News from CMS

PDF4LHC meeting | CERN | 23 November 2022

Daniel Savoiu on behalf of the CMS Collaboration

Jets for precision QCD

- core part of the experimental QCD program at the LHC

- measurements at $\sqrt{s}$ = 13 TeV together with fixed-order pQCD theory at NNLO provide important input for determinations of PDFs and the strong coupling constant $\alpha_s(m_Z)$
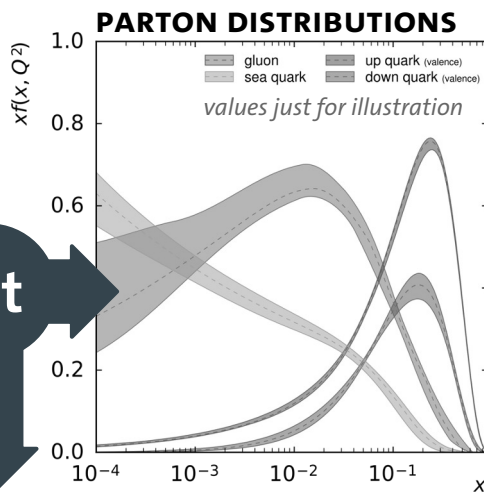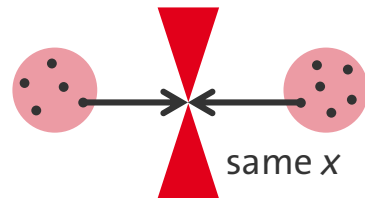
- **_inclusive jet_** production:
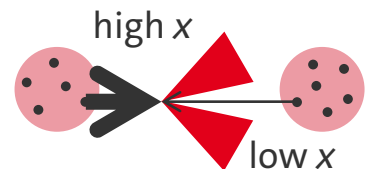 - directly sensitive to PDFs and $\alpha_s(m_Z)$

- **_dijet_** production:
  - **_topology_** provides handle on PDFs over wide range in momentum fraction **_x_**

INPUTS

precision **measurements**
LHC: **jet cross sections** at $\sqrt{s}$ = 13 TeV

fixed-order **theory**
state of the art: **NNLO pQCD**

Fit

PARTON DISTRIBUTIONS

$xf(x, Q^2)$

gluon   up quark (valence)
sea quark   down quark (valence)

values just for illustration

1.0

0.8

0.6

0.4

0.2

0.0

10^{-4} 10^{-3} 10^{-2} 10^{-1} x

STRONG COUPLING
$\alpha_s(m_Z)$
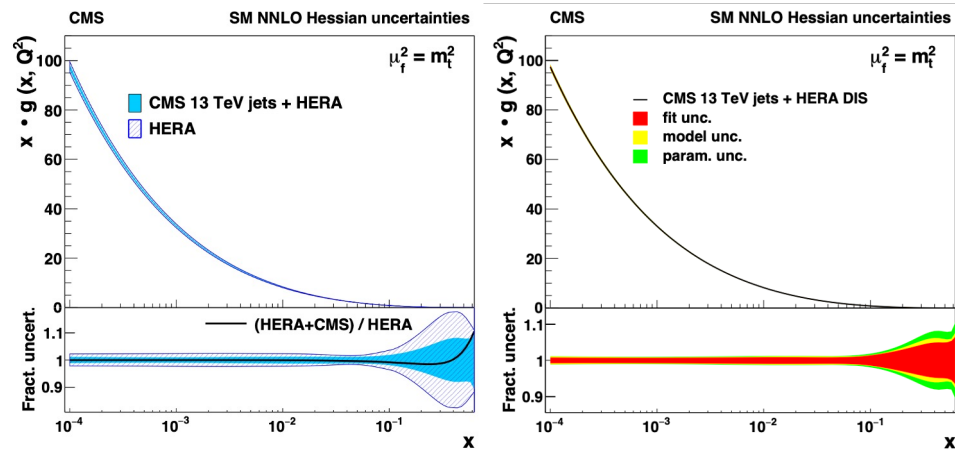
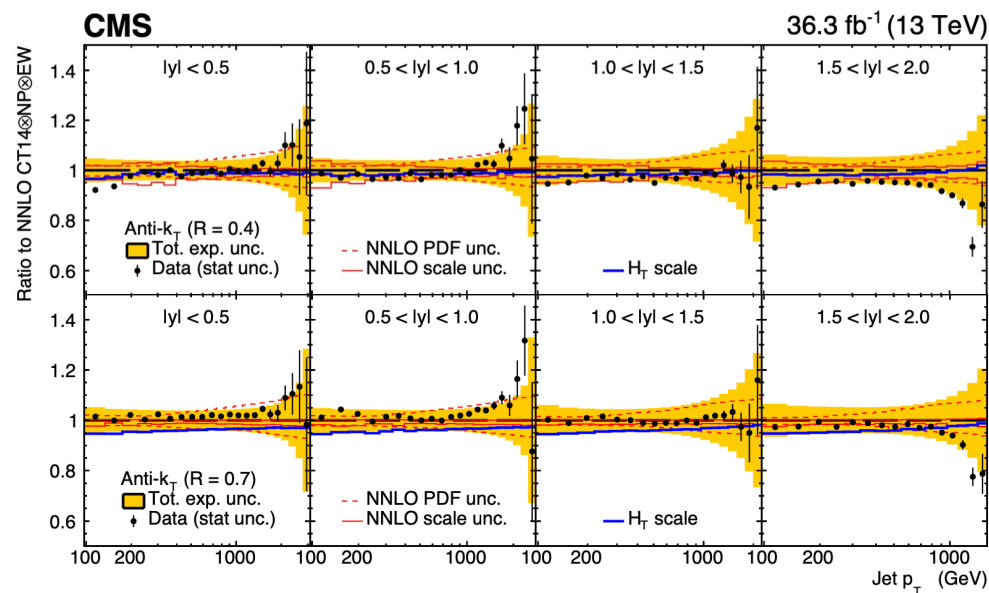_back-to-back_

same x

high x

boosted

low x

Inclusive jet production

- measurement from CMS at 13 TeV was published earlier this year [1]
  - double-differential in jet p_T, $|y|$ with $R = 0.4$ & $R = 0.7$
  - $R = 0.7$ data used for PDF + $\alpha_s(m_Z)$ fits @ NNLO

- theory predictions at NNLO pQCD
  - **NNLOJET** + **fastNLO** interpolation grids
  - NLO grids + binwise NNLO K factors

$\alpha_s(m_Z) = \mathbf{0.1170}\ \mathbf{(14)}_{fit}\ \mathbf{(8)}_{scale}\ \mathbf{(7)}_{model}\ \mathbf{(1)}_{param}$
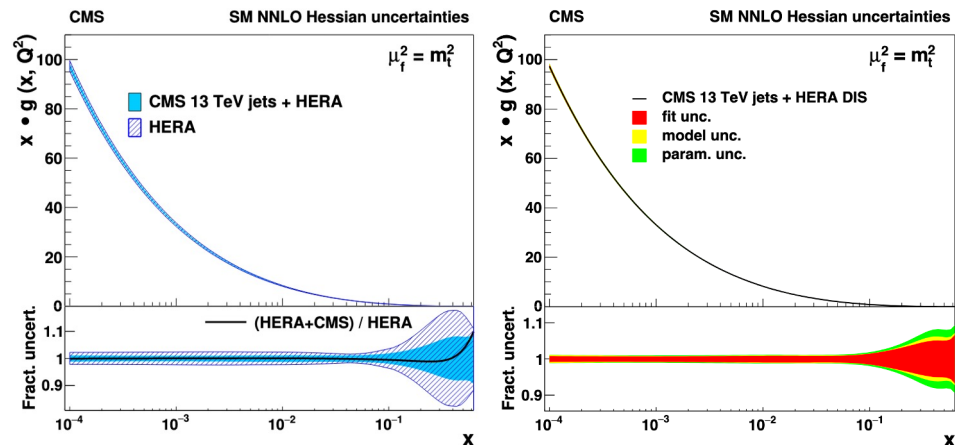
[1] CMS Collaboration, *"Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at √s = 13 TeV"*, JHEP **02** (2022) 142, arXiv:2111.10431
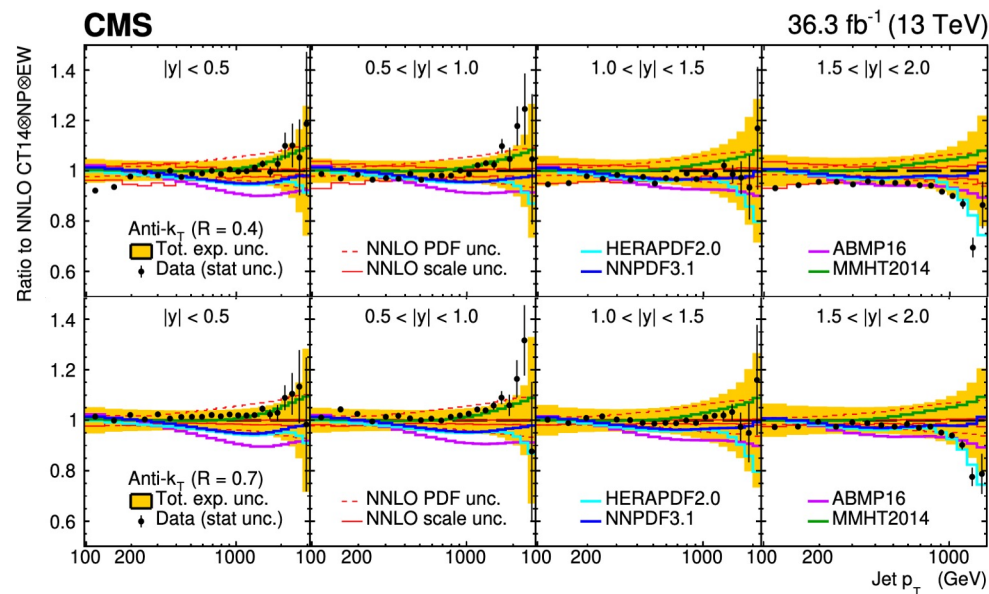
Inclusive jet production

update

- measurement from CMS at 13 TeV was published earlier this year [1]
  - double-differential in jet p_T, $|y|$ with $R = 0.4$ & $R = 0.7$
  - $R = 0.7$ data used for PDF + $\alpha_s(m_Z)$ fits @ NNLO

- addendum accepted by *JHEP* (on arXiv as an Appendix to v3)

- theory predictions at NNLO pQCD
  - ***NNLOJET*** + ***fastNLO*** interpolation grids
  - *K* Factors → NNLO grids [2]

$\alpha_s(m_Z)$ = **0.1166 (14)**$_{fit}$ **(4)**$_{scale}$ **(7)**$_{model}$ **(1)**$_{param}$

[1] CMS Collaboration, "Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at √s = 13 TeV", JHEP **02** (2022) 142, arXiv:2111.10431
[2] D. Britzger et al. "NNLO interpolation grids for jet production at the LHC", Eur. Phys. J. C **82** (2022) 10, doi:10.1140/epjc/s10052-022-10880-2, arXiv:2207.13

# Inclusive jet production

improved fit quality using full NNLO grids

update

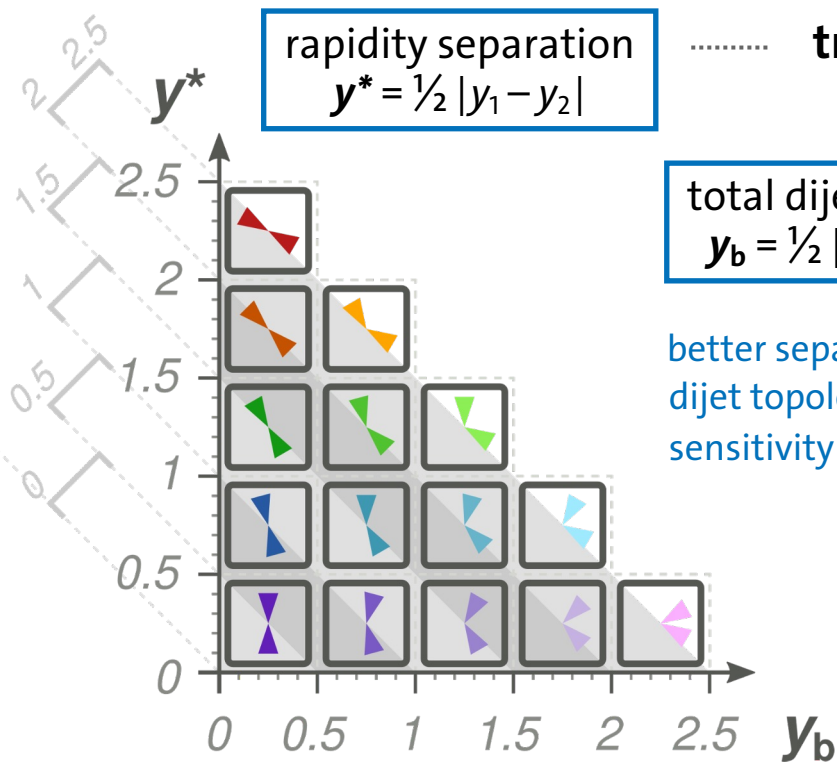| Data sets		HERA-only Partial χ^2/N_{dp}	HERA+CMS Partial χ^2/N_{dp}	HERA+CMS Partial χ^2/N_{dp}
HERA I+II neutral current	e^+p, $E_p = 920\,\mathrm{GeV}$	378/332	375/332	376/332
HERA I+II neutral current	e^+p, $E_p = 820\,\mathrm{GeV}$	60/63	60/63	60/63
HERA I+II neutral current	e^+p, $E_p = 575\,\mathrm{GeV}$	201/234	201/234	202/234
HERA I+II neutral current	e^+p, $E_p = 460\,\mathrm{GeV}$	208/187	209/187	209/187
HERA I+II neutral current	e^-p, $E_p = 920\,\mathrm{GeV}$	223/159	227/159	227/159
HERA I+II charged current	e^+p, $E_p = 920\,\mathrm{GeV}$	46/39	46/39	46/39
HERA I+II charged current	e^-p, $E_p = 920\,\mathrm{GeV}$	55/42	56/42	56/42
CMS inclusive jets 13 TeV	$0.0 < |y| < 0.5$	—	13/22	8.6/22
	$0.5 < |y| < 1.0$	—	31/21	23/21
	$1.0 < |y| < 1.5$	—	18/19	13/19
	$1.5 < |y| < 2.0$	—	14/16	14/16
Correlated χ^2		66	83	81
Global χ^2/N_{dof}		1231/1043	1321/1118	1302/1118

Dijet production

- new set of measurements of the **dijet cross section** at $\sqrt{s}$ = 13 TeV in preparation from CMS
  - extensive set of multi-differential measurements for several combinations of jet radii R and observables

double-differential

outer jet rapidity
$$|y|_{max} = \max(|y_1|, |y_2|)$$

$m_{1,2}$
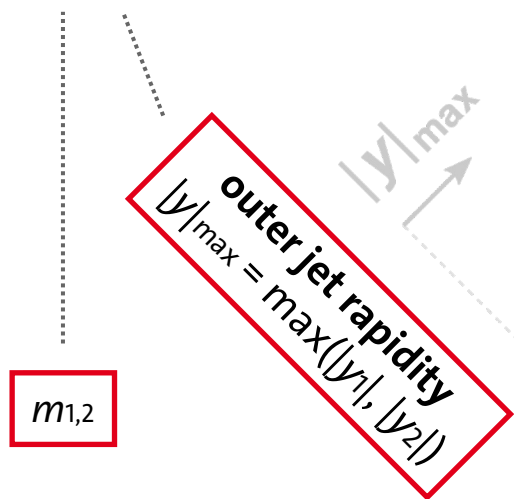
higher statistical precision due to more inclusive 2D binning

rapidity separation
$$y^* = \tfrac{1}{2}\,|y_1 - y_2|$$

triple-differential

total dijet boost
$$y_b = \tfrac{1}{2}\,|y_1 + y_2|$$

$m_{1,2}$ or $\langle p_T \rangle_{1,2}$

better separation of boosted and non-boosted dijet topologies → potentially heightened sensitivity to PDFs


two jet radii

$R = 0.4$

$R = 0.8$

Measurement strategy

- dijet event selection with

  $p_{T,jet\,1} > 100$ GeV $\qquad p_{T,jet\,2} > 50$ GeV

- cross section measured as a function of dijet **invariant mass** and **average transverse momentum**

  $m_{1,2} = 249\text{–}10050$ GeV $\quad \langle p_T \rangle_{1,2} = 147\text{–}2702$ GeV

- simultaneous unfolding in all observables
  - well-conditioned response, no regularization

- dominant systematic uncertainty (4–20%) from determination of the **jet energy scale**
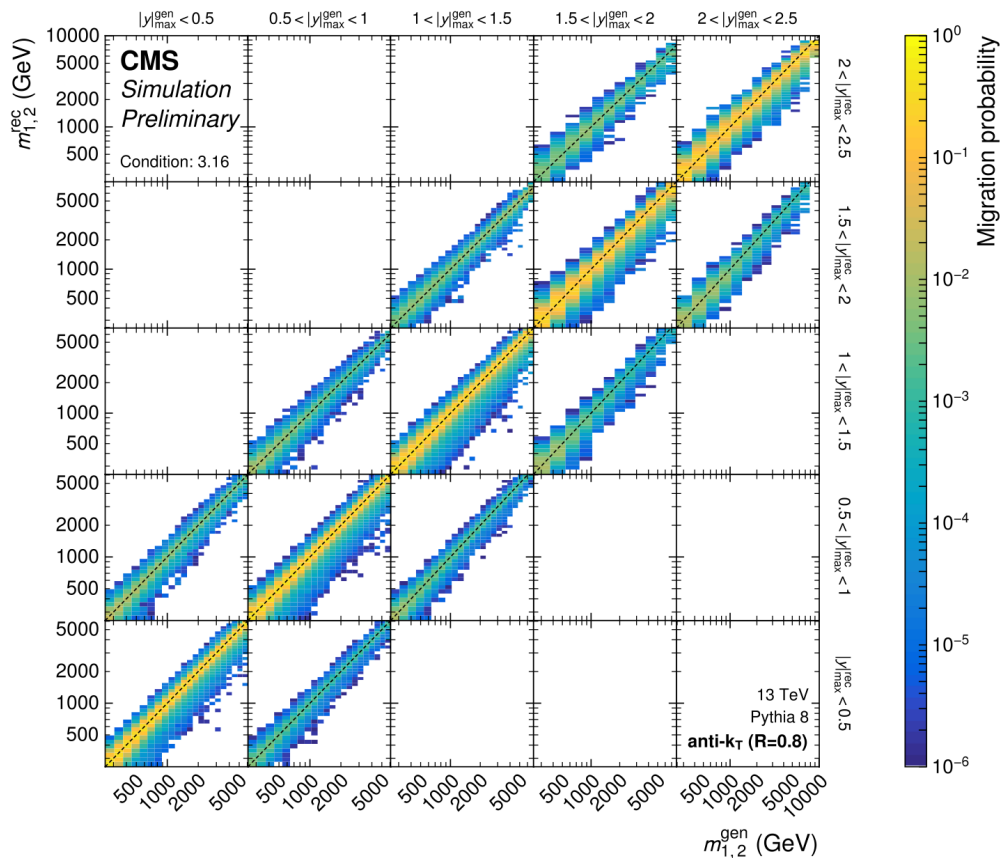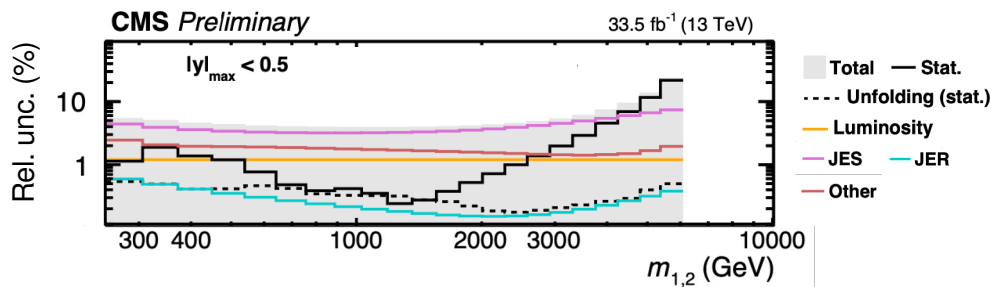
Theory predictions

□ perturbative QCD predictions at NNLO from **NNLOJET** [1]

  ▪ available as **fastNLO** interpolation grids[2] taking into account full dependence on α_s, μ_R, μ_F [1]

  ▪ *central scale choice*: $\mu_R = \mu_F = m_{1,2}$ (dijet invariant mass)

  ▪ NNLO part at leading color

□ mostly good perturbative convergence

  ▪ higher-order results mostly within scale uncertainty of previous order

  ▪ plot shows $R = 0.4$, convergence better for $R = 0.8$

  ▪ reduction of scale uncertainty @ NNLO
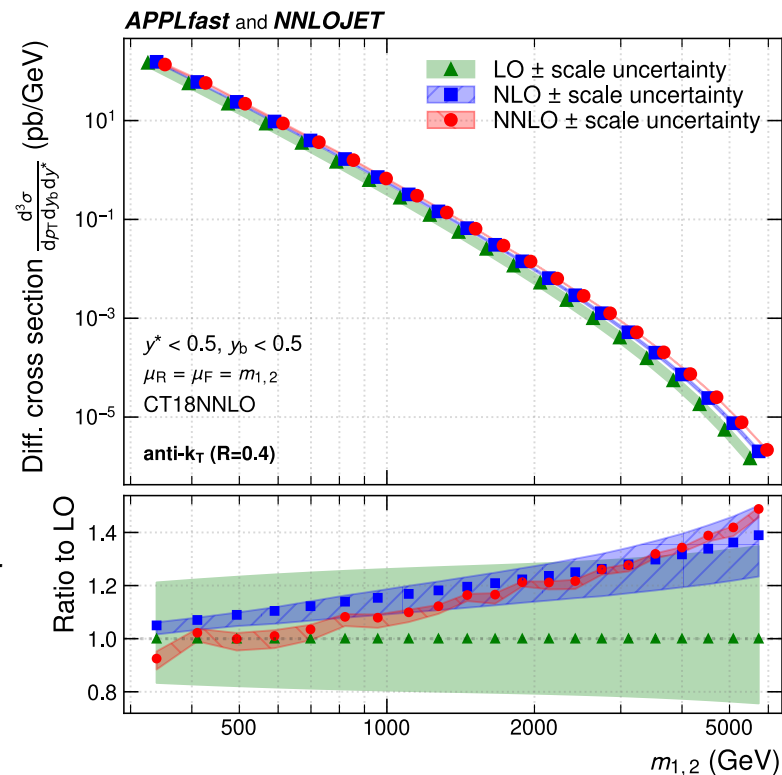
[1] T. Gehrmann *et al.* "*Jet cross sections and transverse momentum distributions with NNLOJET*", *PoS* RADCOR2017 (2018) 074, doi:10.22323/1.290.0074, arXiv:1801.06415

[2] D. Britzger *et al.* "*NNLO interpolation grids for jet production at the LHC*", *Eur. Phys. J. C* **82** (2022) 10, doi:10.1140/epjc/s10052-022-10880-2, arXiv:2207.13735

Theory corrections

correction factors are applied to the theory predictions to account for effects beyond perturbative QCD

Nonperturbative
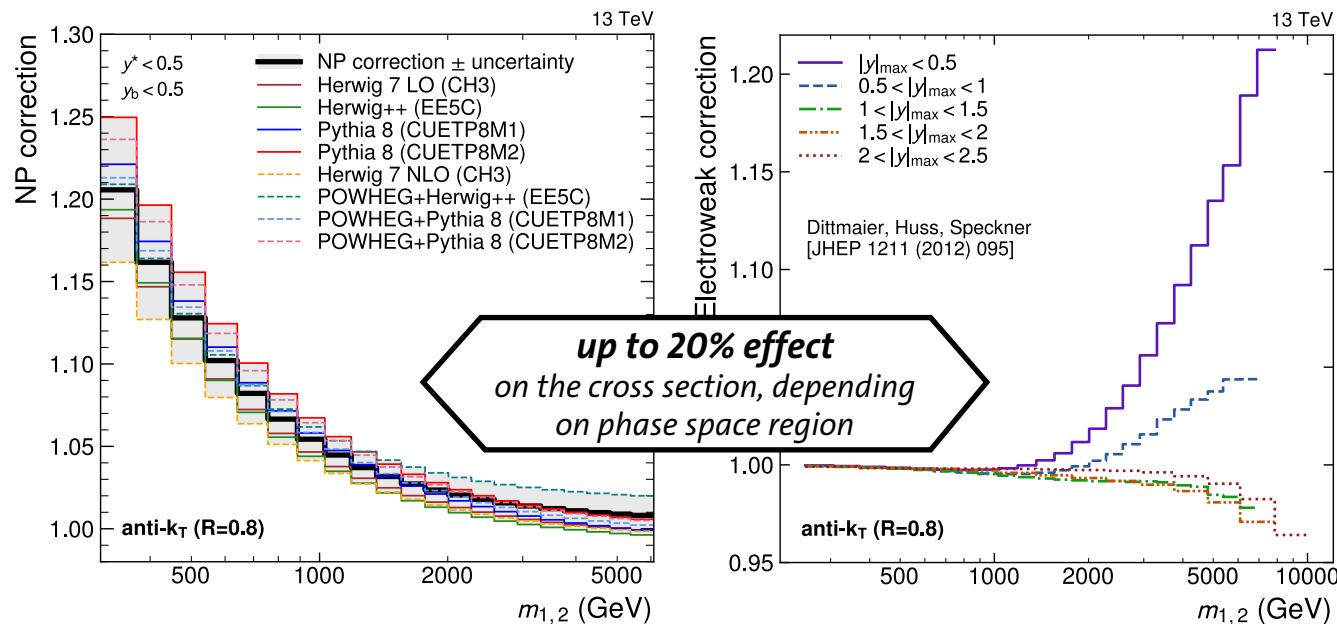
- hadronization
- multi-parton interactions

Electroweak

- virtual W/Z boson exchanges
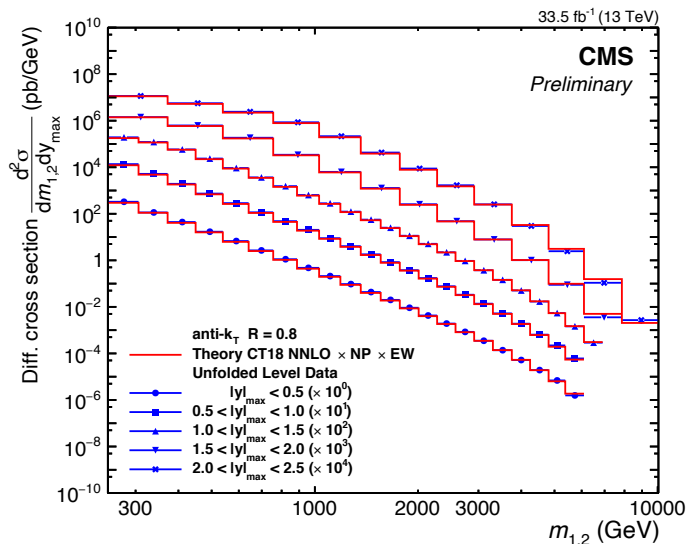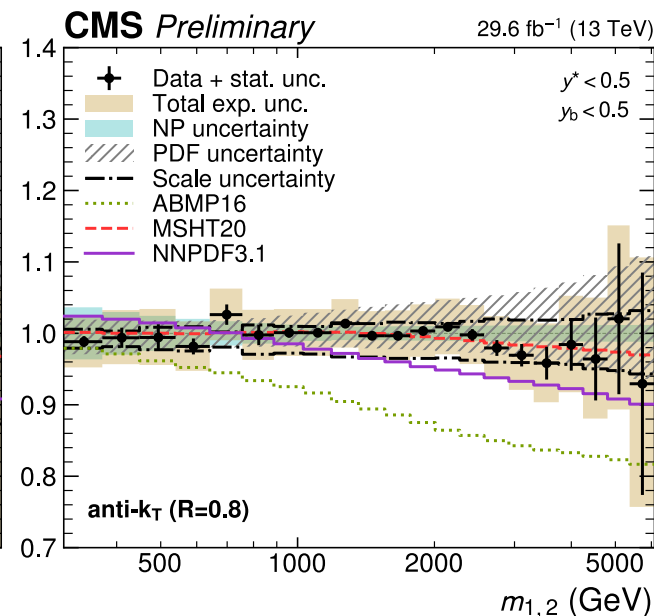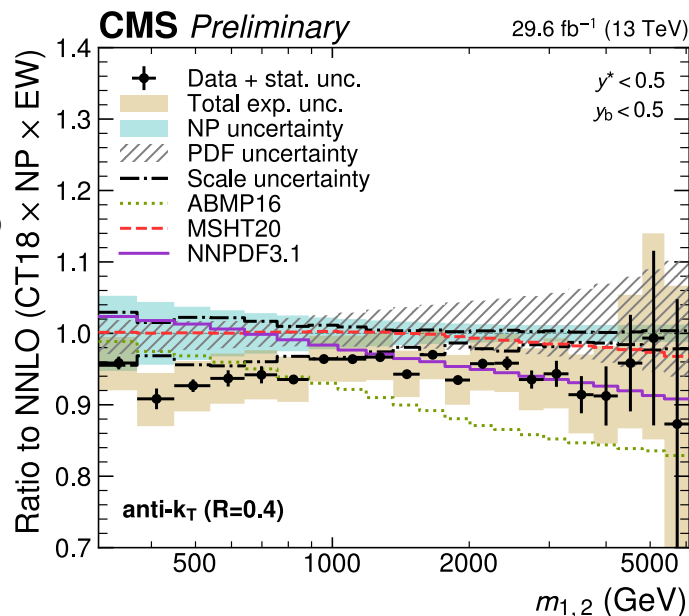
derived
from particle-level MC generators

- central value and uncertainty from **8** different configurations
- study effect of **MC code** (*Herwig* vs *Pythia*), **perturbative order** (LO vs NLO) and **tune**

up to 20% effect
on the cross section, depending on phase space region

Comparison to theory calculations

good data/theory agreement
better for R = 0.8 than R = 0.4

PDF determination strategy

procedure based on **HERAPDF2.0** analysis[1], similar to CMS 13 TeV **inclusive jet** analysis [2]

[1] H1, ZEUS Collaborations. *"Combination of measurements of inclusive deep inelastic e±p scattering cross sections and QCD analysis of HERA data"*, Eur. Phys. J. C **75** (2015) 12, arXiv:1506.06042
[2] CMS Collaboration, *"Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at √s = 13 TeV"*, JHEP **02** (2022) 142, arXiv:2111.10431

- ❑ fit **deep inelastic scattering** (DIS) data from HERA in addition to the CMS dijet jet measurements
  - ▪ limit DIS data to Q^2 > 10 GeV² to minimize impact of higher-twist corrections

- ❑ PDFs are parametrized by the general form

  $$x\, f(x) = A_f\; x^{B_f}\; (1-x)^{C_f}\; (1 + D_f\, x + E_f\, x^2)$$

  - ▪ f = gluon **g**, valence quarks **u$_v$/d$_v$**, sea quarks **Ū/D̄**
  - ▪ **A**, **B** & **C** parameters always included (some fixed by sum rules)
  - ▪ **D** & **E** parameters added as needed based on χ^2 scan

  with CMS jet data:
  *probe & refine gluon PDF
  in high-x region*

CMS *Preliminary*

HERA DIS

$x\, g(x, \mu_F^2)$

μ_F^2 = 1.9 GeV²

Ratio

x
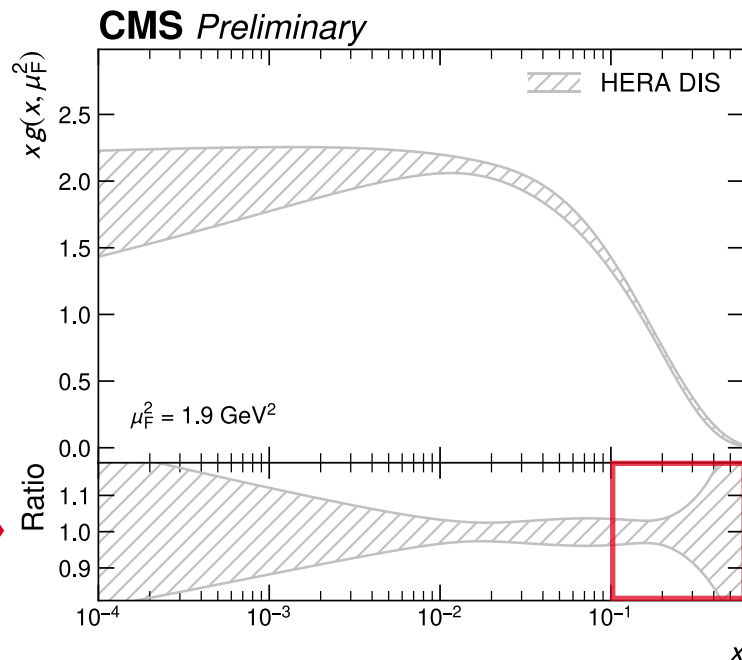
Final parametrizations

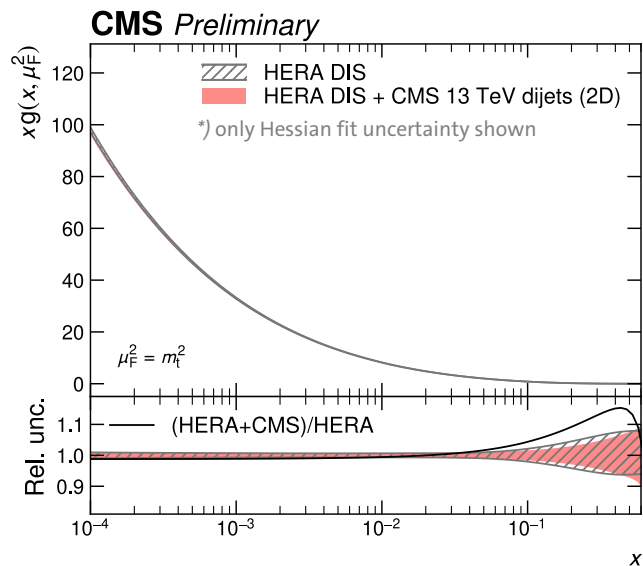χ^2 scan results in similar parametrizations for fits with **2D** and **3D** dijet data

$$x\,g(x) \;= A_g \quad x^{B_g} \quad (1-x)^{C_g}$$
$$x\,u_v(x) = A_{u_v} \; x^{B_{u_v}} \; (1-x)^{C_{u_v}} \quad (1 + D_{u_v}\,x + E_{u_v}\,x^2)$$
$$x\,d_v(x) = A_{d_v} \; x^{B_{d_v}} \; (1-x)^{C_{d_v}}$$
$$x\,\bar{U}(x) \;= A_{\bar{U}} \; x^{B_{\bar{U}}} \; (1-x)^{C_{\bar{U}}} \quad (1 + D_{\bar{U}}\,x)$$
$$x\,\bar{D}(x) \;= A_{\bar{D}} \; x^{B_{\bar{D}}} \; (1-x)^{C_{\bar{D}}}$$

$$x\,g(x) \;= A_g \quad x^{B_g} \quad (1-x)^{C_g}$$
$$x\,u_v(x) = A_{u_v} \; x^{B_{u_v}} \; (1-x)^{C_{u_v}} \quad (1 + D_{u_v}\,x)$$
$$x\,d_v(x) = A_{d_v} \; x^{B_{d_v}} \; (1-x)^{C_{d_v}}$$
$$x\,\bar{U}(x) \;= A_{\bar{U}} \; x^{B_{\bar{U}}} \; (1-x)^{C_{\bar{U}}} \quad (1 + D_{\bar{U}}\,x)$$
$$x\,\bar{D}(x) \;= A_{\bar{D}} \; x^{B_{\bar{D}}} \; (1-x)^{C_{\bar{D}}} \quad (1 + D_{\bar{D}}\,x)$$

CMS *Preliminary*

HERA DIS
HERA DIS + CMS 13 TeV dijets (2D)
*) only Hessian fit uncertainty shown
$\mu_F^2 = m_t^2$
(HERA+CMS)/HERA

increased sensitivity to gluon PDF compared to DIS-only fit (**gray**)

CMS *Preliminary*

HERA DIS
HERA DIS + CMS 13 TeV dijets (3D)
*) only Hessian fit uncertainty shown
$\mu_F^2 = m_t^2$
(HERA+CMS)/HERA

Uncertainties on PDFs

CMS *Preliminary*

Legend:
- HERA DIS + CMS 13 TeV dijets (2D)
- fit unc.
- model unc.
- scale unc.
- param. unc.

$\mu_F^2 = m_t^2$

y-axis: $xg(x, \mu_F^2)$, Rel. unc.
x-axis: x
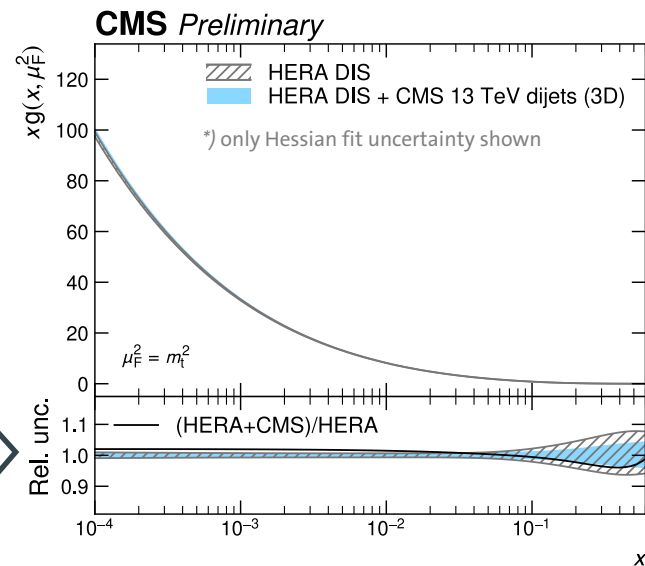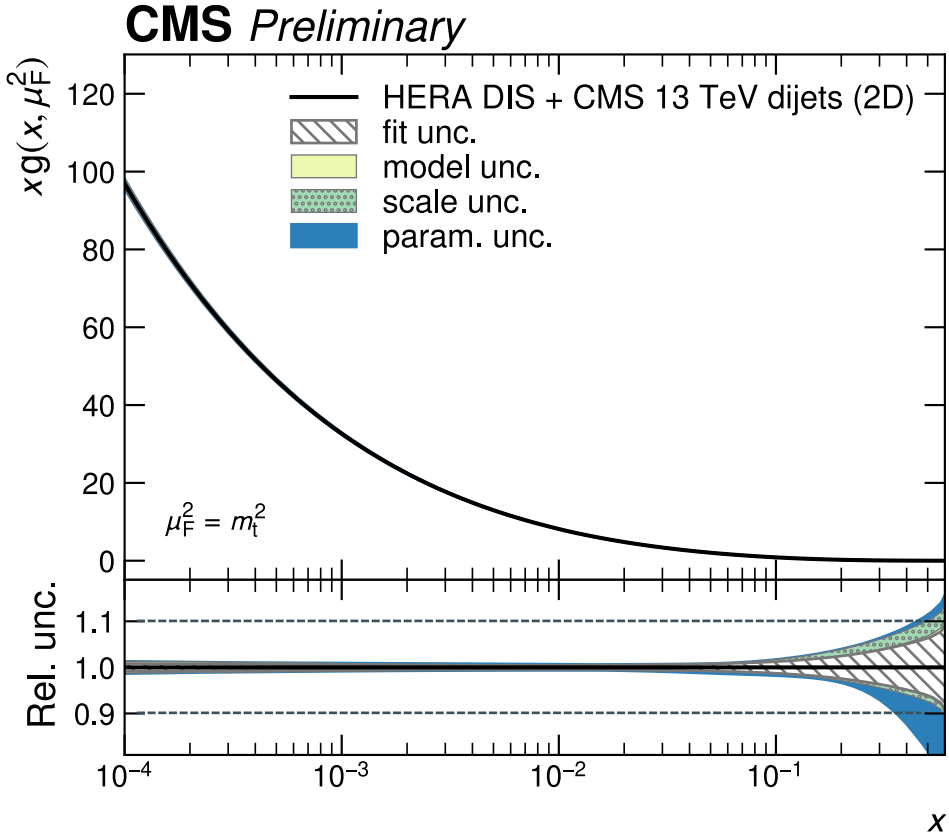
fit
Hessian uncertainty from fit

model
variations of non-PDF parameters

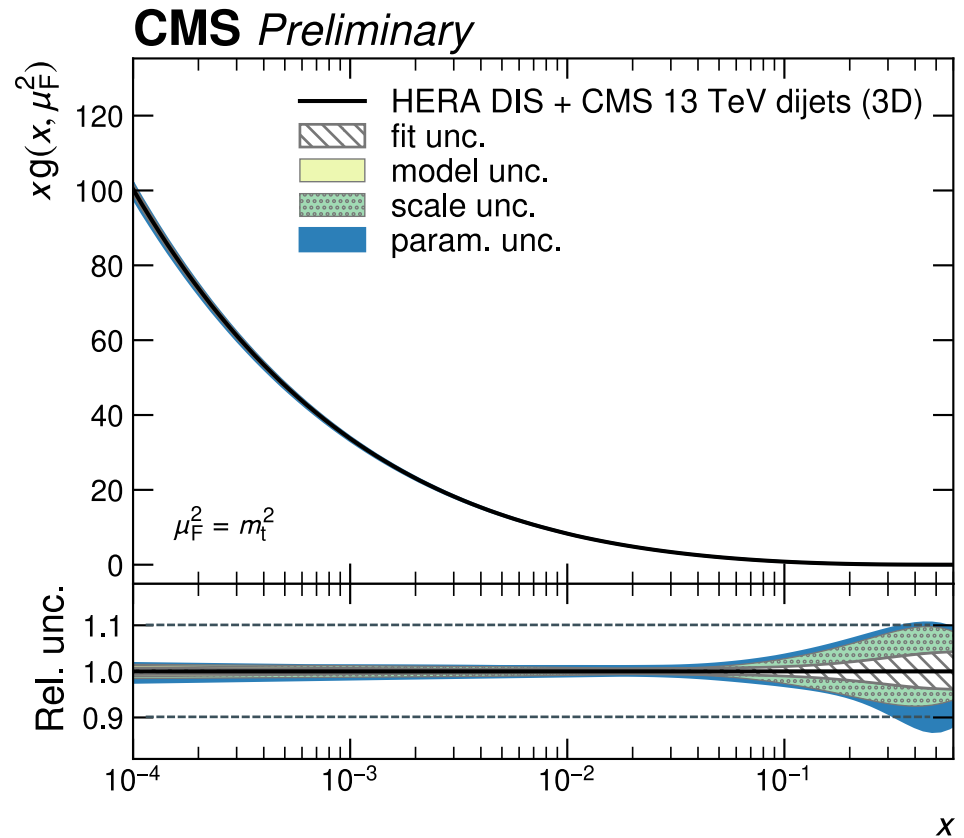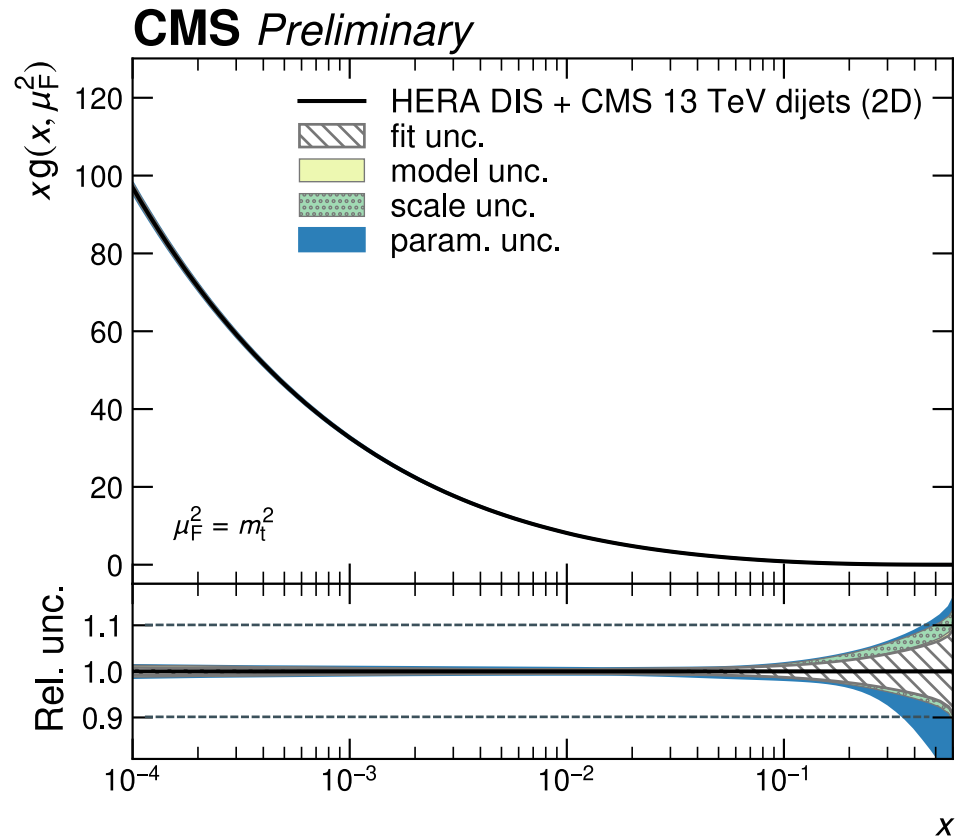| Parameter		Value	Variations	
Q^2 cut for DIS data	Q^2_{min} [GeV^2]	**10**	7.5	12.5
strangeness fraction	f_s	**0.4**	0.3	0.5
c quark mass	M_c [GeV]	**1.43**	–	1.49
b quark mass	M_b [GeV]	**4.5**	4.25	4.75
starting scale	$\mu^2_{F,0}$ [GeV^2]	**1.9**	1.6	–

scale
missing higher orders in perturbation theory

param
envelope of fits with alternative parametrizations

Uncertainties on PDFs

Uncertainties on PDFs

CMS *Preliminary*

— HERA DIS + CMS 13 TeV dijets (2D)
⬚ fit unc.
⬚ model unc.
⬚ scale unc.
⬛ param. unc.

$xg(x, \mu_F^2)$ — 120, 100, 80, 60, 40

CMS *Preliminary*

— HERA DIS + CMS 13 TeV dijets (3D)
⬚ fit unc.
⬚ model unc.
⬚ scale unc.
⬛ param. unc.

$xg(x, \mu_F^2)$ — 120, 100, 80, 60, 40
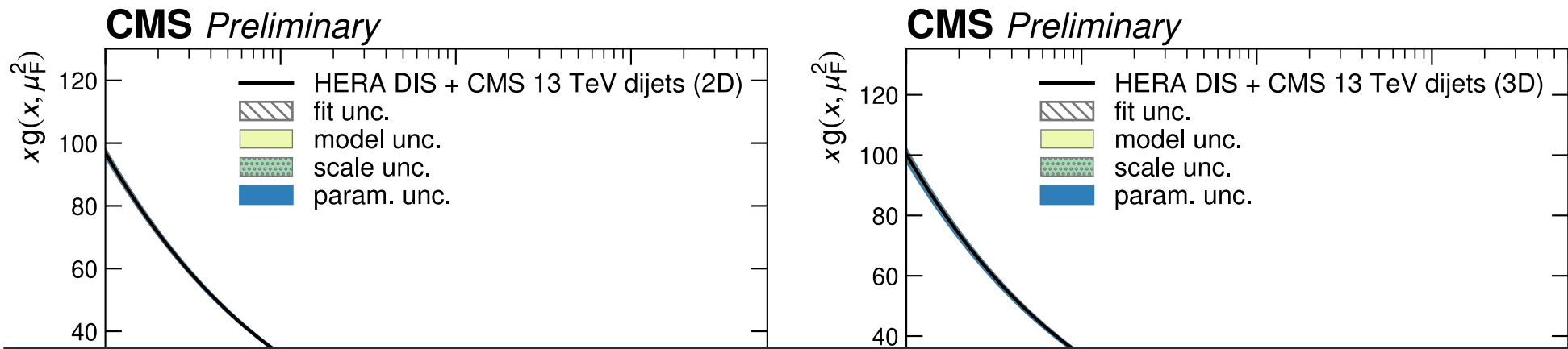
▫ additional fits where ***strong coupling constant*** $\alpha_s(m_Z)$ is determined simultaneously with PDFs:

2D $\alpha_s(m_Z) = \mathbf{0.1201}\ \mathbf{(12)}_{fit}\ \mathbf{(8)}_{scale}\ \mathbf{(8)}_{model}\ \mathbf{(5)}_{param}\ |\ \mathbf{(21)}_{total}$

$\chi^2/n_{dof} = 1280.47/1093 = \mathbf{1.172}$

3D $\alpha_s(m_Z) = \mathbf{0.1201}\ \mathbf{(10)}_{fit}\ \mathbf{(5)}_{scale}\ \mathbf{(8)}_{model}\ \mathbf{(6)}_{param}\ |\ \mathbf{(20)}_{total}$

$\chi^2/n_{dof} = 1553.27/1166 = \mathbf{1.332}$

▫ ca. 1 standard deviation away from world average value:

WA $\alpha_s(m_Z) = \mathbf{0.1179}\ \mathbf{(10)}_{total}$

Caveat
impact of subleading-color
NNLO contribution not known yet

Summary

- updated results for QCD analysis of **inclusive jet cross sections** at 13 TeV (addendum in preparation)
  - using recently-published NNLO interpolation grids
  - precision on strong coupling constant improved compared
    to previous result using K factors

    Incl $\alpha_s(m_Z) = \mathbf{0.1166}\ (\mathbf{14})_{fit}\ (\mathbf{4})_{scale}\ (\mathbf{7})_{model}\ (\mathbf{1})_{param}$

- extensive differential measurements of **dijet cross sections** at 13 TeV in preparation
  - double- & triple-differential   jets with $R = 0.4$ & $R = 0.8$ vs. invariant mass $m_{1,2}$ & avg. transverse momentum $\langle p_T \rangle_{1,2}$

- QCD analysis of **double-** (2D) and **triple-differential** (3D) cross sections vs. $m_{1,2}$ ($R = 0.8$)
  - inclusion of CMS data results in improved constraints on gluon PDFs
  - strong coupling constant determined simultaneously with PDFs

    2D $\alpha_s(m_Z) = \mathbf{0.1201}\ (\mathbf{12})_{fit}\ (\mathbf{8})_{scale}\ (\mathbf{8})_{model}\ (\mathbf{5})_{param}$

    3D $\alpha_s(m_Z) = \mathbf{0.1201}\ (\mathbf{10})_{fit}\ (\mathbf{5})_{scale}\ (\mathbf{8})_{model}\ (\mathbf{6})_{param}$

Thank you for your attention!