PDF4BSM
Parton Distributions in the Higgs Boson Era

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PDFs: future needs, and role of LHC data in addressing them

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Why improved PDFs?

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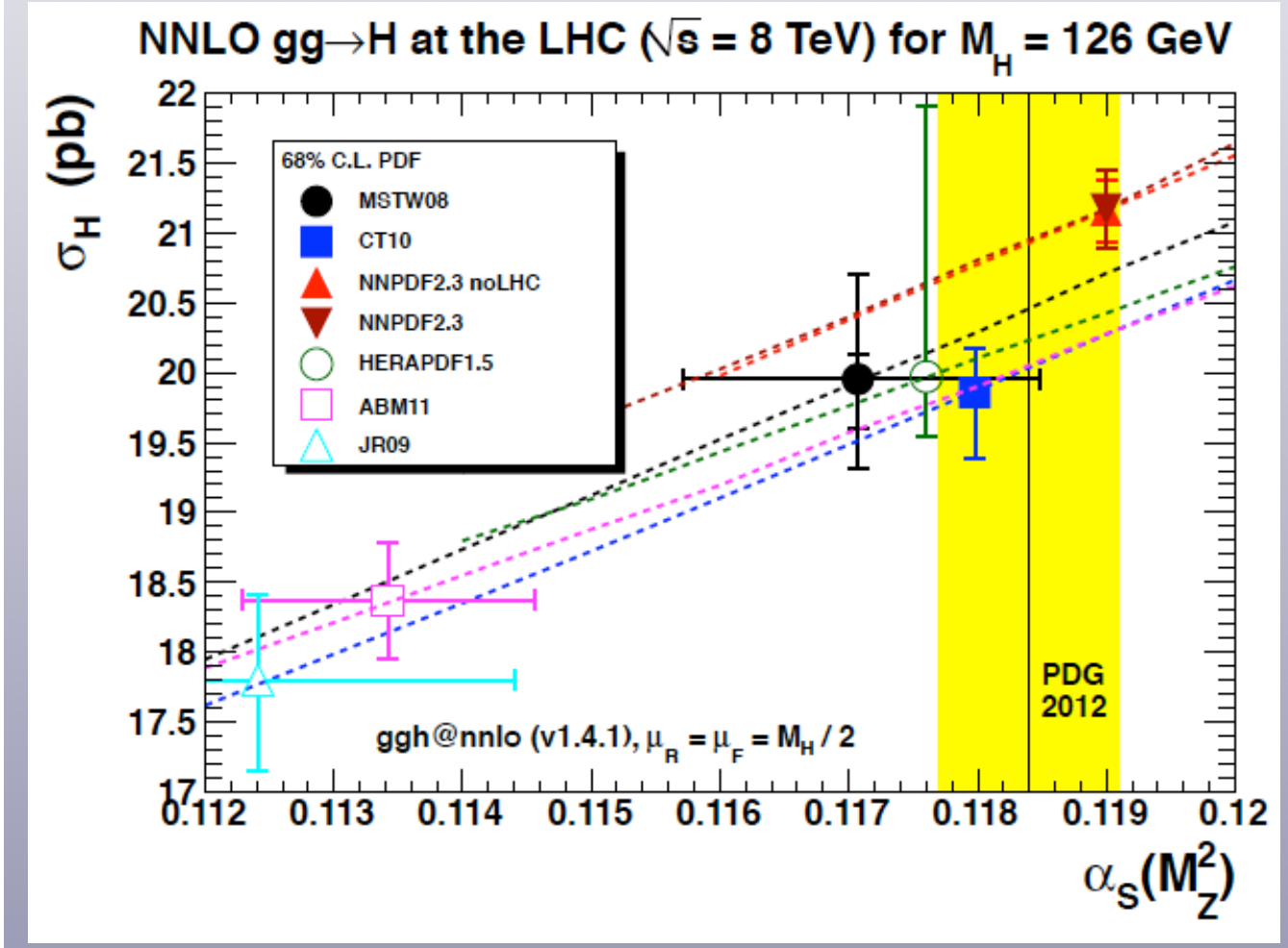
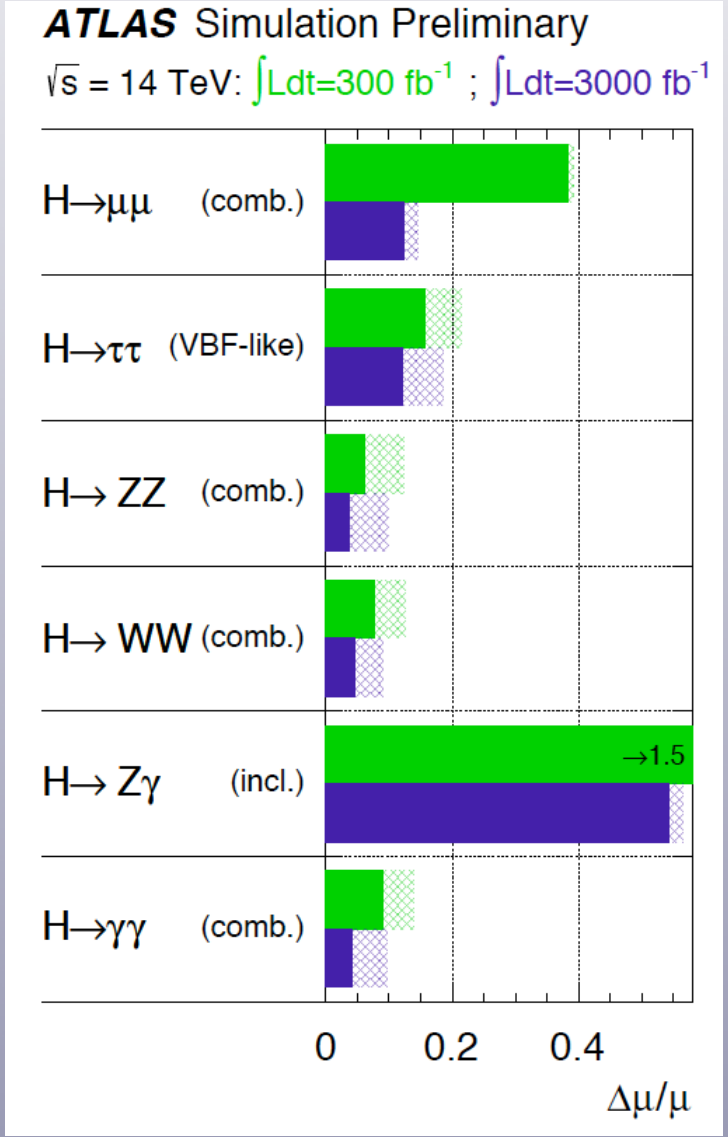
1) PDFs fundamental limit for Higgs boson characterization in terms of couplings

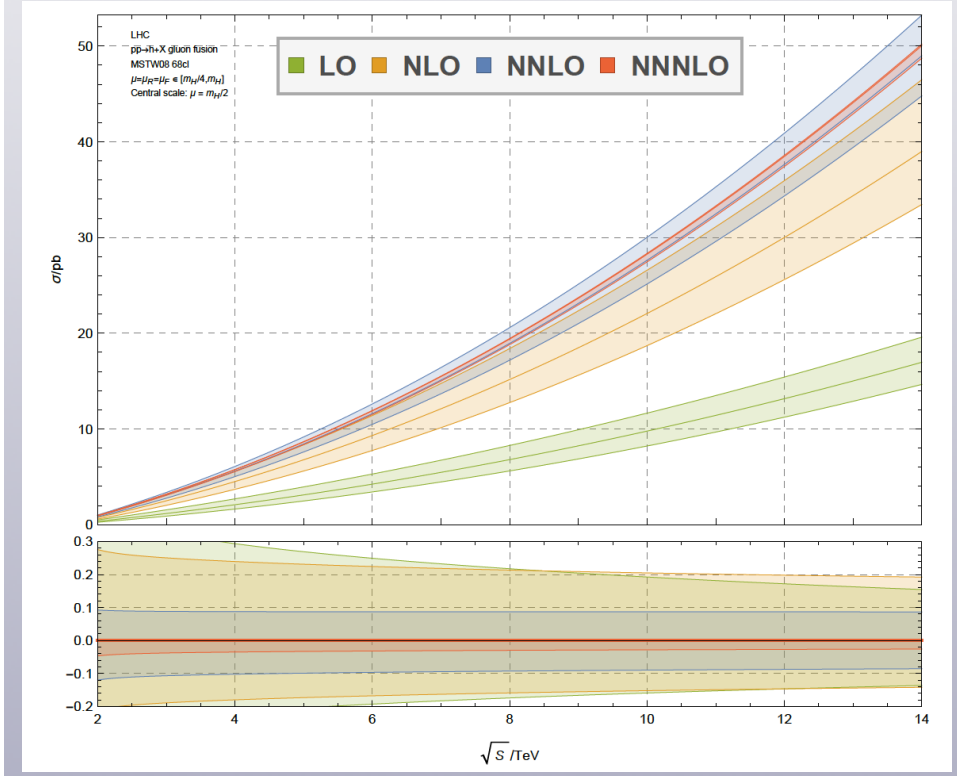


Solid: no TH unc
Hatched: with TH unc



Why improved PDFs?

- Recently **impressive development of NNLO higher-order calculations …**
- **…** now we even have the **Higgs gluon fusion xsec at N3LO, with scale uncertainties down to 2%**



Finally, the computation of the hadronic cross-section relies crucially on the knowledge of the strong coupling constant and the parton densities. After our calculation, the uncertainty coming from these quantities has become dominant. Further progress in the determination of parton densities must be anticipated in the next few years due to the inclusion of LHC data in the global fits and the impressive advances in NNLO computations, improving the theoretical accuracy of many standard candle processes.

Anastasiou et al, arxiv:1503.06056

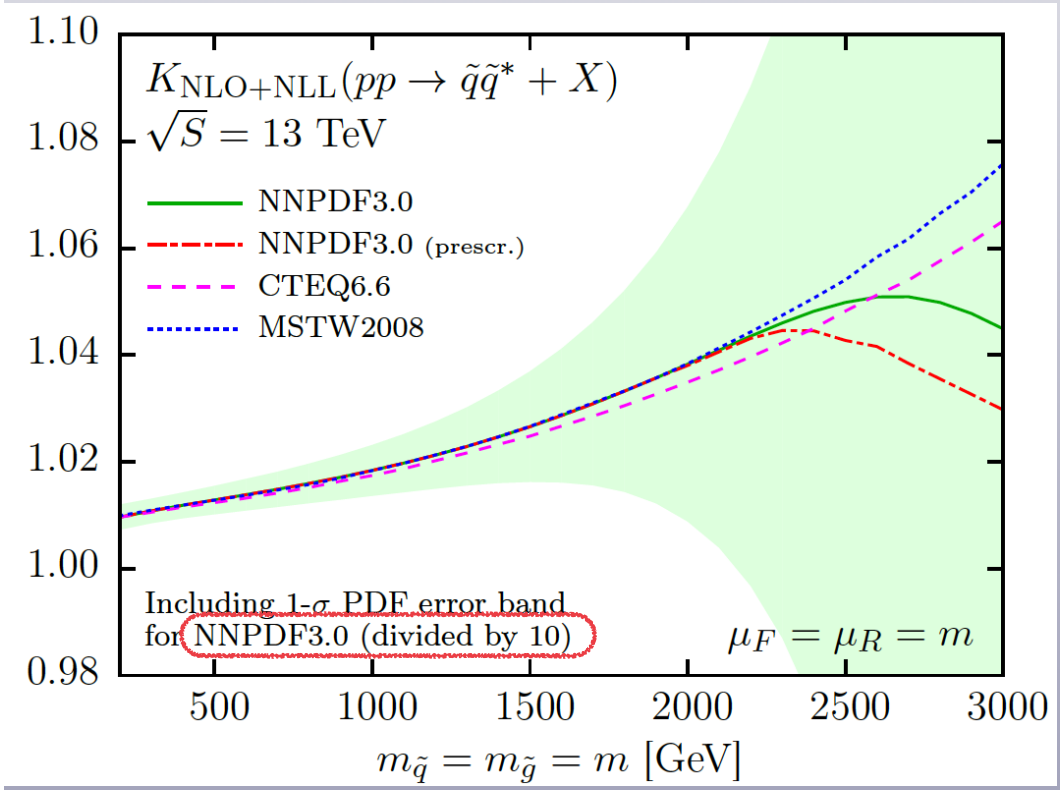
- PDF uncertainties are now **dominant** for a number of crucial LHC processes, and thus it is crucial to match the **accuracy of hard-cross section calculations** with that of the PDFs

Why improved PDFs?

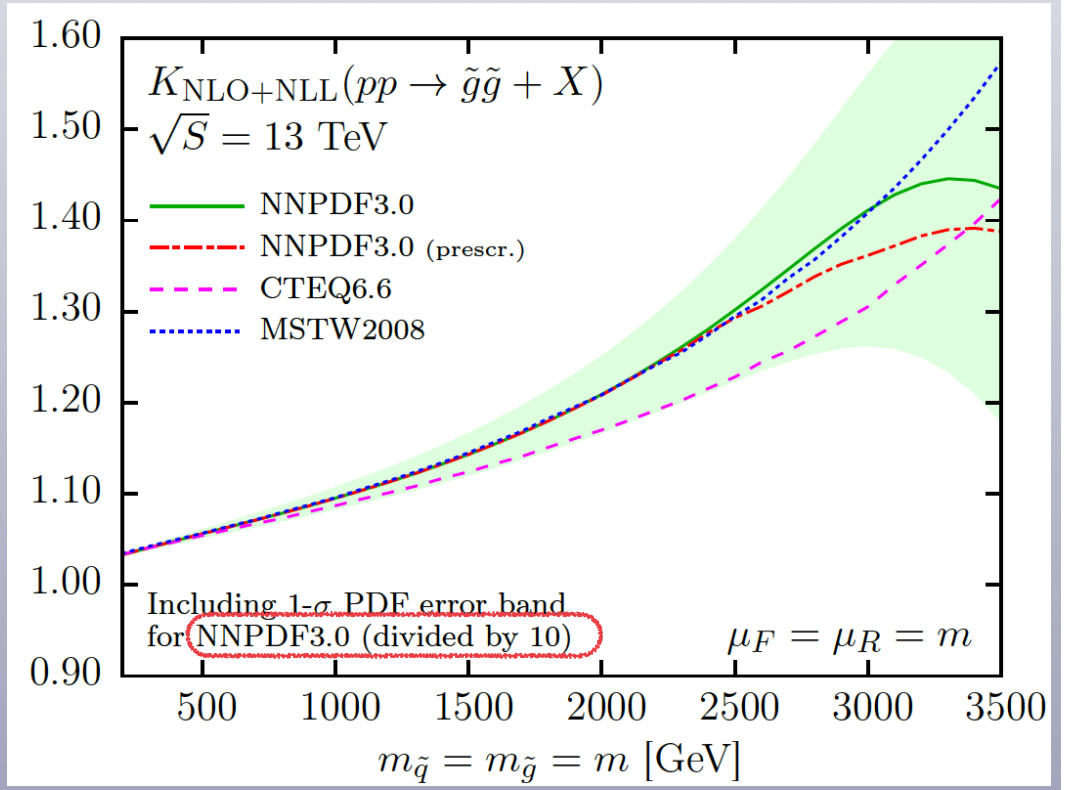
2) Very large PDF uncertainties (>100%) for BSM heavy particle production

$K_{NLO+NLL}$ = (NLO+NLL)/NLO

Squark Pair Production



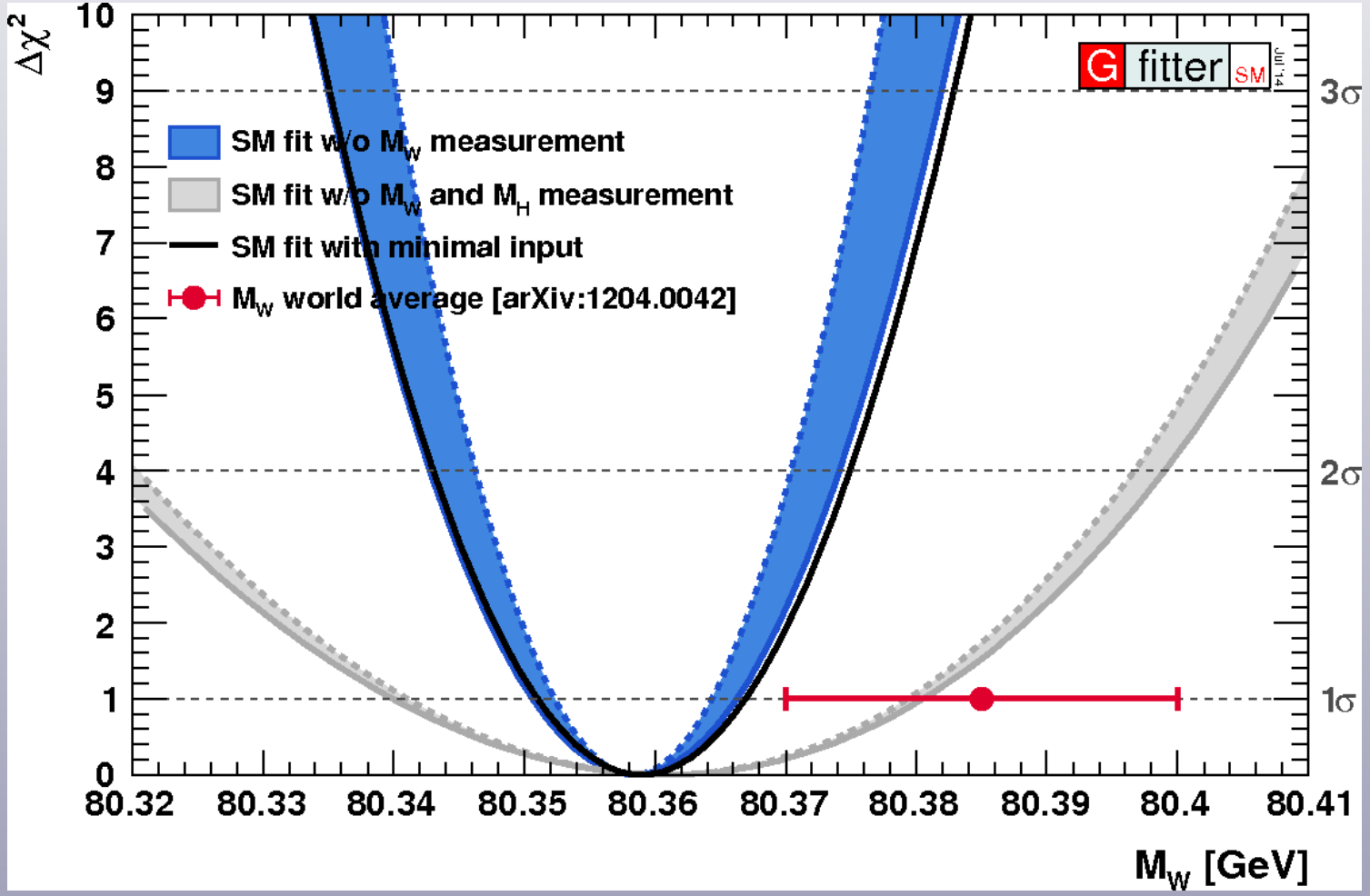
Gluino Pair Production



NLO+NLL calculations by Kulesza et al, NLL-fast collaboration

Why improved PDFs?

3) PDFs dominant systematic for precision measurements, like W boson mass, that provide consistency stress-tests of the Standard Model



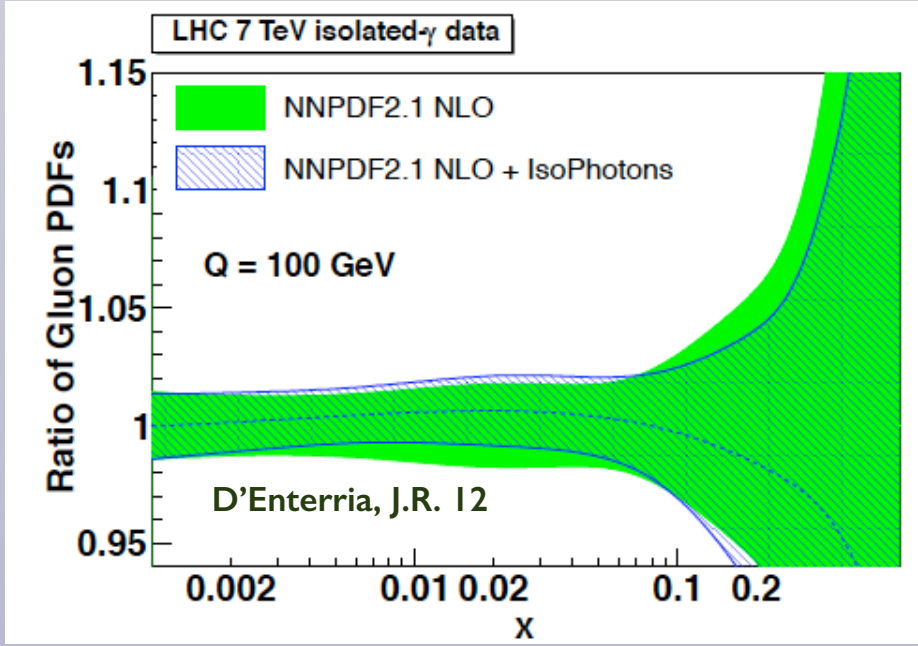
- Reducing TH systematics could lead to **indirect BSM discovery** from precision measurements
- Precision in M_W will **improve by a factor 3** in 10 years
- If SM confirmed, **ruled out a broad class of BSM scenarios**

1.8-sigma tension between direct M_W measurement and global EW fit

Constraining PDFs with LHC data (and with better theory)

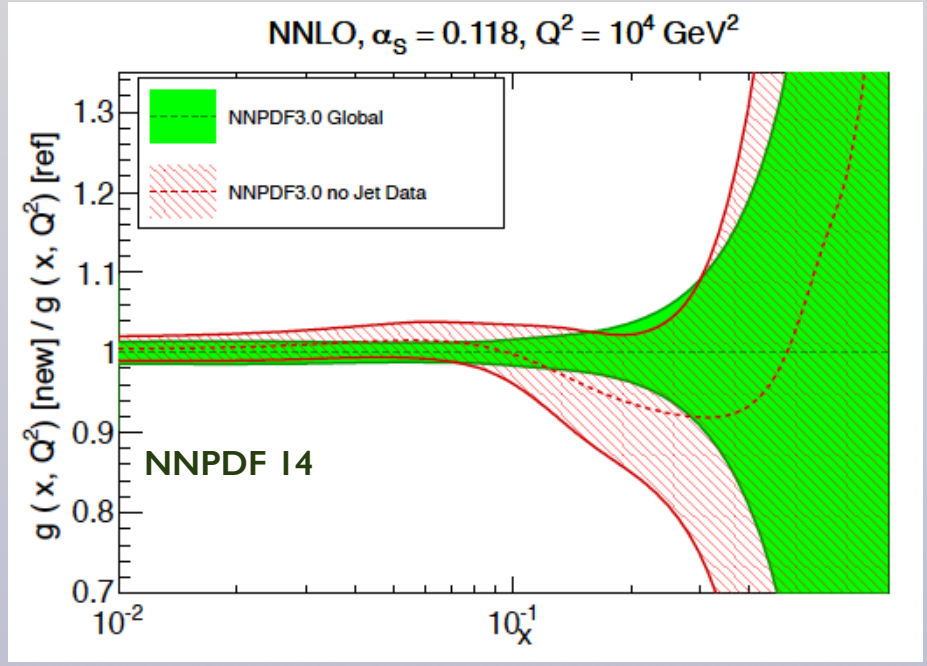
Parton Distributions with LHC data

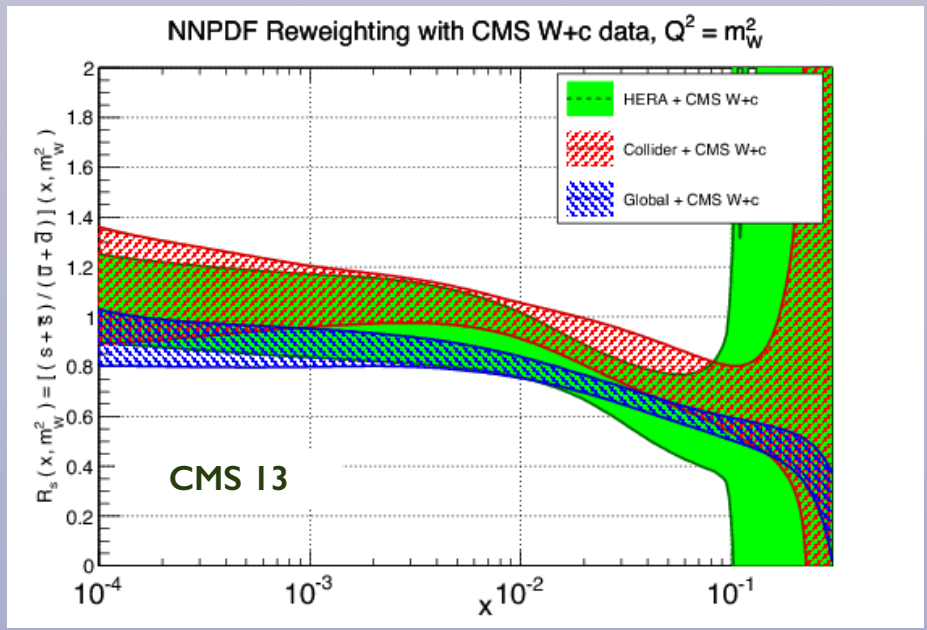
- A major breakthrough in the recent years has been the inclusion of **LHC data** into **global PDF fits**
- PDF constraints from a wide variety of LHC processes have been studied, many of which **for first time**



Isolated photon LHC data constraints **gluons at medium-x**: relevant for **Higgs production in gluon fusion**

Large-x gluon from inclusive Jet production

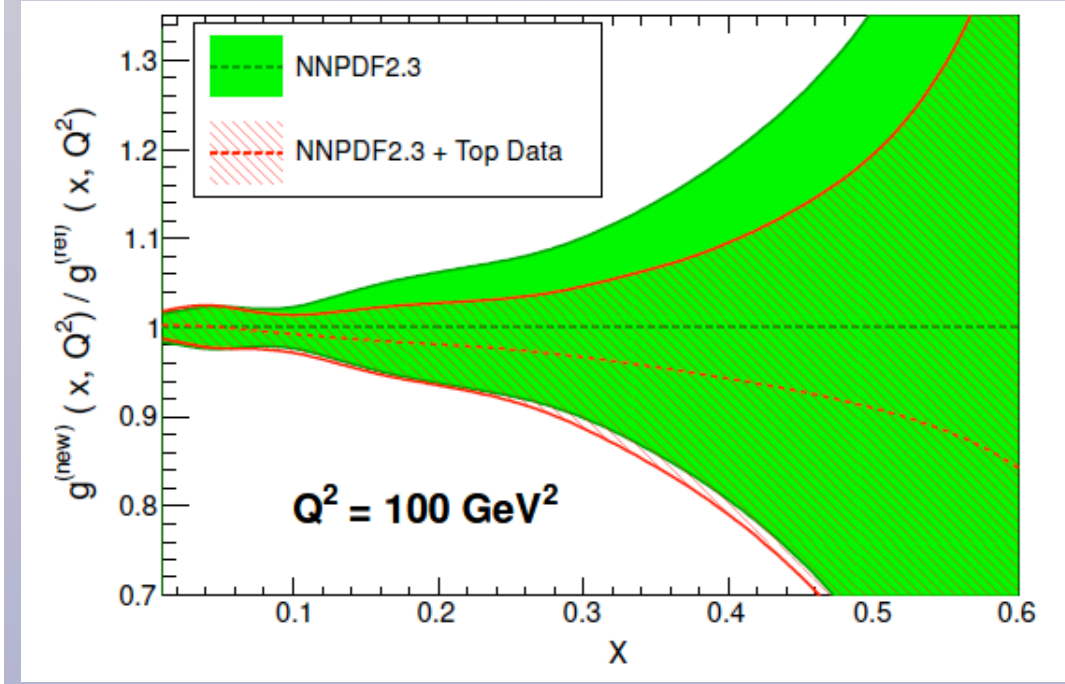


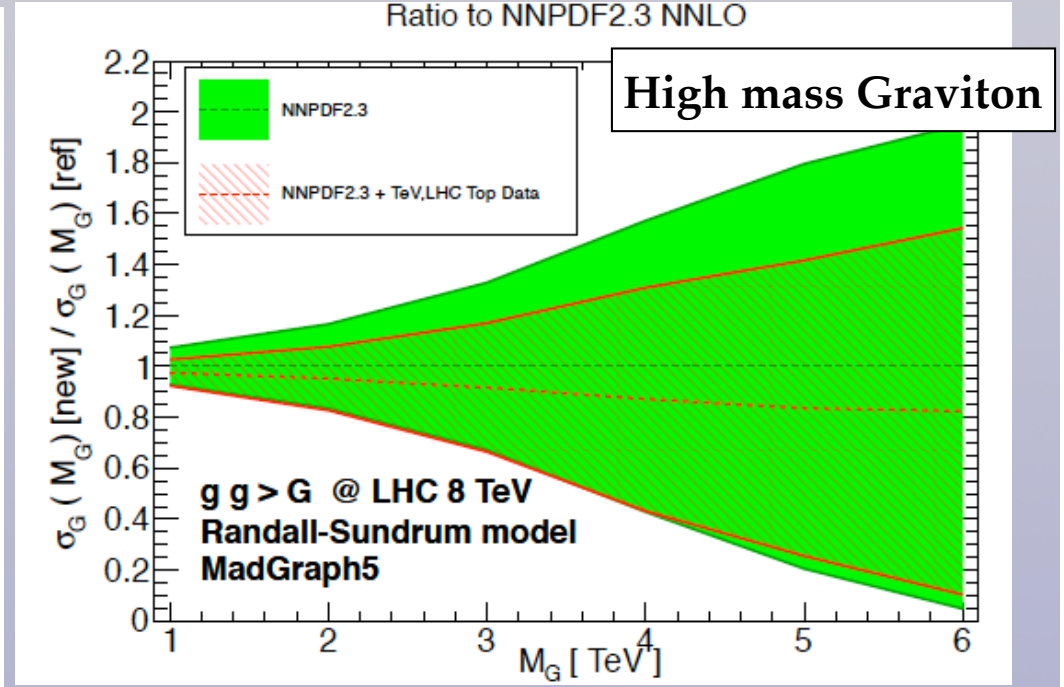


W production in association with charm quarks provides direct access to the proton strangeness

Top quarks as gluon luminometers

- The recent **NNLO top quark cross section** make top data the **only LHC observable** that is both **directly sensitive to the gluon PDF** and can be included consistently in a **NNLO global analysis**
- The precise 7 and 8 TeV LHC data can be used to **discriminate between PDF sets** and **to reduce the PDF uncertainties on the poorly known large-x gluon**
- The **improved large-x gluon** leads to more accurate theory predictions for **BSM searches**





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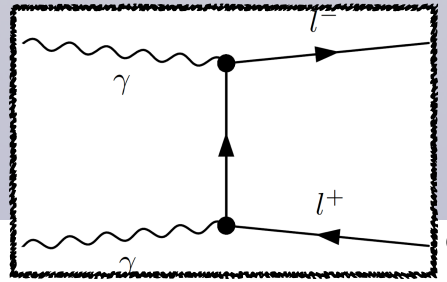
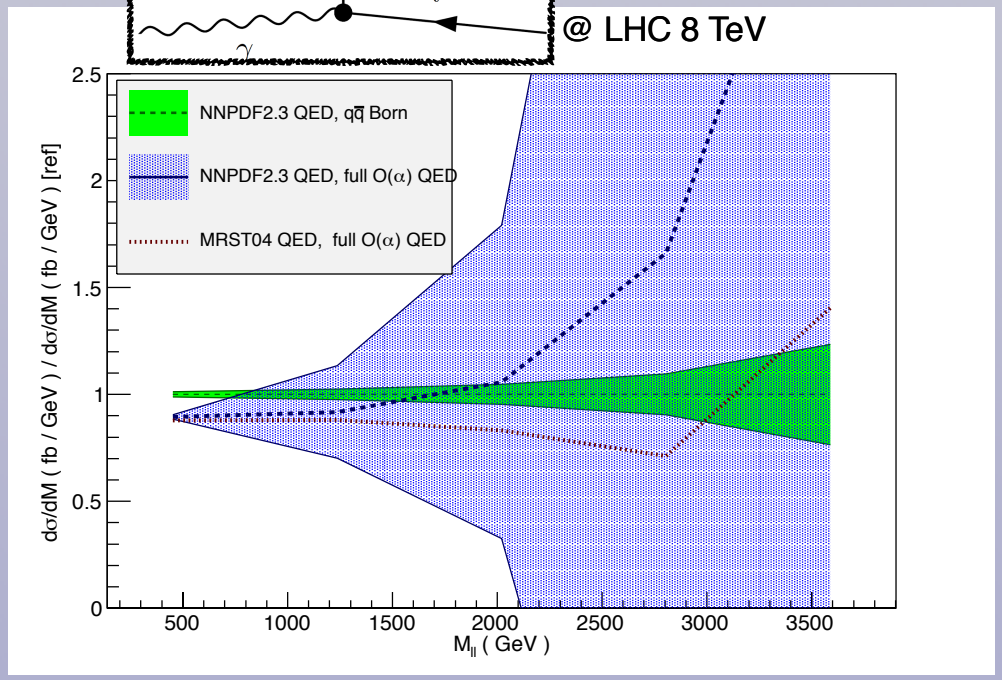
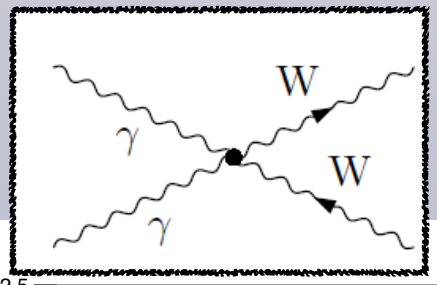
PDFs with QED corrections

- **QED** and **electroweak corrections** are essential for **precision LHC phenomenology**: **W and Z production**, **W mass determination**, **WW boson pair** production, **TeV scale** jet and top quark pair production, searches for new **W', Z' bosons**
- Consistent inclusion of **electroweak effects** require PDFs with **QED corrections** and a **photon PDF**
- **NNPDF2.3 QED:** first-ever determination of the **photon PDF** from **LHC data**
- Neglecting **photon-initiated contributions** leads to systematically underestimating theory errors in **crucial BSM search channels**

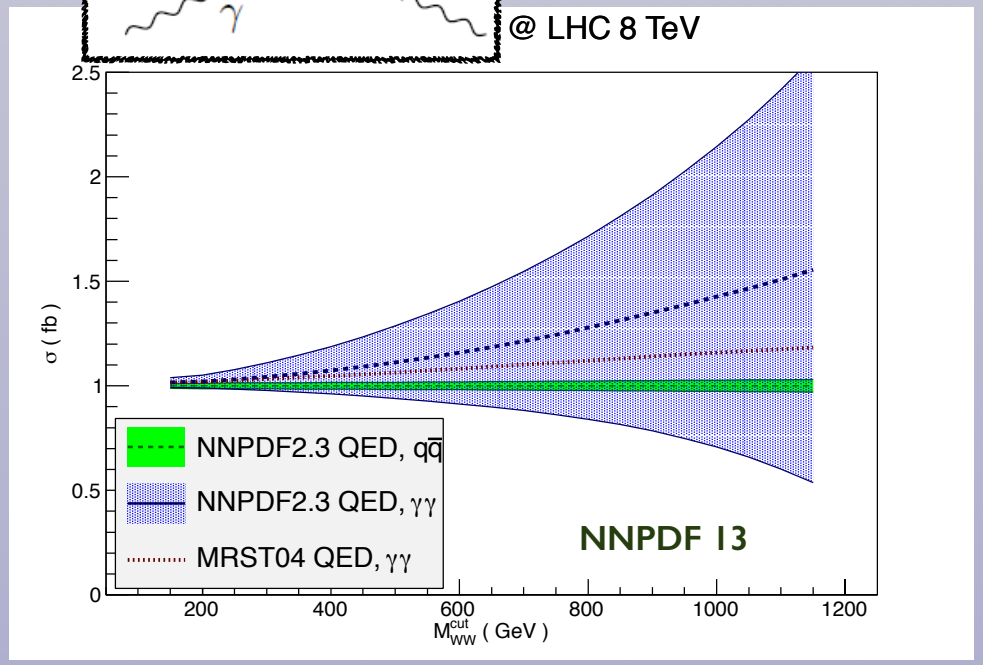


High-Mass Drell-Yan





High-Mass WW prod



PDFs with threshold resummation

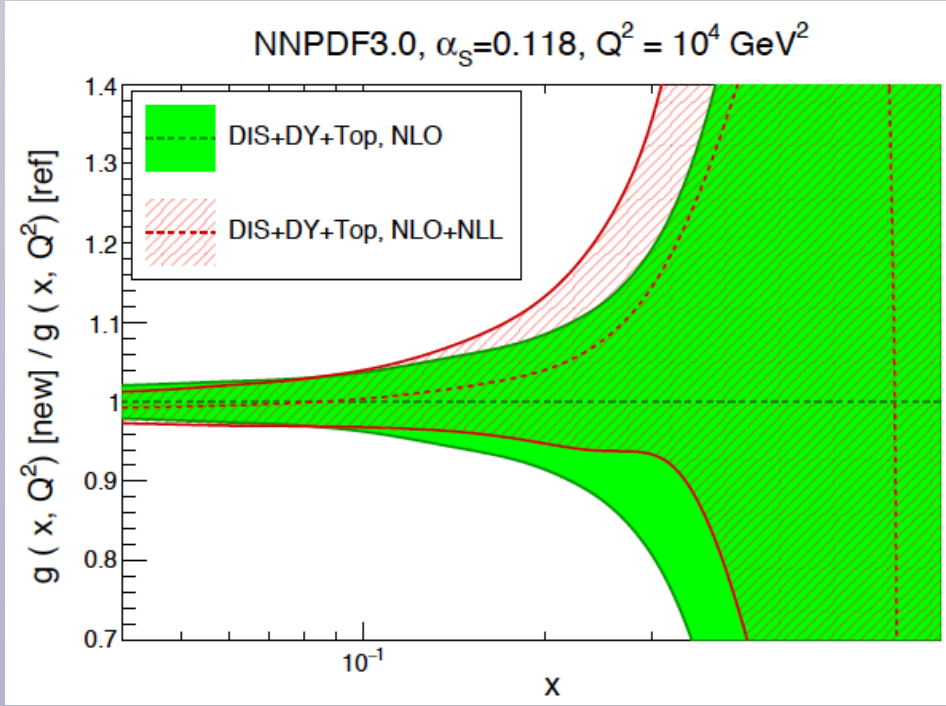
☑ Many LHC calculations supplement **NLO and NNLO fixed-order results** with the **resummation of soft threshold logarithms to all orders**: Higgs, top pair production, high-mass supersymmetry ….

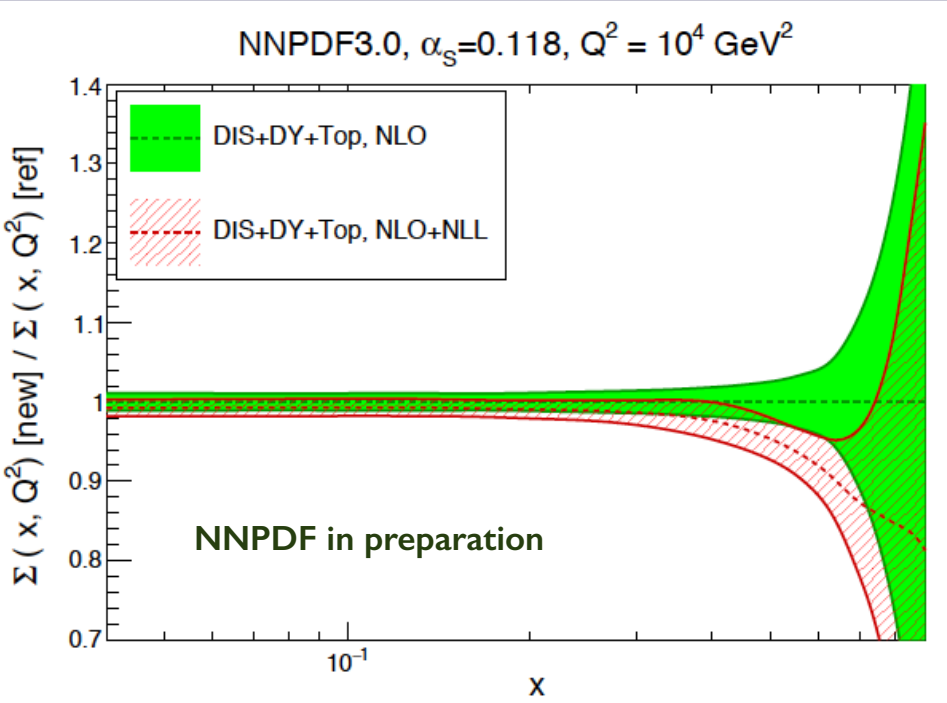
☑ NNPDF is producing for the first time **PDF sets at NLO+NLL and NNLO+NNLL**, to be submitted to LHAPDF6 very soon

$$\hat{\sigma}_{ab}^{(\mathrm{res})}(N,\alpha_s) = \sigma_{ab}^{(\mathrm{born})}(N,Q^2,\alpha_s)\, C_{ab}^{(\mathrm{res})}(N,\alpha_s),$$

$$C^{(N\text{-soft})}(N,\alpha_s) = g_0(\alpha_s)\exp\mathcal{S}(\ln N,\alpha_s),$$

$$\mathcal{S}(\ln N,\alpha_s) = \left[\frac{1}{\alpha_s}g_1(\alpha_s \ln N) + g_2(\alpha_s \ln N) + \alpha_s g_3(\alpha_s \ln N) + \ldots\right]$$





☑ In the **NLO+NLL fit**, effects of resummation can be large, **up to -20% (for quarks) and +40% (for gluons) at high-x,** relevant for the production of **new BSM particles**

Quantifying PDF constraints at the High-Luminosity LHC

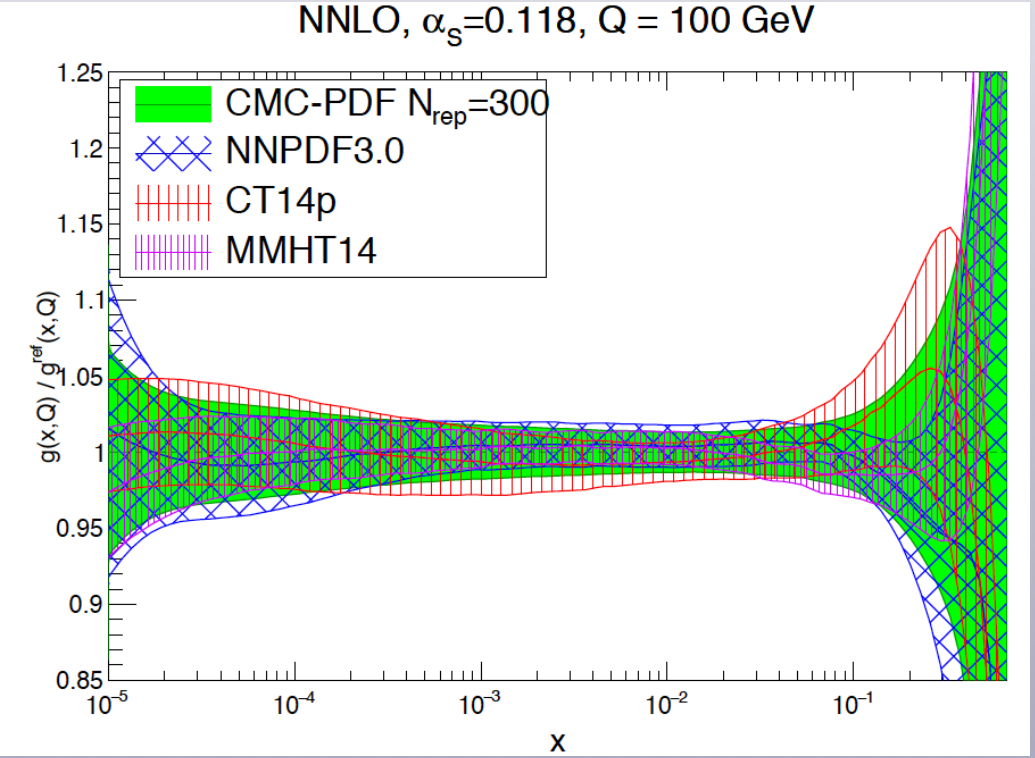
PDF sensitivity at the HL-LHC

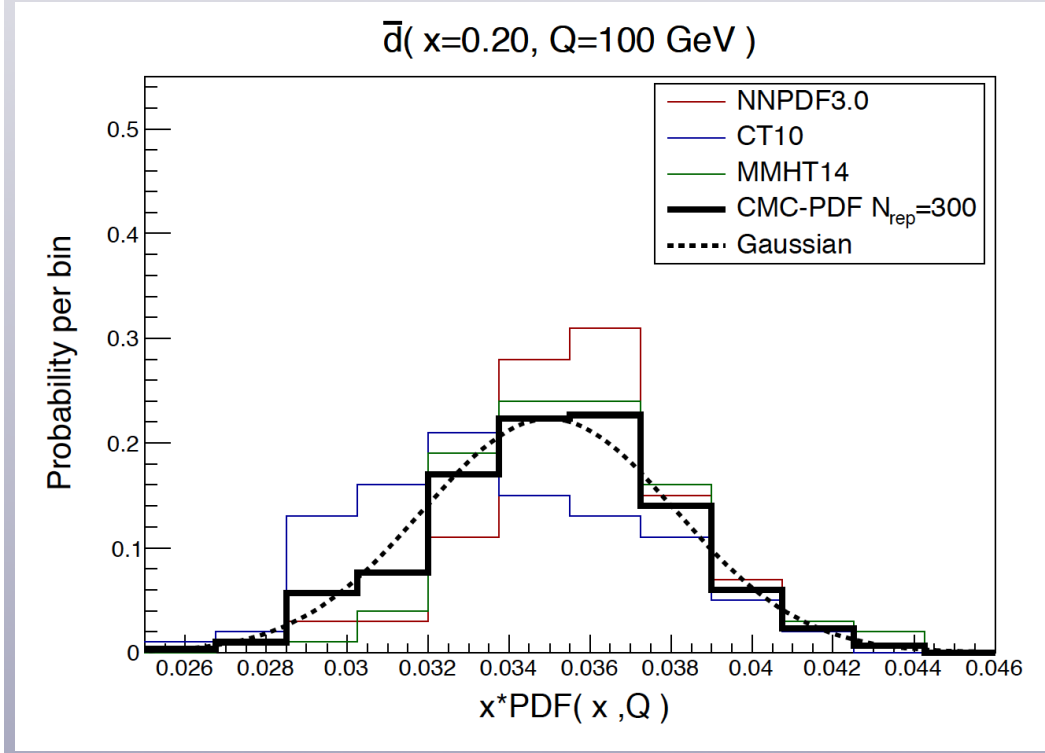
"It's though to make predictions, specially for the future" **(Yogi Berra)**

- In the case of **PDFs uncertainties for 10 years from now**, this is specially difficult
- Most of the LHC data used to constrain PDFs are **limited by systematics**, not statistics: non-trivial to quantify the impact of future measurements. Also, PDFs will already be **improved after Run II**.
- There is a case in which the advantages of the HL-LHC are however evident: the **high-mass tail of cross-sections, which will be limited by statistics**
- At high-masses, we are probing **PDFs at large-*x***, which are **poorly constrained**, and that are i**mportant for many BSM searches**
- Here we consider three representative processes:
  - **Top quark pair production**: gluon-gluon luminosity
  - The **transverse momentum of the Z boson**: quark-gluon luminosity
  - **High-mass Drell-Yan production**: quark-antiquark luminosity
- The scope of this exercise is more to **start a discussion** that to be able to draw any robust conclusion. All results extremely preliminary
- To generate pseudo-data, we use **MadGraph5_aMC@NLO** using **NNPDF2.3NLO** as input
- **Default theory setting**s, including scales (dynamical)

Compressed MC PDFs

- As a baseline, we will use the recently developed **Compressed Monte Carlo PDFs (CMC-PDFs)**
- **MC statistical combination of NNPDF3.0, CT14 and MMHT14**, then compression algorithm
- Will be used in the **updated PDF4LHC recommendations**





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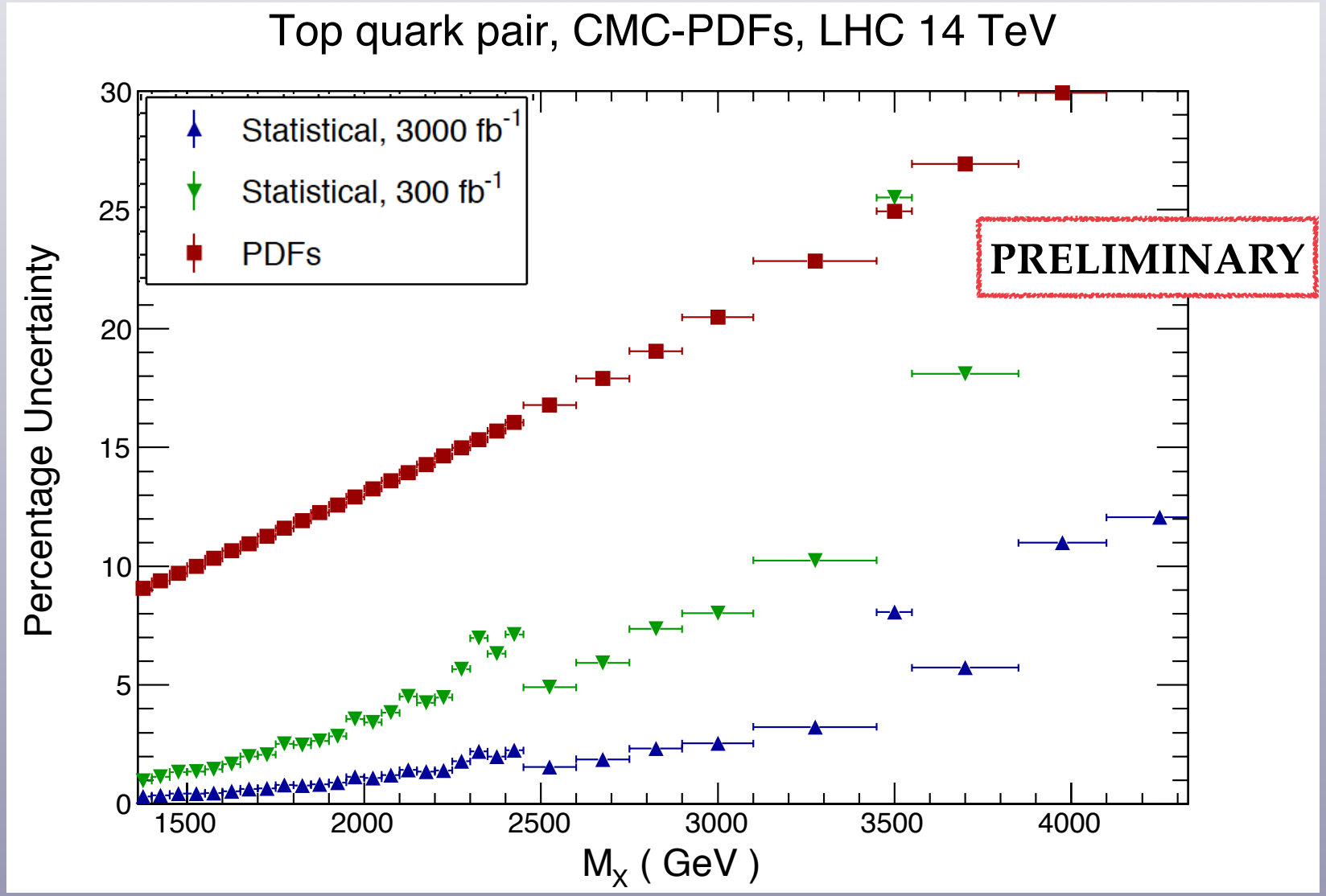
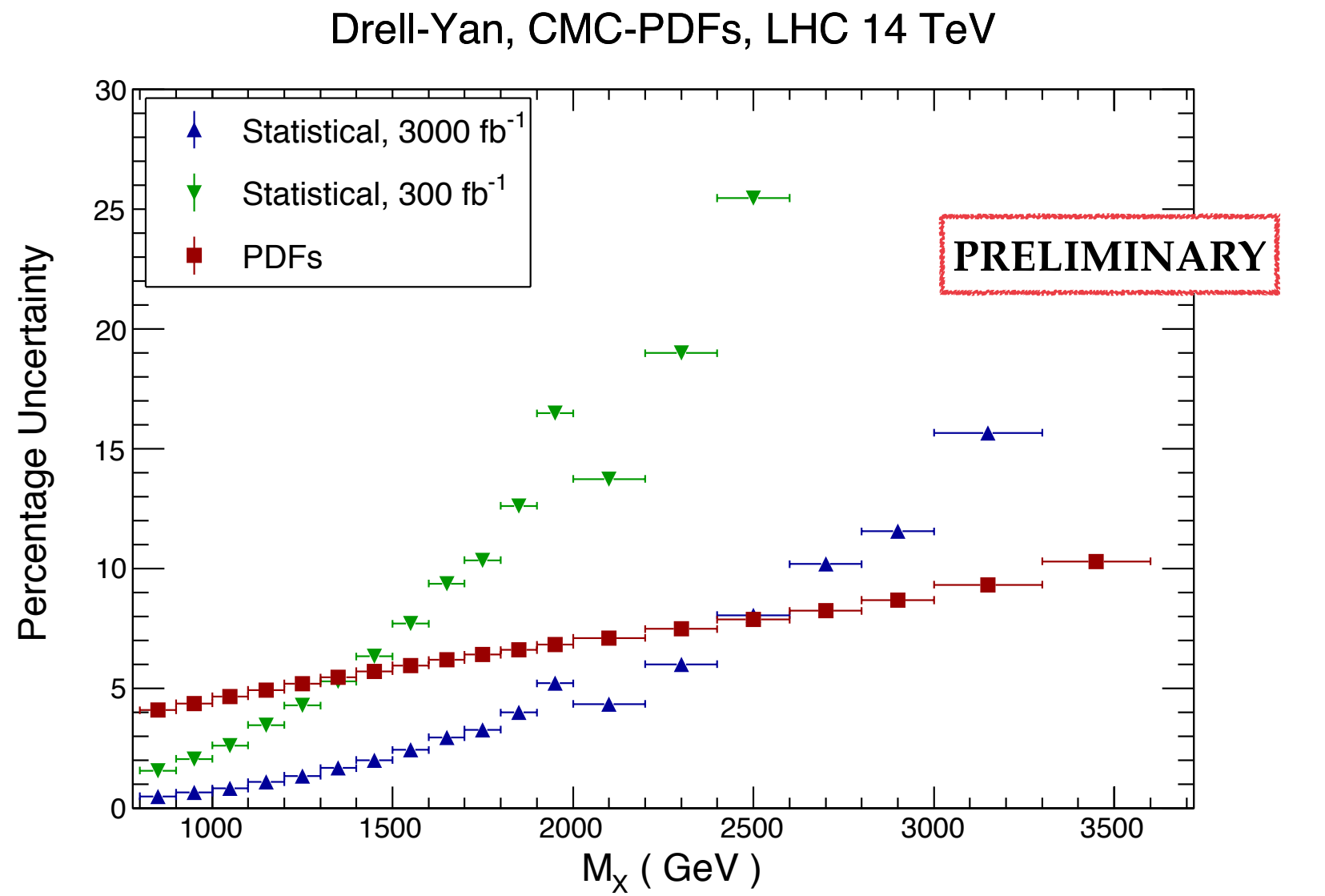
Generation of pseudo-data: top quark pair

- Generate pseudo-data for the **invariant mass distribution** in the **leptonic final state**
- Statistical uncertainties determined from **number of events per bin**, after a binning optimisation
- Added a **3% systematic uncertainty** to the statistical uncertainty



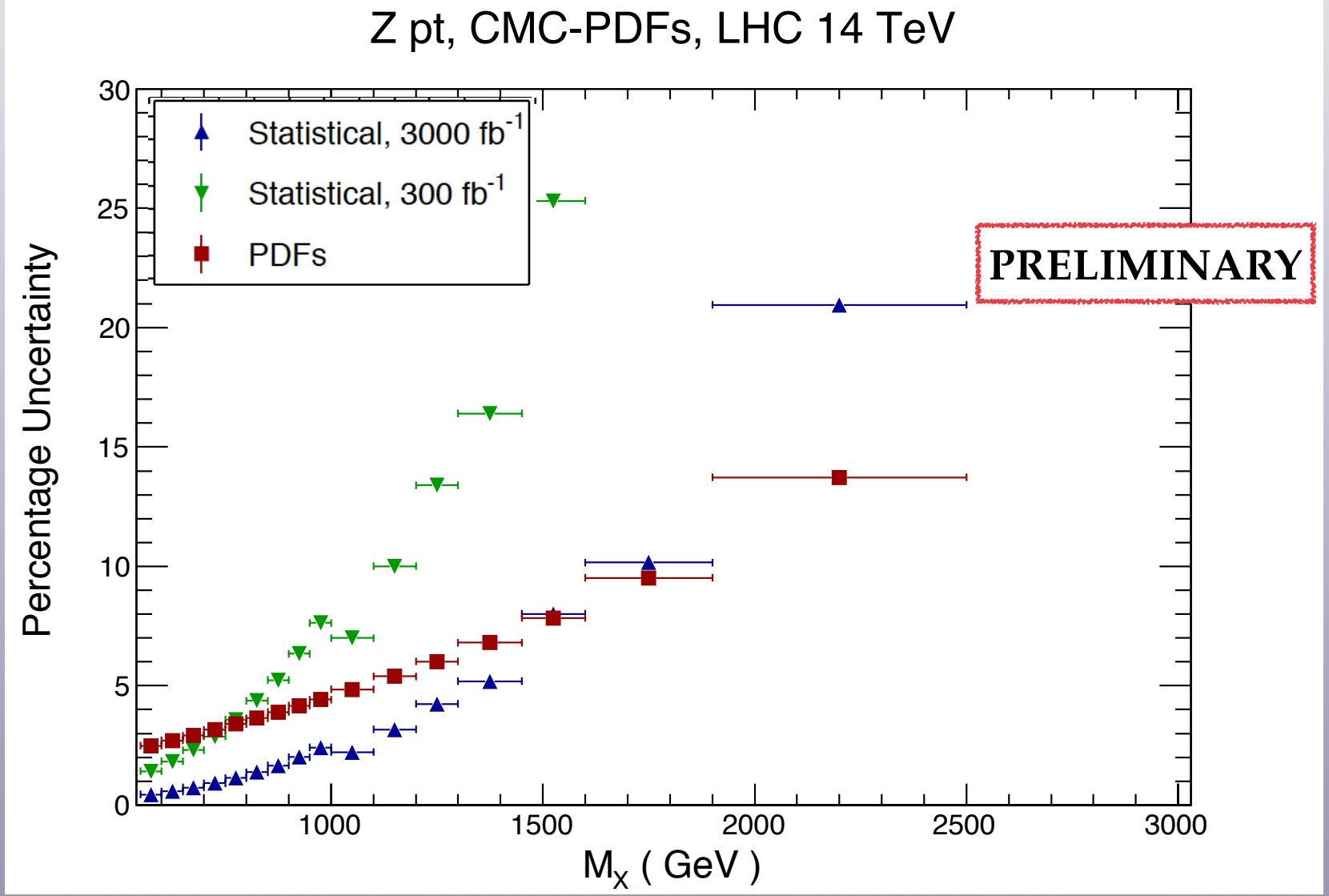
Generation of pseudo-data: high-mass Drell-Yan

- Generate pseudo-data for the **invariant mass distribution** of **di-electrons** and **di-muons**
- Statistical uncertainties determined from **number of events per bin**, after a binning optimisation
- Added a **2% systematic uncertainty** to the statistical uncertainty



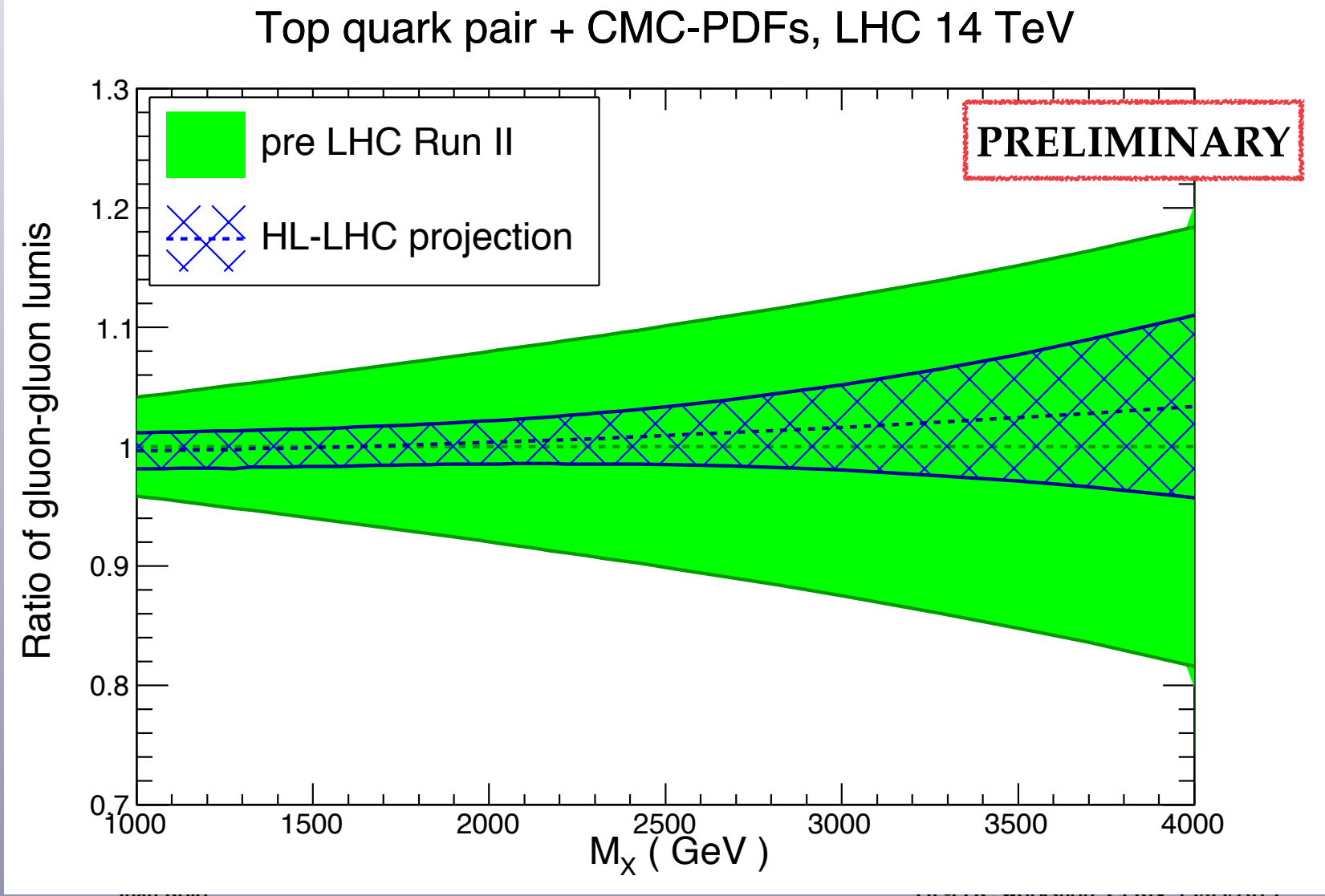
Generation of pseudo-data: the Z pt

- Generate pseudo-data for the **transverse momentum distribution** of **Z bosons decaying into leptons**
- Statistical uncertainties determined from **number of events per bin**, after a binning optimisation
- Added a **2% systematic uncertainty** to the statistical uncertainty



Impact on PDFs: top quark pair production

- The **CMC-PDFs** have been **reweighted by the HL-LHC pseudo-data** (each observable separately), to estimate the reduction in the size of the PDF uncertainties
- Compare the **relevant PDF luminosities** before and after including the HL-LHC pseudo-data
- For **gg channel**, top quark data leads to a **very substantial reduction** of PDF uncertainties



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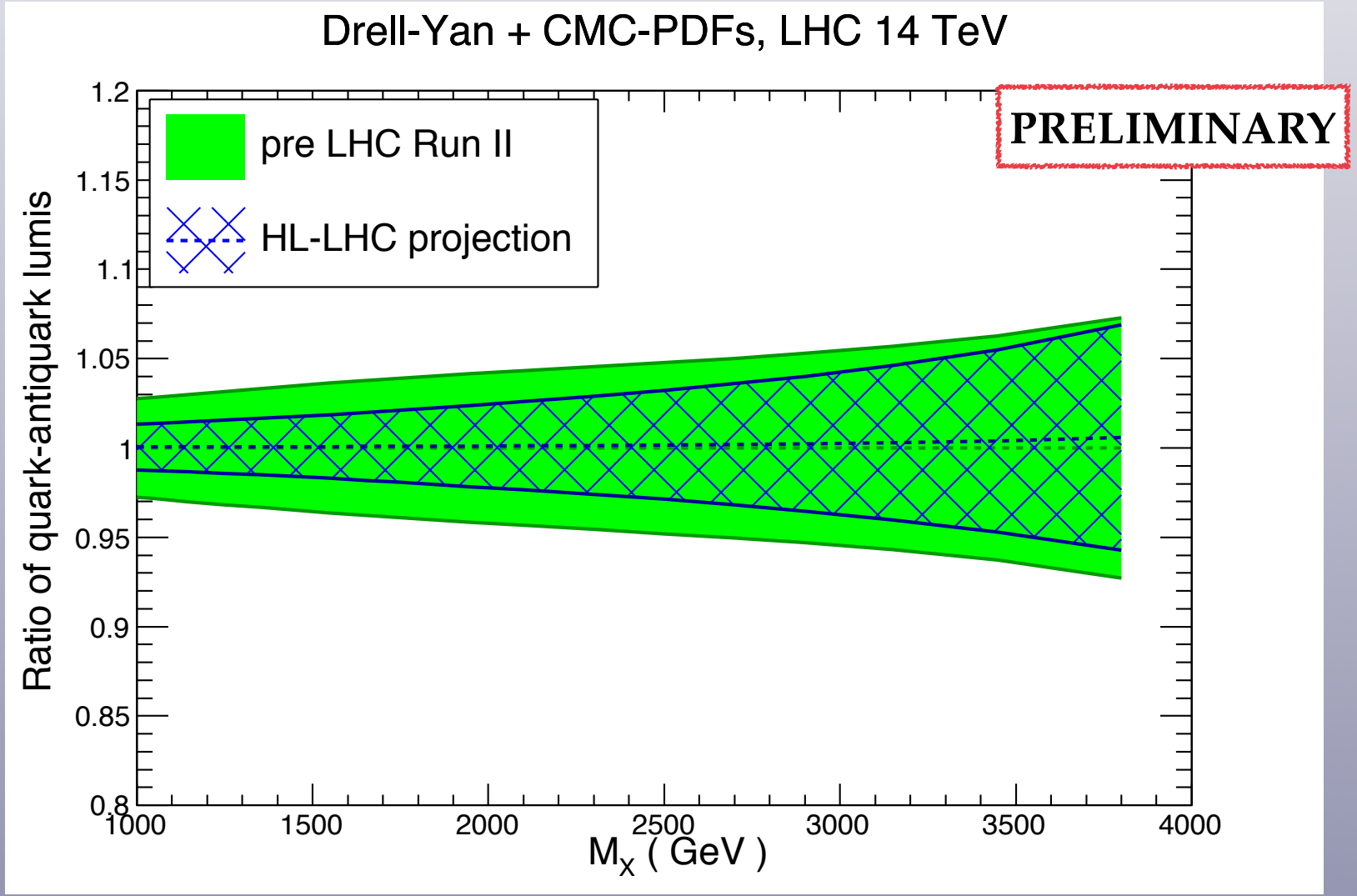
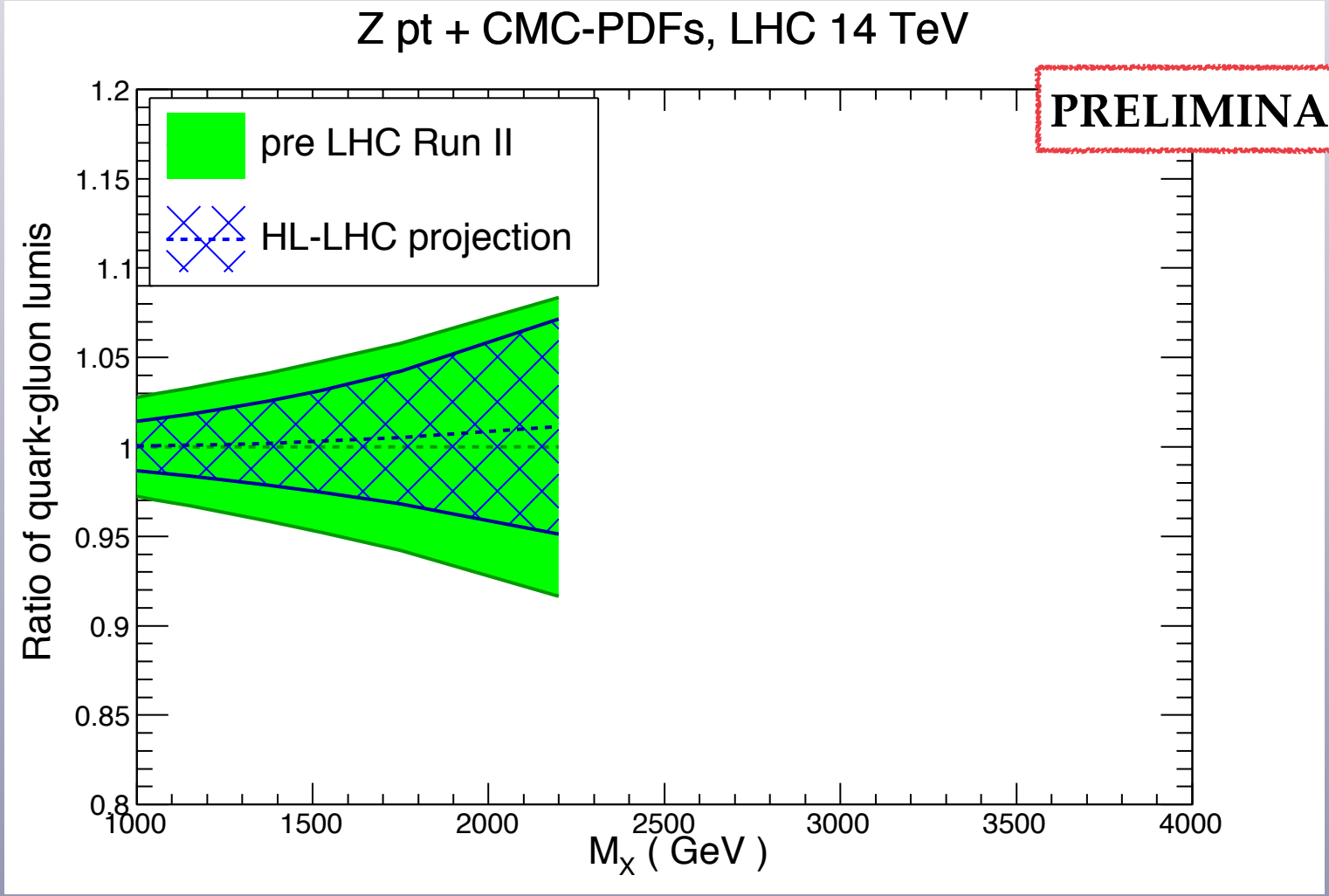
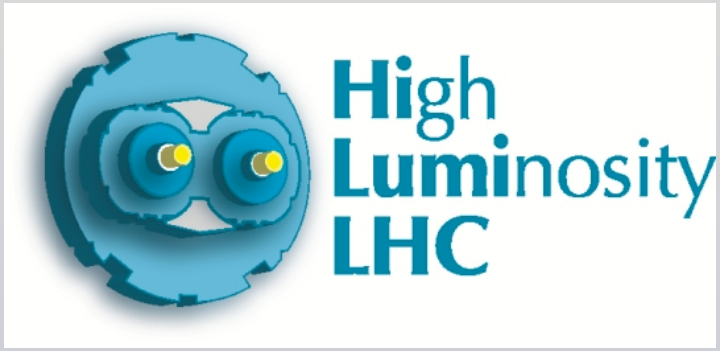
- Compare the **relevant PDF luminosities** before and after including the HL-LHC pseudo-data
- For **antiquarks, Drell-Yan data** also helps in reducing PDF uncertainties



Impact on PDFs: top quark pair production

- The **CMC-PDFs** have been r**eweighted by the HL-LHC pseudo-data** (each observable separately), to estimate the **reduction in the size of the PDF uncertainties**
- Compare the r**elevant PDF luminosities** before and after including the HL-LHC pseudo-data
- For the **quark-gluon channel,** measurements of the **Z pt** helps in reducing PDF uncertainties, though the **coverage is limited by statistics** as compared to high-mass Drell-Yan and top quark pair production





- **Parton Distributions** are an essential ingredient for LHC phenomenology
- Regardless of what is found at Run II, accurate PDFs will be mandatory for the LHC program in the **next 20 years**, as required for **precision SM measurements, Higgs characterisation** and **New Physics searches**
- At the High-Luminosity LHC, **many opportunities to improve PDFs**, though is non-trivial to quantify the expected PDF uncertainty reduction
- Here we have concentrate on **high-mass production, which is limited by statistics,** and that is directly sensitive to large-x PDFs, a central ingredient for BSM searches
- We have found that in all cases, with reasonable assumptions, **PDF uncertainties at large-x can be reduced**, specially for the gluon (from top quarks) and the antiquarks (from Drell-Yan)
- More work to be done to ensure that these estimates are robust enough
- In addition, it will be important to ensure that the **theoretical accuracy** of PDFs mathces the precision of the HL-LHC measurements: **PDFs with threshold resummation, approximate N3LO PDFs, PDFs with QED and weak corrections ….**