# Parton Distributions at a 100 TeV Hadron Collider

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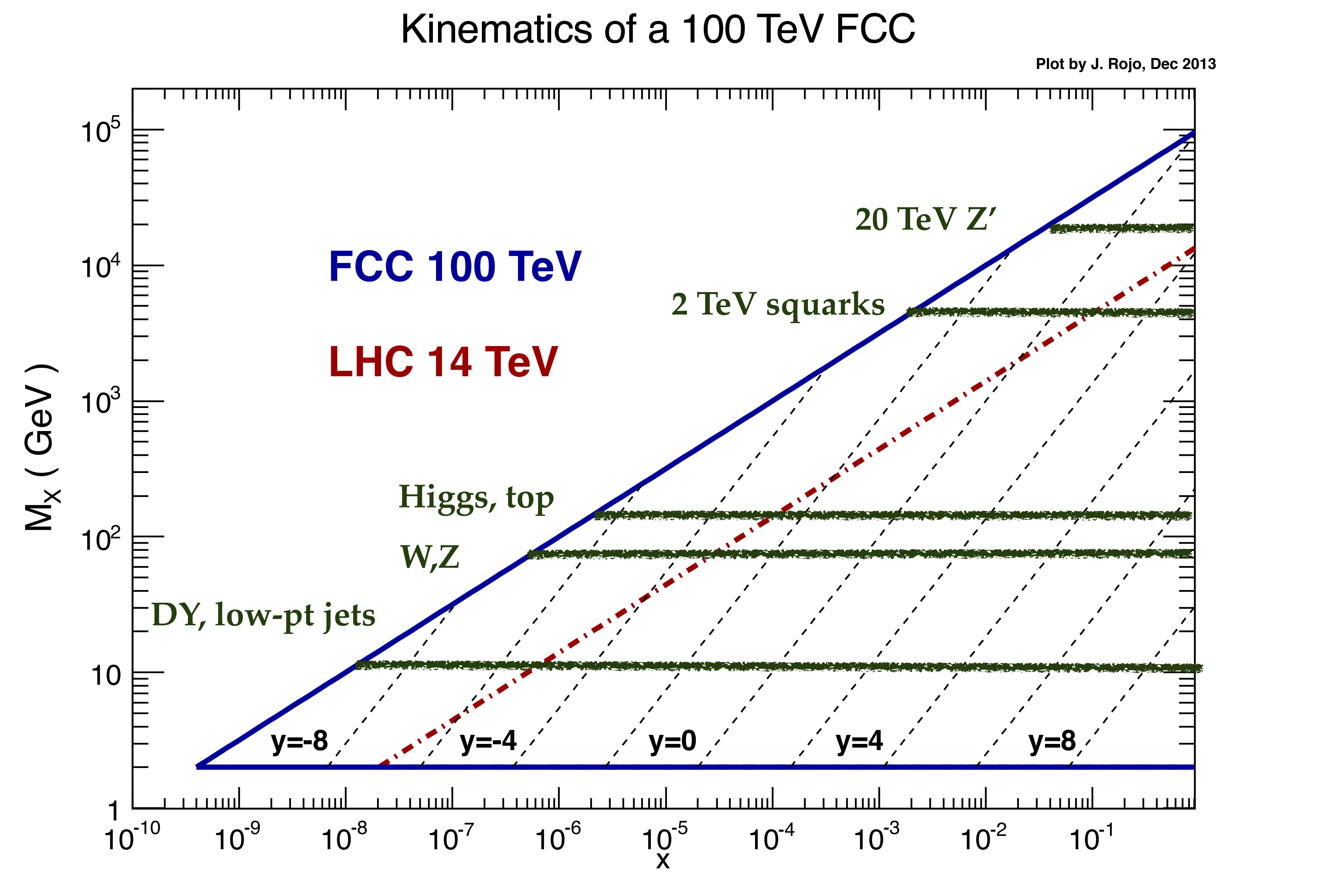
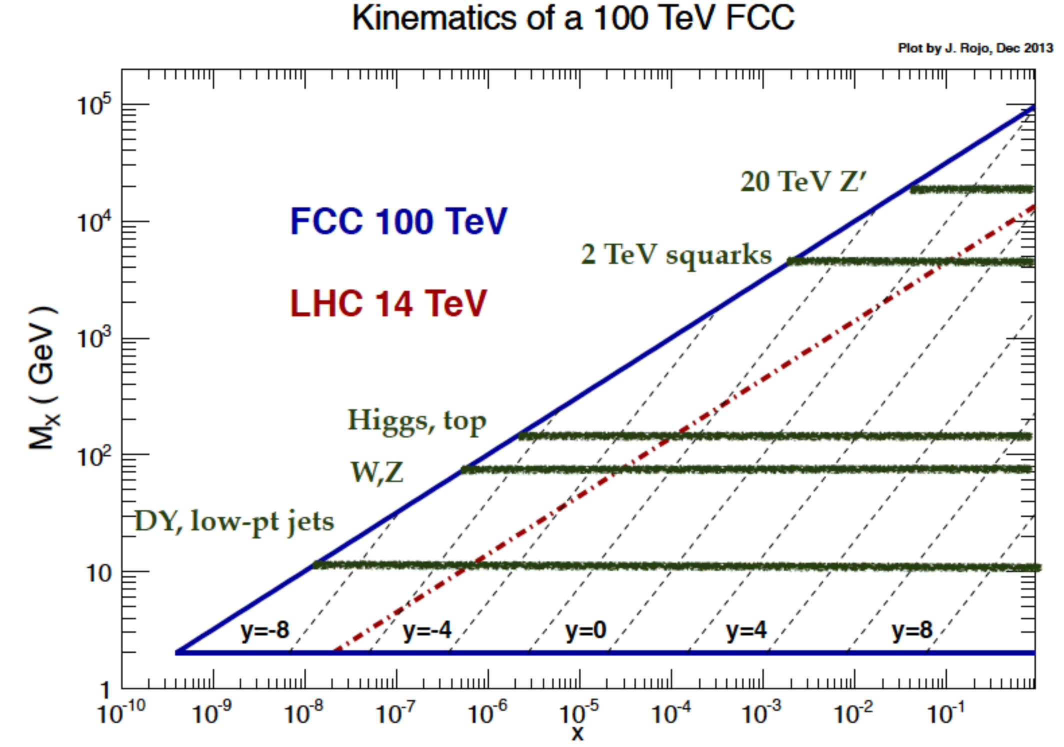
Based on ``*Physics at a 100 TeV pp collider: Standard Model processes"*
to appear in the arXiv next week

**Deep Inelastic Scattering 2016**
**DESY, 12/04/2016**

# Kinematical coverage



# Kinematical coverage



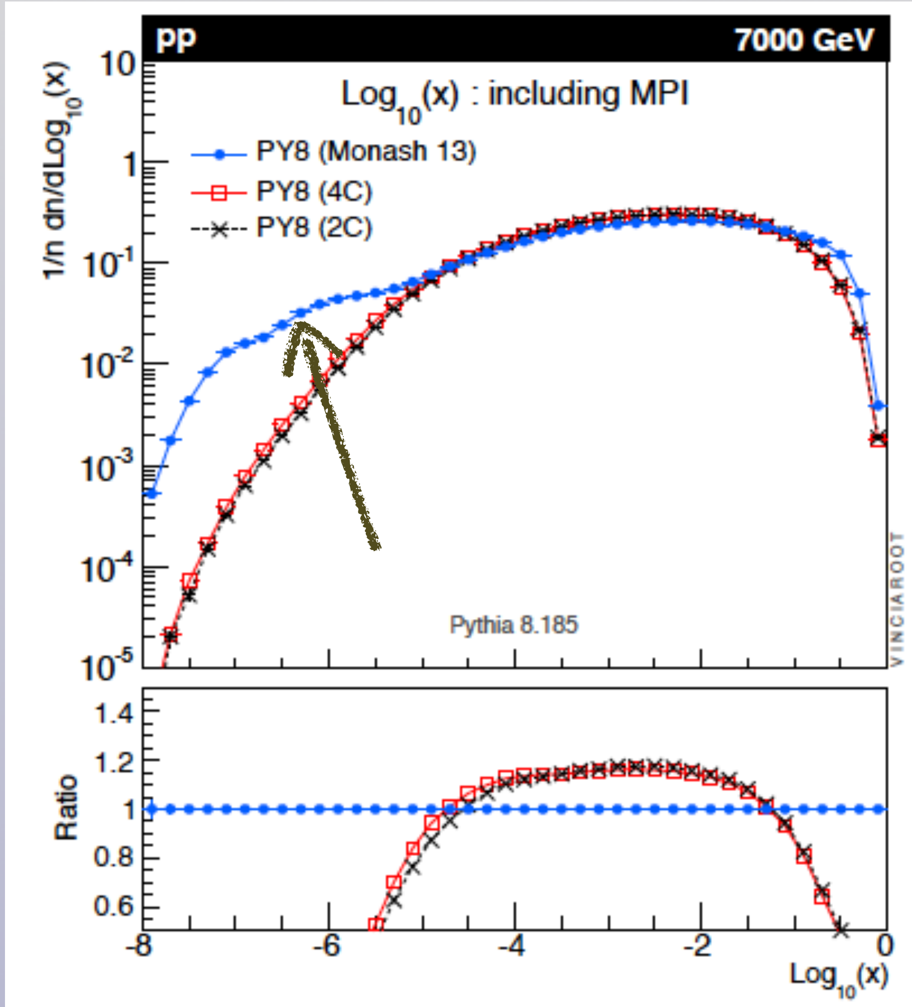

- For the same $M_X$ and **y, FCC100** probes values of **x** smaller by **0.14** as compared to LHC14

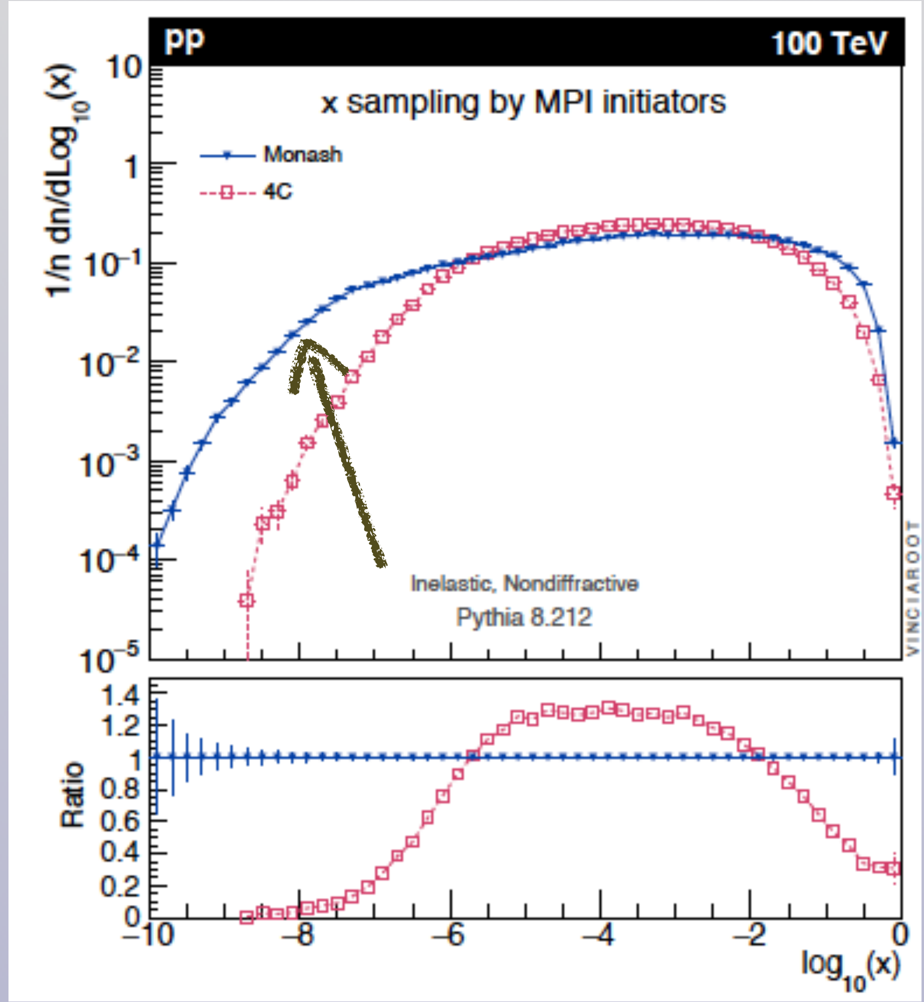
$$x_{1,2} = \frac{M_X}{\sqrt{s}} \exp(\pm y)$$

- At the FCC100, knowledge of PDFs is required in extreme kinematical regions: **very small-x, very large-x, very large** $M_X$

| Process | $M_X$ | $x_{\rm min}$ $y=0$ | $x_{\rm min}$ $\|y\|=2$ | $x_{\rm min}$ $\|y\|=4$ |
|---|---|---|---|---|
| Soft QCD<br>Charm pair production<br>Low-mass Drell-Yan | 1 – 10 GeV | $2\cdot10^{-5}$ | $2\cdot10^{-6}$ | $4\cdot10^{-7}$ |
| $W$ and $Z$ production<br>Top pair production<br>Inclusive Higgs | 80 – 400 GeV | $2\cdot10^{-3}$ | $8\cdot10^{-4}$ | $7\cdot10^{-5}$ |
| Heavy New Physics | $M_X \gtrsim 5$ TeV | 0.05 | 0.01 | – |

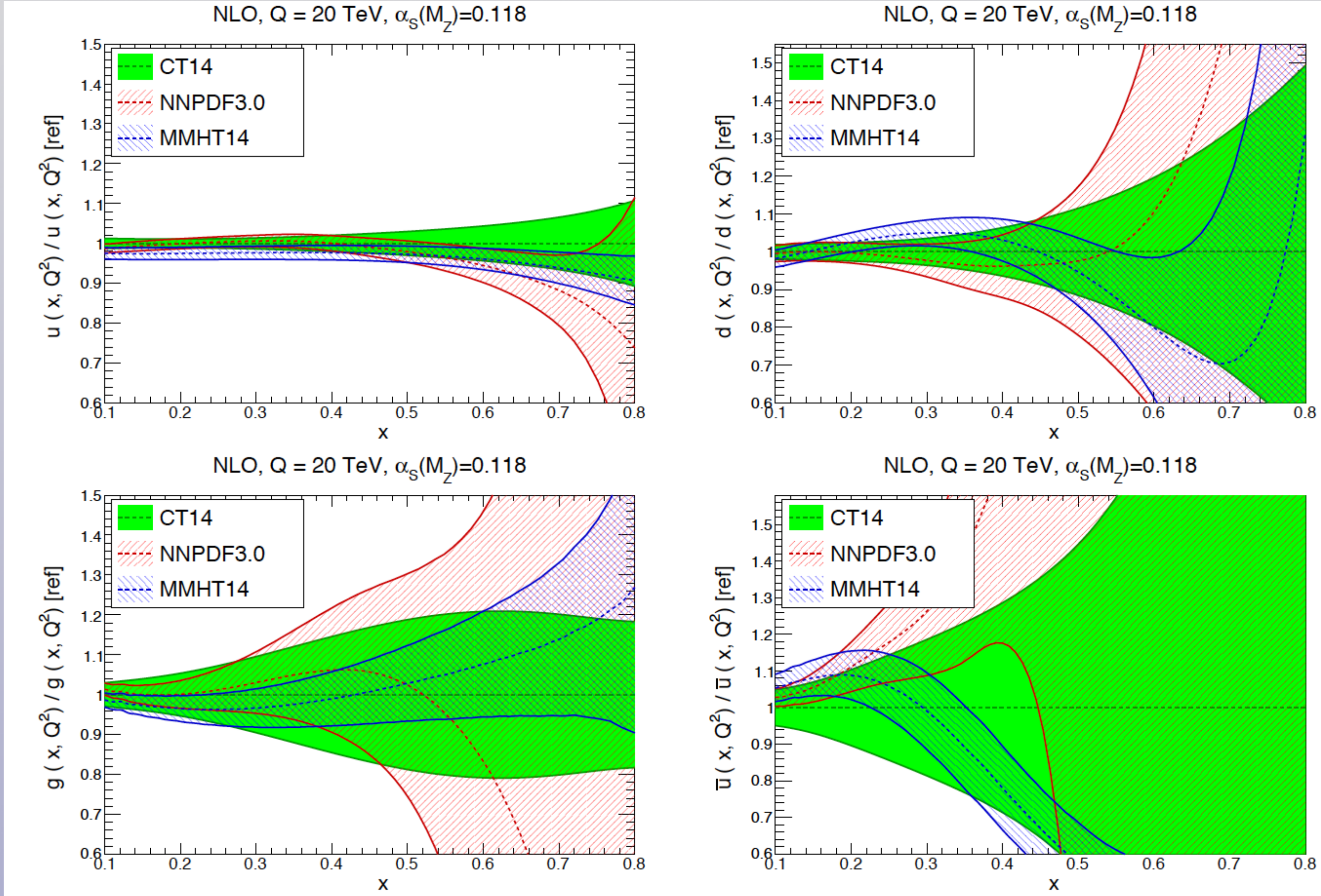
# Small-x PDFs at 100 TeV




- **Small-x, small-Q PDFs** are required for the description of **soft 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 **$10^{-6}$** while at the **FCC** we require **$10^{-8}$**

# Large-x PDFs at 100 TeV



# Large-x PDFs at 100 TeV

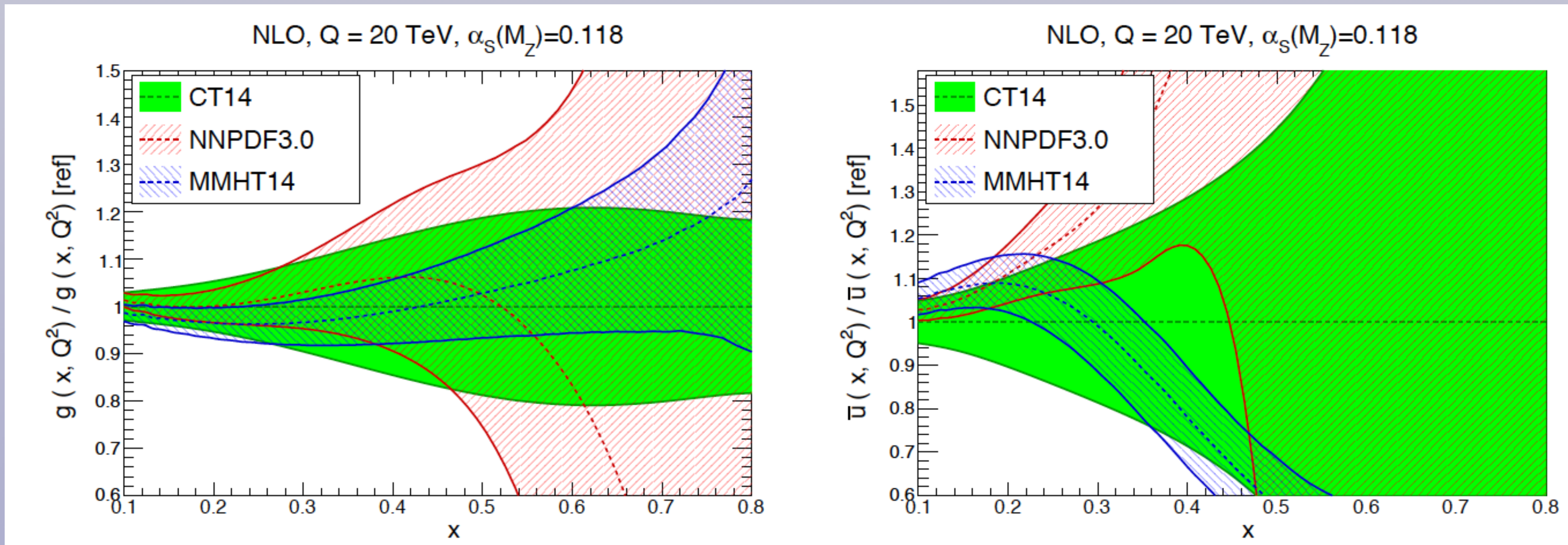
- Modern sets **extrapolate to very large-x without technical problems** in LHAPDF6.1.5
- **PDF uncertainties very large in this region**, due to limited experimental constraints at **large-x**
- Expect improvement in the coming years from **LHC Run I and Run II data**

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

***arXiv:1507.00556***

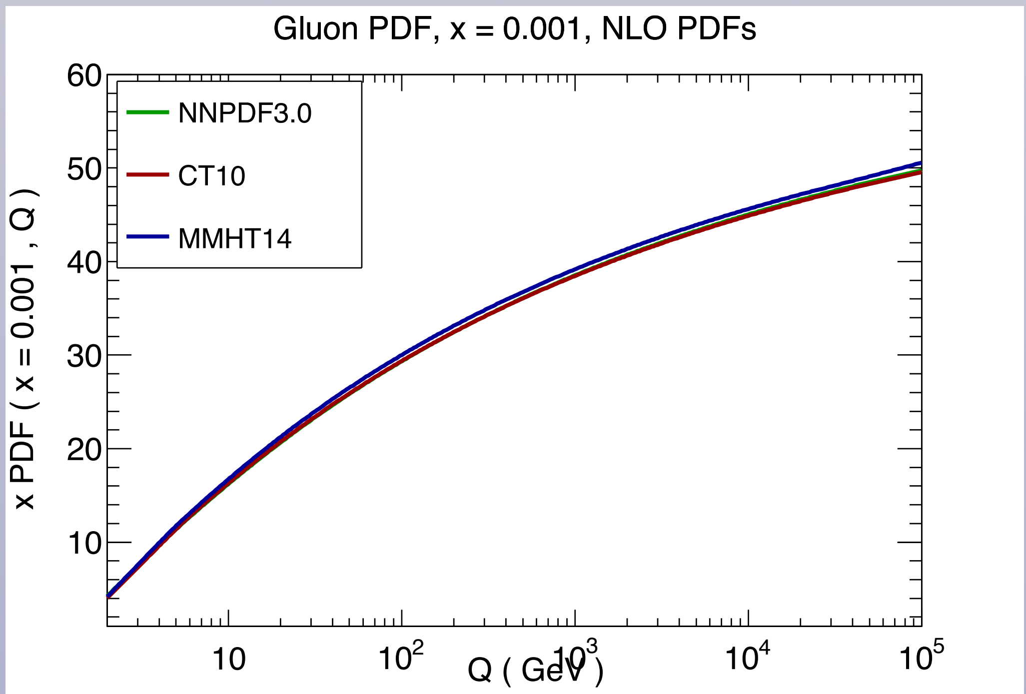
*Juan Rojo[1], Alberto Accardi[2,3], Richard D. Ball[4,5], Amanda Cooper-Sarkar[6], Albert de Roeck[5,7], Stephen Farry[8], James Ferrando[9], Stefano Forte[10], Jun Gao[11], Lucian Harland-Lang[12], Joey Huston[13], Alexander Glazov[14], Maxime Gouzevitch[15], Claire Gwenlan[6], Katerina Lipka[14], 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]*

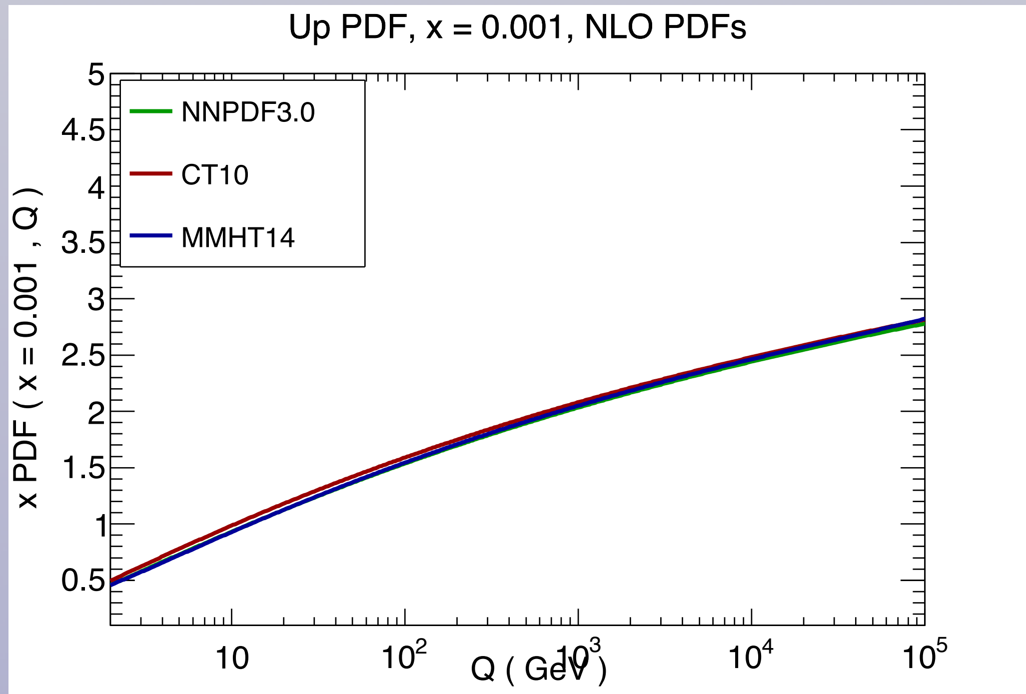
searches. A major recent development in modern PDF analyses has been to exploit the wealth of new information contained in precision measurements from the LHC Run I, as well as progress in tools and methods to include these data in PDF fits. In this report we summarise the information that PDF-sensitive 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 $\alpha_S$(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 there
- However, this does not account for **genuinely new effects for the FCC kinematics**: W,Z PDFs, BFKL effects, ……



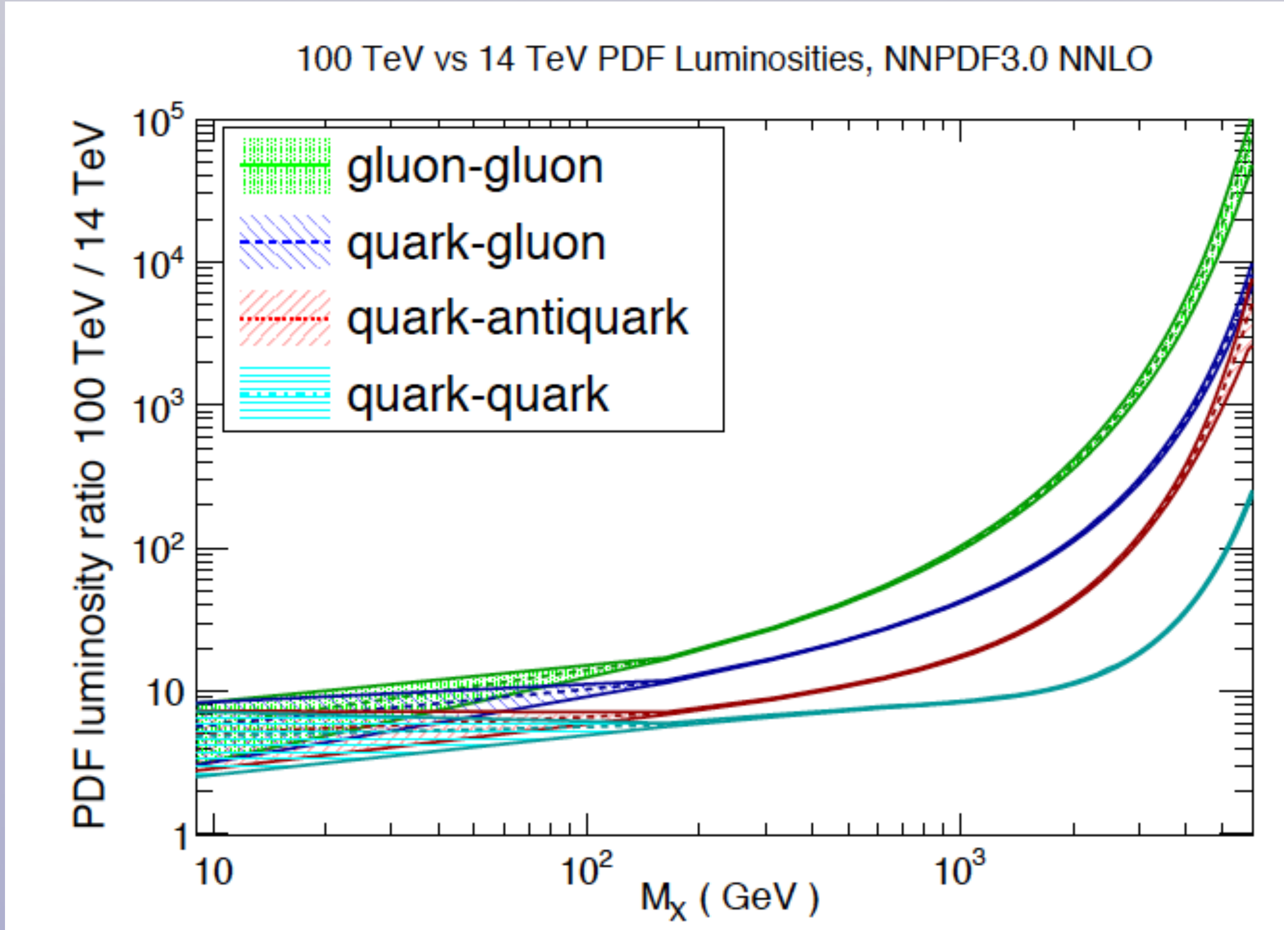



# PDF luminosities

**Ratio of PDF luminosities between 100 TeV and 14 TeV** in different channels as a function of **$M_X$**

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

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




- 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 $10^5$** for ***M* = 6 TeV**
- **Gluon-gluon** and **quark-gluon luminosoties** increase faster

# PDF luminosities

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

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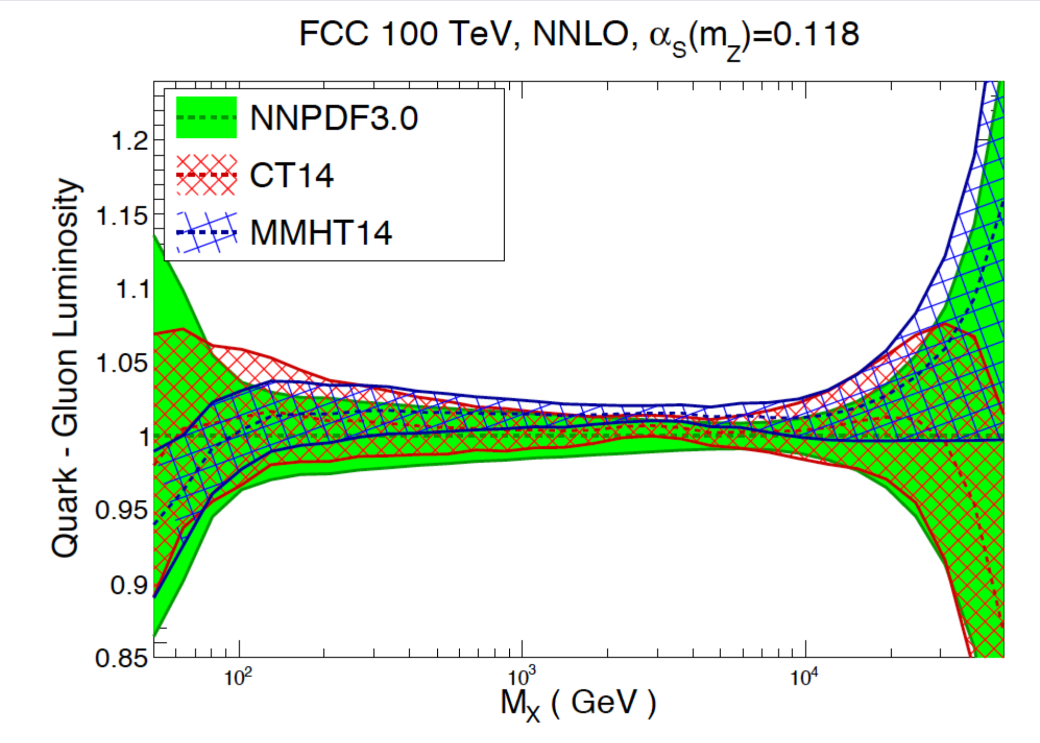
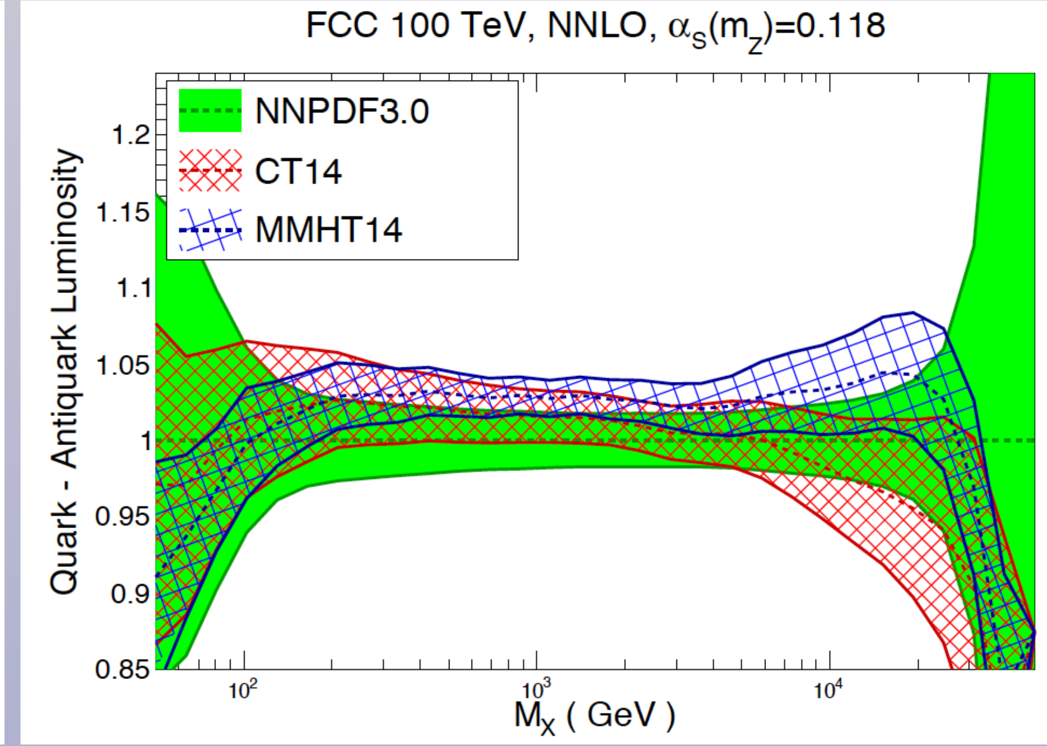
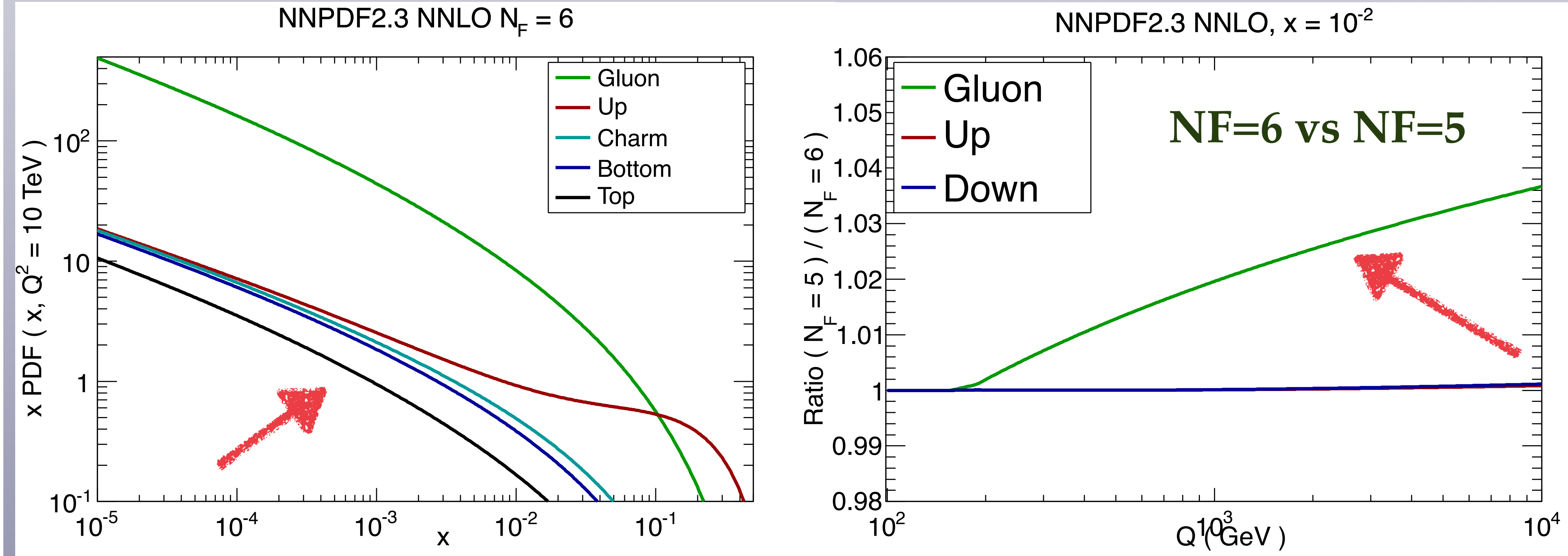


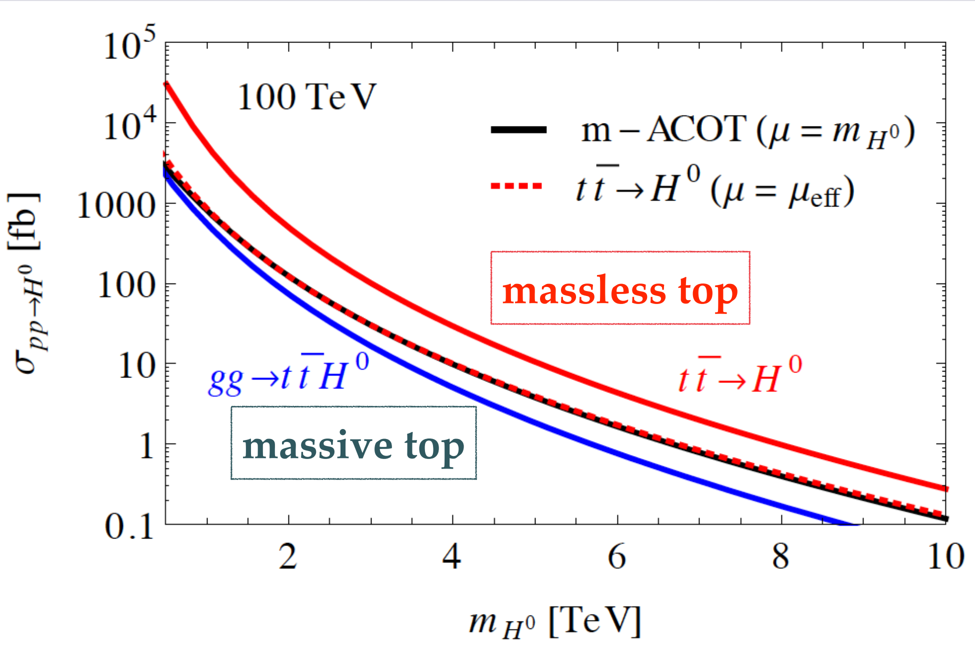
# Heavy quark PDFs at the FCC

- 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

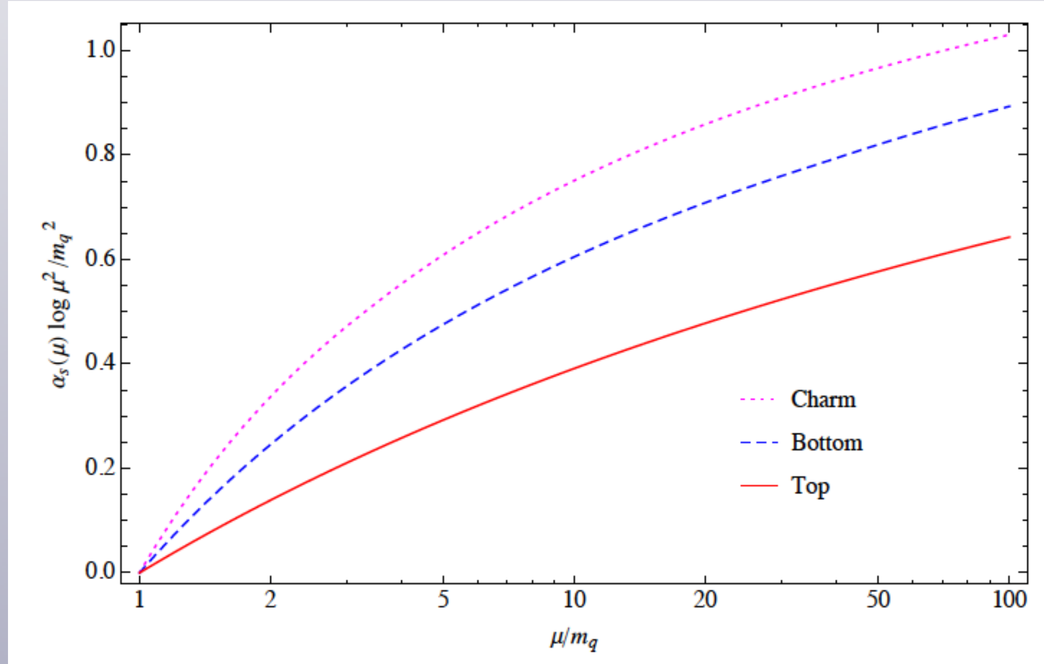


# Heavy quark PDFs at the FCC

- Various studies indicate that **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*



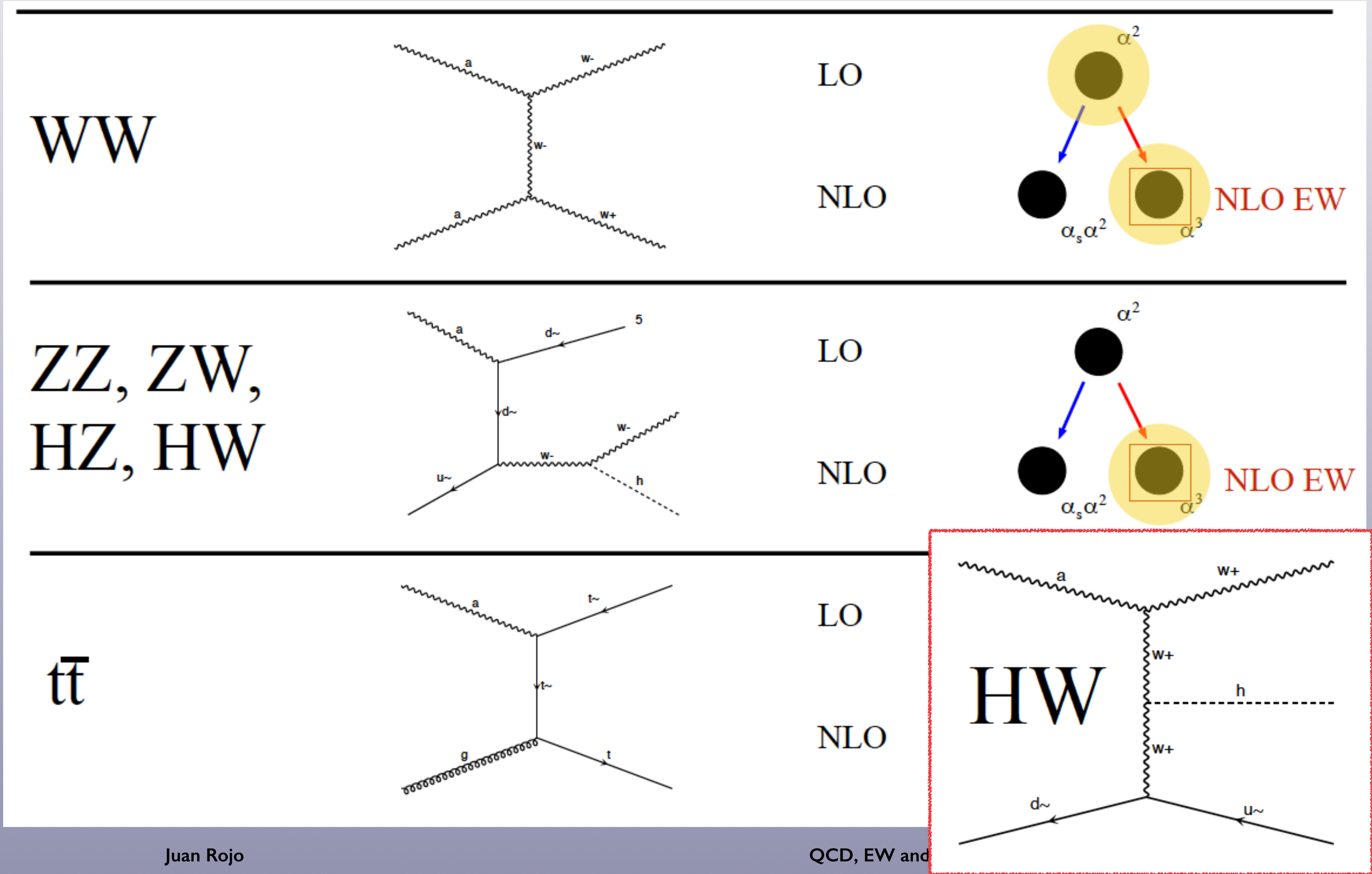

*Dawson, Ismail, Low, 1405.6211*

- **Resummation of collinear top logs at FCC l**ess important than charm and bottom at LHC:
  - ☑ Collinear logs are suppressed by the smaller value of $\boldsymbol{\alpha_S(m_{top})}$
  - ☑ Suppression due to universal phase space factors and the steep fall-off of **large-x gluon**

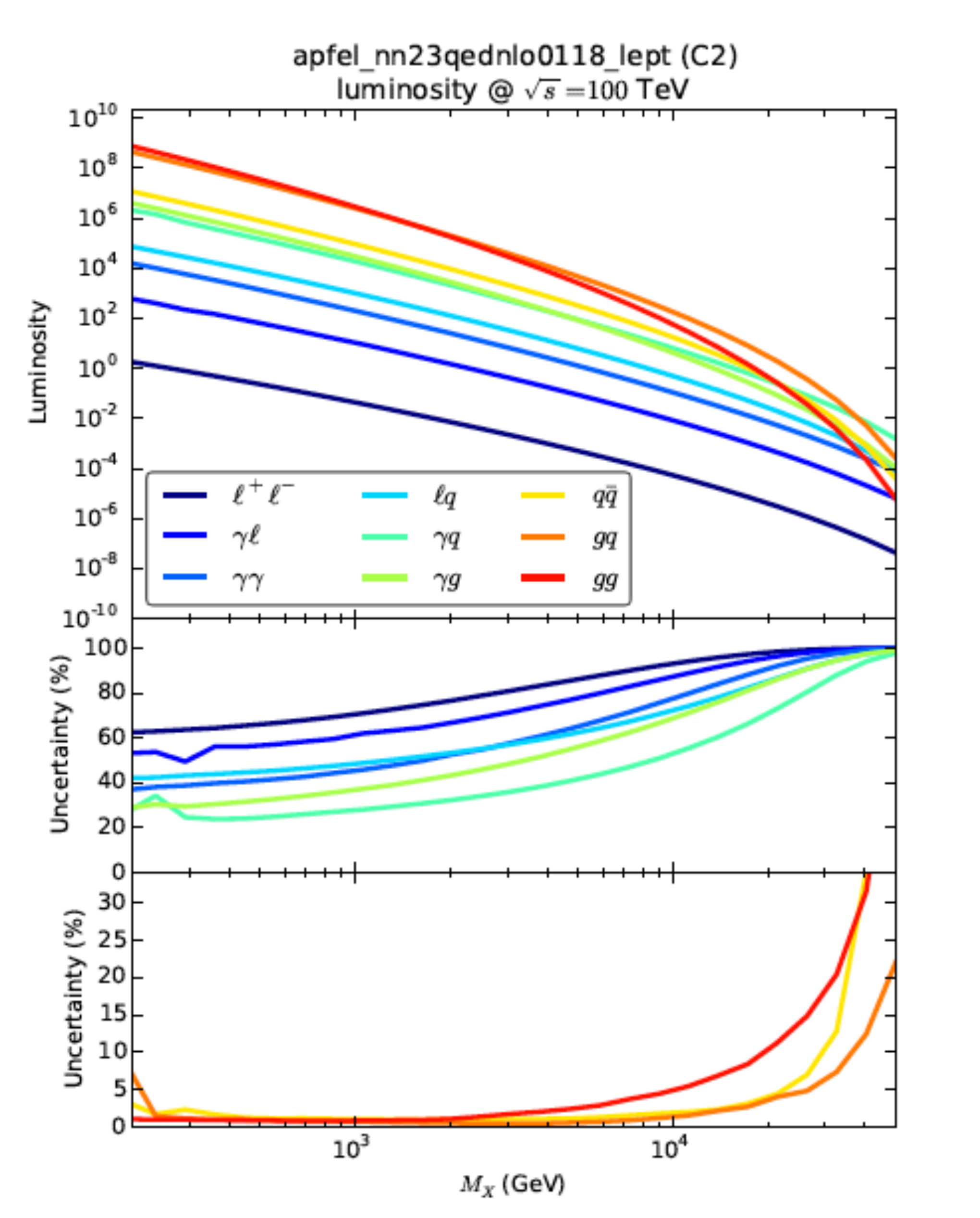
*Maltoni, Ridolfi, Ubiali, 1203.6393*

# Photon-initiated processes at 100 TeV

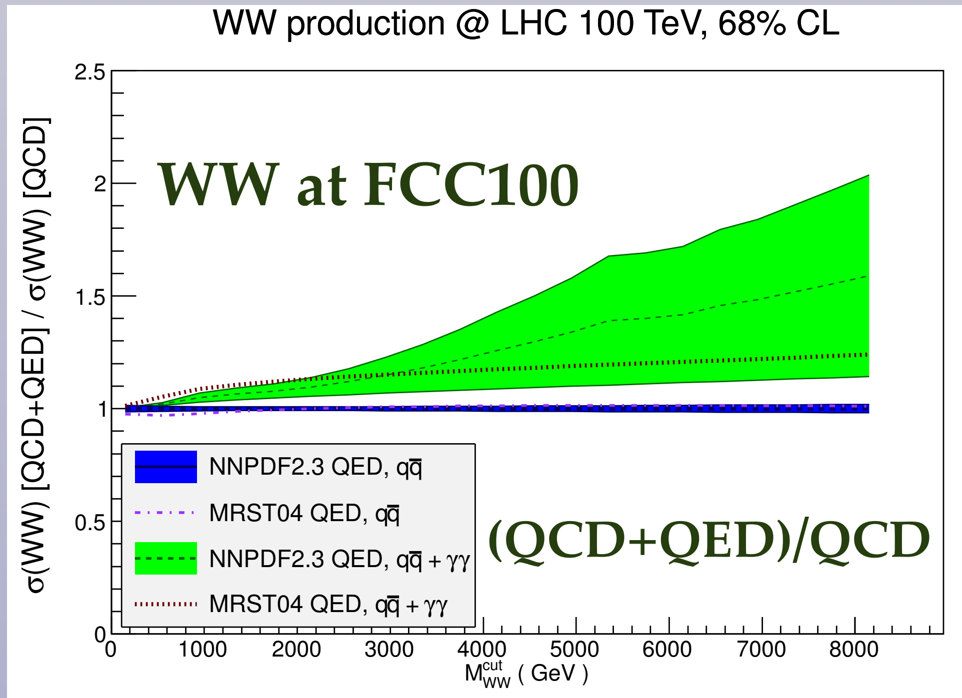
- **Photon-initiated corrections** are remarkably important for a variety of collider applications
- Main limitation is the **poor knowledge on the photon PDF**, leading to large PDF uncertainties



# PDFs with QED corrections at FCC

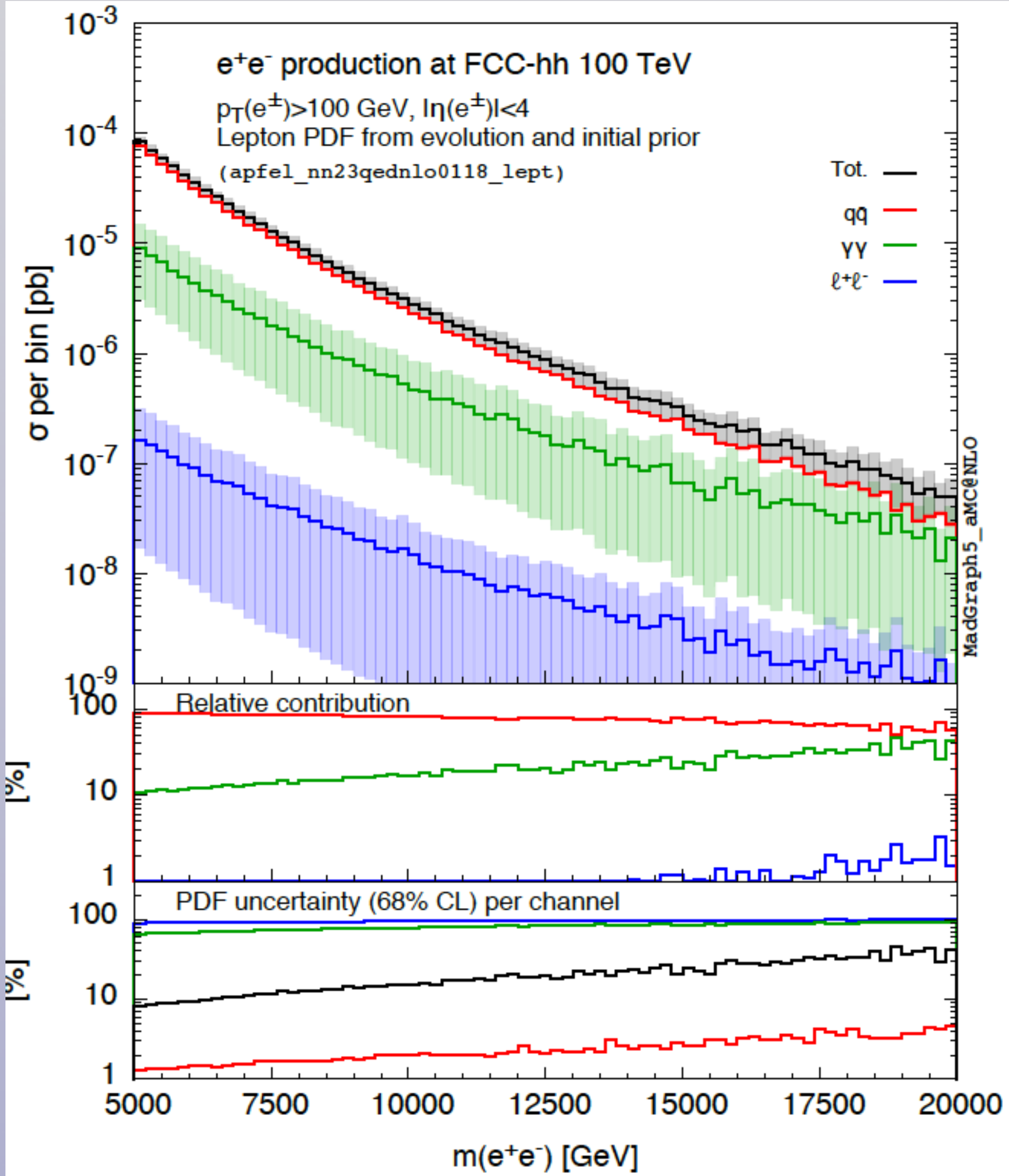



- Uncertainties related to the **photon PDF** are large at high-invariant masses: up to **100% effects at FCC** for WW, high-mass Drell-Yan, high-pt top
- The crucial point now is to identify the best measurements to **constrain the photon PDF** and use these to reduce its uncertainty
- Surely the situation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

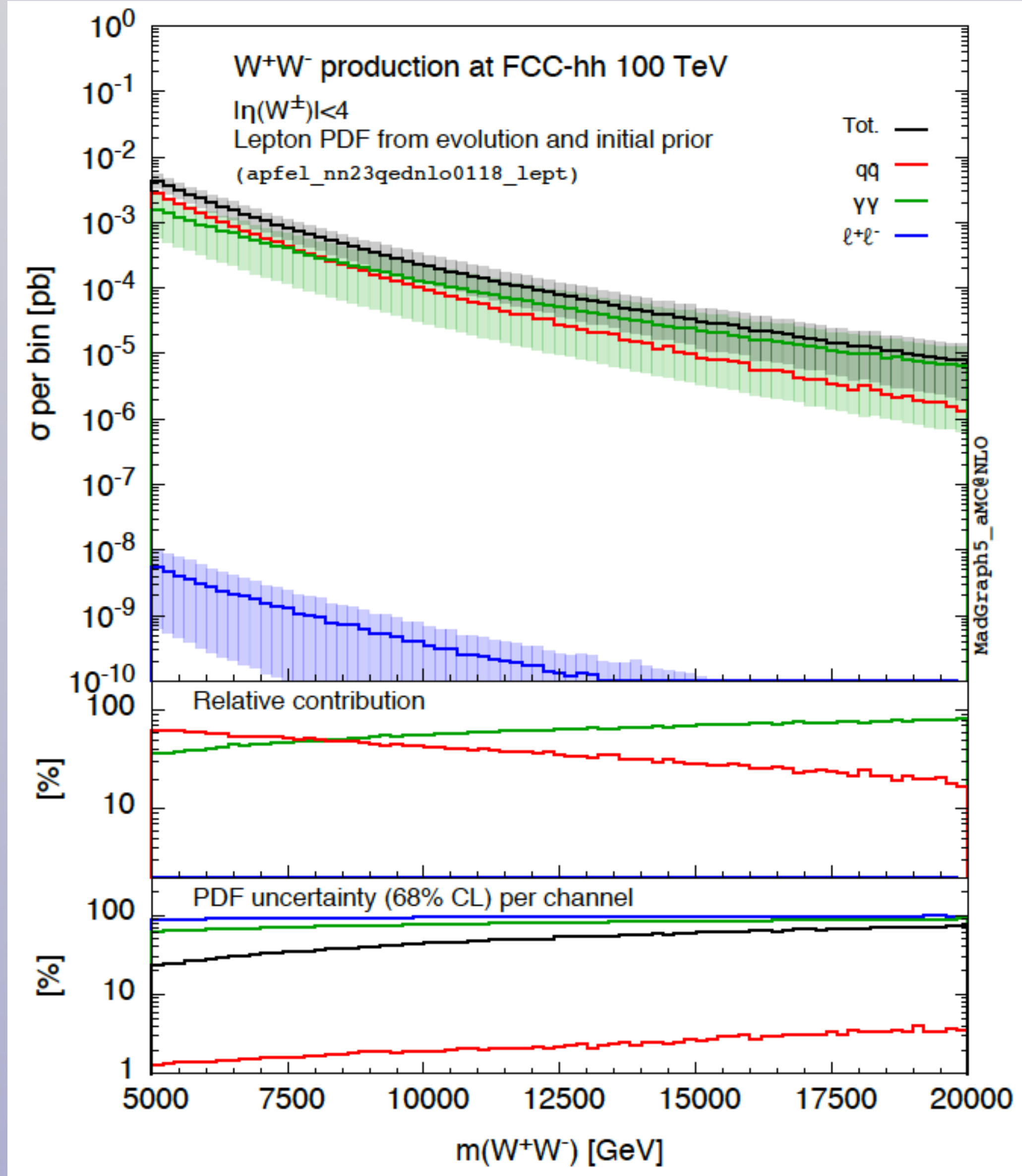


# PDFs with QED corrections at FCC

**High-mass Drell-Yan**




**WW production**

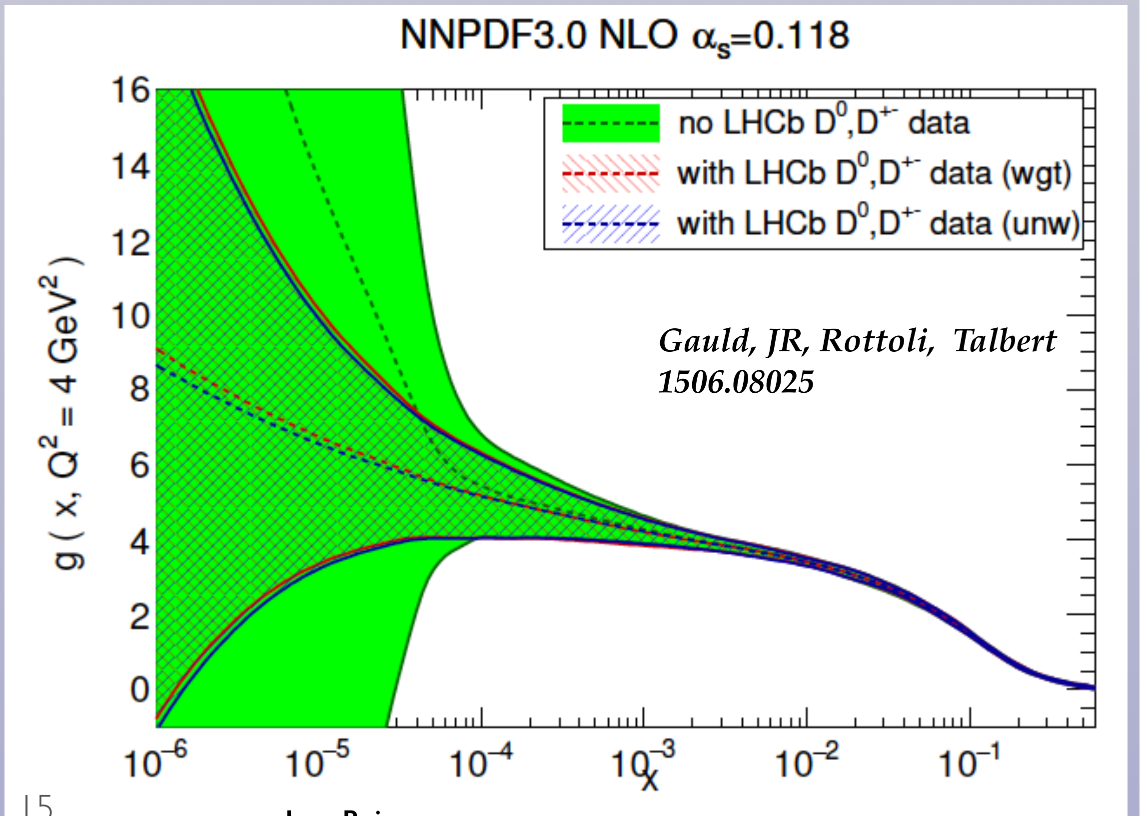


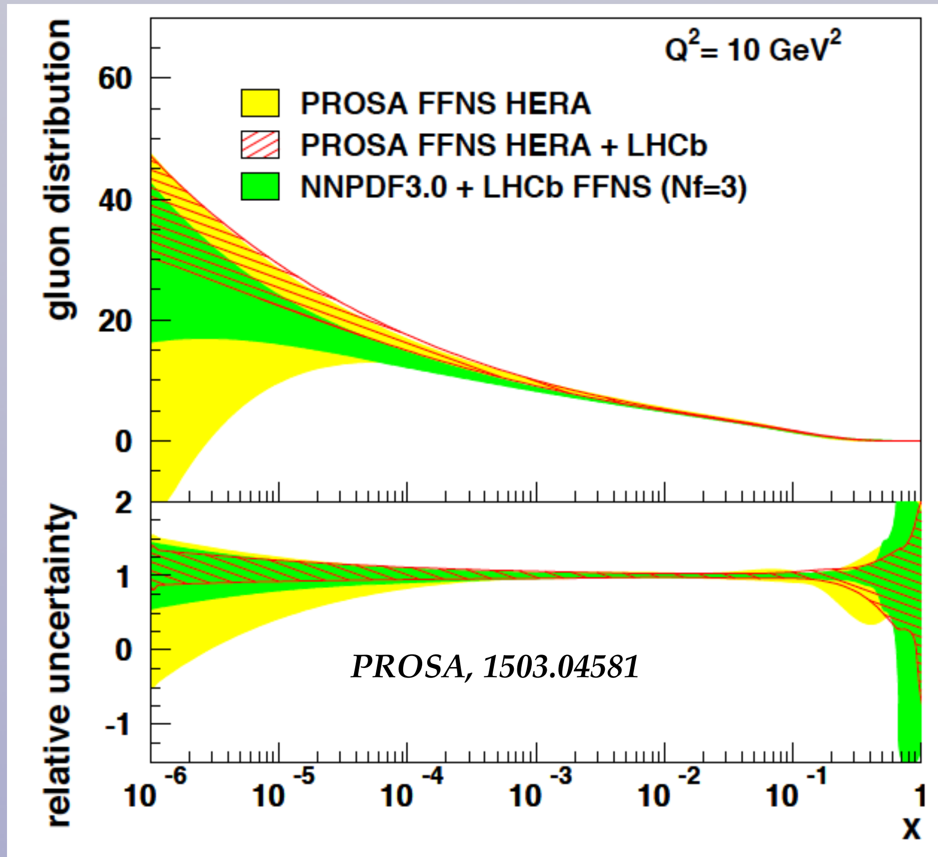
# Ultra low-x physics

- 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*



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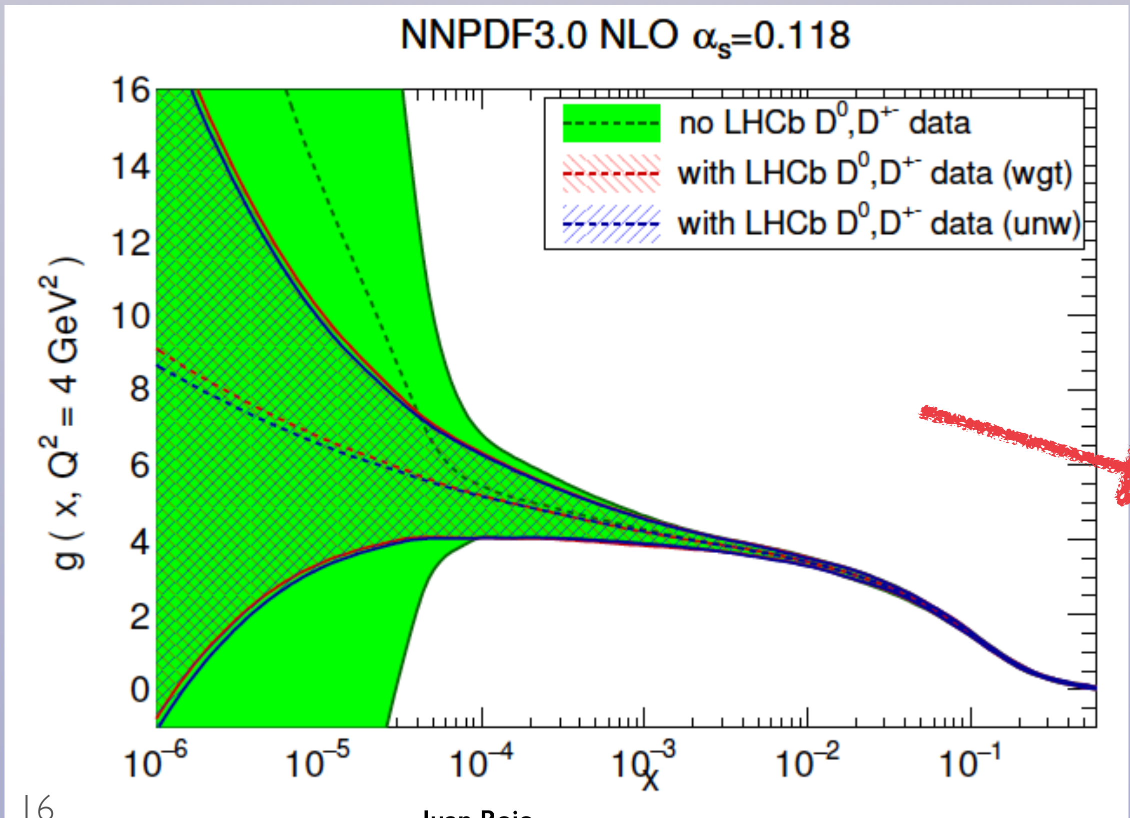
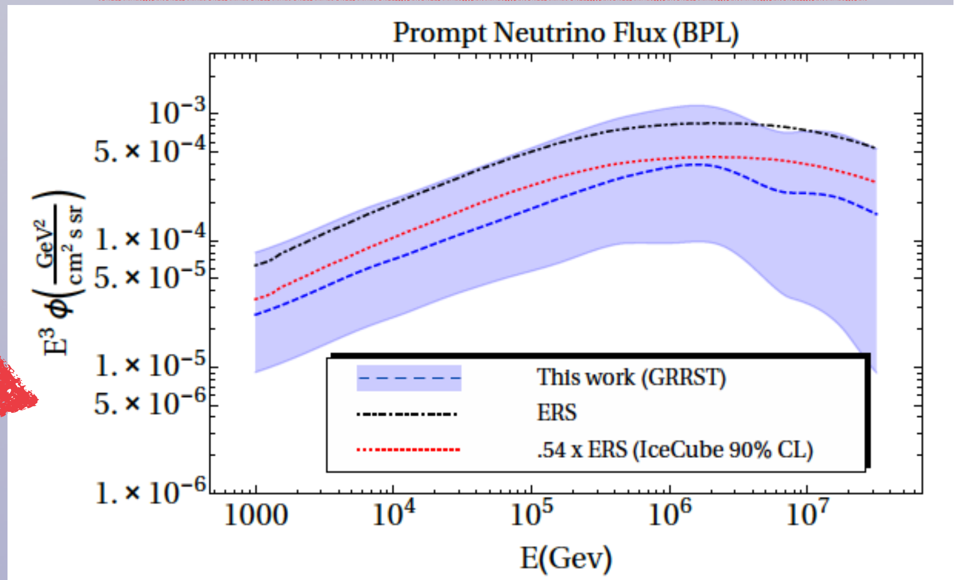
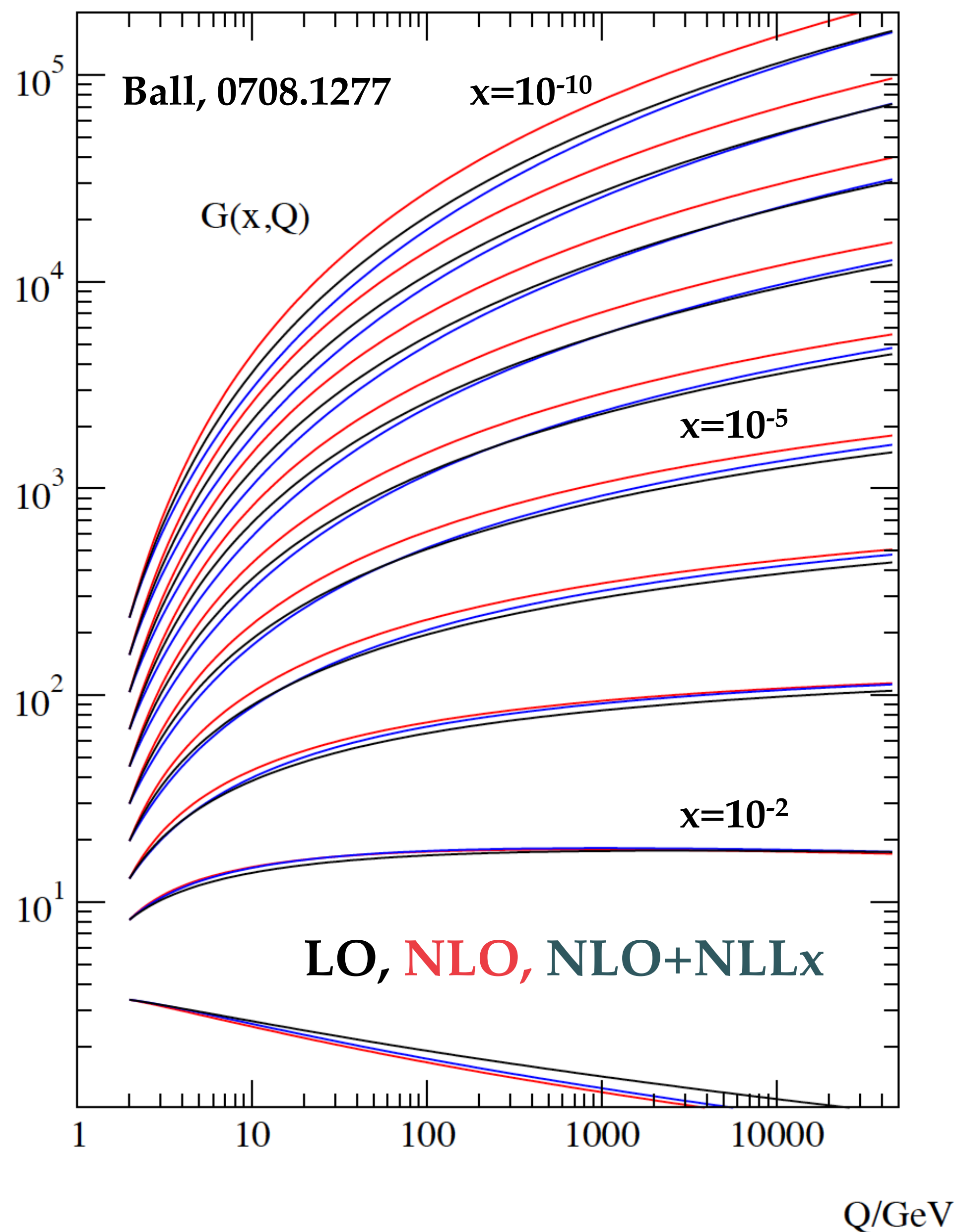



**Prompt neutrino fluxes at IceCube**

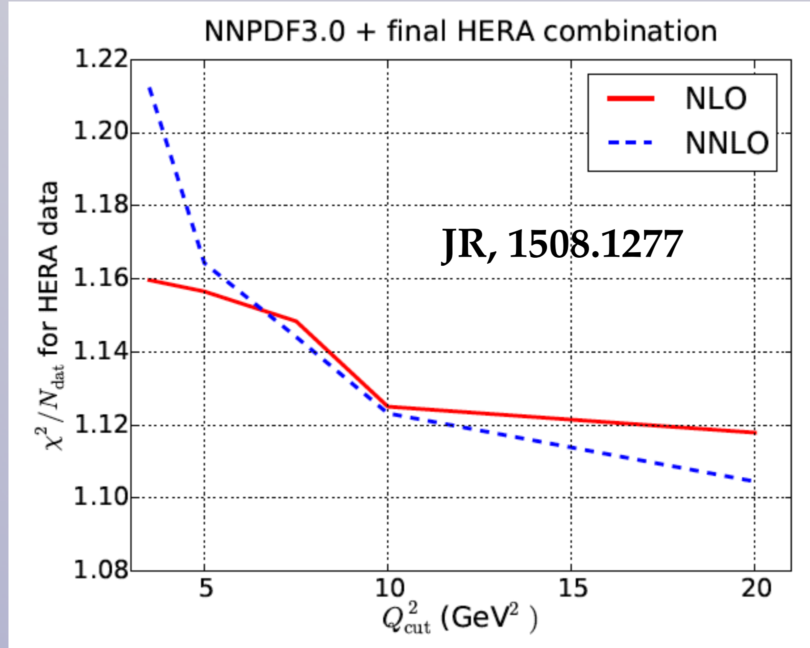



*Gauld, JR, Rottoli, Sarkar, Talbert 2015*

# High-energy resummation at 100 TeV

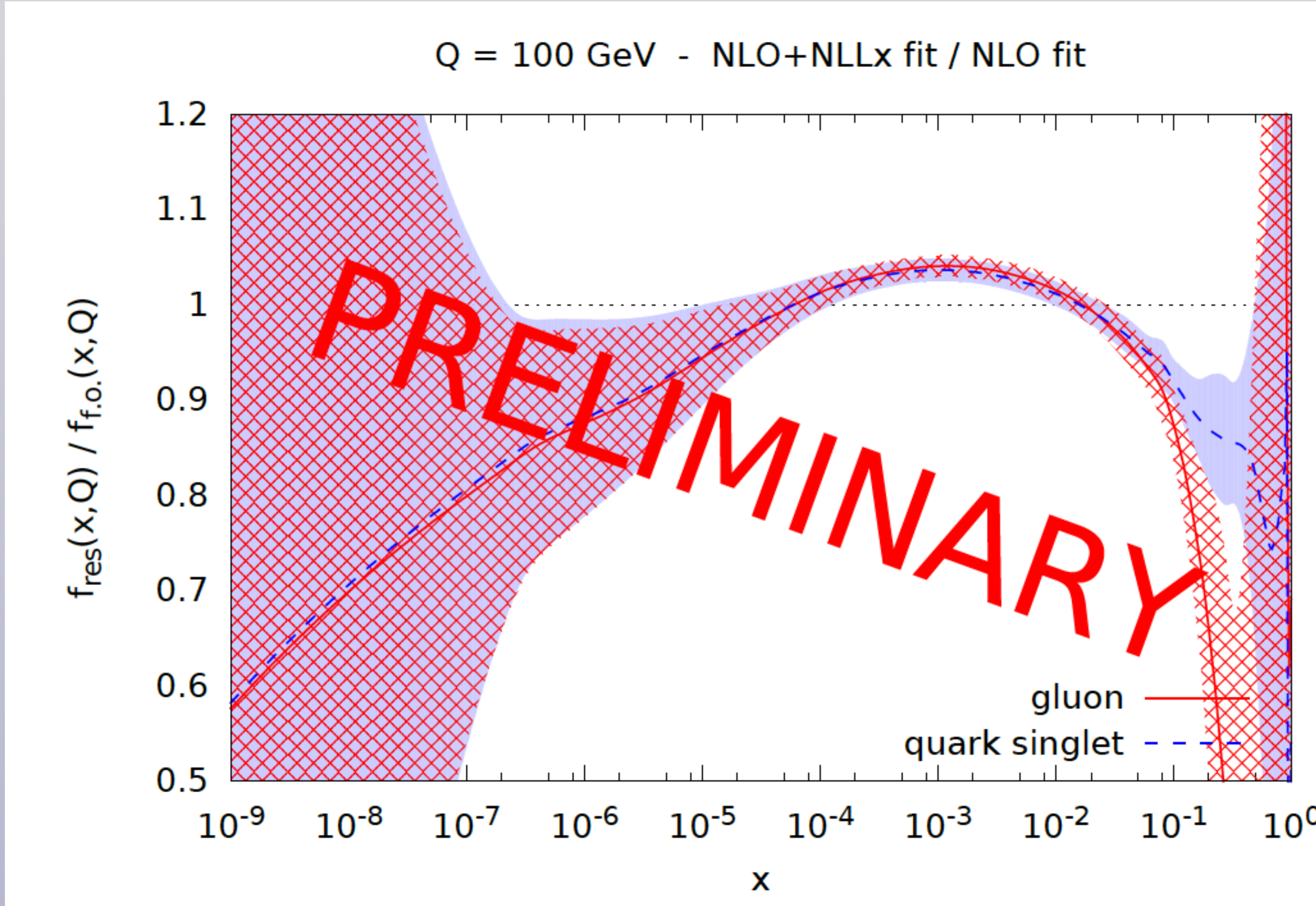



- So far no clear evidence **of departures from fixed-order DGLAP** has been presented
- One hint that small-x resummation might be relevant is the **small-Q instability** of the PDF fits to the **legacy HERA combination**




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

# High-energy resummation at 100 TeV




- **Preliminary NNPDF NLO+NLLx DIS-only fit**, normalized to NLO baseline
- **Gluon and quark sea suppressed by up to 20% at Q=100 TeV** in the FCC100 kinematics
- Few-percent enhancement at intermediate-x
- More work required to quantify the **relevance of BFKL resummation at a 100 TeV collider**

# 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)

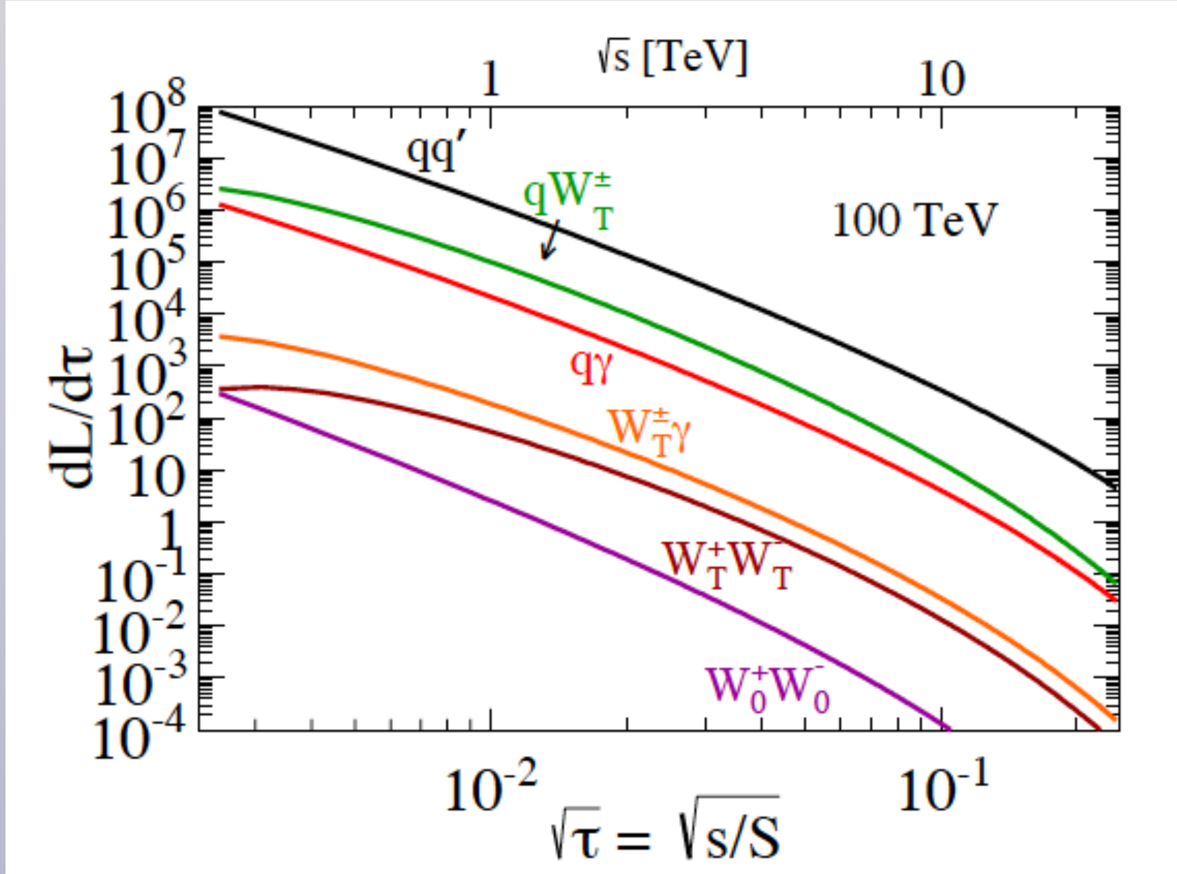
$$-\frac{\partial}{\partial t}\underset{g}{\mathcal{F}}_{AB}=\frac{\alpha_W}{2\pi}\left\{C_g\underset{g}{\mathcal{F}}_{AB}\otimes P_{gg}^V+(T_V^C\underset{g}{\mathcal{F}}T_V^C)_{AB}\otimes P_{gg}^R+\left(\sum_L \mathrm{Tr}\left[t^B\underset{L}{\mathcal{F}}\,{}^t t^A\right]+\sum_{\bar{L}}\mathrm{Tr}\left[t^A\underset{L}{\mathcal{F}}\,t^B\right]\right)\otimes P_{fg}^R+\mathrm{Tr}\left[T_L^B\underset{\phi}{\mathcal{F}}\,{}^t T_L^A\right]\otimes P_{\phi g}^R\right\}$$

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?**

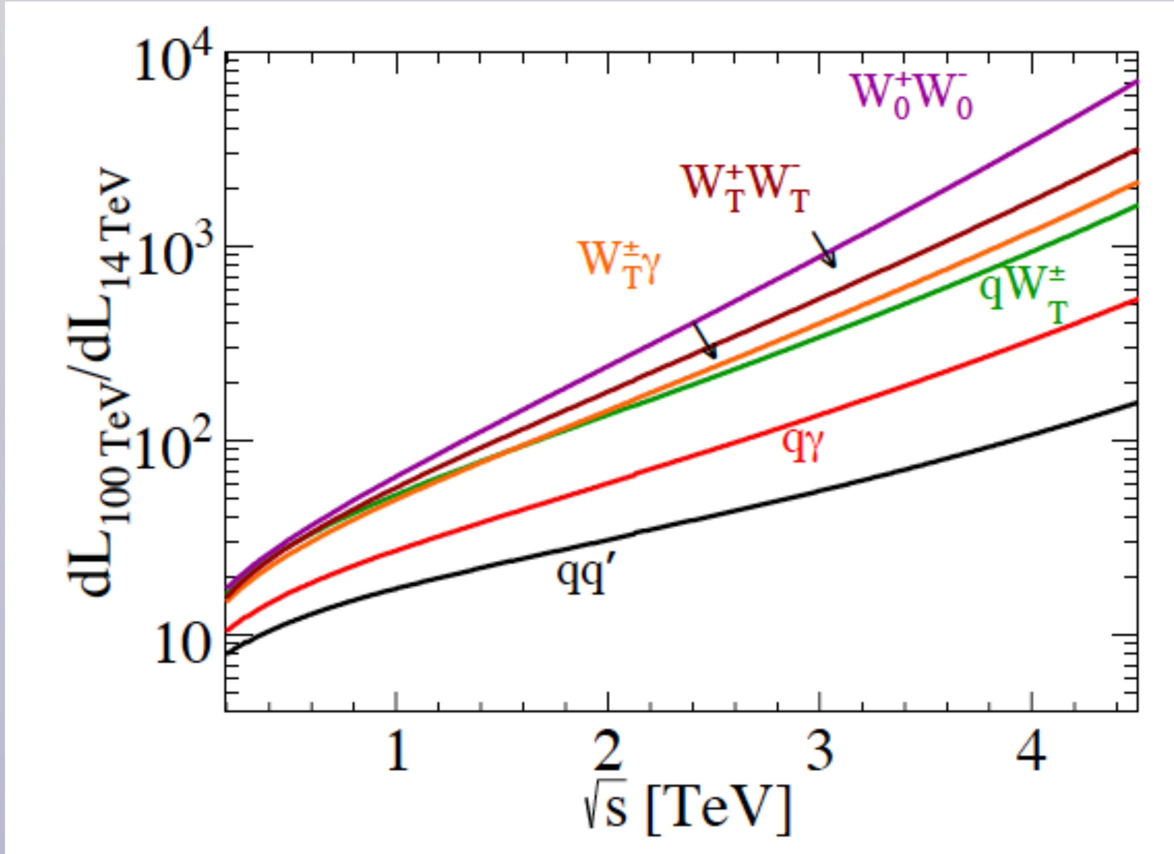
# Electroweak Parton Distributions




- **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?**

Using **fixed-order electroweak splitting rates** from the effective W/Z approximation

# Electroweak Parton Distributions

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- What is the **Higgs content of the proton?**

# Summary and outlook

- At 100 TeV, as in any hadron collider, parton distributions are an essential ingredient for **Higgs and BSM physics**.
- In the SM FCC100 Report, we have studied:
  - ☑ **validation of available PDF sets** for FCC simulations
  - ☑ **Generic features of PDFs at 100 TeV**
  - ☑ Interplay between **photon-initiated contributions** and electroweak corrections
  - ☑ **Connection with ultra low-x physics**, cosmic rays and astrophysics
- In addition, PDFs exhibit several **qualitatively new behaviourd at 100 TeV,** making their study a fascinating topic by itself:
  - ☑ (massless) **top quark PDFs,**
  - ☑ **Electroweak PDFs**
  - ☑ **PDFs with BFKL** (high-energy) resummation