Parton Distributions and Lattice Calculations: Towards a wishlist and accuracy targets

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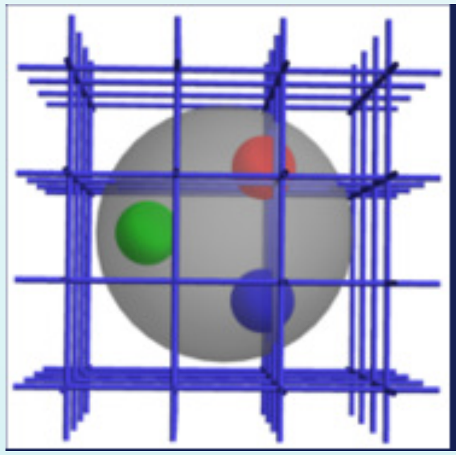
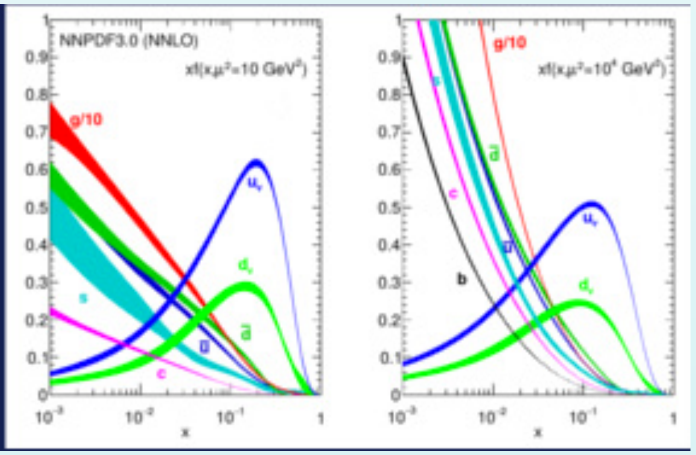




What could/should lattice QCD compute?

- Some PDF combinations and related physical observables are known with *very high precision,* also with reasonable agreement between various PDF groups: **Benchmarks**
  - *Non-singlet first and second moments*
  - *Valence quarks at large-x*
  - *DGLAP evolution*

- Some PDF combinations and related physical observables are known with *rather less precision*, and sizeable differences between PDF groups, lattice QCD could have an impact here: **Opportunities**
  - *Large-x PDFs, specially gluons and antiquarks*
  - *High-mass BSM particle production: SUSY, dark matter, Z'*
  - *The strange and charm content of the proton*
  - *Quark-flavor separation*

Benchmark I

Valence quarks at large-x relatively well known from fixed-target DIS experiments

$$\int_0^1 dx\, x\, \left(u(x,Q^2) - d(x,Q^2)\right)$$

Q = 5 GeV	Central Value	PDF error	Shift From Ref
NNPDF3.0	**0,136**	**2.4%**	**-**
CT14	**0,140**	**3.4%**	**+2.5%**
MMHT14	**0,134**	**2.6%**	**-1.5%**
ABMP16	**0,150**	**1.9%**	**+10%**

NNPDF3.0, CT14 and MMHT14 **agree within 4%**

A lattice calculation with O(5%) precision would help to disentangle between PDF sets

Benchmark I

Valence quarks at large-x relatively well known from fixed-target DIS experiments

$$\int_0^1 dx\, x\, \left(u(x,Q^2) - d(x,Q^2)\right)$$

Q = 100 GeV	Central Value	PDF error	Shift From Ref
NNPDF3.0	**0,102**	**2.4%**	**-**
CT14	**0,104**	**3.2%**	**+2.4%**
MMHT14	**0,101**	**2.6%**	**-1.5%**
ABMP16	**0,113**	**1.9%**	**+11%**

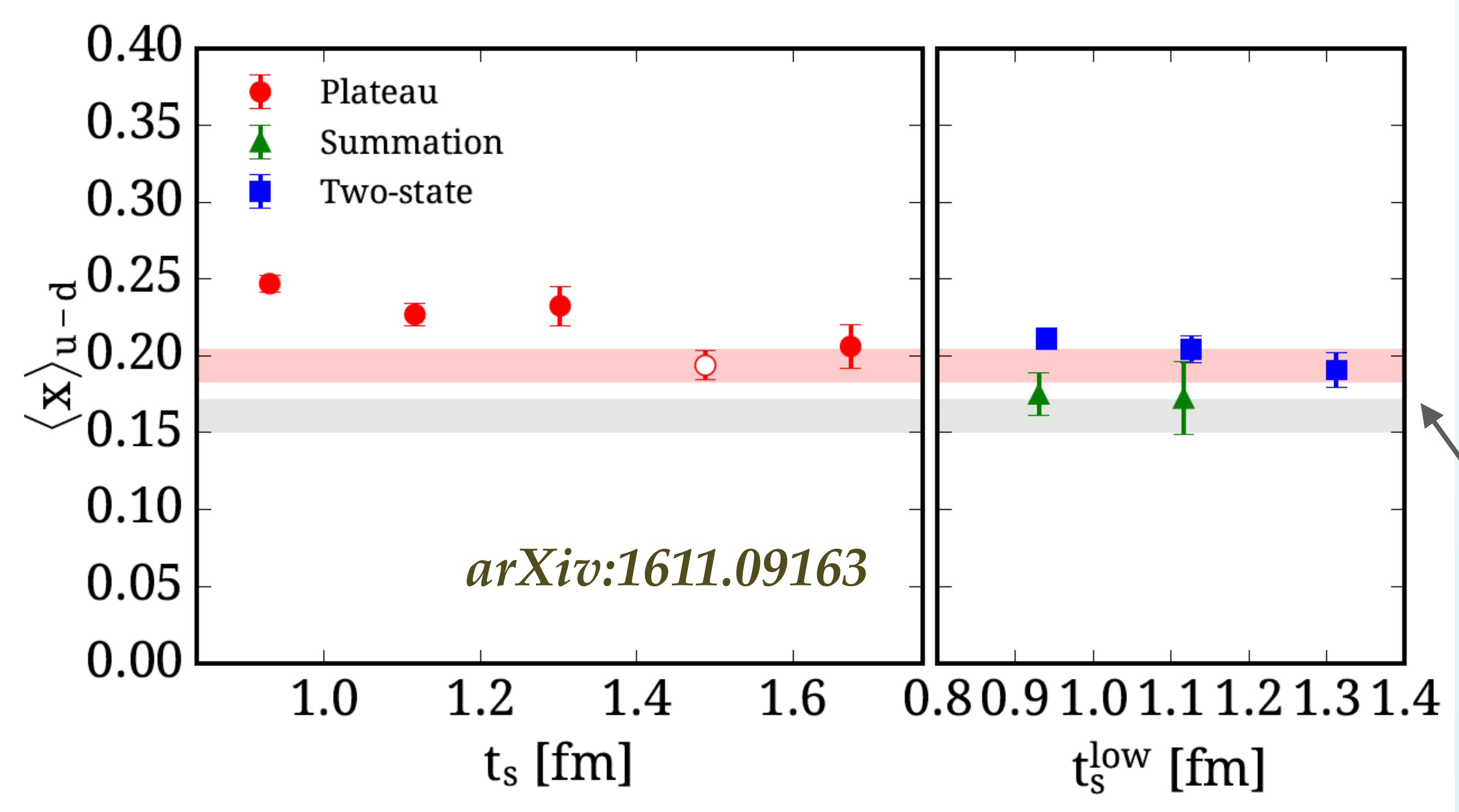
Note dependence on the value of the factorization scale

Importance of **consistent scale choices** in the PDF fit and lattice QCD calculations

Benchmark I

Valence quarks at large-x relatively well known from fixed-target DIS experiments

$$\int_0^1 dx\, x\, \left(u(x,Q^2) - d(x,Q^2)\right)$$



arXiv:1611.09163

This is not ``experiment"!
Global QCD analysis combines theory+data+statistical analysis

Lattice QCD might be getting close to the point of **discriminating between PDF sets**

Opportunity I

Sea quarks at large-x poorly known from lack of direct constraints

$$\int_0^1 dx\, x\, \left(\bar{u}(x,Q^2) - \bar{d}(x,Q^2)\right)$$

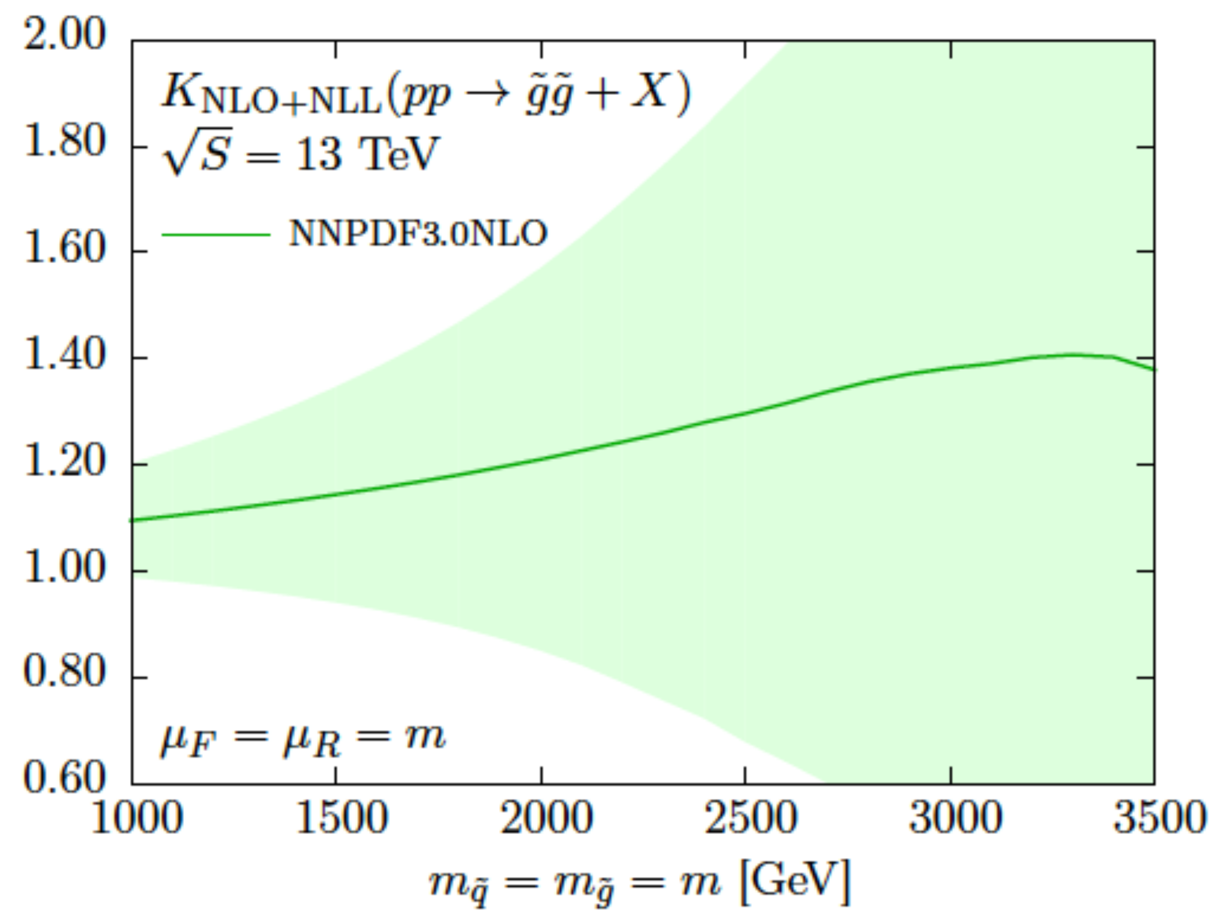
Q = 5 GeV	Central Value	PDF error	Shift From Ref
NNPDF3.0	**-0.0038**	**51%**	**-**
CT14	**-0.0055**	**25%**	**+43%**
MMHT14	**-0.0060**	**14%**	**+57%**
ABMP16	**-0.0059**	**11%**	**+54%**

Even a lattice calculation with O(20%) uncertainties would make a crucial impact on our **understanding of large-*x* sea quark PDFs**

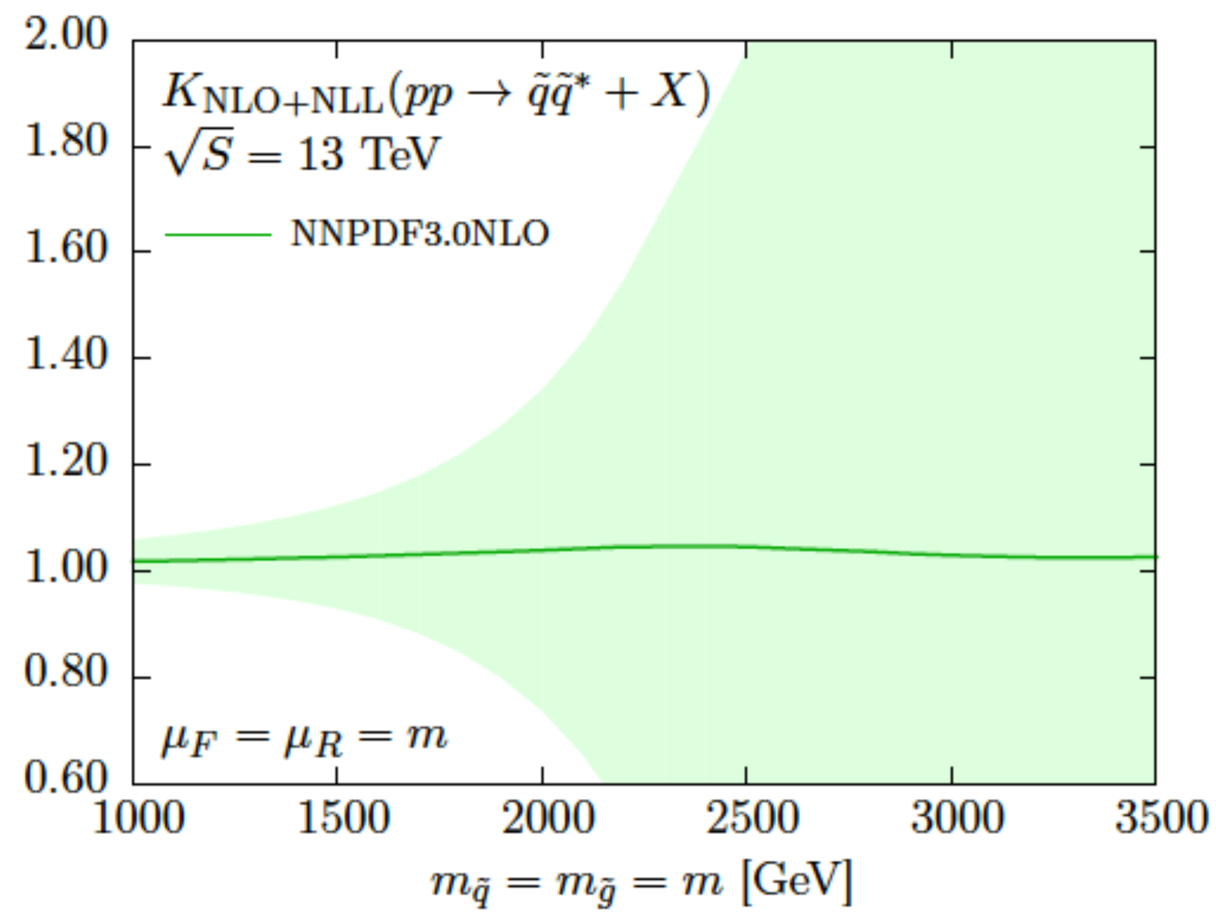
Opportunity I

Direct sensitivity to **high-mass BSM particle production**, ie, squarks, at the LHC

Beenakker, Borchensky, Kramer, Kulesza, Laenen, Marzani, Rojo 15



PDF uncertainties in gluino pair production



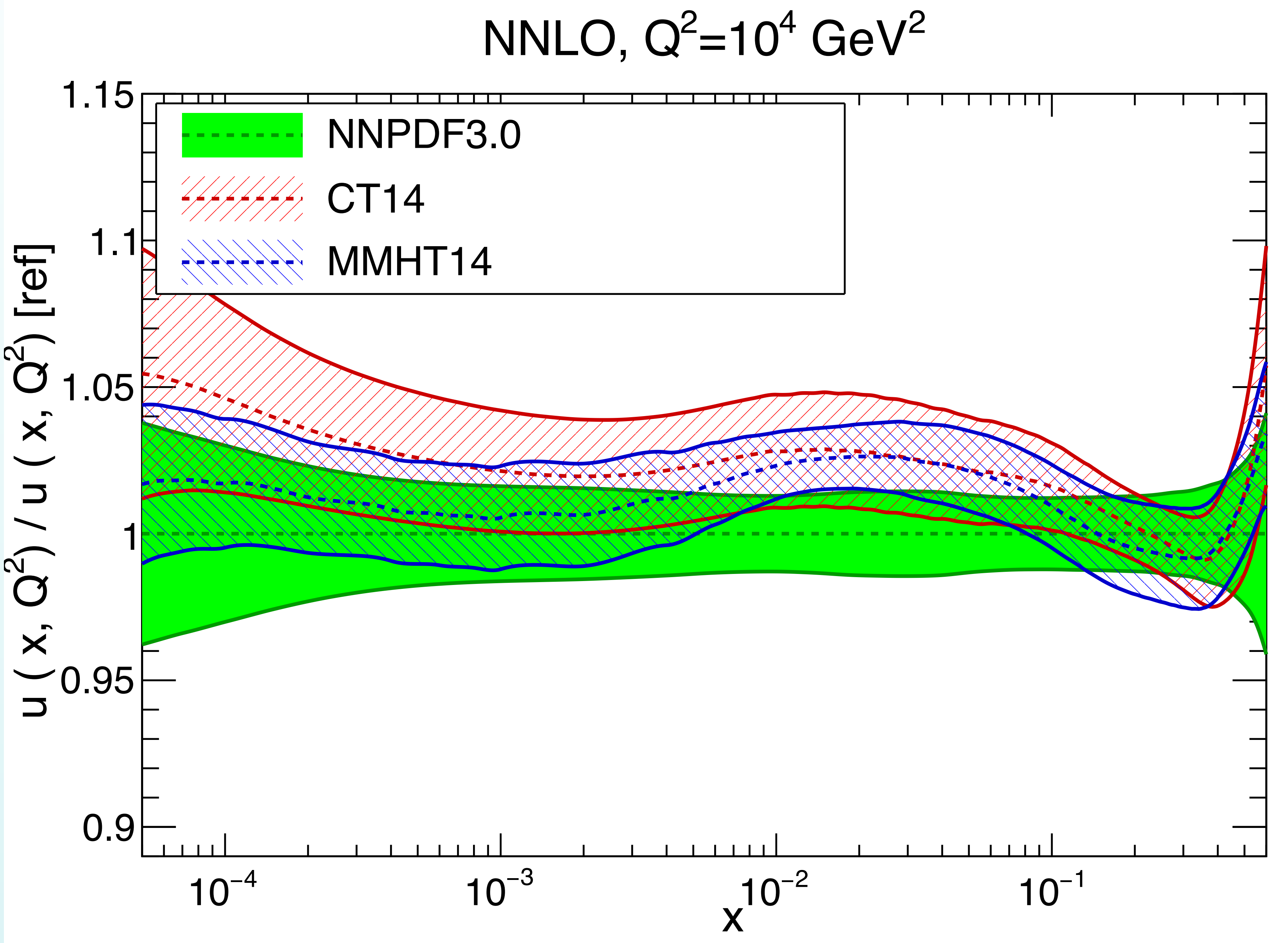
PDF uncertainties in squark pair production

Large PDF errors driven by lack of knowledge of **gluon and anti-quark PDFs at large-*x***

Possible accuracy target: *``**high-mass BSM cross-sections with few-percent PDF uncertainties**"*

Benchmark II

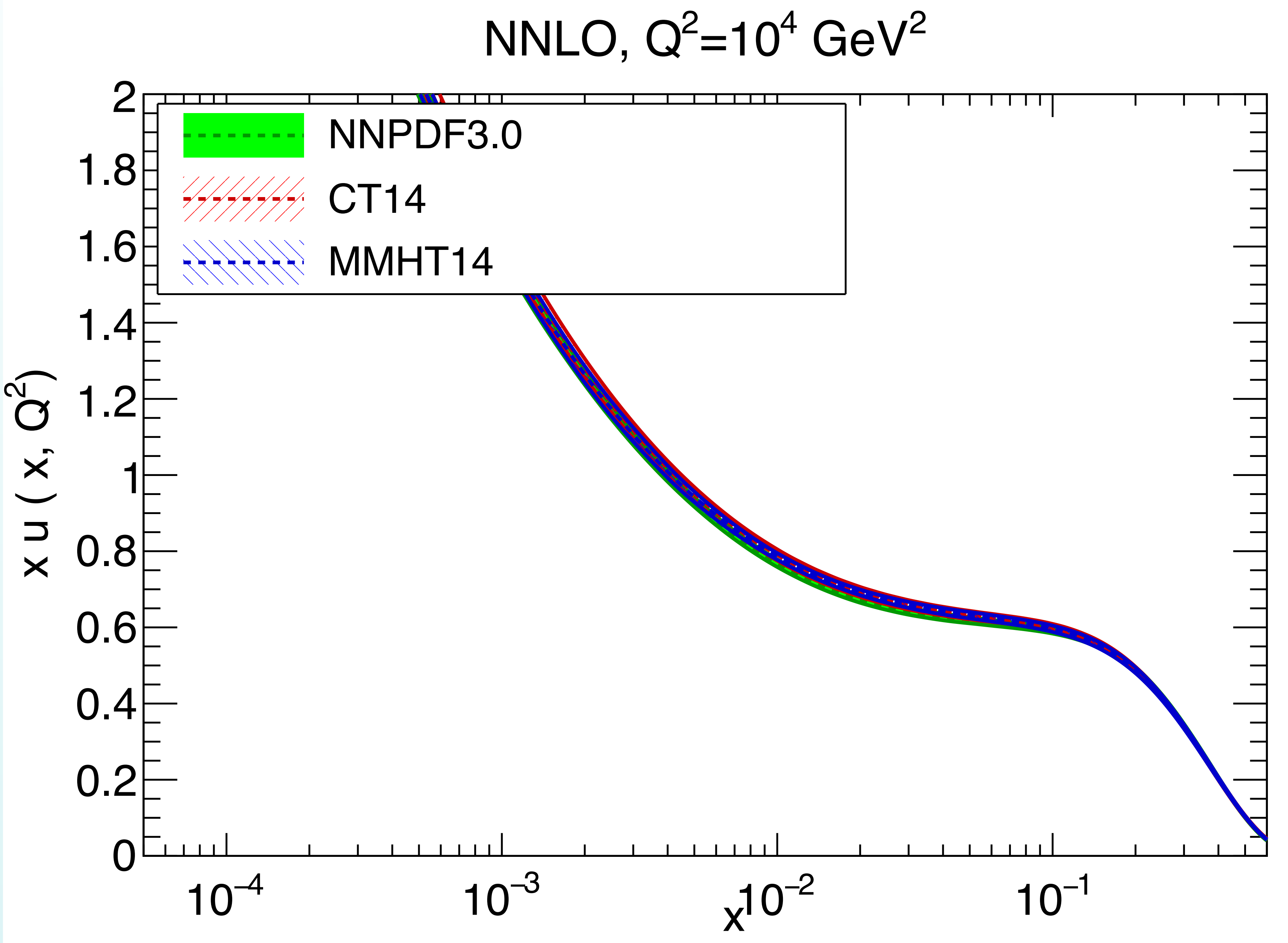
The large-*x* up quark is the most precisely known PDF



PDF uncertainties at the **few percent level** in the entire range of Bjorken x

Benchmark II

The large-*x* up quark is the most precisely known PDF



PDF uncertainties at the **few percent level** in the entire range of Bjorken x

Opportunity II

Currently some controversy about **how large is strangeness in the proton**

$$\int_0^1 dx\, x\, \left(\bar{s}(x,Q^2) + \bar{s}(x,Q^2)\right)$$

Q = 5 GeV	Central Value	PDF error	Shift From Ref
NNPDF3.1	**0,46**	**6%**	**-**
CT14	**0,43**	**18%**	**-7%**
MMHT14	**0,43**	**16%**	**-7%**
ABMP16	**0.47**	**3%**	**+2%**

Large PDF uncertainties imply that it lattice QCD could have an impact here, since experimental data with **direct strangeness sensitivity is scarce**

Opportunity II

an even better quantity to compute is ratio of strange over non-strange sea quarks

$$\frac{\int_0^1 dx\, x\, \left(\bar{s}(x,Q^2)+\bar{s}(x,Q^2)\right)}{\int_0^1 dx\, x\, \left(\bar{u}(x,Q^2)+\bar{d}(x,Q^2)\right)}$$

Q = 5 GeV	Central Value	PDF error	Shift From Ref
NNPDF3.1	**0.64**	**8%**	**-**
CT14	**0.62**	**21%**	**-3%**
MMHT14	**0.59**	**19%**	**-7%**
ABMP16	**0.66**	**4%**	**4%**

Large PDF uncertainties imply that it lattice QCD could have an impact here, since experimental data with **direct strangeness sensitivity is scarce**

Opportunity II

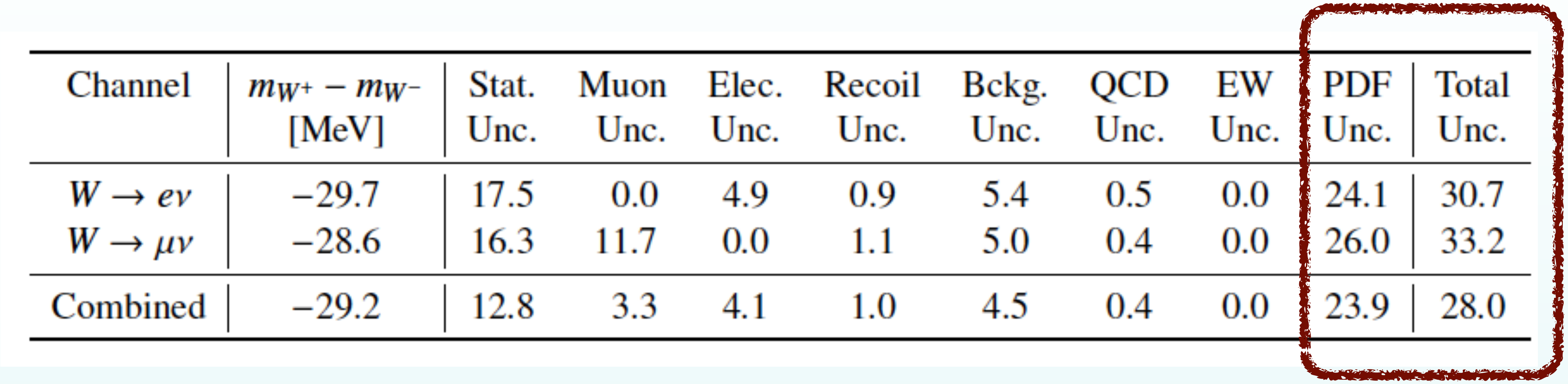
Some data sets in the global fit **strongly prefer a symmetric strange sea**

$$\frac{\int_0^1 dx\, x\ \left(\bar{s}(x,Q^2)+\bar{s}(x,Q^2)\right)}{\int_0^1 dx\, x\ \left(\bar{u}(x,Q^2)+\bar{d}(x,Q^2)\right)}$$

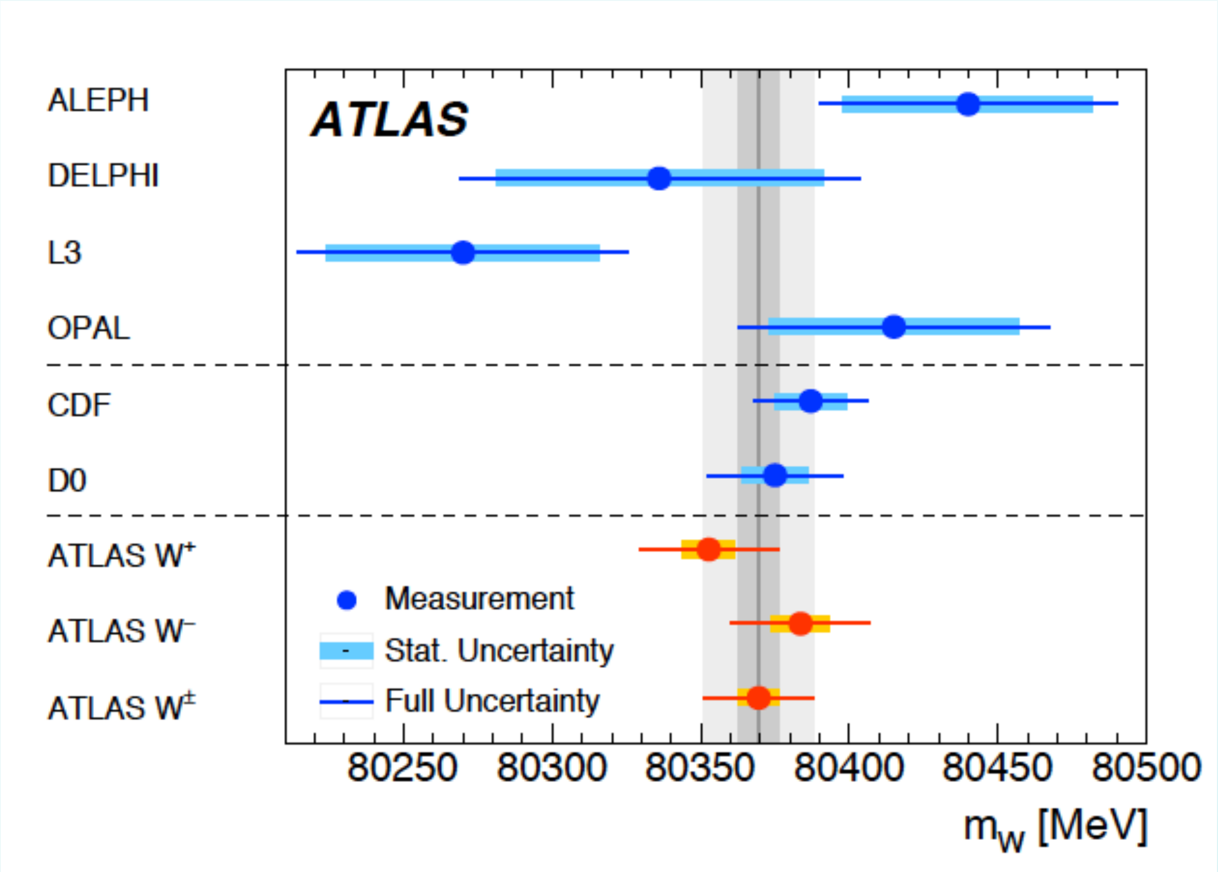
Q = 5 GeV	Central Value	PDF error	Shift From Ref
NNPDF3.1 Global	**0.64**	**8%**	**-**
NNPDF3.1 HERA + ATLASWZ11	**3.3**	**65%**	**a lot!**

Indications from lattice QCD about **whether strangeness is suppressed or not** as compared to the light quark sea would be most valuable

Opportunity II



Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0



☑ The recent landmark measurement of the **W mass at 7 TeV by ATLAS is dominated by PDF uncertainties**

☑ Can lattice QCD have an impact here? Define **accuracy target for the reduction of PDF uncertainties in W mass** measurements?

☑ Note that this is decisive indirect probe of BSM physics due to over-constrained global EW fit

Including lattice ‘data’ in PDF fits

- Assume we have computed using lattice QCD **N$_{\text{lat}}$ ``observables”**: moments, values of the (quasi-)PDFs at specific *x*, PDF ratios, cross-sections …. Each of ``observable” has **total error δ$_{\text{lat}}$**

- The **goodness-of-fit** between the same ``observables” computed from PDFs and those from lattice QCD can be quantified by a statistical estimator:

$$\chi^2_{\text{lat}} = \sum_{i=1}^{N_{\text{lat}}} \frac{\left(\mathcal{O}_i^{\text{lat}} - \mathcal{O}_i^{\text{PDF}}\right)^2}{\delta^2_{\text{lat}}}$$

- Within a Monte Carlo PDF set, this information can be used to **update** the PDF fit as dictated by Bayesian inference, where each replica is **reweighted** by its agreement (or lack of) with the lattice ``data”

$$w_k \propto \mathcal{P}(f_k|\chi_k) \propto \chi_k^{n-1} e^{-\frac{1}{2}\chi_k^2}$$

NNPDF reweighting: arXiv:1108.1758,1012.0836

- Also can be used with pseudo-data, ie, to quantify impact of a lattice calculation 5 yrs from now

- A similar technique, called **Profiling**, is available for **Hessian PDF sets**

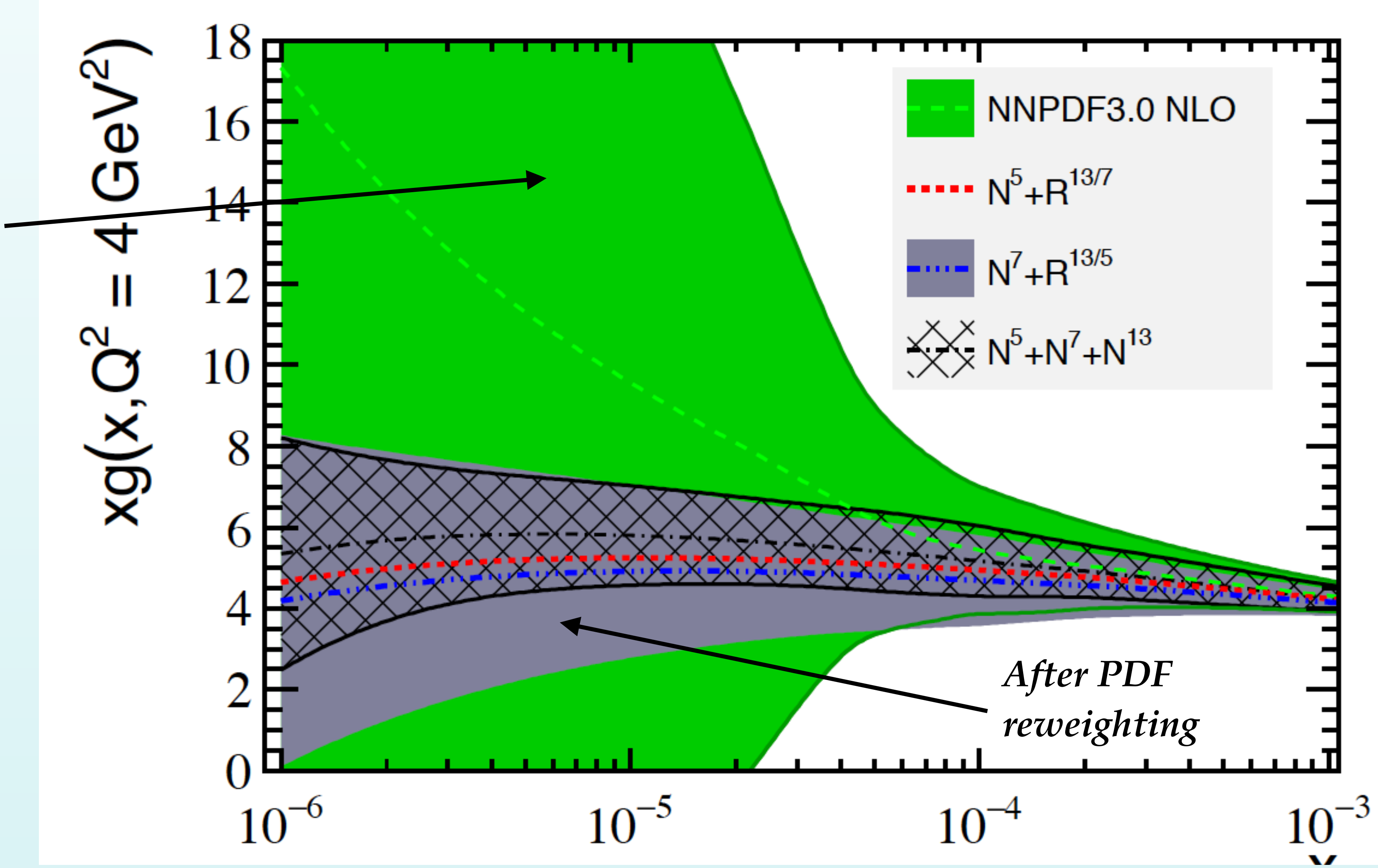
Including lattice ‘data’ in PDF fits

- Example: use LHCb charm production cross-sections **at 5, 7 and 13 TeV** to constrain **the small-x gluon**

- The $N^5+N^7+N^{13}$ combination leads to a **reduction of the small-x gluon PDF errors by an order of magnitude**

- Can we achieve same impact (for other polarized/unpolarized PDF combinations) using ``lattice data''?

Before PDF reweighting



After PDF reweighting

Gauld and Rojo PRL17

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

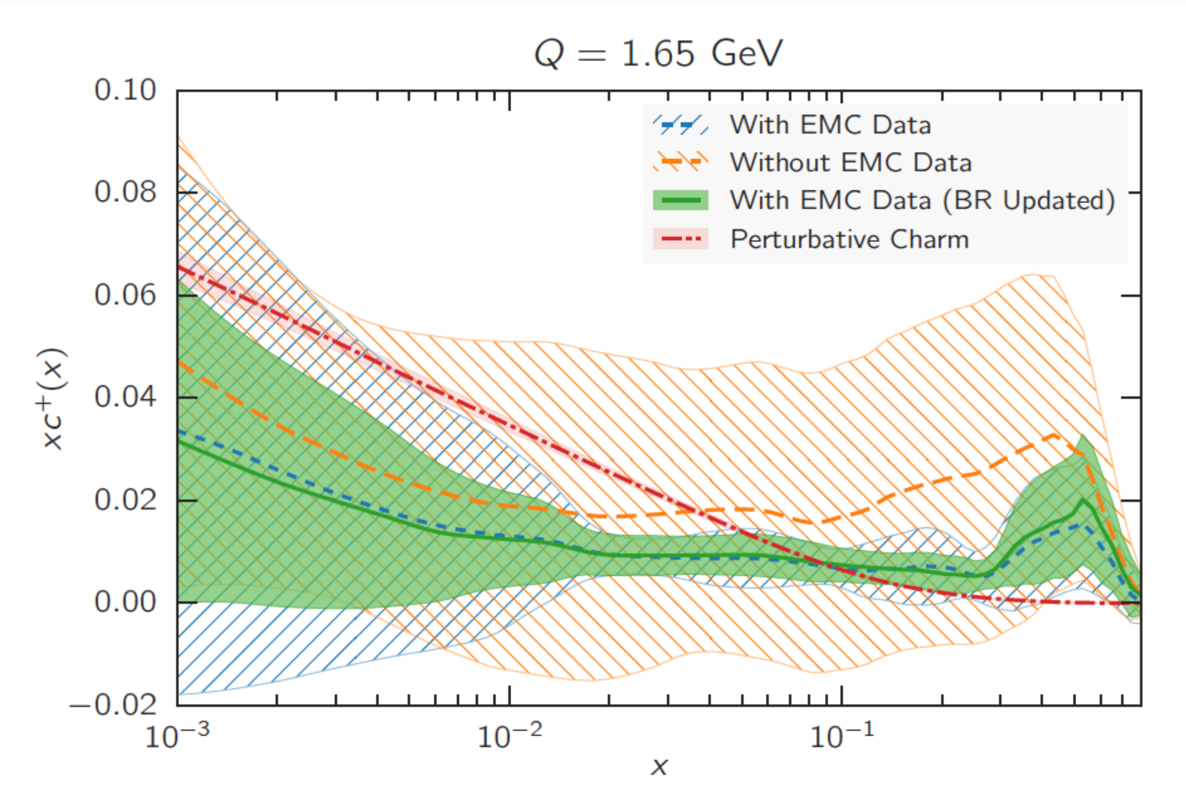
NNPDF3.1 fits obtained **both** for a **fitted** and for a **perturbative charm PDF**

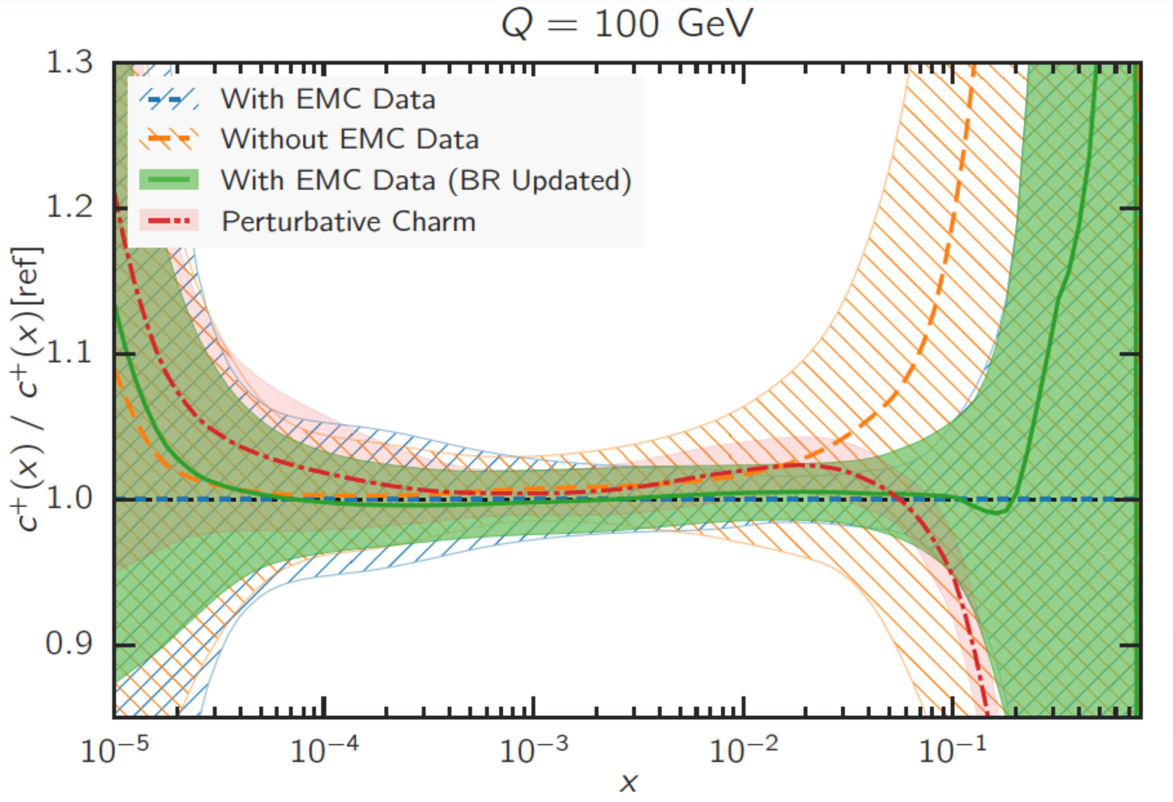
Ball, Bonvini, Rottoli, JHEP 17

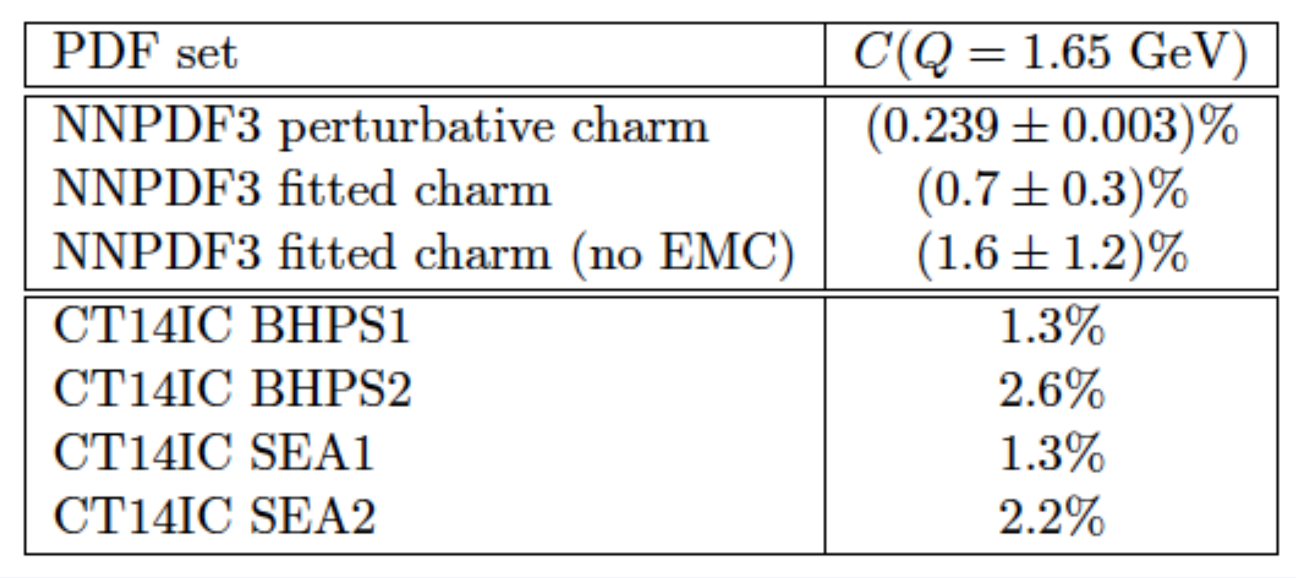
Ball et al, PLB 17

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	$C(Q = 1.65\ \text{GeV})$
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

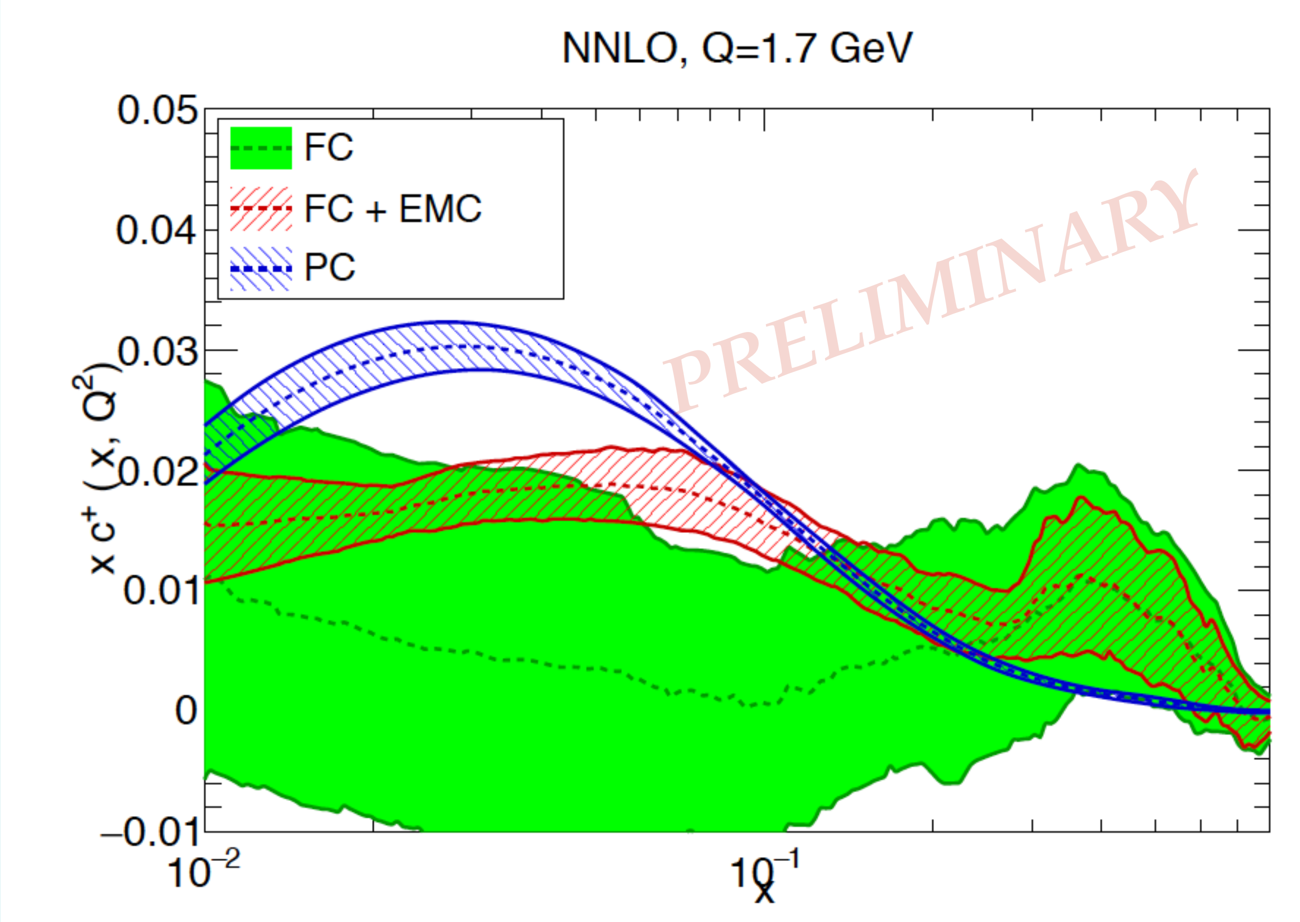
Charm content of proton revisited

- 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**

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

PDF set	$C(Q = 1.65\ \mathrm{GeV})$	$C(Q = 100\ \mathrm{GeV})$
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**

What can lattice QCD say about the **charm content of the nucleon?**

Outlook

- Recent impressive progress in both the **global QCD analysis** and the **lattice QCD communities** in the **understanding of the proton structure** provides a strong motivation to increase the cross-talk between the two communities

- PDF-related quantities can be divided into **Benchmarks,** which lattice QCD must reproduce if we are to trust their calculations, and **Opportunities,** where lattice QCD can provide valuable input for global PDF fits

- When comparing lattice QCD calculations with global PDF fits, crucial to specify carefully **where the PDF results come from**, theory settings of the PDF fits, which PDF error treatment has been assumed

- Using **Bayesian Reweighting**, possible to quantify the impact of **lattice QCD observables** in the PDF fit => exercise to be performed in the **Whitepaper!**

- Also a **systematic comparison** of state-of-the-art PDF fits (polarized and unpolarized) with lattice QCD calculations is of outmost importance

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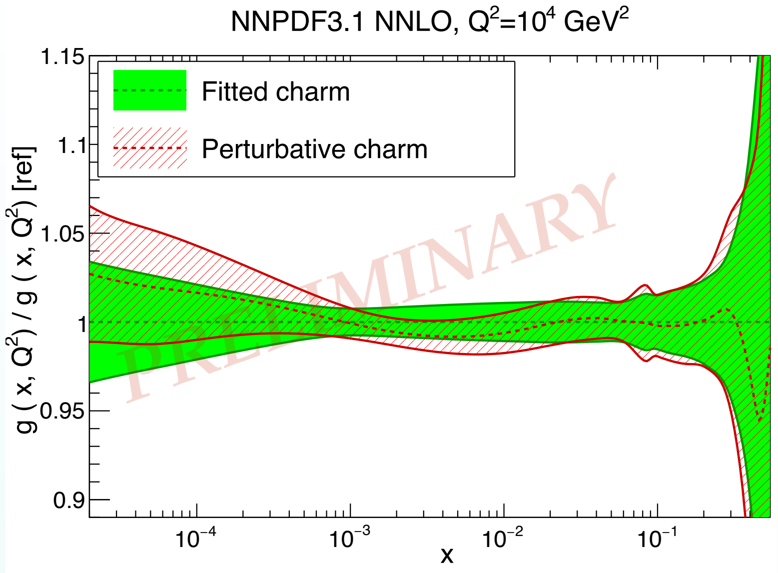
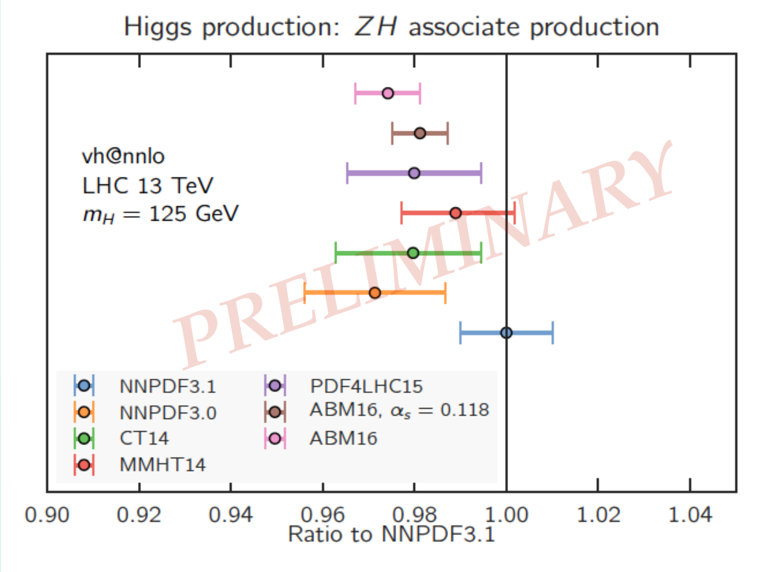
Thanks for your attention!


NNPDF3.1 NNLO, $Q^2=10^4$ GeV^2
Fitted charm
Perturbative charm
PRELIMINARY
$g(x, Q^2) / g(x, Q^2)$ [ref]
1.15
1.1
1.05
1
0.95
0.9
10^{-4}
10^{-3}
10^{-2}
10^{-1}
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, $\alpha_s = 0.118$
ABM16
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
Ratio to NNPDF3.1

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.

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

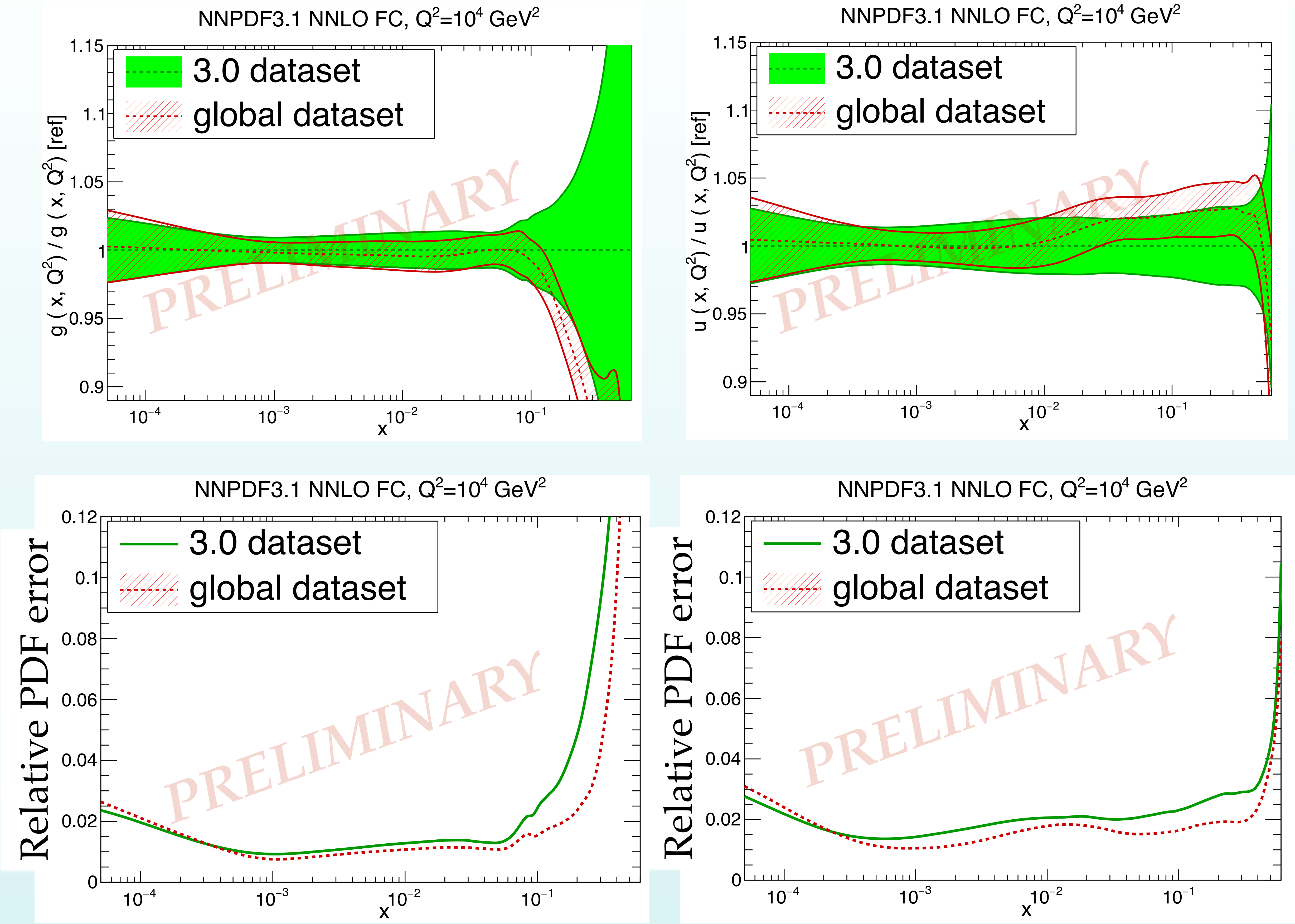
	NNLO FittedCharm	**NNLO PertCharm**	**NLO FittedCharm**	**NLO PertCharm**
HERA	**1.16**	**1.20**	**1.16**	**1.16**
ATLAS	**1.13**	**1.19**	**1.45**	**1.50**
CMS	**1.04**	**1.06**	**1.20**	**1.20**
LHCb	**1.46**	**1.46**	**1.94**	**1.93**

- 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)

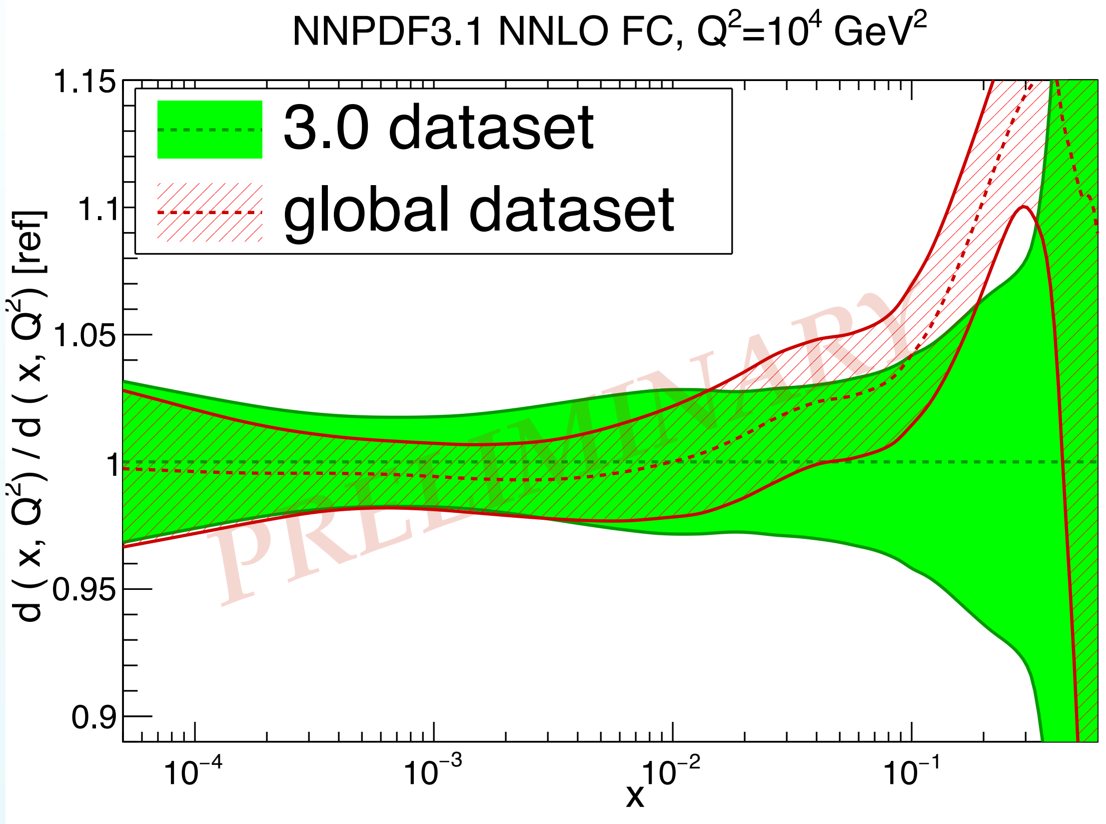
- The global PDF analysis where the charm PDF is fitted leads to a **slightly superior fit quality** than assuming a perturbatively generated charm PDF

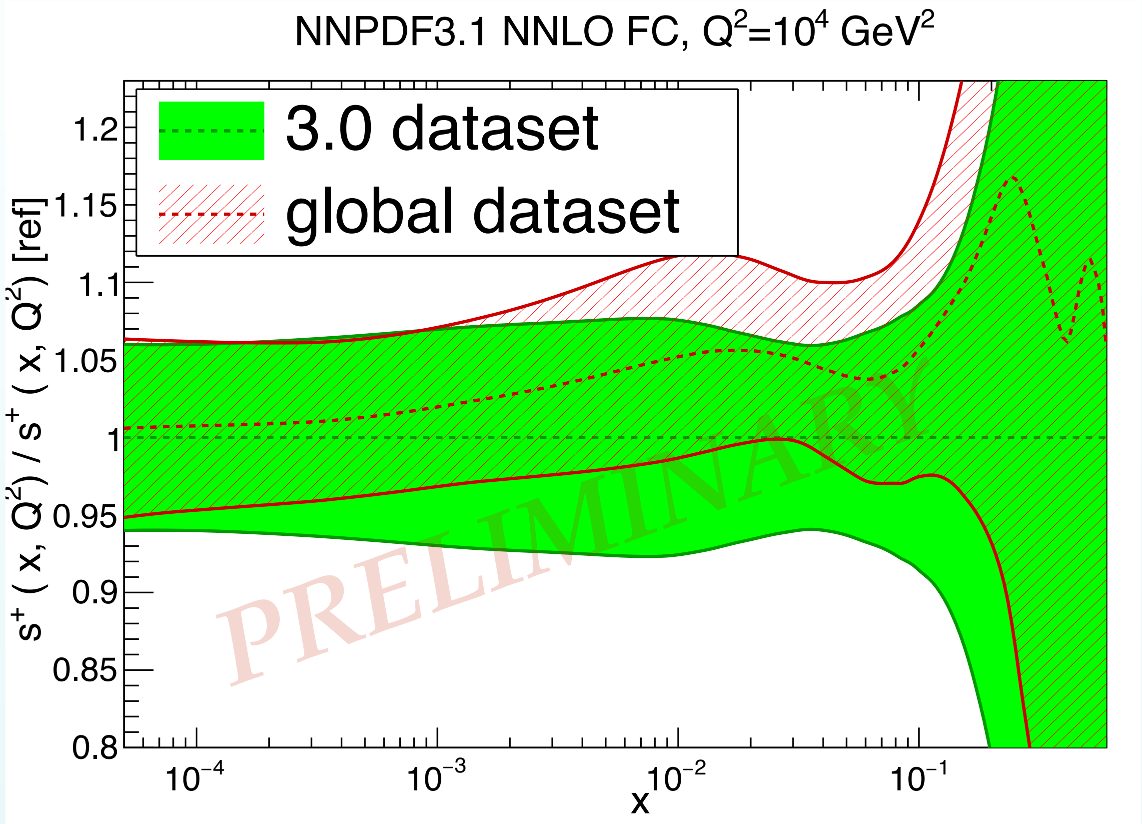
- In general **good description of all the new collider measurements** included in NNPDF3.1

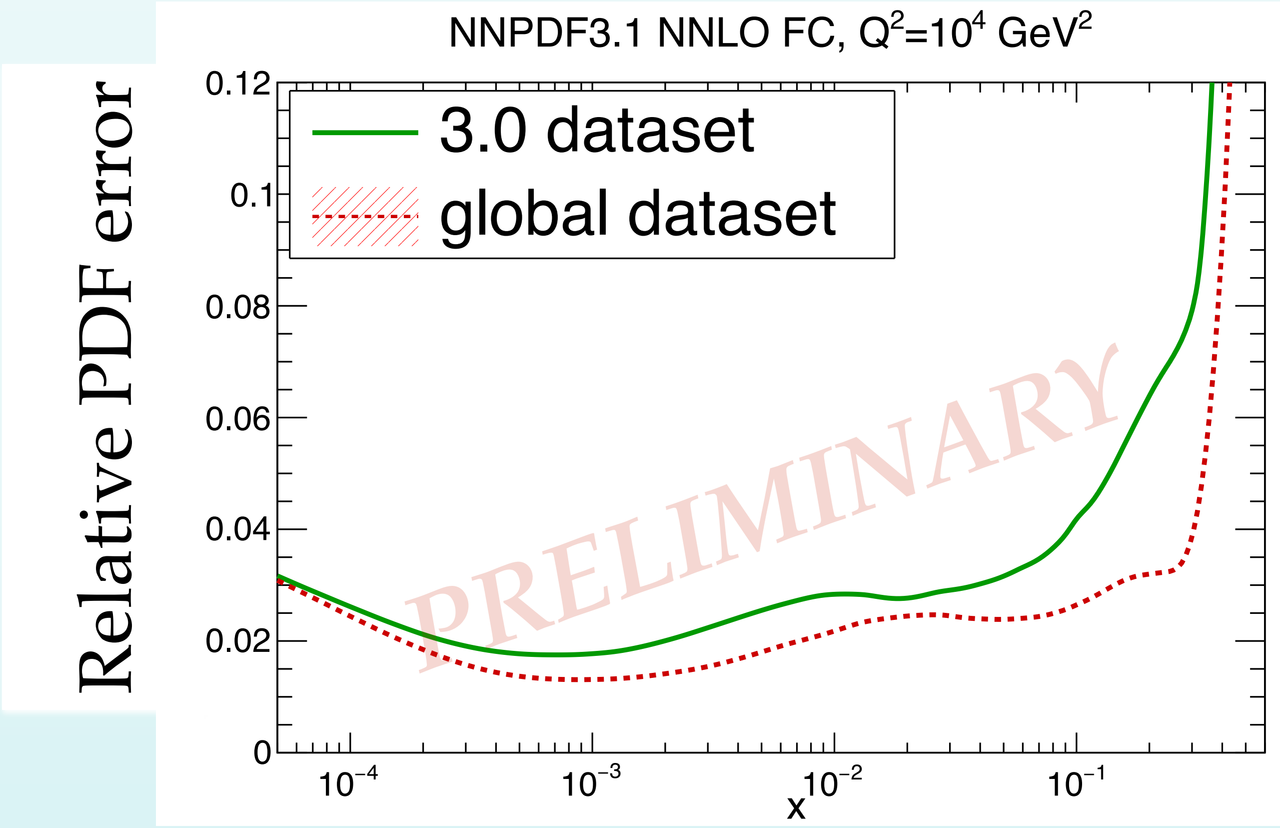
Impact of new data

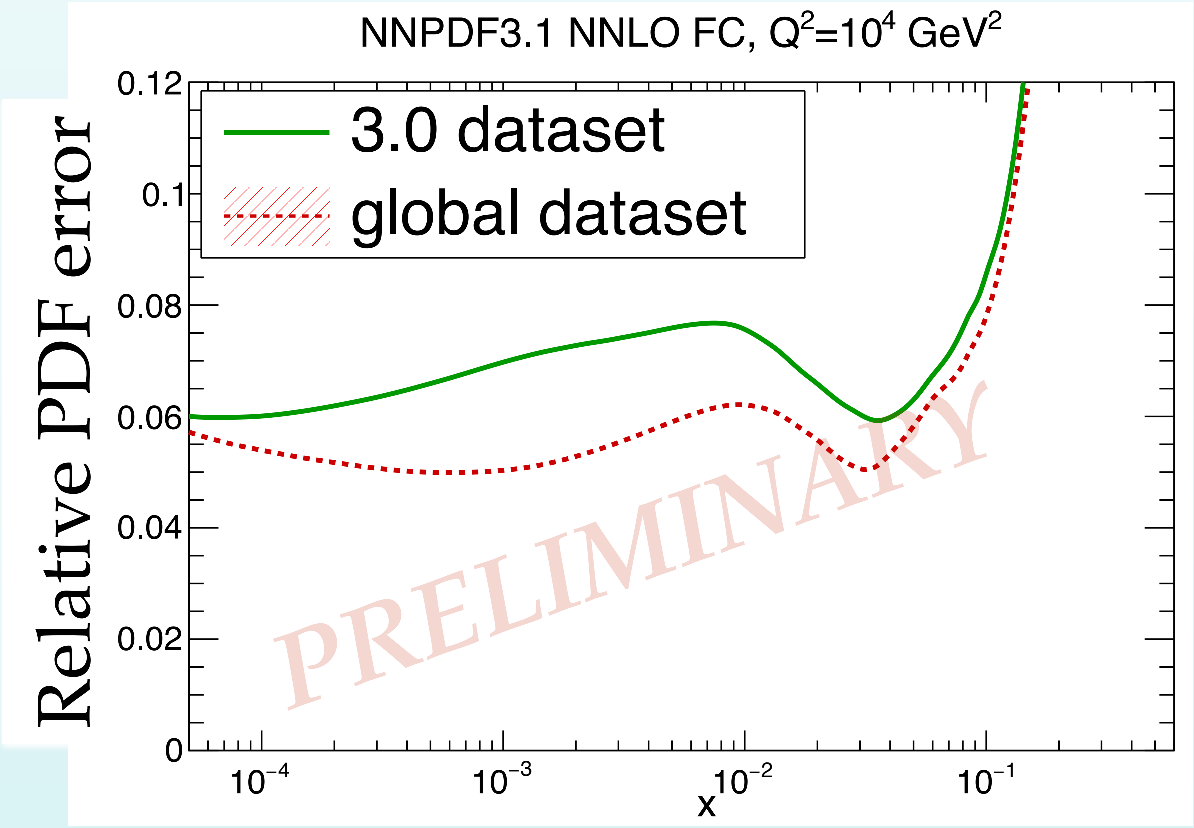


Impact of new data

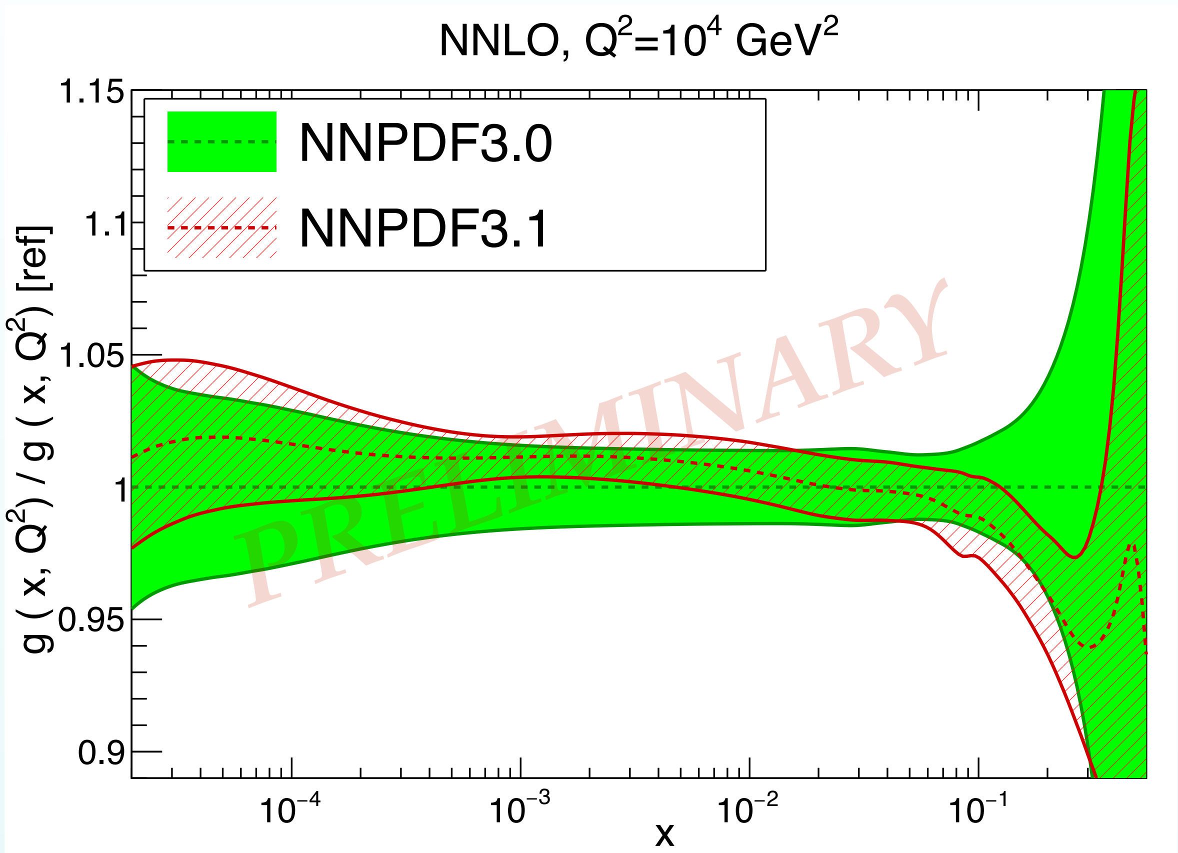


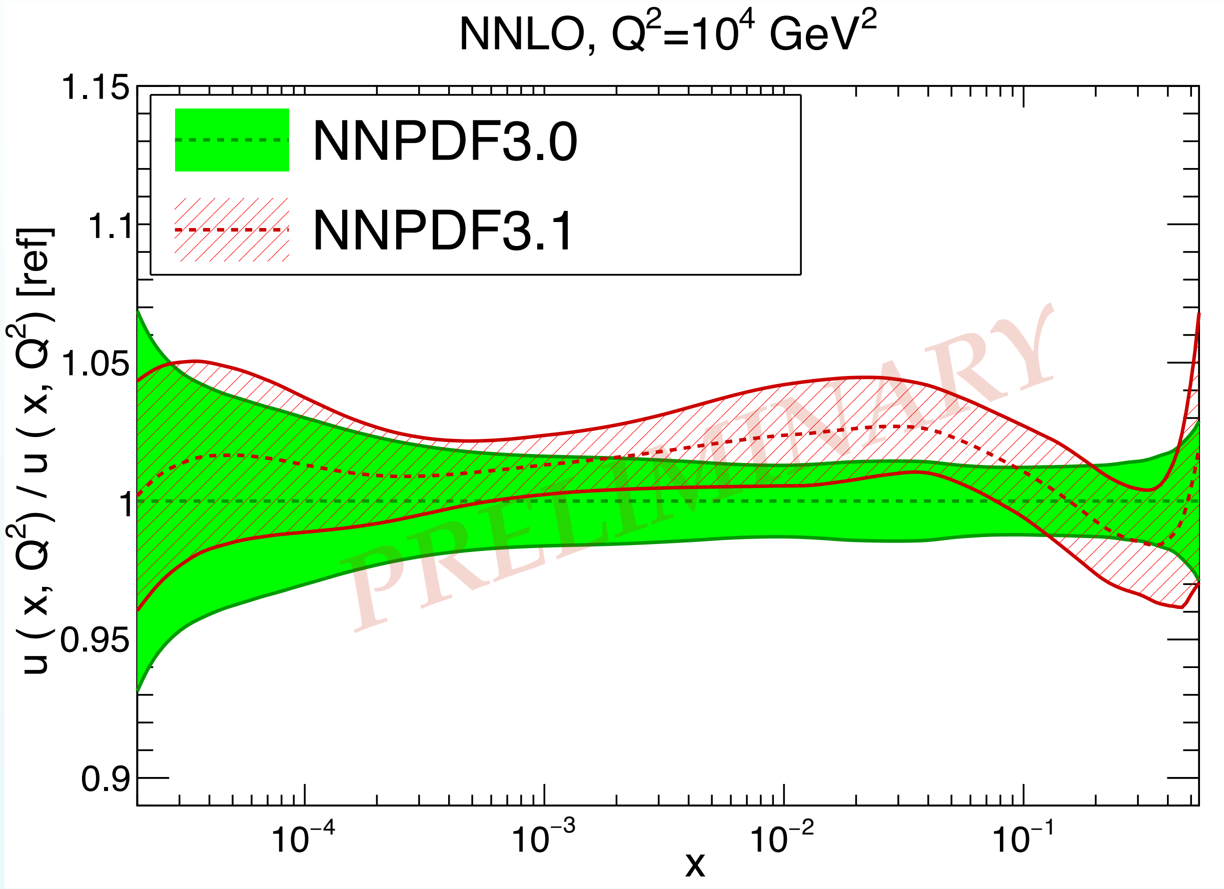


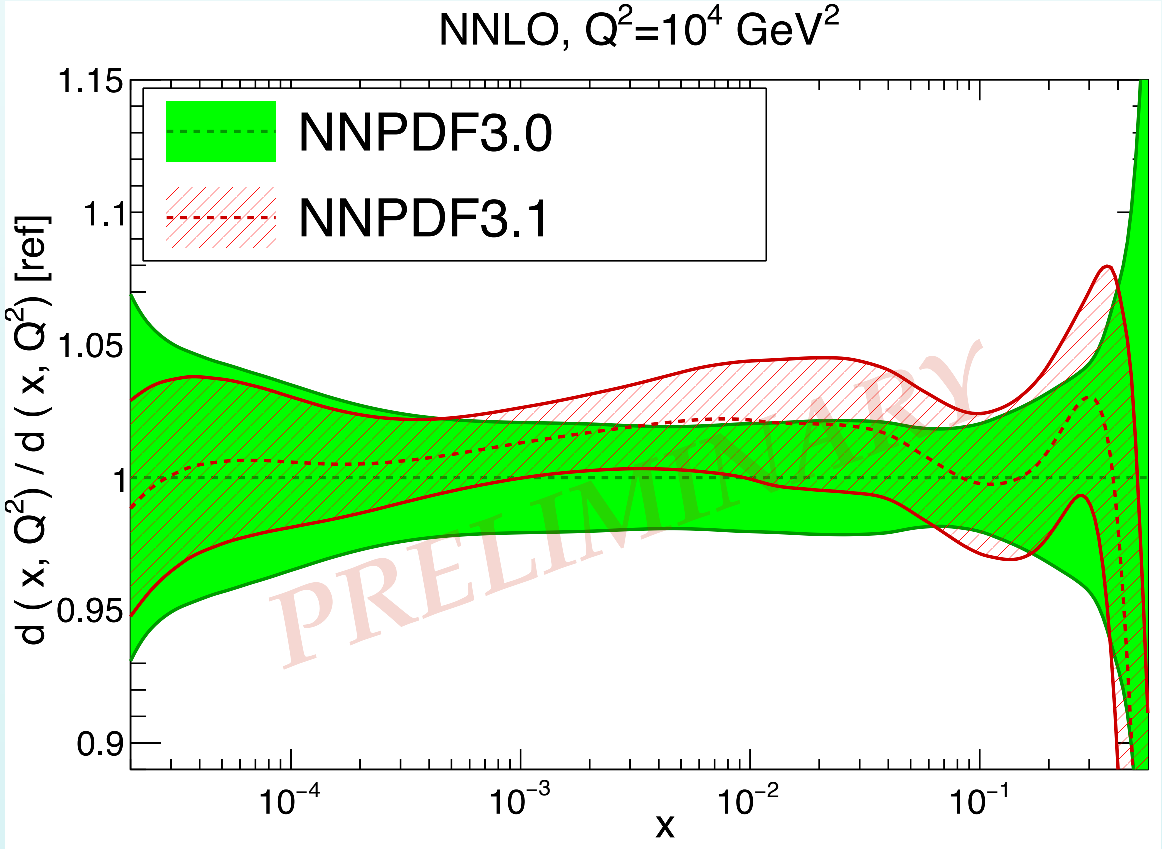


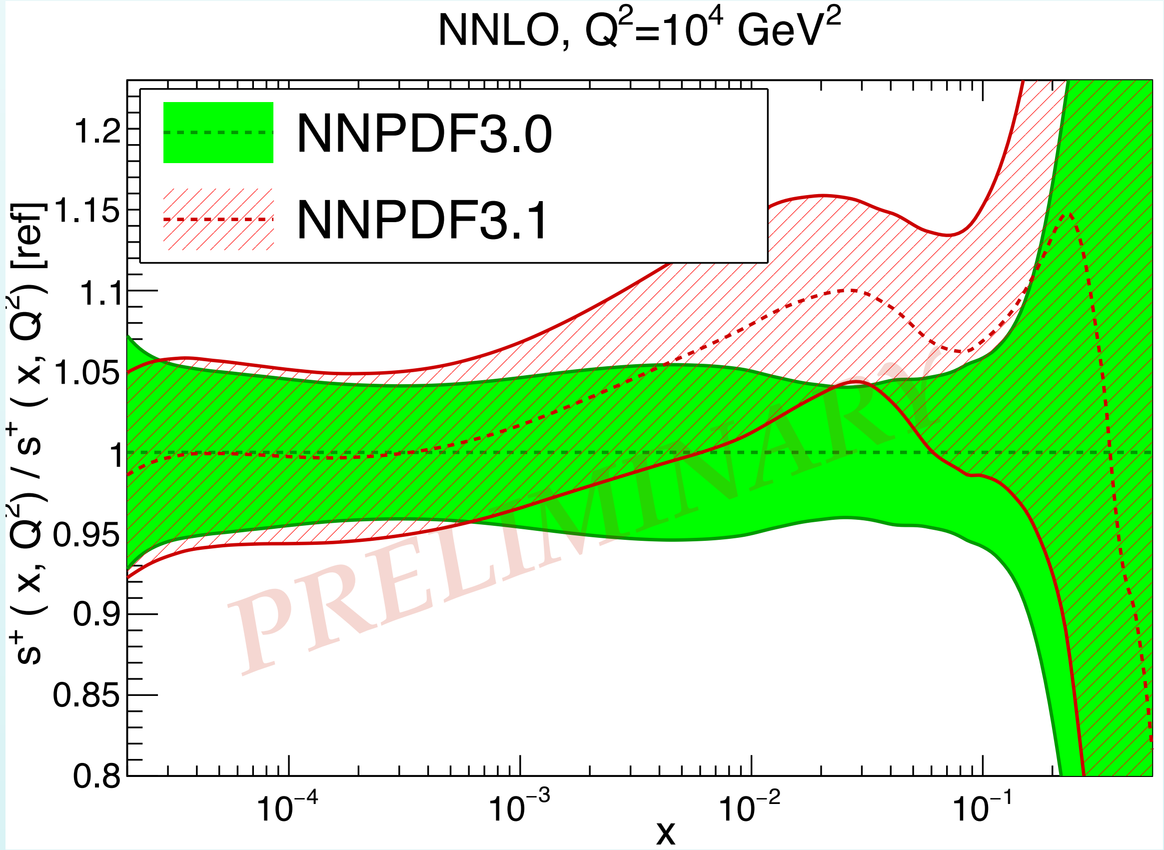


Comparison with NNPDF3.0



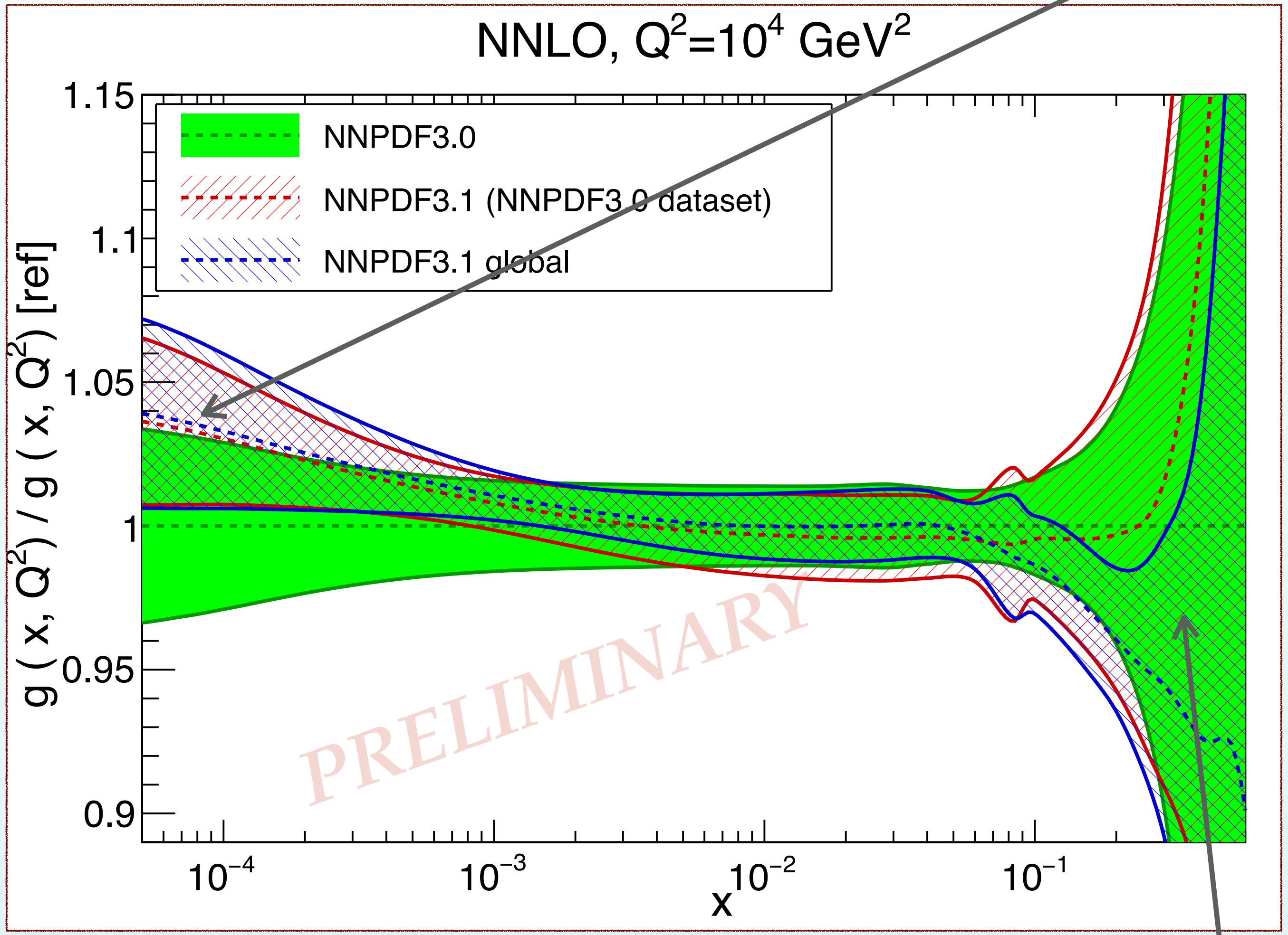


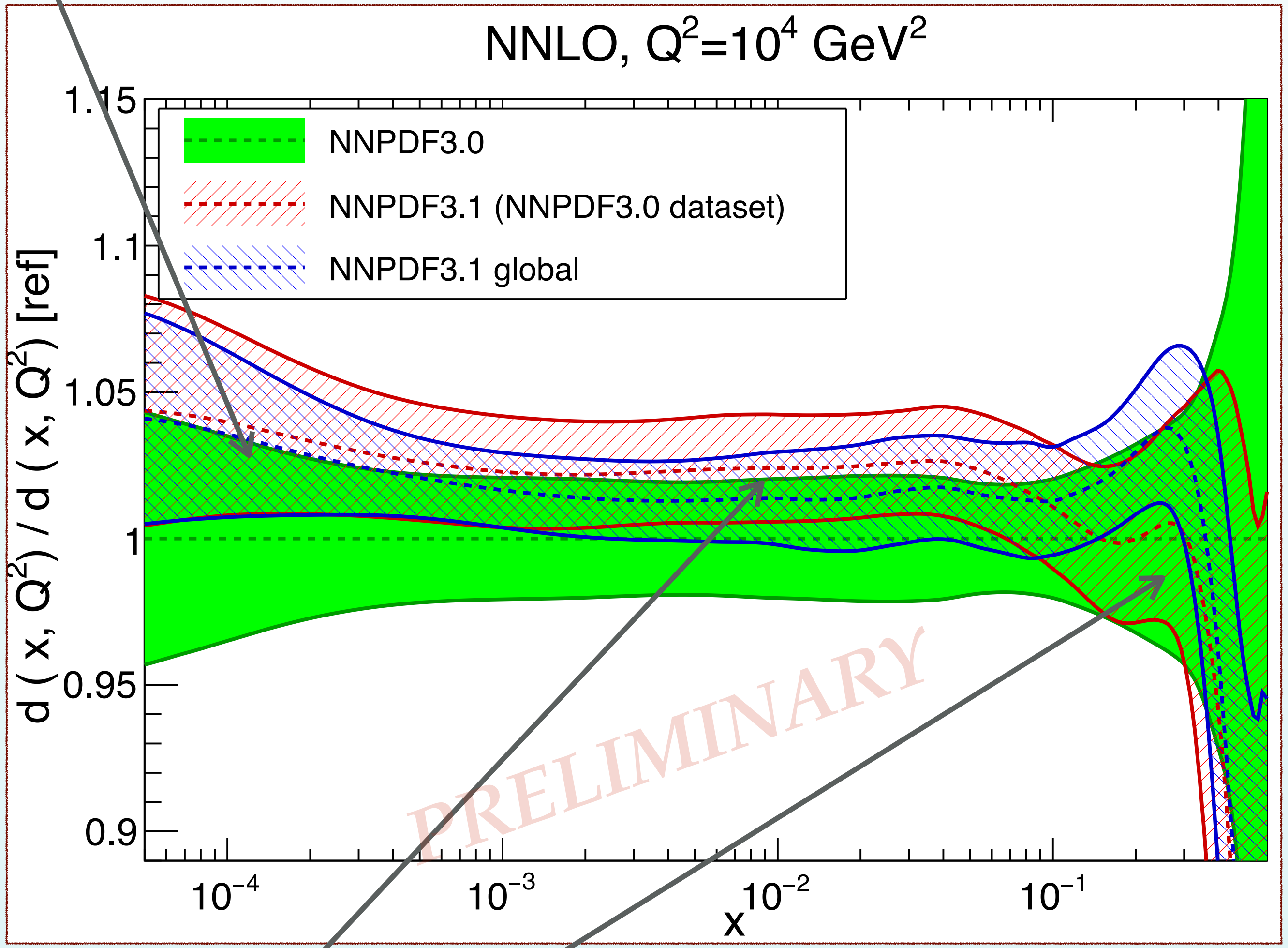




new data vs new methodology

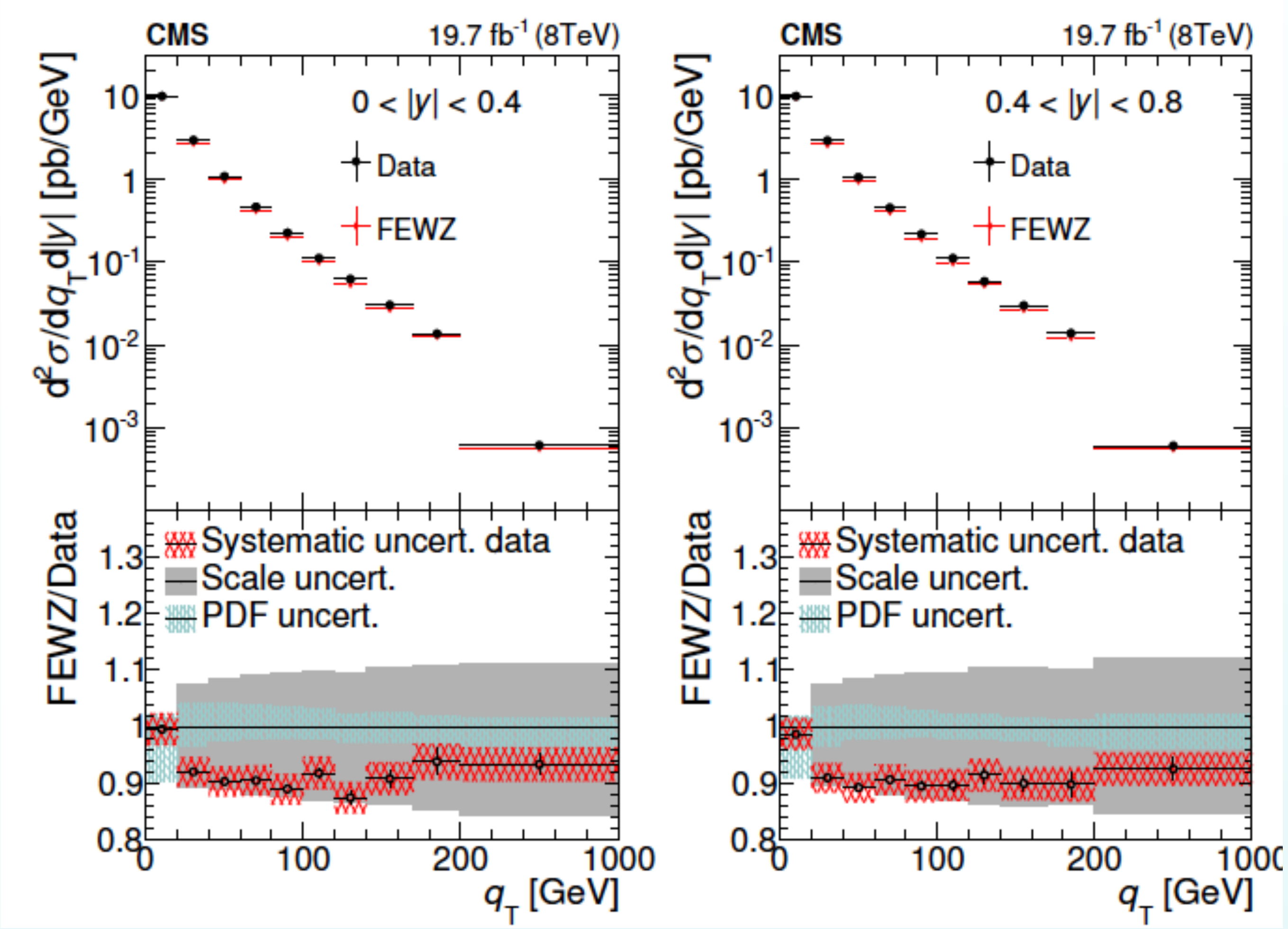
new methodology (mostly fitting charm)

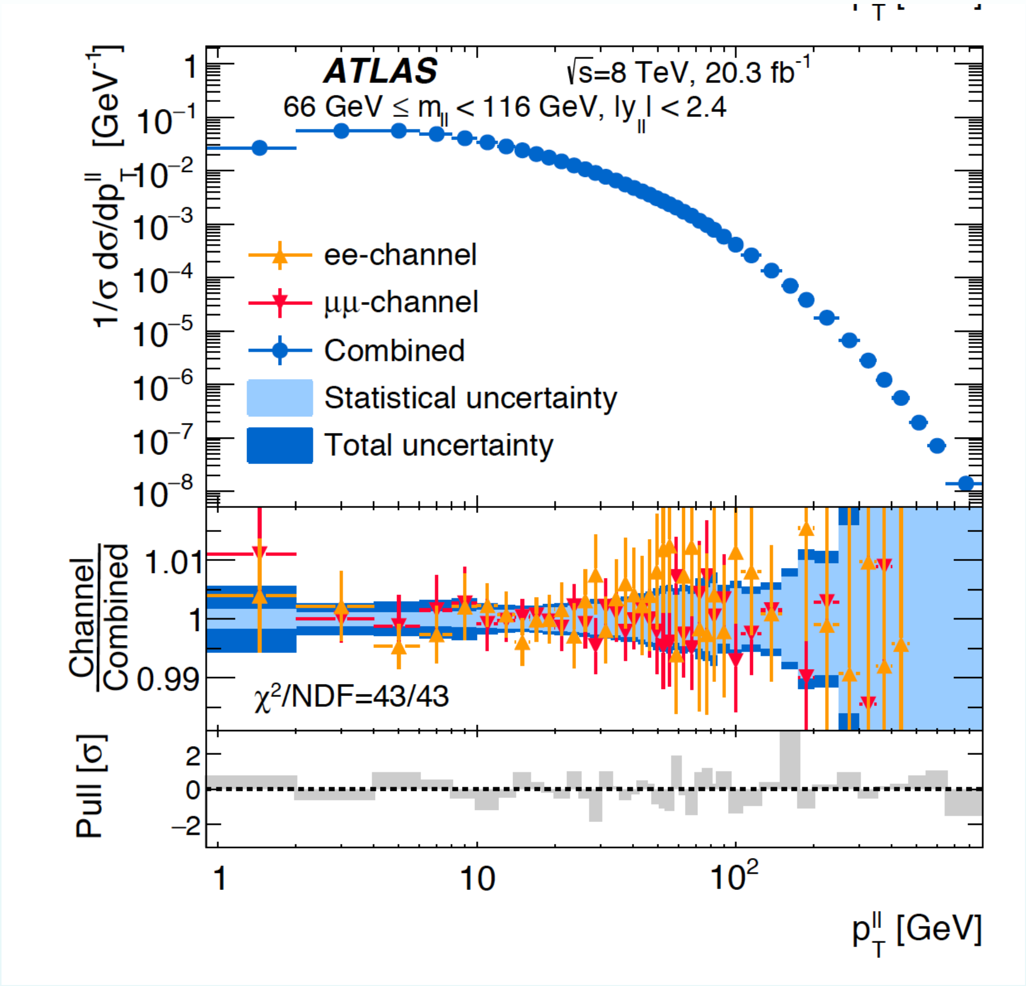




Impact of new data

Impact of Z pt data

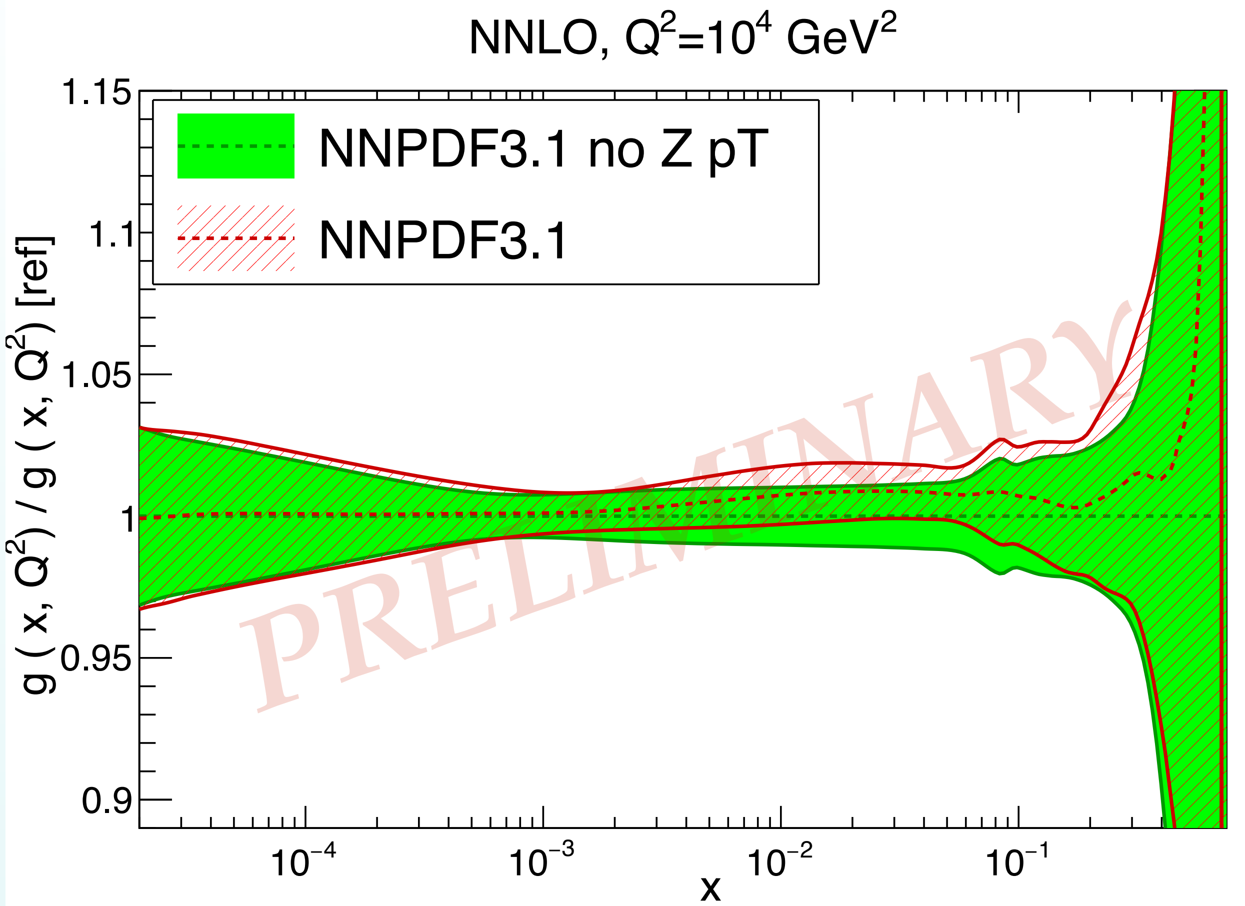


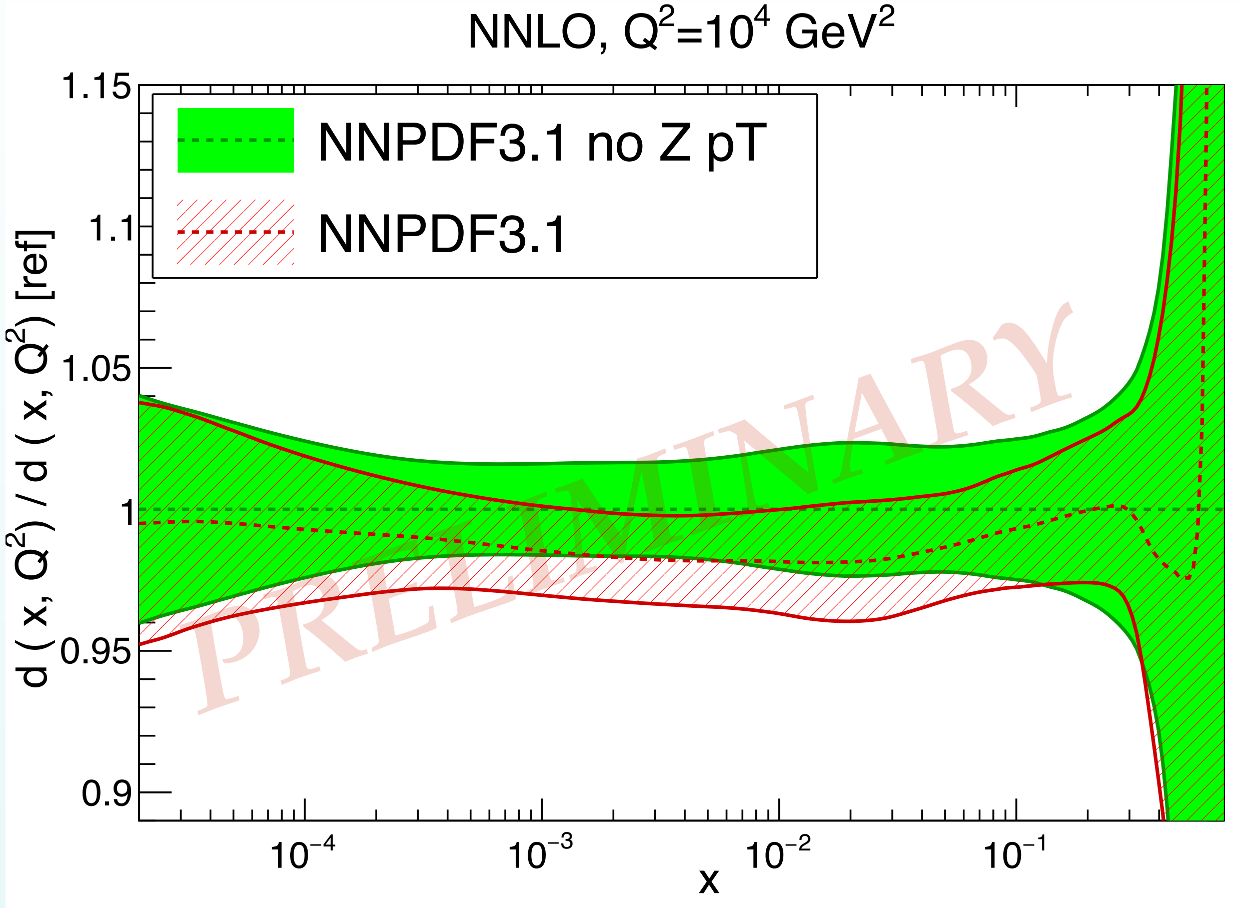


- **For the first time in a global fit, the transverse momentum of the Z boson has been included**
- **NNLO calculations for K-factors** from Boughezal and Petriello, very CPU time intensive!
- All the Z p_T measurements from ATLAS and CMS at 8 TeV included

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

Impact of Z p_T data


NNLO, $Q^2=10^4$ GeV^2


NNLO, $Q^2=10^4$ GeV^2

- Impact on many PDFs: **harder gluon at medium-x** (relevant for ggF Higgs) and softer quarks in the same region.

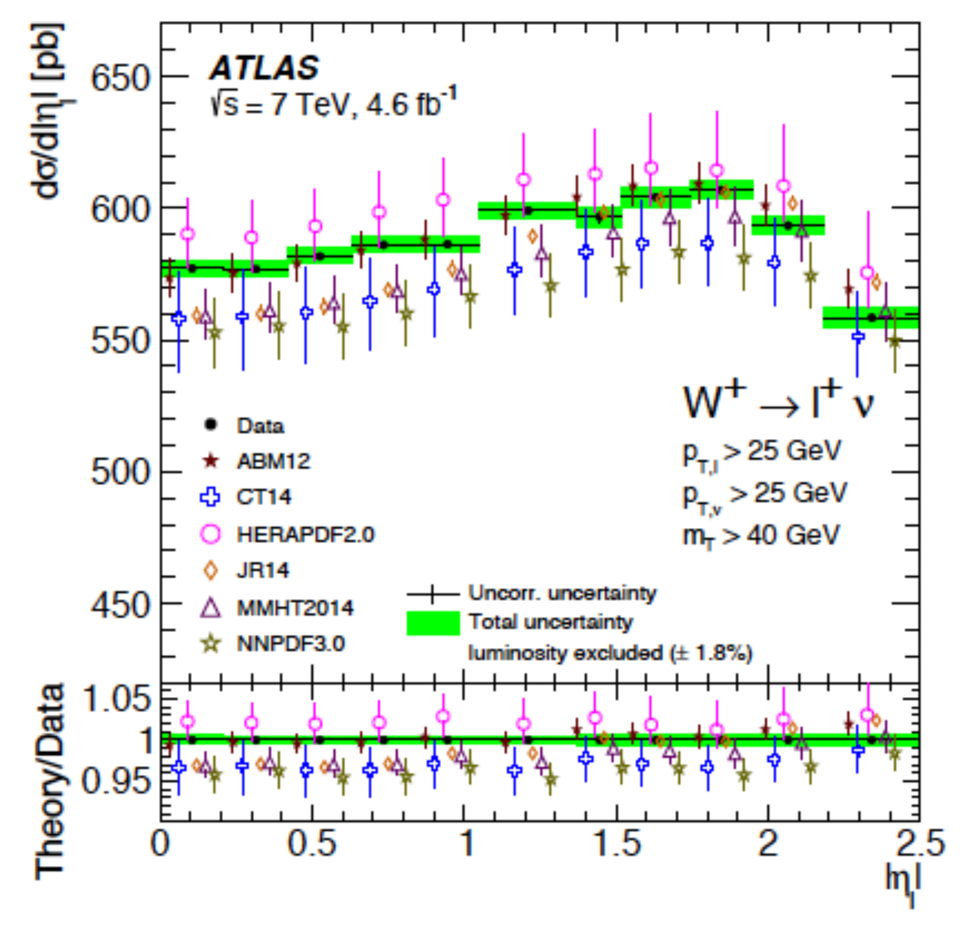
- The region of intermediate-x is the region where Z pT data is expected to have most sensitivity

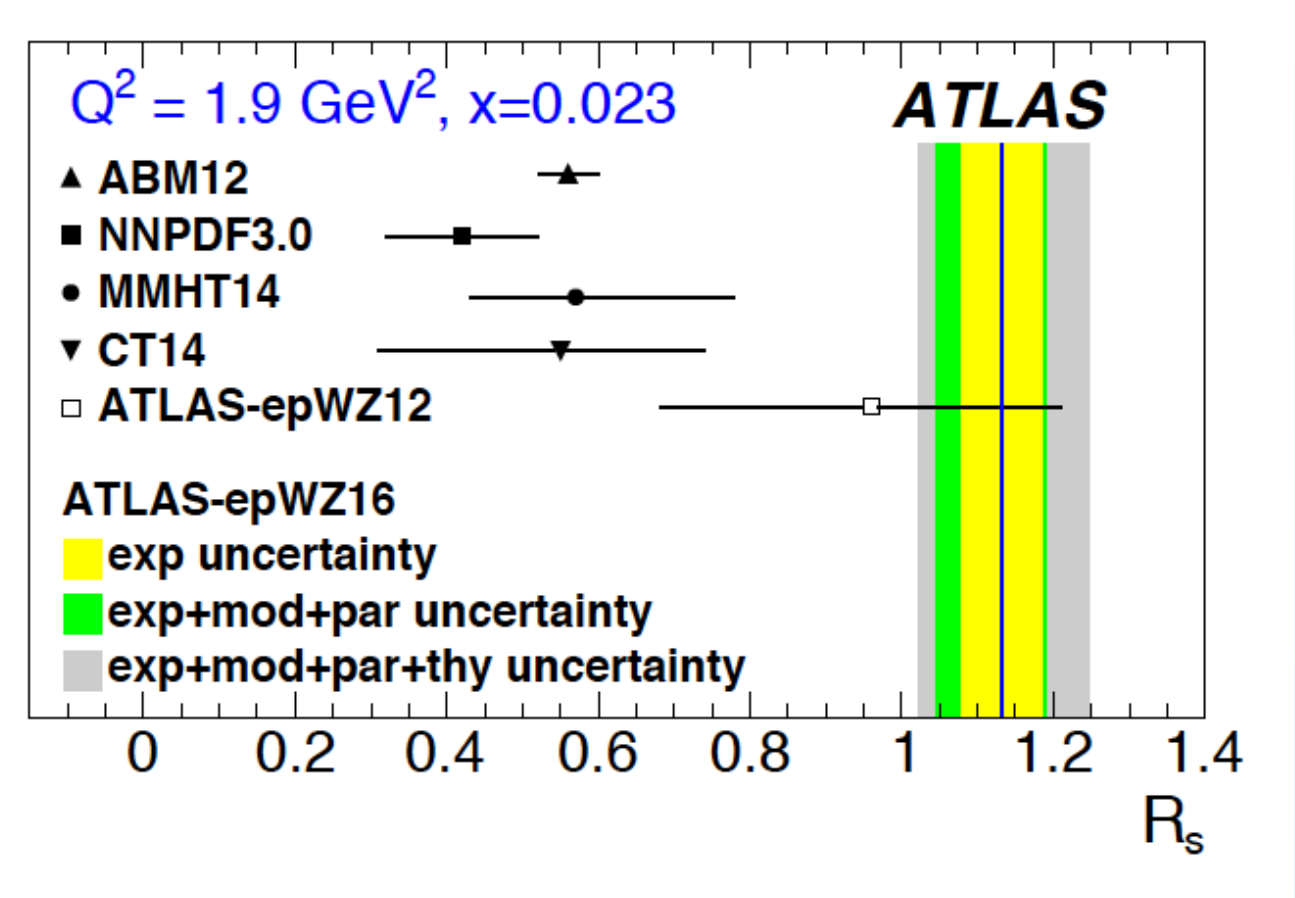
- New important addition to the toolbox of global PDF fits!

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

The strangeness content of the proton

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



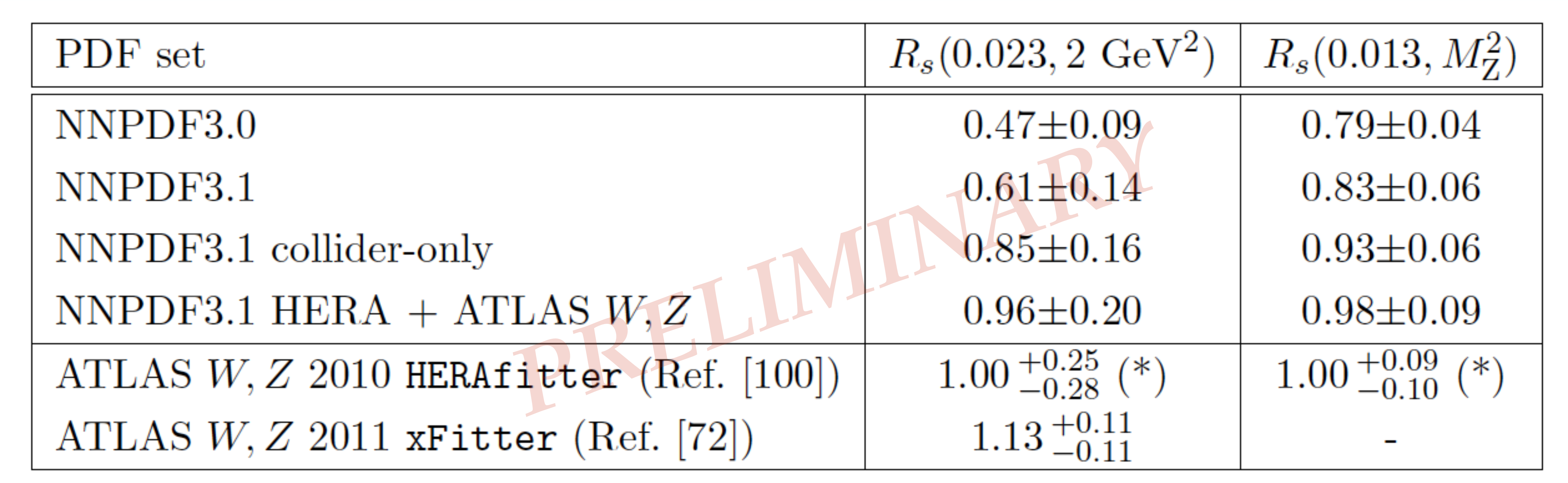


- **xFitter analysis** of the ATLAS W,Z 2011 inclusive data prefers a **symmetric strange sea** with small uncertainty, at odds with all other PDF fits

- 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])	$1.13^{+0.11}_{-0.11}$	-

- **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 (**χ^2_{nutev}=1.1, χ^2_{AWZ11}=1.8**) finding a compromise value for **R_S=0.61+-0.14**

- **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

The large-x gluon from top-quark production

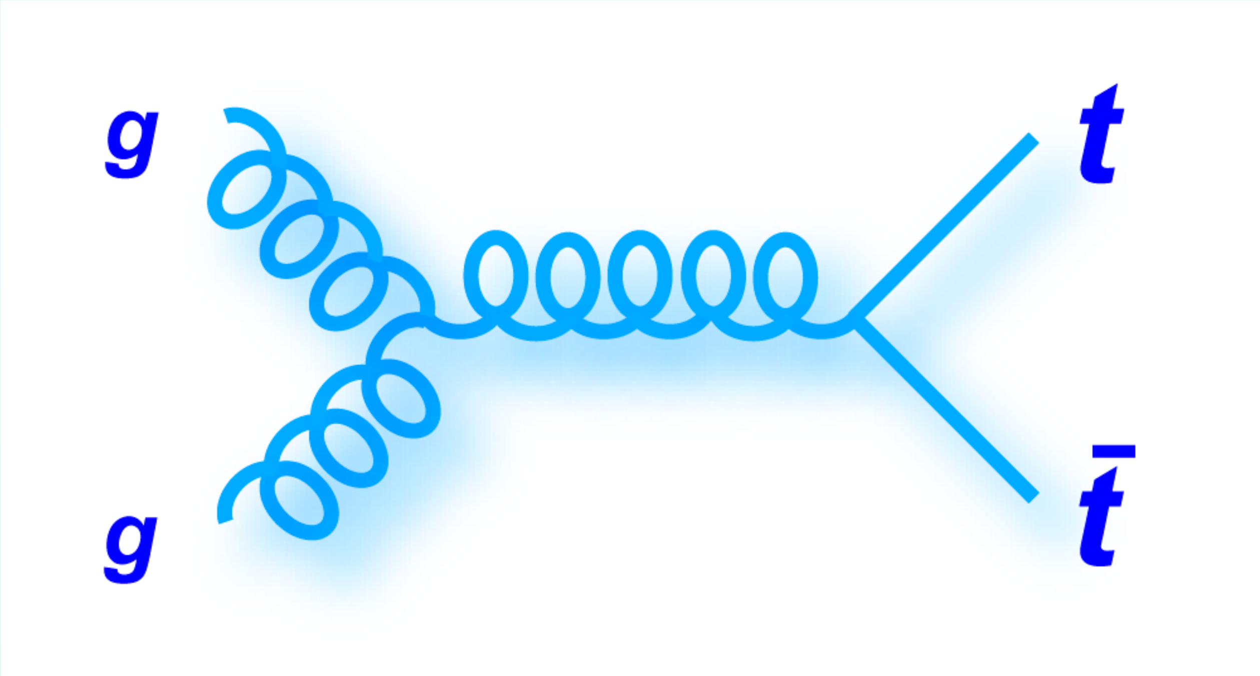
- Top-quark pair production driven by the **gluon-gluon luminosity**

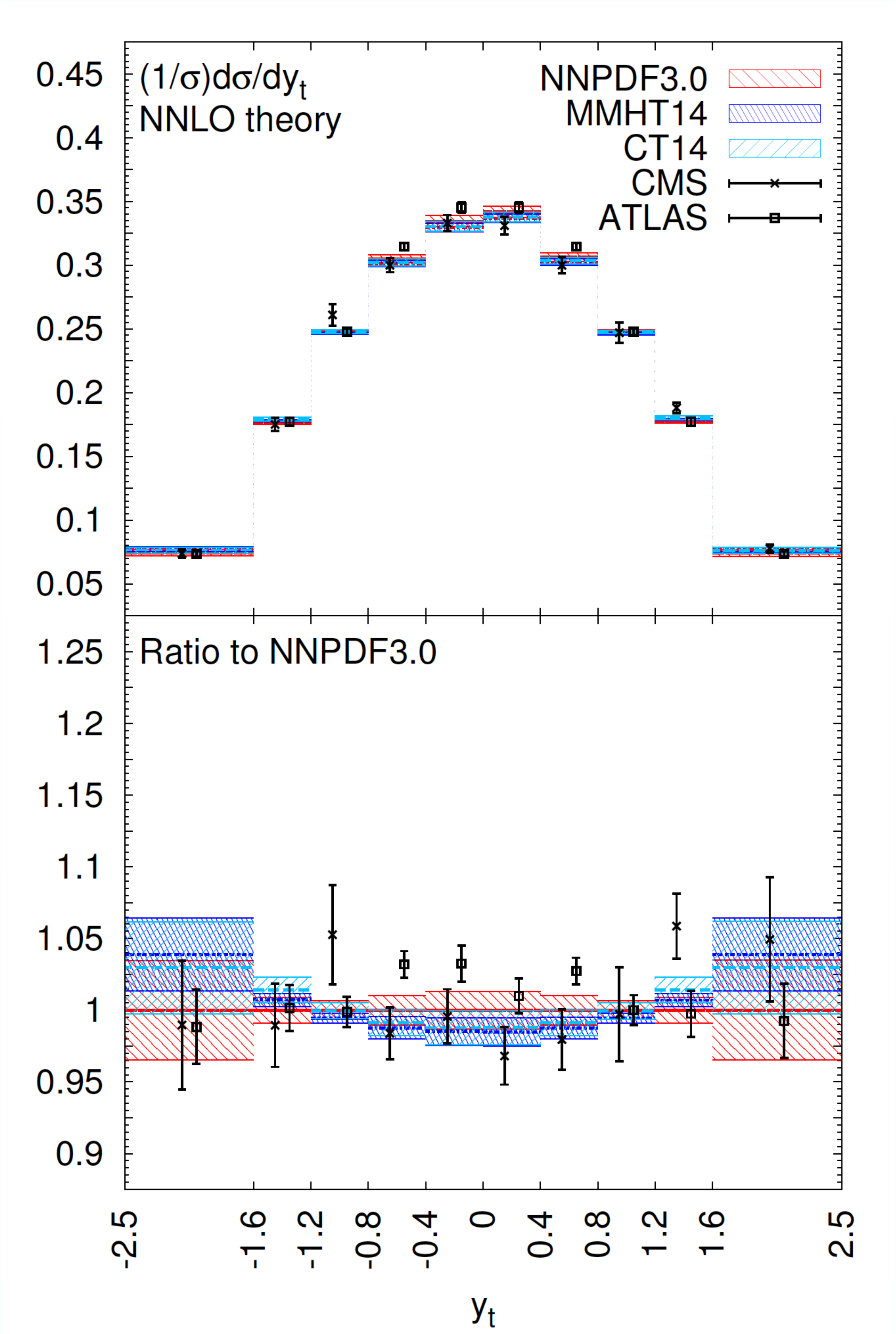
- **NNLO calculations for stable top quarks** available (with decays in the pipeline)

- 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





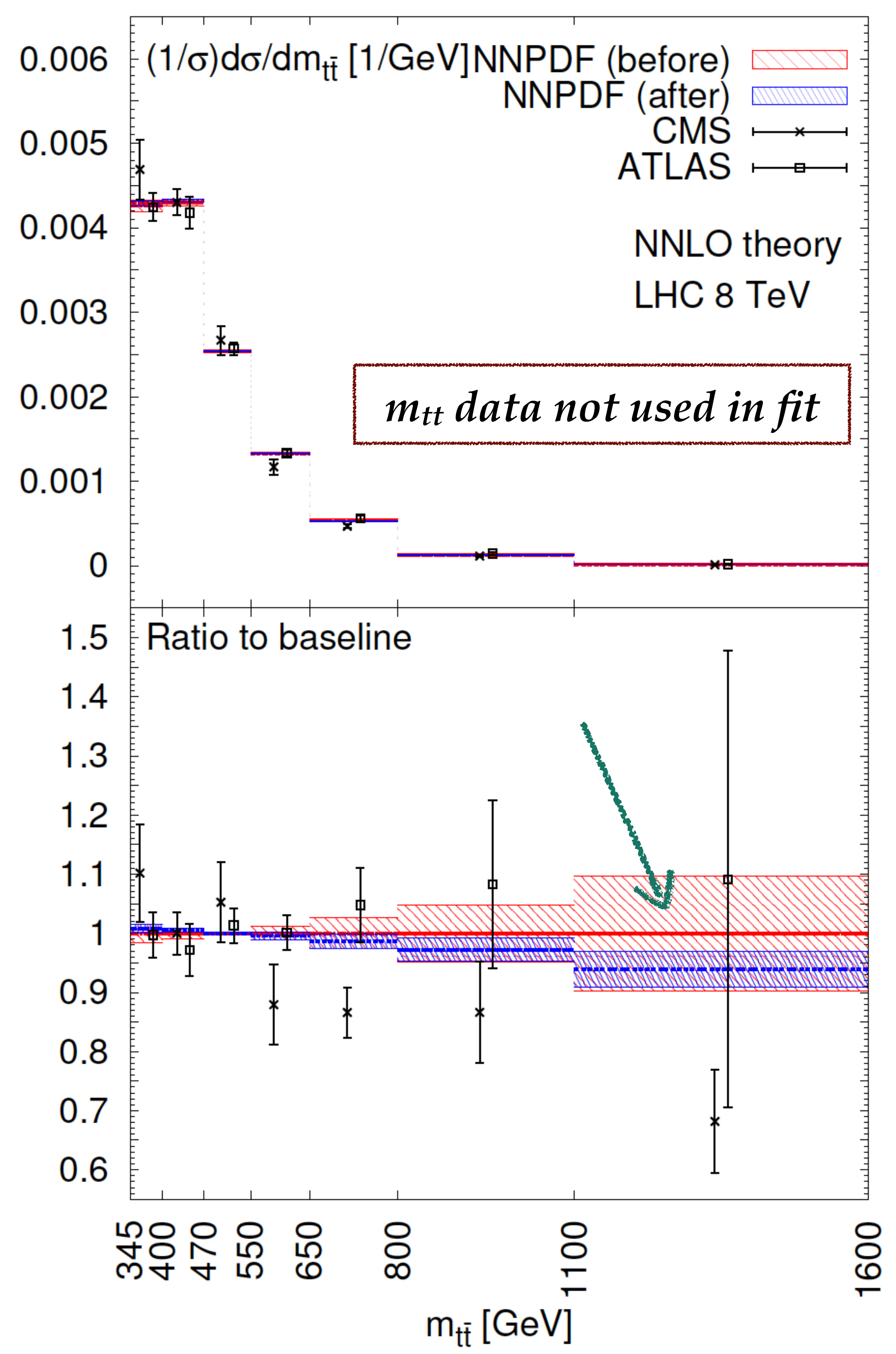
The large-x gluon from top-quark production

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



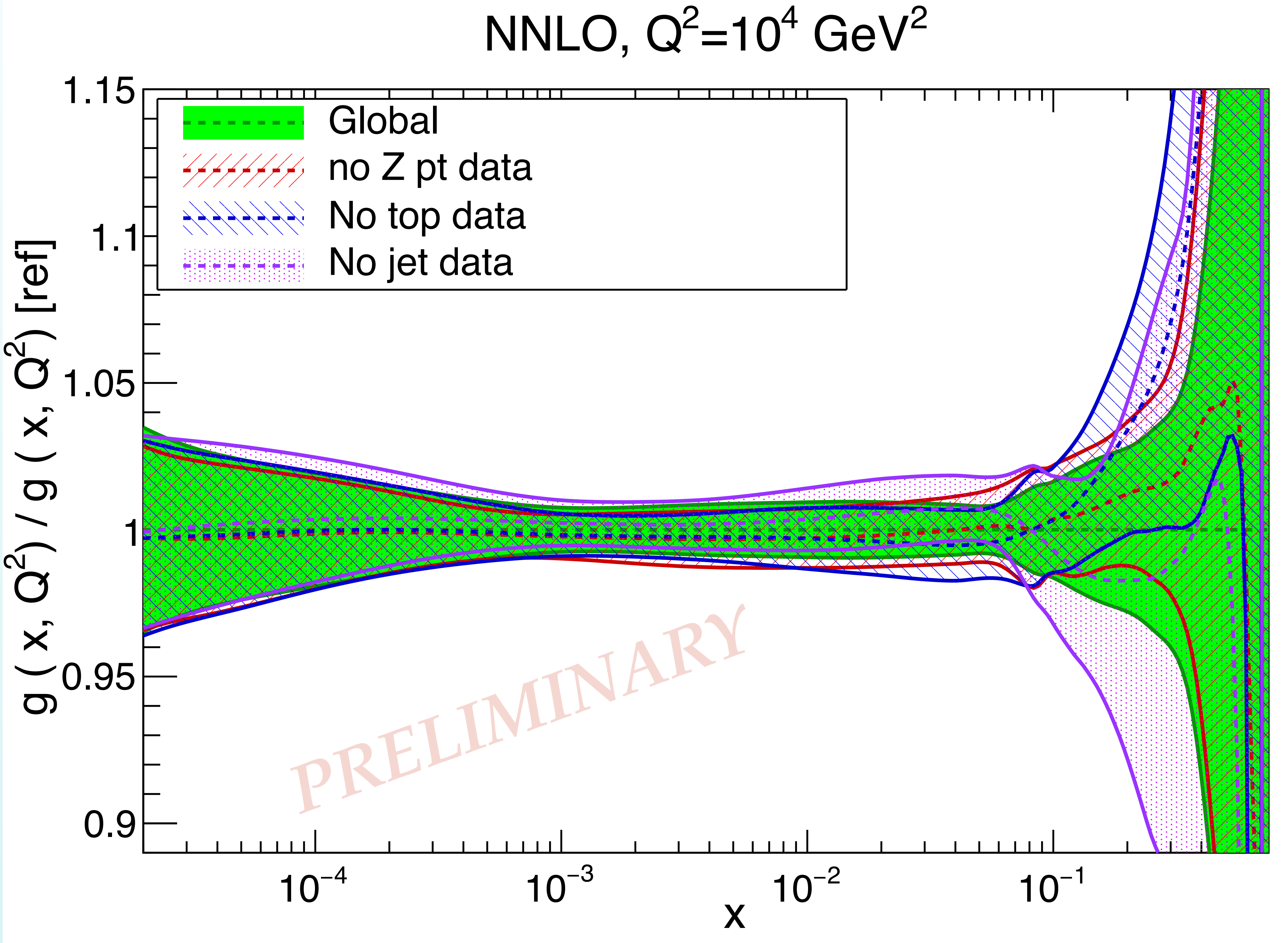
m_{tt} data not used in fit

Czakon, Hartland, Mitov, Nocera, Rojo 16

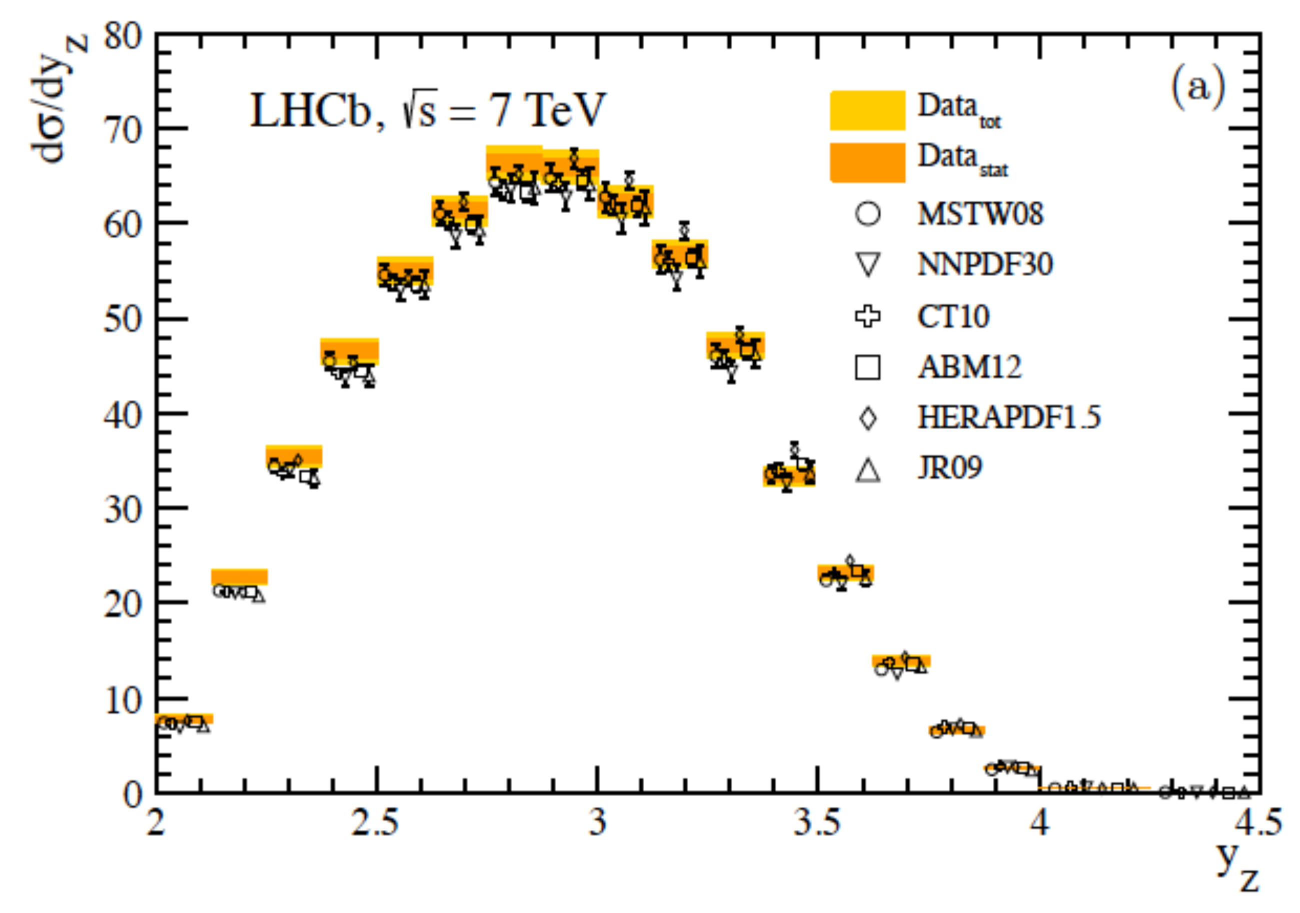
Impact on the gluon

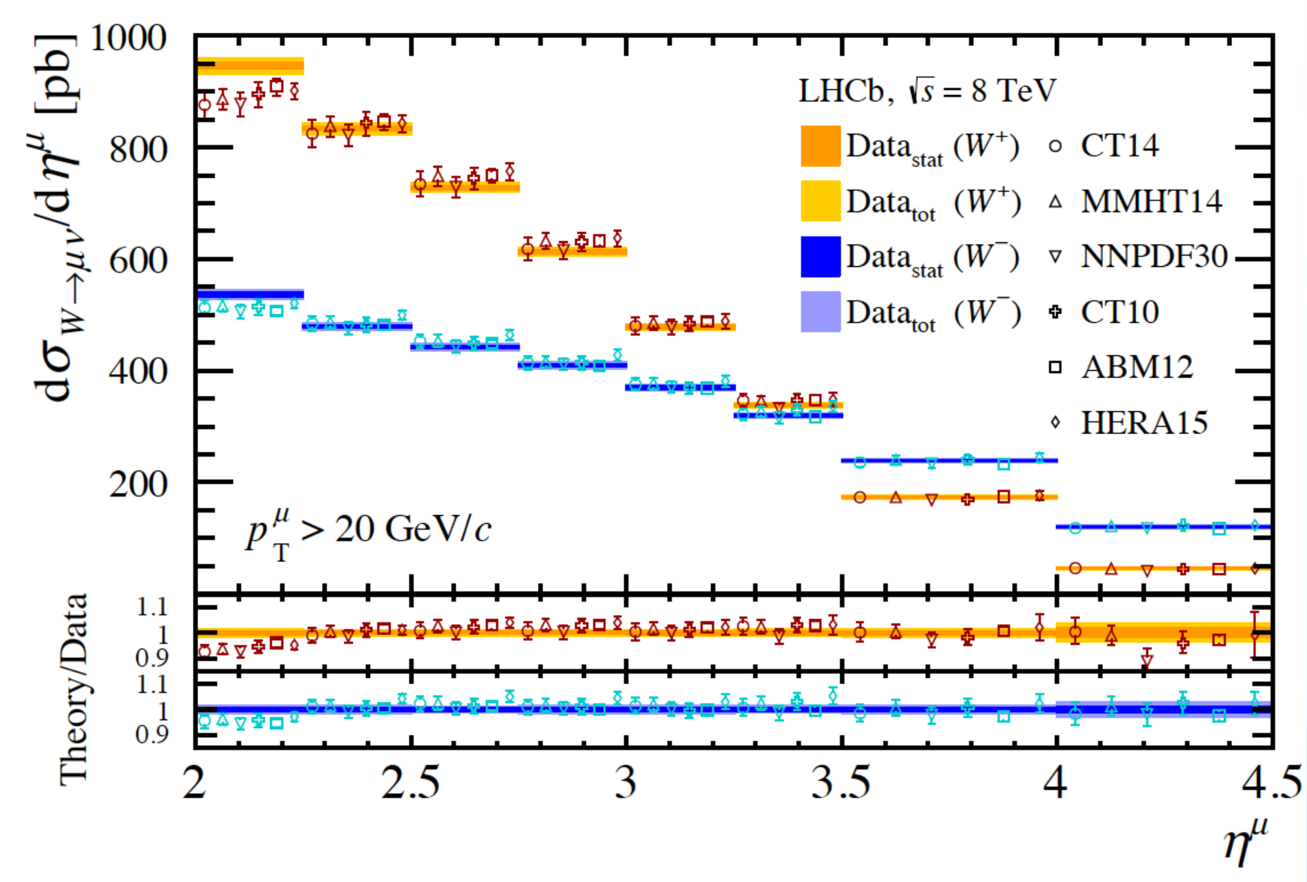
- In NNPDF3.1 we have three groups of processes that provide **direct information on the gluon**: inclusive jets, top pair differential, and the Z transverse momentum

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



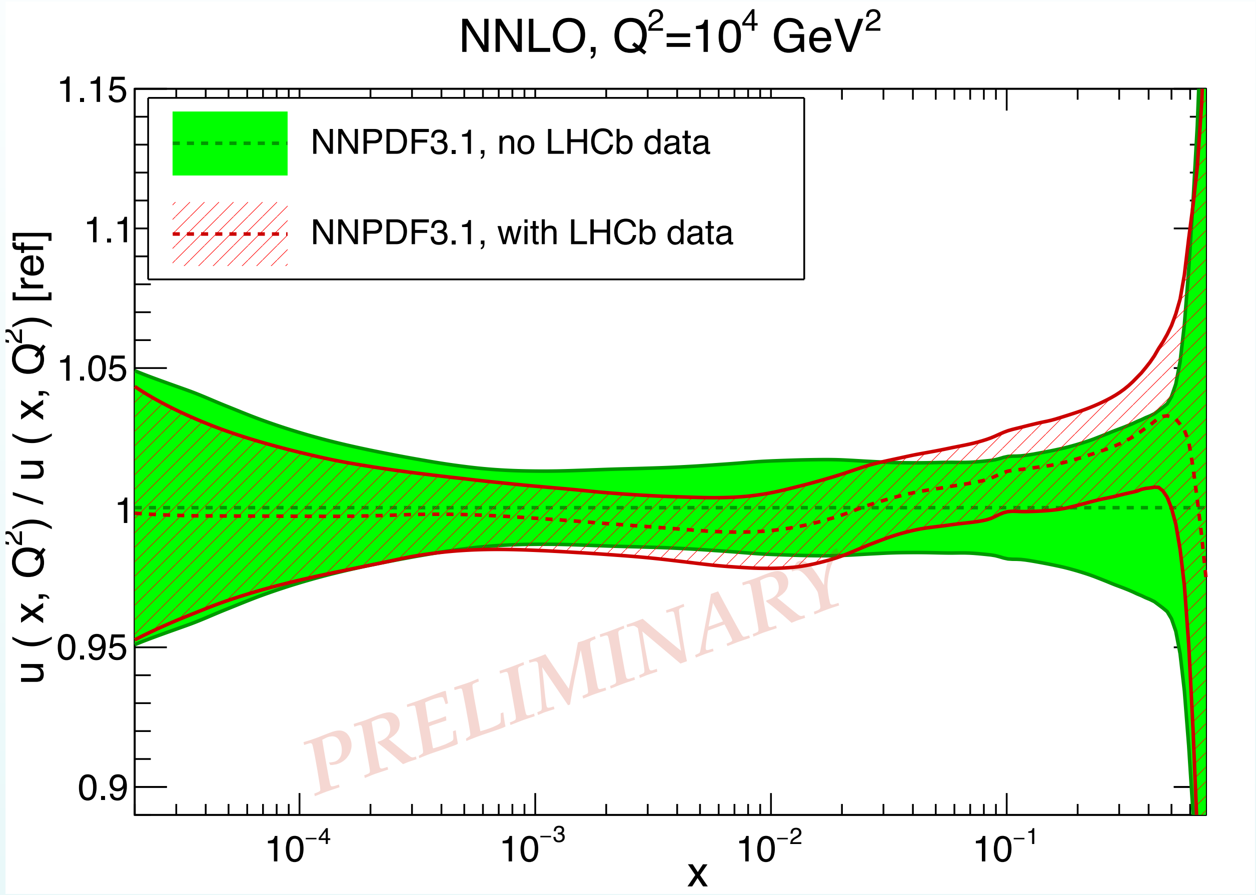
Forward W,Z production at LHCb

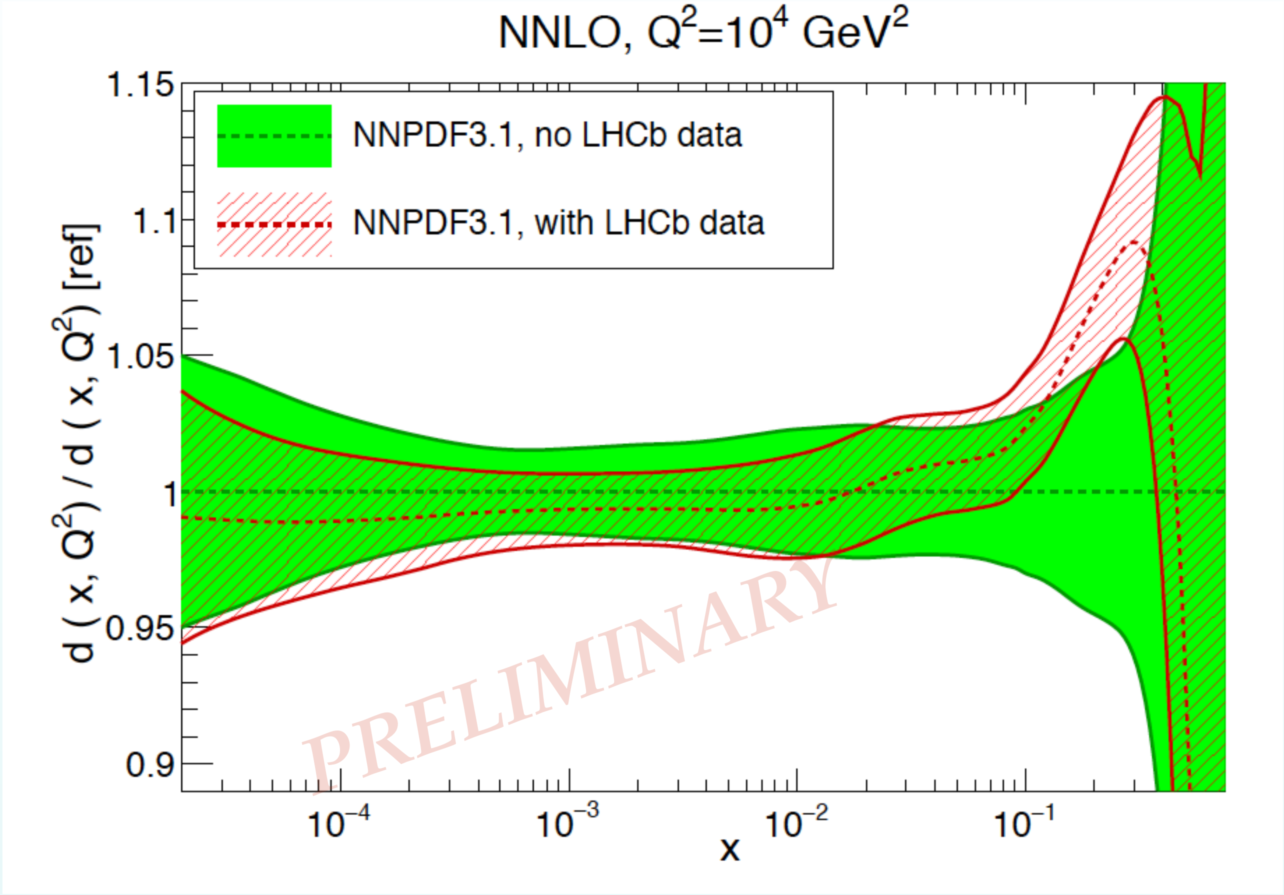




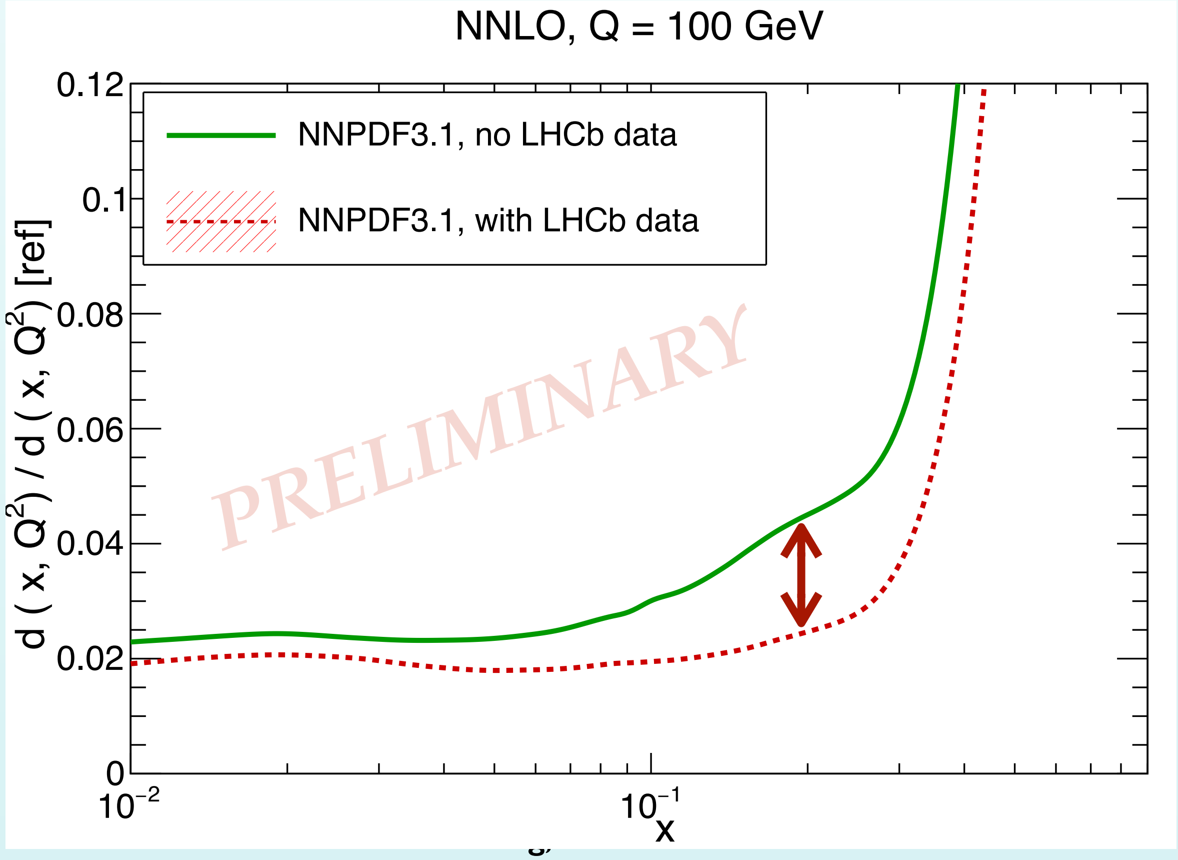
- NNPDF3.1 includes the **complete 7 TeV and 8 TeV W,Z measurements** in the muon channel, as well as **most of the electron channel measurements**
- Crucial to account for the **cross-correlations** between the W and Z data
- Expect improved **quark-flavor separation** for **large-x quarks,** thanks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

Forward W,Z production at LHCb





- 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

- **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!**

Extra Material

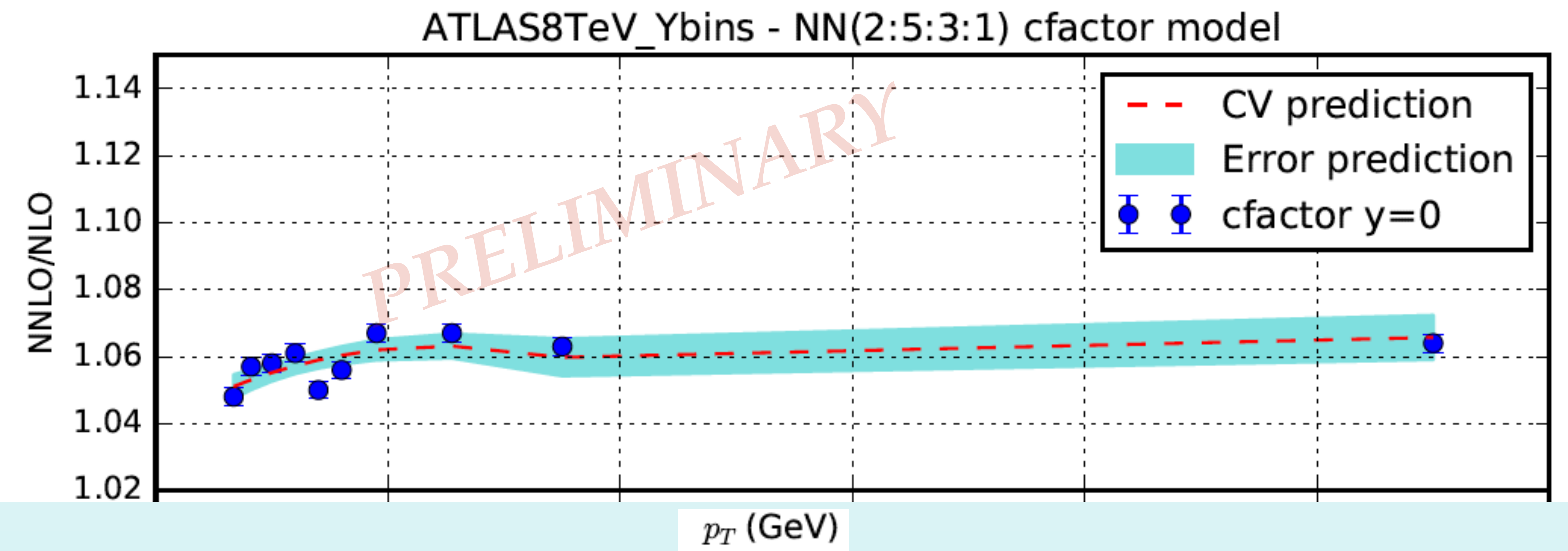
Fitting data with sub-percent errors

- 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**

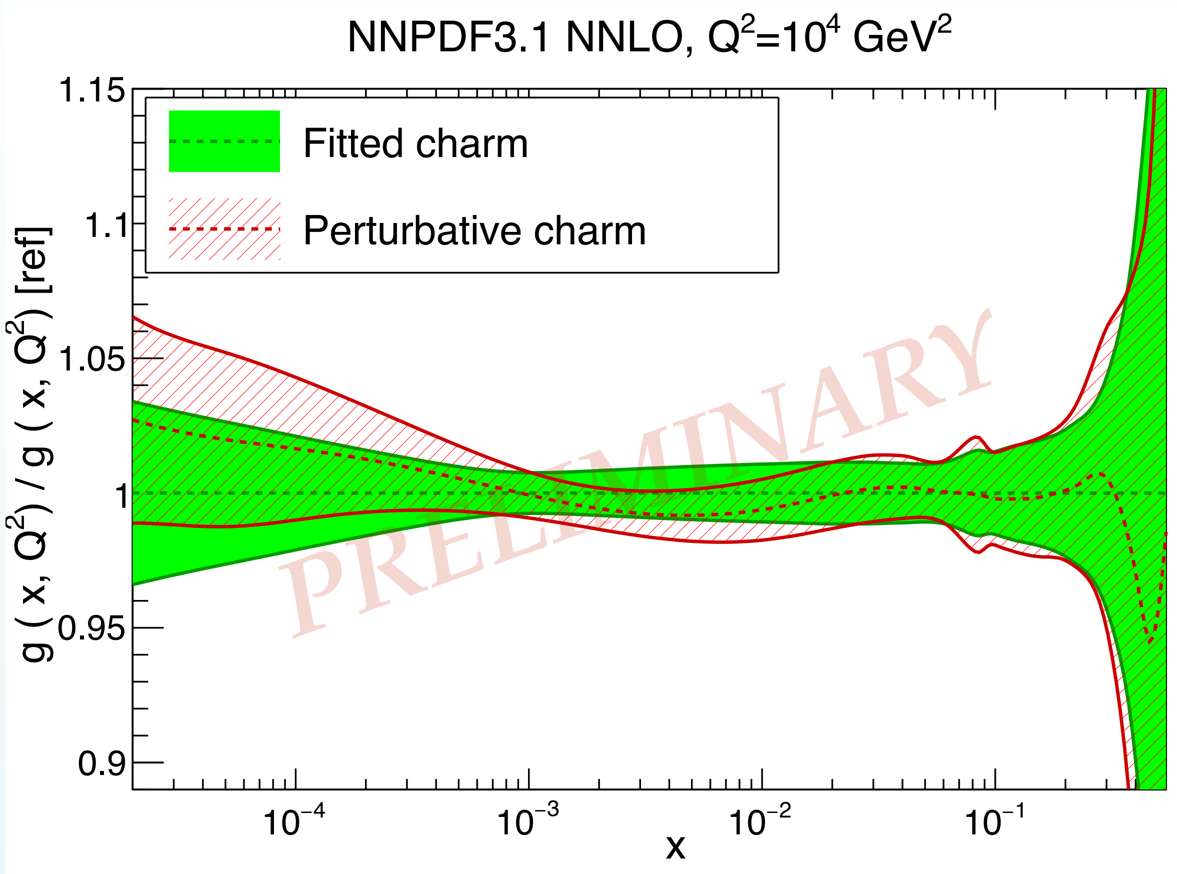
- We tackle this by including the MC stat integration error from the theory prediction as an **additional uncorrelated systematic error** in the χ^2

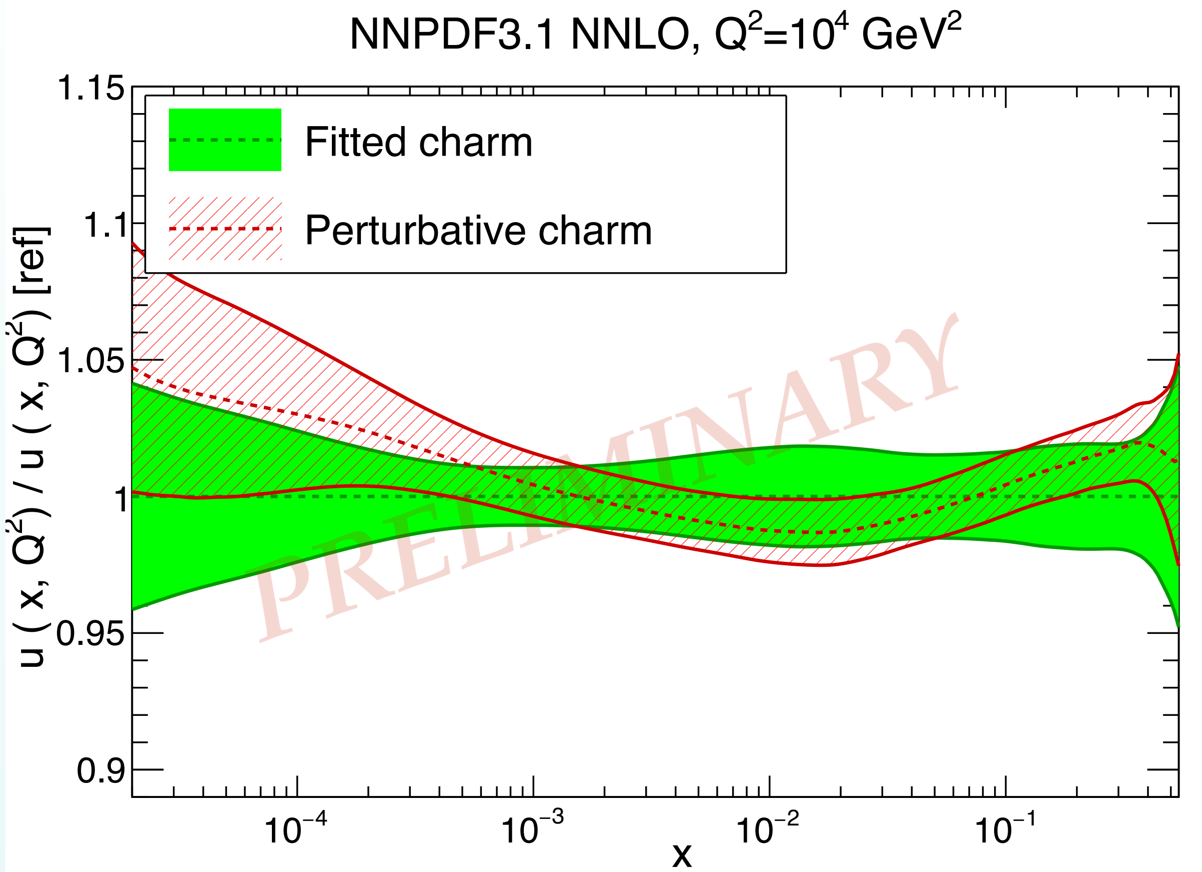
- This also implies that even **very small variations of the correlation model** (which ultimately determines what is correlated and what uncorrelated) can lead to very large variations of the χ^2 for same input theory

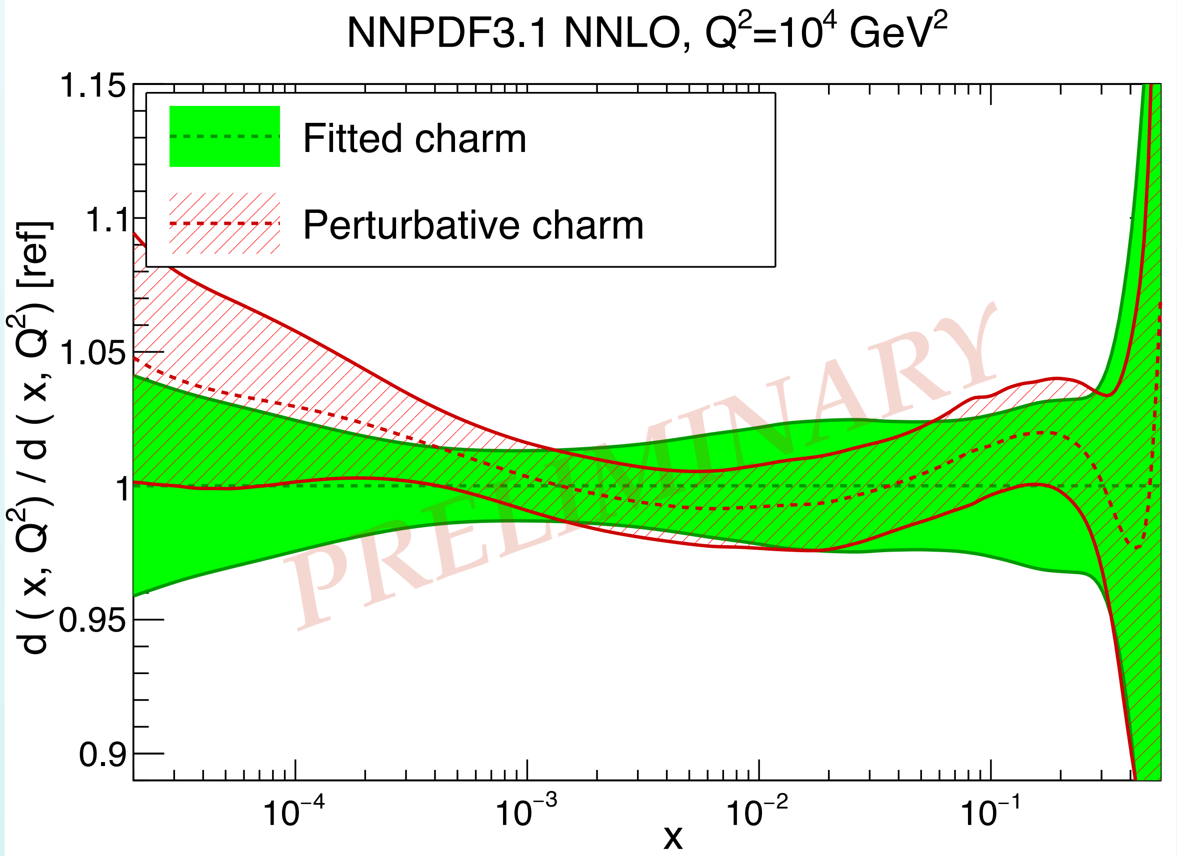
- To avoid this, measurements should provide an **estimate of the uncertainty associated with correlations**

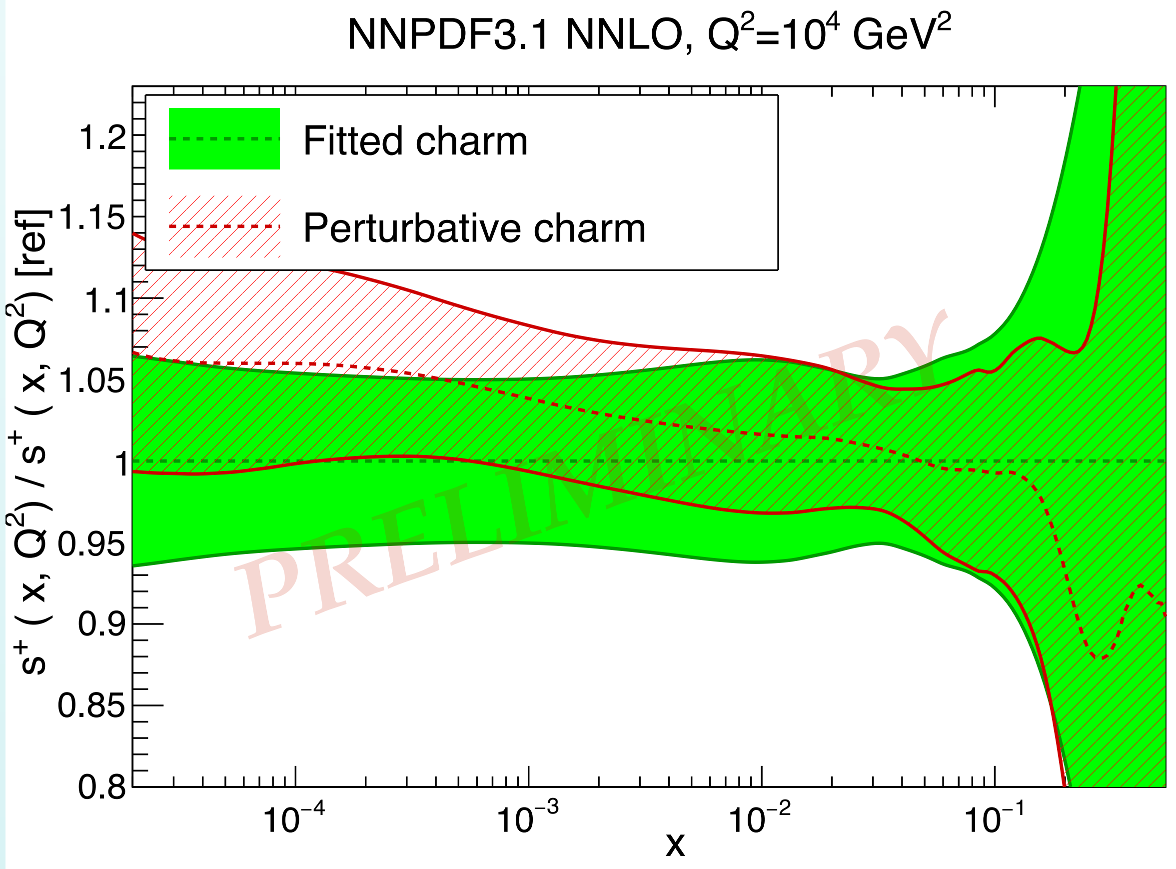


Fitted charm vs perturbative charm

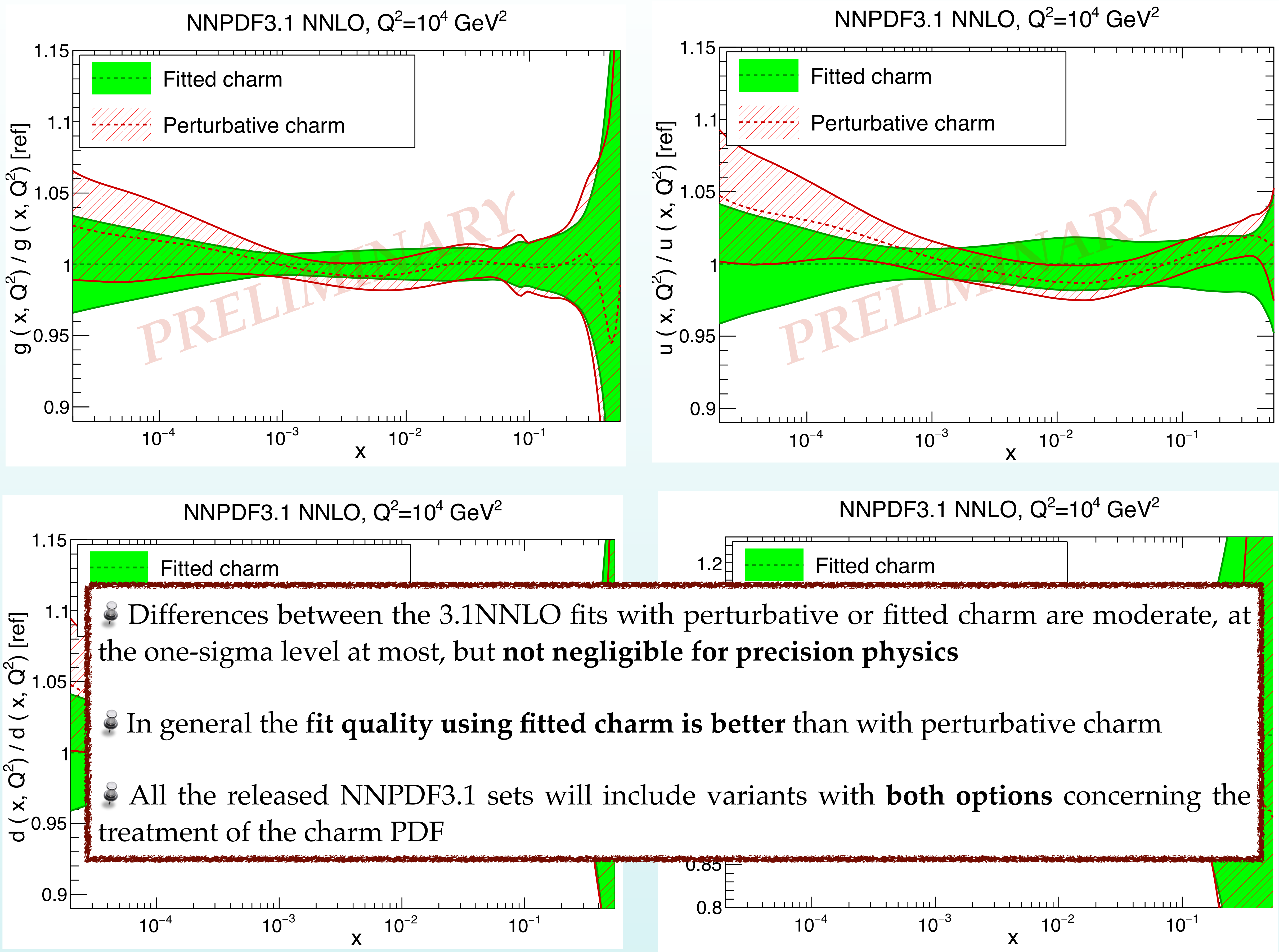






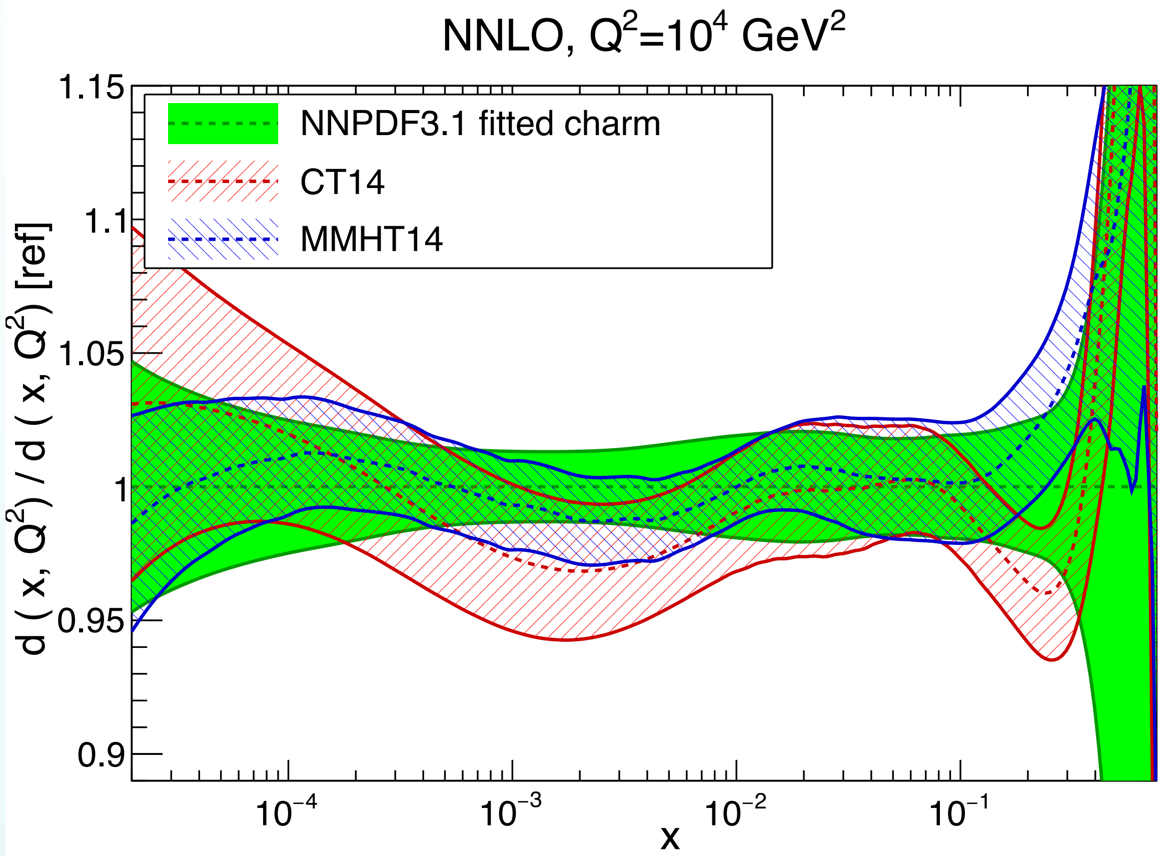


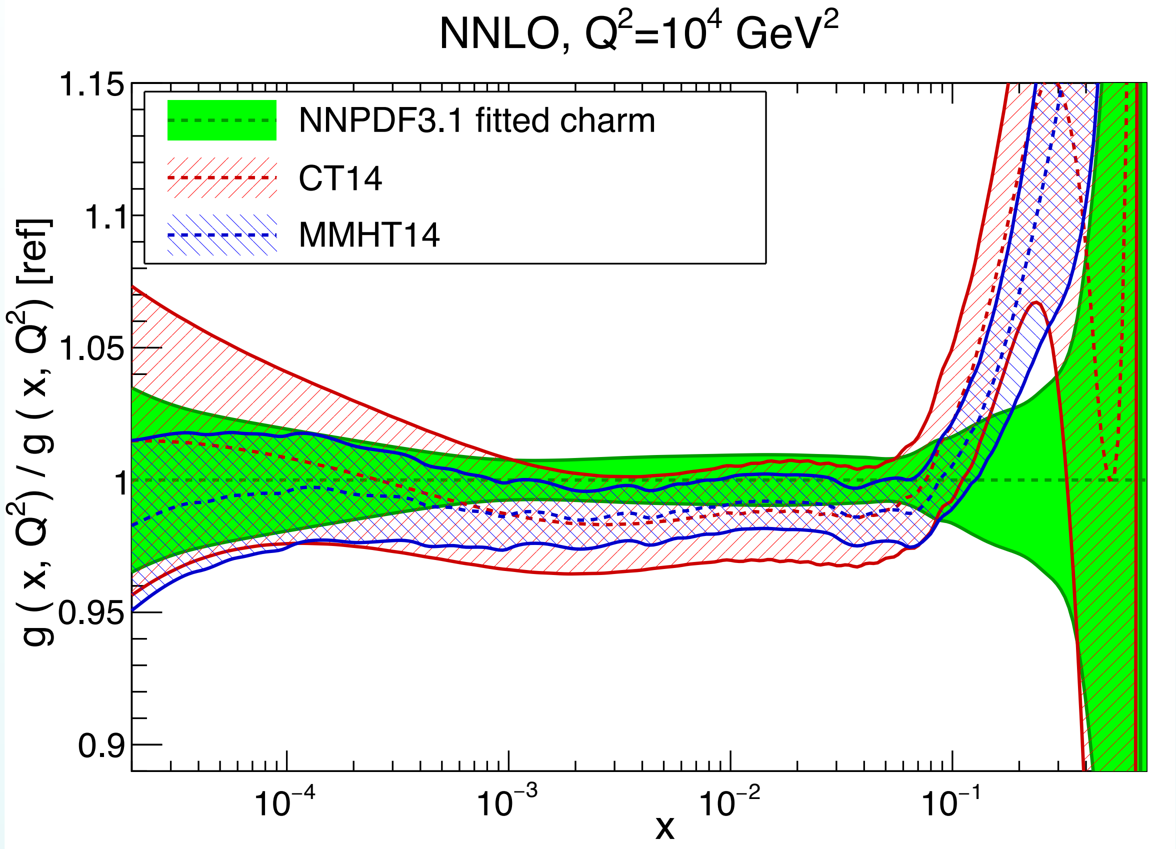
Fitted charm vs perturbative charm

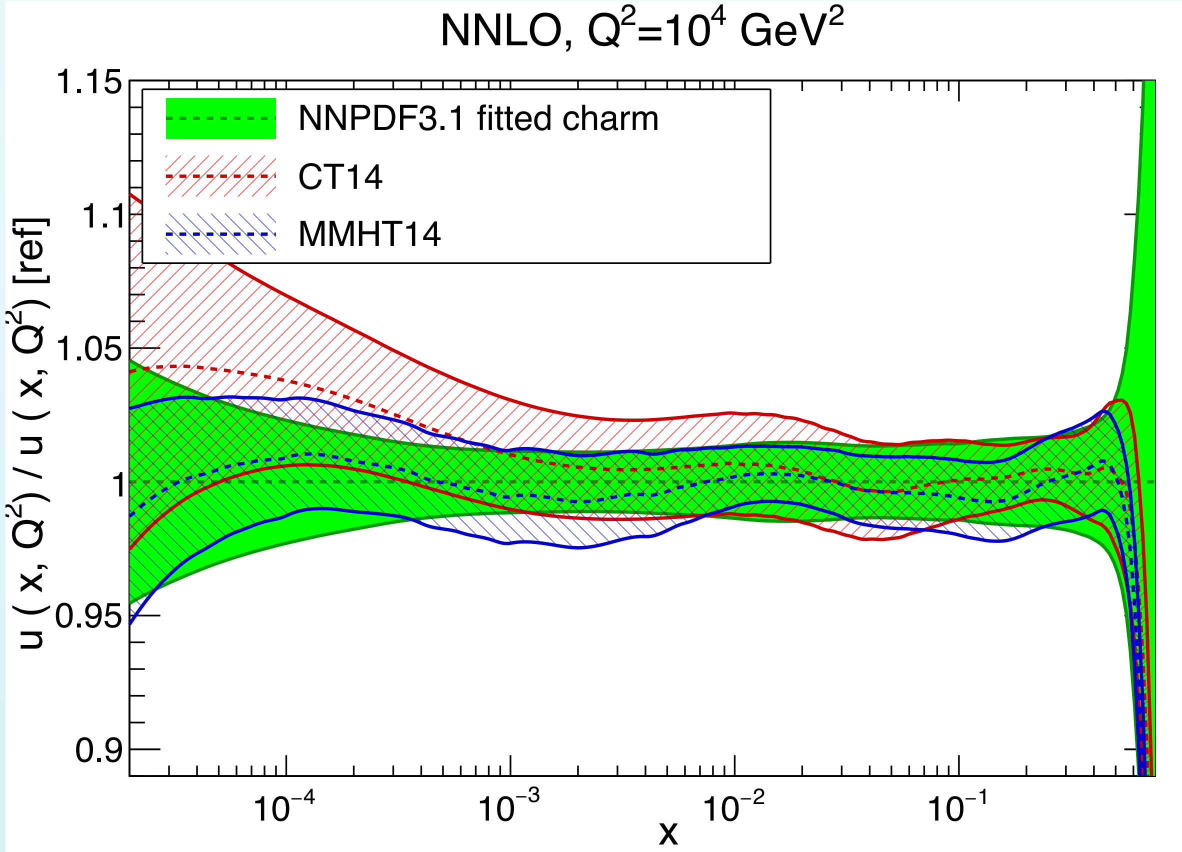


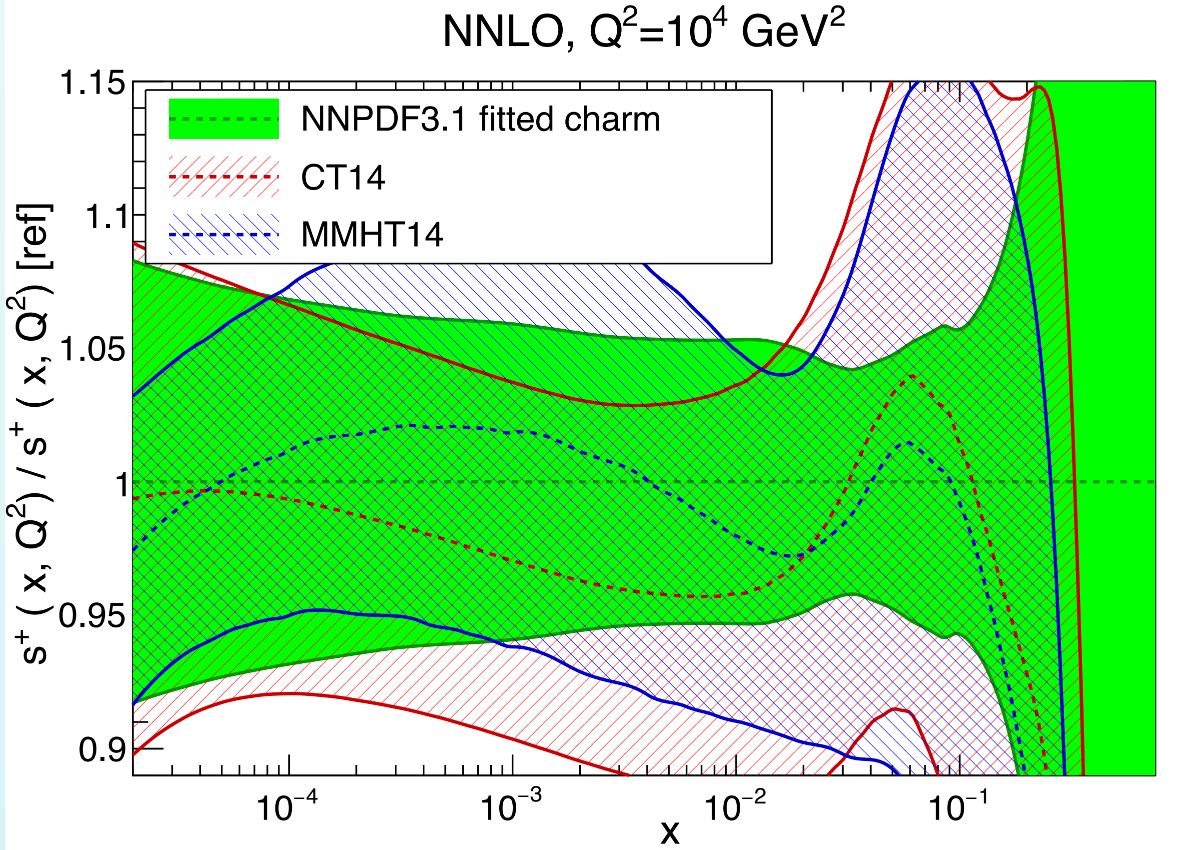
- Differences between the 3.1NNLO fits with perturbative or fitted charm are moderate, at the one-sigma level at most, but **not negligible for precision physics**
- In general the **fit quality using fitted charm is better** than with perturbative charm
- All the released NNPDF3.1 sets will include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

Comparison with MMHT and CT

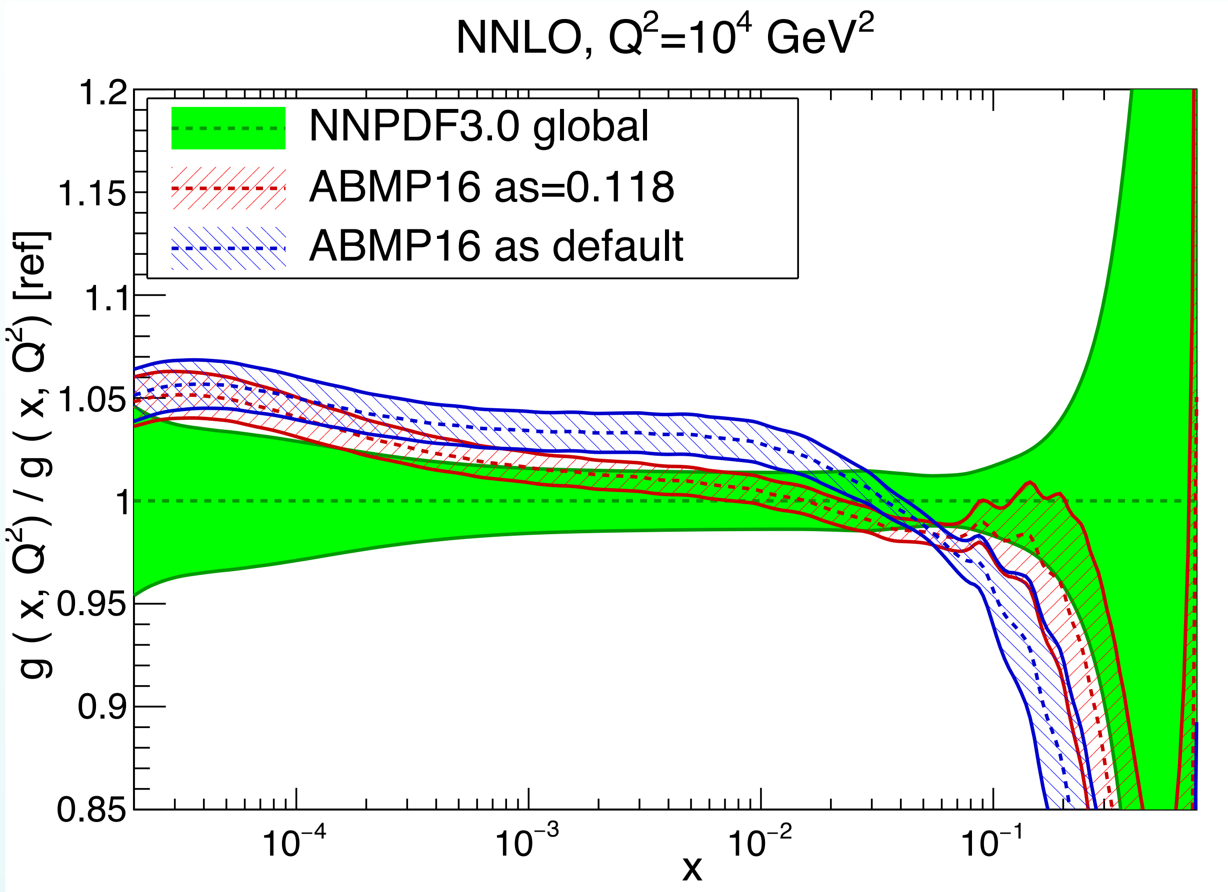


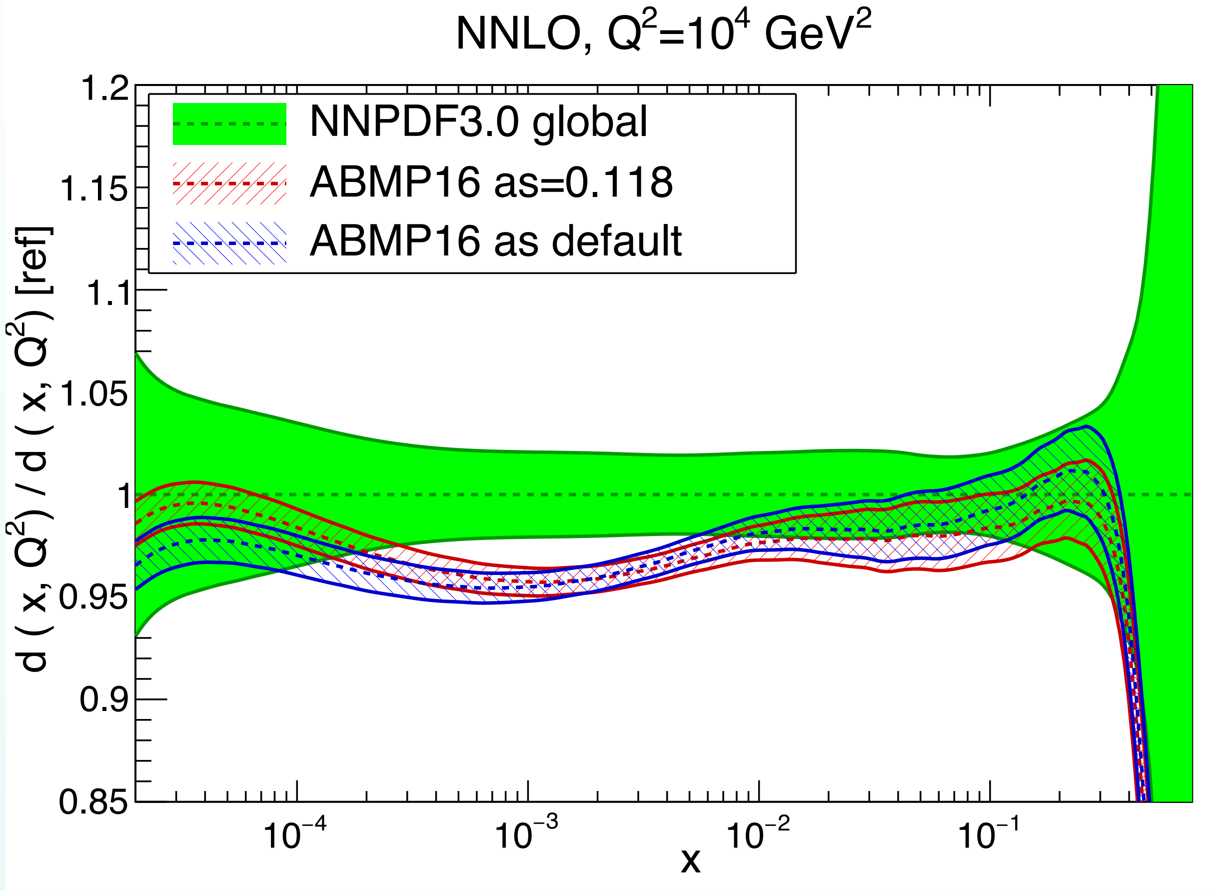


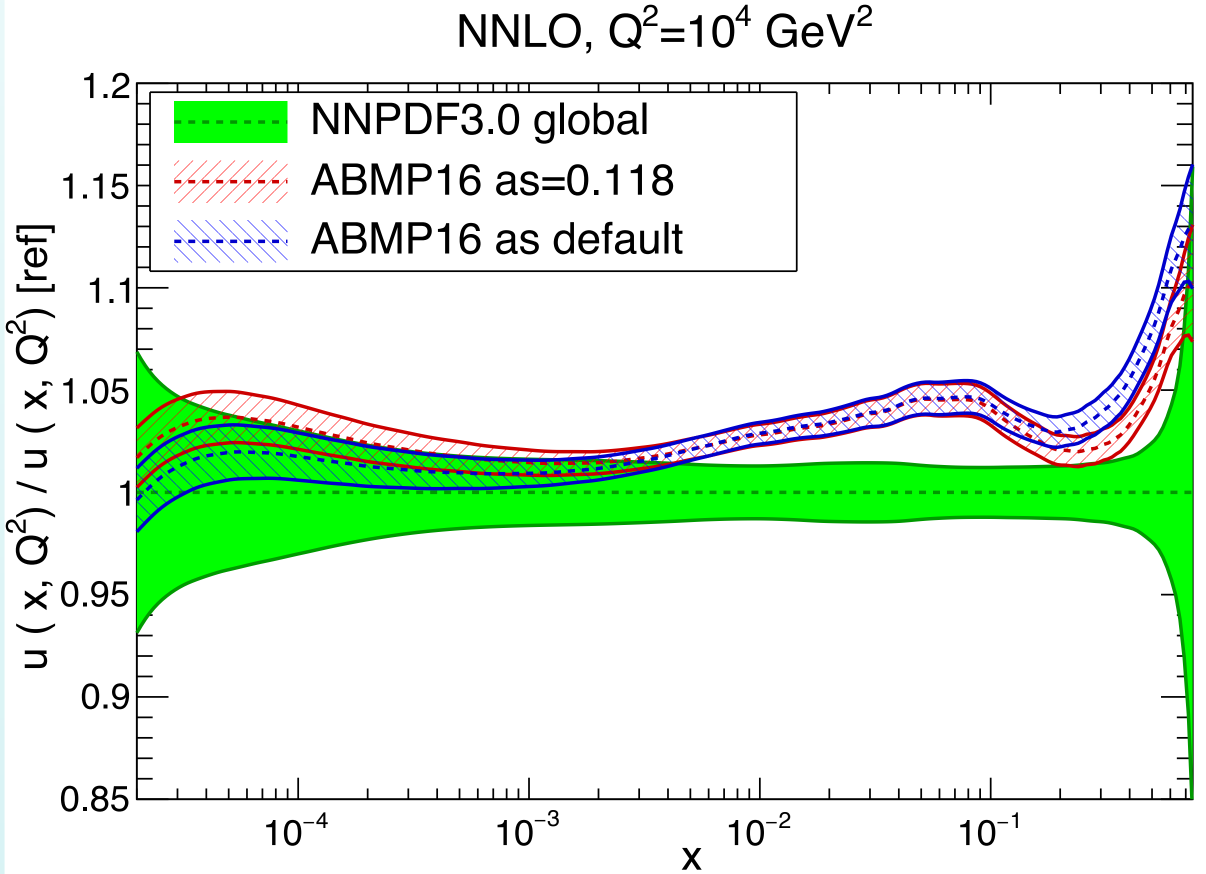


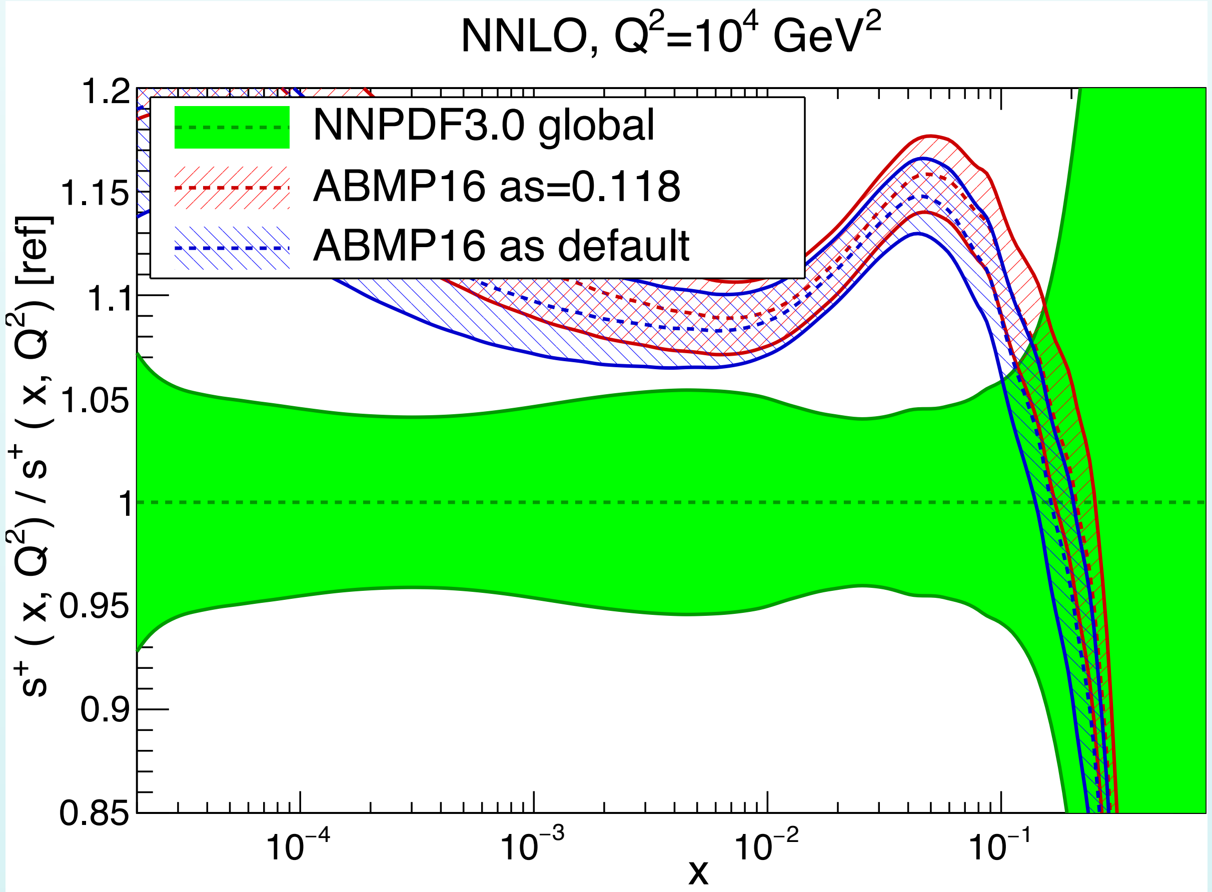


Comparison with ABMP16

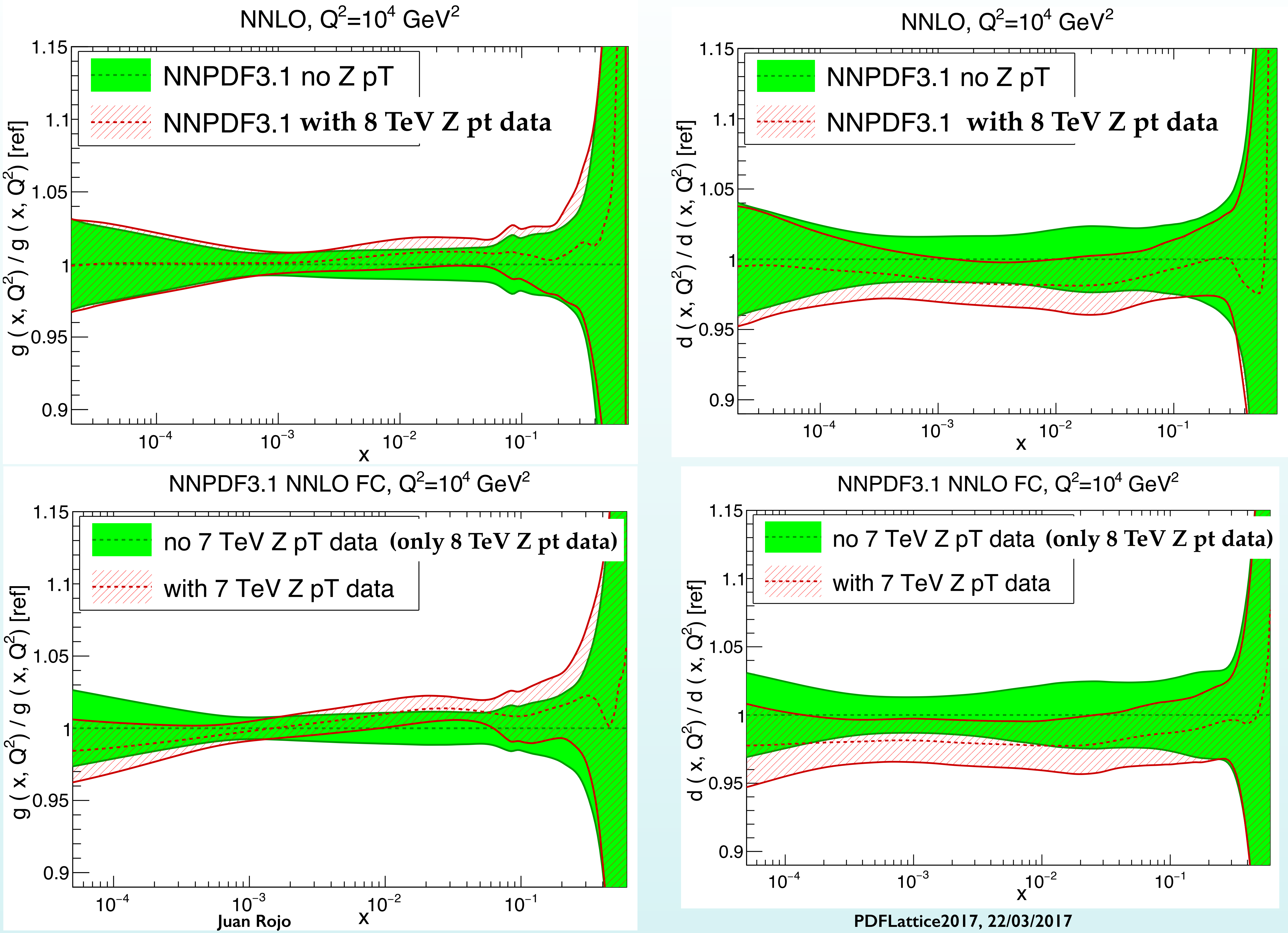




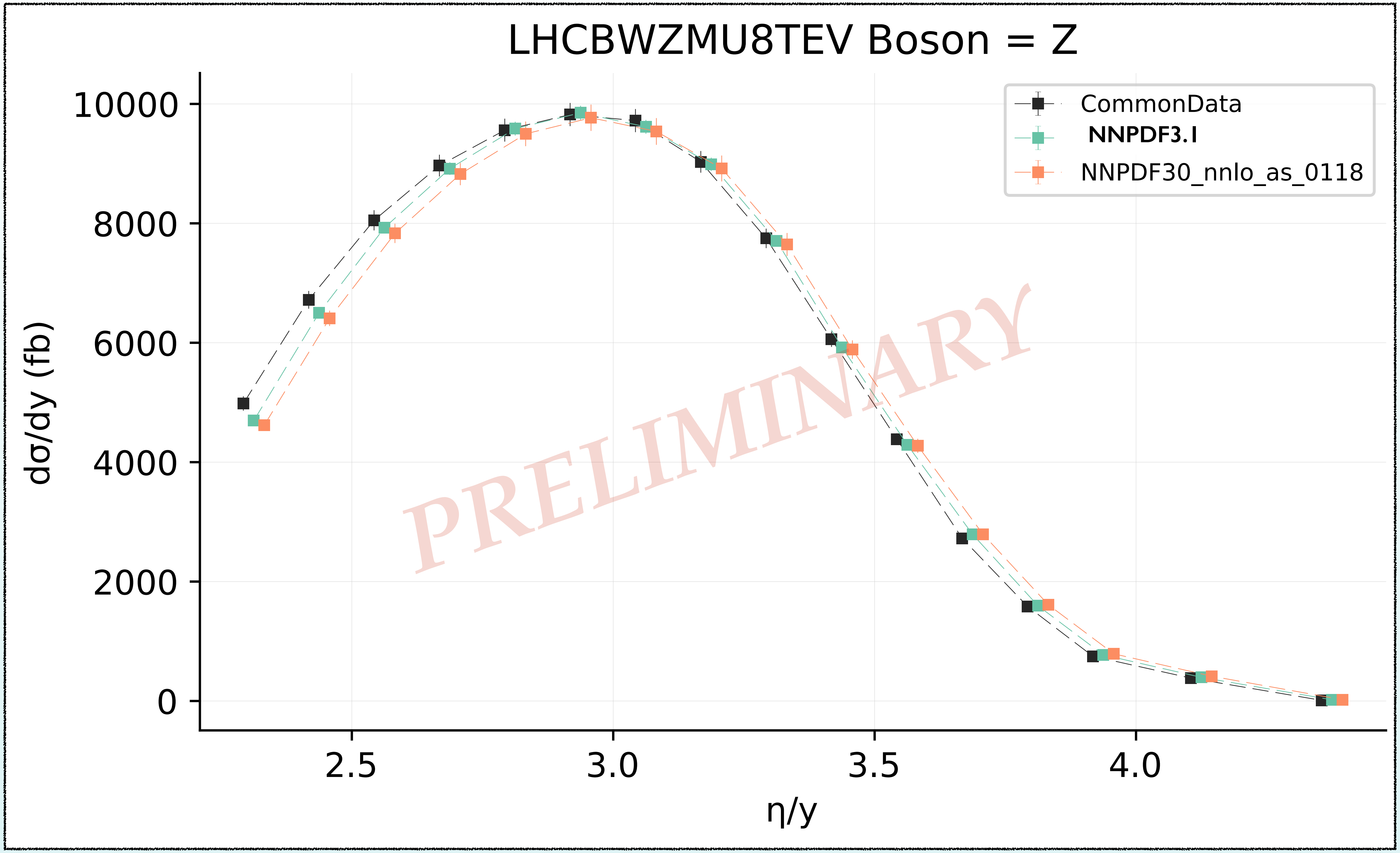




Impact of ATLAS 7 TeV Z p_T data



Forward W,Z production at LHCb

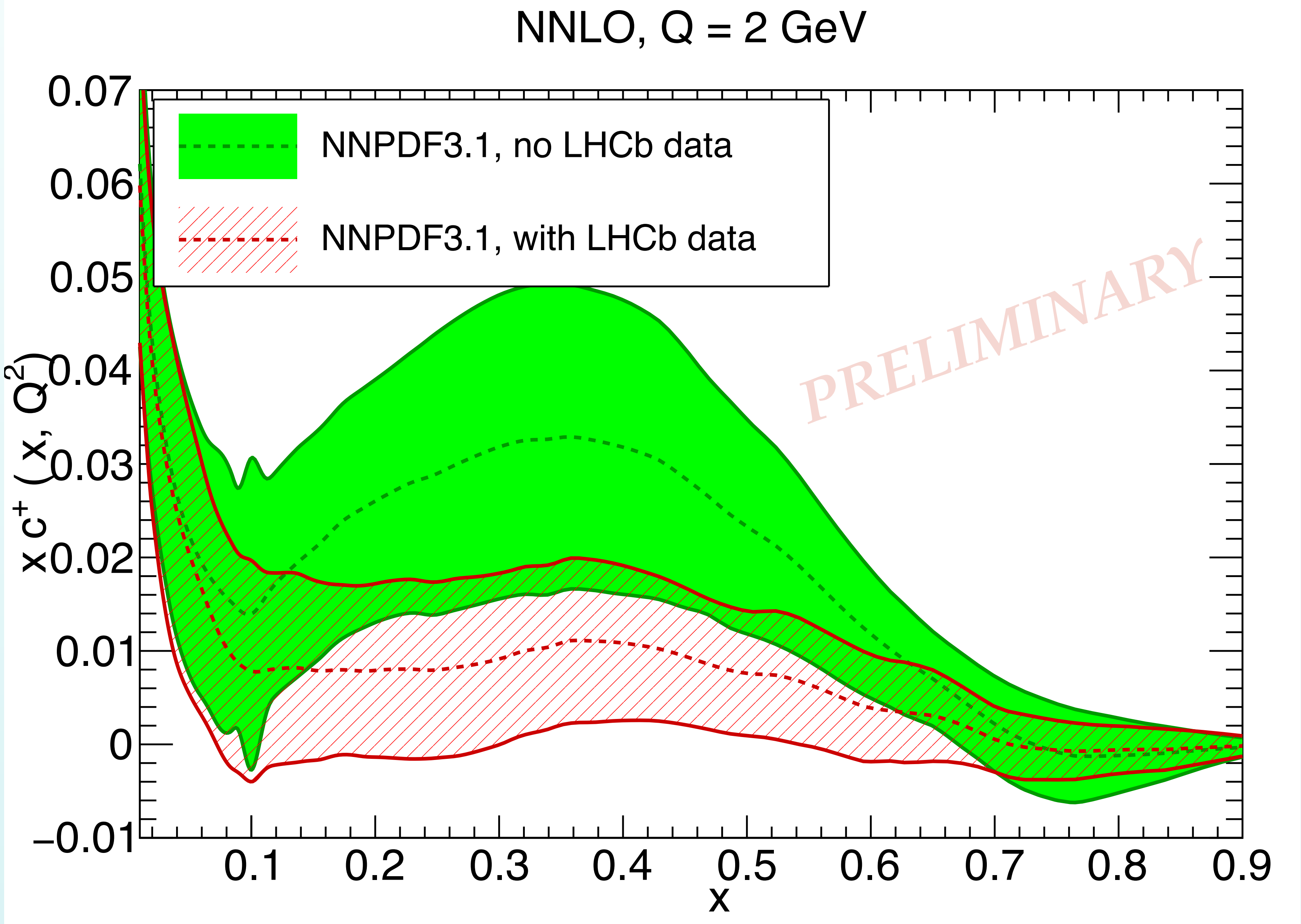


- For Z production, also improved **shape agreement** in NNPDF3.1
- Overall fit quality for LHCb experiments: **$\chi^2/N = 1.4$ (1.9) at NNLO (NLO**). Note NNLO crucial!

Charm content of proton revisited

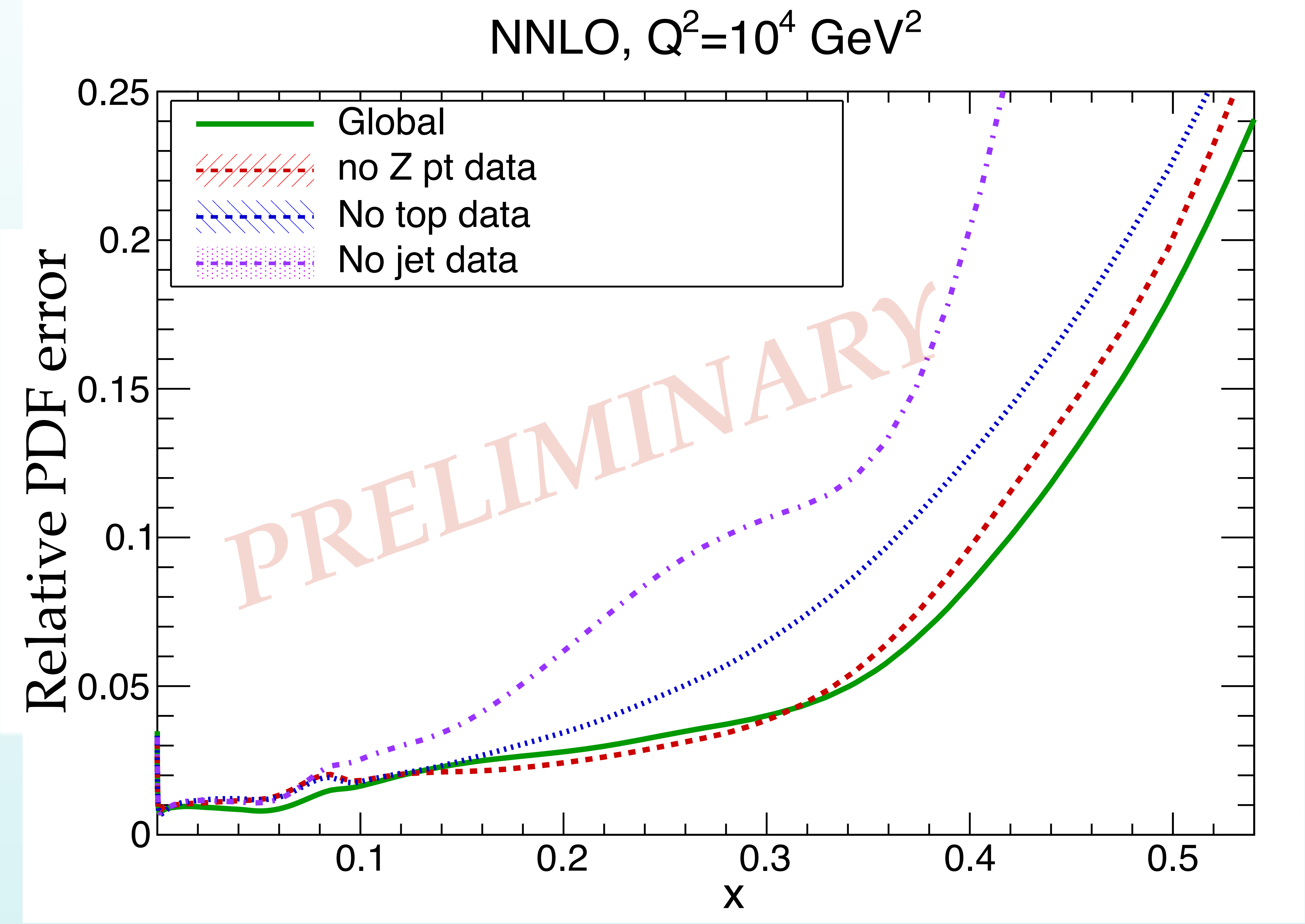
- The **new collider measurements** provide important constraints on the **large-x charm PDF**, for instance, the 7 and 8 TeV W,Z measurements from LHCb

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

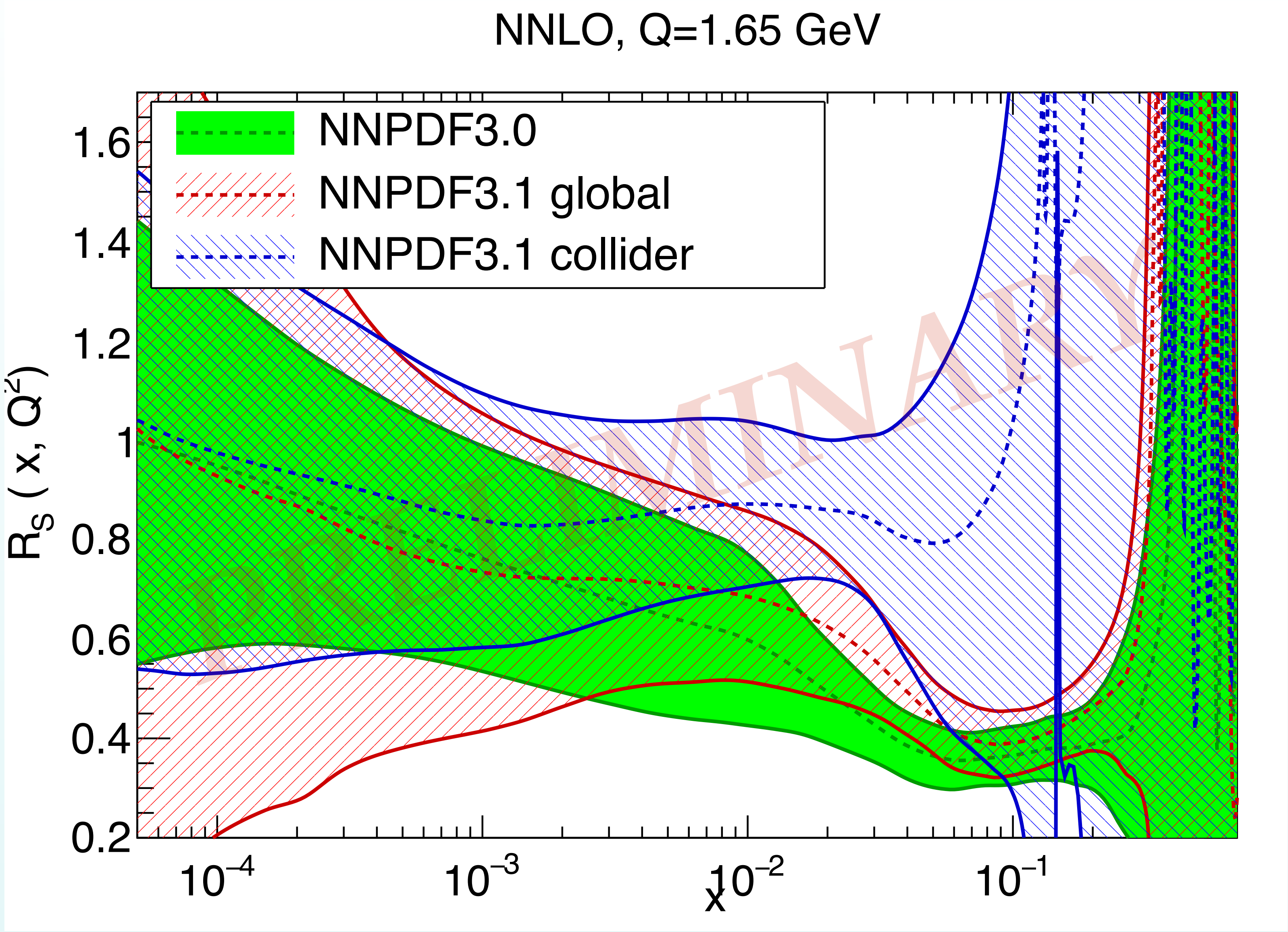


Impact on the gluon

- 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

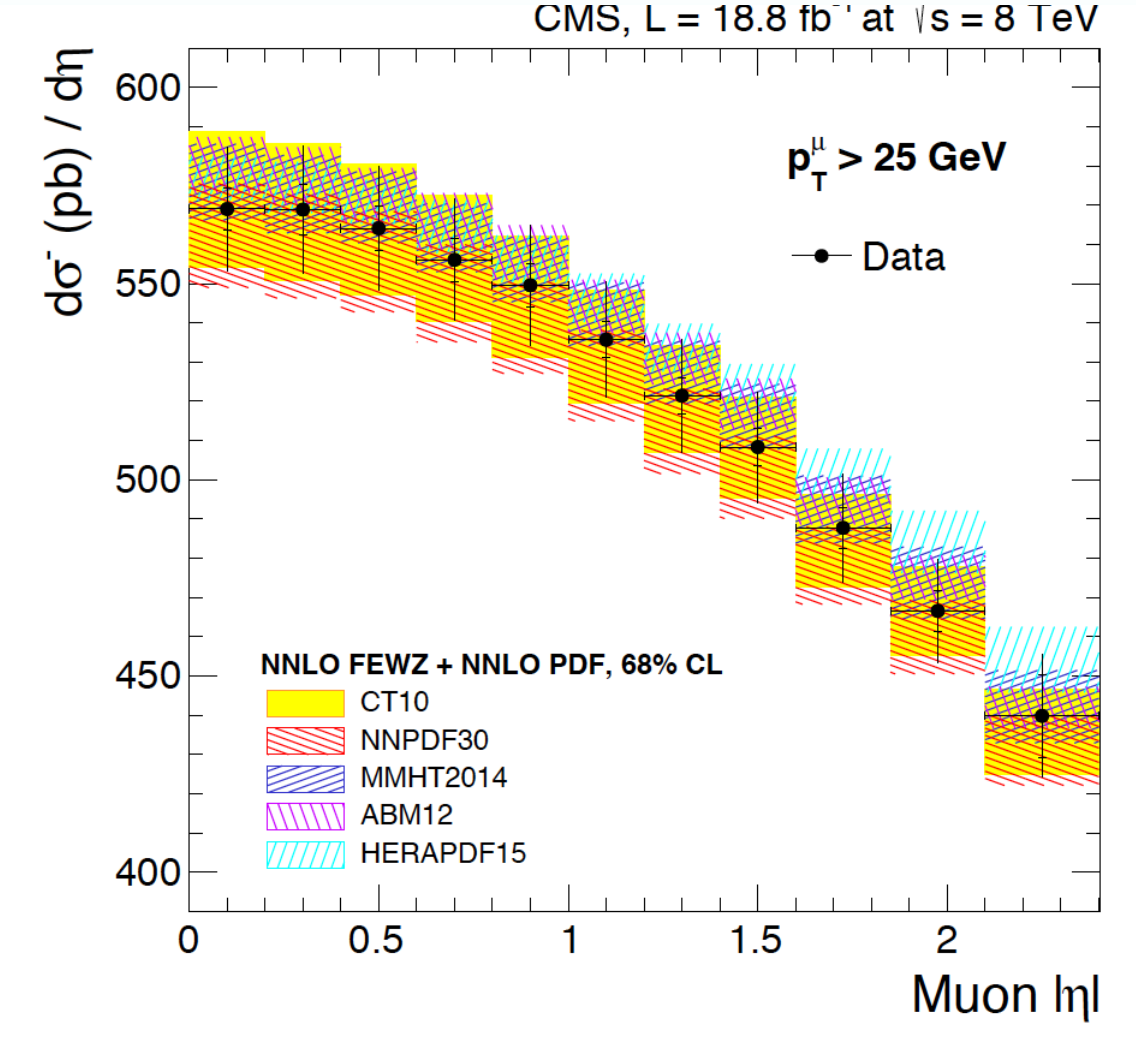


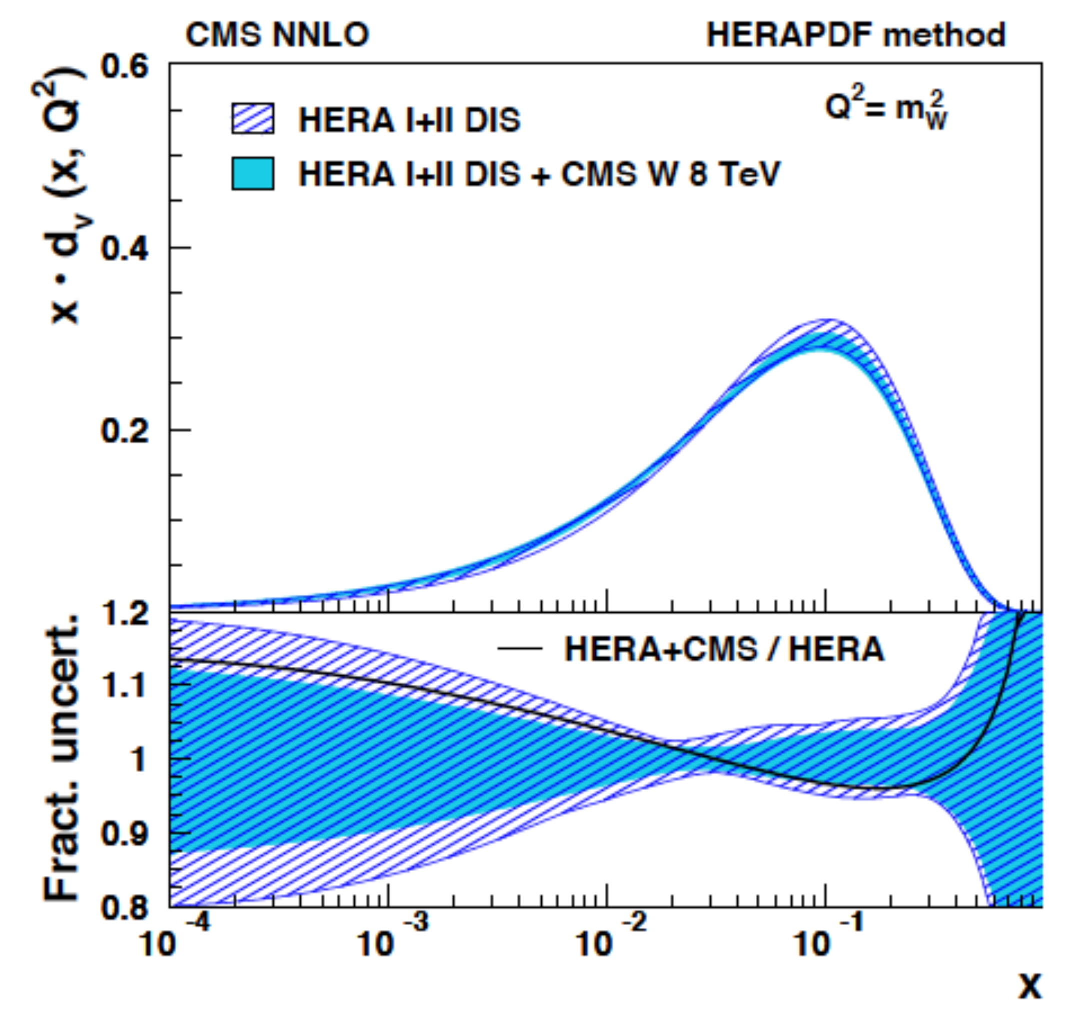
- **Collider-only and global fits** in agreement within PDF uncertainties

- 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**!

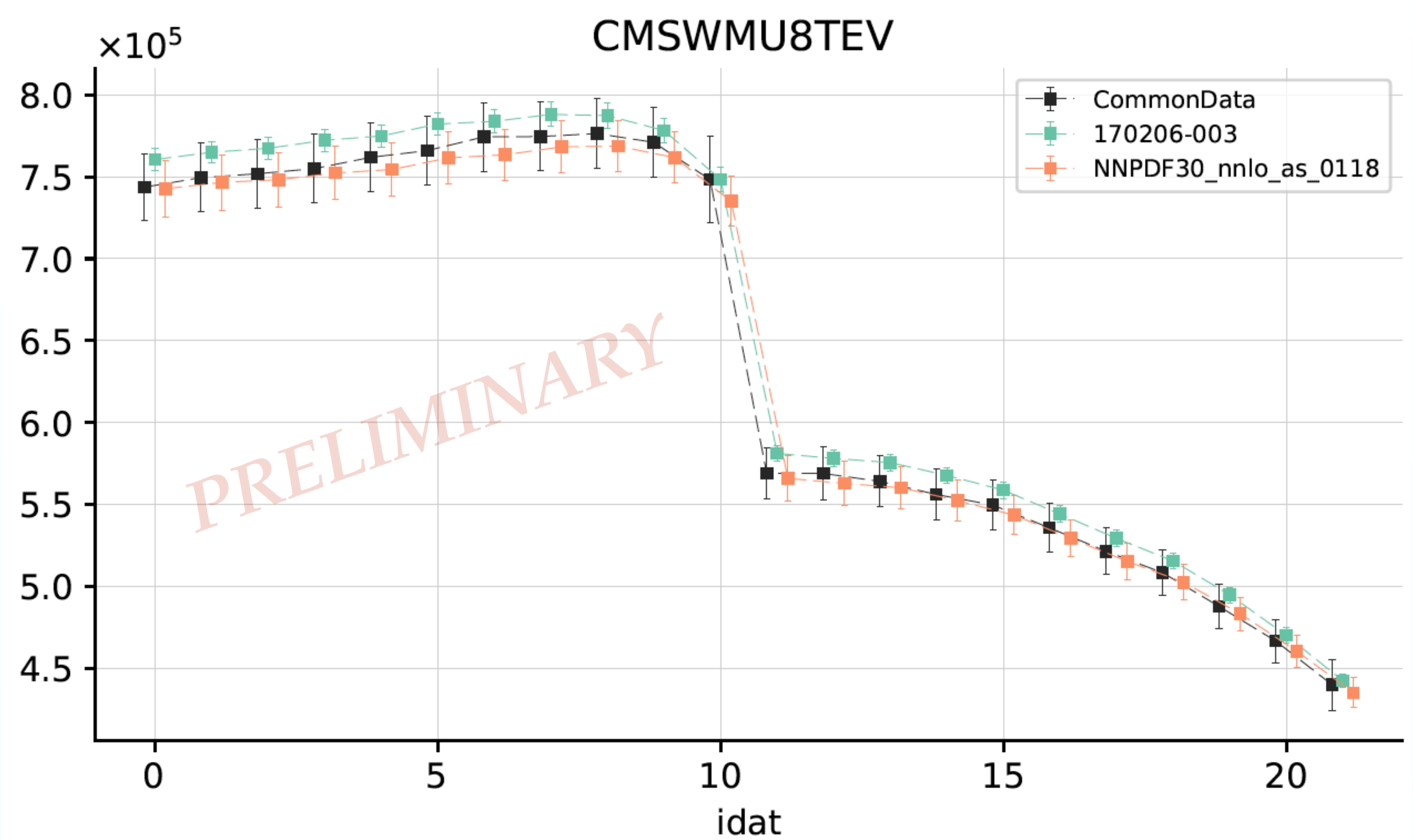
CMS 8 TeV W rapidity





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

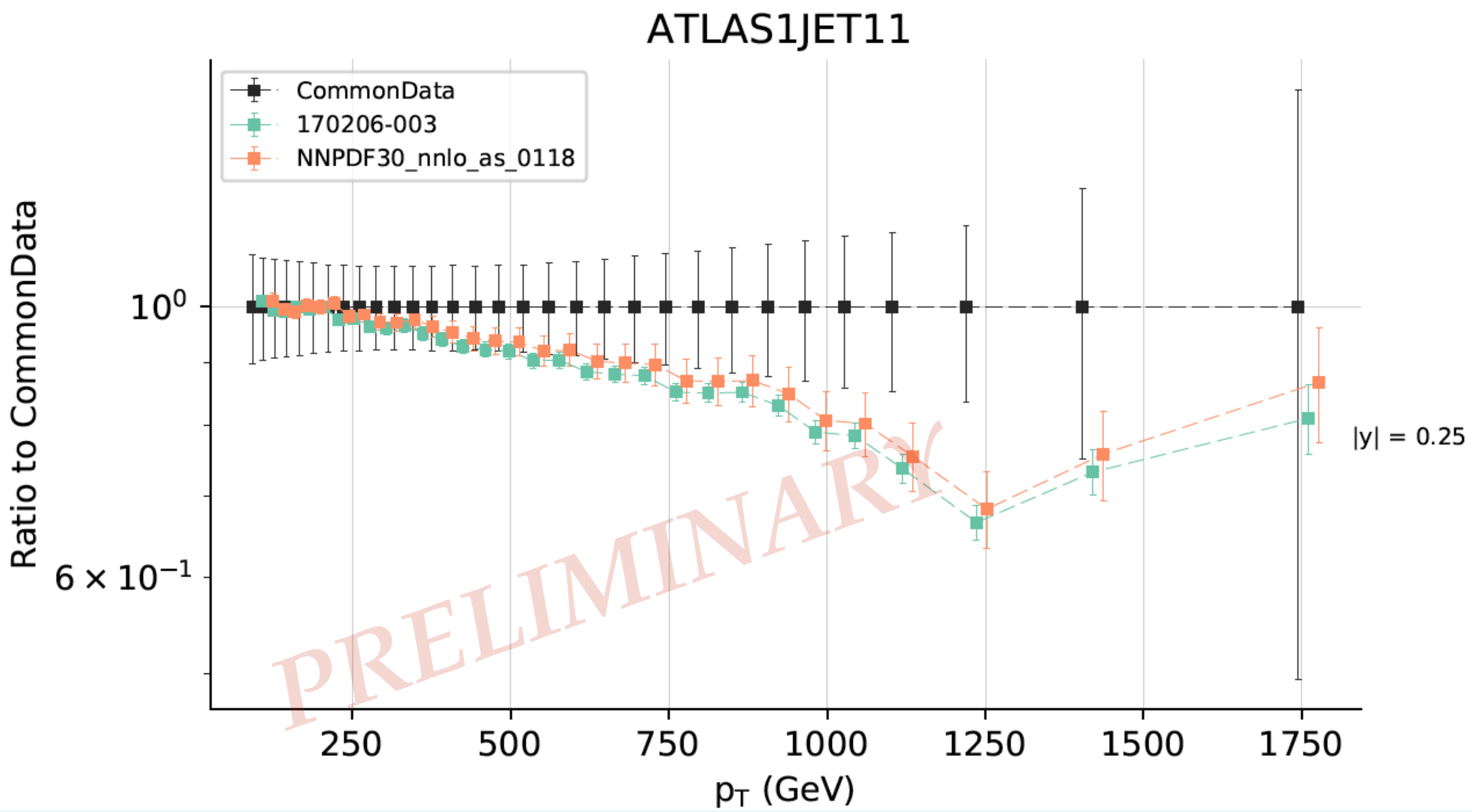
CMS 8 TeV W rapidity



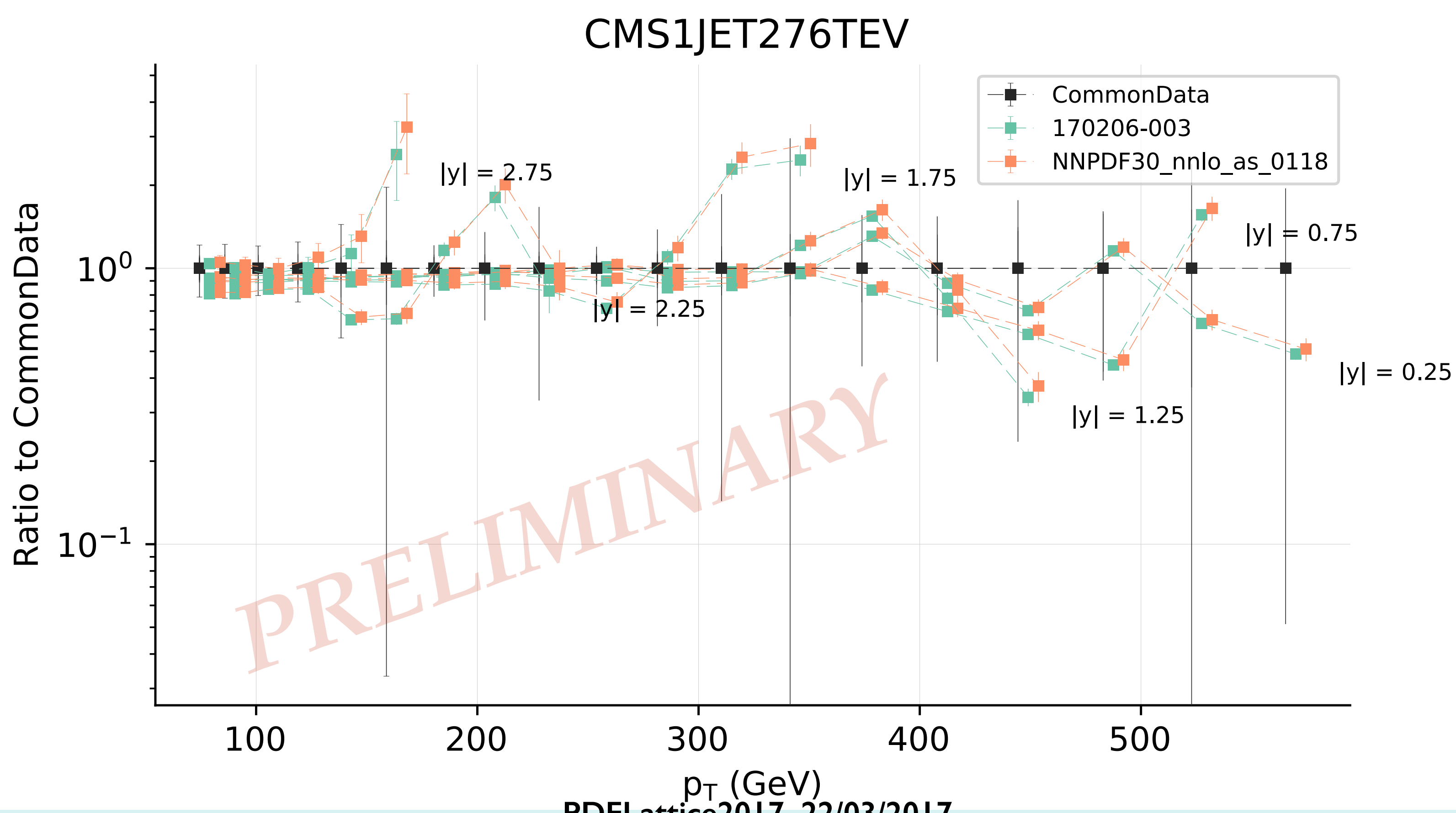
- Good agreement data / theory, similar to that in NNPDF3.0, with **χ^2/N_{dat} = 1.0** at NNLO

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

Inclusive jets in NNPDF3.1

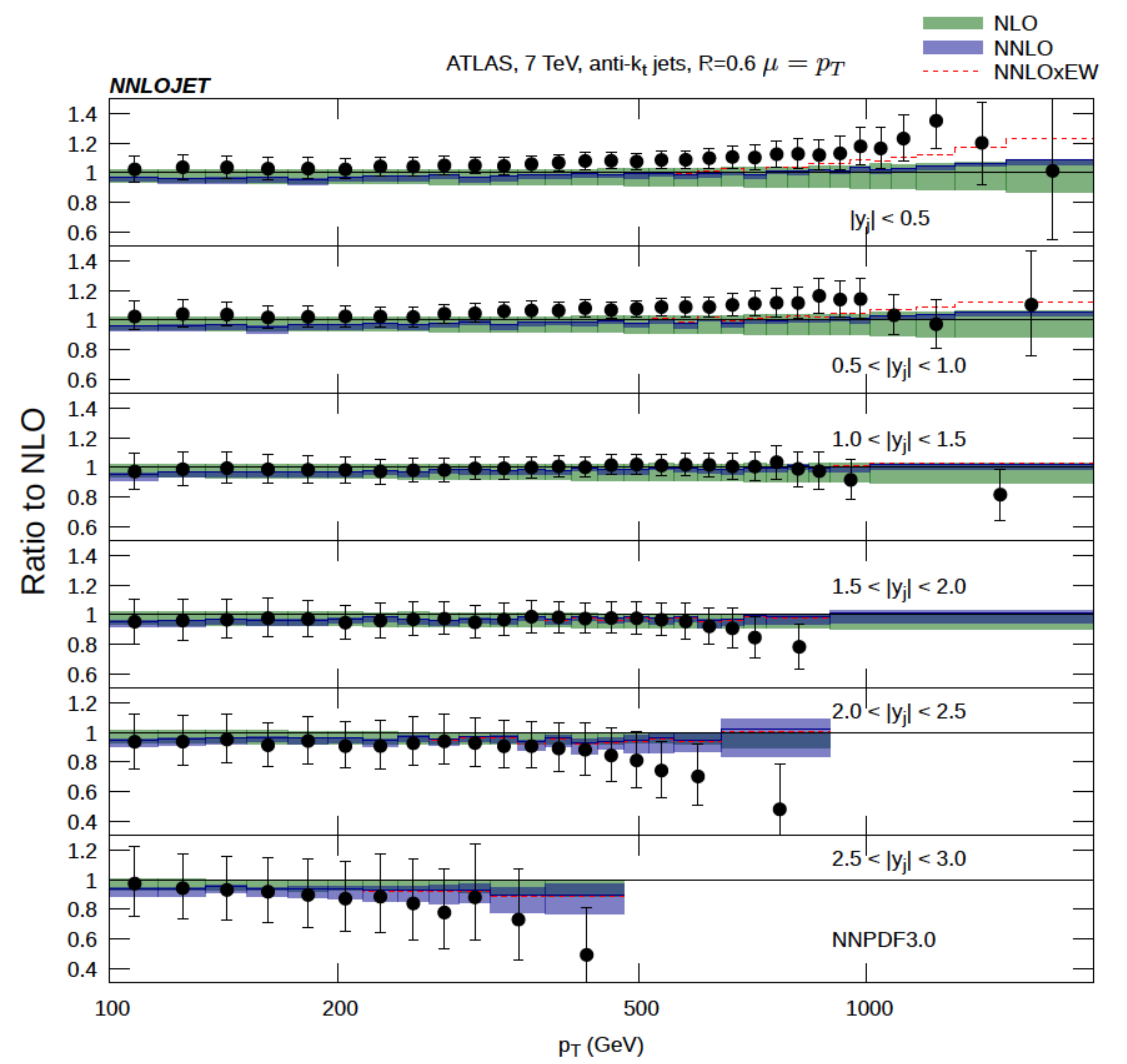


Good agreement with experimental data, as was the case in NNPDF3.0



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

Jets at NNLO



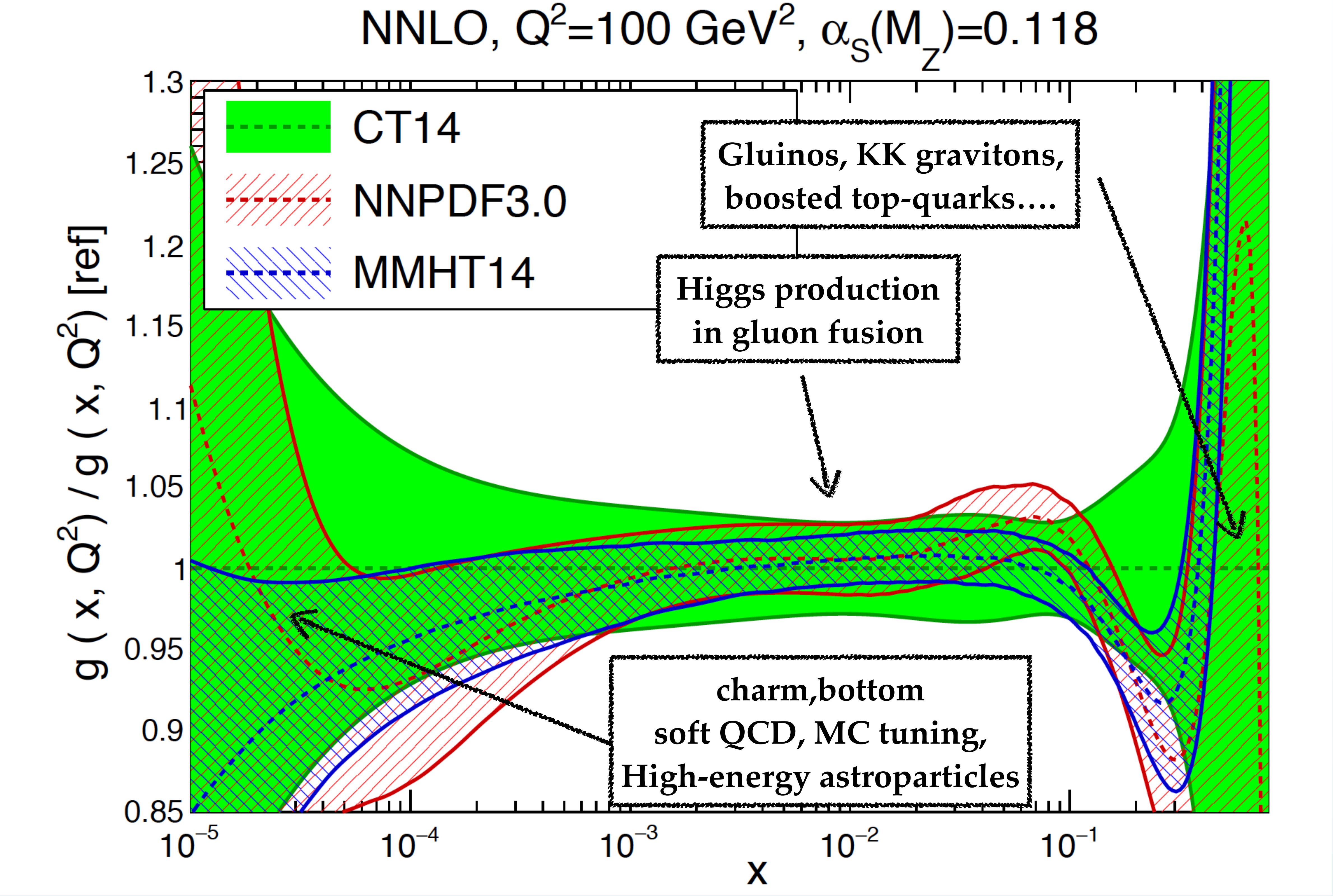
- If the **jet pT is used as central scale**, NNLO/NLO K-factors only a few percent

- 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



Gluinos, KK gravitons, boosted top-quarks….

Higgs production in gluon fusion

charm,bottom
soft QCD, MC tuning,
High-energy astroparticles

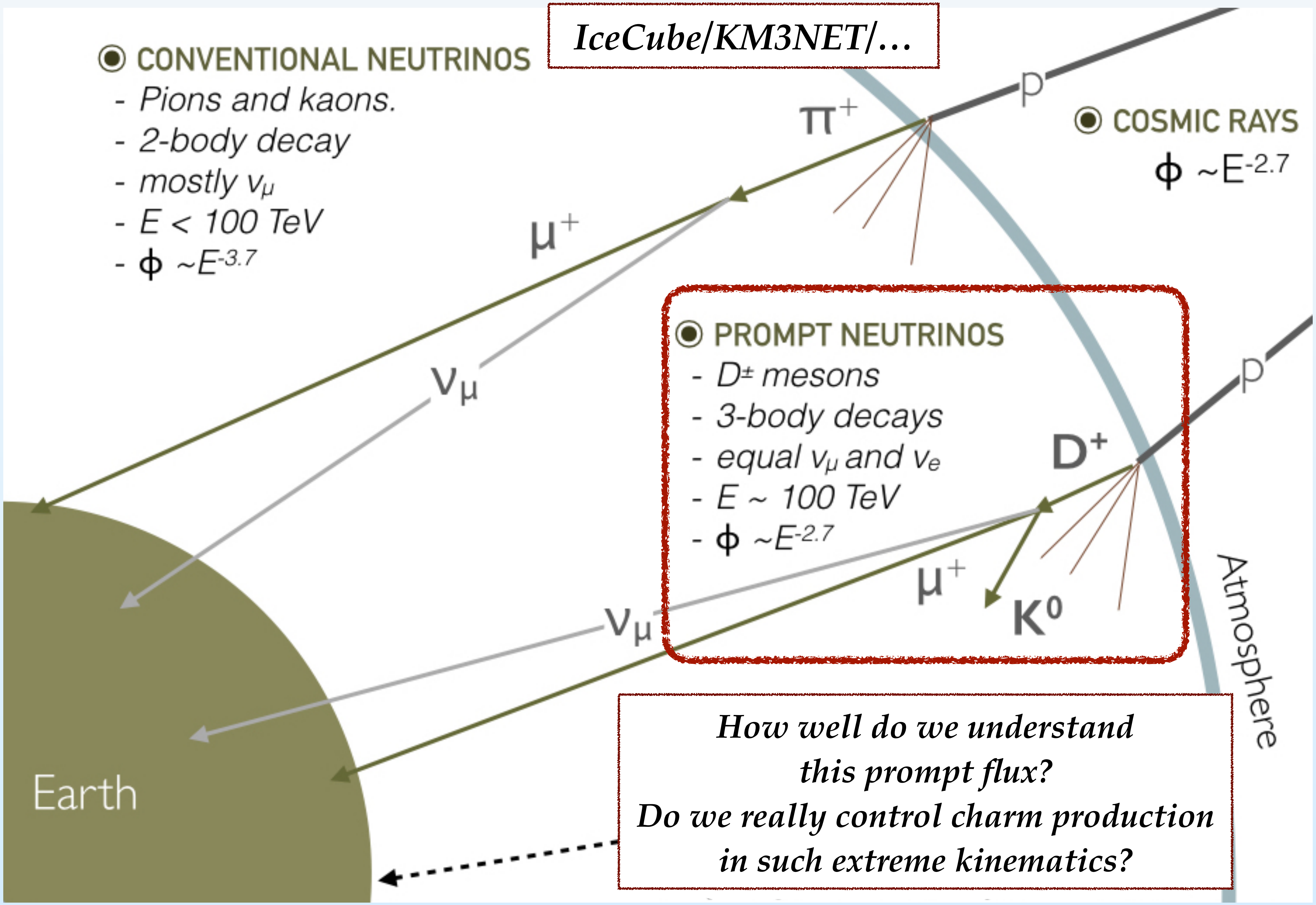
Exploit PDF-sensitive LHC measurements to **constrain the gluon at small-x!**

The prompt flux at neutrino telescopes

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

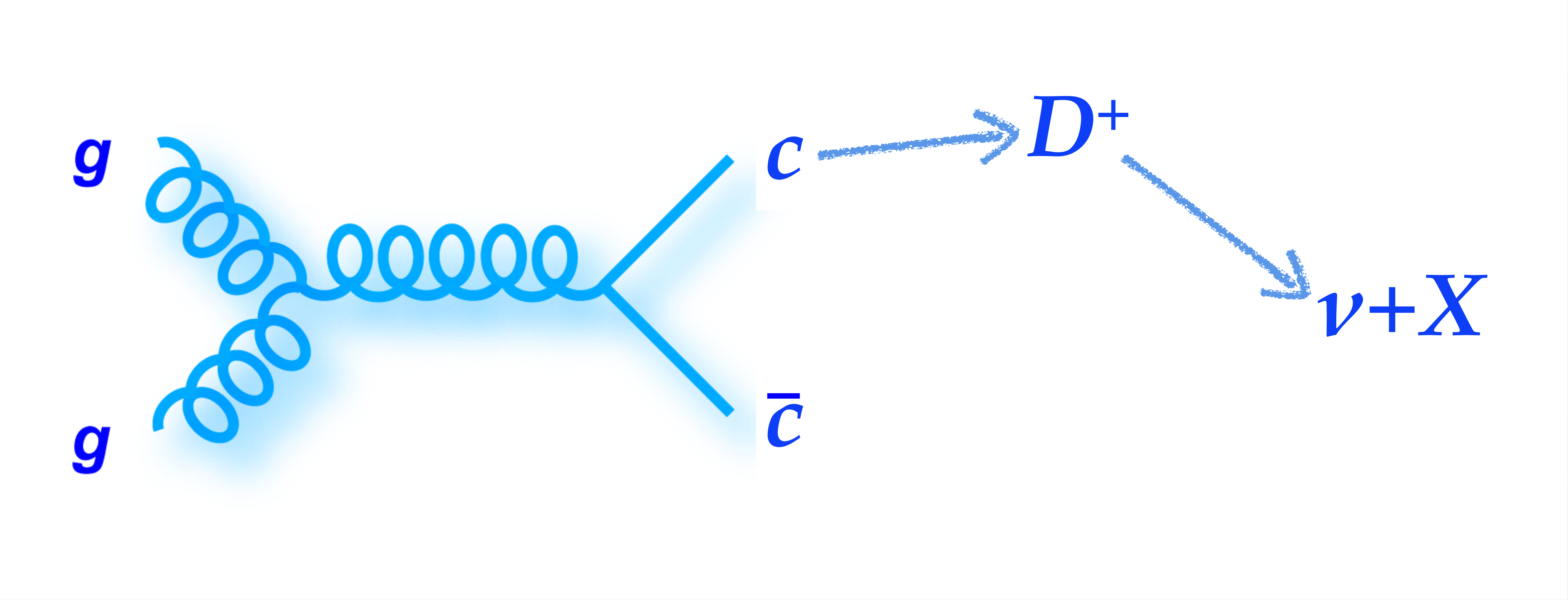
New window to the Universe, but interpretation of UHE data requires **control over backgrounds**

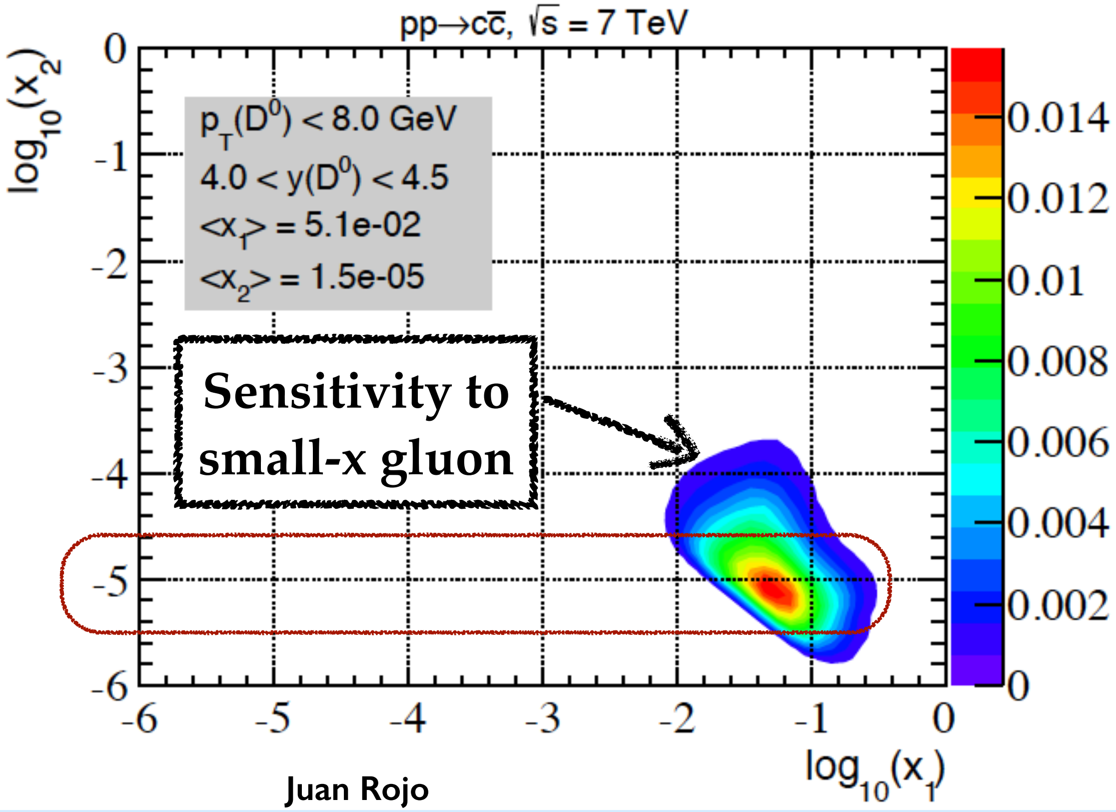
IceCube/KM3NET/…



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 $E_{lab} = (2m_pE_{CR})^{1/2}$

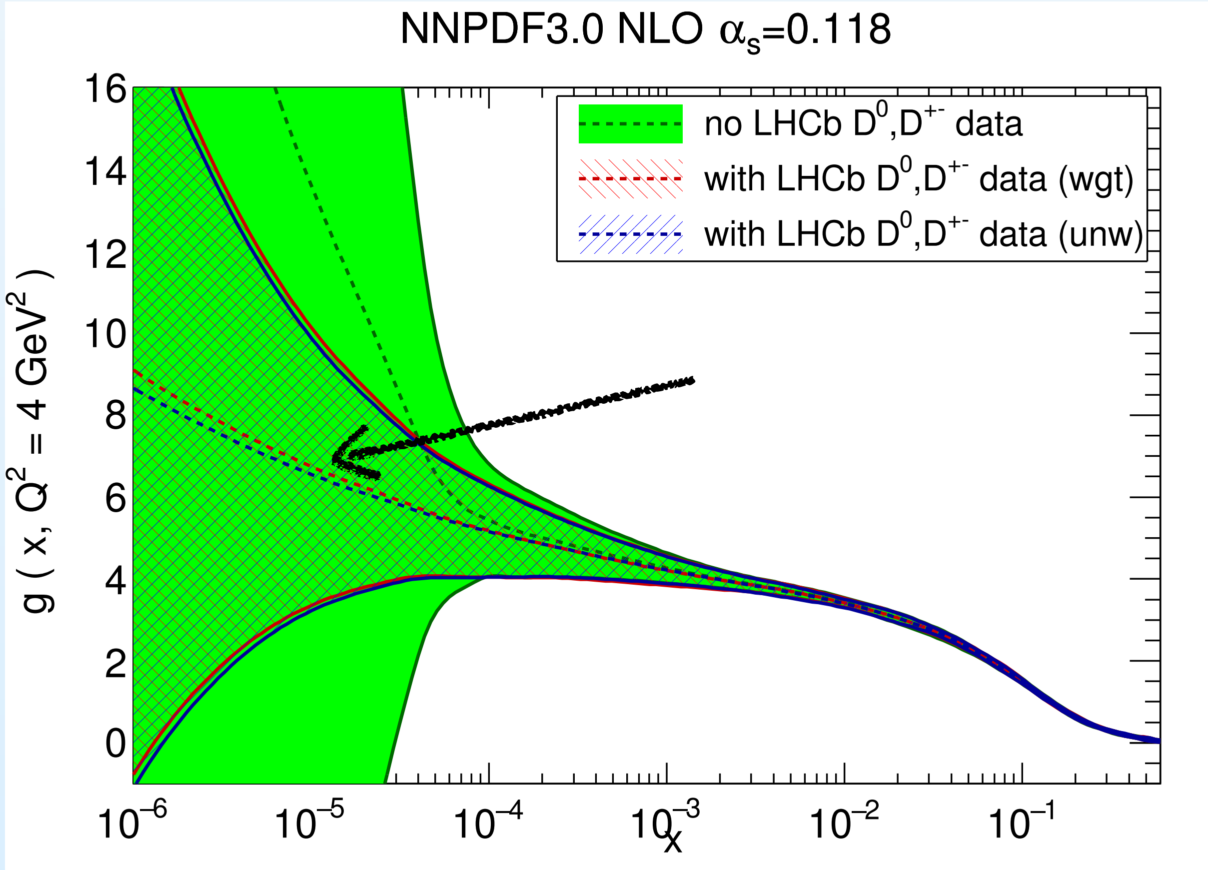
$E_{CR} = 100$ *PeV* ⟶ $E_{lab} \approx 14$ *TeV*

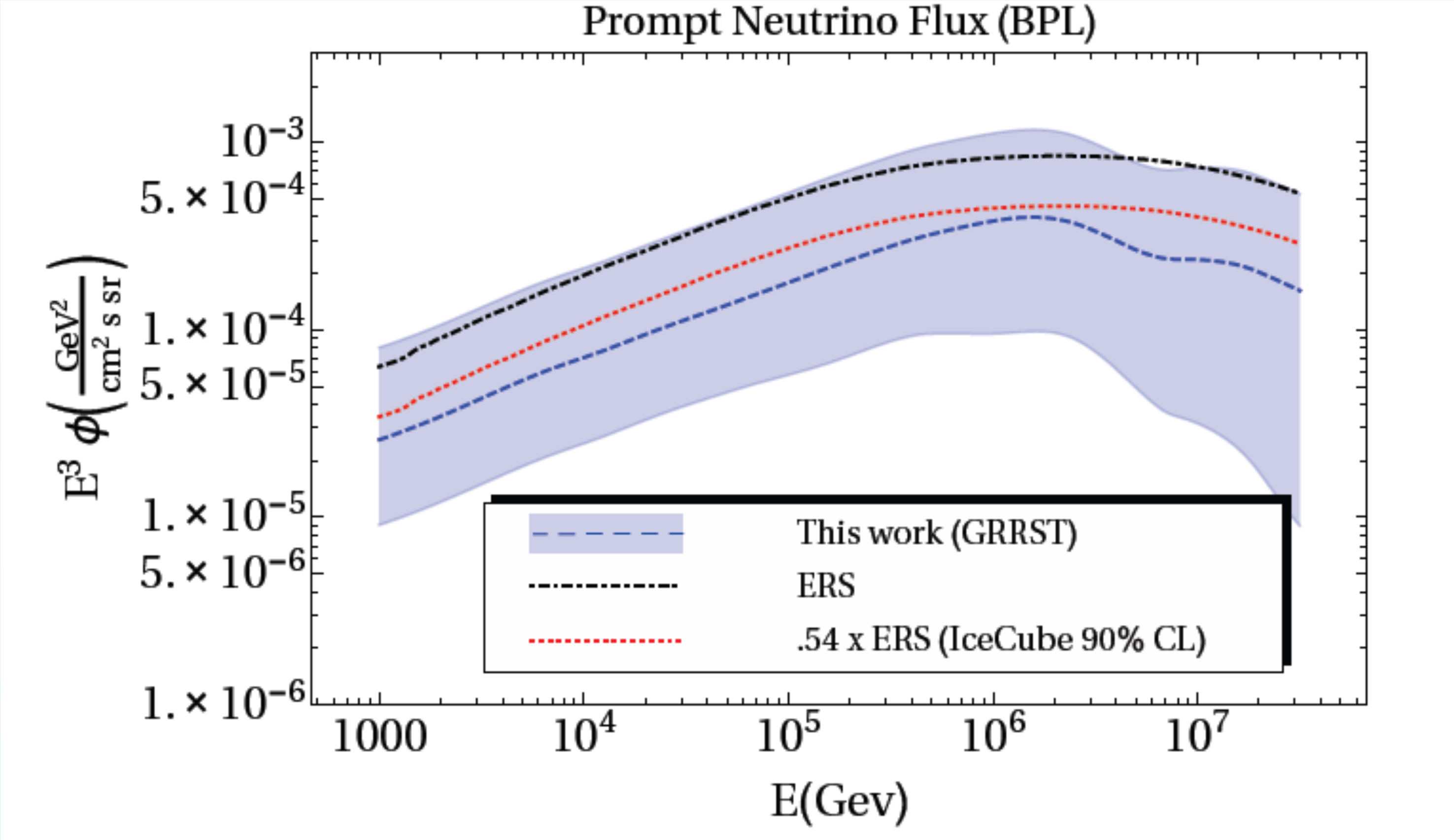
Overlap kinematics between charm production in UHE cosmic rays and at the LHC

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**





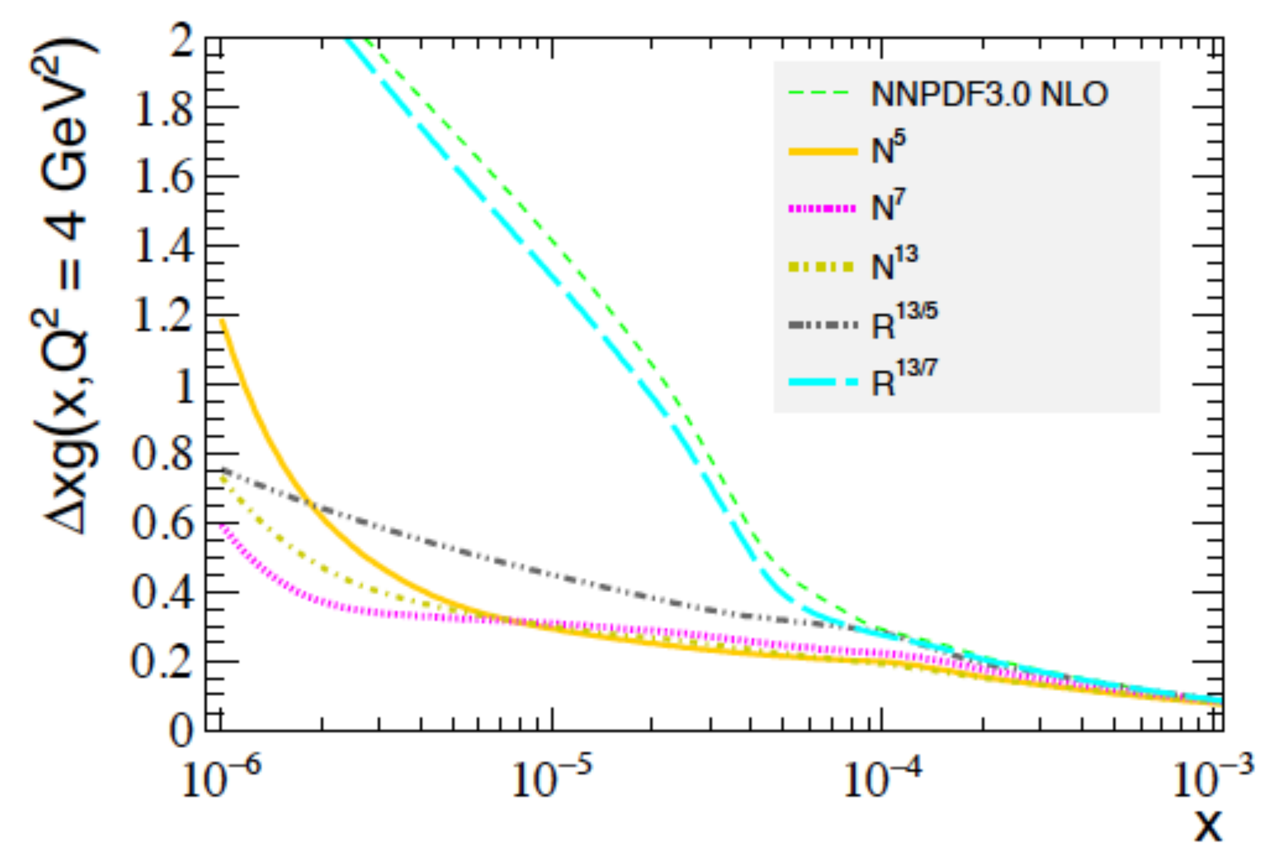
We predict that detection of the prompt neutrino flux should be within reach

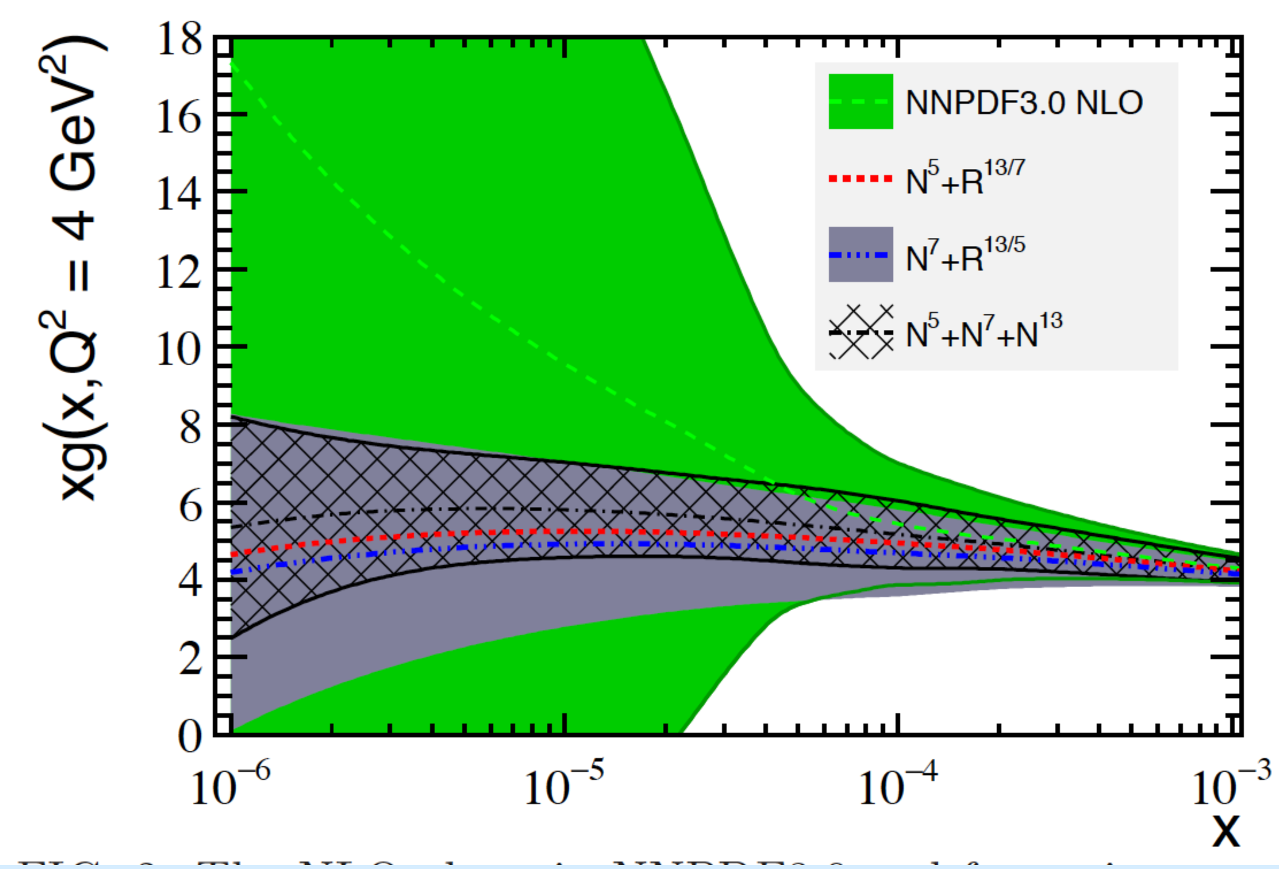
LHCb charm production from 5 to 13 TeV

- 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?**

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

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

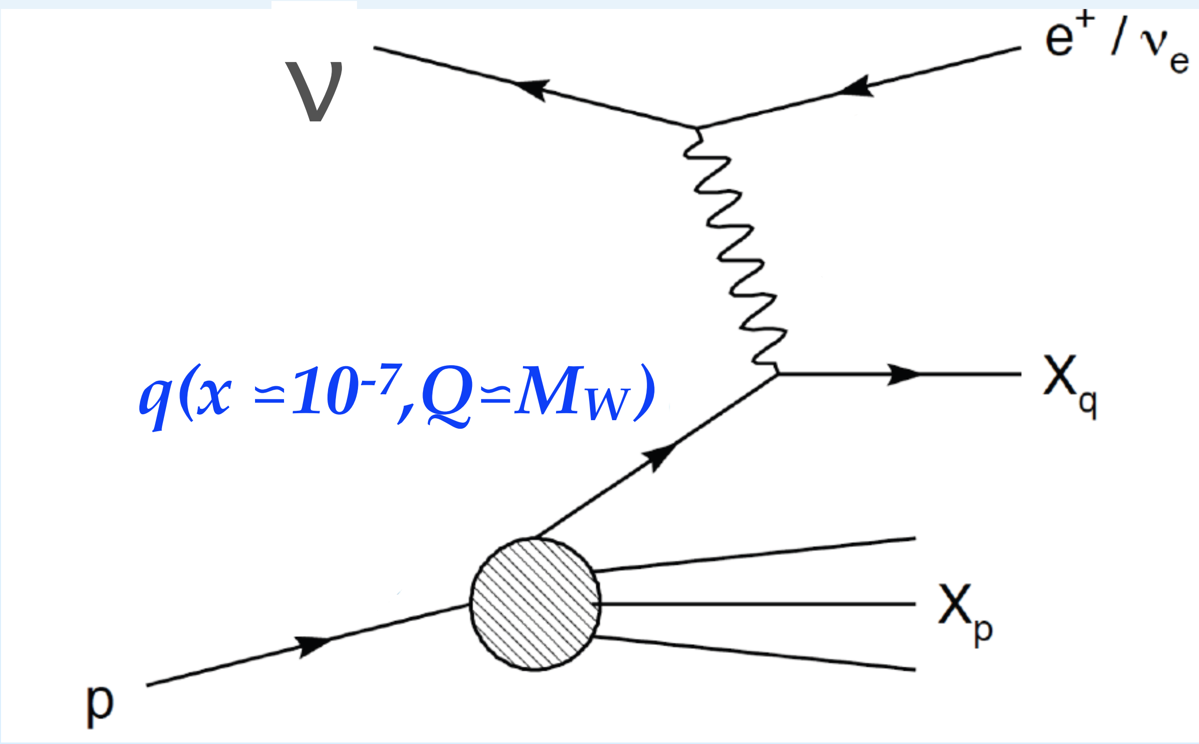




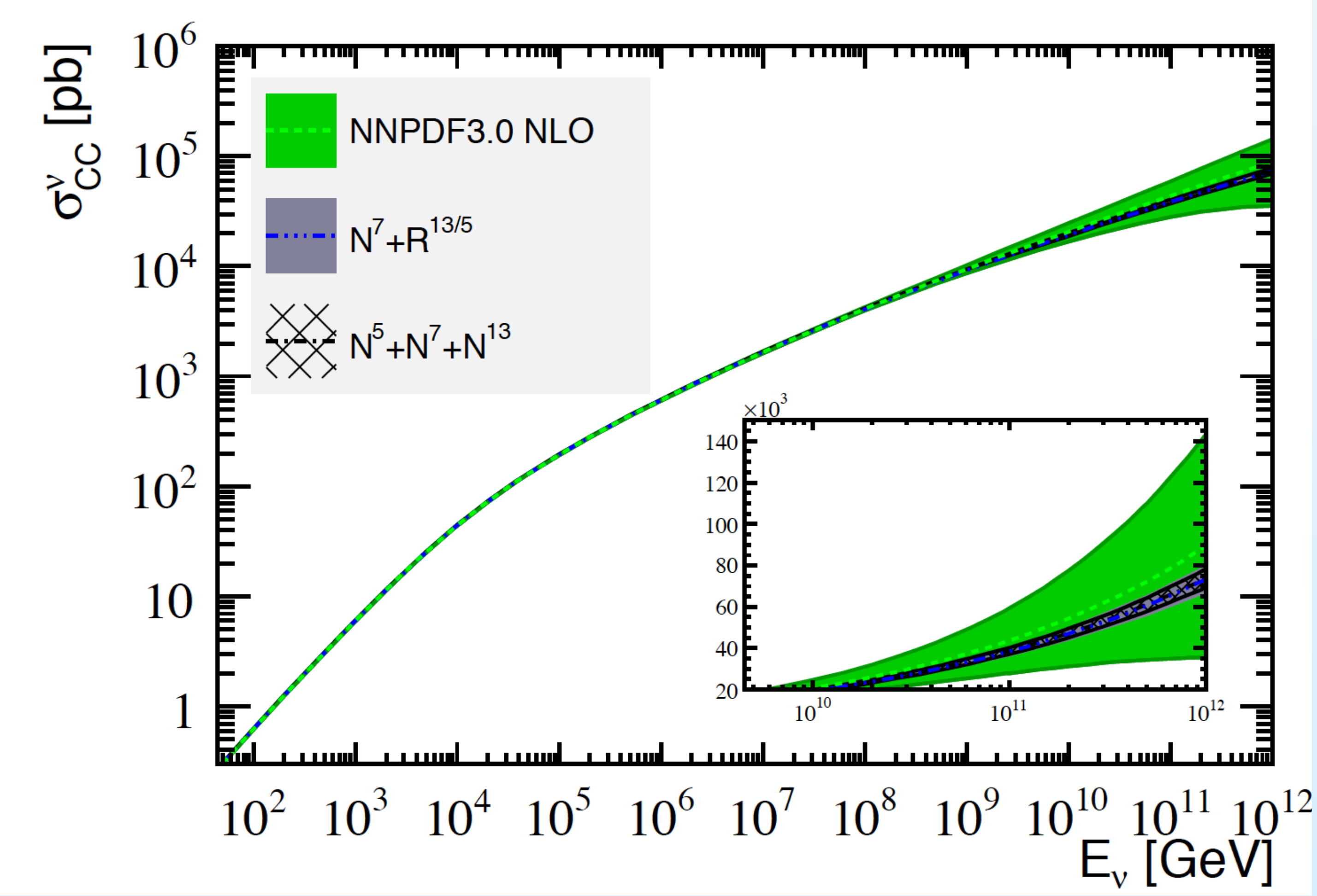
UHE neutrino-nucleus cross-sections

- 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

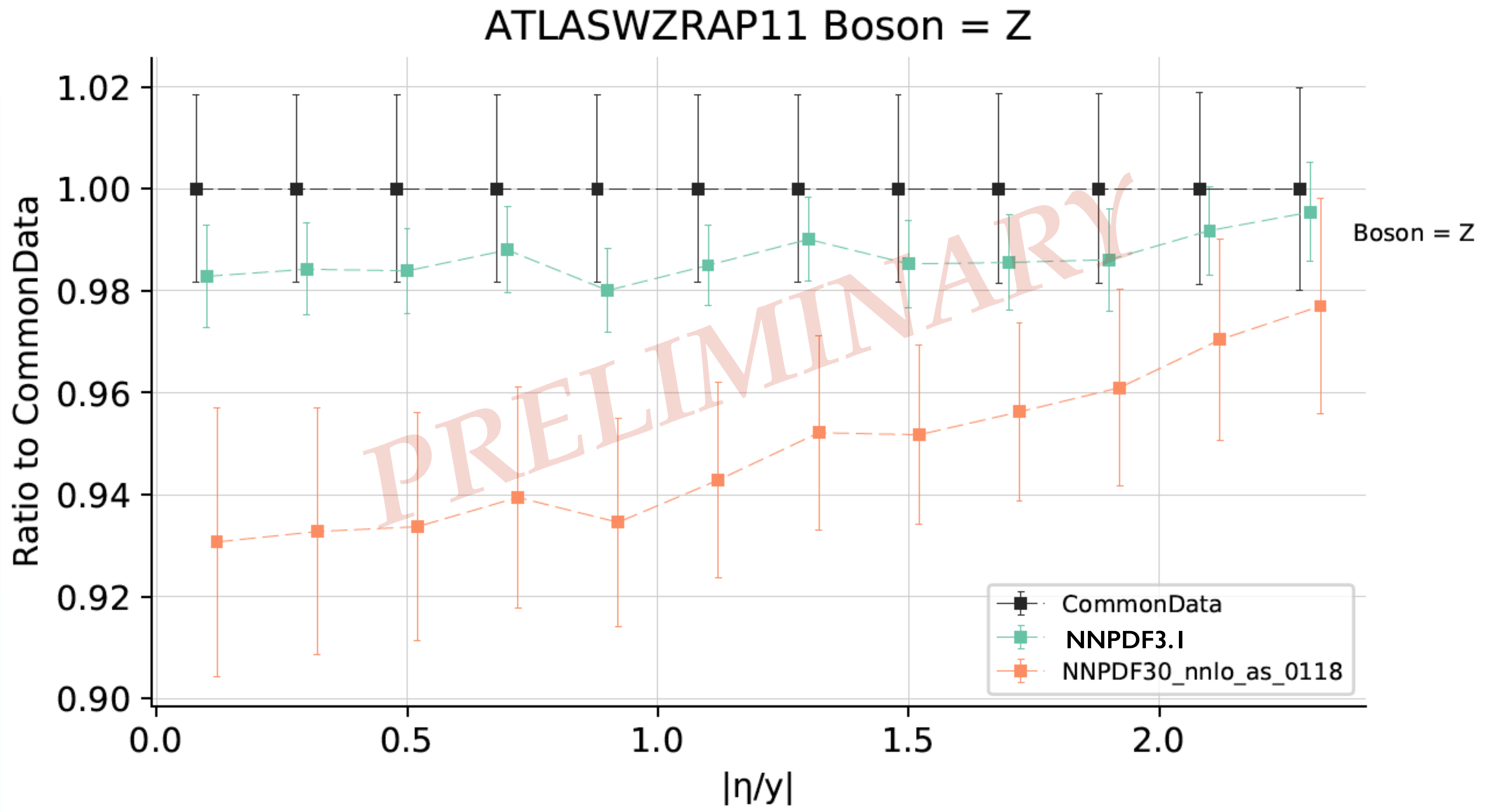


$q(x \simeq 10^{-7}, Q \simeq M_W)$



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

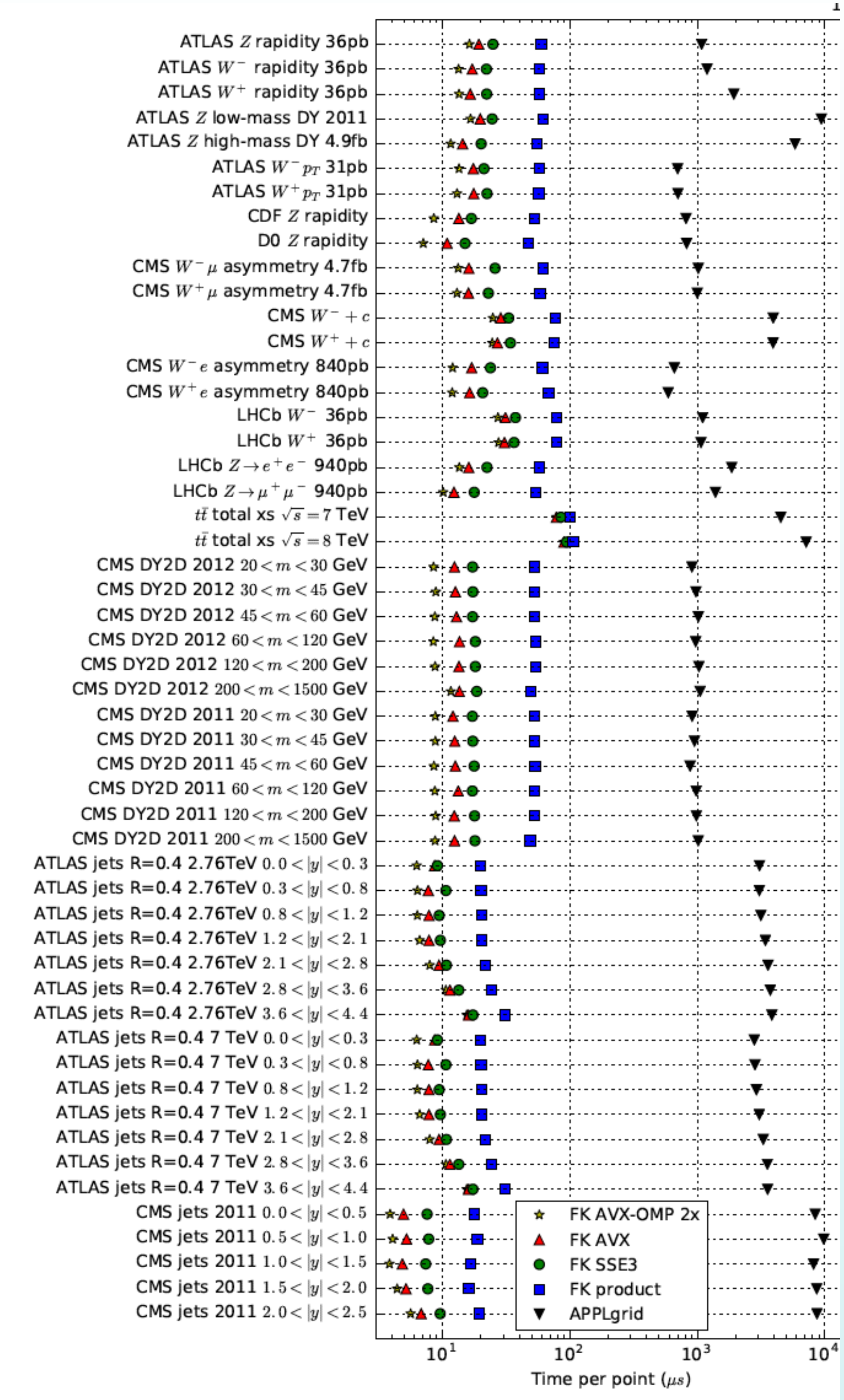
NNPDF3.1: fit settings

- **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

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



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