PDFs: New Constraints and Novel Directions

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QCD@LHC2020, 1 September 2020

QCD@LHC

Aug 31–Sept 3 · 2020

QCD@LHC-X, the 2020 edition of the joint theoretical-experimental conference on applications of QCD to collider physics, will be held online via Zoom.

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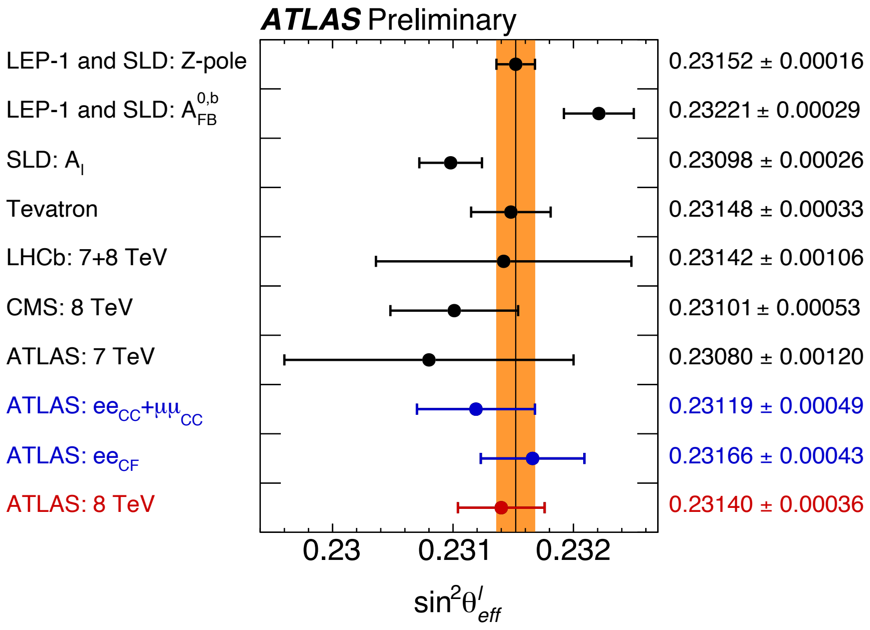
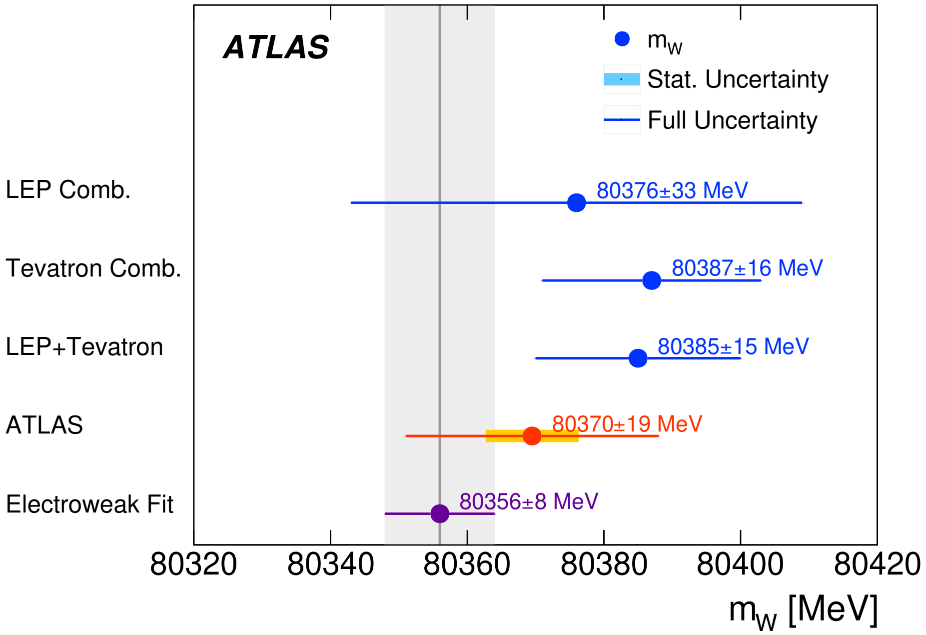
Motivation

EW Precision

See P. Francavilla's talk

- LHC officially in the **precision EW race**:





★ ATLAS/CMS measurements of $\sin^2\theta_W$ starting to bear down on LEP precision.

★ ATLAS measurement of M_W from Run-I data comparable to Tevatron/LEP determination.

- In both cases **PDF uncertainty** major component:

Value [MeV]	PDF Unc.	Total Unc.
80369.5	9.2	18.5

ATLAS:

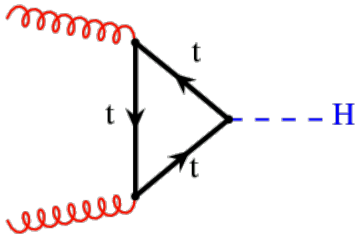
$$0.23140 \pm 0.00021\,(\text{stat.}) \pm \underline{0.00024\,(\text{PDF})} \pm 0.00016\,(\text{syst.}),$$

CMS:

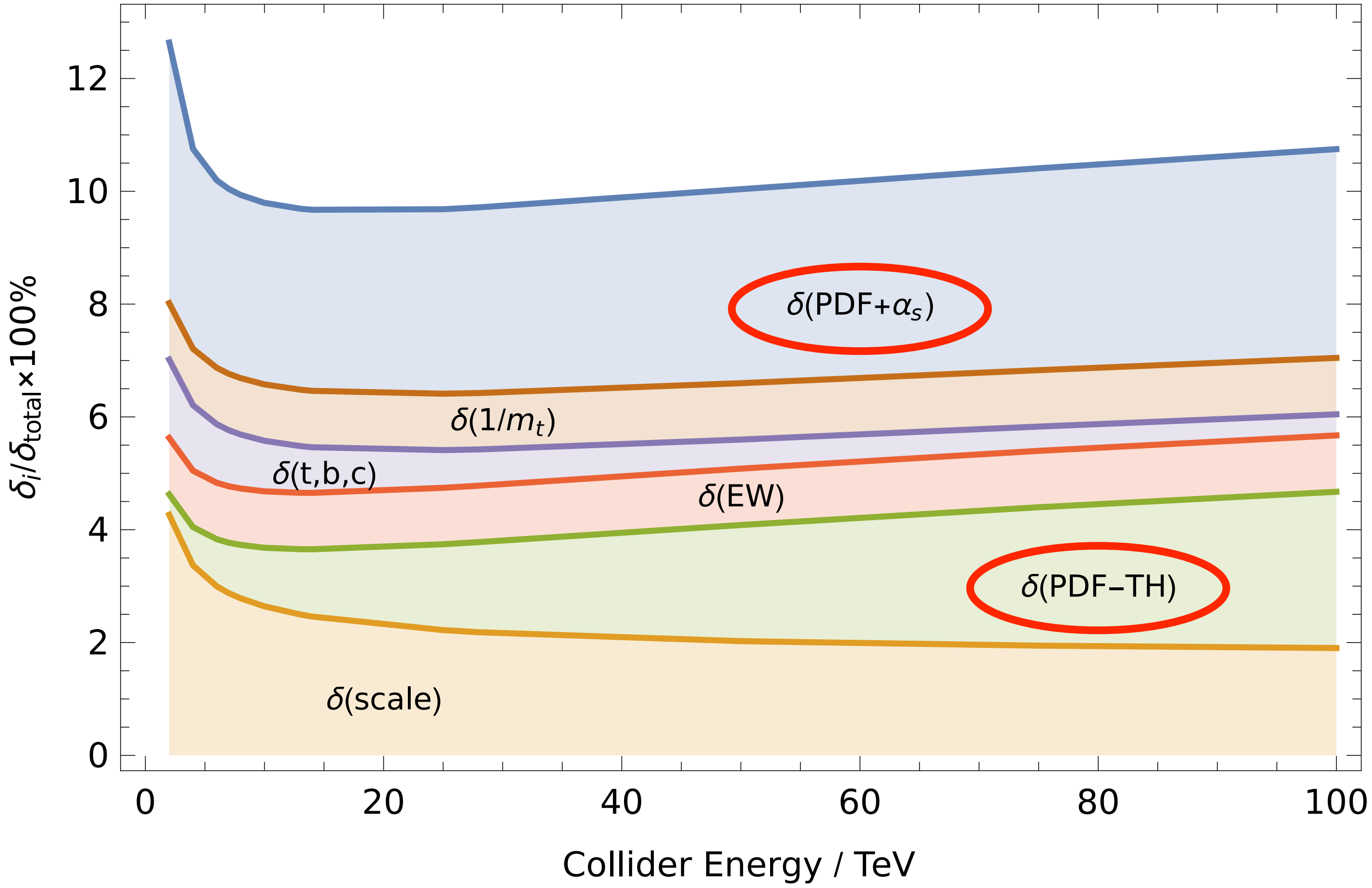
$$0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm \underline{0.00031\,(\text{PDF})},$$

Higgs

- Major (ongoing) aim of LHC: pin down the **Higgs sector** as precisely as we can.



★ PDF uncertainty important limiting factor in this.



M. Cepeda et al., 1902.00134

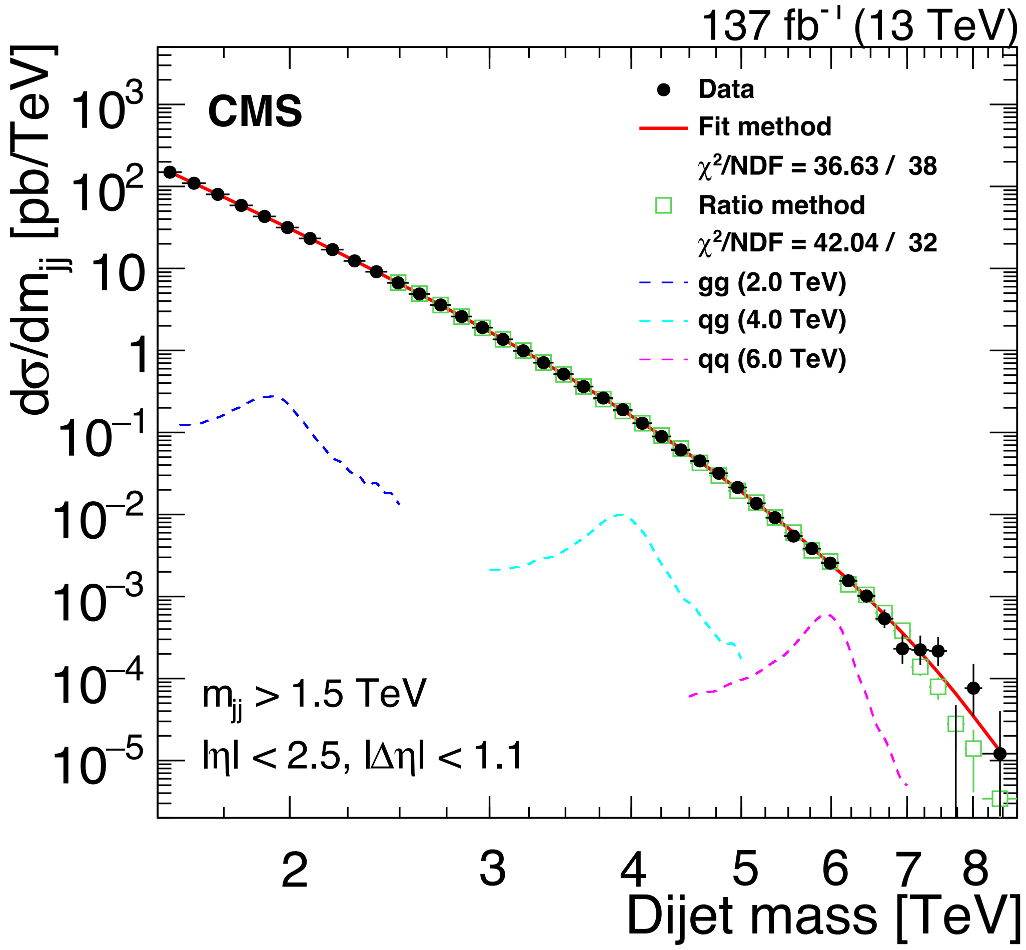
★ Not just gg fusion: significant for VBF, associated production…

BSM

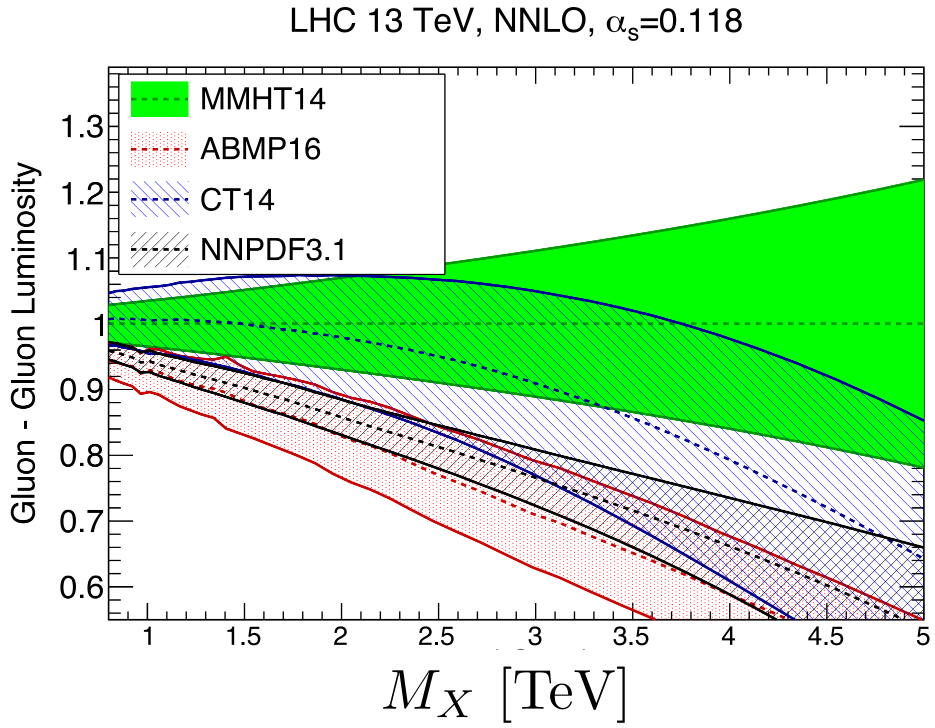
M. Voutilainen's talk.

- **High mass searches** for new resonances/contact interactions - PDFs in high x region.

1911.03947 (JHEP05 (2020) 033)



- PDF uncertainties larger here (less constraints). Though see later for more on that.

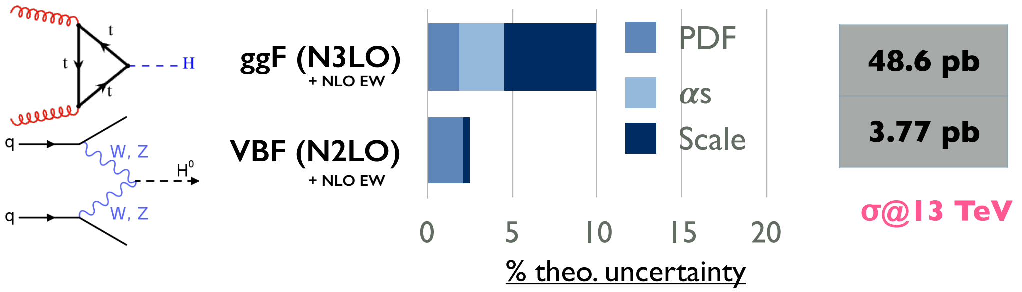


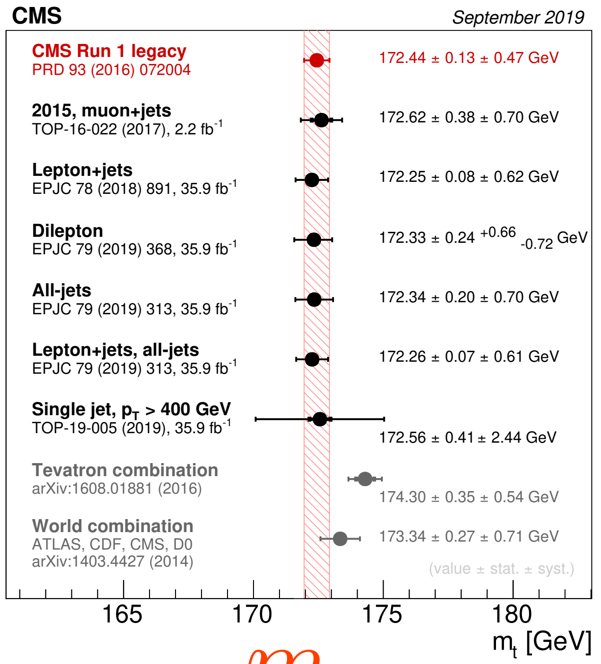
Bottom Line:

- (HL)-LHC: exciting precision physics programme ahead…
- …but **PDFs** key **constraining factor** and uncertainty source.

$\longrightarrow$ Precise understanding of PDFs and their uncertainties/biases crucial to pursuing precision LHC programme.

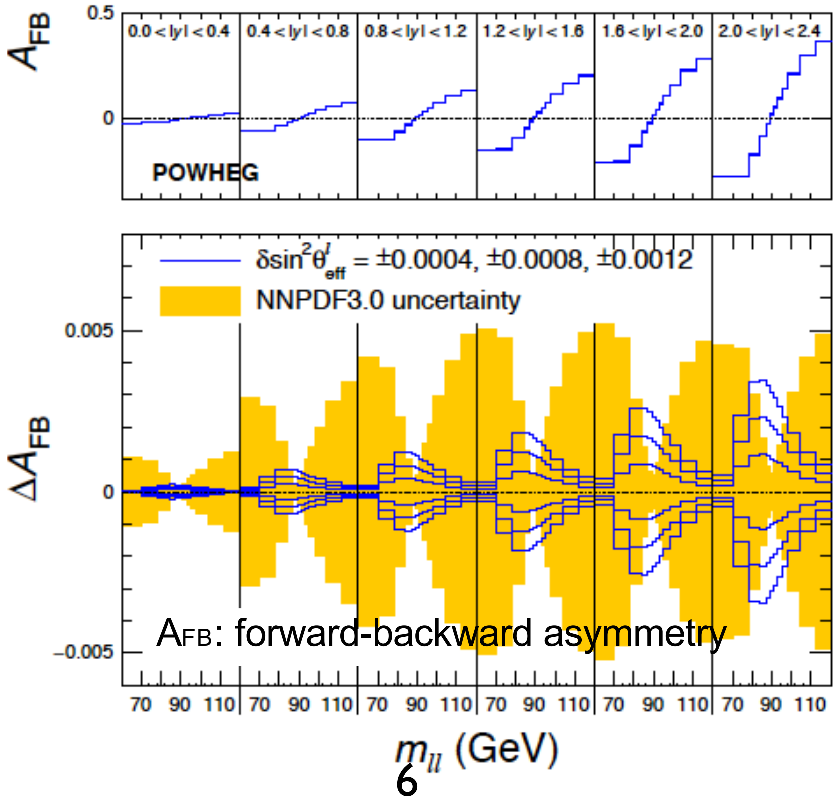
Higgs



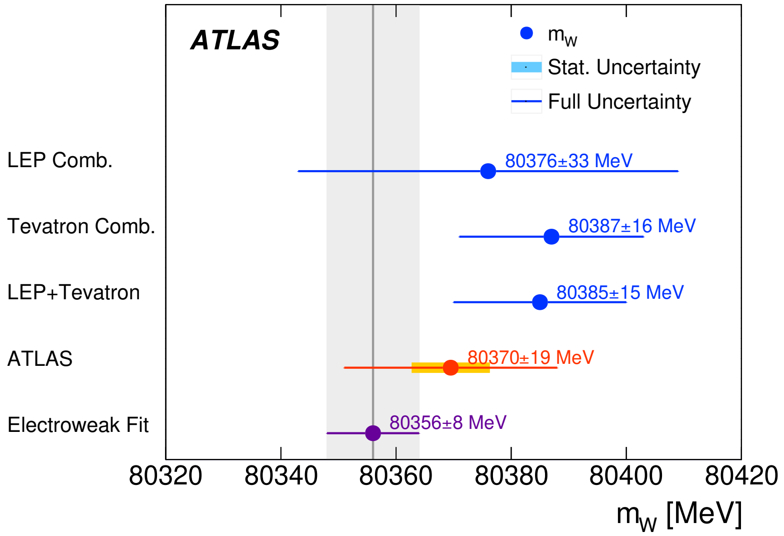


m_t

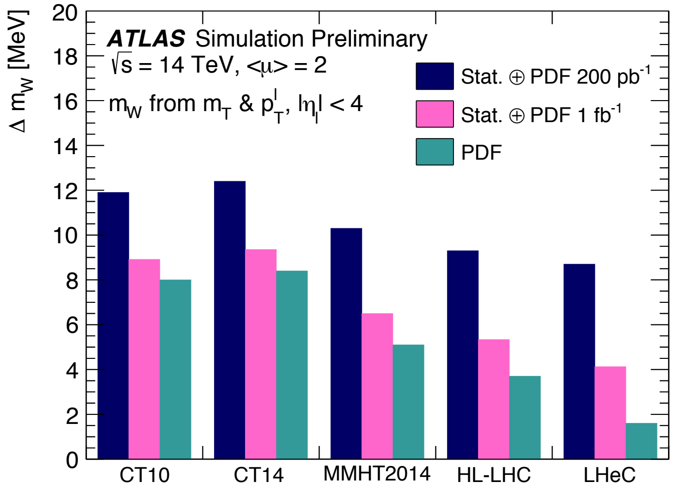
$\sin^2\theta_W$



AFB: forward-backward asymmetry



M_W



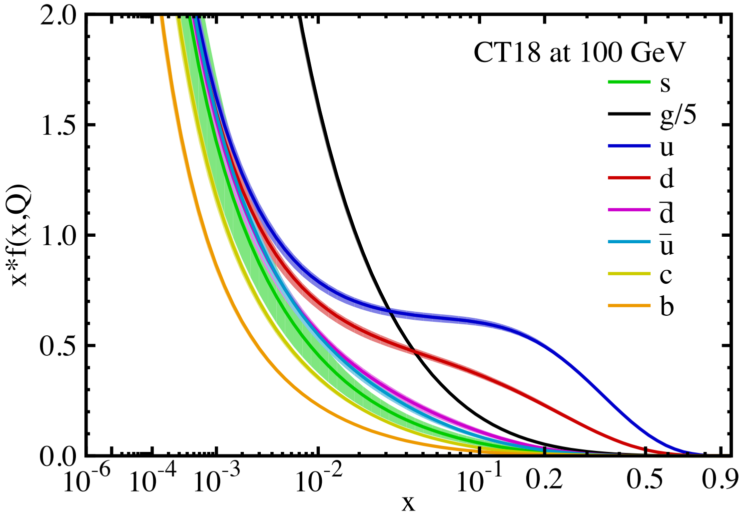
PDF Fits Today

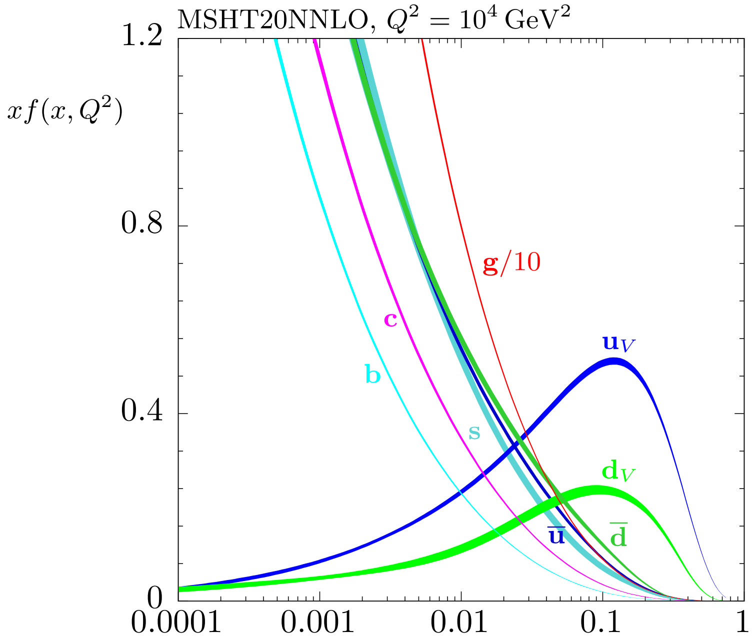
Latest Releases

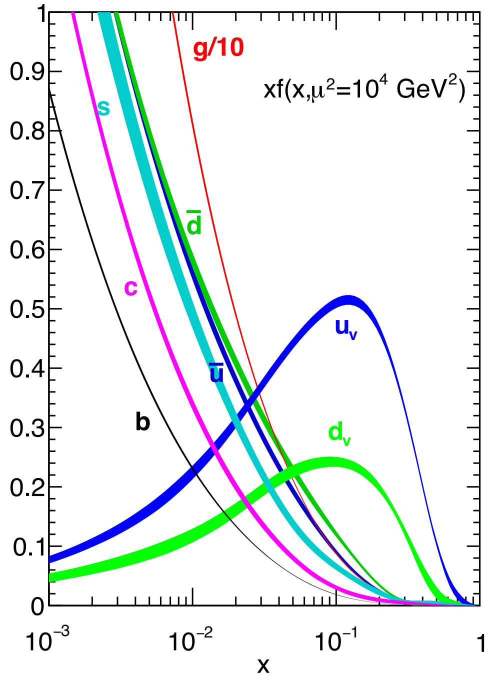
- **Projection studies**: (sub) % level PDF uncertainty achievable by end of HL-LHC (**Backup**). Can we get there? Where are we are now?
- 'Post-Run I' sets now exist from three major global fitters:

CT18 **MSHT20*** **NNPDF3.1**

- In all cases, focus on including significant amount of **new data**, higher **precision theory** and on **methodological improvements**.







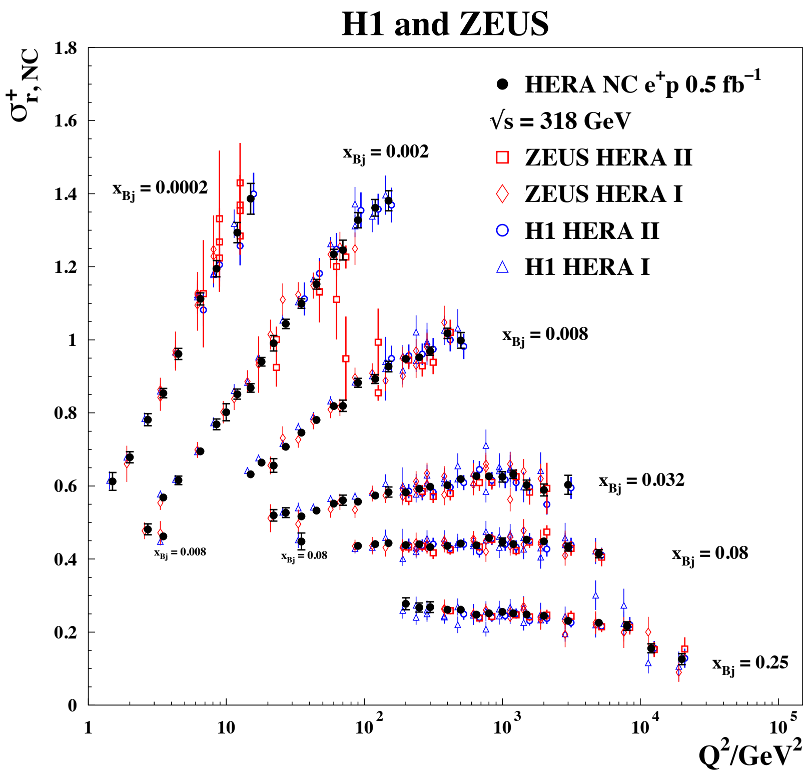
- LHC data also playing key role in **ABM** fits, while ATLAS/CMS continue to provide their own PDF analyses.

*Paper in prep., PDFs available on request.

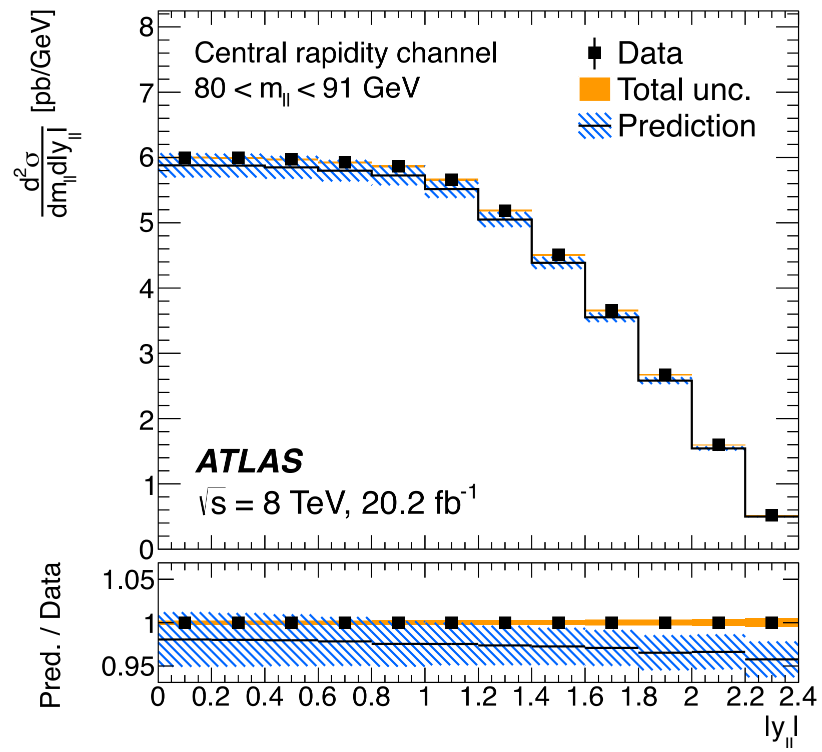
New Data

See S. Carmada's talk.
See M. Voutilainen's talk.

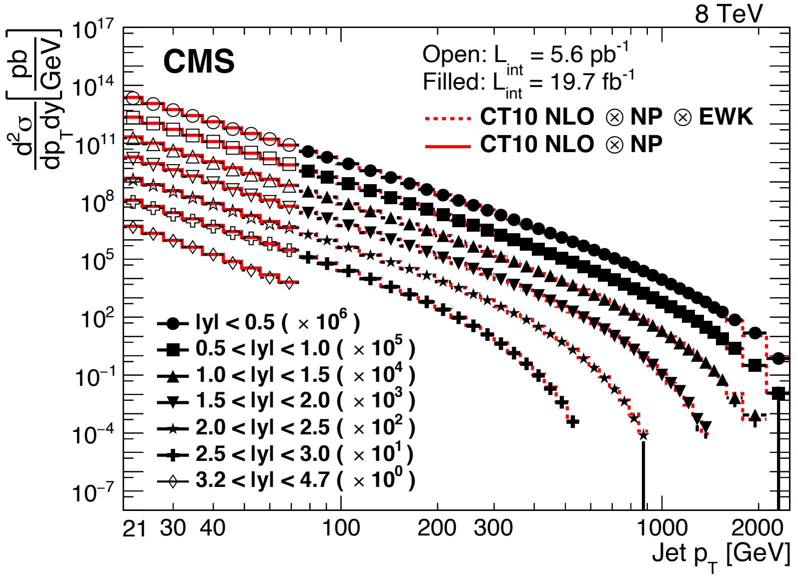
- Can divide into 3 broad (non-exhaustive) categories:



★ Final HERA H1 + ZEUS combination data on inclusive and heavy flavour **DIS**.



★ High precision multi-differential **DY** data. Flavour decomposition.

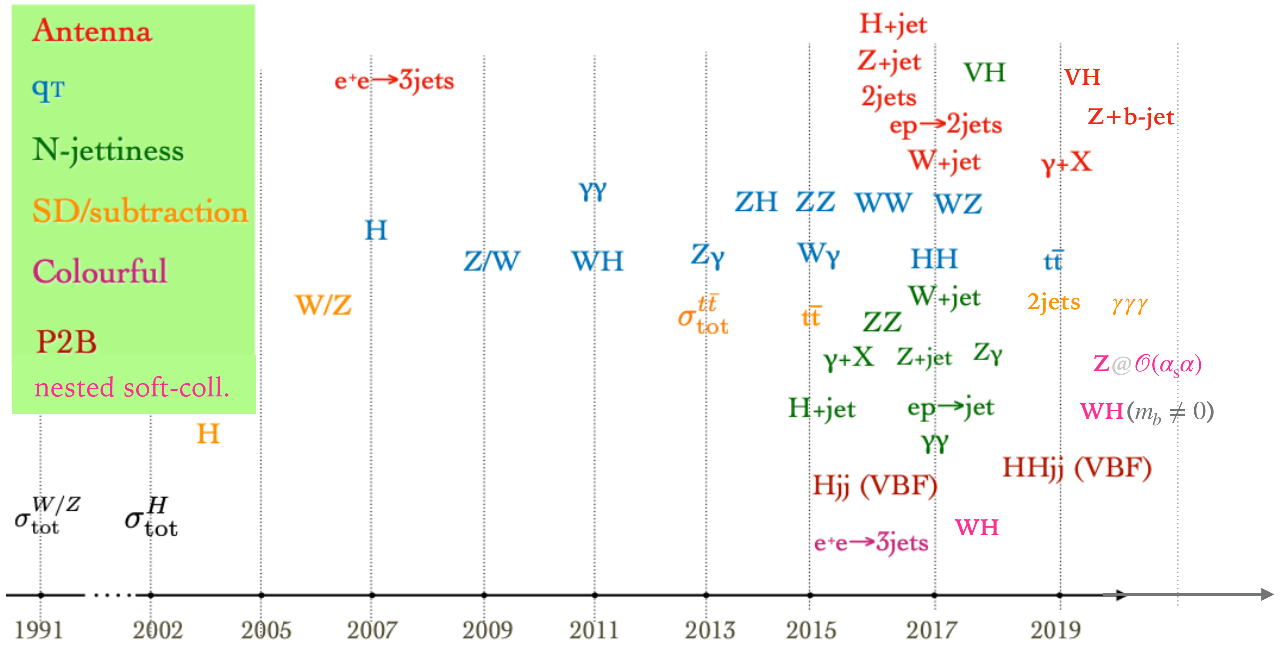


★ Inclusive jet, $Z\, p_\perp$, differential $t\bar{t}$. High x partons.

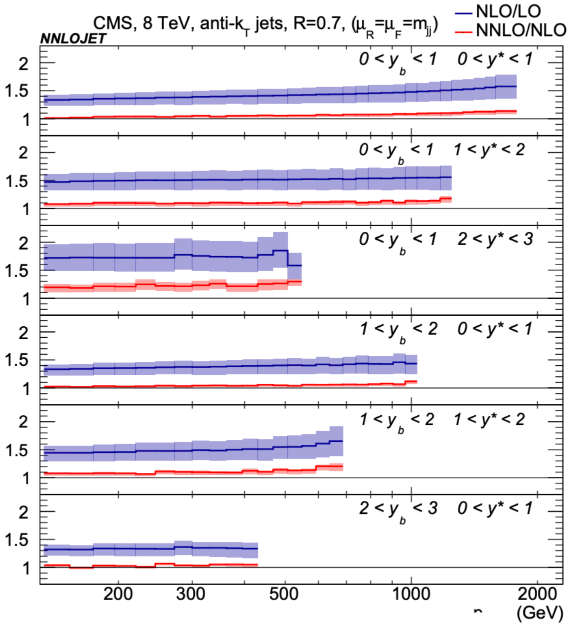
Precision Theory

A. Huss's talk

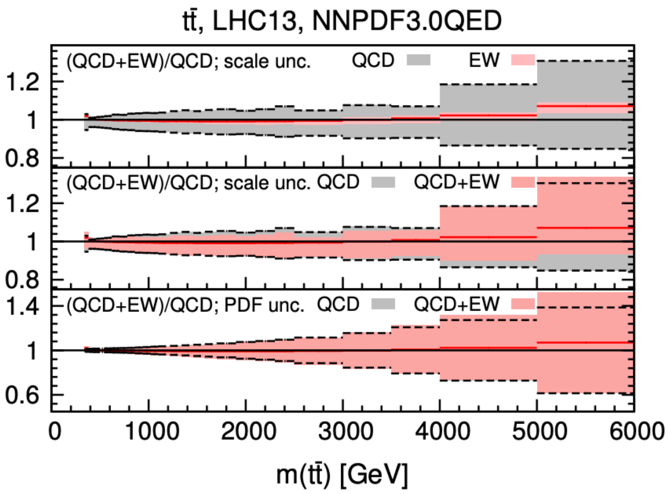
- Vast majority of processes included in fits have full NNLO QCD theory (+ NLO EW where relevant) available and included.



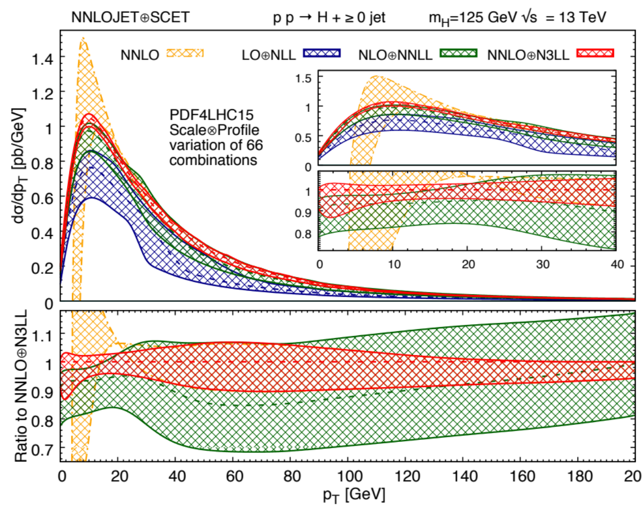
[based on slide by M. Grazzini; QCD@LHC 2019]



Inclusive jets/dijets



Top quarks - single/ double differential



W, Z transverse momentum distributions

New Collider Data

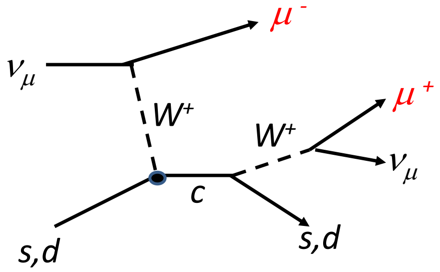
MSHT20: new collider data

MSHT20 fit (MMHT14 prediction)

	Points	NLO χ^2/N_{pts}	NNLO χ^2/N_{pts}
DØ W asymmetry	14	0.94 (2.53)	0.86 (14.7)
$\sigma_{t\bar{t}}$ [69]- [70]	18	1.27 (1.31)	0.81 (0.83)
LHCb 7+8 TeV $W+Z$ [71, 72]	67	1.71 (2.35)	1.48 (1.55)
LHCb 8 TeV $Z \to ee$ [73]	17	2.29 (2.89)	1.54 (1.78)
CMS 8 TeV W [74]	22	1.05 (1.79)	0.58 (1.30)
CMS 7 TeV $W+c$ [75]	10	0.82 (0.85)	0.86 (0.84)
ATLAS 7 TeV jets $R=0.6$ [18]	140	1.62 (1.59)	1.59 (1.68)
ATLAS 7 TeV $W+Z$ [20]	61	5.00 (7.62)	1.91 (5.58)
CMS 7 TeV jets $R=0.7$ [76]	158	1.27 (1.32)	1.11 (1.17)
ATLAS 8 TeV Zp_T [54]	104	2.26 (2.31)	1.81 (1.59)
CMS 8 TeV jets $R=0.7$ [77]	174	1.64 (1.73)	1.50 (1.59)
ATLAS 8 TeV $t\bar{t} \to l+j$ sd [78]	25	1.56 (1.50)	1.02 (1.14)
ATLAS 8 TeV $t\bar{t} \to l^+l^-$ sd [79]	5	0.94 (0.82)	0.68 (1.10)
ATLAS 8 TeV high-mass DY [52]	48	1.79 (1.99)	1.18 (1.26)
ATLAS 8 TeV W^+W^-+ jets [80]	25	1.36 (1.36)	0.72 (0.69)
CMS 8 TeV $(d\sigma_{\bar{t}t}/dp_{T,t}dy_t)/\sigma_{\bar{t}t}$ [81]	15	2.19 (2.20)	1.50 (1.47)
ATLAS 8 TeV W^+W^- [82]	22	3.85 (13.9)	2.61 (5.25)
CMS 2.76 TeV jets [83]	81	1.53 (1.59)	1.27 (1.39)
CMS 8 TeV $\sigma_{\bar{t}t}/dy_t$ [84]	9	1.43 (1.02)	1.47 (2.14)
ATLAS 8 TeV double differential Z [53]	59	2.67 (3.26)	1.45 (5.16)

- Impact of data on fit clear via **MMHT14/MSHT20** difference.
- With the addition of newer higher precision LHC data, the necessity of **NNLO** becoming increasingly clear.

Precision W,Z



- Precision W, Z has significant impact on proton quark content.
- ATLAS 7 TeV W,Z: larger strangeness required than previous global fits, driven by neutrino induced dimuon production ($\overline{\nu}s \to lc$).

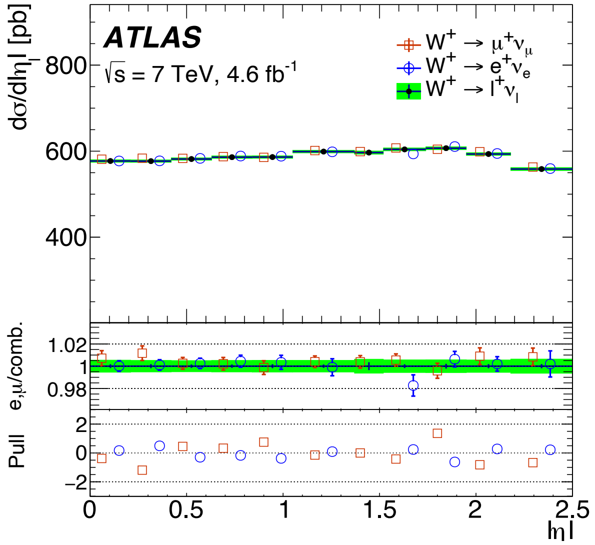
ATLAS collab., Eur. Phys. J C77 (2017) 367

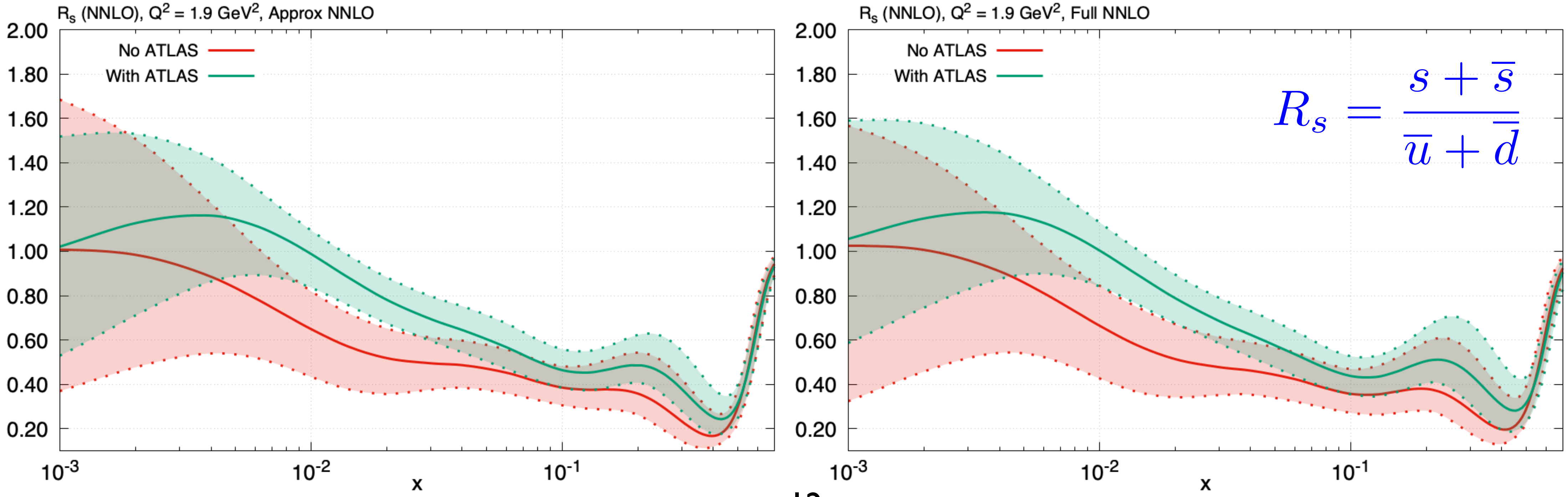
- **Updates** since original analysis:

★ In global fit can account for both datasets, with mild tension. Strangeness increased.

★ Full NNLO corrections for dimuon data now included. Alleviates tension somewhat.

J. Gao, JHEP 1802 (2018) 026

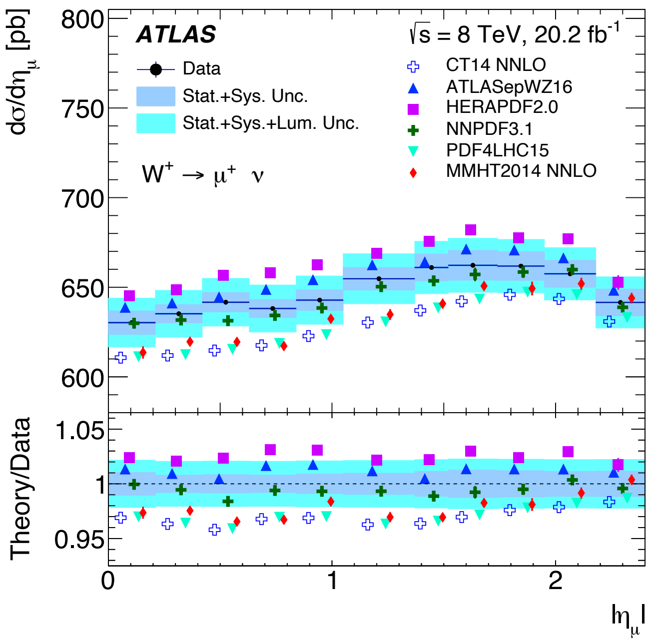




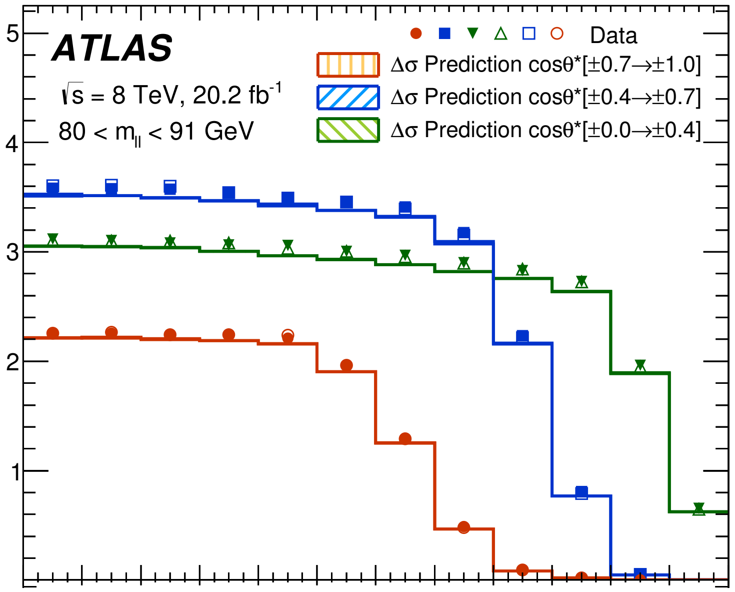
$$R_s = \frac{s + \overline{s}}{\overline{u} + \overline{d}}$$

- ★ ATLAS 8 TeV W and triple differential lepton pair production available. Do they have the same impact?

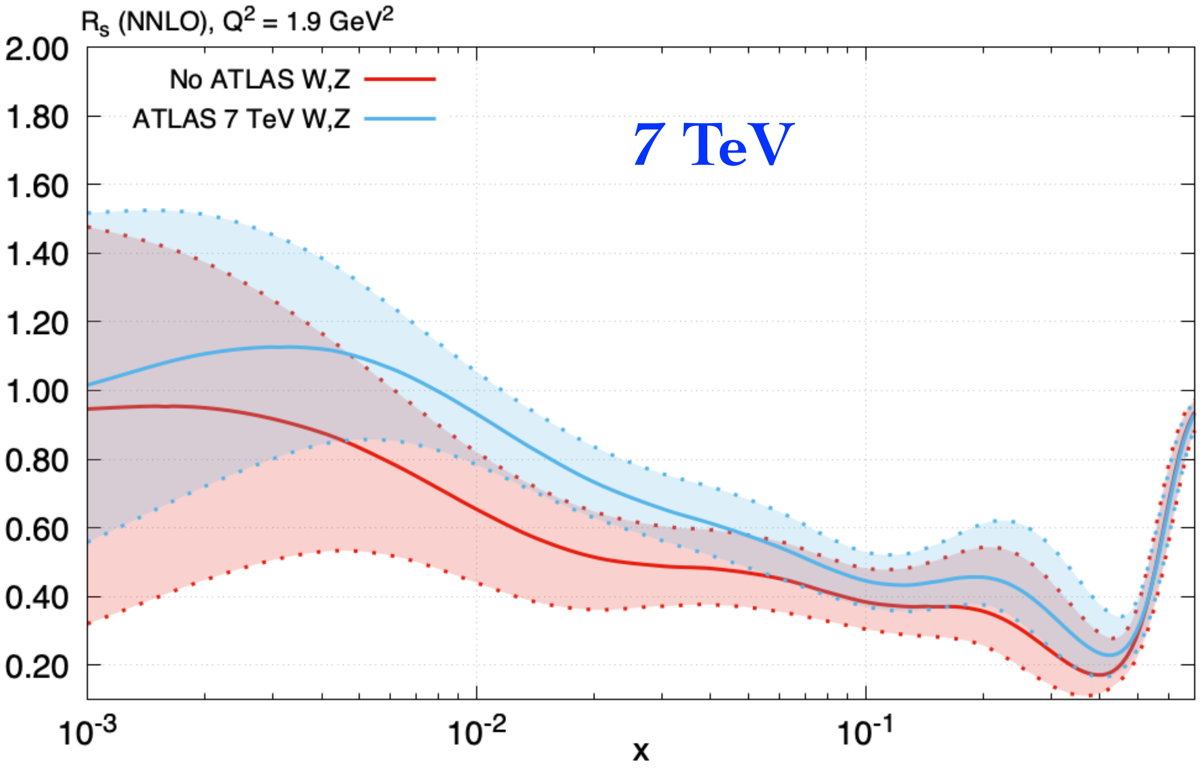
ATLAS collab., Eur. Phys. J. C 79 (2019) 760

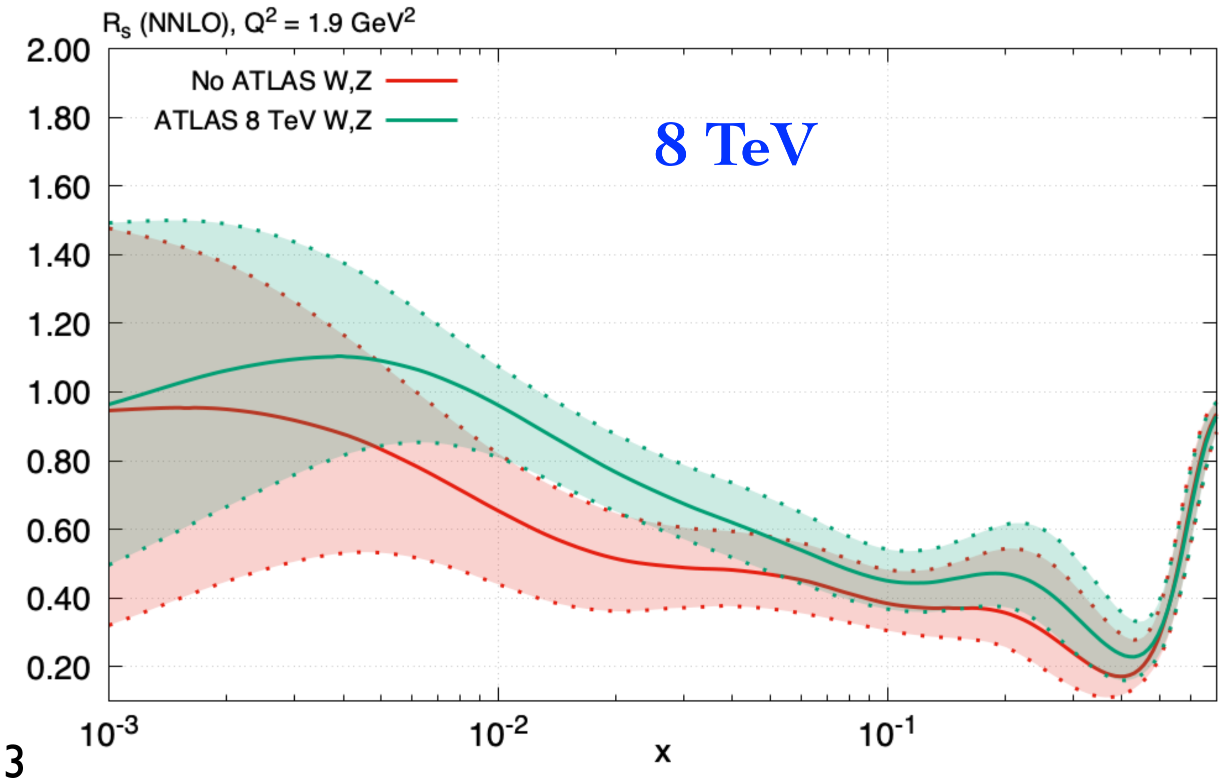


ATLAS collab., JHEP 12 (2017) 059



- ★ Yes! Nice consistent picture develops.





Jet (and dijet) production

- Recent **NNPDF + NNLOJET** study: impact of inclusive jet and **dijet** data at NNLO QCD + NLO EW on global PDF fit.

R. Abdul Khalek et al., 2005.11327

Experiment	Measurement	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	R	Distribution	$n_{\rm dat}$	Reference
ATLAS	Inclusive jets	7	4.5	0.6	$d^2\sigma/dp_T d\|y\|$	140	[14]
CMS	Inclusive jets	7	4.5	0.7	$d^2\sigma/dp_T d\|y\|$	133	[16]
ATLAS	Inclusive jets	8	20.2	0.6	$d^2\sigma/dp_T d\|y\|$	171	[15]
CMS	Inclusive jets	8	19.7	0.7	$d^2\sigma/dp_T d\|y\|$	185	[17]
ATLAS	Dijets	7	4.5	0.6	$d^2\sigma/dm_{jj} d\|y^*\|$	90	[18]
CMS	Dijets	7	4.5	0.7	$d^2\sigma/dm_{jj} d\|y_{\rm max}\|$	54	[16]
CMS	Dijets	8	19.7	0.7	$d^3\sigma/dp_{T,{\rm avg}} dy_b dy^*$	122	[19]

- Scale $\mu = \hat{H}_T$ taken, based on earlier work.

J. Currie et al., JHEP 10 (2018) 155

- Detailed study, considering consistency of datasets, perturbative stability, impact on PDFs…

See A. Huss's talk

- **Intriguing picture** found. For **dijet** data, clear preference for NNLO:

NLO :

$$\chi^2/N_{\rm pts} = 2.44$$

NNLO :

$$\chi^2/N_{\rm pts} = 1.65$$

- Whereas for **inclusive** jets, the trend is opposite (!):

NLO :

$$\chi^2/N_{\rm pts} = 1.25$$

NNLO :

$$\chi^2/N_{\rm pts} = 1.88$$

- NNLO fit quality slightly better for dijets (1.65 vs. 1.88) and moreover global fit quality is better (driven by top data):

Fitting inclusive:

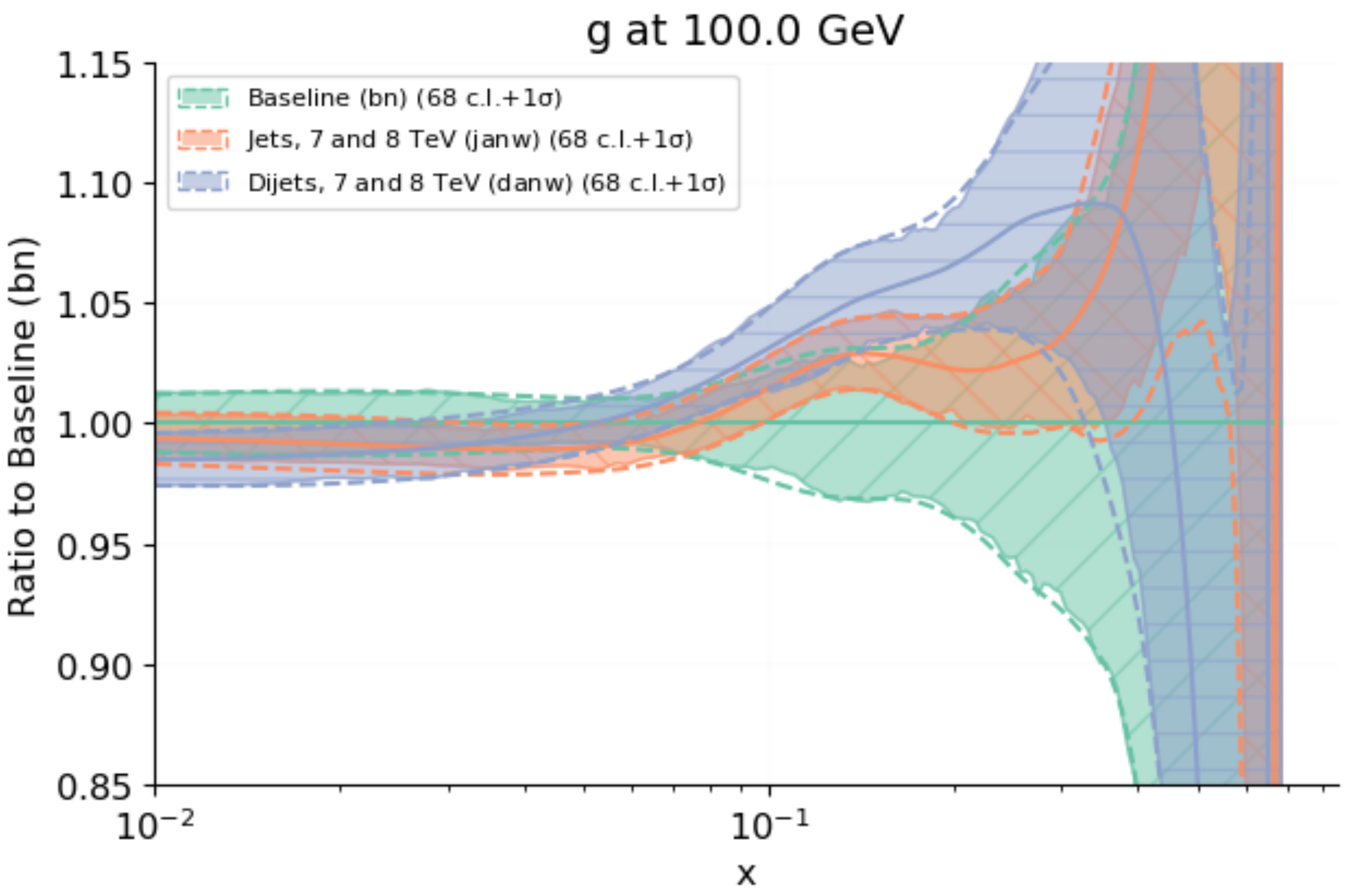
$$\chi^2_{\rm global}/N_{\rm pts} = 1.28$$

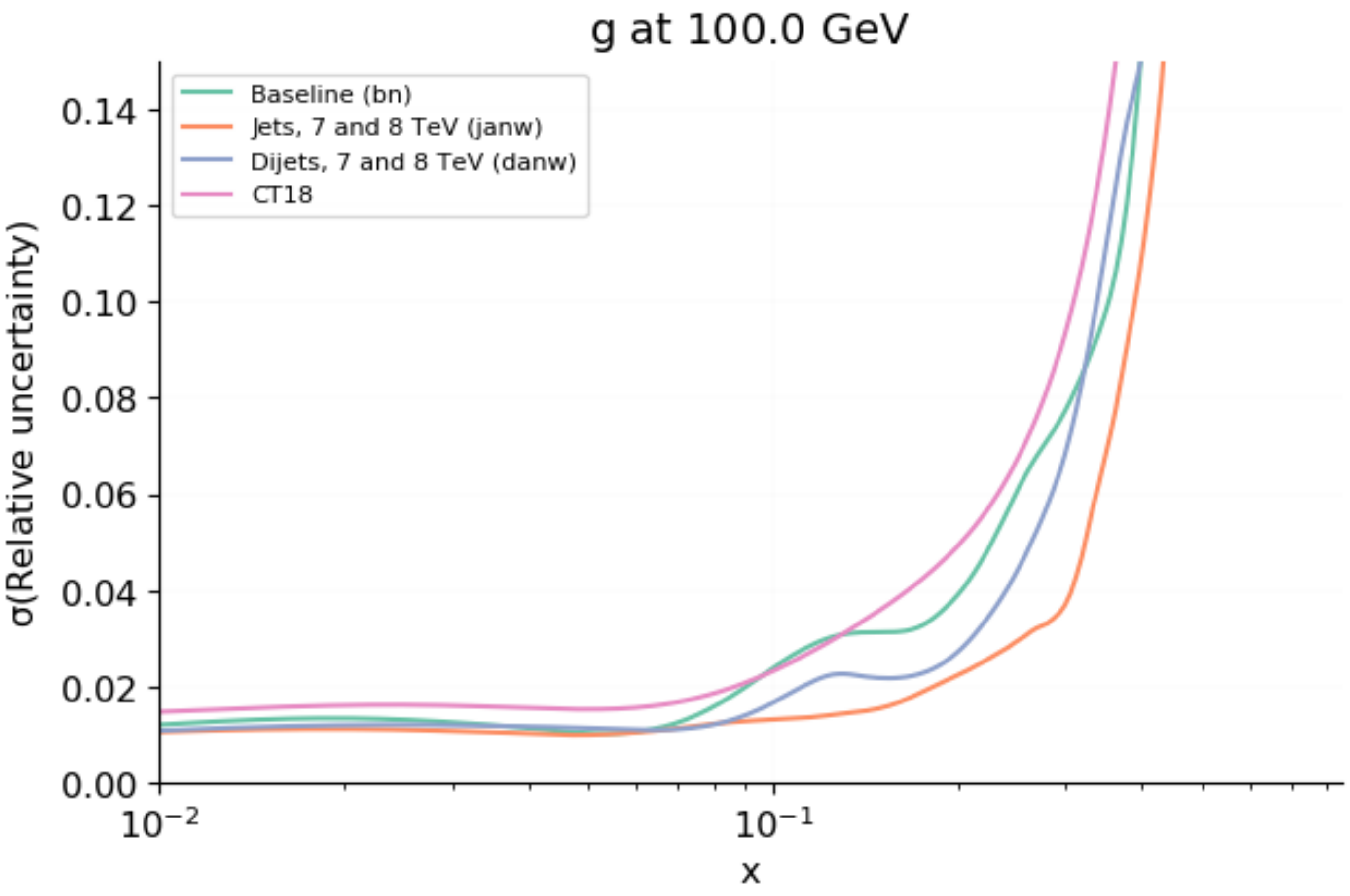
Fitting dijets:

$$\chi^2_{\rm global}/N_{\rm pts} = 1.22$$

- Prediction for inclusive/dijets reasonable when fitting dijets/inclusive - no big tensions between them.
- Interesting to see results for other groups (impact of $t\bar{t}$ not always same, MSHT see improvement at NNLO vs. NLO in inclusive…).

- Relatively **consistent impact** on gluon when fitting inclusive v.s dijets.





- Sizeable **uncertainty reduction** at high x, impact somewhat more in inclusive case (more data).

Methodological Improvements

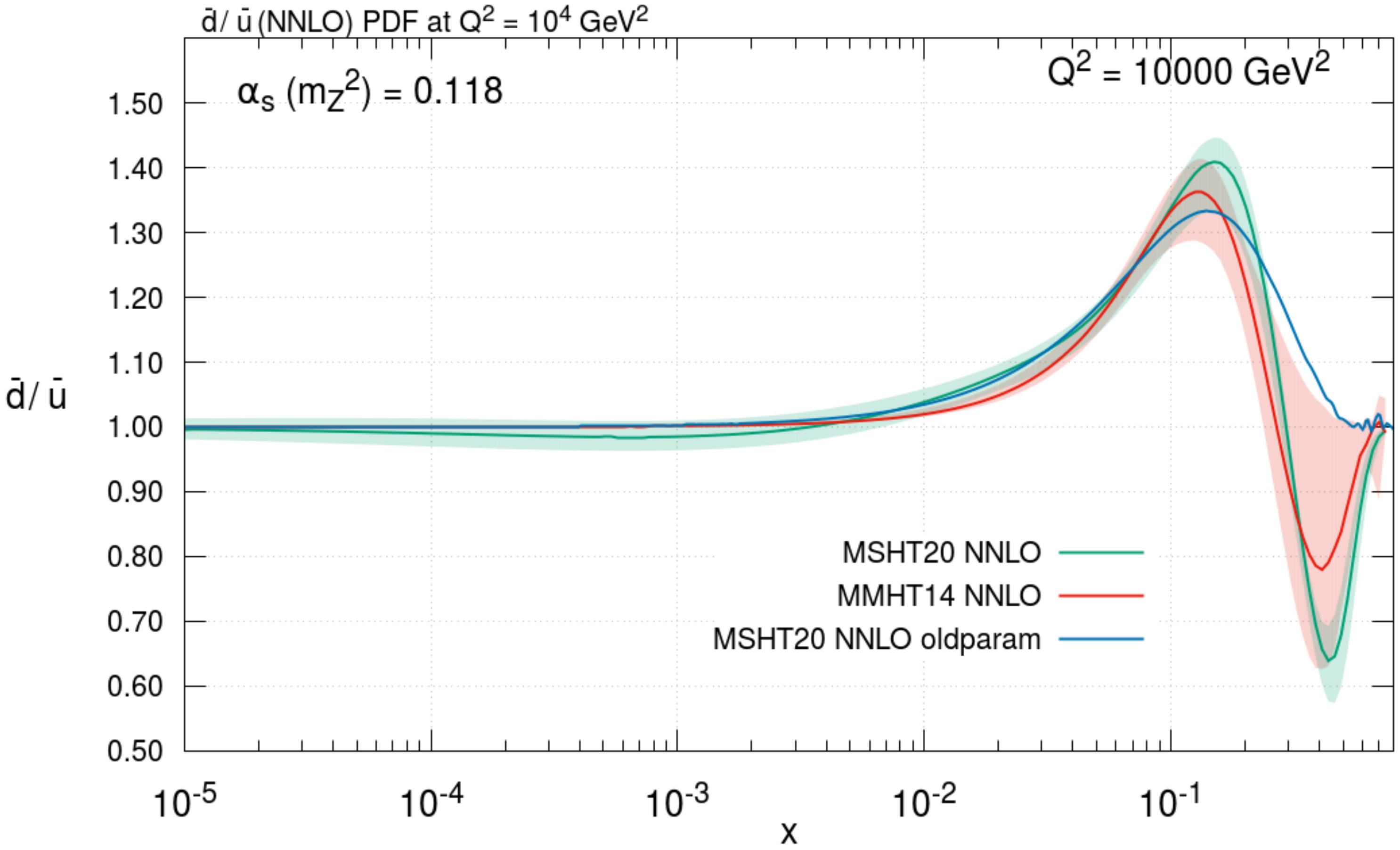
Parameterisation Flexibility

- Necessary to continually update PDF parameterisation to account for increasingly precise data.
- MSHT20 - additional Chebyshev polynomials used vs MMHT14:

$$xf(x,Q_0^2) \;=\; A(1-x)^\eta x^\delta \left(1+\sum_{i=1}^{n} a_i T_i^{\mathrm{Ch}}(y(x))\right) \qquad n=6$$

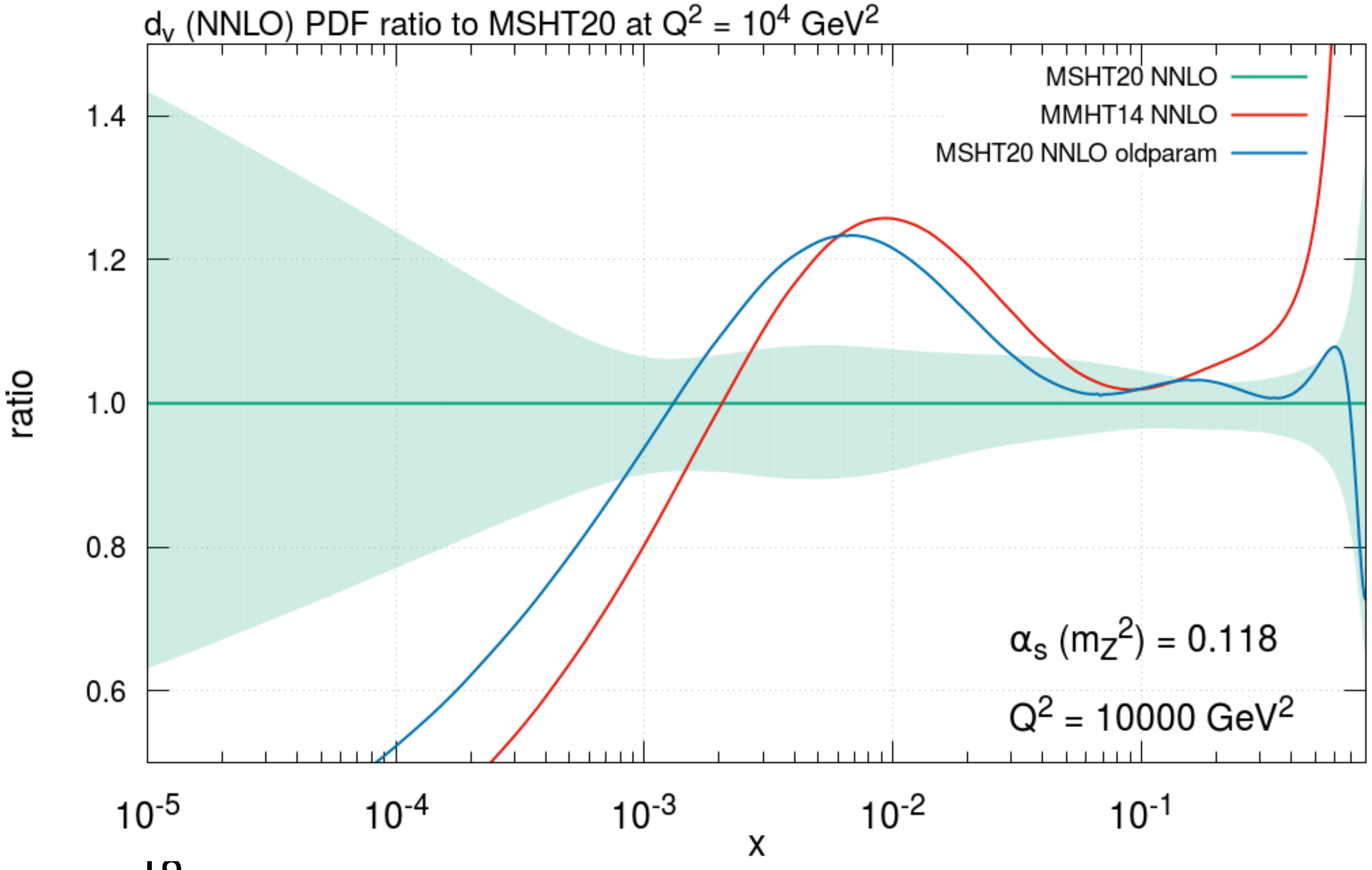
and use $\bar{d}/\bar{u}$ rather than $\bar{d}-\bar{u}$. **16** extra parameters in total.

- These choices are driven by observed improvement in fit quality up to certain point (χ^2 ‘saturation’).
- Improvement in fit quality significant: ~ *73* for the 16 extra parameters, with $\Delta\chi^2/N_{\mathrm{pts}} \sim -0.02$. Eases tension between e.g. fixed target data and high precision LHC W,Z data.



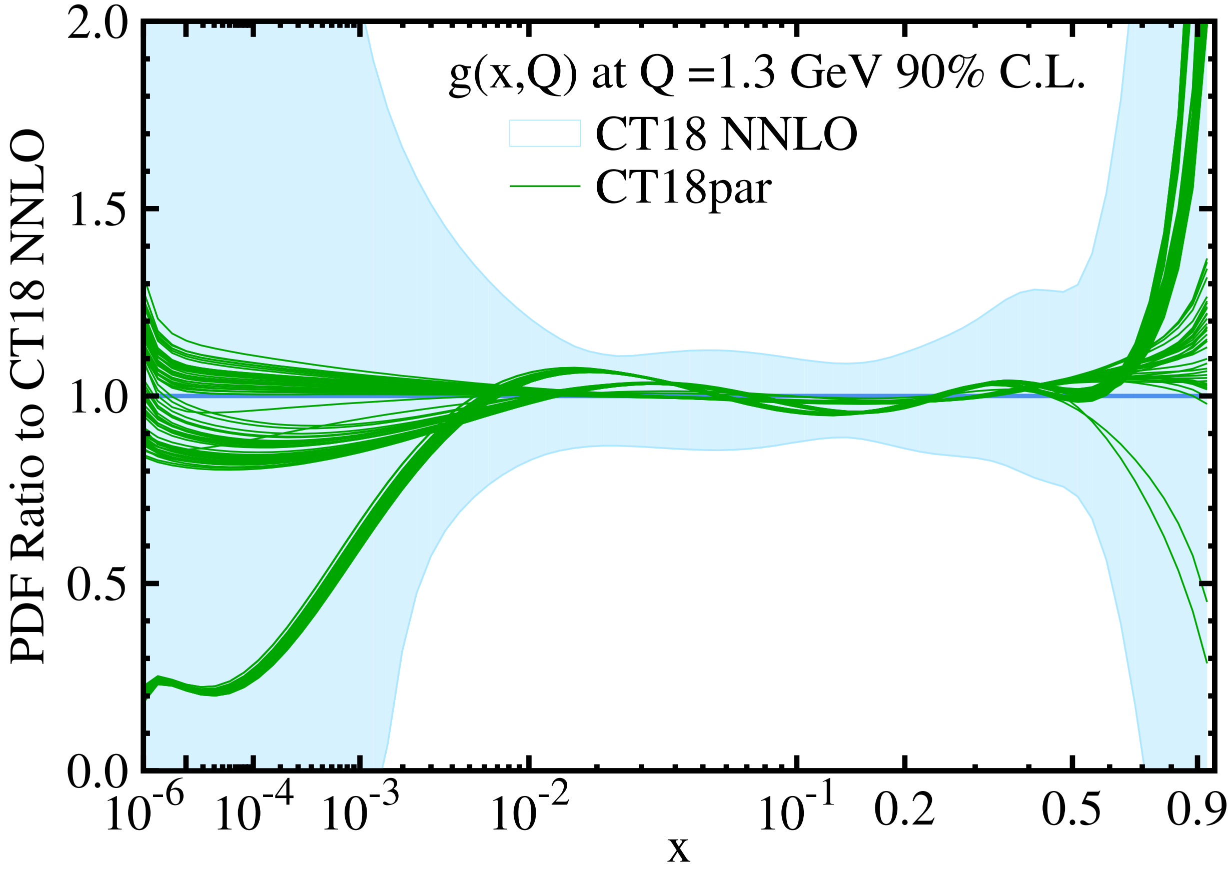
- Increased flexibility needed for $\bar{d}/\bar{u}$ in order to describe high x region (tension between ATLAS W,Z + E866 DY).
- Also gives more reasonable PDF uncertainties at low x ($x \to 1$ at low scale not required but ~ found!).

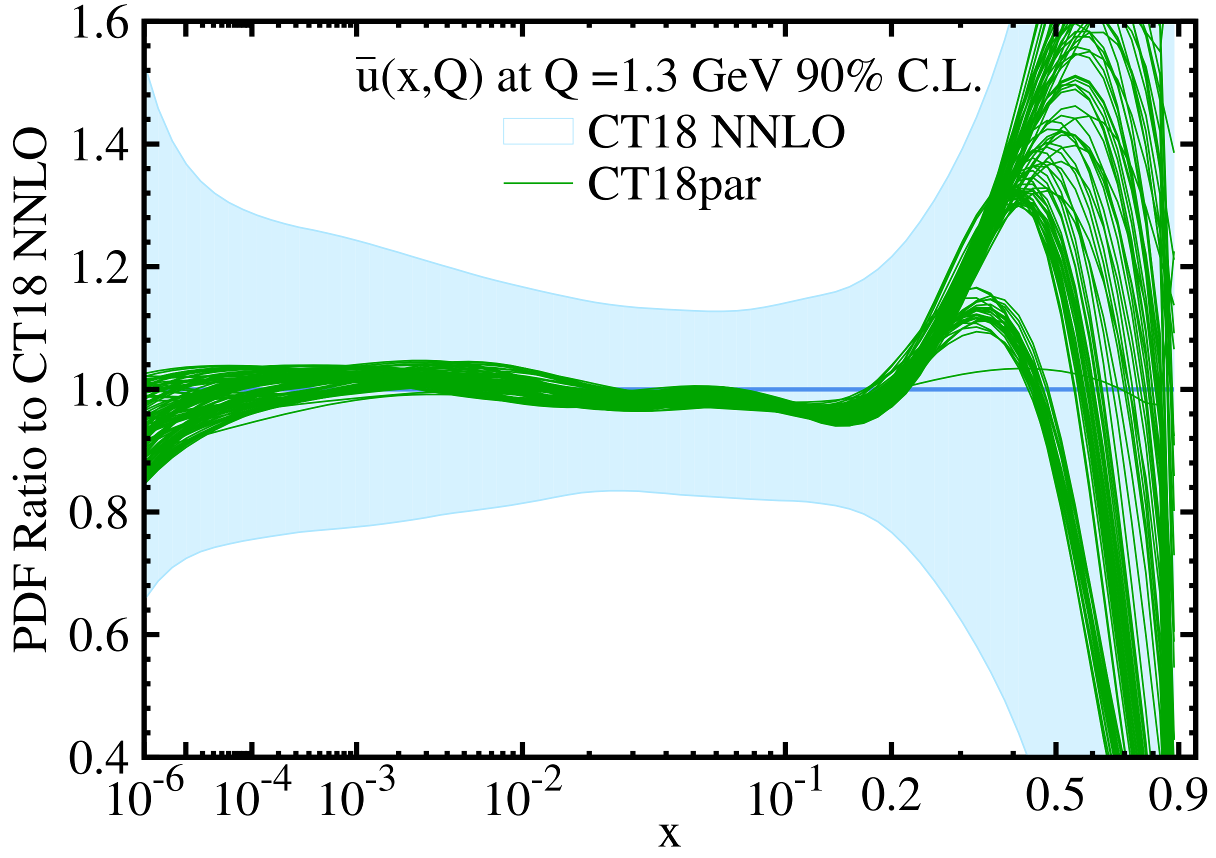
- Large change in d_V at intermediate to low x . Direction driven by new data, size allowed by more flexible parameterisation.
- In region where constraints limited.



Parameterisation Uncertainty

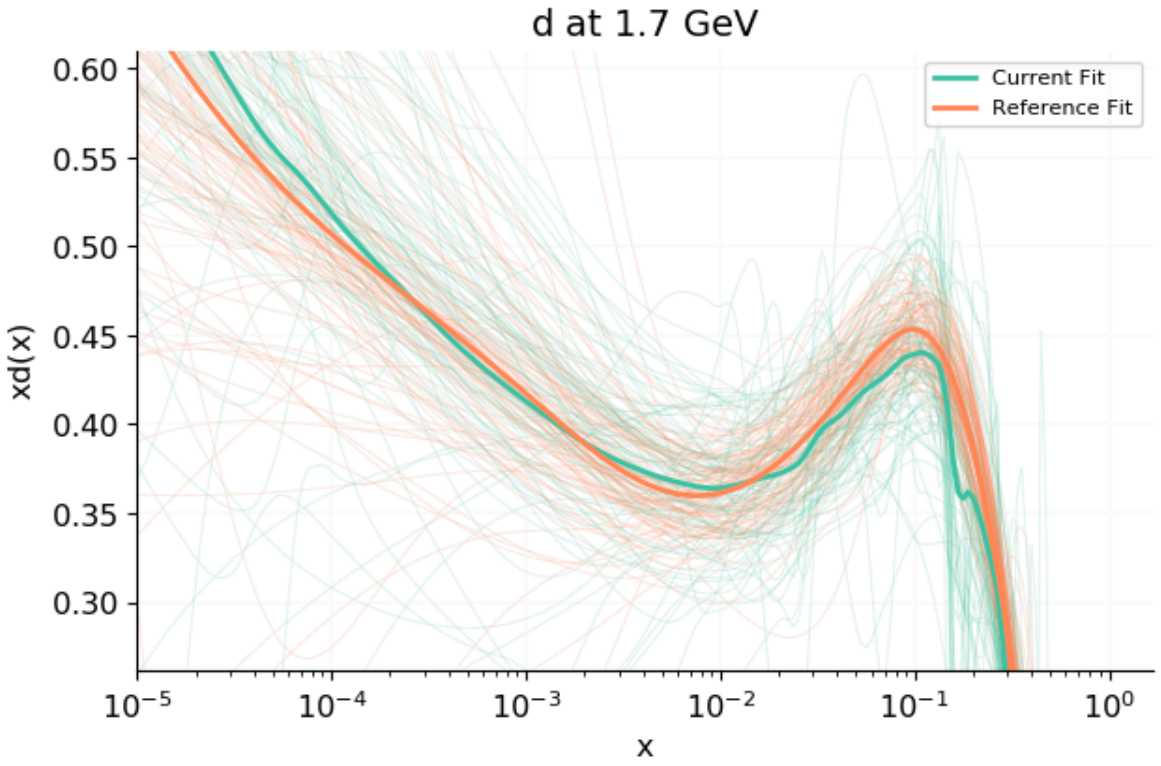
- **CT study**: perform $\gtrsim 100$ alternative fits with modified input parameterisations.
- PDF uncertainty with default parameterisation then increased in order to account for resulting spread in results.





NNPDF: Hyperoptimisation

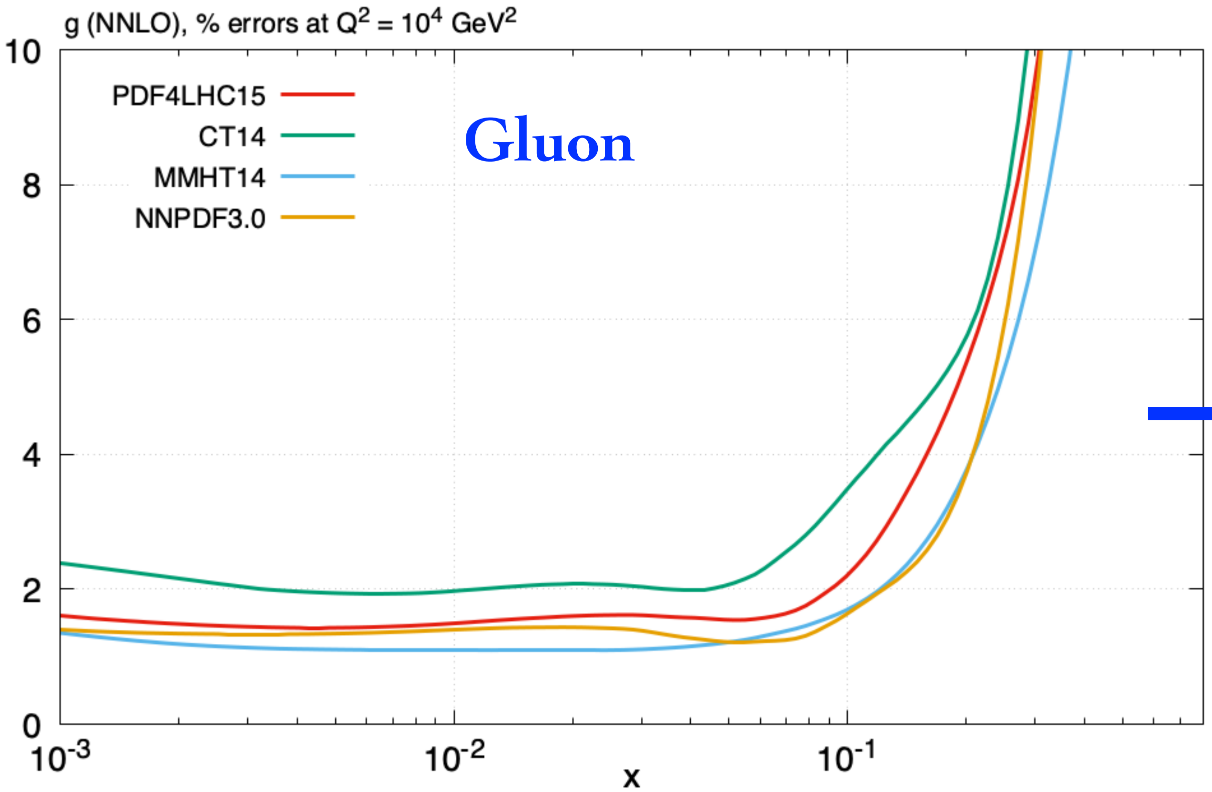
- NNPDF3.1: choices related to network architecture, minimisation, learning rate etc set by hand.
- This can now be determined algorithmically, by ‘hyperoptimising’ via a closure test.
- Gives smoother replicas, and mores satisfying quality requirements.

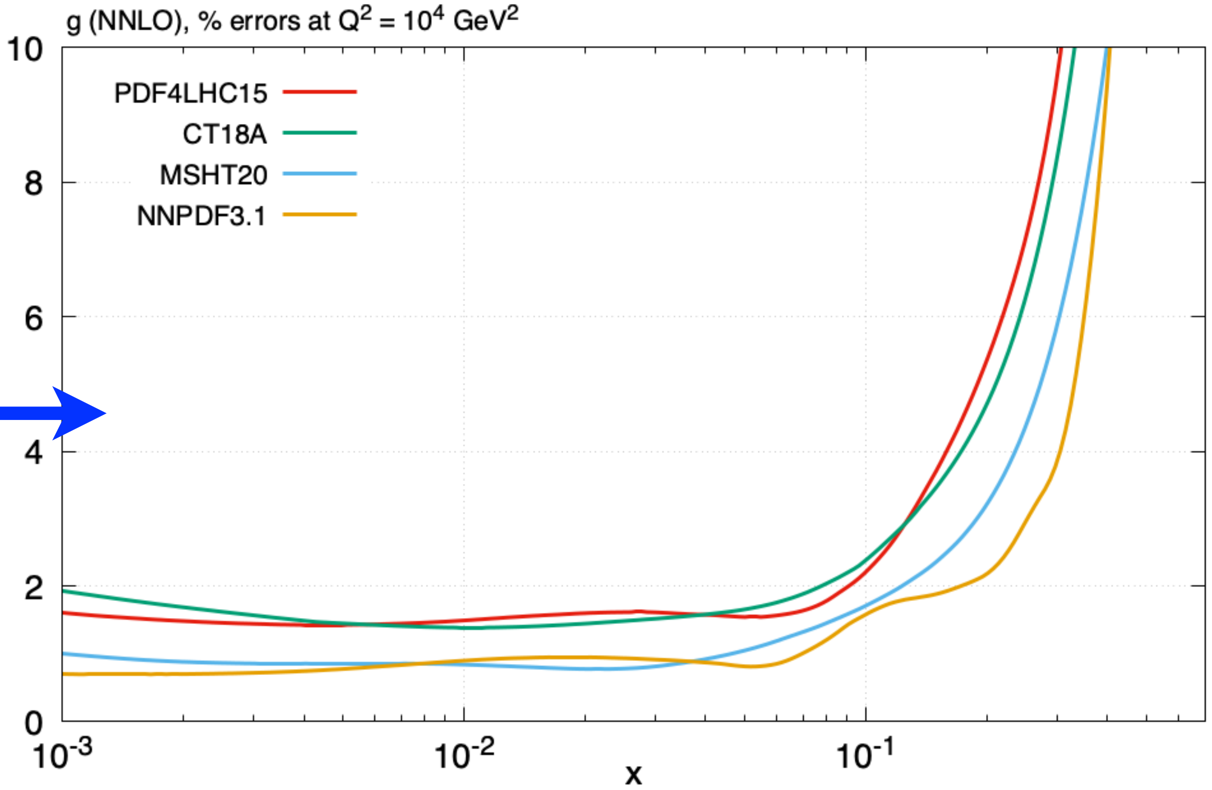


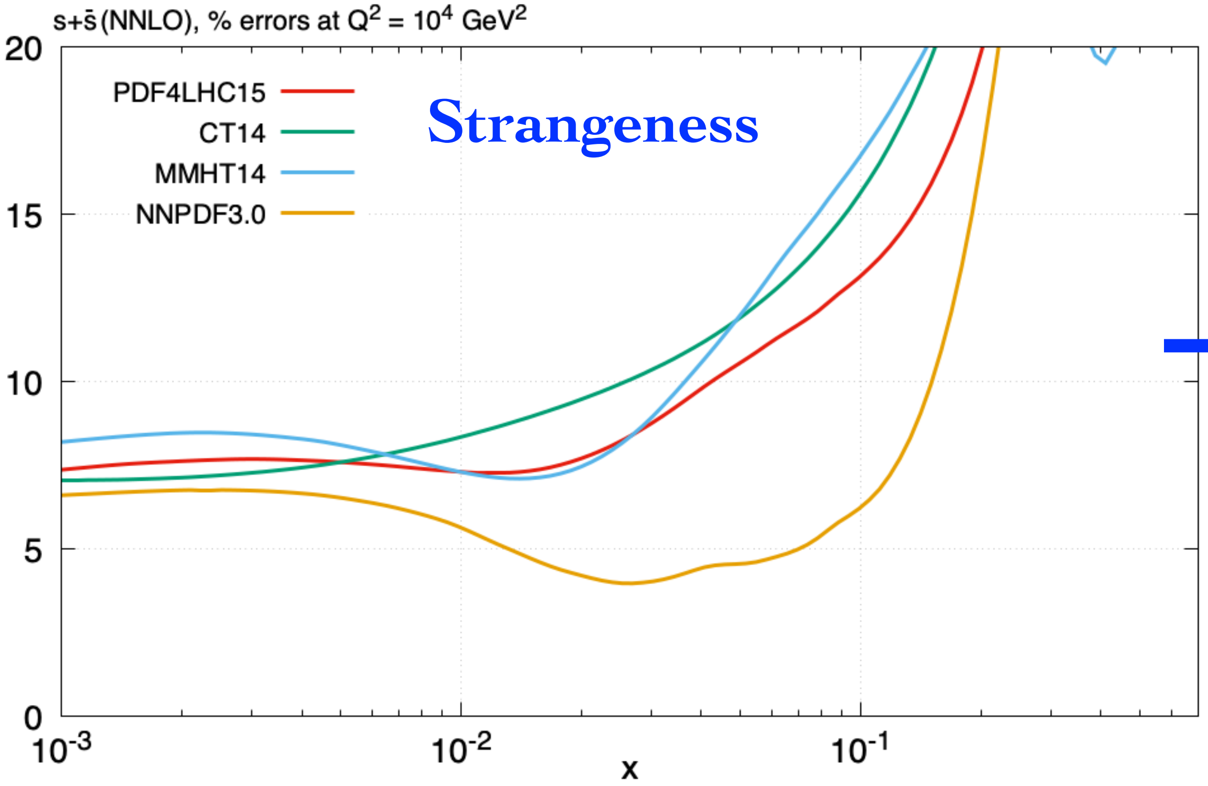
	`n3fit`	NNPDF 3.1
χ^2	1.149	1.158
Avg time	70 minutes	35 hours
Memory	16 Gb	5 Gb
Good replicas	95%	70%

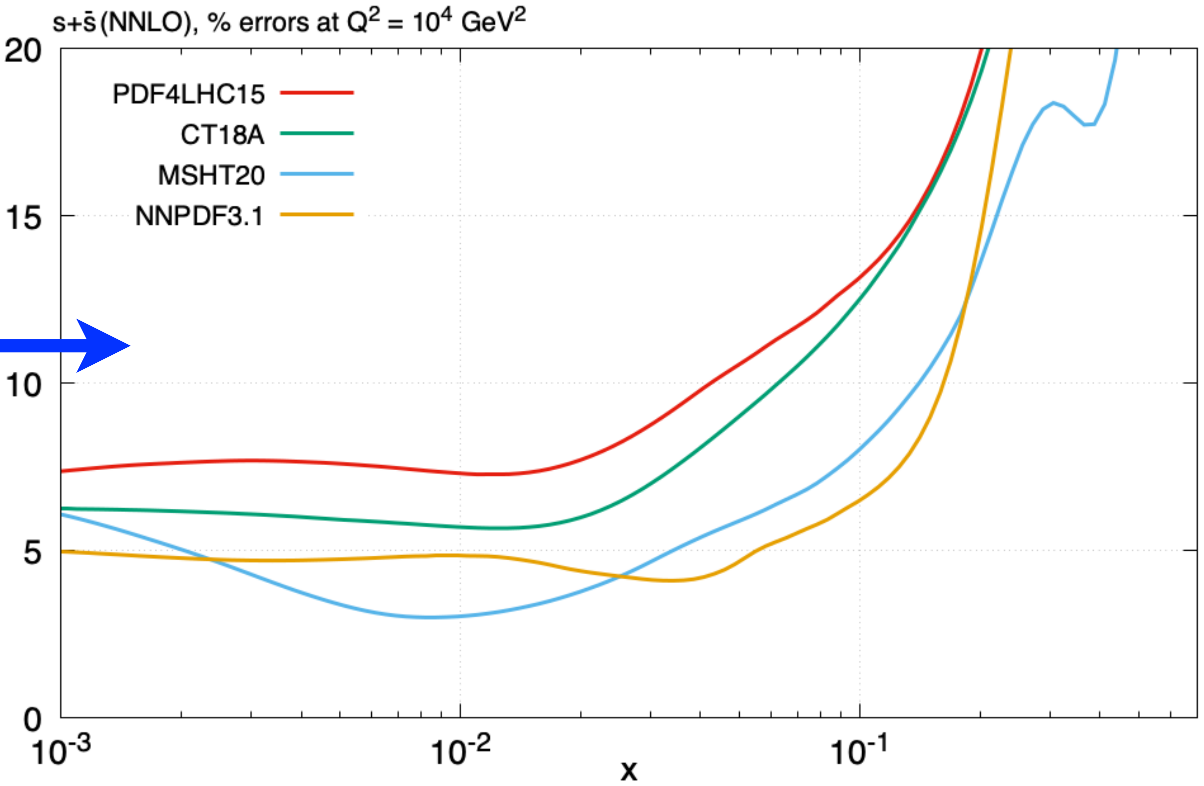
What do the PDFs look like?

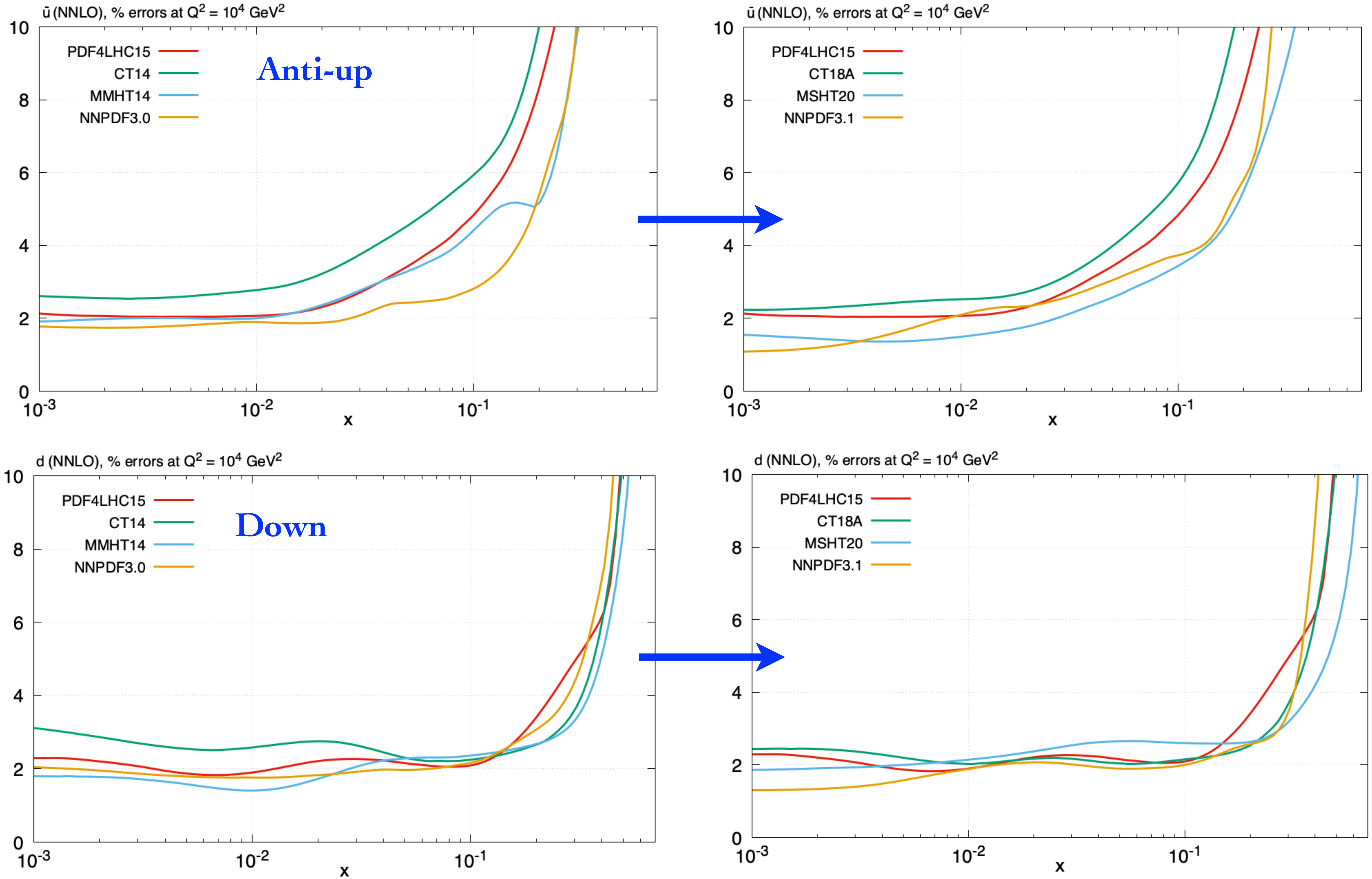
- For most recent public fits, in general clear reduction in **individual errors**. Driven by greatly increased datasets, in particular from **LHC**.



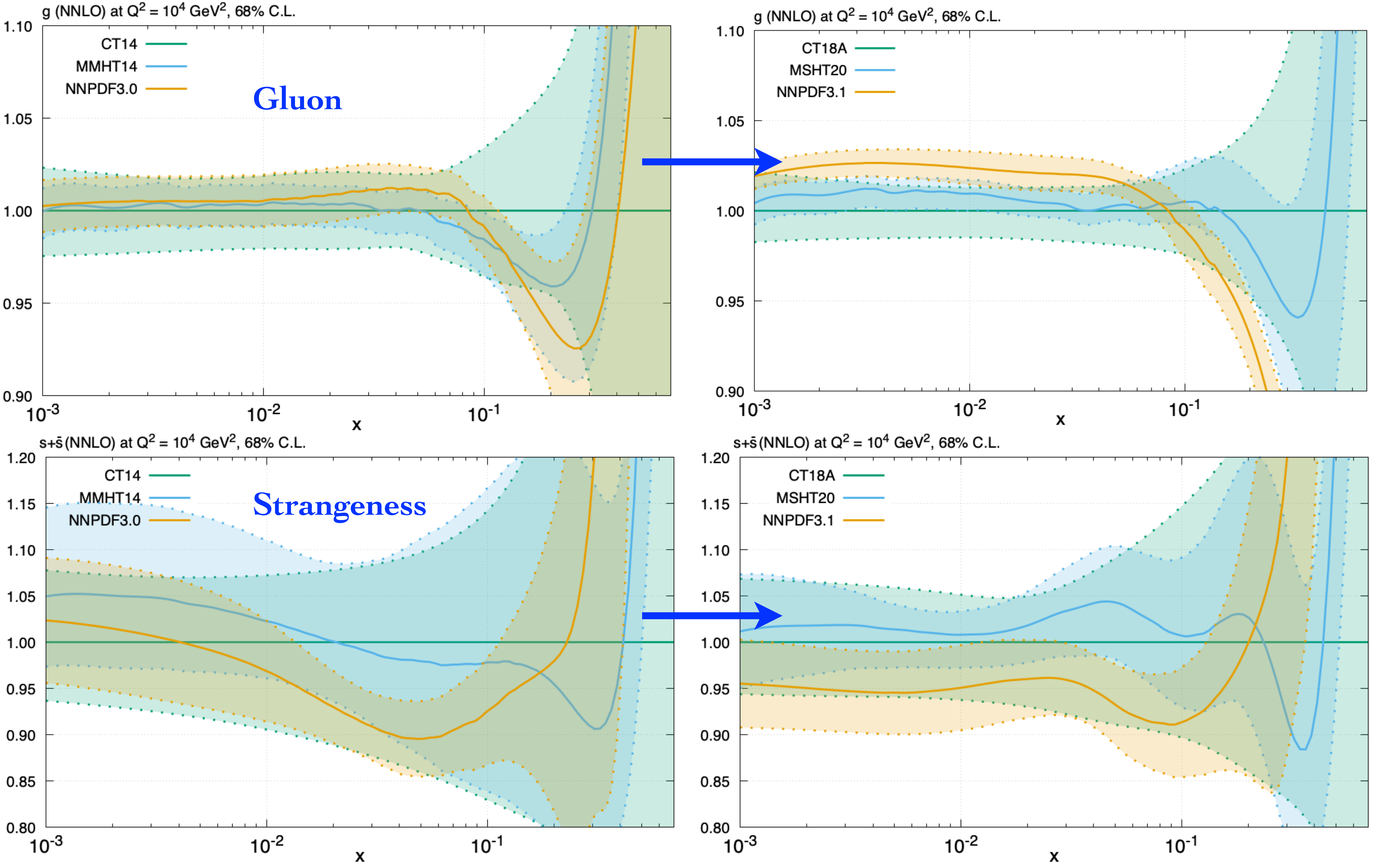




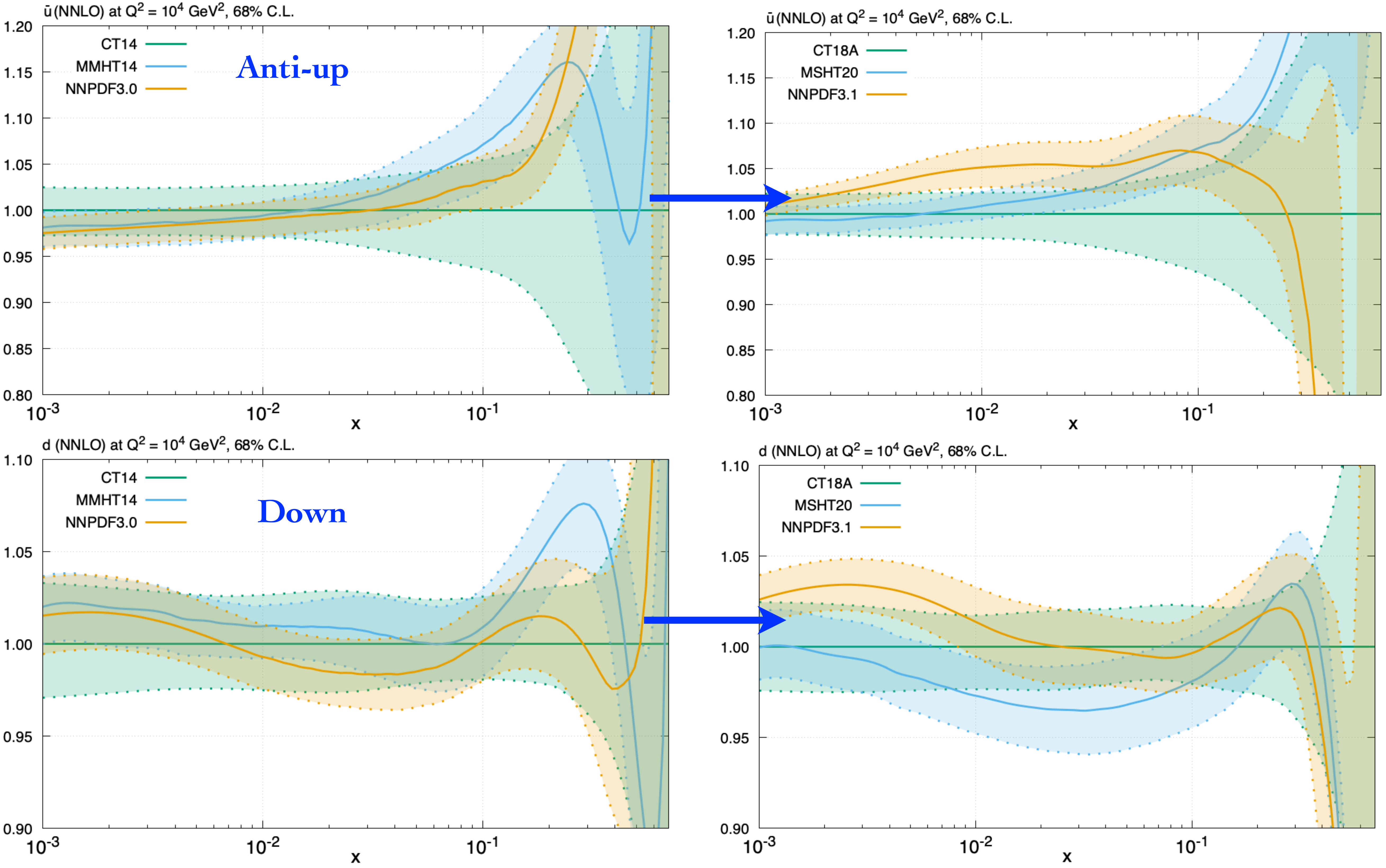




- However picture less clear when looking at central values….



- Encouraging picture for strangeness, but spread in gluon not necessarily reduced/has even increased!



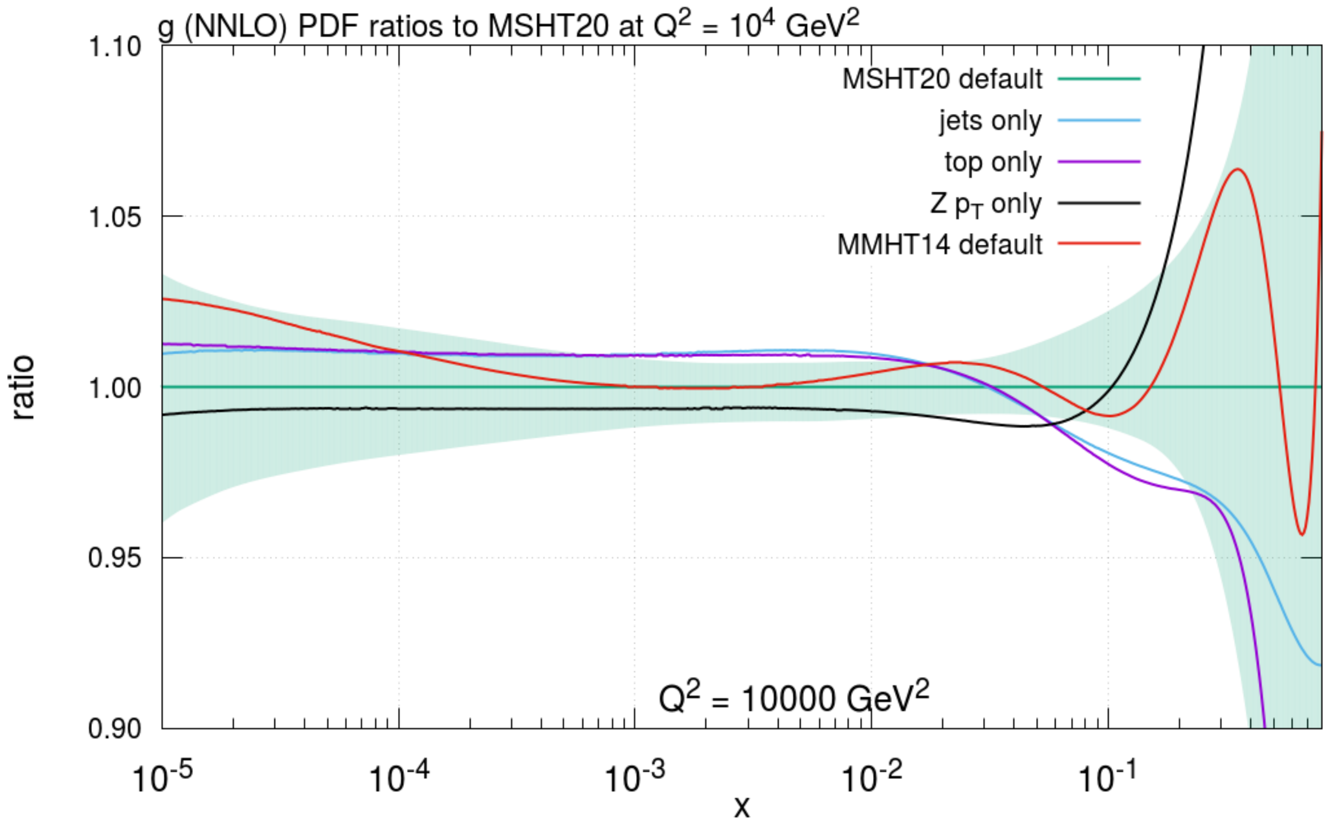
- Similarly mixed picture for light quarks. Understanding of these questions crucial in future. **Benchmarking** needed.

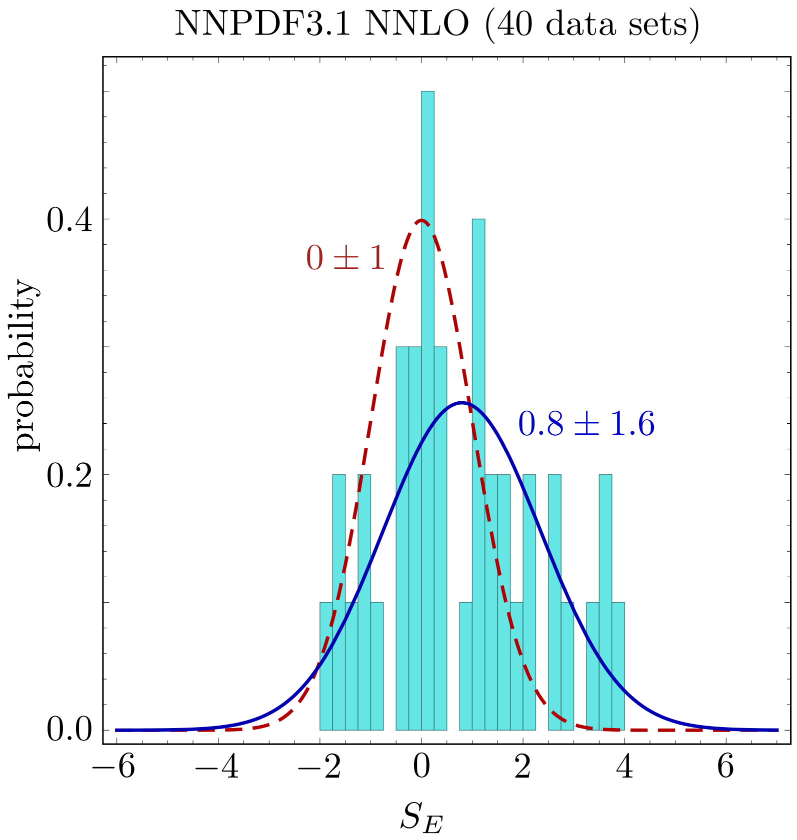
Challenges in reaching high precision

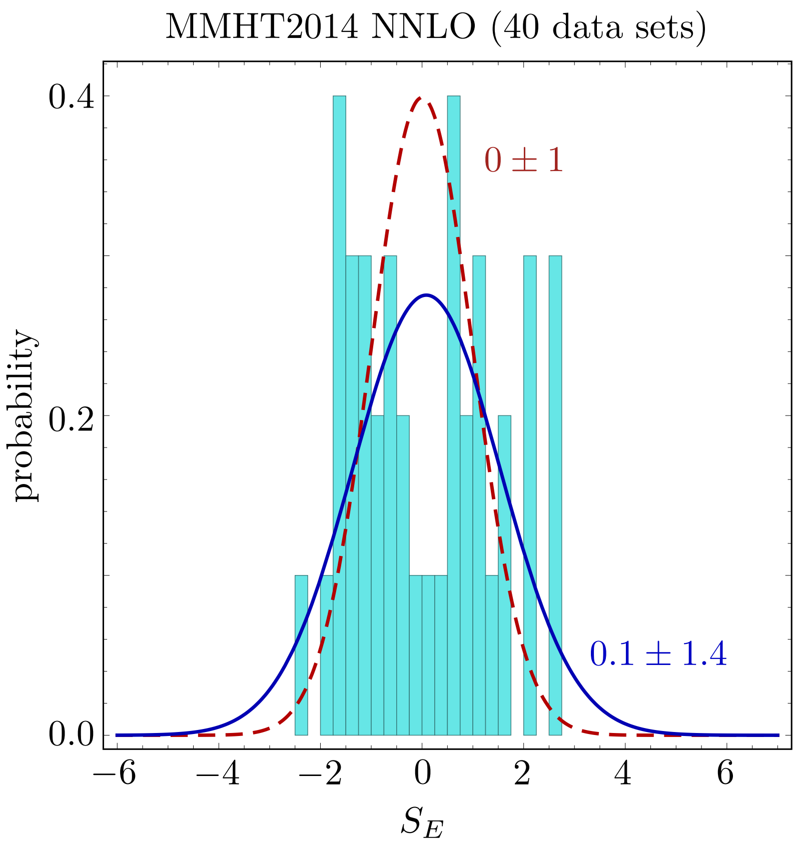
A Global Fit

- Global PDF fits delivers both robustness but also challenges.
- **Robustness**: many datasets entering, insensitivity to any particular experiment/assumption.
- **Challenges**: data often in tension, fit quality far from idealised textbook case.

- Various ways data/theory may not follow textbook expectations: **experimental** and **theoretical**.







K. Kovarik, P. Nadolsky, D. Soper, arXiv:1905.06957

Confronting Precise Data

- LHC data playing increasingly important role in PDF fits.

Basic motivation:

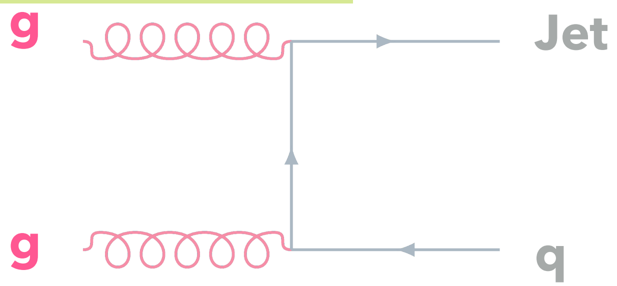
★ High precision, multi-differential data.

★ High precision theory: NNLO QCD 'standard'.

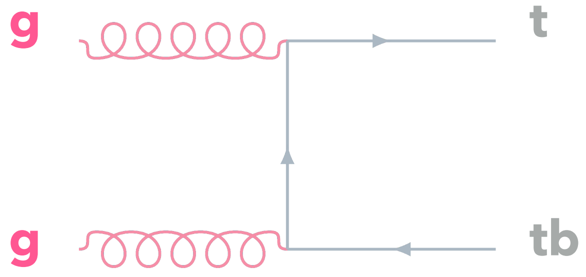
⟶ **High precision** PDF determination.

- However in a number of cases we are seeing **difficulty** in confronting such high precision data in PDF fits.
- Occurs in three 'textbook' LHC processes for PDF determination:

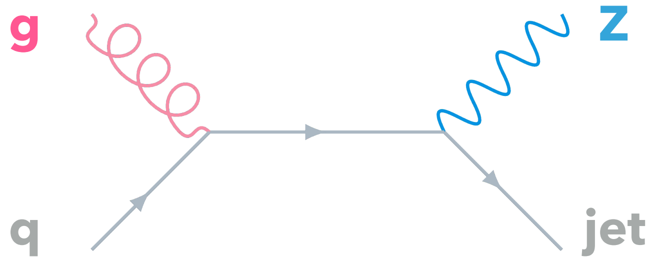
INCLUSIVE JETS



TOP PAIR



Z P_T



M. Ubiali, Higgs Coupling 2019

Top Quark Pair Production

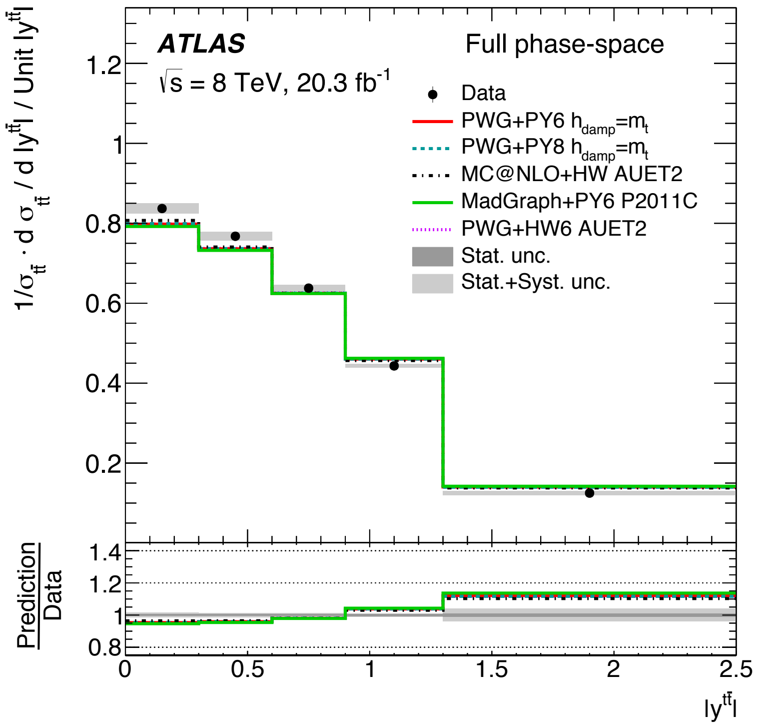
- ATLAS 8 TeV top quark pair production*: presented differentially in four relevant kinematic variables w. all cross-correlations $\Rightarrow$ **simultaneous fits**.
- Significant issues in fit quality…

$$\chi^2/N_{\rm pts}\ (N^{\rm tot}_{\rm pts} = 25)$$

p_T	0.53
y_t	3.12
y_{tt}	3.51
M_{tt}	0.70
$p_T + M_{tt}$	5.73
Combined	7.00

S. Bailey & LHL, *Eur.Phys.J.C* 80 (2020) 1, 60

$$y_t,\ y_{t\bar{t}},\ p_\perp^t,\ M_{t\bar{t}}$$



ATL-PHYS-PUB-2018-017

***In addition issues with fit quality in CMS 8 TeV lepton + jet data for certain individual distributions seen by both CT and MMHT.**

- Data dominated by **systematics**. In particular, **two-point** MC uncertainties in correction back to top quark level by far the largest:
  - ★ Parton Shower: `POWHEG` + `Herwig` vs. `POWHEG` + `Pythia`
  - ★ Hard Scattering: `MC@NLO` + `Herwig` vs. `POWHEG` + `Herwig`
  - ★ ISR/FSR: `POWHEG` + `Pythia`(1) vs. `POWHEG` + `Pythia`(2)

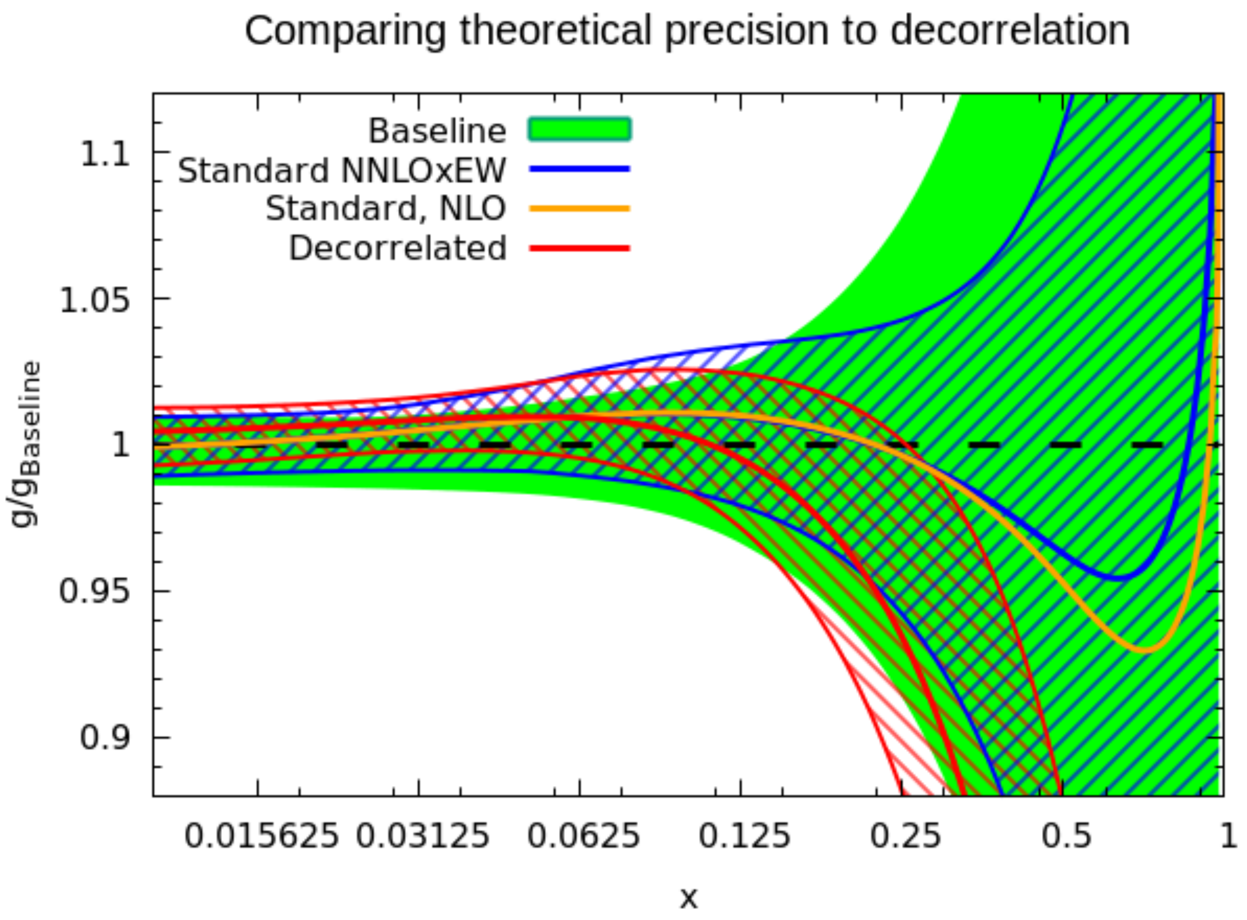
ATL-PHYS-PUB-2018-017

- Uncertainty **and** correlation effectively given by envelope of two MCs. Clear this method will not capture the true degree of correlation.
- Our study*: try some reasonable **loosening** of the assumed **correlation.**

- Decorrelation improves fit quality a lot, but gluon sensitive to it!
- Dependence larger than on e.g. NLO vs. NNLO theory input: **Care needed!**

Distribution	p.s. correlated	p.s. decorrelated
Combined	7.00	1.80
$p_\perp^t + M_{tt}$	5.73	0.66

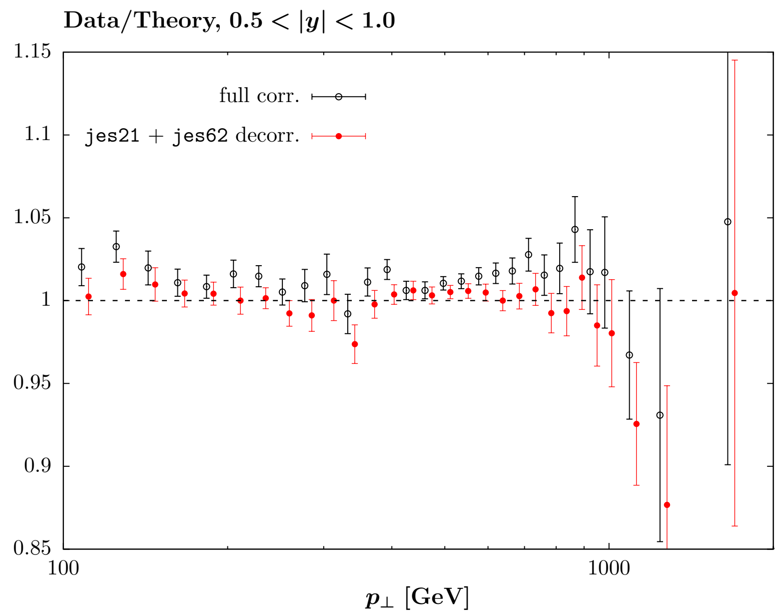
***Similar more limited study in ATL-PHYS-PUB-2018-017**



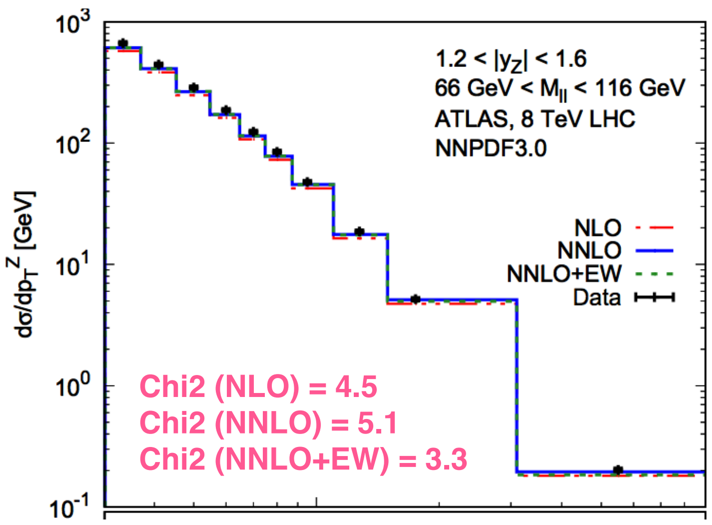
Other Examples: Jets and Z pt

- ATLAS inclusive **Jet data**: again systematics dominated, and fit quality highly sensitive to correlations.
- Decorrelation improves things again. **NNPDF**: dijets potentially less sensitive to these effects? Aside: decorrelated inclusive + dijet gluon agree better (**Backup**).

LHL, R.S. Thorne, A.D. Martin, EPJC78 (2018) no.3, 248



R. Boughezal et al., JHEP 1707 (2017) 130



- **Z boson** transverse momentum distribution: similar situation.
- **NNPDF**- improve by adding in uncorrelated source of uncertainty (missing theory, underestimated experimental errors…).

$\longrightarrow$ **Care needed** in interpreting what precision data is telling us. Best dealt with case by case and with full breakdown of experimental systematics provided.

Uncertainties from Missing Higher Orders

Why Theory Uncertainties?

- Consider fit quality:

$$\chi^2(\{a\},\{\lambda\}) = \sum_{k=1}^{N_{pt}} \underset{\substack{\uparrow \\ \textbf{Uncorrelated errors}}}{\frac{1}{s_k^2}} \left(D_k - T_k - \underset{\substack{\uparrow \\ \textbf{Correlated errors}}}{\sum_{\alpha=1}^{N_\lambda} \beta_{k,\alpha}\lambda_\alpha} \right)^2 + \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha^2 \,,$$

- Even if experimental systematics perfectly accounted for, in $s_k \to 0$ limit the theory T_k will not by default match the data D_k, and $\chi^2 \to \infty$.
- Why? Because T_k given by (fixed order) pQCD, and uncertainty on this due to **missing higher orders** (MHOs) not generally included.

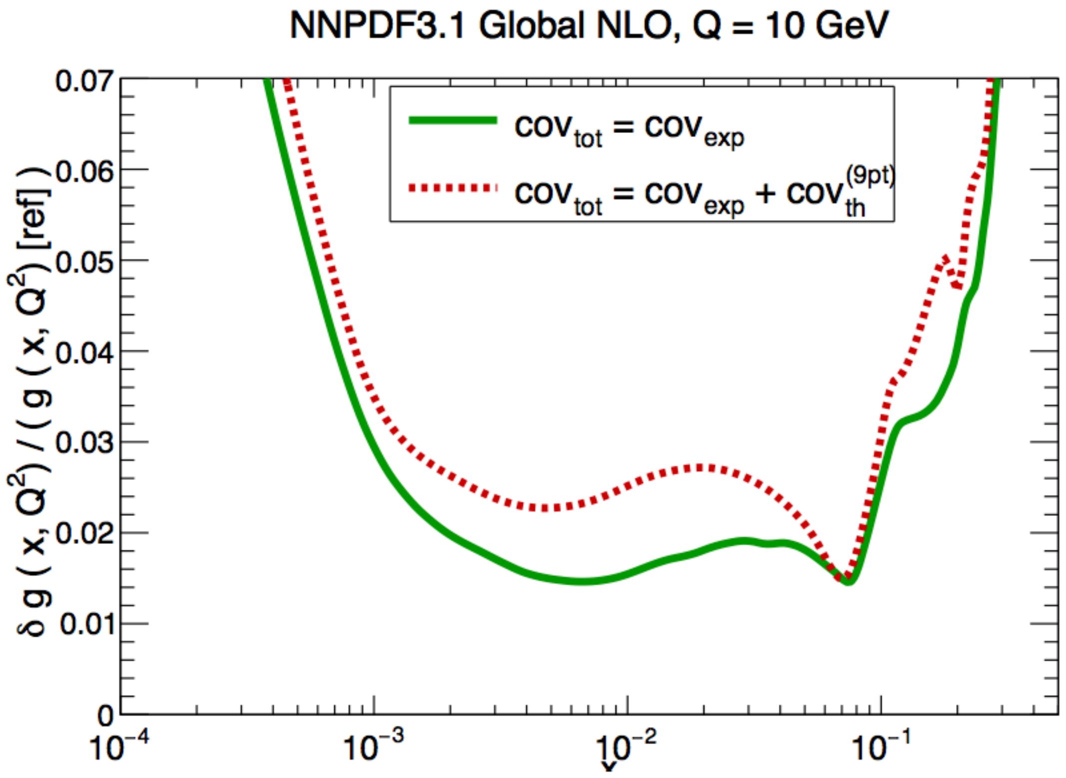
→ Essential to include measure of this if we are to have reasonable/viable interpretation of **fit quality** at high precision, in particular if default poor. Without this may be biasing fit.

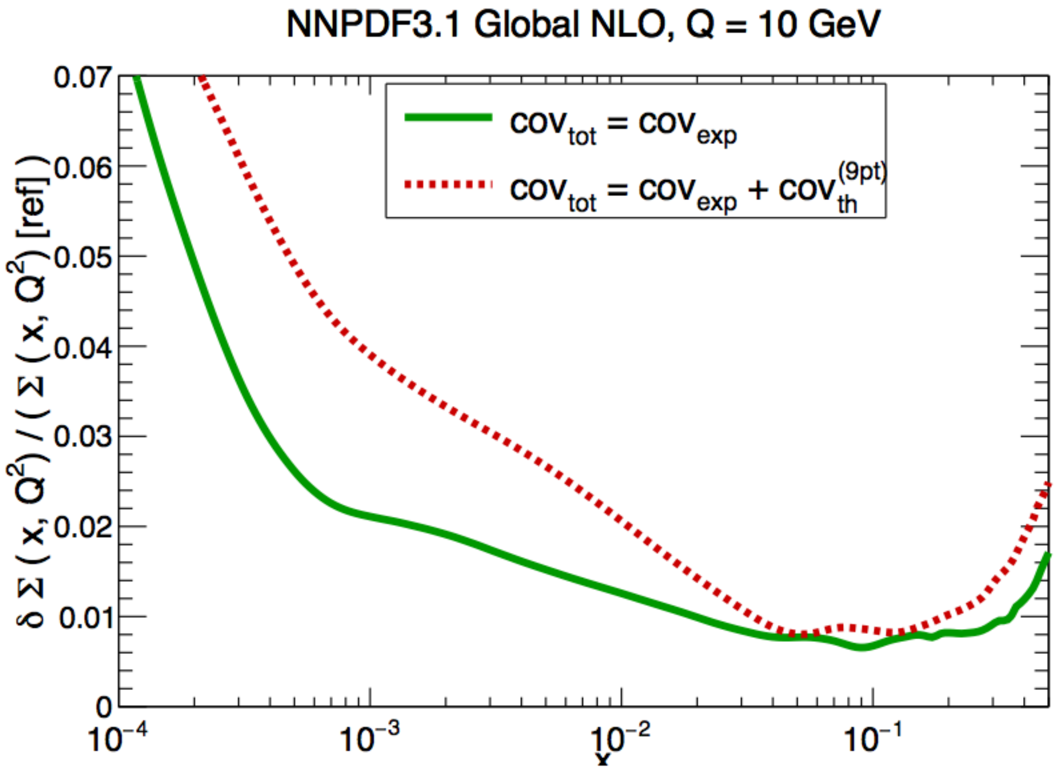
→ Additional motivation, to give estimation of **uncertainty** in extracted PDFs due to MHOs in fit.

MHO Uncertainties

- How to account for MHO uncertainties? Obvious (first?) choice: include these in fit via **scale variations** - NNPDF study.

R. Abdul Khalek et al., *Eur.Phys.J.C* 79 (2019) 11, 931





$\chi^2/N_{\rm dat}$ in the NNPDF3.1 global fits

C	$C + S^{(9\rm pt)}$	$C + S^{(7\rm pt)}$	$C + S^{(3\rm pt)}$	$C + S^{(9\rm pt)}_{\rm fit}$	$C + S^{(9\rm pt)}_{\rm samp}$
1.139	**1.109**	**1.129**	**1.139**	**1.113**	**1.220**

- At NLO find **moderate** improvement in overall fit quality, and **larger** PDF **errors**. Would expect smaller impact at NNLO.

Issues/Open Questions

- ★ We already include MHO uncertainty by scale variation when predicting observables with PDFs. Risk of **double counting**?
- ★ Simplified study: recast PDF fit as direct relationship between fit and predicted observables. Find clear risk of **overestimating** errors due to factorization scale variation in certain regions (low/high x).

LHL and R. S. Thorne, EPJC79 (2019), no.1, 39

Fit

$$\begin{tikzcd}
O_{\rm fit} \arrow[dd, "A"] & \sim f_i(\mu^2)\otimes\sigma_i(\mu^2) \sim f_i(\mu^2)\otimes\left(\sigma_i^{(0)}(\mu^2)+\alpha_S\,\sigma_i^{(1)'}(\mu^2)+\cdots\right) \arrow[d, "B"] \\
 & f_i \arrow[d, "C"] \\
O_{\rm pred} & \sim f_i(\mu^2)\otimes\sigma_i'(\mu^2) \sim f_i(\mu^2)\otimes\left(\sigma_i^{(0)'}(\mu^2)+\alpha_S\,\sigma_i^{(1)'}(\mu^2)+\cdots\right)
\end{tikzcd}$$

$i:$ PDF type

Prediction

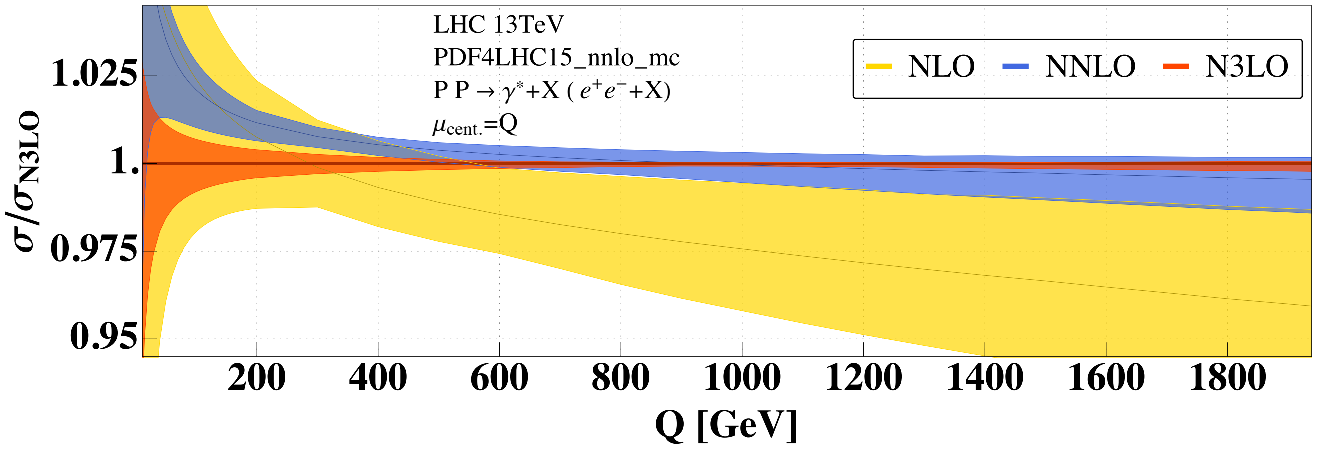
- ★ **Open question** how effectively we can deal with this in actual fit. NNPDF: at worst these missing correlations will lead to overestimate of PDF errors (conservative = good).
- ★ Beyond this: are scale variations even the appropriate thing?

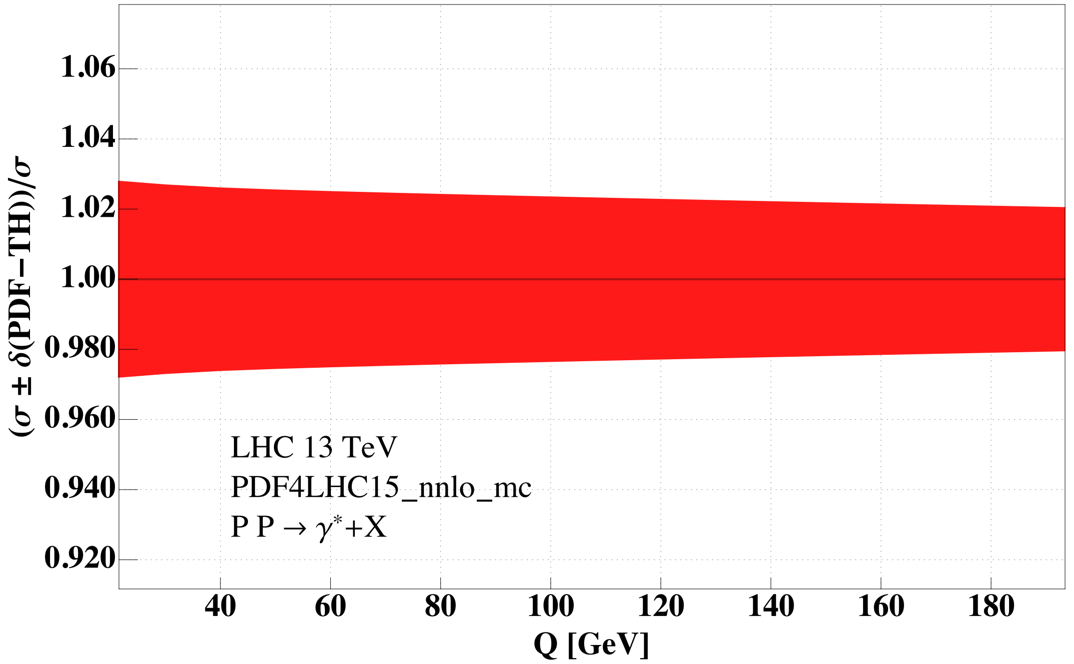
M. Bonvini, arXiv:2006.16293

Connection to DY @ N3LO

C. Duhr, F. Dulat and B. Mistlberger, arXiv:2001.07717, 2007.13313

- Recent first calculation of DY via virtual $\gamma, W^\pm$ at N3LO in QCD.
- Find for $50 \lesssim Q \lesssim 400$ that $\overset{\times}{\div} 2$ scale variation bands do not overlap between NNLO and N3LO.





- However this uses NNLO PDFs. The non-overlap is at the same level as the difference one might get from using N3LO PDFs, if available:

$$\delta(\text{PDF-TH}) = \frac{1}{2}\left|\frac{\sigma^{(2),\ \text{NNLO-PDFs}}_{W^\pm} - \sigma^{(2),\ \text{NLO-PDFs}}_{W^\pm}}{\sigma^{(2),\ \text{NNLO-PDFs}}_{W^\pm}}\right| .$$

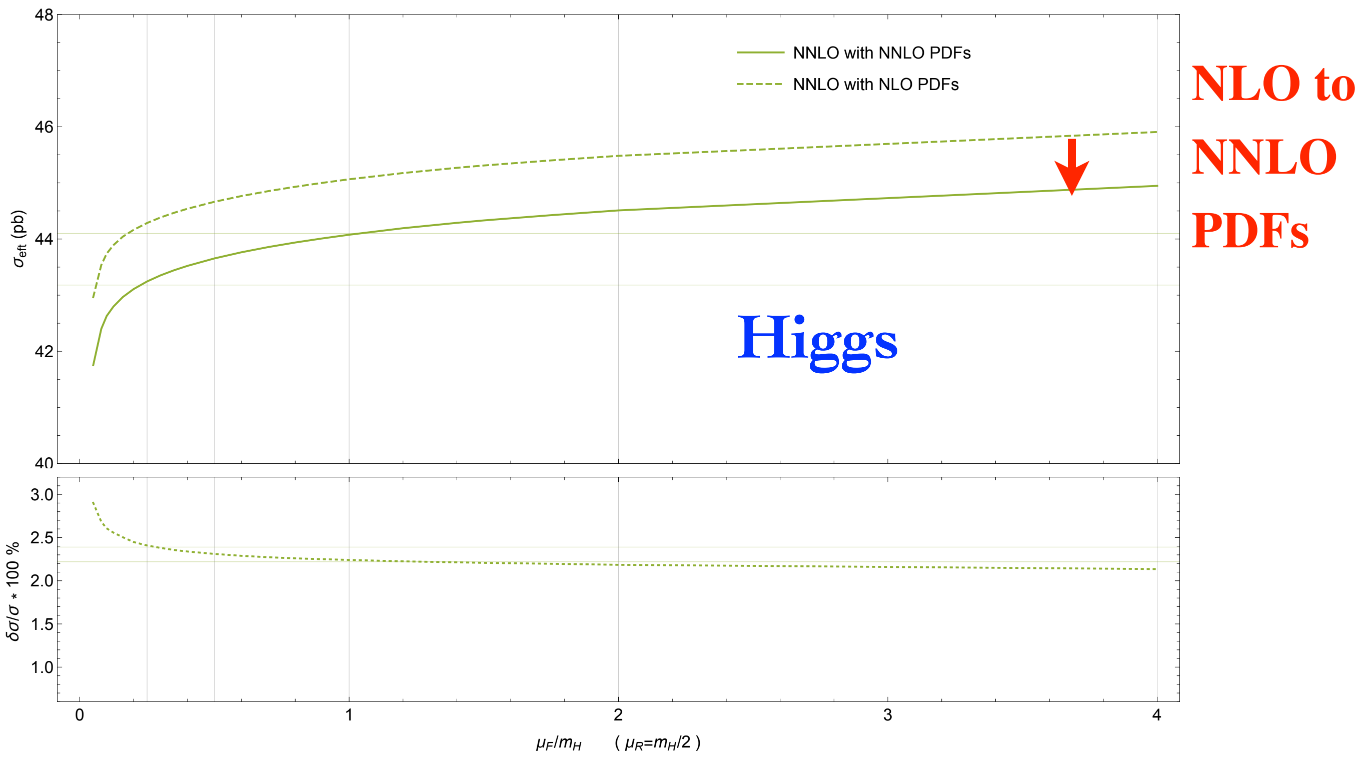
See B. Mistlberger's talk

N3LO PDFs

- N3LO PDFs in principle needed to match this precision. Currently no full N3LO evolution and limited calculations for processes that enter fits, but approximations available.
- Important **future** milestone, but advances/time needed. Took ~ 10 years from first NNLO contributions in global fits to benchmark NNLO fits!

- **More immediate goal**: systematic inclusion of MHO uncertainties at NNLO with correlations.

- Higgs: the NLO to NNLO PDF difference at NNLO ~ constant with μ.
- Suggests due to difference in PDF inputs from fit precision.
- **Work ongoing** towards NNLO MHO uncertainties!



NLO to NNLO PDFs

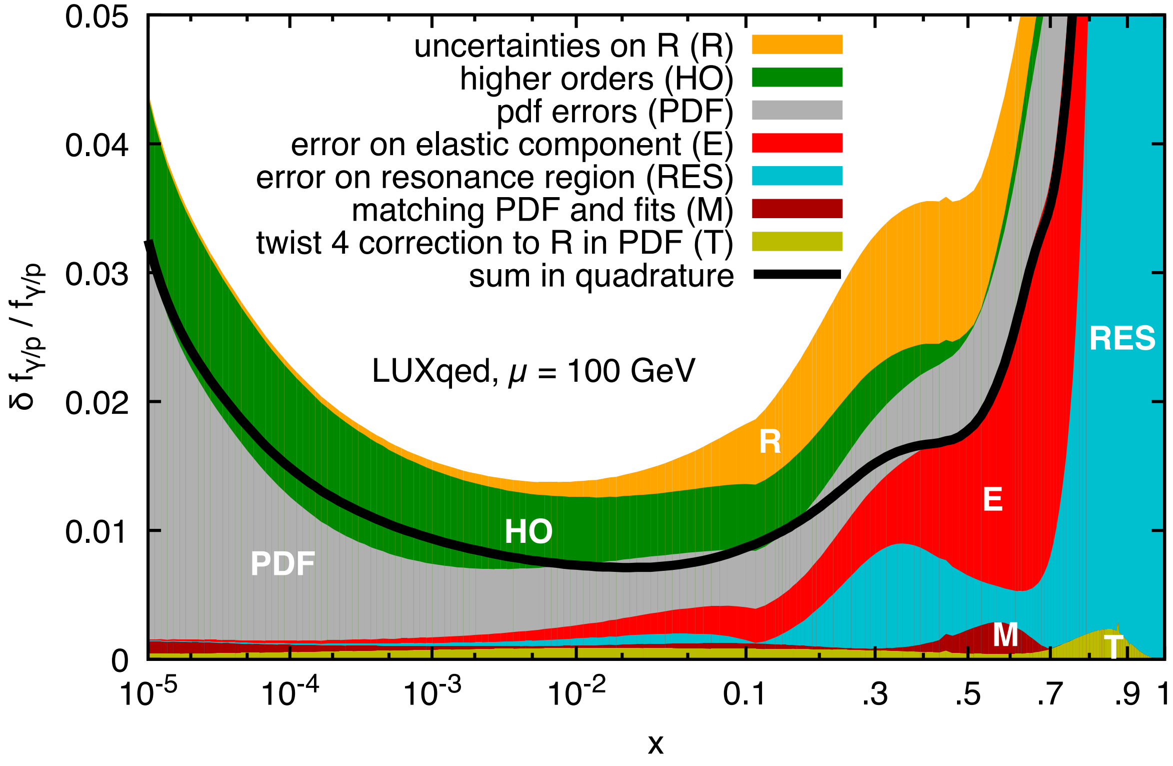
Other Progress/Possibilities

Photon PDF/EW corrections

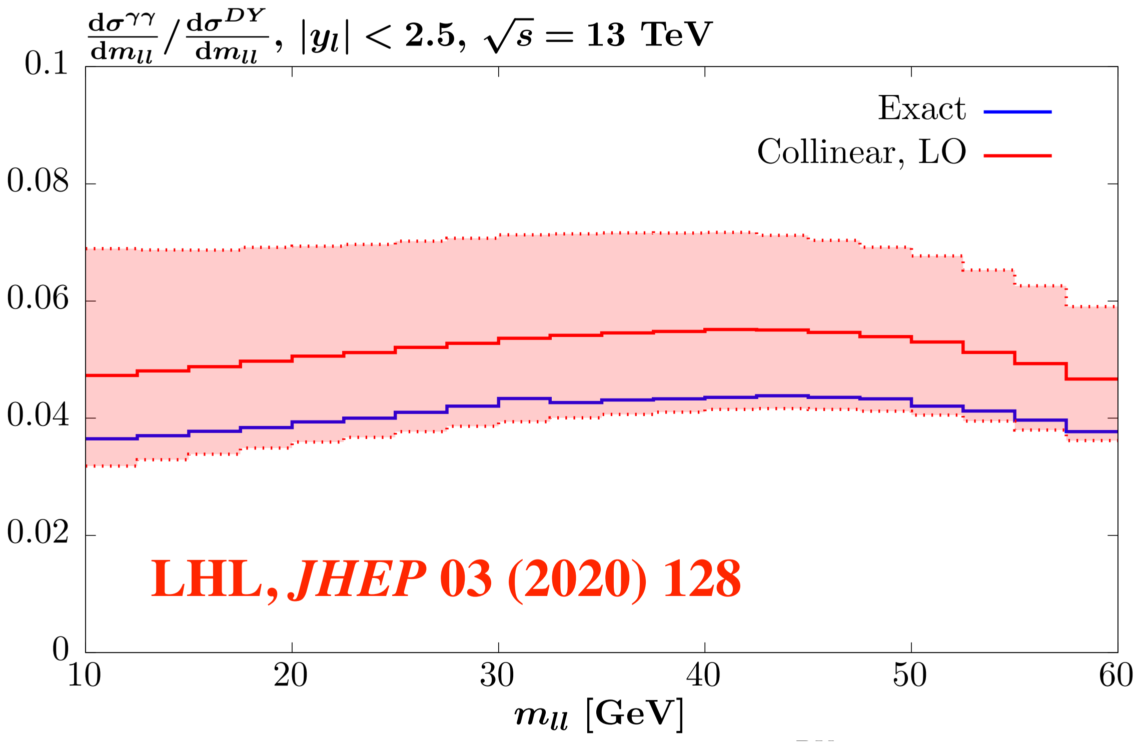
- Inclusion of precise photon PDF via relation to ep structure functions now standard approach in global fits.

LHL et al., *Eur.Phys.J.C* 79 (2019) 10, 811
V. Bertone et al., *SciPost Phys.* 5 (2018) 1, 008

- Likewise NLO EW included where relevant.
- However the LO $\gamma\gamma \to X$ process still has large $\mu_{F,R}$ variation uncertainties. Absent if one calculates instead in the structure function approach directly.
- Hybrid approach under investigation (still need QED DGLAP…), but in MSHT20 the SF approach is used for photon-initiated contributions.



A. Manohar et al., JHEP 1712 (2017) 046

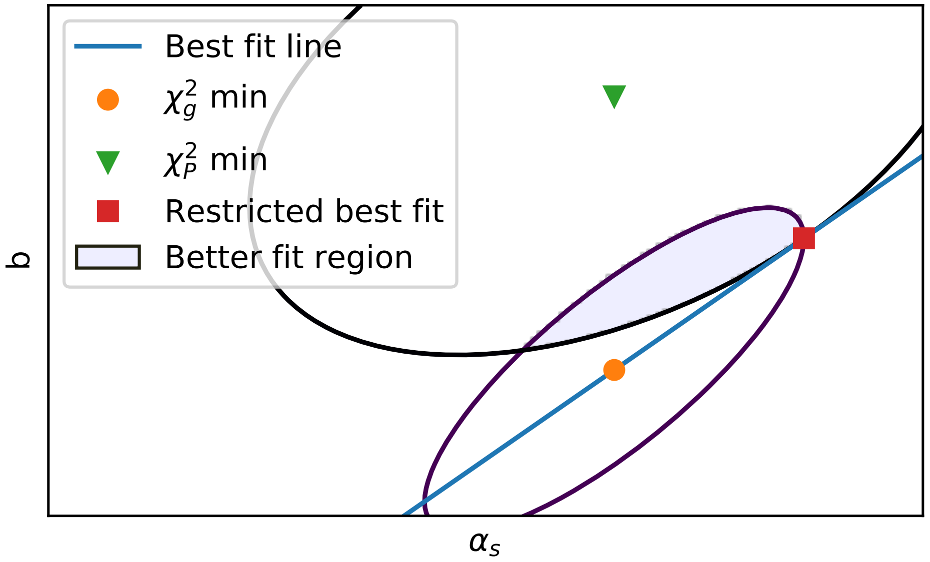


LHL, *JHEP* 03 (2020) 128

S. Forte and Z. Kassabov, Eur.Phys.J.C 80 (2020) 3, 182

PDFs and the Strong Coupling

- PDFs from a global fit and the value of α_s used in the fit highly correlated.
- As a result great care is needed in interpreting what the preferred value of α_s is from a given hadronic dataset.

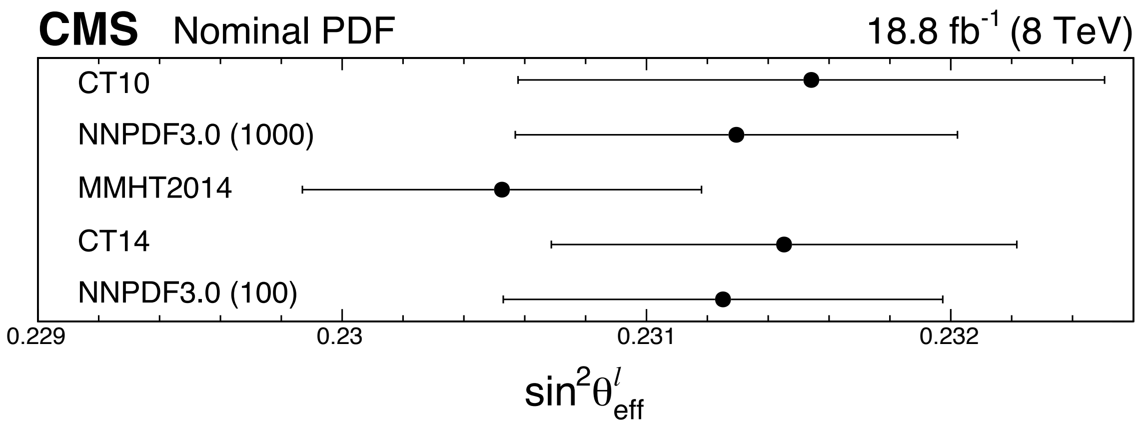


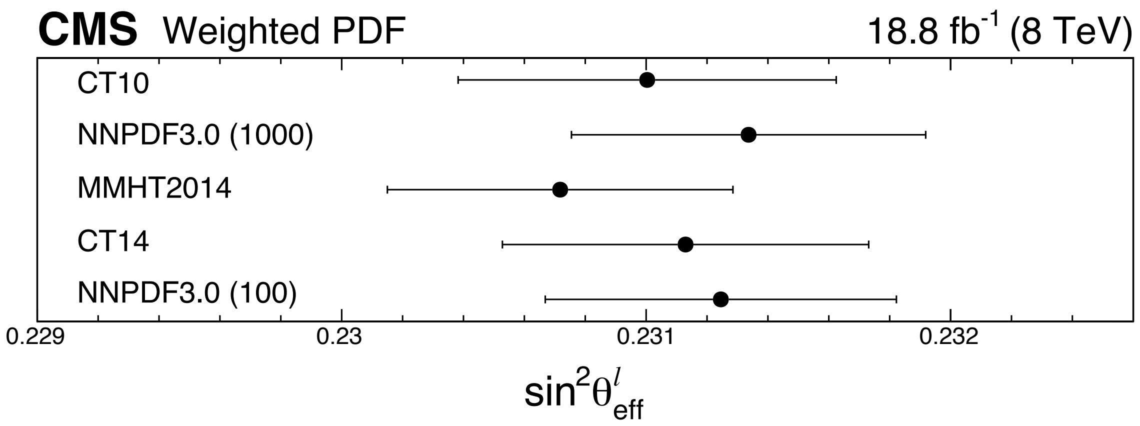
- Using a publicly available PDF(α_s) sets will not give α_s that corresponds to a full refit of the PDFs + α_s to the global dataset + the new dataset.

$\longrightarrow$ No short cut available, must do full global PDF refit.

- Though situation with α_s rather special, worth recalling that 'in-situ' PDF constraints being used for EW precision measurements. Simultaneous global PDF + SM always optimal (though challenging!).

CMS collab., EPJC78 (2018) no.9, 701





Other Progress/Possibilities

★ Many other topics with no time to discuss here:

- Progress towards simultaneous fits to PDFs + possible BSM in EFT framework.

  S. Carazza et al., *Phys.Rev.Lett.* 123 (2019) 13, 132001
- Progress in approximate techniques for assessing impact of future data without performing full refit (PDFsense…) applied in multiple cases.

  Y. Fu et al., arXiv:2008.03853
- Very promising prospects for clean and precise PDF determination via the LHeC.

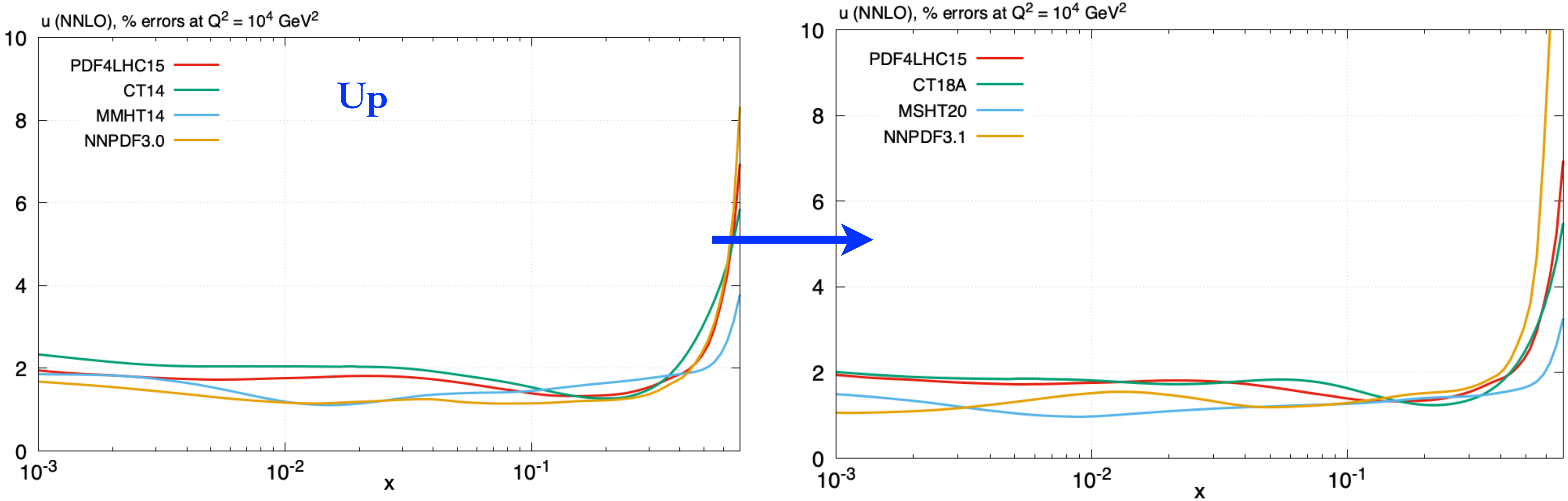
  P. Agostini et al., arXiv:2007.14491
- Progress in nuclear PDFs, polarized PDFs/their interplay with fragmentation functions.
- Connection to lattice: possibilities for input in global fits?
- …

Summary/Outlook

- ★ Precision LHC era: **significant opportunity** for PDF determination.
- ★ Precise data from LHC + precise theory already having **significant impact** on PDF fits. Multiple 'Post Run-I' sets available.
- ★ But **significant challenges** before us: confronting high precision data in fits, dealing with tensions, poor fit quality, including theory uncertainties effectively…
- ★ LHC data playing key role in global fits. But not only question of adding ever more data to PDF fits. Much work ahead to make sense of what we are seeing…

Thank you for listening!

Backup


u (NNLO), % errors at $Q^2 = 10^4$ GeV^2
PDF4LHC15
CT14
MMHT14
NNPDF3.0
Up
10
8
6
4
2
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10^{-3}
10^{-2}
10^{-1}
x
u (NNLO), % errors at $Q^2 = 10^4$ GeV^2
PDF4LHC15
CT18A
MSHT20
NNPDF3.1
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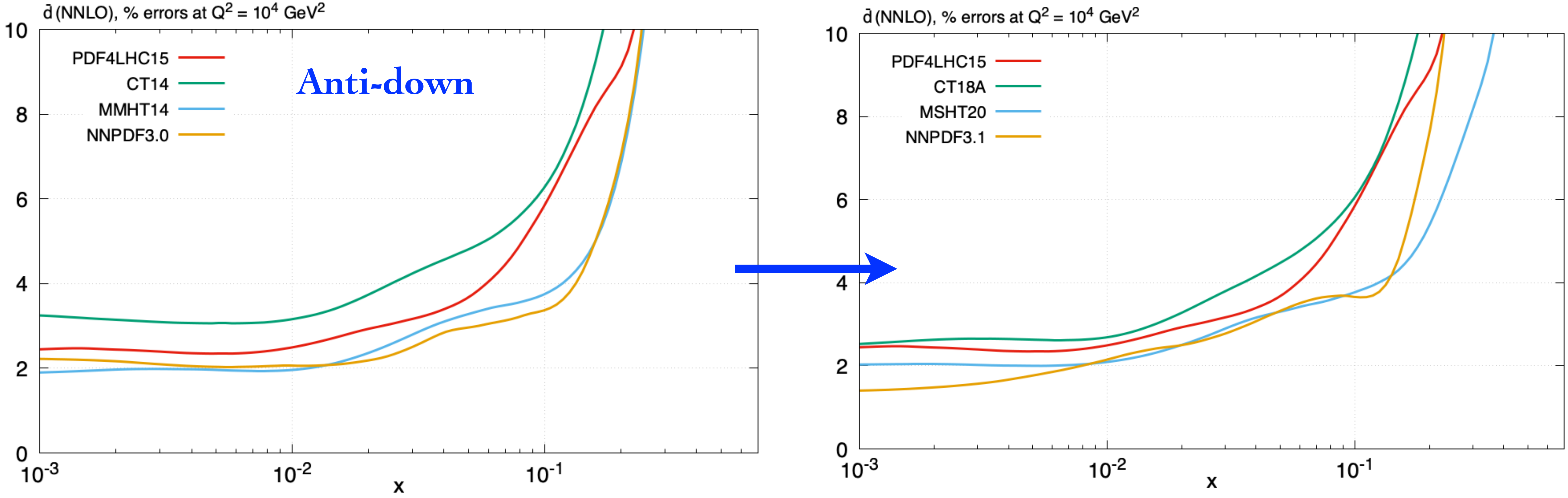
$\bar{d}$ (NNLO), % errors at $Q^2 = 10^4$ GeV^2
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MMHT14
NNPDF3.0
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$\bar{d}$ (NNLO), % errors at $Q^2 = 10^4$ GeV^2
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CT18A
MSHT20
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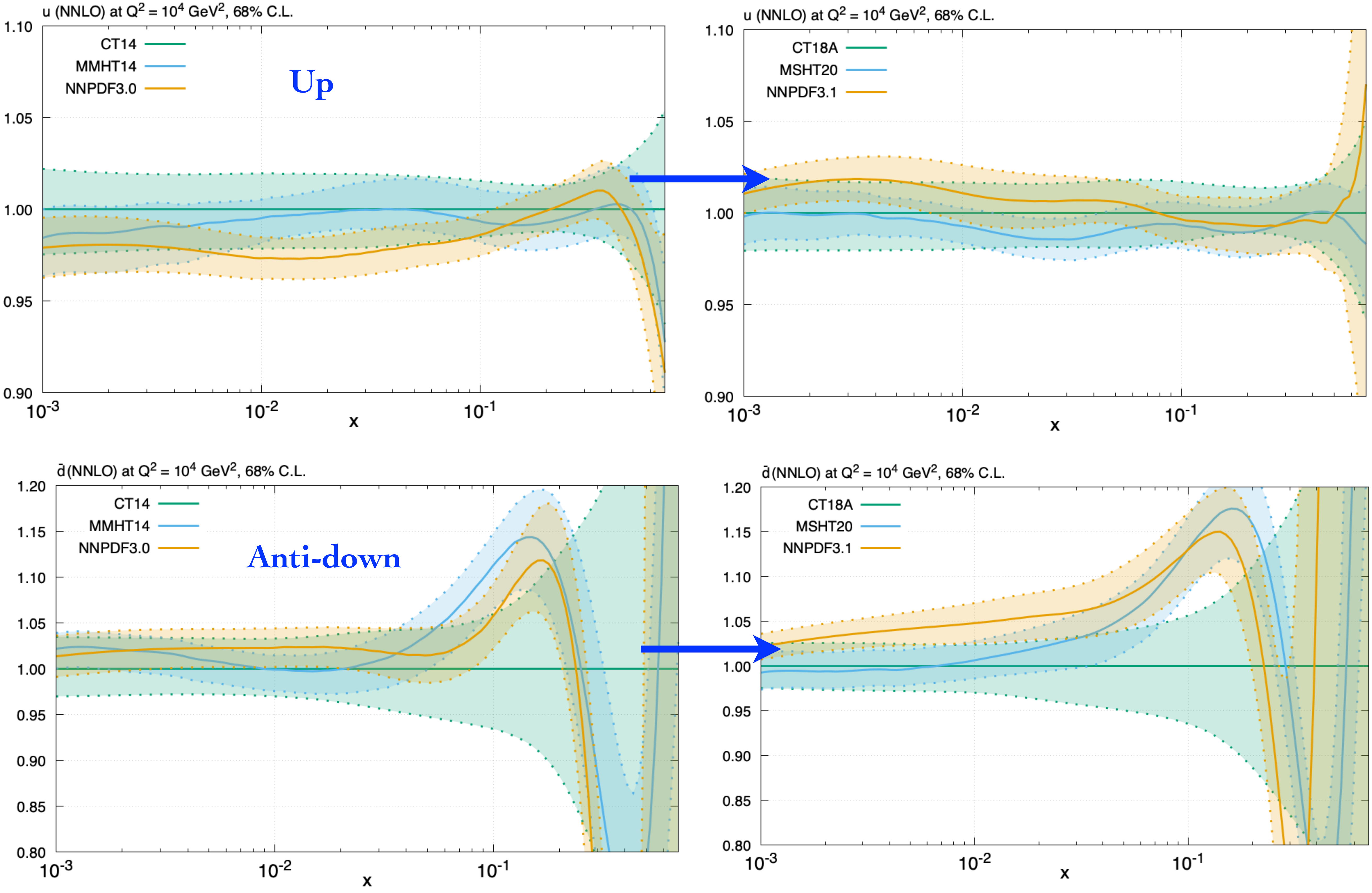
u (NNLO) at $Q^2 = 10^4$ GeV^2, 68% C.L.
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MMHT14
NNPDF3.0
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u (NNLO) at $Q^2 = 10^4$ GeV^2, 68% C.L.
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$\bar{d}$ (NNLO) at $Q^2 = 10^4$ GeV^2, 68% C.L.
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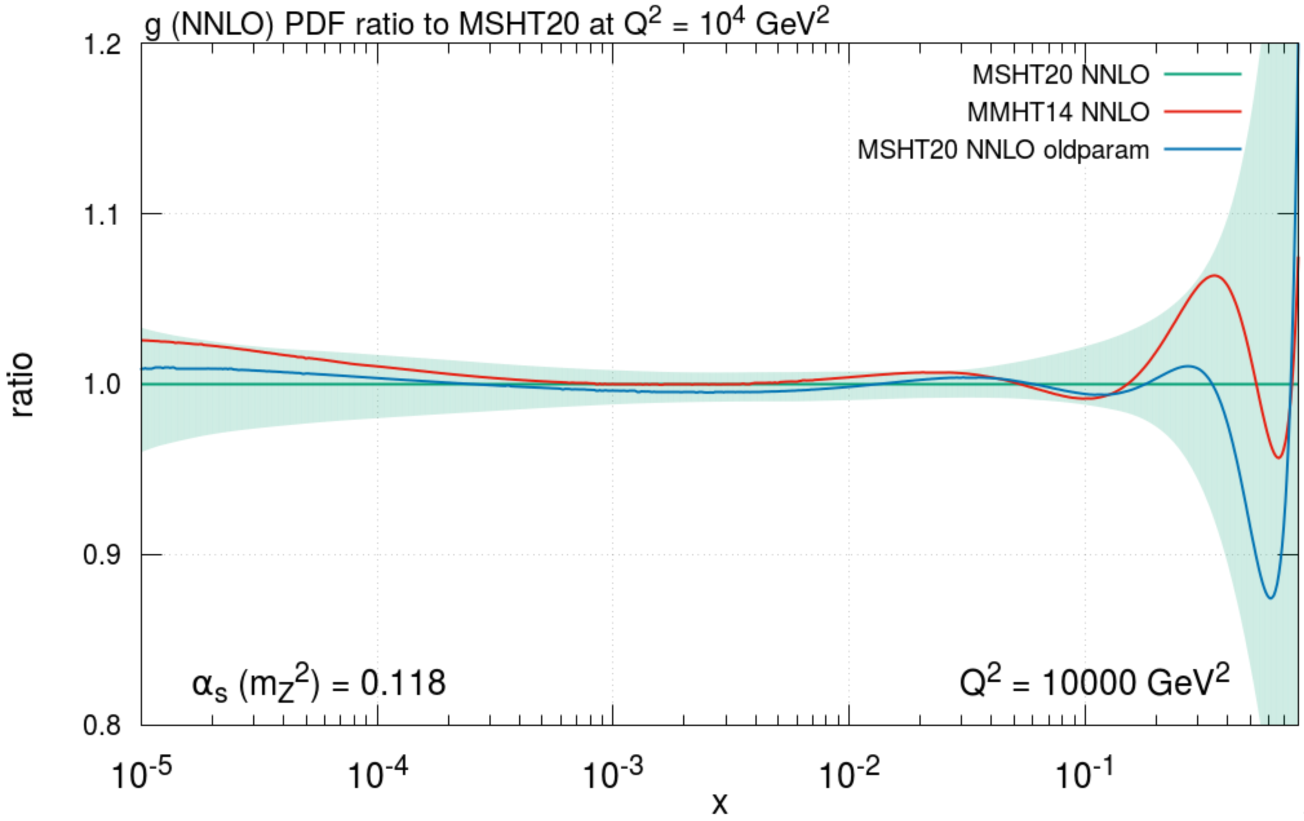
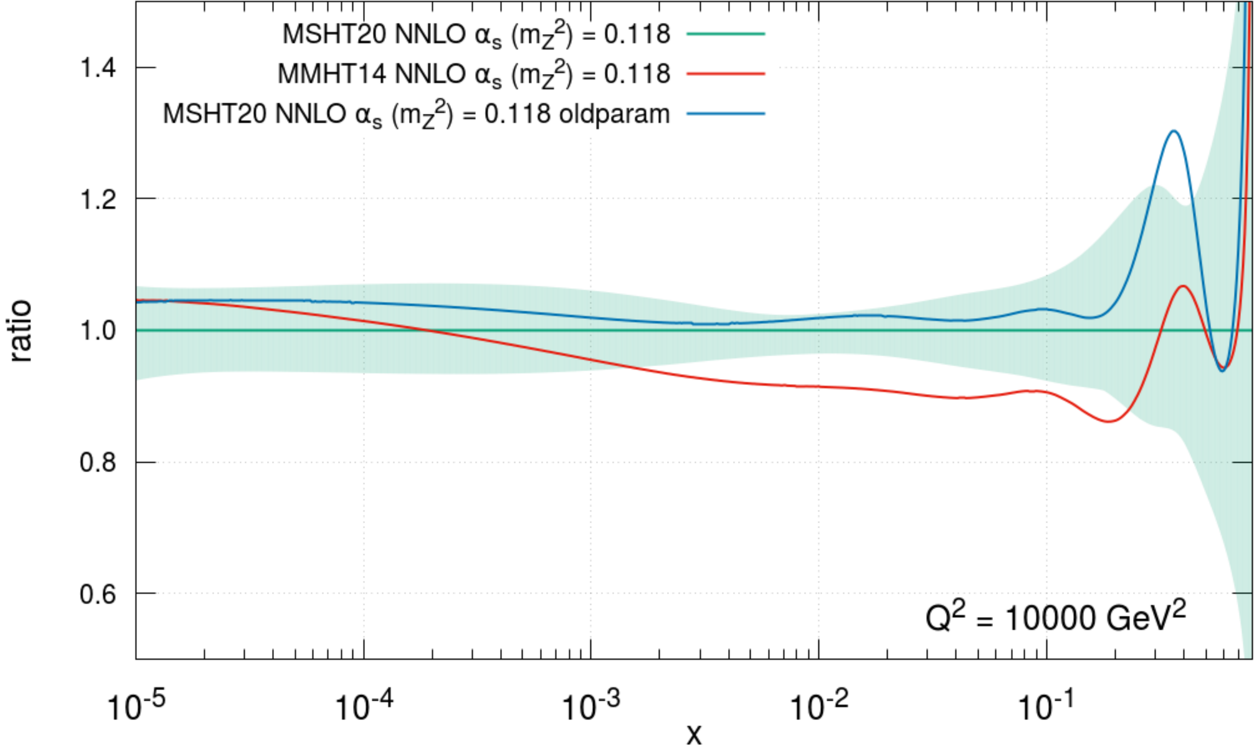
10^{-1}
x

Parameterisation Flexibility


g (NNLO) PDF ratio to MSHT20 at $Q^2 = 10^4$ GeV^2

s + $\bar{s}$ (NNLO) PDF ratio to MSHT20 at $Q^2 = 10^4$ GeV^2



Fit Quality: General Context

- Before considering specific examples, quick **recap** of fit quality.
- The χ^2 can in presence of correlated errors can be written as:

$$\chi^2(\{a\},\{\lambda\}) = \sum_{k=1}^{N_{pt}} \frac{1}{s_k^2}\left(D_k - T_k - \sum_{\alpha=1}^{N_\lambda}\beta_{k,\alpha}\lambda_\alpha\right)^2 + \sum_{\alpha=1}^{N_\lambda}\lambda_\alpha^2\ ,$$

$$D_k \to D_k - \sum_{\alpha=1}^{N_\lambda} \beta_{k,\alpha}\hat{\lambda}_\alpha$$

Uncorrelated errors

Correlated errors

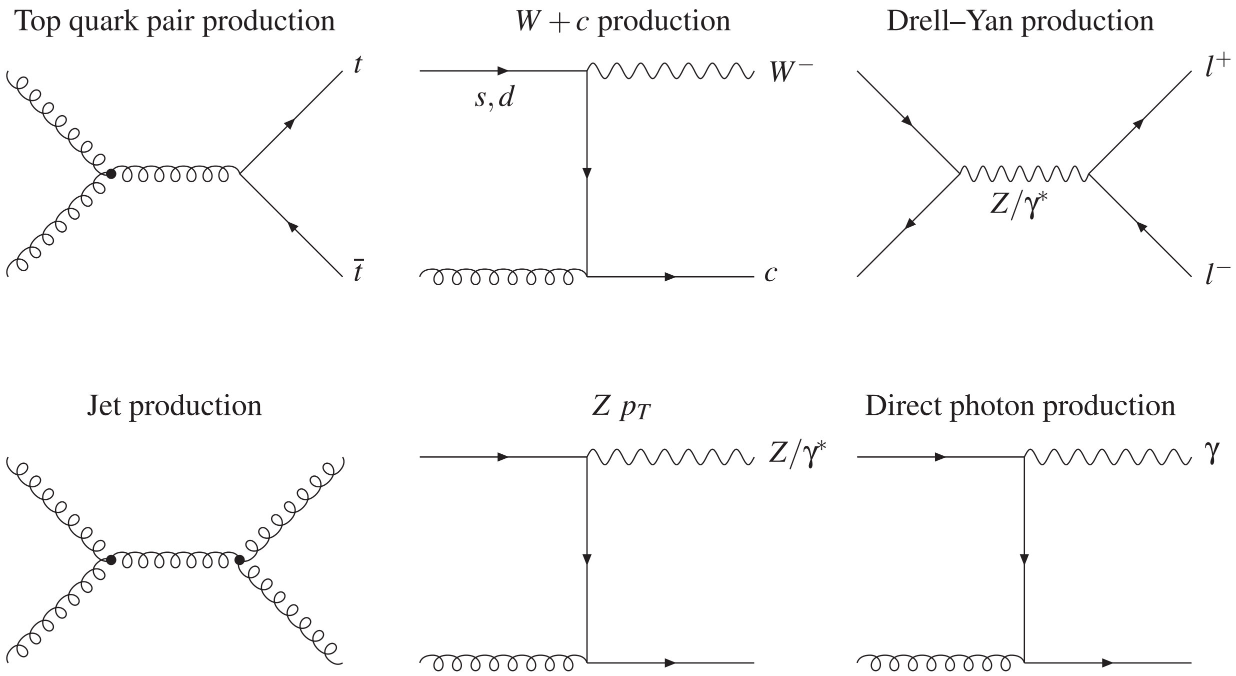
Penalty for shifts

- The set of N_λ nuisance parameters λ_α take values so as to minimise χ^2, effectively shifting data points D_k.
- In PDF fits this is always achieved analytically by assuming purely Gaussian errors.
- For $s_k \to 0$ the fit quality is dominated by the $\beta_{k,\alpha}$, i.e. the **systematic errors** and in particular their **correlations**.

PDFs in the future: what we are aiming/hoping for

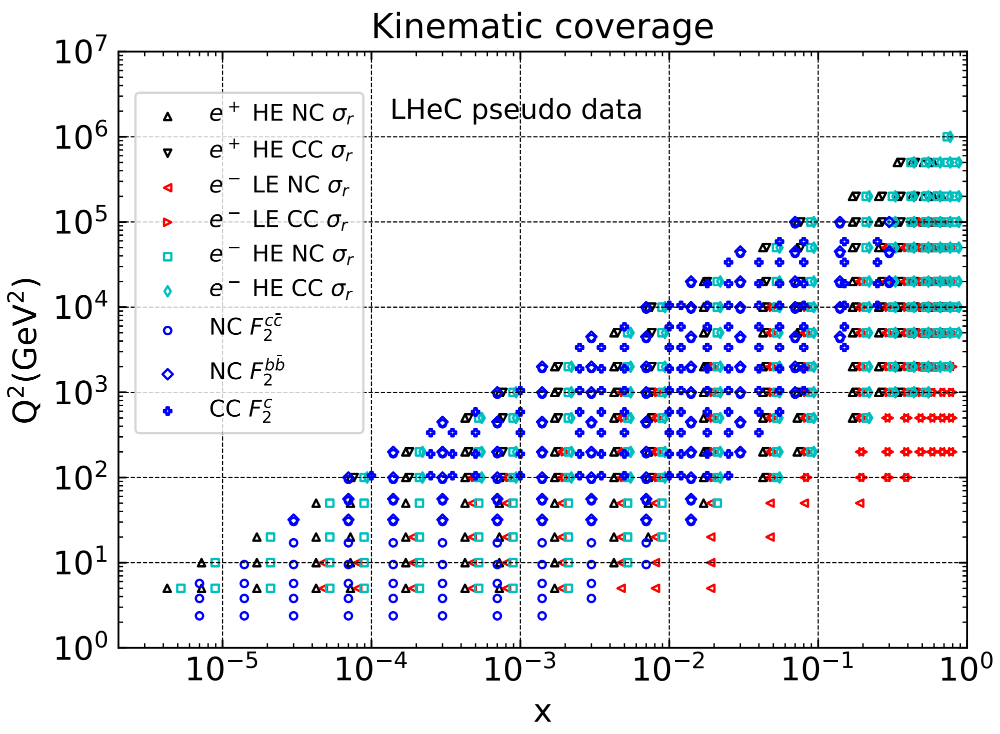
- Earlier studies to estimate impact of final HL-LHC (and potential LHeC) data on PDFs.
- Based on straightforward extrapolations of statistical errors and estimates of improvements in systematics.
- Datasets considered non-exhaustive and some allowance for tensions built in.

R. Abdul Khalek, S. Bailey, J. Gao, LHL, J. Rojo. Eur.Phys.J. C78 (2018) no.11, 962

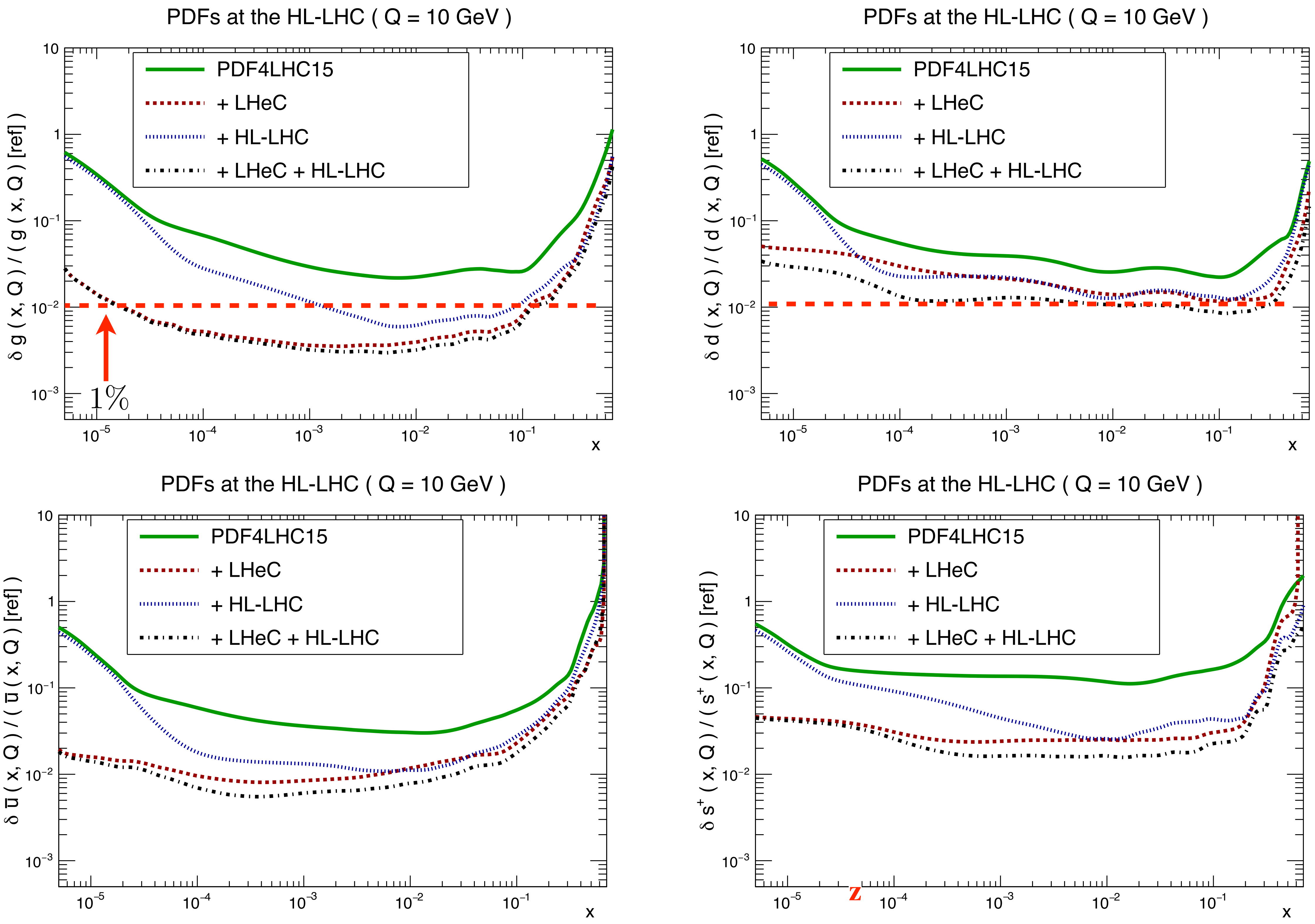


HL-LHC

R. Abdul Khalek, S. Bailey, J. Gao, LHL, J. Rojo. SciPost Phys. 7, 051 (2019)



LHeC



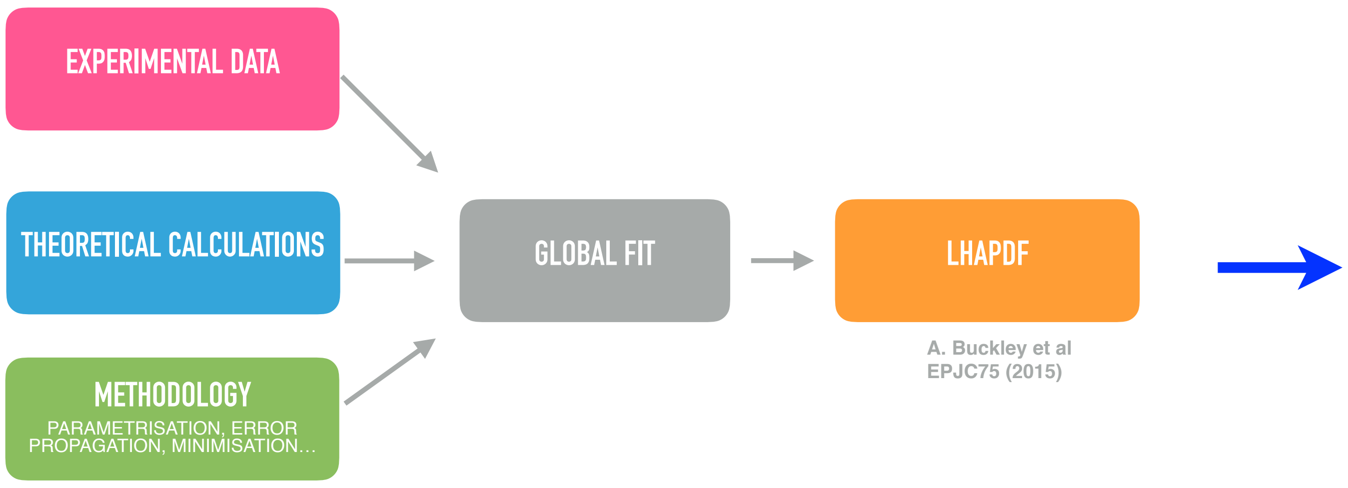
- **Sub percent level** uncertainty in e.g. gluon in some x regions.
- **Can we get there?**

Interplay Between PDF Fits and SM Precision Measurements

PDFs and SM Precision tests

- **‘Standard’ paradigm**: global PDF fits produced independently. Input in precision measurements from individual experiments.

ATLAS collab., EPJC78 (2018) no.2, 110



EXPERIMENTAL DATA

THEORETICAL CALCULATIONS

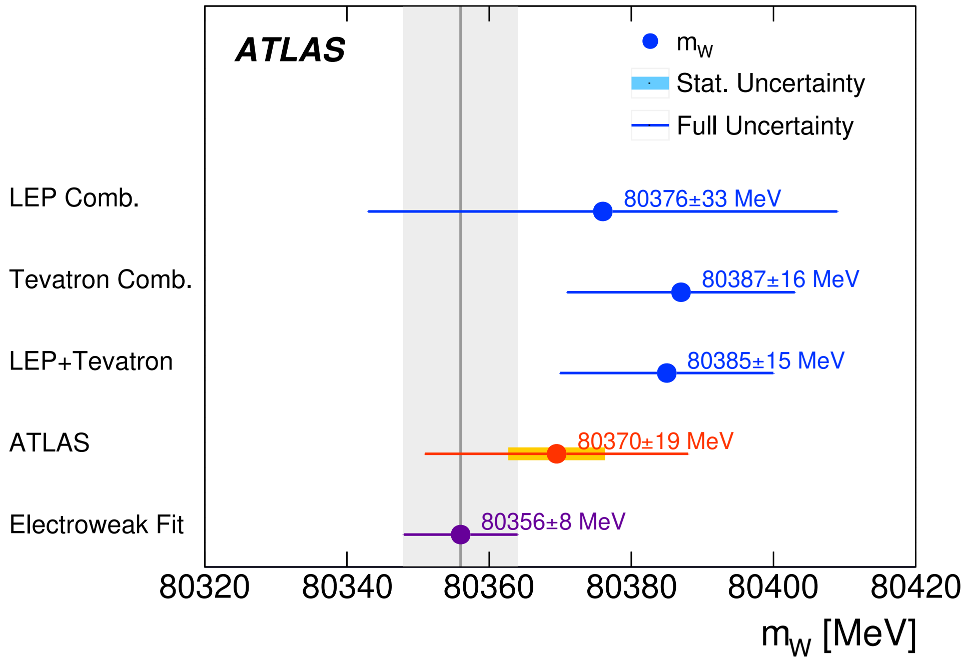
METHODOLOGY

PARAMETRISATION, ERROR PROPAGATION, MINIMISATION…

GLOBAL FIT

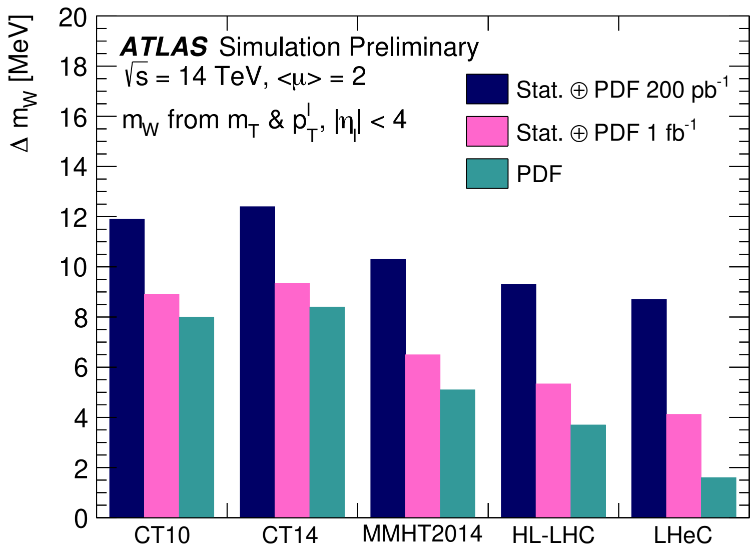
LHAPDF

A. Buckley et al EPJC75 (2015)



M. Ubiali, Higgs Couplings 19

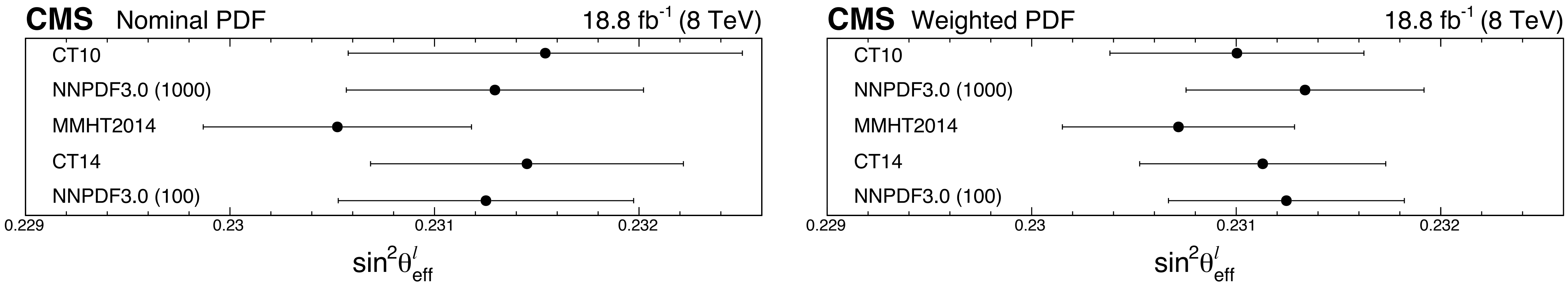
- However, with PDF uncertainties becoming so important, this might not be the only (best?) way to do things.



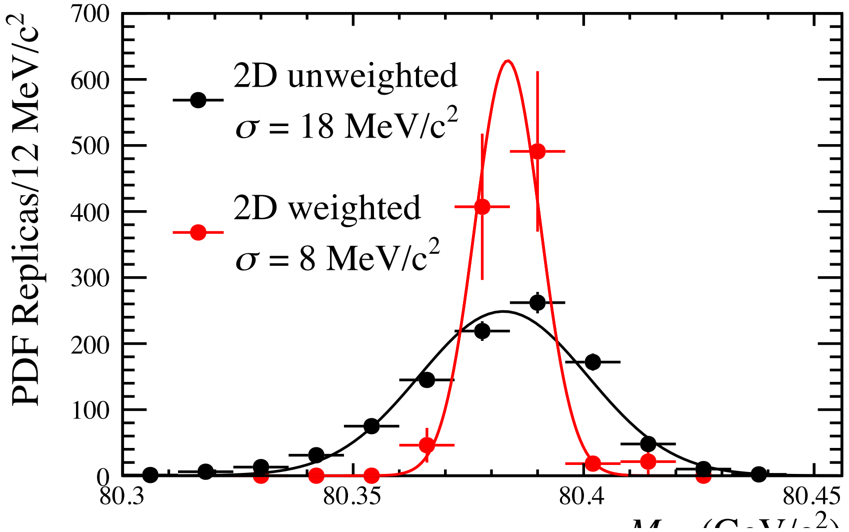
HL-LHC collab., arXiv:1902.04070

- Indeed, already ‘**in-situ**’ constraints, i.e. simultaneously constraining PDFs and EW parameters known to be powerful tool.

CMS collab., EPJC78 (2018) no.9, 701



- Information from e.g. η^l and $p^l_\perp$ sensitive to PDFs **and** M_W.
- Role of PDFs **and** $\sin^2\theta^l_{\rm eff}$ more relevant in different regions of m_{ll}.



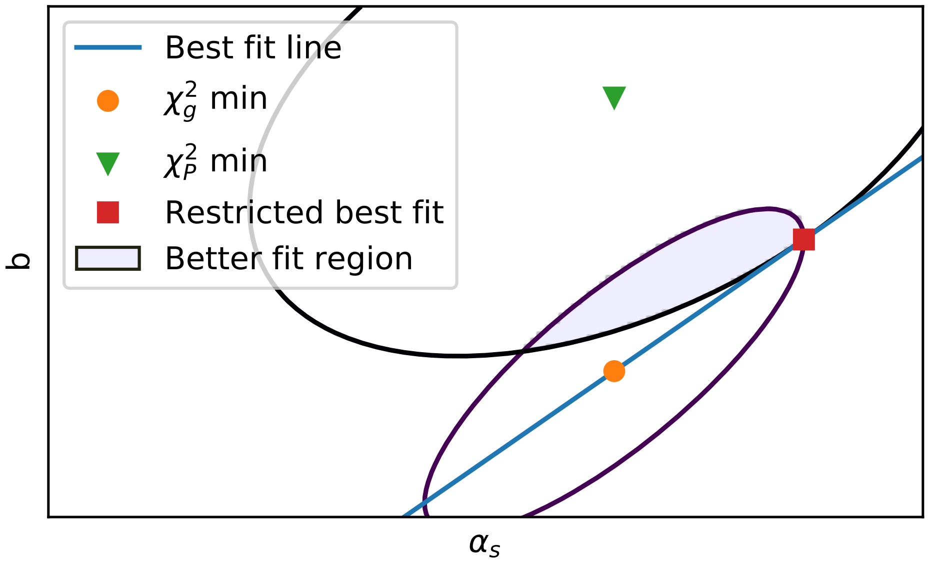
S. Farry et al., EPJC79 (2019) no.6, 497

- However quantitative relationship between these (necessarily approximate) in-situ constraints and result of full global PDF + SM parameter refit unclear.
- A full refit may/will give different results. Simultaneous global PDF + SM optimal (though challenging).

S. Forte and Z. Kassabov, Eur.Phys.J.C 80 (2020) 3, 182

PDFs and the Strong Coupling

- PDFs from a global fit and the value of α_s used in the fit highly correlated.
- As a result great care is needed in interpreting what the preferred value of α_s is from a given hadronic dataset.

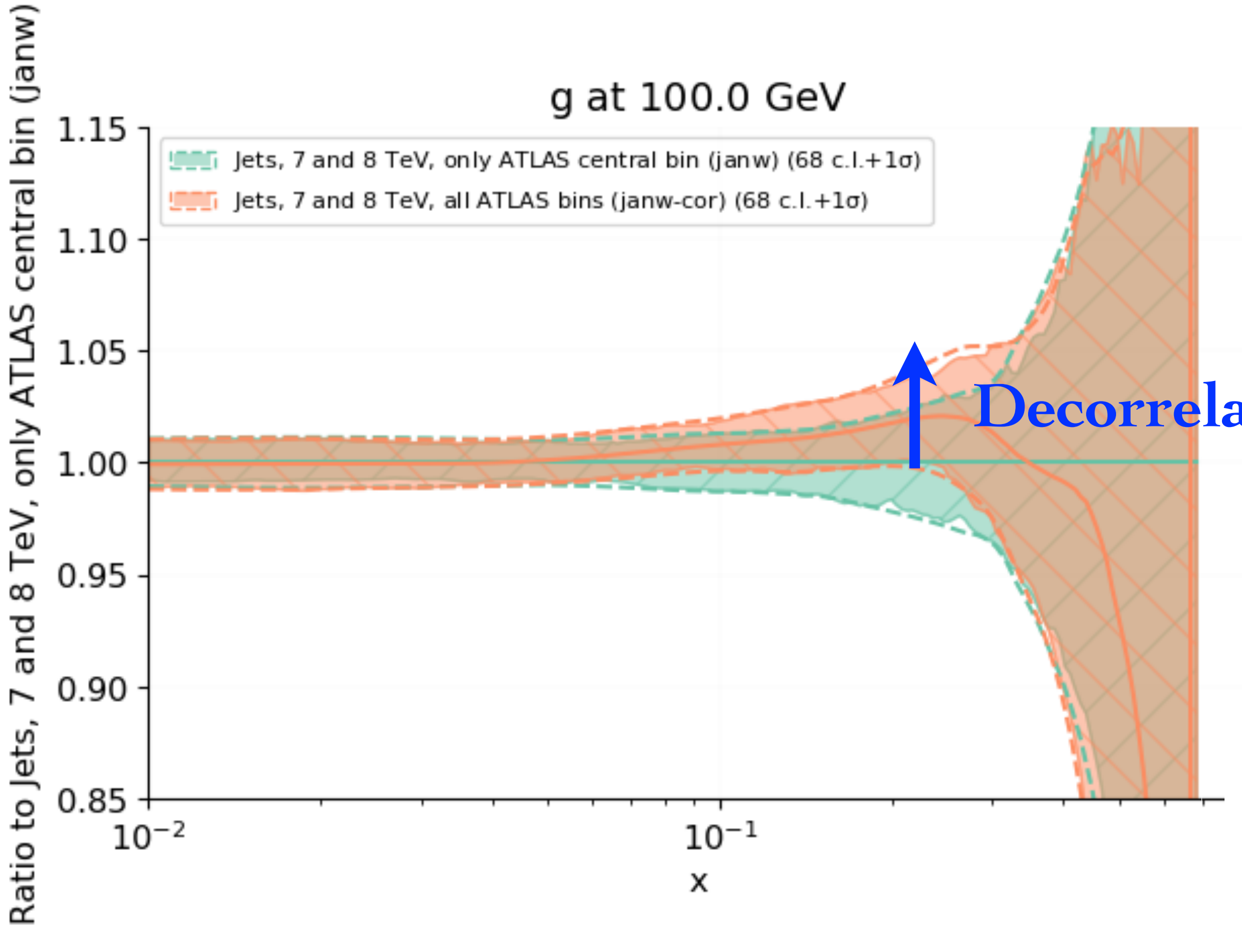


- In particular the question of value of α_s that is preferred by the dataset clearly depends on the PDFs themselves.
- Using a publicly available PDF(α_s) sets will not in general give an α_s that corresponds to doing a full refit of the PDFs + α_s to the global dataset + the new dataset.

$\longrightarrow$ No short cut available, must do full global PDF refit.

- In principle relevant for other SM parameters (M_W...) though clearly correlation with PDFs much weaker here.

Inclusive jet (decorrelated) vs. Dijets



- Inclusive jets (decorrelated) appears to bring inclusive jets + dijets into even better agreement.