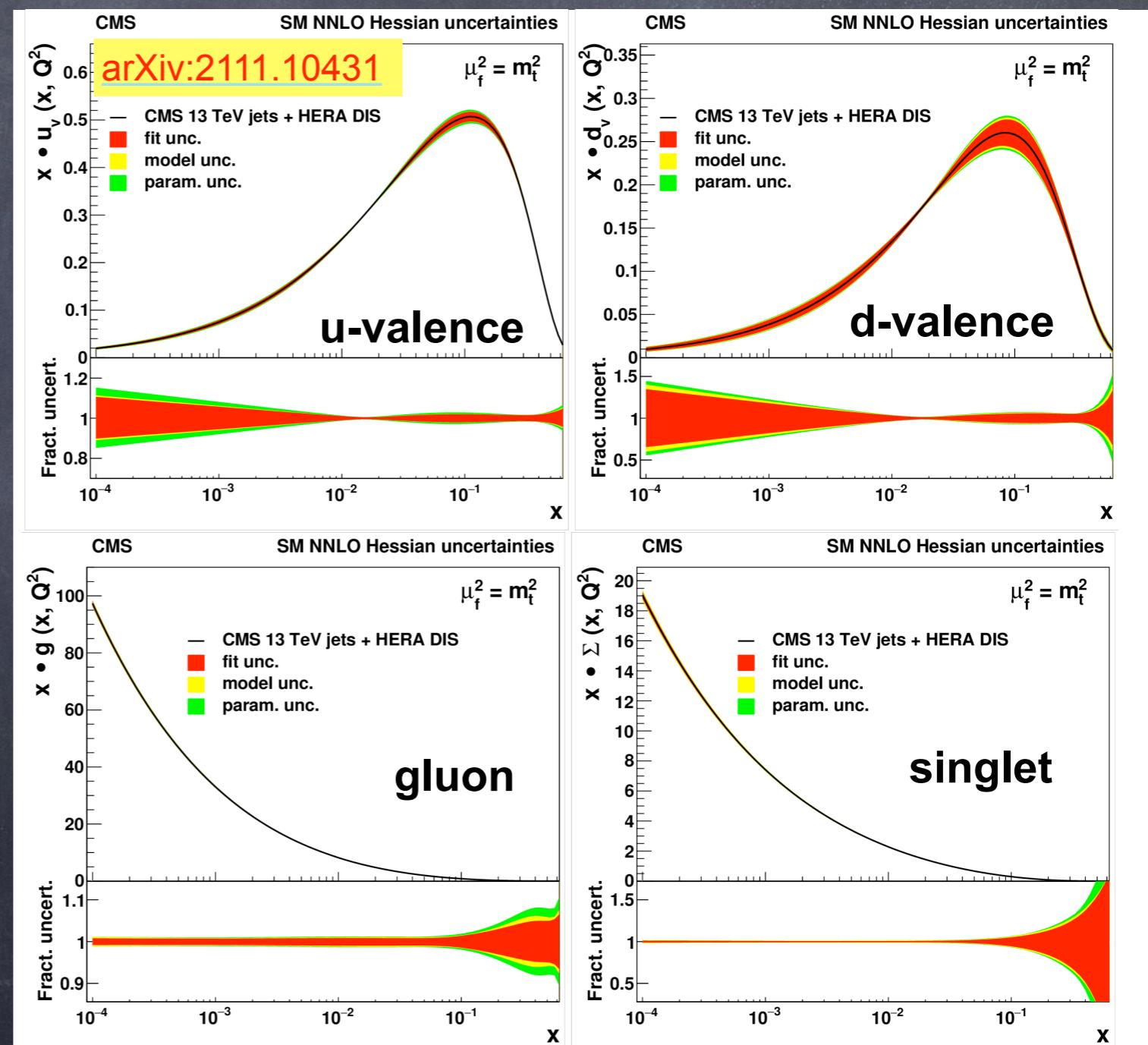


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$$\begin{aligned}
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 xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1+E_{u_v} x^2), \\
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 \end{aligned}$$



FULL QCD FIT @ NNLO: PDF + $\alpha_s(m_Z)$

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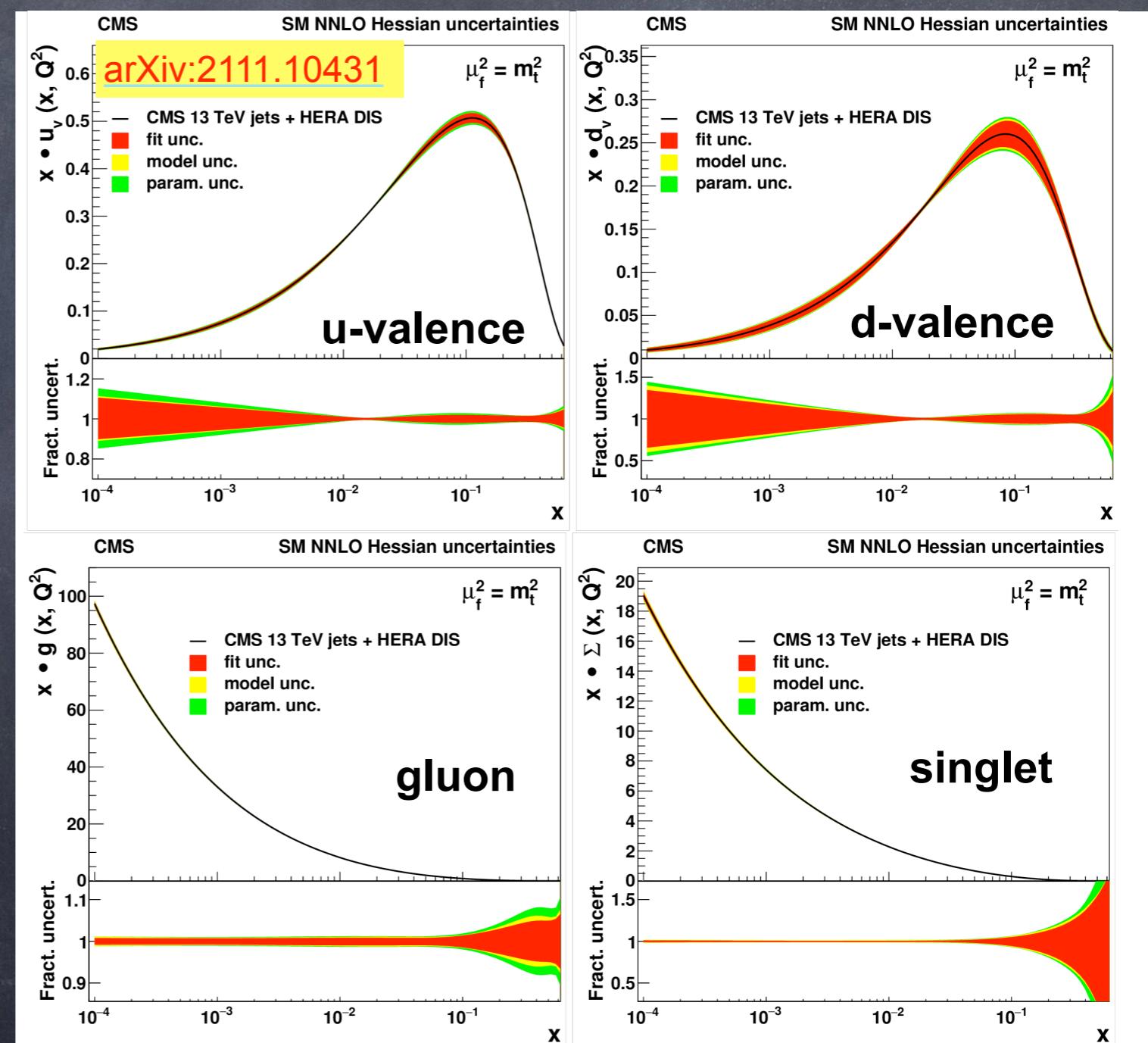
- Strong coupling constant

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

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

PDF and $\alpha_s(m_Z)$

obtained simultaneously !



FULL QCD FIT @ NNLO: PDF + $\alpha_s(m_Z)$

- 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]

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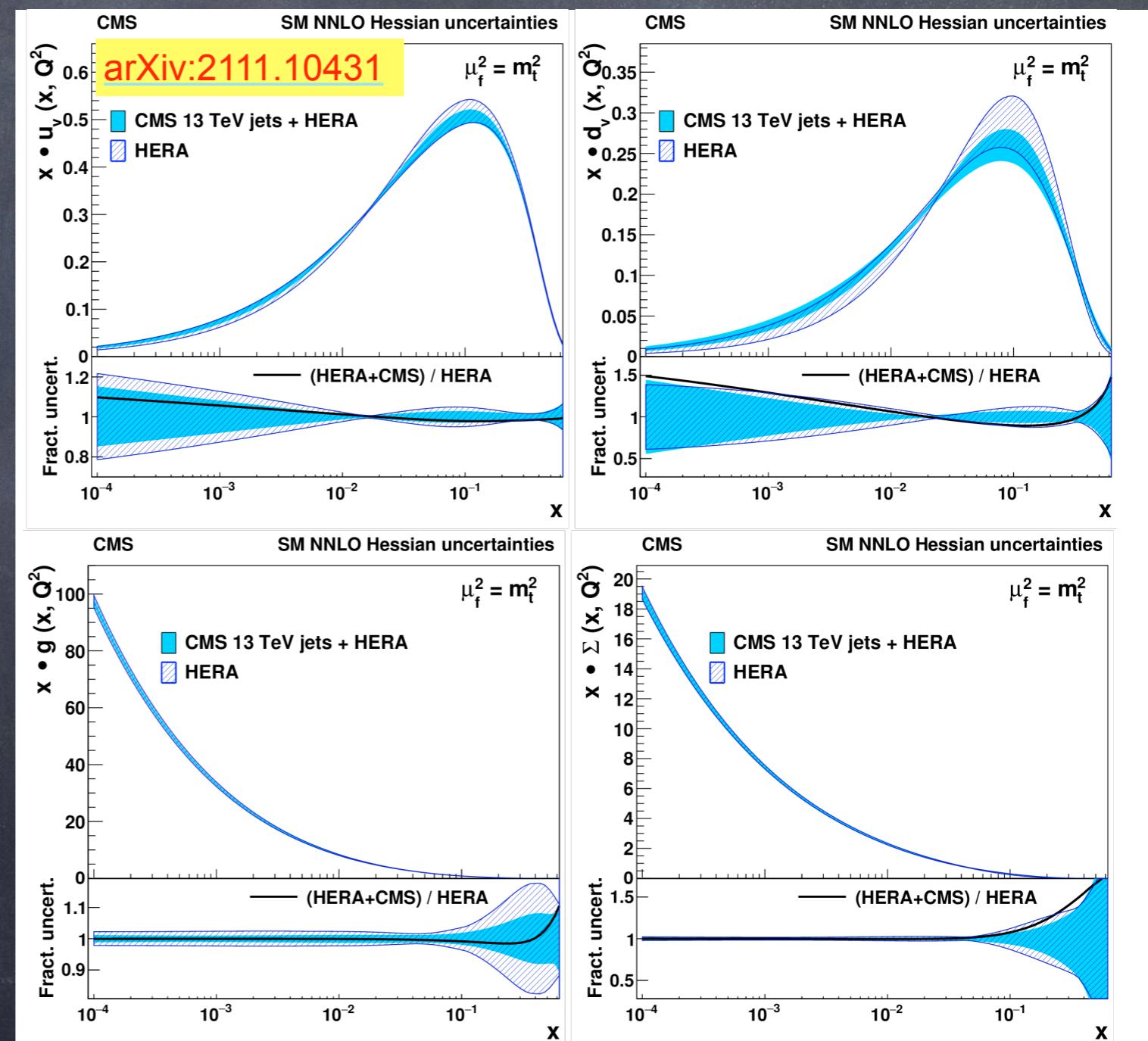
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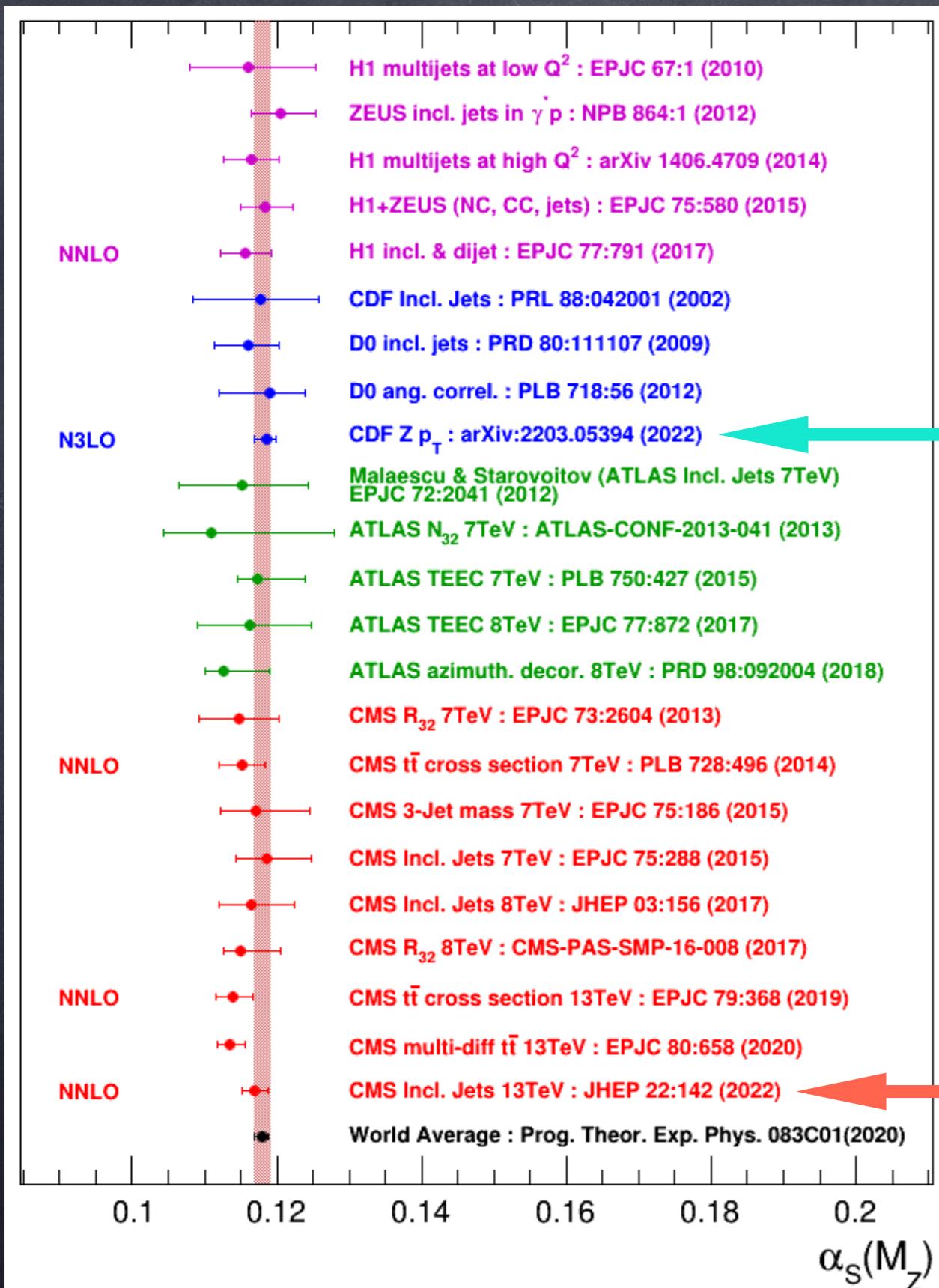
$$\alpha_s(m_Z) = 0.1170 \pm 0.0019$$

- compared to HERA-only fit:
 $\{ \alpha_s(m_Z) \text{ fixed} \}$

Improved precision
of the gluon at high x !



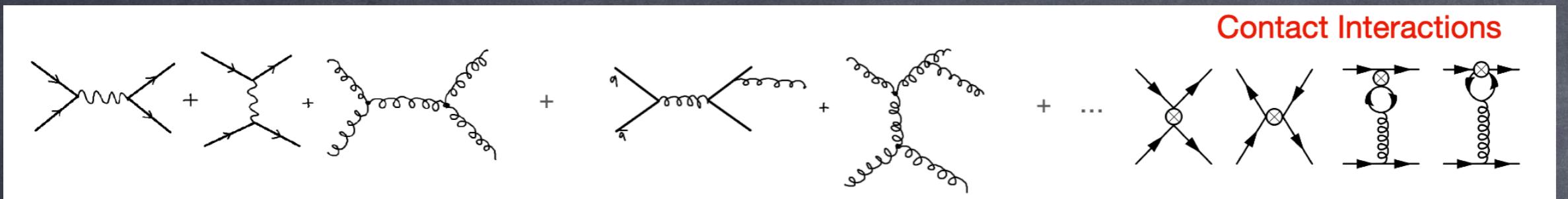
$\alpha_s(m_Z)$ value from jets compared to other results



brand new: best precision at N3LO

This measurement:
high precision (error 1.6%)
mitigated dependence on PDFs

JET PRODUCTION AT LHC: PROBE OF NEW PHYSICS

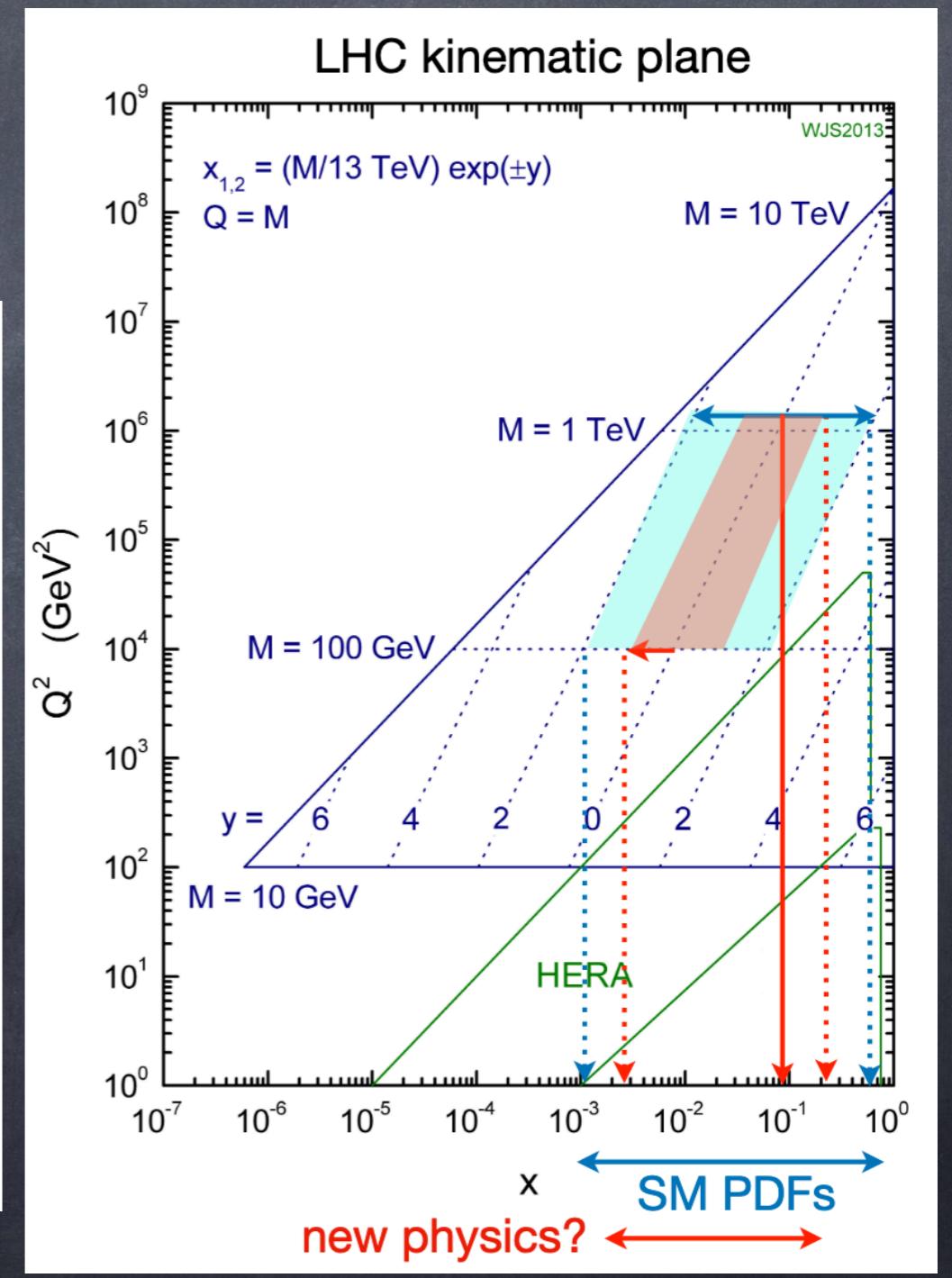
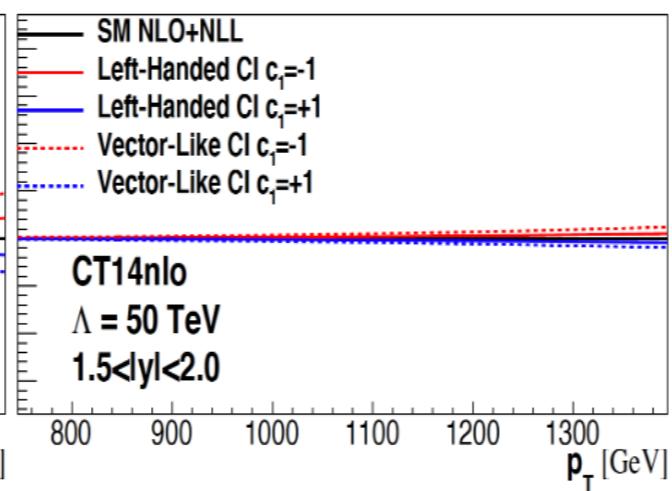
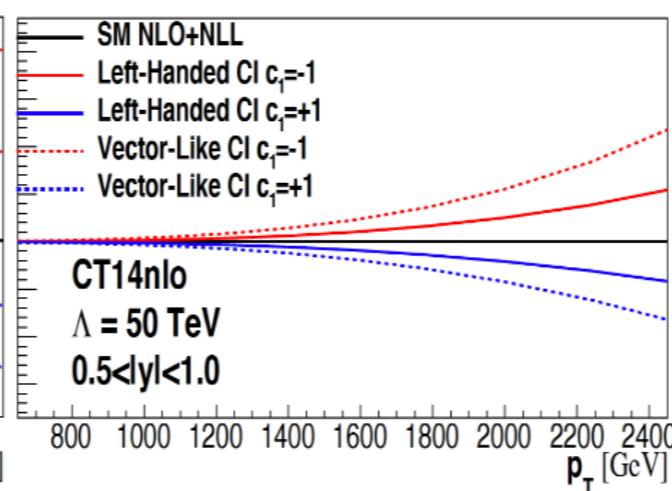
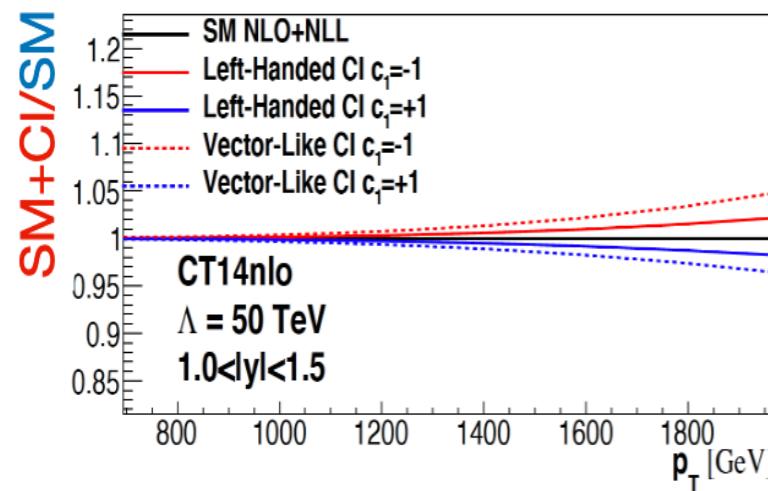
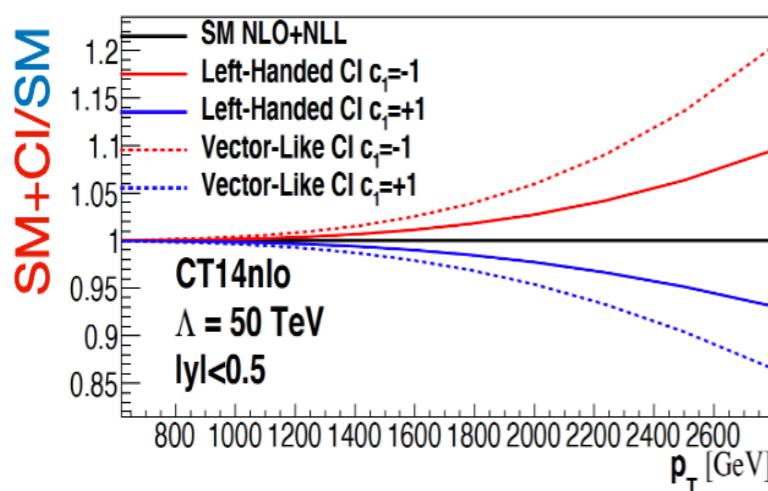


SMEFT

Lagrangian: $L_{SMEFT} = L_{SM} + \frac{2\pi \times c_i}{\Lambda_{NP}^2} \mathcal{O}_i^{d=6}$

Wilson coefficient
(effective coupling)

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



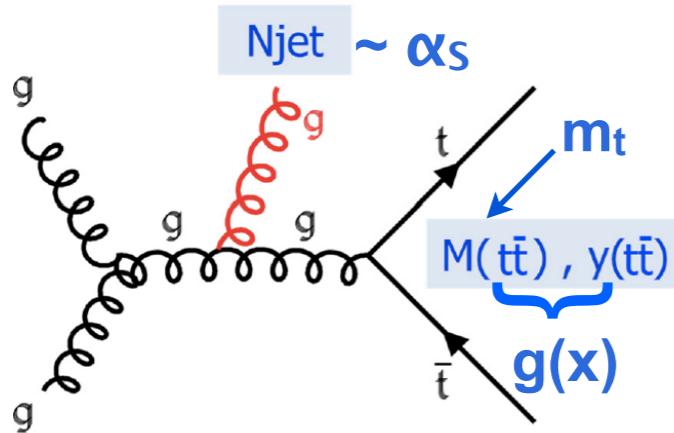
SMEFT ANALYSIS

- SM prediction for jet production extended by EFT contributions (available at NLO)
- Idea: extract simultaneously CI coefficients, PDFs and QCD parameters
- can include more data sensitive to high-x gluon: CMS 3d $t\bar{t}$ at 13 TeV (theory at NLO)

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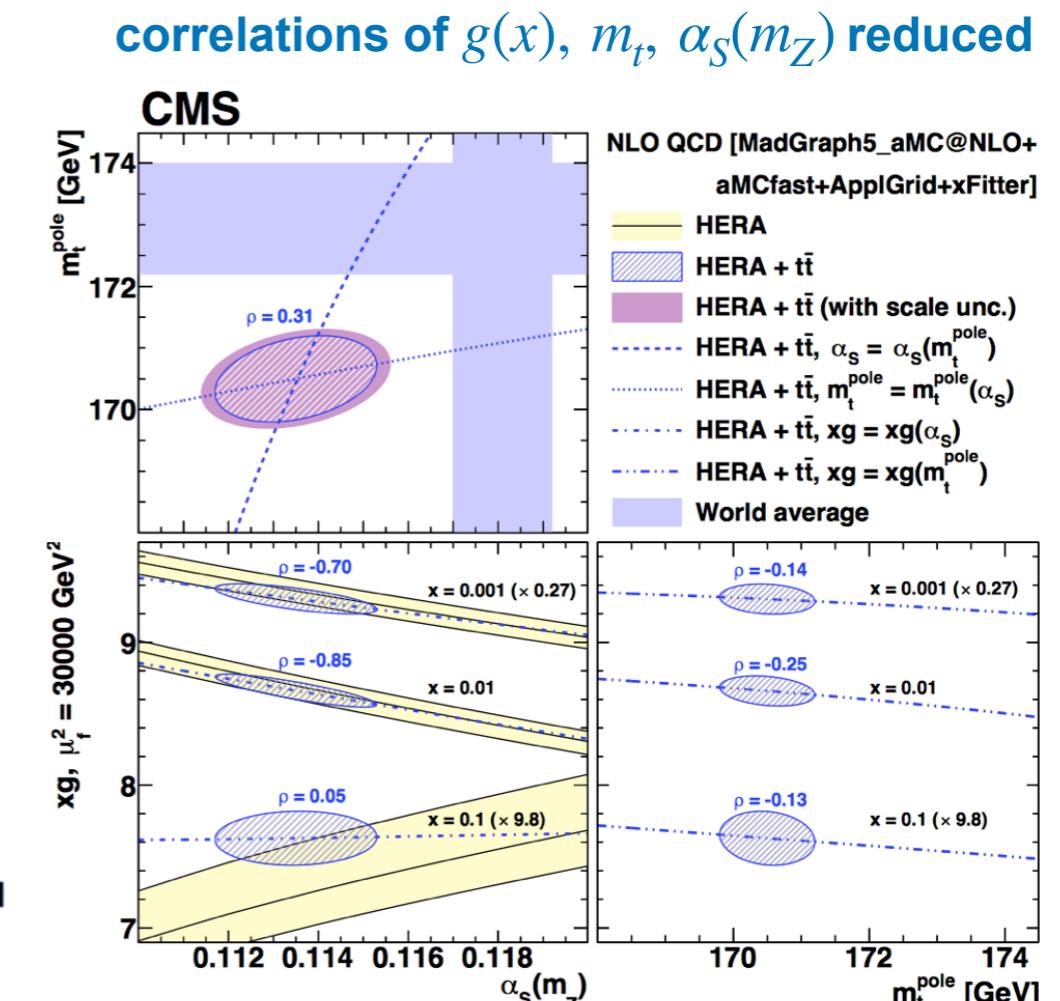
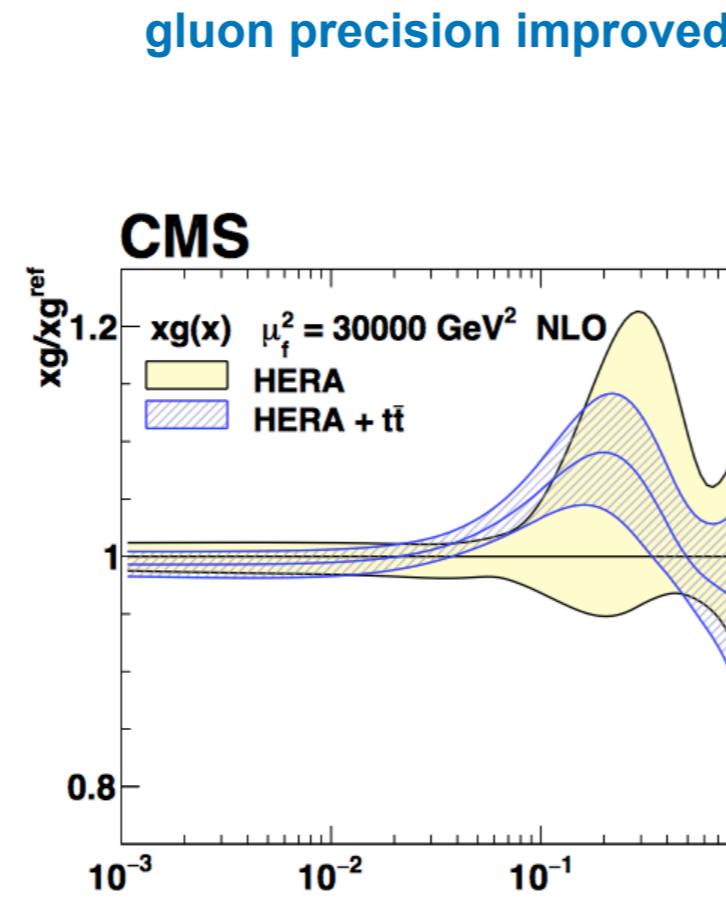
[arXiv:1904.05237]: extracted PDFs, m_t and α_S



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

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

small-ish: $\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}$



$m_t^{pole} = 170.5 \pm 0.8 \text{ GeV}$

SMEFT ANALYSIS

- **SM prediction for jet production extended by EFT contributions (available at NLO)**
- **Idea: extract simultaneously CI coefficients, PDFs and QCD parameters**
- **can include more data sensitive to high- x gluon: CMS 3d $t\bar{t}$ at 13 TeV (theory at NLO)**

General idea for the SMEFT analysis:

- parameterise PDFs at a starting scale $\mu^2_0 : f(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$
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SMEFT predictions for every jet measurement in (x, μ^2) – plane
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SMEFT FIT @ NLO: $c_1 + \text{PDF} + \alpha_s(m_Z) + m_t^{\text{pole}}$

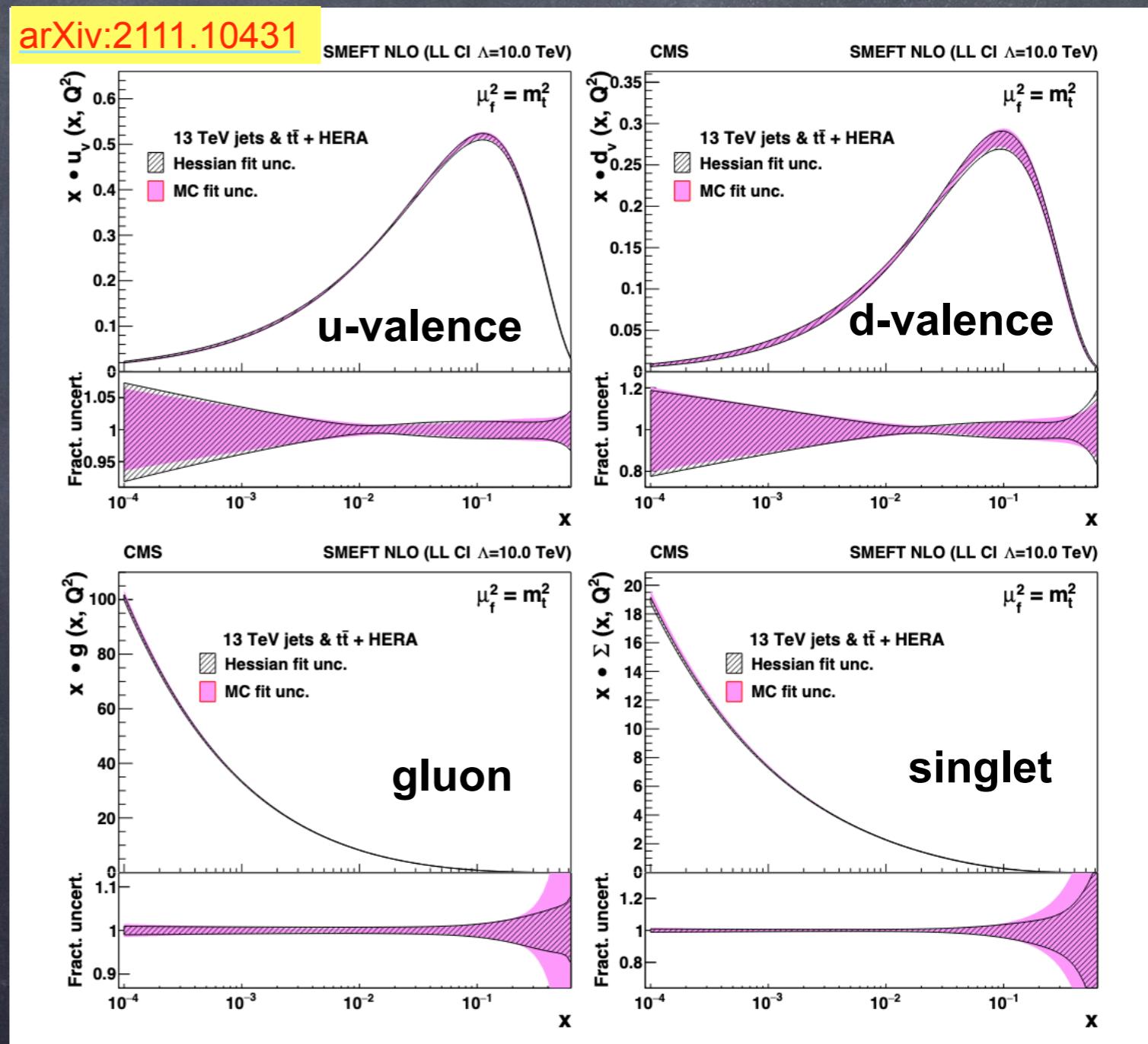
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- **Predictions for jet x-sections: QCD NLO+NLL + EFT 4-quark CI (LL, VV, A-V models)**

- **Parametrisation:**

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

somewhat different from NNLO fit
(impact of $t\bar{t}$ data)

- **Fit uncertainties:**
Hessian vs Monte-Carlo



SMEFT FIT @ NLO: $c_1 + \text{PDF} + \alpha_s(m_Z) + m_t^{\text{pole}}$

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

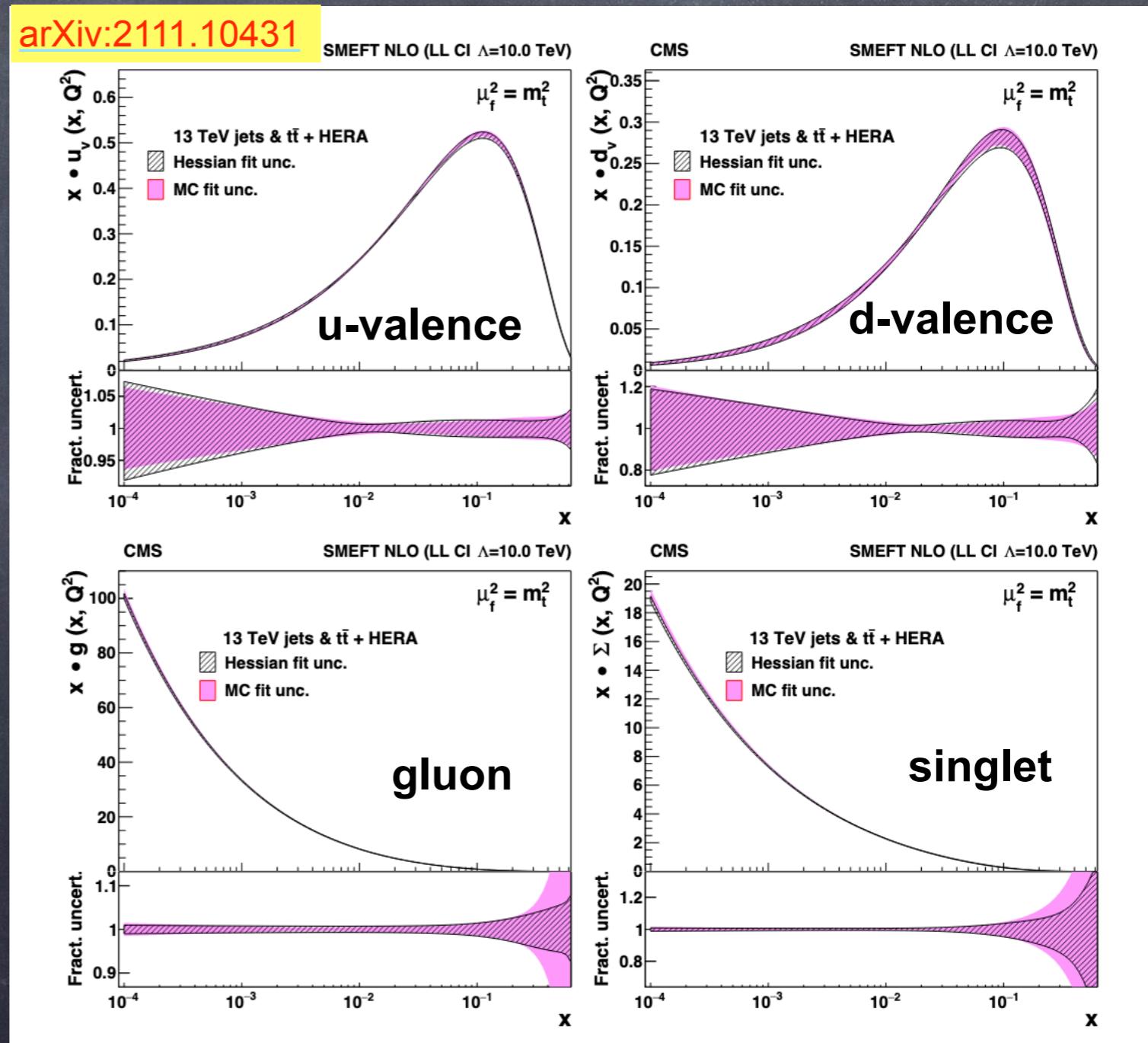
$$m_t^{\text{pole}} = 170.4 \pm 0.7 \text{ GeV}$$

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

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

SM +BSM

obtained simultaneously !



SMEFT FIT @ NLO: $c_1 + \text{PDF} + \alpha_s(m_Z) + m_t^{pole}$

- **Full QCD fit at NNLO:** basis data - ep inclusive DIS cross sections (HERA) [arXiv:1506.06042]
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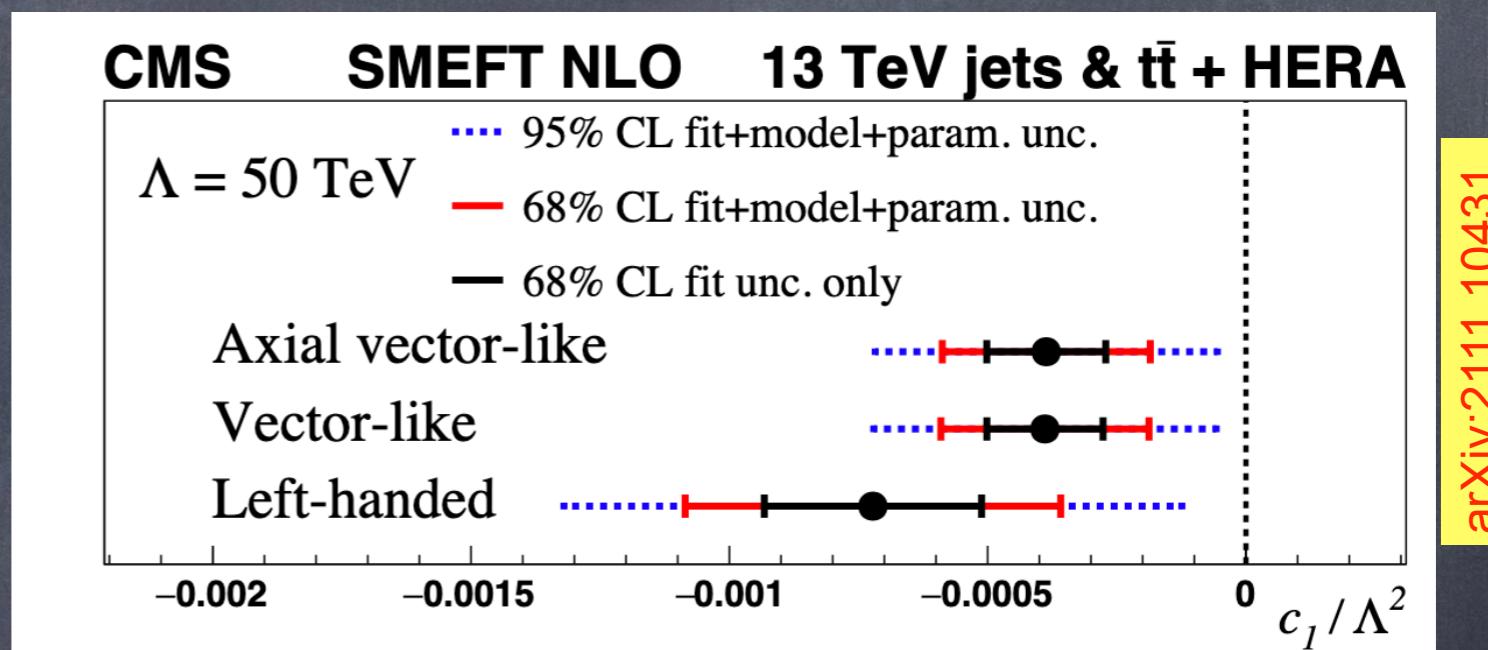
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- **CI parameters (for $\Lambda_{NP} = 10$ TeV):**

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

SM +BSM
obtained simultaneously !



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

LL : $\Lambda > 24$ TeV ATLAS [arXiv:1703.09127]: > 22 TeV

V: $\Lambda > 32$ TeV

AV: $\Lambda > 31$ TeV

SMEFT FIT VS SM FIT @ NLO

- 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]
 - + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]:
- Alternative fit in SM:
- Parametrisation (same solution)

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1+E_g x^2),$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1+D_{u_v} x + E_{u_v} x^2),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} (1+D_{d_v} x),$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}},$$

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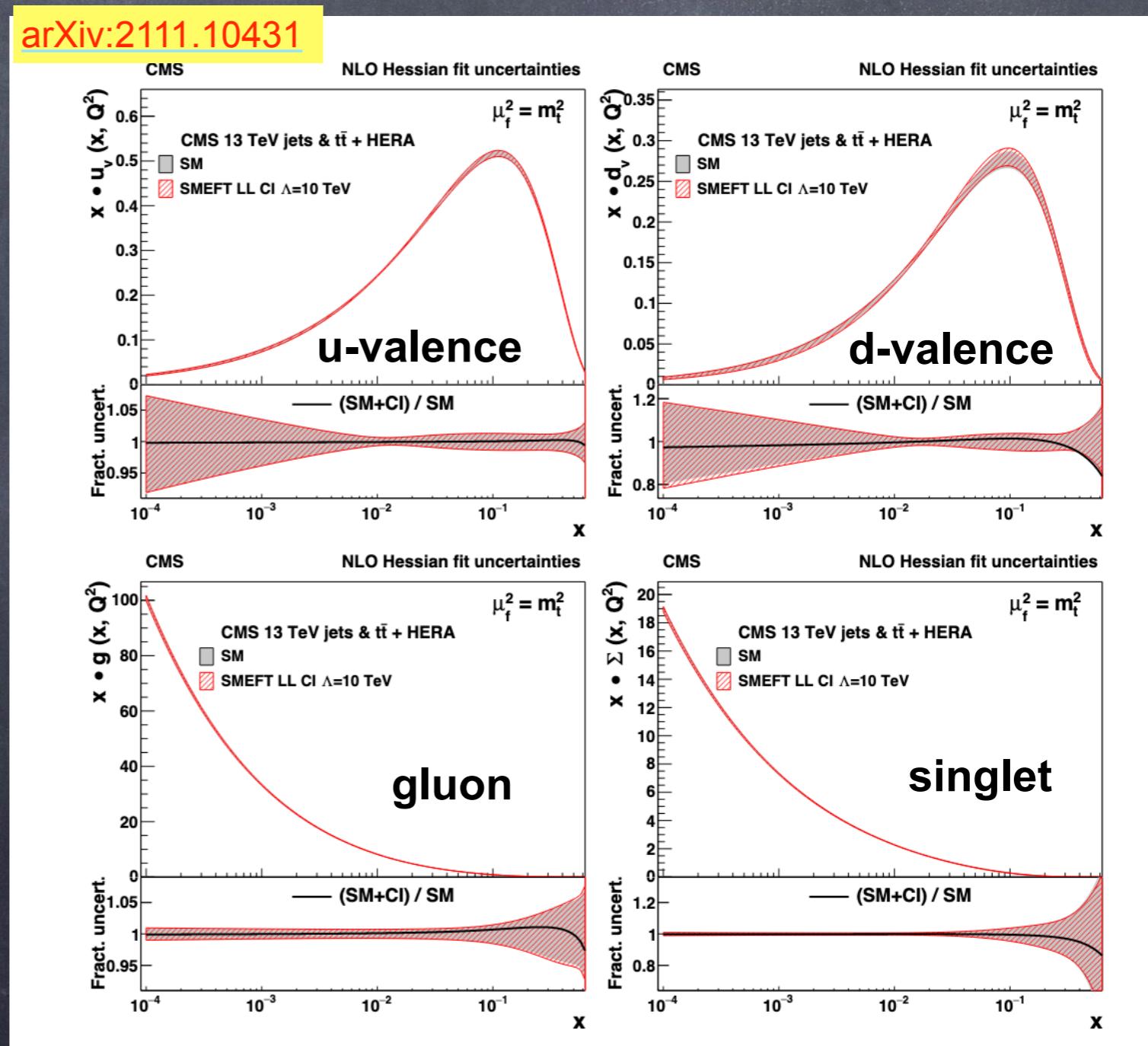
$$\alpha_S(m_Z) = 0.1188 \pm 0.0026$$

NB: in agreement with WA

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

NB: most precise

PDFs and QCD parameters
similar in SMEFT fits



SUMMARY

- New measurement of inclusive jet cross section at 13 TeV (2016 data) available
- NNLO result on strong coupling: precision of 1.6 %
- pave the way towards global SMEFT fit

BACKUP

FULL QCD FIT @ NNLO: PDF + $\alpha_s(m_Z)$

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

- **Goodness of fit:**

Data sets		HERA-only	HERA+CMS
		Partial χ^2/N_{dp}	Partial χ^2/N_{dp}
HERA I+II neutral current	$e^+p, E_p = 920 \text{ GeV}$	378/332	375/332
HERA I+II neutral current	$e^+p, E_p = 820 \text{ GeV}$	60/63	60/63
HERA I+II neutral current	$e^+p, E_p = 575 \text{ GeV}$	201/234	201/234
HERA I+II neutral current	$e^+p, E_p = 460 \text{ GeV}$	208/187	209/187
HERA I+II neutral current	$e^-p, E_p = 920 \text{ GeV}$	223/159	227/159
HERA I+II charged current	$e^+p, E_p = 920 \text{ GeV}$	46/39	46/39
HERA I+II charged current	$e^-p, E_p = 920 \text{ GeV}$	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

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

- QCD parameters:

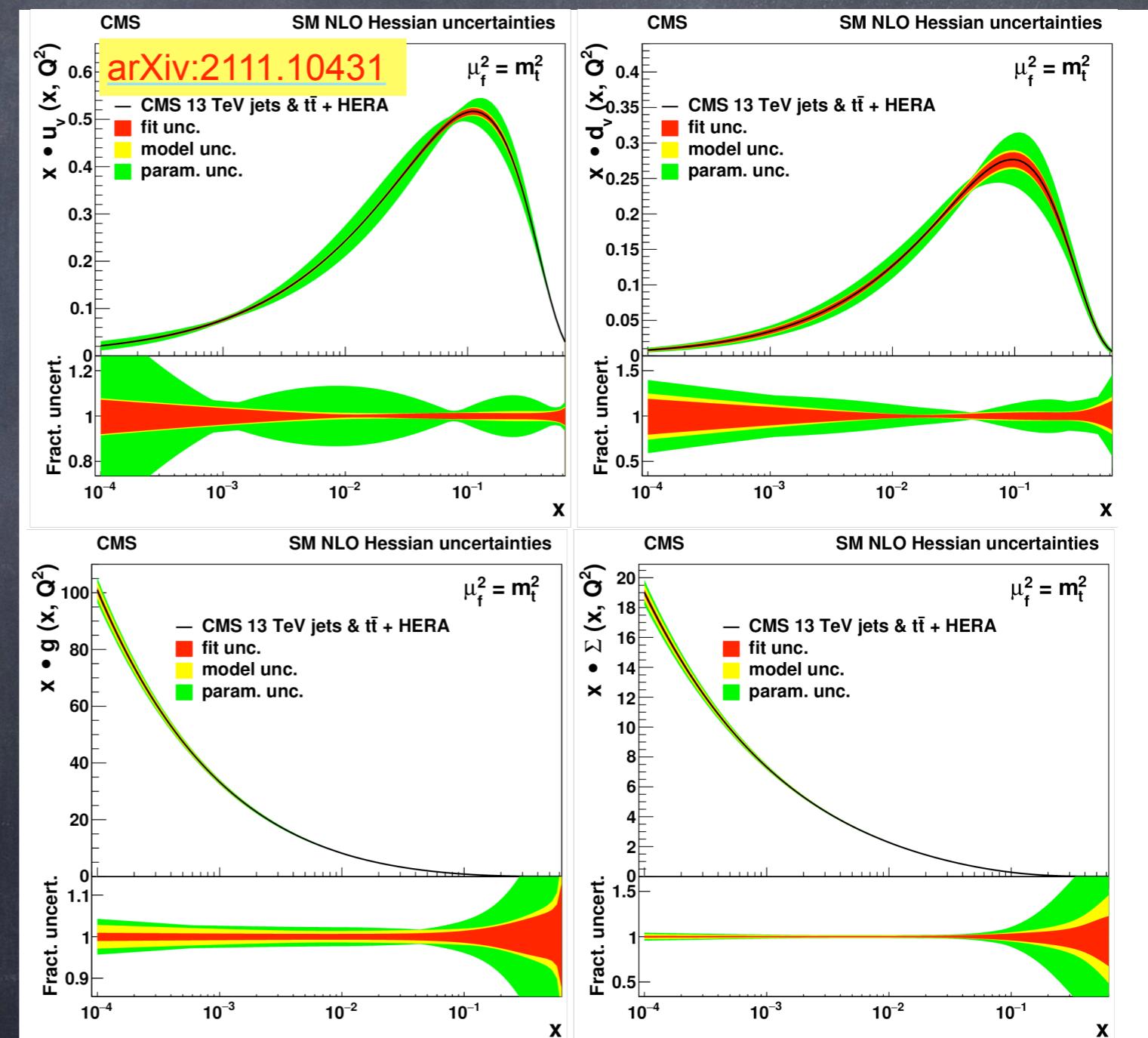
$$\alpha_s(m_Z) = 0.1188 \pm 0.0026$$

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

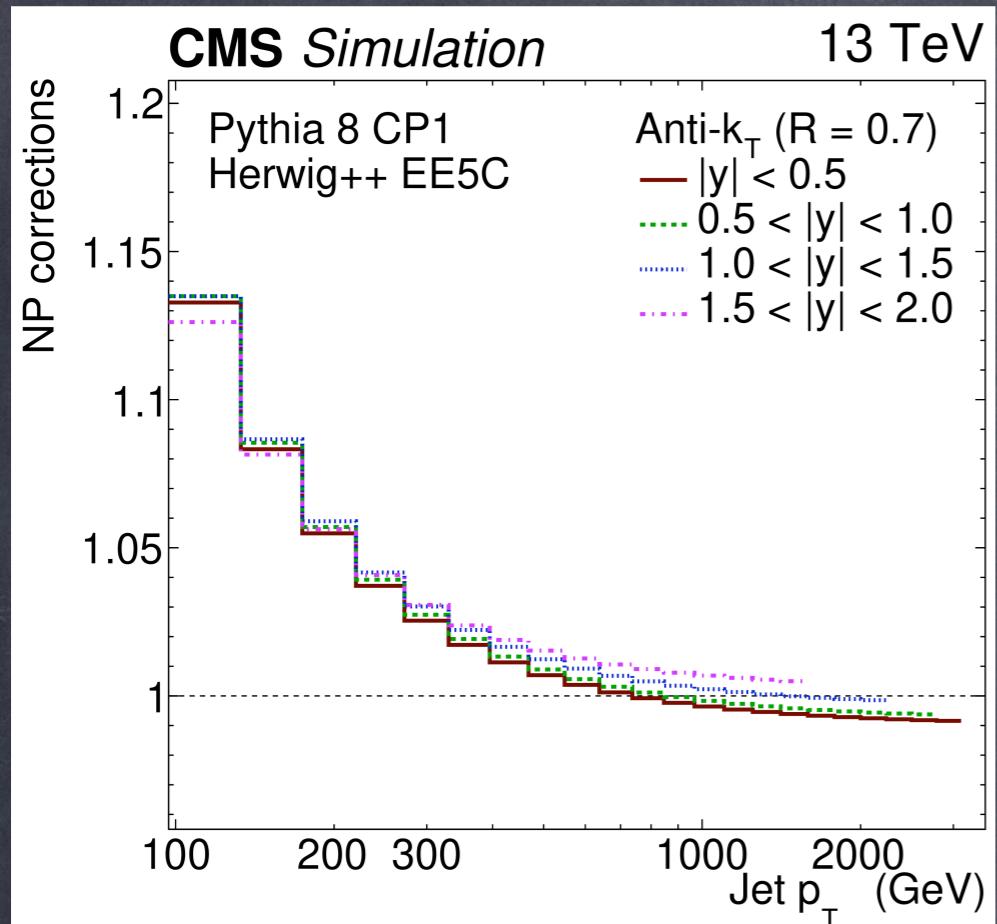
$$m_t^{pole} = 170.4 \pm 0.7 \text{ GeV}$$

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

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

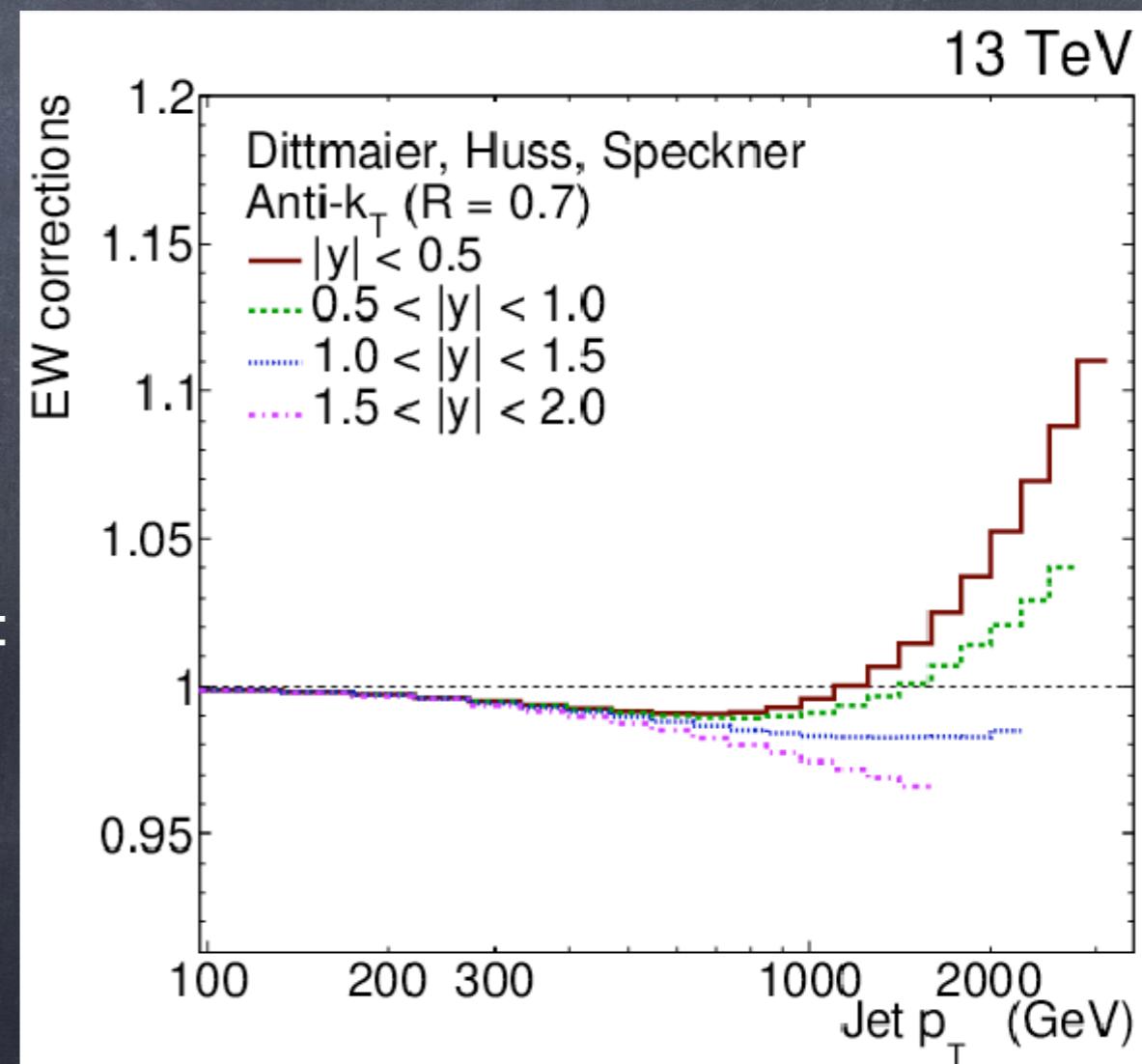


CORRECTIONS TO NLO/NNLO



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

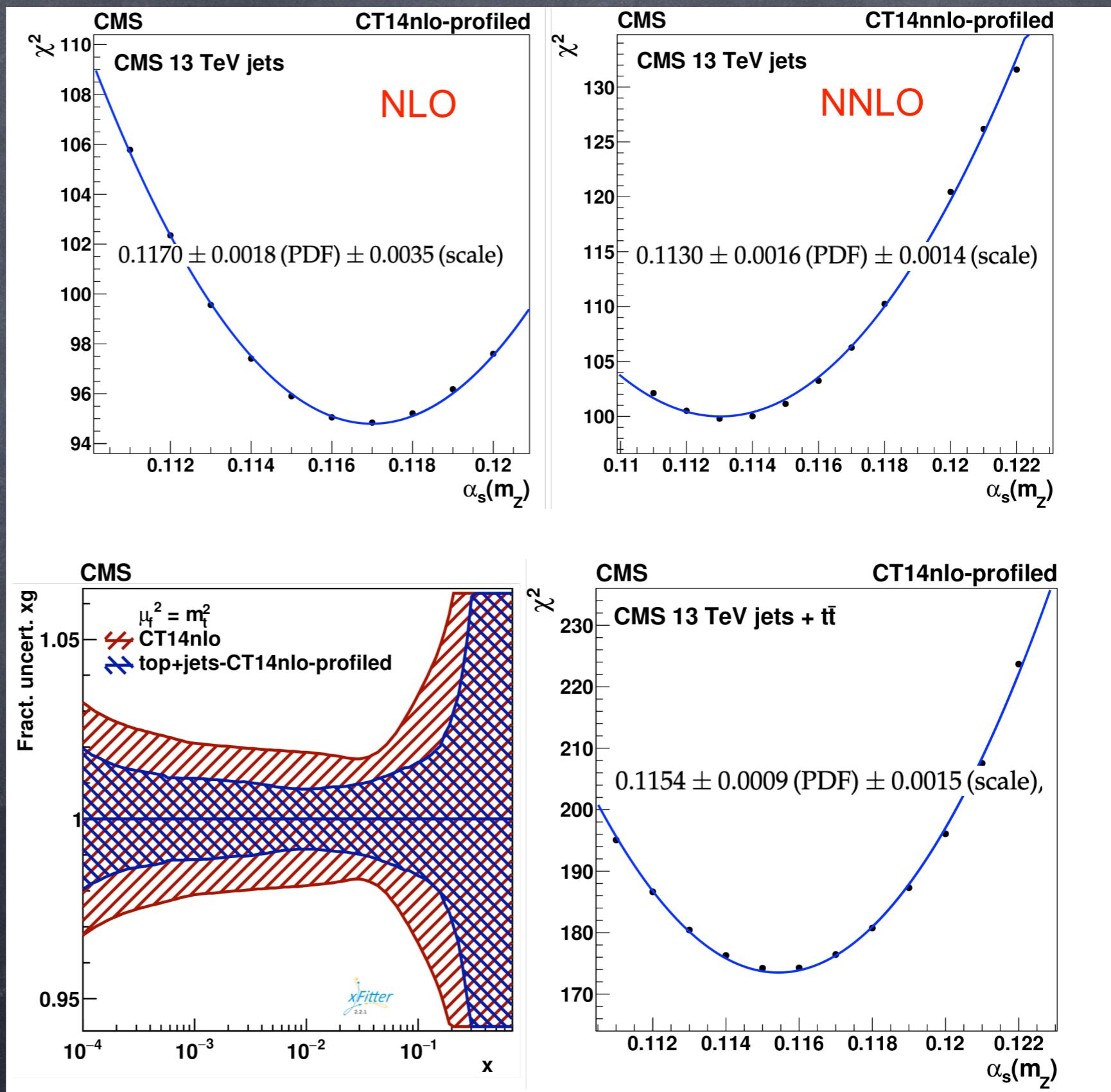
average + envelope of PYTHIA and HERWIG used



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 + \underline{D}_g x + \underline{E}_g x^2), \\
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HERA I+II neutral current	$e^+ p, E_p = 460 \text{ GeV}$	208/187	209/187
HERA I+II neutral current	$e^- p, E_p = 920 \text{ GeV}$	223/159	227/159
HERA I+II charged current	$e^+ p, E_p = 920 \text{ GeV}$	46/39	46/39
HERA I+II charged current	$e^- p, E_p = 920 \text{ GeV}$	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 + $t\bar{t}$):

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

Goodness of Fit NLO:

Data sets		SM fit	SMEFT fit
		Partial χ^2/N_{dp}	Partial χ^2/N_{dp}
HERA I+II neutral current	$e^+ p, E_p = 920 \text{ GeV}$	402/332	404/332
HERA I+II neutral current	$e^+ p, E_p = 820 \text{ GeV}$	60/63	60/63
HERA I+II neutral current	$e^+ p, E_p = 575 \text{ GeV}$	198/234	198/234
HERA I+II neutral current	$e^+ p, E_p = 460 \text{ GeV}$	208/187	208/187
HERA I+II neutral current	$e^- p, E_p = 920 \text{ GeV}$	223/159	223/159
HERA I+II charged current	$e^+ p, E_p = 920 \text{ GeV}$	46/39	46/39
HERA I+II charged current	$e^- p, E_p = 920 \text{ GeV}$	55/42	54/42
CMS 13 TeV $t\bar{t}$ 3D		23/23	23/23
CMS inclusive jets 13 TeV	$0.0 < y < 0.5$	13/22	20/22
	$0.5 < y < 1.0$	28/21	27/21
	$1.0 < y < 1.5$	13/19	11/19
	$1.5 < y < 2.0$	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 (b_{th} are the PDF uncertainties)

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

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

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

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

Minimisation of $\chi^2(\mathbf{b}_{\text{exp}}, \mathbf{b}_{\text{th}})$ 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 $\mathbf{b}_{\beta_{\text{th}}}^{\min}$ 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 $\chi^2(\beta_{\text{exp}}) \rightarrow \chi^2(\beta_{\text{exp}}, \beta_{\text{th}})$
 - Propagate the shifts and the reduction of the uncertainties to the PDFs

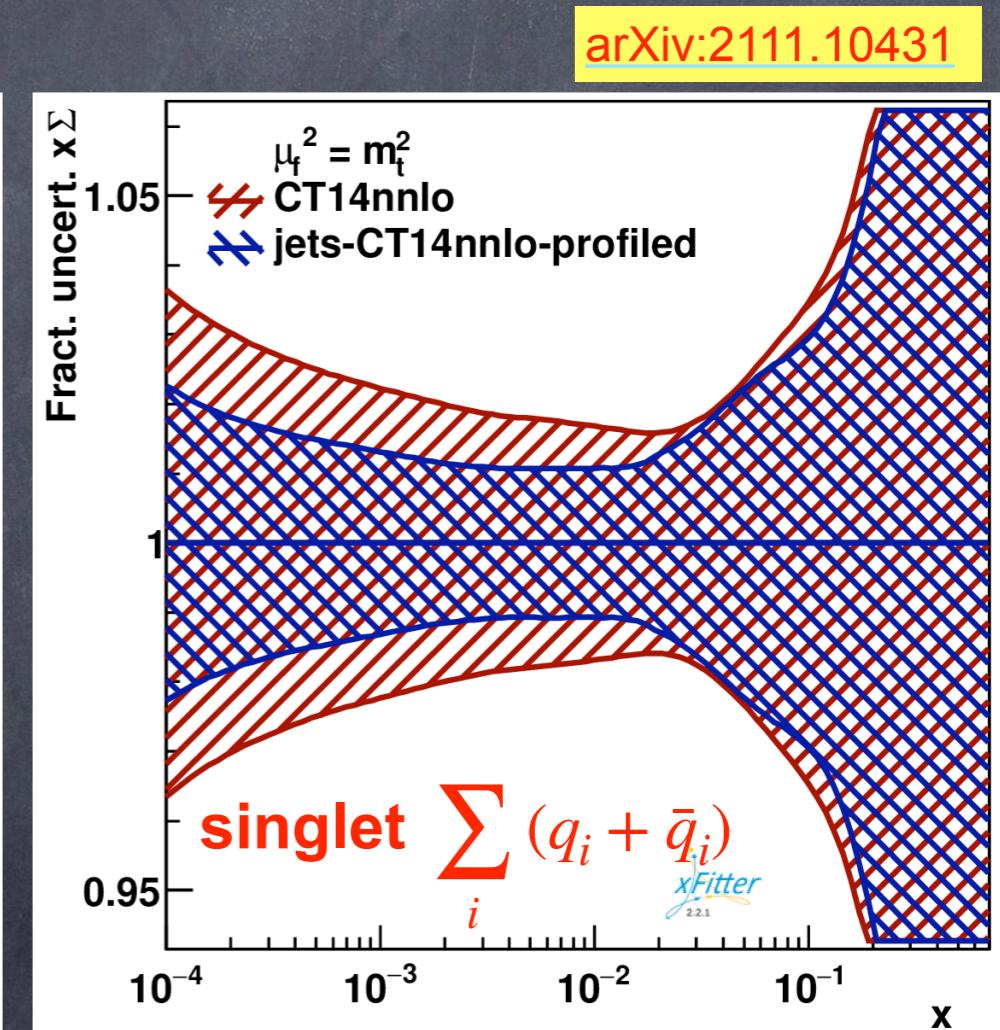
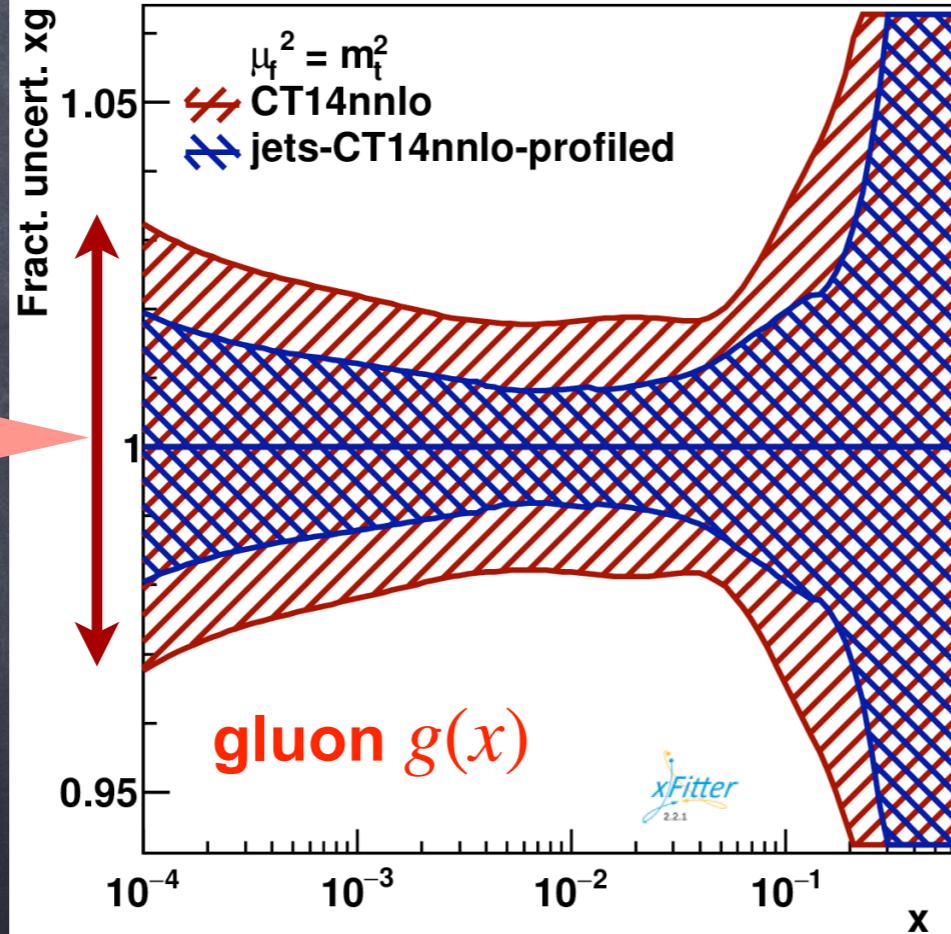
IMPACT ON GLOBAL PDF VIA PROFILING

- 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

uncertainty
in
original PDF



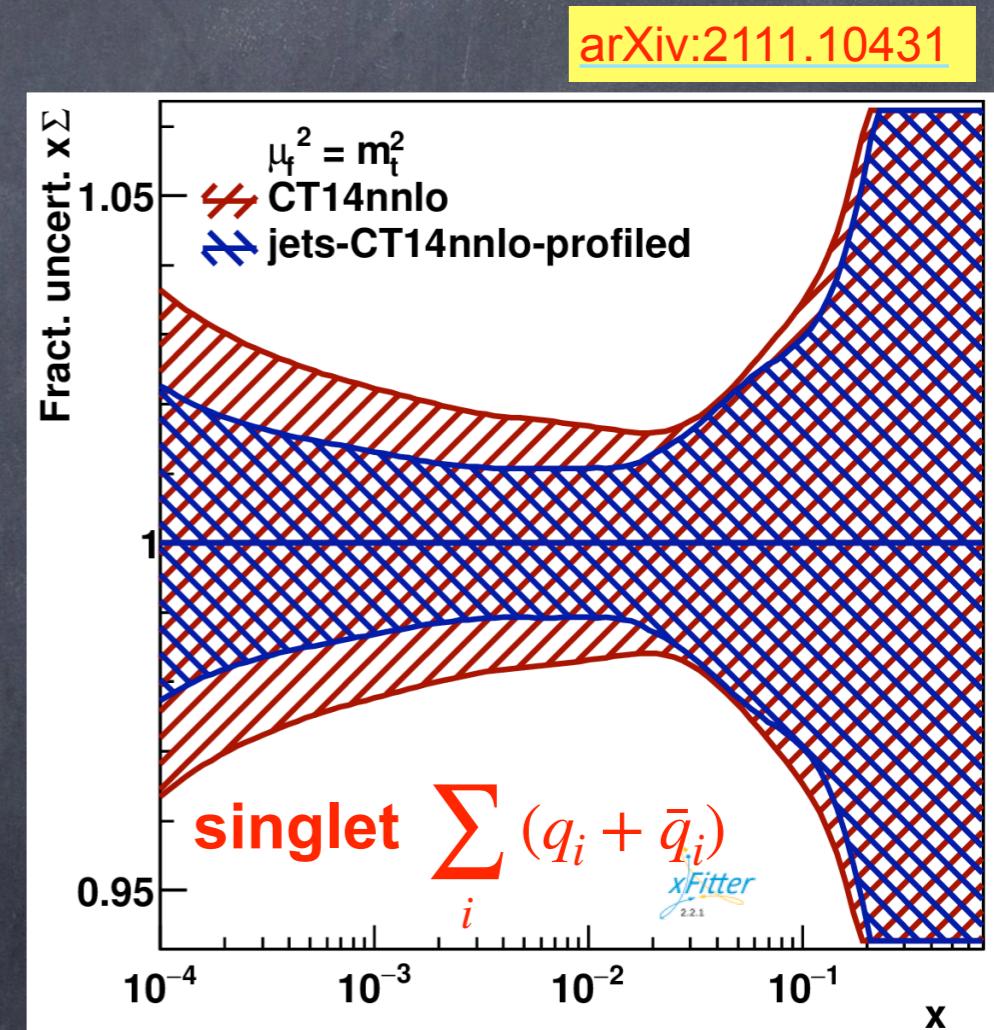
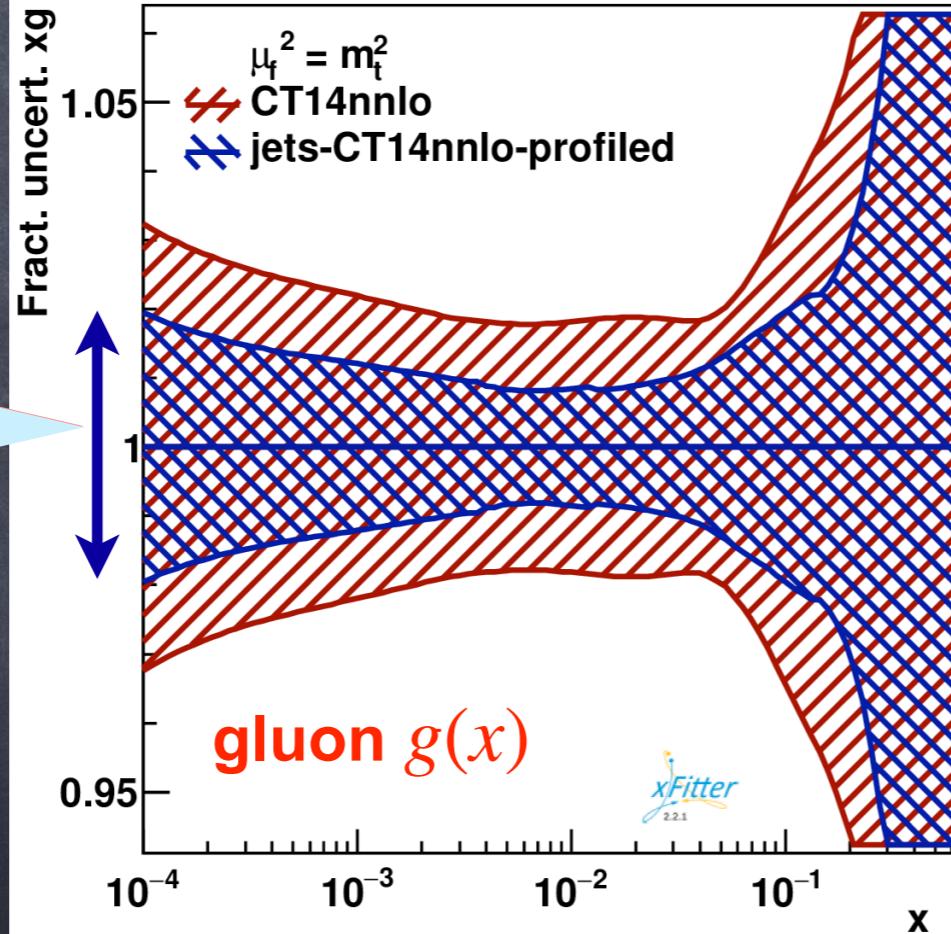
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improved by
jet data



Significant improvements in PDF uncertainties expected for global PDF analyses