NNPDF3.1

Juan Rojo
VU Amsterdam & Theory group, Nikhef

on behalf of the NNPDF Collaboration

PDF4LHC Working Group meeting
07/03/2017

Why NNPDF3.1?

An **update of the NNPDF global analysis** was motivated by:

- ☑ The availability of a wealth of **high-precision PDF-sensitive measurements** from the Tevatron, ATLAS, CMS and LHCb, including processes such as the **Z p_T** and **differential distributions in top-quark production** that have never been used before in a PDF fit

- ☑ The striking **recent progress in NNLO QCD calculations**, which allows to include the majority of PDF-sensitive collider measurements into a **fully consistent NNLO global analysis**

- ☑ The recent realisation that **fitting the charm PDF** has several advantages in the global QCD fit (beyond comparison with non-perturbative models), in particular **stabilise the dependence with m_{charm}** and improve the **data/theory agreement** for some of the most precise collider observables.

NNPDF3.1: fit settings

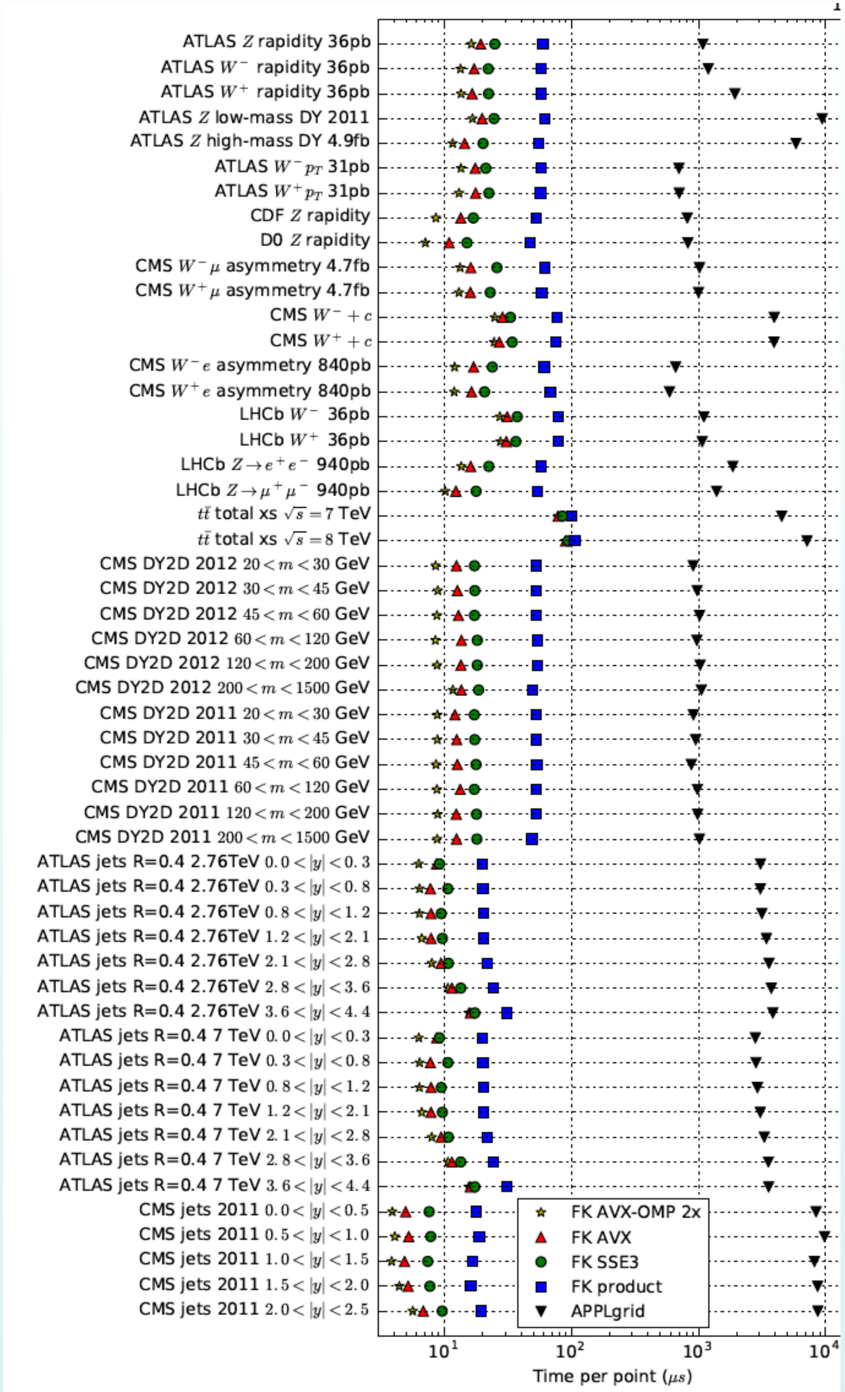
- **PDF evolution** and **DIS structure functions** up to NNLO are computed with **APFEL** in the FONLL GM-VFN scheme

- Hadronic data included using **APPLgrid/FastNLO** interfaced to **MCFM/aMC@NLO/NLOjet++**, supplemented by bin-by-bin NNLO/NLO K-factors obtained separately for each specific process

- The **APFELgrid** tool is used to combine a priori **PDF evolution with applgrid interpolated coefficient functions,** achieving an speed-up by up to **three orders of magnitude** for the evaluation of hadronic cross-sections during the PDF fit

$$\sigma_{pp\to X} = \sum_{k,l}\sum_{\delta,\gamma} \widetilde{W}_{kl,\delta\gamma}\, f_k(x_\delta, Q_0^2) f_l(x_\gamma, Q_0^2),$$

Bertone, Carrazza, Hartland CPC 16



Fitted vs Perturbative charm

- The **change of scheme** between a theory with *3 active quarks* and another with *4 active quarks* is determined by the **matching conditions:**

$$\alpha_s^{(4)}(m_h^2) = \alpha_s^{(3)}(m_h^2) + \mathcal{O}(\alpha_s^3)\,,$$
$$f_i^{(4)}(m_h^2) = \sum_j K_{ij}(m_h^2) \otimes f_j^{(3)}(m_h^2)$$

- Most global fits (including NNPDF3.0) **assume that $c^{(3)}(x)=0$,** in other words, the scale-independent (intrinsic) charm content of the proton vanishes

- Whether or not **$c^{(3)}(x)=0$ is a good assumption** can only be **determined from data**

- Releasing this assumption leads to the **modified matching conditions**

$$f_h^{(3)} = f_h^{(4)}(Q^2) - \alpha_s^{(4)}(Q^2)\left(K_{hh}^{(1)}(m_h^2) + P_{qq}^{(0)}L\right) \otimes f_h^{(4)}(Q^2) - \alpha_s^{(4)}(Q^2)LP_{qg}^{(0)} \otimes g^{(4)}(Q^2)$$

Scale-independent (intrinsic) charm

Scale-dependent charm PDF: to be determined from data at $Q_0>m_c$

Perturbative contribution from charm-anticharm radiation off gluons

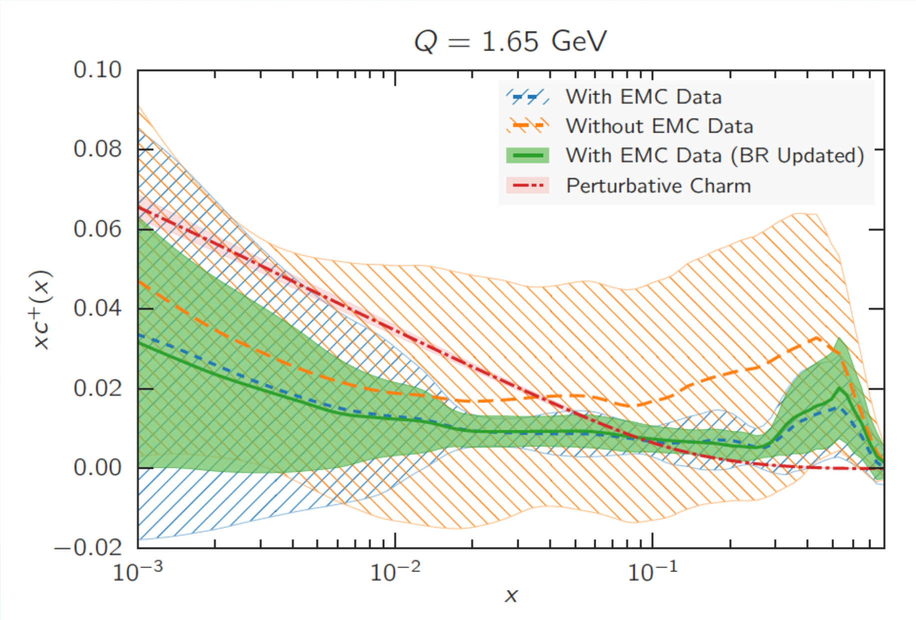
NNPDF3.1 fits obtained **both** for a **fitted** and for a **perturbative charm PDF**

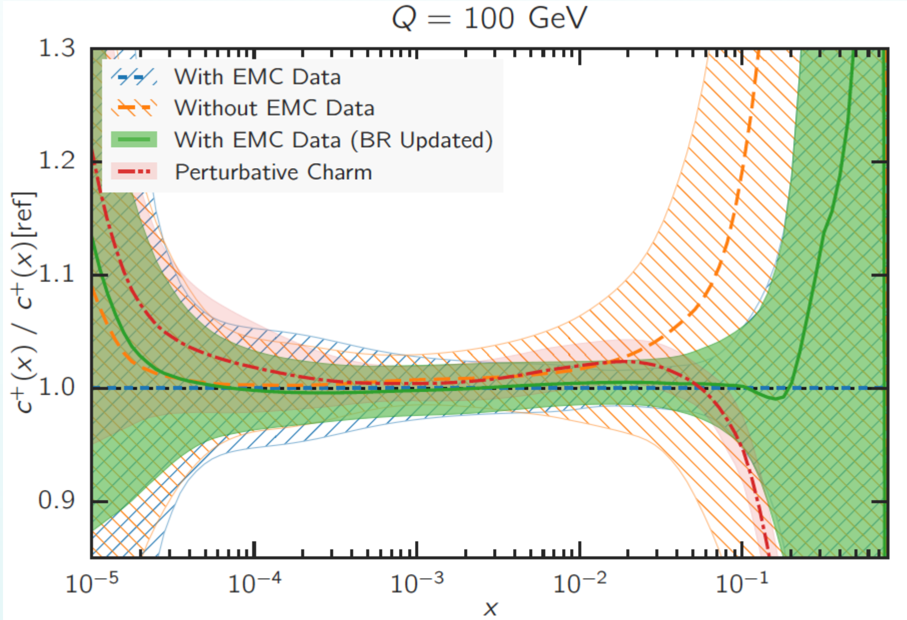
Ball, Bonvini, Rottoli, JHEP 17

Ball et al, PLB 17

Fitted charm recap

- Based on the NNPDF3.0 settings, we produced **NLO PDF sets with fitted charm** *NNPDF, EPJC 2016*
- Small differences on light quarks and gluons
- For the charm PDF at high scales, **differences only for large-x**, x < 0.08





PDF set	$C(Q = 1.65$ GeV$)$
NNPDF3 perturbative charm	$(0.239 \pm 0.003)\%$
NNPDF3 fitted charm	$(0.7 \pm 0.3)\%$
NNPDF3 fitted charm (no EMC)	$(1.6 \pm 1.2)\%$
CT14IC BHPS1	1.3%
CT14IC BHPS2	2.6%
CT14IC SEA1	1.3%
CT14IC SEA2	2.2%

NNPDF, EPJC 2016

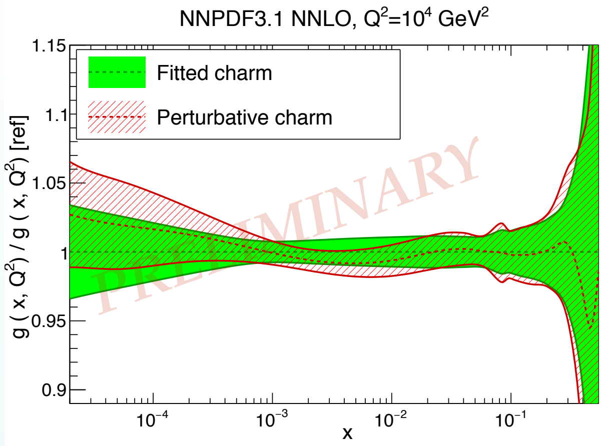
- Fitting the charm PDF leads to an **improved data/theory agreement**, a **reduced dependence on $\mathbf{m_{charm}}$** and allows to compare with non-perturbative models of the proton structure
- In NNPDF3.1, the **new collider data allow a precise determination of the charm PDF**, avoiding the need to rely on the EMC charm data

Outline

- ***NNPDF3.1:***
  - *Fit quality*
  - *Fitted charm vs perturbative charm*
  - *Comparison with NNPDF3.0 and other recent PDF sets*
  - *A bit of phenomenology*

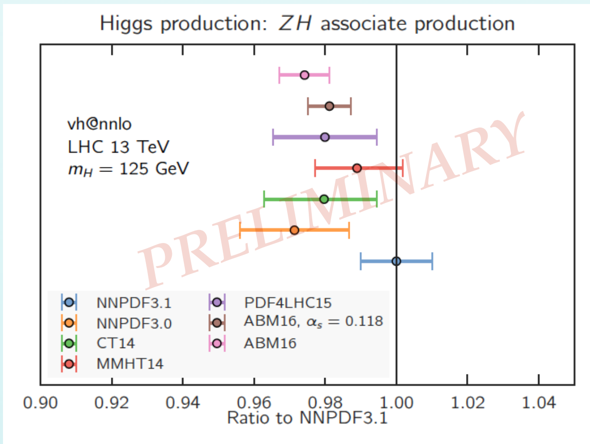
- ***Impact of individual datasets:***
  - *Jets at NNLO*
  - *The Z p_T*
  - *top quark distributions*
  - *Gauge boson production*
  - *The strange and charm content of the proton*

Disclaimer*: I will certainly not have enough time for all these results, please see backup for more. All these results will be discussing in great detail in the upcoming paper!*



NNPDF3.1 NNLO, $Q^2=10^4$ GeV^2
Fitted charm
Perturbative charm
PRELIMINARY
g (x, Q^2) / g (x, Q^2) [ref]
x

NNPDF3.1



Higgs production: ZH associate production
vh@nnlo
LHC 13 TeV
m_H = 125 GeV
PRELIMINARY
NNPDF3.1
NNPDF3.0
CT14
MMHT14
PDF4LHC15
ABM16, α_s = 0.118
ABM16
Ratio to NNPDF3.1

New datasets in NNPDF3.1

Measurement	Data taking	Motivation
Combined HERA inclusive data	Run I+II	quark singlet and gluon
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive W, Z rap 7 TeV	2011	strangeness
ATLAS inclusive jets 7 TeV	2011	large-x gluon
ATLAS low-mass Drell-Yan 7 TeV	2010+2011	small-x quarks
ATLAS Z pT 7,8 TeV	2011+2012	medium-x gluon and quarks
ATLAS and CMS tt differential 8 TeV	2012	large-x gluon
CMS Z (pT,y) 2D xsecs 8 TeV	2012	medium-x gluon and quarks
CMS Drell-Yan low+high mass 8 TeV	2012	small-x and large-x quarks
CMS W asymmetry 8 TeV	2012	quark flavor separation
CMS 2.76 TeV jets	2012	medium and large-x gluon
LHCb W,Z rapidity dists 7 TeV	2011	large-x quarks
LHCb W,Z rapidity dists 8 TeV	2012	large-x quarks

Fit quality: χ^2

	NNLO FittedCharm	NNLO PertCharm	NLO FittedCharm	NLO PertCharm
HERA	1.16	1.20	1.16	1.16
ATLAS	1.13	1.19	1.45	1.50
CMS	1.04	1.06	1.20	1.20
LHCb	1.46	1.46	1.94	1.93

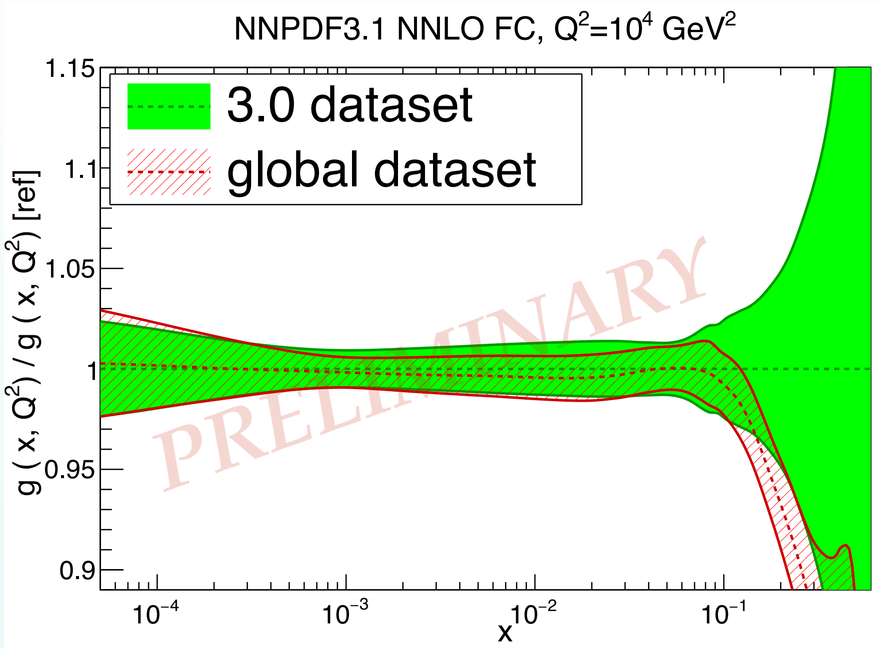
PRELIMINARY

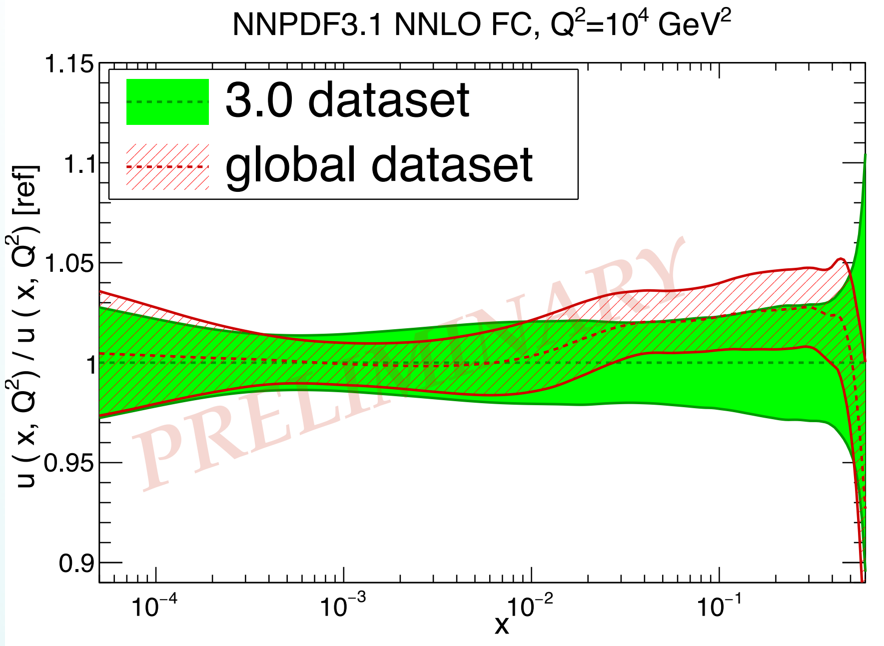
- For collider data, **NNLO theory** leads to a markedly better fit quality that than **NLO** (since the new data included has small experimental uncertainties, and NNLO corrections mandatory)

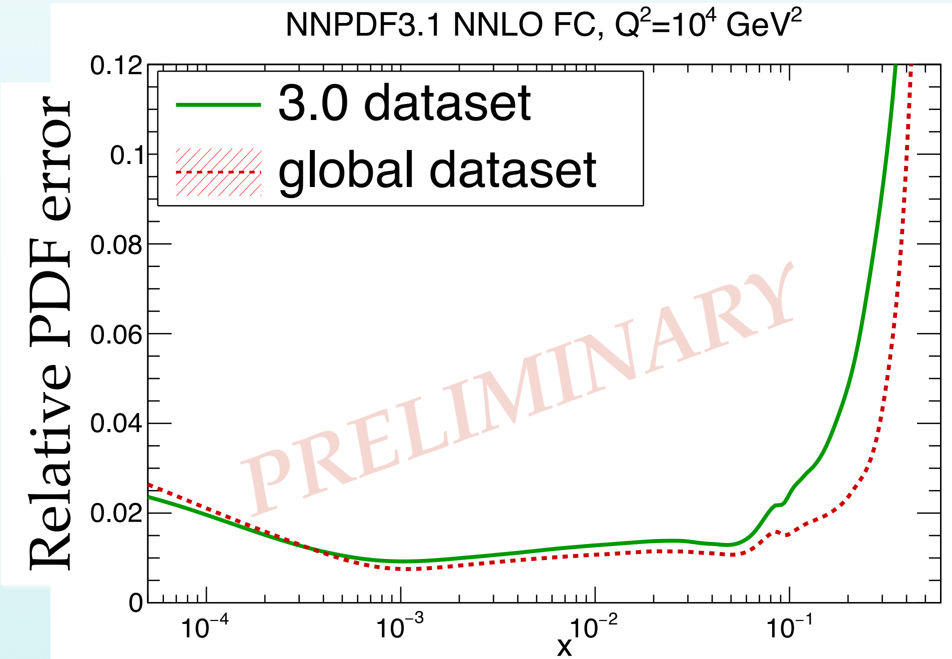
- The global PDF analysis where the charm PDF is fitted leads to a **slightly superior fit quality** than assuming a perturbatively generated charm PDF

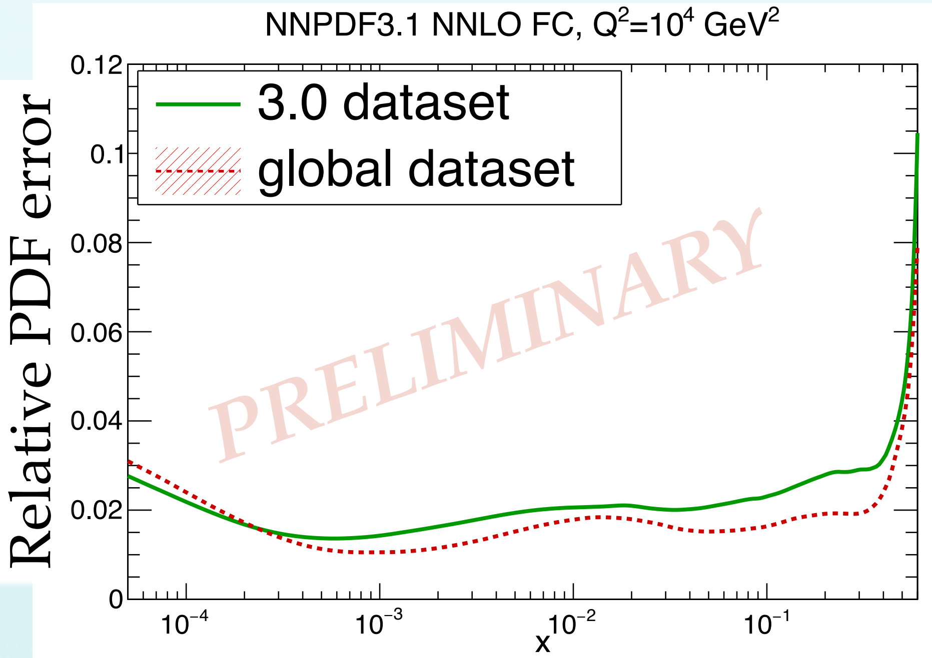
- In general **good description of all the new collider measurements** included in NNPDF3.1

Impact of new data

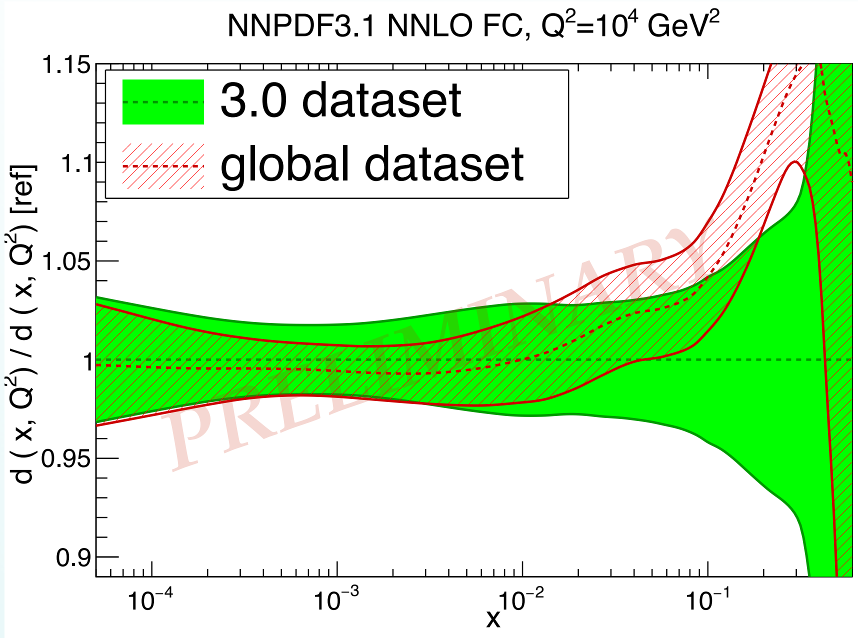


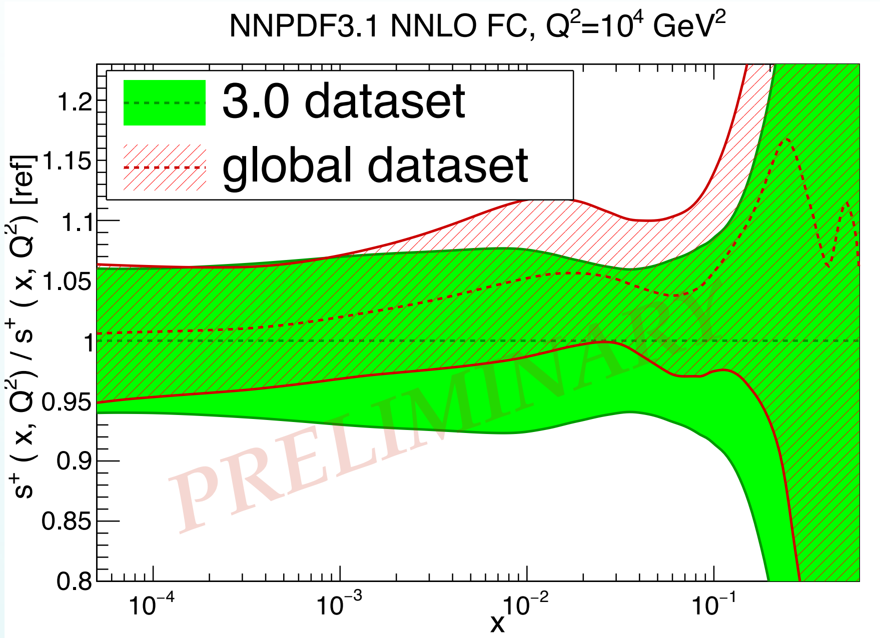


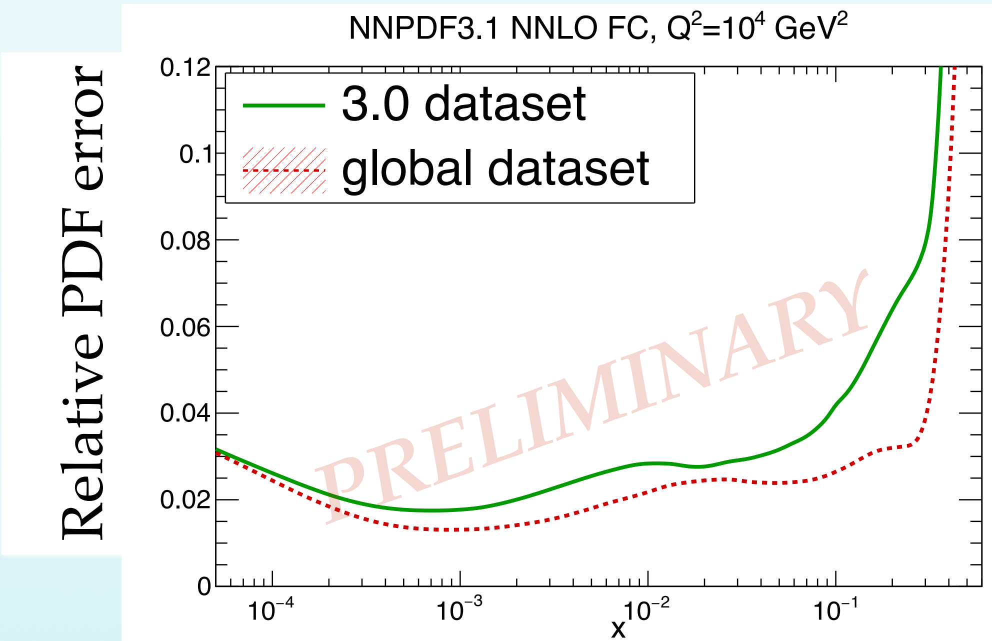


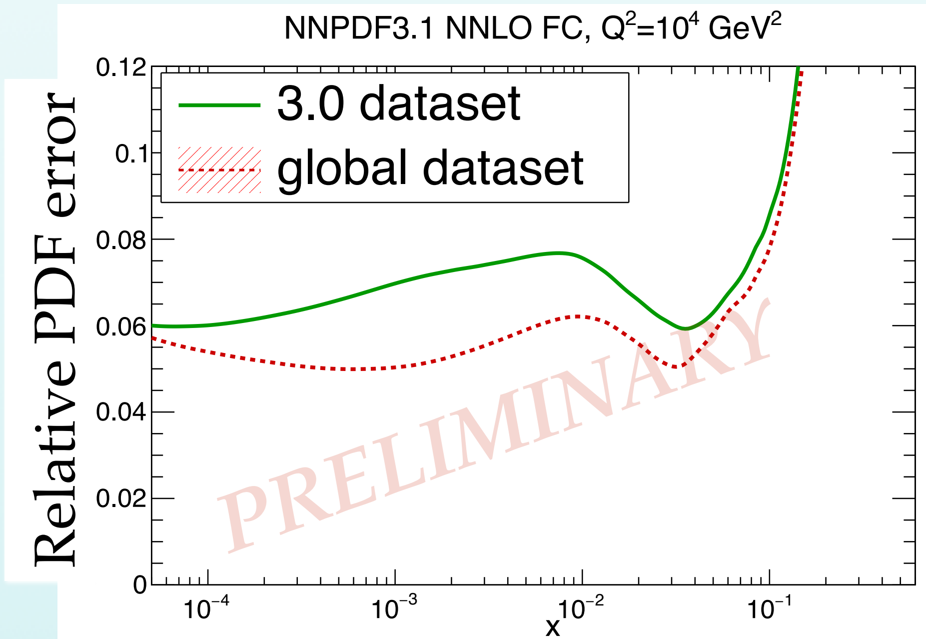


Impact of new data

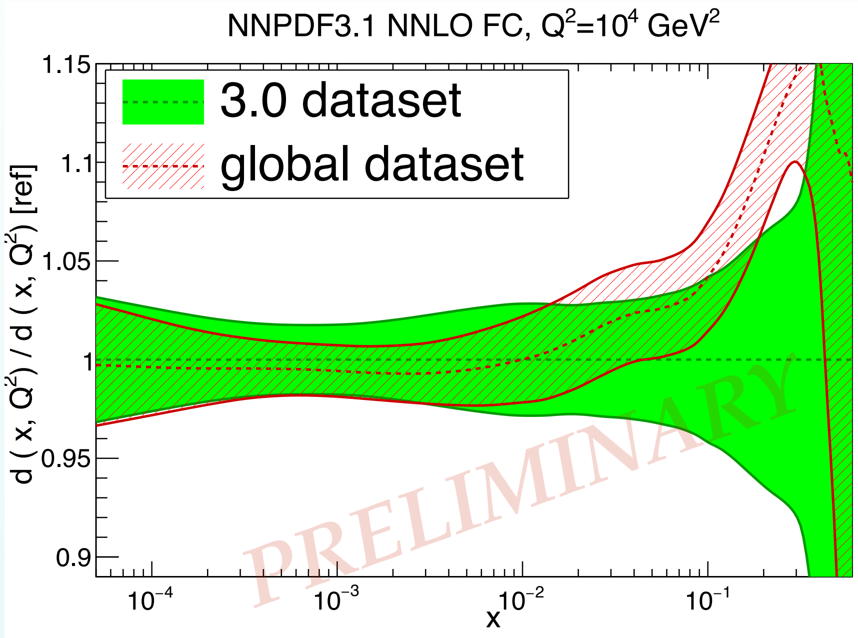


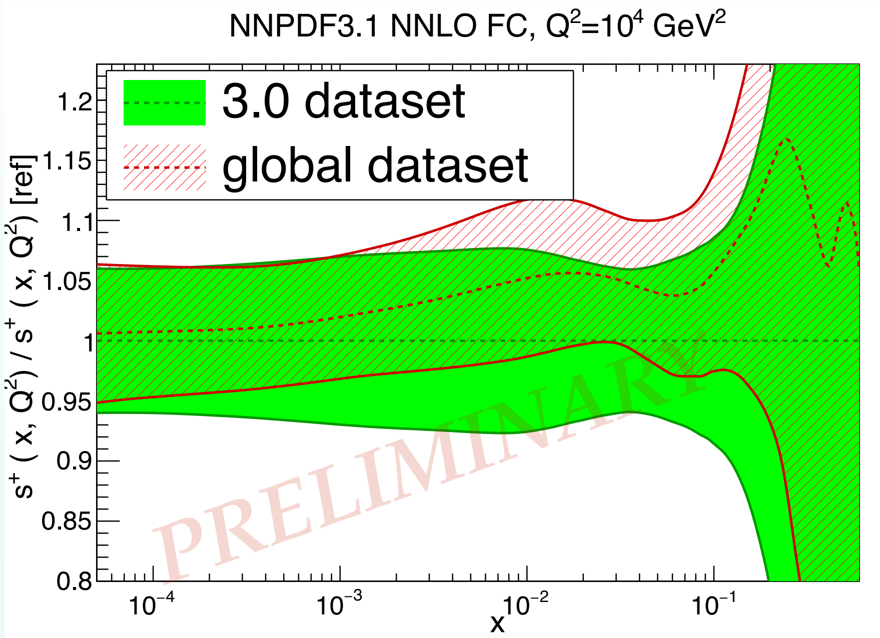


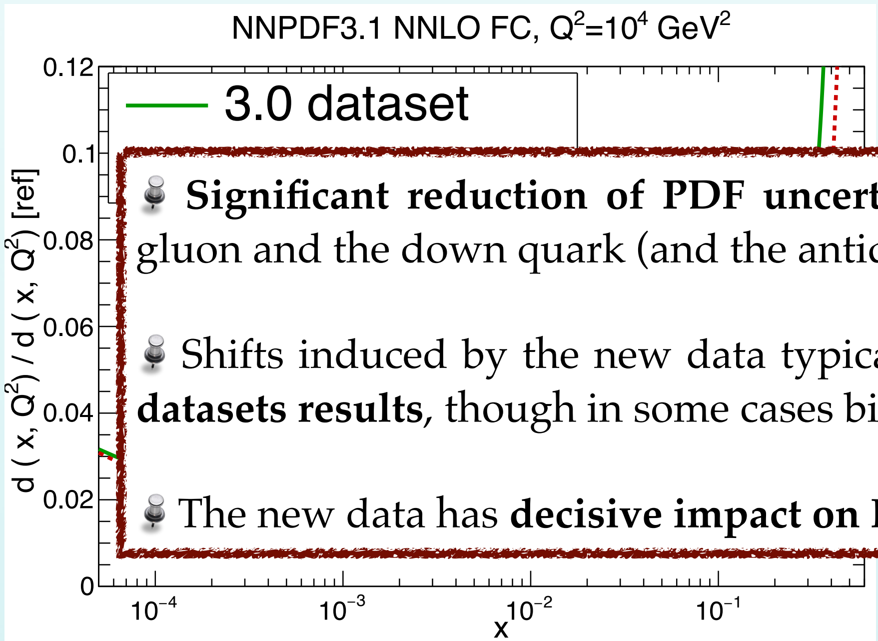


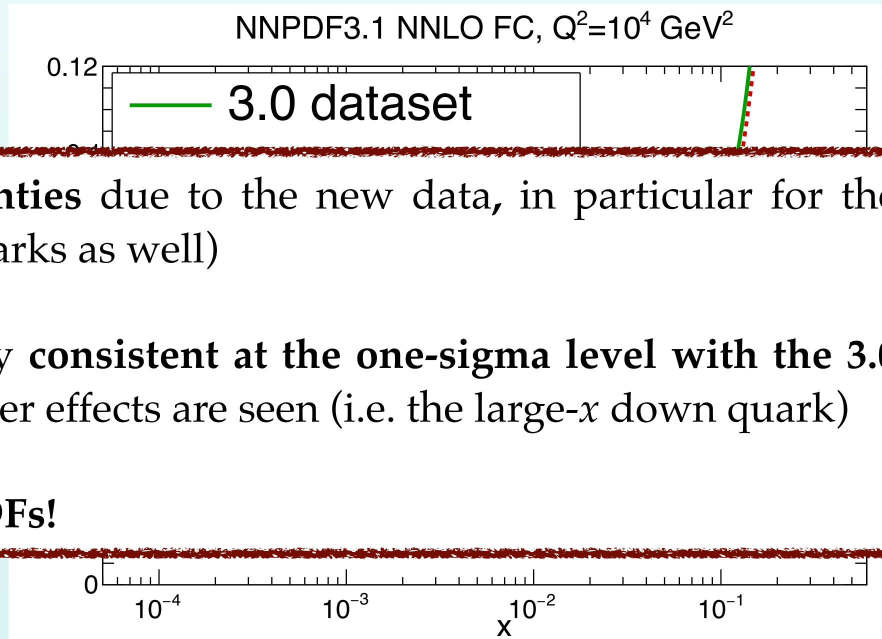


Impact of new data



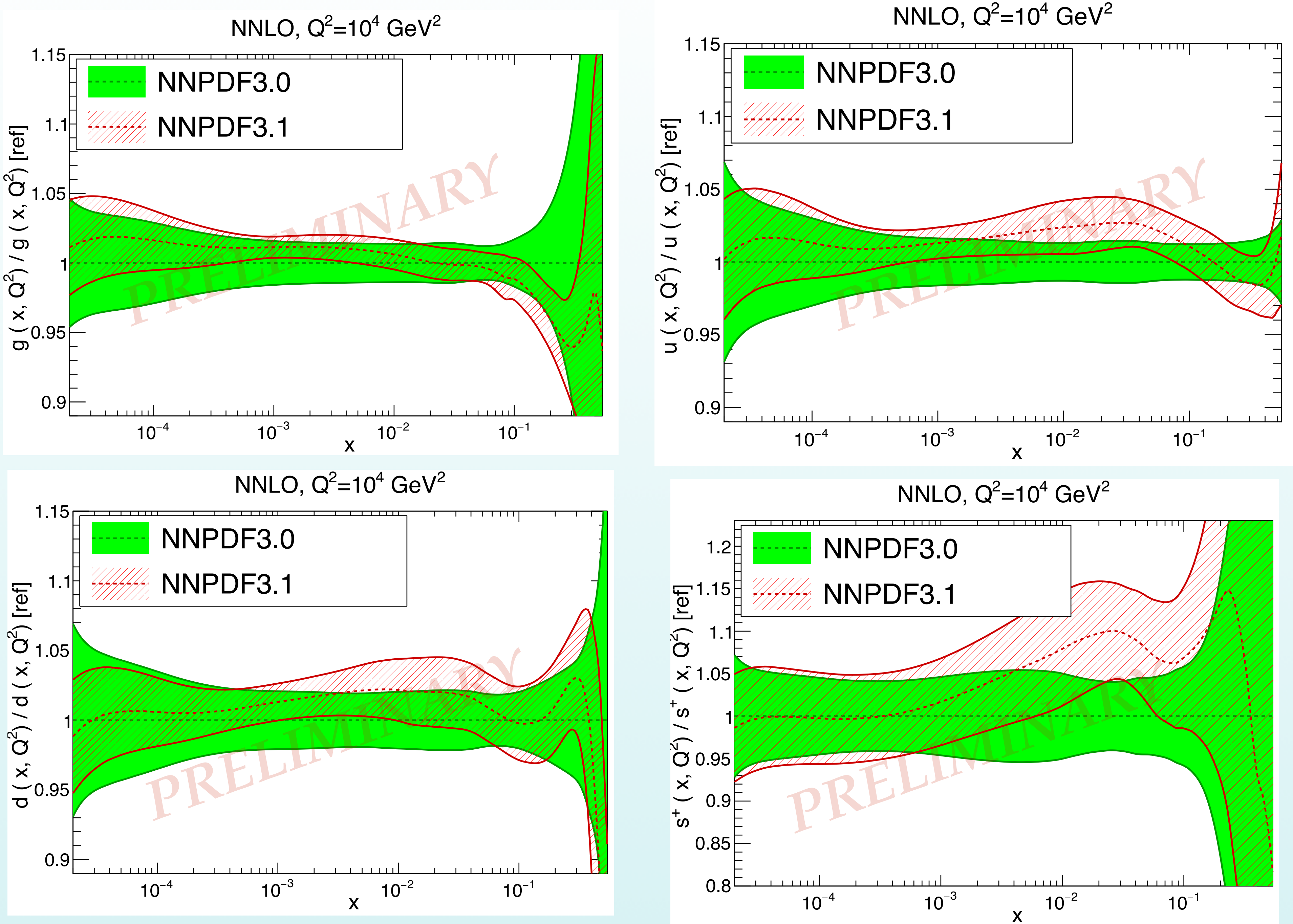




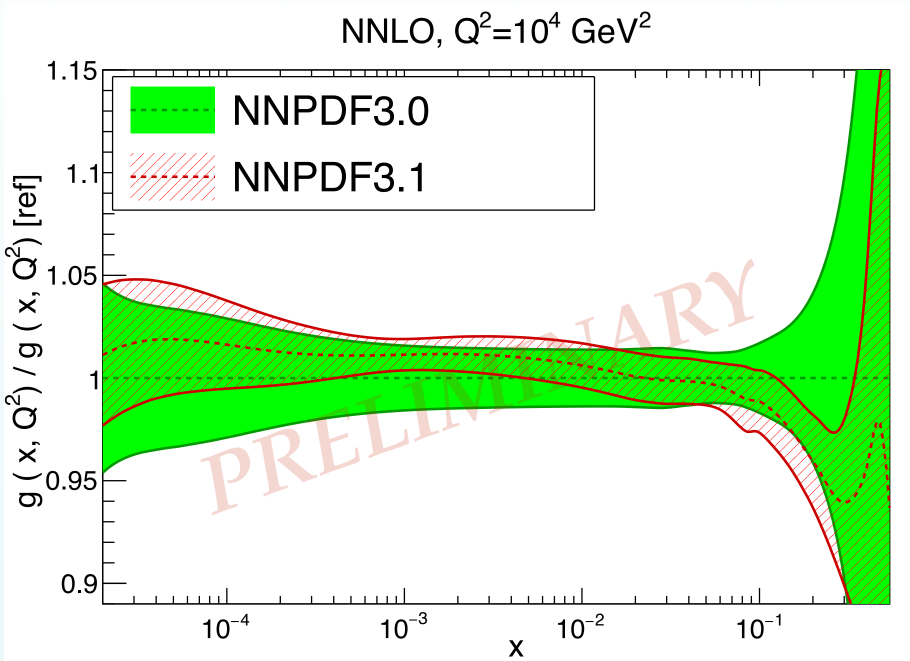


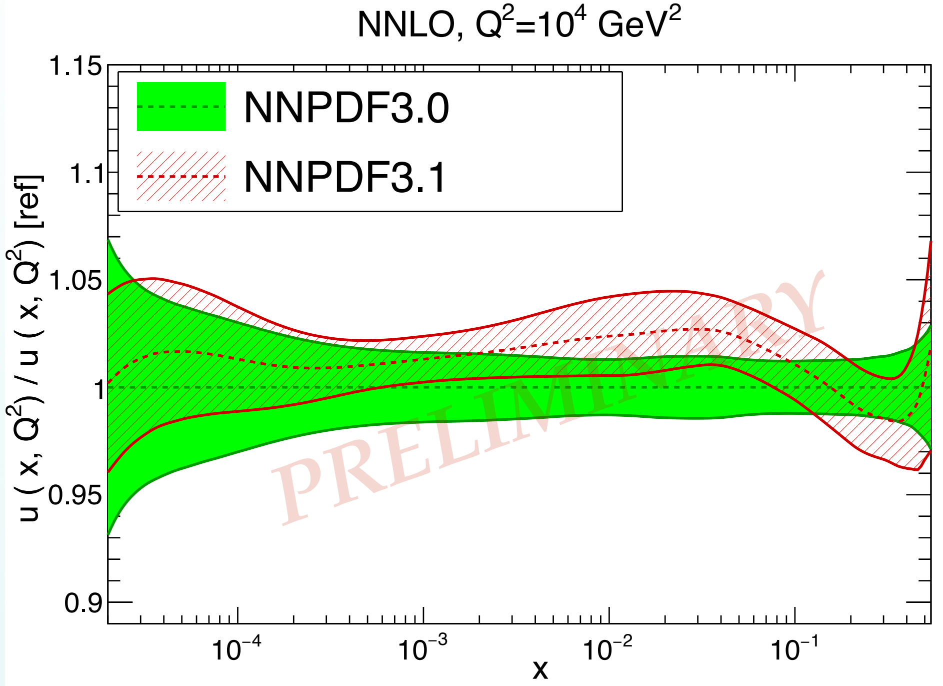
- **Significant reduction of PDF uncertainties** due to the new data, in particular for the gluon and the down quark (and the antiquarks as well)
- Shifts induced by the new data typically **consistent at the one-sigma level with the 3.0 datasets results**, though in some cases bigger effects are seen (i.e. the large-x down quark)
- The new data has **decisive impact on PDFs!**

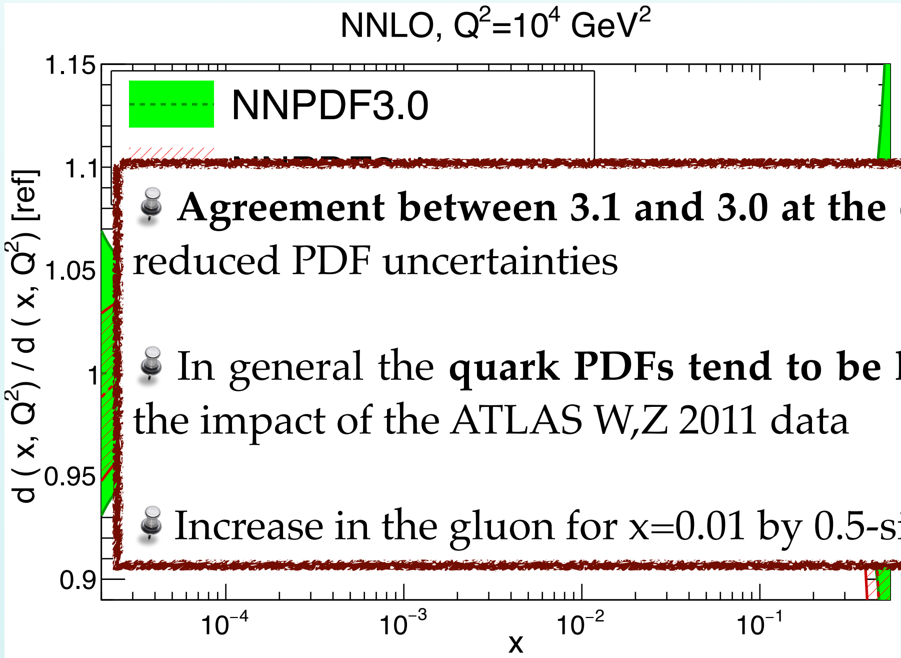
Comparison with NNPDF3.0

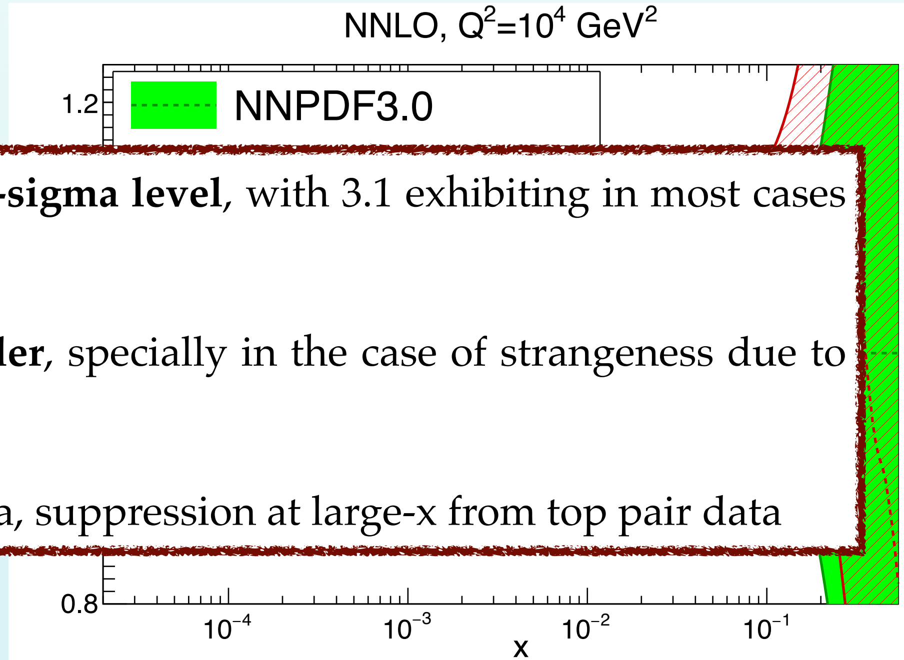


Comparison with NNPDF3.0









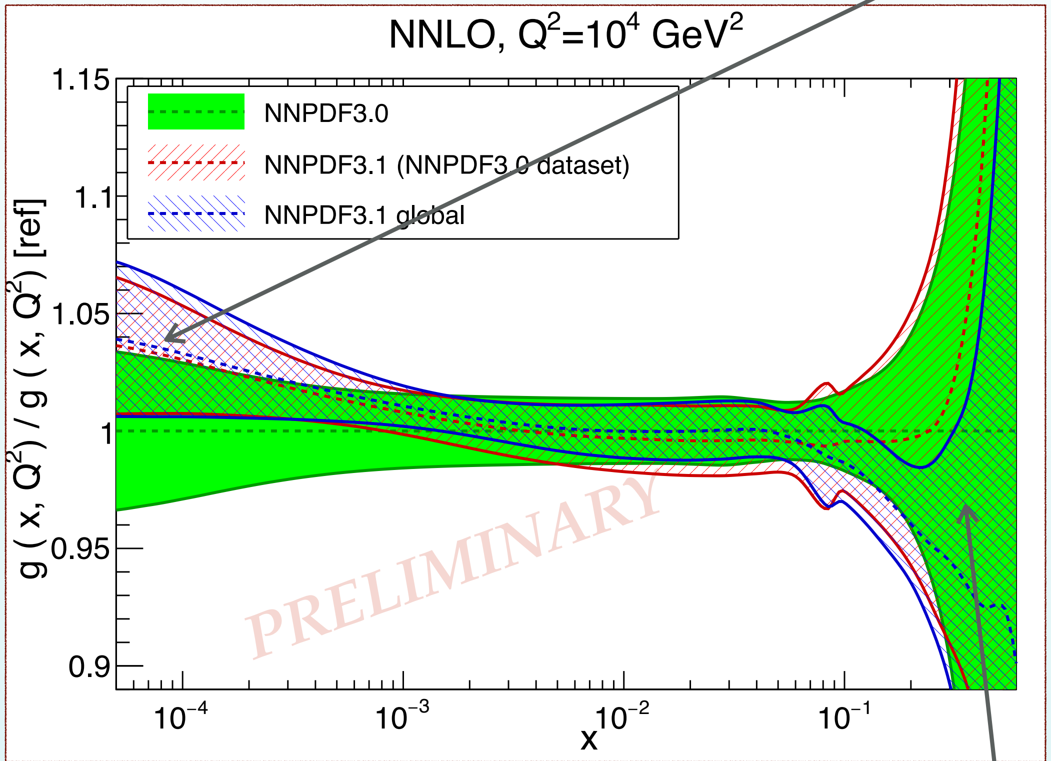
- **Agreement between 3.1 and 3.0 at the one-sigma level**, with 3.1 exhibiting in most cases reduced PDF uncertainties

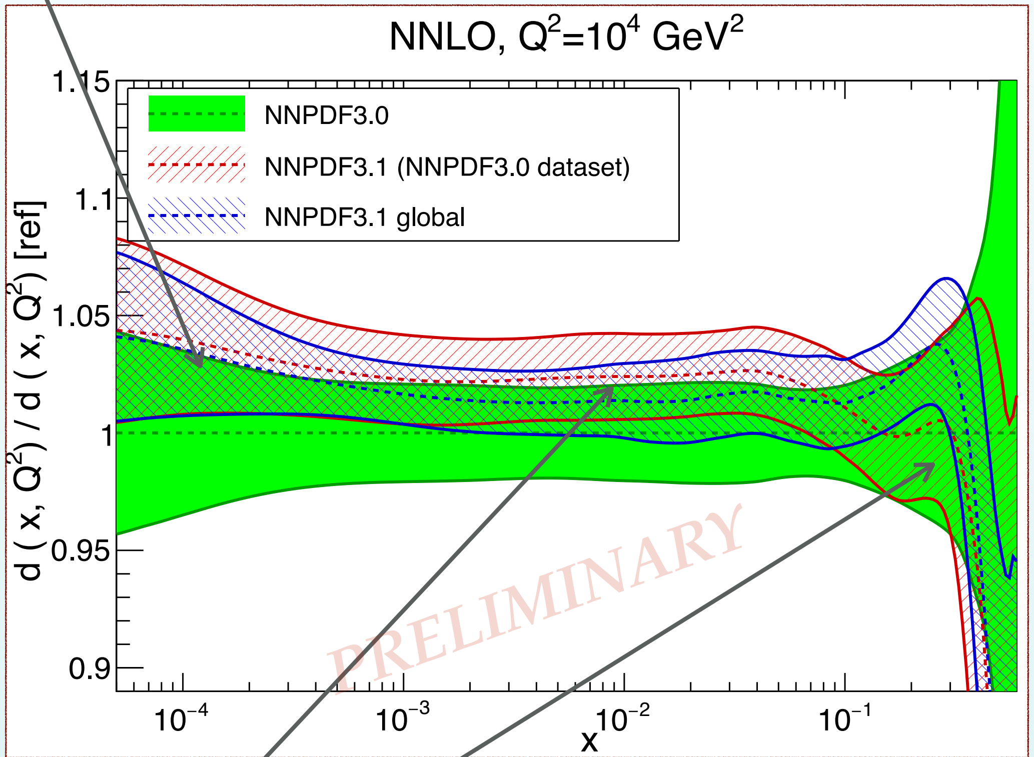
- In general the **quark PDFs tend to be harder**, specially in the case of strangeness due to the impact of the ATLAS W,Z 2011 data

- Increase in the gluon for x=0.01 by 0.5-sigma, suppression at large-x from top pair data

new data vs new methodology

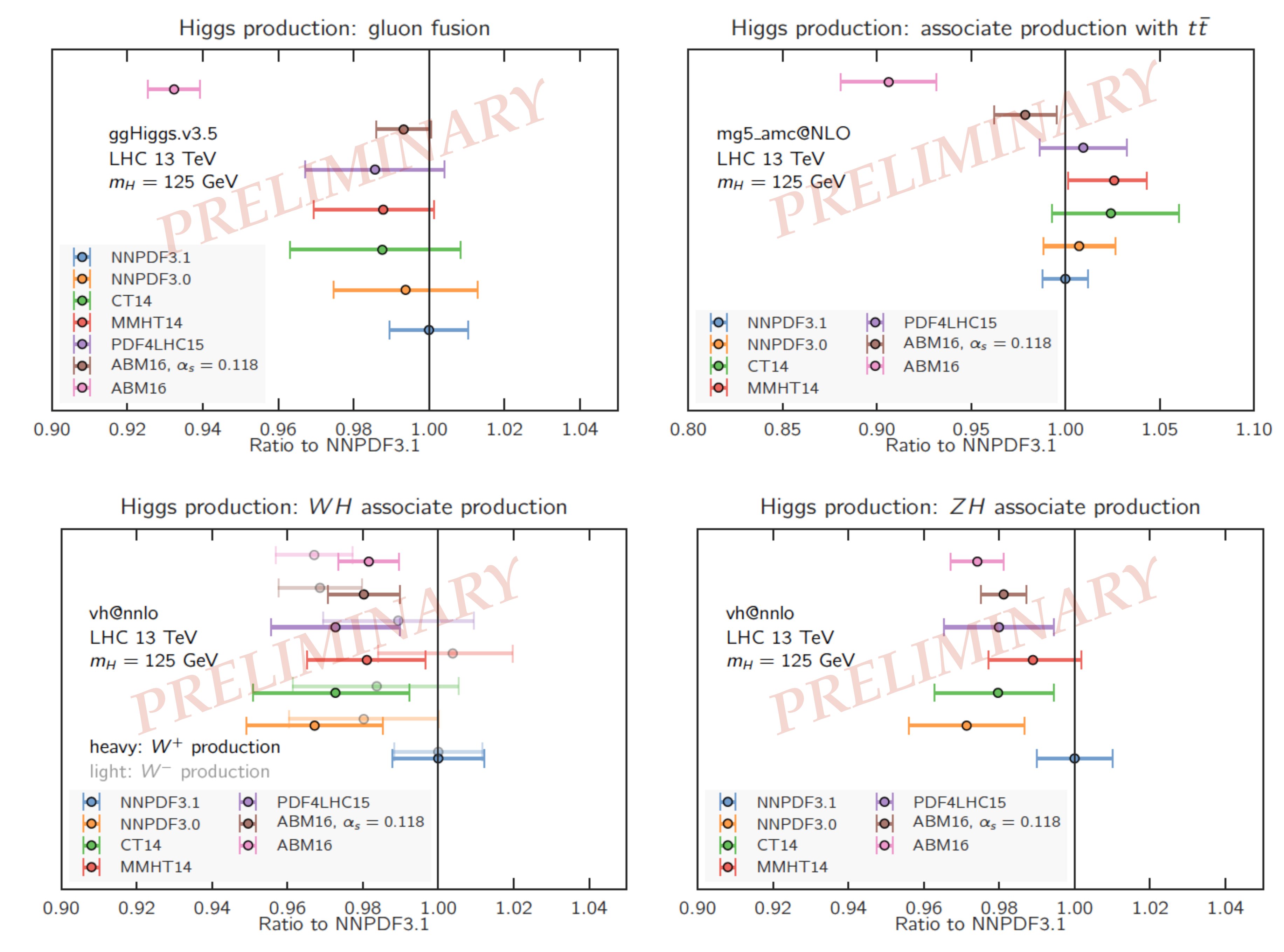
new methodology (mostly fitting charm)



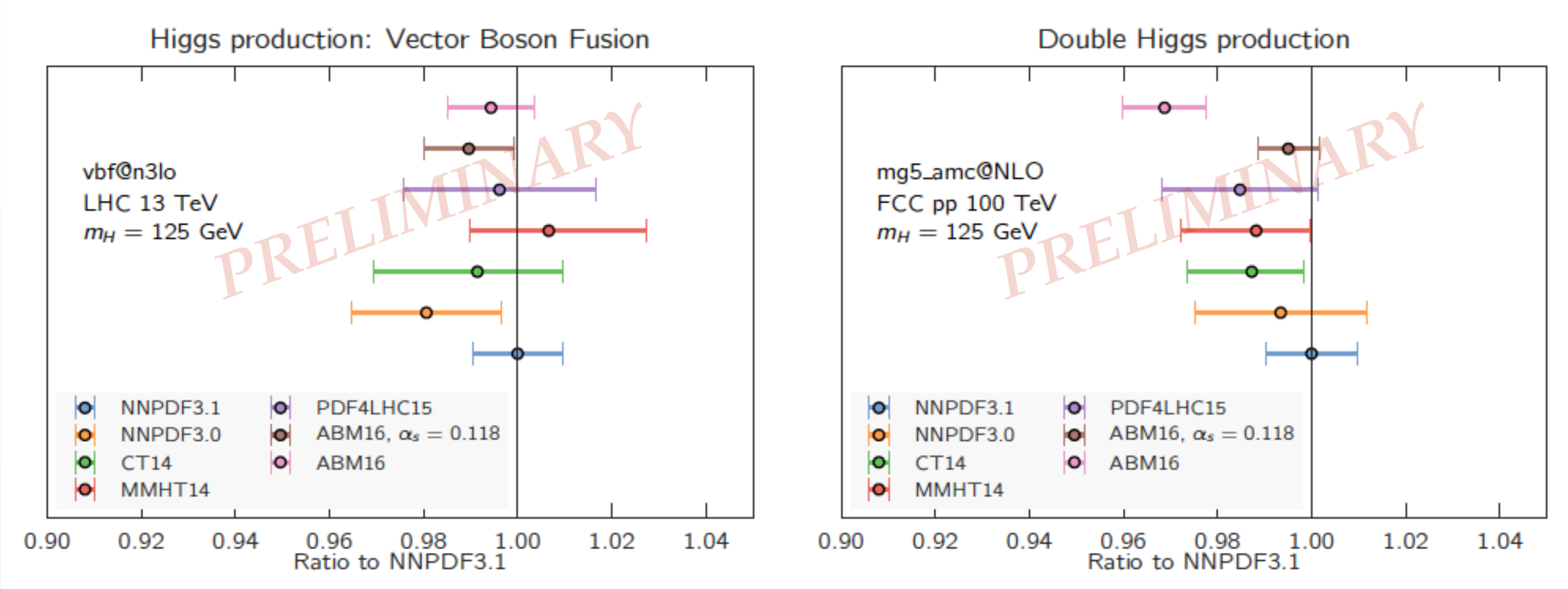


Impact of new data

Higgs production cross-sections



Higgs production cross-sections

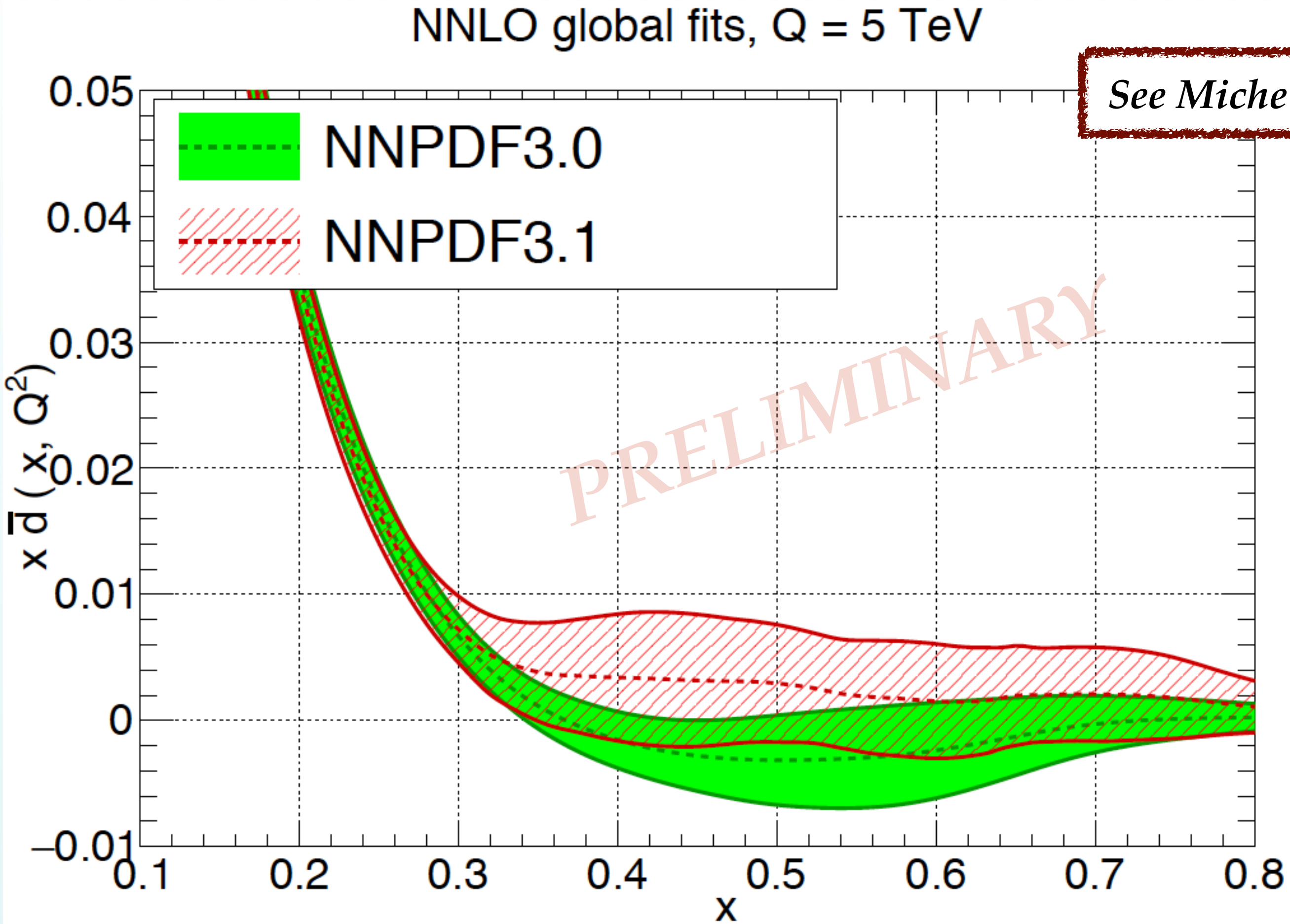


- For **gluon-initiated processes**, good agreement between 3.1 and 3.0 with reduced PDF uncertainties in the latter case

- For **quark-initiated processes**, the new collider data pulls towards higher cross-sections

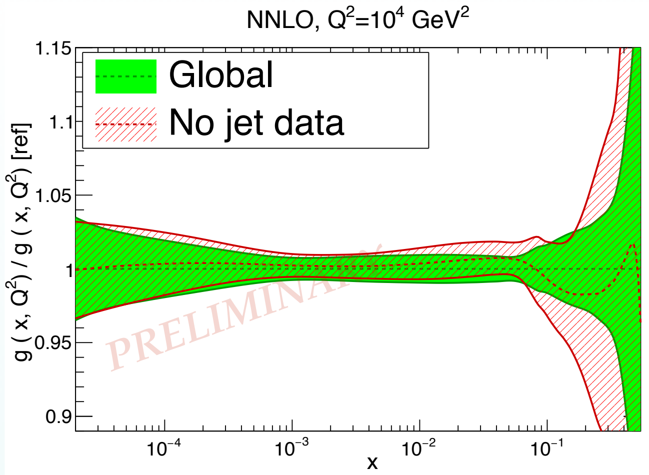
- The new **ABMP16 set** is in reasonable agreement with the other sets provided the PDG value of the strong coupling is used

Large-x PDF positivity

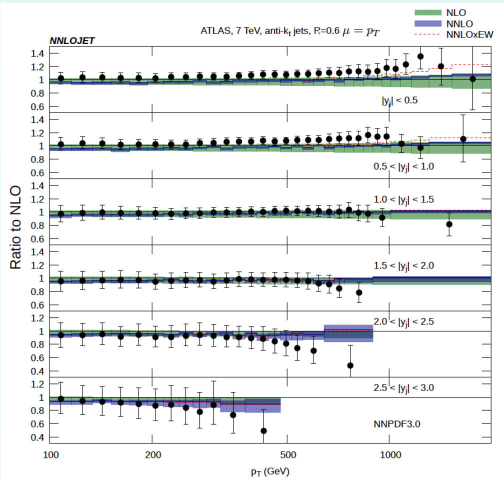


See Michelangelo's talk!

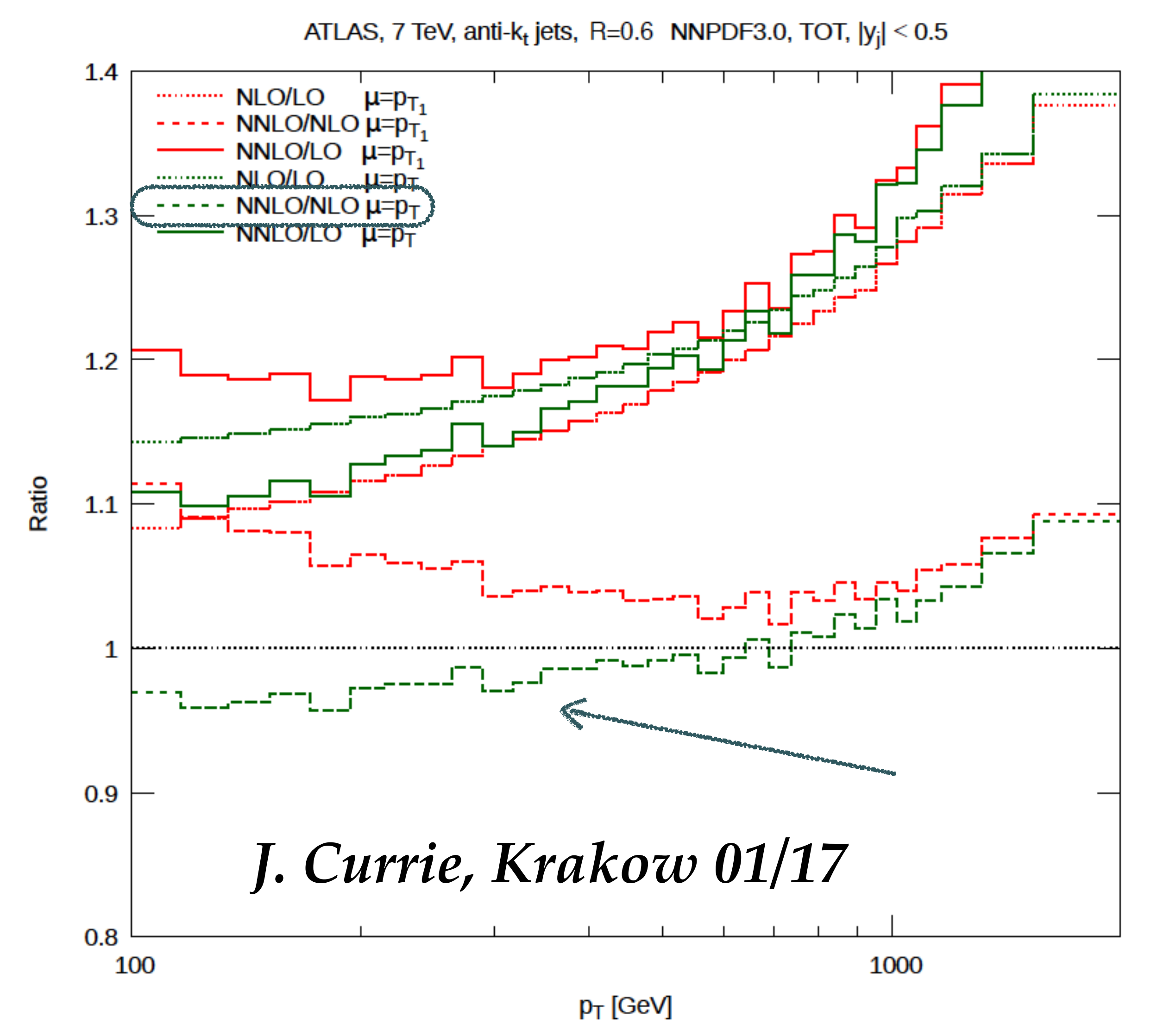
- Ideally, **allow PDFs to become negative** but ensure that a **large number of ``mock" observables are positive-definite** (i.e. W' cross-section at 5 TeV)
- In NNPDF3.0 we already include **DIS SFs** and **DY u*ubar, d*dbar, s*sbar xsecs**, and we will include more in our next release (non-trivial improvement of neural network training algorithm required)
- Adding the **many new LHC observables** already improves a lot the large-x positivity issues in NNPDF3.1!



Jet production



Jets at NNLO



- If the **jet pT is used as central scale**, NNLO/NLO K-factors only a few percent
- NNLO/NLO shift **within NLO scale uncertainties**
- This trend holds for **all rapidity regions**

- NNLO results available **only** for then **ATLAS 7 TeV 2011 measurement**
- In NNPDF3.1, use NLO matrix elements for jets, **computed with p_T as central scale,** and add the **NLO scale uncertainties** as additional theory uncertainty

Inclusive jets in NNPDF3.1

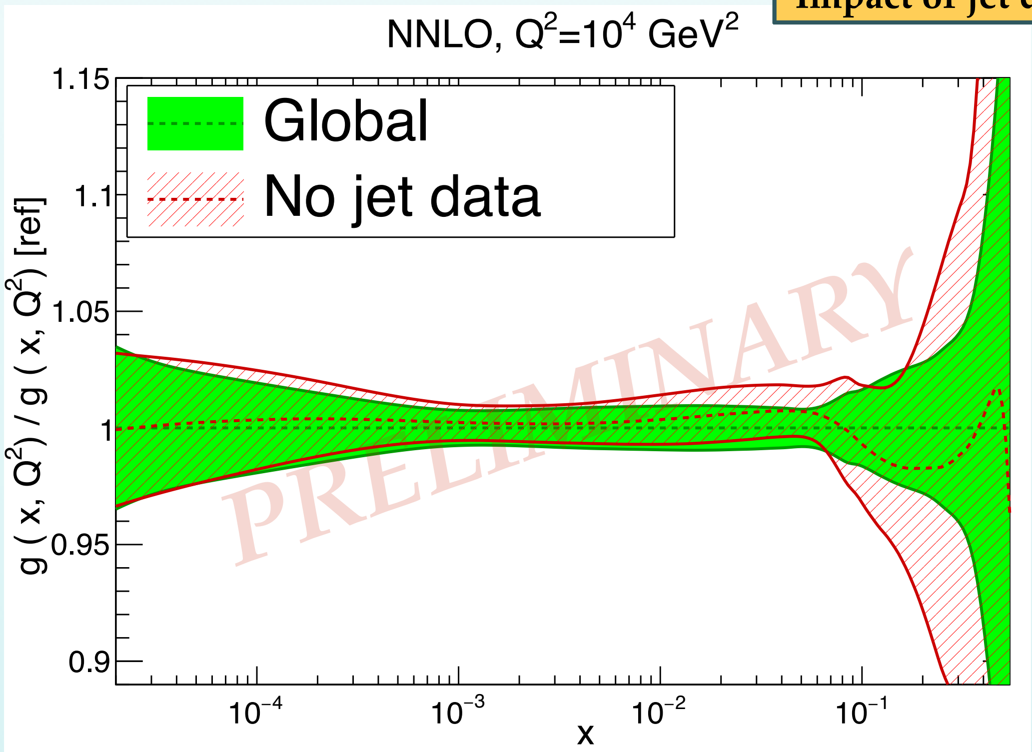
- In NNPDF3.1, we include the central rapidity bin of the **ATLAS 7 TeV 2011 inclusive jets**, finding good fit quality: **χ^2 (NNLO)=1.06** and **χ^2 (NLO)=1.12**

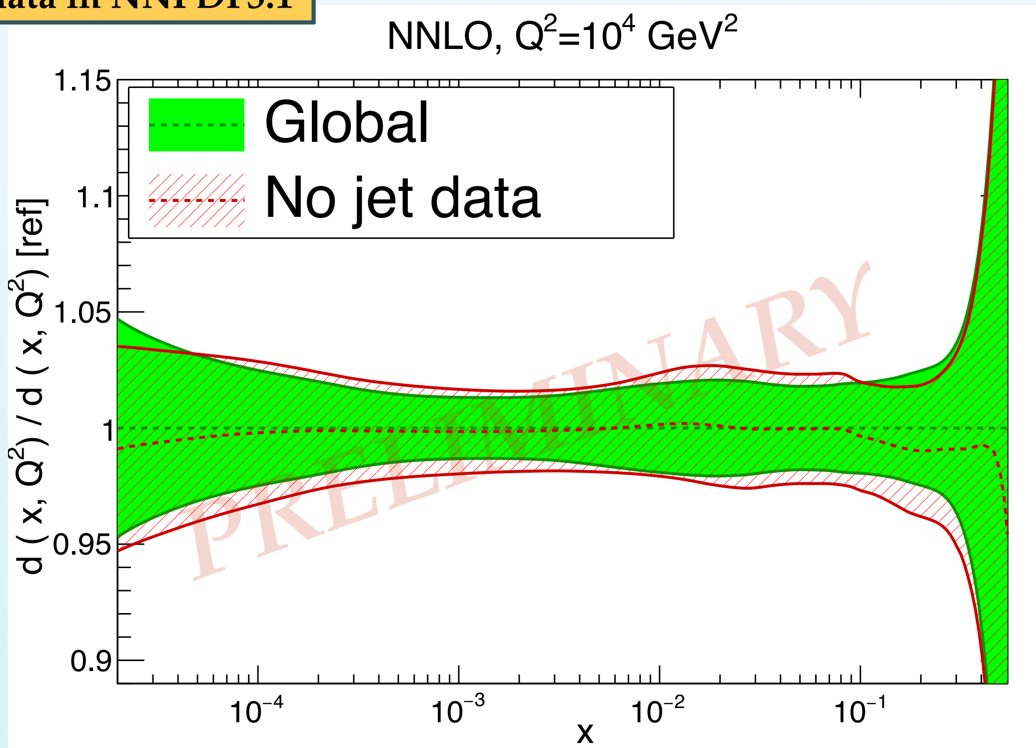
- For CMS we include the **inclusive jets at 2.76 TeV**, also good data/theory agreement

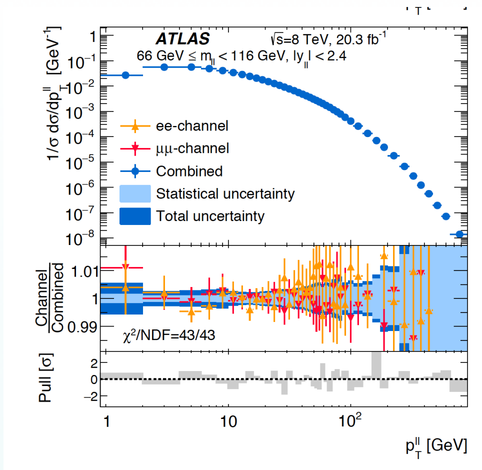
- Good description of all other jet datasets, **already included in NNPDF3.0**

- Jet data still quite **constraining for the large-x gluon**, though impact less dramatic as in previous NNPDF releases due to the presence of other gluon-sensitive measurements in the fit (more later)

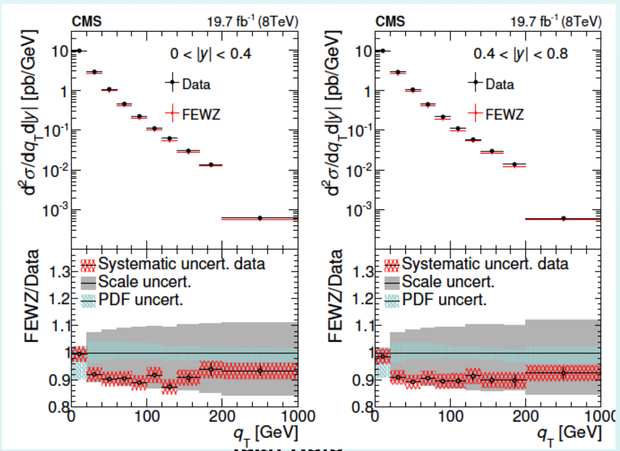
Impact of jet data in NNPDF3.1



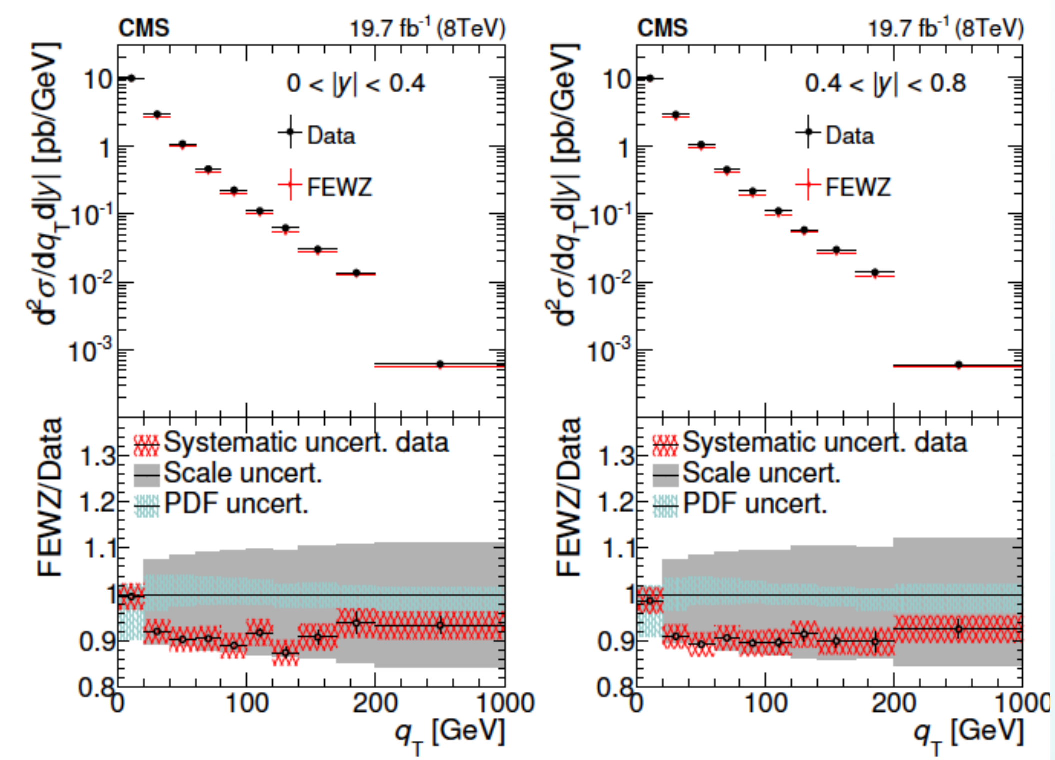


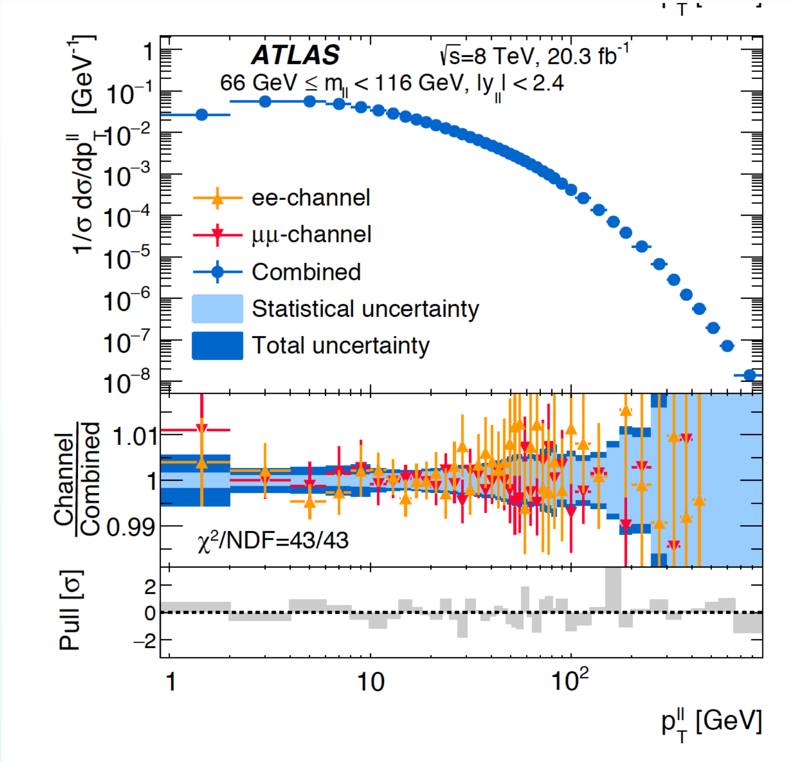


The Z transverse momentum



Impact of Z pt data



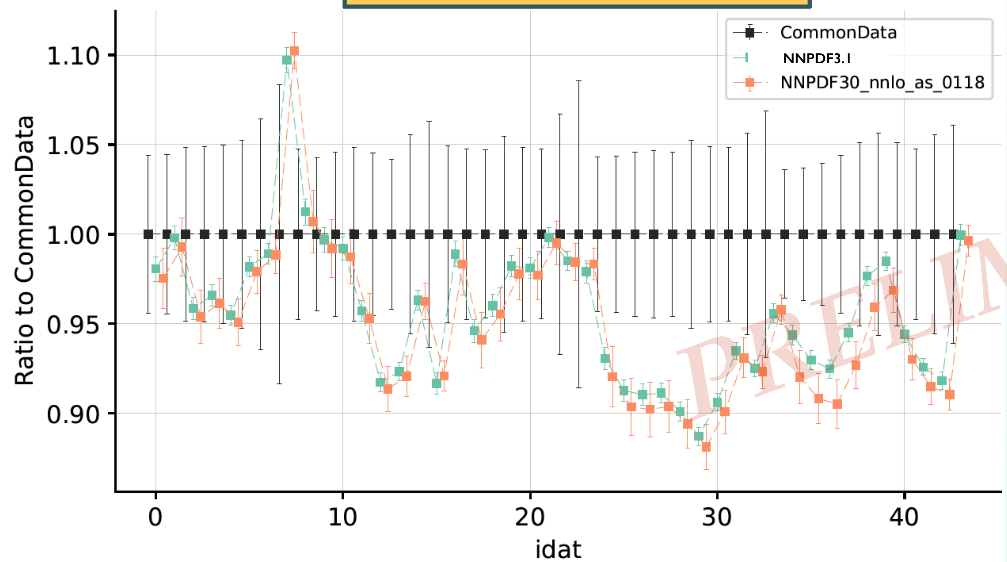


- **For the first time in a global fit, the transverse momentum of the Z boson has been included**
- **NNLO calculations for K-factors** from Boughezal and Petriello, very CPU time intensive!
- All the Z p_T measurements from ATLAS and CMS at 8 TeV included

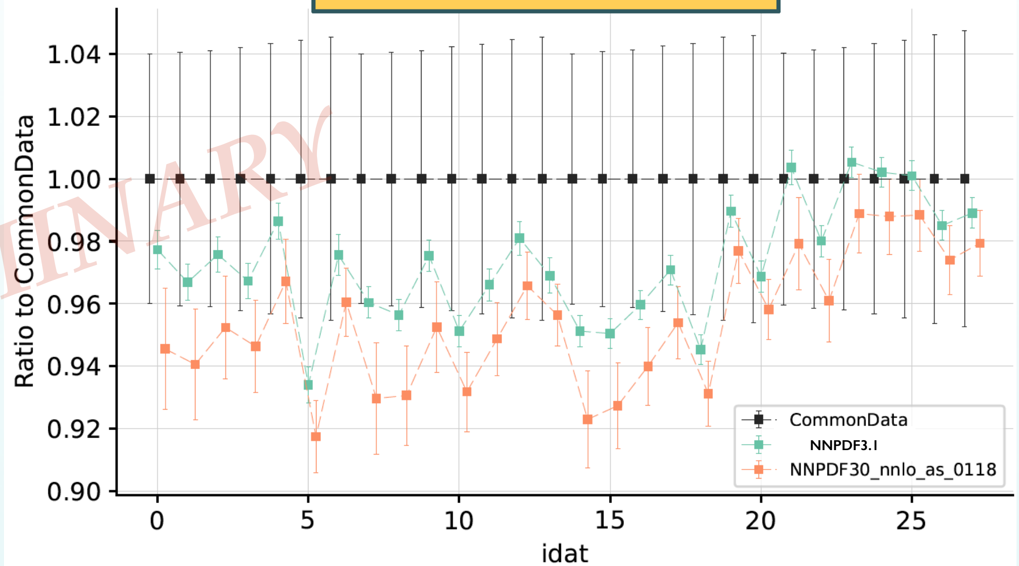
Dedicated study: Boughezal, Guffanti, Petriello, Ubiali, in preparation

Impact of Z pt data

ATLAS 8 TeV (M,pT)



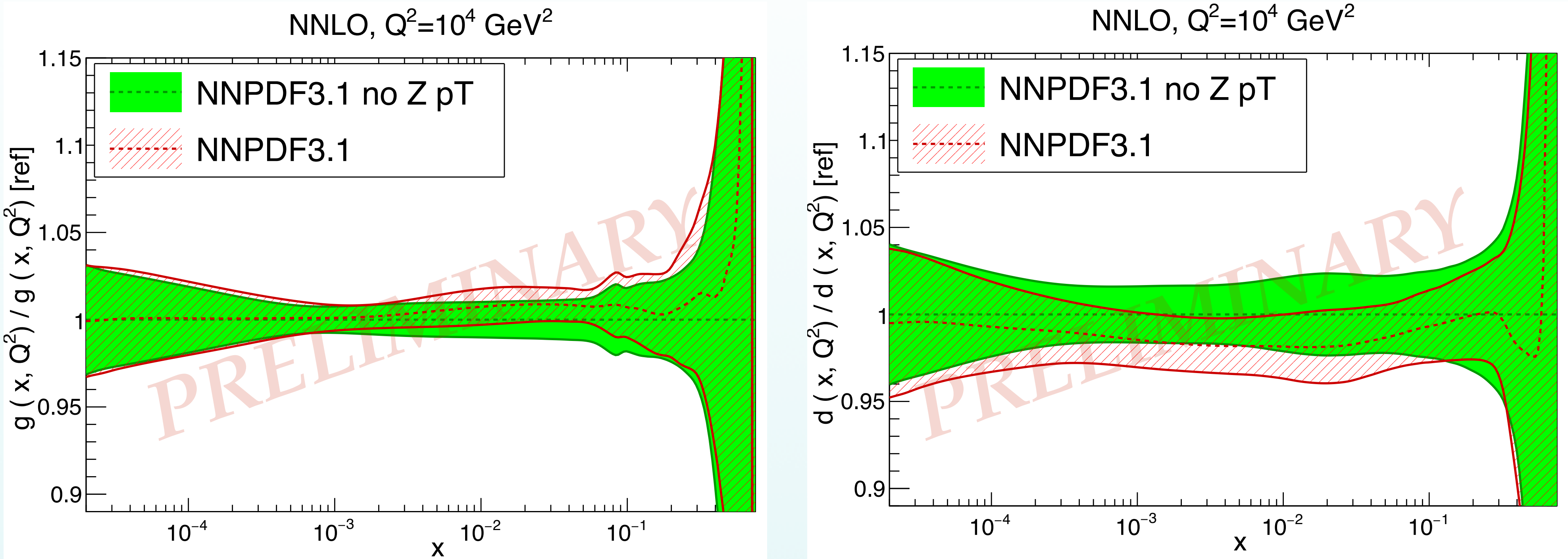
CMS 8 TeV (y,pT)



- **Good fit quality to 8 TeV ATLAS and CMS**, though very sensitive to stat fluctuations
- Included **1% of residual stat uncertainty from K-factor calculation**, else χ^2 (NNLO) worse by factor 4. Tiny changes in shape of TH prediction **worsen significantly fit quality** since exp uncorr errors v small
- Despite fitting 8 TeV data, **worse description of 7 TeV data** (tension between 7 and 8 TeV?)

	ATLAS 8 TeV (y,pT)	ATLAS 8 TeV (M,pT)	CMS 8 TeV (y,pT)
χ	0.9	0.9	1.3
χ	2.4	1.2	3.6

Impact of Z p_T data



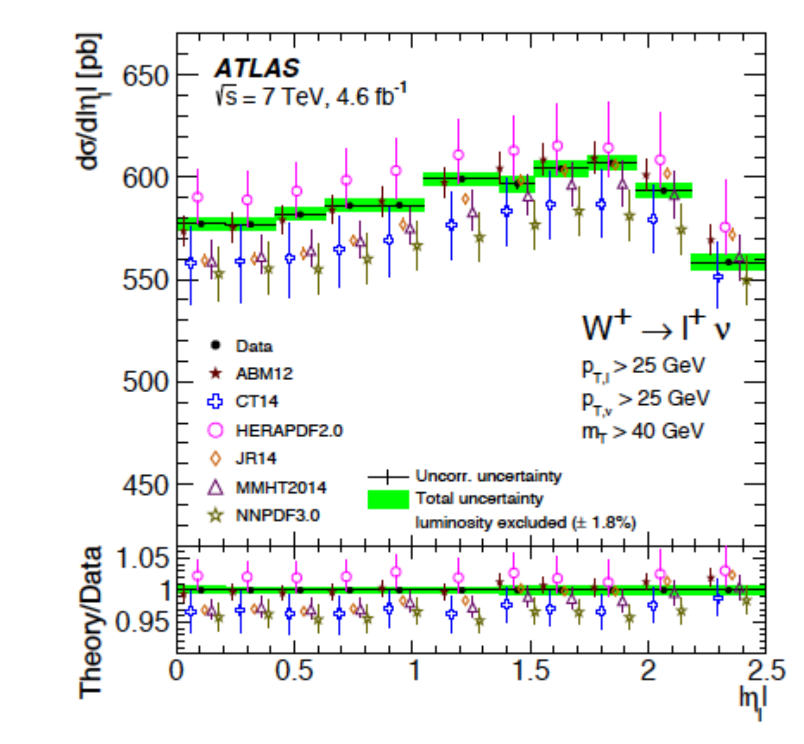
- Impact on many PDFs: **harder gluon at medium-x** (relevant for ggF Higgs) and softer quarks in the same region.
- The region of intermediate-x is the region where Z pT data is expected to have most sensitivity
- New important addition to the toolbox of global PDF fits!

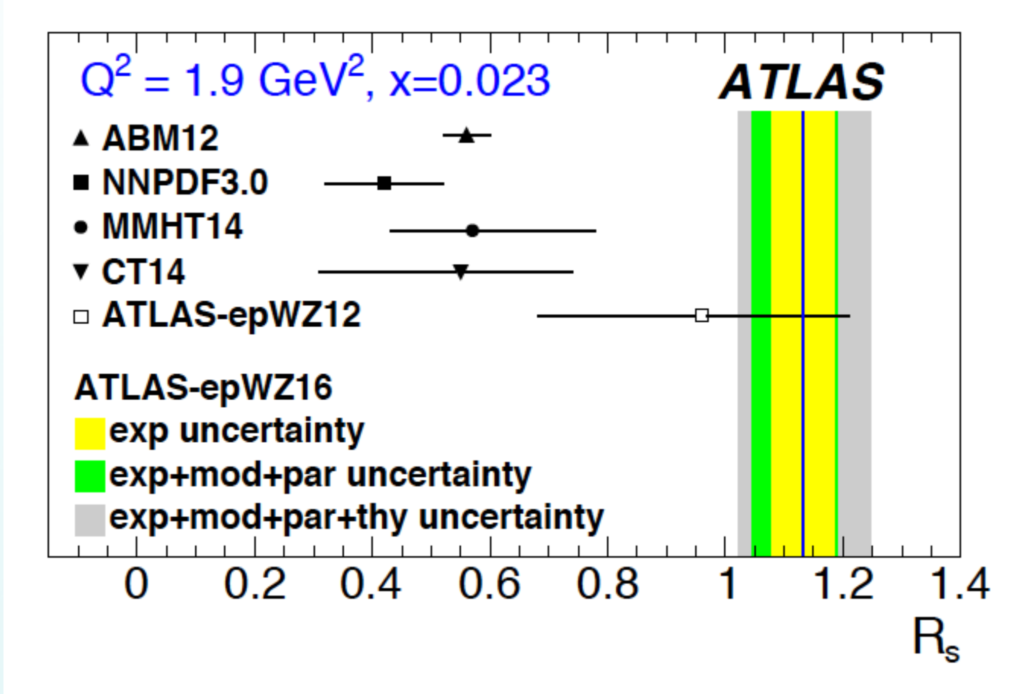
*NB the **ATLAS Z pt 7 TeV** data not included in these fits*

The strange and charm content of the proton

The strangeness content of the proton

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}$$





- **xFitter analysis** of the ATLAS W,Z 2011 inclusive data prefers a **symmetric strange sea** with small uncertainty, at odds with all other PDF fits

- Actually the ATLAS data suggest that there are **more strange than up and down sea quarks in the proton**, which is **very difficult to understand** from non-perturbative QCD arguments

- Can one accommodate the ATLAS W,Z 2011 data in the **global fit**? What happens to strangeness?

The strangeness content of the proton

PDF set	$R_s(0.023, 2\ \mathrm{GeV}^2)$	$R_s(0.013, M_Z^2)$
NNPDF3.0	0.47±0.09	0.79±0.04
NNPDF3.1	0.61±0.14	0.83±0.06
NNPDF3.1 collider-only	0.85±0.16	0.93±0.06
NNPDF3.1 HERA + ATLAS W, Z	0.96±0.20	0.98±0.09
ATLAS W, Z 2010 `HERAfitter` (Ref. [100])	$1.00^{+0.25}_{-0.28}$ (*)	$1.00^{+0.09}_{-0.10}$ (*)
ATLAS W, Z 2011 `xFitter` (Ref. [72])	$1.13^{+0.11}_{-0.11}$	-

PRELIMINARY

- **Confirmed the strange symmetric fit** preferred by the ATLAS W,Z 2011 measurements, though we find PDF uncertainties larger by a factor 2

- The **global fit** accommodates both the neutrino data and the ATLAS W,Z 2011 ($\boldsymbol{\chi^2_{\mathrm{nutev}}=1.1}$, $\boldsymbol{\chi^2_{\mathrm{AWZ11}}=1.8}$) finding a compromise value for $\boldsymbol{R_S=0.61\pm0.14}$

- **Mild tension** in the global fit (1.5-sigma level at most) when simultaneously included neutrino data, CMS W+charm and ATLAS W,Z 2010+2011

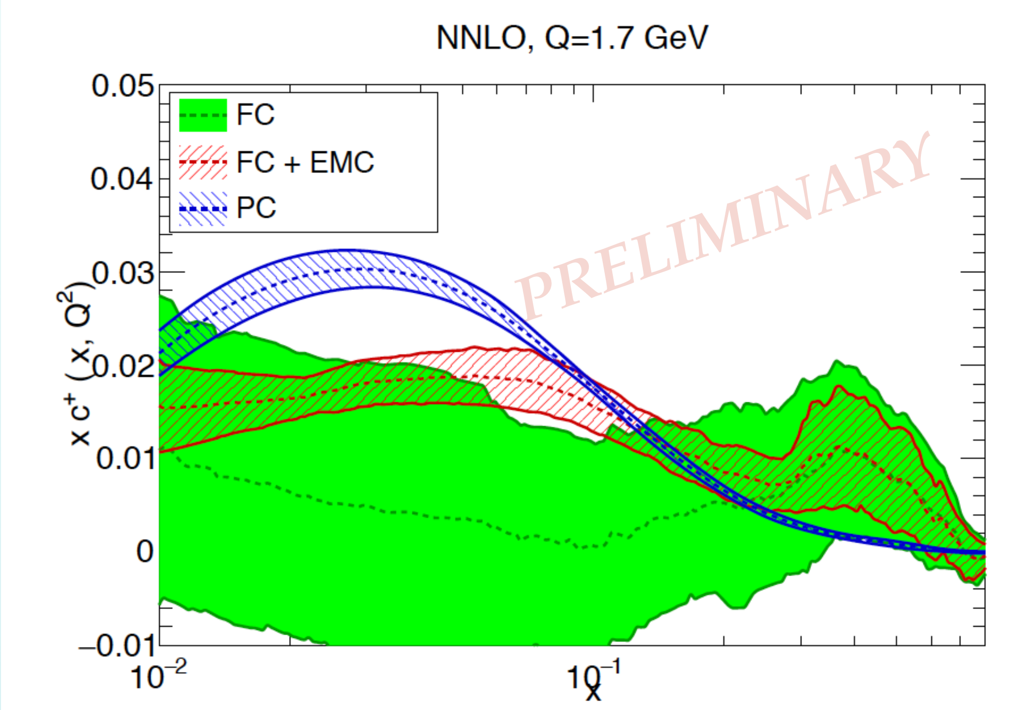
Charm content of proton revisited

- The new LHC experiments provide additional constraints on **non-perturbative charm**

- Including the EMC charm data, we find **evidence for non-perturbative charm at the 1.5 sigma level.** Even without EMC data**, non-perturbative charm bounded < 0.5% at the 68% CL**

$$C(Q = 1.65\ \text{GeV})_{\text{FC}} - C(Q = 1.65\ \text{GeV})_{\text{PC}} = (0.24 \pm 0.16)\,\%$$

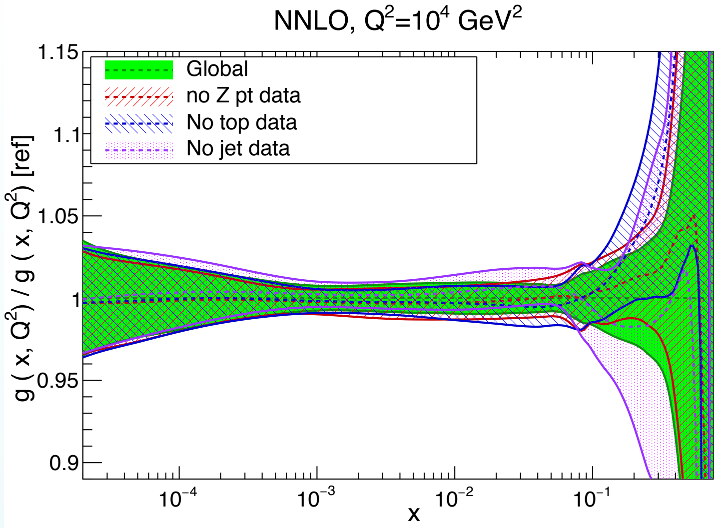
PDF set	$C(Q = 1.65\ \text{GeV})$	$C(Q = 100\ \text{GeV})$
NNPDF3.1PC	$(0.360 \pm 0.007)\%$	$(4.48 \pm 0.03)\%$
NNPDF3.1FC	$(0.3 \pm 0.4)\%$	$(4.4 \pm 0.2)\%$
NNPDF3.1FC no ATLAS W, Z 2011	$(0.8 \pm 0.5)\%$	$(4.7 \pm 0.3)\%$
NNPDF3.1FC with EMC	$(0.60 \pm 0.16)\%$	$(4.6 \pm 0.1)\%$



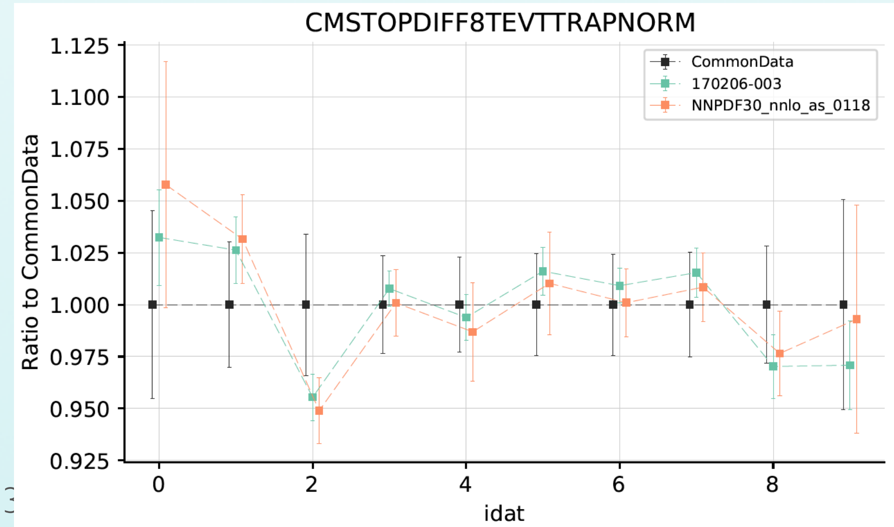
NNPDF3.0 dataset (no EMC): 1.6 +- 1.2%

NNPDF3.1 dataset (no EMC): 0.3 +- 0.4%

Non-perturbative charm is certainly small, but data exhibit **preference for non-zero value**



Top-quark pair differential distributions



The large-x gluon from top-quark production

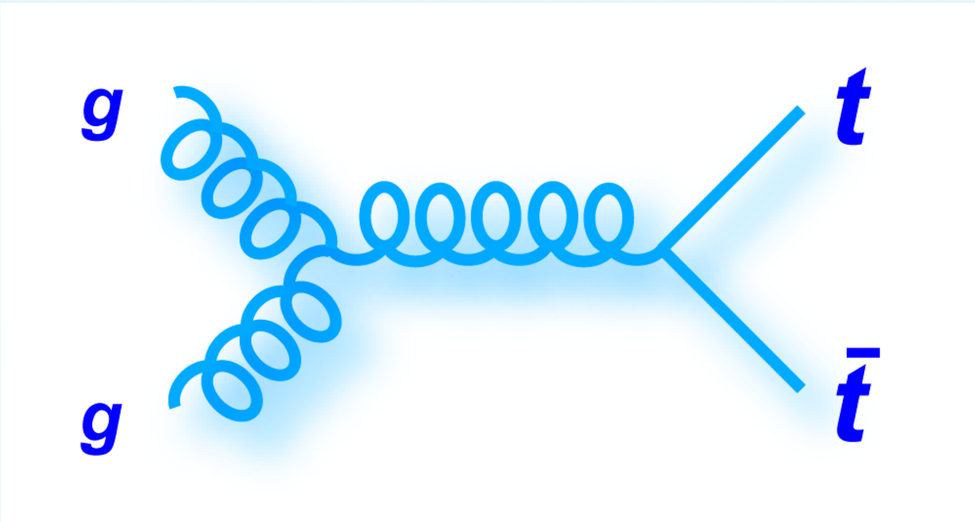
- Top-quark pair production driven by the **gluon-gluon luminosity**

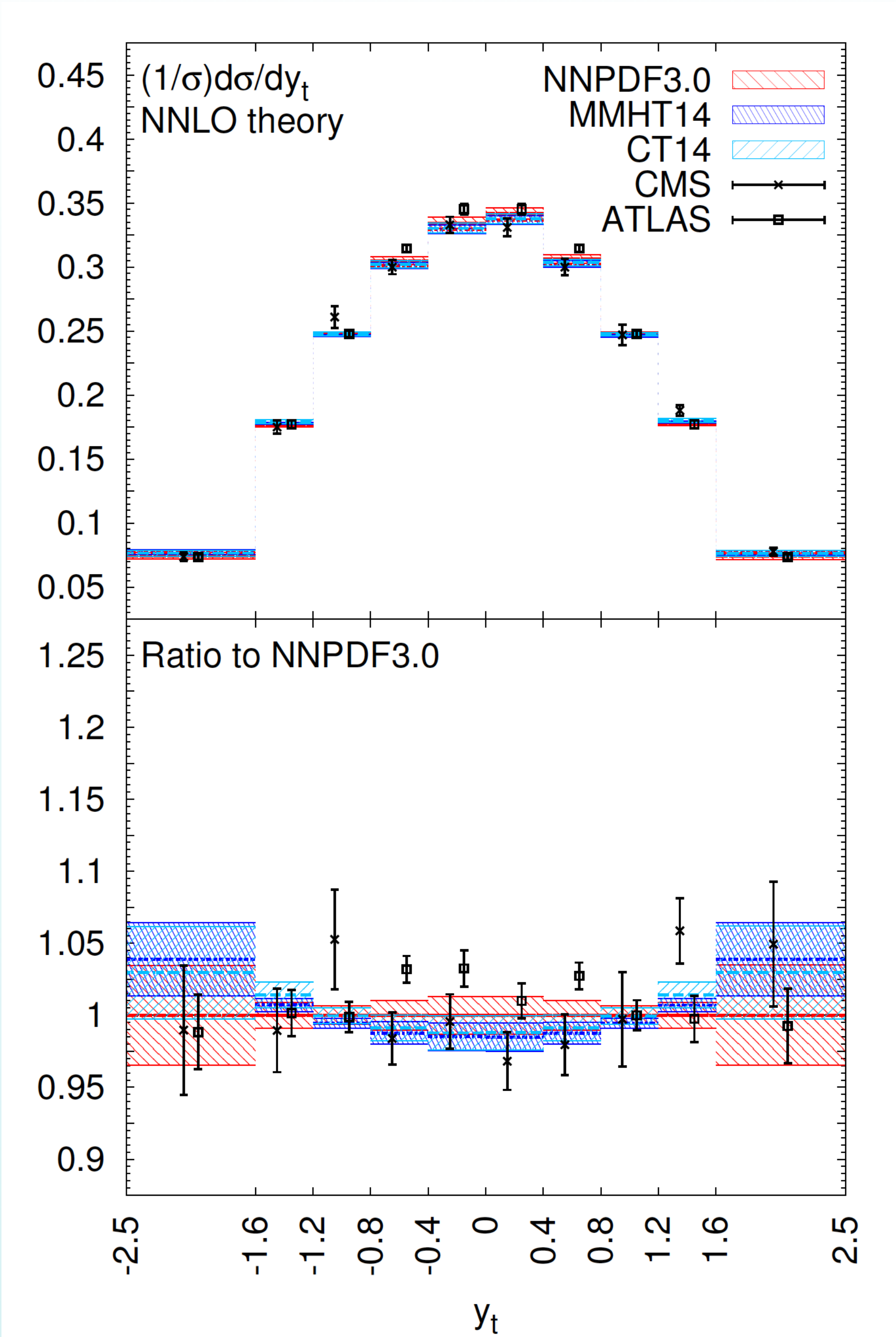
- **NNLO calculations for stable top quarks** available (with decays in the pipeline)

- Recent **precision data from ATLAS and CMS at 8 TeV** with full breakdown of statistical and systematic uncertainties

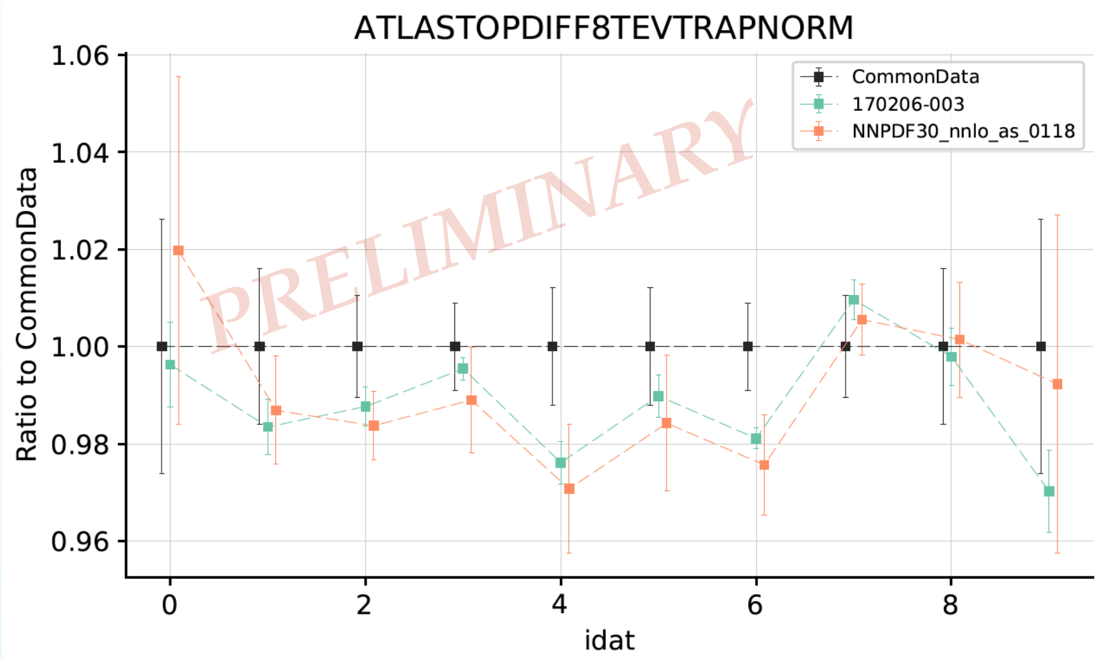
- For the first time, included ATLAS+CMS 8 TeV differential top measurements into the **global PDF fit**

Czakon, Hartland, Mitov, Nocera, Rojo 16





The large-x gluon from top-quark production



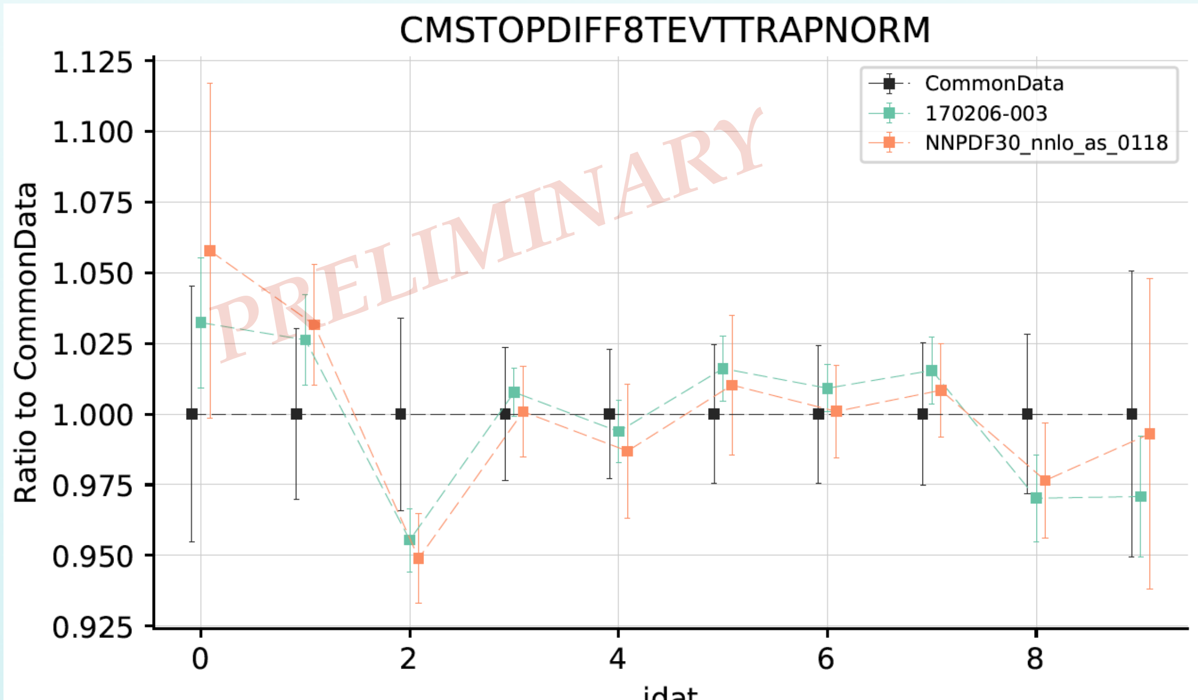
- From CMS we include the **normalised top-quark pair rapidity at 8 TeV**

- From ATLAS we include the **normalised top pair rapidity at 8 TeV**

- From CMS we include the **normalised top-quark pair rapidity at 8 TeV**

- In addition we include **total cross-section data** at 7,8 and 13 TeV

- Good agreement between NNLO theory and the LHC data



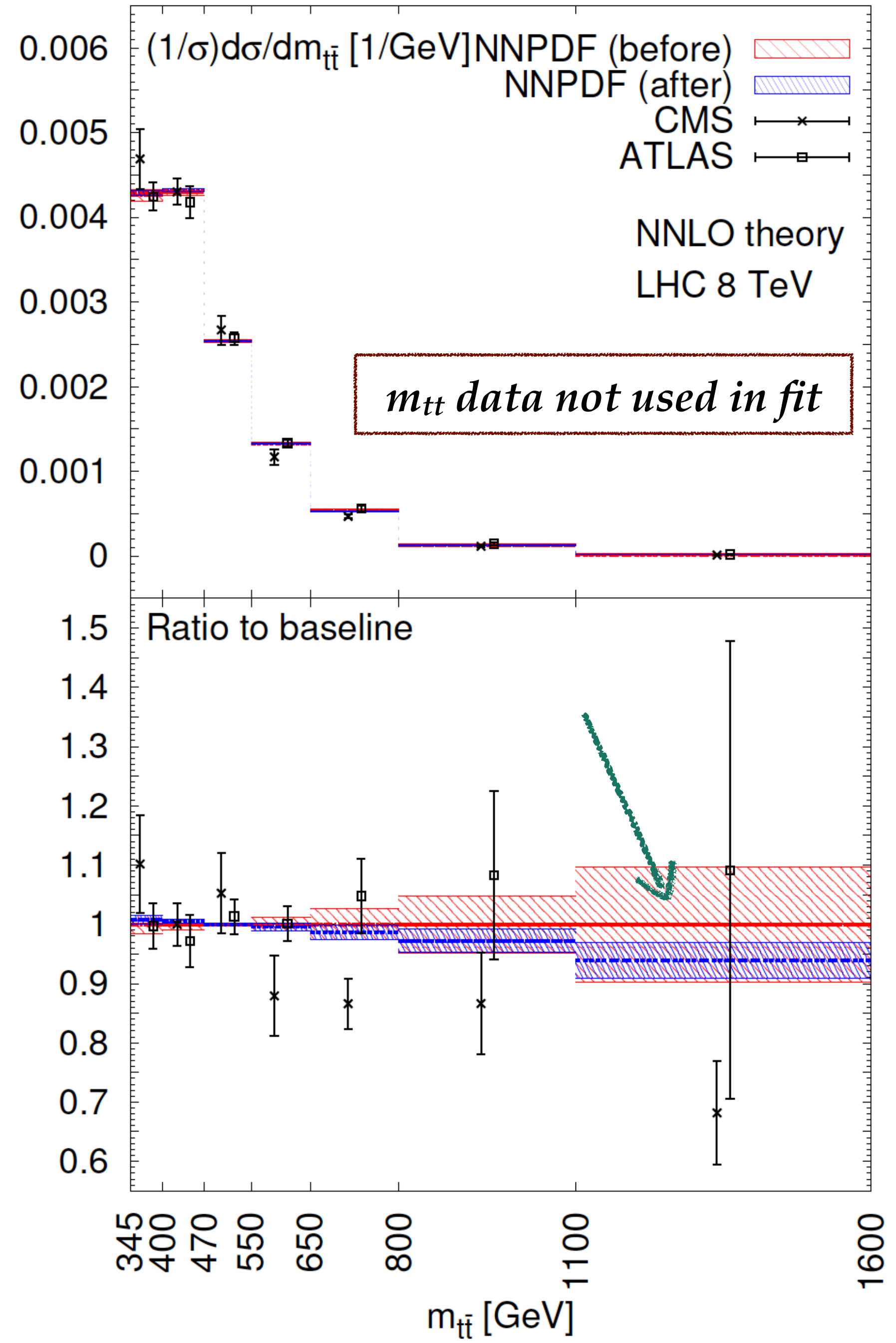
The large-x gluon from top-quark production

- PDF uncertainties reduced by more than a factor two for $m_{tt} \gtrsim$ **500 GeV**

- Our choice of fitted distributions, $\mathbf{y_t}$ and $\mathbf{y_{tt}}$, reduces the **risk of *BSM contamination*** (kinematical suppression of resonances), which might show up instead in $\mathbf{m_{tt}}$ and $\mathbf{p^t_T}$, where PDF uncertainties are now much smaller

- Self-consistent program to **use top data to provide better theory predictions**

Improved sensitivity to BSM dynamics with top-quark final states!

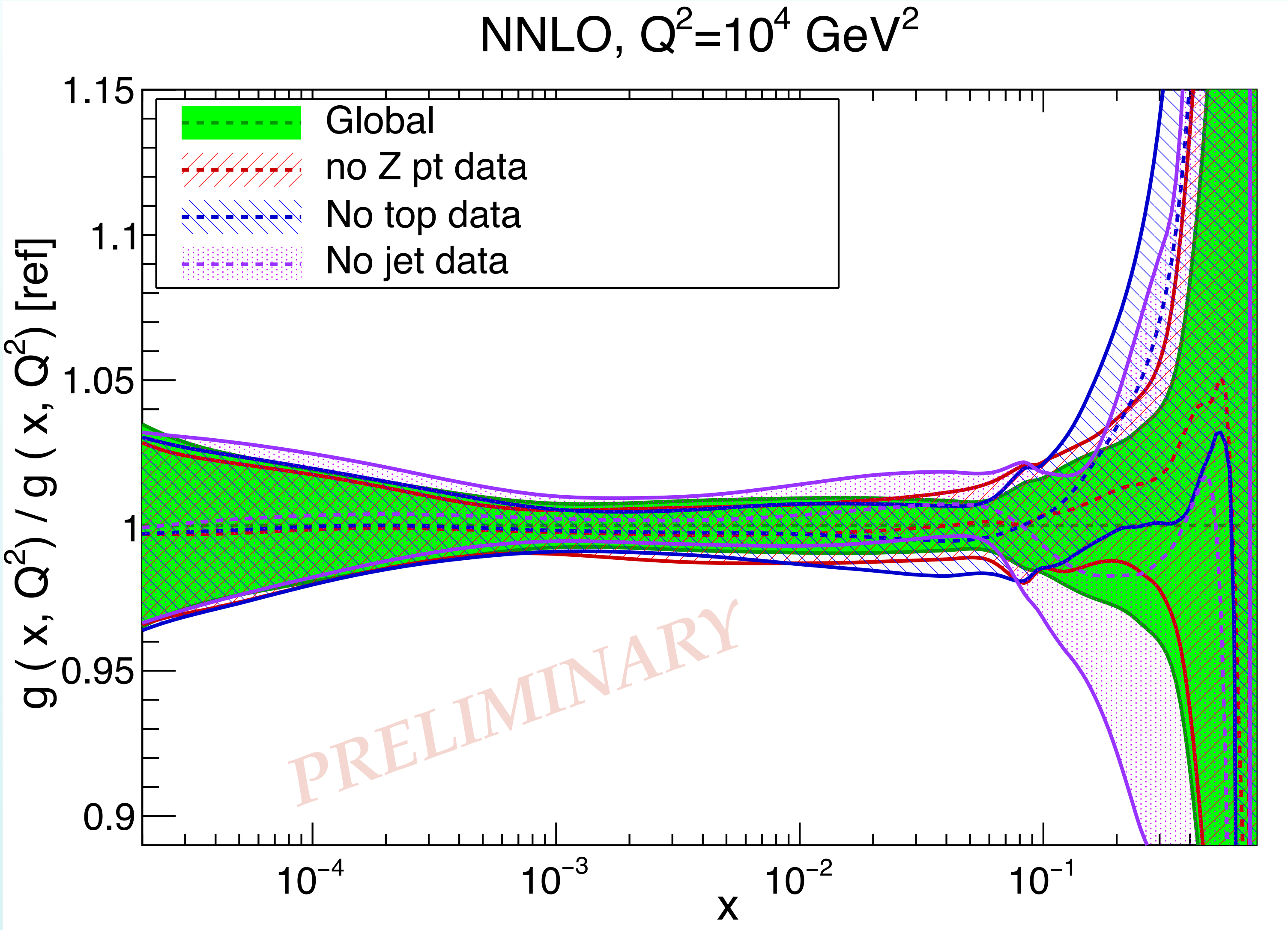


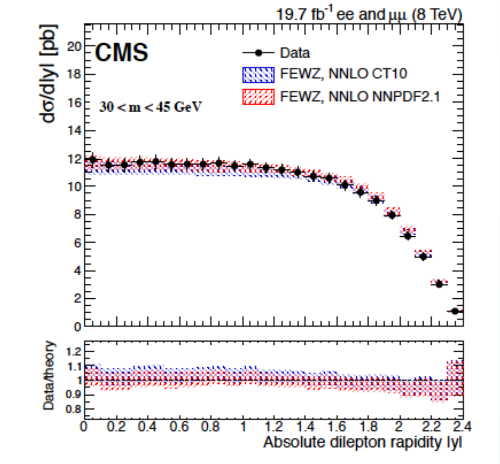
Czakon, Hartland, Mitov, Nocera, Rojo 16

Impact on the gluon

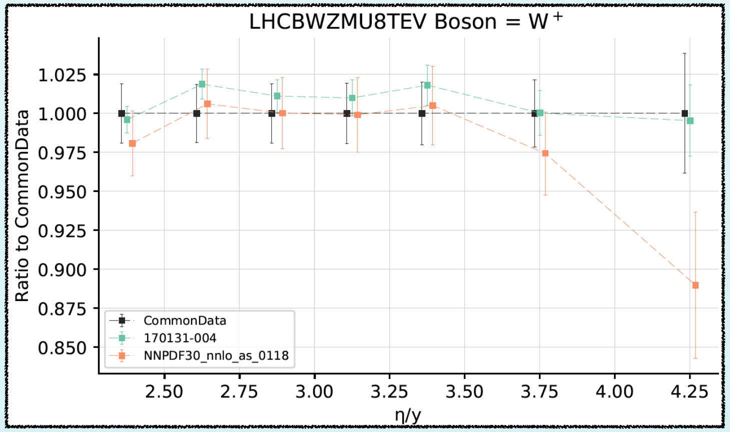
- In NNPDF3.1 we have three groups of processes that provide **direct information on the gluon**: inclusive jets, top pair differential, and the Z transverse momentum

- Are the constraints from each of these groups **consistent among them?** Yes!

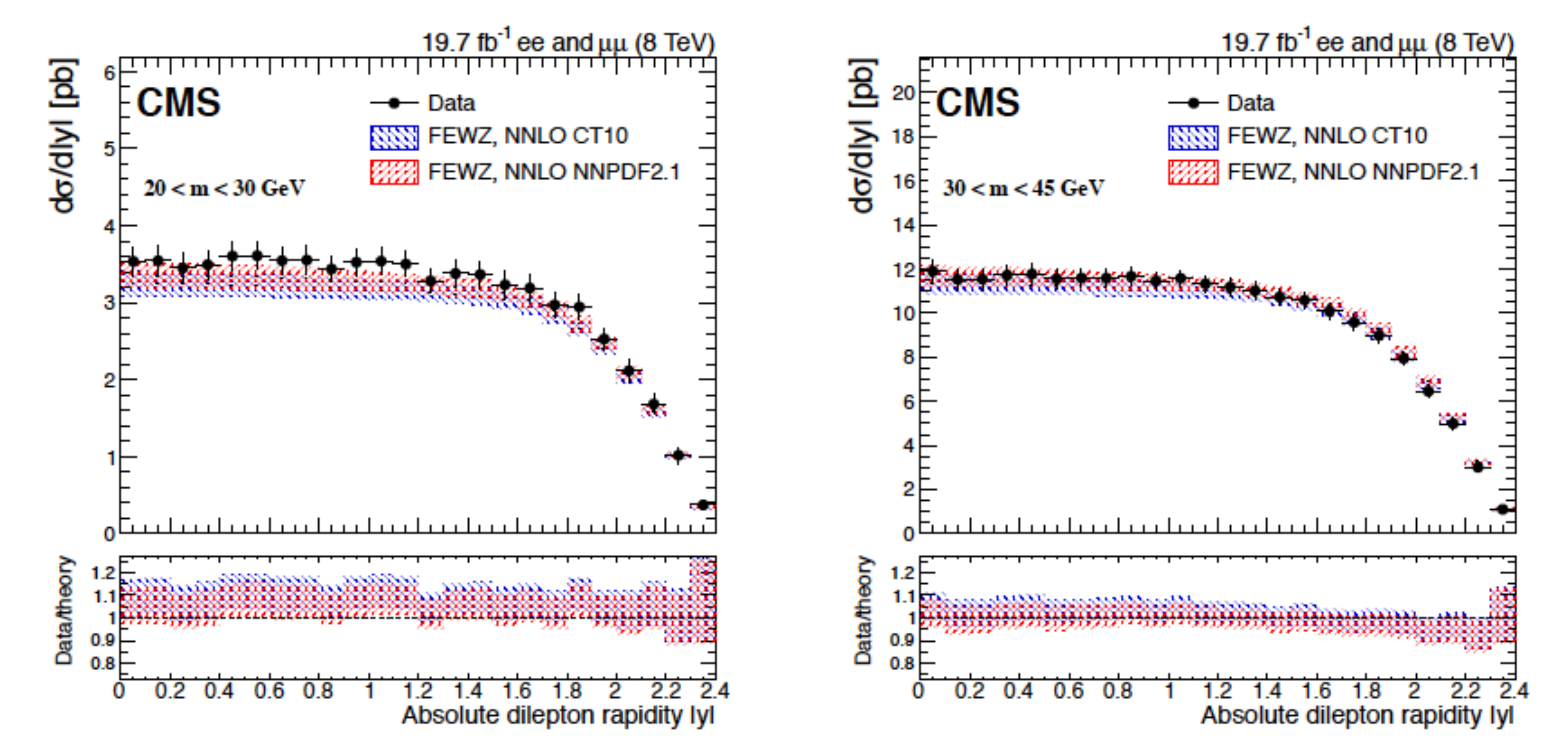




Inclusive weak boson production



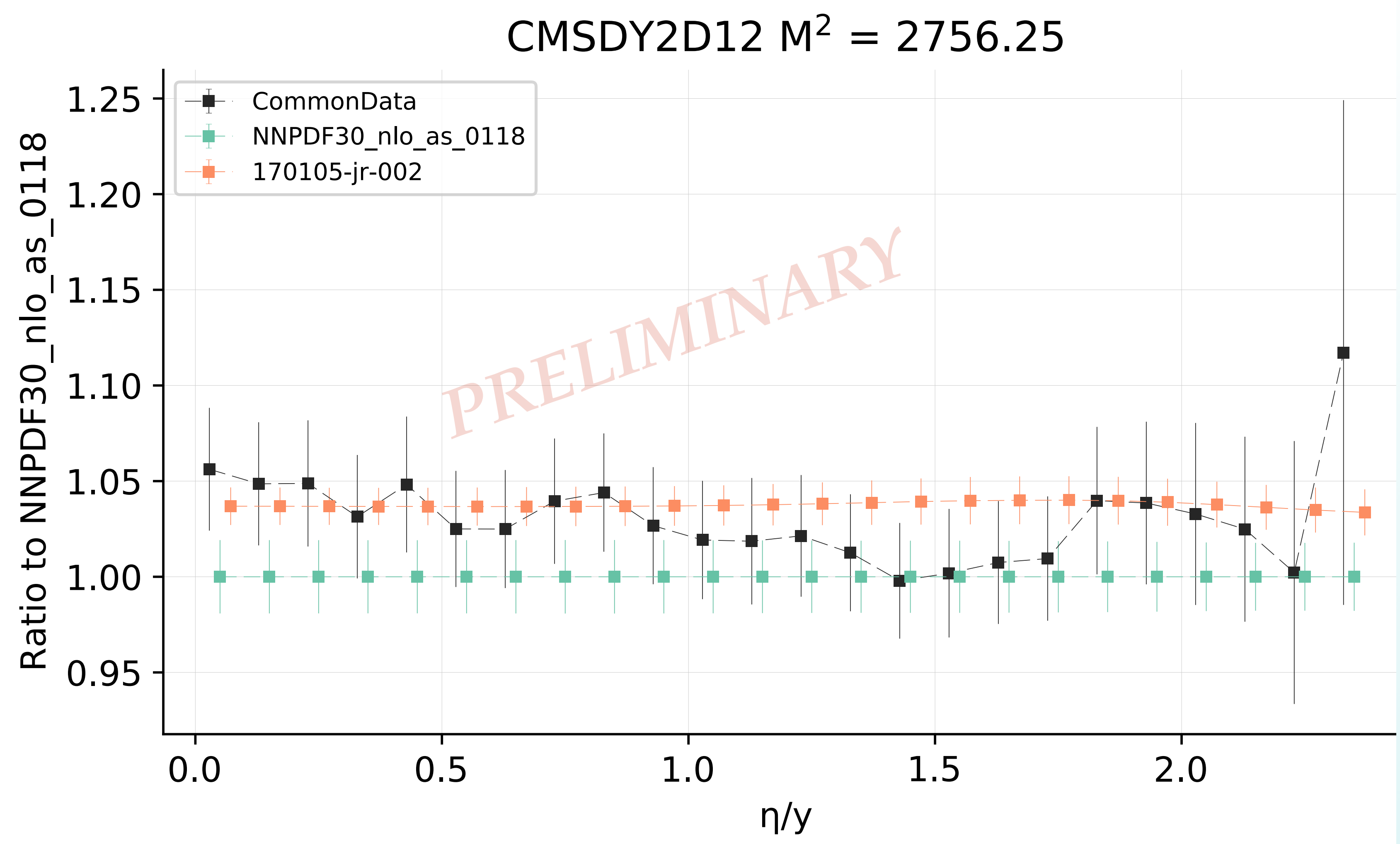
CMS Drell-Yan 8 TeV



- **Drell-Yan production at 8 TeV** updates a previous 7 TeV measurement (already in NNPDF3.0) and is expected to provide useful information on quark flavour separation
- Intensive **NNLO calculation** to achieve good enough statistical accuracy.
- Kinematical cuts exclude **the first rapidity bin**, which vanishes at LO due to lepton acceptance cuts

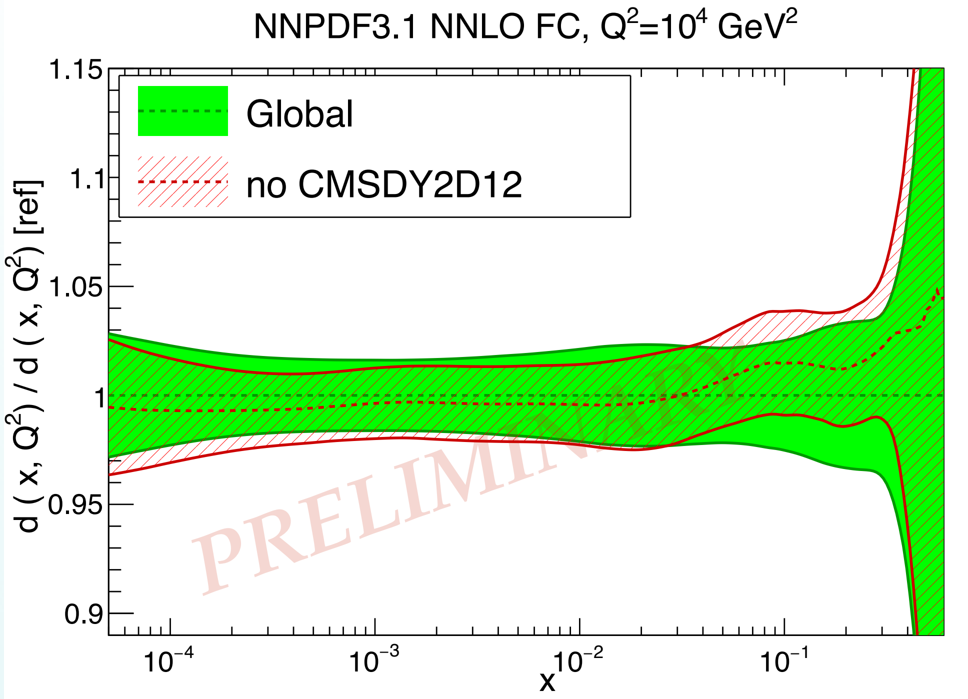
CMS Drell-Yan 2D 8 TeV	$M_{ll} \geq 30$ GeV	$M_{ll} \geq 30$ GeV

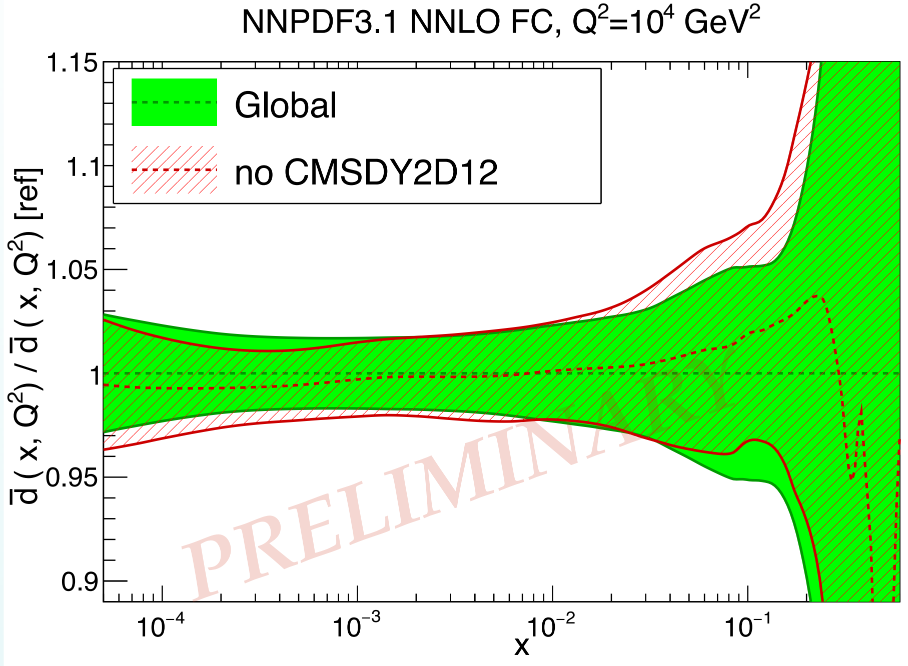
CMS Drell-Yan 8 TeV



- **Improved description** as compared to NNPDF3.0
- Despite good visual data/theory agreement, the fit description is **poor: χ^2/N_{dat} = 3.3**
- Difficult to trace the origin of the problem since only **full covariance matrix** (no breakdown of systematics) is provided

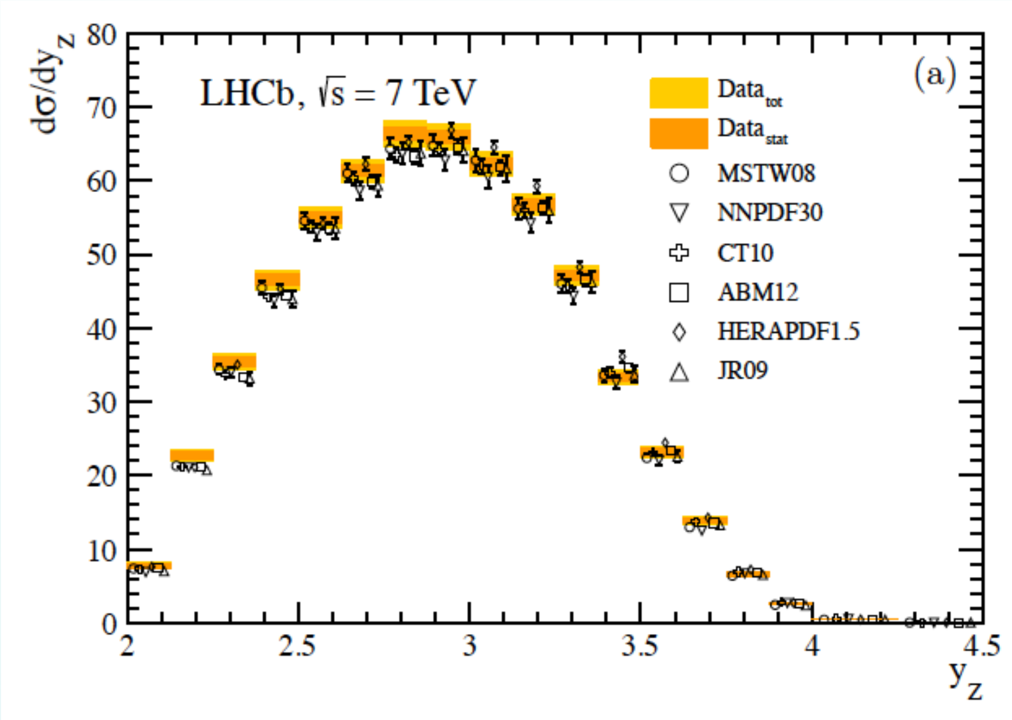
CMS Drell-Yan 8 TeV

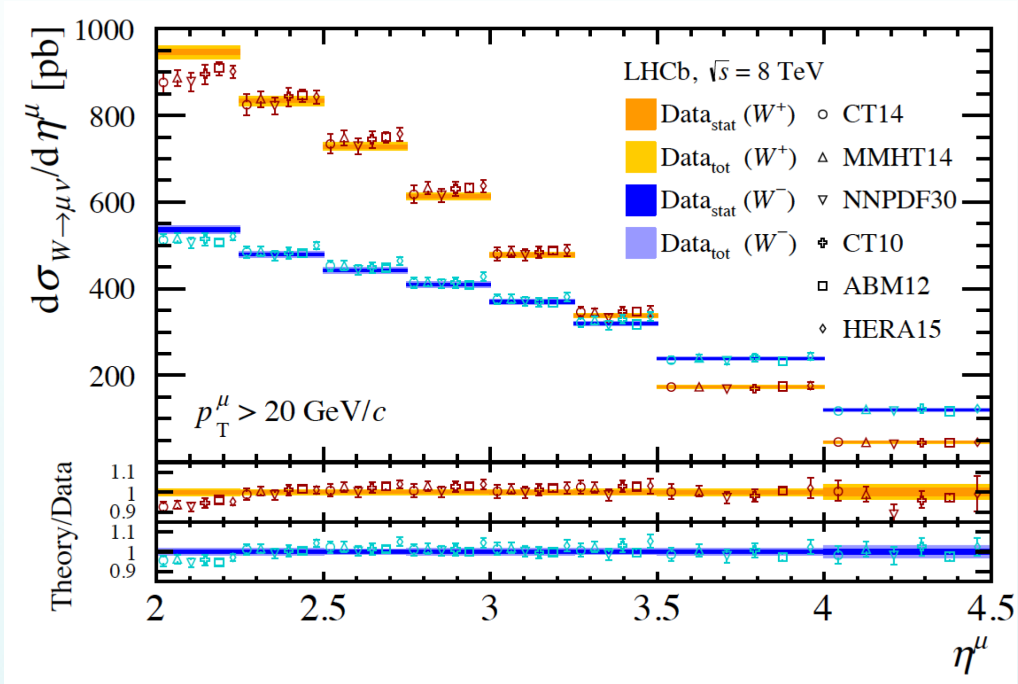




- This measurement indeed affects large-x quarks and antiquarks …
- … but only shift in central values, with PDF errors stable or **even increasing** in some cases
- **Tension** with other experiments in global fit? **Internal tensions**?

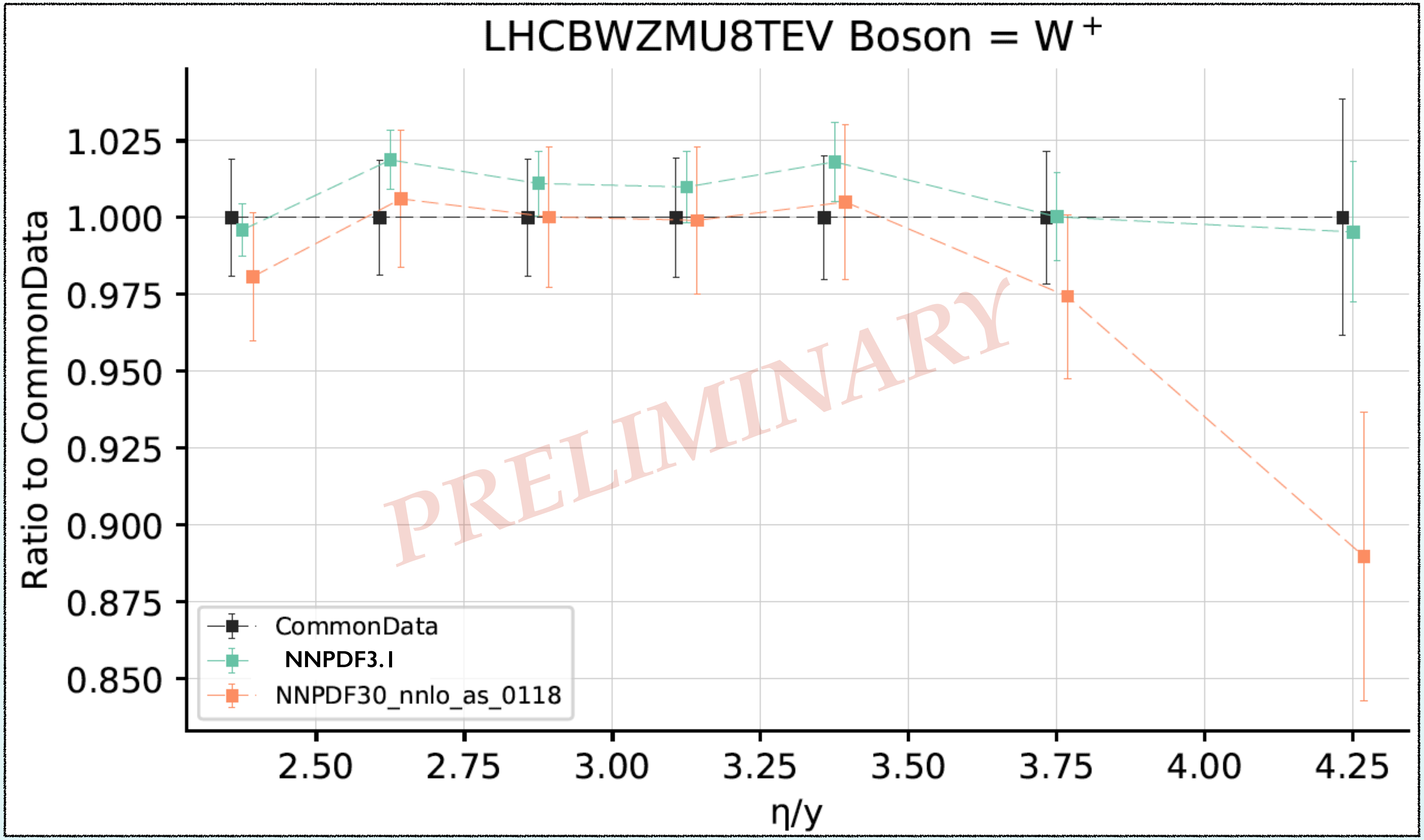
Forward W,Z production at LHCb





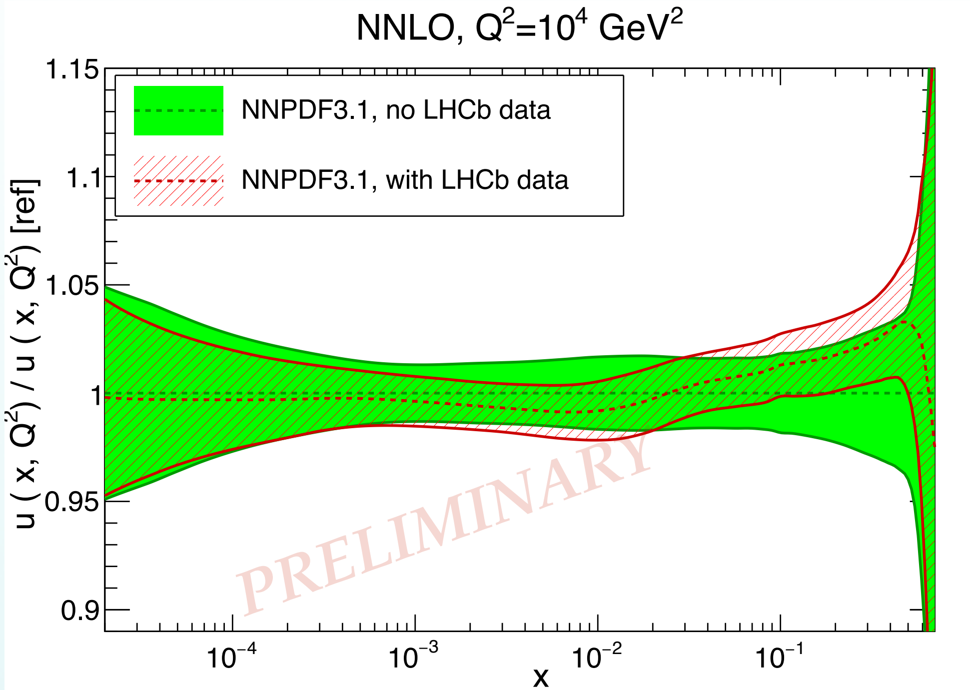
- NNPDF3.1 includes the **complete 7 TeV and 8 TeV W,Z measurements** in the muon channel, as well as **most of the electron channel measurements**
- Crucial to account for the **cross-correlations** between the W and Z data
- Expect improved **quark-flavor separation** for **large-x quarks,** thanks to LHCb **forward kinematics**
- **Complementary information** to that from W, Z production from ATLAS and CMS

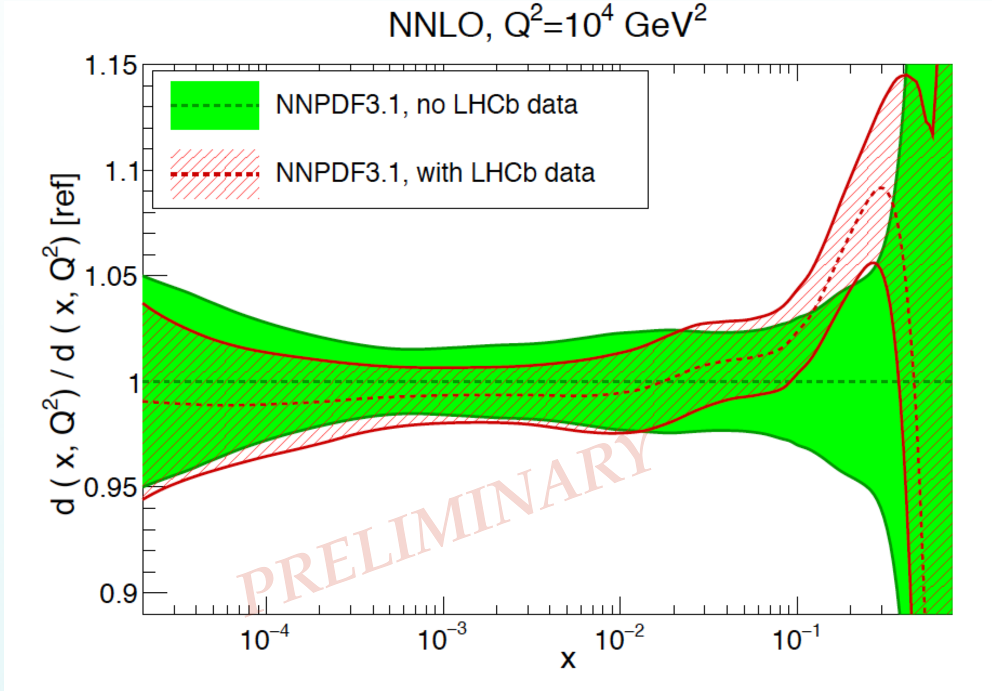
Forward W,Z production at LHCb



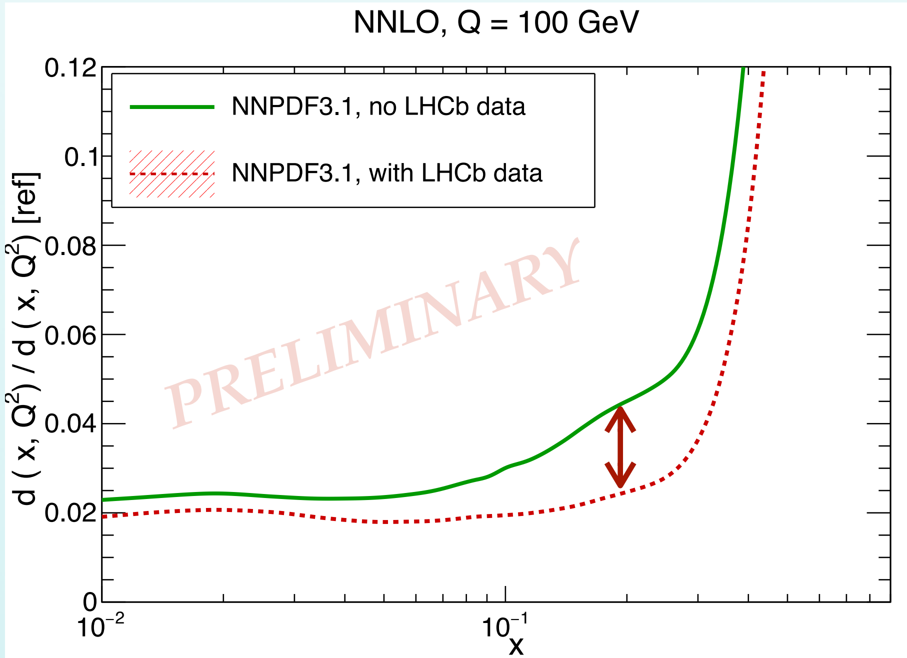
- Improved agreement as compared to NNPDF3.0, specially in the forward region
- Significant reduction of PDF uncertainties wrt to NNPDF3.0, by almost factor 2
- NNLO QCD does not describe the **most central bin of the 8 TeV W data**: excluded from fit

Forward W,Z production at LHCb





- The reduction of PDF uncertainties from the LHCb data is more marked for the **large-x quarks**
- Note **shift on central values**, in addition to reducing PDF errors
- For the down quark, PDF errors decrease by almost a **factor 2** for *x=0.2*



NNPDF3.1: summary and outlook

- **Several new datasets included**, from the HERA and Tevatron legacy data to precision LHC electroweak production measurements, the 8 TeV Z p_T data, and top quark production differential distributions

- Good **stability with respect to NNPDF3.0,** with main differences being a **reduction of the large-*x* PDF uncertainties** and an **improved quark flavour separation**

- **Improved stability of the gluon** from the combination of **top, Z p_T, and jet data**

- **Increase in strangeness** from inclusion of the ATLAS W,Z 2011 data

- **Improved fit quality once the charm PDF is fitted**, rather than perturbatively generated. Non-negligible differences at the PDF level. NNPDF3.1 fits for the **two options** will be released.

- **NNPDF3.1 will be available in LHAPDF very soon!**

NNPDF3.1: summary and outlook

- **Several new datasets included**, from the HERA and Tevatron legacy data to precision LHC electroweak production measurements, the 8 TeV Z p_T data, and top quark production differential distributions

- Good **stability with respect to NNPDF3.0,** with main differences being a **reduction of the large-*x* PDF uncertainties** and an **improved quark flavour separa**

- **Improved stability of the gluon** from the com **data**

- **Increase in strangeness** W,Z 2011 data

- **Improv harm PDF is fitted**, rather than perturbatively generated. Non-negli at the PDF level. NNPDF3.1 fits for the **two options** will be released.

- **NNPDF3.1 will be available in LHAPDF very soon!**

Thanks for your attention!

Extra Material

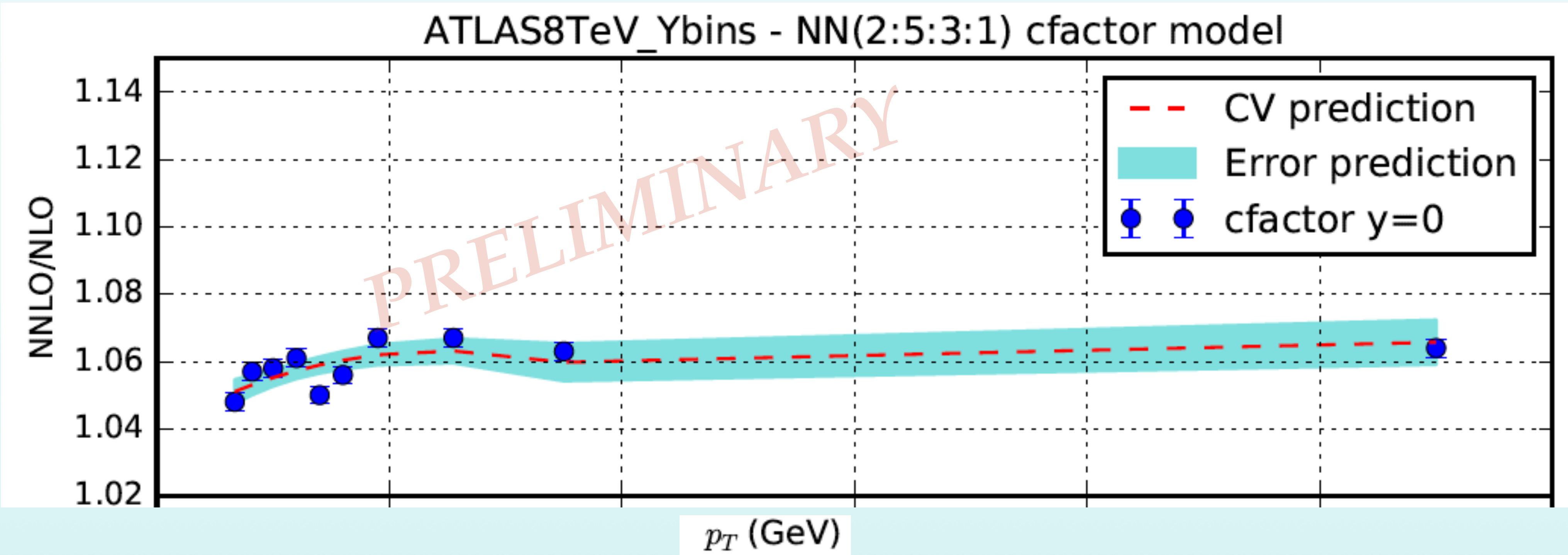
Fitting data with sub-percent errors

- In several of the new experiments in NNPDF3.1, uncorrelated uncertainties are very small, **at the few permille level**. This implies that is required to get the **shape of the theory prediction** correct to the same accuracy, which can be very challenging for **CPU-intensive NNLO calculations**

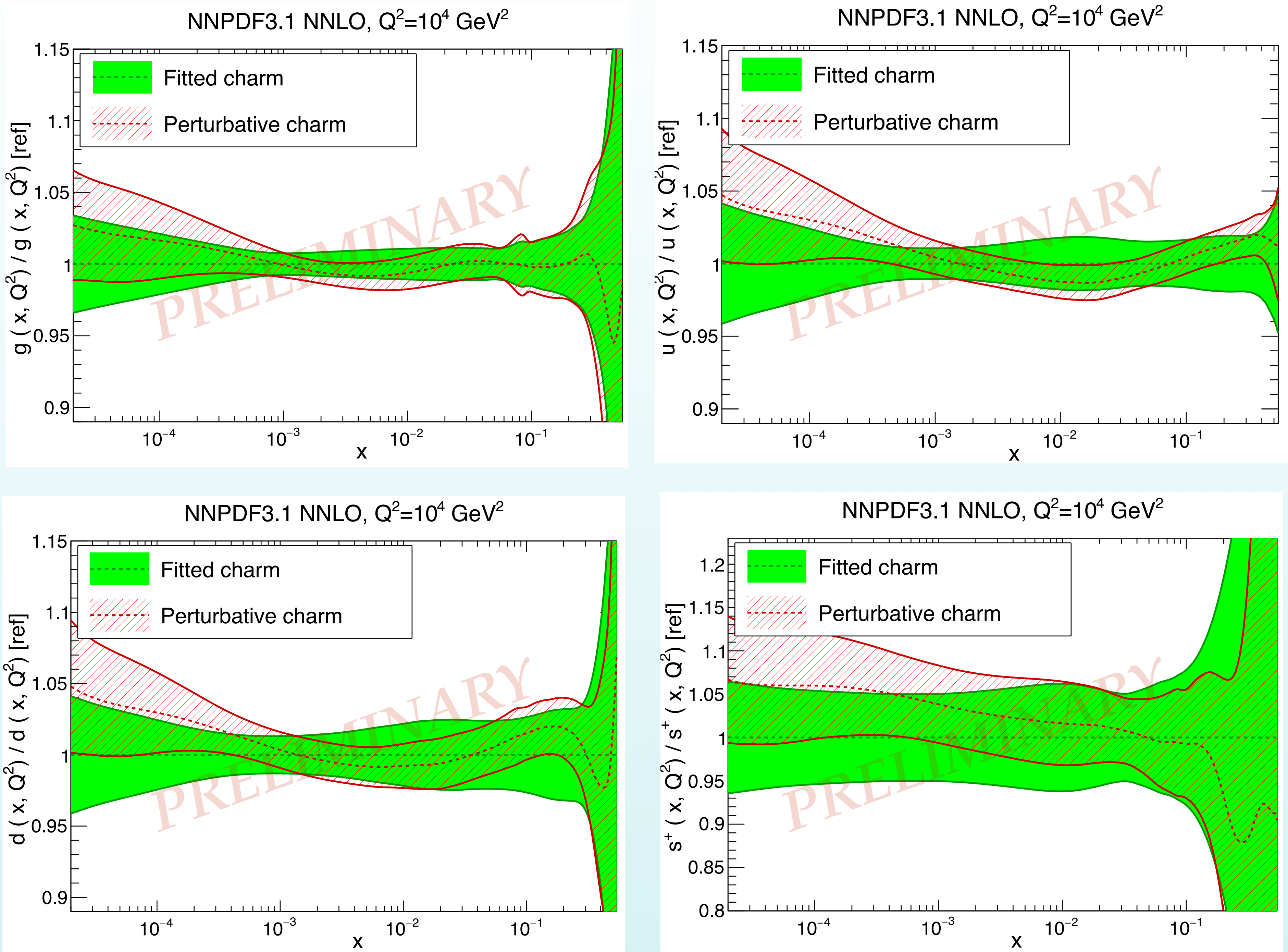
- We tackle this by including the MC stat integration error from the theory prediction as an **additional uncorrelated systematic error** in the χ^2

- This also implies that even **very small variations of the correlation model** (which ultimately determines what is correlated and what uncorrelated) can lead to very large variations of the χ^2 for same input theory

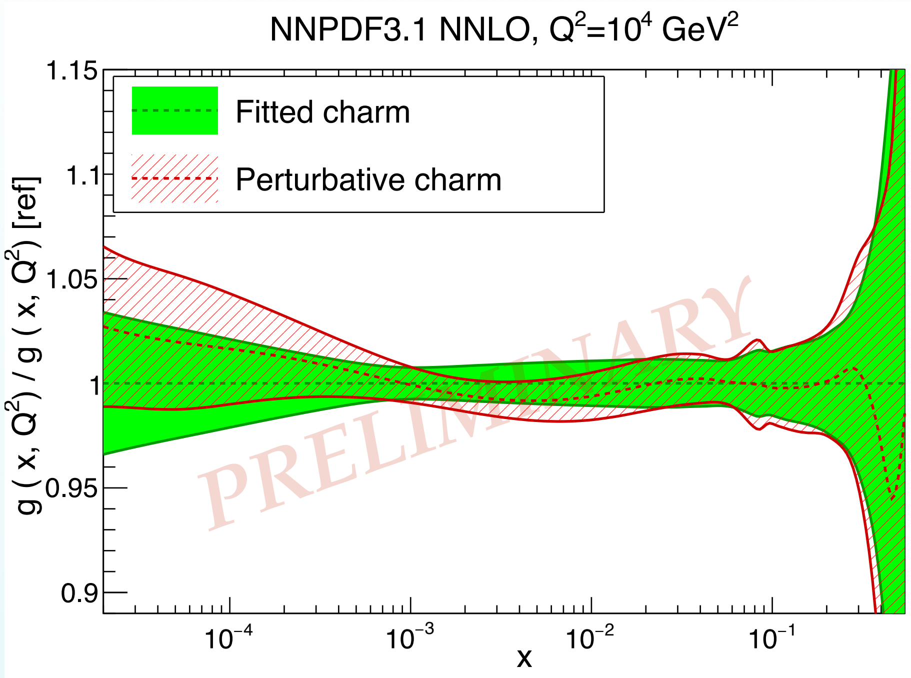
- To avoid this, measurements should provide an **estimate of the uncertainty associated with correlations**

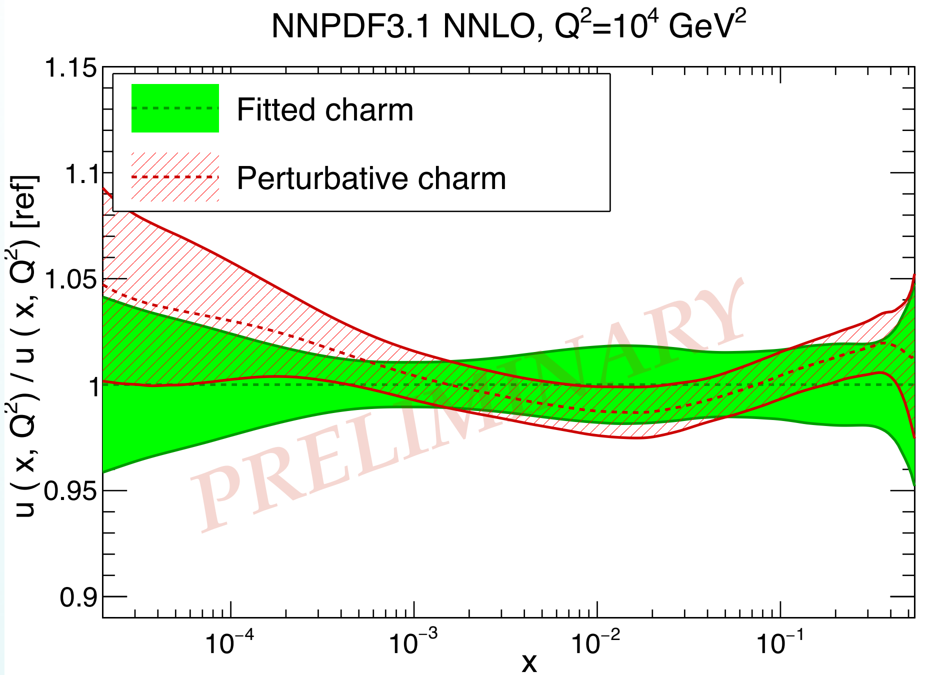


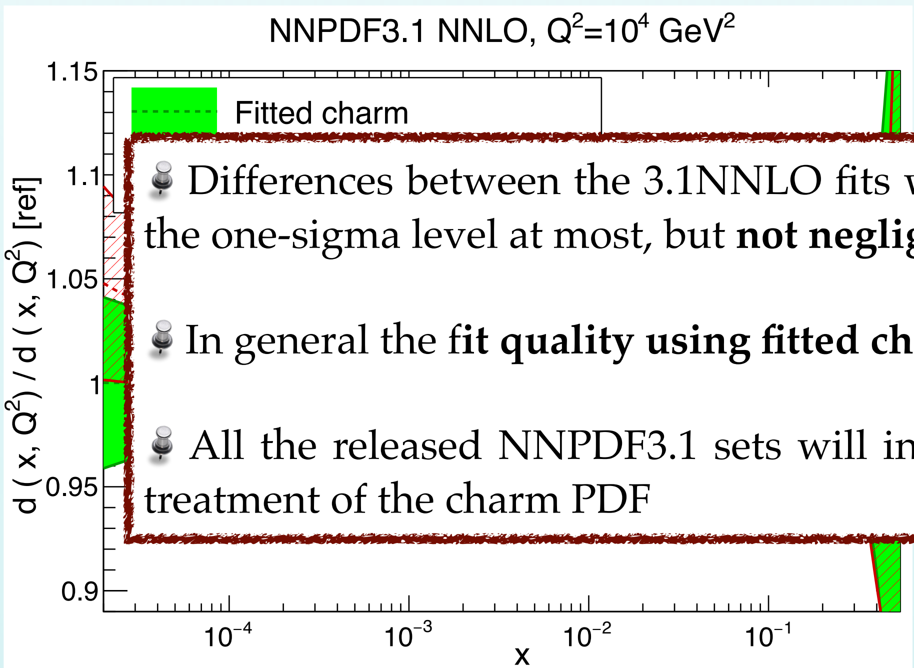
Fitted charm vs perturbative charm

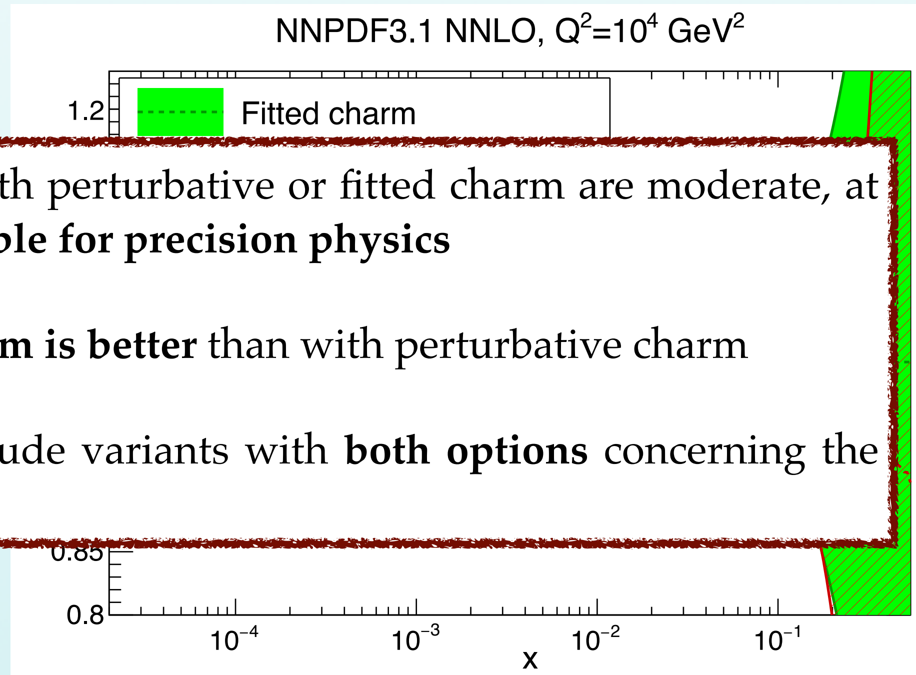


Fitted charm vs perturbative charm



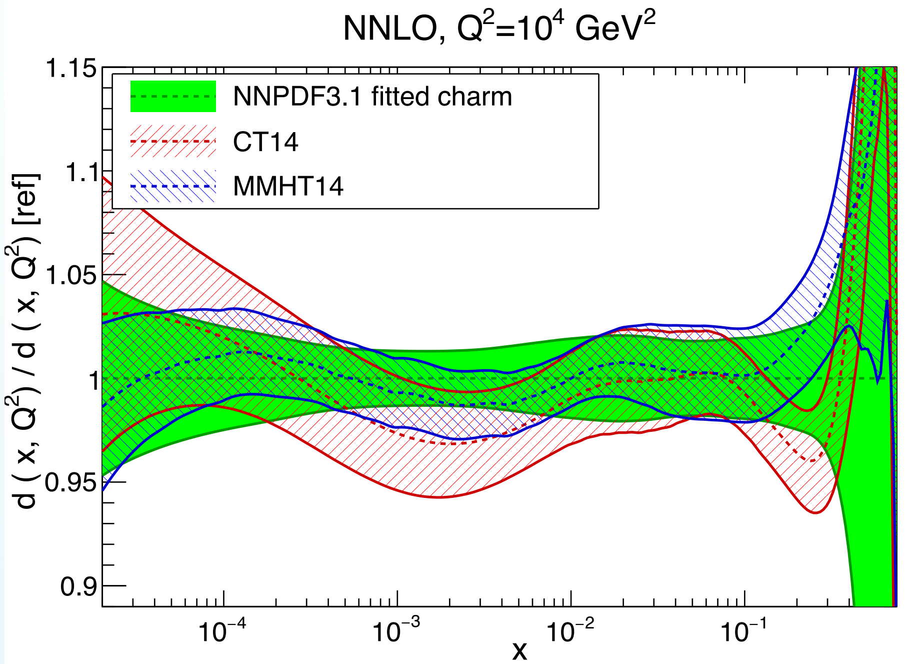


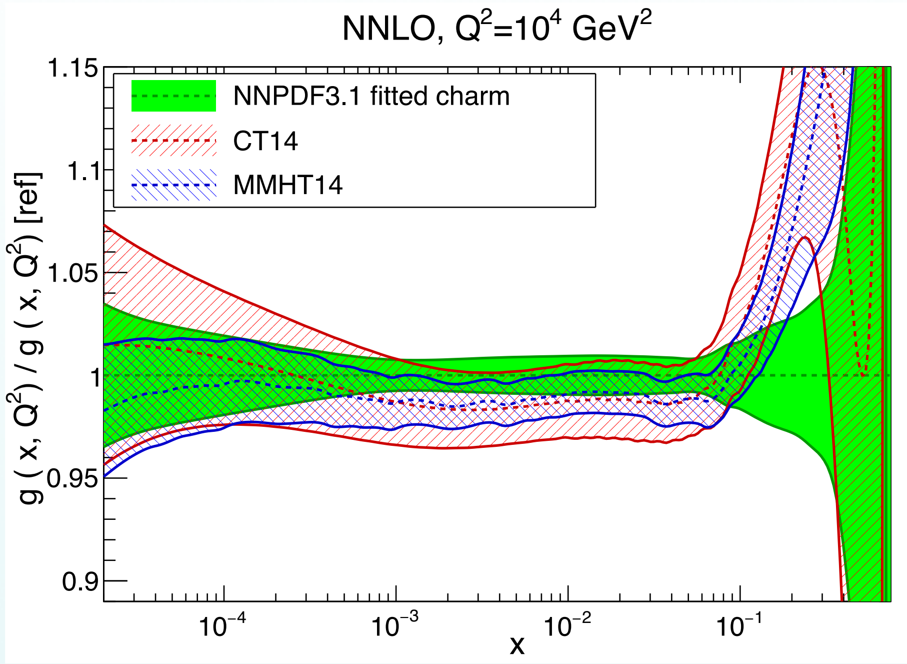


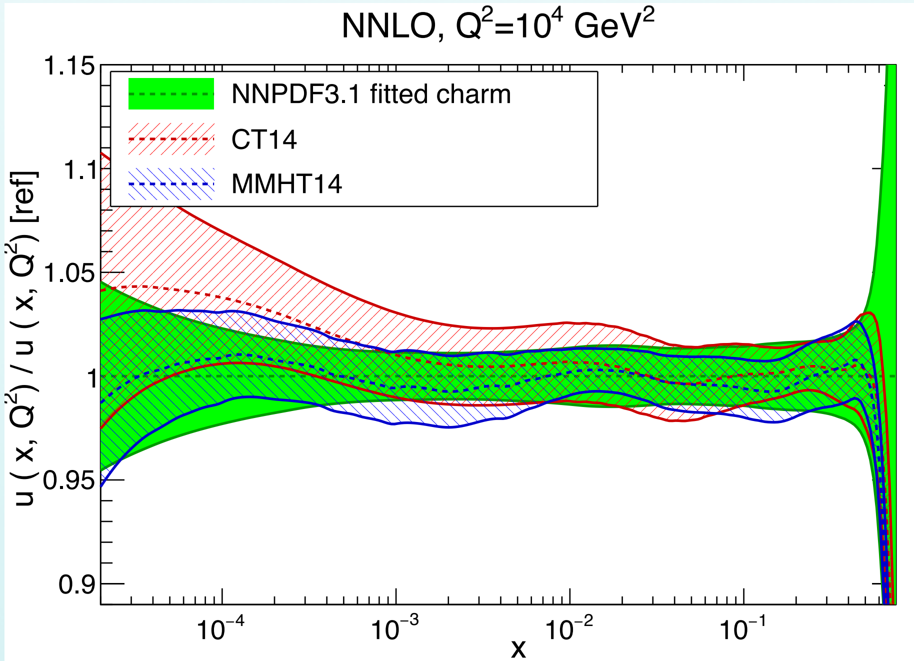


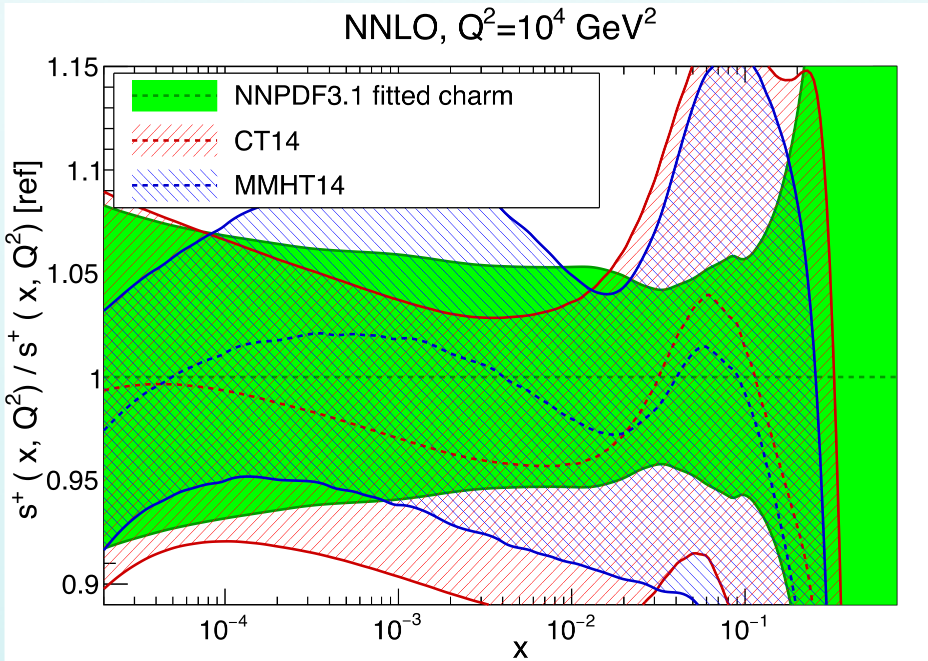
- Differences between the 3.1NNLO fits with perturbative or fitted charm are moderate, at the one-sigma level at most, but **not negligible for precision physics**
- In general the **fit quality using fitted charm is better** than with perturbative charm
- All the released NNPDF3.1 sets will include variants with **both options** concerning the treatment of the charm PDF

Comparison with MMHT and CT

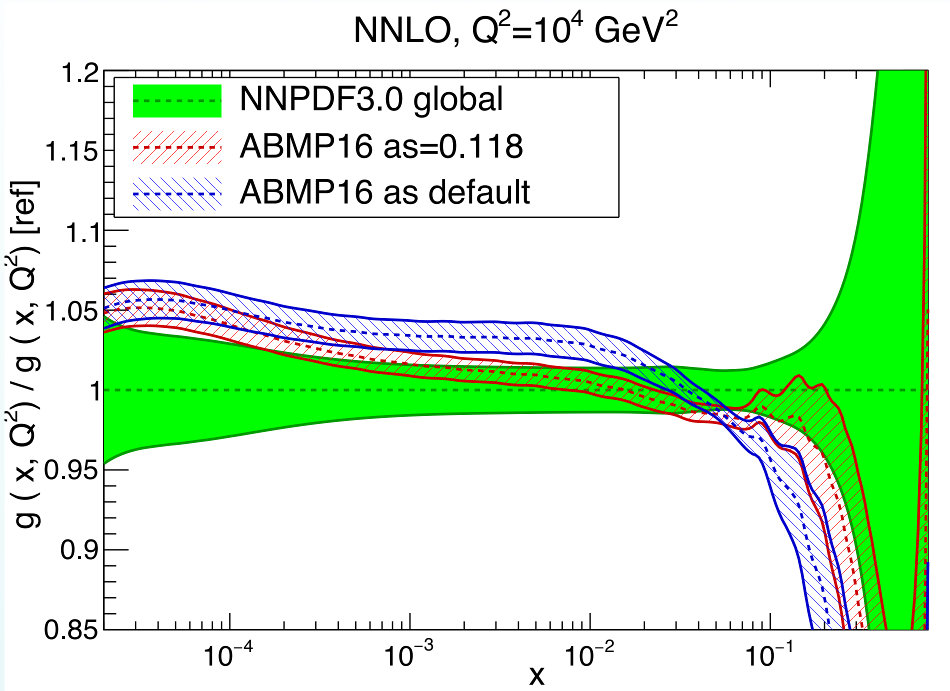


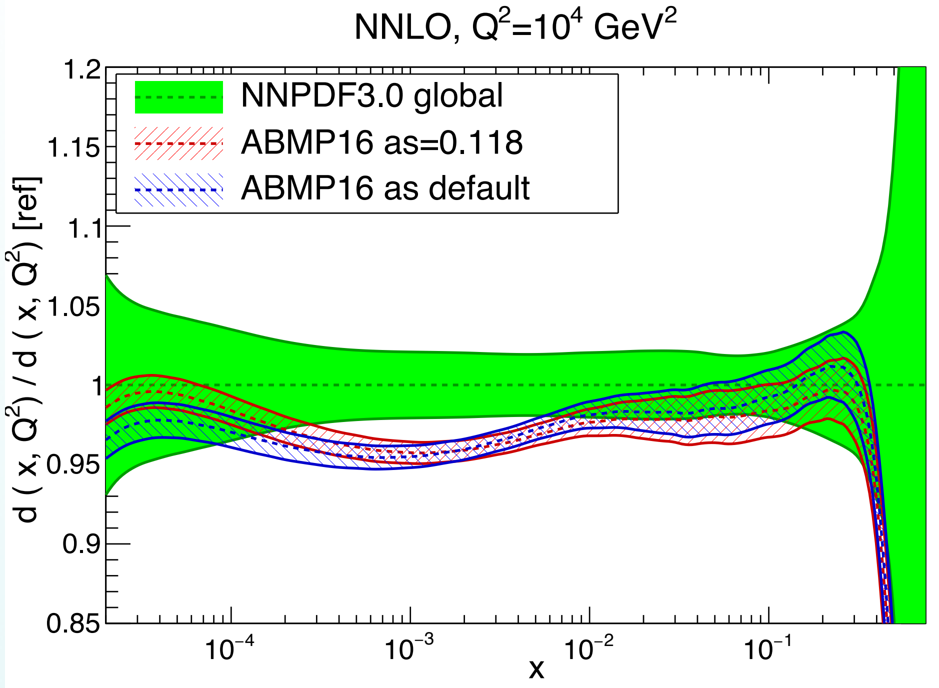


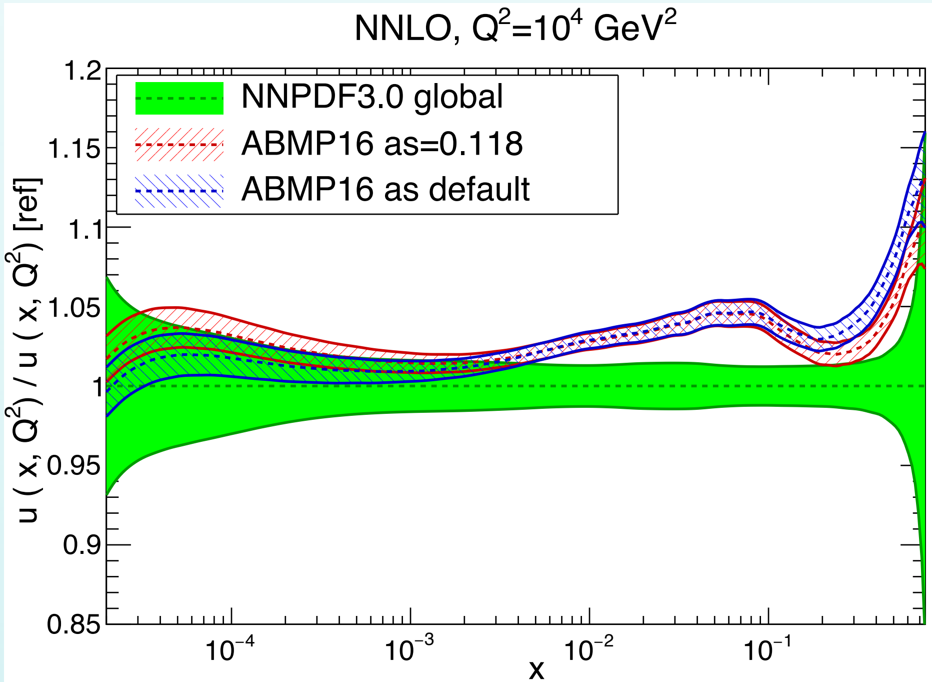


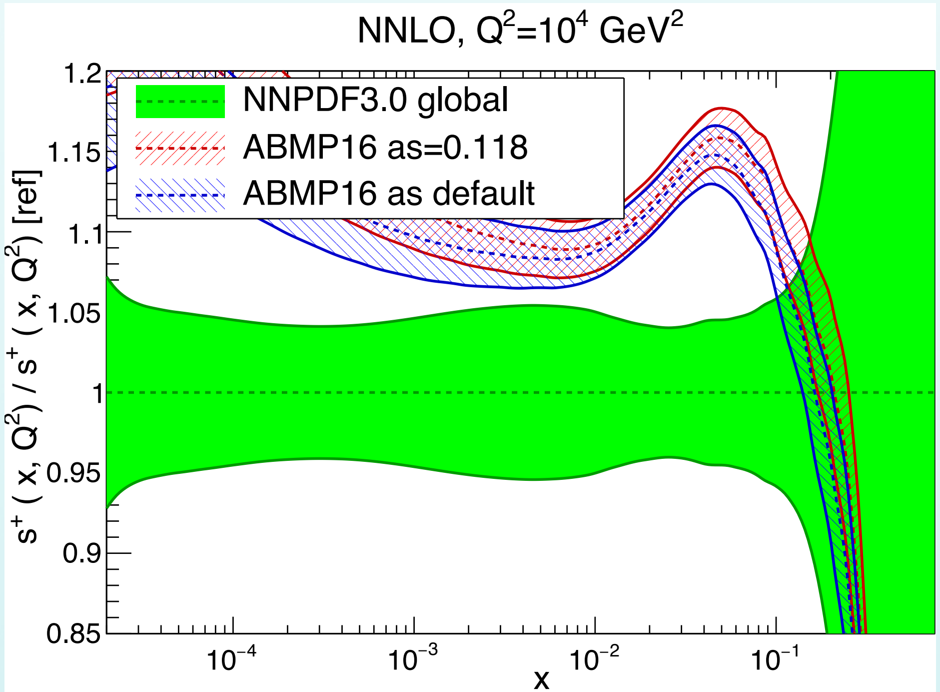


Comparison with ABMP16

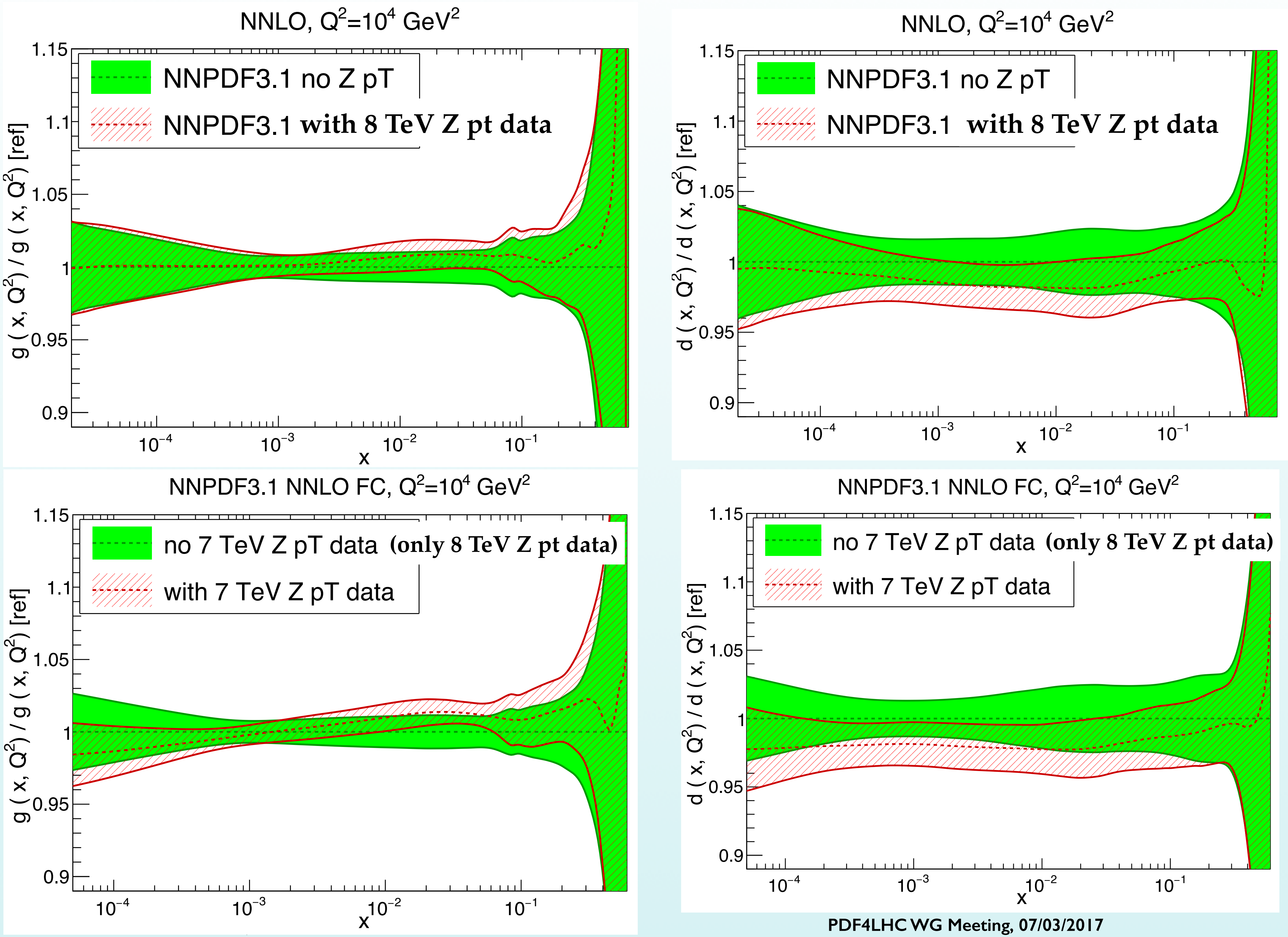




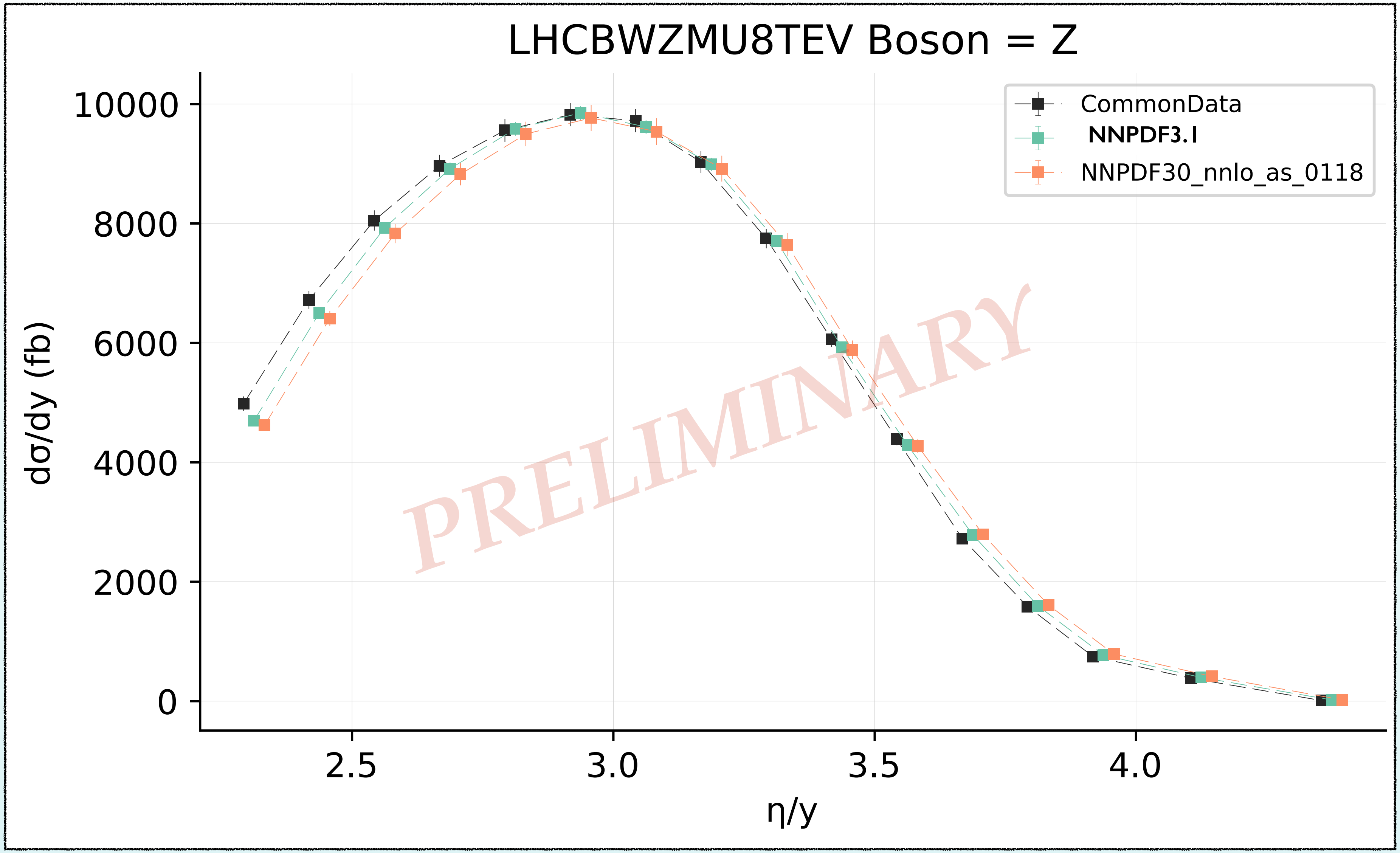




Impact of ATLAS 7 TeV Z p_T data



Forward W,Z production at LHCb

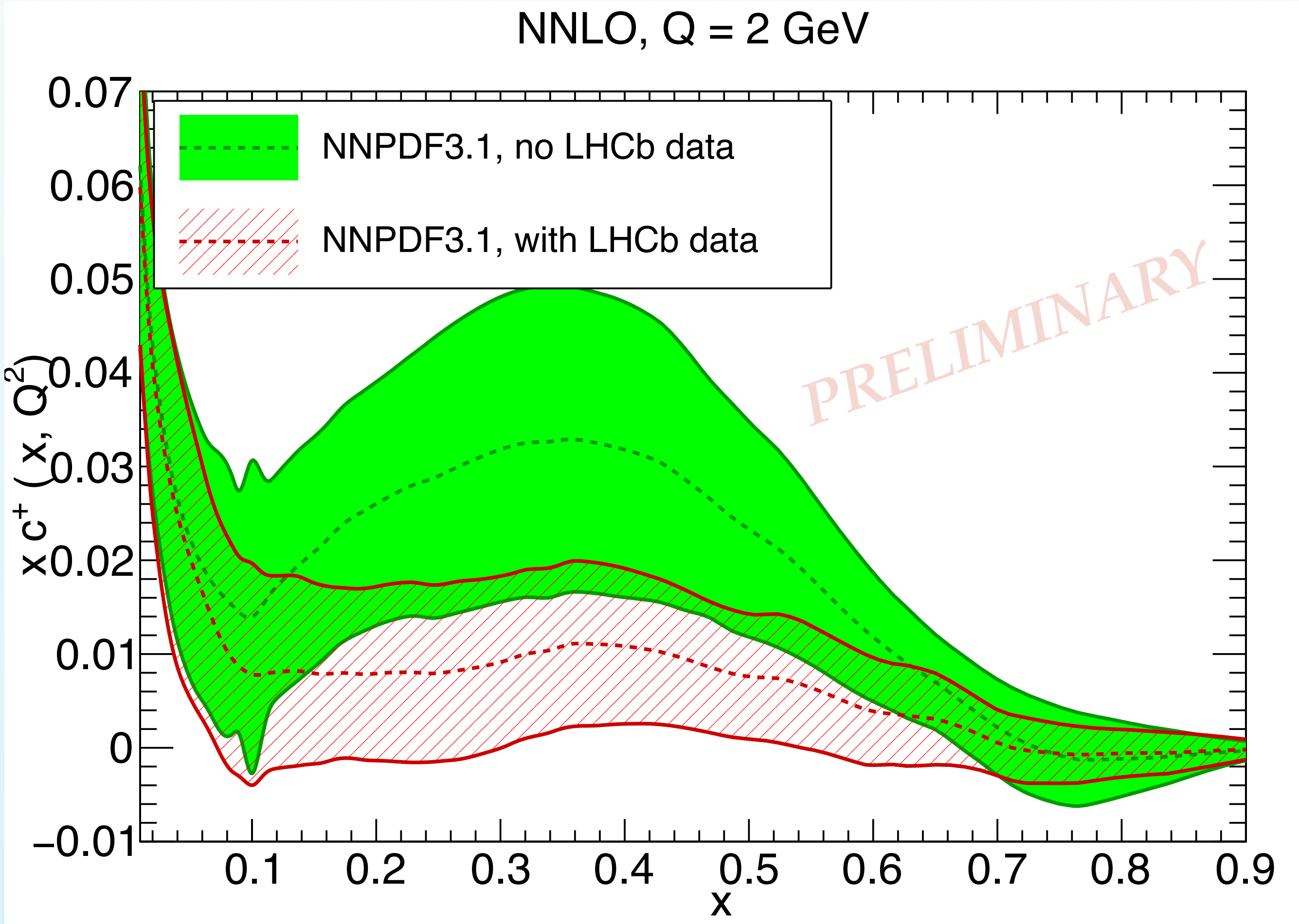


- For Z production, also improved **shape agreement** in NNPDF3.1
- Overall fit quality for LHCb experiments: **χ^2/N = 1.4 (1.9) at NNLO (NLO**). Note NNLO crucial!

Charm content of proton revisited

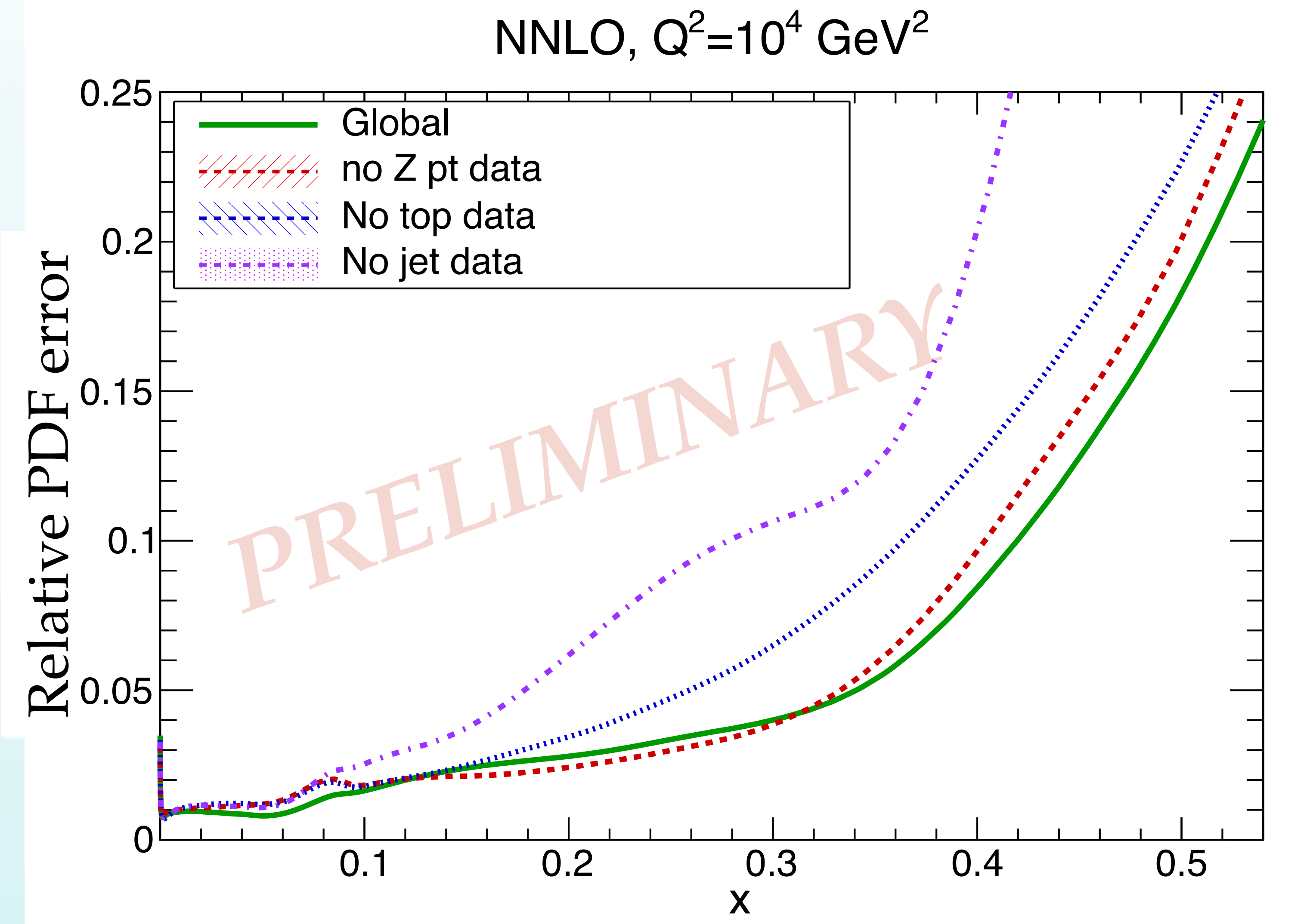
- The **new collider measurements** provide important constraints on the **large-x charm PDF**, for instance, the 7 and 8 TeV W,Z measurements from LHCb

- Models where non-perturbative charm can carry **much more than 1% of the total proton's momentum** are strongly disfavoured by the LHCb data

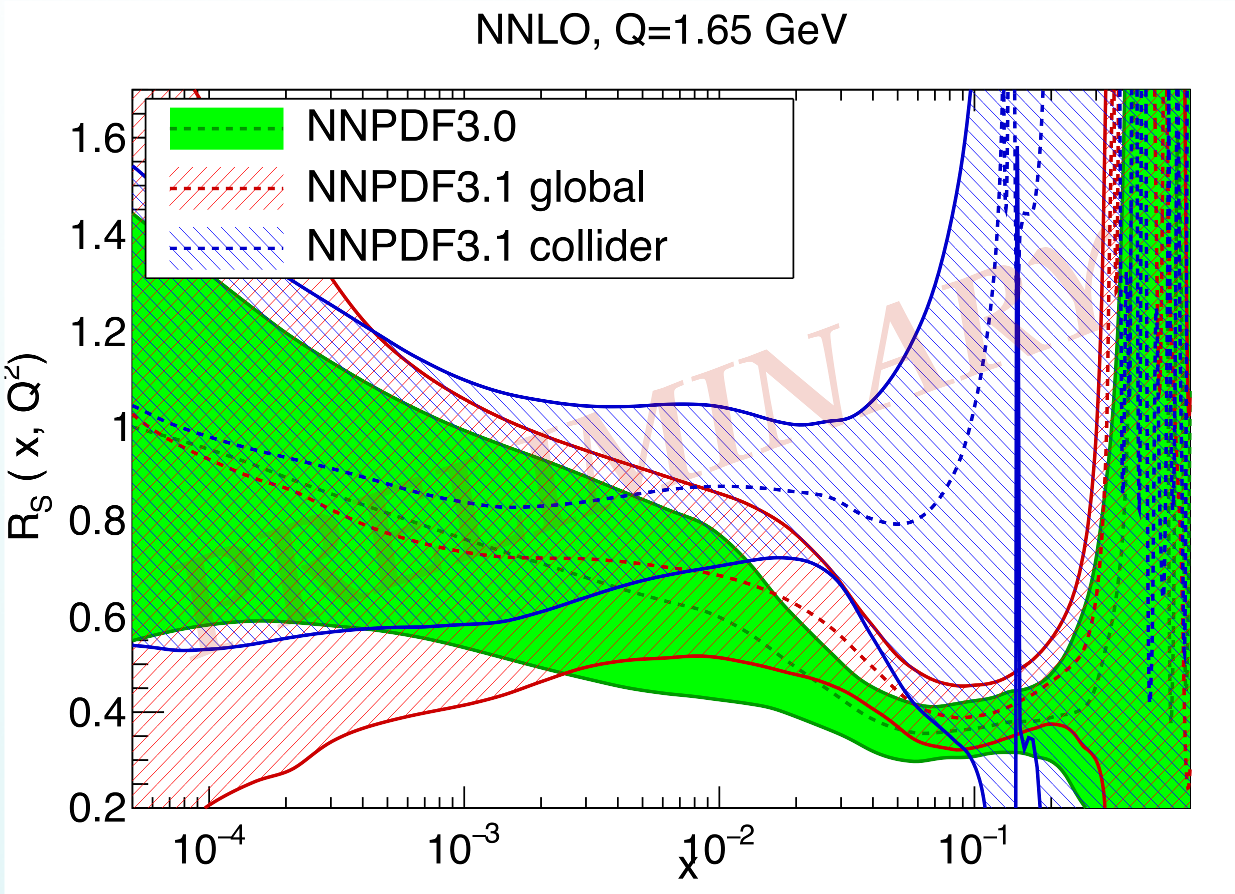


Impact on the gluon

- The **best precision in the large-x gluon** is achieved by **combining jets with top-pair and Z pt data**
- In terms of constraining power at large-x, we find the hierarchy: **jets > ttbar differential > Z pt**



The strangeness content of the proton

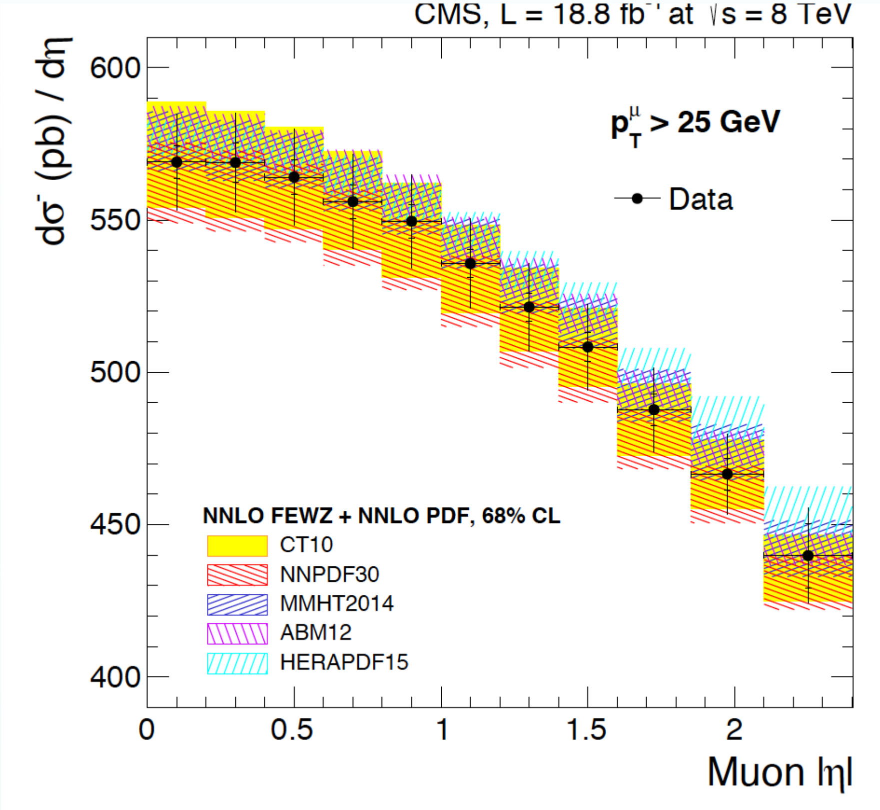


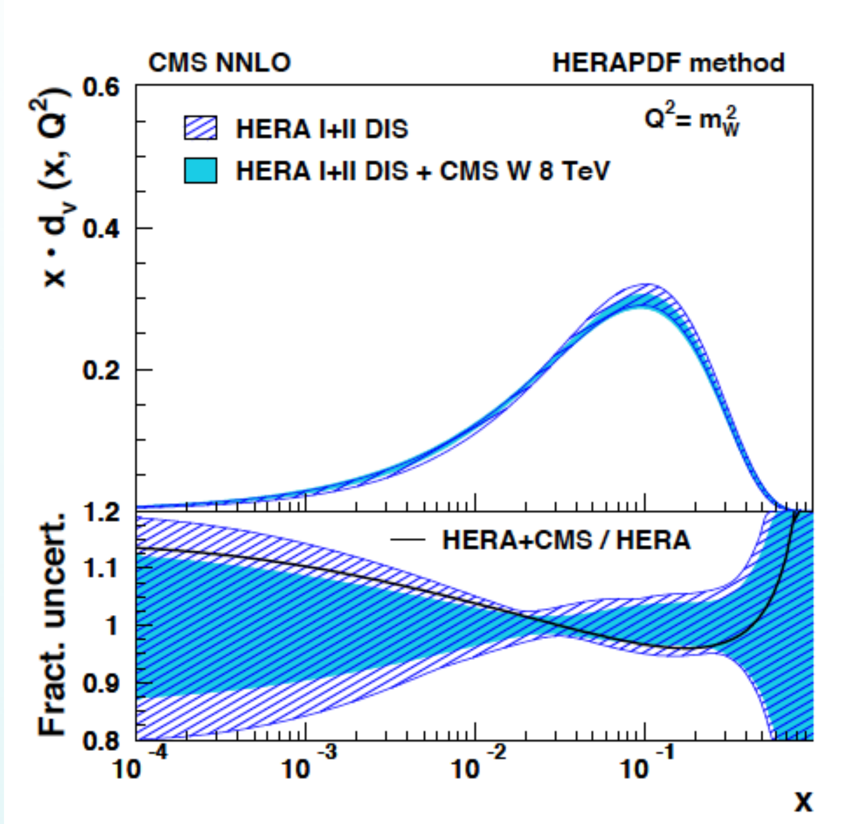
- **Collider-only and global fits** in agreement within PDF uncertainties

- In NNPDF3.1 strangeness is less suppressed than in NNPDF3.0 (mostly due to the new data) but still in agreement within PDF uncertainties

- The collider-only fit is becoming **competitive with the global fit**!

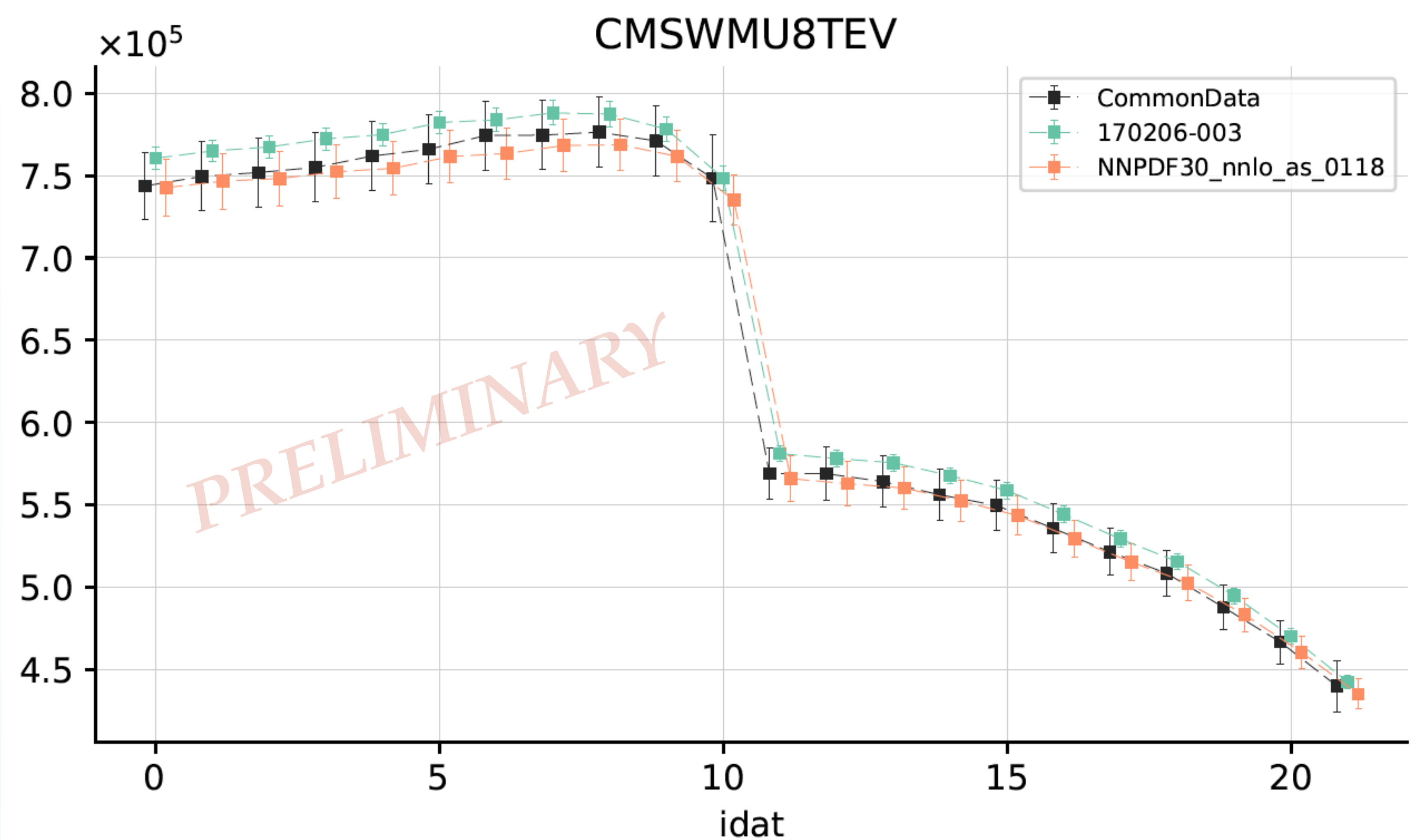
CMS 8 TeV W rapidity





- Useful for quark flavour separation
- **xFitter analysis** has demonstrated **usefulness for PDF constraints**
- This measurement was already in good agreement with NNPDF3.0

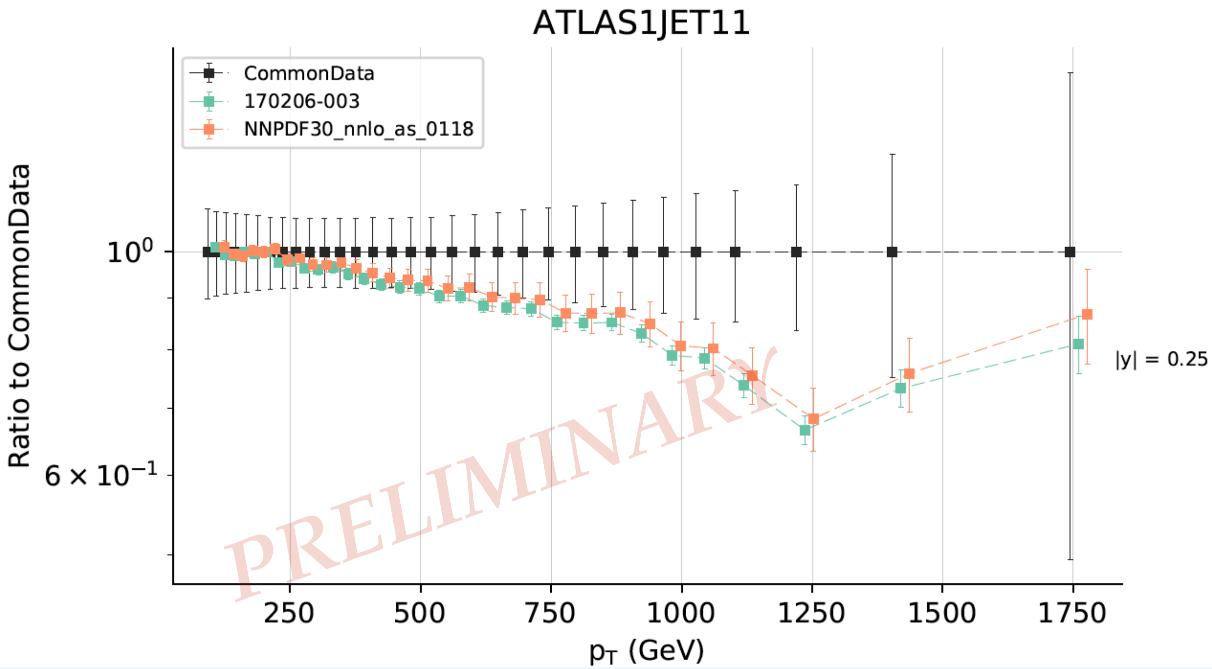
CMS 8 TeV W rapidity



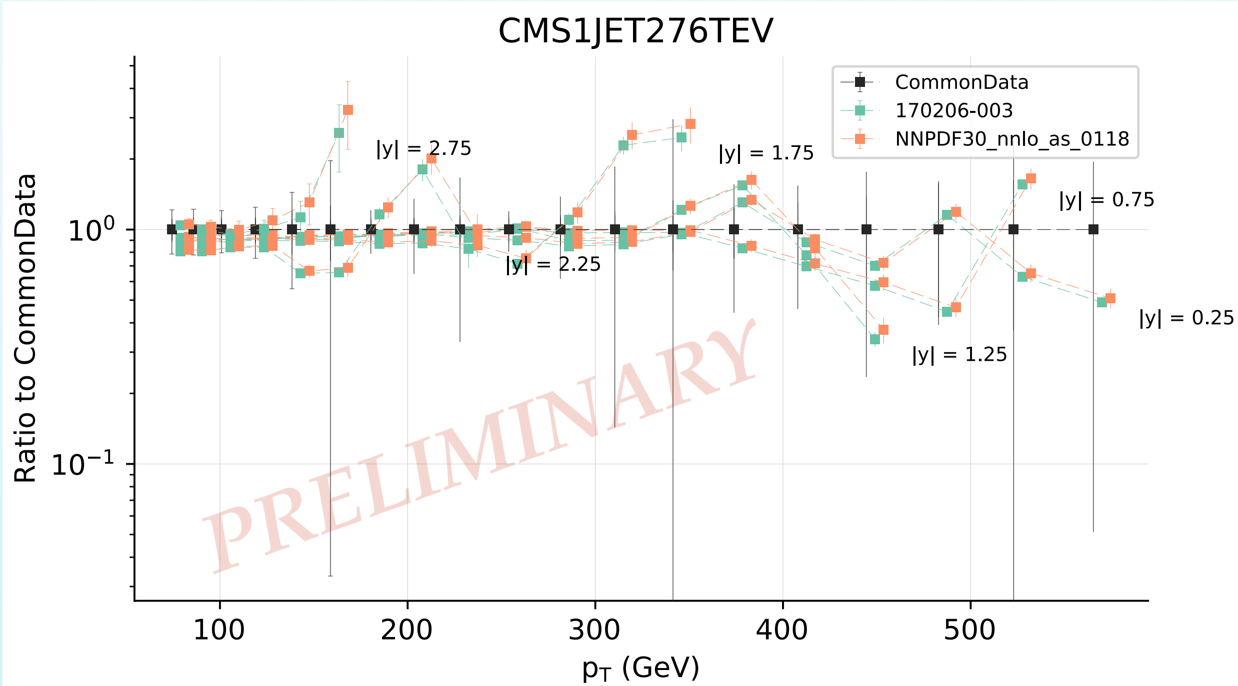
- Good agreement data / theory, similar to that in NNPDF3.0, with $\chi^2/N_{dat} = 1.0$ at NNLO

- Note **reduction of PDF uncertainties** in the cross-section predictions from all the new electroweak production data included

Inclusive jets in NNPDF3.1

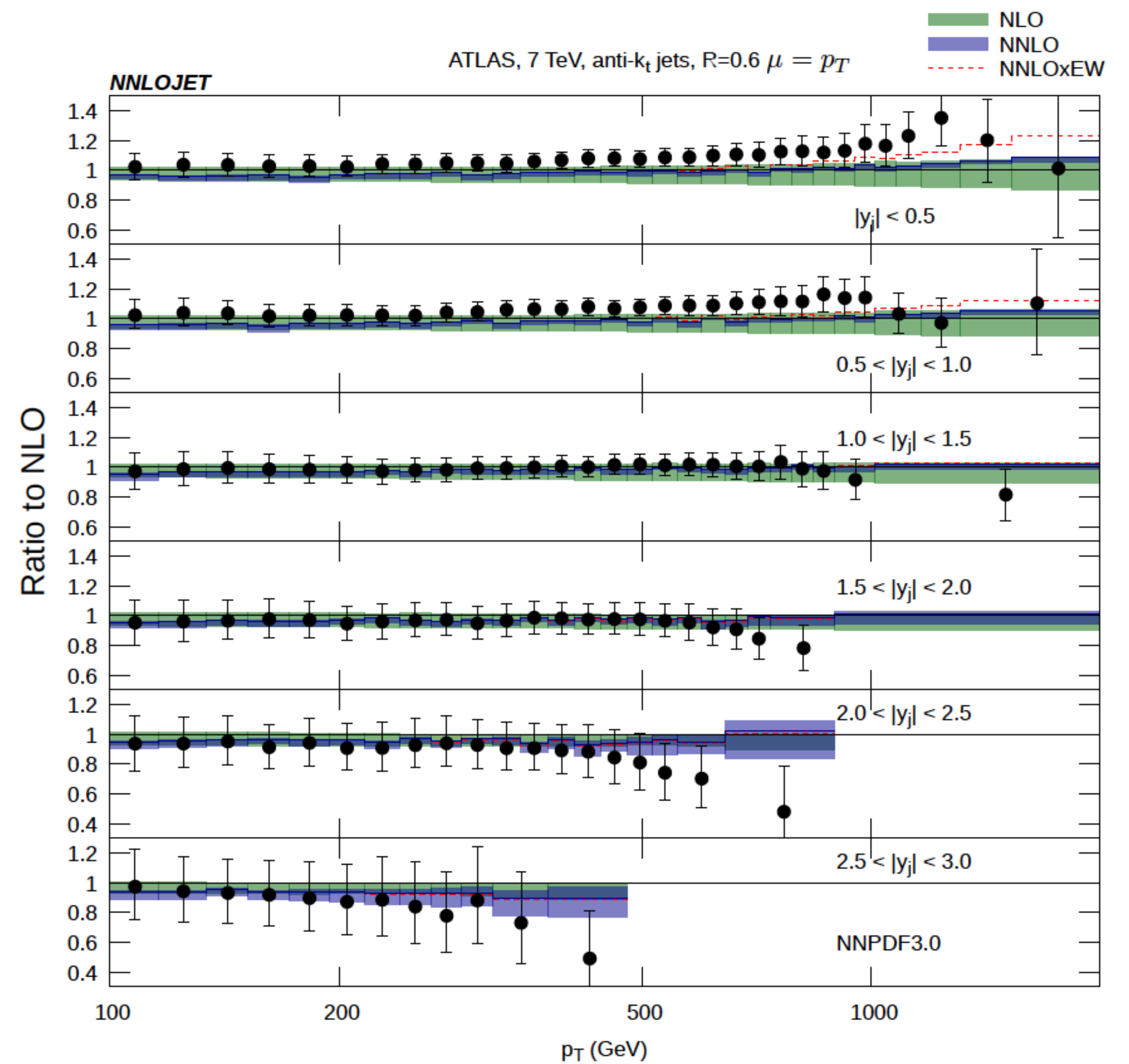


Good agreement with experimental data, as was the case in NNPDF3.0



Looking forward to the **13 TeV data!**

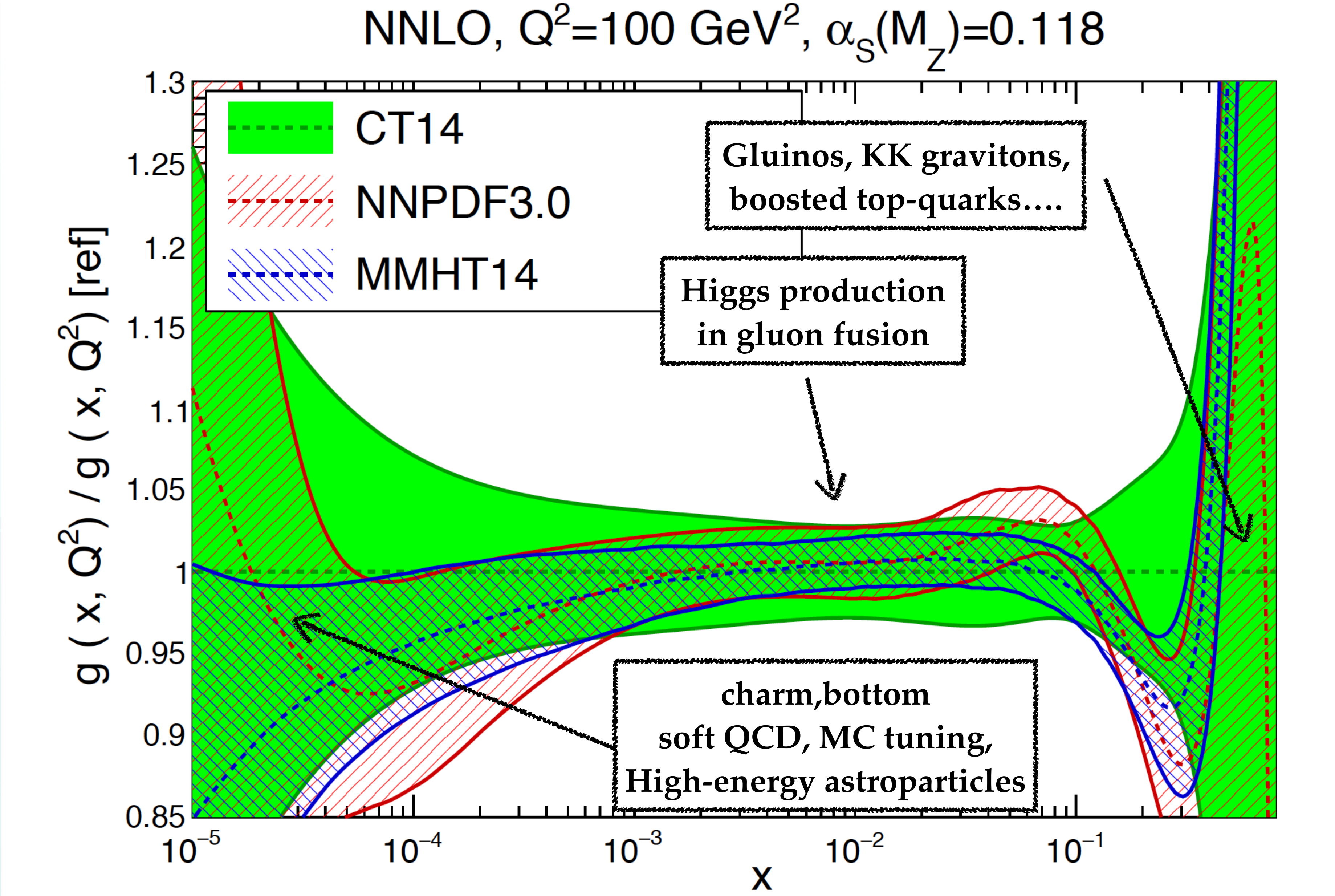
Jets at NNLO



- If the **jet pT is used as central scale**, NNLO/NLO K-factors only a few percent
- NNLO/NLO shift **within NLO scale uncertainties**
- This trend holds for **all rapidity regions**

J. Currie, Krakow 01/17

One glue to bind them all



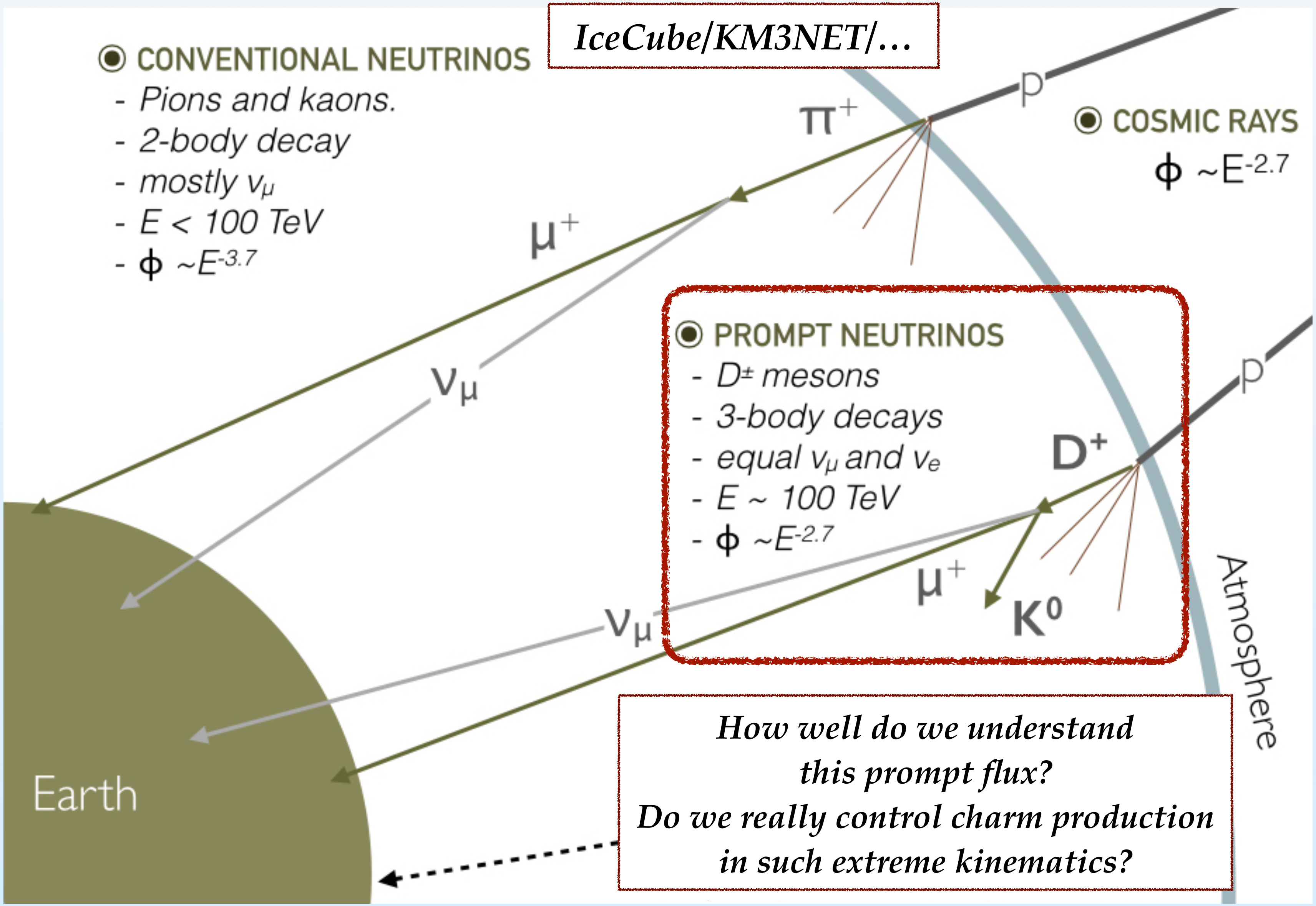
Exploit PDF-sensitive LHC measurements to **constrain the gluon at small-x!**

The prompt flux at neutrino telescopes

Observation of Ultra-High Energy (UHE) neutrino events heralds start of **Neutrino Astronomy**

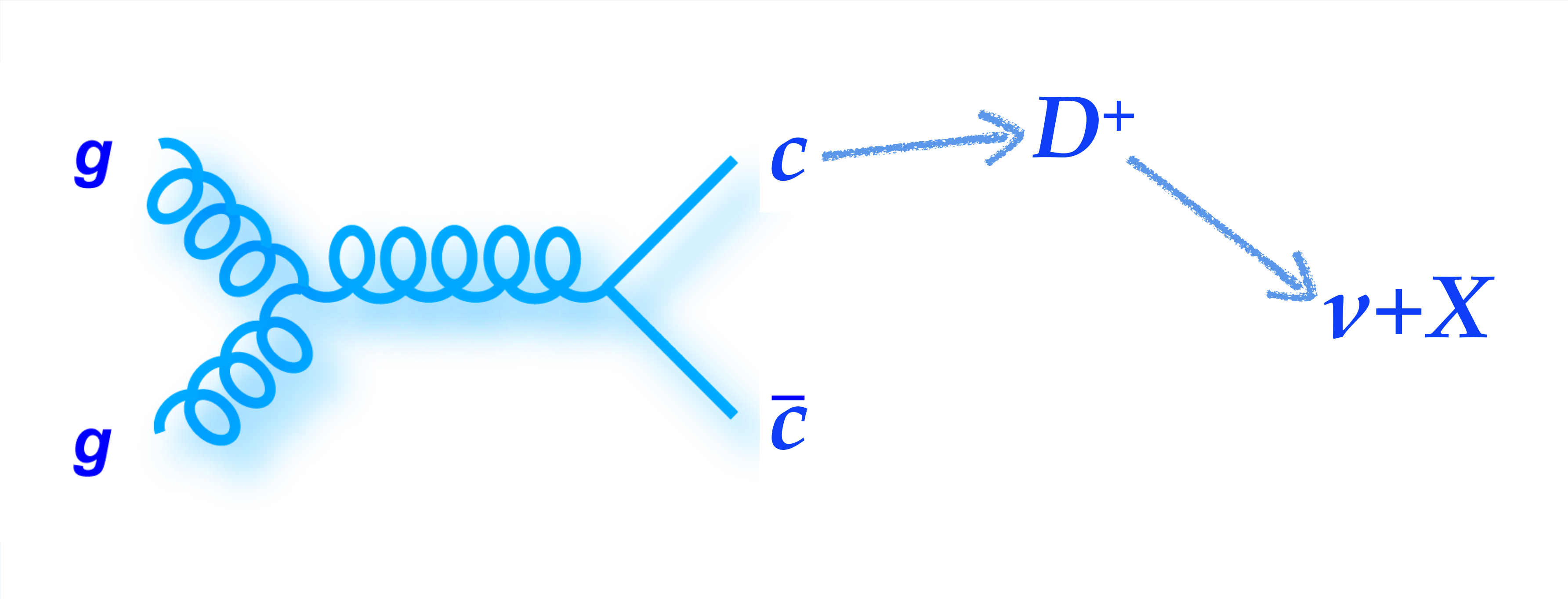
New window to the Universe, but interpretation of UHE data requires **control over backgrounds**

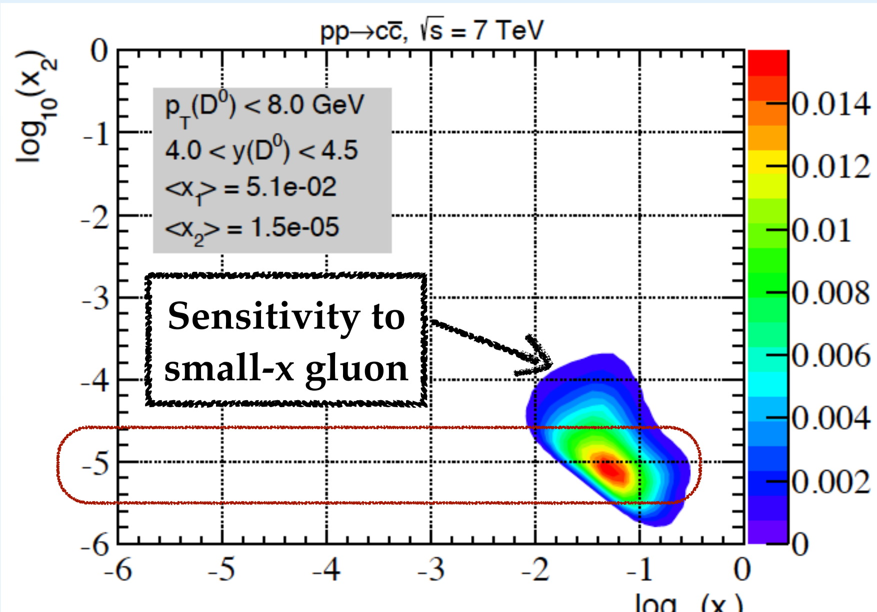
IceCube/KM3NET/…



How well do we understand this prompt flux?
Do we really control charm production in such extreme kinematics?

The low-x gluon from charm production





Lab frame $E_{lab} = (2m_p E_{CR})^{1/2}$

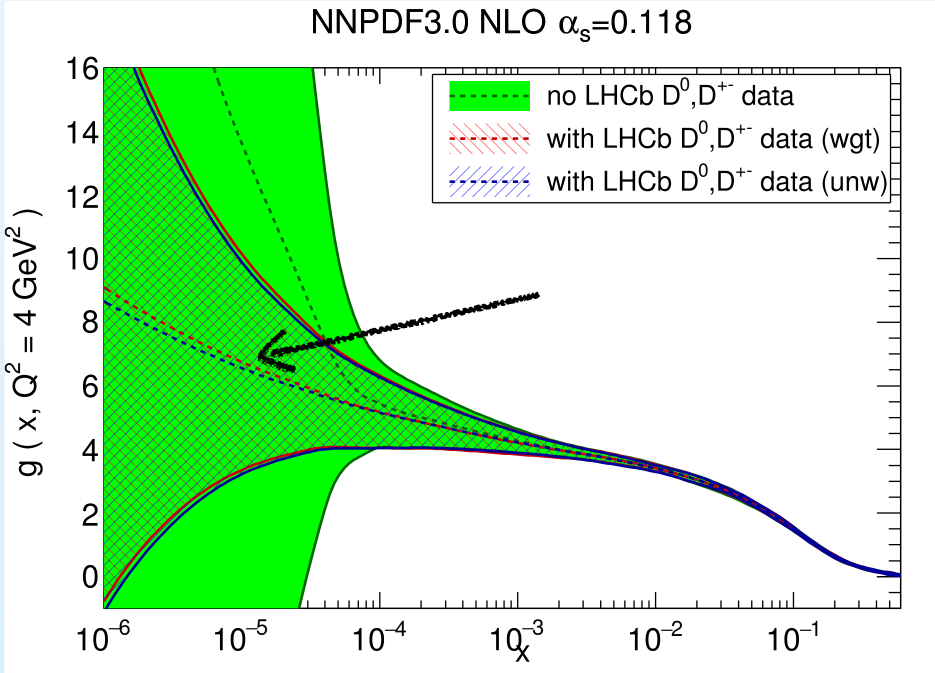
$E_{CR} = 100$ *PeV* $\longrightarrow E_{lab} \approx 14$ *TeV*

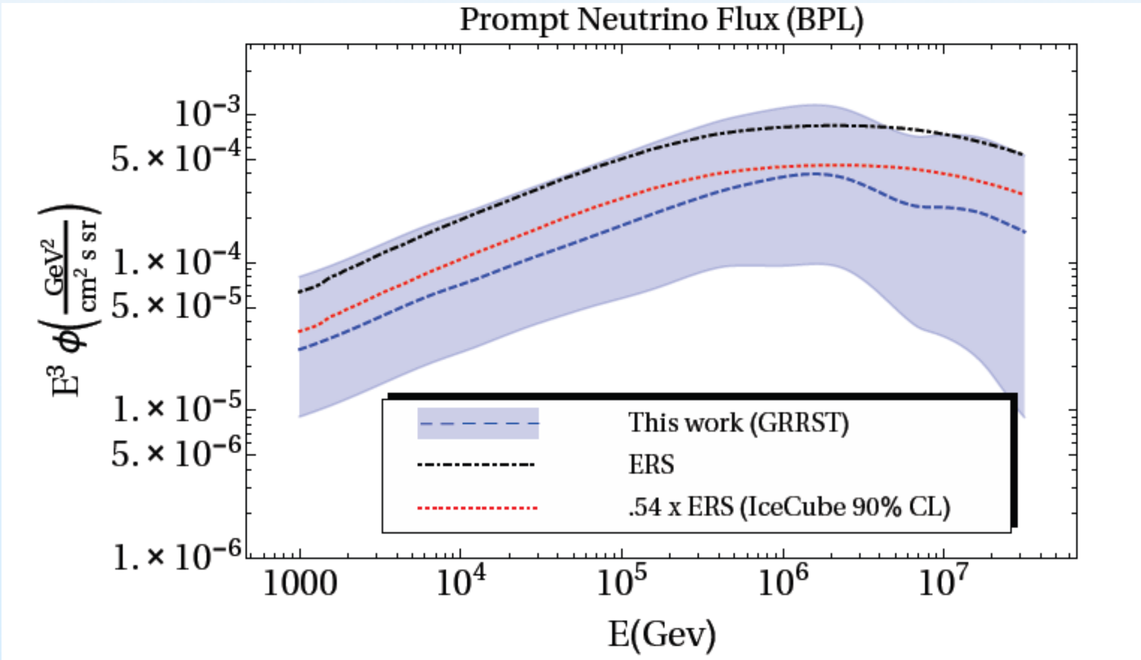
Overlap kinematics between charm production in UHE cosmic rays and at the LHC

The low-x gluon from charm production

Strategy: use **LHC data** to provide state-of-the-art **predictions for backgrounds at neutrino telescopes**

- ☑ Include **7 TeV LHCb forward charm production data** in the global fit
- ☑ Validate **perturbative QCD calculations** on collider data, and **constrain the small-x gluon**
- ☑ Compute optimised predictions for **prompt neutrino fluxes at high energies**





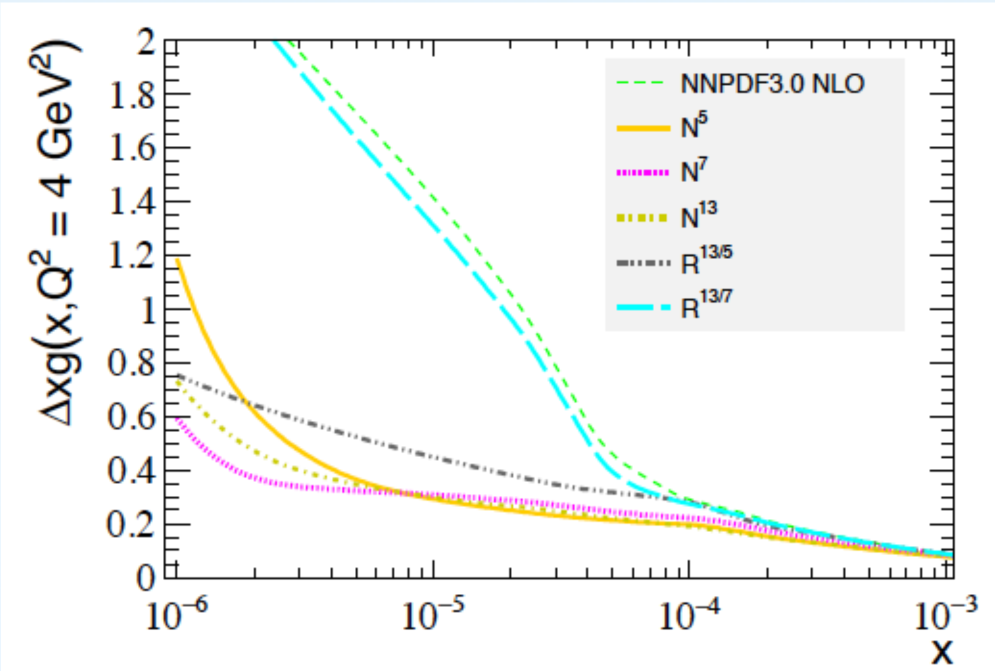
We predict that detection of the prompt neutrino flux should be within reach

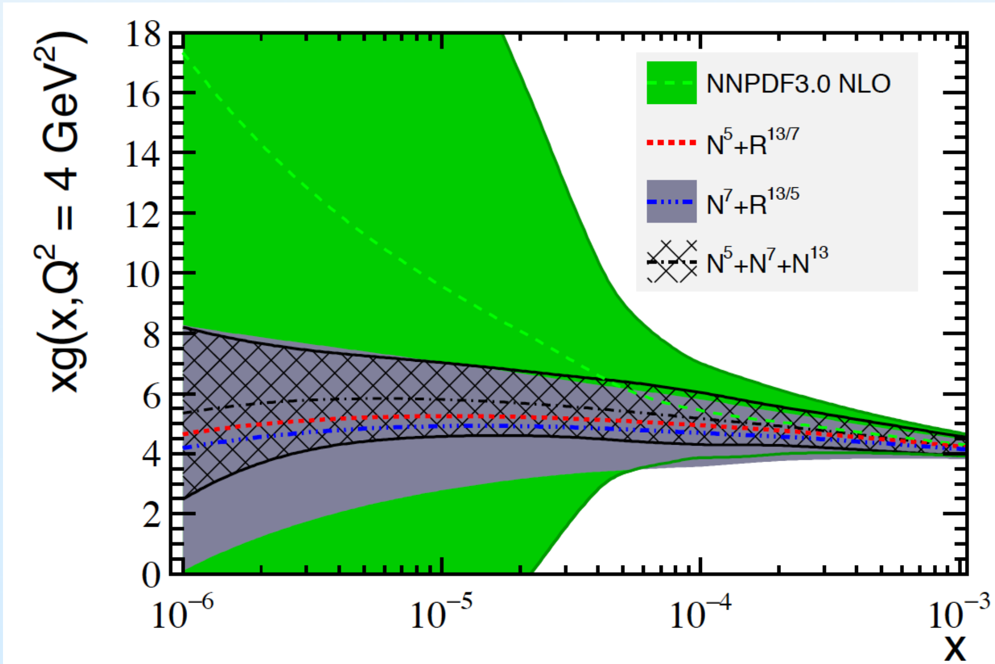
LHCb charm production from 5 to 13 TeV

- Updated analysis based on **normalized cross-sections at 5, 7 and 13 TeV** and **cross-section CoM energy ratios** (avoiding double counting)
- Good description of all datasets, **compatible pull on the small-x gluon** except the R13/7 ratio
- The $N^5+N^7+N^{13}$ combination leads to a **reduction of the small-x gluon PDF errors by an order of magnitude**!
- The most precise D0 data at 5 and 13 TeV cannot be described by NLO QCD and are excluded from the fit: **NNLO calculation needed?**

$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j};$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(13\ \mathrm{TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j}$$

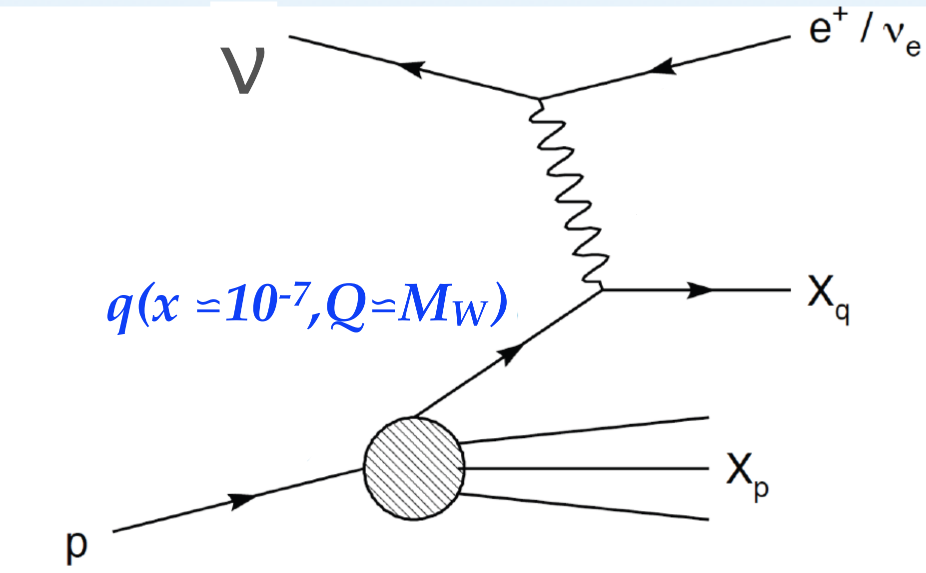


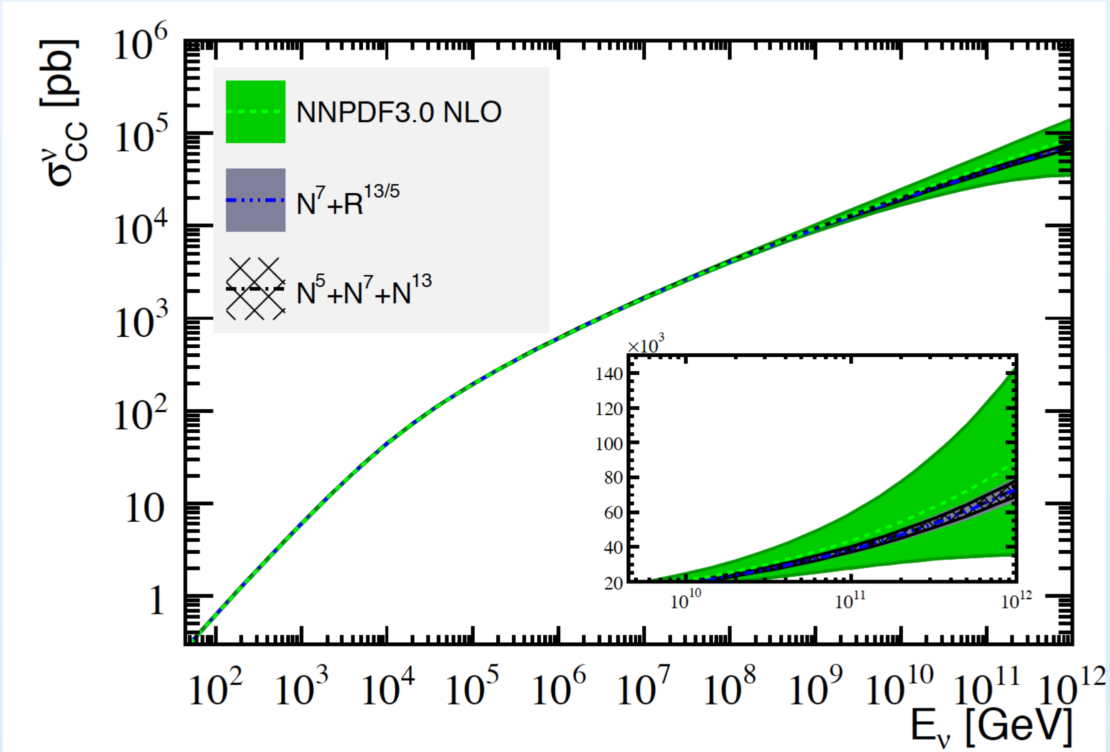


UHE neutrino-nucleus cross-sections

- High-precision QCD predictions of **neutrino-nucleus cross-section up to 10^6 PeV** (low-x sea quarks driven by gluon through DGLAP evolution)

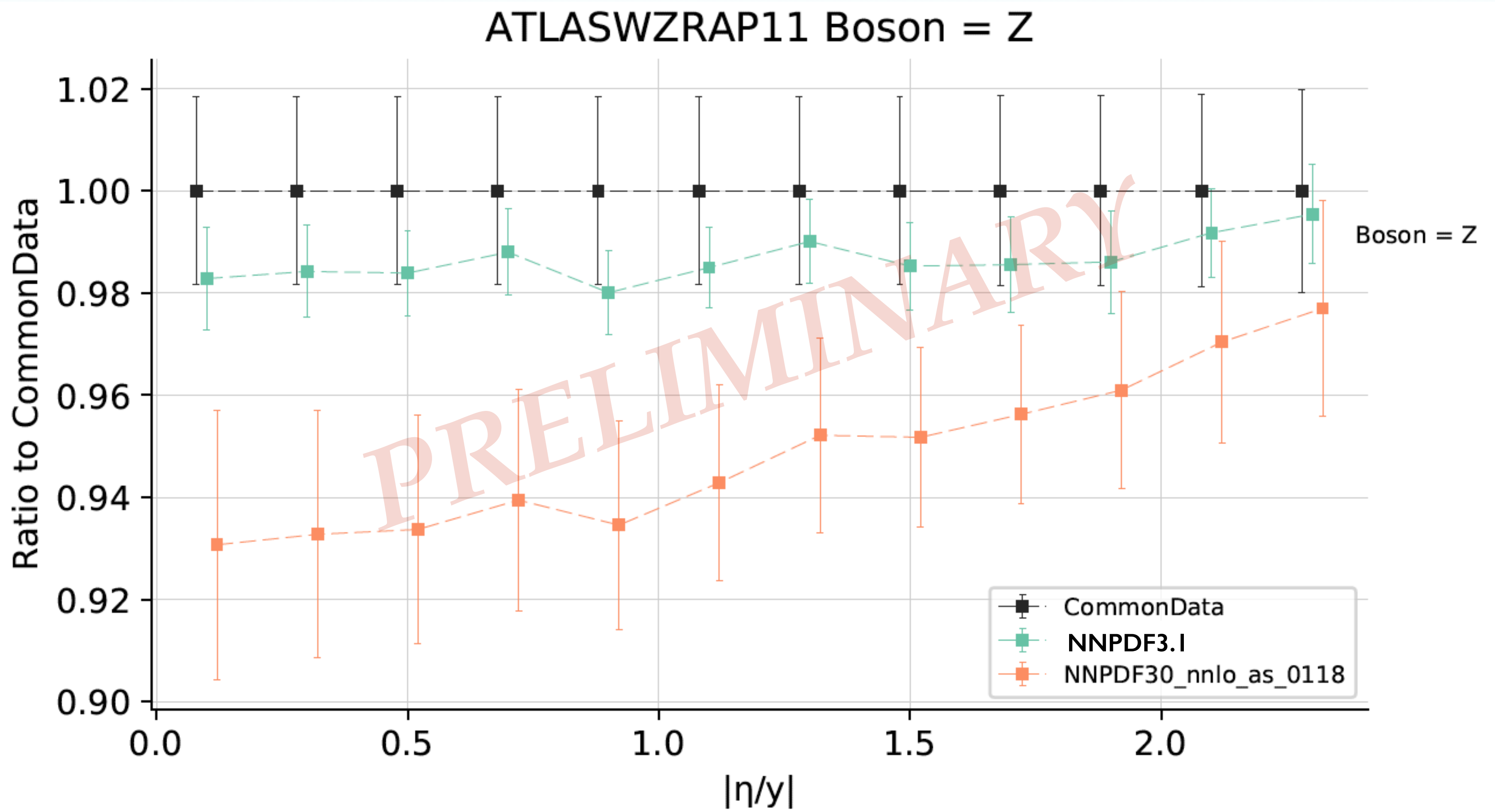
- **Few-percent QCD uncertainties in the UHE cross-sections up to the highest energies**: unique opportunity for BSM searches and precision astrophysical studies





Precision studies of **extreme QCD** with **IceCube/KM3NET: the ultimate DIS experiments!**

The strangeness content of the proton



Significant improvement in description of the experimental data in NNPDF3.1 as compared to 3.0