Global analysis of QCD and SMEFT boosted with Machine Learnings

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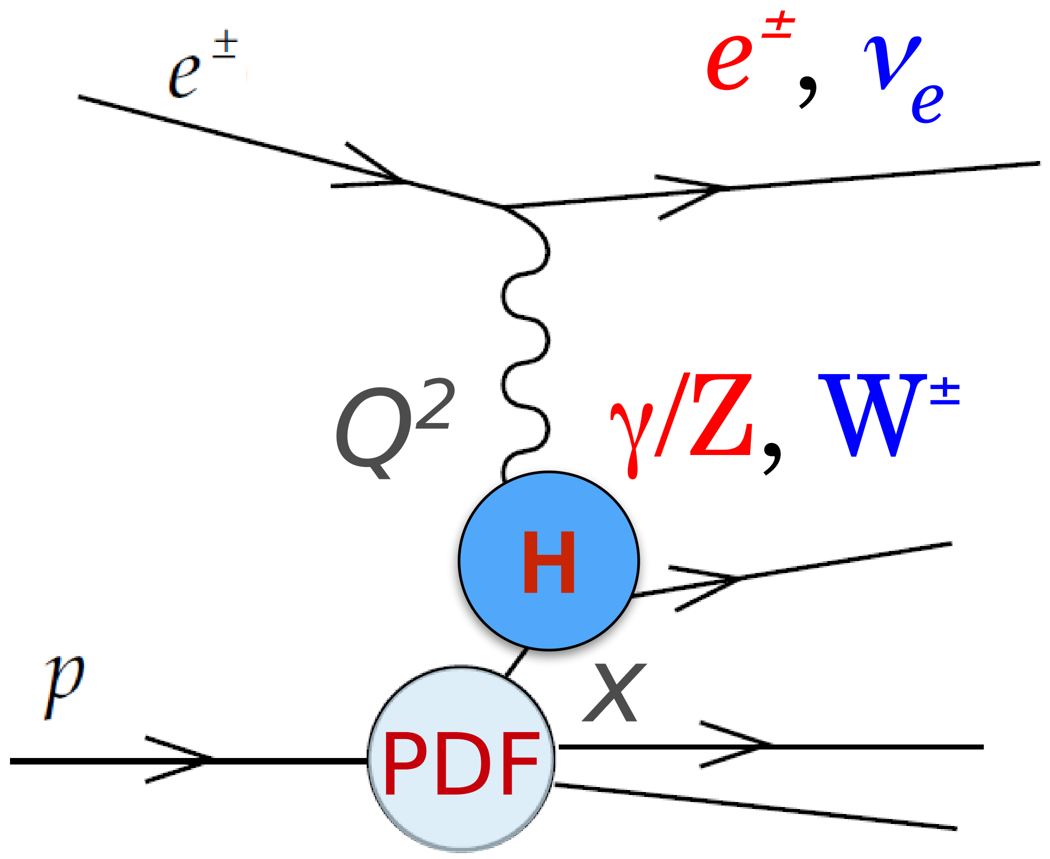
Outline

- 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

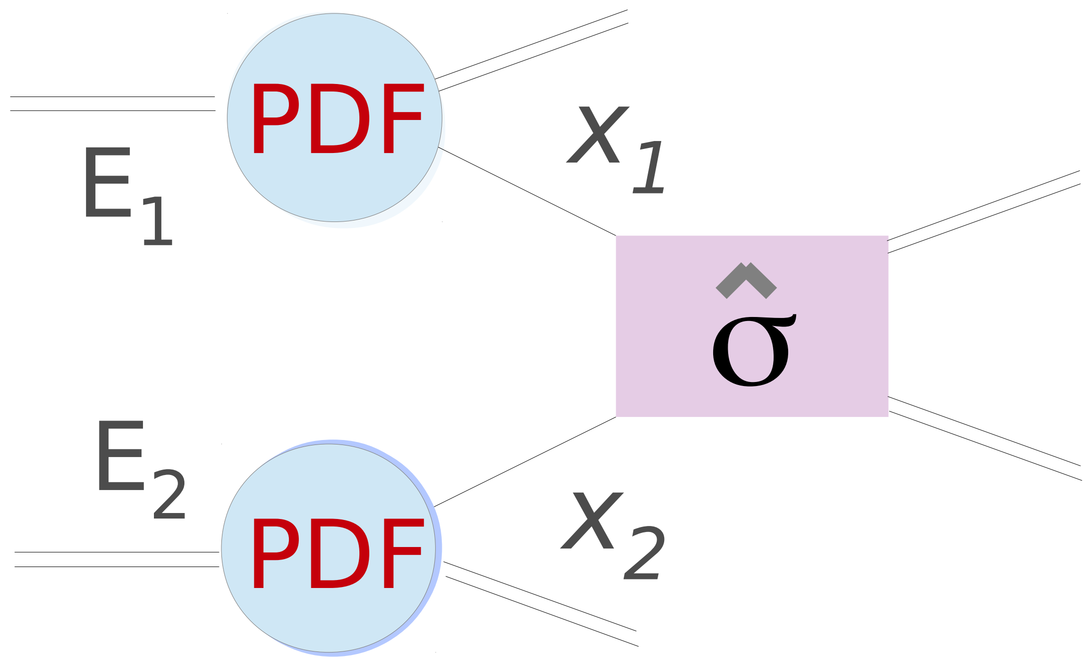
QCD collinear factorization

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

DIS structure functions



hadron-hadron collision



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

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

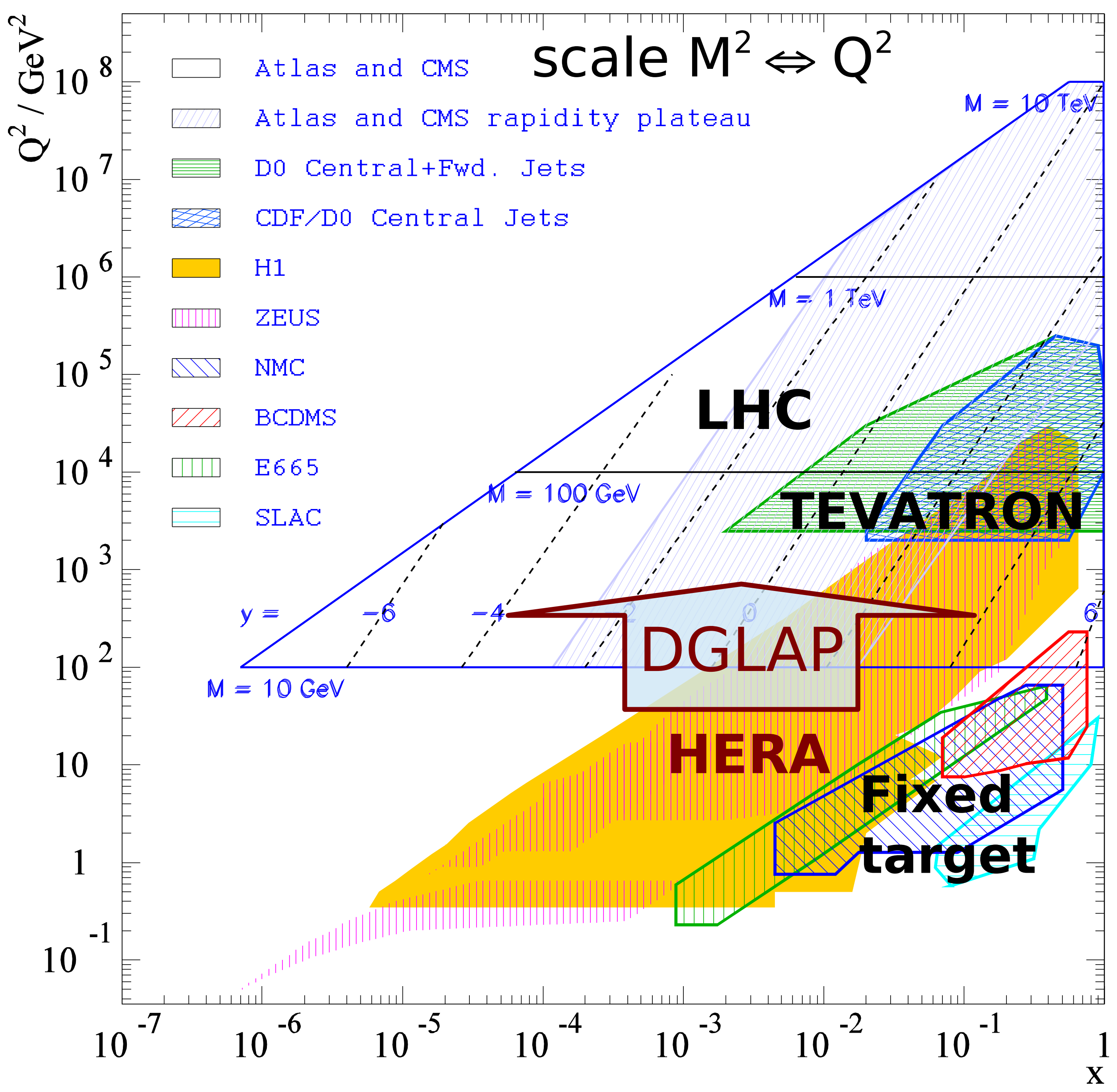
[Collins, Soper, Sterman, 1989]

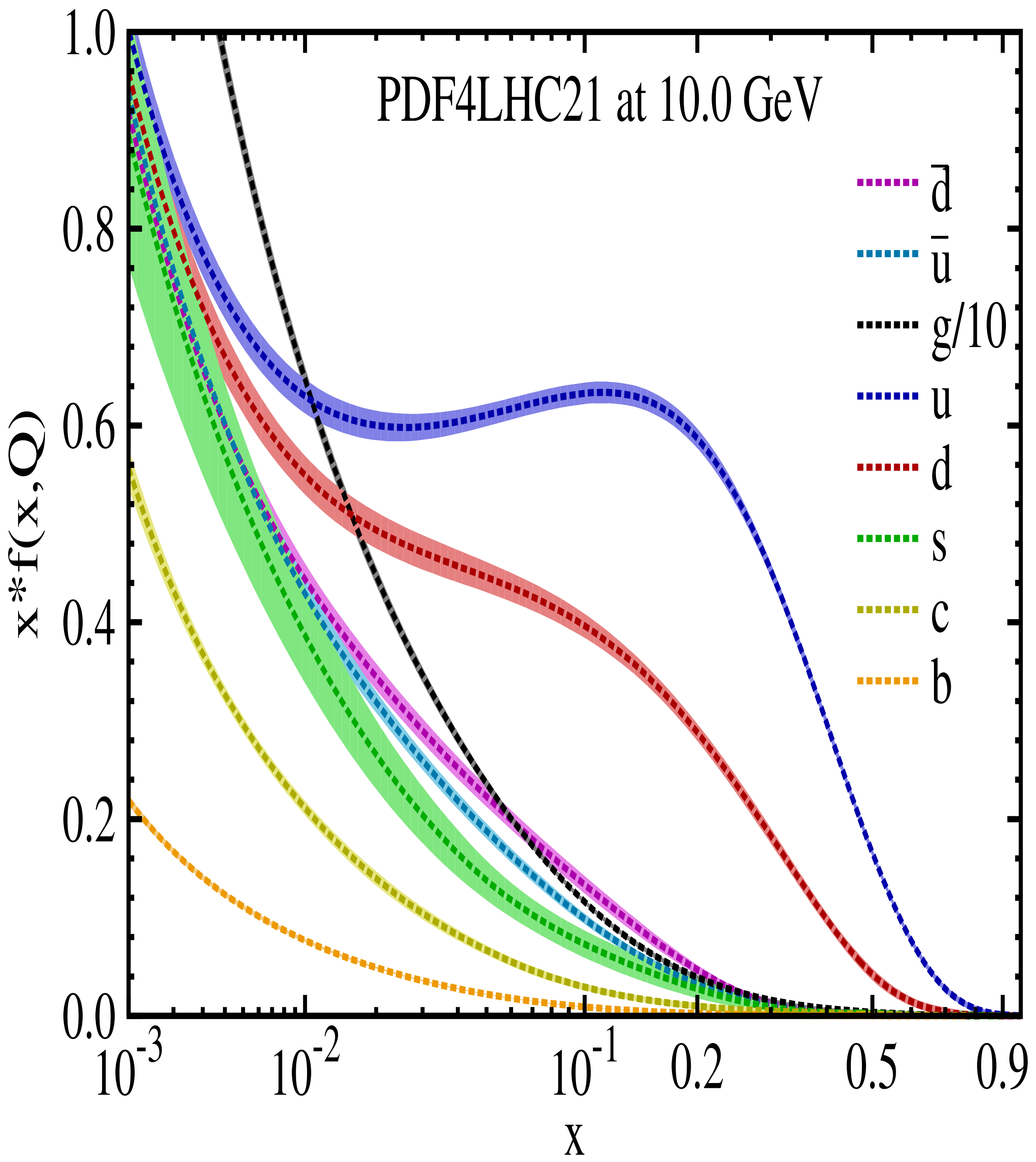
- coefficient functions, hard scattering; infrared (IR) safe, calculable in pQCD, independent of the hadron
- PDFs, reveal inner structure of hadrons; non-perturbative (NP) origin, universality, e.g. DIS vs. pp collisions
- factorization scale μ_f
- runnings of $f_{i/h}$ with μ_f are governed by the 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 JG, Harland-Lang, Rojo 1709.04922 for review article]**





parameter variations

α_S(Mz)

Mc, Mb, Mt

QCD/EW corrections

nuclear corrections

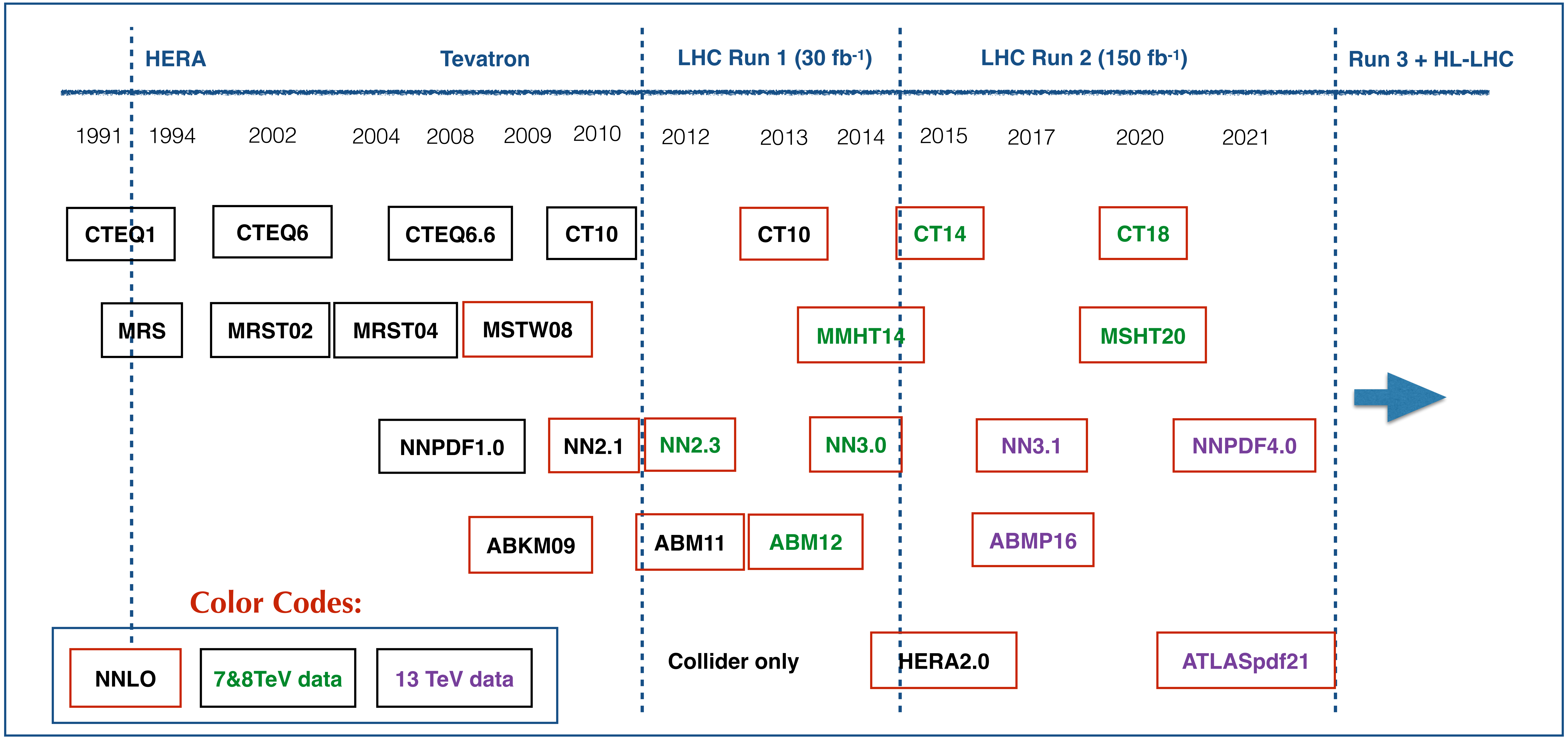
EW parameters

New Physics

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

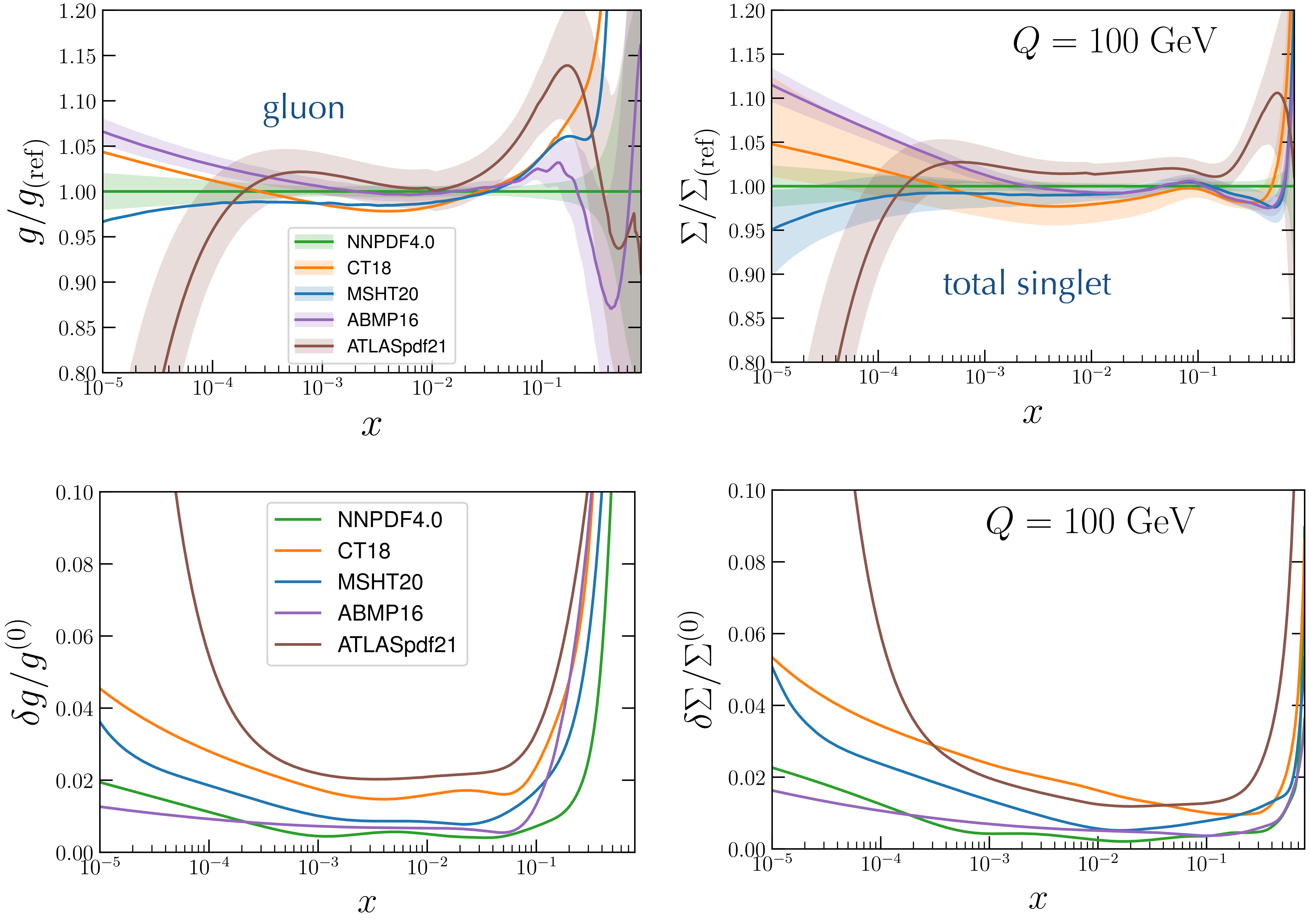


must have as many independent analyses as possible to have a faithful determination of PDFs and their uncertainties; state of the art PDFs are extracted at NNLO in QCD (+NLO EW) and with numerous LHC data

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
- 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

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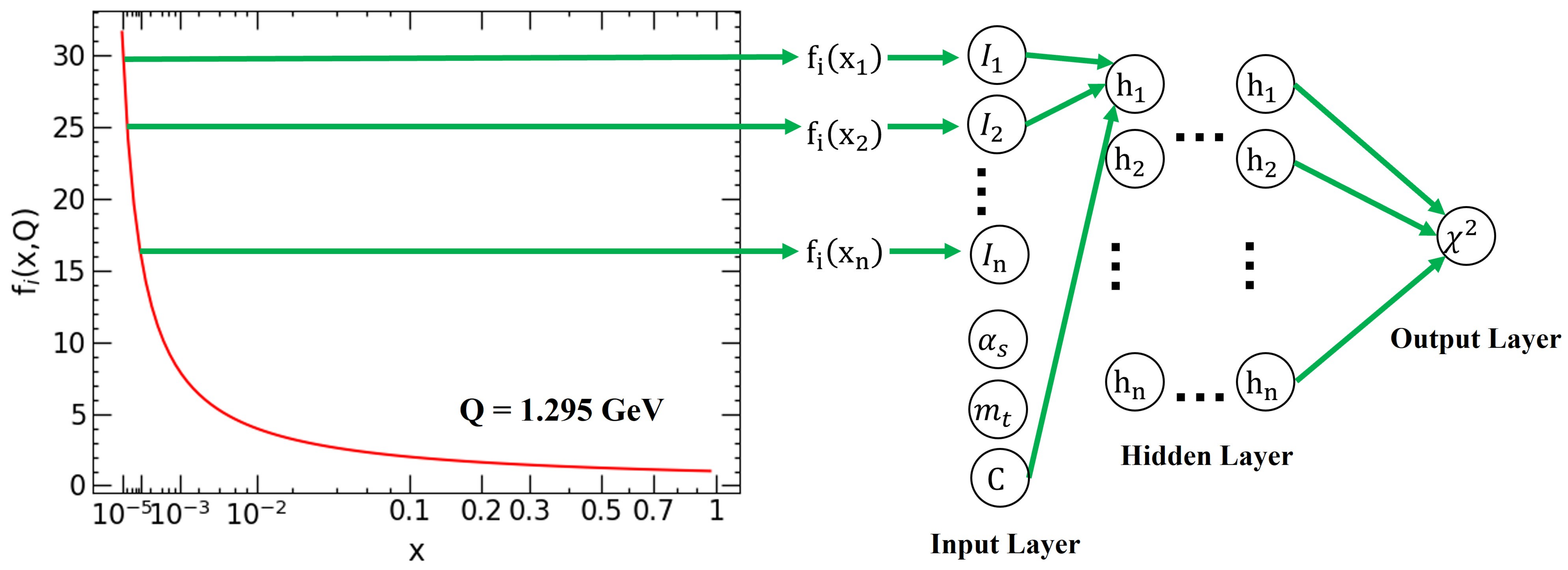
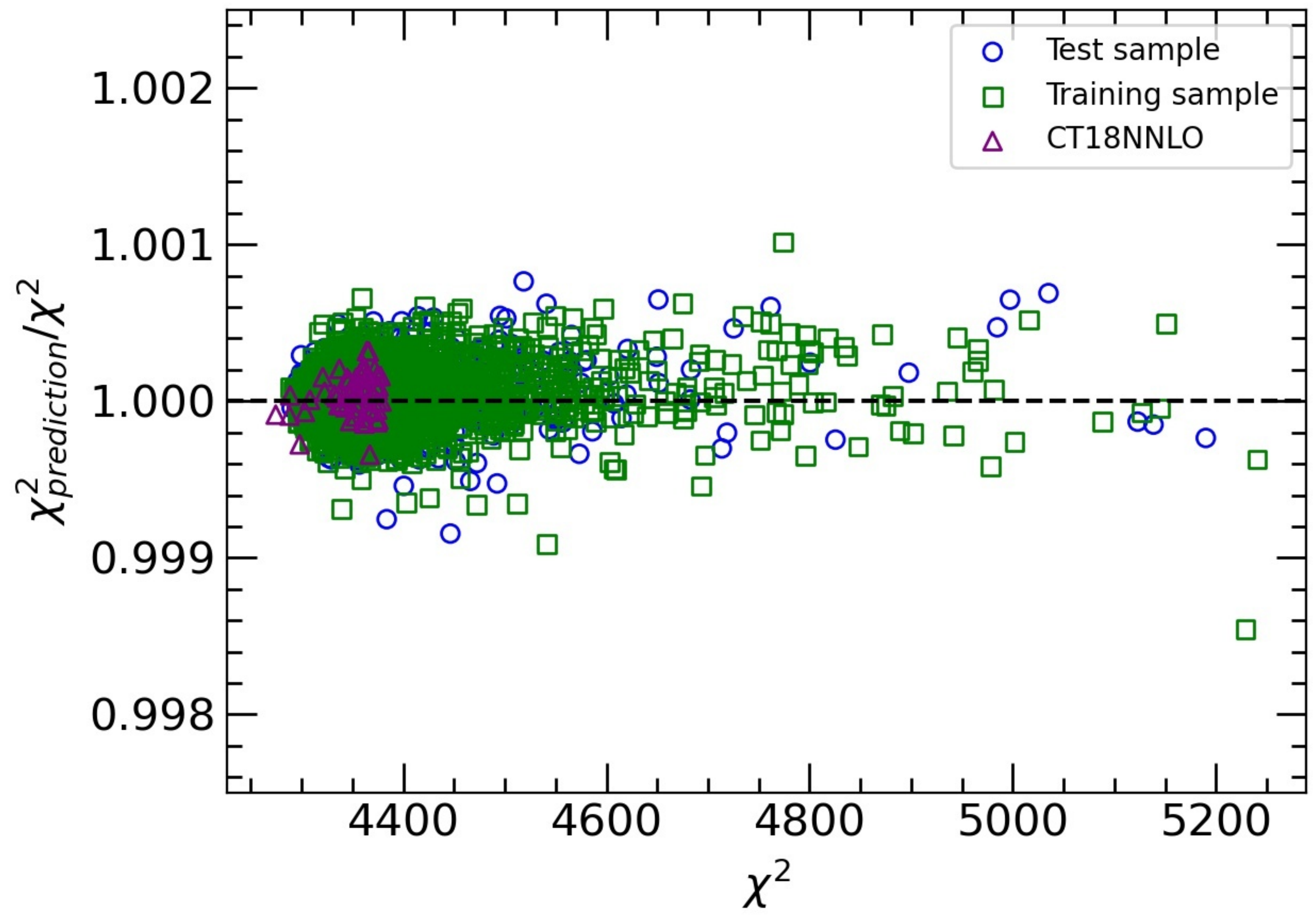
Global analysis with Machine Learnings

- We developed an efficient framework of using neural networks and machine learnings to modeling dependencies of the log-likelihood functions (χ^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



modeling accuracy



- multi-layer NNs with discretized PDFs as input; trained with a large sample from CT18 MC PDFs
- reproduction accuracy of χ^2 better than one per mille
- almost costless comparing to traditional methods that requires extensive calculations of cross sections

computing efficiency per parameter point

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

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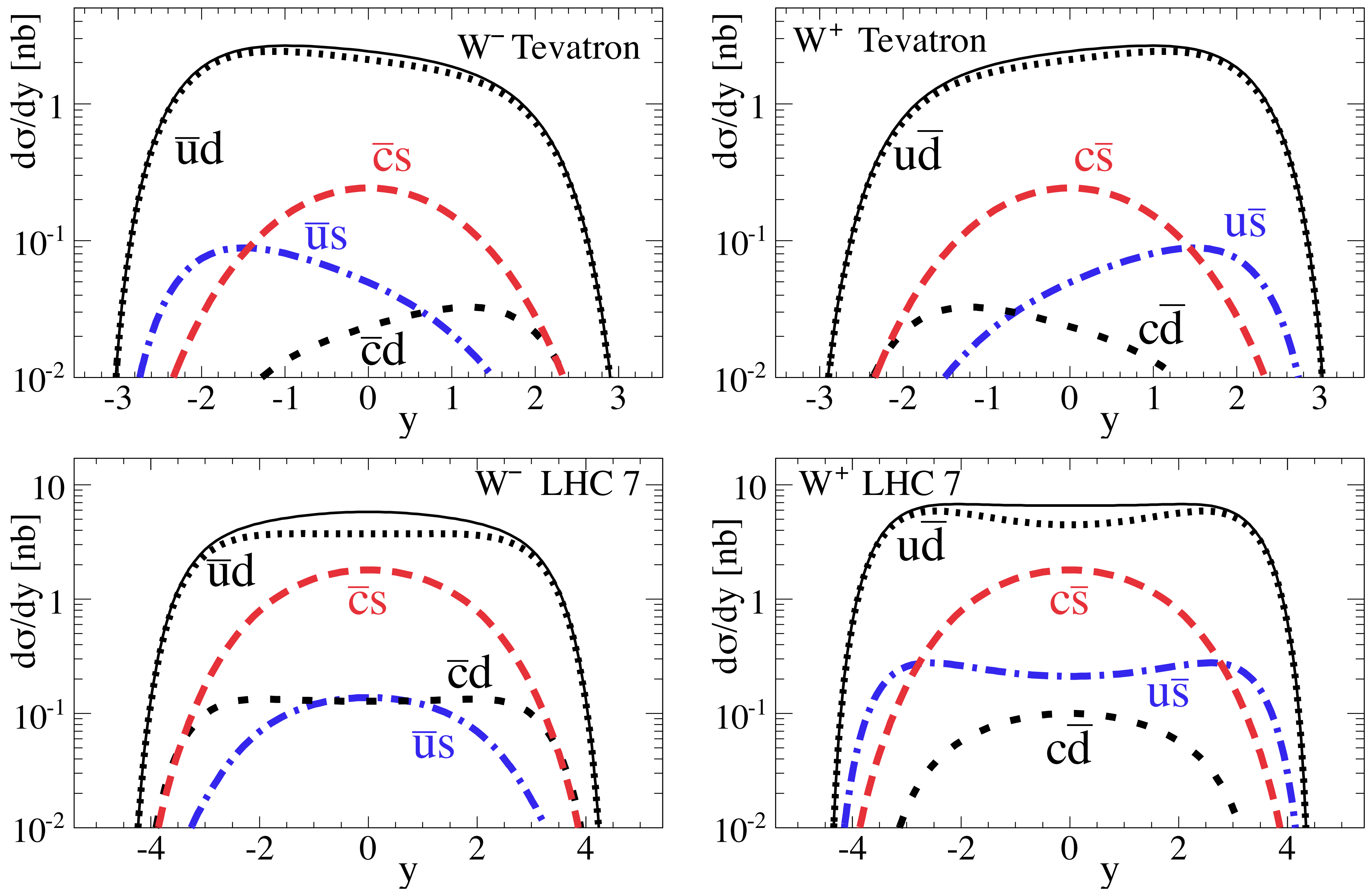
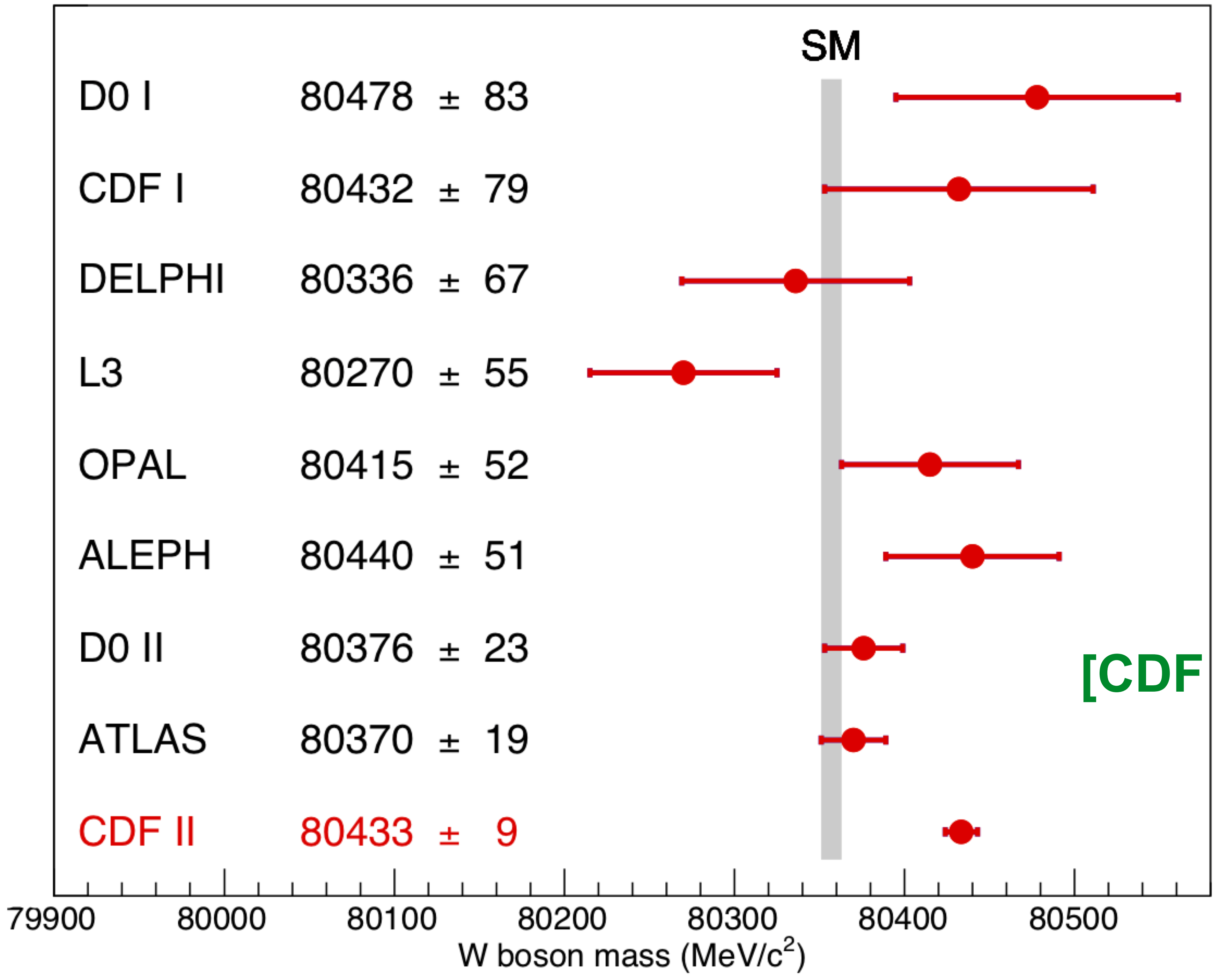
Question 1: PDF uncertainties in W-mass direct measurements

- 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]**



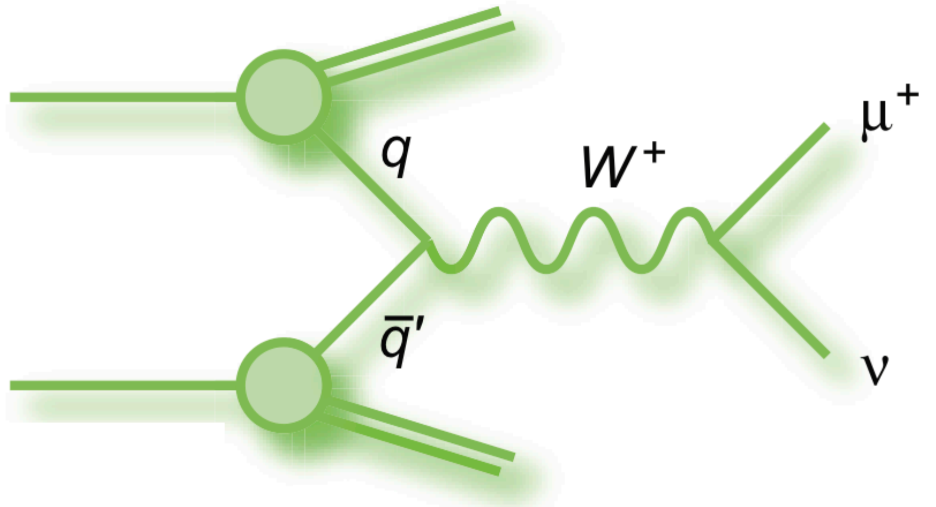
W boson mass from different experiments



[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)]

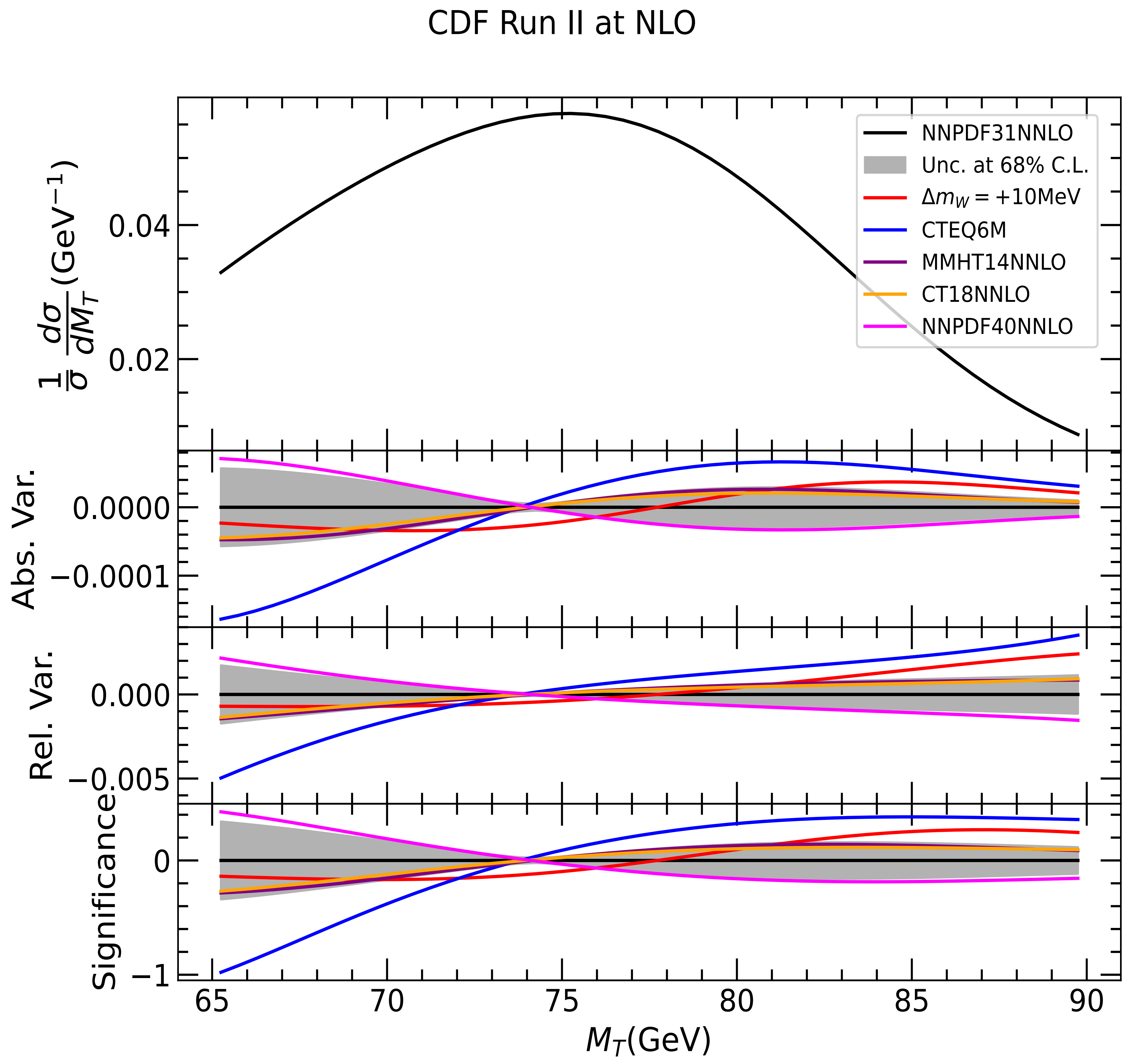
PDF unc. of CDF / ATLAS / LHCb: 3.9 / 8 / 9 MeV

PDF variations can not explain CDF discrepancy

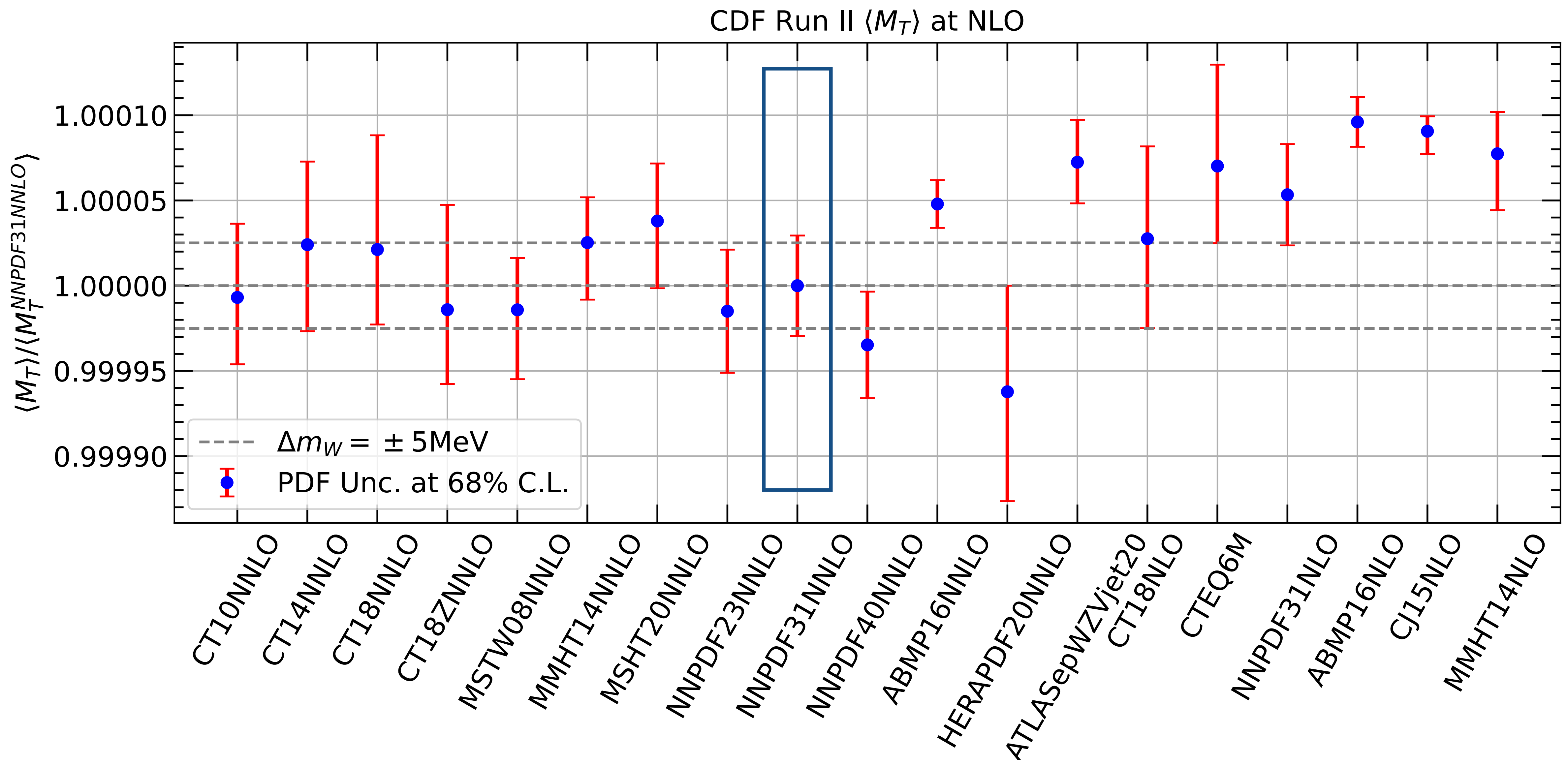
- We estimate shift of extracted W boson mass induced by variation of PDFs, and the associated PDF uncertainty for a variety of PDFs, focusing on the kinematic variable of transverse mass at CDF

[JG, DY Liu, KP Xie, 2205.03942]

normalized m_T distribution
PDF var. vs. M_W var.



mean value of m_T



estimated shift and PDF unc. of W mass

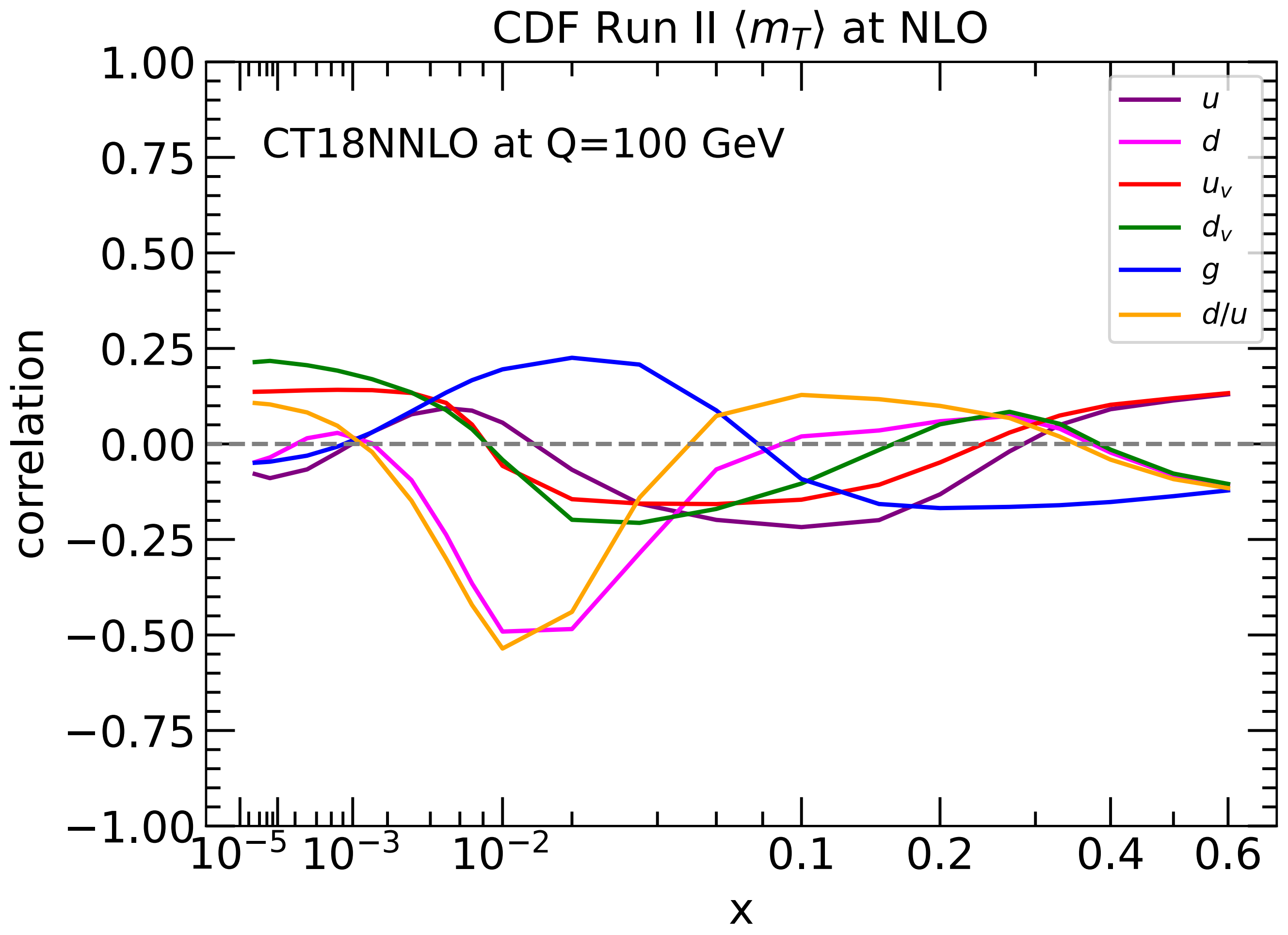
δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT2014	NNPDF4.0	MSHT2020
$\langle M_T\rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$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

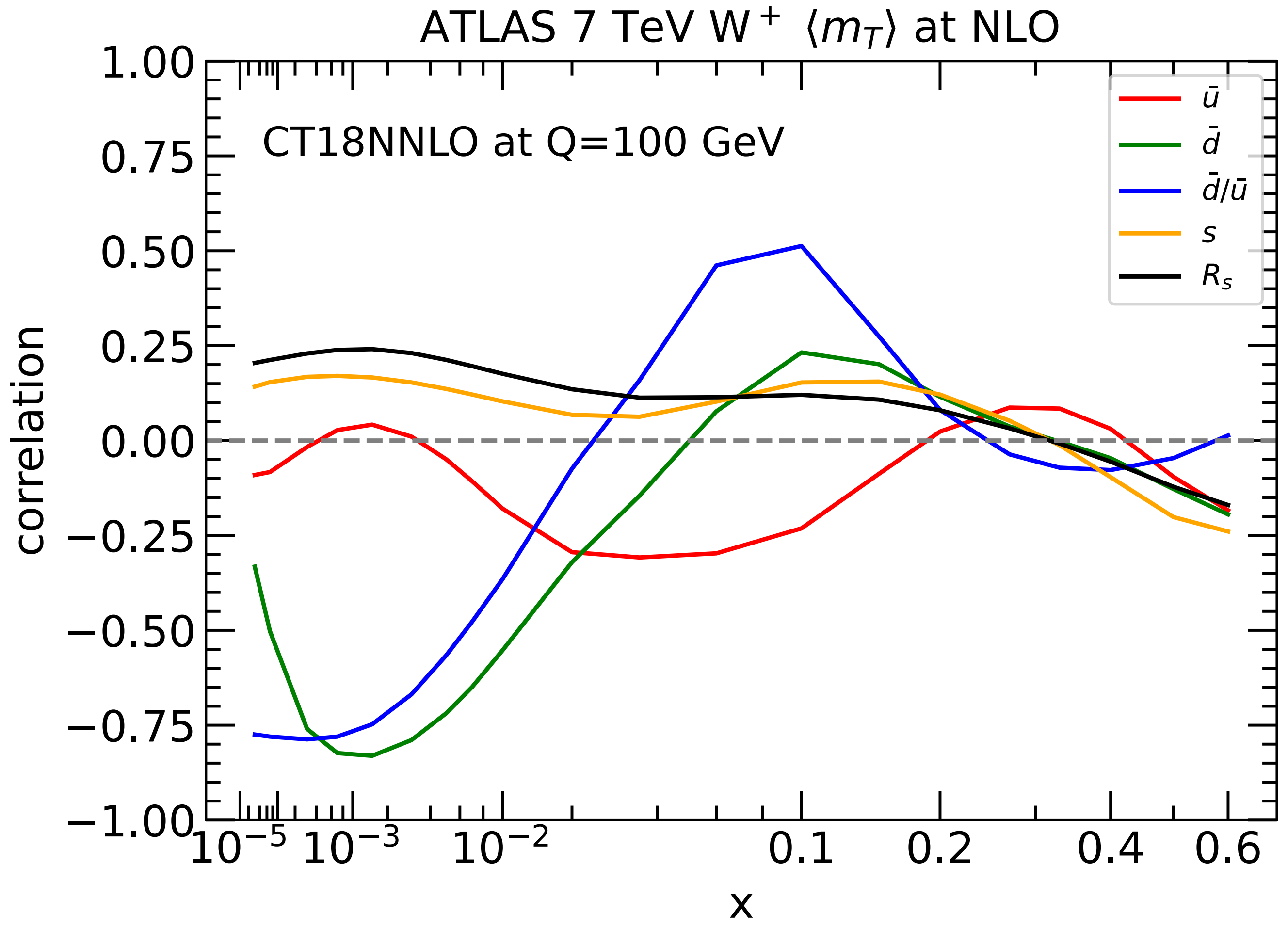
PDF variations can not explain CDF discrepancy

- 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

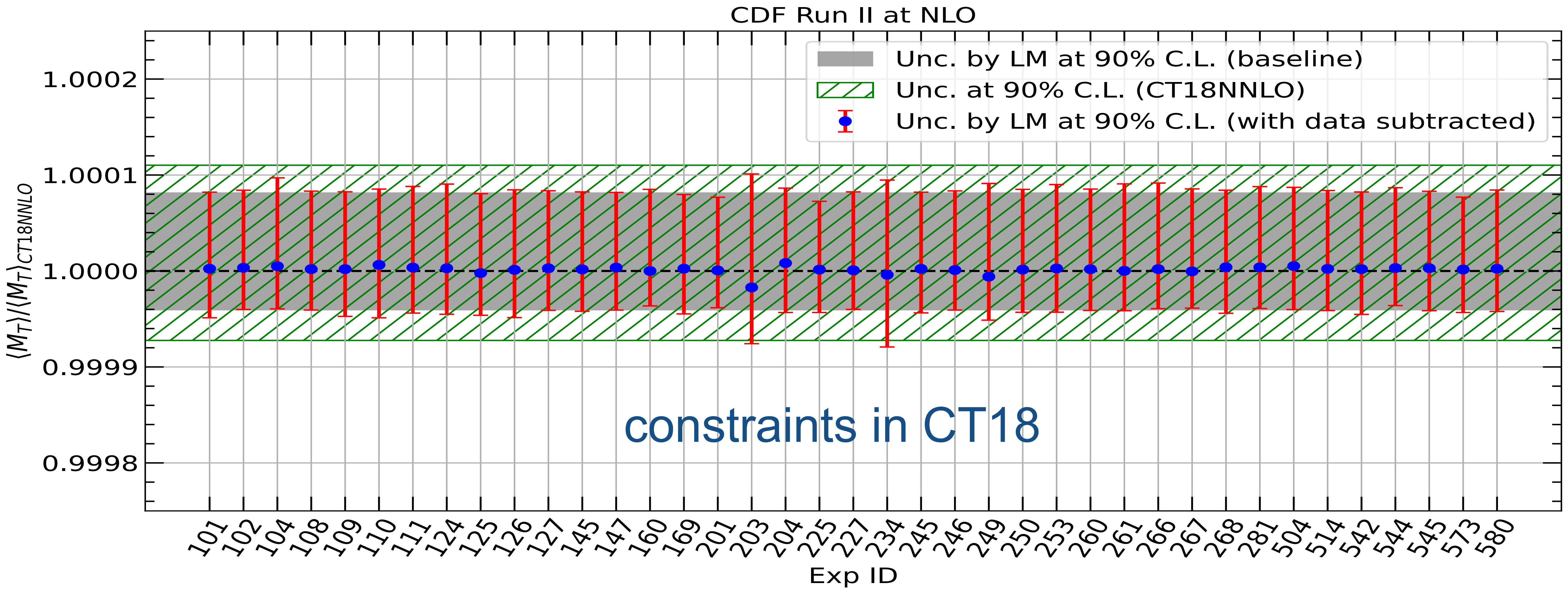
PDF induced correlations

[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



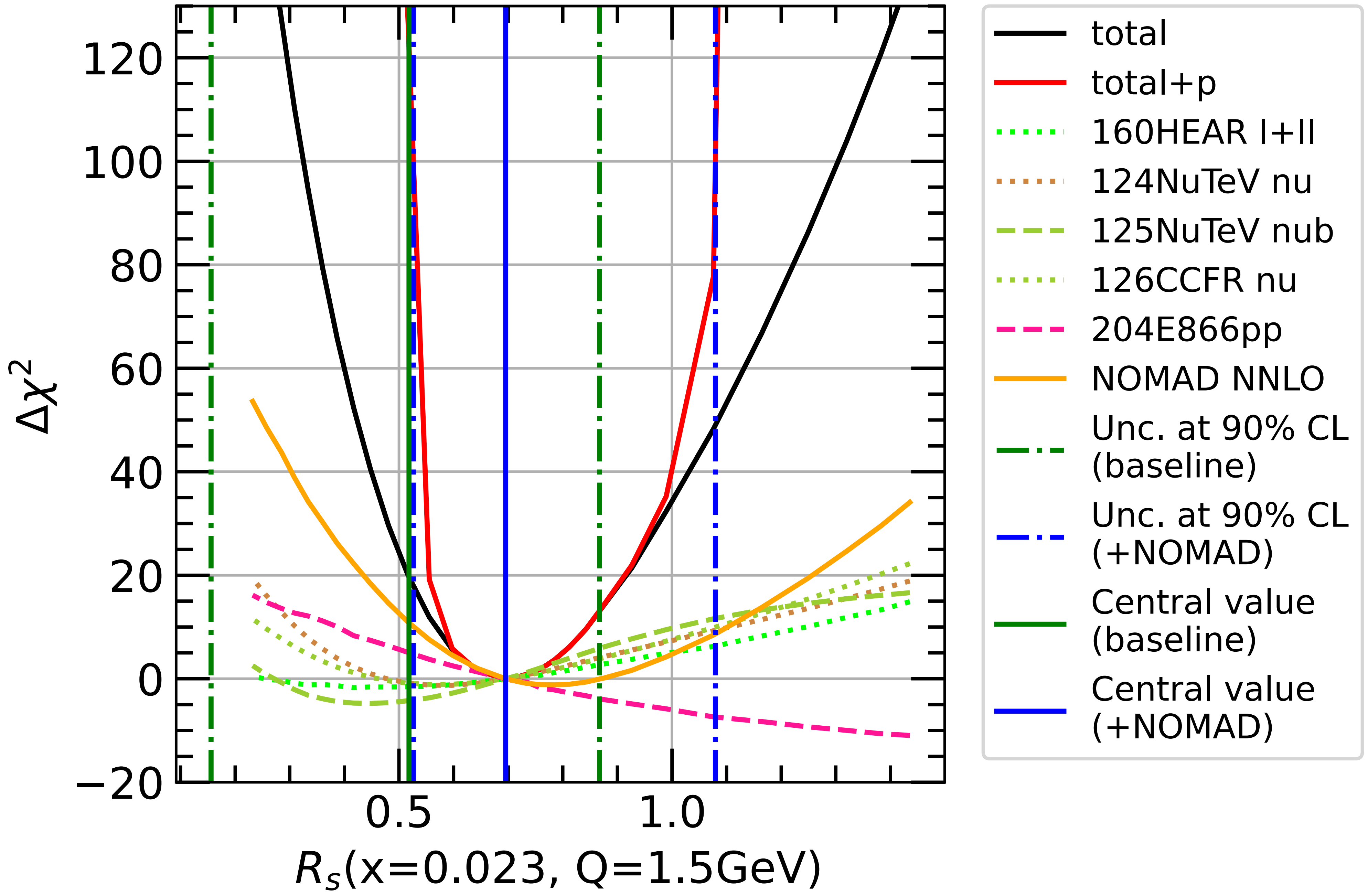
- m_T at CDF is largely constrained by the DIS and Drell-Yan data on deuteron target, the Tevatron lepton charge asymmetry data; at ATLAS also the CMS charge asymmetry data

Strangeness is moderately suppressed

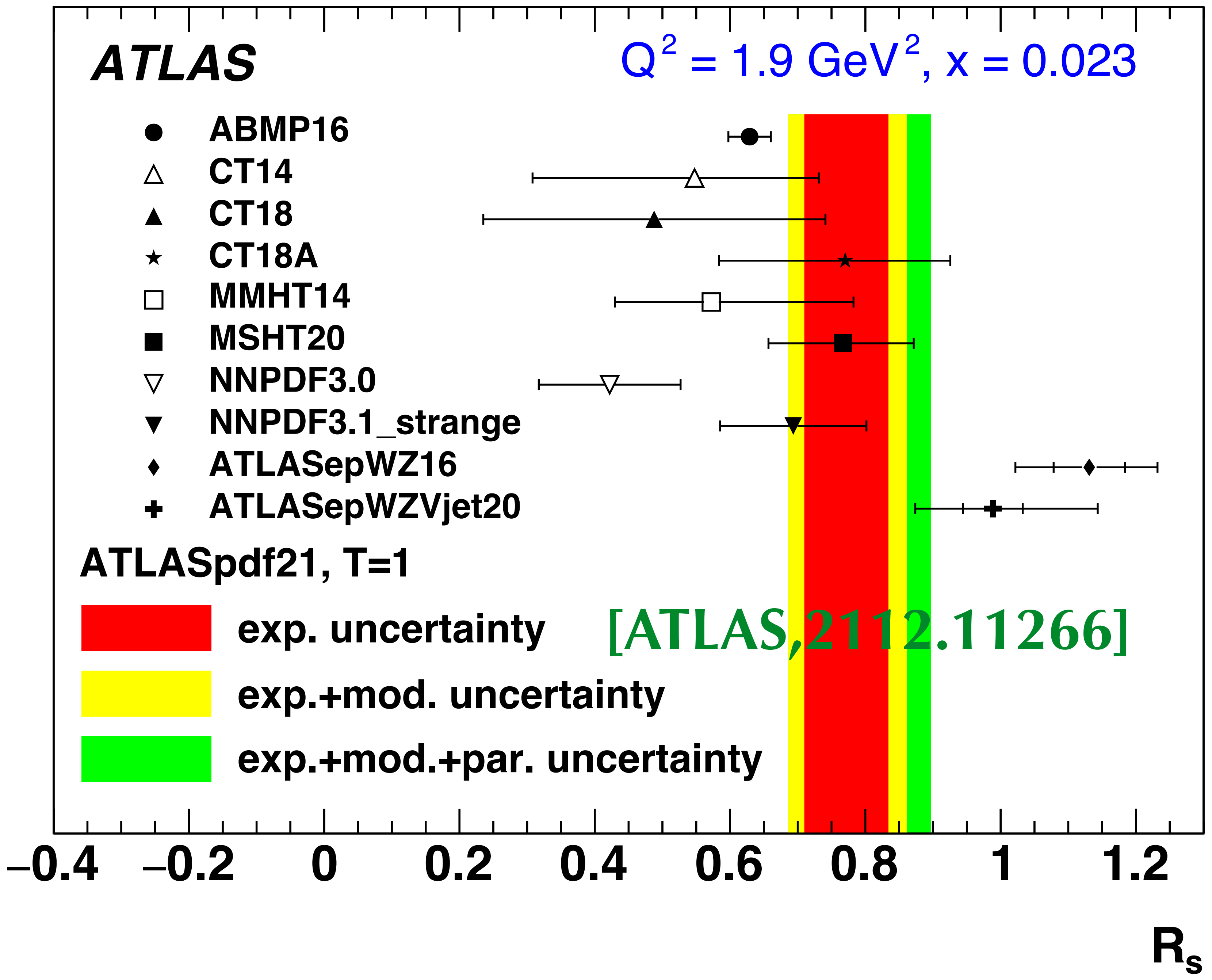
- We include NOMAD data into a global analysis of PDFs (CT18 as the baseline), and analysis its impact to PDFs, especially focusing on strange-quark PDF and strange to light sea-quark ratio Rs=(s+sb)/(ub+db)

[JG, DY Liu, CL Sun 2201.06586]

LM scans on Rs



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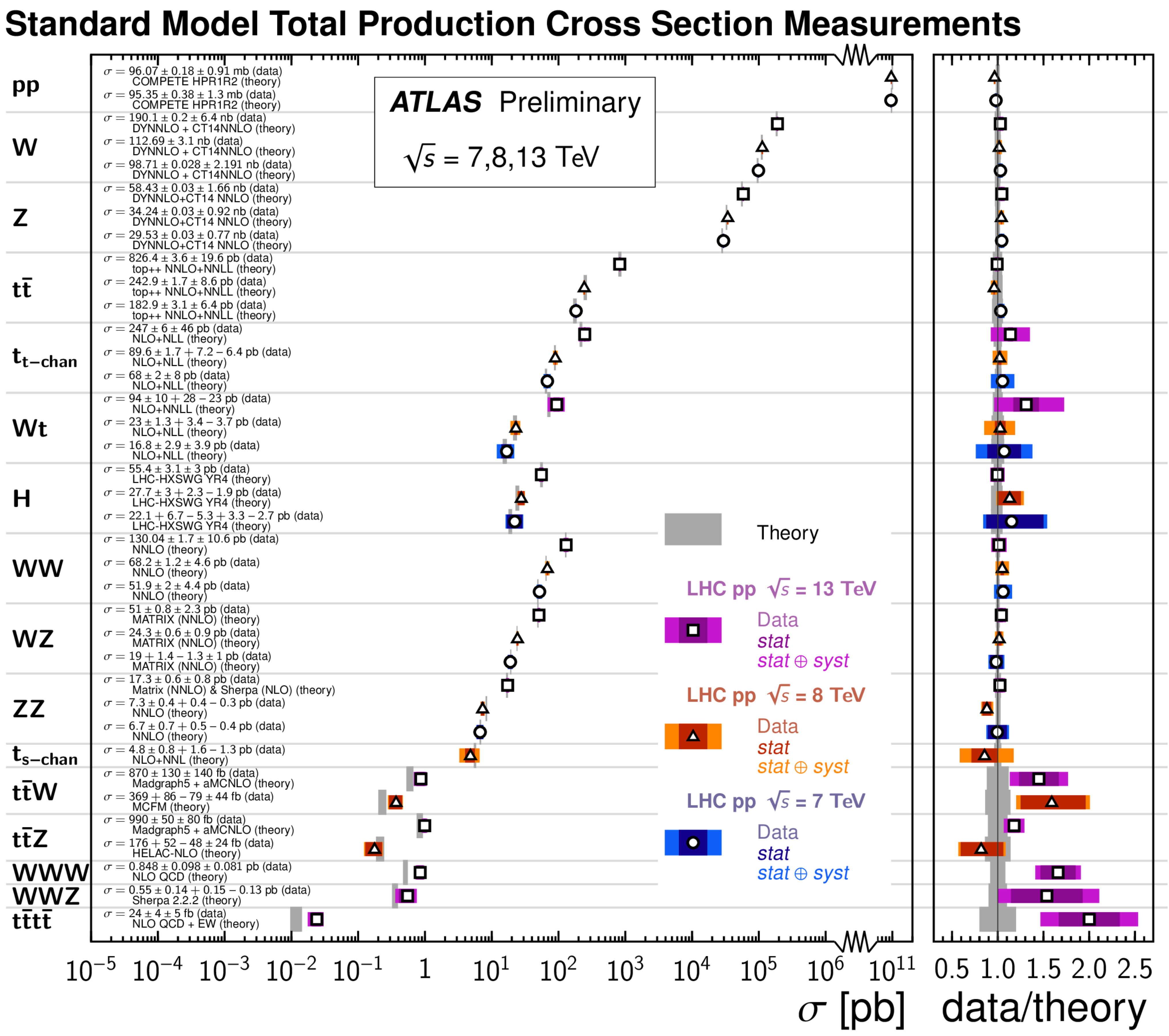
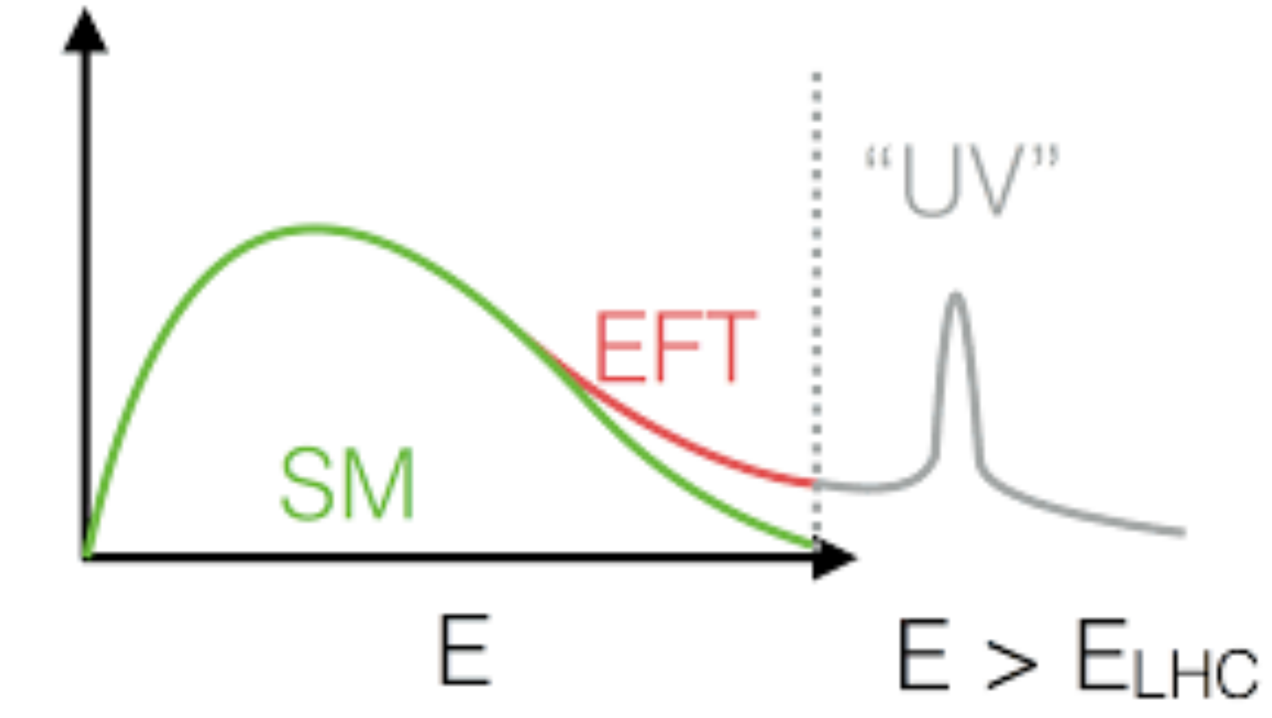
Question 2: PDF bias in searches of new physics at the LHC

- 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

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



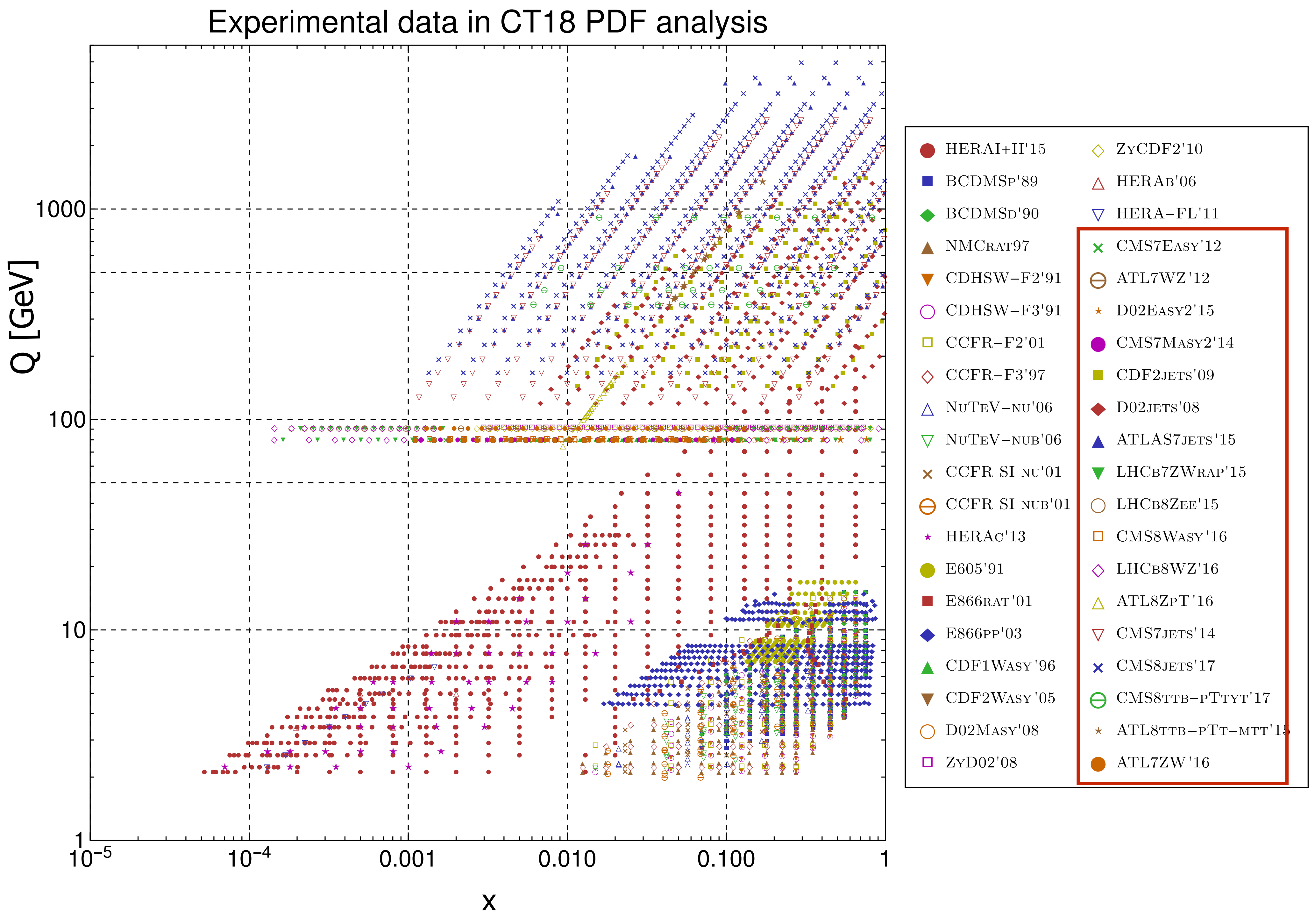
conventionally, constraints on NP are determined using PDFs extracted from similar data sets but with pure SM assumptions

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

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) **[JG, DY Liu+, 2022]**



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

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

Experiments	$\sqrt{s}$(TeV)	$\mathcal{L}$(fb^{-1})	observable		$N_{\rm pt}$
*† 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

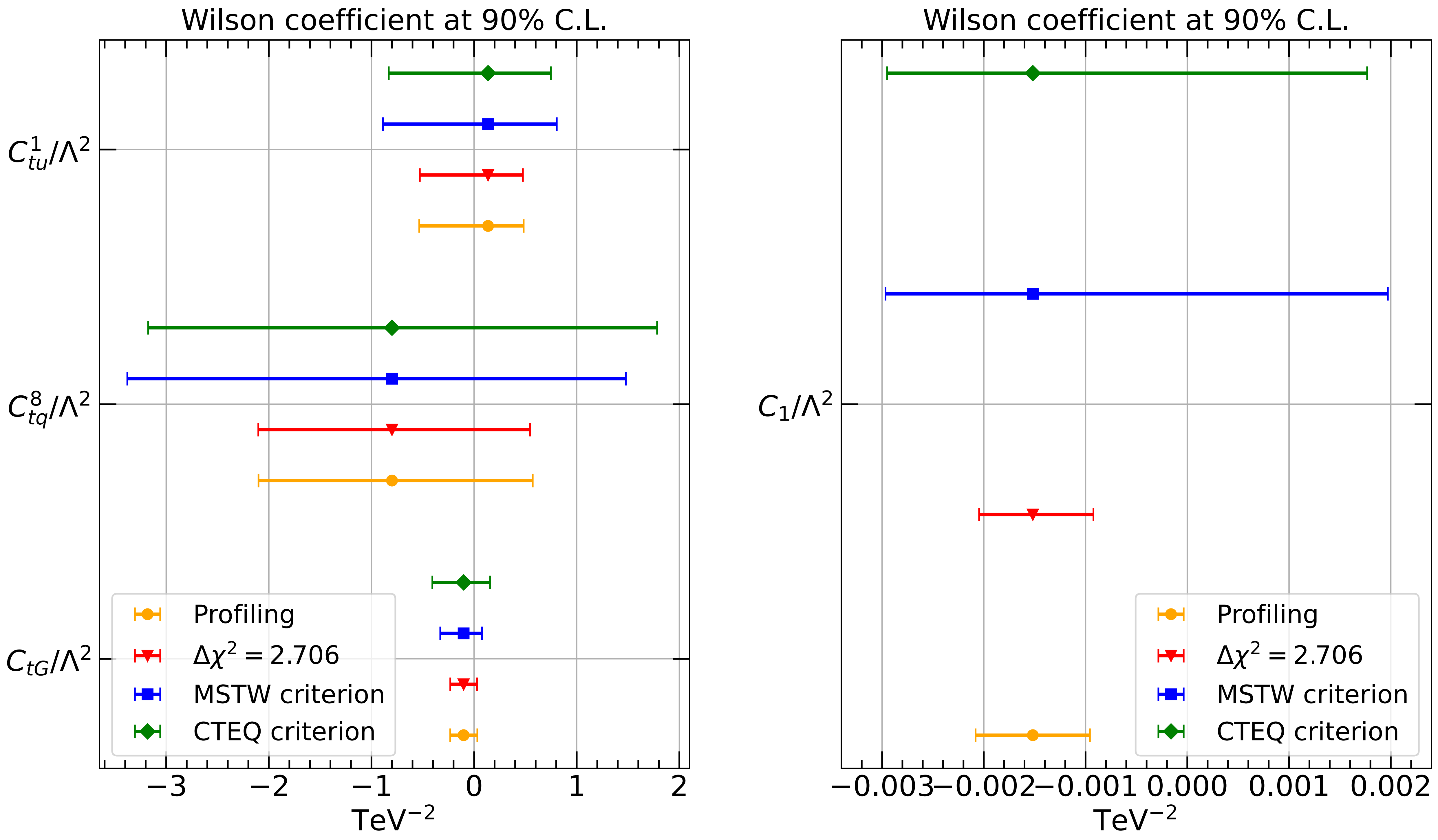
$$\frac{d\sigma}{d\mathcal{O}} = \frac{d\sigma_{\rm SM}}{d\mathcal{O}} + \sum_i \frac{d\tilde{\sigma}_i}{d\mathcal{O}}\frac{C_i}{\Lambda^2} + \sum_{i,j} \frac{d\tilde{\sigma}_{ij}}{d\mathcal{O}}\frac{C_iC_j}{\Lambda^4}$$

observable	μ_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

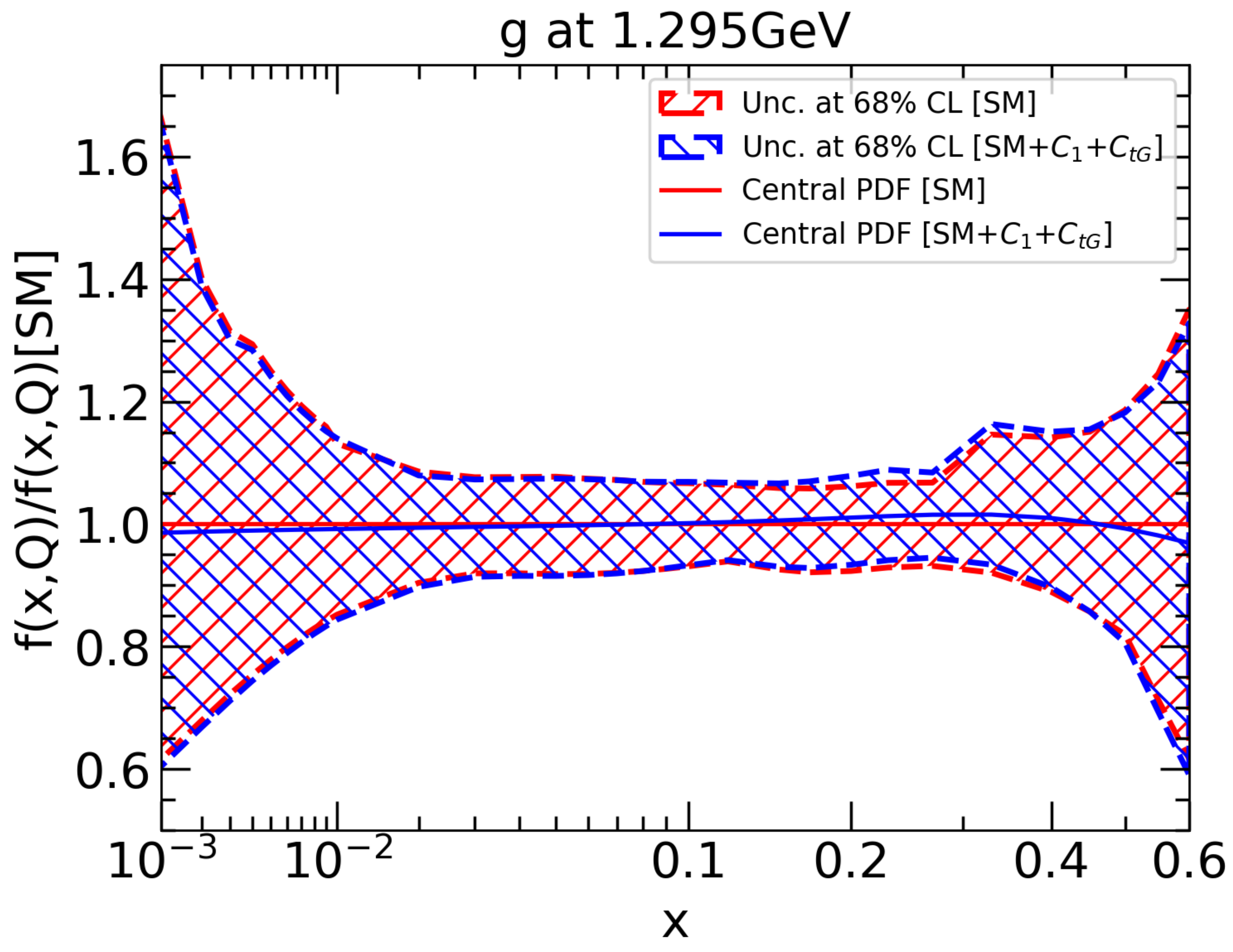
Correlations of PDFs and BSM are mild

- 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



gluon PDFs from SM/SM+EFT fits



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

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

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

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

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

SMEFT Operators

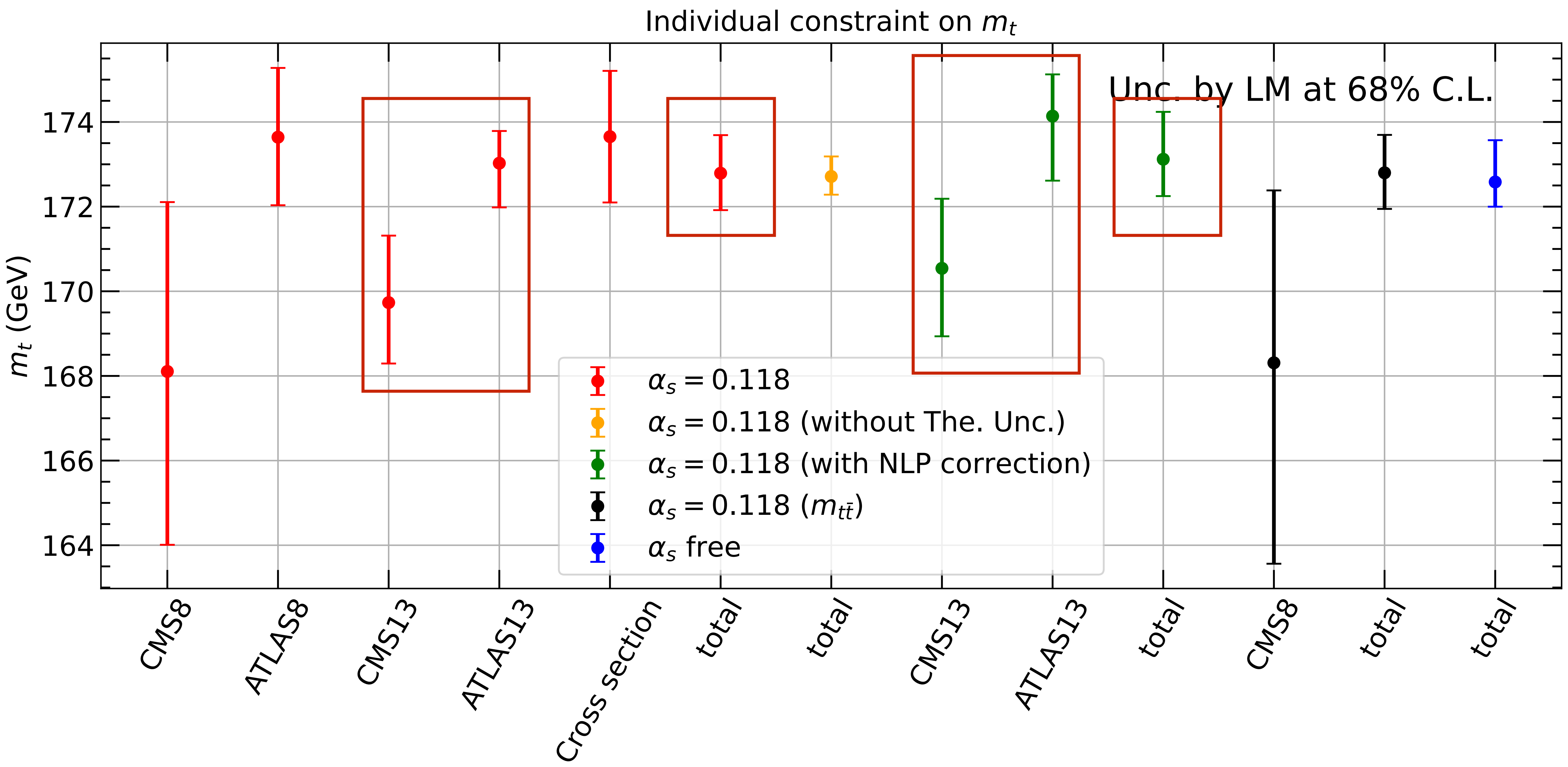
PDFs are essentially unchanged indicating weak correlations between PDF and BSM, and robustness of global analysis of QCD due to variety of experimental data

Top-quark mass from global analysis

- Meanwhile we extract the top-quark mass from the global analyses including the same data sets on total and differential cross sections of top-quark pair production **[JG, DY Liu+, 2022]**

setup	nominal	nominal	nominal	PDF fixed	no the. unc.	NLP
$\alpha_s(M_Z)$	free	0.1162	0.118	0.118	0.118	0.118
m_t(GeV)	$172.58^{+0.99}_{-0.58}$	$172.58^{+0.98}_{-0.58}$	$172.79^{+0.90}_{-0.87}$	$172.79^{+0.90}_{-0.86}$	$172.71^{+0.43}_{-0.43}$	$173.12^{+1.12}_{-0.87}$

PDG world average
172.7±0.3 GeV



top-quark pole mass extracted at various conditions

- top-mass variations induce changes on total cross sections and kinematic bins close to threshold
- individual data sets from LHC are more or less consistent with preference on the central values lower for CMS than ATLAS
- theoretical unc. (beyond NNLO) are dominant; Coulomb corrections lead to larger top mass but can not account for differences between ATLAS and CMS

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Summary

- We developed a framework of global analysis for efficient evaluation on uncertainties of QCD inputs and BSM parameters using machine learnings and neural networks

- 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 of the CDF measurement

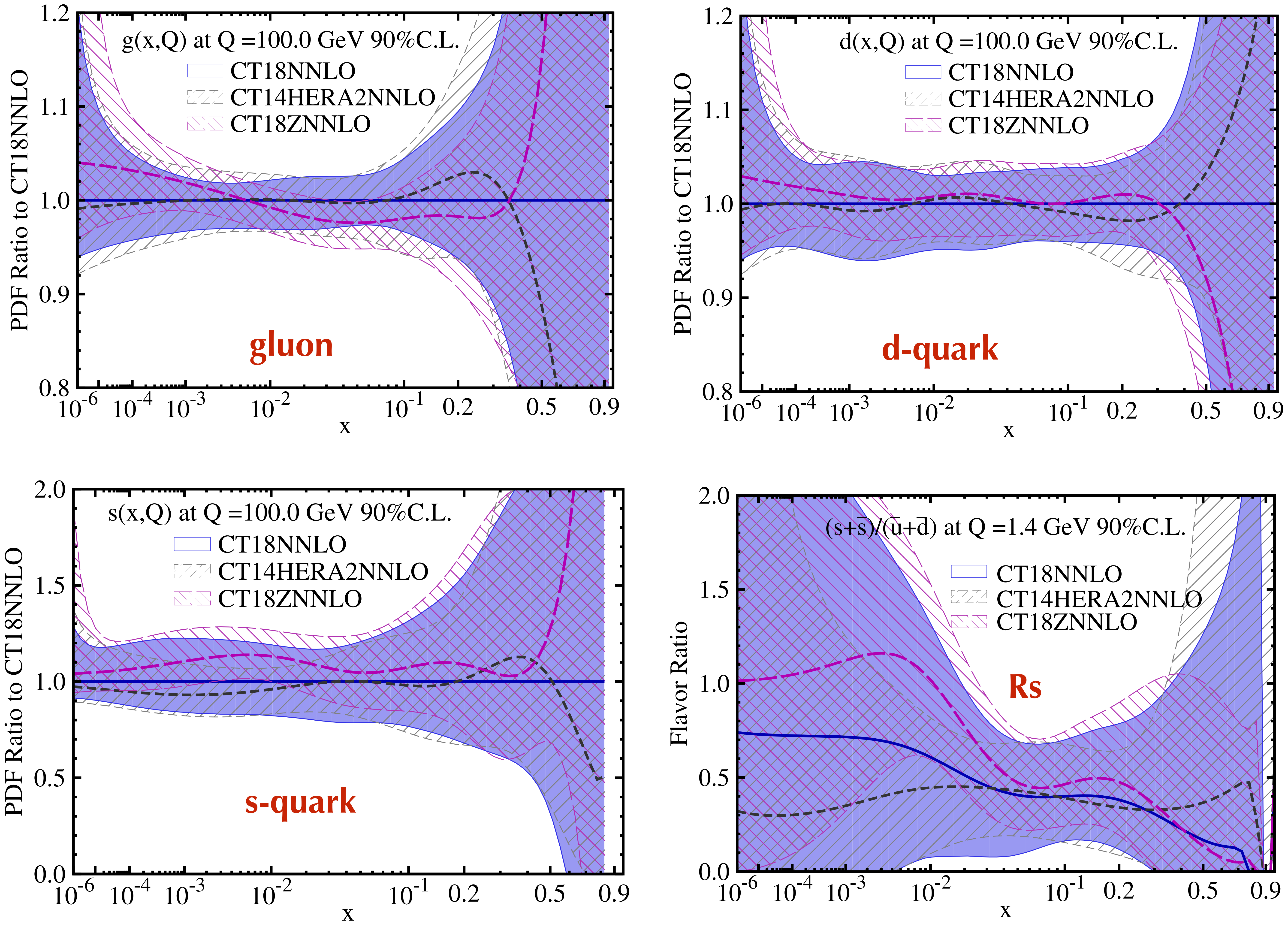
- Strange-quark PDFs are slightly suppressed at x~0.02 as now supported by both DIS and LHC data

- 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 QCD

- Top-quark mass determinations from measurements of total and differential cross sections are consistent with those determinations based on kinematic reconstructions

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]