Parton Distributions at a 100 TeV Hadron Collider

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QCD, EW and Tools at 100 TeV
CERN, 09/10/2015

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Juan Rojo, Valerio Bertone, Stefano Carrazza, Tao Han, Joey Huston, Davide Pagani, Peter Skands, Brock Tweedie, Susanne Westhoff, Marco Zaro, ...

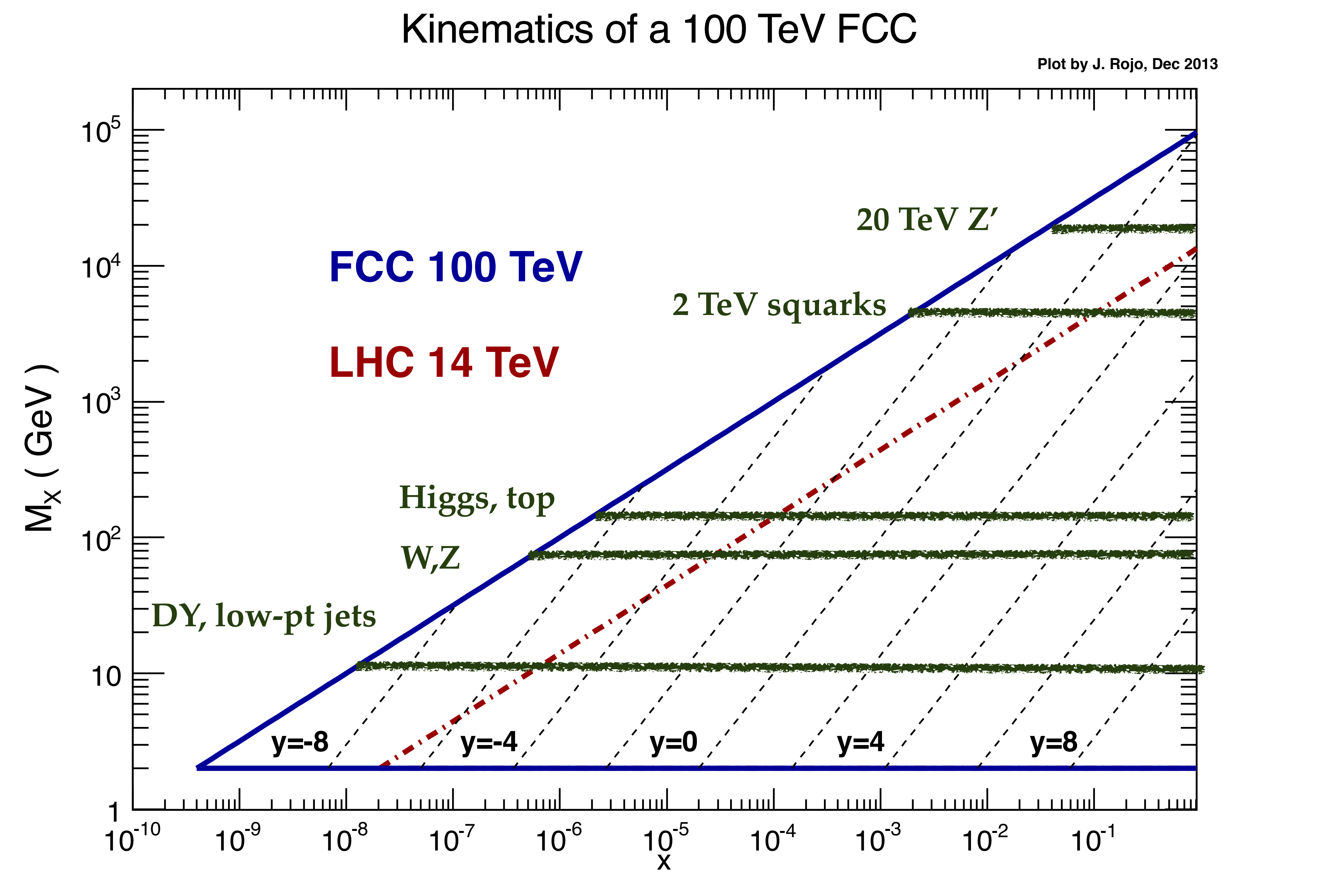
Abstract

In this section we discuss issues related to Parton Distribution Functions (PDFs) at a future 100 TeV Hadron Collider.

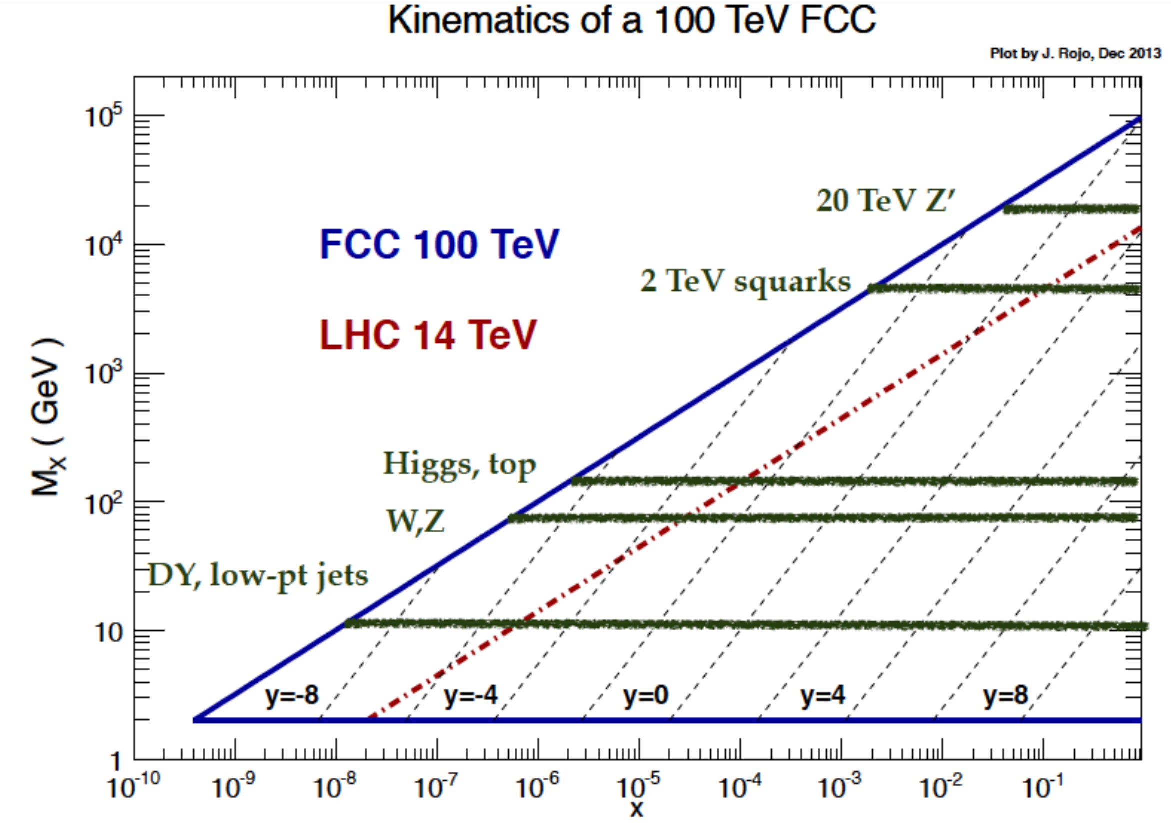
Contents

Kinematic coverage of PDFs at 100 TeV

Kinematical coverage



Kinematical coverage



- For the same **M$_X$** and **y, FCC100** probes values of **x** smaller by **0.14** as compared to LHC14

$$x_{1,2} = \frac{M_X}{\sqrt{s}} \exp(\pm y)$$

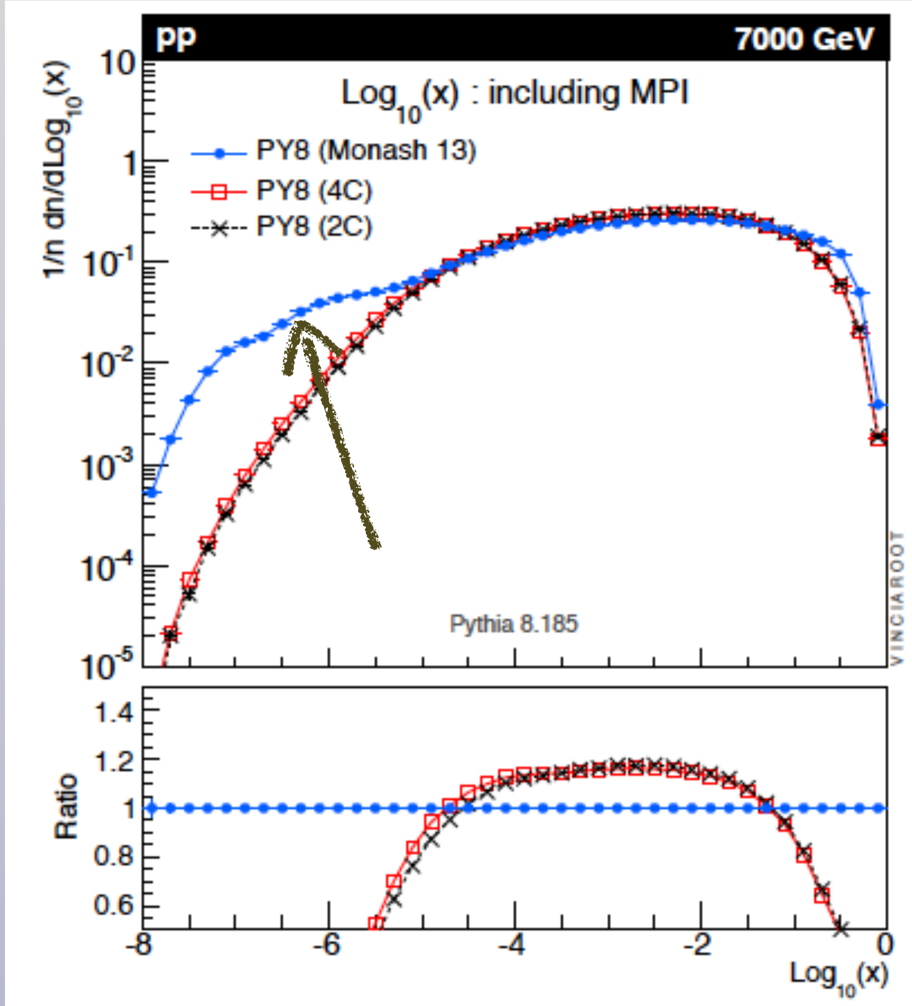
- At the FCC100, knowledge of PDFs is required in extreme regions: **very small-x, very large-x, very large M$_X$**
- Can we trust existing PDFs to **extrapolate** there?

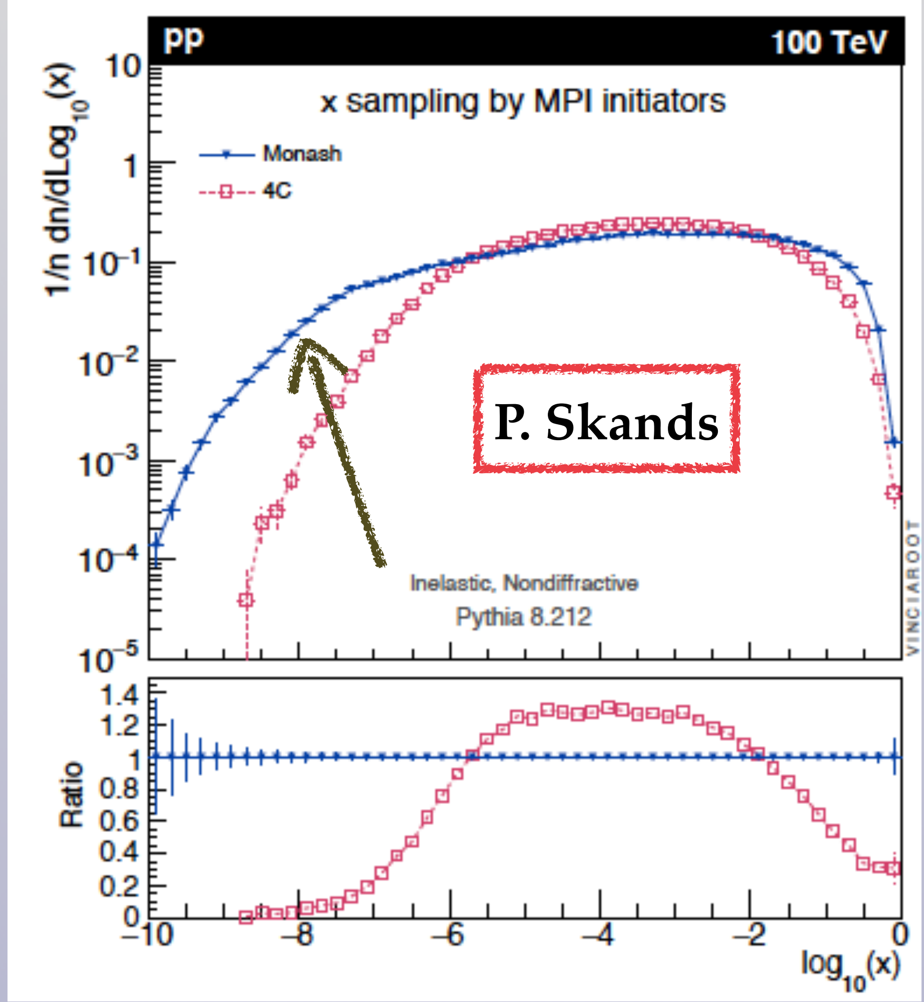
Process	M_X	$x_{\rm min}\,(y=0)$	$x_{\rm min}\,(y=2)$	$x_{\rm min}\,(y=4)$
Soft QCD	1–10 GeV	$\sim 2\,10^{-5}$	$\sim 2\,10^{-6}$	$\sim 4\,10^{-7}$
W, Z, top, Higgs	80-180 GeV	$\sim 10^{-3}$	$\sim 8 \cdot 10^{-4}$	$\sim 7 \cdot 10^{-5}$
2 TeV squarks	2 TeV	$\sim 10^{-2}$	$\sim 10^{-3}$	-
20 TeV Z'	20 TeV	0.05	-	-

Stress-testing PDFs at 100 TeV

- Compare the three recent **global PDF fits**, NNPDF3.0, CT14 and MMHT14, in the kinematic region relevant for FCC100
- Motivation is to identify any obvious problem (unphysical extrapolations, limited coverage …) that might affect FCC simulations
- Setup: **LHAPDF6 v6.1.5** with the latest versions of the PDF grid files
- It is **crucial** to use for FCC simulations **(a)** the **most updated version of LHAPDF6** (at least v6.1.5) and **(b)** the **more recent PDF sets.**
- Important problems affect older sets and LHAPDF versions that could substantially affect FCC simulations

Small-x PDFs at 100 TeV

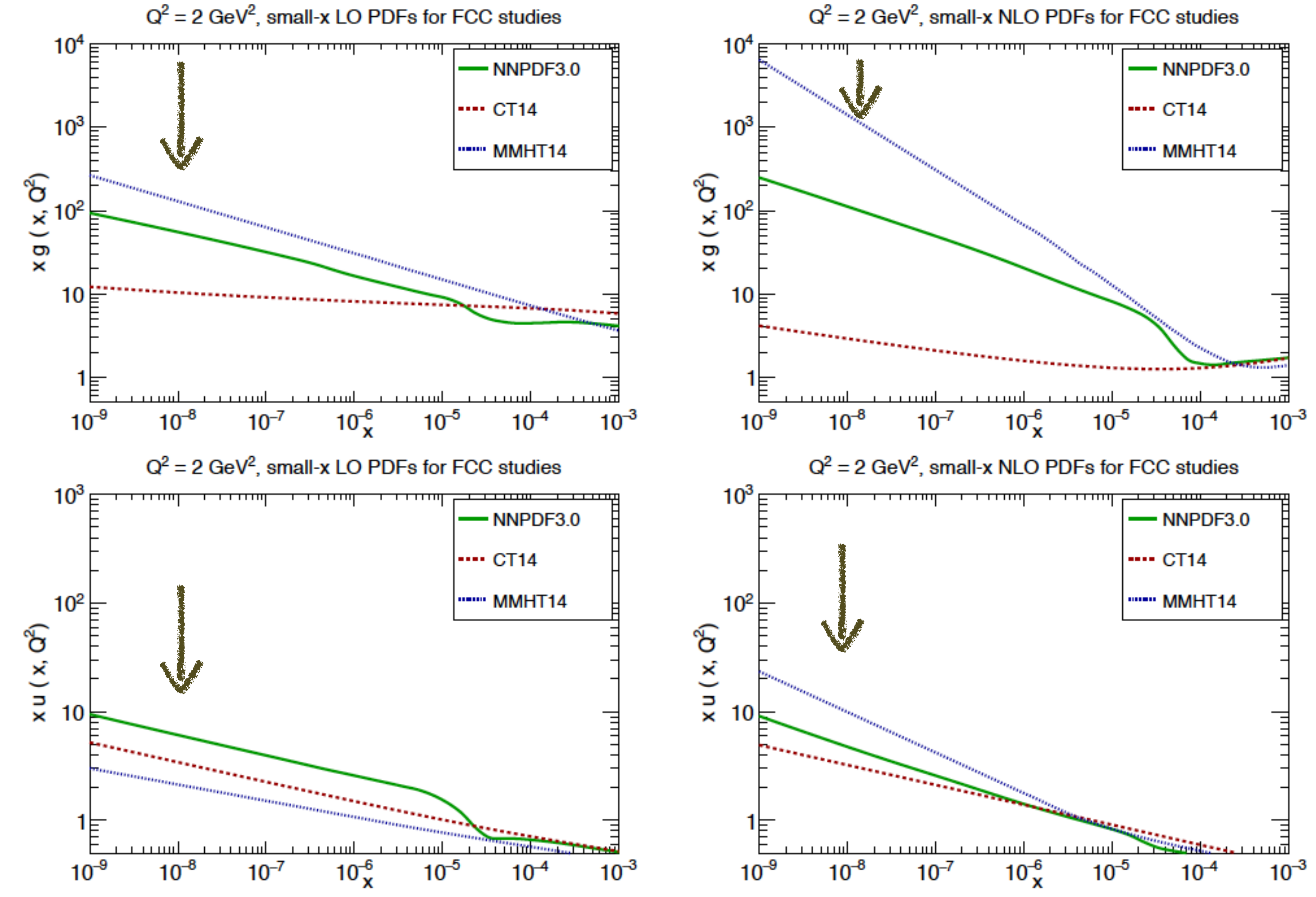




- Small-x, small-Q PDFs are required for the description of **soft and semi-hard physics in MC generators**. Can be quantified by **sampling of Bjorken-x in Pythia8** at 7 and 100 TeV
- At the **LHC, small-x PDFs** are required down to $\mathbf{10^{-6}}$ while at the **FCC** we require $\mathbf{10^{-8}}$

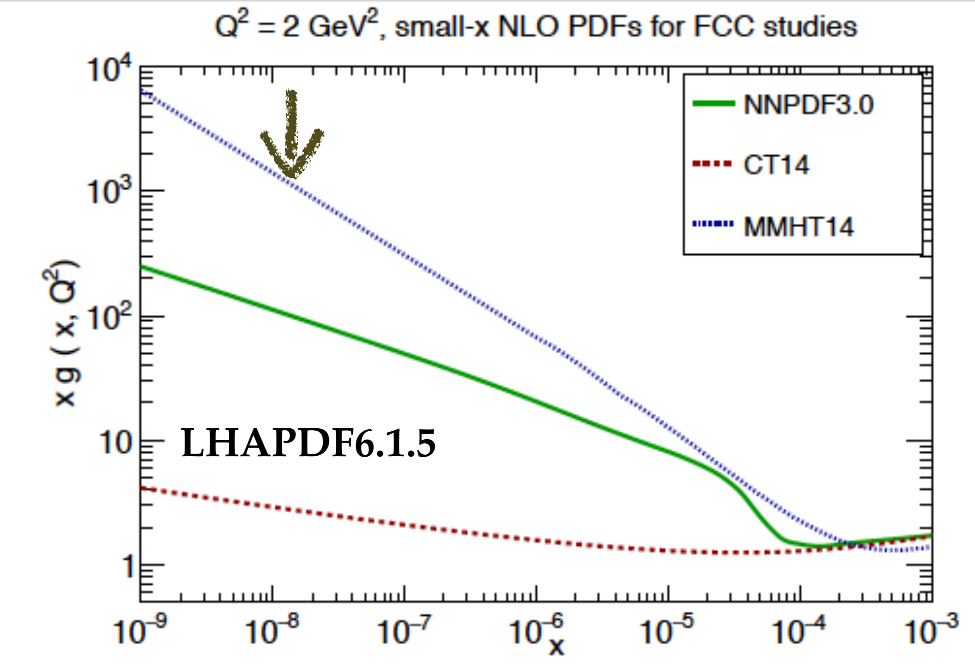
Pythia8 Monash Tune: Skands, Carrazza, JR, 1404.5630

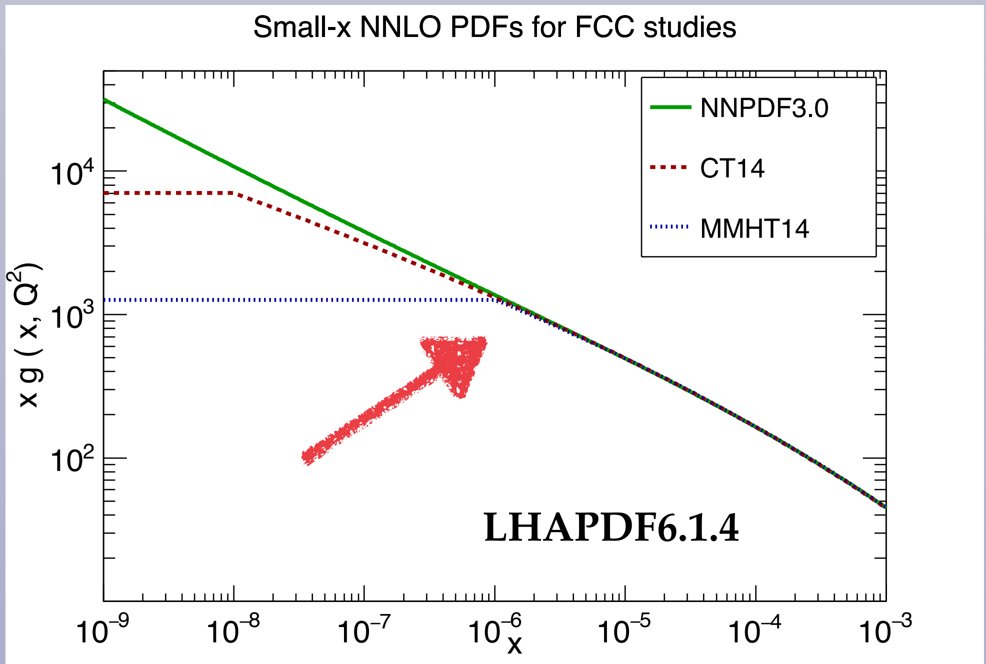
Small-x PDFs at 100 TeV

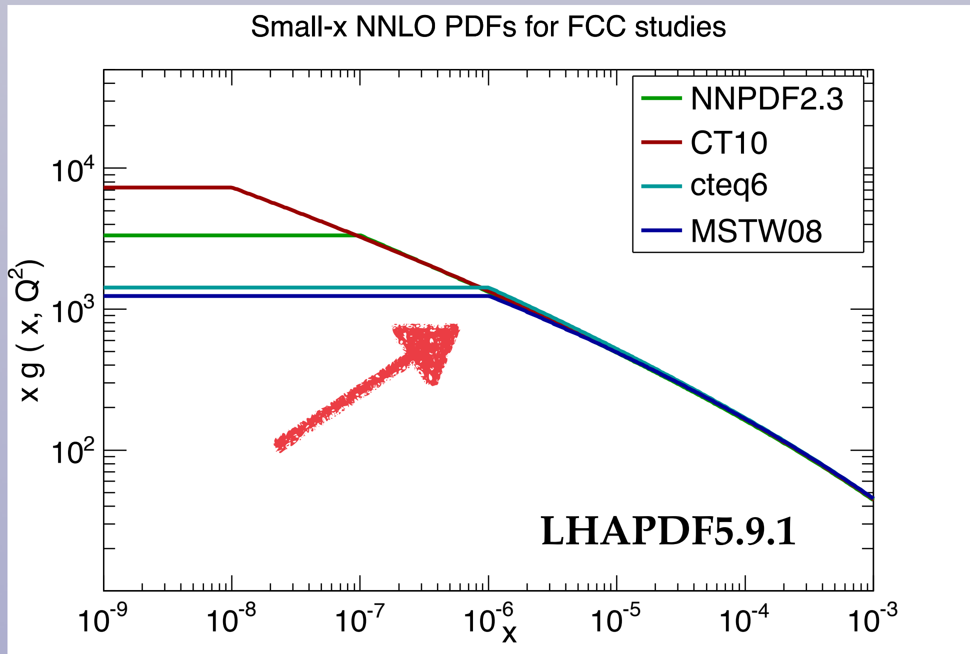


Small-x PDFs at 100 TeV

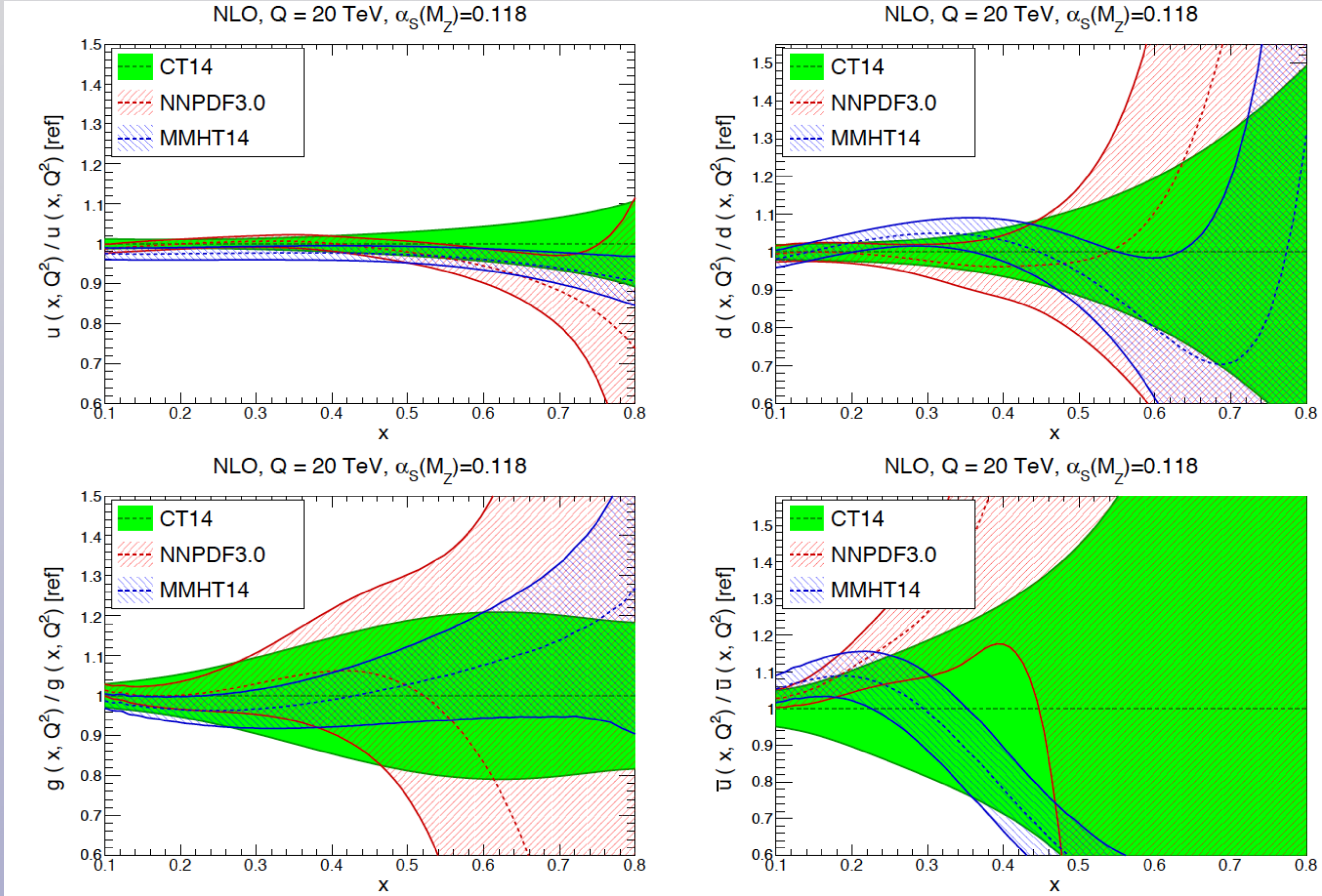
- Modern sets **extrapolate to very small-x without technical problems** in LHAPDF6.1.5
- PDF uncertainties are huge in this region, but basic constraints (DGLAP evolution, sum rules) must still hold
- **Unexpected behaviour** arise if older LHAPDF versions are used
- Take into account for FCC simulations!







Large-x PDFs at 100 TeV



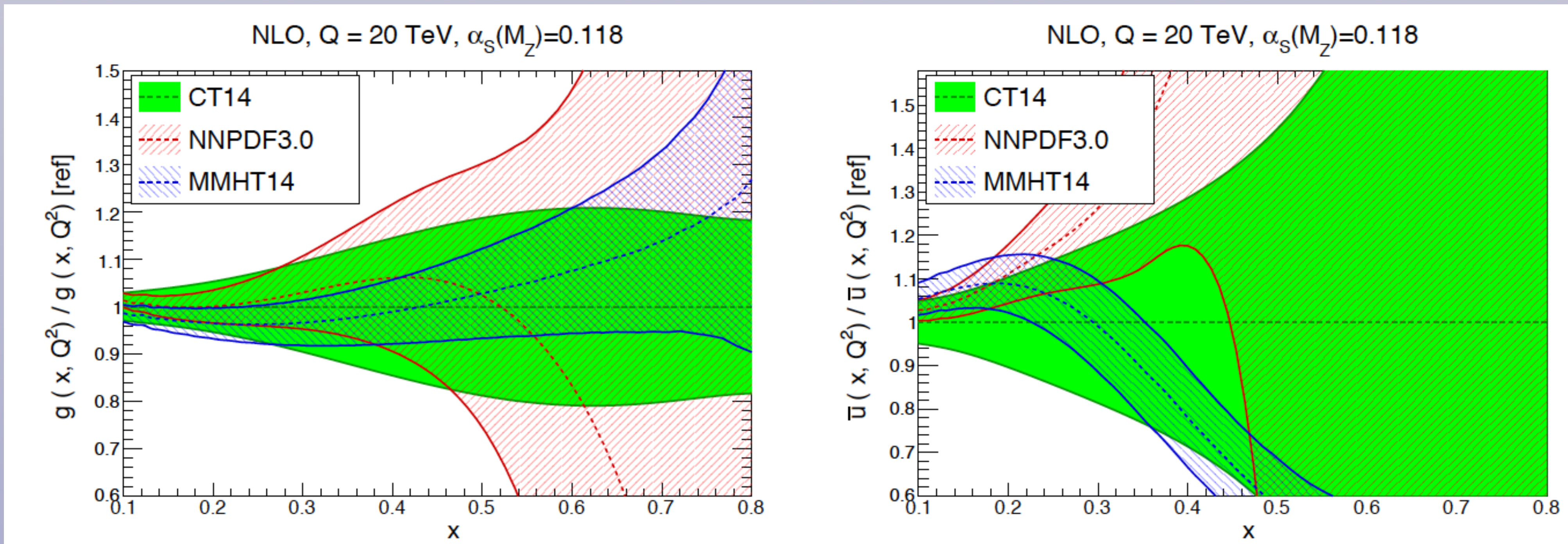
Large-x PDFs at 100 TeV

- Modern sets **extrapolate to very large-x without technical problems** in LHAPDF6.1.5
- **PDF uncertainties very large in this region**, due to limited experimental constraints
- Expect substantial improvement in the coming years from **LHC Run I and Run II data**
- More in **Stefano's talk**

The PDF4LHC report on PDFs and LHC data: Results from Run I and preparation for Run II *arXiv:1507.00556*

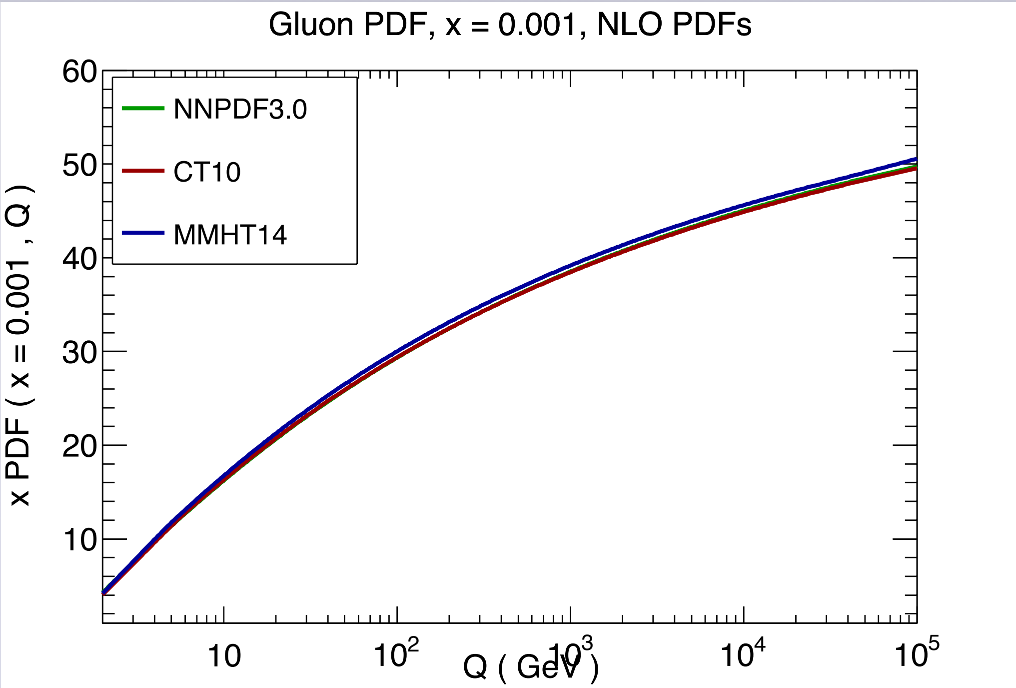
Juan Rojo[1], Alberto Accardi[2,3], Richard D. Ball[4,5], Amanda Cooper-Sarkar[6], Albert de Roeck[5,7], Stephen Farry[8], James Ferrando[9], Stefano Forte[10], Jun Gao[11], Lucian Harland-Lang[12], Joey Huston[13], Alexander Glazov[14], Maxime Gouzevitch[15], Claire Gwenlan[6], Katerina Lipka[14], Mykhailo Lisovyi[16], Michelangelo Mangano [5], Pavel Nadolsky[17], Luca Perrozzi[18], Ringaile Plačakytė[14], Voica Radescu[16], Gavin P. Salam[5] and Robert Thorne[12]*

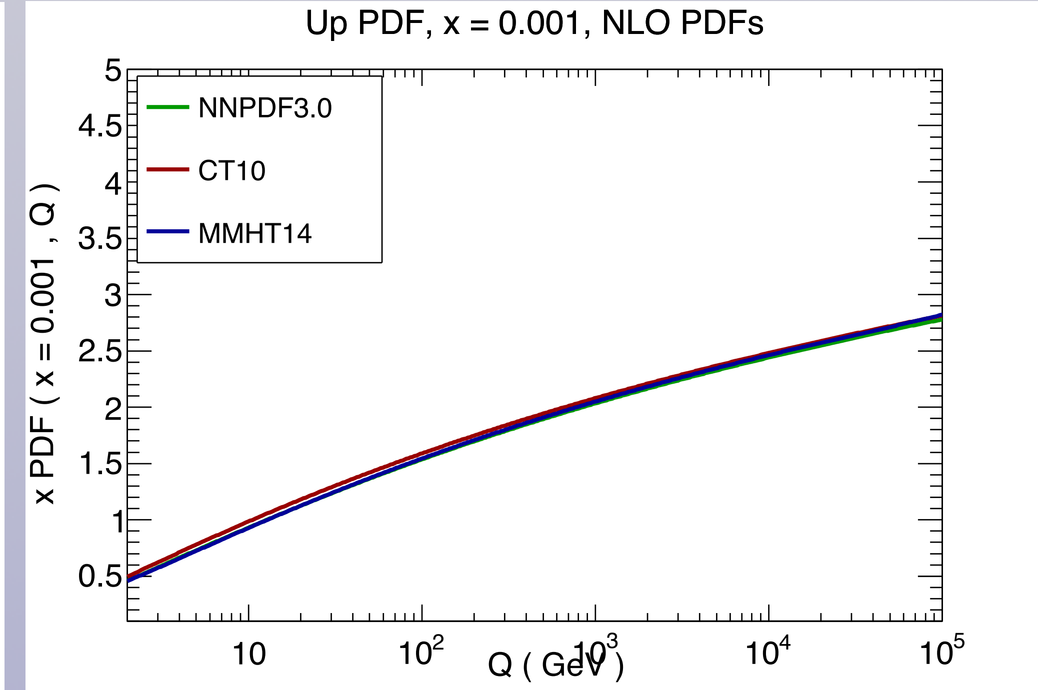
searches. A major recent development in modern PDF analyses has been to exploit the wealth of new information contained in precision measurements from the LHC Run I, as well as progress in tools and methods to include these data in PDF fits. In this report we summarise the information that PDF-sensitive measurements at the LHC have provided so far, and review the prospects for further constraining PDFs with data from the recently started Run II. This doc-



Large-Q^2 PDFs at 100 TeV

- Effects of **QCD DGLAP evolution** decrease with Q, due to **smaller α_S(Q)**
- DGLAP evolution "flattens out" PDF in the multi-TeV region
- Provided the **LHAPDF interpolating grids cover the region up to 100 TeV**, modern PDF sets can be safely used
- However, this does not account for **genuinely new effects in the FCC kinematics**: W,Z PDFs, BFKL effects. ………..





Large-Q^2 PDFs at 100 TeV

Usage of modern PDF sets with LHAPDF6 v6.1.5 is suitable for FCC studies and simulations

This is not true for older PDF sets and LHAPDF5

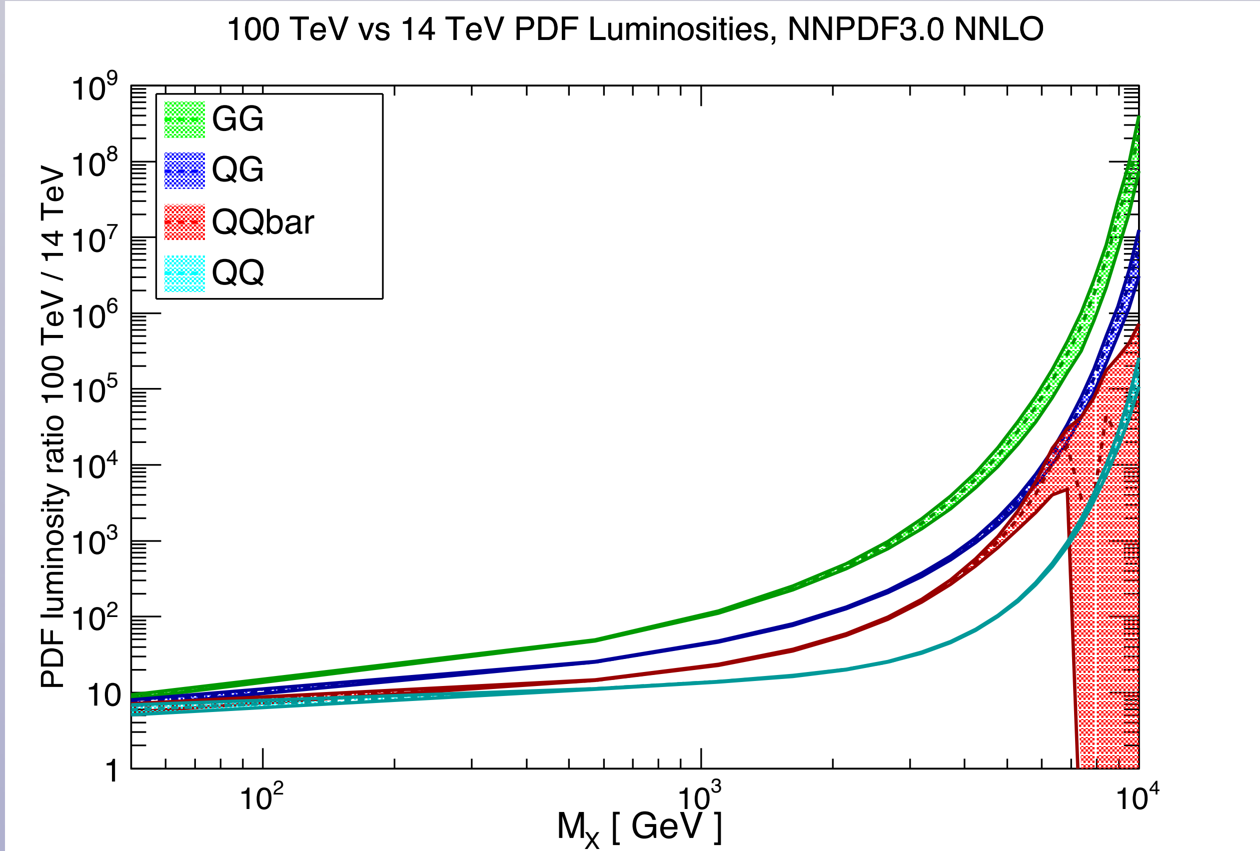
PDF luminosities at 100 TeV

PDF luminosities

- Compare the **ratio of PDF luminosities between 100 TeV and 14 TeV** in different channels as a function of the final state mass

$$\Phi_{gg}\left(M_X^2\right) = \frac{1}{s}\int_\tau^1 \frac{dx_1}{x_1} g\left(x_1, M_X^2\right) g\left(\tau/x_1, M_X^2\right) ,$$

$$\Phi_{gq}\left(M_X^2\right) = \frac{1}{s}\int_\tau^1 \frac{dx_1}{x_1} \left[g\left(x_1, M_X^2\right) \Sigma\left(\tau/x_1, M_X^2\right) + (1 \to 2)\right]$$



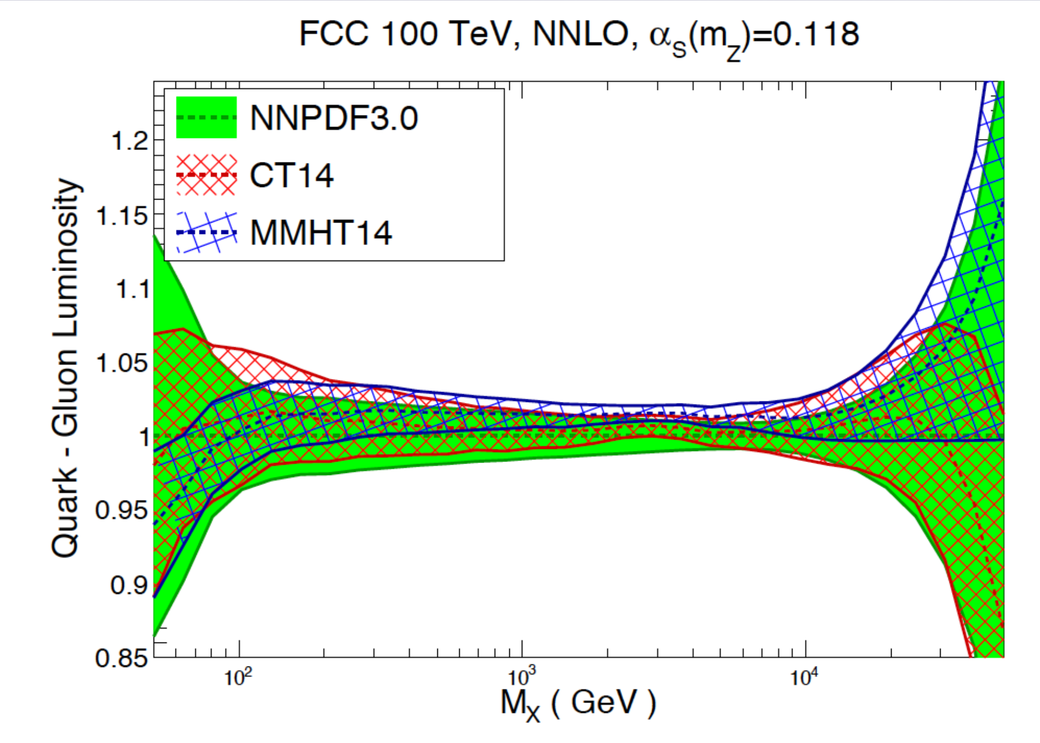
- For final state masses ***M* < 1 TeV** moderate increase in PDF luminosity, between a factor 10 and 100
- For ***M* > 1 TeV**, much steeper increase (since 14 TeV lumis damped by large-x PDFs), up to a factor 10^8 for ***M* = 10 TeV**
- **Gluon-gluon** and **quark-gluon lumi** rise faster than the others
- Prepare **look-up** tables for ratios of PDF luminosities for the **FCC report**

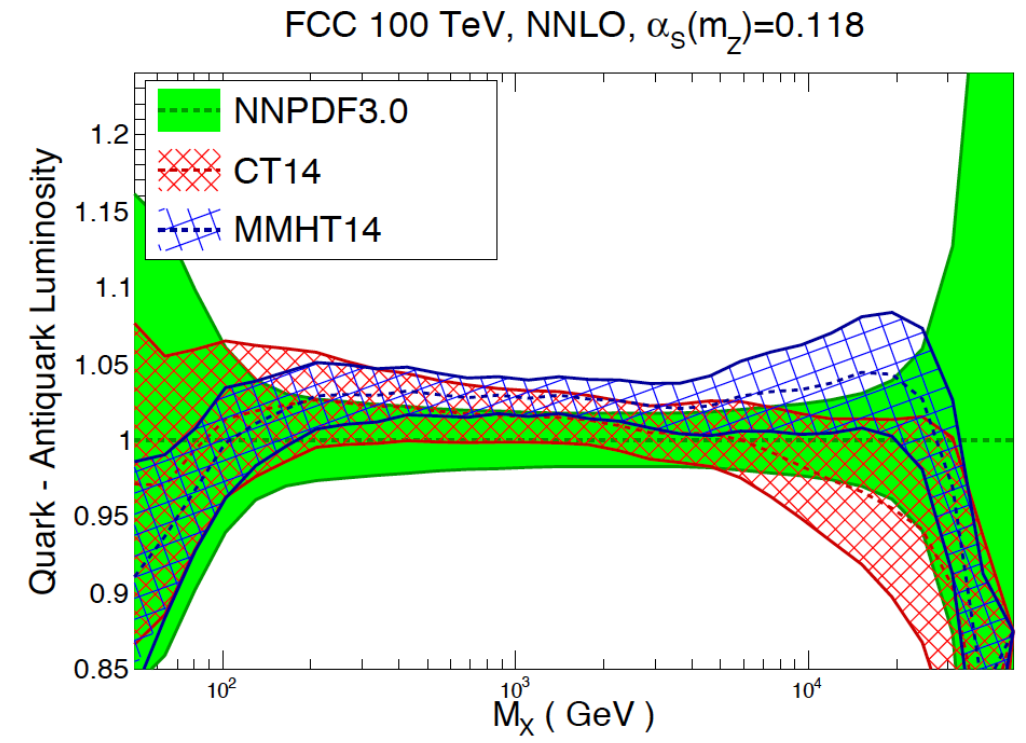
PDF luminosities

- **PDF luminosities** at 100 TeV are a **rescaled version** of PDF luminosities at 14 TeV

$$\Phi_{gg}\left(M_X^2\right) = \frac{1}{s}\int_\tau^1 \frac{dx_1}{x_1} g\left(x_1, M_X^2\right) g\left(\tau/x_1, M_X^2\right) \ ,$$

$$\Phi_{gq}\left(M_X^2\right) = \frac{1}{s}\int_\tau^1 \frac{dx_1}{x_1}\left[g\left(x_1, M_X^2\right)\Sigma\left(\tau/x_1, M_X^2\right) + (1\to 2)\right]$$

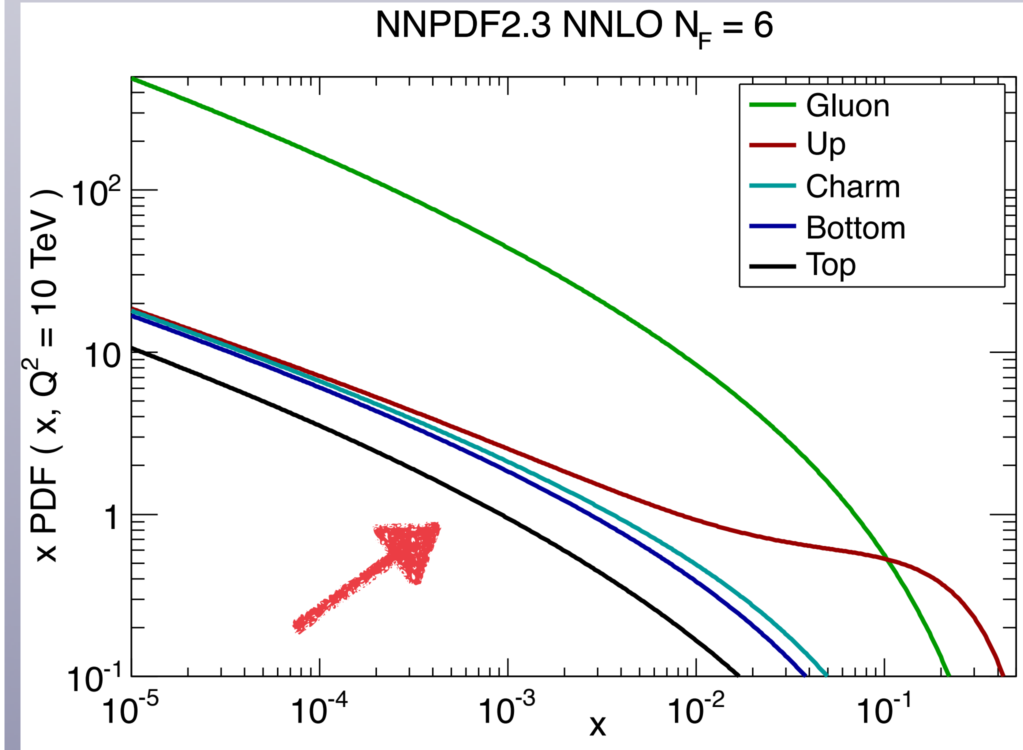


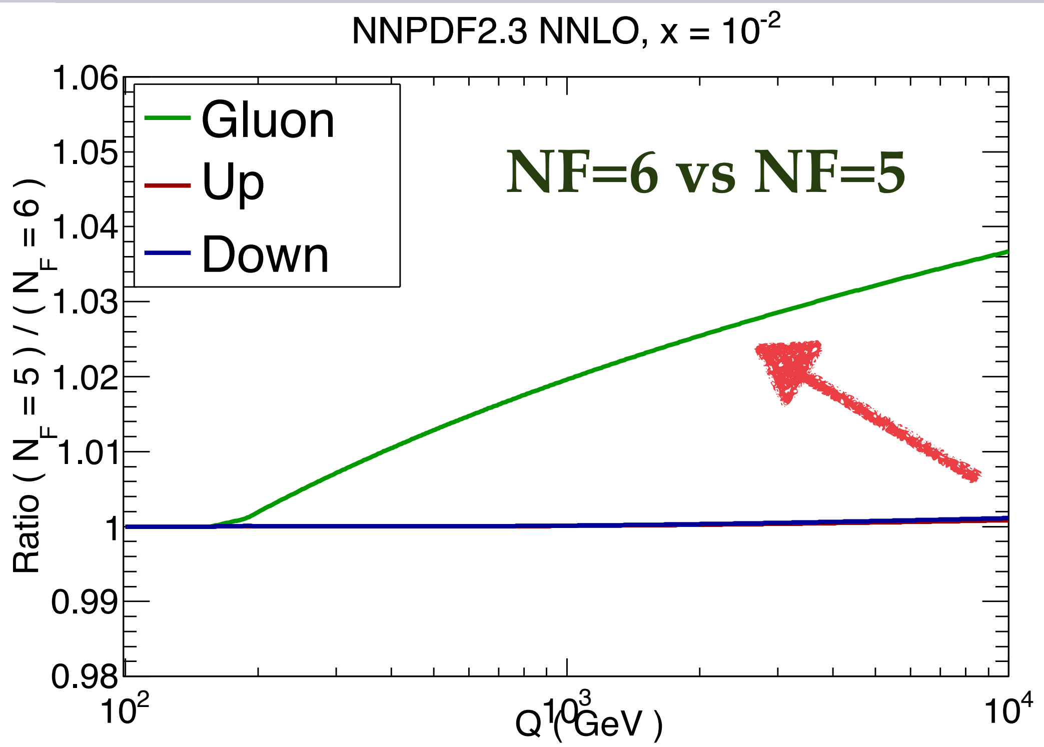


Heavy Quark PDFs at 100 TeV

Heavy quark PDFs at the FCC

- The **resummation of collinear logarithms of the charm and bottom masses** into heavy quark PDFs and **matched GM-VFN schemes** is routinely implemented in LHC phenomenology
- At the FCC, can we consider the **top quark as massless**?
- This question is a purely **practical**: what is **computational scheme** is more advantageous for **FCC calculations involving tops**? massive $N_F=5$ scheme? a massless $N_F=6$ scheme? A matched scheme?
- At the FCC the **top PDF can be numerically large**. Other PDFs, in particular **the gluon**, are modified sizably between the **$N_F=5$ and $N_F=6$** schemes



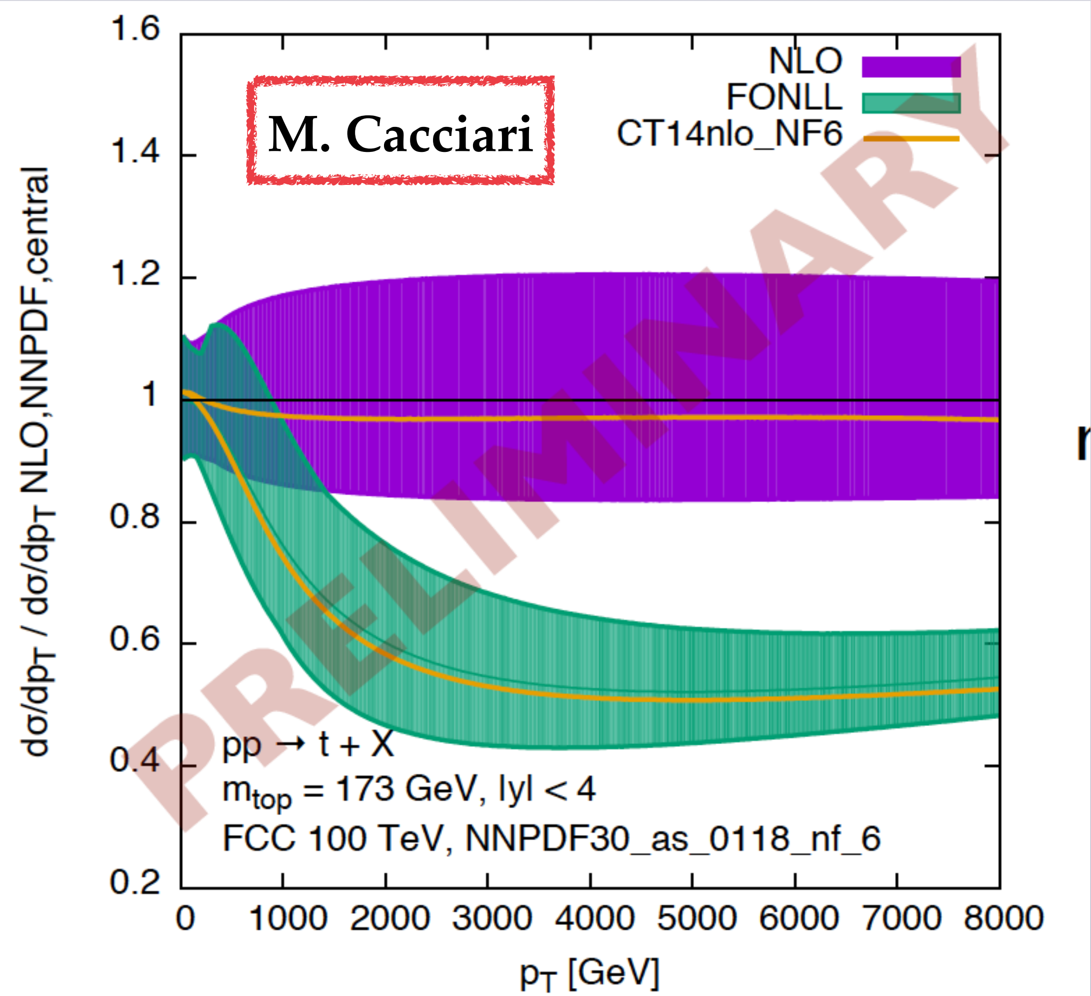


Heavy quark PDFs at the FCC

- Recall that using DGLAP, **heavy quark PDFs** constructed from **resummation of collinear splittings** from gluons and light quarks

$$f_h(y,Q^2) = f_{\bar{h}}(y,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} L \int \frac{dz}{z} T_f(z^2 + (1-z)^2) g\left(\frac{x}{y}, Q^2\right) + \mathcal{O}(\alpha_s^2).$$

$$L \equiv \log Q^2/m^2.$$



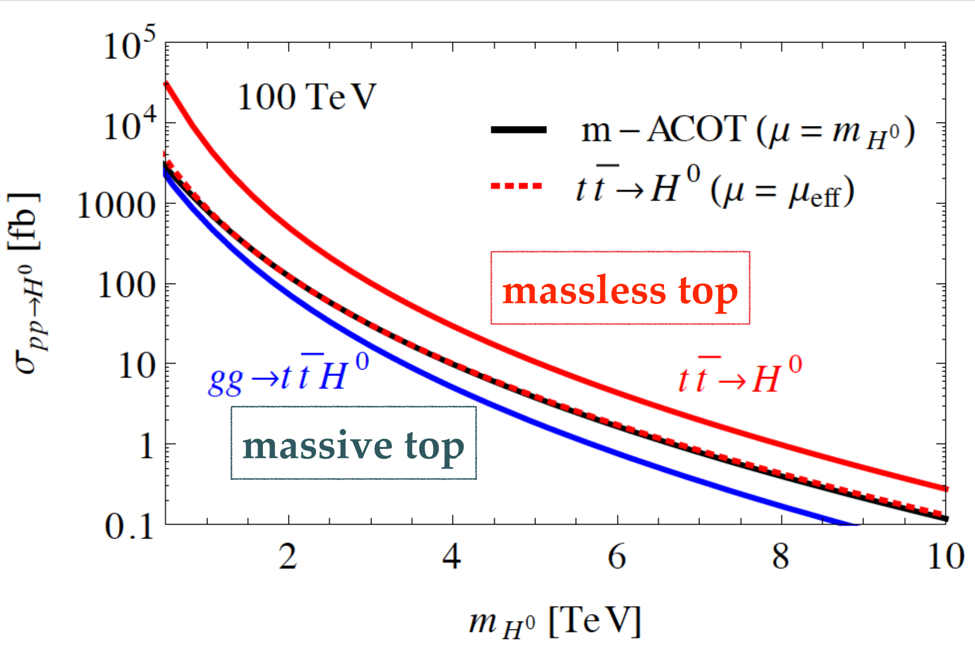
- An important application of **top PDFs** are **matched calculations**, as **FONLL for the top quark pT**, which combine 5FS with the 6FS

- Can improve the **perturbative convergence** of fixed-order calculations

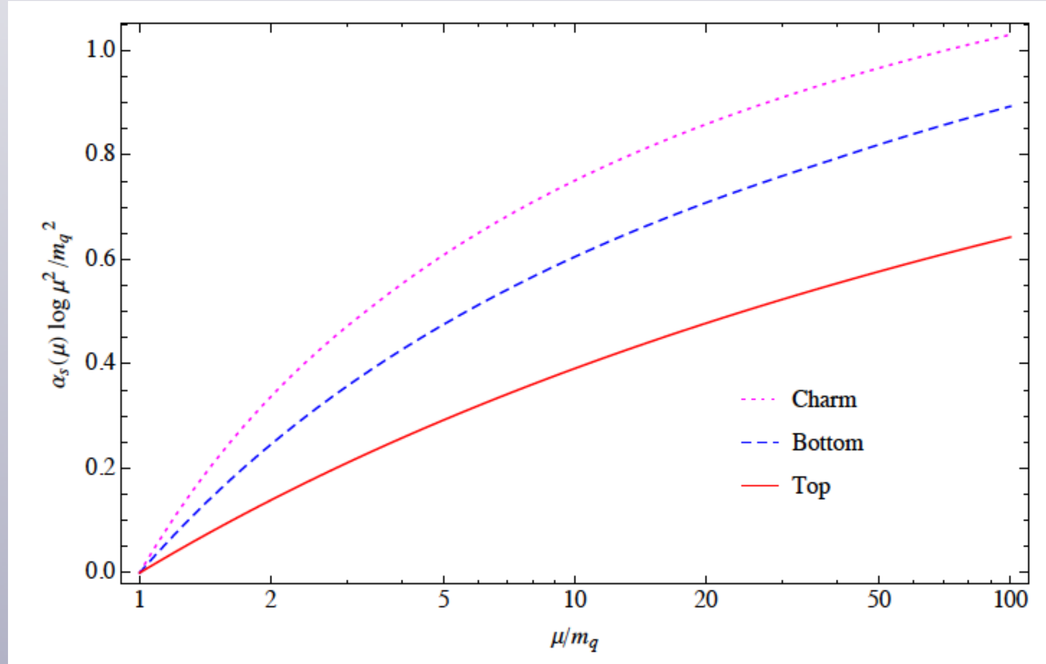
- A **purely massless calculation** would fail except **very far from the top threshold**

Heavy quark PDFs at the FCC

Similar conclusions from other studies: **purely massless calculations for top-related processes at the FCC** are not reliable, but top PDFs are necessary to construct **matched calculations**



Han, Sayre, Westhoff 1411.2588



Dawson, Ismail, Low, 1405.6211

The fact that **resummation of collinear top logs at FCC** is less important than that of charm and bottom at LHC has two origins

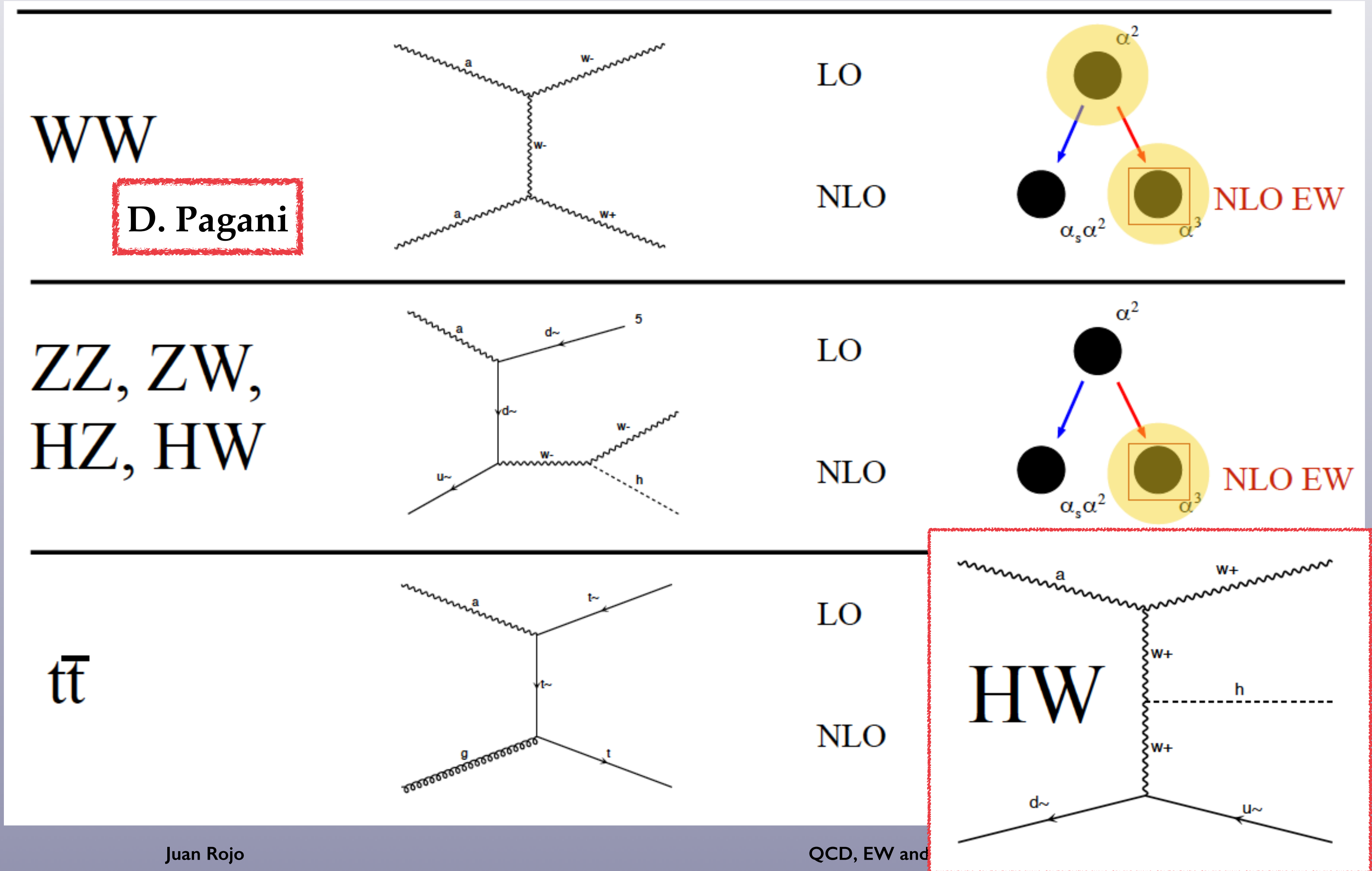
- Collinear logs are suppressed by the smaller value of **α_S(mtop)**
- Suppression due to universal phase space factors and the steep fall-off of large**-x gluon**

Maltoni, Ridolfi, Ubiali, 1203.6393

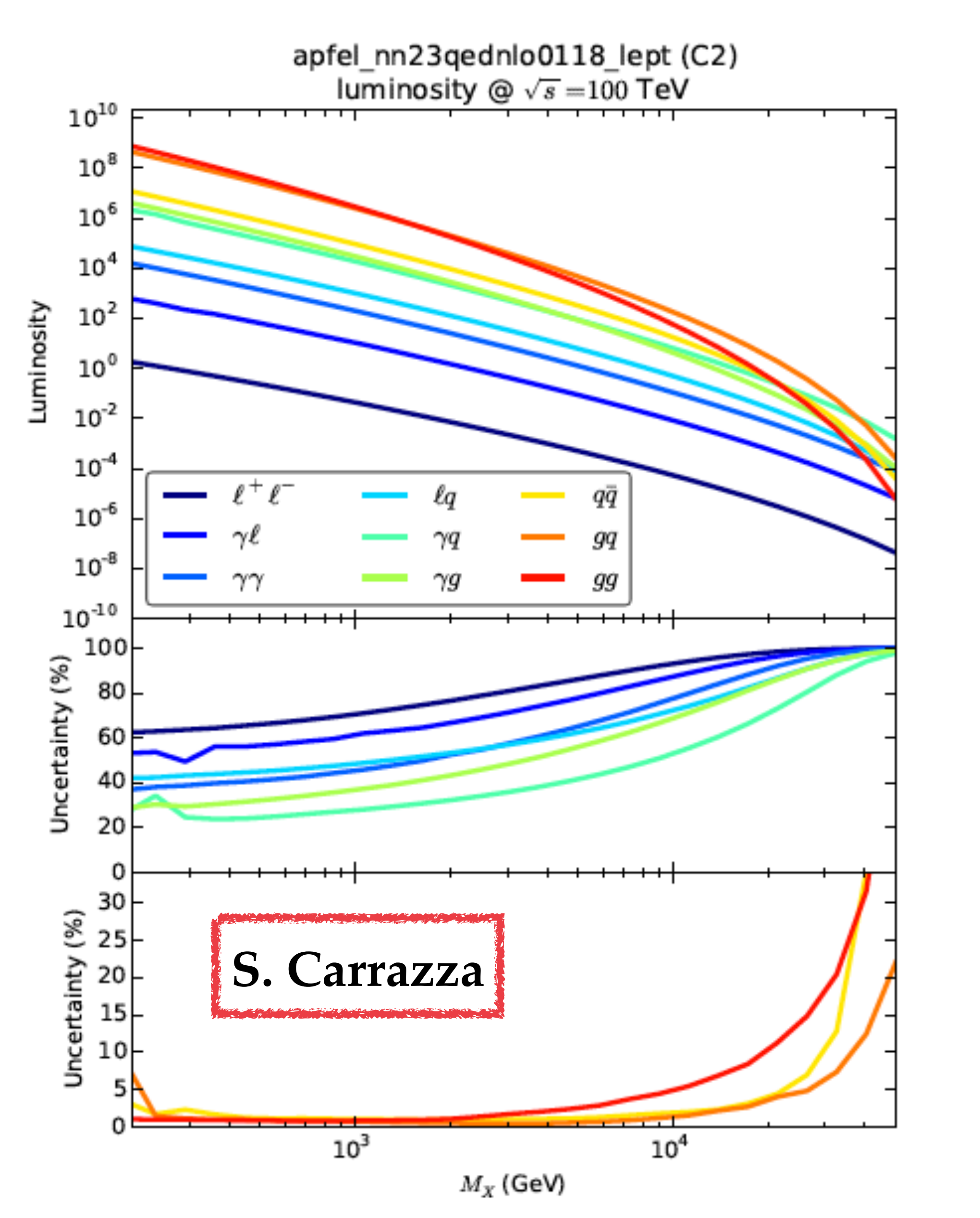
Photon- (and lepton-) initiated processes at 100 TeV

Photon-initiated processes at 100 TeV

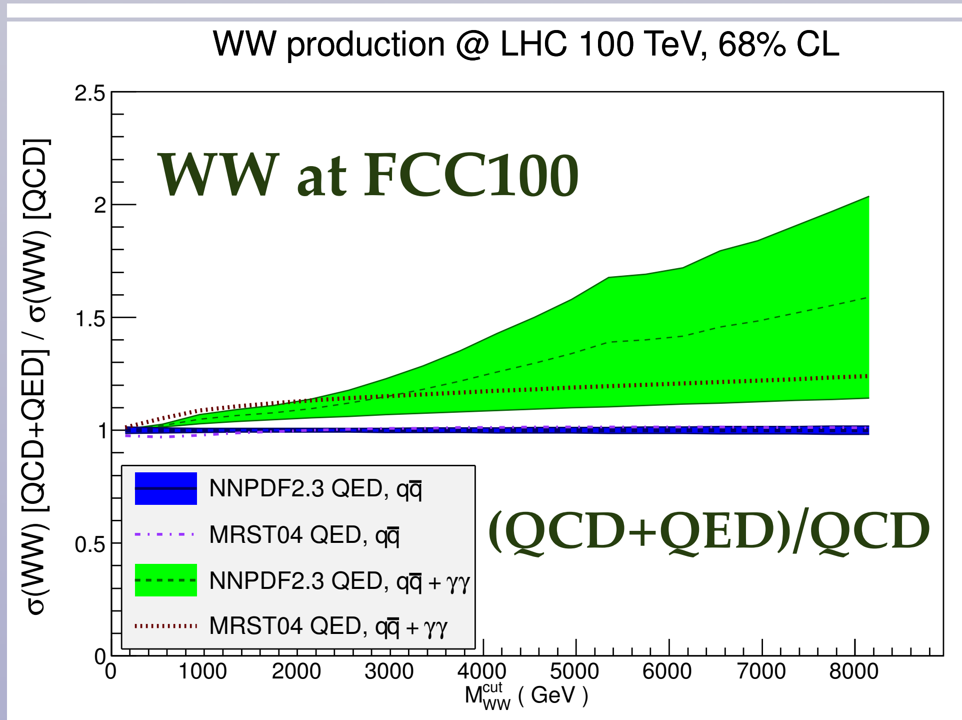
- **Photon-initiated corrections** are remarkably important for a variety of collider applications
- Main limitation is the **poor knowledge on the photon PDF**, leading to large PDF uncertainties



PDFs with QED corrections at FCC

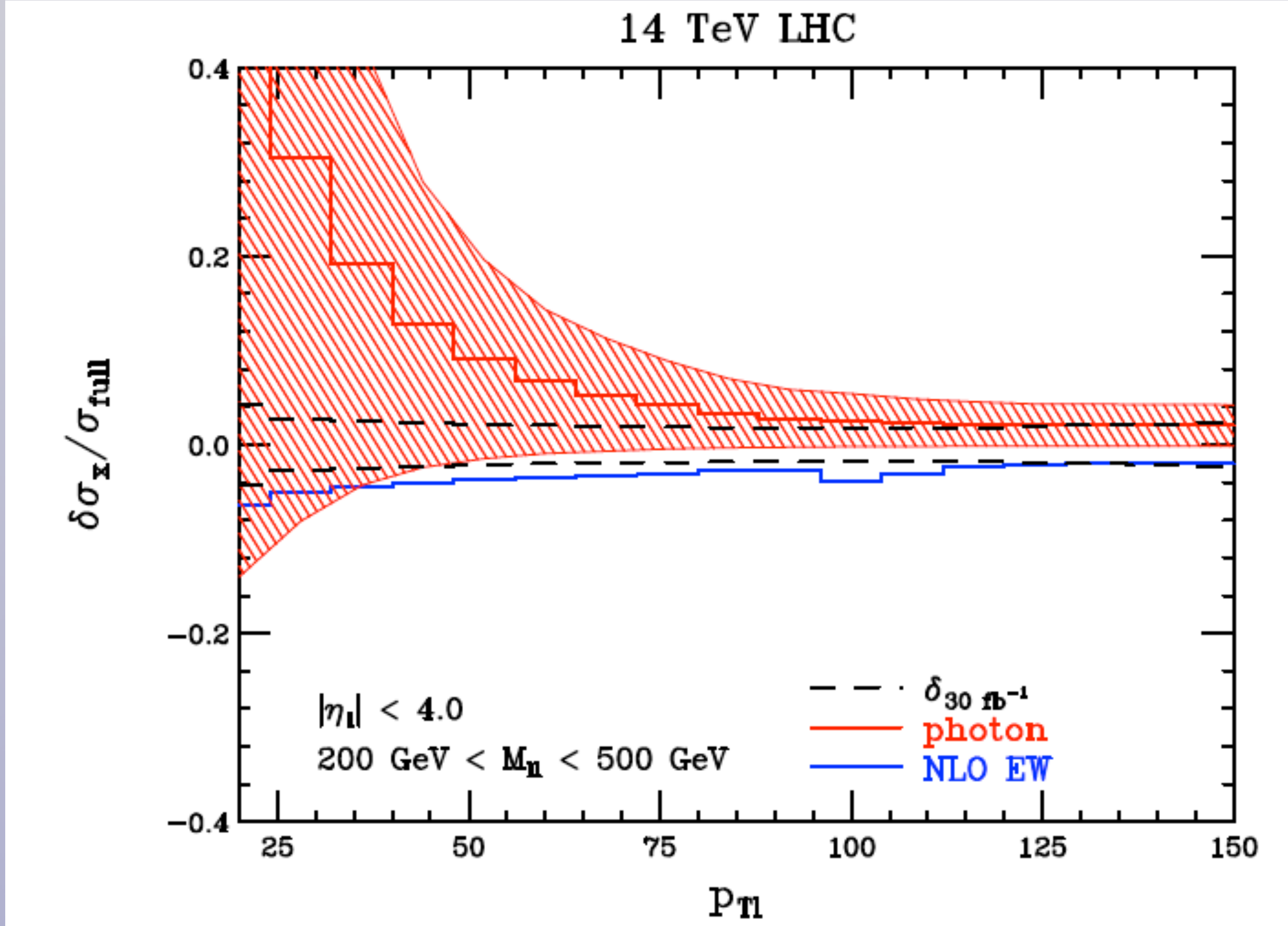


- Uncertainties related to the **photon PDF** are large at high-invariant masses: up to 100% effects at FCC for WW, high-mass Drell-Yan, high-pt top
- The crucial point now is to identify the best measurements to **constrain the photon PDF** and use these to reduce its uncertainty
- Surely the situation will be much better once **LHC data included in the QCD+QED fit**



Pinning down the photon PDF at Run II

- To include LHC data and constrain the photon PDF, first of all one should ensure to **disentangle photon-initiated effects** from **purely electroweak corrections**
- With this requirement one can define observables, such as the lepton **pT** in **high-mass DY,** which exhibits large photon PDF uncertainties and thus can be used to **constrain $\gamma(x,Q)$**



Boughezal, Li, Petriello 2013

Pinning down the photon PDF at Run II

The large uncertainties on the photon PDF are unavoidable consequence of flexible modelling and limited dataset

Will be substantially improved in the next years: for the FCC, photon PDF uncertainties should be similar to quark and gluon PDF uncertainties

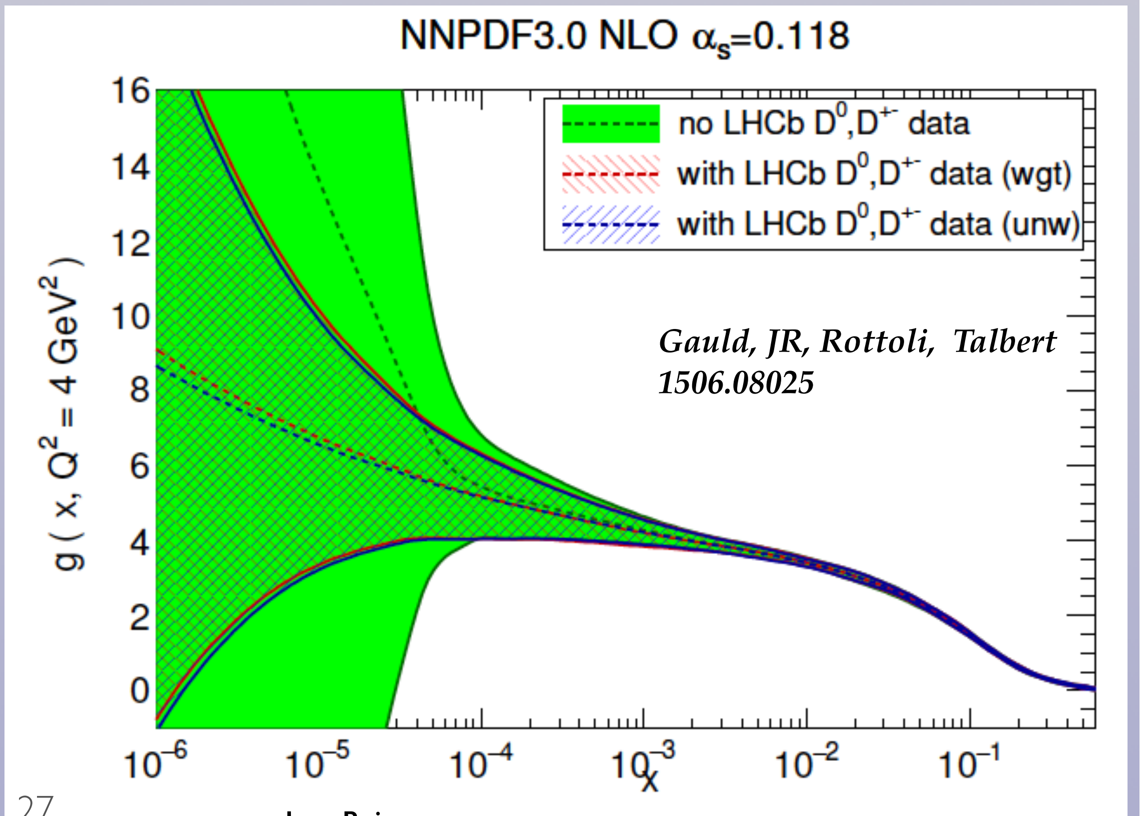
Ultra Low-x Physics at 100 TeV

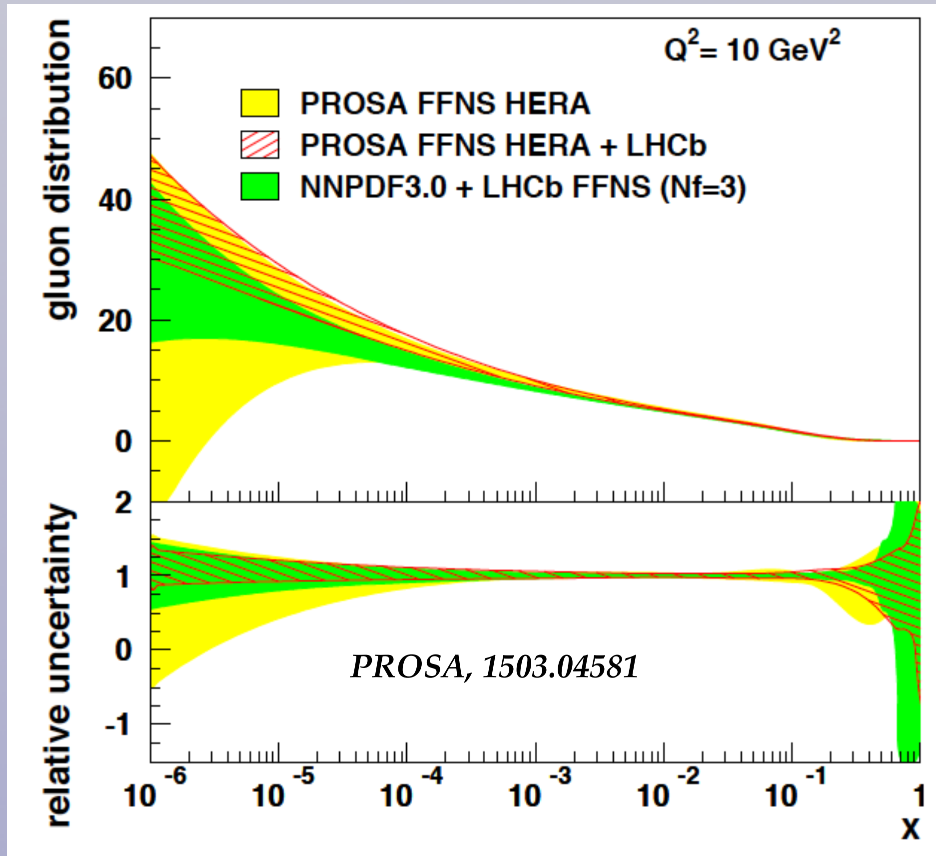
Ultra low-x physics

- The extreme kinematical range of the FCC **accesses the ultra low-x region**, where no experimental constraints on PDFs are available
- To tame the huge small-x PDF uncertainties, one can use processes such **open heavy quark production or low mass Drell-Yan**,
- In addition, ultra-low-x measurements provide important input for **cosmic ray experiments** and for **neutrino telescopes** such as IceCube, which require knowledge of **very small-x PDFs**

PDF fits with LHCb charm data

Also Cacciari, Mangano, Nason 1507.06197





Ultra low-x physics

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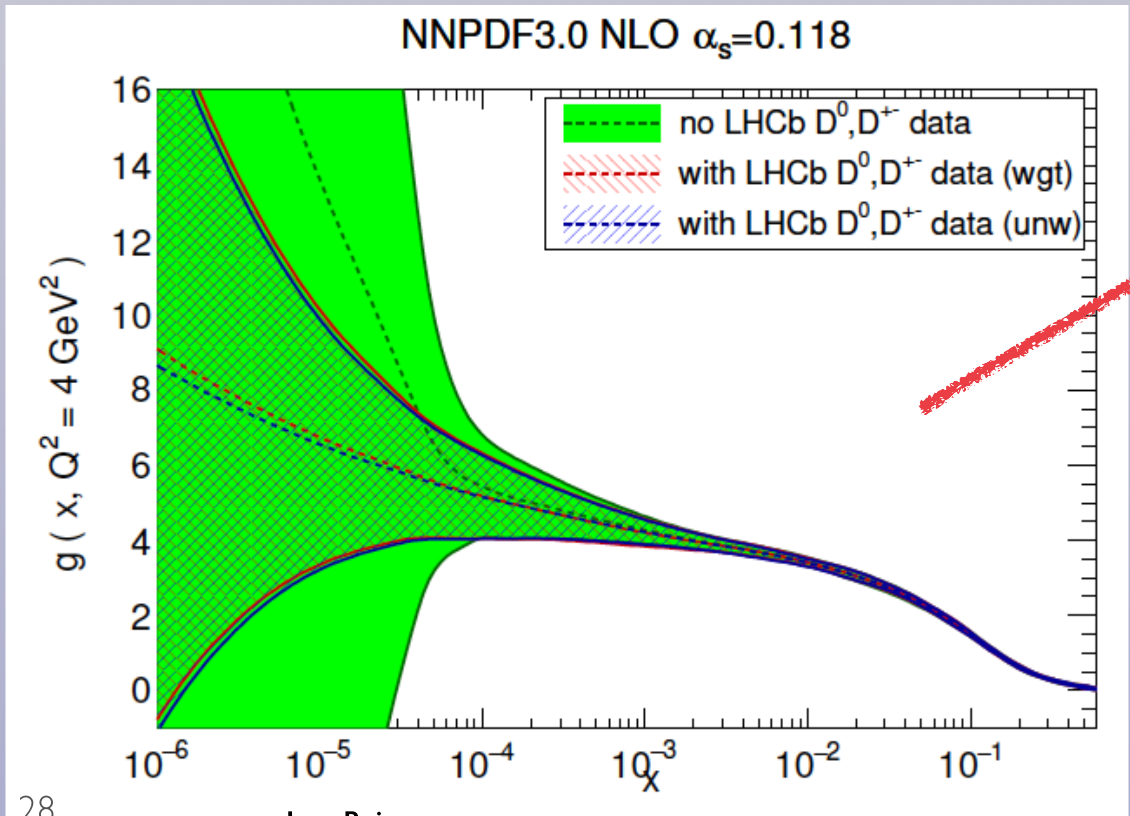
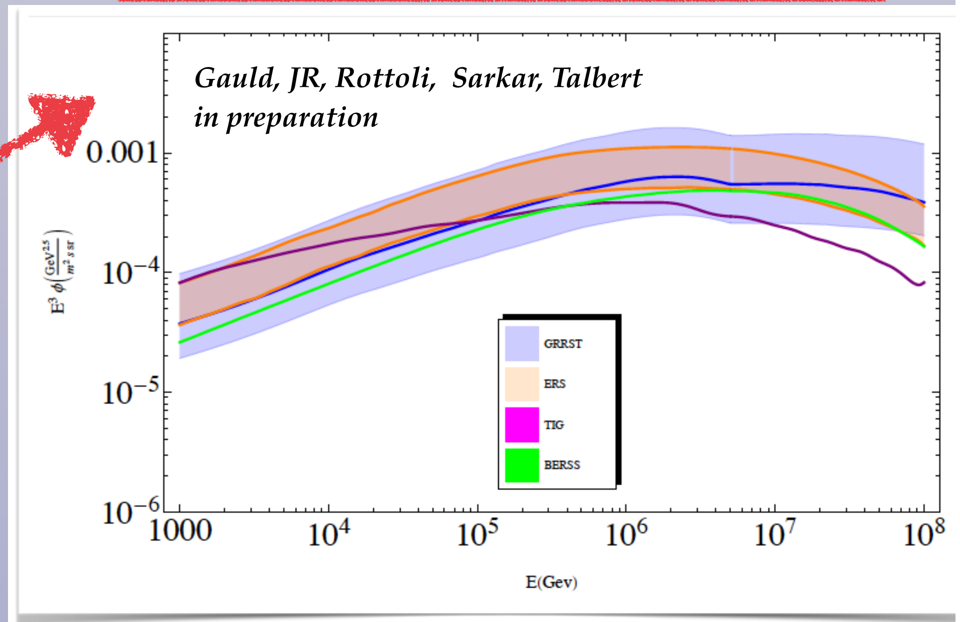
PDF fits with LHCb charm data



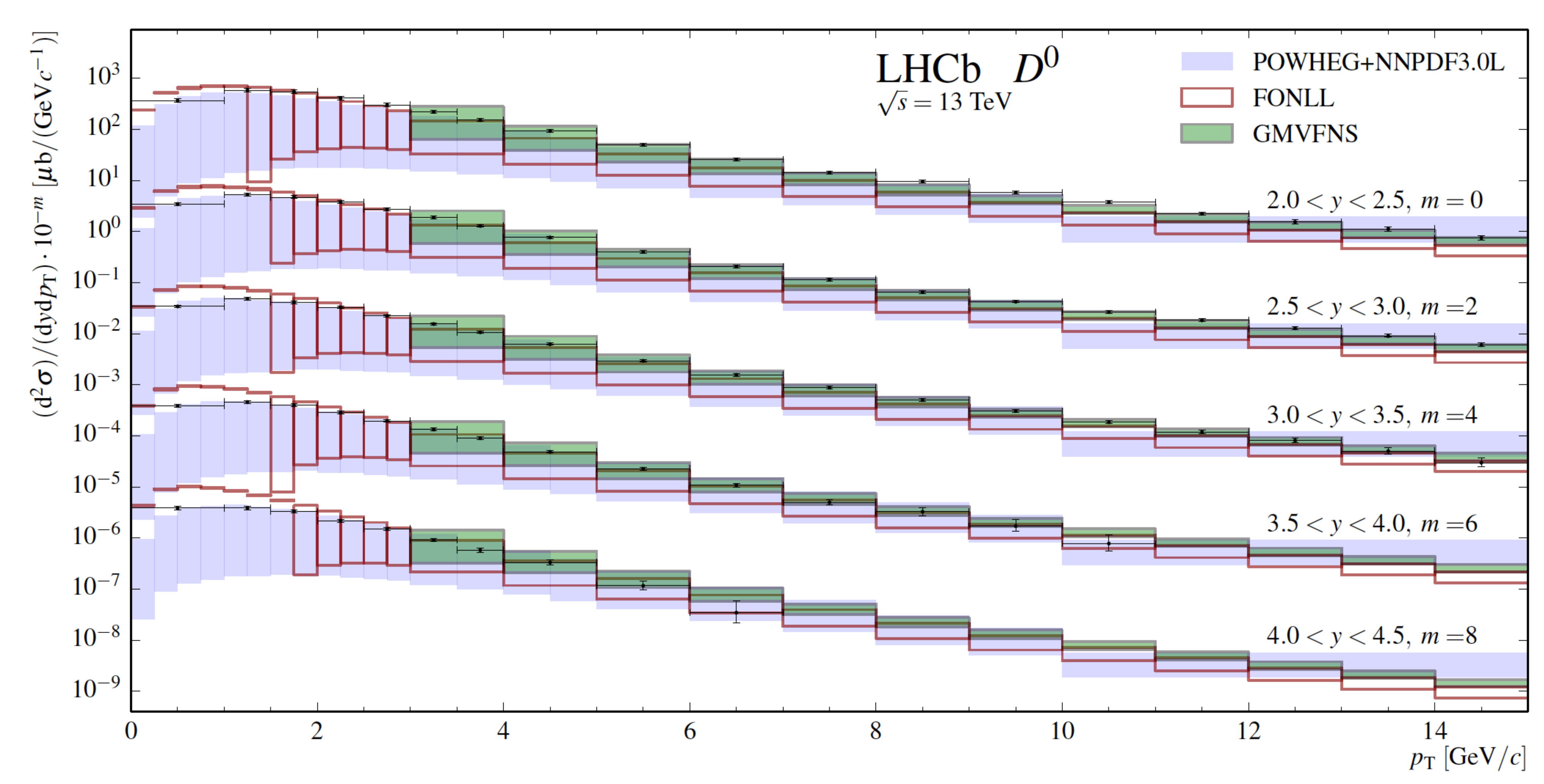
Prompt neutrino fluxes at IceCube



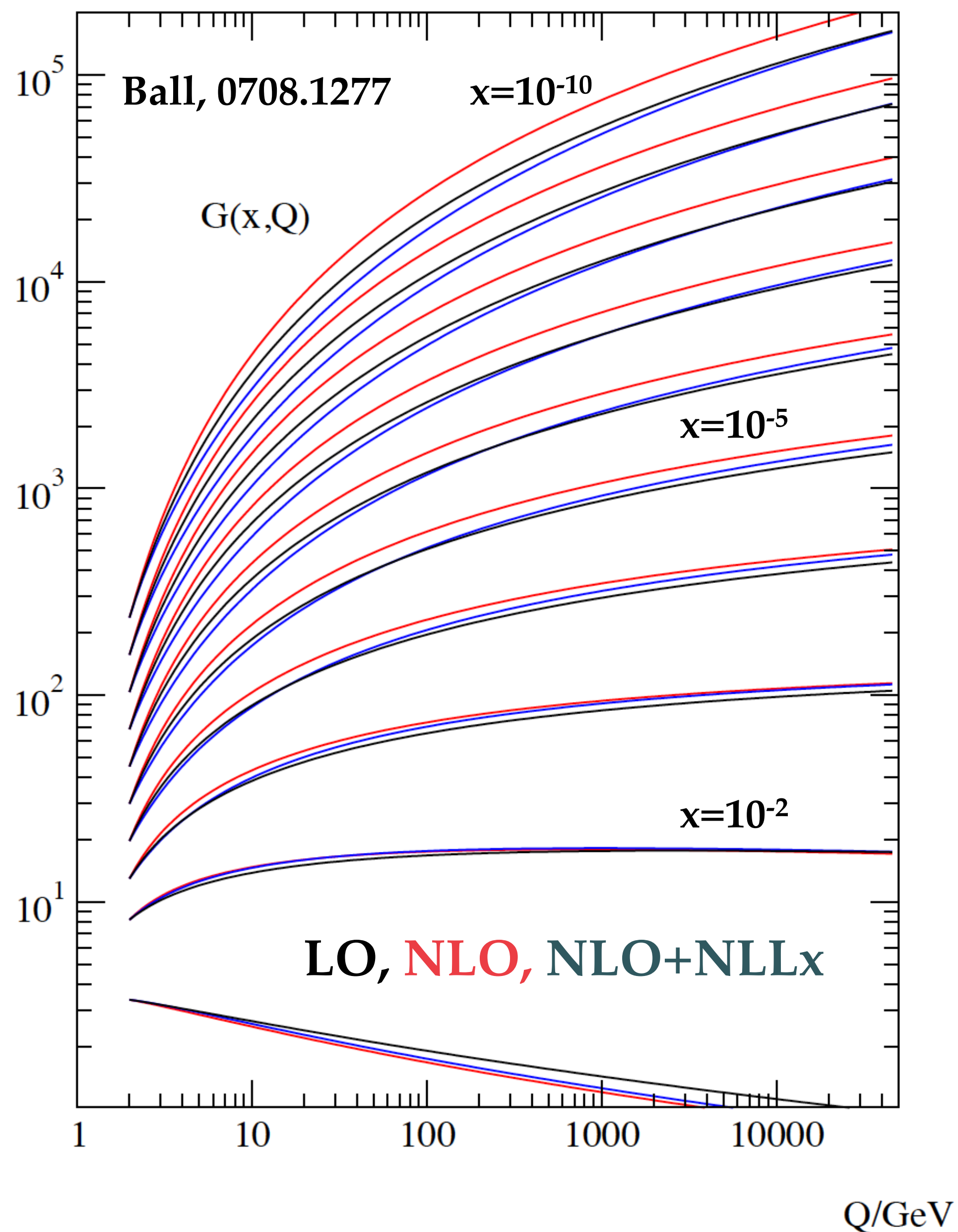
PRELIMINARY-SCALE UNCERTAINTY ONLY

Ultra low-x physics

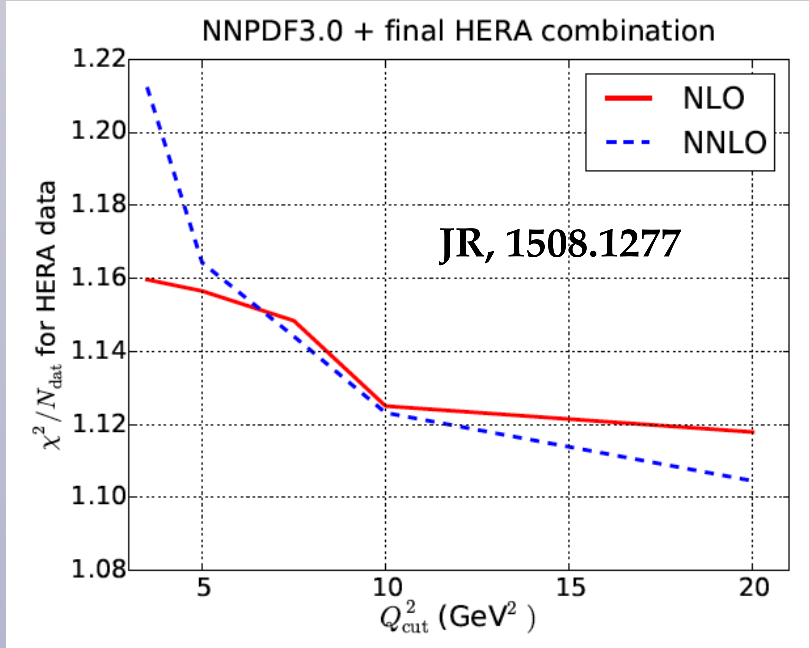
- These predictions have now been validated by the **LHCb 13 TeV charm measurement**
- 13 TeV data, and the ratio of 13/7 cross-sections, should provide **further information on the very small-x gluon PDF**



High-energy resummation at 100 TeV



- So far no clear evidence **of departures from fixed-order DGLAP** has been presented
- One hint that small-x resummation might be relevant is the **small-Q instability** of the PDF fits to the **legacy HERA combination**



- At the **FCC, BFKL resummation** might be an issue. Ongoing study within NNPDF **using NLO +NLLx resummed fits**

Electroweak Parton Distributions

Electroweak Parton Distributions

- The analogous of **DGLAP** evolution equations in QCD can be derived in the **electroweak sector** of the Standard Model, but the resulting equations are quite different

Evolution equation for the structure function of W bosons (Ciafaloni and Comelli, 2002,2005)

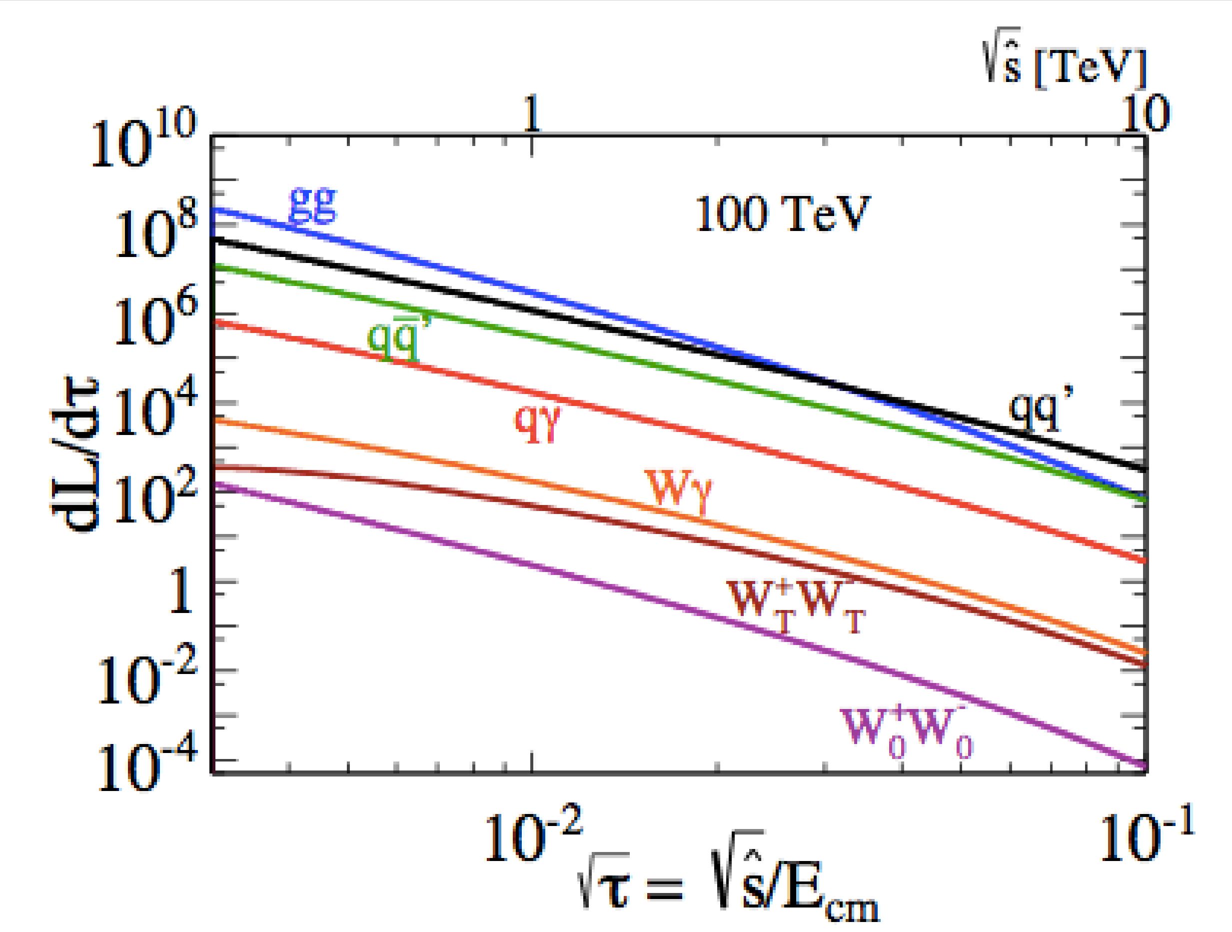
$$-\frac{\partial}{\partial t}\underset{g}{\mathcal{F}}_{AB} = \frac{\alpha_W}{2\pi}\left\{C_g \underset{g}{\mathcal{F}}_{AB}\otimes P^V_{gg} + (T^C_V \underset{g}{\mathcal{F}} T^C_V)_{AB}\otimes P^R_{gg} + \left(\sum_L \mathrm{Tr}\left[t^B \underset{L}{\mathcal{F}}\,{}^t t^A\right] + \sum_{\bar{L}} \mathrm{Tr}\left[t^A \underset{L}{\mathcal{F}}\, t^B\right]\right)\otimes P^R_{fg} + \mathrm{Tr}\left[T^B_L \underset{\phi}{\mathcal{F}}\,{}^t T^A_L\right]\otimes P^R_{\phi g}\right\}$$

- No **numerical implementation of EW evolution** equations available. **Very different flavour/coupling structure** as compared to QCD evolution equations

- In addition, **EW evolution must be combined with pure QED evolution**, and then combined with **QCD** into a **complete set of Standard Model PDF evolution equations**

- How important are **electroweak PDFs** for FCC phenomenology? If we have the evolution equations, is it **enough to generate the W,Z PDFs radiately?**

Electroweak Parton Distributions



Han, Tweedie

- We will discuss in this session new results on **EWK PDFs**
- **W,Z PDFs** could be useful to improve calculations of vector-boson fusion at the FCC
- What are the most striking experimental signatures of EWK PDFs at the FCC?
- Relation to **electroweak parton showers?**
- New qualitative behaviours? **Spontaneous proton polarization? CP violating effects in DGLAP?**
- What is the **Higgs content of the proton?**

Summary and plans for report

- It is extremely difficult to forecast how **PDFs will look like in 20 years**
- For the report, we plan to focus instead on
  - ☑ **Validation of available PDF sets** for general FCC simulations
  - ☑ **Generic features of PDFs at 100 TeV** (including look-up luminosity tables)
  - ☑ **Qualitatively new effects** in PDF evolution that could be relevant at 100 TeV: top PDFs, EWK PDFs, PDFs with BFKL resummation
  - ☑ Interplay between **photon-initiated contributions** and electroweak corrections
  - ☑ **Connection with ultra low-x physics**, cosmic rays and astrophysics
- In addition to being an important tool for Higgs and BSM studies at the FCC, **parton distributions at 100 TeV are a really fascinating topic with itself**, with many qualitatively new effects arising: the FCC is much more than a rescaled LHC!