# Implications of Parton Distributions for W boson production and searches of New Physics

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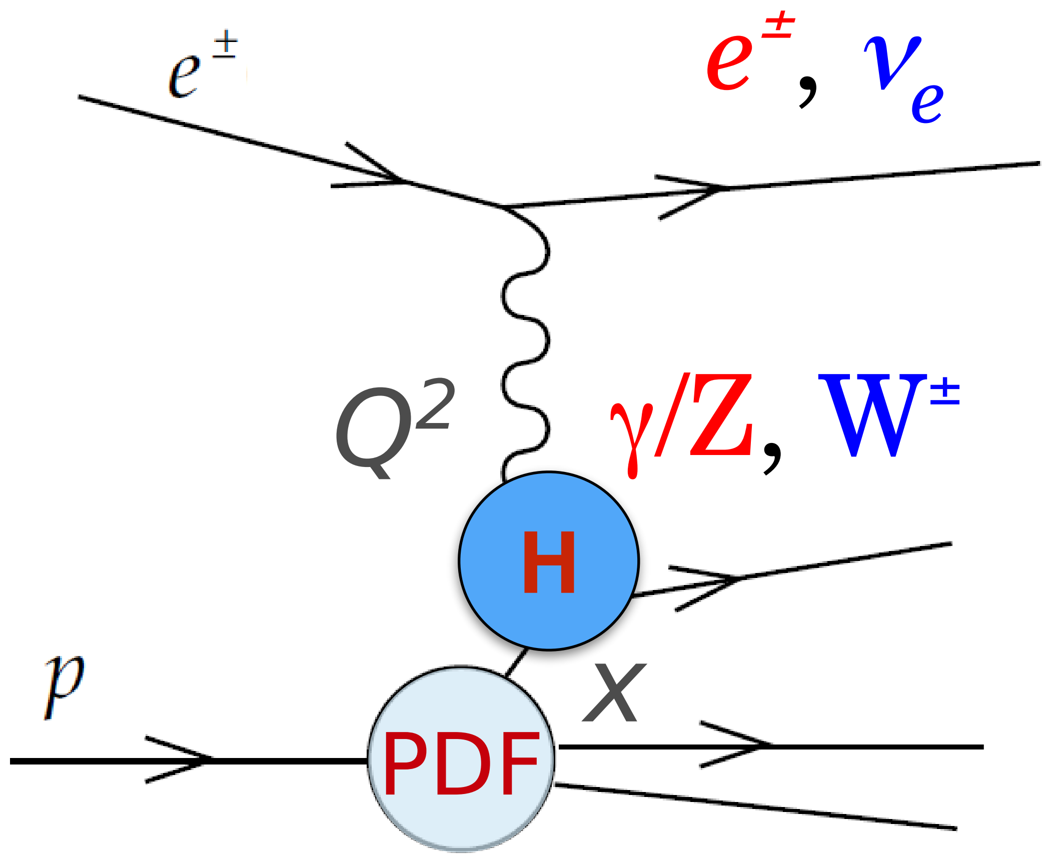
# Outline

- 1. Introduction to PDFs for LHC
- 2. A framework of Global analysis boosted with machine learnings and applications
  - Understanding PDF uncertainties in W mass direct measurements
  - Implications of PDF for searches of new physics at the LHC
- 3. Summary

# 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 of cross sections at LHC

**DIS structure functions**

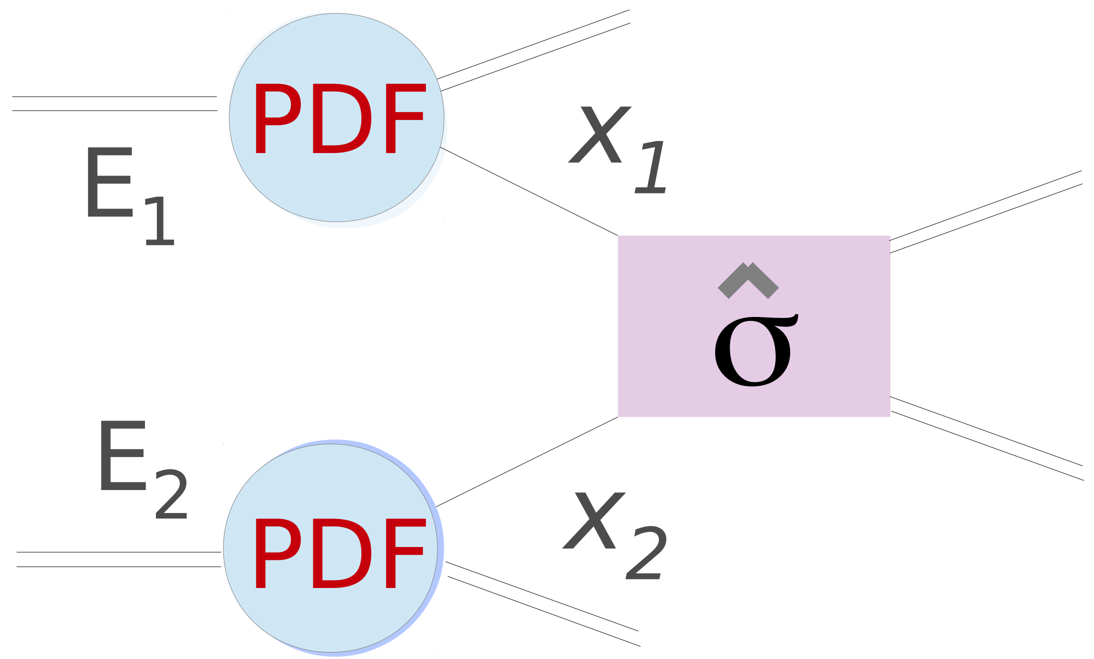



$$F_2(x,Q^2) \;=\; \sum_{i=q,\bar{q},g} \int_0^1 d\xi\, C_2^i(x/\xi, Q^2/\mu_r^2, {\mu_f}^2/\mu_r^2, \alpha_s(\mu_r^2)) \times f_{i/h}(\xi, \mu_f)$$

**[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 $\mu_f$
- runnings of $f_{i/h}$ with $\mu_f$ are governed by the DGLAP equation

**hadron-hadron collision**

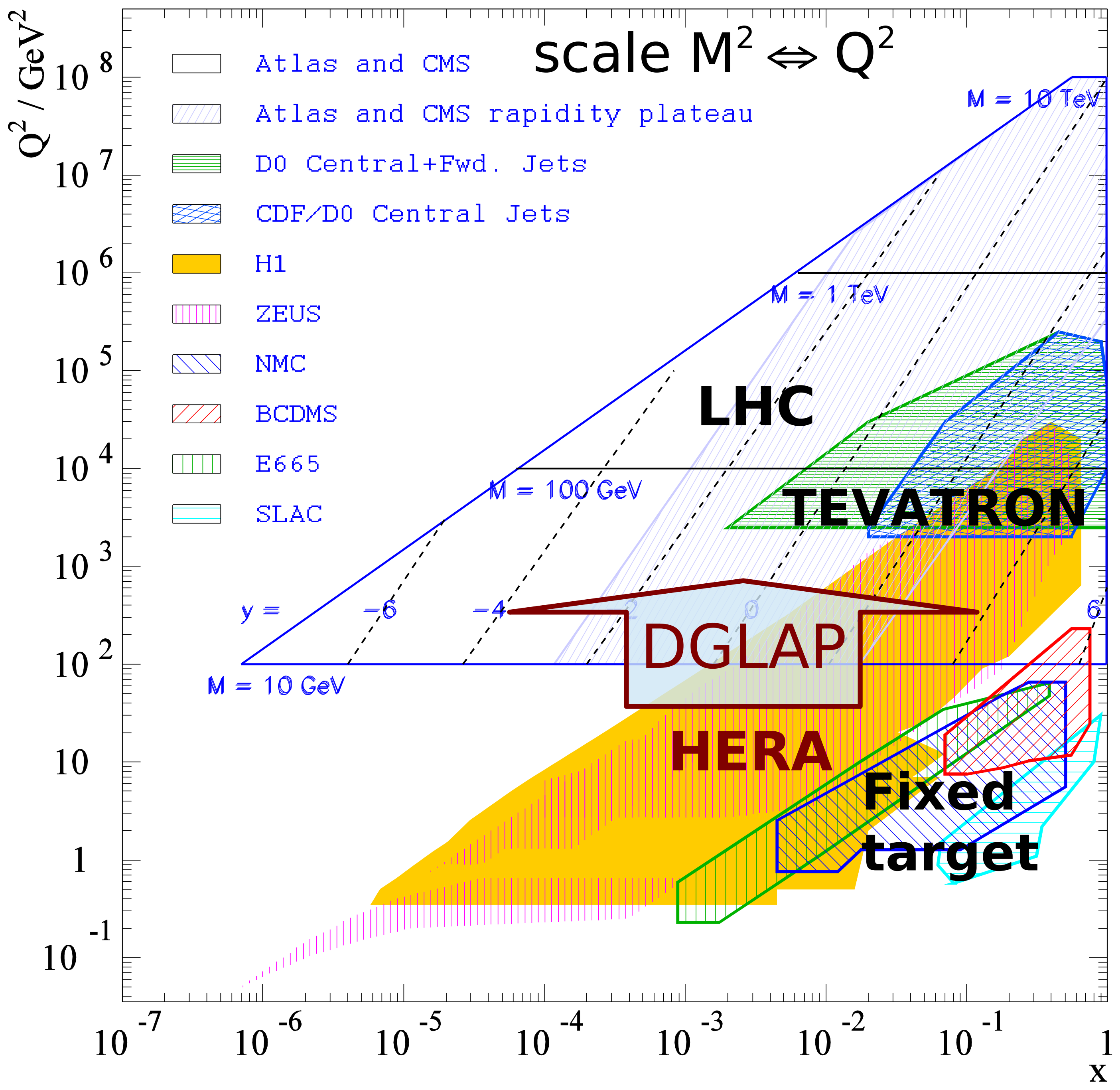


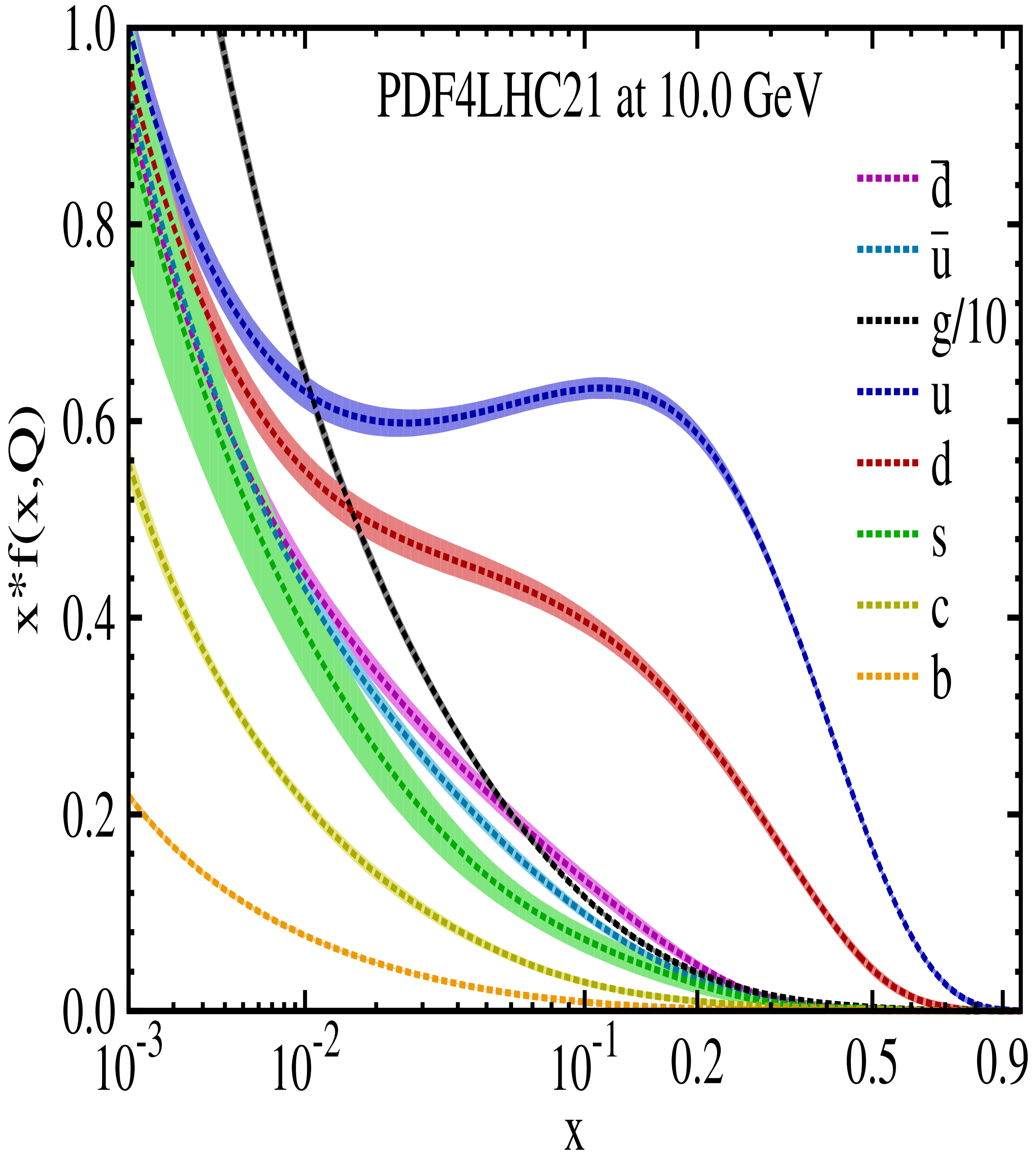

$$\sigma = \hat{\sigma} \otimes f_1 \otimes f_2$$

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 JG, Harland-Lang, Rojo 1709.04922 for review article]**




**parameter variations**

**$\alpha_S$(Mz)**

**Mc, Mb, Mt**

**QCD/EW corrections**

**nuclear corrections**

**EW parameters**

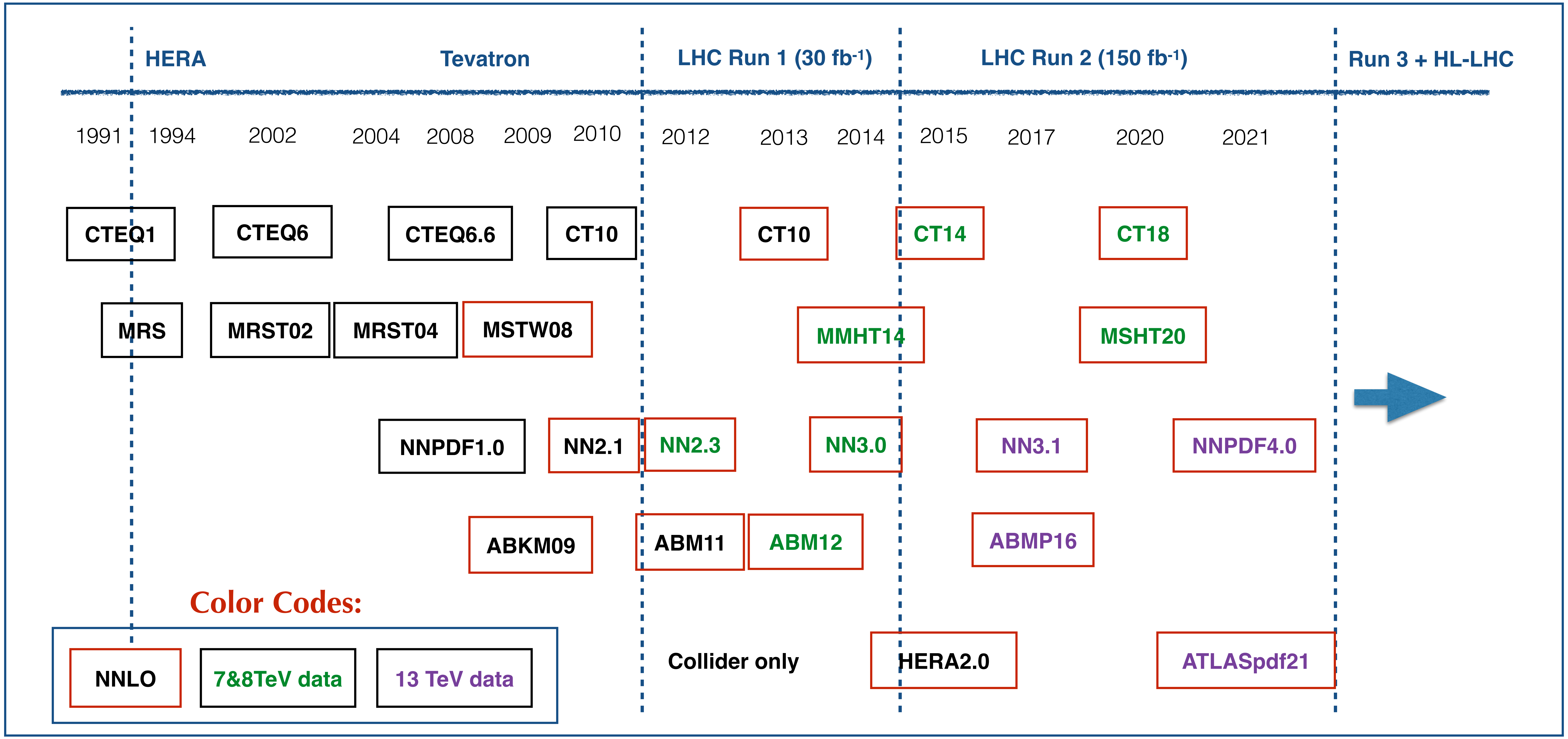
**New Physics**

❖ diversity of the analysed data are important to ensure flavor separation and to avoid theoretical/experimental bias; 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]**

# Major analysis groups

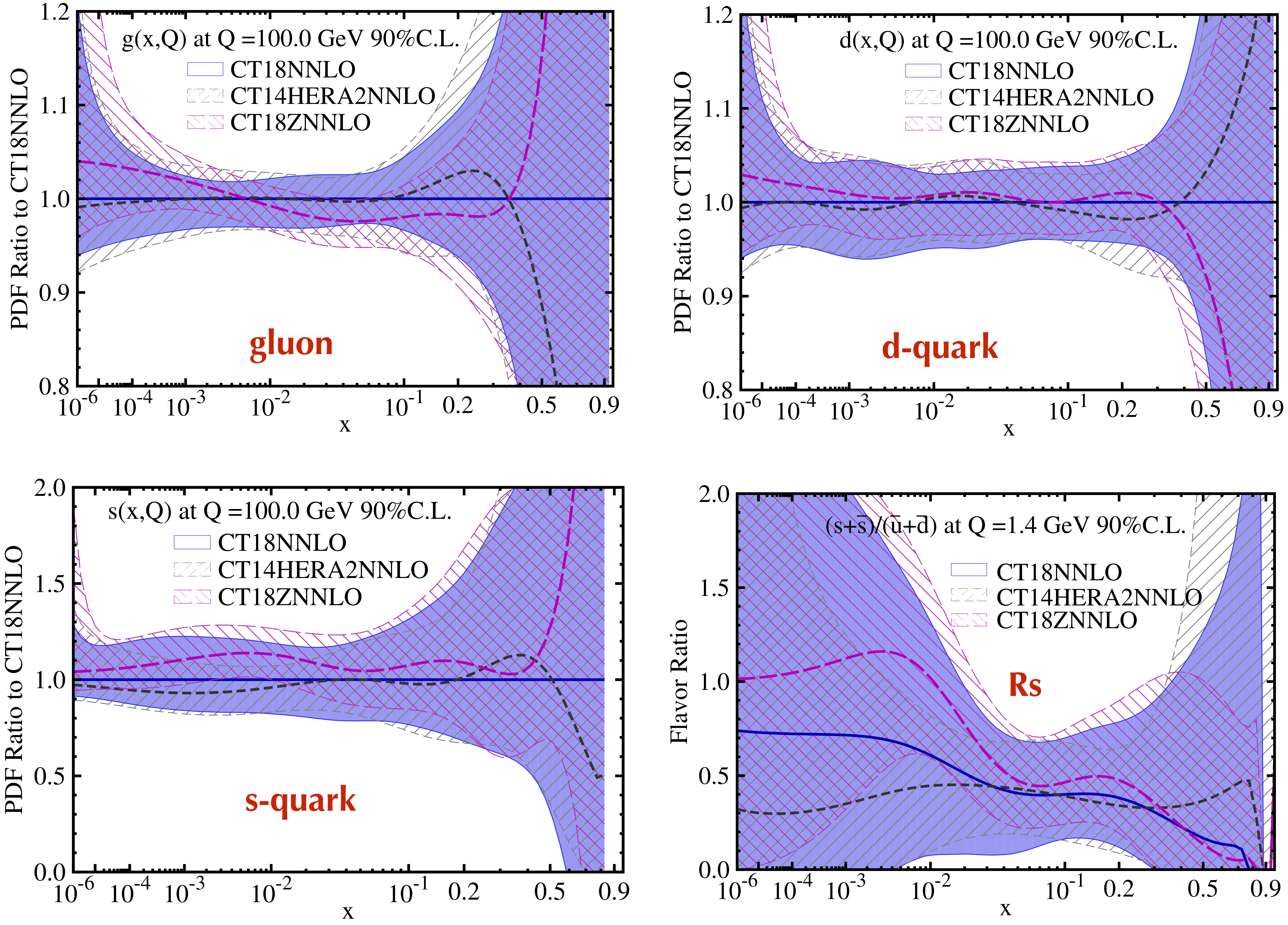
- PDFs provided by several major analysis groups (CT, MSHT, NNPDF, ABM, HERAPDF, ATLASpdf, CJ, JAM…) using slightly different heavy-quark schemes, selections of data, and methodologies




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 (+NLO EW) 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



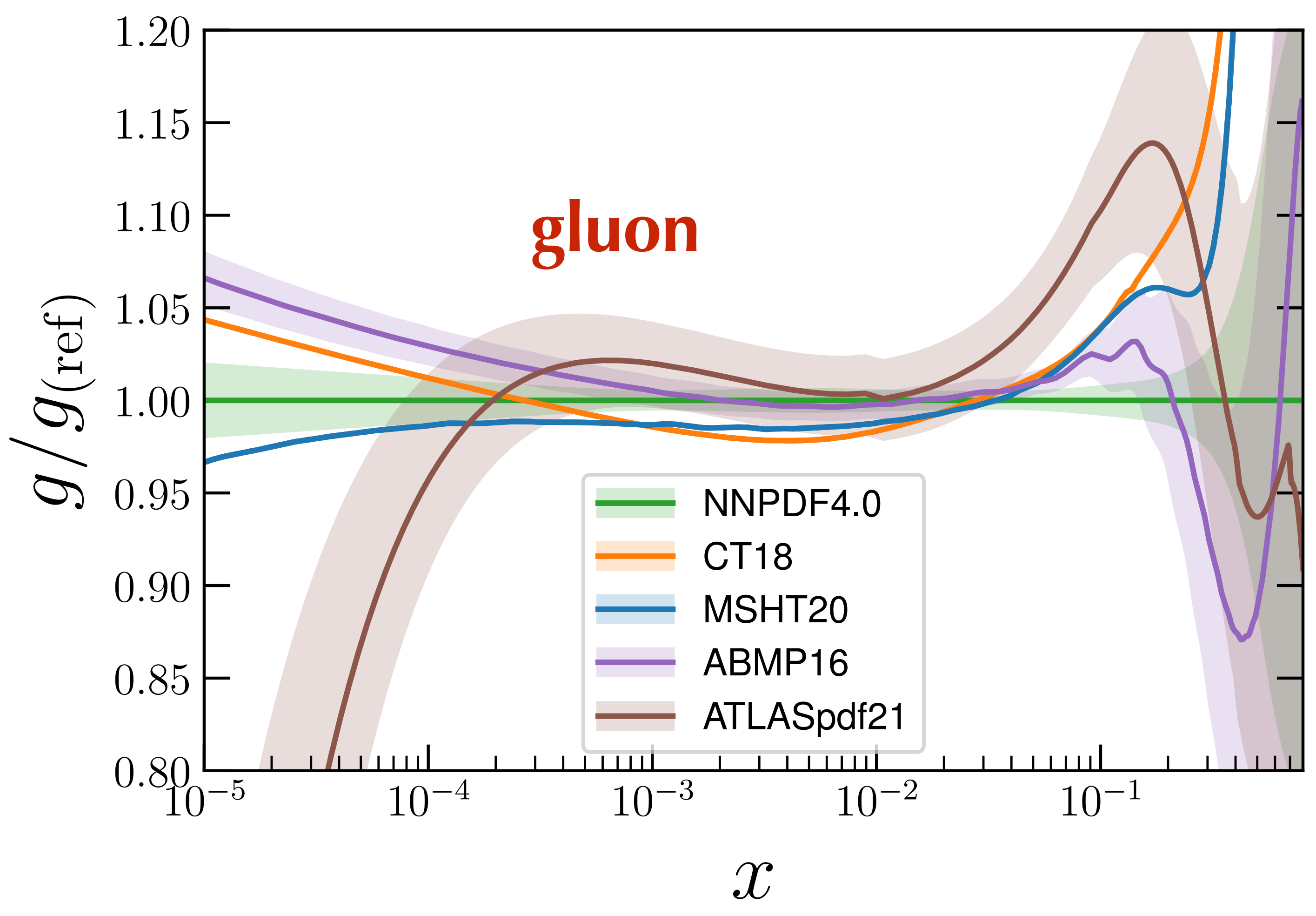

- CT18 vs CT14: gluon unc. reduced everywhere (jets, Z pT, top); d-quark unc. reduced at x~0.2 (LHCb W/Z); s-quark almost unchanged
- ATLAS 7 TeV W/Z data are not included in CT18 fit but in CT18A; CT18X uses a x-dependent scale in DIS to mimic small-x resummations
- CT18Z includes both variations, differences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

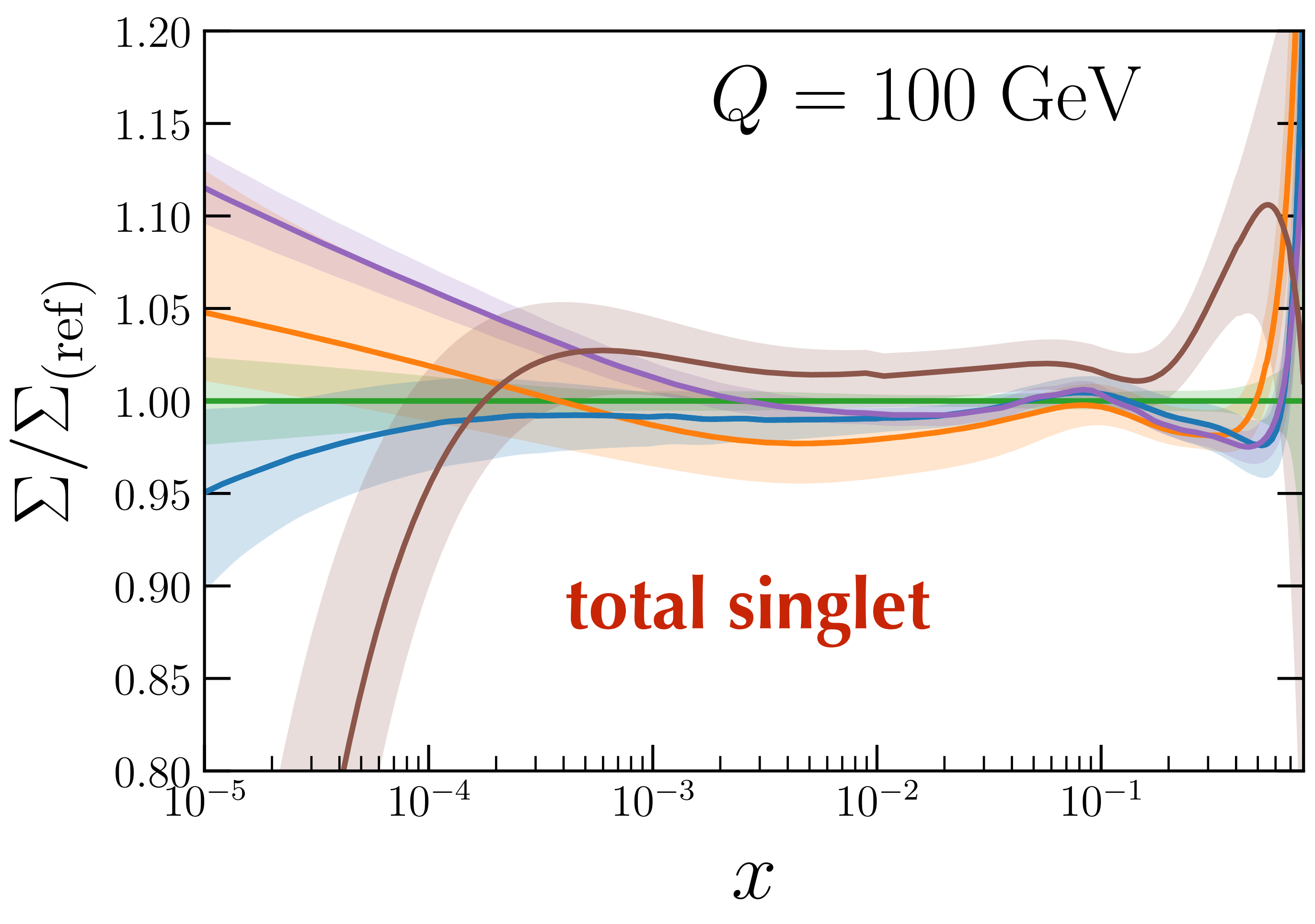
**[CT18, 1912.10053]**

# PDF comparisons

- 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

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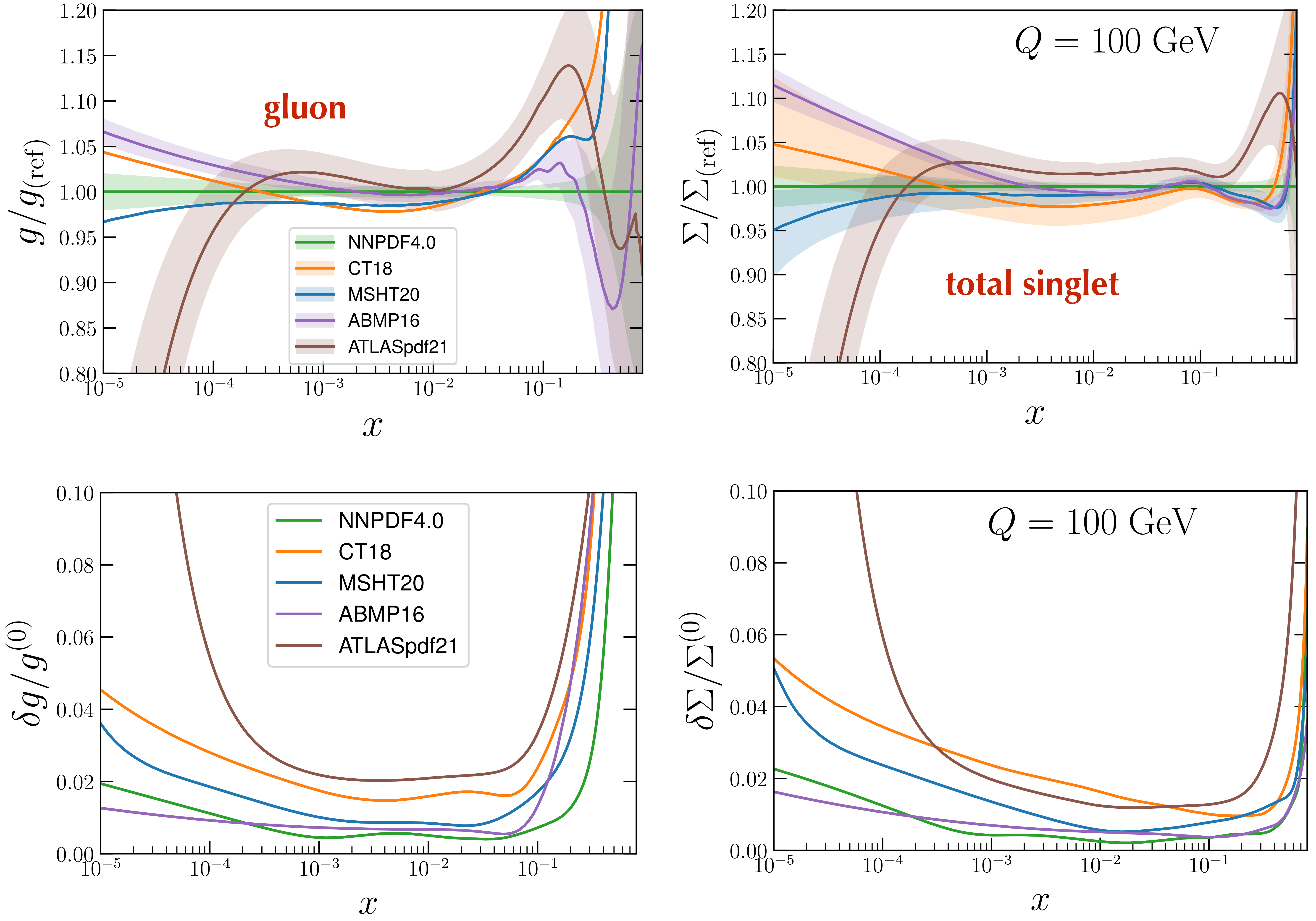


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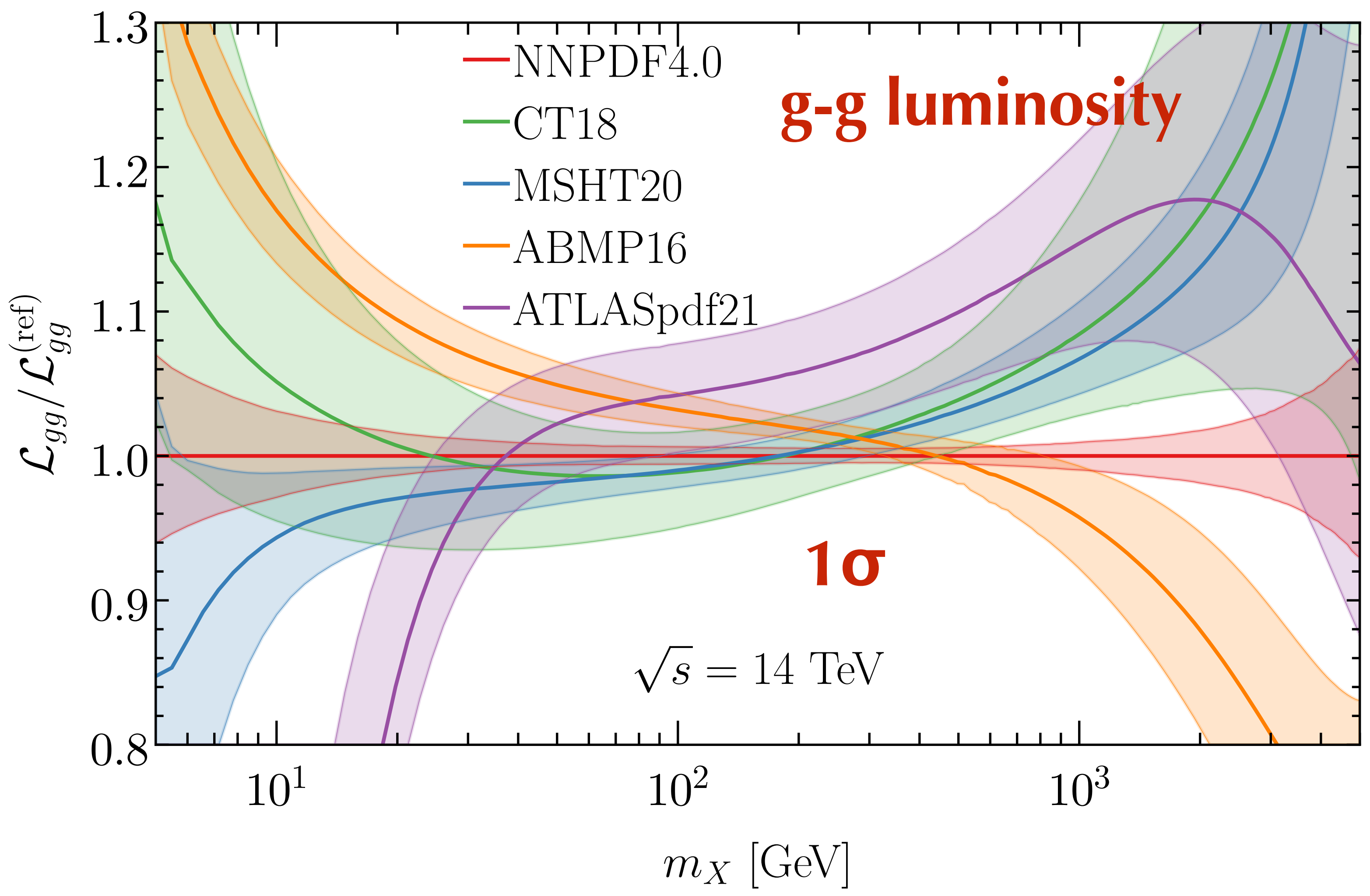
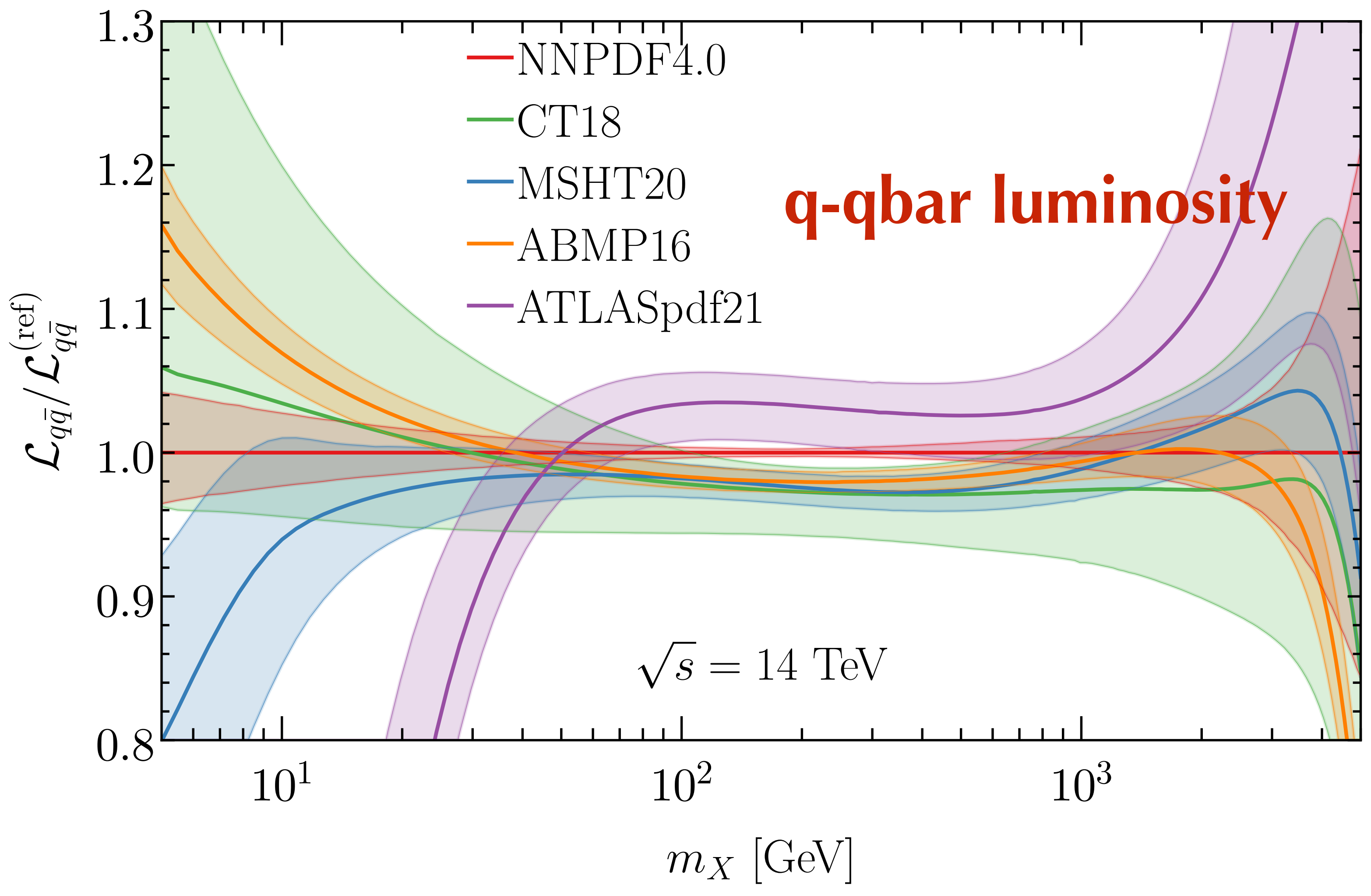
- NN and ABMP show uncertainty of ~1-2% in constrained region mostly due to methodologies; CT18 being conservative among all fits; ATLAS unc. blow up in unconstrained region

# PDF comparisons

- Spread of PDFs from different groups propagates into the parton-parton luminosity or cross sections at the LHC 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

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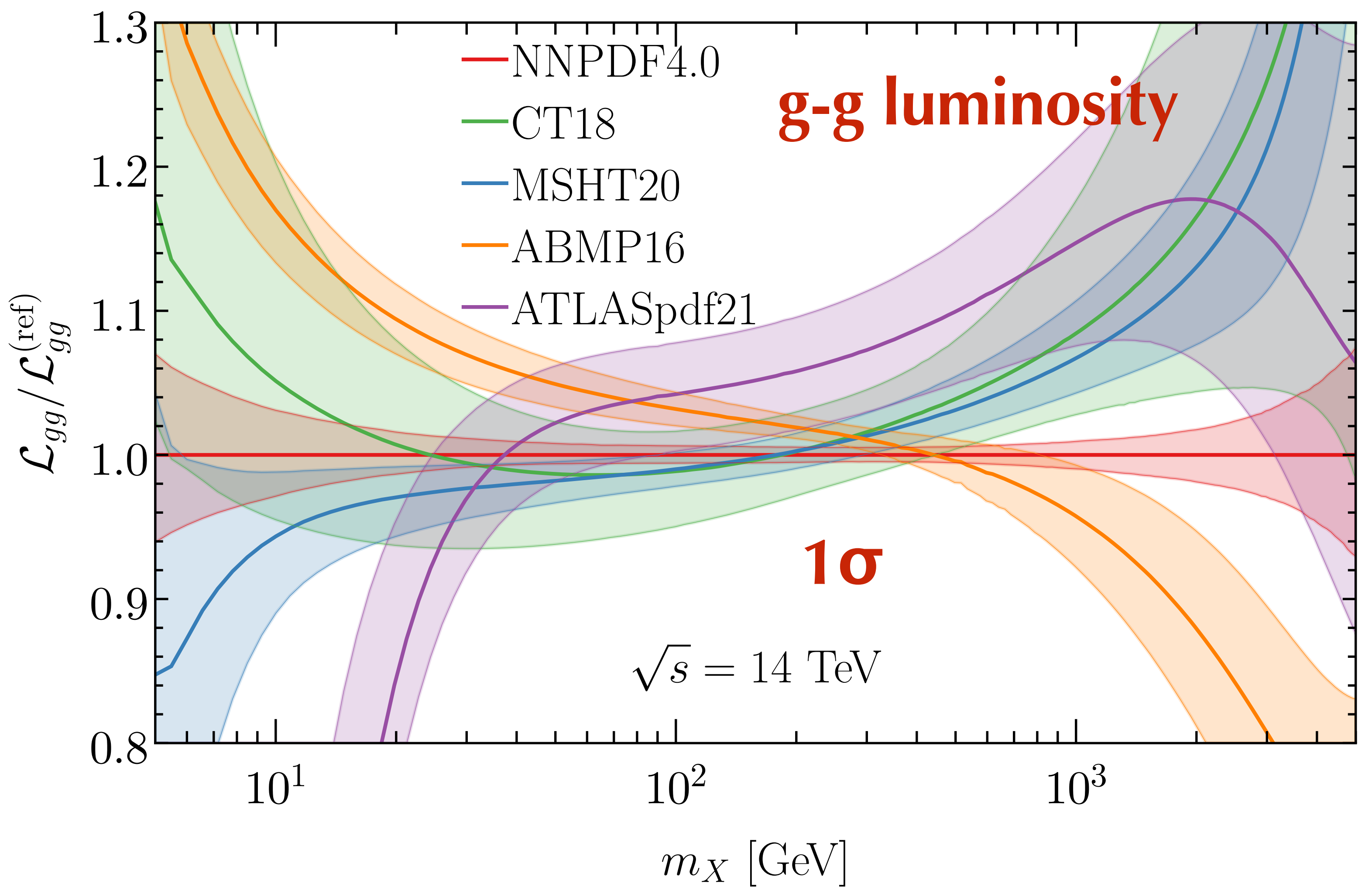
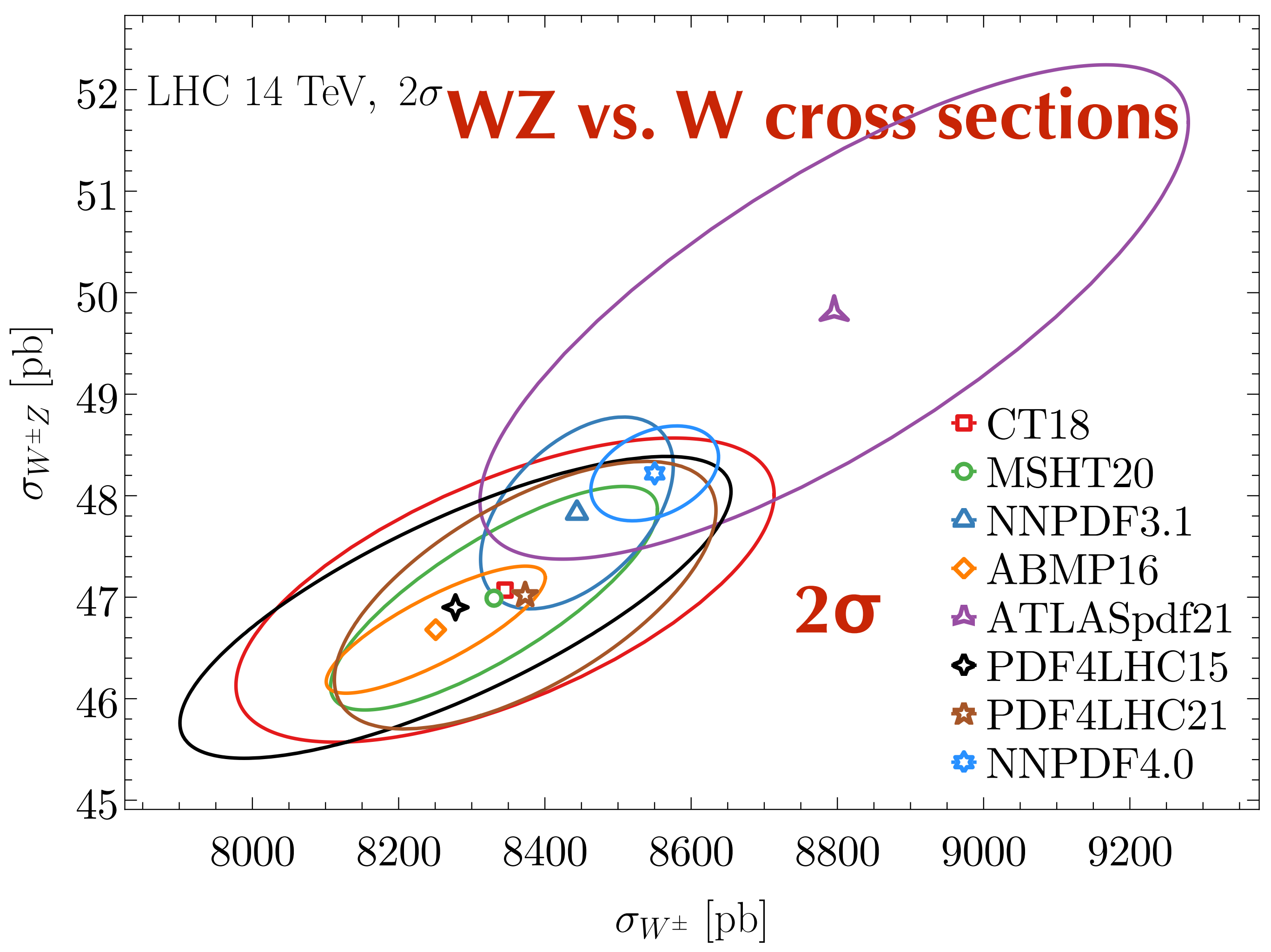
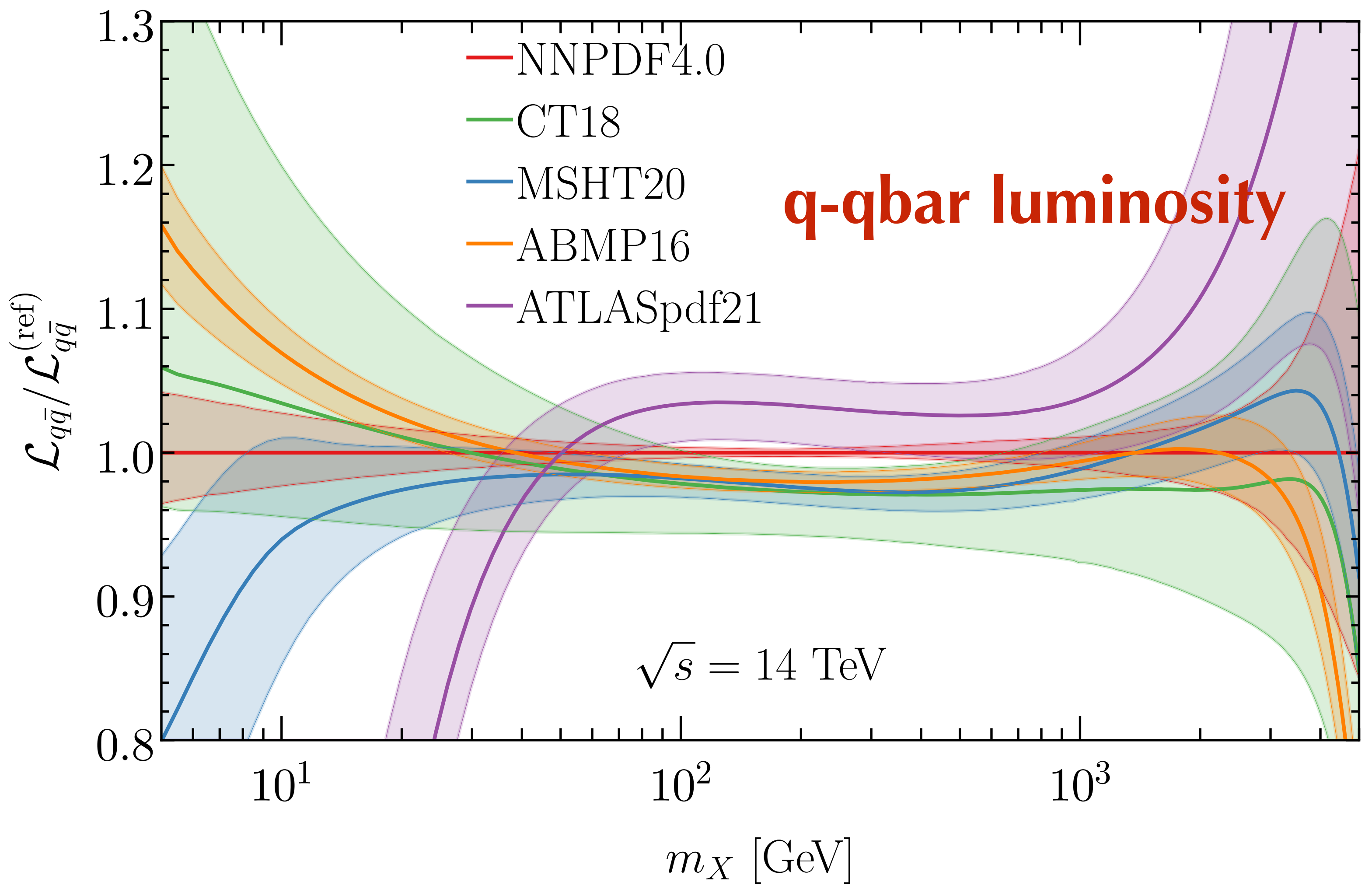
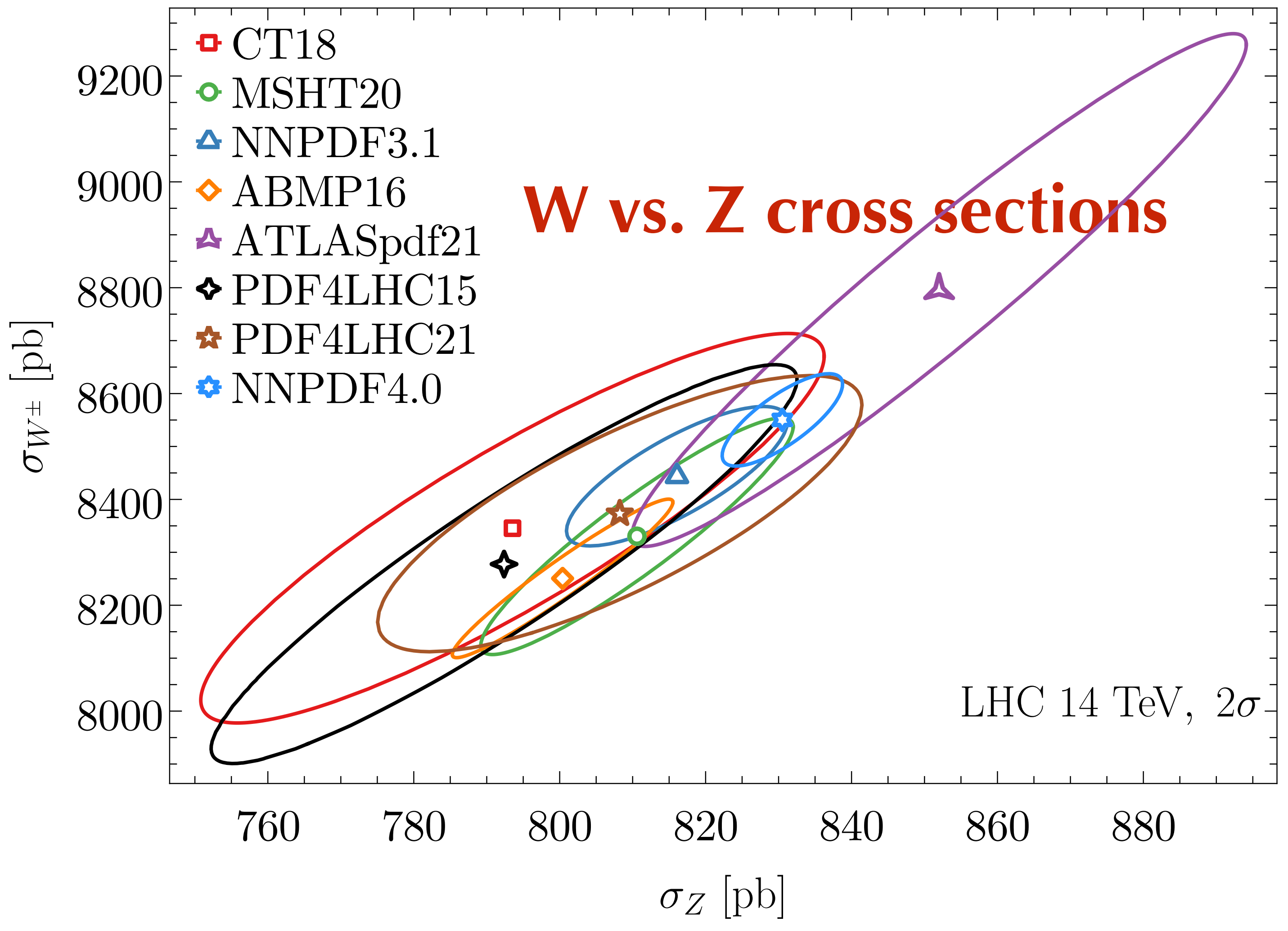


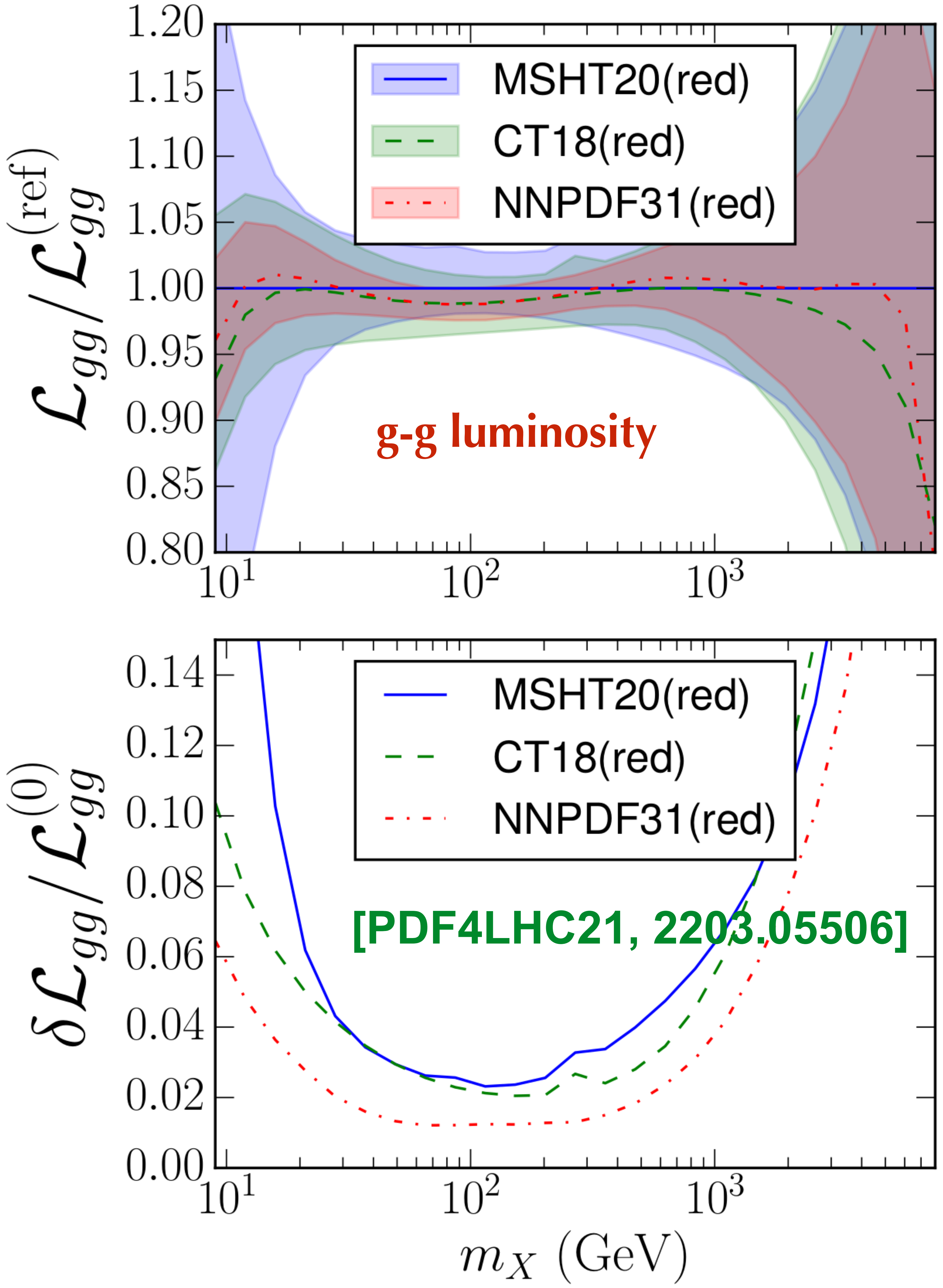

- g-g luminosity shows a spread of more than 20% in the multi-TeVs region; q-qbar luminosity agrees better in general except at a mass around 300 GeV
- 2σ error ellipse shown for cross sections of standard candle processes; NNPDF4.0 shows an uncertainty of less than 1.0% while CT18 2σ ellipse seems to cover most groups

**[Snowmass 2021, 2203.13923]**

# Methodology and uncertainties

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

**PDFs from reduced fits**




- 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 (much) smaller than CT and MSHT as checked explicitly from reduced fits

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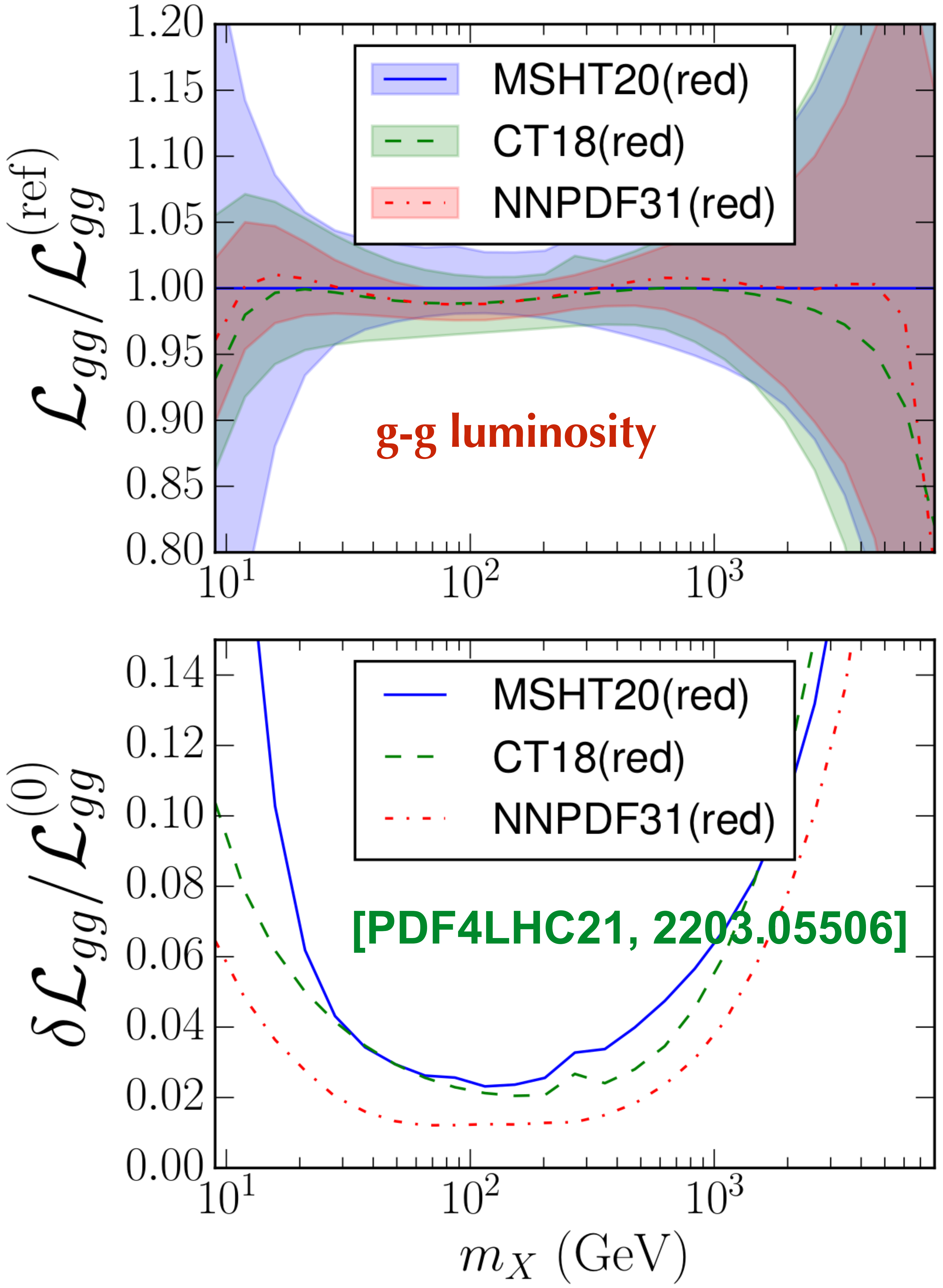
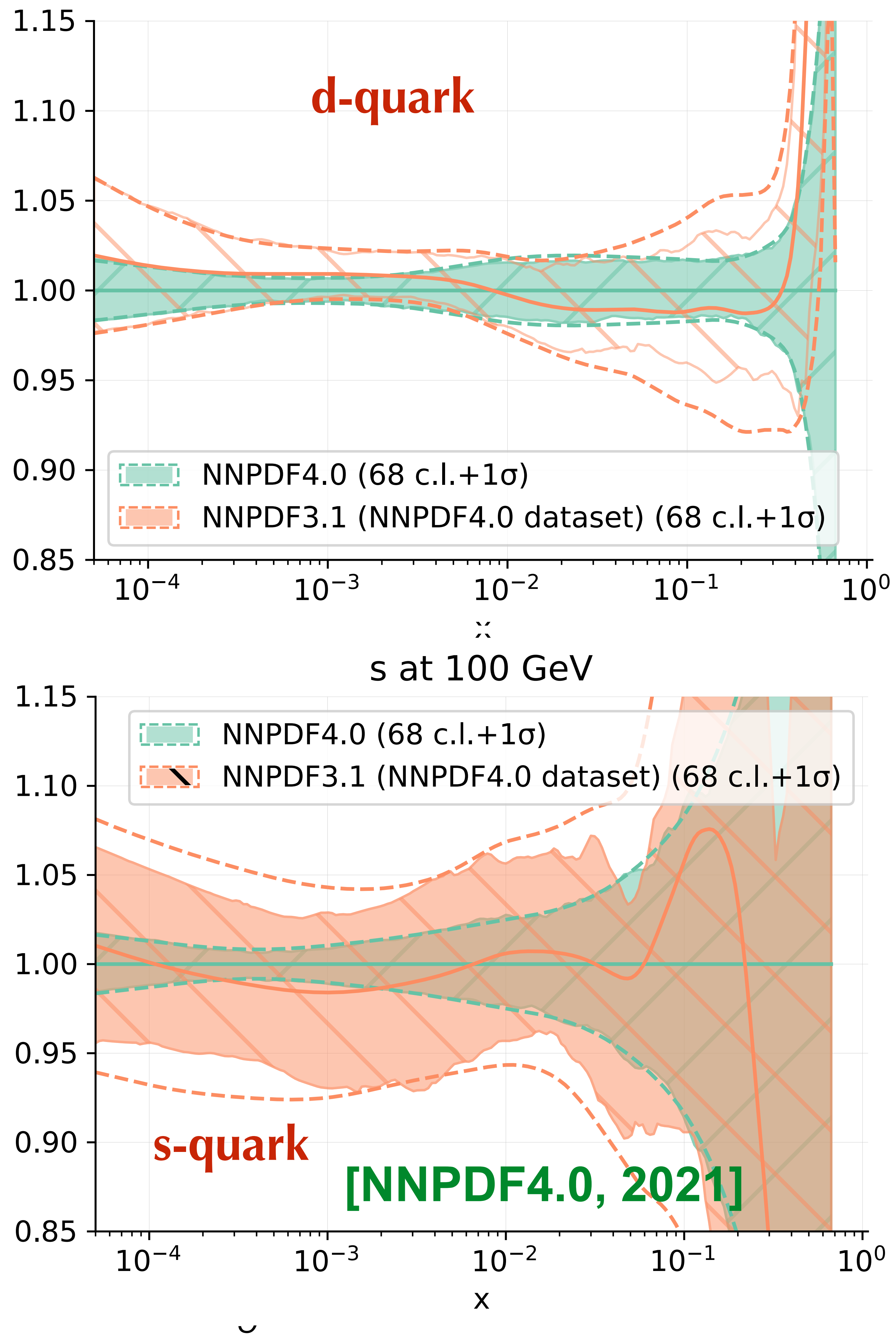



**NNPDF methodology update**




- 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 (much) 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

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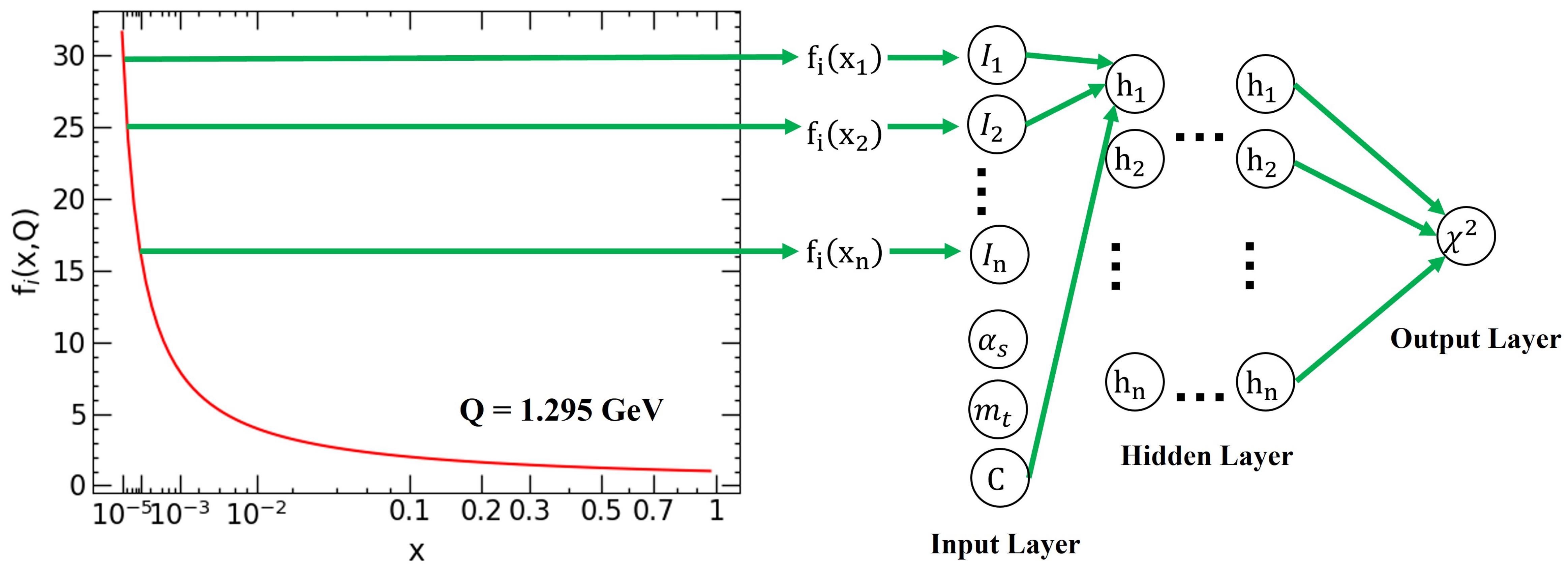
# Global analysis boosted with Machine Learnings

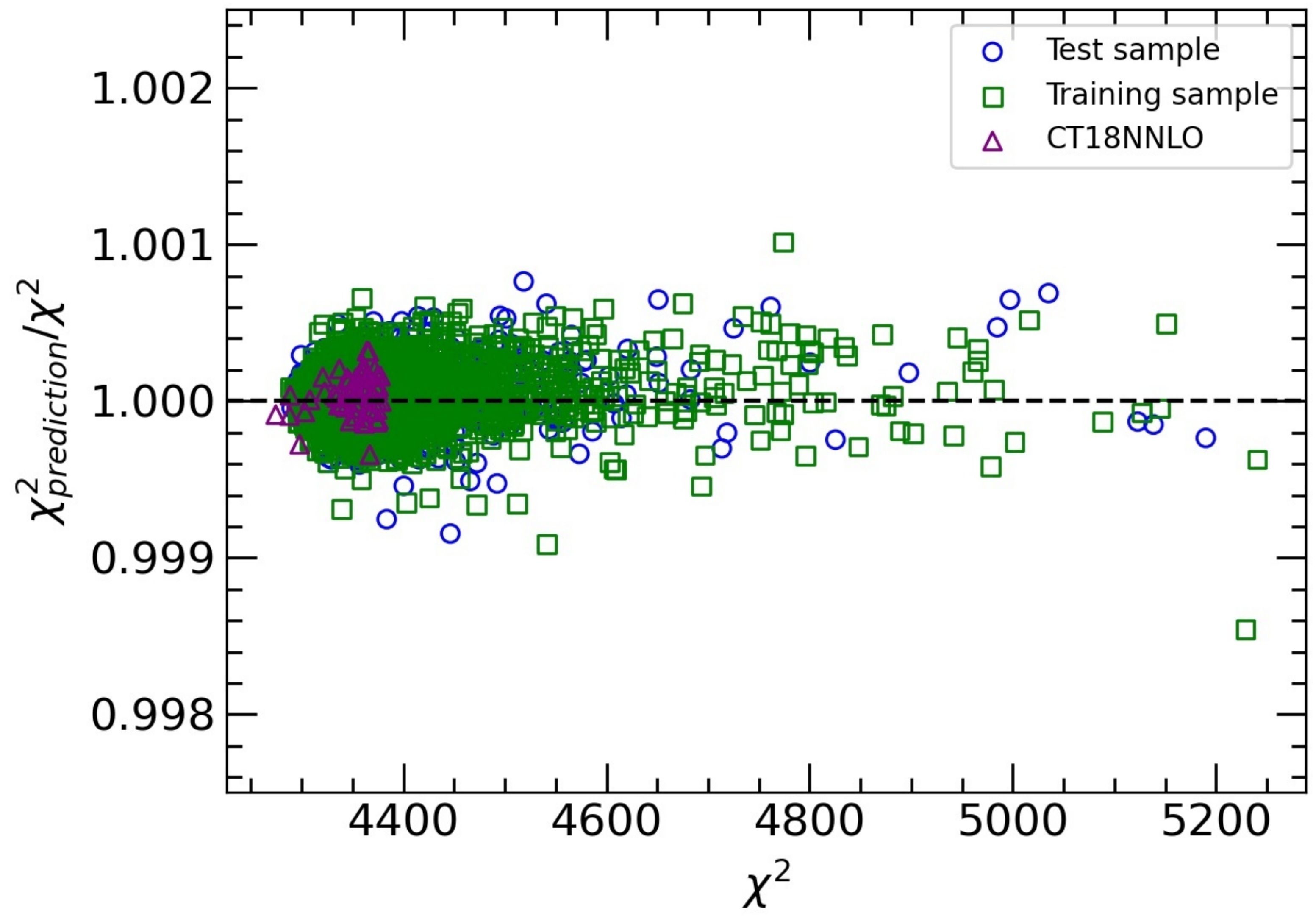
- We developed an efficient framework of using neural networks and machine learnings to modeling dependencies of the log-likelihood functions ($\chi^2$) or cross sections on parton distributions; the computing efficiency improved by orders of magnitudes comparing to traditional method **[JG, DY Liu, CL Sun 2201.06586]**

sketch of NN architecture




- multi-layer NNs with discretized PDFs as input; trained with a large sample from CT18 MC PDFs
- reproduction accuracy of $\chi^2$ better than one per mille
- almost costless comparing to traditional methods that requires extensive calculations of cross sections
- ensuring efficient scan of the PDF parameter space without relying on Hessian approximations

modeling accuracy




computing efficiency per parameter point

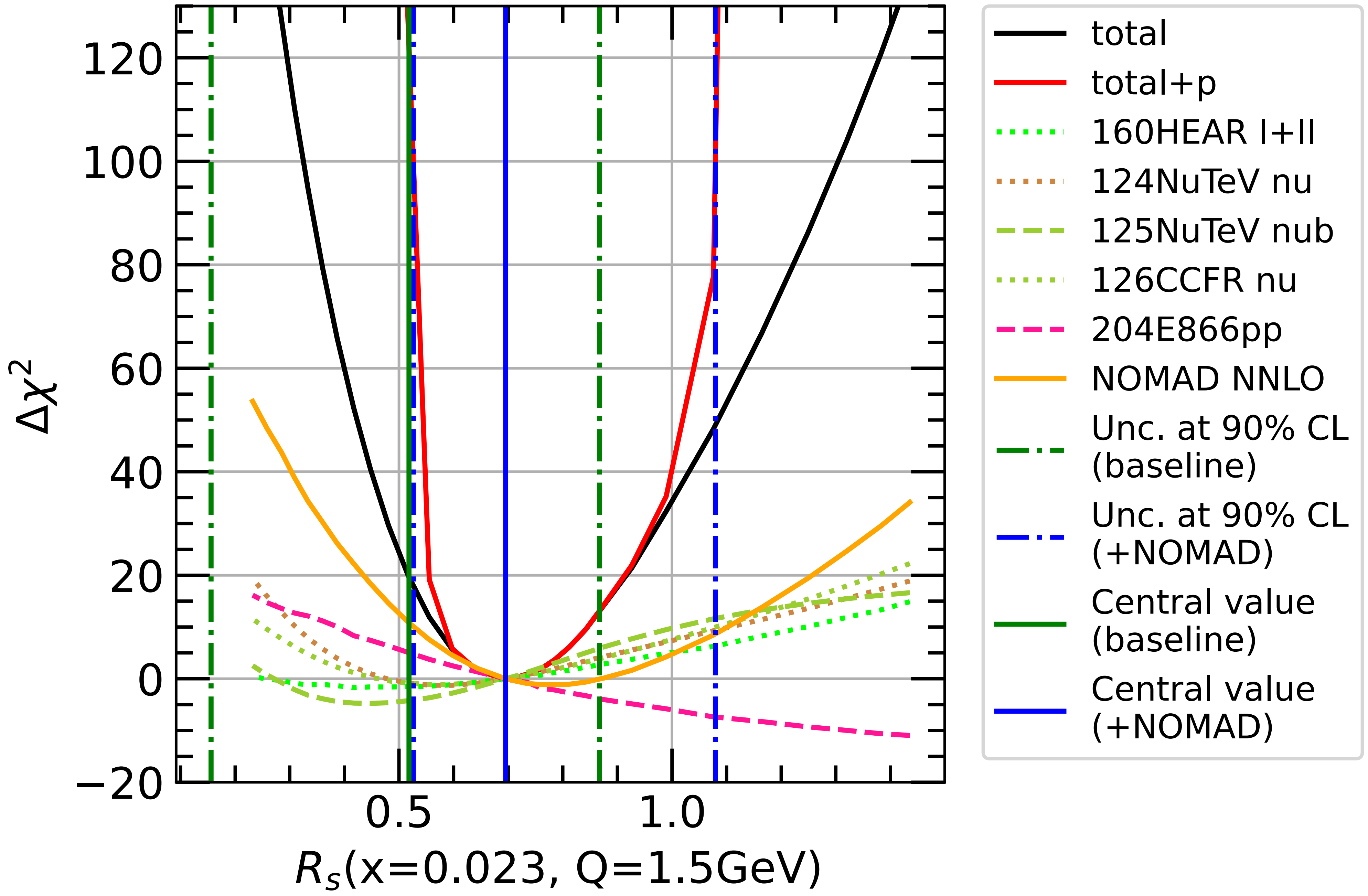
| cost \ target / method | $\chi^2$ | $\sigma$ | $f(x,Q)$ |
|---|---|---|---|
| NNs | 0.70 ms | 0.41 ms | 0.37 ms |
| traditional | $10^7(300)$ ms | $10^6(30)$ ms | 20(2) ms |

# Strangeness is moderately suppressed

- We include NOMAD (dimuon) data into a global analysis of PDFs (CT18 as baseline), and analysis its impact to PDFs, especially focusing on strange PDF and strange to light sea-quark ratio Rs=(s+sb)/(ub+db)

**[JG, DY Liu, CL Sun 2201.06586]**

LM scans on Rs




- 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 by more than 30%

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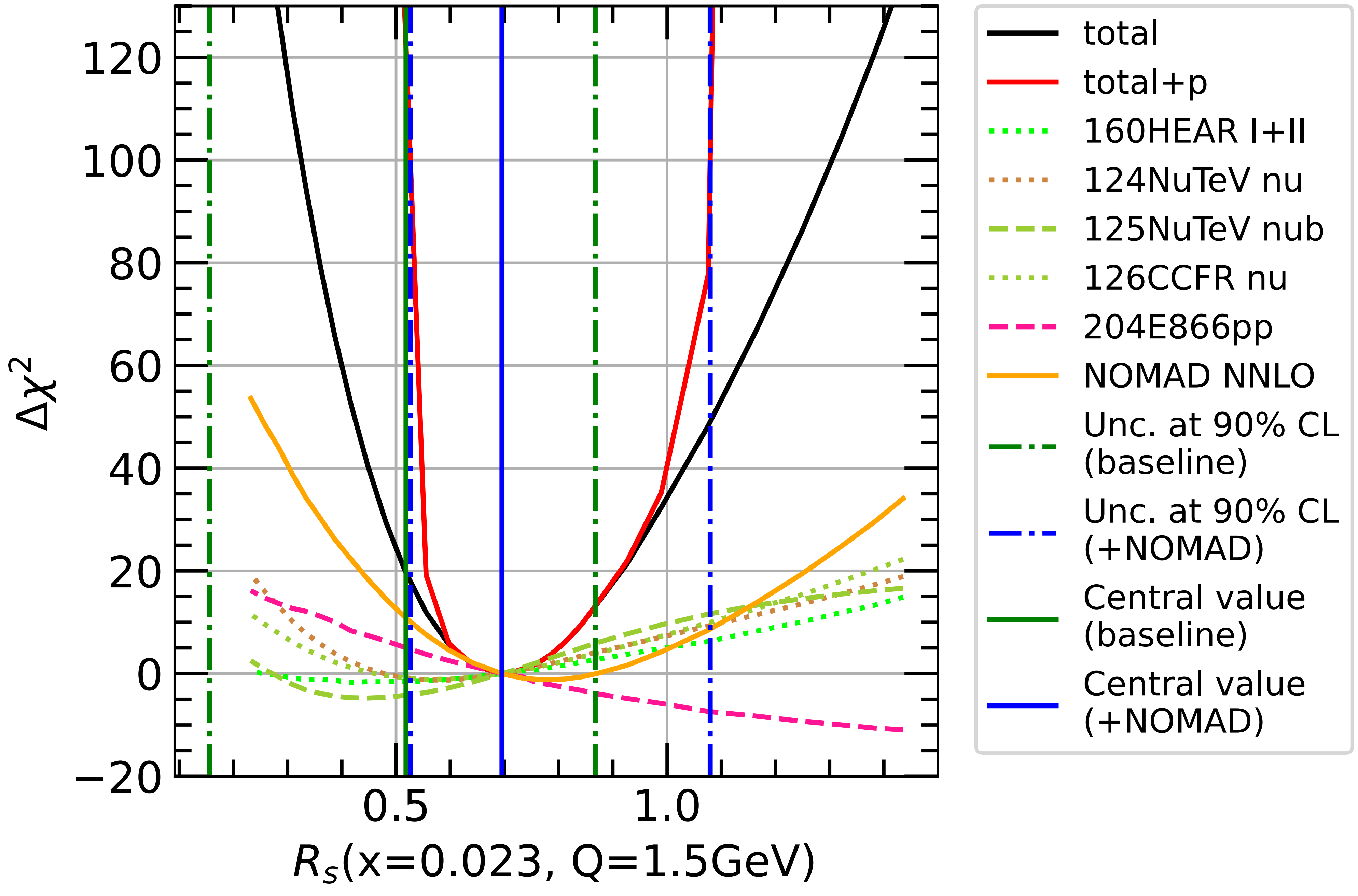
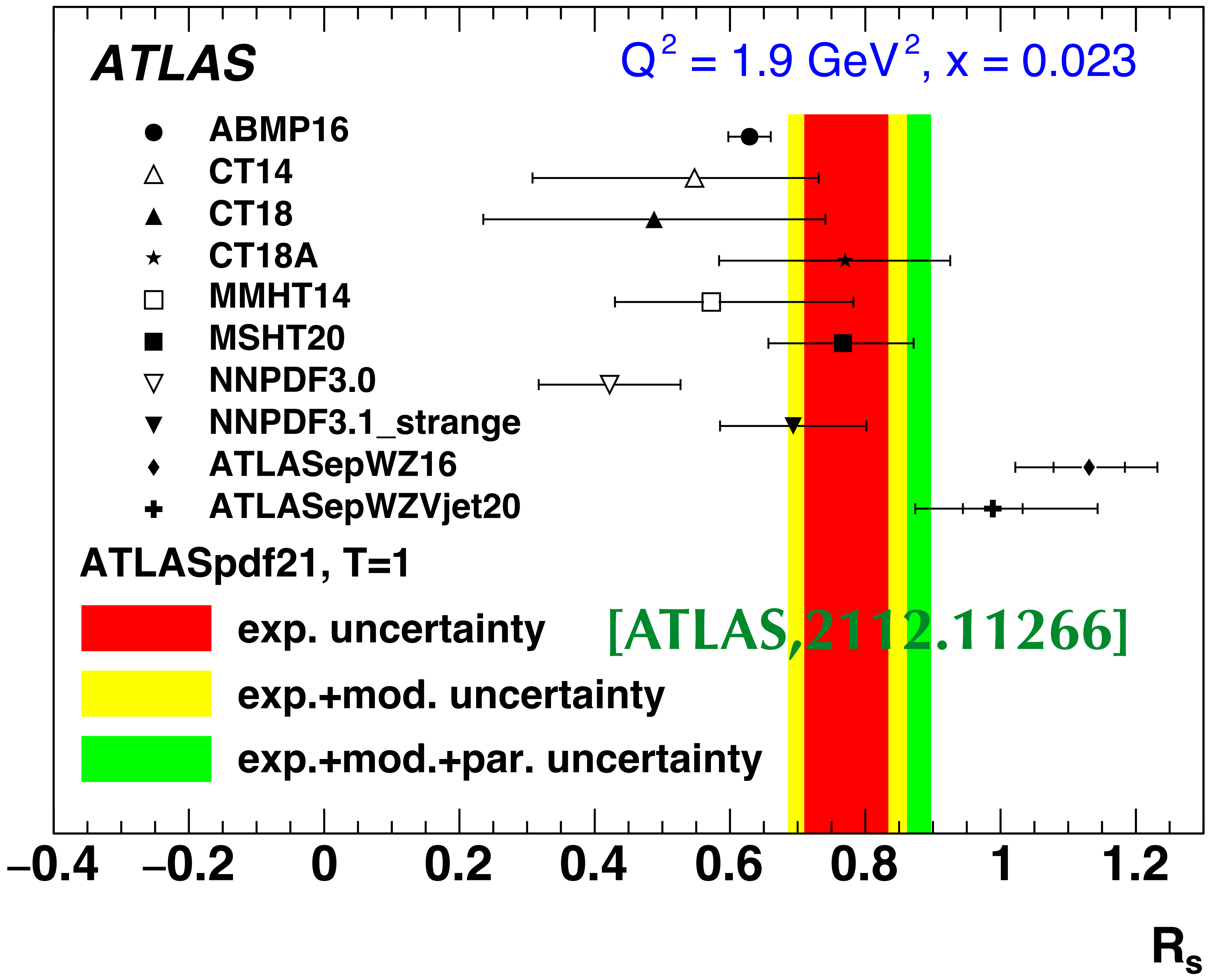



recent ATLAS W/Z measurement




❖ 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 by more than 30%

❖ tensions between dimuon data (Rs~0.5) and LHC data (Rs~1) exist for years; now relieved

❖ most recent ATLAS data shows Rs~0.8

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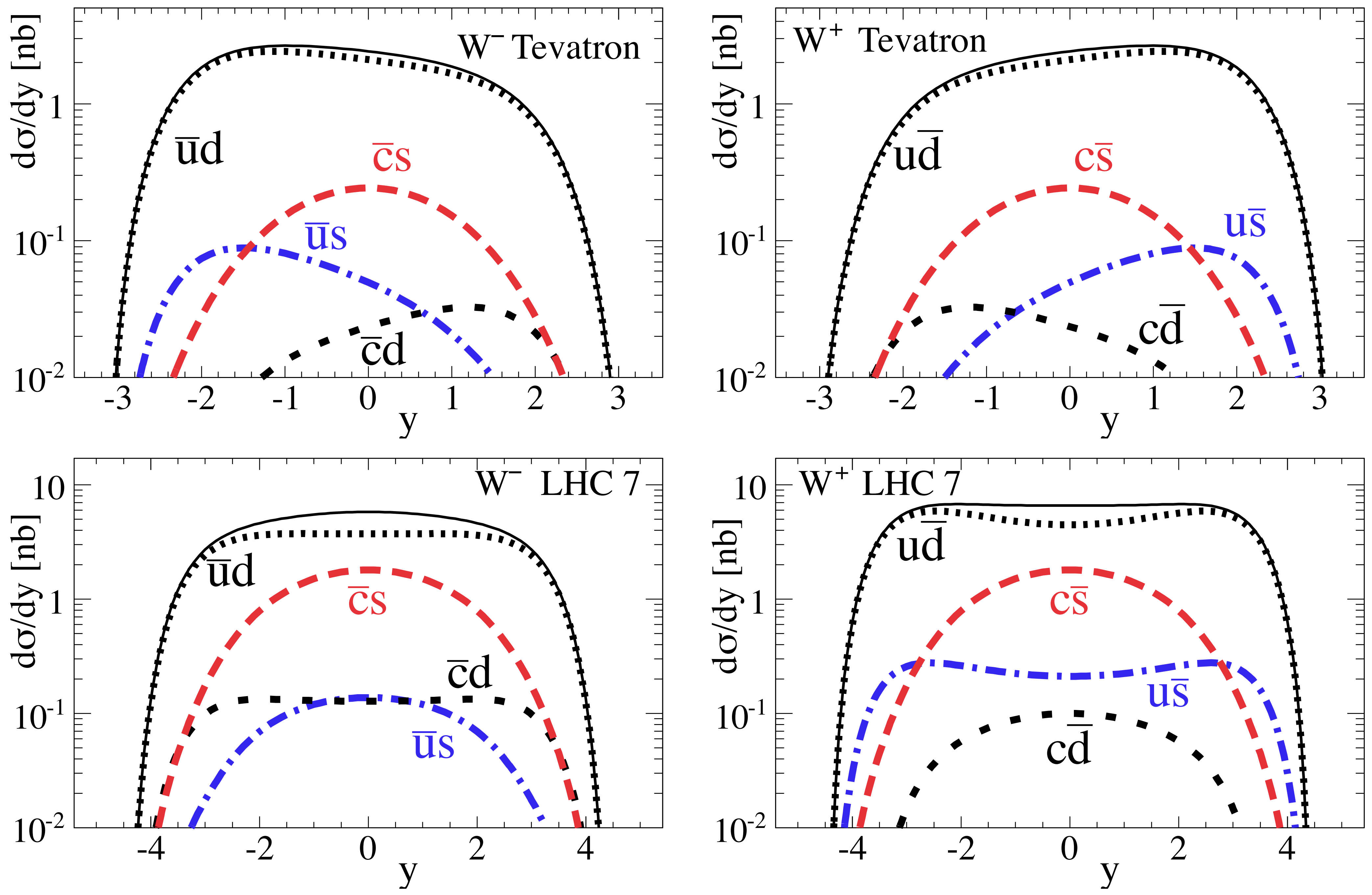
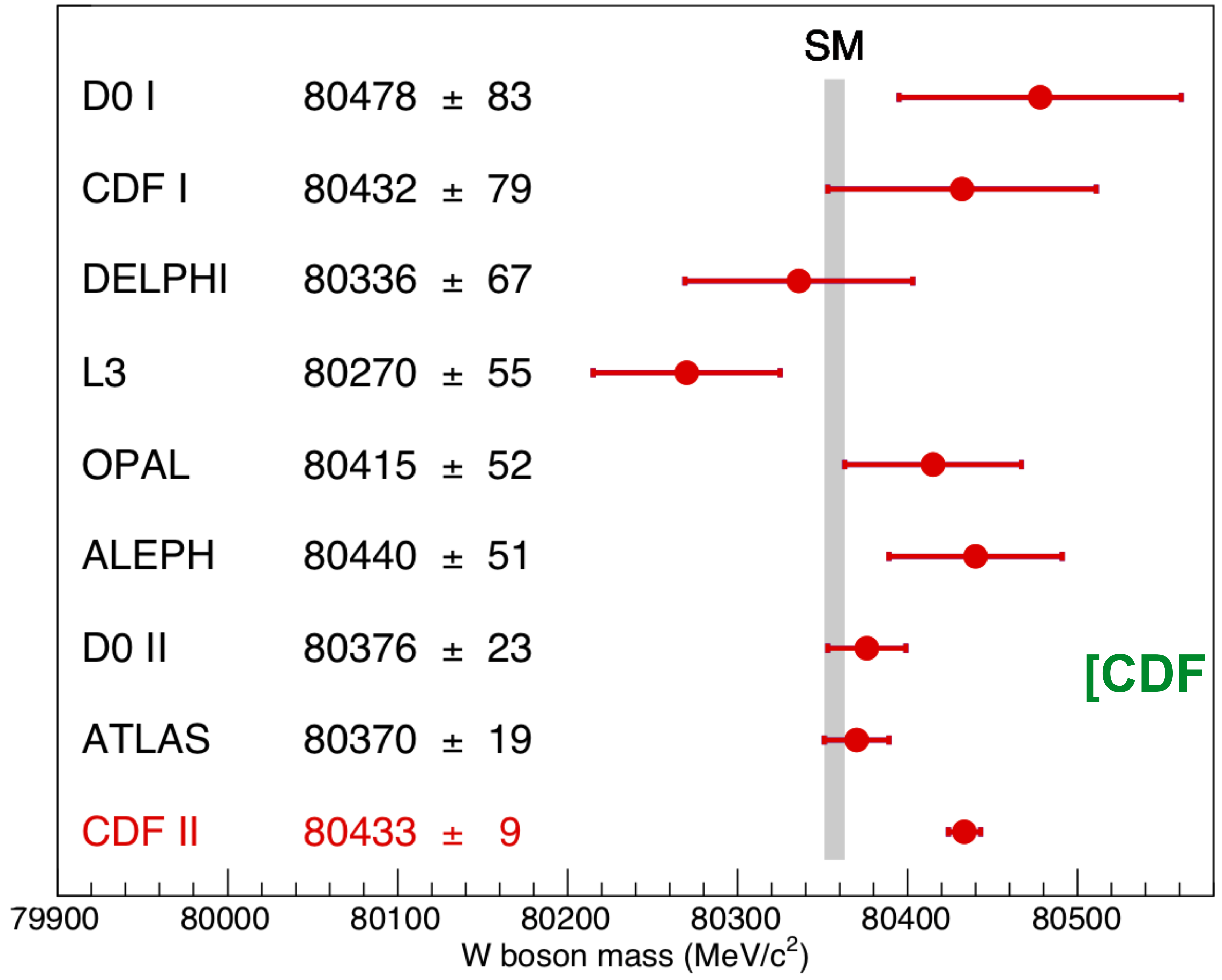
# Question 1: PDF uncertainties in W mass direct measurements

- PDFs are key inputs for precision programs at hadron colliders, e.g., direct measurements on the W boson mass and the weak mixing angle

W boson rapidity distribution [1203.1290]



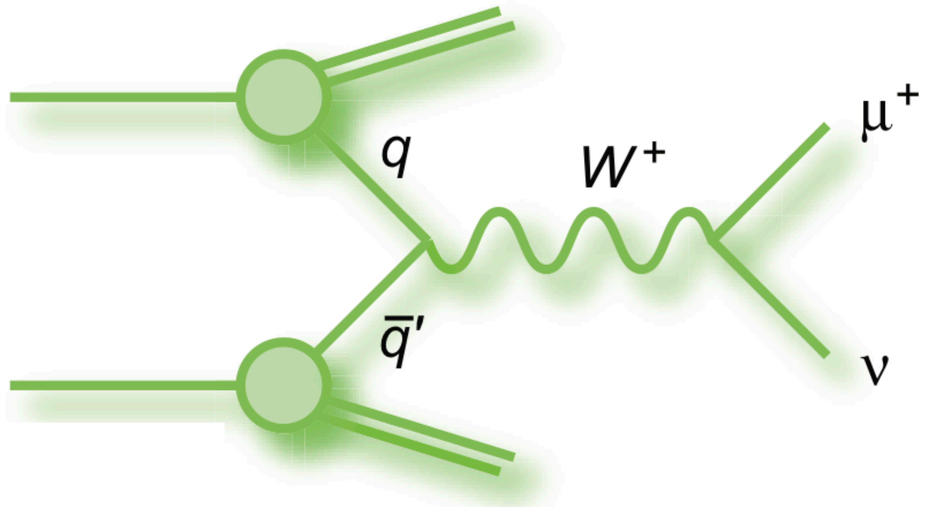

W boson mass from different experiments




[CDF 2022]

Fig. 5

Drell-Yan production




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)]

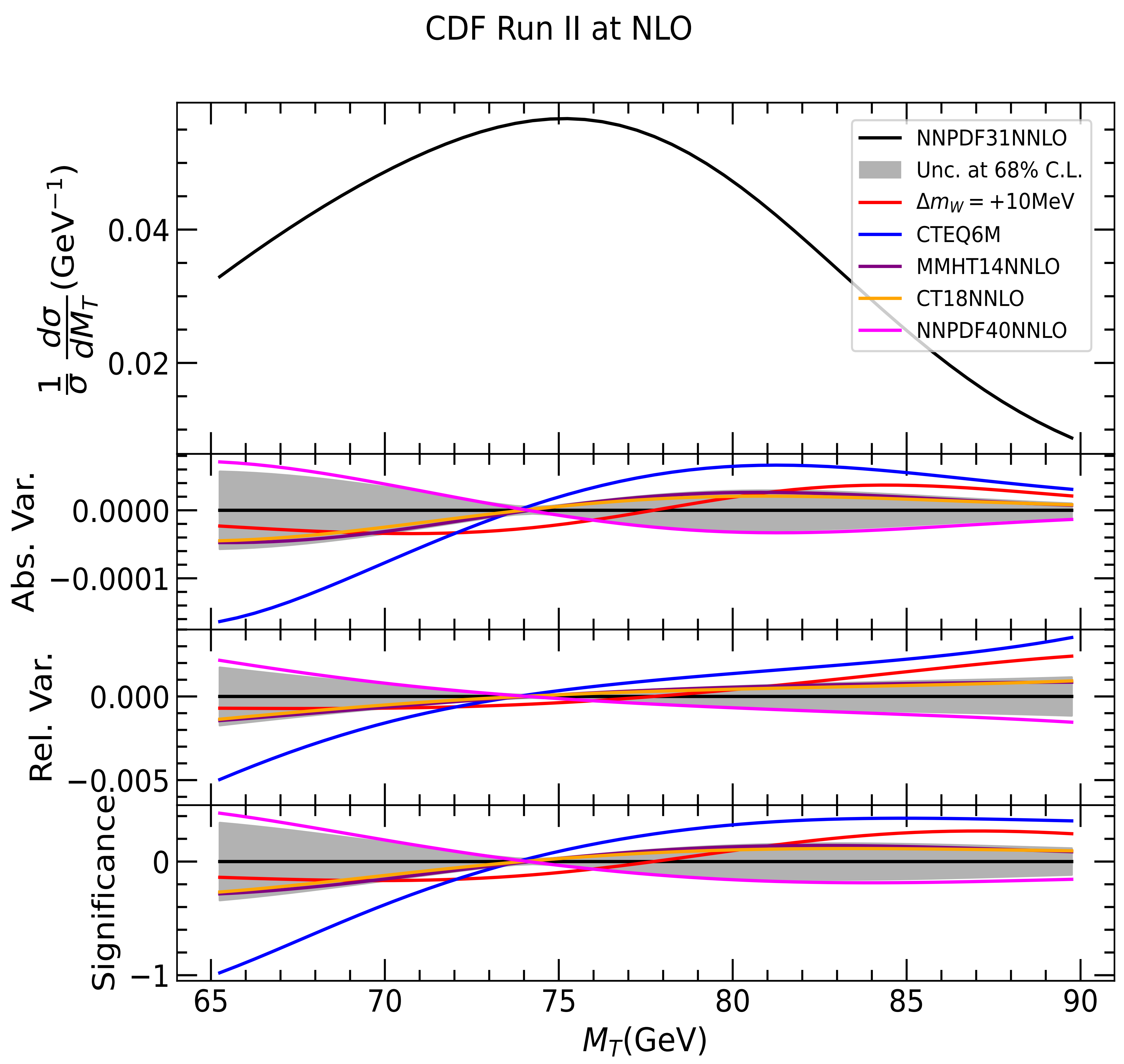
**PDF unc. of CDF / ATLAS / LHCb: 3.9 / 8 / 9 MeV**

# PDF variations can not explain CDF discrepancy

- We estimate shift of extracted W boson mass induced by variation of PDFs, and the associated PDF uncertainty for a variety of PDFs, focusing on the kinematic variable of transverse mass at CDF

**[JG, DY Liu, KP Xie, 2205.03942]**

normalized $m_T$ distribution
PDF var. vs. $M_W$ var.



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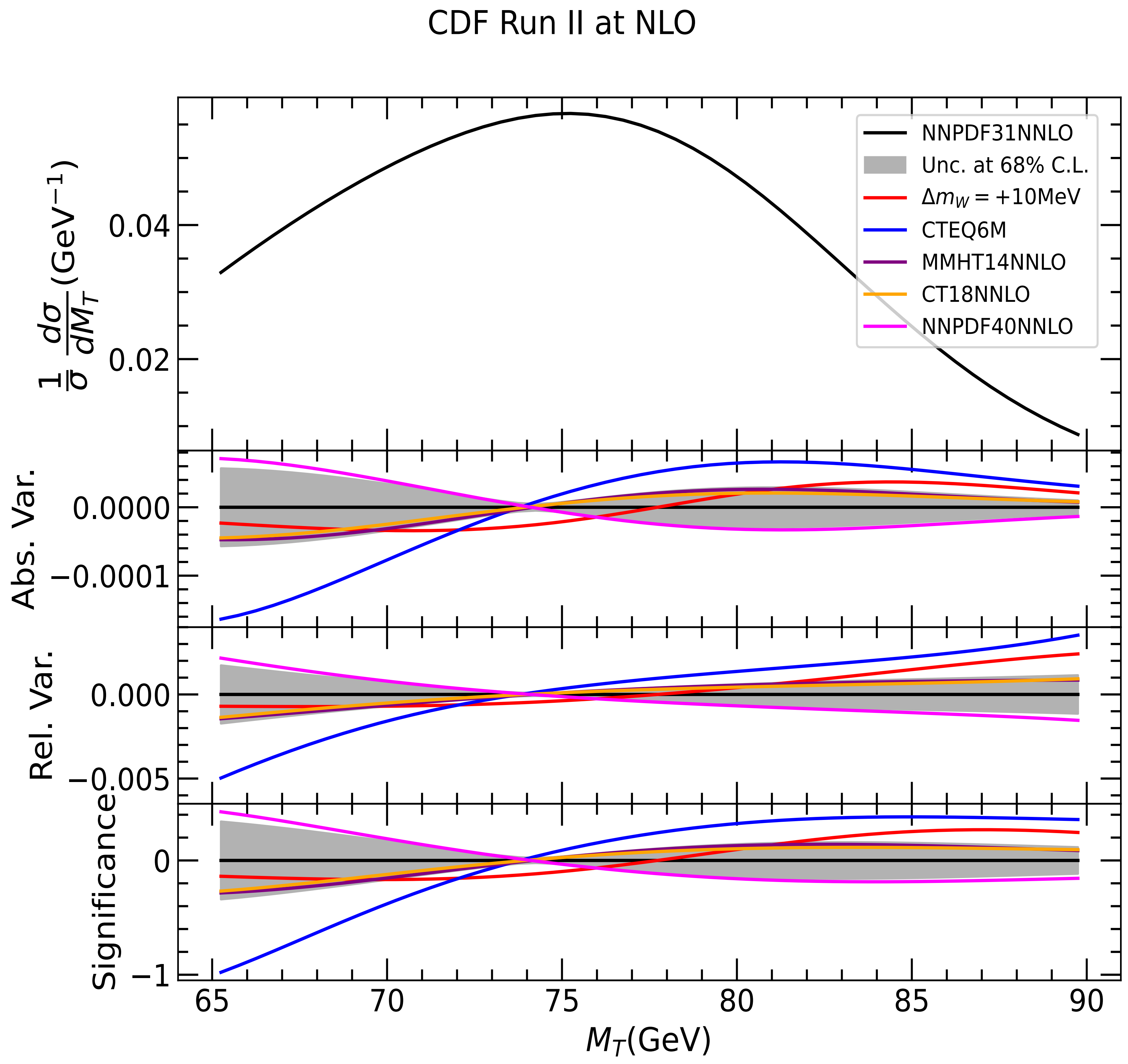
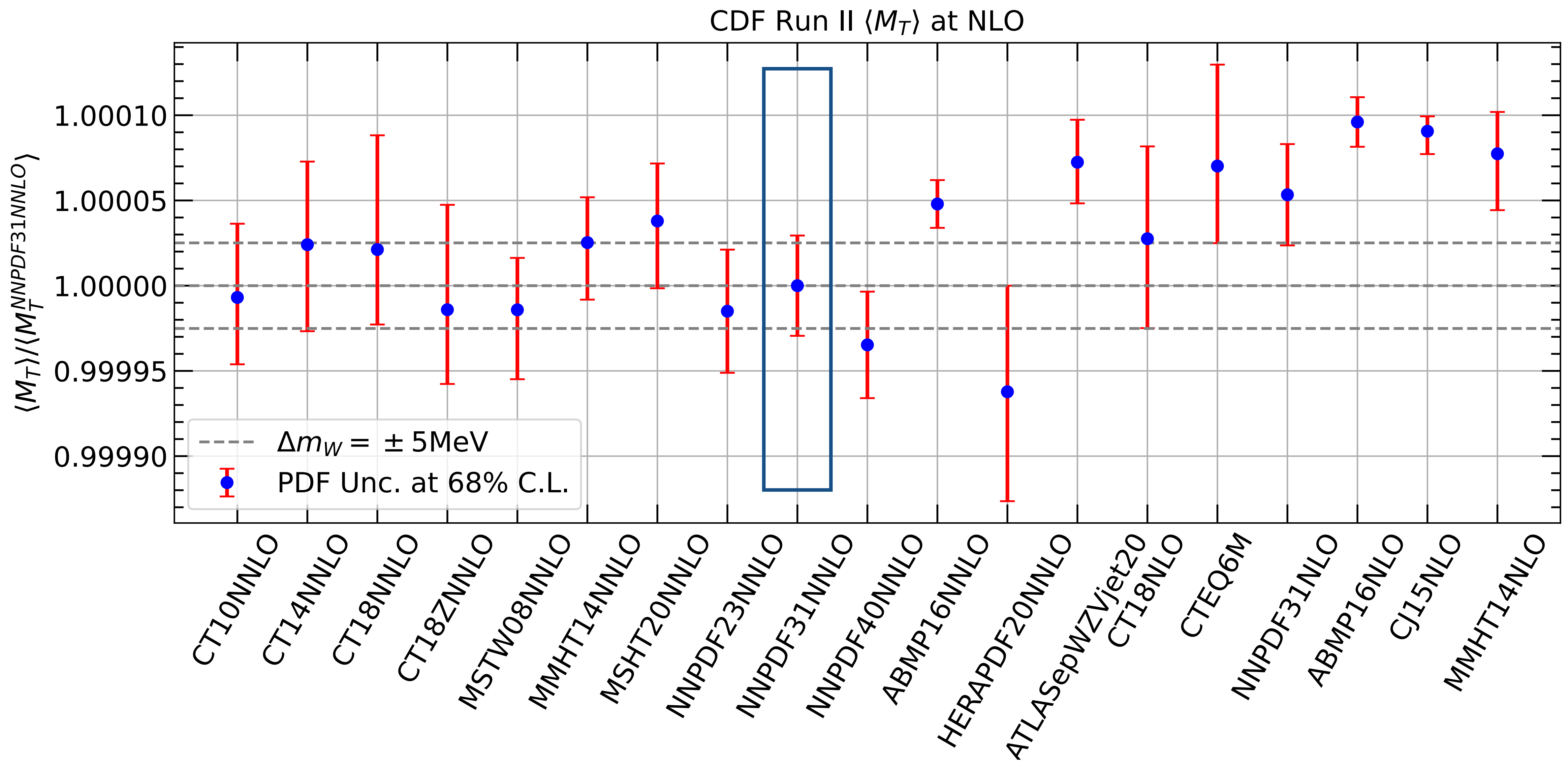



mean value of $m_T$



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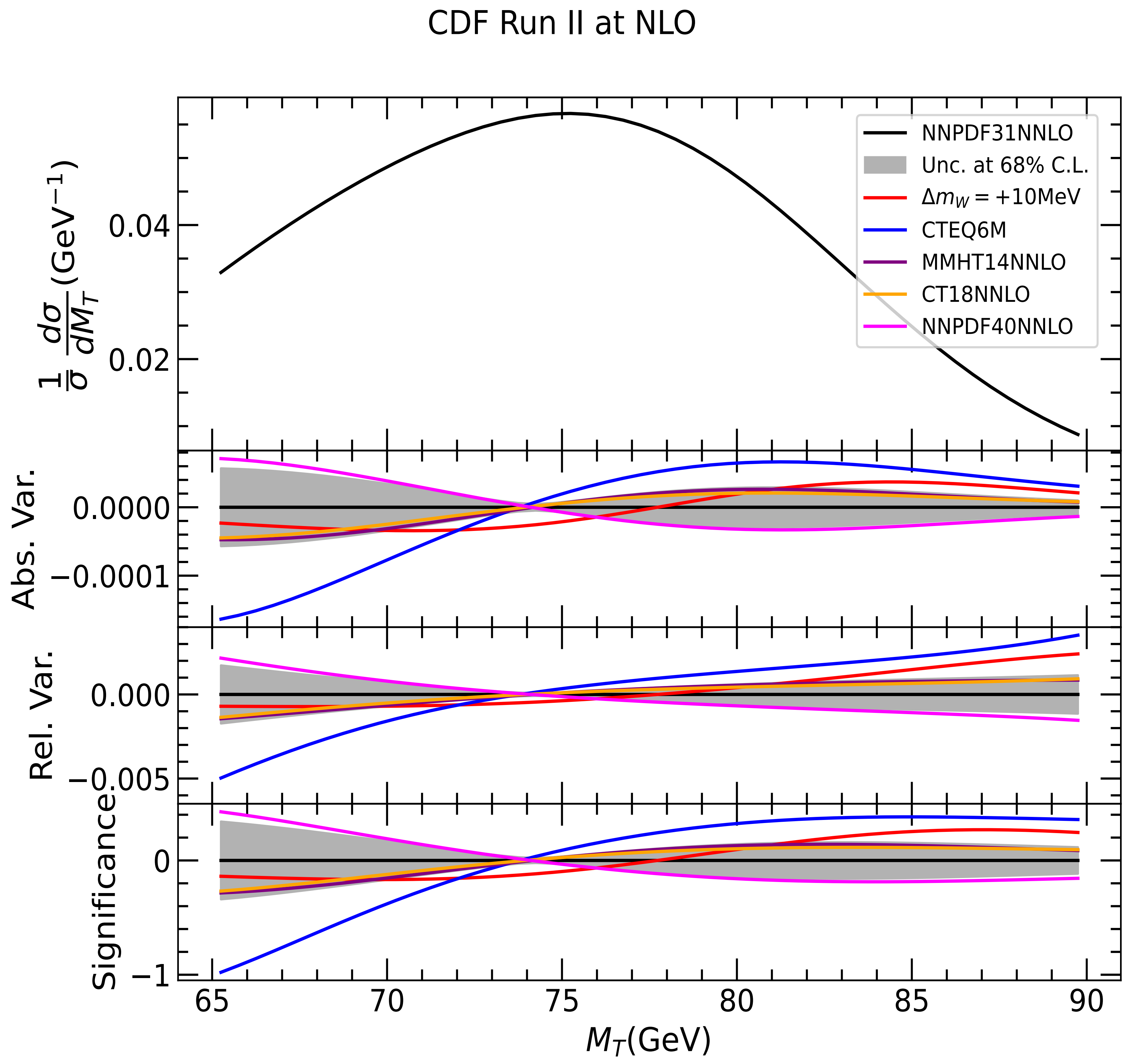


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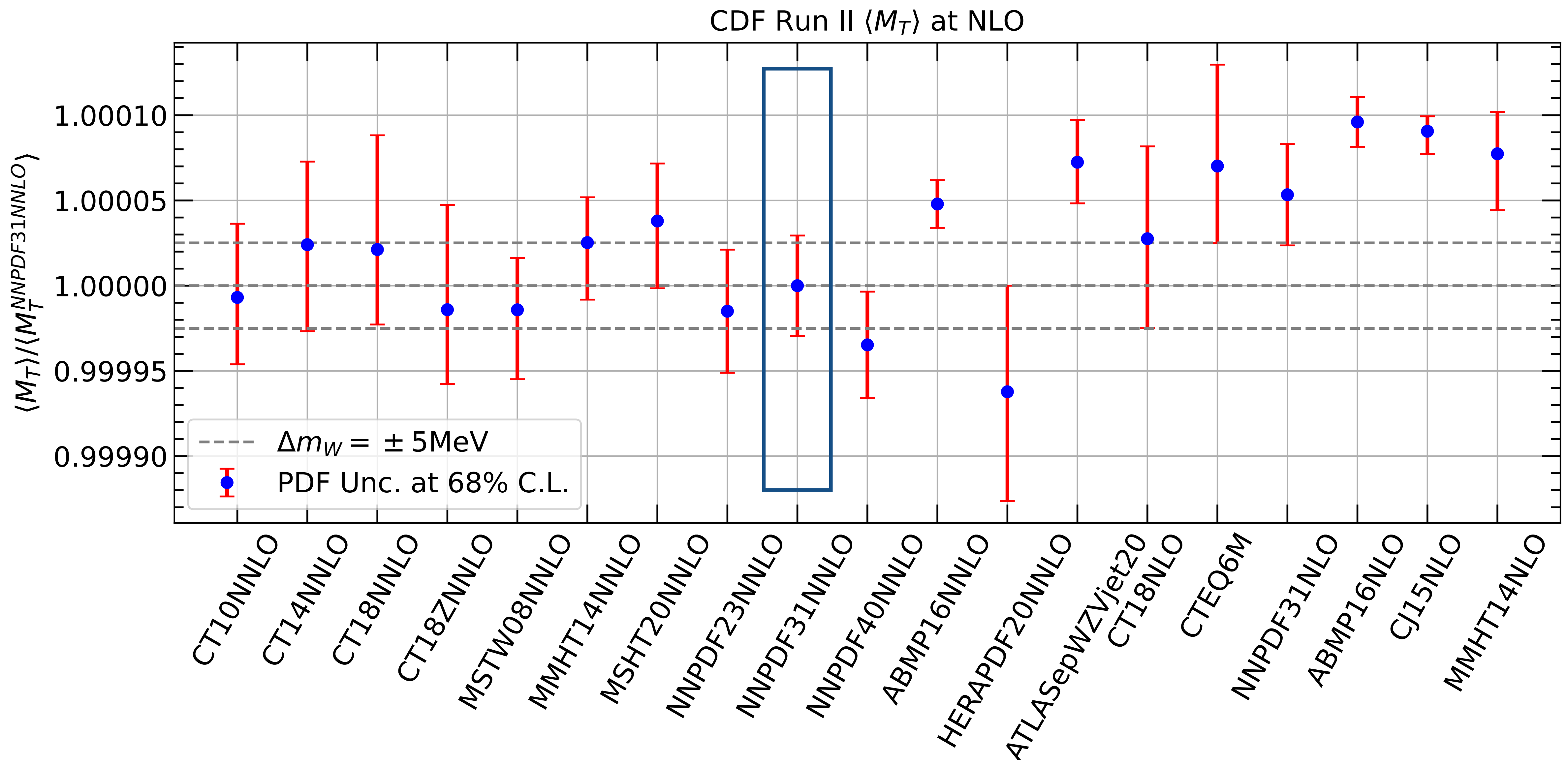



estimated shift and PDF unc. of W mass

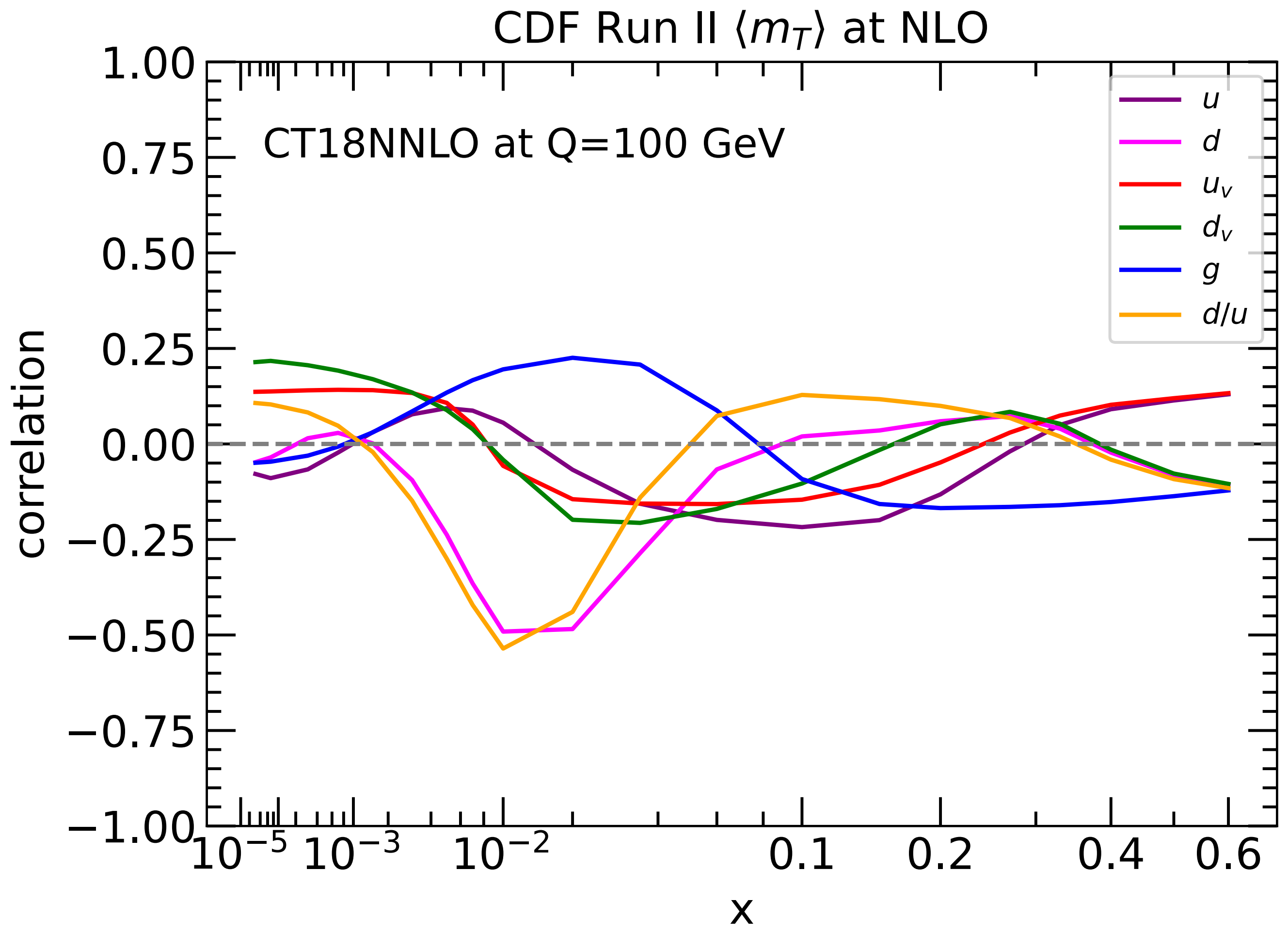
| $\delta M_W$ in MeV | sta. | NNPDF3.1 | CT18 | MMHT2014 | NNPDF4.0 | MSHT2020 |
|---|---|---|---|---|---|---|
| $\langle M_T \rangle$(LO) | – | $0^{+8.3}_{-8.3}$ | $-1.0^{+8.3}_{-11.4}$ | $-3.3^{+7.4}_{-4.2}$ | $+7.8^{+5.1}_{-5.1}$ | $-3.1^{+6.7}_{-5.7}$ |
| $\chi^2$ fit (LO) | 8.0 | $0^{+7.6}_{-7.6}$ | $-1.0^{+5.4}_{-8.6}$ | $-3.3^{+6.1}_{-3.0}$ | $+8.0^{+3.7}_{-3.7}$ | $-3.0^{+5.0}_{-4.0}$ |
| $\langle M_T \rangle$(NLO) | – | $0^{+5.9}_{-5.9}$ | $-4.2^{+8.8}_{-13.3}$ | $-5.0^{+6.7}_{-5.3}$ | $+6.9^{+6.2}_{-6.2}$ | $-7.6^{+7.9}_{-6.7}$ |
| $\chi^2$ fit (NLO) | 8.0 | $0^{+4.2}_{-4.2}$ | $-4.3^{+5.4}_{-10.1}$ | $-5.1^{+4.8}_{-3.4}$ | $+7.1^{+4.5}_{-4.5}$ | $-7.8^{+5.7}_{-4.5}$ |
| CDF | 9.2 | $0^{+3.9}_{-3.9}$ | – | – | – | – |

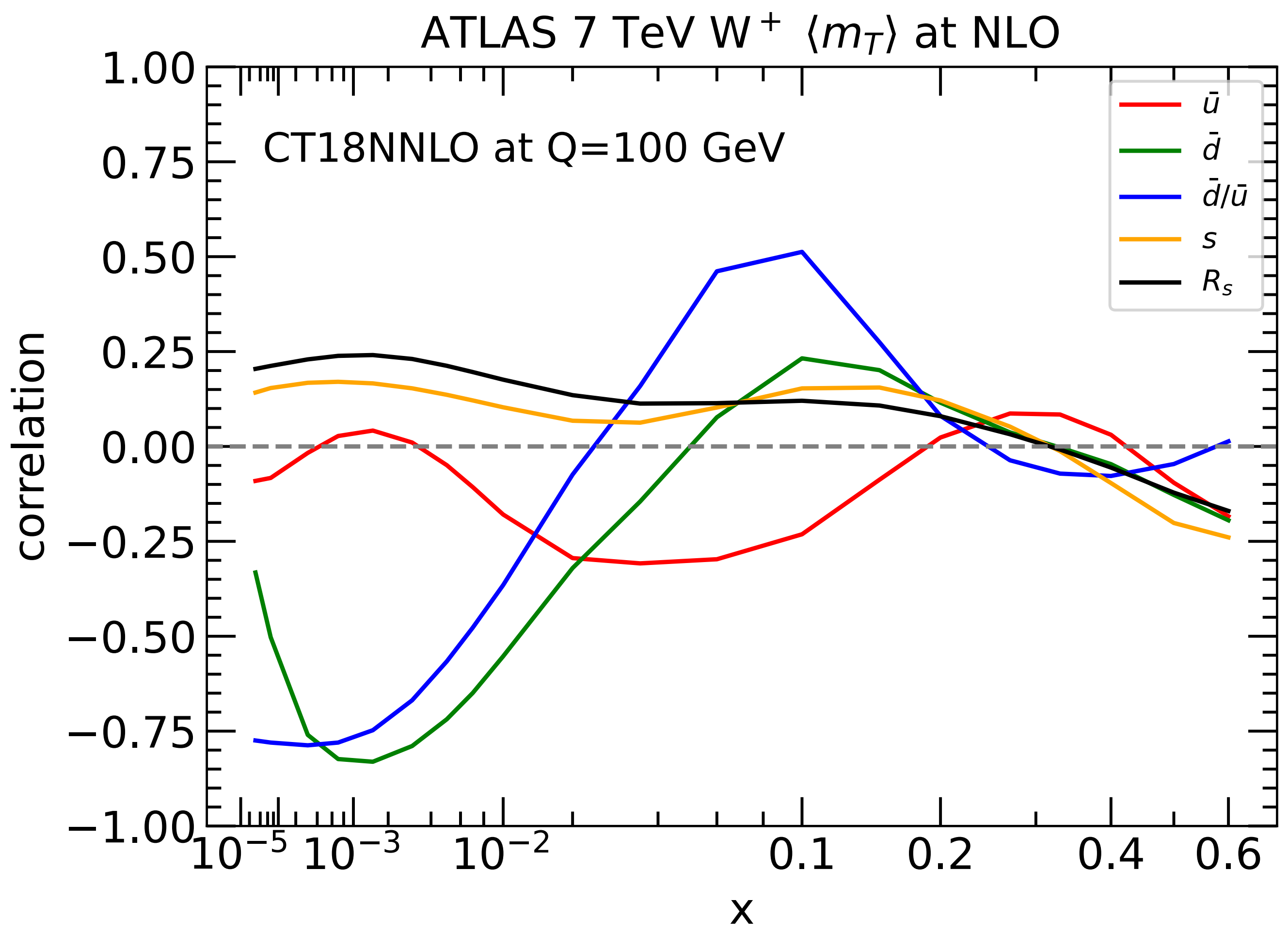
# PDF variations can not explain CDF discrepancy

- We carry out a series of Lagrange multiplier scans to identify the constraints on the transverse mass distribution (using mean $M_T$) imposed by individual data sets in the CT18 global analysis

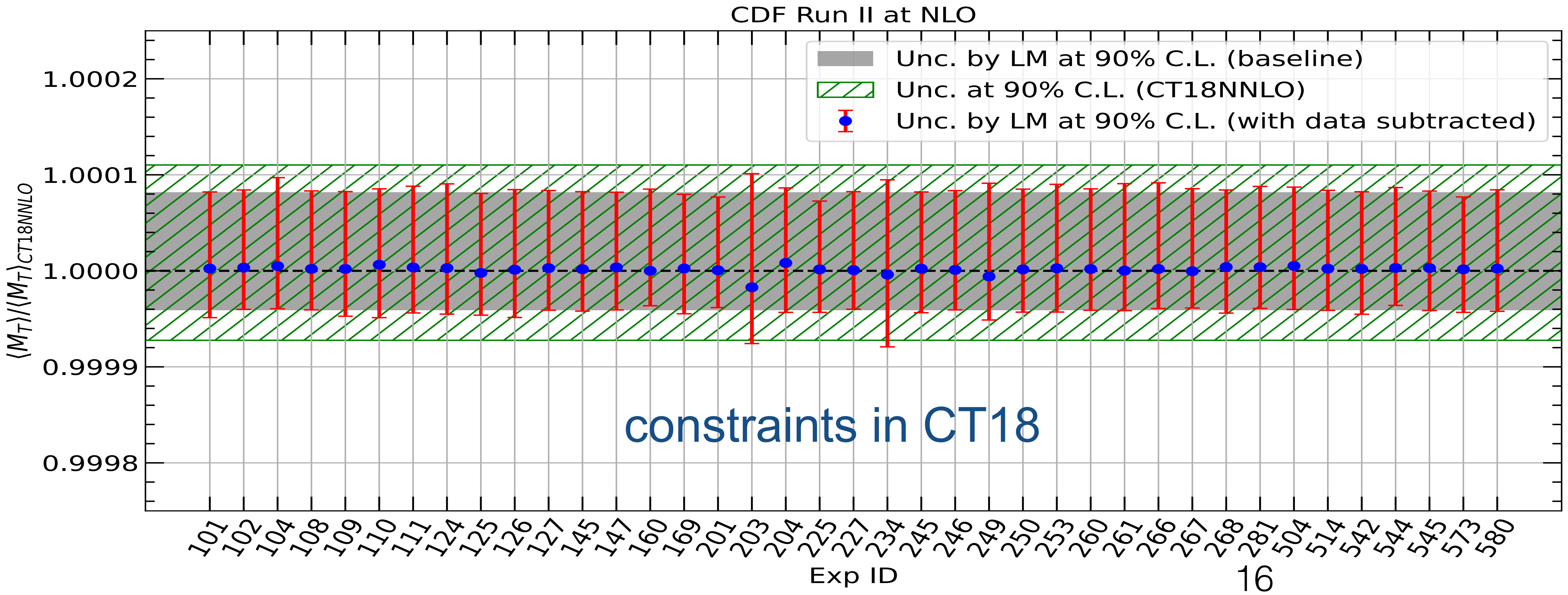
## PDF induced correlations

**[JG, DY Liu, KP Xie, 2205.03942]**




- $m_T$ at CDF (ATLAS) is mostly sensitive to the d-quark (dbar-quark) at x~0.01(0.001); CDF and ATLAS are largely uncorrelated

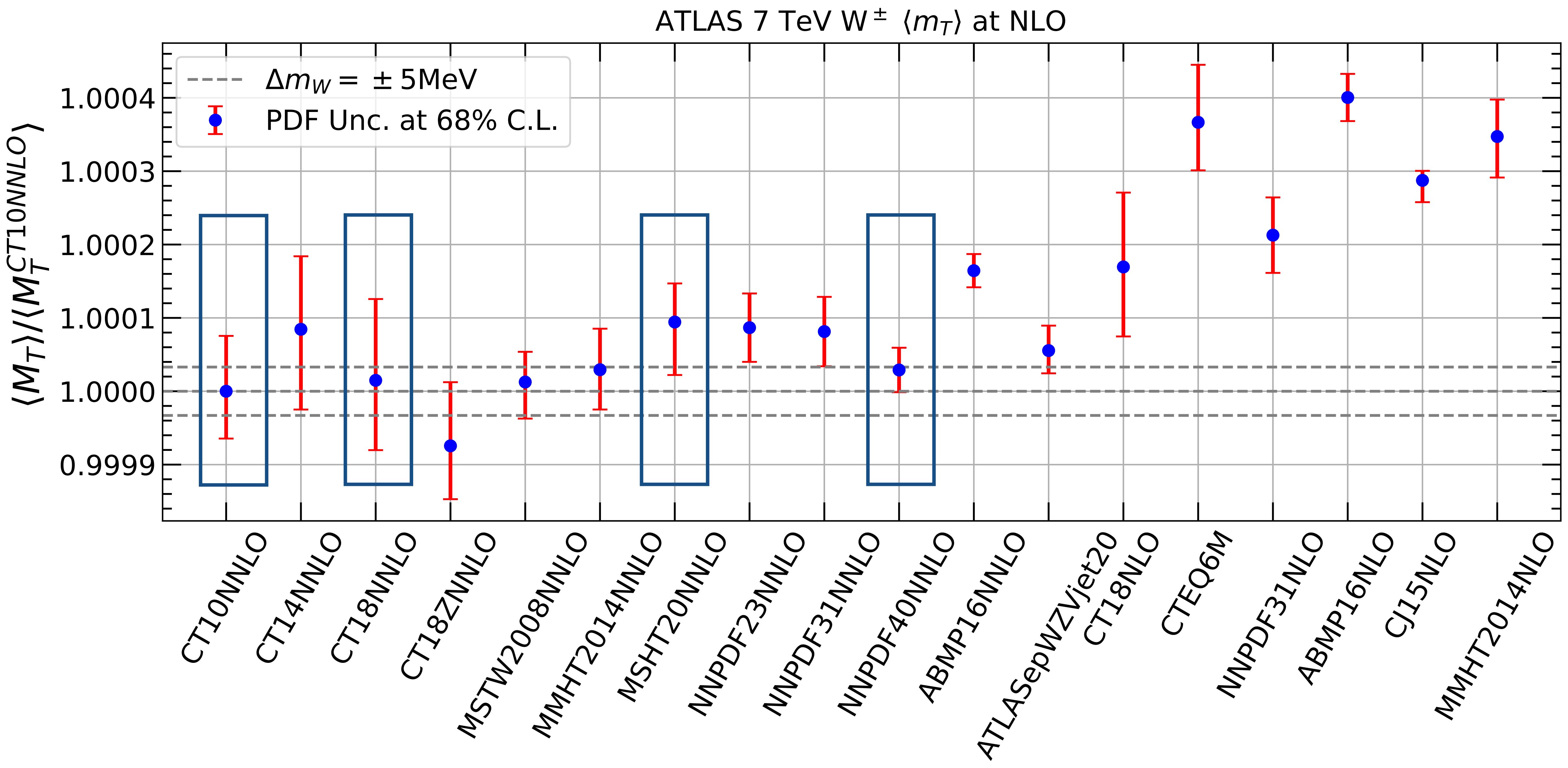



- $m_T$ at CDF is largely constrained by the DIS and Drell-Yan data on deuteron target, the Tevatron lepton charge asymmetry data; at ATLAS also the CMS charge asymmetry data

# Transverse mass at ATLAS

- We further investigate PDF variations on transverse mass distribution focusing on the ATLAS 7 TeV measurement; note the transverse momentum distribution has a relatively larger weight in ATLAS

mean value of $m_T$




- spread of predictions from different PDFs could be much larger than the PDF unc. of a specific 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**

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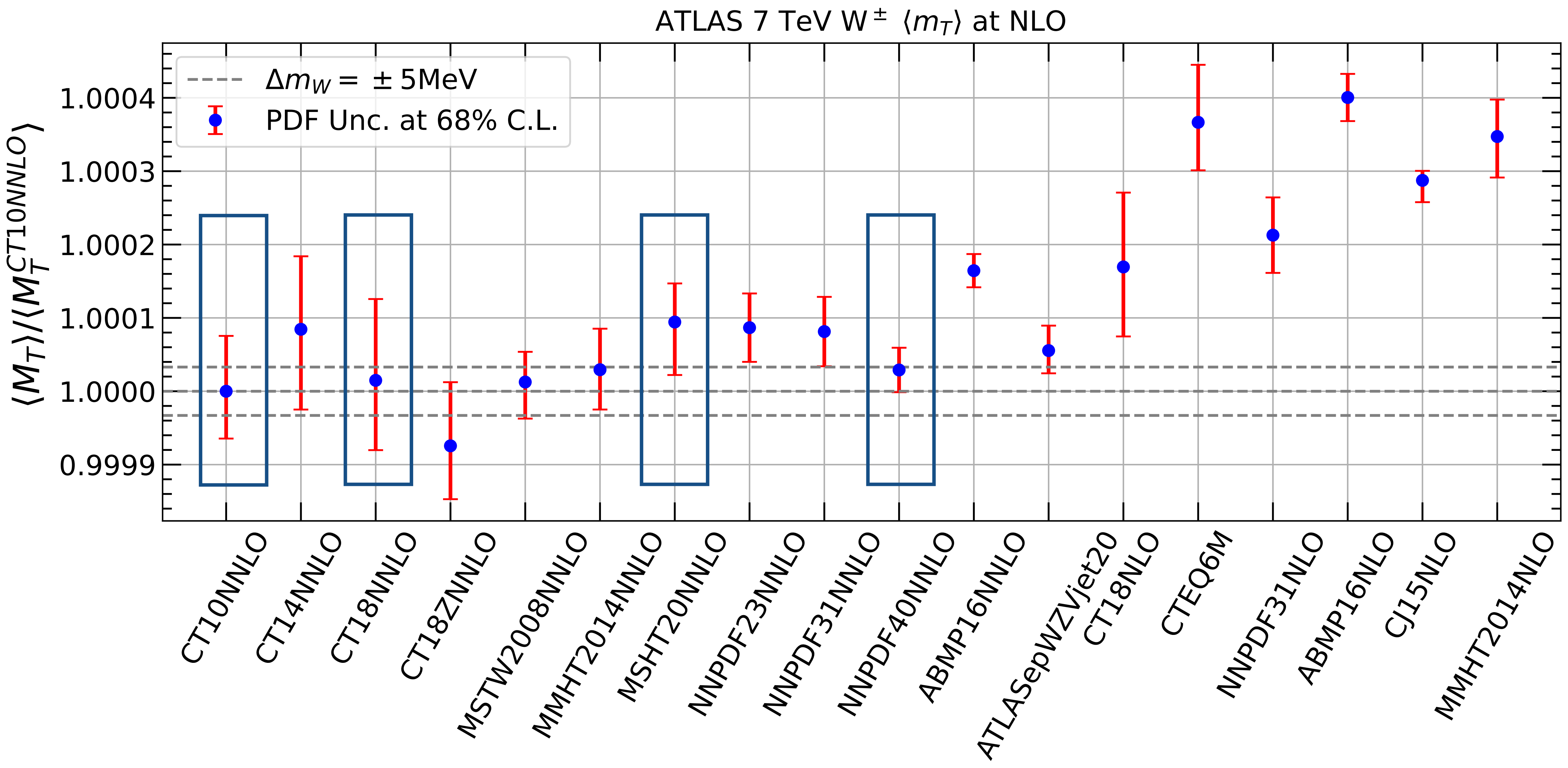


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PDF unc. at LHCb, NNPDF3.1, CT18, MSHT20

$$m_W = 80362 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 9_{\rm PDF}\ {\rm MeV},$$
$$m_W = 80350 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 12_{\rm PDF}\ {\rm MeV},$$
$$m_W = 80351 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 7_{\rm PDF}\ {\rm MeV},$$

ATLAS, CT10 + 3.8 MeV (MMHT14-CT14)

| $W$-boson charge | $W^+$ | | $W^-$ | | Combined | |
|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [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 |

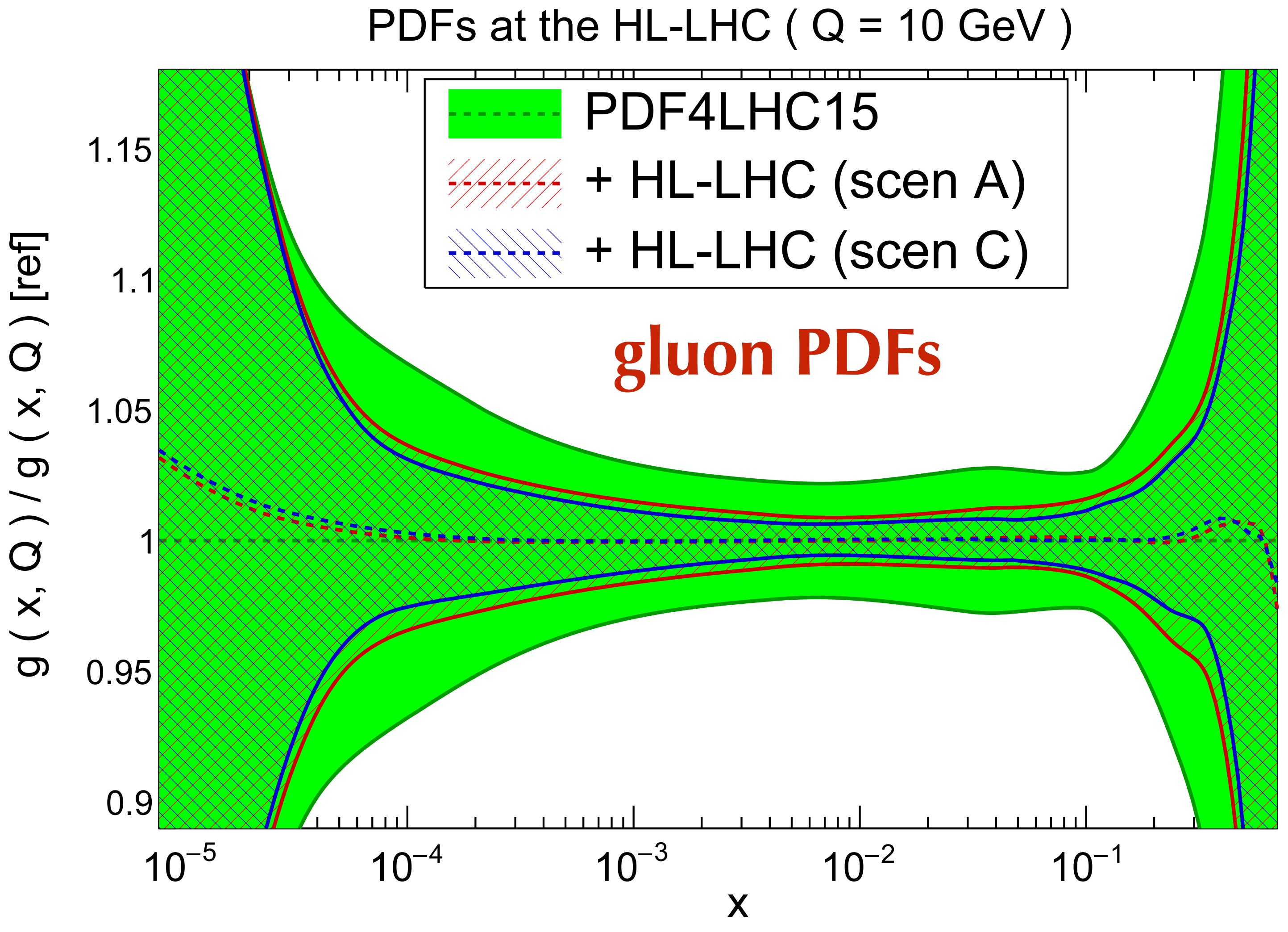
**[LHCb 2022; ATLAS 2017]**

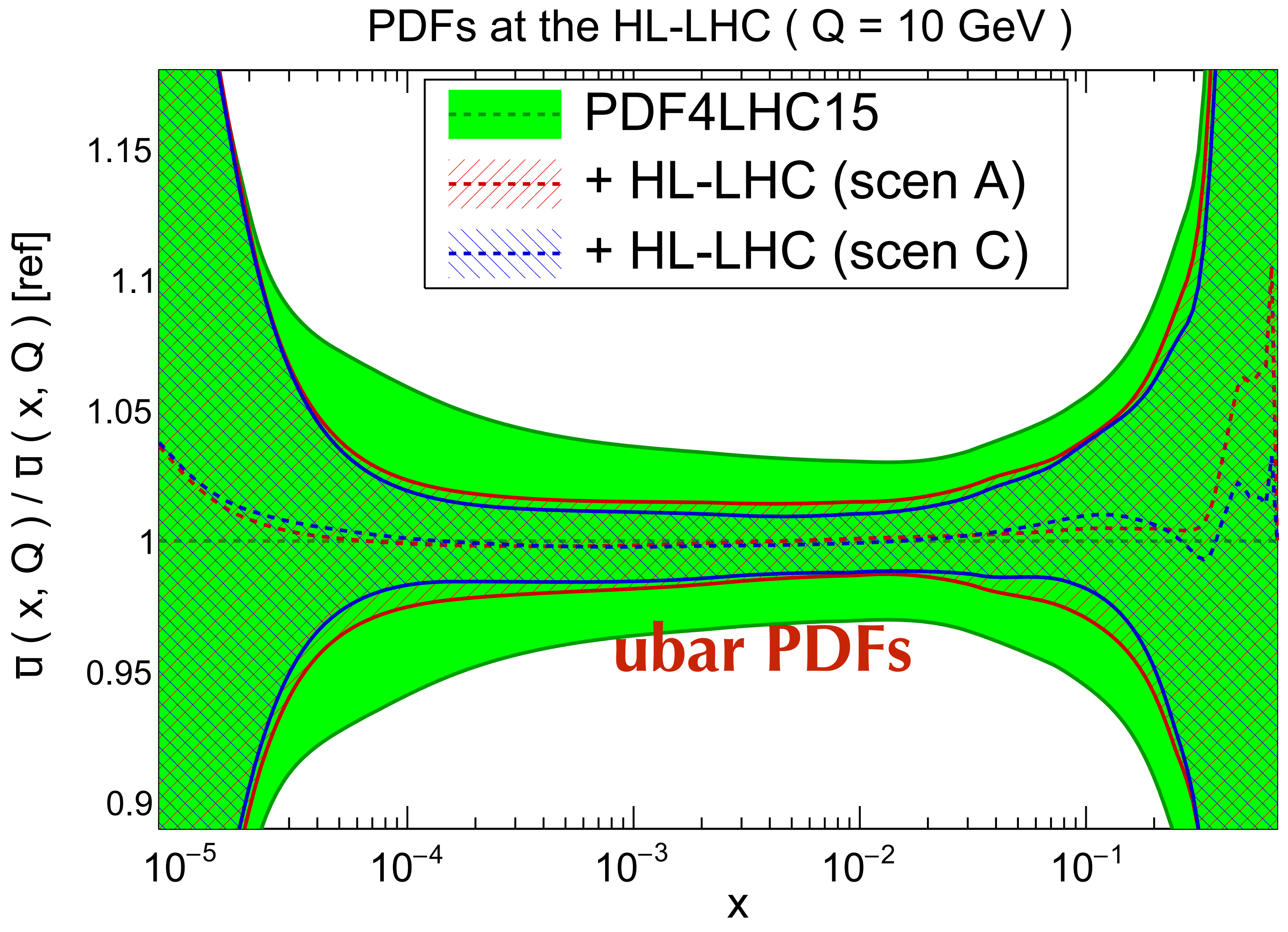
**Analyzing of W mass data with most UP-TO-DATE PDFs will be highly desirable**

# Future prospect on PDF unc.

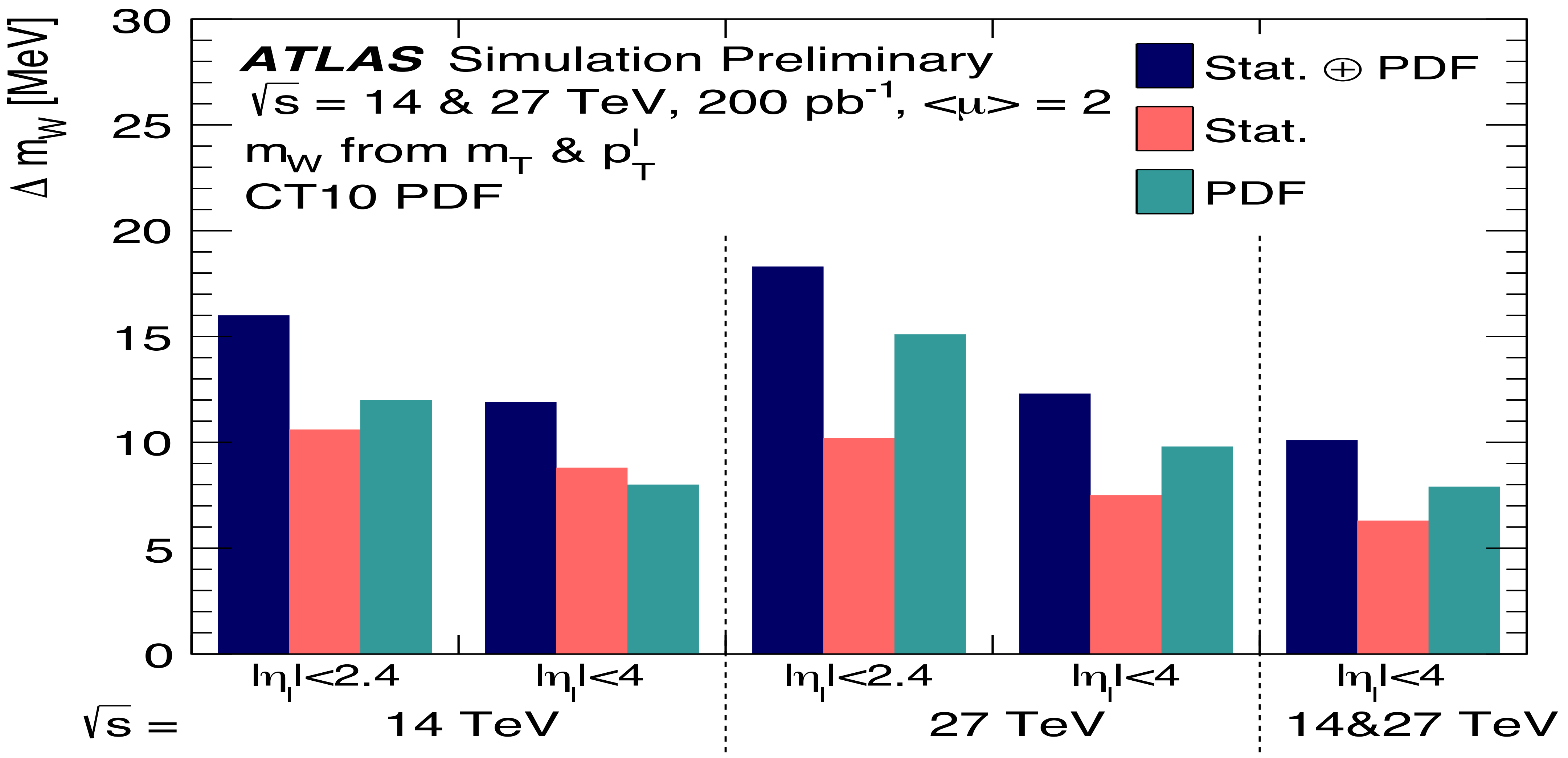
- Precision on PDFs can be further improved with upcoming data from EIC(c), HL-LHC, or ultimately if LHeC is possible; projections on $M_W$ have been made with PDFs fitted to pseudo-data

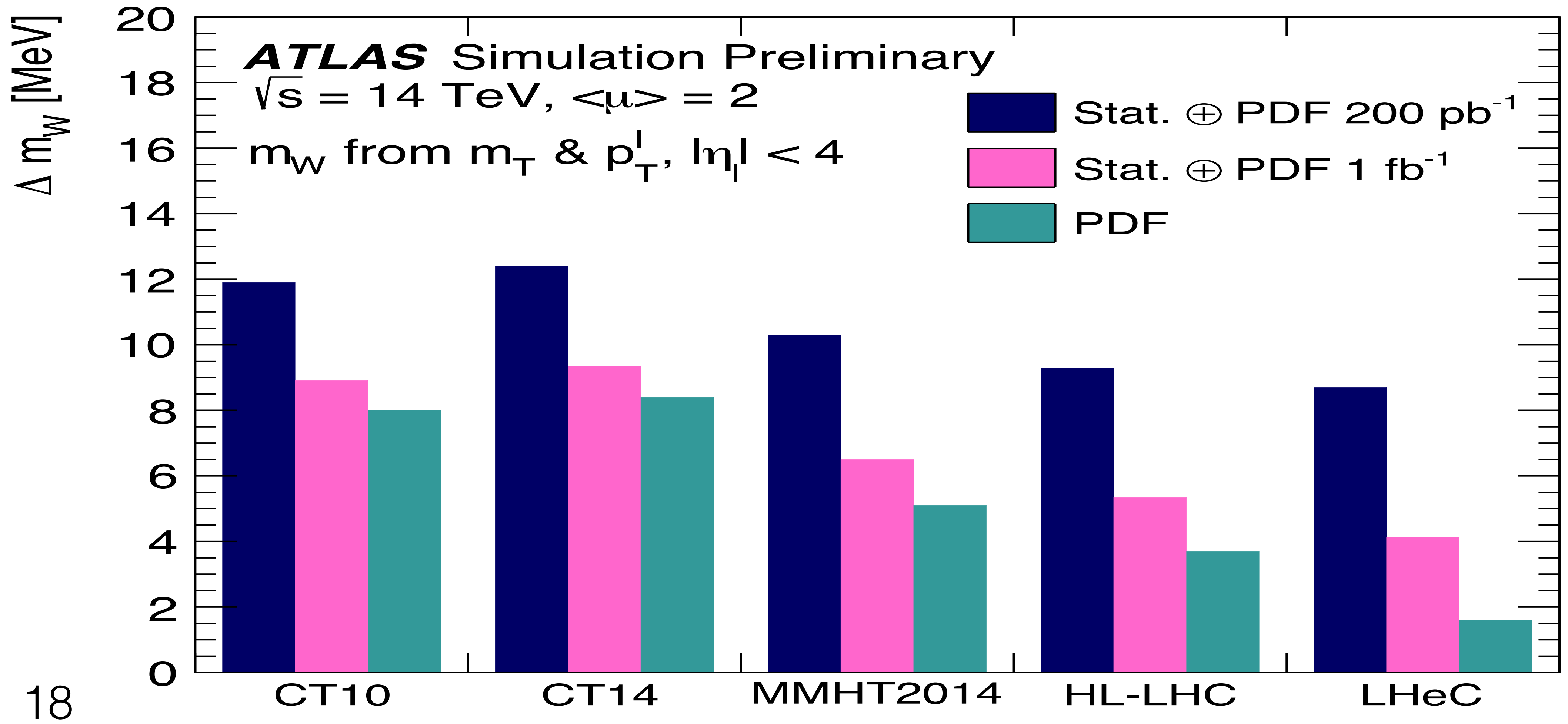
**[JG, Harland-Lang, Rojo+, 2018]**




**[SM Report, 1902.04070]**

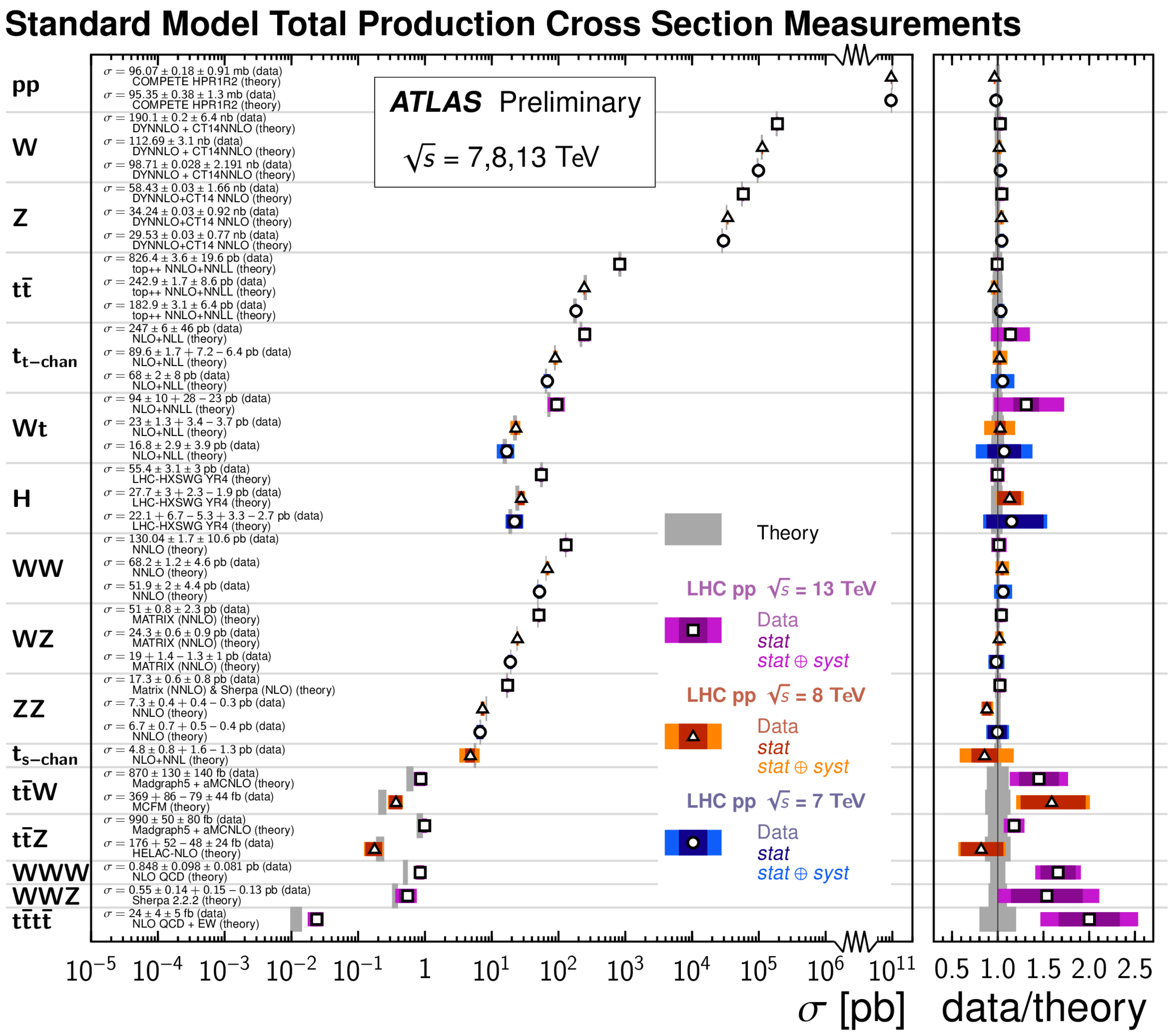


- ✦ 1. Introduction to PDFs for LHC
- ✦ 2. A framework of Global analysis boosted with machine learnings and applications
  - Understanding PDF uncertainties in W mass direct measurements
  - Implications of PDF for searches of new physics at the LHC
- ✦ 3. Summary

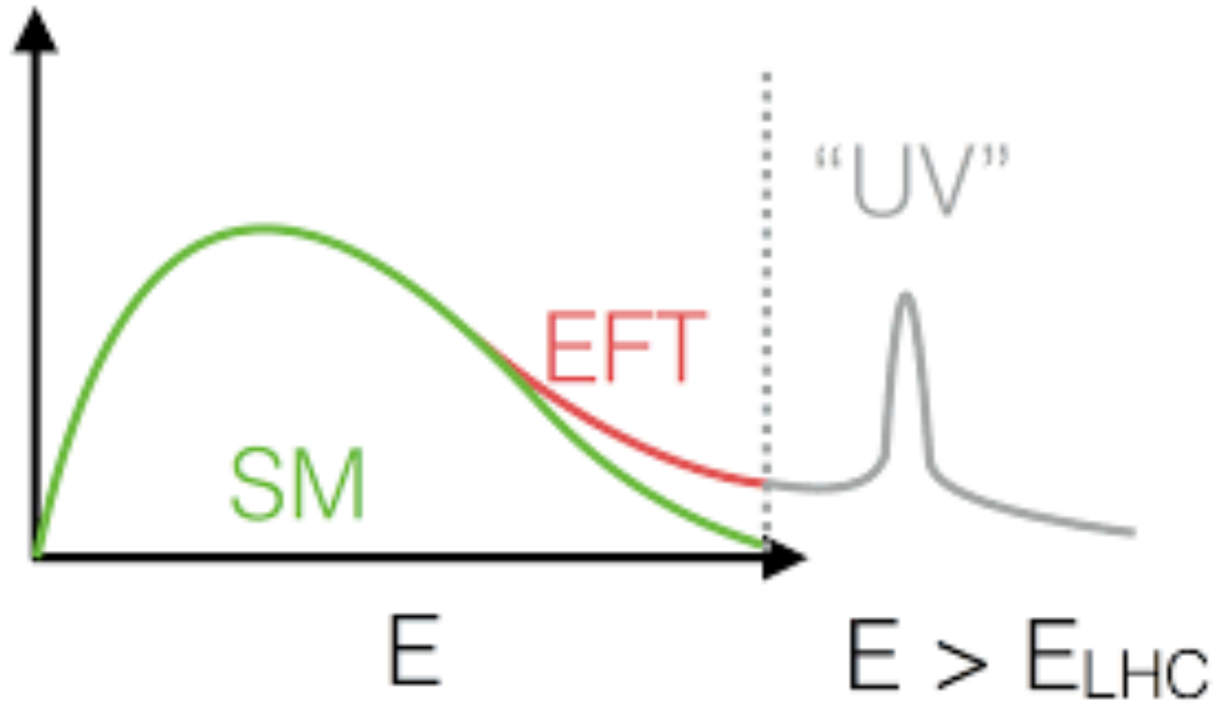
# Question 2: PDF bias in searches of new physics at the LHC

- PDFs are key inputs for searches of new physics beyond the SM at hadron colliders, especially non-resonance signatures hiding in high mass tails taking SM effective theory (SMEFT) as an example




SM cross sections from ATLAS

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2}$$



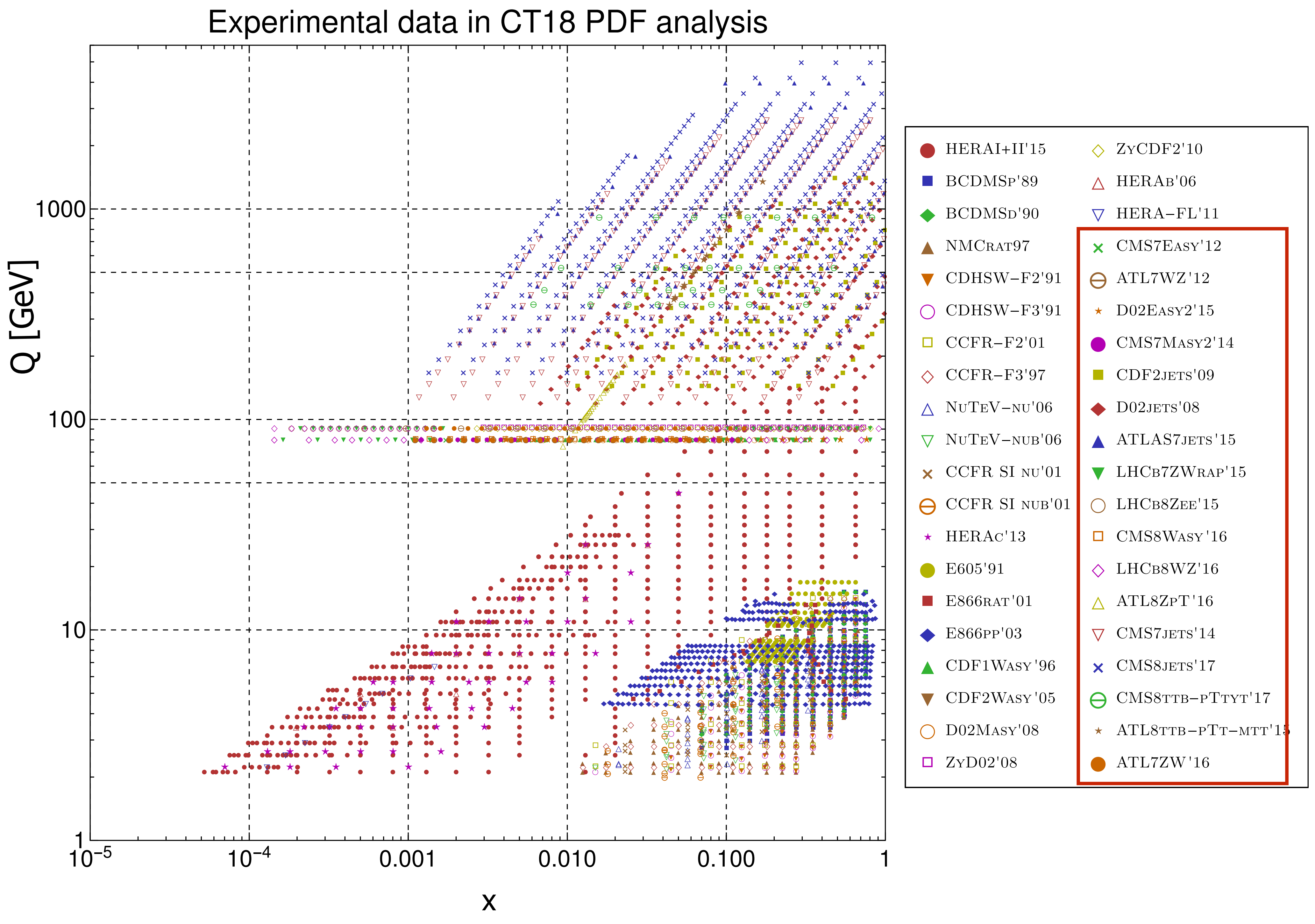

**conventionally, constraints on NP are determined using PDFs extracted from similar data sets but with pure SM assumptions**

$$\frac{d\sigma}{dp_T} = f_1(x_1) \otimes f_2(x_2) \otimes \frac{d\hat{\sigma}_{SM}}{dp_T}[1 + O(\alpha_s) + O(\alpha_{EW}) + O(\frac{1}{\Lambda^2})]$$

# Joint fit of PDFs and BSM

- Based on our framework of neural networks we performed a joint fit of PDFs and new physics beyond the SM (PDF+BSM); the later are described by EFT couplings of operators in SMEFT

full data set (CT18 as baseline) **[CTEQ-TEA, 2022]**




**focusing on BSM relevant for top pair and jet production that are both used to constrain gluon PDFs**

subset of data (top pair, jet) directly constrain EFT

| Experiments | $\sqrt{s}$(TeV) | $\mathcal{L}$(fb$^{-1}$) | observable | | $N_{pt}$ |
|---|---|---|---|---|---|
| *† LHC(Tevatron) | 7/8/13(1.96) | — | $t\bar{t}$ total cross section | [16–21] | 8 |
| *† ATLAS $t\bar{t}$ | 8 | 20.3 | 1D dis. in $p_{T,t}$ or $m_{t\bar{t}}$ | [22] | 15 |
| *† CMS $t\bar{t}$ | 8 | 19.7 | 2D dis. in $p_{T,t}$ and $y_t$ | [23] | 16 |
| CMS $t\bar{t}$ | 8 | 19.7 | 1D dis. in $m_{t\bar{t}}$ | [24] | 7 |
| *† ATLAS $t\bar{t}$ | 13 | 36 | 1D dis. in $m_{t\bar{t}}$ | [25] | 7 |
| *† CMS $t\bar{t}$ | 13 | 35.9 | 1D dis. in $m_{t\bar{t}}$ | [26] | 7 |
| *† CDF II inc. jet | 1.96 | 1.13 | 2D dis. in $p_T$ and $y$ | [27] | 72 |
| *† D0 II inc. jet | 1.96 | 0.7 | 2D dis. in $p_T$ and $y$ | [28] | 110 |
| *† ATLAS inc. jet | 7 | 4.5 | 2D dis. in $p_T$ and $y$ | [29] | 140 |
| *† CMS inc. jet | 7 | 5 | 2D dis. in $p_T$ and $y$ | [30] | 158 |
| * CMS inc. jet | 8 | 19.7 | 2D dis. in $p_T$ and $y$ | [31] | 185 |
| † CMS dijet | 8 | 19.7 | 3D dis. in $p_T^{ave.}$, $y_b$ and $y^*$ | [32] | 122 |
| † CMS inc. jet | 13 | 36.3 | 2D dis. in $p_T$ and $y$ | [8] | 78 |

theoretical calculations

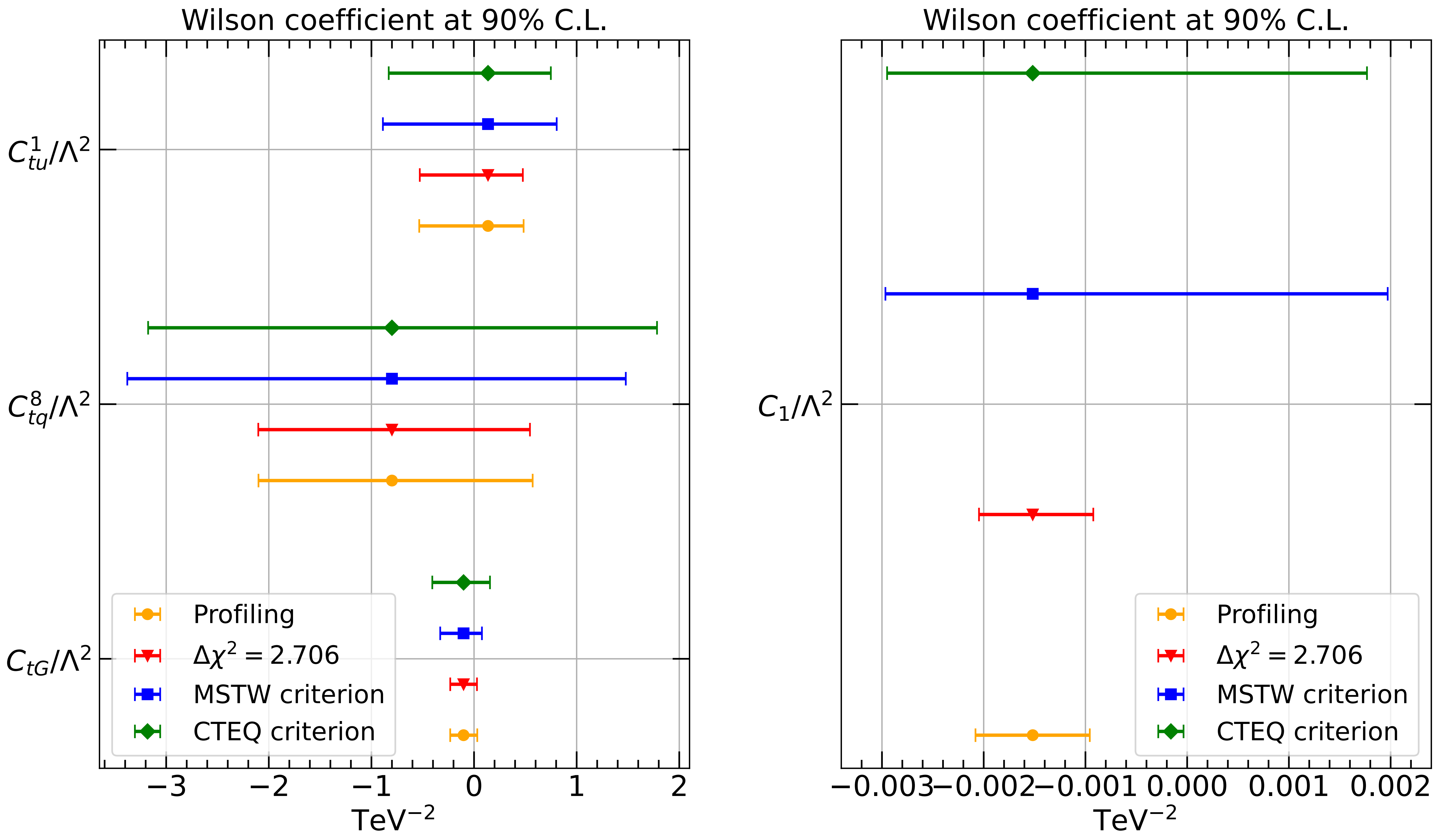
$$\frac{d\sigma}{d\mathcal{O}} = \frac{d\sigma_{\rm SM}}{d\mathcal{O}} + \sum_i \frac{d\tilde{\sigma}_i}{d\mathcal{O}}\frac{C_i}{\Lambda^2} + \sum_{i,j} \frac{d\tilde{\sigma}_{ij}}{d\mathcal{O}}\frac{C_iC_j}{\Lambda^4}$$

| observable | $\mu_0$ | SM QCD | SM EW | SMEFT QCD | th. unc. |
|---|---|---|---|---|---|
| $t\bar{t}$ total | $m_t$ | NNLO+NNLL | no | NLO | $\mu_{F,R}$ var. |
| $t\bar{t}$ $p_T$ dist. | $m_T/2$ | NNLO | NLO | NLO | $\mu_{F,R}$ var. |
| $t\bar{t}$ $m_{t\bar{t}}$ dist. | $H_T/4$ | NNLO(+NLP) | NLO | NLO | $\mu_{F,R}$ var. |
| $t\bar{t}$ 2D dist. | $H_T/4$ | NNLO | no | NLO | no |
| inc. jet | $p_{T,j}$ | NNLO | NLO | NLO | 0.5% uncor. |
| dijet | $m_{jj}$ | NNLO | NLO | NLO | 0.5% uncor |

# Correlations of PDFs and BSM are mild

- Unbiased results on four-quark and gluonic operators are obtained using global data sets with different tolerance criteria; current correlations between EFT and PDFs in global analyses are found to be mild

SMEFT coefficients extracted




$$O^1_{tu} = \sum_{i=1}^{2} (\bar{t}\gamma_\mu t)\,(\bar{u}_i\gamma^\mu u_i)\ ,$$

$$O^1_{td} = \sum_{i=1}^{3} (\bar{t}\gamma^\mu t)\,(\bar{d}_i\gamma_\mu d_i)\ ,$$

$$O_1 = 2\pi \left(\sum_{i=1}^{3} \bar{q}_{Li}\gamma_\mu q_{Li}\right)\left(\sum_{j=1}^{3} \bar{q}_{Lj}\gamma^\mu q_{Lj}\right)$$

$$O_{tG} = ig_s(\bar{Q}_{L,3}\tau^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} + \text{h.c.}\,,$$

$$O^8_{tq} = \sum_{i=1}^{2}(\bar{Q}_i\gamma_\mu T^A Q_i)(\bar{t}\gamma^\mu T^A t)\,,$$

SMEFT Operators

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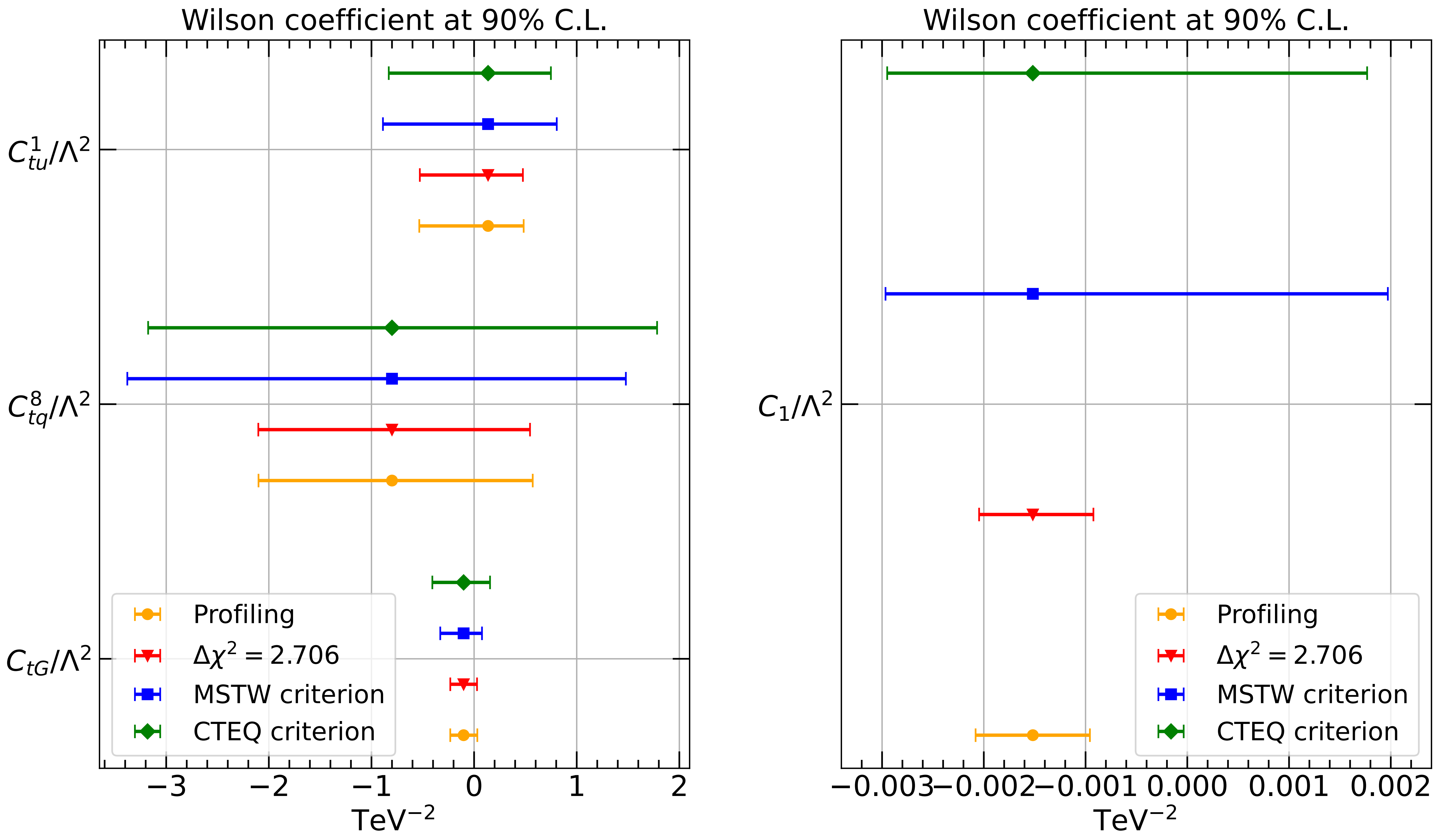
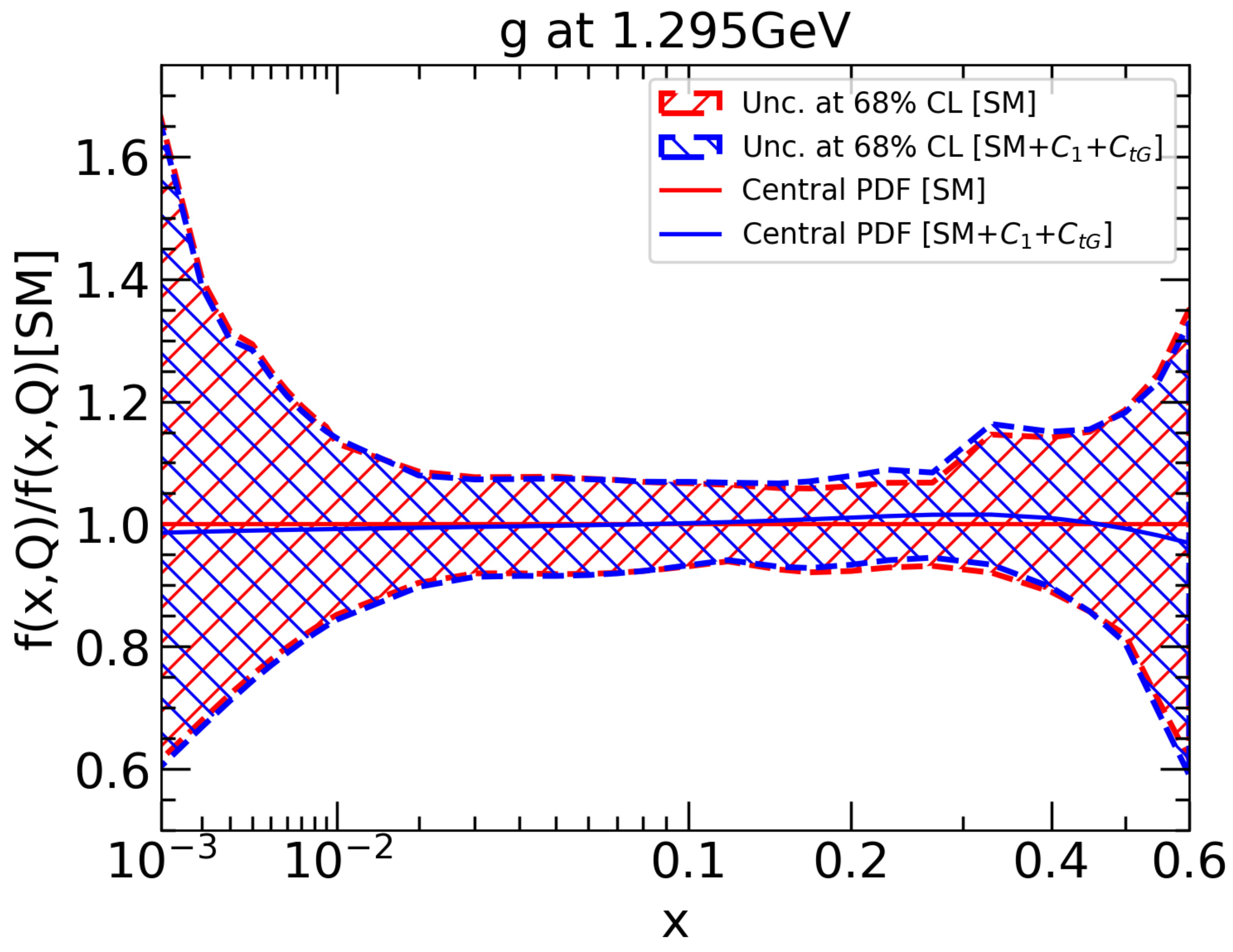



gluon PDFs from SM/SM+EFT fits

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SMEFT Operators

**PDFs are essentially unchanged indicating weak correlations between PDF and BSM, and robustness of global analysis of QCD due to variety of experimental data**

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# Summary

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- Strange-quark PDFs are slightly suppressed at x~0.02 as now supported by both DIS and LHC data

- PDF uncertainties are one of the dominant theoretical uncertainties in direct measurements of the W boson mass; variations due to PDFs are much smaller than discrepancies seen in the CDF measurement

- Correlations between gluon PDFs and BSM effects in global analyses with top-quark pair and jet production data are mild, indicating robustness of the global analyses of PDFs

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**Thank you for your attention!**