Recent progress on determination of PDFs

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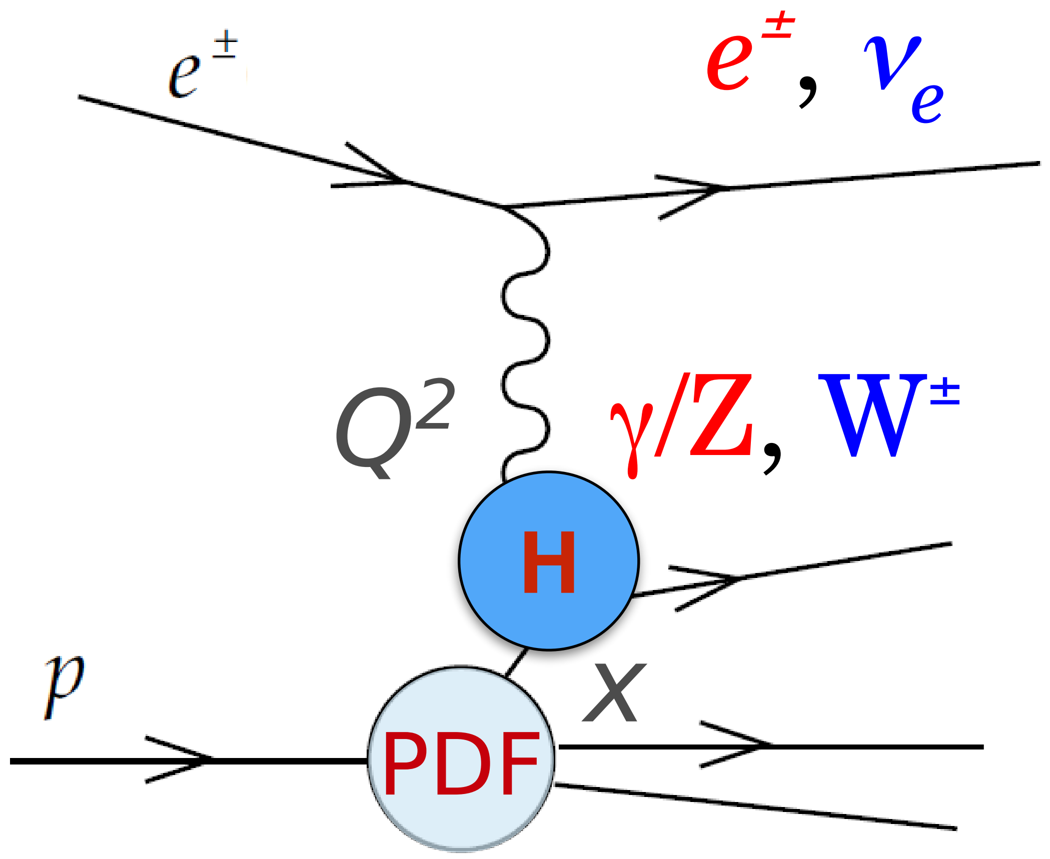
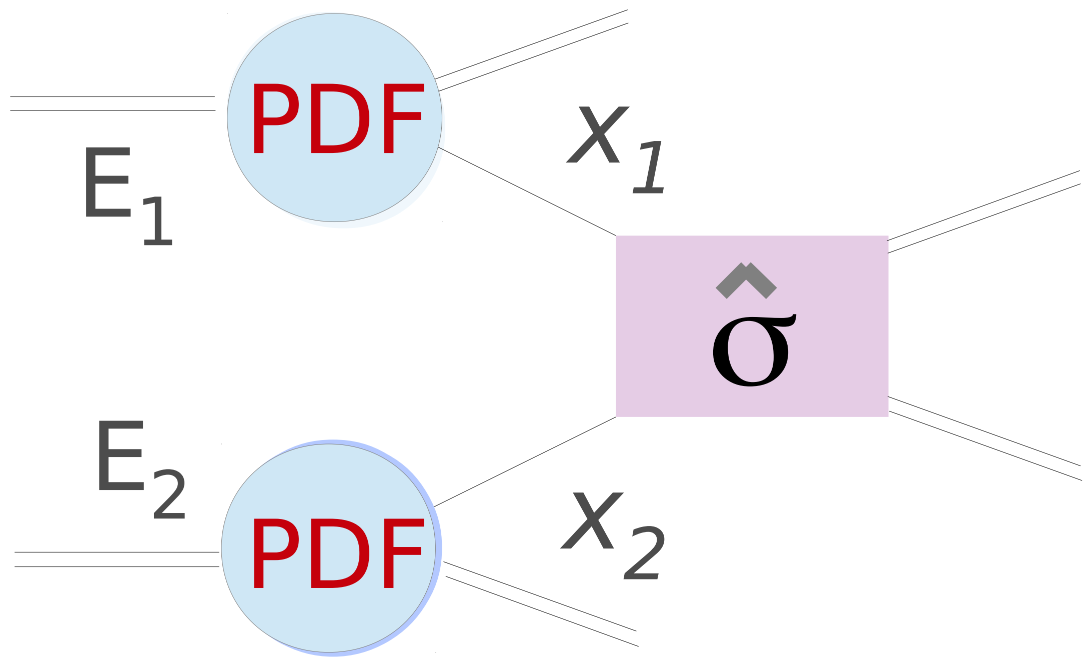
QCD collinear factorization

✦ QCD collinear factorization ensures universal separation of long-distance and short-distance contributions in high energy scatterings involving initial state hadrons, and enables predictions on cross sections

DIS structure functions



hadron-hadron collision



$$\sigma = \hat{\sigma} \otimes f_1 \otimes f_2$$

$$F_2(x, Q^2) = \sum_{i=q,\bar{q},g} \int_0^1 d\xi \, C_2^i(x/\xi, Q^2/\mu_r^2, {\mu_f}^2/\mu_r^2, \alpha_s(\mu_r^2)) \times f_{i/h}(\xi, \mu_f)$$

[Collins, Soper, Sterman, 1989]

❖ coefficient functions, hard scattering; infrared (IR) safe, calculable in pQCD, independent of the hadron

❖ PDFs, reveal inner structure of hadrons; non-perturbative (NP) origin, universality, e.g. DIS vs. pp collisions

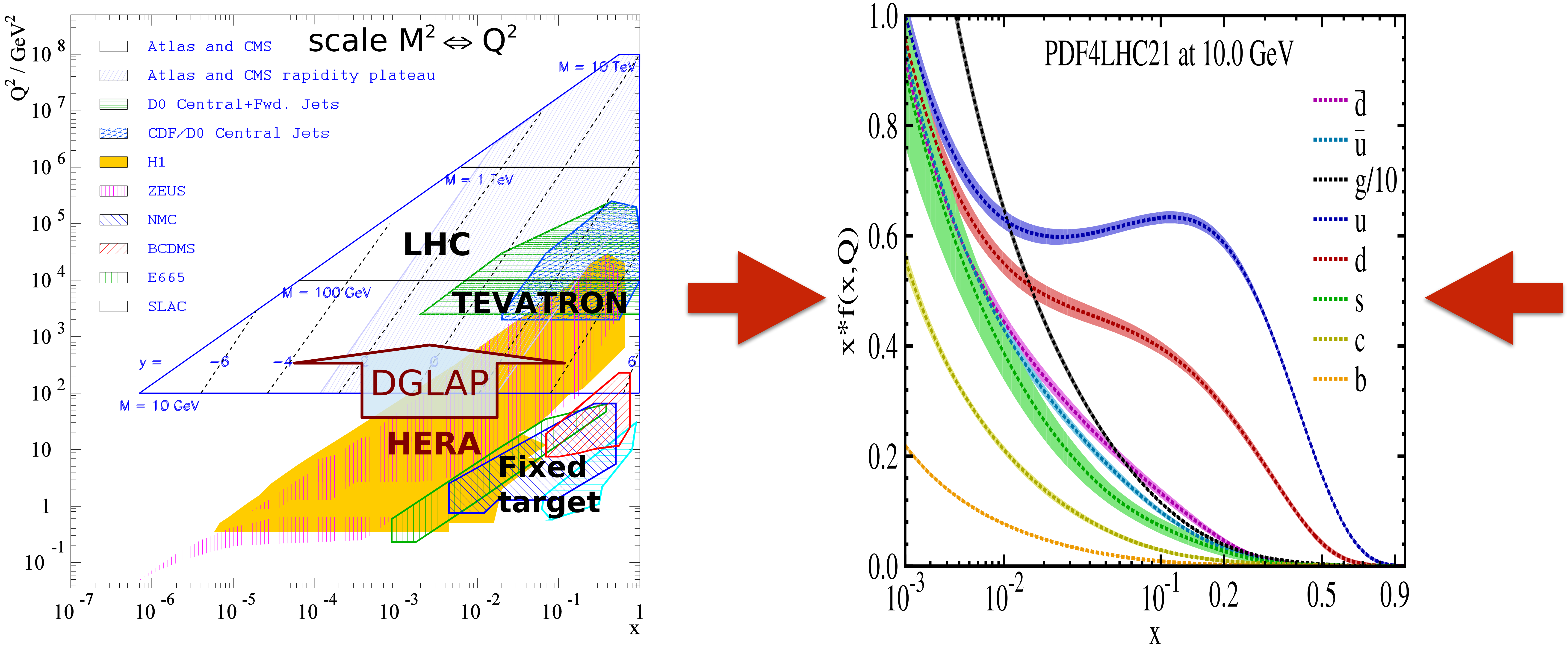
❖ factorization scale μ_f

❖ runnings of $f_{i/h}$ with μ_f are governed by the DGLAP equation

choose $\mu_f = \mu_r = Q$, thus Q dependence (scaling violation) of F_2 are mostly from PDFs and thus are predicted by the DGLAP evolution

Global analysis of PDFs

✦ PDFs are usually extracted from global analysis on variety of data, e.g., DIS, Drell-Yan, jets and top quark productions at fixed-target and collider experiments, with increasing weight from LHC, together with SM QCD parameters [see 1709.04922, 1905.06957 for recent review articles]



parameter variations α_S(Mz) Mc, Mb, Mt
QCD/EW corrections nuclear corrections EW parameters New Physics

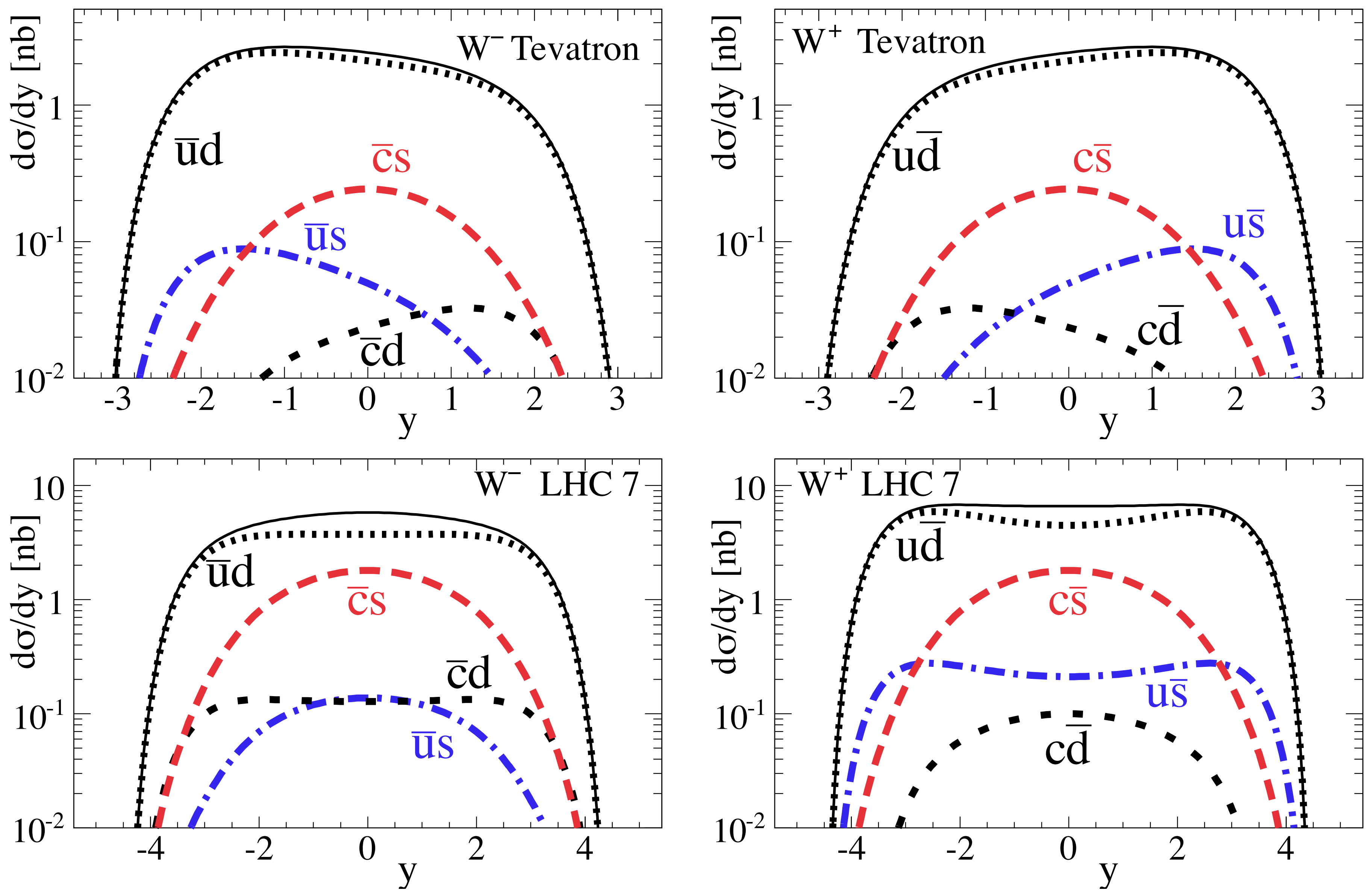
❖ diversity of the analysed data are important to ensure flavor separation and to avoid theoretical/experimental bias; possible extensions to include EW parameters and possible new physics for a self-consistent determination

❖ alternative approach from lattice QCD simulations, for various PDF moments or PDFs directly calculated in x-space with large momentum effective theory or pseudo-PDFs [2004.03543]

W boson mass measurement

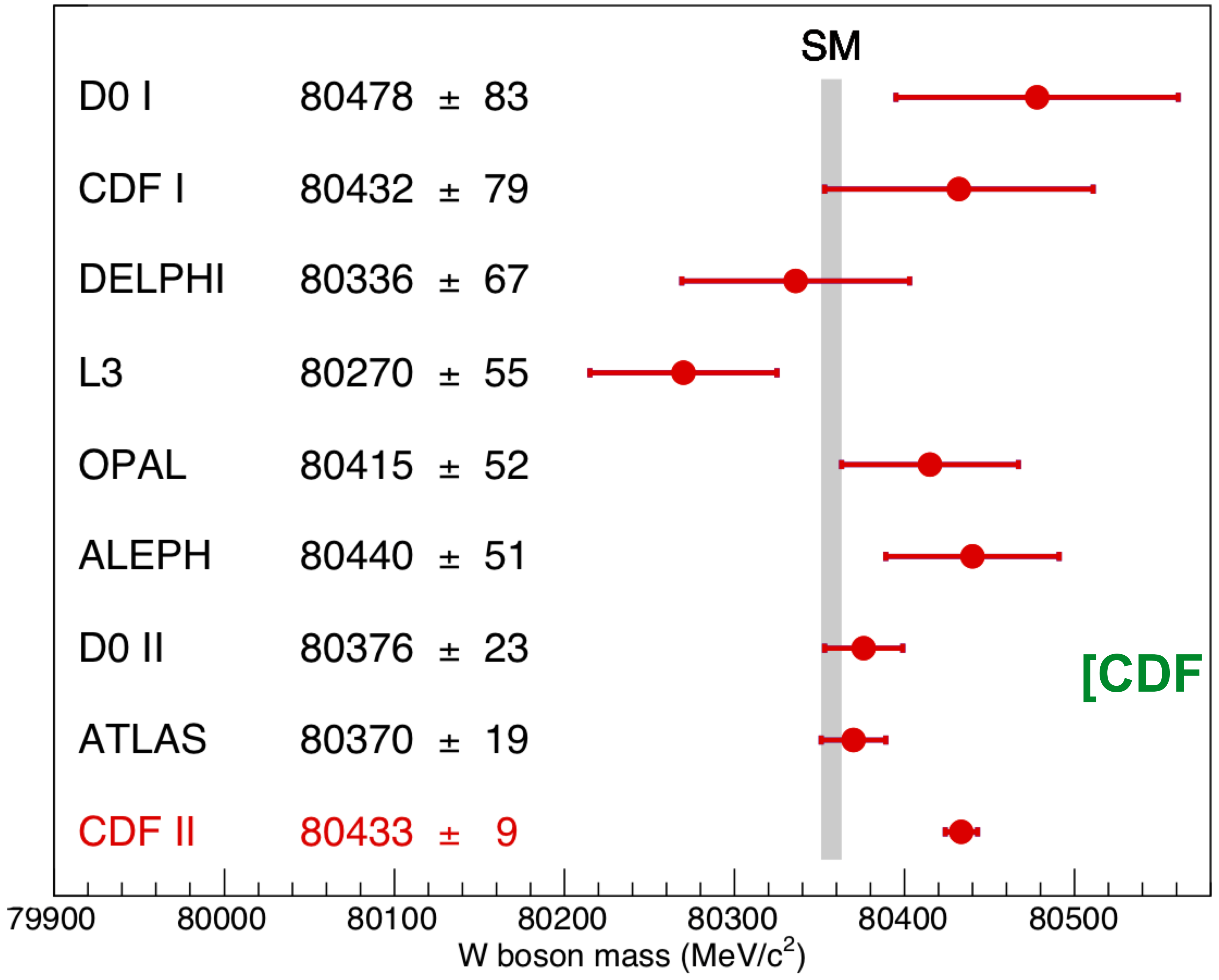
- PDFs are key inputs for precision programs at hadron colliders, e.g., precision electroweak measurements, searches for new physics beyond the SM, especially non-resonance signatures hiding in high mass tails

W boson rapidity distribution [1203.1290]



W-boson charge Kinematic distribution **[ATLAS 2018]**	W^+ p_T^ℓ	W^+ m_T	W^- p_T^ℓ	W^- m_T	Combined p_T^ℓ	Combined m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

W boson mass from different experiments



[CDF 2022]

Fig. 5

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

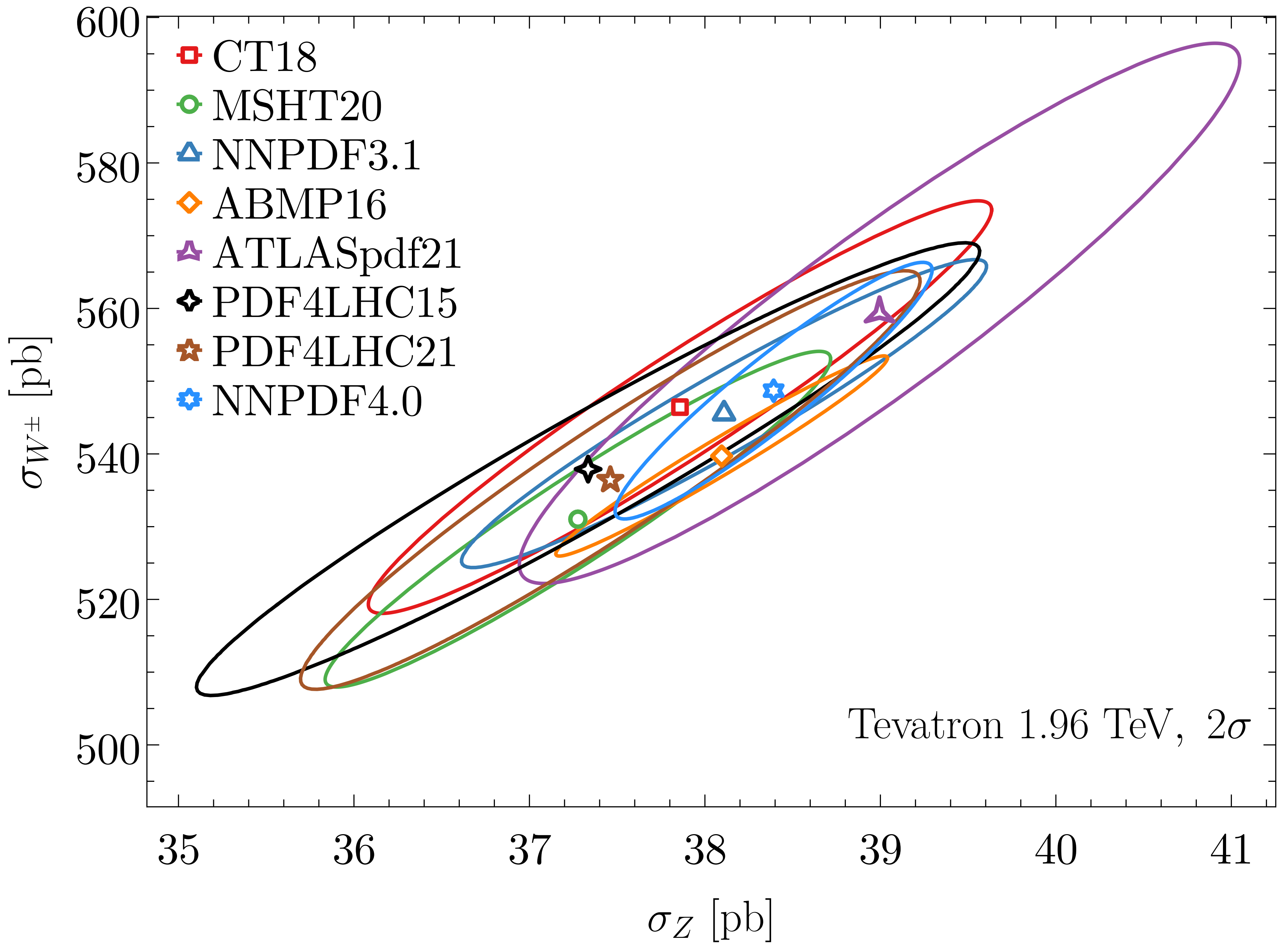
LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ [*JHEP* **2022,** 36 (2022)]

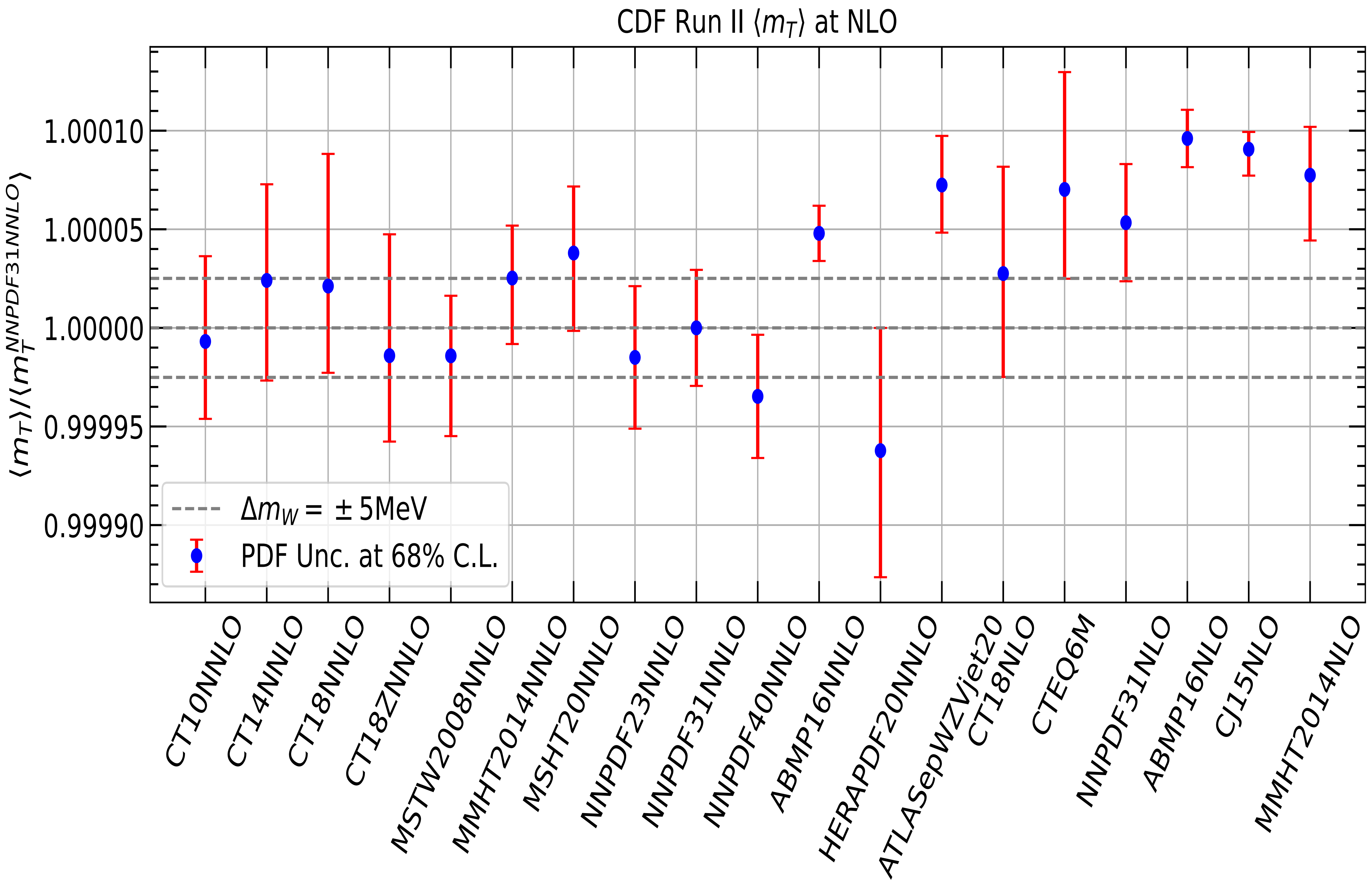
PDF unc. of CDF / ATLAS / LHCb: 3.9 / 8 / 9 MeV

W boson mass measurement

- PDFs are key inputs for precision programs at hadron colliders, e.g., precision electroweak measurements, searches for new physics beyond the SM, especially non-resonance signatures hiding in high mass tails

W/Z fiducial cross sections at Tevatron (95% C.L.) **[CT, 2022]** mean transverse mass (68% C.L.)



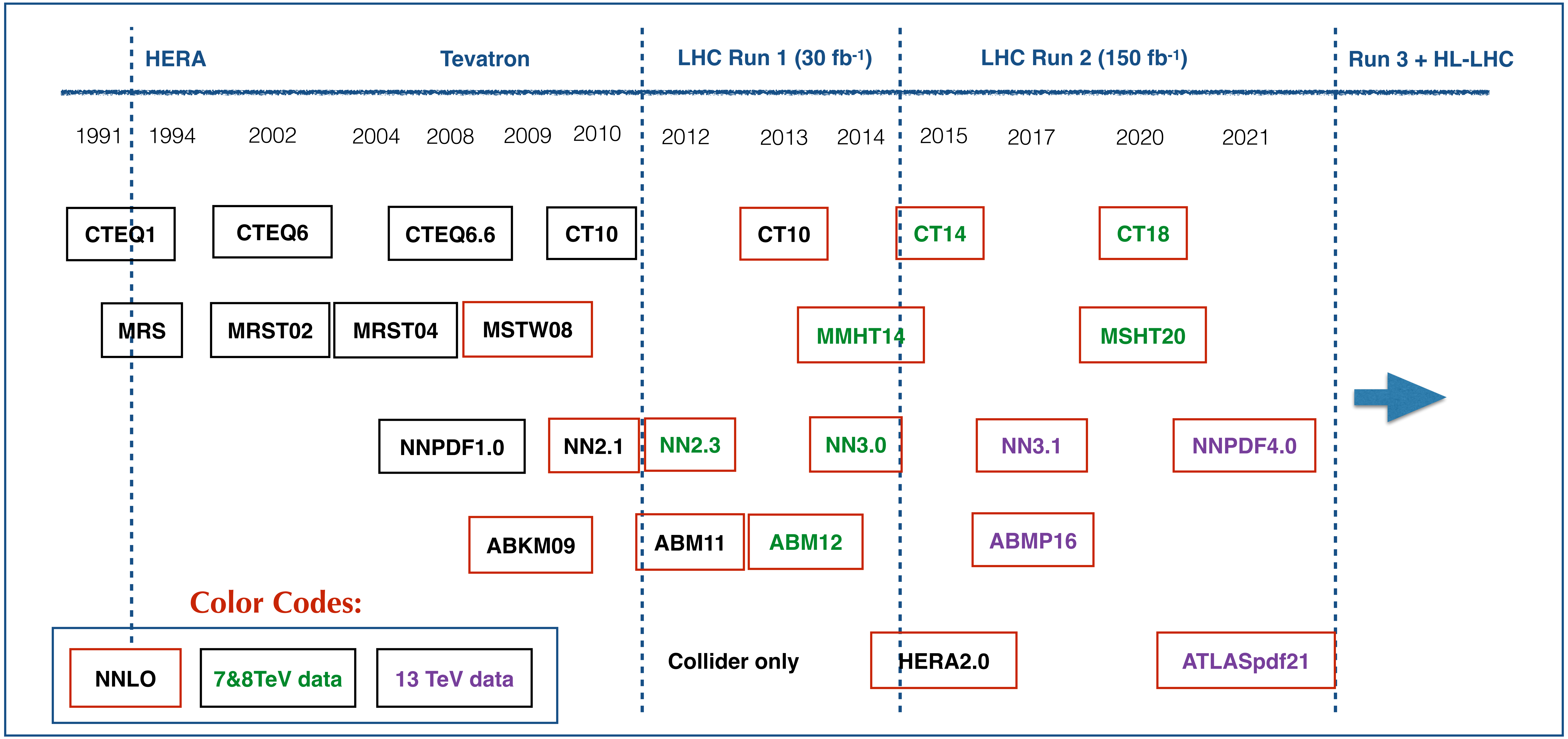


spread of predictions from different PDFs can be much larger than the PDF unc. of a single set; even for the same group the PDF unc. not necessarily decrease with time

Analyzing of W mass data with most up-to-date PDFs will be highly desirable

Major analysis groups

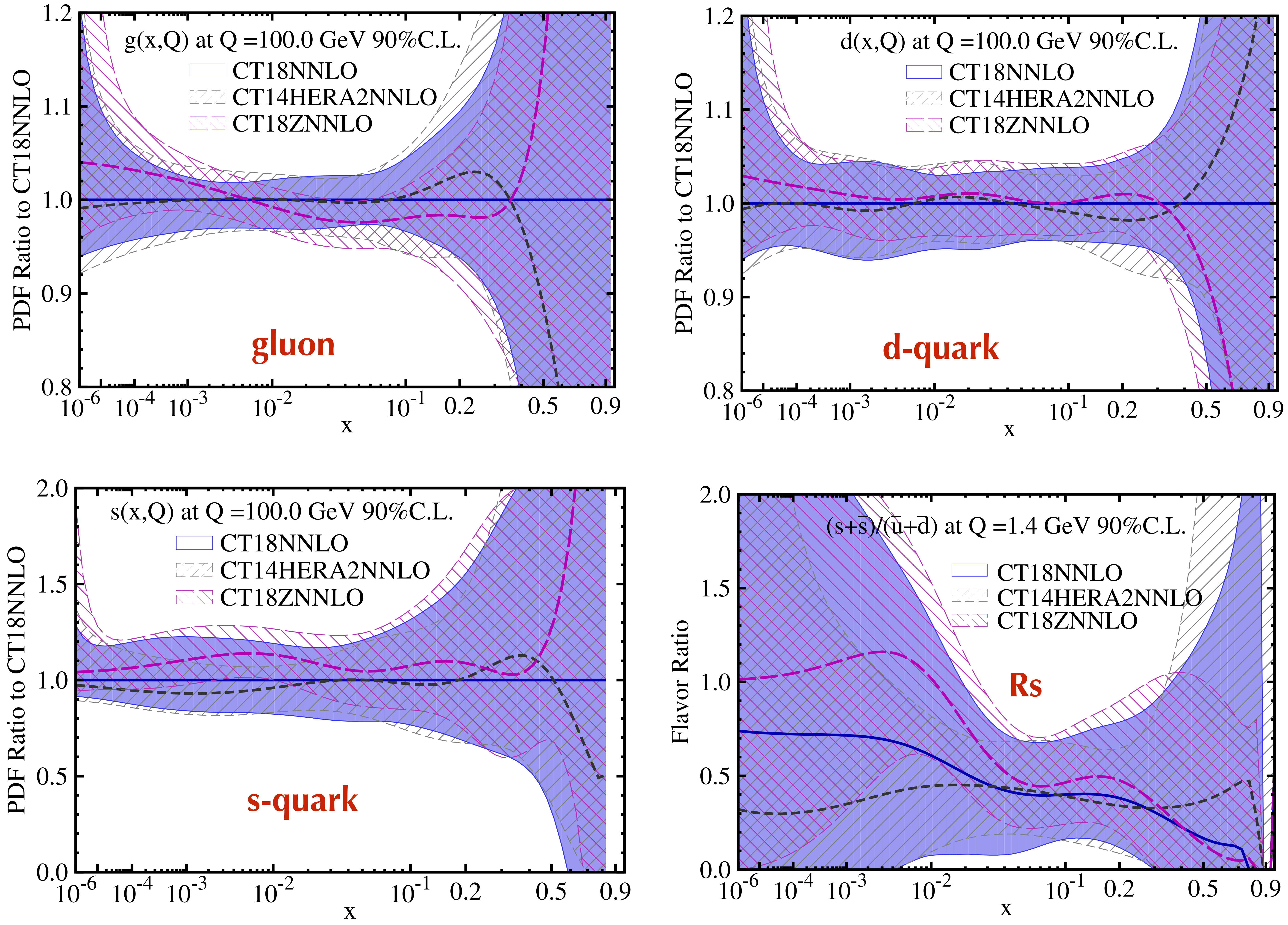
- PDFs provided by several major analysis groups (CT, MSHT, NNPDF, ABM, HERAPDF, ATLASpdf, CJ, JAM…) using slightly different heavy-quark schemes, selections of data, and methodologies



must have as many independent analyses as possible to have a faithful determination of PDFs and their uncertainties; state of the art PDFs are extracted at NNLO in QCD and with numerous LHC data

CTEQ-TEA PDFs

- CT18 PDFs show moderate reductions of PDF uncertainties due to new LHC data sets, and agree with previous CT14 within uncertainties; alternative fits CT18Z/A/X for evaluation of certain systematic effects

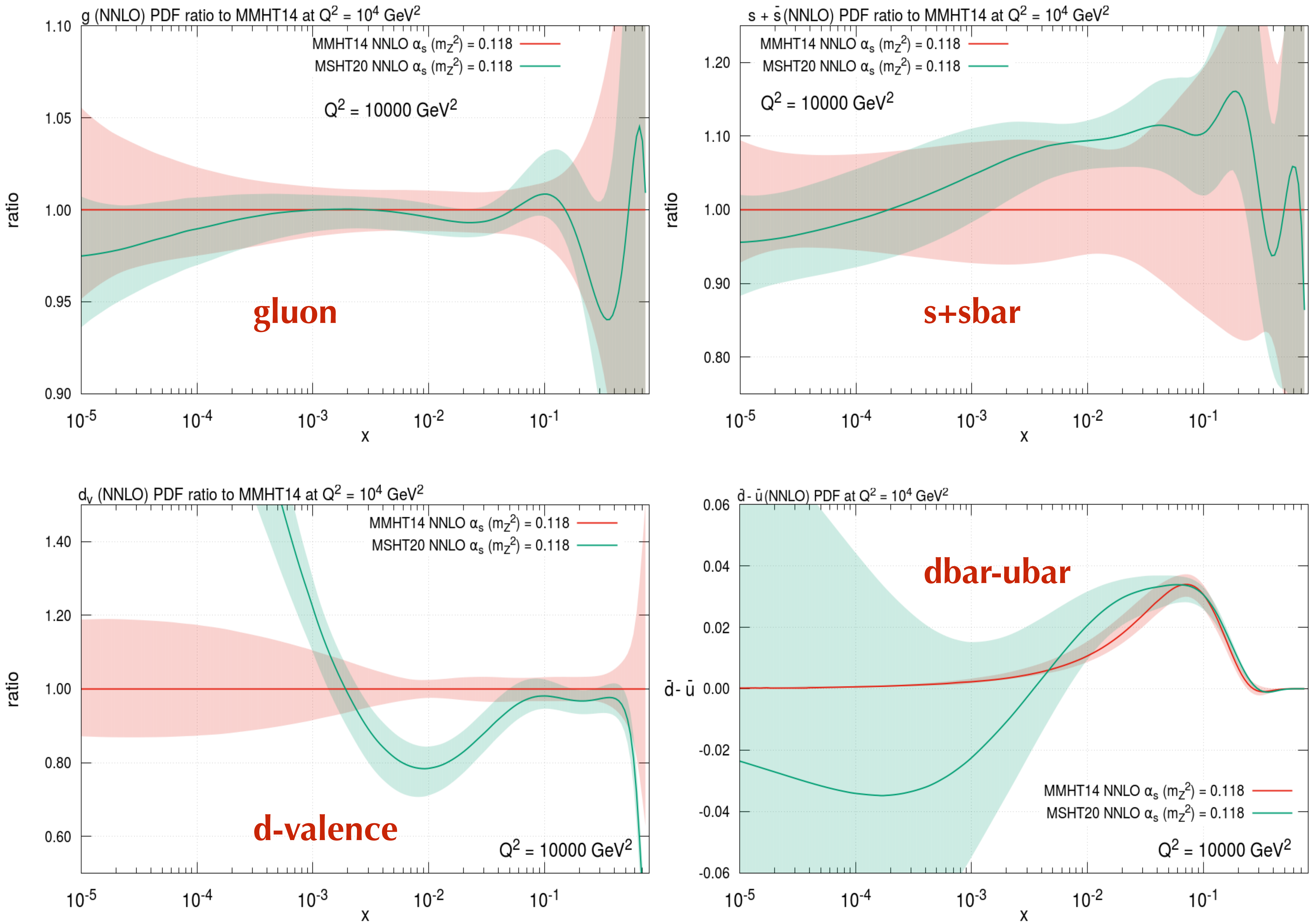


- CT18 vs CT14: gluon unc. reduced everywhere (jets, Z pT, top); d-quark unc. reduced at x~0.2 (LHCb W/Z); s-quark almost unchanged
- ATLAS 7 TeV W/Z data are not included in CT18 fit but in CT18A; CT18X uses a x-dependent scale in DIS to mimic small-x resummations
- CT18Z includes both variations, differences wrt. CT18 are most significant in s-quark and gluon/sea-quarks

[CT18, 1912.10053]

MSHT PDFs

- MSHT20 (Mass Scheme Hessian Tolerance) PDFs adopt an extended parametrization form, as comparing to MMHT14, to accomodate for newly included LHC precision data

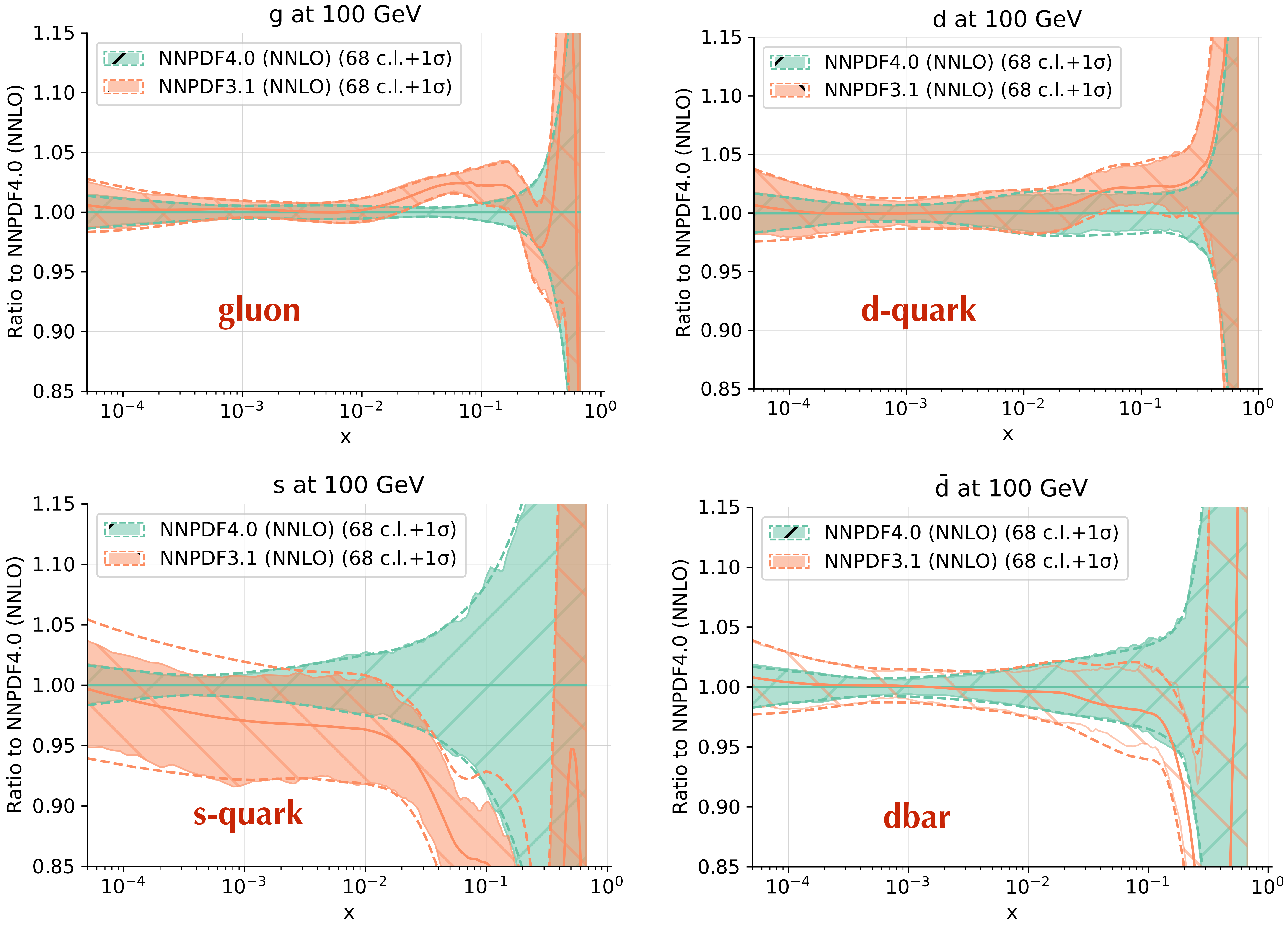


- central of gluon PDF remains mostly unchanged except for a suppression at x>0.2; moderate reduction on gluon uncertainty
- enhancement of s-quark at intermediate x region and large reduction on uncertainty, due to LHC 7 TeV W/Z data and update of dimuon theory calculations
- new parametrization allows a change of d-valence shape to better fit LHC W/Z data, and also large uncertainties of isospin asymmetry in small-x region

[MSHT20, 2012.04684]

NNPDFs

- NNPDF4.0 PDFs improves previous NNPDF3.1 with a major update on methodologies and a dedicated global survey and selection of available LHC data



- changes on parametrization and NN architecture, optimization algorithm; additional positivity and integrability constraints and post-fit selections

- central PDF of NNPDF4.0 is generally consistent with NNPDF3.1 except for a notable decrease of gluon PDF at x~0.1 and moderate increase of strangeness

- NNPDF4.0 shows PDF uncertainty of ~1-2% at data constrained region, largely reduced comparing to NNPDF3.1

[NNPDF4.0, 2109.02653]

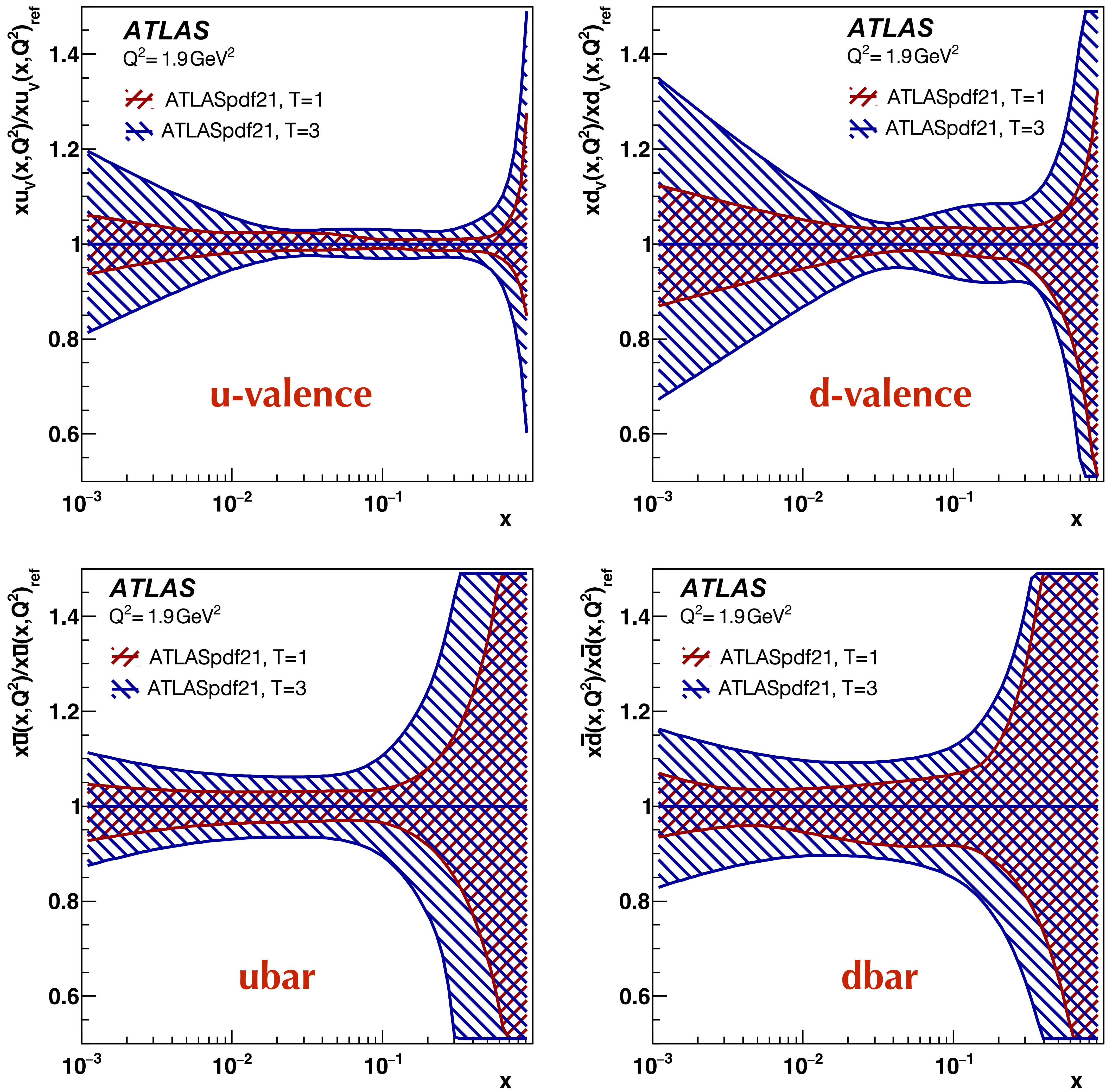
ATLAS PDFs

- ATLAS releases the most recent 2021 PDFs based on a NNLO analysis of HERA combined data and a variety of ATLAS data from 7, 8 to 13 TeV and with several new features explored

Data sets included and χ^2 **[ATLAS,2112.11266]**

Total χ^2/NDF	2010/1620
HERA χ^2/NDP	1112/1016
HERA correlated term	50
ATLAS W, Z 7 TeV χ^2/NDP	68/55
ATLAS Z/γ^* 8 TeV χ^2/NDP	208/184
ATLAS W 8 TeV χ^2/NDP	31/22
ATLAS W and Z/γ^* 7 and 8 TeV correlated term	71 = (38 + 33)
ATLAS direct γ 13/8 TeV χ^2/NDP	27/47
ATLAS direct γ 13/8 TeV correlated term	6
ATLAS V+jets 8 TeV χ^2/NDP	105/93
ATLAS $t\bar{t}$ 8 TeV χ^2/NDP	13/20
ATLAS $t\bar{t}$ 13 TeV χ^2/NDP	25/29
ATLAS inclusive jets 8 TeV χ^2/NDF	207/171
ATLAS V+jets 8 TeV and $t\bar{t}$ + jets 8,13 TeV and $R = 0.6$ inclusive jets 8 TeV correlated term	87 = (16 + 9 + 21 + 41)

full uncertainty consists of experimental, theoretical, model, and parametrization uncertainties; evaluated either using $\Delta\chi^2$=1 or $\Delta\chi^2$=9 (a global tolerance of T=3)



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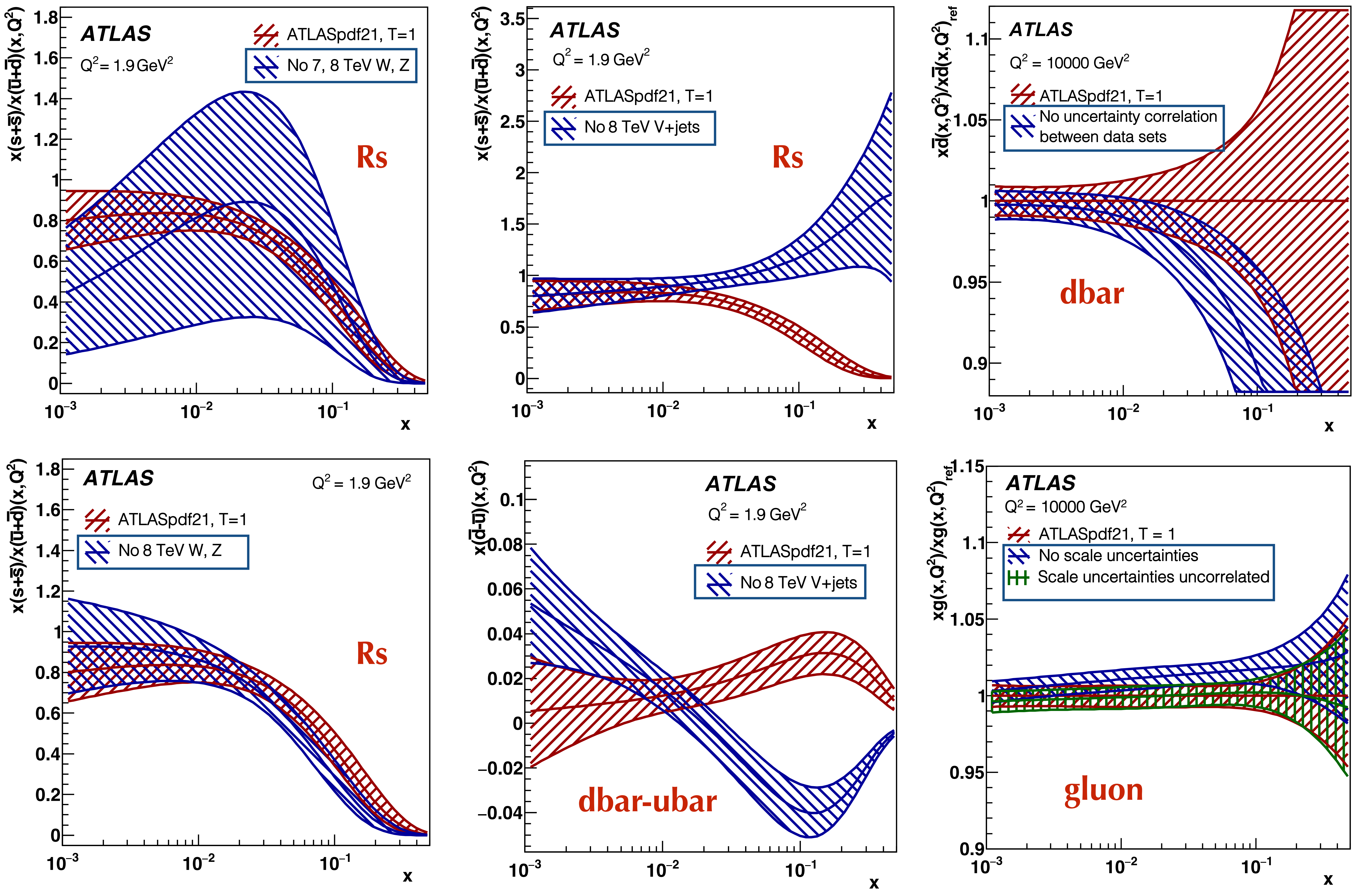


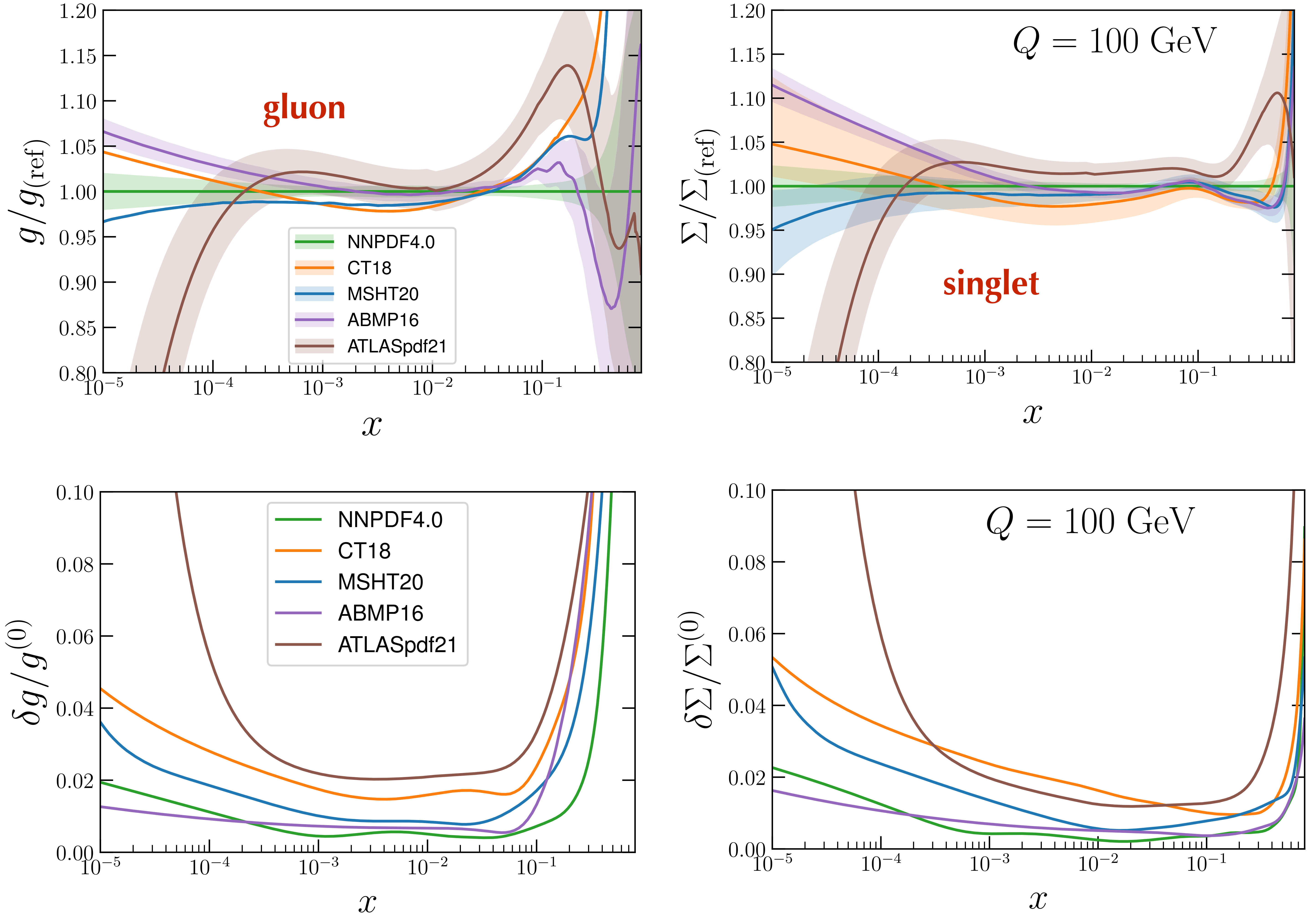
- consistent pull from 7, 8 TeV inclusive W/Z data on strangeness to light-sea ratio Rs
- W/Z+jet data stabilize sea-quarks at large-x close to preferences from fixed-target experiments
- impact of correlation of experimental uncertainties across different data sets, and of scale variations are investigated

[ATLAS,2112.11266]

PDF benchmarking

- Many ongoing efforts on comparisons and understanding of differences of up-to-date PDFs, in order to have a faithful determination of PDFs and its uncertainties

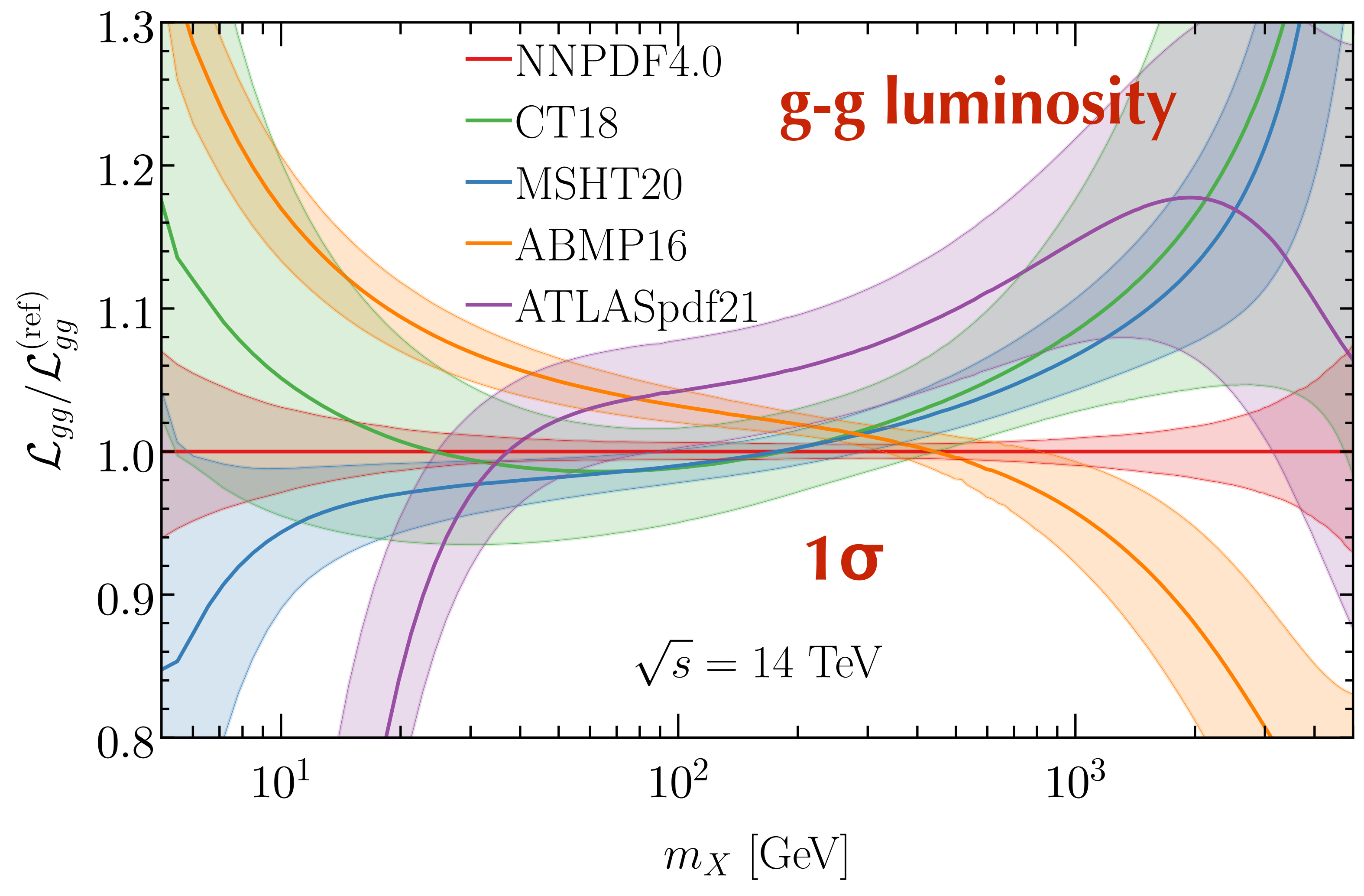
[Snowmass 2021, 2203.13923]

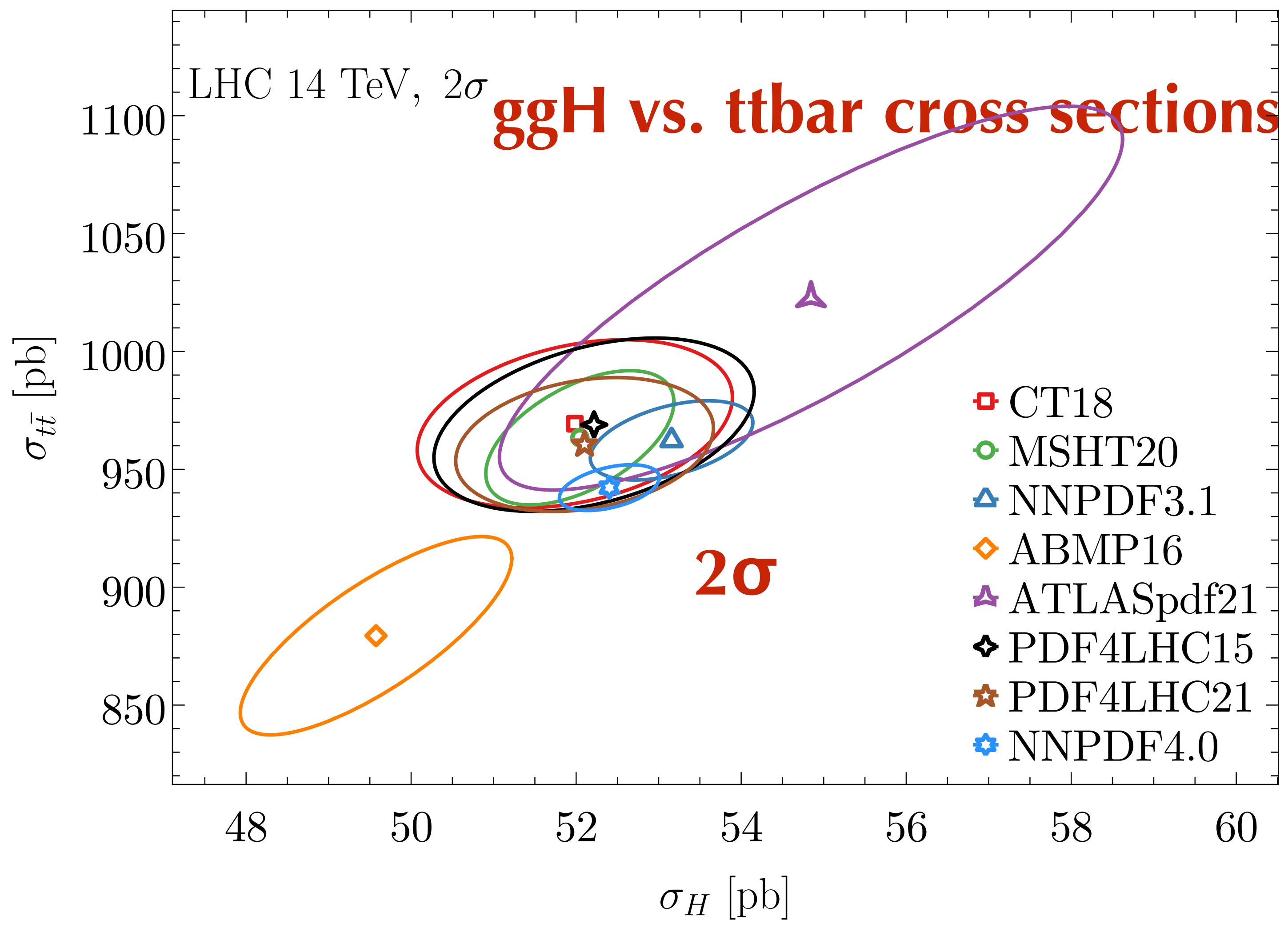


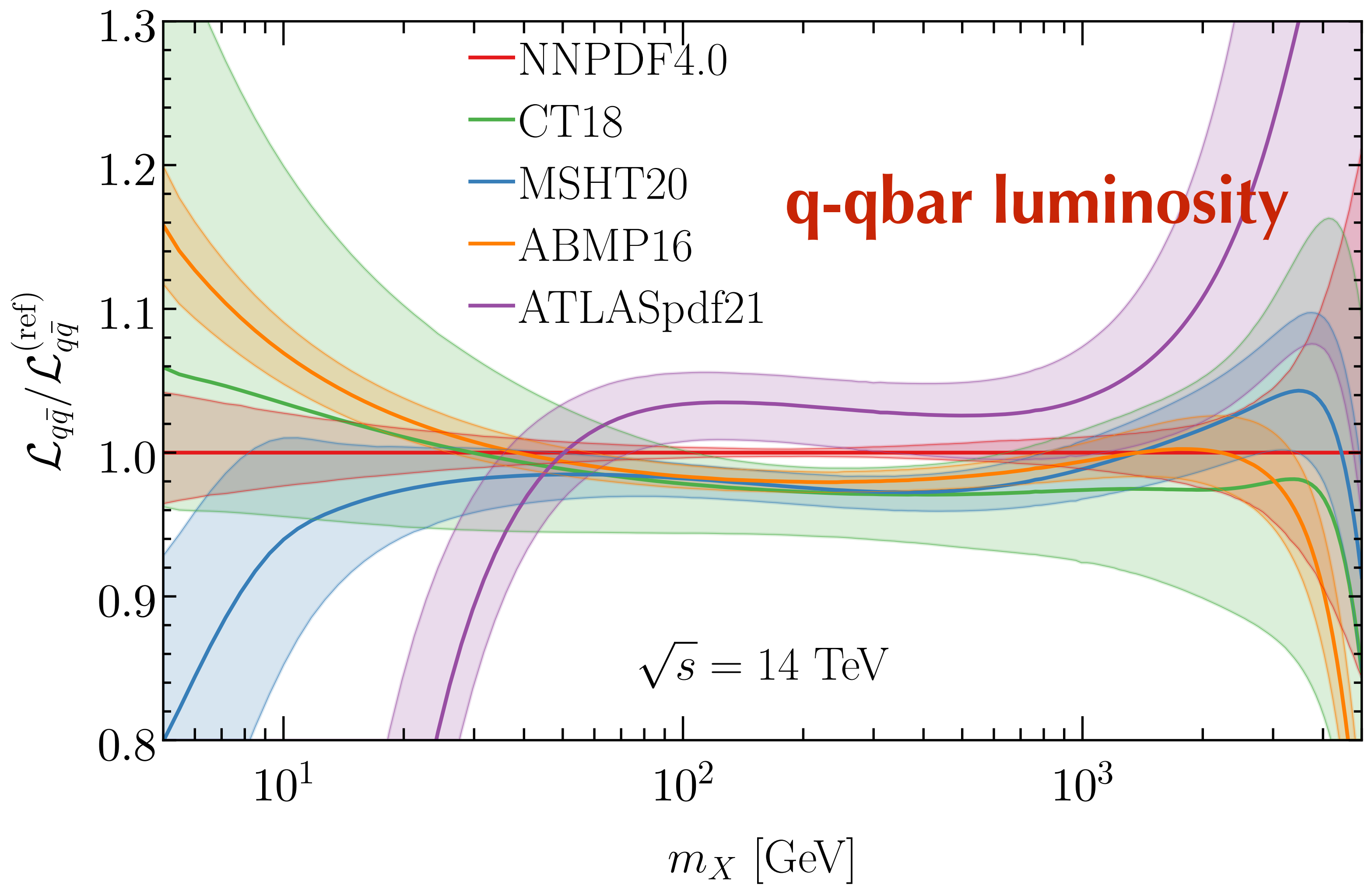
- general agreement between different groups (NN4.0, CT18, MSHT20, ABMP16, ATLAS21) over the range of x in 10^{-4} to 10^{-1} within uncertainties
- gluon: notable differences at x~0.2, with 2σ for NN vs. CT&MSHT; singlet: ATLASpdf deviate at x<10^{-4} due to Q^2>10 GeV^2 applied on HERA data, and at x>0.2 due to lack of fixed-target data
- NN and ABMP show uncertainty of ~1-2% in constrained region mostly due to methodologies; CT18 being conservative among all fits; ATLAS unc. blow up in unconstrained region

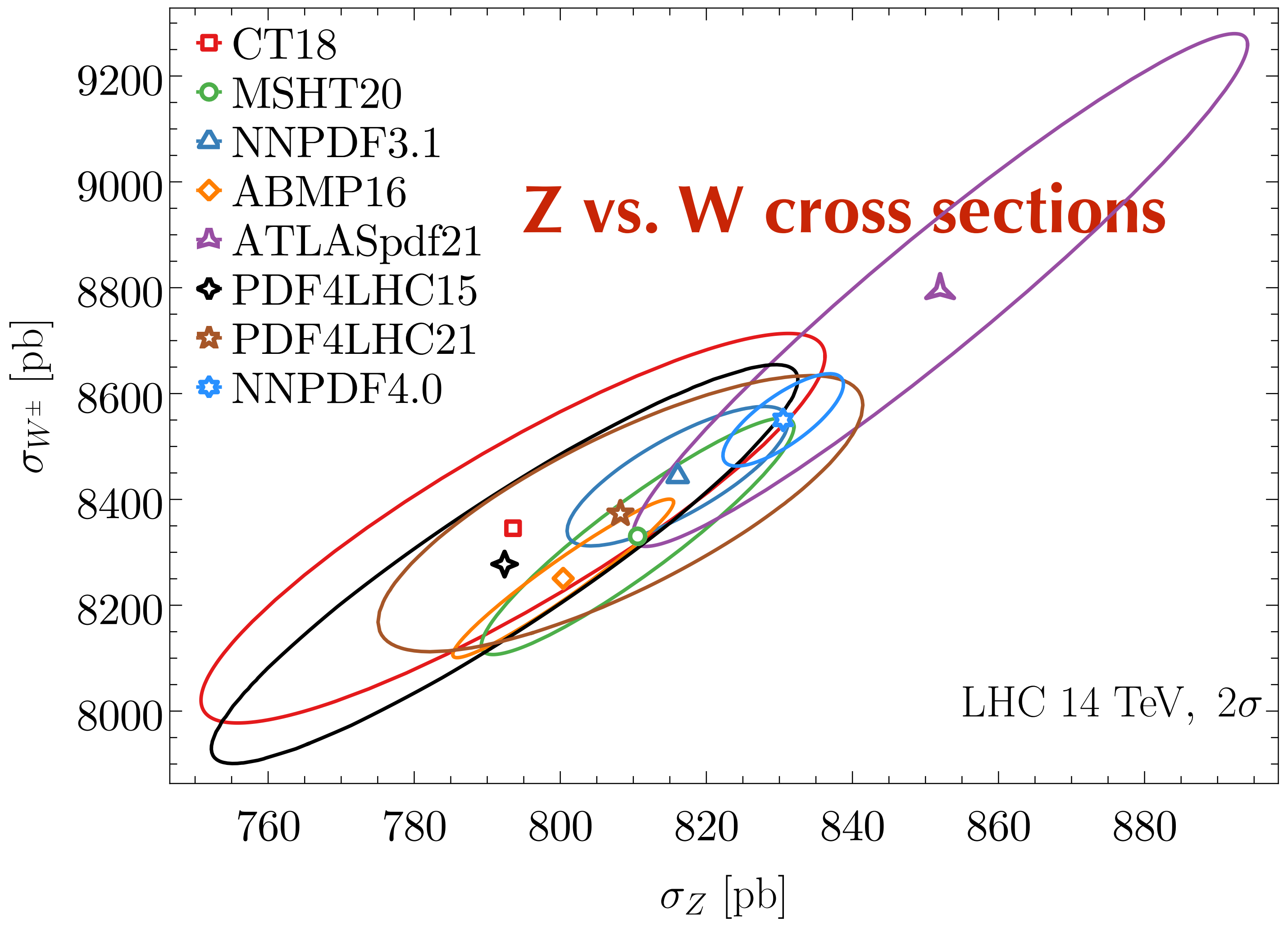
PDF benchmarking

- Spread of PDFs from different groups propagates into the parton-parton luminosity or cross sections at the LHC 14 TeV and some cases enlarged due to (anti-)correlations between different x-regions/flavors









- g-g luminosity shows a spread of more than 20% in the multi-TeVs region; q-qbar luminosity agrees better in general except at a mass around 300 GeV

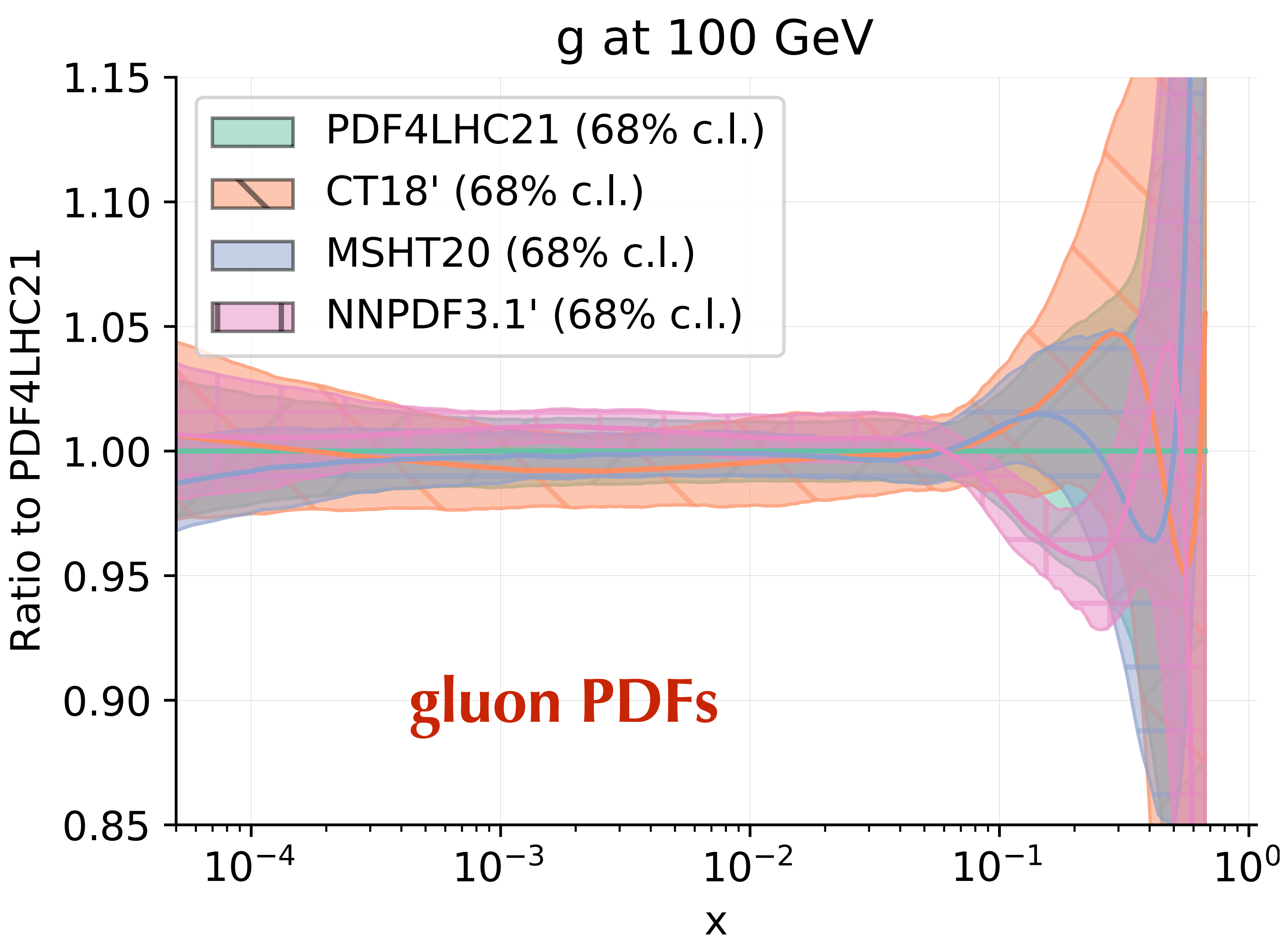
- 2σ error ellipse shown for cross sections of standard candle processes; NNPDF4.0 shows an uncertainty of less than 1.0% while CT18 2σ ellipse seems to cover most groups

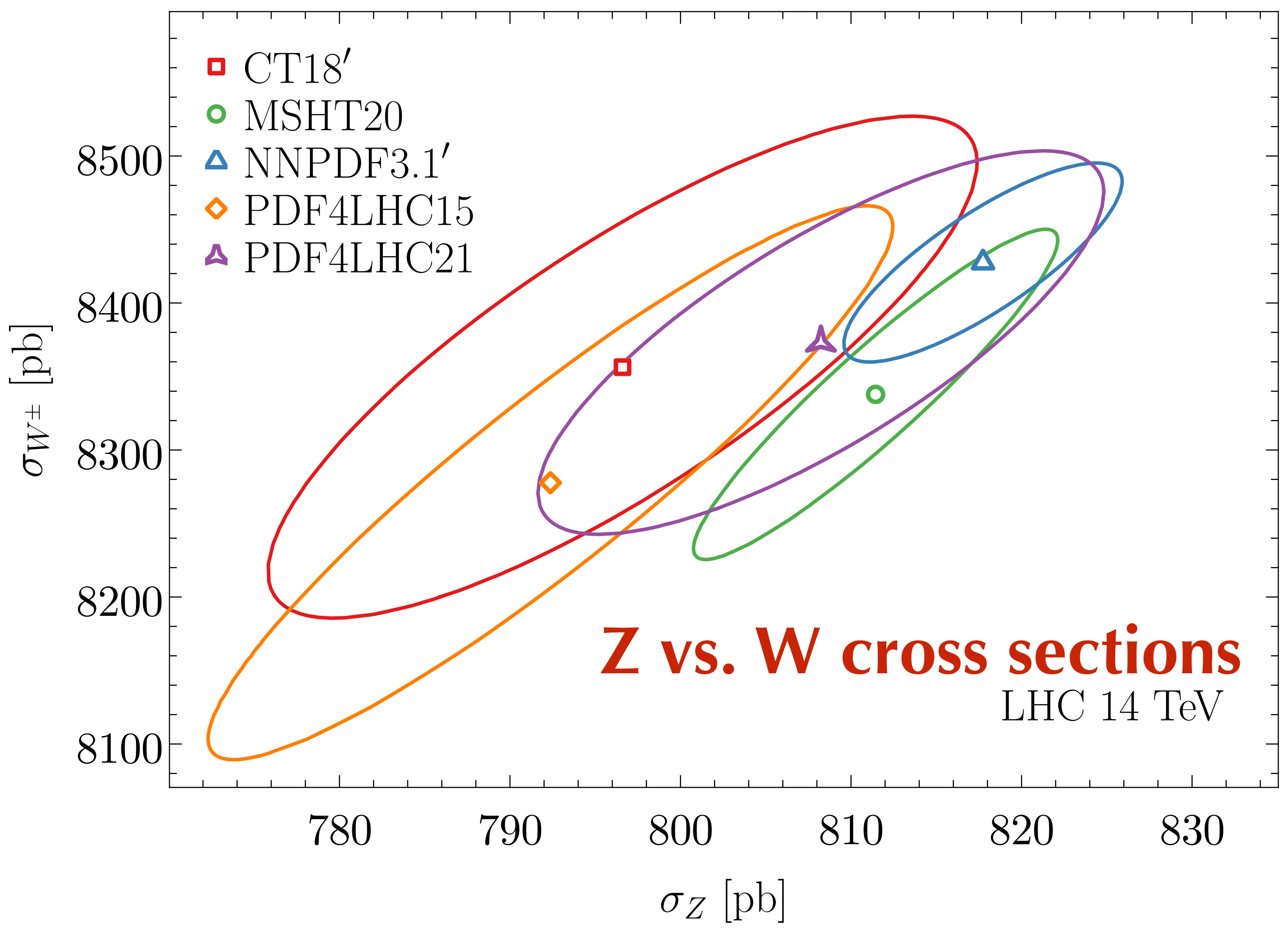
[note the cross section plots have been corrected in 2203.13923, and updated here]

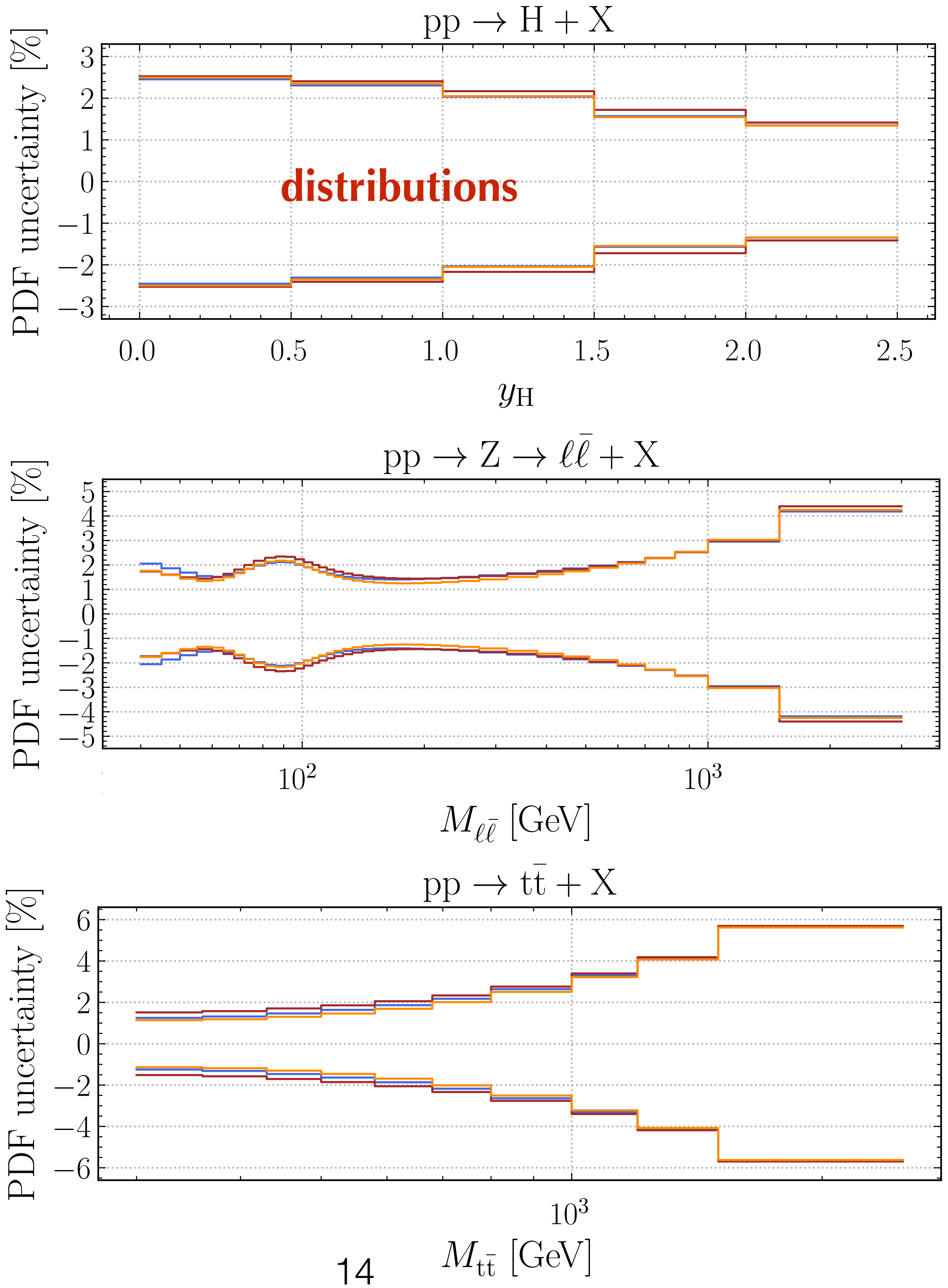
[Snowmass 2021, 2203.13923]

PDF4LHC recommendations

- The PDF4LHC group performs extensive benchmarks on methodologies of several groups, and presents the PDF4LHC21 PDFs, an effective combination of CT18′, MSHT20 and NNPDF3.1′, for LHC Run3 usage





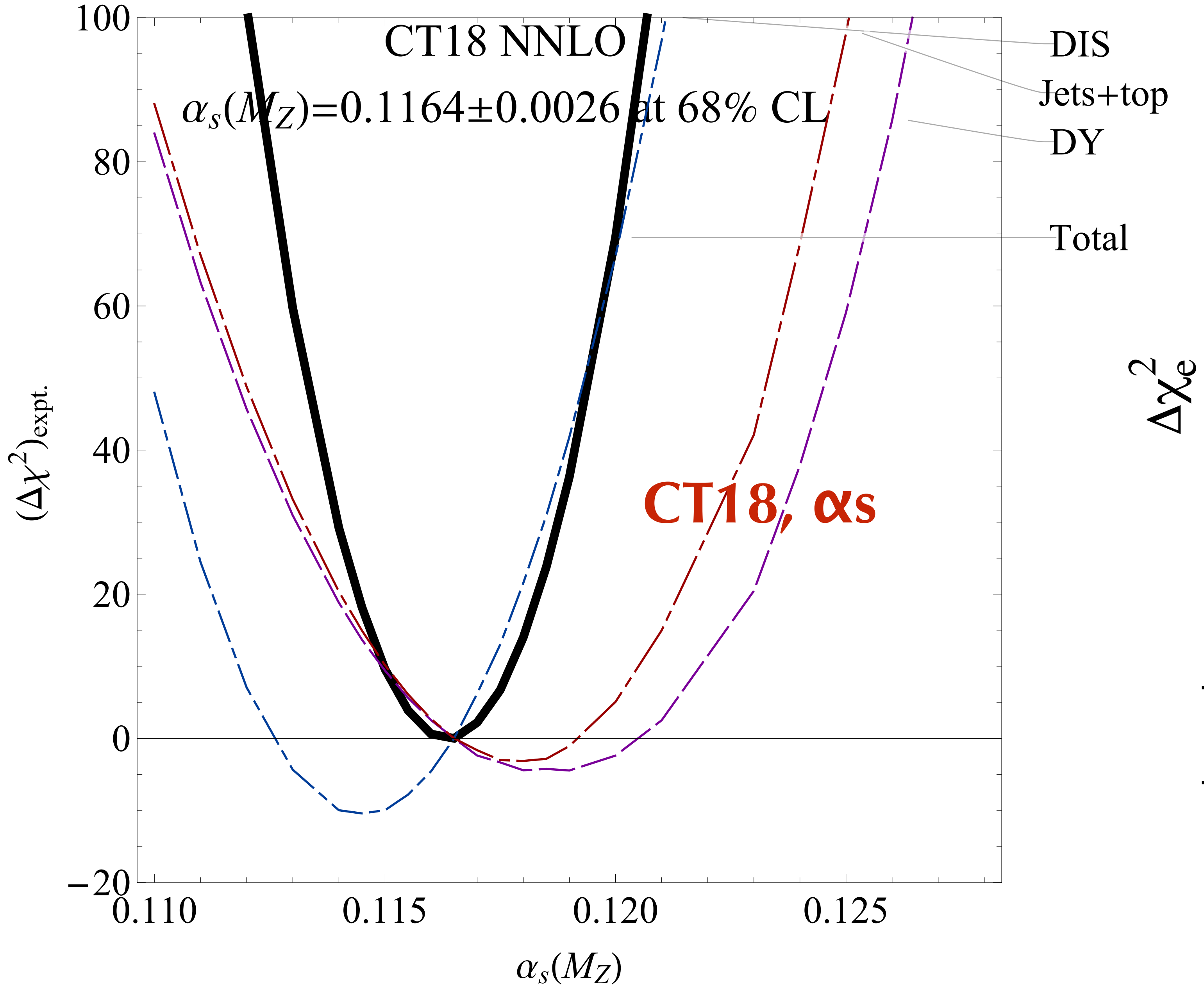


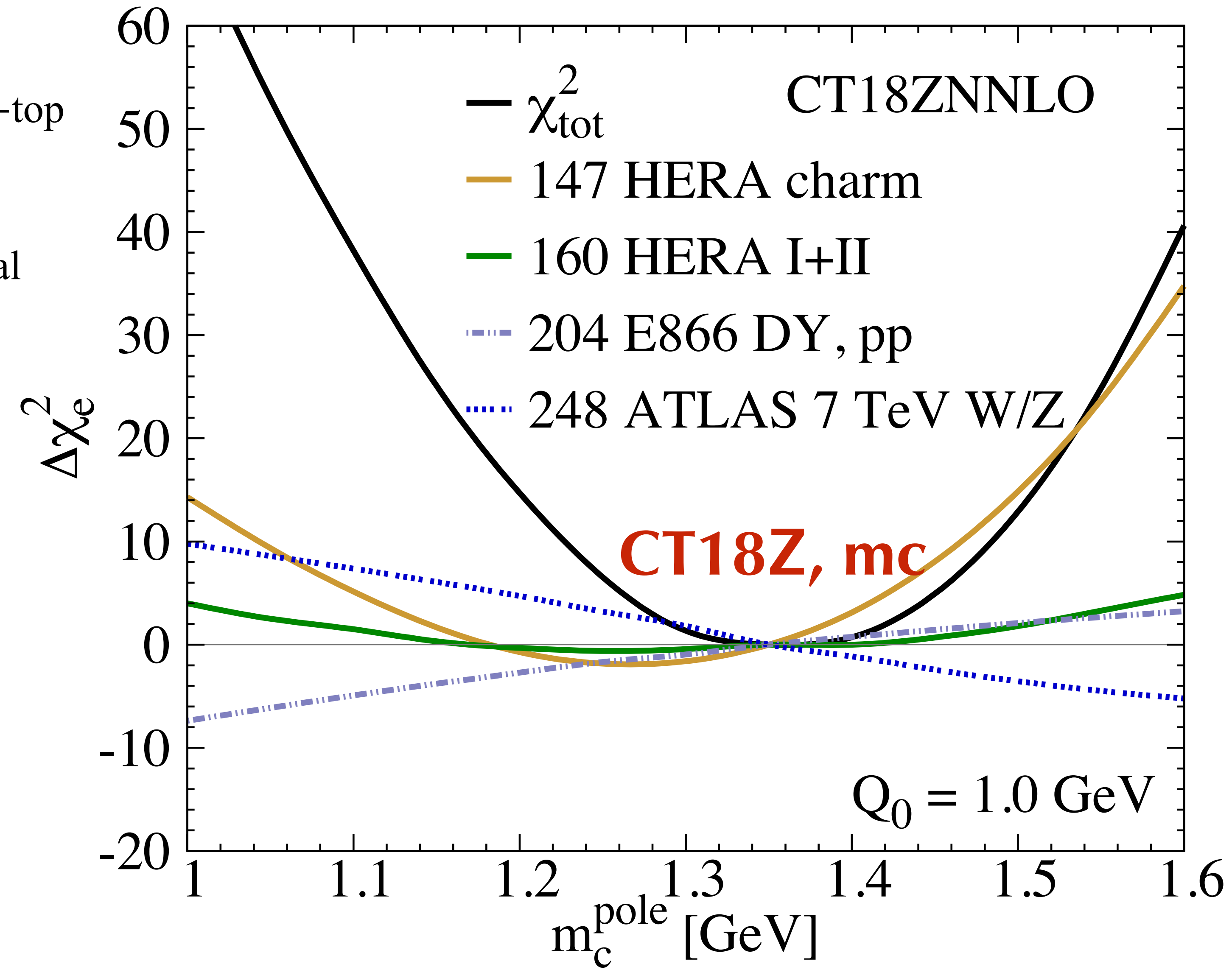
- CT18′ differs slightly from CT18 by using m_c=1.4 GeV; NNPDF3.1′ differs from 3.1 by including additional jet and top-quark data
- PDF4LHC21 PDFs are presented in the form of either a MC set of 100 replica PDFs or a Hessian set of 40 PDFs
- PDF unc. at the level of 2~3% for the inclusive cross section and 5~10% for distribution at multi-TeVs region

[PDF4LHC21, 2203.05506]

QCD parameters

- From global analysis of PDF one can also extract QCD parameters including strong coupling at NNLO with compatible precision, and the heavy-quark pole masses

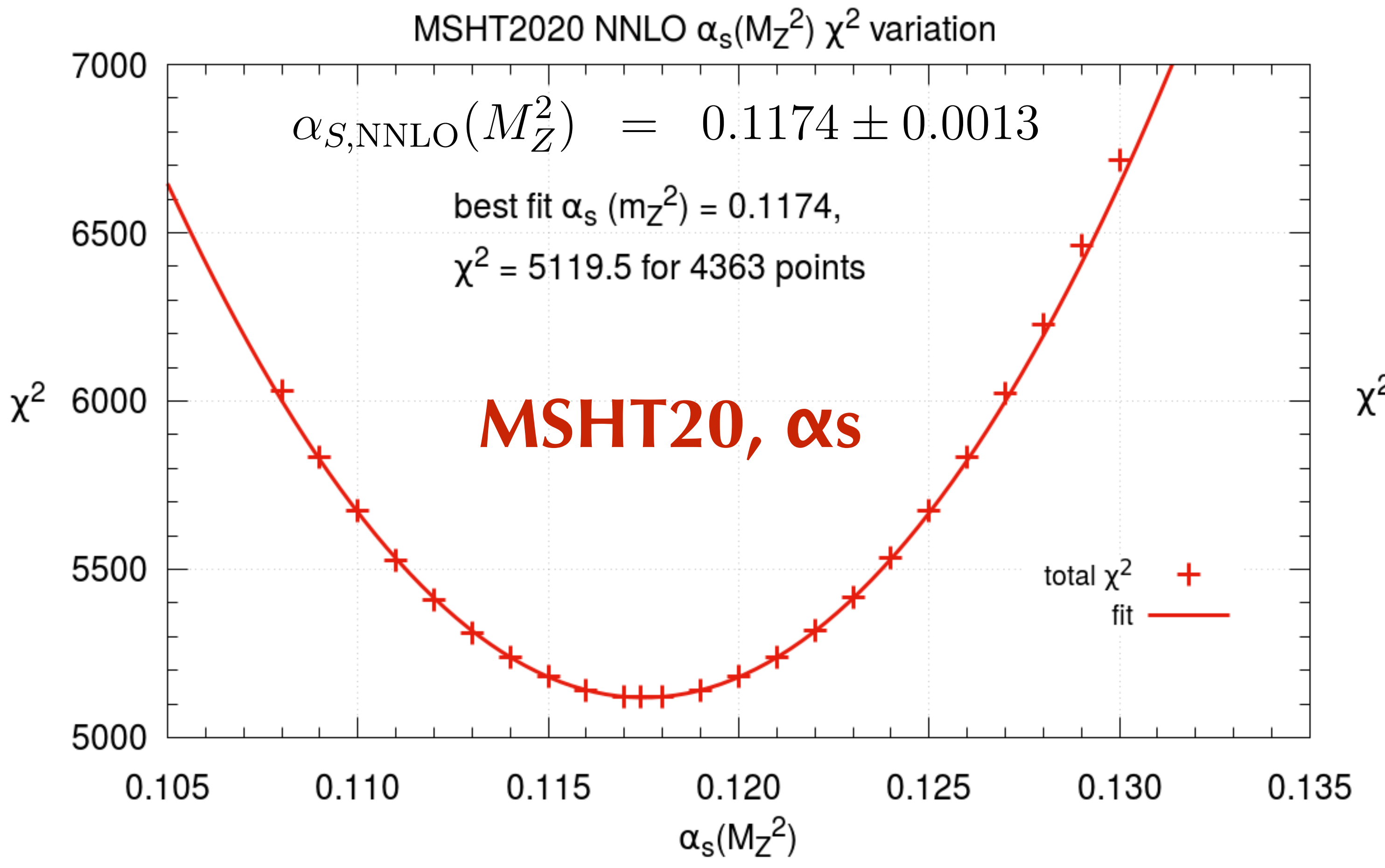


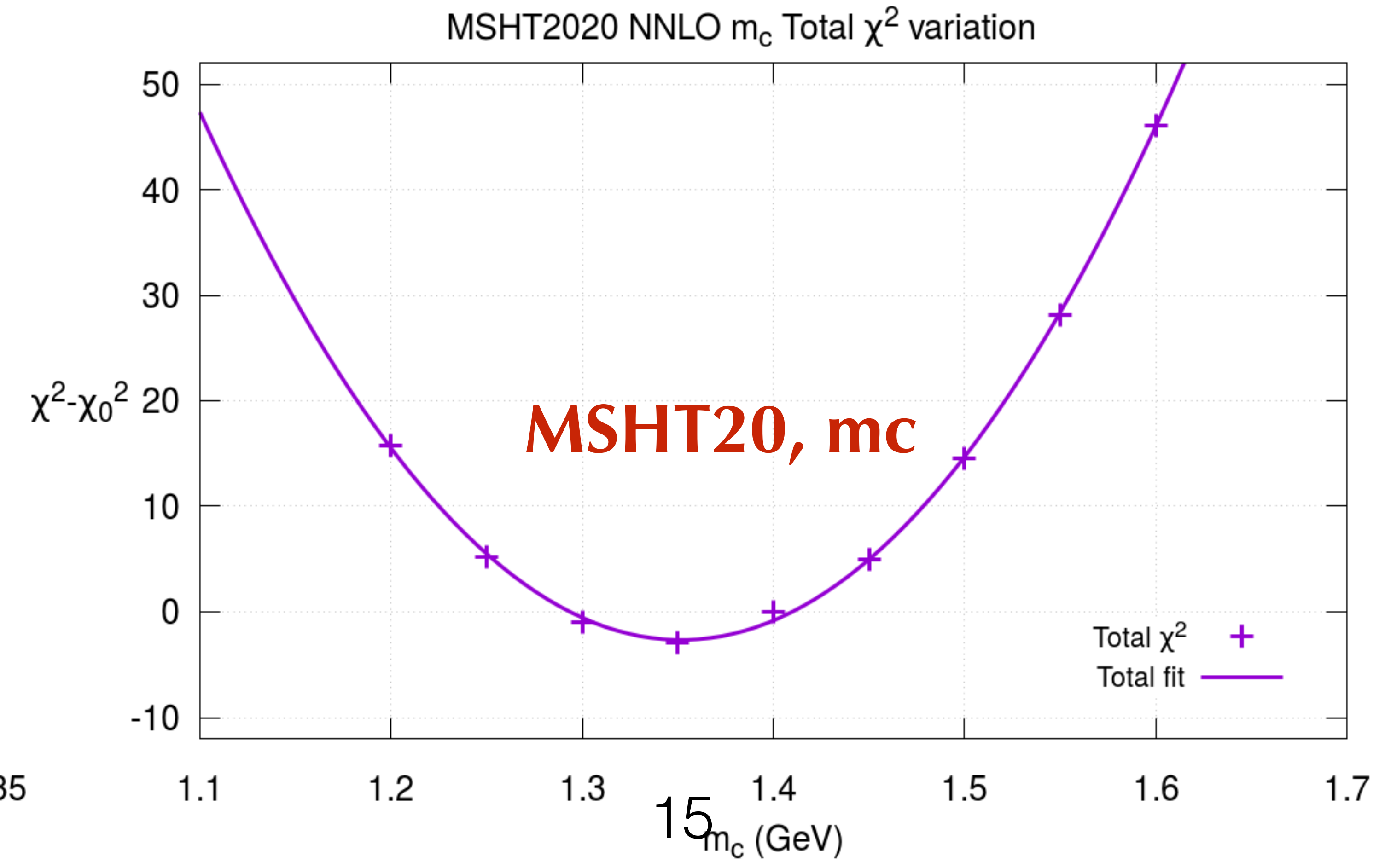


$\alpha_s(m_Z)$	0.1175	0.1180	0.1185	0.1900	0.1200
χ^2	1.165	1.162	1.161	1.162	1.168

NNPDF4.0, αs [2109.02653]

- The 3 most recent global fits return a best-fit $\alpha_S(M_Z)$ value of 0.1164, 0.1174, 0.1185 at NNLO for CT18, MSHT20, and NNPDF4.0 respectively





- very mild sensitivity to charm quark mass with a consistent preference of m_c=1.35 GeV for both CT18Z and MSHT20; ATLAS W/Z data prefers a larger m_c similar to the preference of enhanced strangeness

[CT18, 1912.10053]

[MSHT20, 2106.10289]

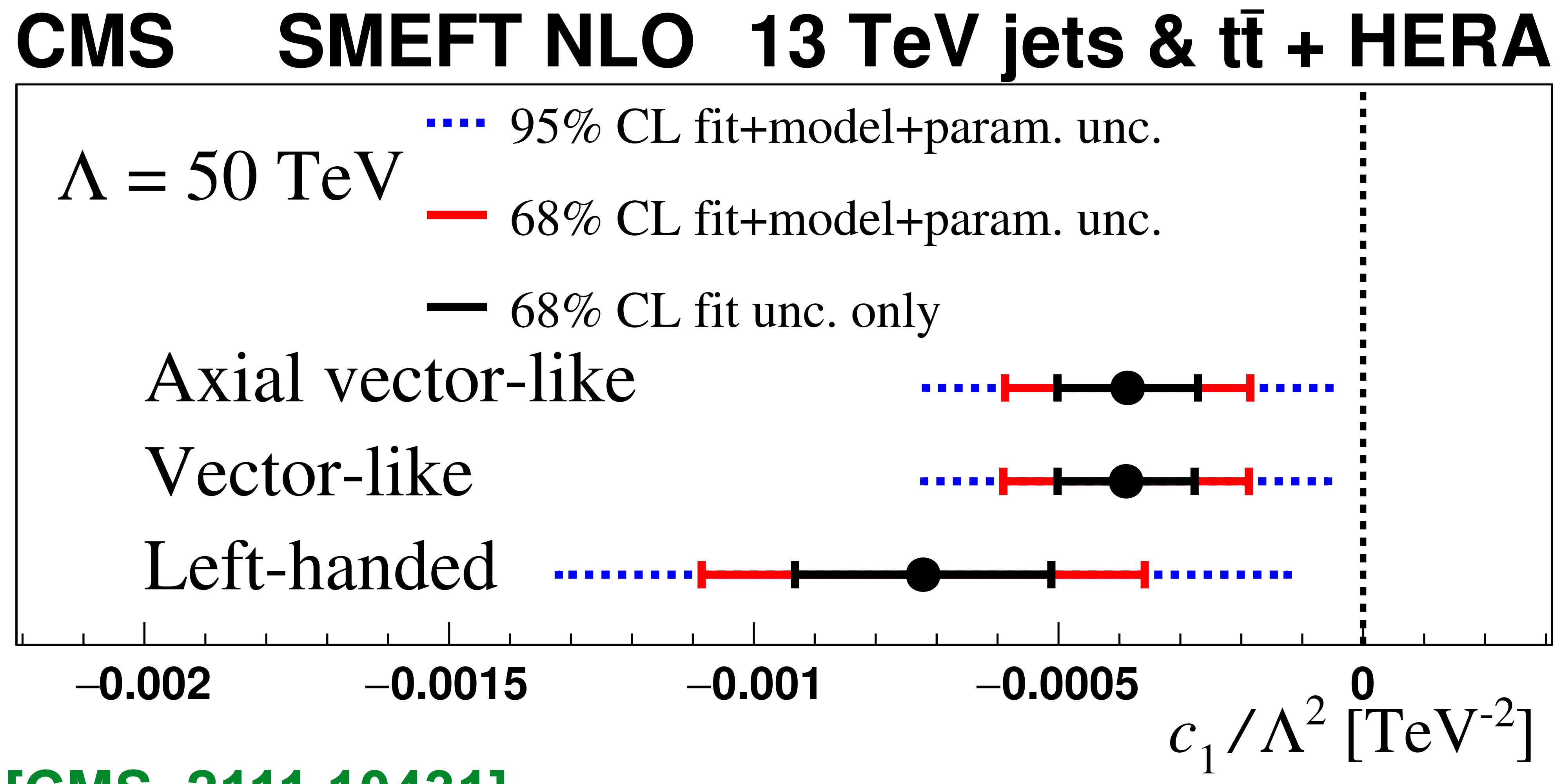
PDFs and SMEFT

- Ideally, a consistent use of PDFs in searches of new physics at the LHC requires a joint fit of both PDFs and new physics, possibly in terms of operators in SM effective field theory (SMEFT)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{2\pi}{\Lambda^2}\sum_{n\in\{1,3,5\}} c_n O_n$$

quark contact interactions

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

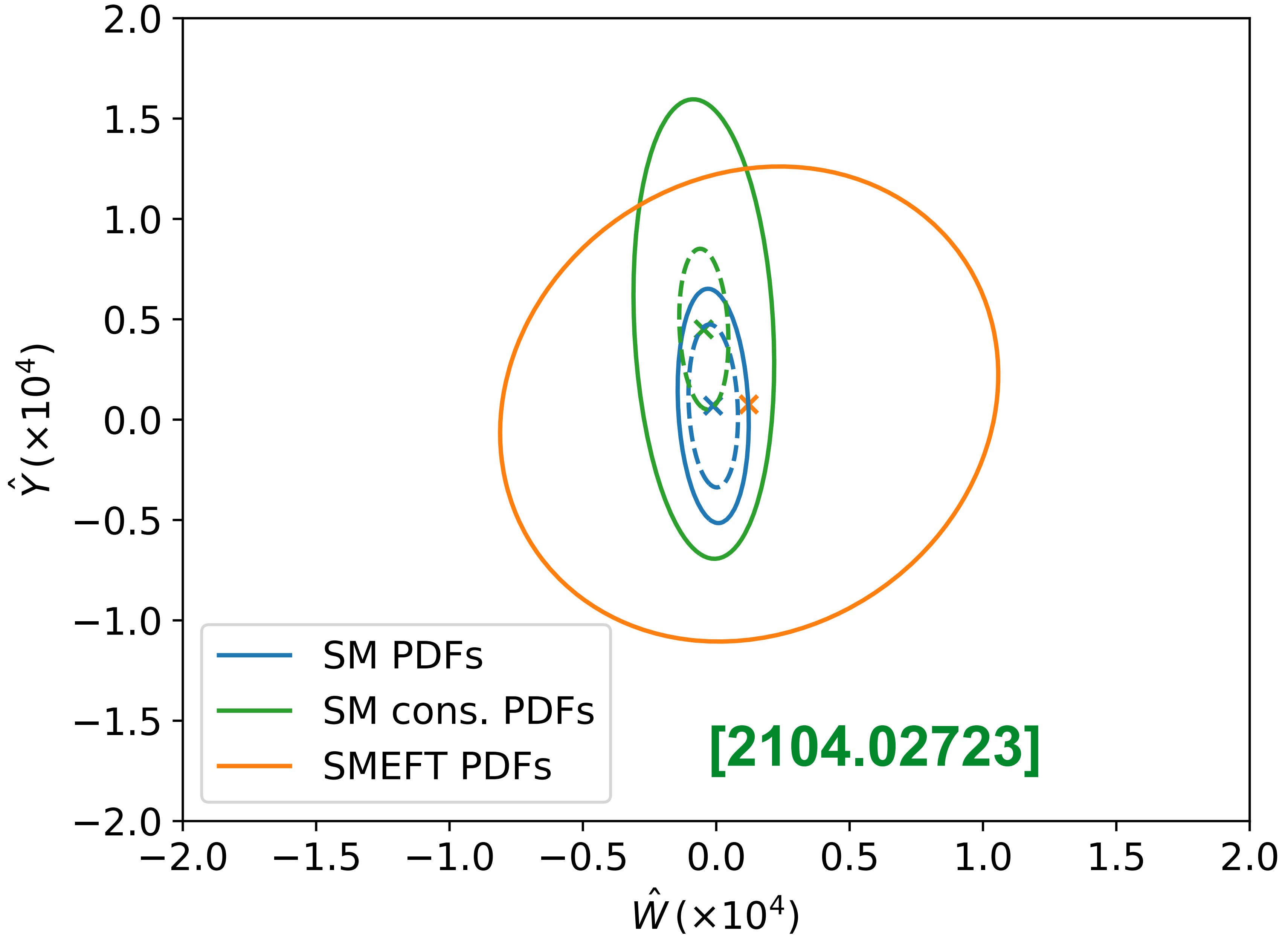


[CMS, 2111.10431]

a self-consistent determination at NLO on 4-quark contact interactions using CMS 13 TeV inclusive jet and top-quark pair together with HERA DIS data

electroweak oblique corrections

$$\mathcal{L}_{\rm SMEFT} \supset -\frac{\hat{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$



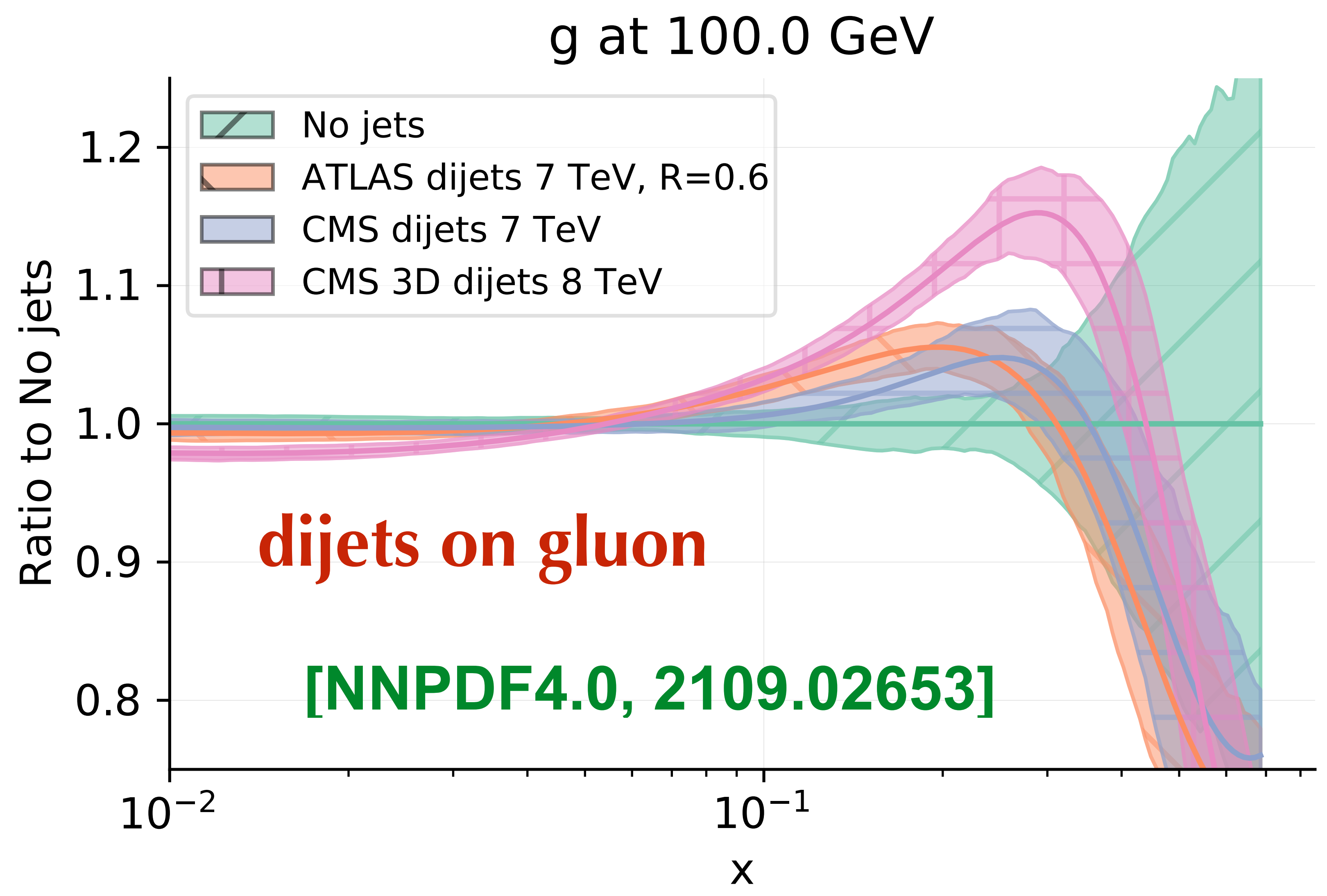
interplays of PDFs and SMEFT constraints with HL-LHC high-mass DY pseudo-data, demonstrating possible bias for not a consistent SMEFT+PDF fit

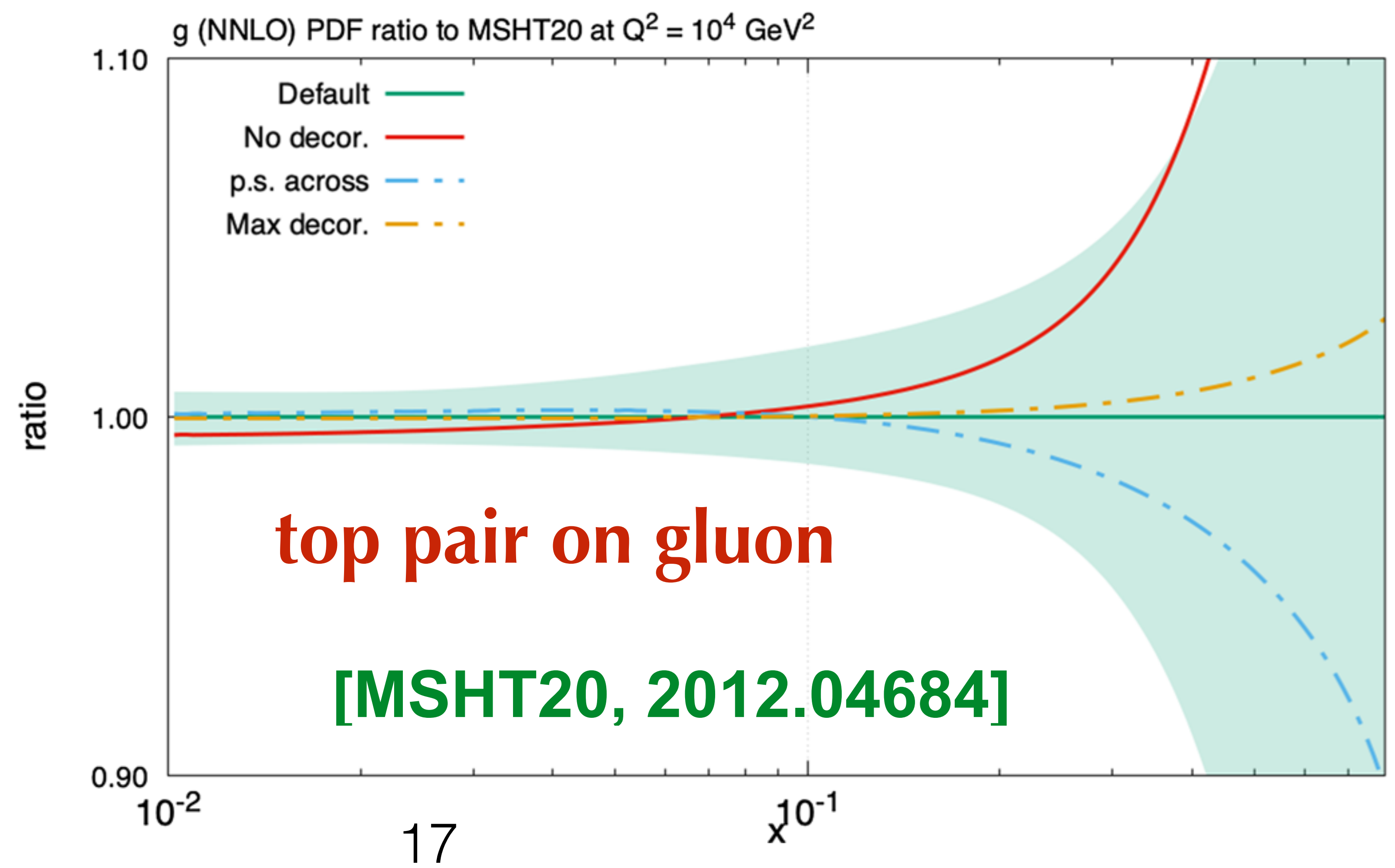
Impact of LHC data

- LHC provides measurements on a variety of PDF-sensitive standard candle processes with precision reaching a few percents; Their impact is subjected to possible tensions among different data and complications of the experimental systematic errors

χ^2 of LHC data in MSHT20

Data set	NLO	NNLO
ATLAS W^+, W^-, Z [118]	34.7/30	29.9/30
CMS W asym. $p_T > 35$ GeV [153]	11.8/11	7.8/11
CMS asym. $p_T > 25, 30$ GeV [154]	11.8/24	7.4/24
LHCb $Z \to e^+e^-$ [155]	14.1/9	22.7/9
LHCb W asym. $p_T > 20$ GeV [156]	10.5/10	12.5/10
CMS $Z \to e^+e^-$ [157]	18.9/35	17.9/35
ATLAS High-mass Drell–Yan [158]	20.7/13	18.9/13
CMS double diff. Drell–Yan [71]	222.2/132	144.5/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [92,93]	22.8/17	14.5/17
LHCb 2015 W, Z [94,95]	114.4/67	99.4/67
LHCb 8 TeV $Z \to ee$ [96]	39.0/17	26.2/17
CMS 8 TeV W [97]	23.2/22	12.7/22
ATLAS 7 TeV jets [18]	226.2/140	221.6/140
CMS 7 TeV $W + c$ [98]	8.2/10	8.6/10
ATLAS 7 TeV high precision W, Z [20]	304.7/61	116.6/61
CMS 7 TeV jets [99]	200.6/158	175.8/158
CMS 8 TeV jets [100]	285.7/174	261.3/174
CMS 2.76 TeV jet [106]	124.2/81	102.9/81
ATLAS 8 TeV Z p_T [74]	235.0/104	188.5/104
ATLAS 8 TeV single diff $t\bar{t}$ [101]	39.1/25	25.6/25
ATLAS 8 TeV single diff $t\bar{t}$ dilepton [102]	4.7/5	3.4/5
CMS 8 TeV double differential $t\bar{t}$ [104]	32.8/15	22.5/15
CMS 8 TeV single differential $t\bar{t}$ [107]	12.9/9	13.2/9
ATLAS 8 TeV High-mass Drell–Yan [72]	85.8/48	56.7/48
ATLAS 8 TeV W [105]	84.6/22	57.4/22
ATLAS 8 TeV W + jets [103]	33.9/30	18.1/30
ATLAS 8 TeV double differential Z [73]	157.4/59	85.6/59
Total	5822.0/4363	5121.9/4363



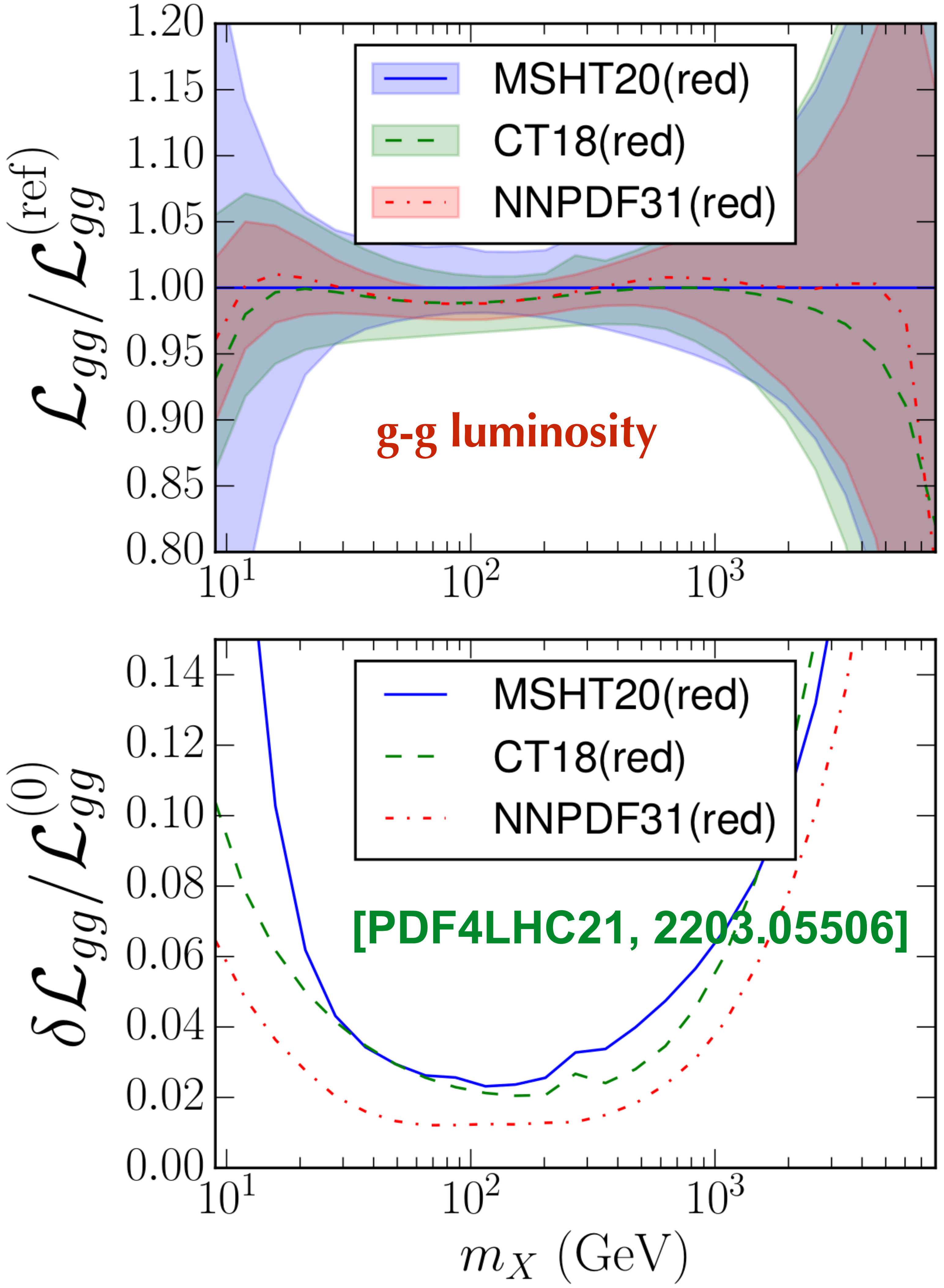


- fit quality to LHC data is moderate in general or very poor for specific data sets
- decorrelation/regularization of experimental systematics or theoretical errors are added to reach a reasonable χ^2
- appraisal and selection of LHC data become a major task

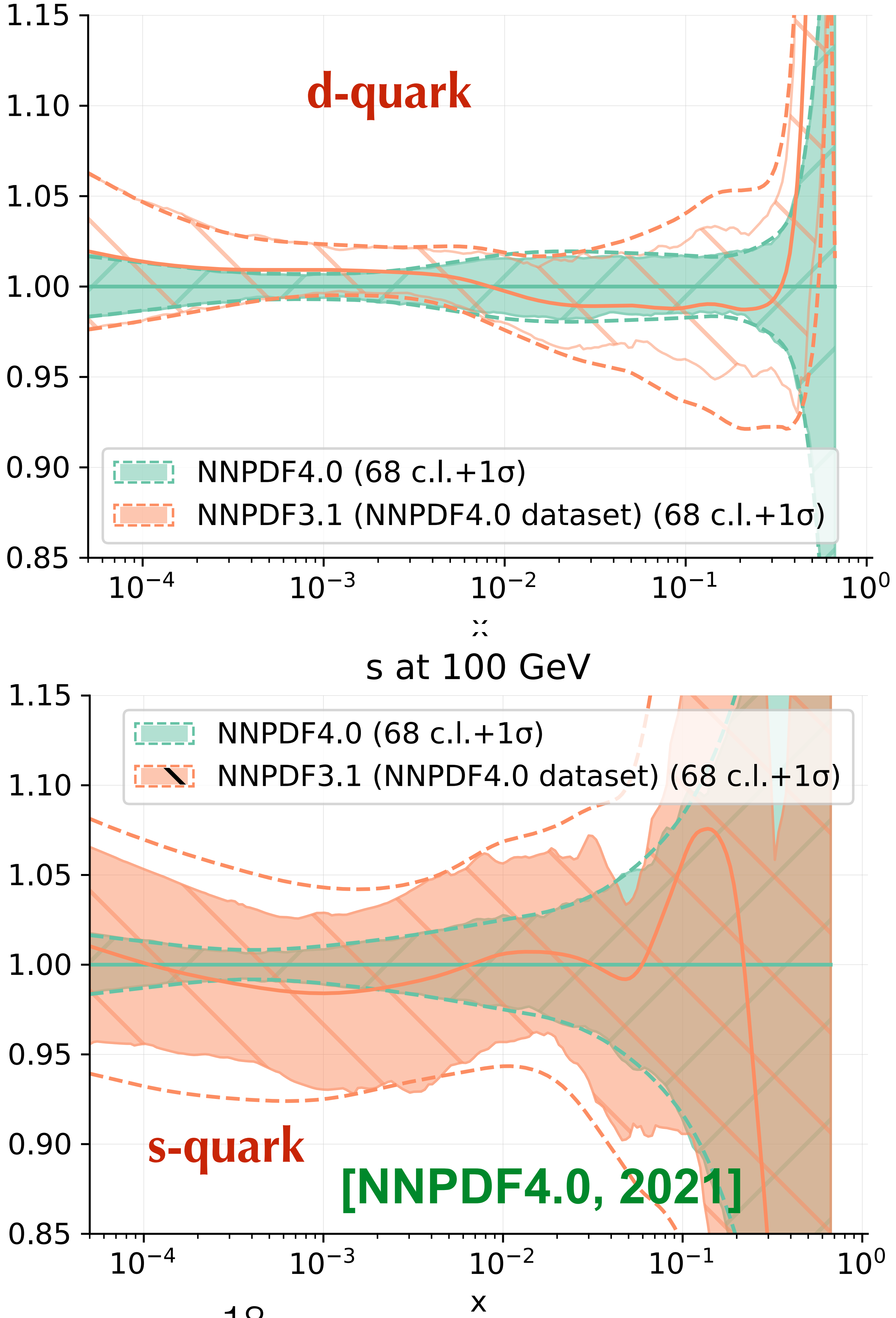
Methodology and uncertainties

- Textbook criterion "$\Delta\chi^2=1$" on estimation of uncertainties is not reliable in global fit, involving large data samples and degrees of freedoms; PDF unc. depends very much on methodologies including "tolerance"

PDFs from reduced fits



NNPDF methodology update



- CT uses tier1+tier2 tolerance, MSHT uses a pure dynamic tolerance, both close to a hypothesis test criterion
- NNPDF3.1 uses ML algorithm with effective tolerance that is smaller than CT and MSHT as checked explicitly from reduced fits
- substantial changes on methodologies for NN4.0 vs. NN3.1 further affect the uncertainty

Methodology and uncertainties

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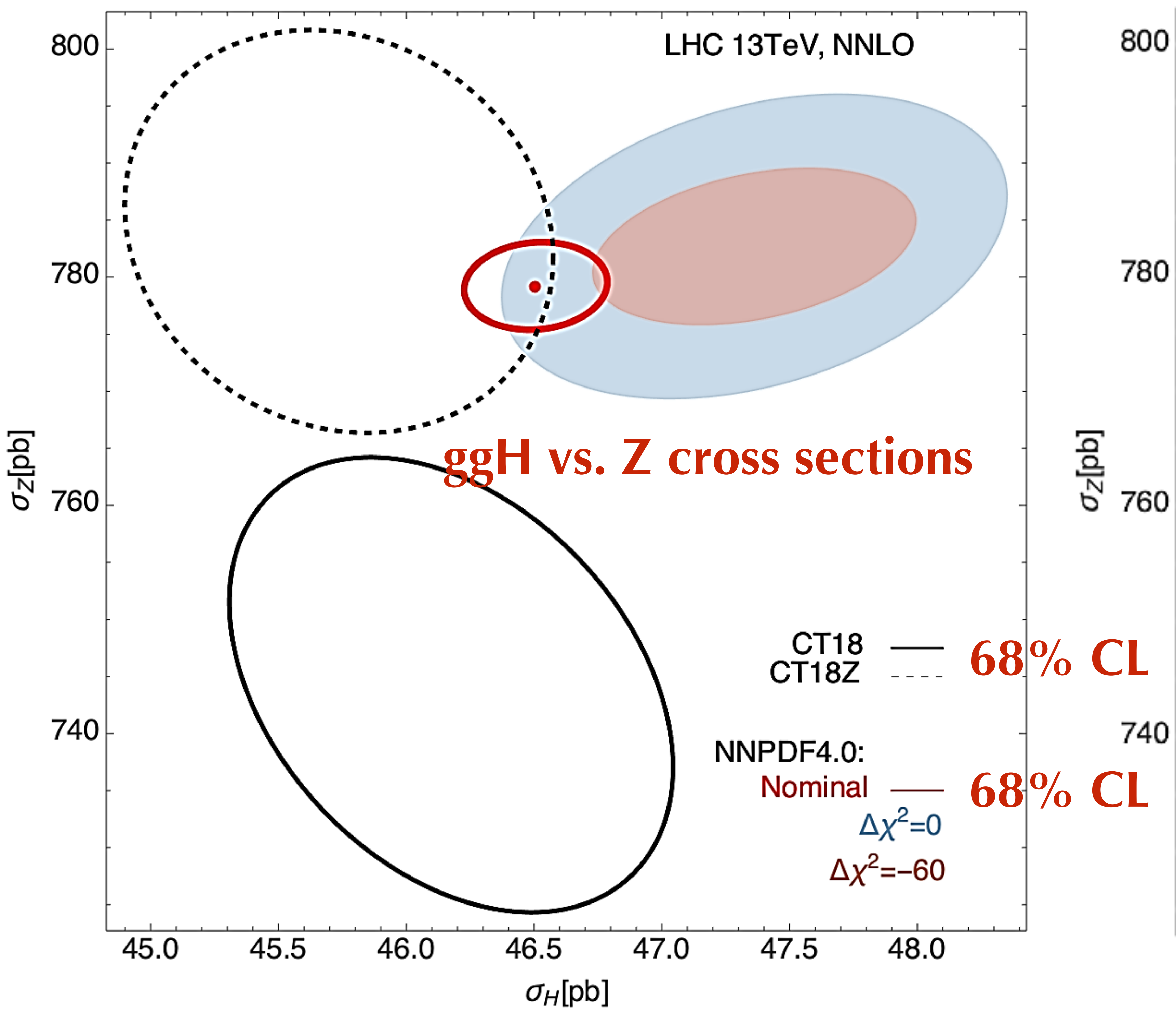
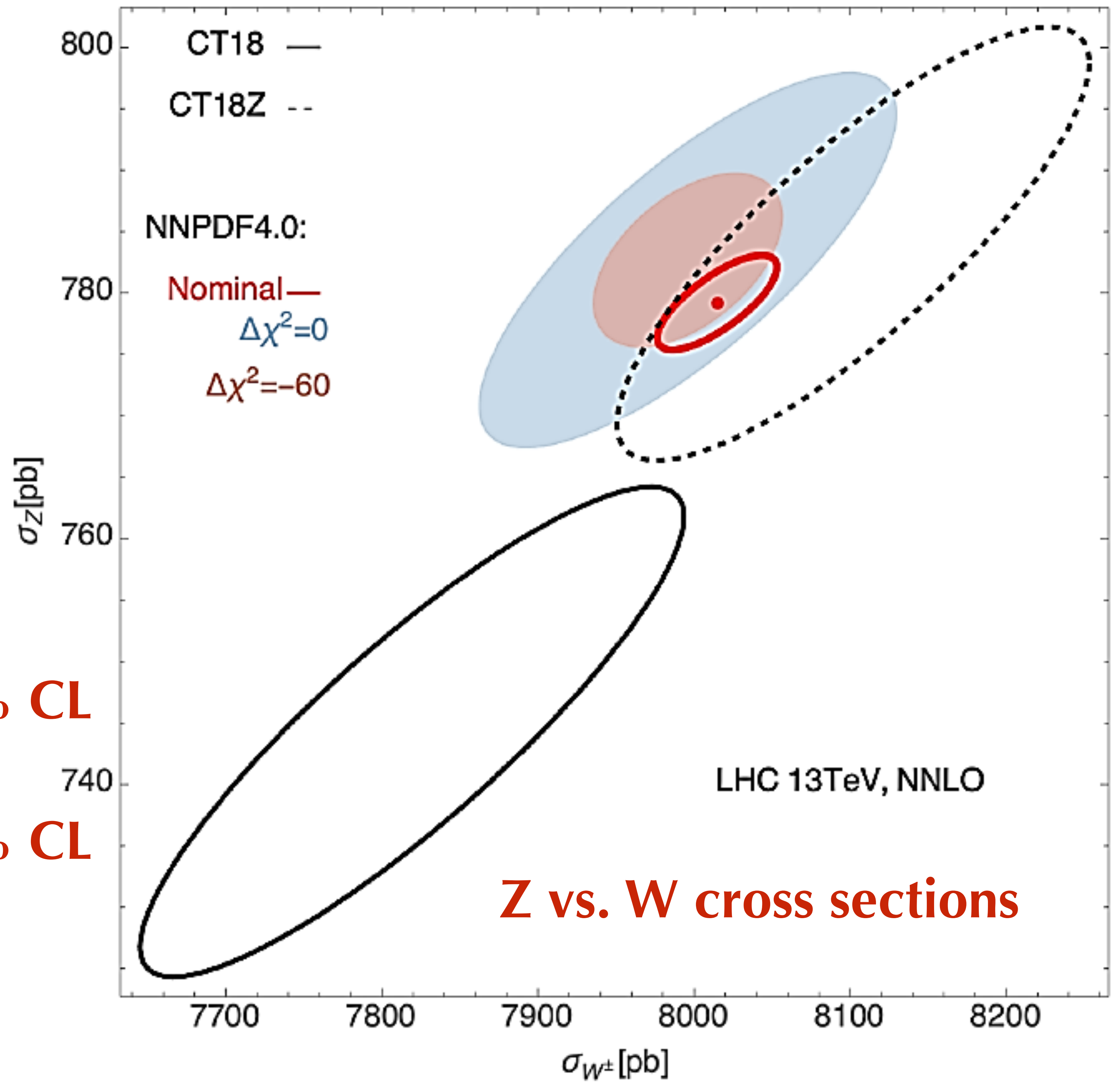
PDF sampling and uncertainty



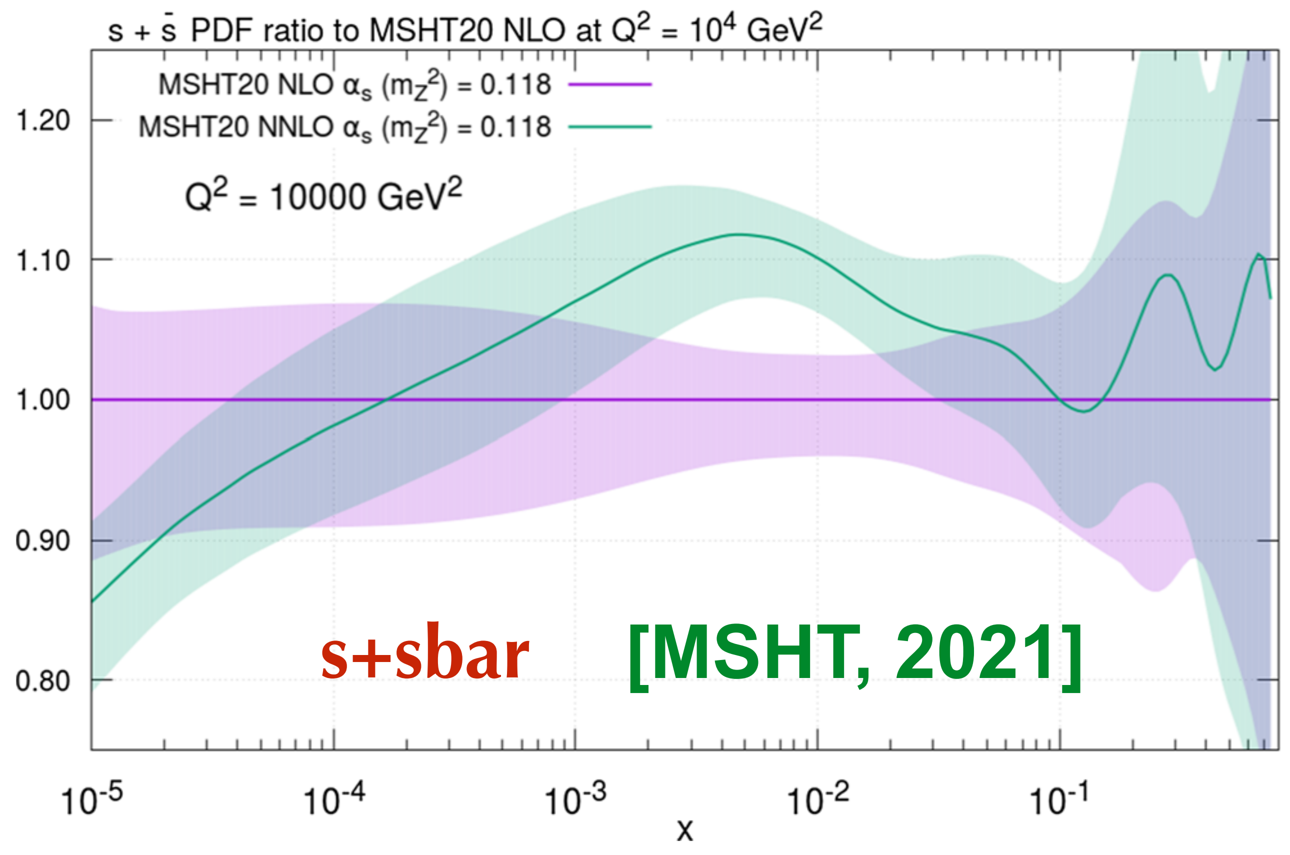


[see talk by A. Courtoy in WG1]

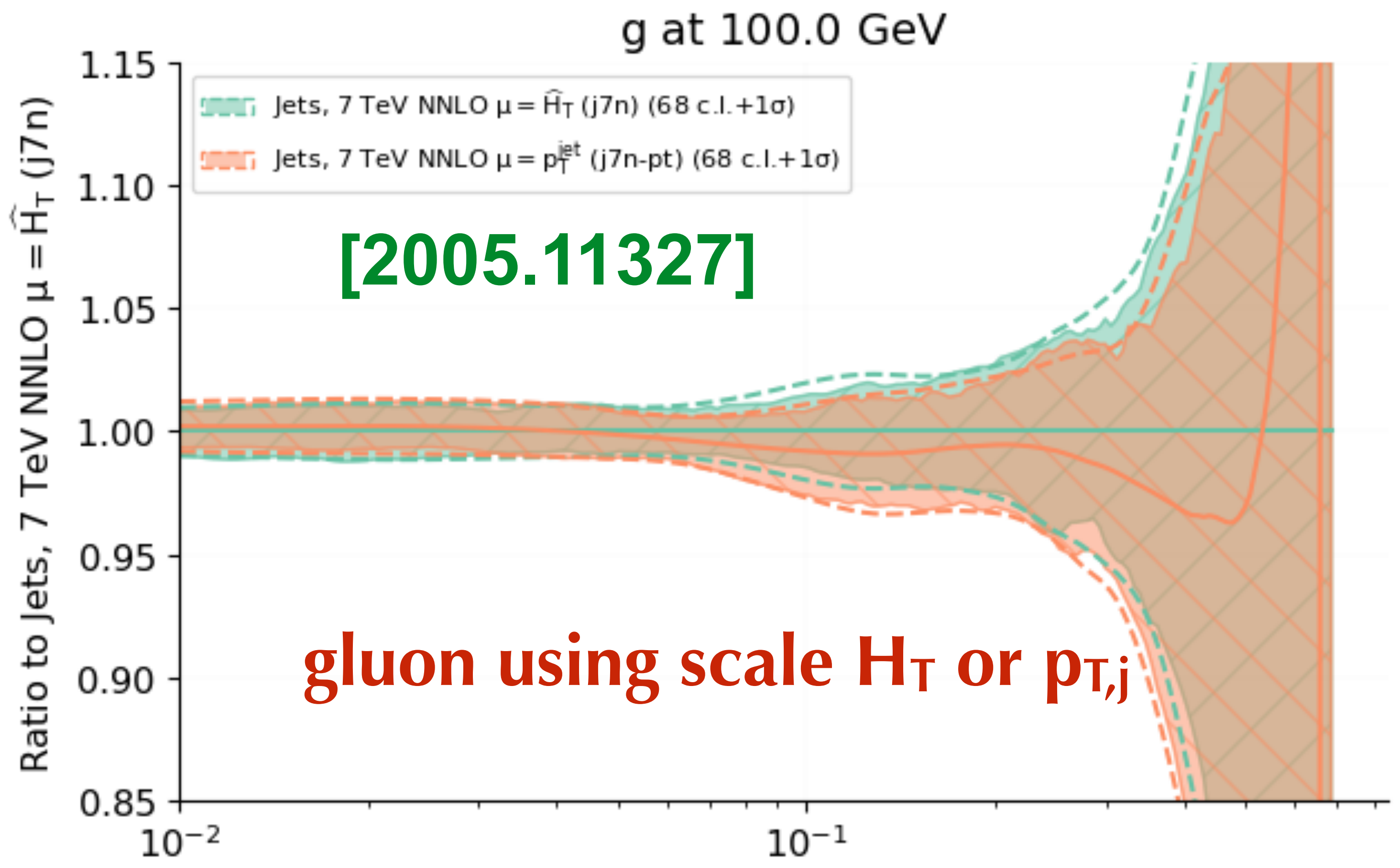
- an ongoing debate on a representative sampling procedure in the PDF parameter space
- Example: a series of scans carried out along eigenvector directions of published NNPDF4.0 with $\Delta\chi^2$ wrt. central set calculated using public NNPDF4.0 code
- the estimated regions with $\Delta\chi^2<0$ (blue shaded ellipses) are shifted and are larger than the nominal NNPDF4.0 PDF uncertainties (red ellipses)

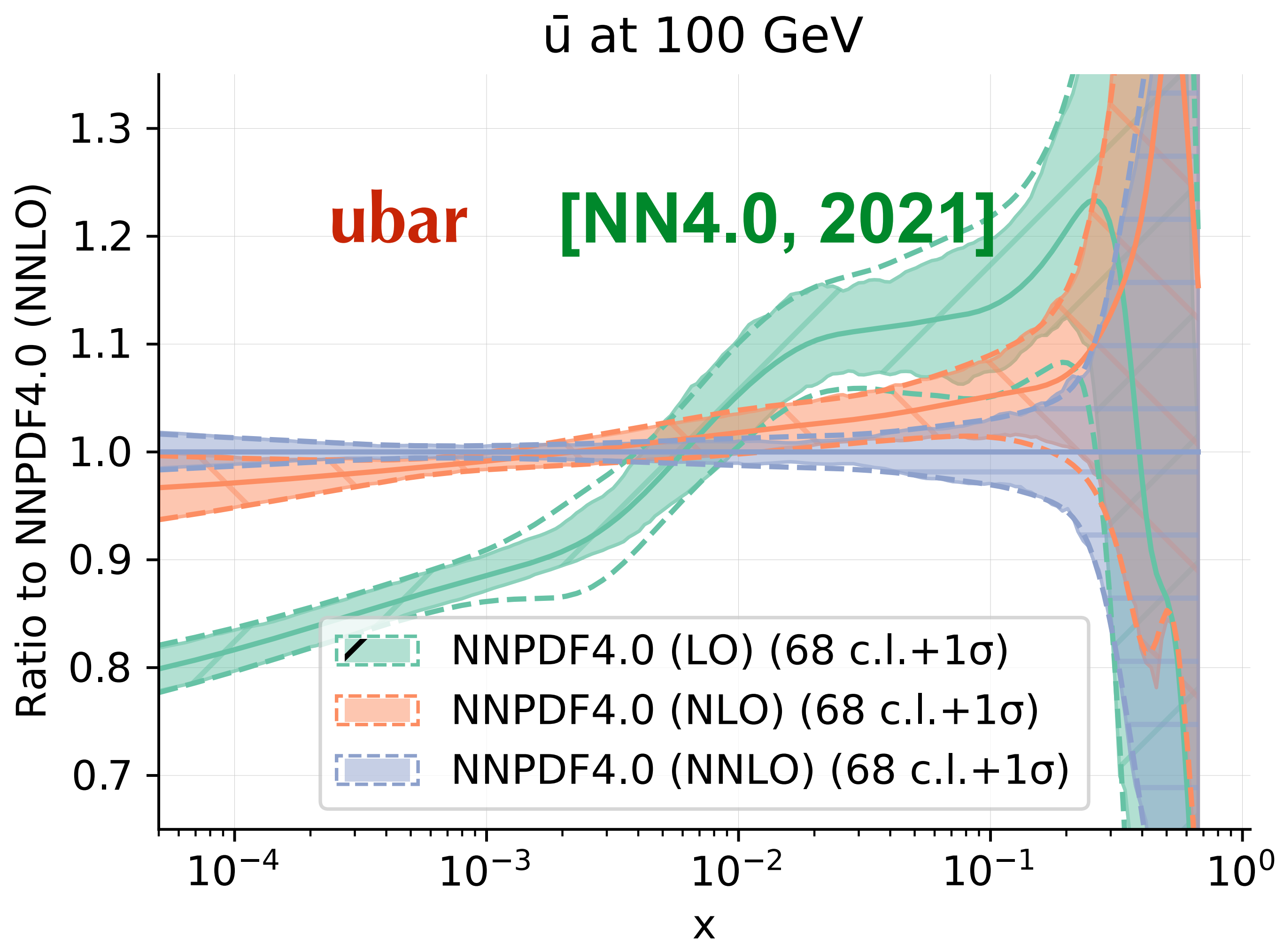
Theoretical uncertainties

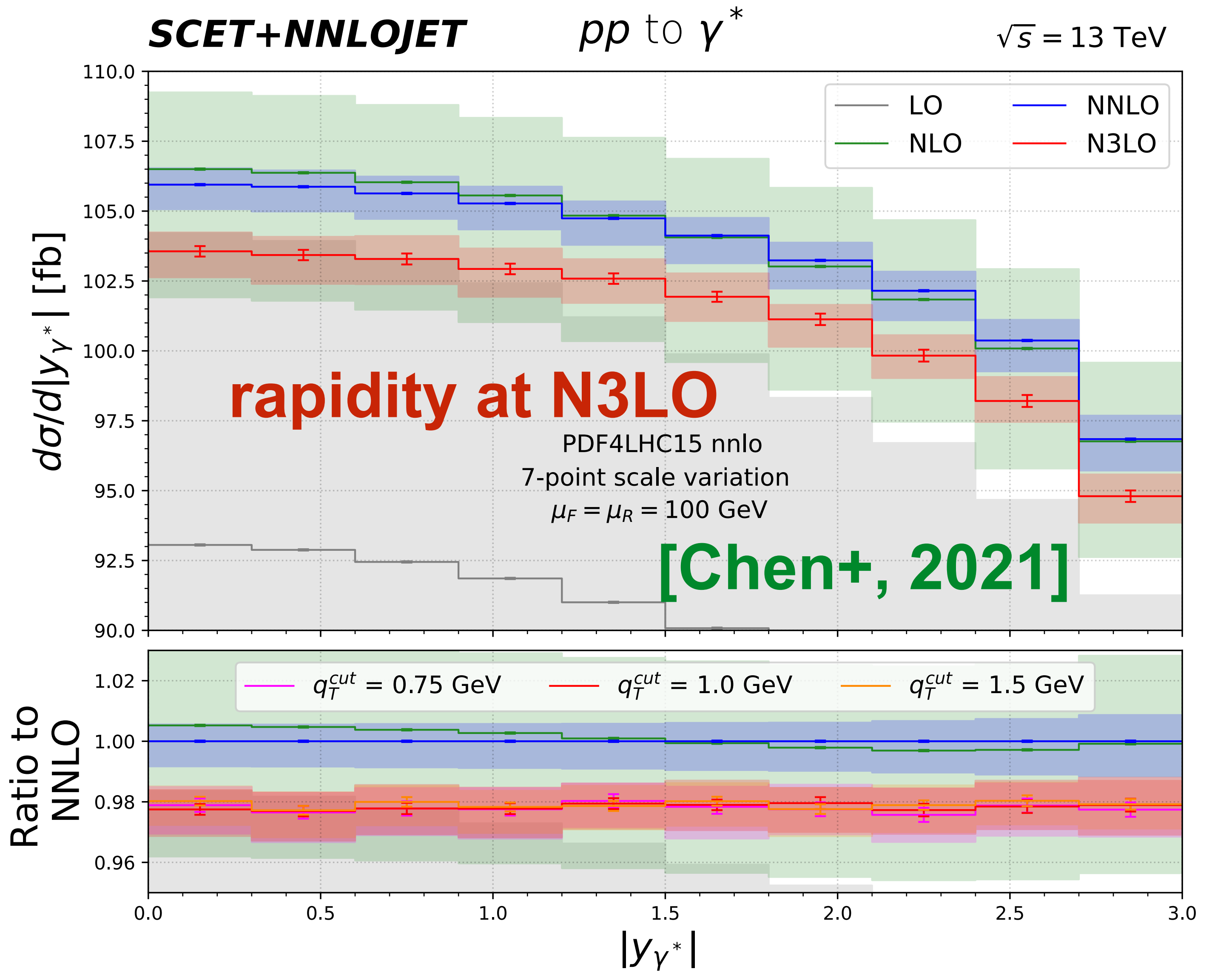
- Impact of perturbative theoretical uncertainties beyond N2LO on PDFs, e.g., from N3LO QCD and possibly mixed QCD-EW corrections, still remains an open question



NLO vs. NNLO PDFs



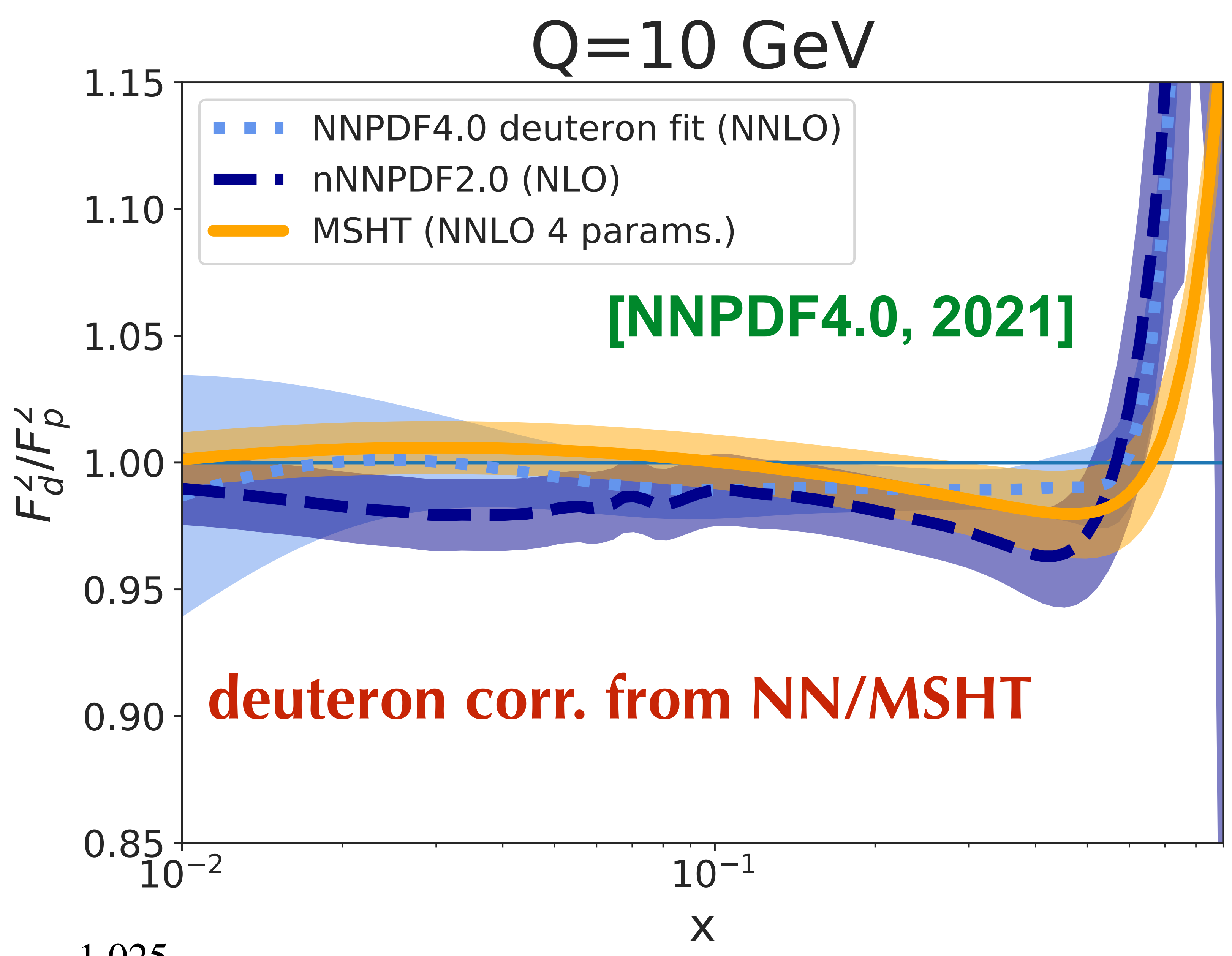


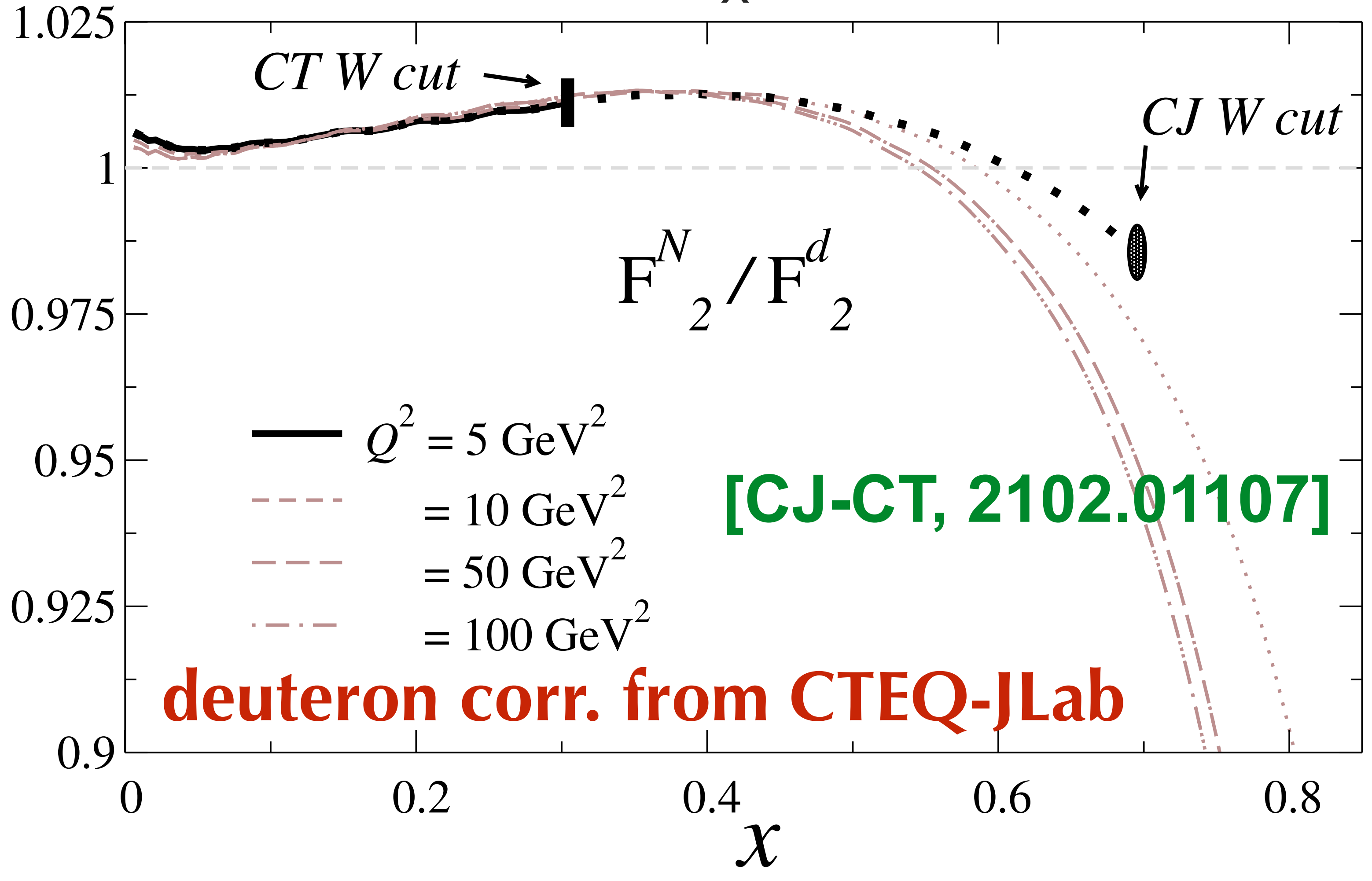


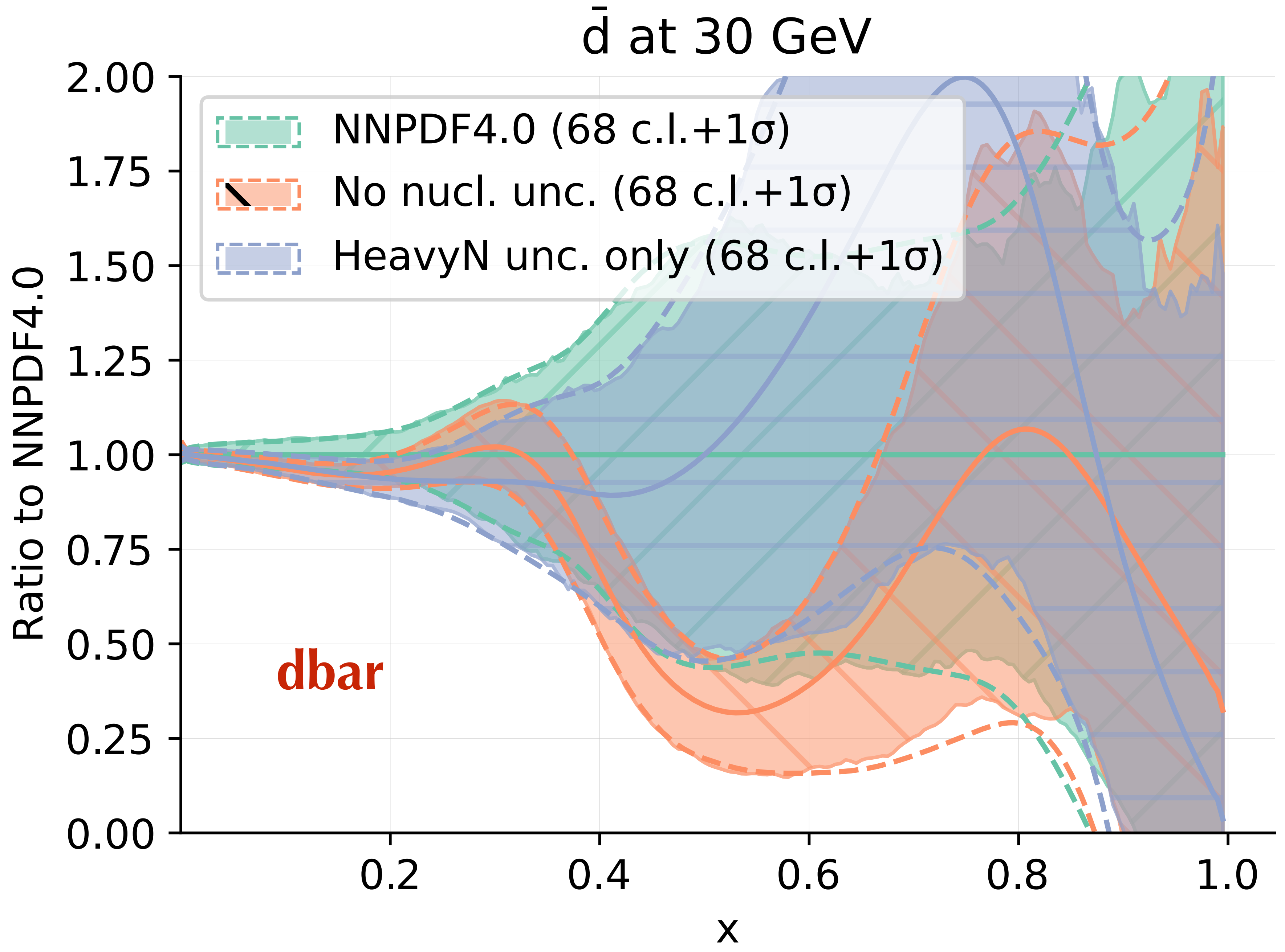
- one can compare PDFs extracted at NLO and NNLO, though the interpretation can be complicated especially due to poor fit at NLO
- currently, PDF groups explore different scale choices and select one given the best fit to data or theoretically well motivated; alternatively can included scale variation into covariance matrix as a systematic error
- at current stage, different scales at NNLO do not change the output PDFs significantly; however, genuine N3LO corrections can be outside the scale variation band

Nuclear corrections

✦ DIS and Drell-Yan production from fixed-target experiments, on either deuteron or heavy nucleus, still play important roles in flavor separation at moderate and large x region





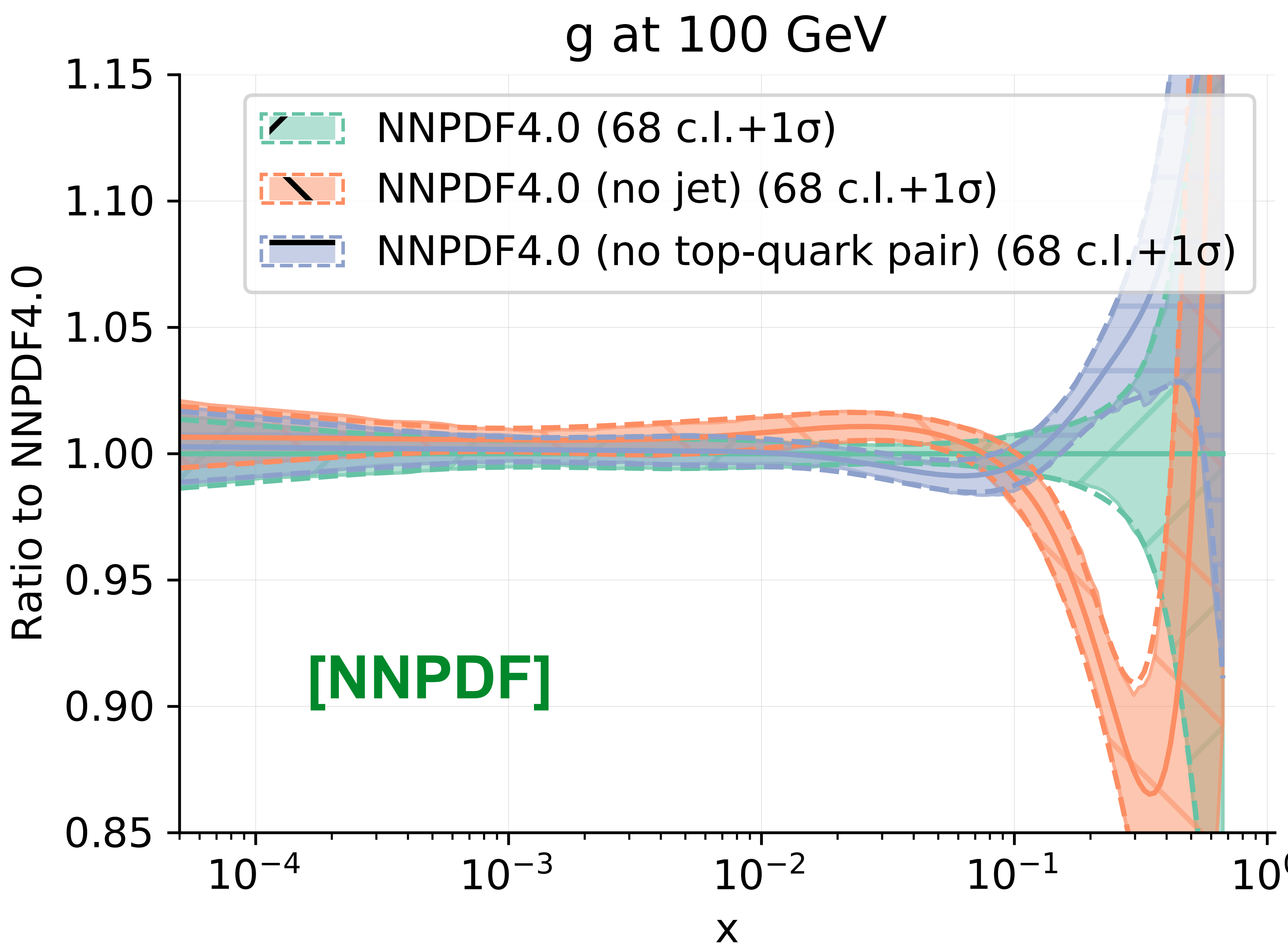


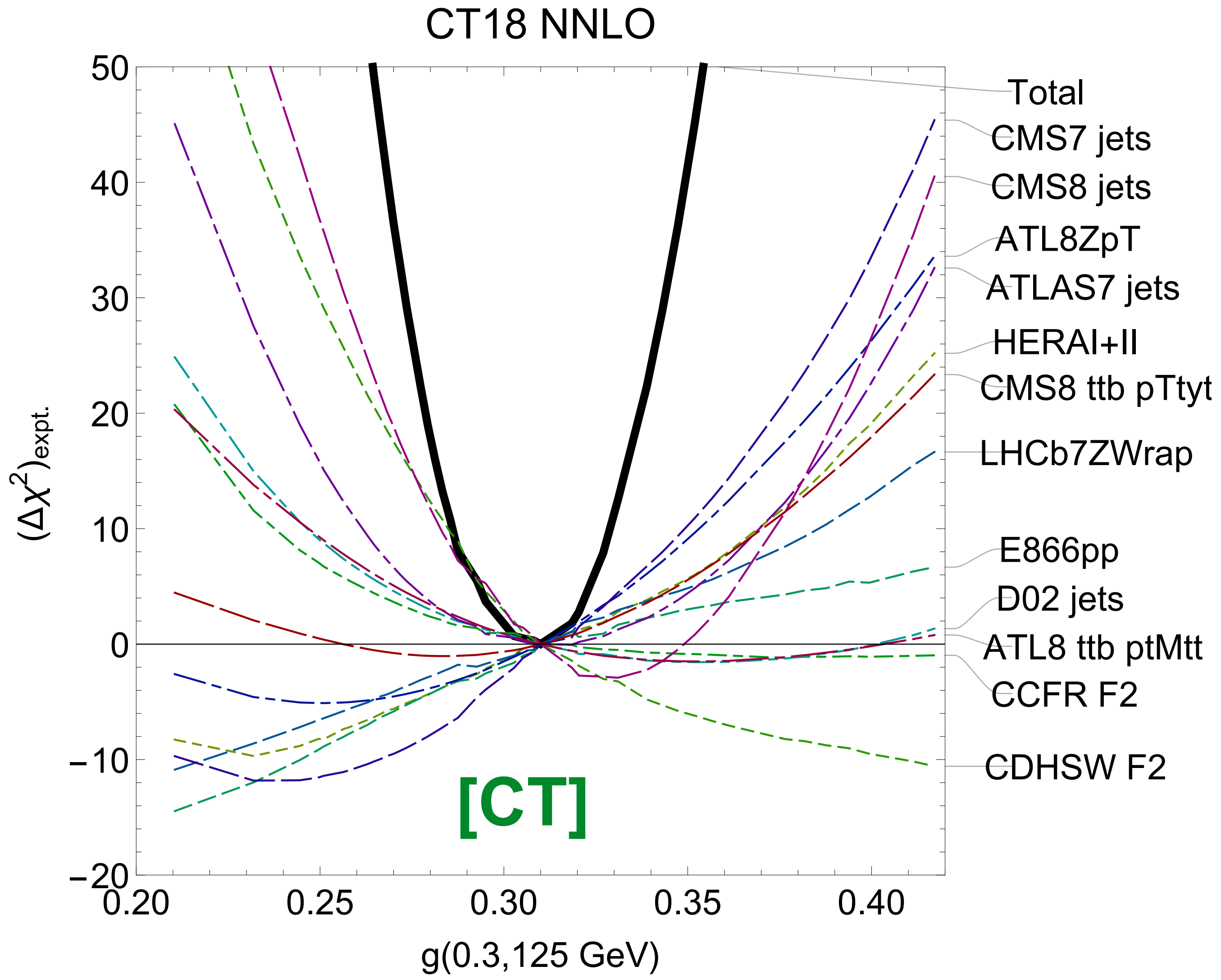
❖ deuteron corrections are better understood and small in general for data region considered in global fit; see **[Alekhin+, 2203.07333]** as well for an update study

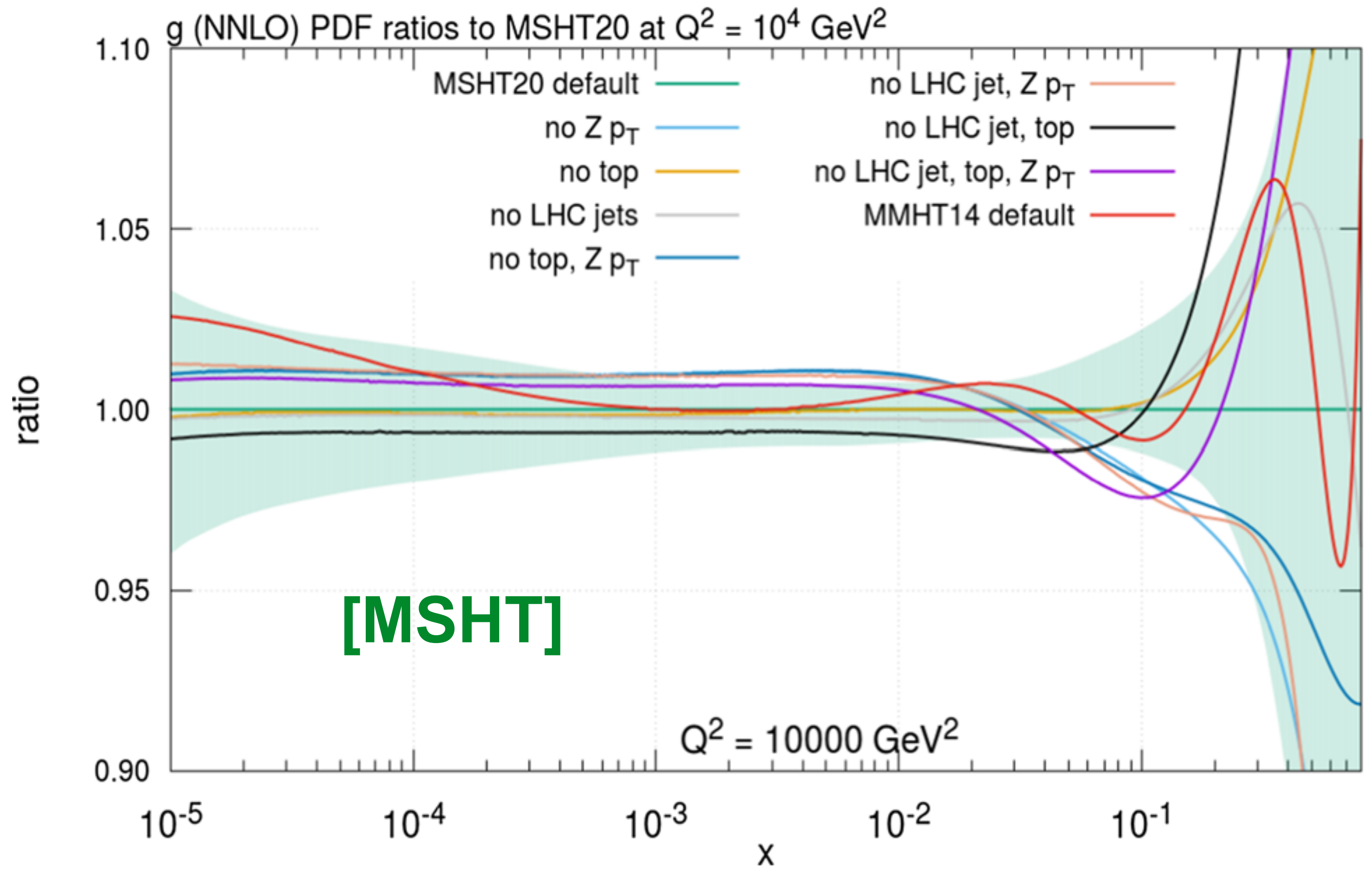
❖ heavy-nuclear corrections and related uncertainties (in neutrino-nucleus scattering) can lead to visible change of PDFs at large-x

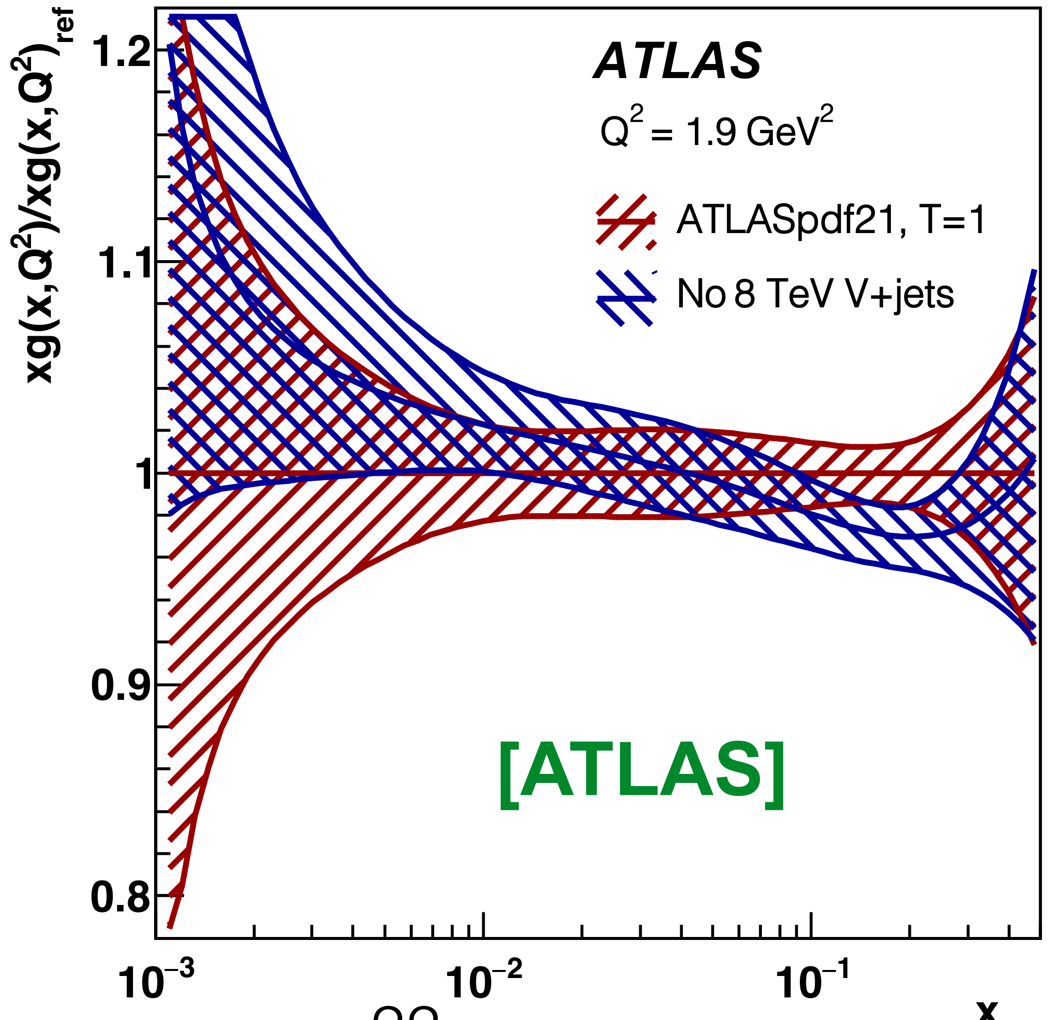
Gluon at large-x

- Gluon PDFs at large-x (>0.1) receive constraints from DIS, Tevatron jet and various LHC data, including inclusive jets, top-quark pair, and Z pT or W/Z+jets productions





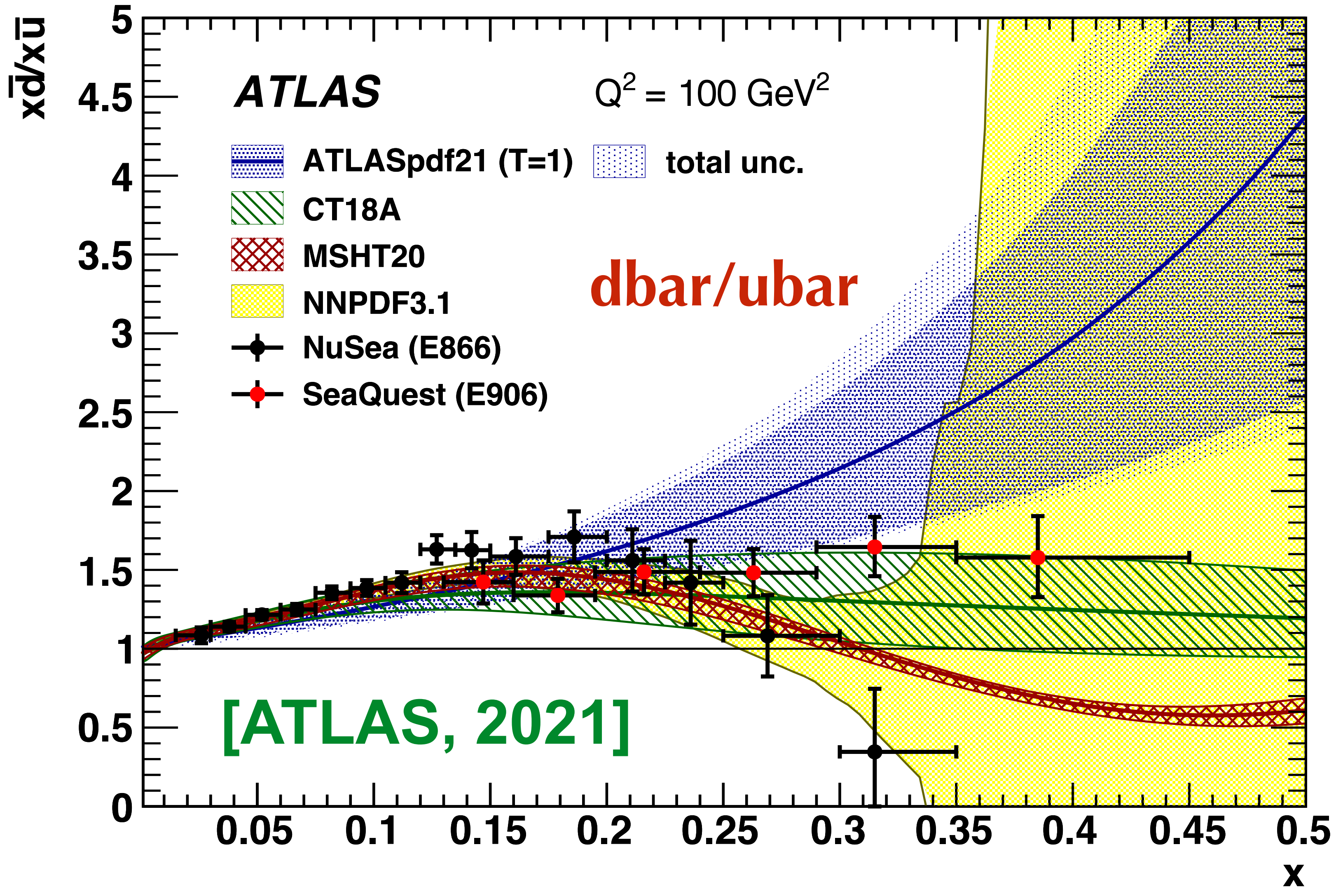


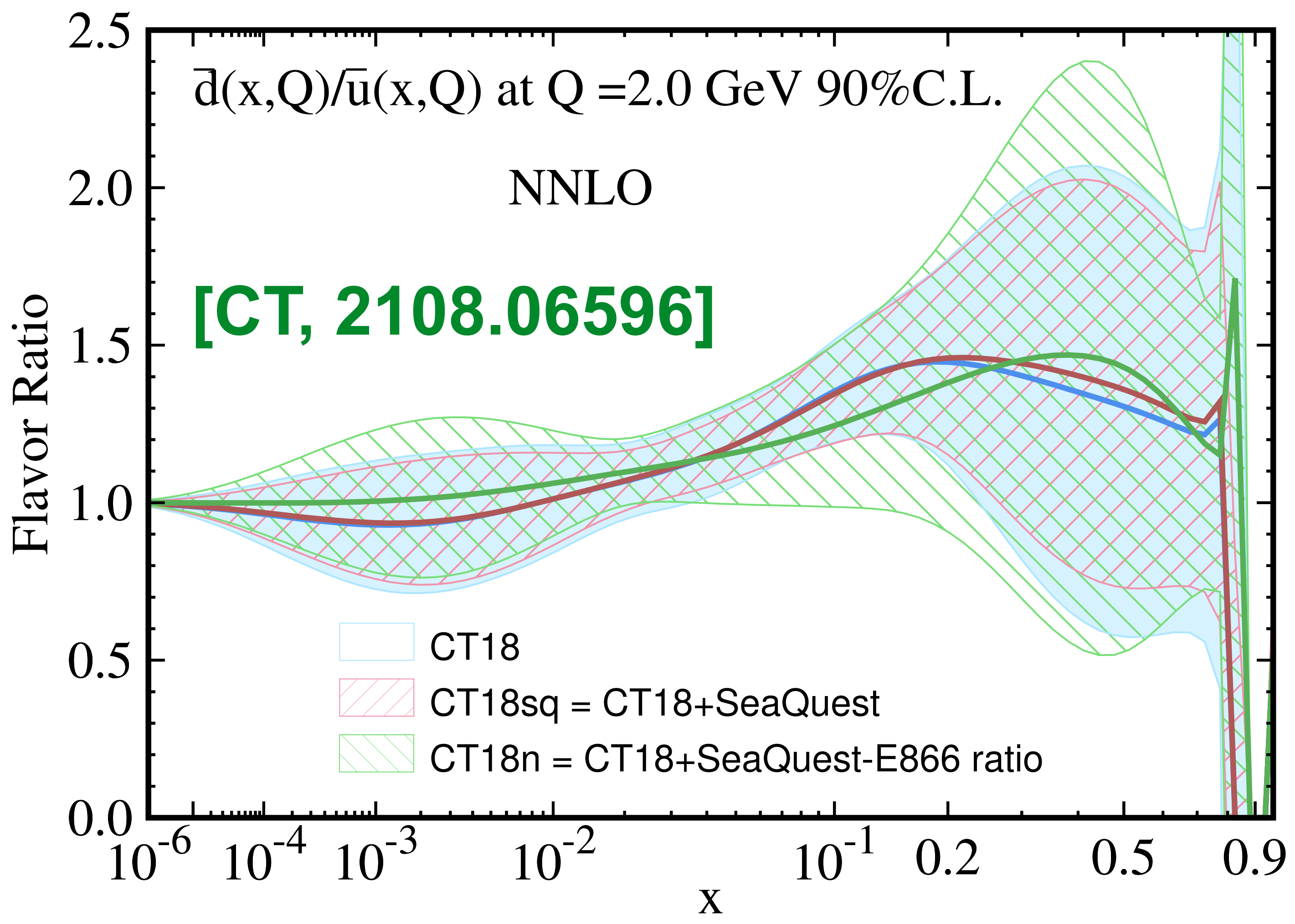


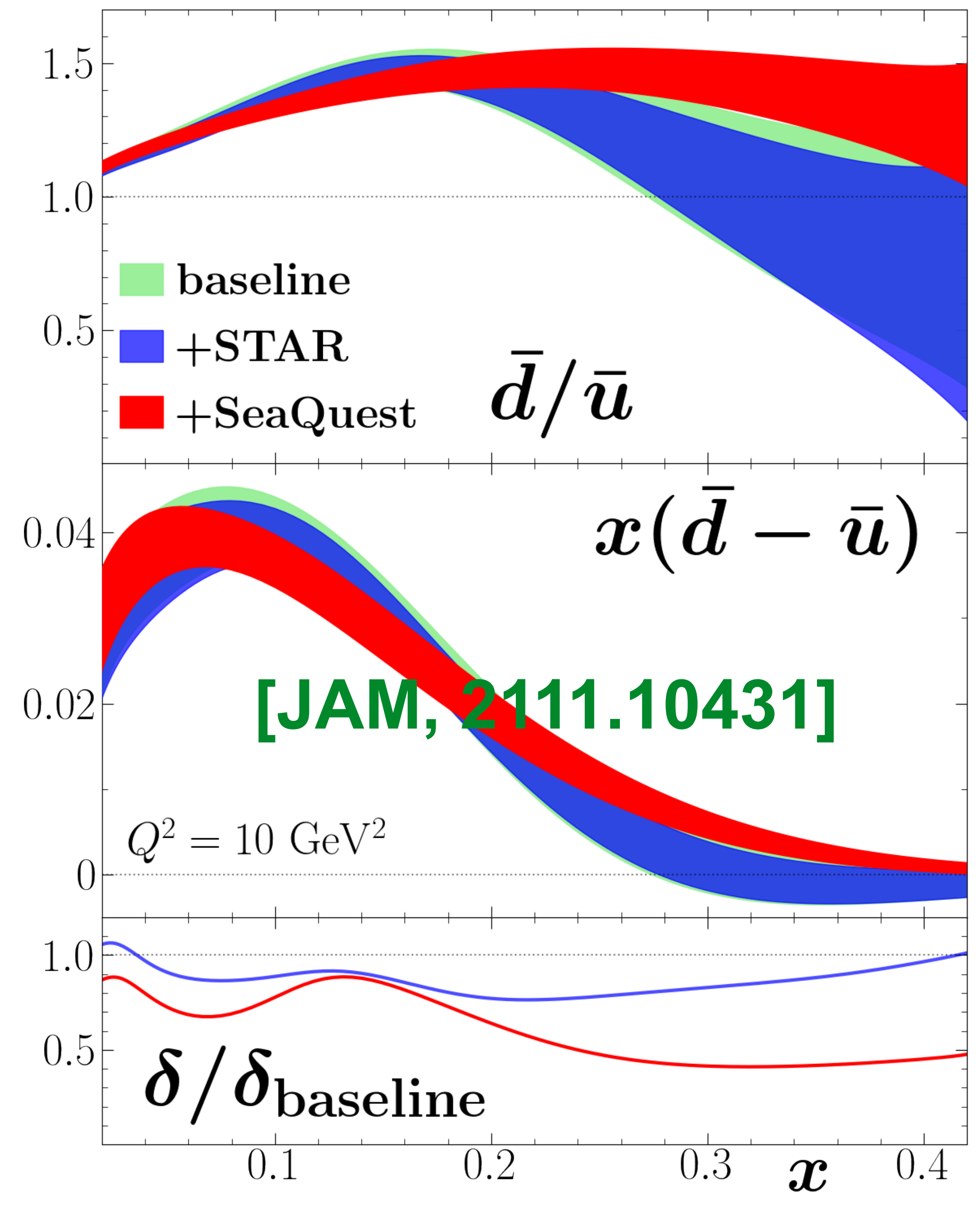
- different LHC data can have very different pulls, and are not necessarily consistent in different groups or even between sub-sets of the data
- top-pair data generally pull the gluon down while for inclusive jets or Z pT it can go either ways
- large spread of LHC data pulls indicate the necessary of a "global data sets" and methodologies with "tolerance" criterion

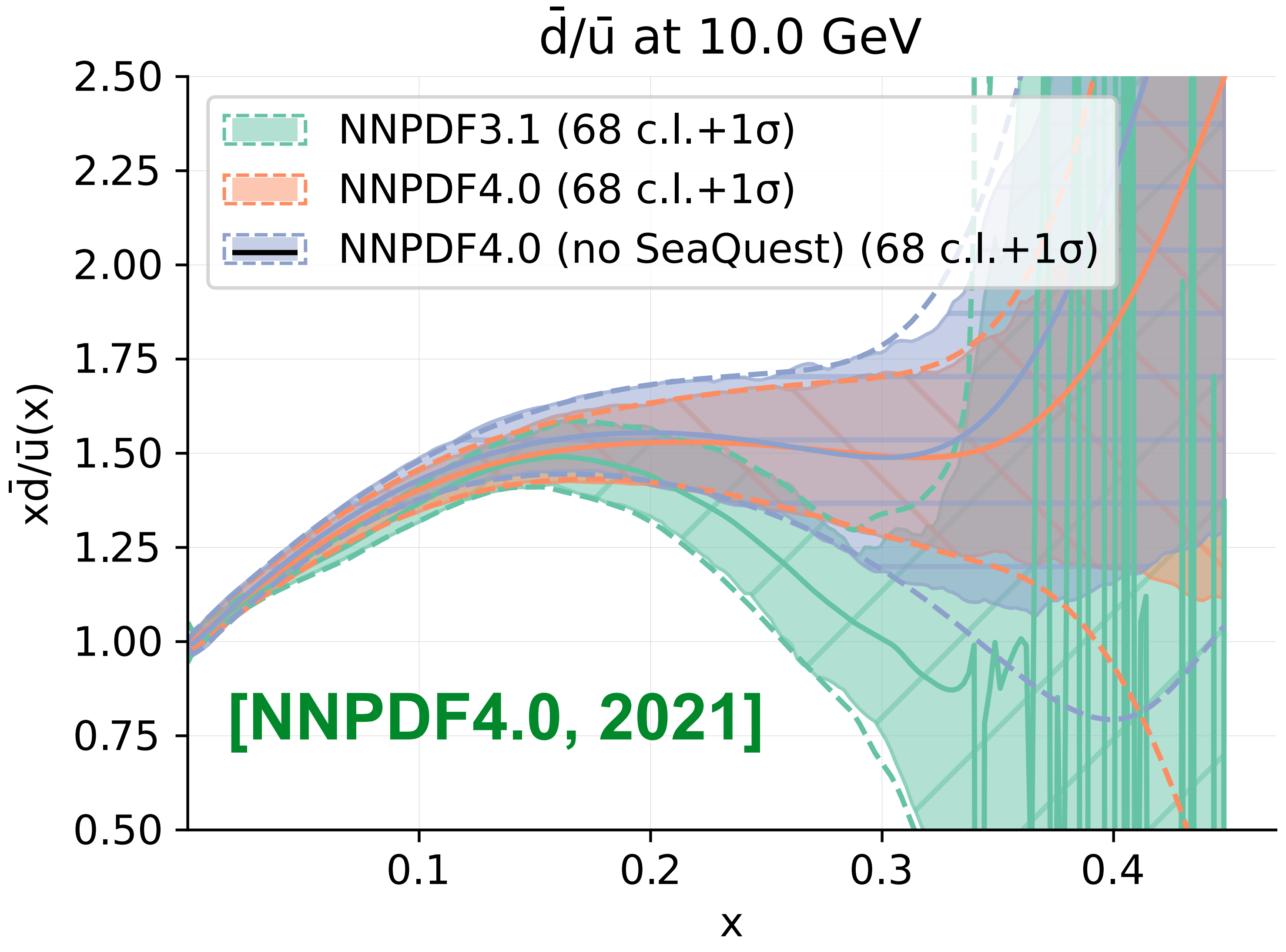
Sea-quark at large-x

- E906 (SeaQuest) fixed-target Drell-Yan data have been studied by several global analysis groups, CT, NNPDF, JAM and ATLASpdf; the impact on sea-quark asymmetry dbar/ubar at large-x is mild









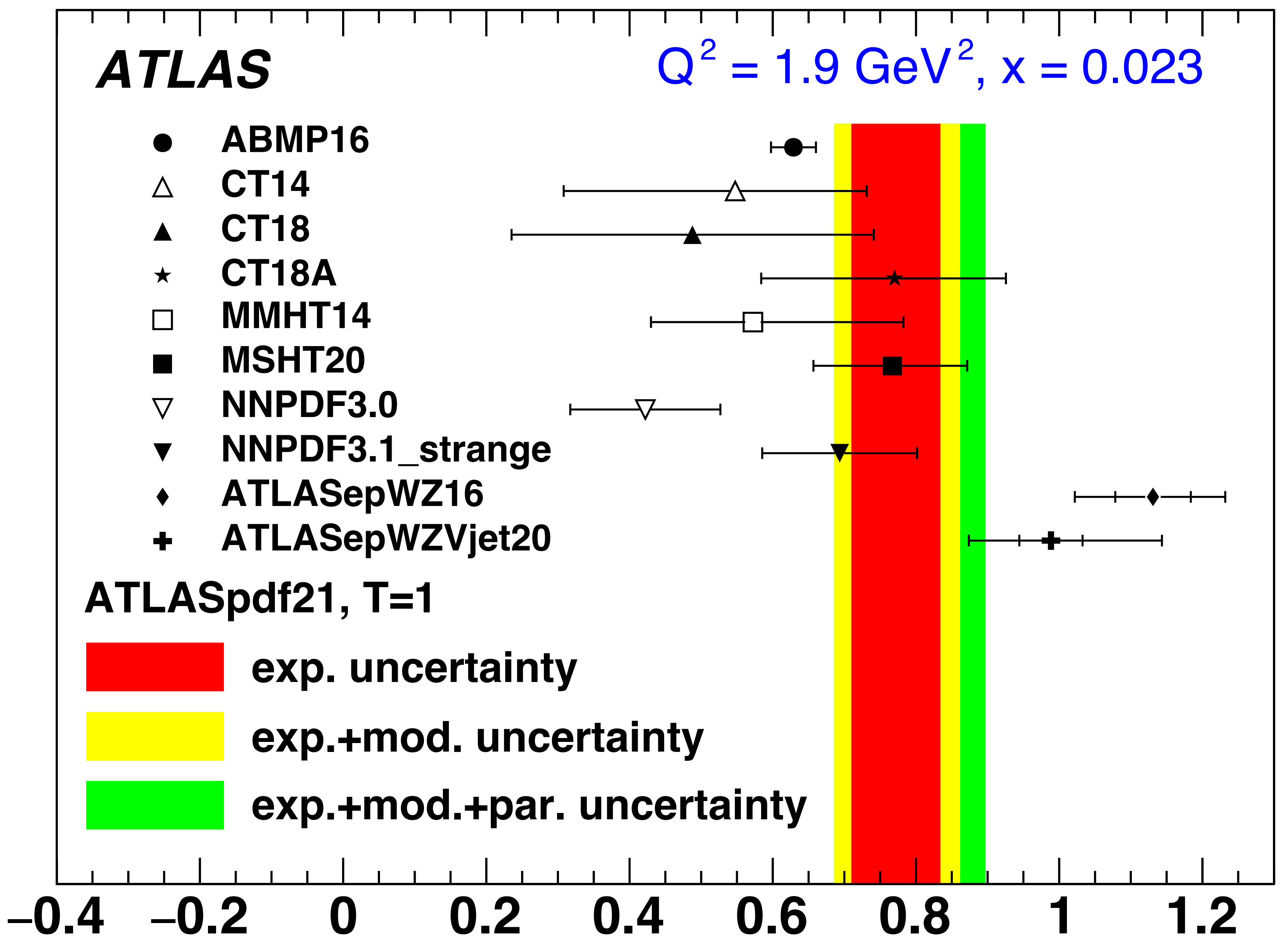
- even though not including E906 data in the global analysis, CT18A, NNPDF3.1 and ATLASpdf21 agree with E906 within uncertainties; MSHT20 shows a much smaller uncertainty

- impact of E906 data in the global fit is mild for CT and NNPDF (a modest increase of dbar/ubar at large-x and slight reduction of uncertainties), while the impact is larger in JAM fit

Strangeness suppression

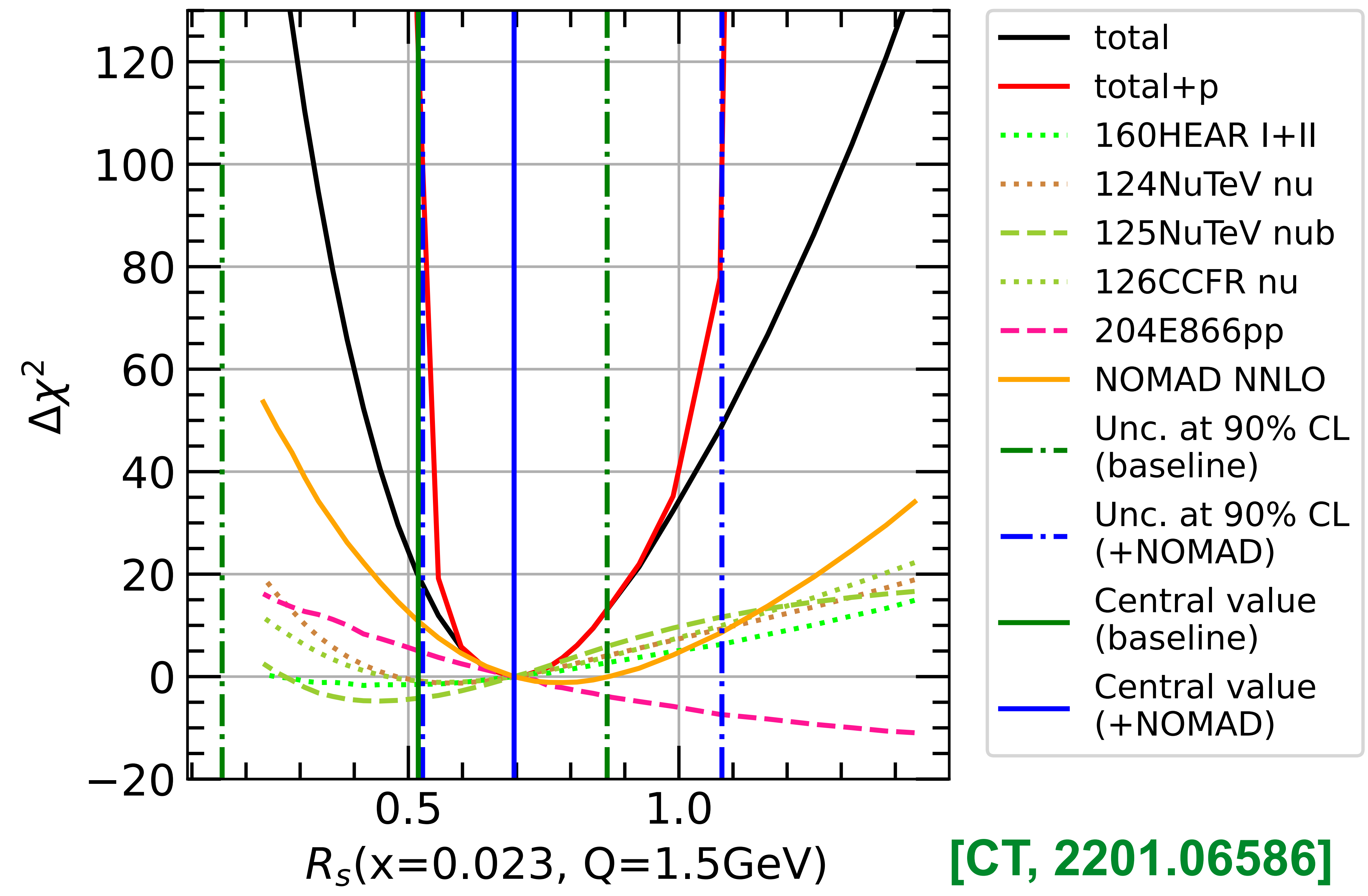
- Suppression of s-quark PDFs comparing to u/d sea-quarks are of particular interests, especially concerning interplay of dimuon and ATLAS W/Z data on strange to light sea-quark ratio Rs=(s+sb)/(ub+db) at x=0.023

ATLAS measurement



[ATLAS,2112.11266]

CT LM scans on Rs with NOMAD



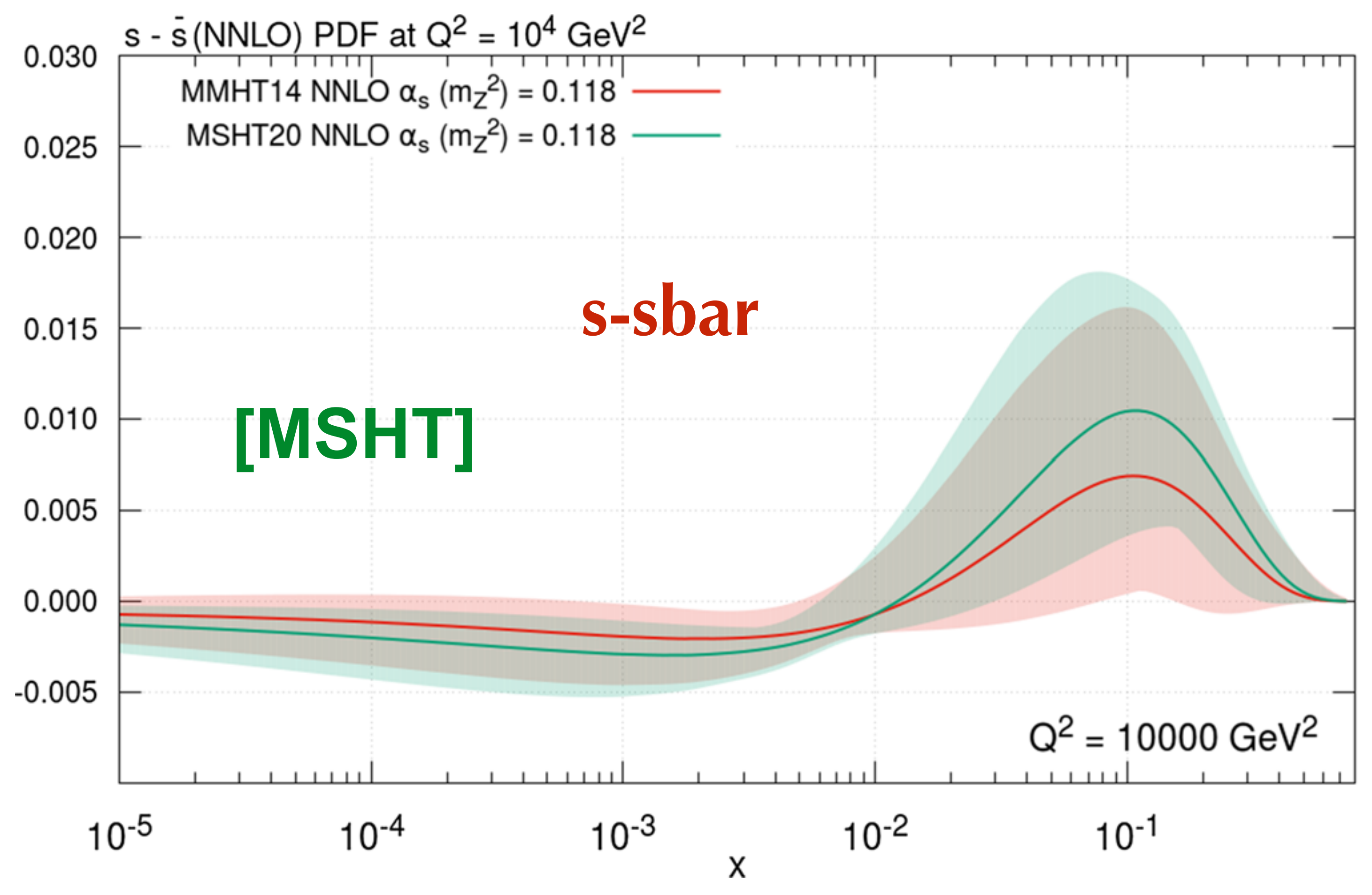
[CT, 2201.06586]

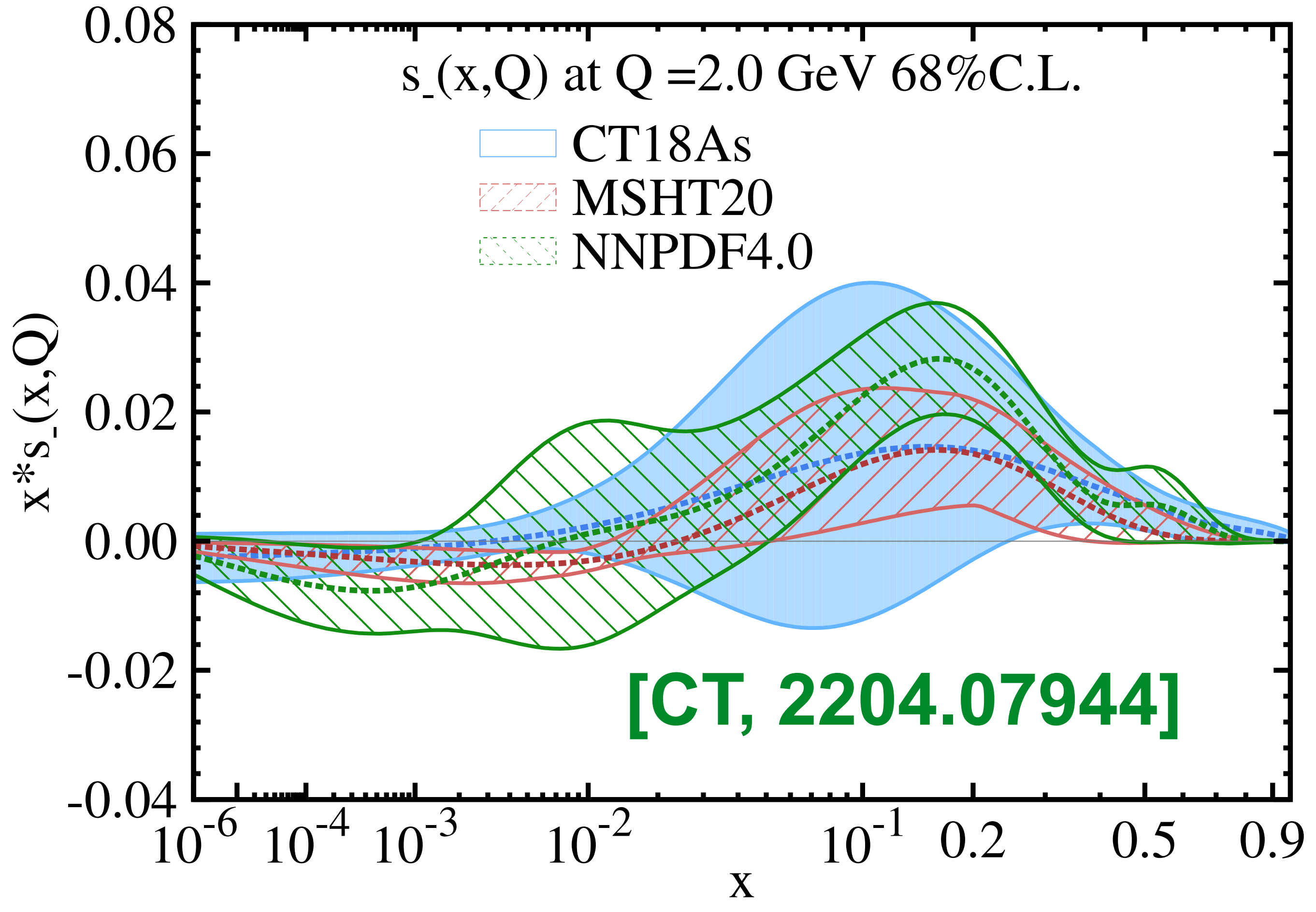
- previous tensions between dimuon data (Rs~0.5) and LHC data (Rs>1)
- most recent ATLAS data shows Rs~0.8, now both prefer slightly suppressed strangeness

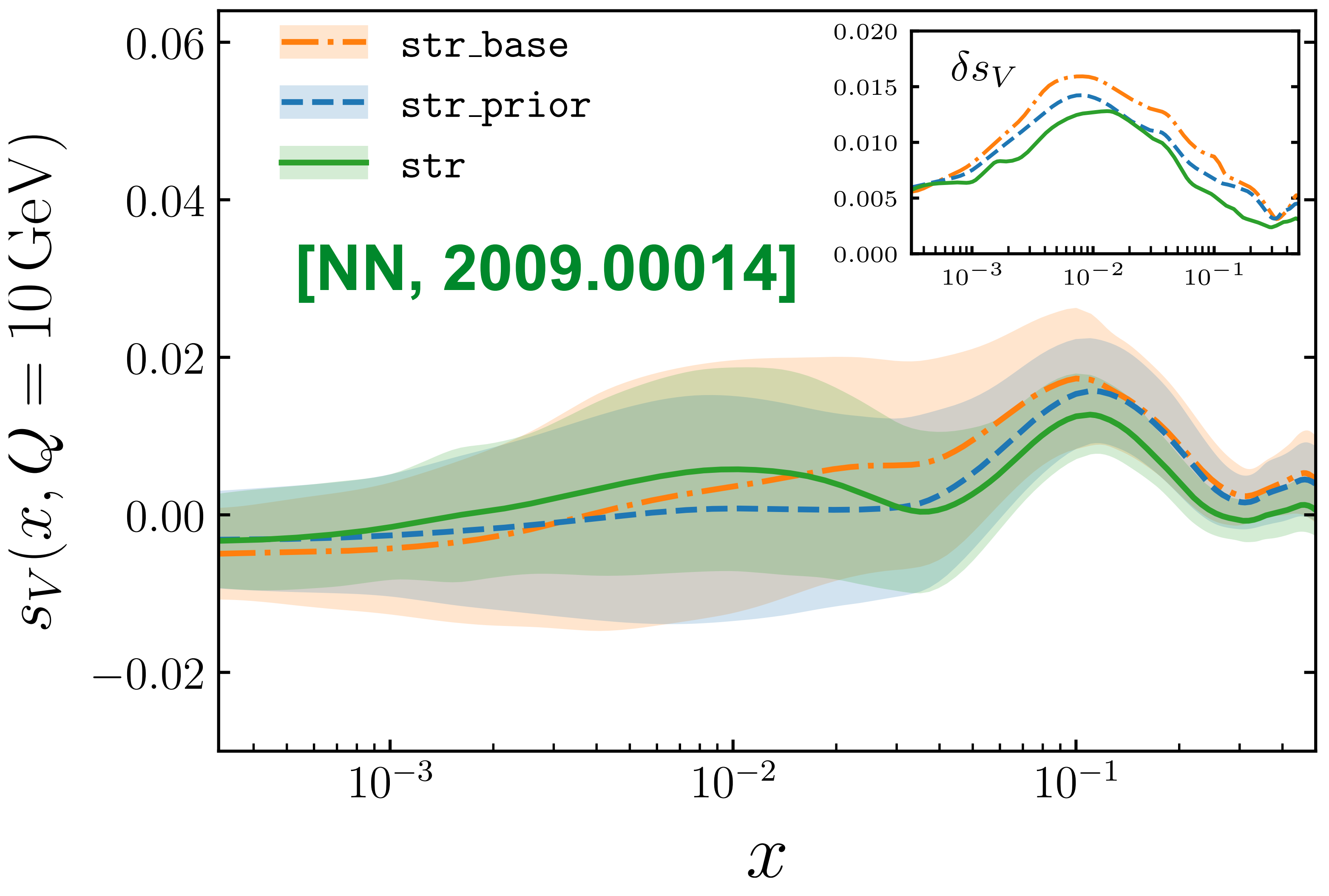
- In CT, NOMAD prefers larger s-PDF comparing to NuTeV and CCFR dimuon; leads to increase of Rs, from 0.5 to 0.7; reduction of PDF uncertainty of about 30%
- see [ABMP16, 1701.05838; NN, 2009.00014] as well for impact of NOMAD data

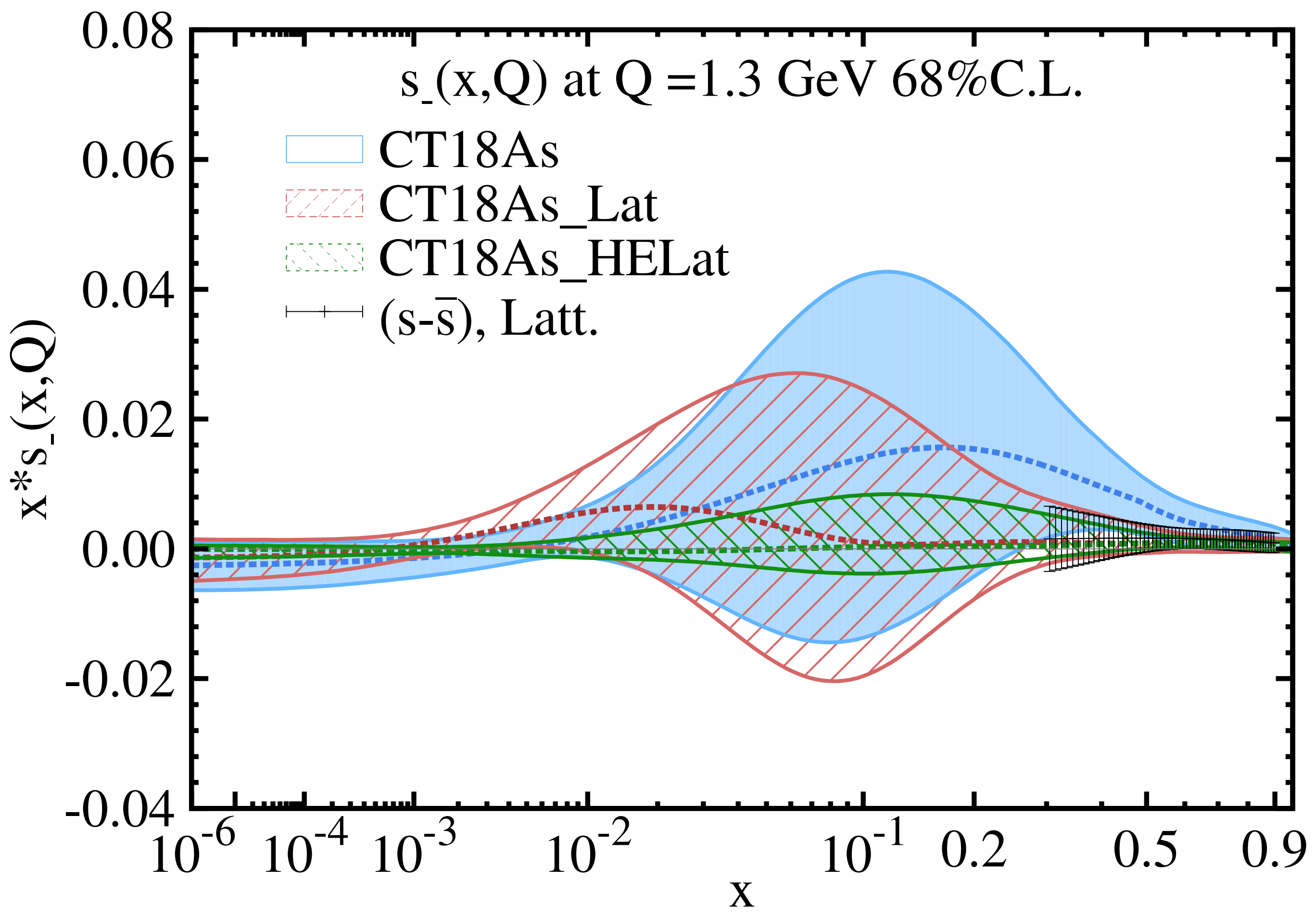
Strangeness asymmetry

- Strangeness asymmetry (s-sbar) is loosely constrained by dimuon data from NuTeV and CCFR, and W/Z data at the LHC which prefer s-sbar > 0 at x about 0.1; lattice inputs can potentially play an import role





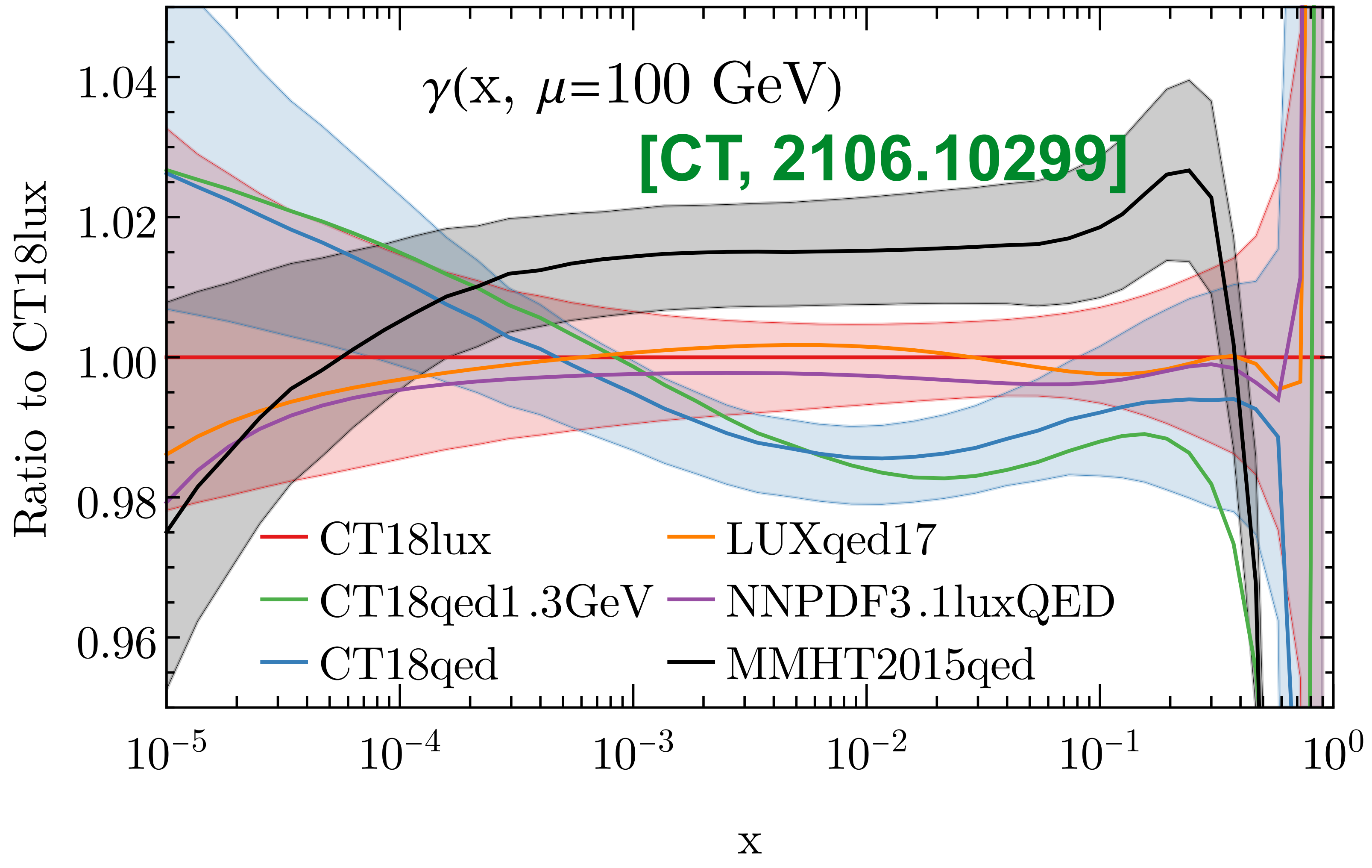


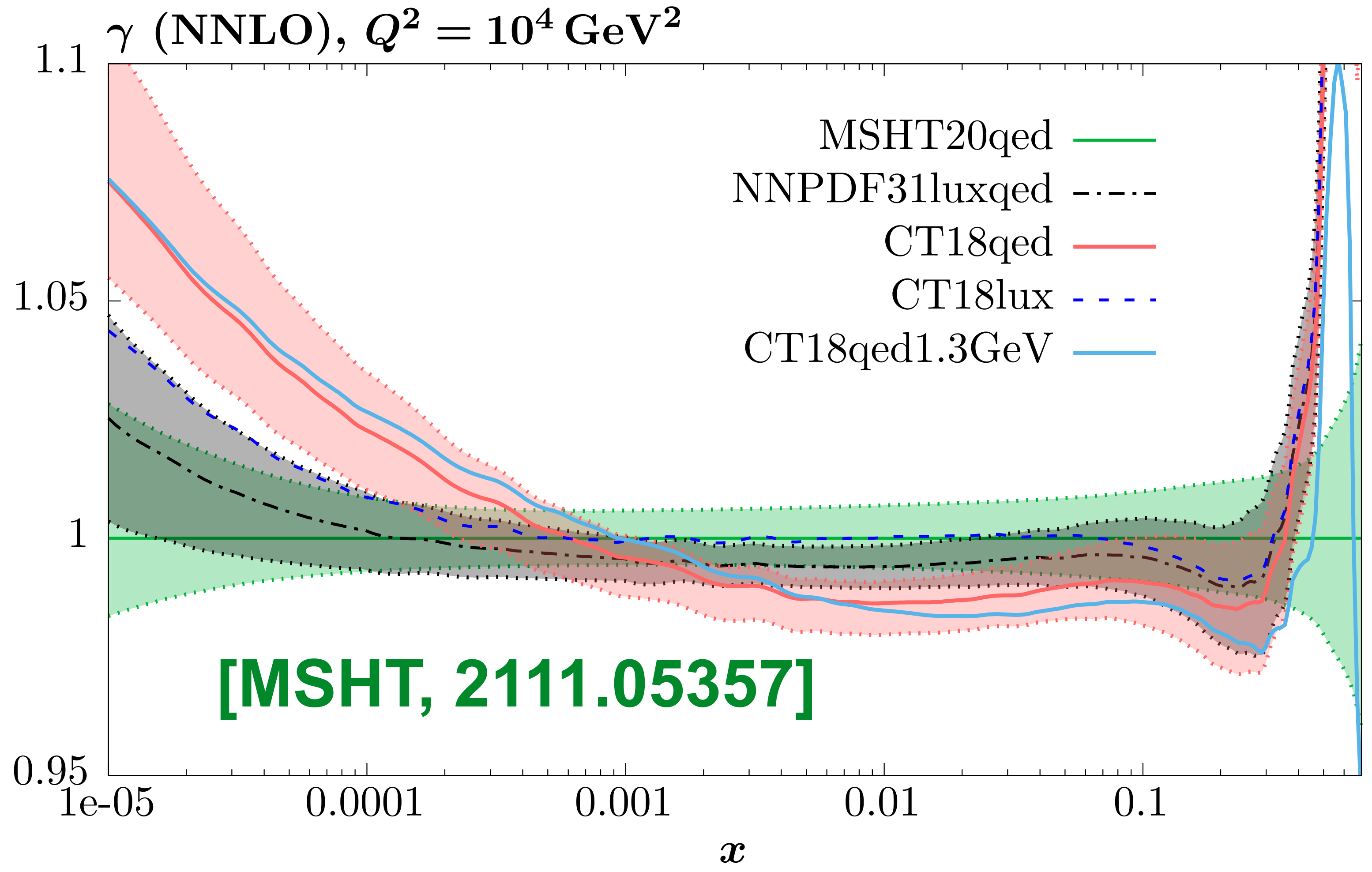


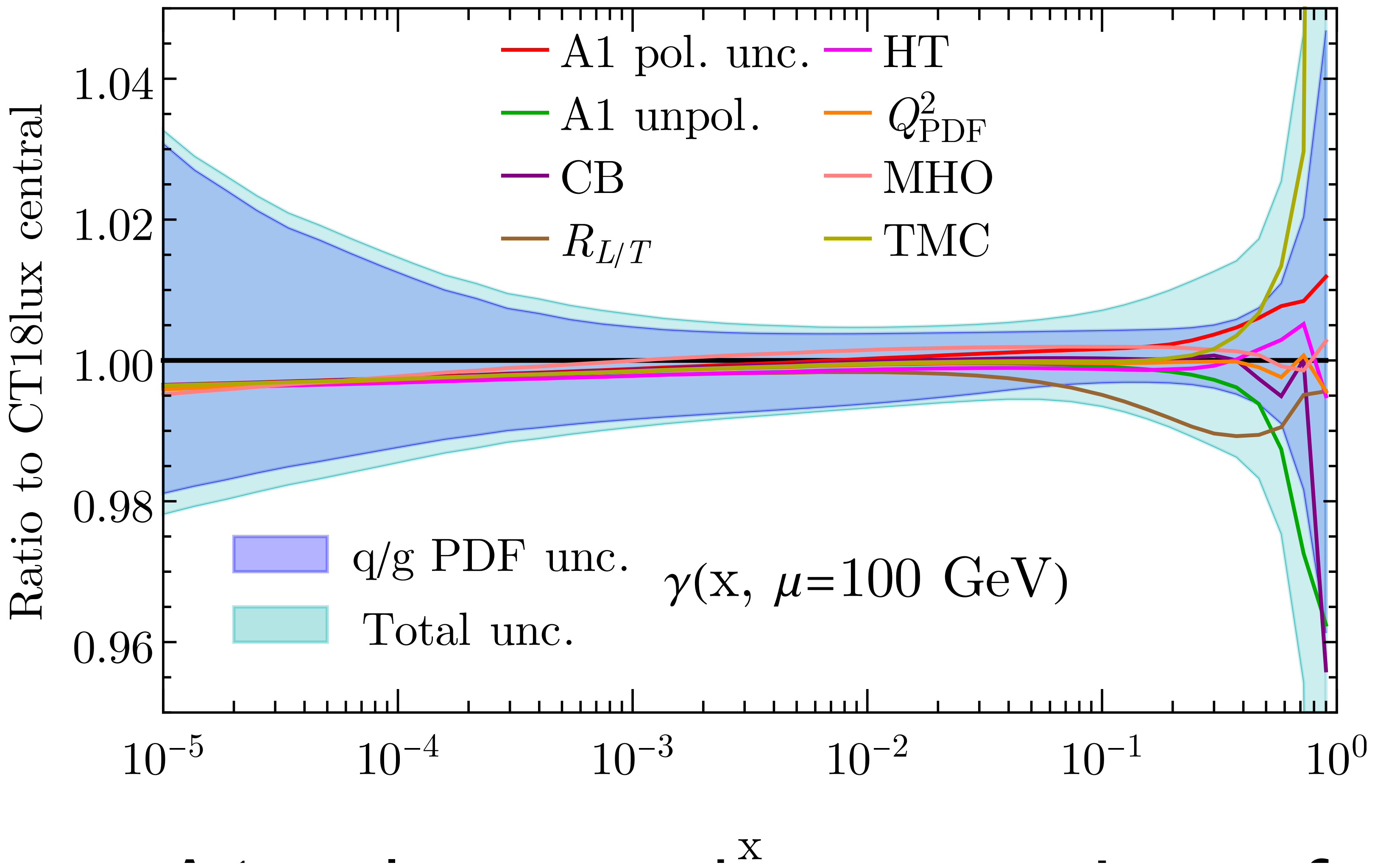
- parametrization with strangeness asymmetry has been revested in CT18As; relieve tensions to ATLAS W/Z data; prefer positive s-sbar at x~0.1 but with large uncertainties
- MSHT, NNPDF and CT18As show similar shape on the central prediction, with MSHT and NNPDF clearly indicate s-sbar>0 at x~0.1 at 2σ level
- lattice inputs from MILC (MSU) collaboration indicate a compatible constraint consistent with s-sbar=0 at x>0.3

Photon PDF

- The photon PDF inside proton is required for a consistent treatment of QED effects; the original LUX approach has been applied in most recent global fits and resulted in very consistent photon PDF





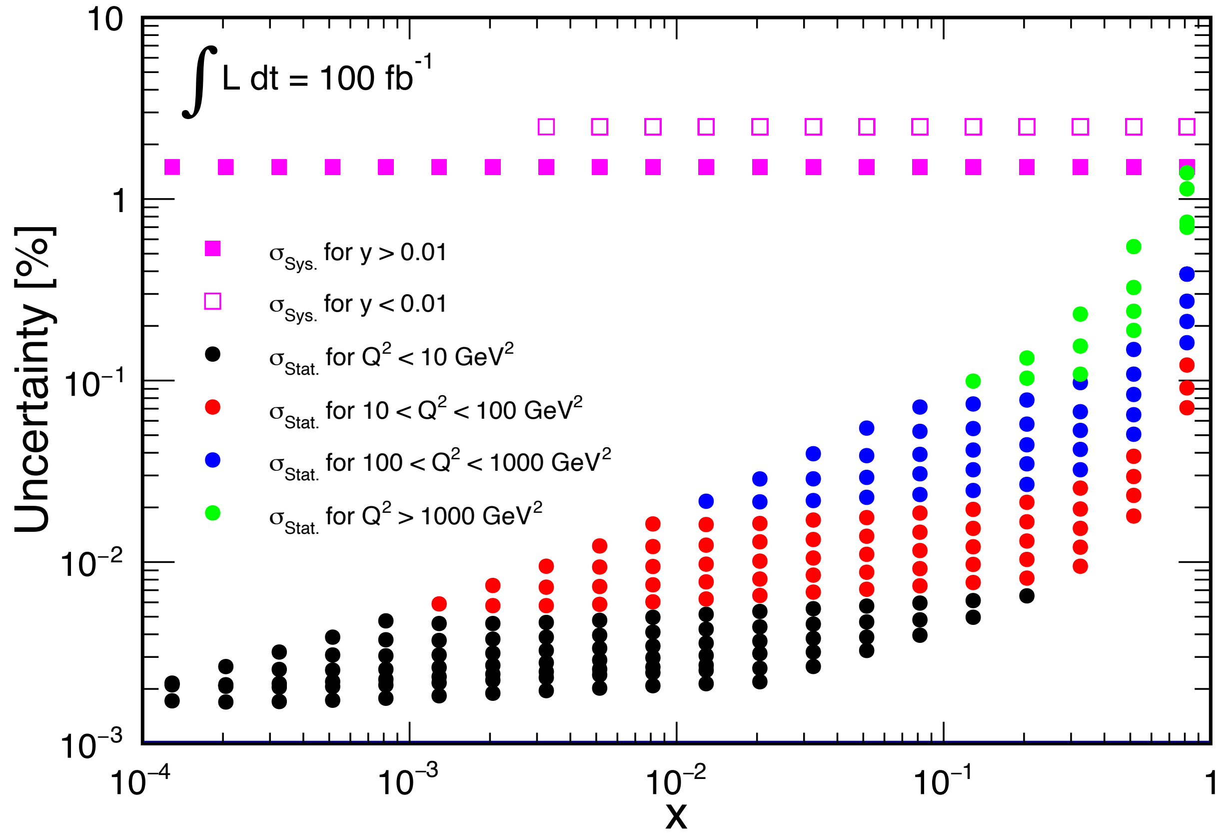


- CT18lux calculate the photon PDF at all scales; CT18qed initializes photon PDF at Q_0, and evolve to high scales; differences reflect sys. effects of matching

- MSHT20qed supersedes previous MMHT15qed, in good agreement with CT18 and NNPDF3.1luxqed

Future DIS experiments

- The EIC/EICc will provide significant PDF constraints through precision QCD measurements in the quark-hadron transition region; LHeC would provide high-impact TeV-scale DIS data

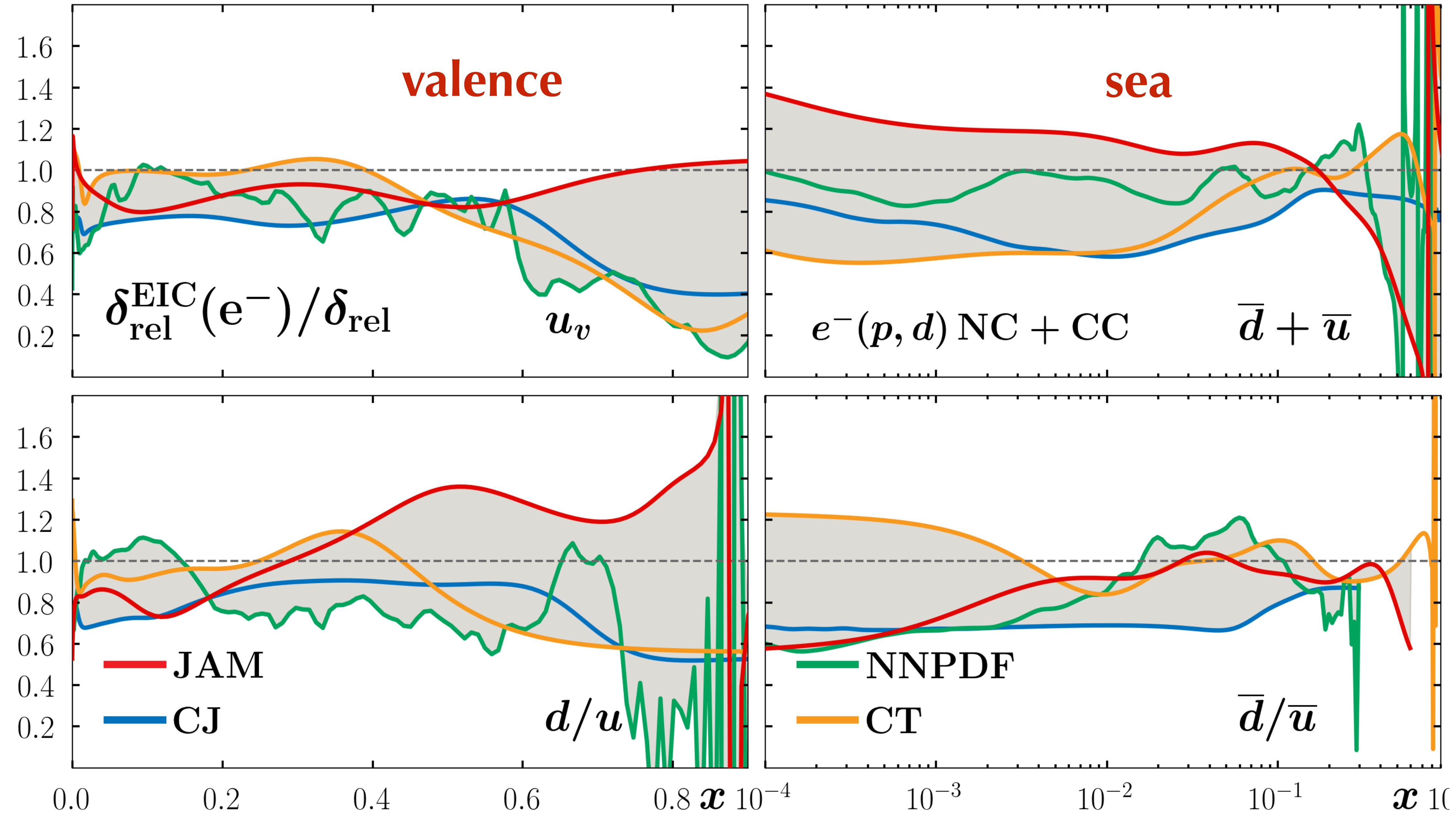


EIC projection

Left: exp. uncertainties

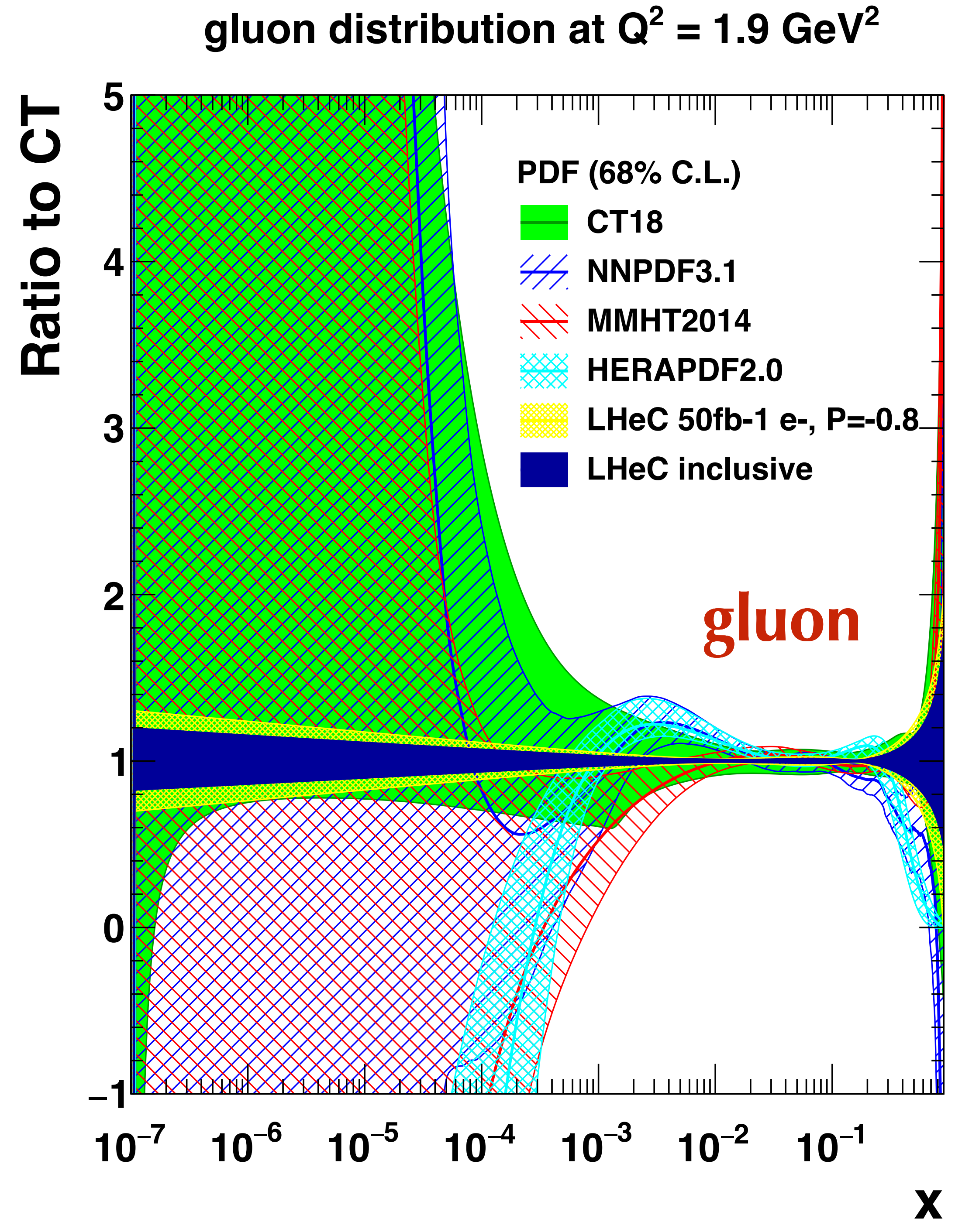
Bottom: impact of e-p(d) inclusive NC/CC DIS pseudodata

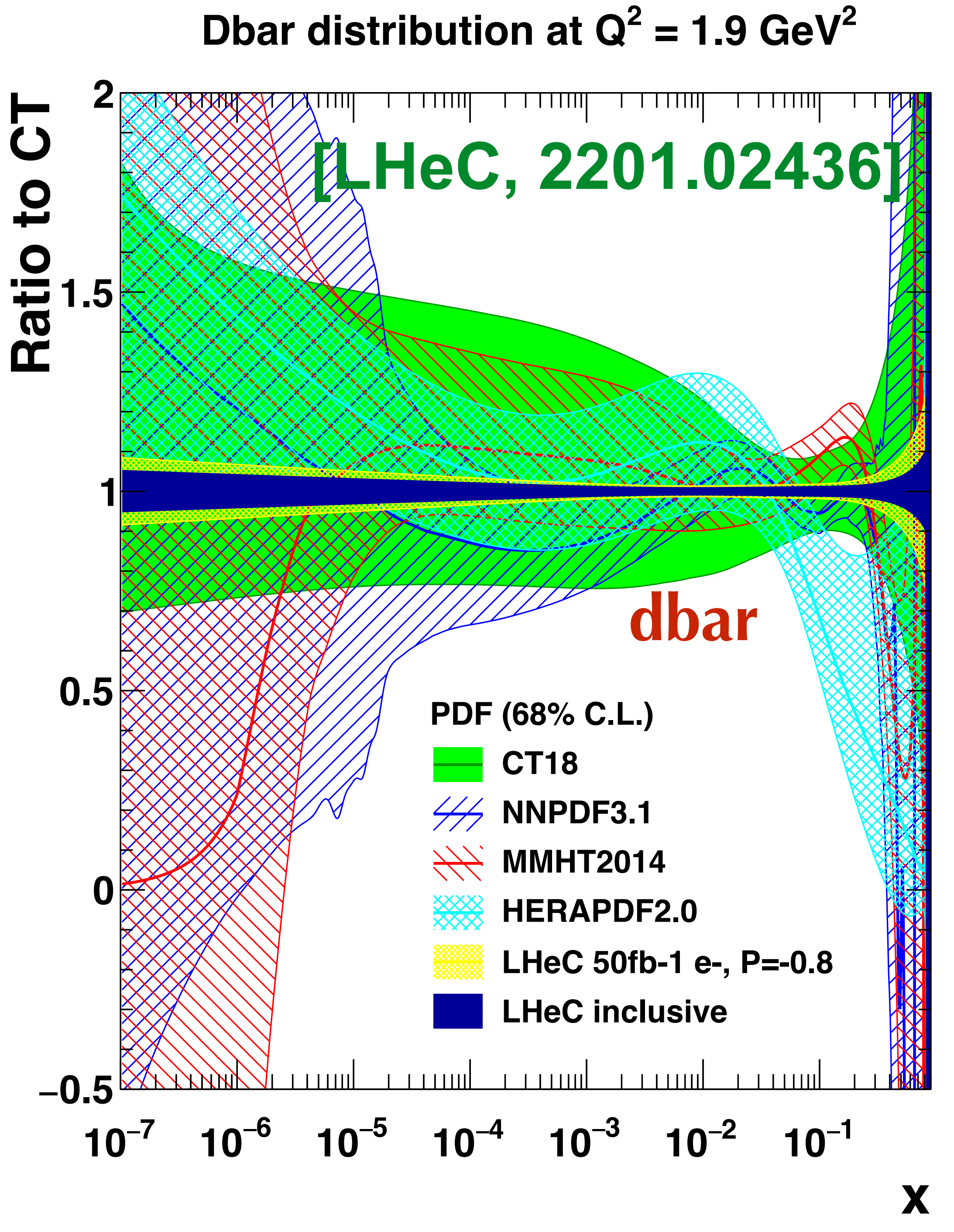
[EIC, 2103.05419]



LHeC projection

Parameter	Unit	D1	D2	D3	D4	D5	D6	D7	D8	D9
Proton beam energy	TeV	7	7	7	7	1	7	7	7	7
Lepton charge		−1	−1	−1	−1	−1	+1	+1	−1	−1
Longitudinal lepton polarisation		−0.8	−0.8	0	−0.8	0	0	0	+0.8	+0.8
Integrated luminosity	fb^{-1}	5	50	50	1000	1	1	10	10	50





Tools and computing

- Development of various PDF related tools are mandatory for modern PDF fits, e.g., grid interpolation techniques interfaced with various NNLO QCD, NLO EW, SMEFT computing programs; open source fitting code, xFitter2.0 and NNPDF4.0

Grid interpolation techniques

fastNLO

fast pQCD calculations for hadron-induced processes

the APPLgrid project

PineAPPL

PineAPPL is not an extension of APPLgrid.

Ploughshare

for all your interpolation grid needs

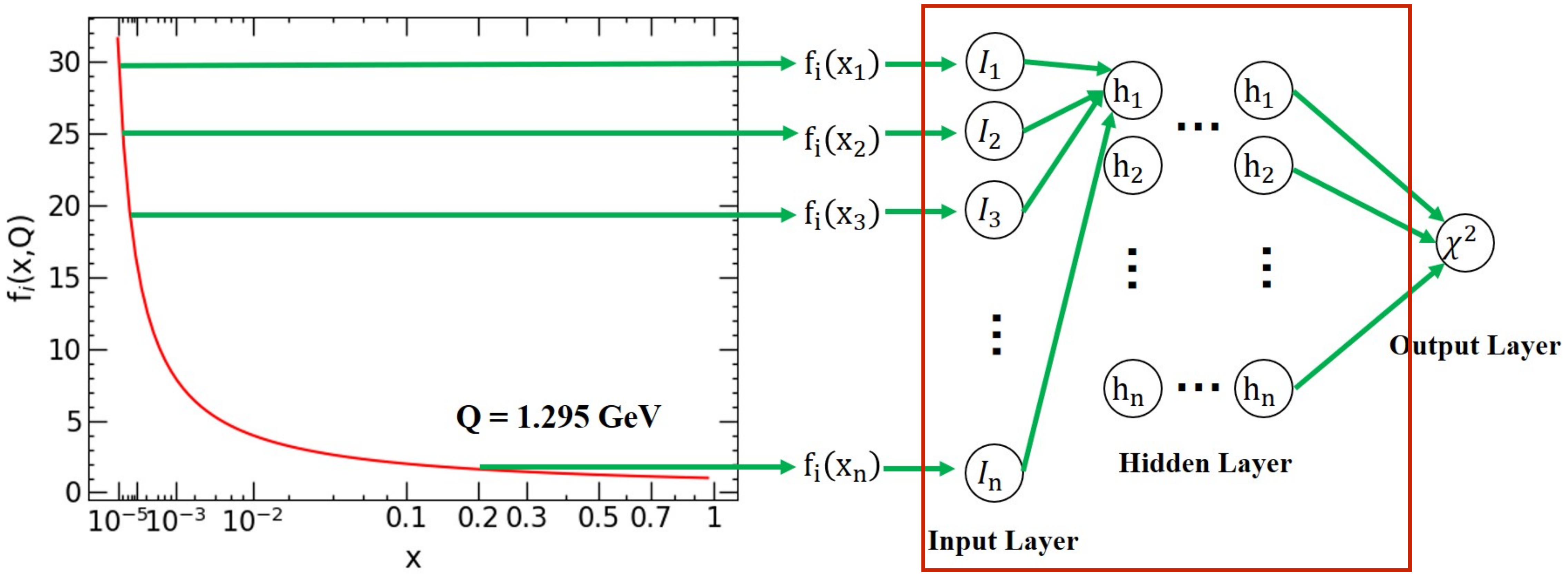
Open source fitting code

xFitter

NNPDF code

The NNPDF software framework is released under an open source
examples. The code base is composed by a PDF fitting package, t

ML on PDF-dependent variables [CT, 2201.06586]



Summary

- Global analyses of parton distributions demonstrate great success of QCD and on understanding internal structures of proton, and phenomenologically become more and more prominent for electroweak precision test and searches for new physics at the (HL-)LHC

- LHC delivers plenty of PDF sensitive data with high statistics and with theory evaluated almost all at NNLO; some of the N3LO calculations are already available; however, an advance on the treatment of the LHC experimental systematics and methodologies of PDF determinations can be crucial

- With the global efforts from many groups, we are gradually approaching PDFs precision of a few percents; while LHC-independent inputs on PDFs, for instance from future DIS experiments or lattice QCD simulation with improved precisions will be highly valuable

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[Snowmass 2021 PDF white paper, 2203.13923]

NEW TASKS in the HL-LHC ERA:

Obtain complete N2LO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast N2LO interfaces	Estimate N2LO theory uncertainties	New methods to combine PDF ensembles, estimate PDF uncertainties, deliver PDFs for applications

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Thank you for your attention!