Physics potential of precision measurements of the LHC luminosity

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LHC Lumi Days 2012
CERN, 29/02/2012

Outline

- ☑ Accuracy of benchmark LHC processes
- ☑ Impact of LHC data in PDF determinations
- ☑ Physics opportunities at 8 TeV

cross section for the elementary process $ij \to O$, function of M_O, g_{ijO}

strength of the coupling between i,j and O

$$\sigma(pp \to O + X) = \int dx_1\, dx_2 \sum_{i,j} f_i(x_1)\, f_j(x_2)\, \hat{\sigma}_{(ij\to O)}(M_O, g_{ijO}, \ldots)$$

N of partons of type "i", "j", carrying a fraction $x_{i,j}$ of the proton momentum

mass of O

- A theory of particle physics is defined by parameters like M_O, g_{ijO}
- Their extraction, by inverting the above relation, is the ultimate goal of the cross-section measurement (eg. M_Z and $\sin^2\theta_W$ at LEP, and $M_{top,Higgs}$ and y_t at LHC)
- The precision of this extraction is determined by:

↓ **Theory**

  - The precision of the calculation of the elementary cross section in terms of M_O, g_{ijO}
  - The precision in the knowledge of the "parton densities" $f_i(x)$ (PDFs) ← **Theory + exp**
  - The precision of the cross section measurement, defined by:

MLM LumiDays11

$$\sigma(pp \to O + X) = \frac{N_{events}(O)}{\text{Luminosity}}$$

← **exp**

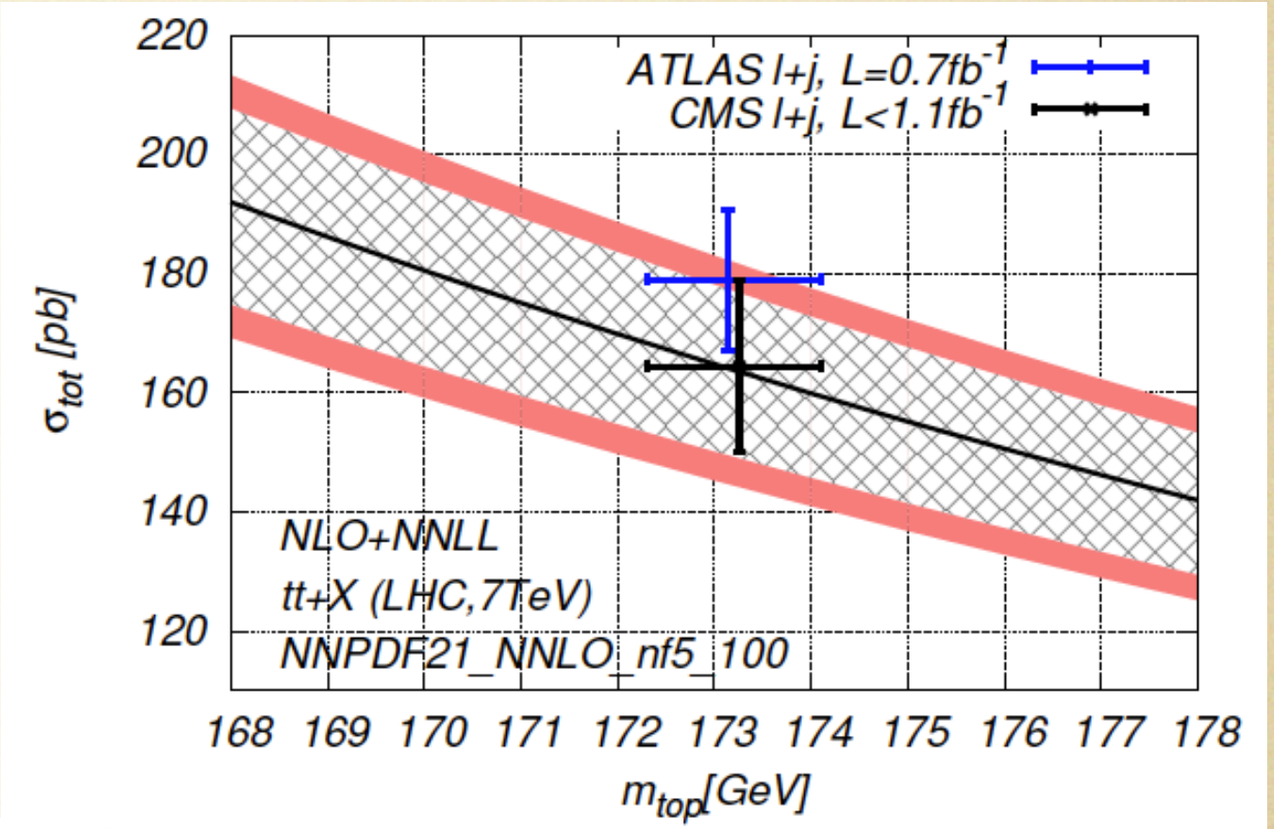
← **this meeting**

3

Accuracy of benchmark LHC processes

Top quark pair production

- Theoretical accuracy: **NLO+NNLL**
- Dominated by scale errors, to be reduced when full NNLO available
- Best TH estimate from Cacciari et al. (**arXiv:1111.5869**)
- In near future TH error down to **3-5 pb**



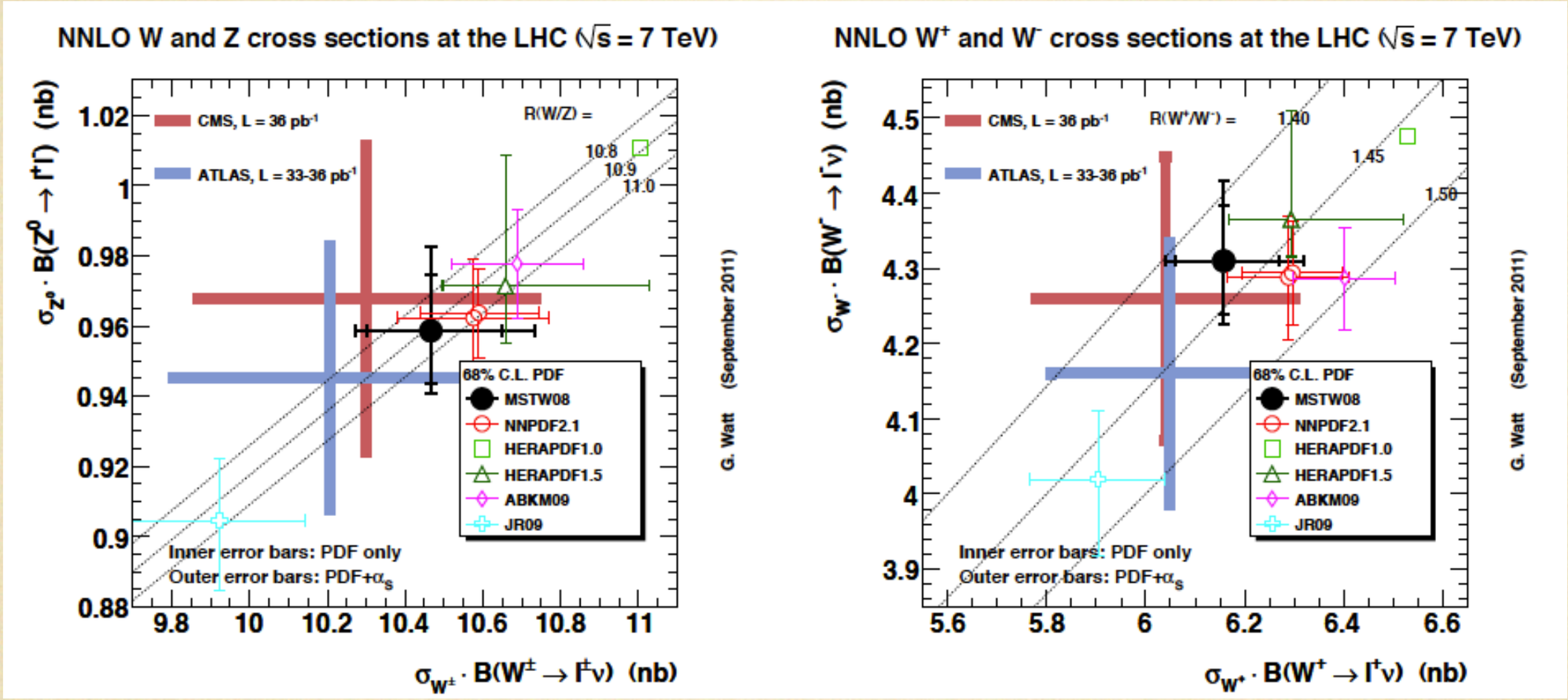
$$\sigma_{\rm tot}^{\rm NLO+NNLL}(\mathrm{LHC}_{7\rm TeV};\ m_t = 173.3\ \mathrm{GeV}) = 163.1\ ^{+12.9\,(7.9\%)}_{-14.2\,(8.7\%)}\ [\mathrm{scales}]\ ^{+4.9\,(3.0\%)}_{-4.9\,(3.0\%)}\ [\mathrm{PDF}]\ \mathrm{pb}$$

- LHC data consistent with TH estimates, but will soon be **limited by luminosity errors**

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\mathrm{stat.}) \pm 10.6(\mathrm{syst.}) \pm 7.8(\mathrm{lumi.})\ \mathrm{pb}$$ **CMS combination, dileptons 1.1 fb-1**

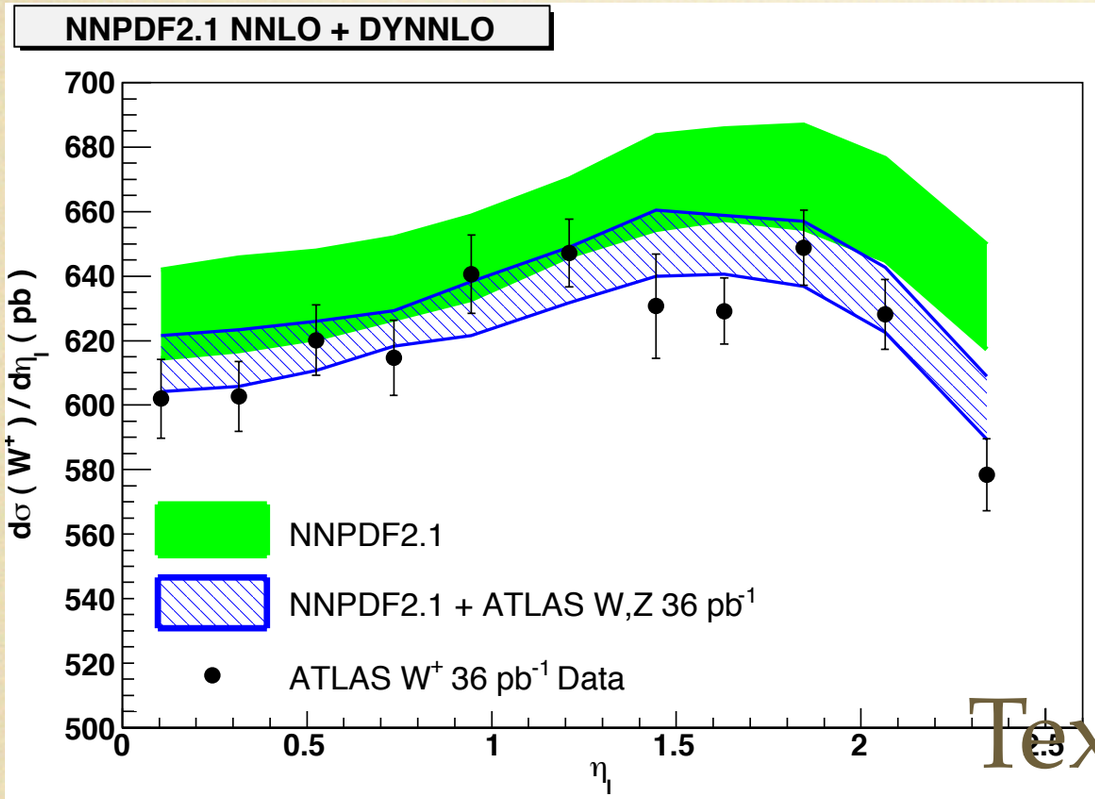
$$\sigma_{t\bar{t}} = 176 \pm 5(\mathrm{stat.})^{+14}_{-11}(\mathrm{syst.}) \pm 8(\mathrm{lum.})\ \mathrm{pb}$$ **ATLAS, dileptons 0.7 fb-1**

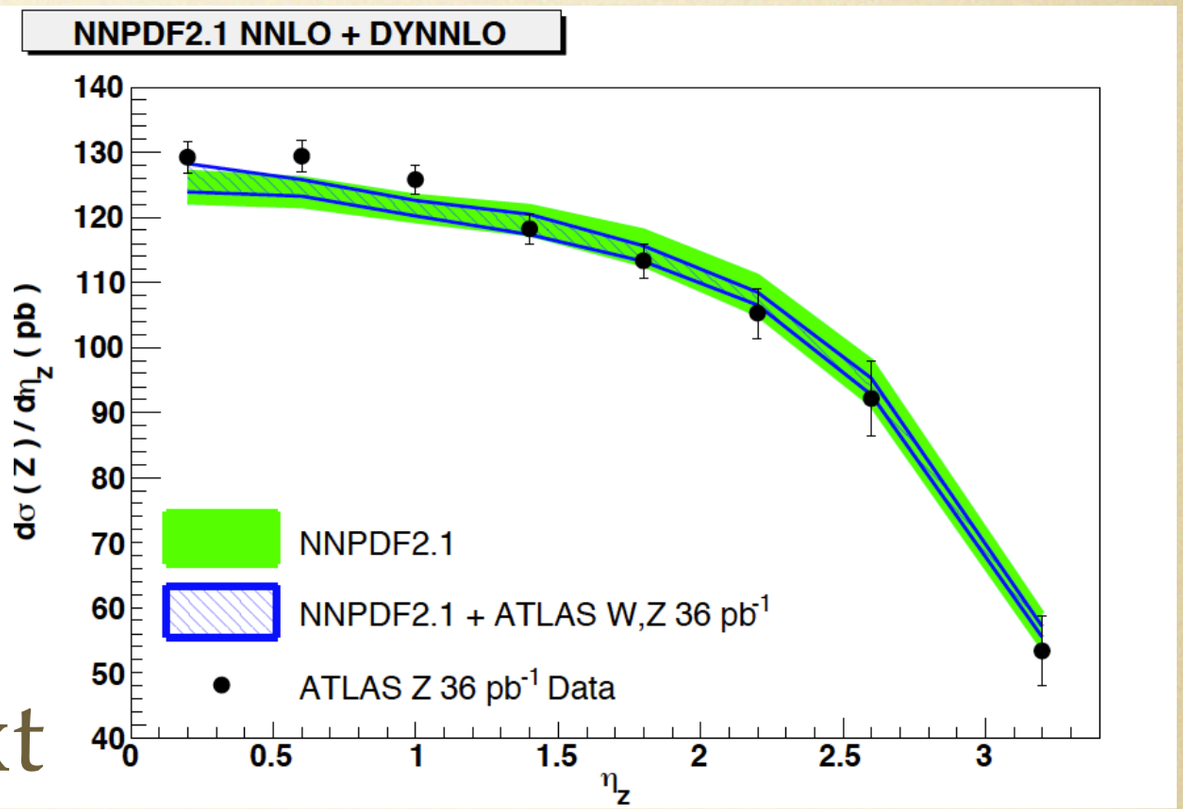
Electroweak boson production



- Theory known up to **NNLO, fully differential distributions available**
- **TH uncertainty 2-3**% in total cross section: comparison with data limited by **lumi uncertainties**
- **Z cross sections** used to calibrate LHC luminosity
- PDF is dominant theory uncertainty, **normalization error** dominant exp. error
- The information on the **individual W+ and W- distributions** can be combined a posteriori within a global analysis if the covariance matrix available: no need to measure the W asymmetry or ratios

Electroweak boson production





Text

- Theory known up to **NNLO, fully differential distributions available**
- PDF is dominant theory uncertainty, **normalization error** dominant exp. error

Data Set	Ref.	N_{dat}	$[\eta_{min}, \eta_{max}]$	$\langle\sigma_{stat}\rangle$ (%)	$\langle\sigma_{sys}\rangle$ (%)	$\langle\sigma_{norm}\rangle$ (%)
CMS Z rapidity 36 pb^{-1}	[8]	35	[0, 3.6]	12.3	-	0
CMS muon asymmetry 234 pb^{-1}	[6]	11	[0, 2.4]	3.6	-	0
ATLAS W,Z 36 pb^{-1}	[4]	30	[0, 3.2]	1.9	1.7	3.4
ATLAS W^+ 36 pb^{-1}	[4]	11	[0, 2.4]	1.4	1.3	3.4
ATLAS W^- 36 pb^{-1}	[4]	11	[0, 2.4]	1.6	1.4	3.4
ATLAS Z 36 pb^{-1}	[4]	8	[0, 3.2]	2.8	2.4	3.4
LHCb Z rapidity 36 pb^{-1}	[9]	5	[2, 4.5]	22.3	-	3.4
LHCb W lepton asymmetry 36 pb^{-1}	[9]	5	[2, 4.5]	26.1	-	0

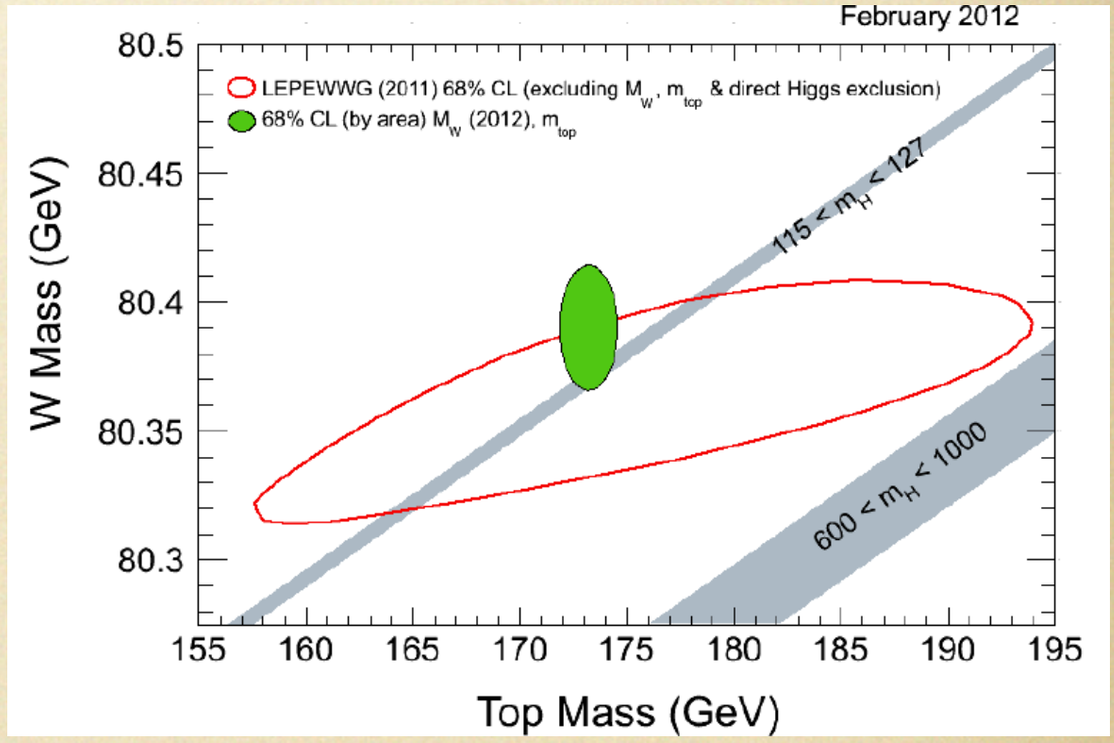
Impact of LHC data in PDF determinations

Theory Motivation

- Determining with precision the **Parton Distributution Functions** is crucial for precision phenomenology at hadron colliders
- For example, the current best determination of **MW from CDF** is completely **dominated by PDF uncertainties**
- Implications for **indirect new physics searches**

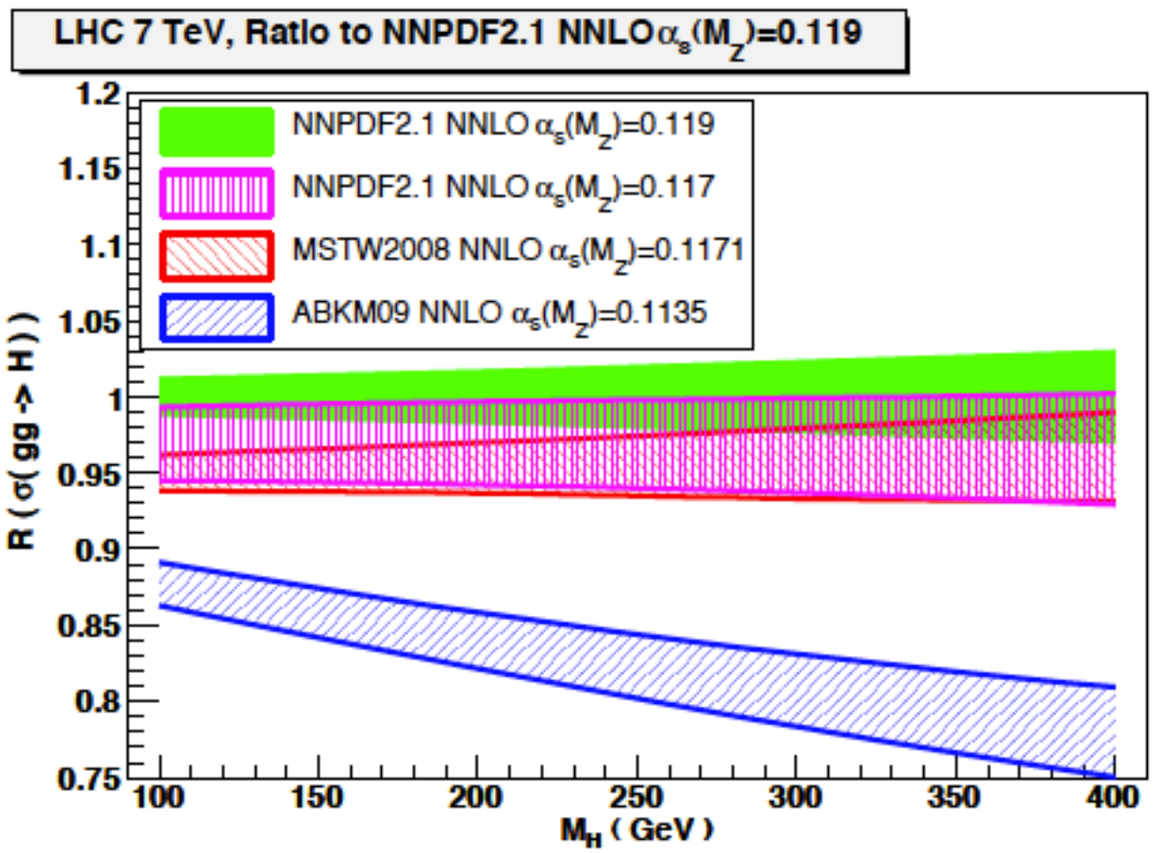
New CDF Result (2.2 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

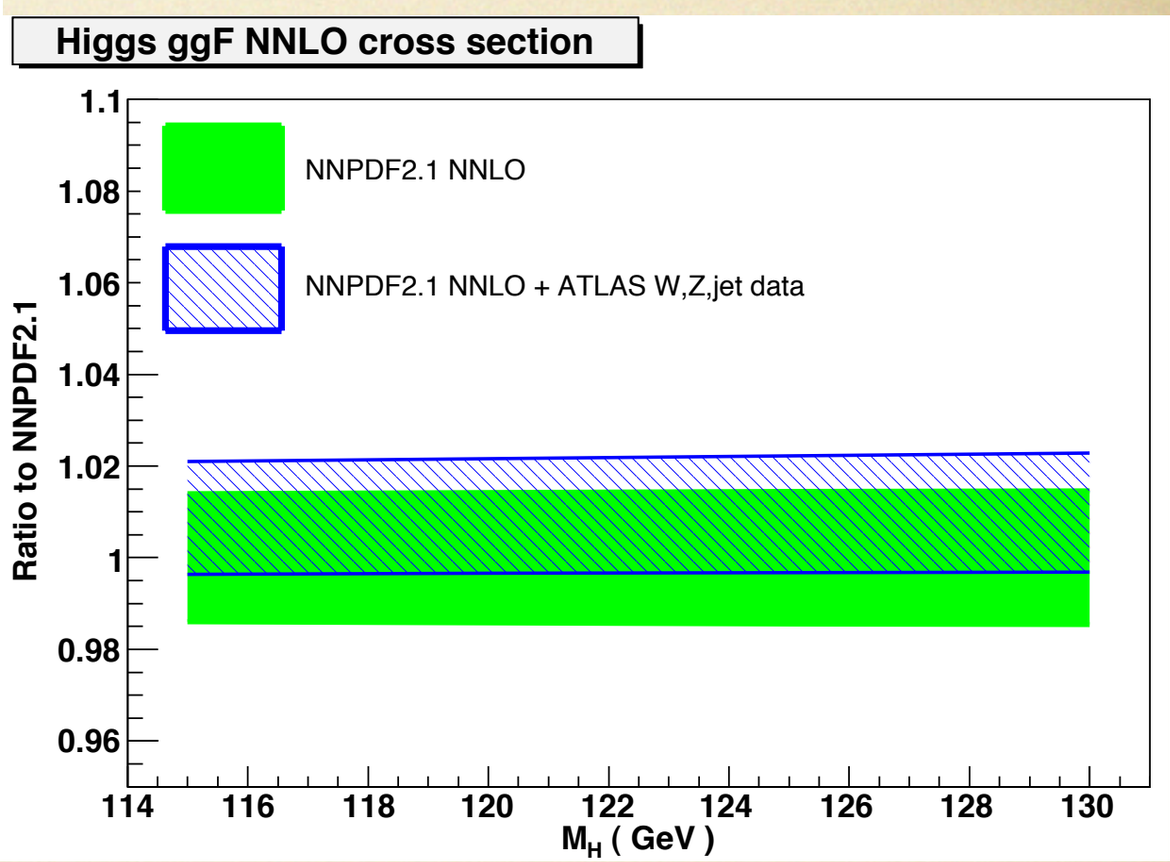
	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic	18	16	15



Theory Motivation

- Determining with precision the **Parton Distributution Functions** is crucial for precision phenomenology at hadron colliders
- For example, the **current exclusion bounds on SM Higgs cross section** depend heavily on PDF uncertainties
- Accurate PDFs impact on many SM and BSM analysis



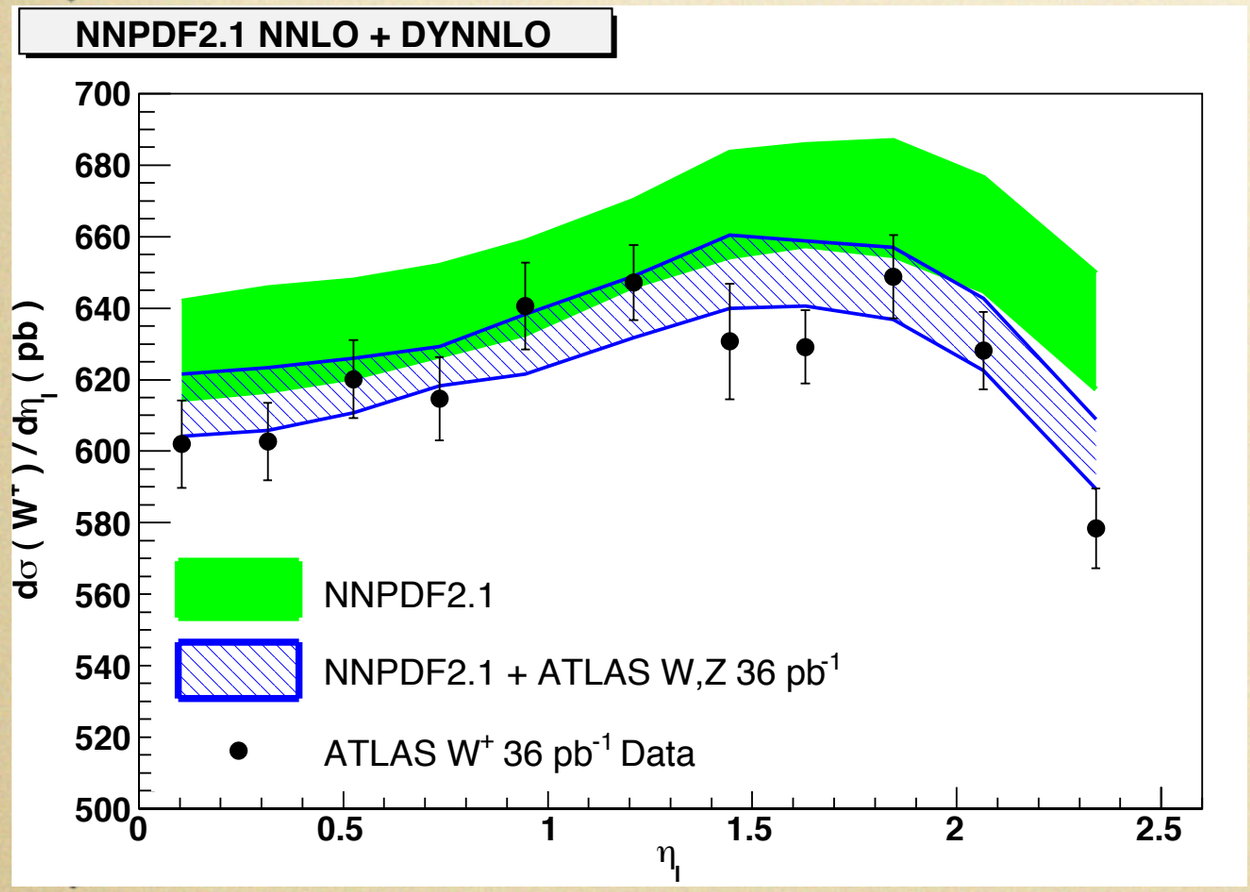


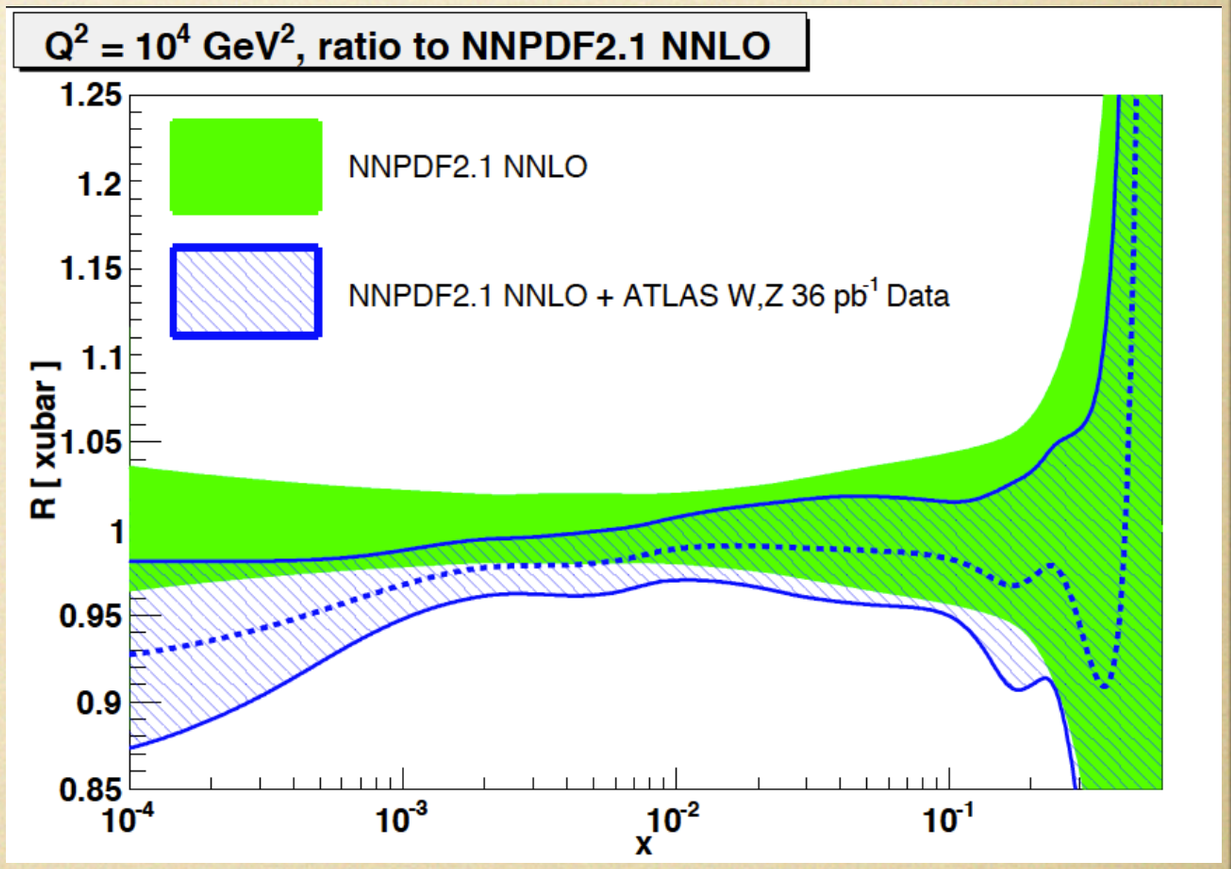
PDF Constraints from LHC data

- **Electroweak Vector Boson** production
  - W/Z rapidity distributions: ATLAS, CMS, LHCb
  - W lepton asymmetry: ATLAS, CMS, LHCb
  - W+charm production: CMS
  - Low and high mass Drell-Yan production: CMS
- **Jet and photon** production
  - Inclusive jets: ATLAS, CMS
  - Dijet distributions: ATLAS, CMS
  - Direct photon production: ATLAS, CMS
- **Top quark** production
  - Top quark pair distributions: ATLAS, CMS
  - Single top production

ATLAS W/Z measurements 36 pb^{-1}

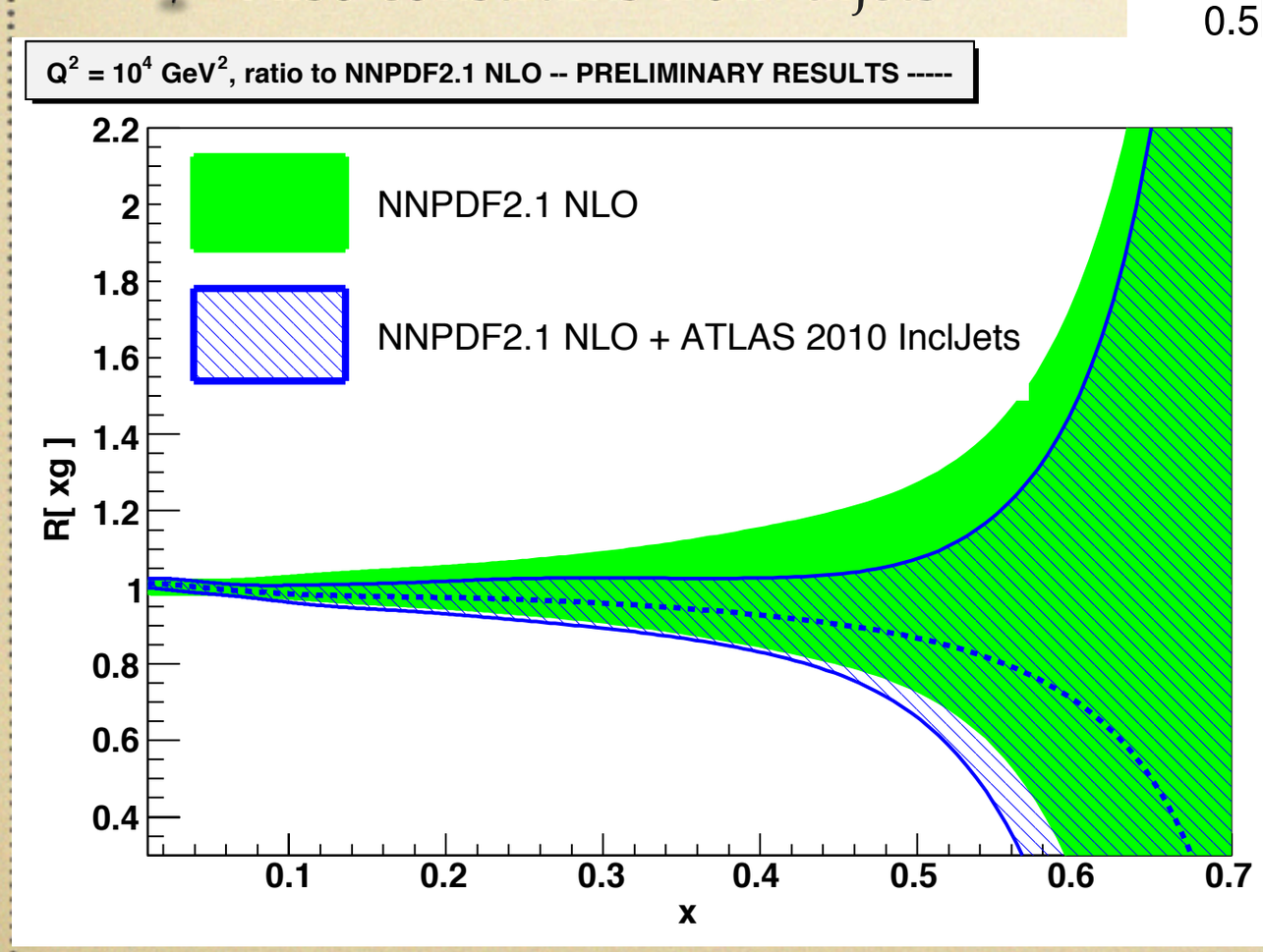
- ATLAS has published the W and Z lepton rapidity distributions with experimental covariance matrix
- This measurement includes the **same information as in the W asymmetry** and in addition extra info from the absolute shapes of the W and Z distributions
- **Separate W+ and W- distributions** preferred over the **W asymmetry**
- ATLAS data: Reduction of PDF uncertainties in medium and small-x (anti)quarks, softer quark sea at small-x

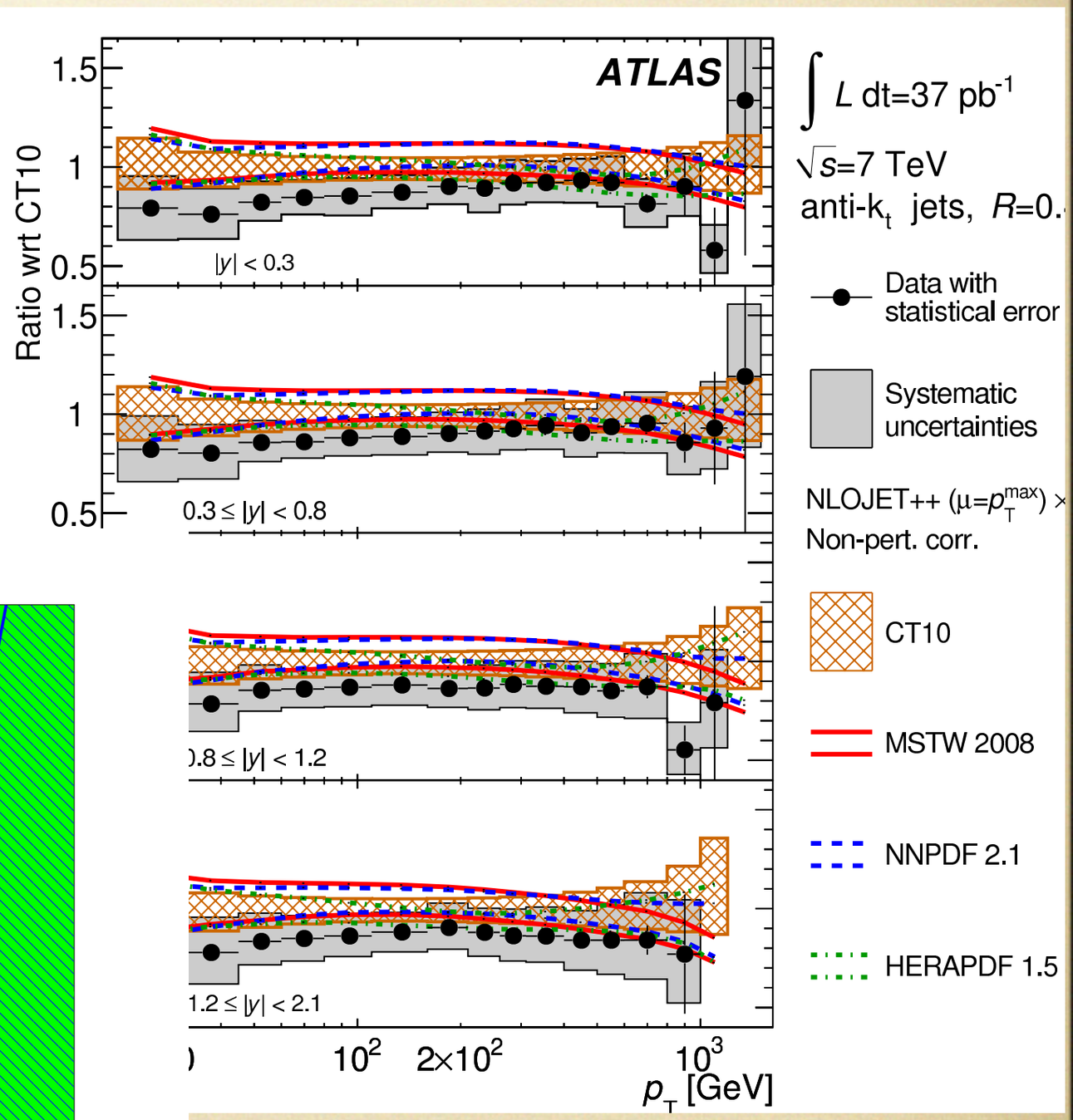




Inclusive jets

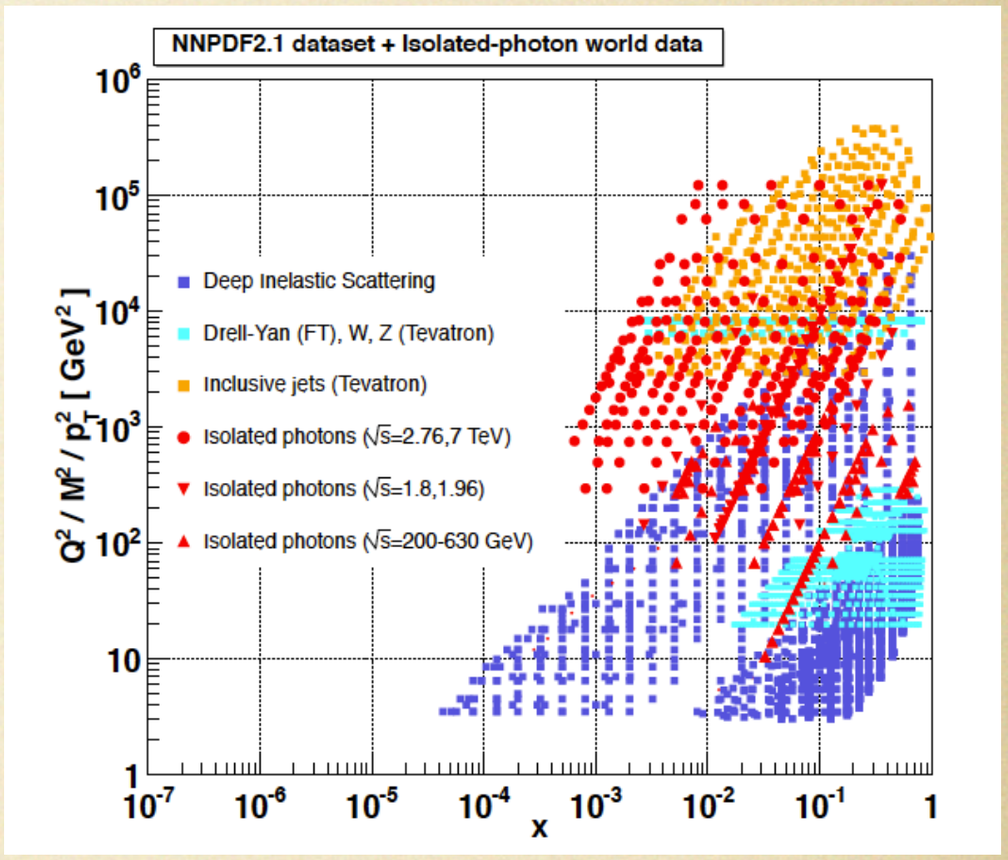
- Available LHC jet data constrain the **large-x gluon**
- Relevant for robust predictions for **Higgs boson cross sections**
- Also constrains from dijets

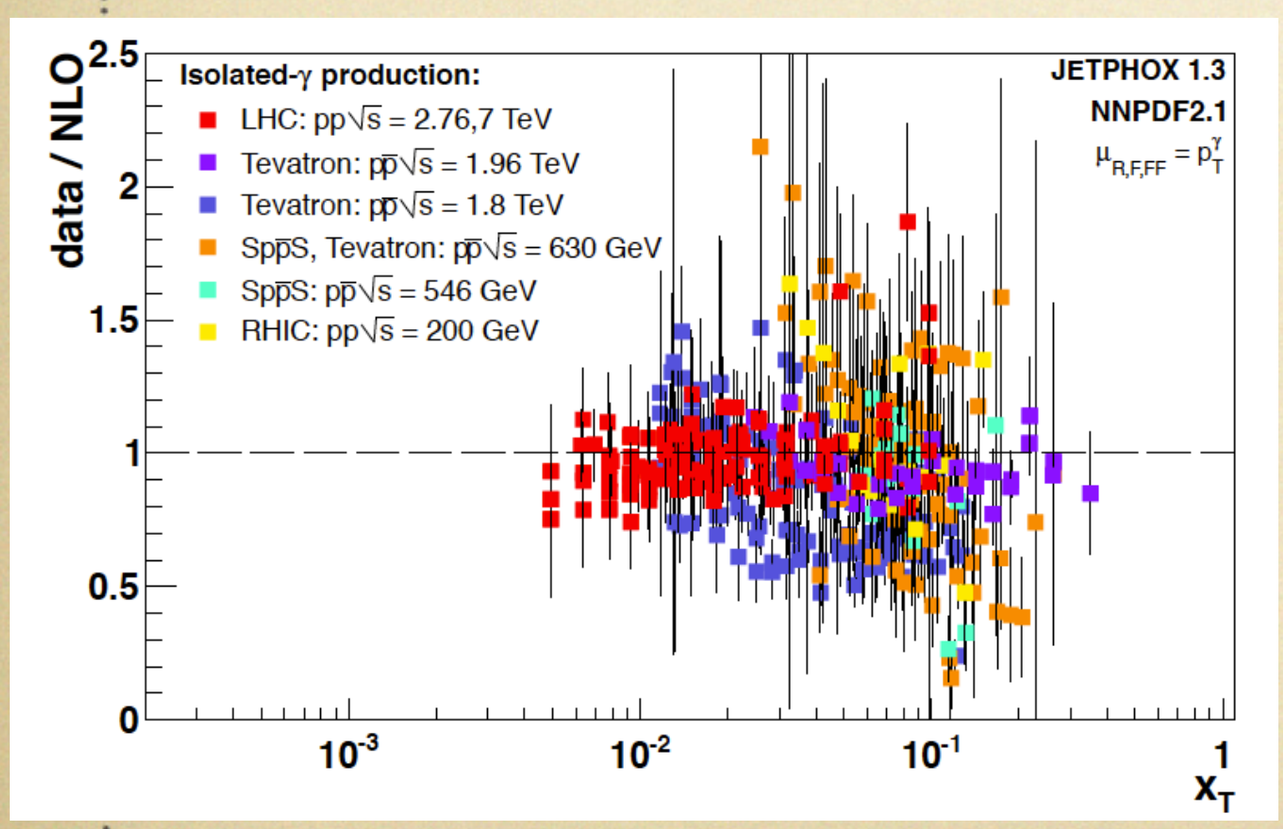


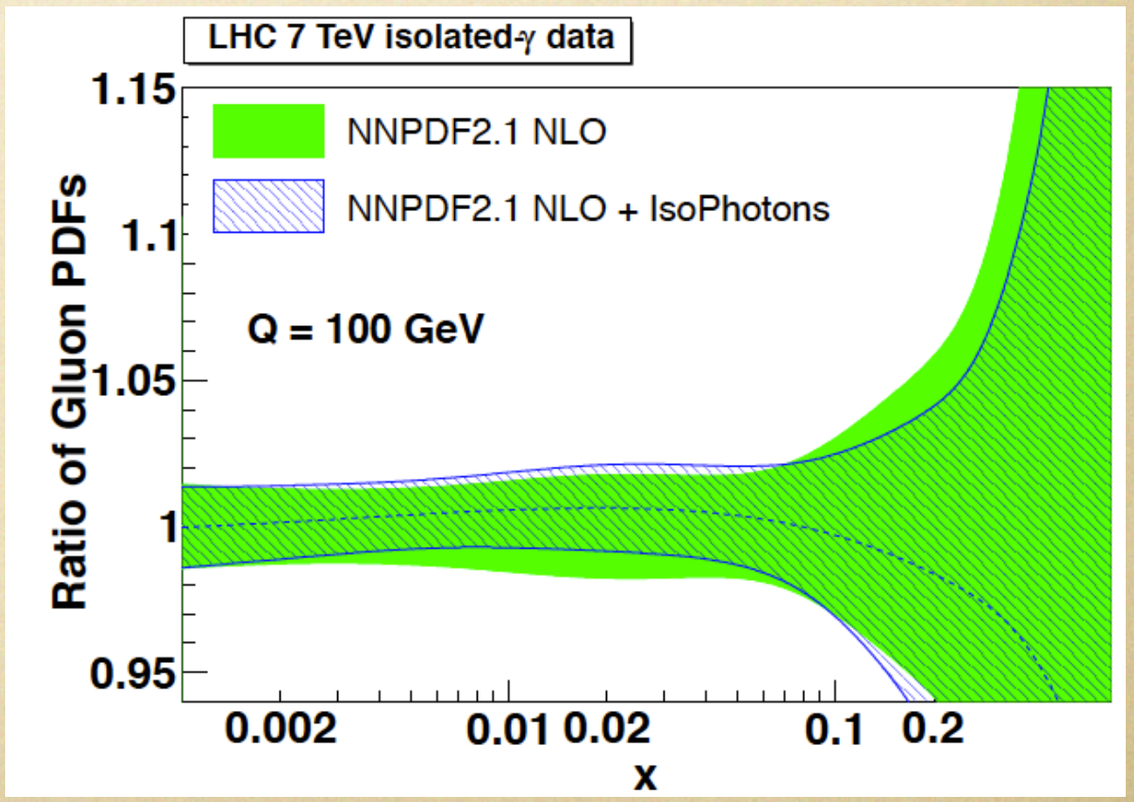


Isolated Photons

- Isolated photons probe directly the **gluon distribution**
- Abandoned for PDFs around 13 years ago. Recent reanalysis (D. D'Enterria + J.R., arXiv:1202.1762): excellent agreement NLO QCD and isolated photon data from PHENIX to LHC energies
- Isolated photon data from the LHC provides moderate constraints on the gluon PDFs and **improve Higgs cross section predictions**







Global analysis and luminosity uncertainties

- Within a global PDF analysis, the information from all datasets are consistently combined into a uniform framework
- In particular, normalization errors from data from the same experiment **should be treated as correlated** if this is the case
- By including different data into a global PDF analysis, one can reduce the impact of normalization uncertainties, since some data constrain other
- To properly **include normalization errors**, we need to know:
  - Is the luminosity error between say **two CMS 2010 datasets** 100% correlated?
  - Is the luminosity error between say **two CMS 2011 and 2012 datasets** 100% correlated?
  - Is possible to quantify the **correlation between ATLAS and CMS luminosity measurements**?

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Treatment of normalization errors

- Important to account for *correlated* systematic uncertainties of experimental data points [CTEQ6, hep-ph/0201195]:

$$\chi^2 = \sum_{i=1}^{N_{\text{pts.}}} \left(\frac{\hat{D}_i - T_i}{\sigma_i^{\text{uncorr.}}} \right)^2 + \sum_{k=1}^{N_{\text{corr.}}} r_k^2, \quad \text{where } \hat{D}_i \equiv D_i - \sum_{k=1}^{N_{\text{corr.}}} r_k \, \sigma_{k,i}^{\text{corr.}}.$$

G. Watt, PDF4LHC, 03/11

- Trade-off between systematic shifts r_k and gluon parameters.
- Restrict shift in luminosity uncertainty, $r_{k,\text{lumi.}} \in [-1, +1]$. Otherwise find $r_{k,\text{lumi.}} \sim 3$–$5$ for some PDF sets with soft high-x gluon distributions (e.g. ABKM and HERAPDF).
- In MSTW08 global fit, CDF luminosity is determined by $\mathrm{d}\sigma_Z/\mathrm{d}y$.

- Within a global analysis, the normalization uncertainties for different datasets from the same experiment **are fully correlated**

- Important to consistently include this information: for example, in a combined fit of LHC **W/Z and jet data**, the former could fix the jet normalization and improve the fit quality to the latter

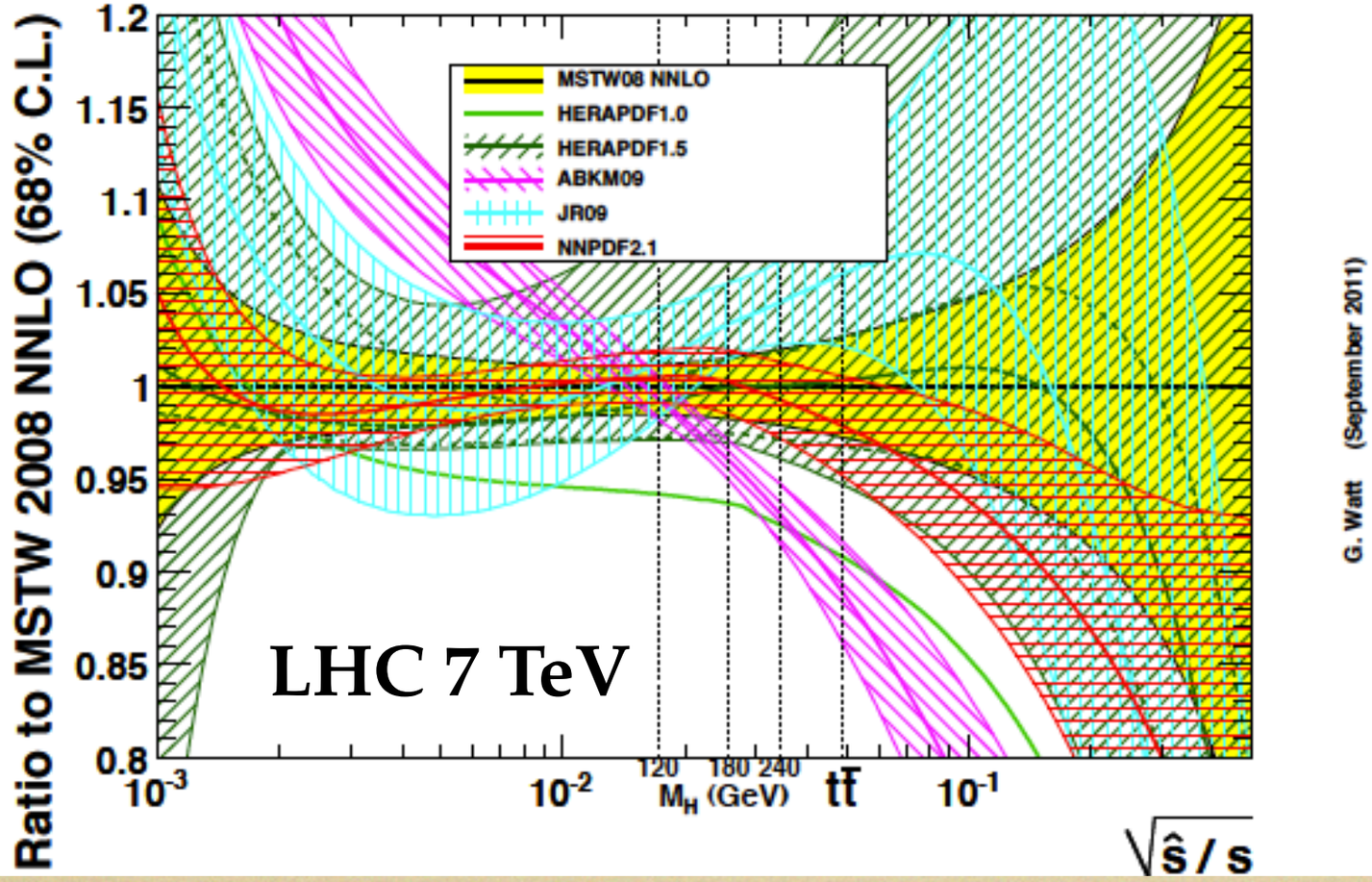
Physics opportunities at 8 TeV

Opportunities at 8 TeV

- The **2012 8 TeV run** offers new possibilities for interesting measurements

- However, these require to assume that the **normalization errors from the 2011 and 2012 datasets are fully correlated** (or know accurately their correlation)

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



- Consider one example: **large-x PDFs**

- Large-x PDFs are poorly know -> **Large TH uncertainties for high mass particle production**

- Decrease sensitivity to **many BSM searches**

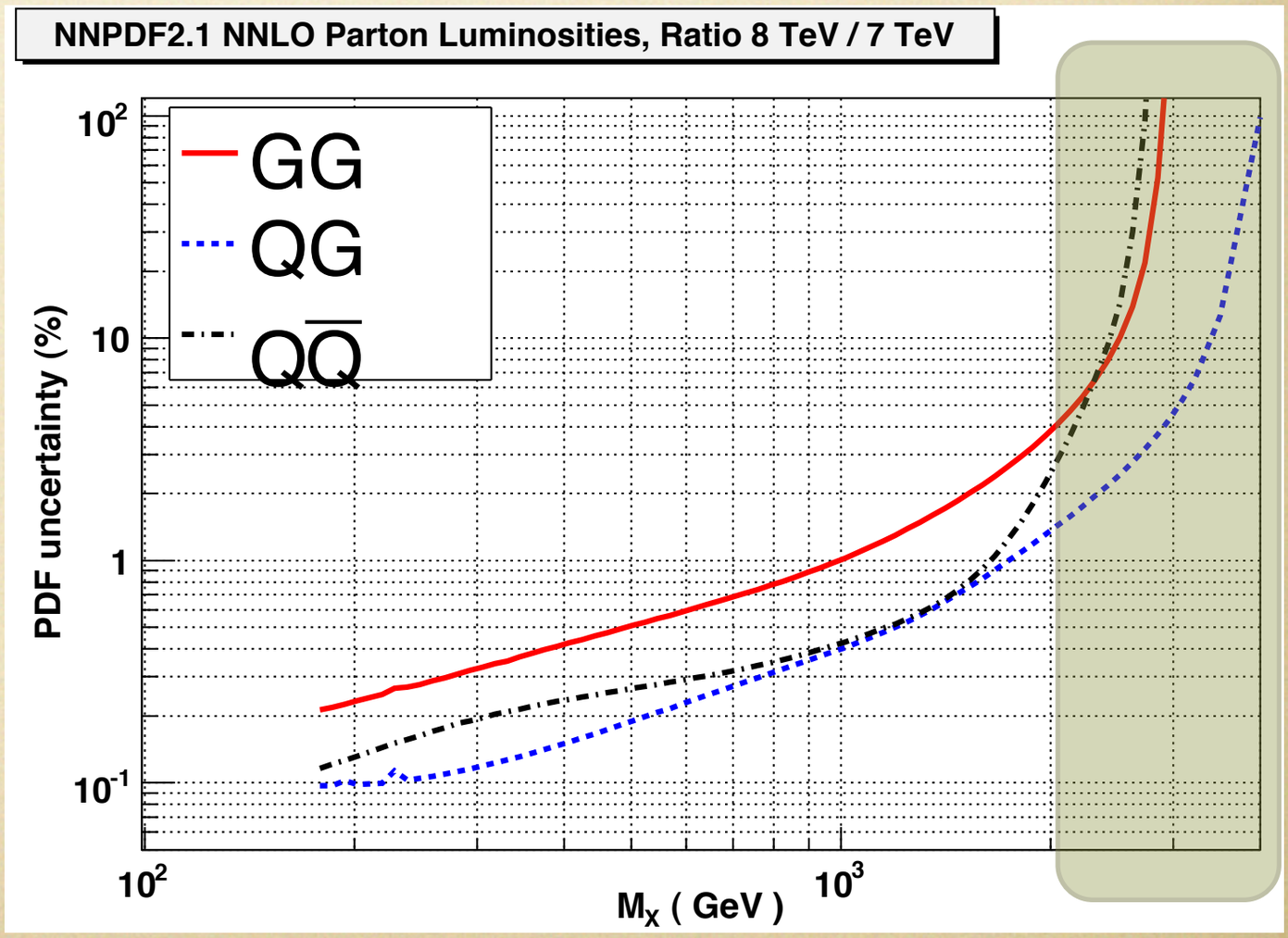
Opportunities at 8 TeV

- PDF uncertainties in the **8 TeV / 7 TeV ratio** blow up for for final state invariant masses above 2 TeV
- For M_X **= 2-3 TeV**, PDF error on the **GG lumi** grow up up to 100%
- Unique opportunity to **constrain large x PDF**

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

Ratios of cross sections for M_X**>2 TeV** will have very small statistical and systematic errors, but **large sensitivity to large x PDFs**

For example: measure **dijets at large invariant mass** in the same kin binnings in the 7 TeV and 8 TeV data



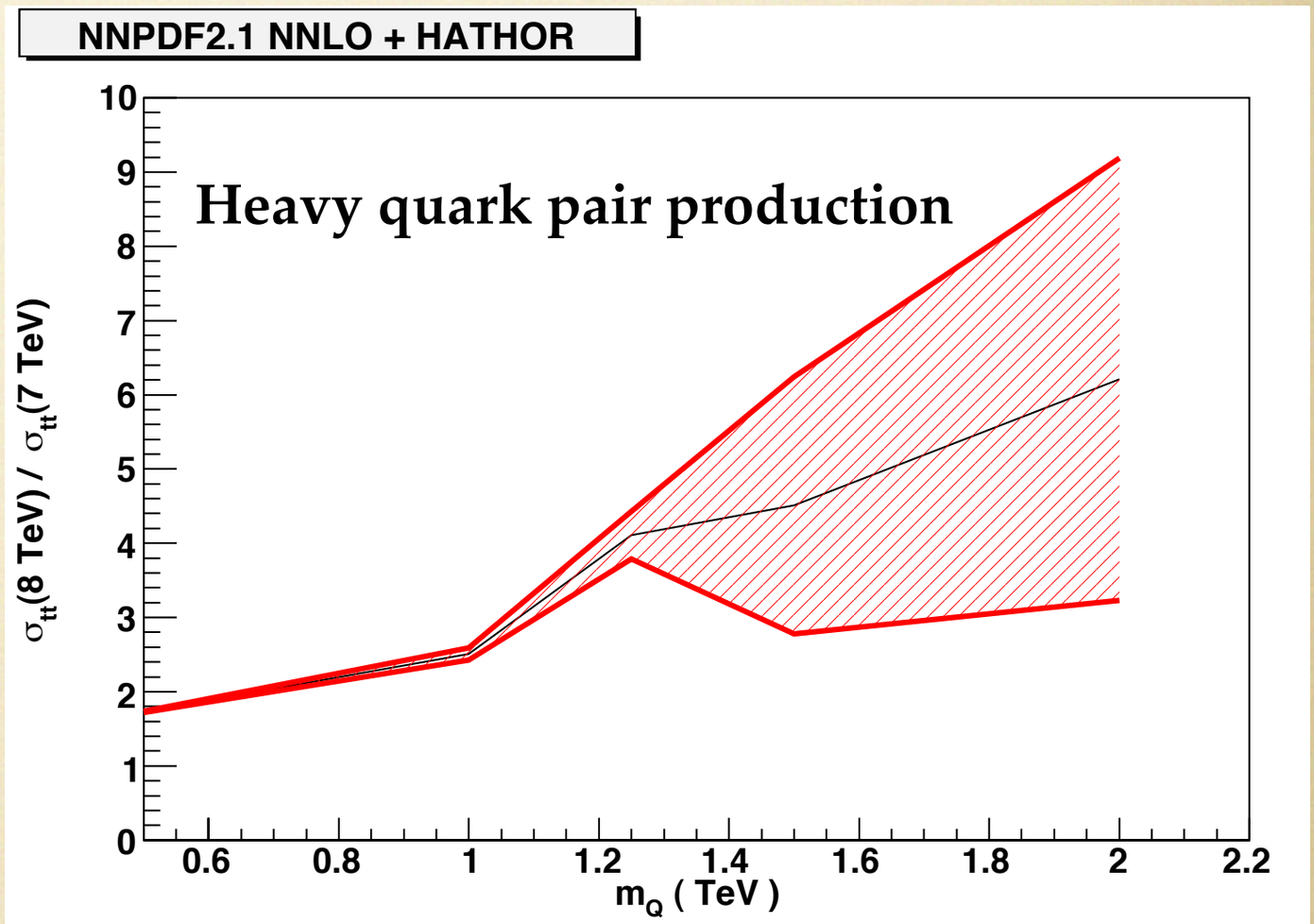
Opportunities at 8 TeV

- As an example, consider **heavy quark pair production** with mass $\mathbf{m_Q}$ in the TeV range

- Experimental uncertainties large, but **cancellations in ratio**

- PDF uncertainties blow up in ratio: measure ratios to **constrain large-x PDF**

- Important to be able to **cancel most or all luminosity error between 2011 and 2012 datasets**



- xsec ratios useful in many processes: **W/Z production inclusive and with jets, QCD jets and dijets, direct photons**, ...

- Physics potential **unexplored**

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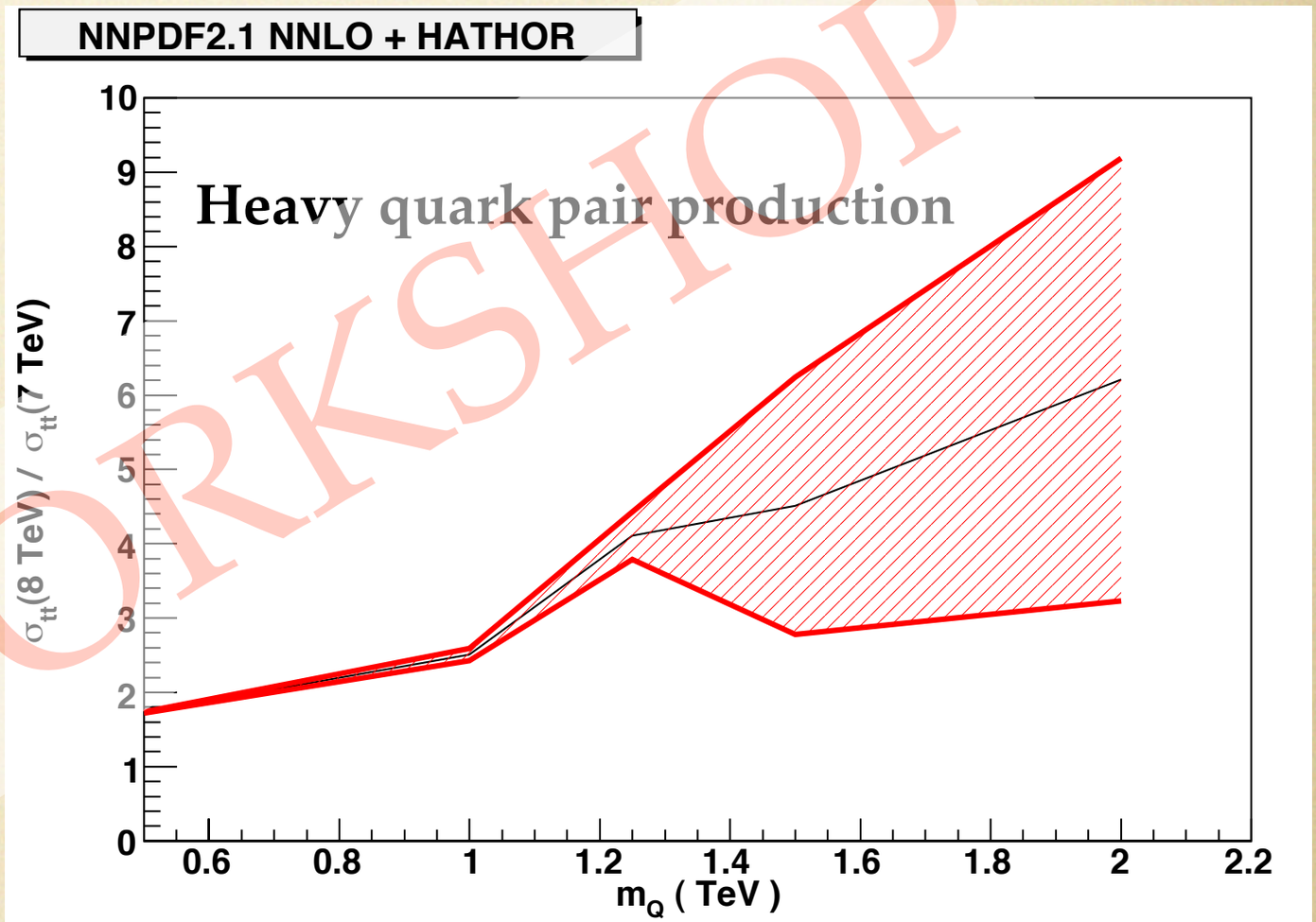

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Summary and outlook

- The LHC is **operating extremely well**, to the point where one needs to worry about luminosity uncertainties

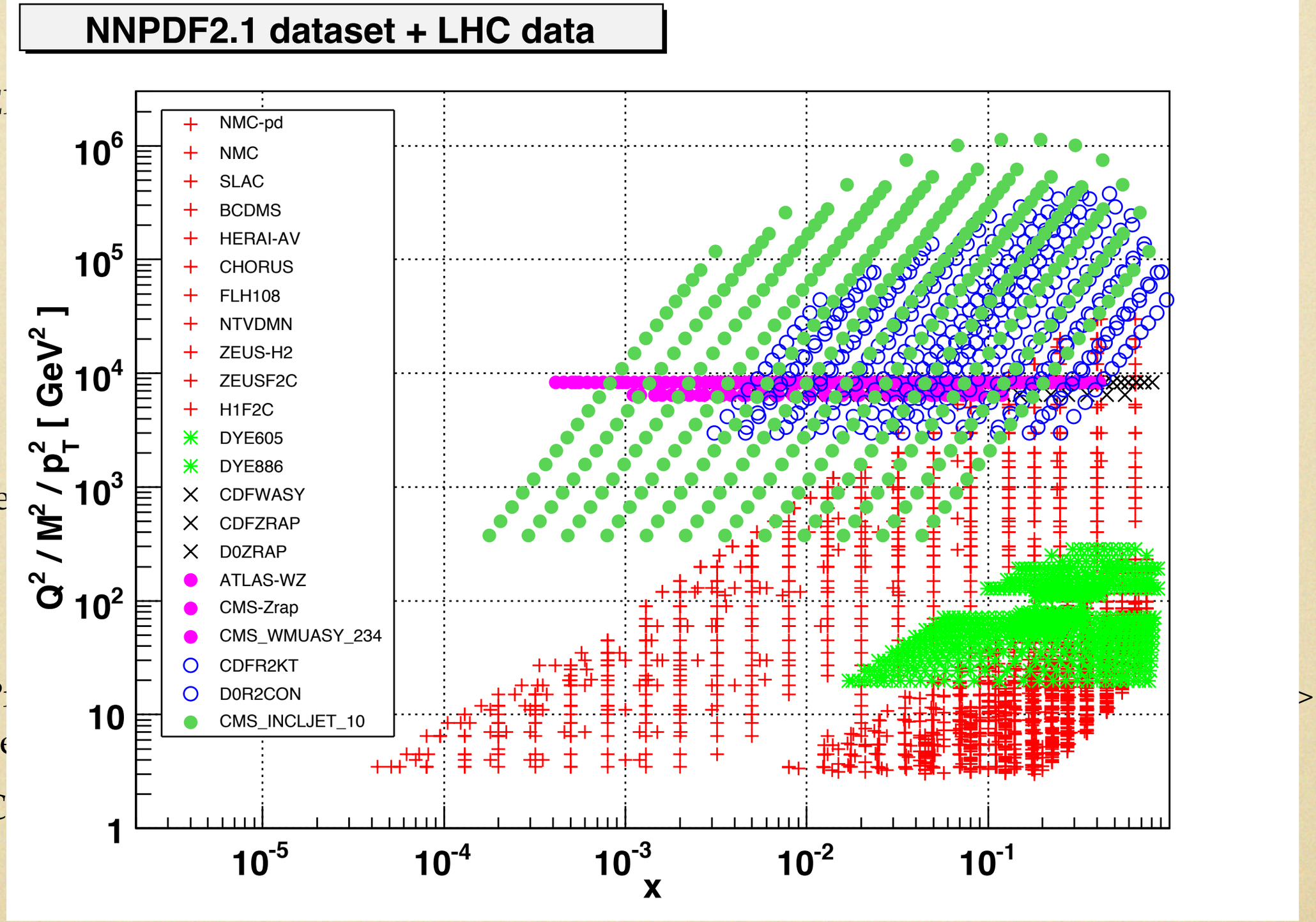
- A **precise determination of the luminosity** uncertainty strongly beneficial for many physics analysis

- LHC data provides **stringent constraints on PDFs,** most of which would benefit from a reduced luminosity uncertainty

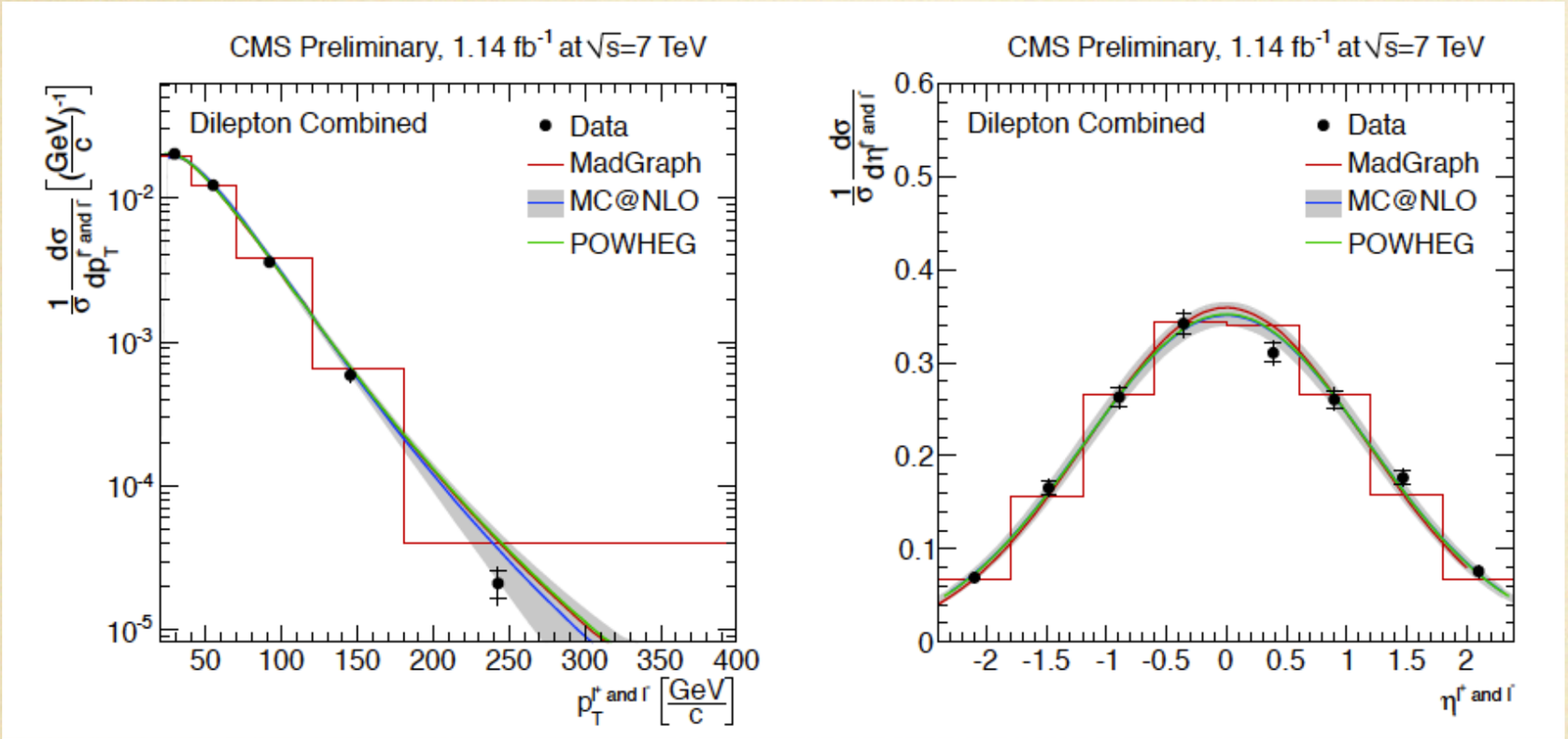
- The 8 TeV run offers new physics opportunities, like ratios of 8/7 cross sections, but this requires to accurate determine the **correlations between 2011 and 2012 systematic uncertainties, as well as between luminosity measurements**

Extra Material

PDF Constraints from LHC data



Top quark pair differential distributions



CMS TOP-11-013

- More sensitive to **new physics** that total cross section
- Normalization errors will also be important
- By including this data into a global PDF analysis, one can get a handle on normalization error from other processes (like W/Z)
- Could be combined to produce a **simultaneous PDF and top mass determination**

Impact of LHC W asymmetry in PDFs

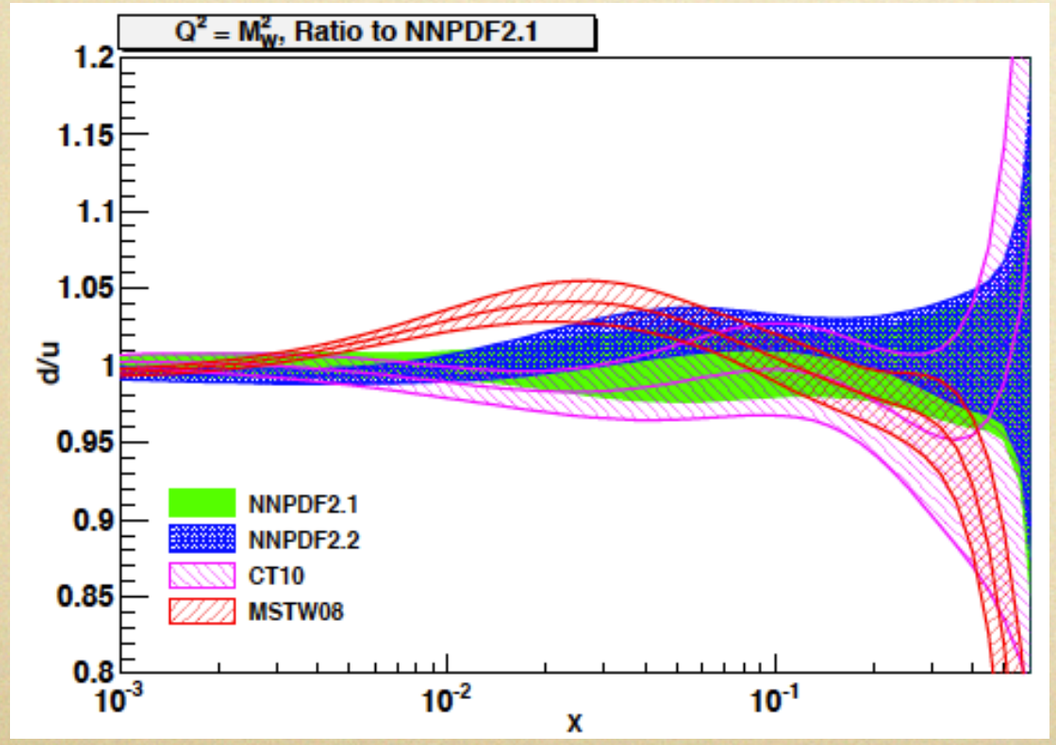
- NNPDF2.2 (**arXiv:1108.1758**) is the **only public PDF set** (available in LHAPDF) with LHC data included
- CMS (arXiv:1103.3470) and ATLAS (arXiv:1103.2929) 36 pb^{-1} W lepton asymmetry data
- Excellent description of all datasets, **reduced (anti)quarks PDF uncertainties**

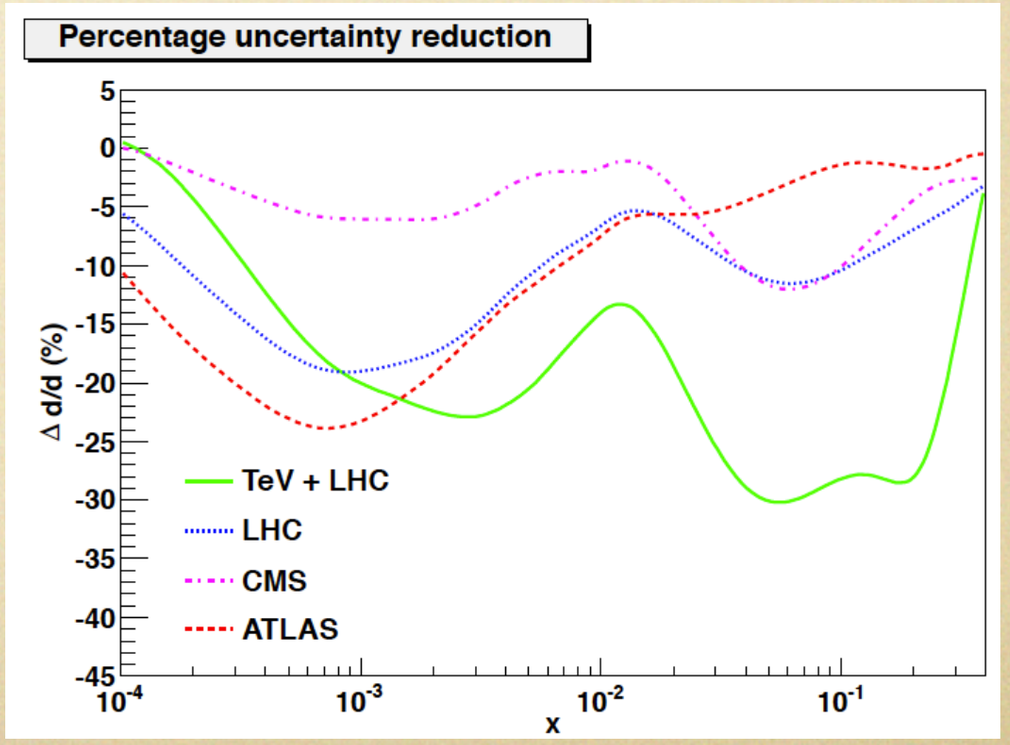
	$N_{\rm dat}$	NNPDF2.1	CT10	MSTW08
ATLAS(31pb^{-1})	11	0.76	0.77	3.32
CMS(36pb^{-1}) electron $p_T > 25$ GeV	6	1.83	1.19	1.70
CMS(36pb^{-1}) muon $p_T > 25$ GeV	6	1.24	0.73	0.77

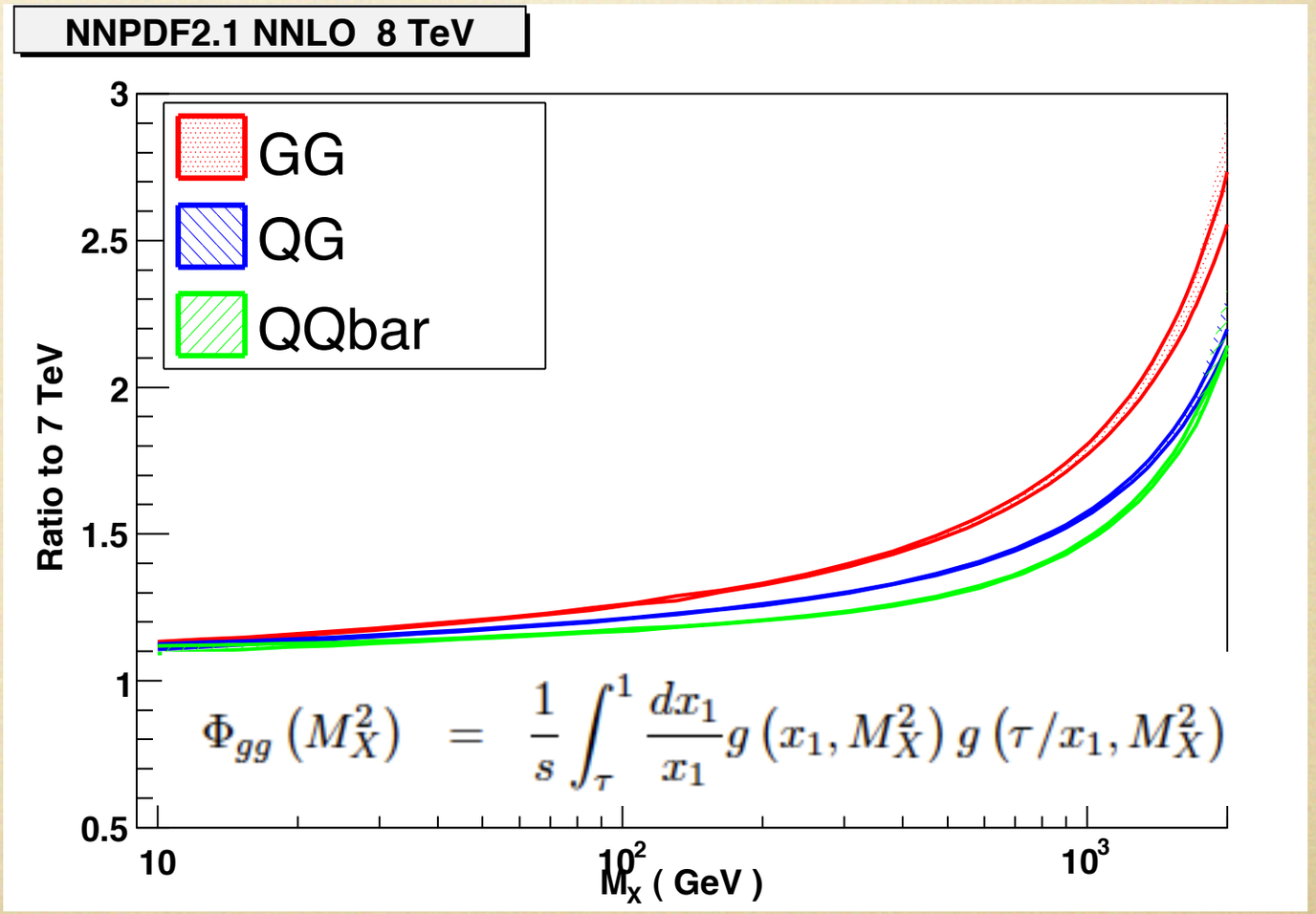
After the fit

Experiment	$N_{\rm dat}$	NNPDF2.1	NNPDF2.1 LHC	NNPDF2.2
ATLASmuASY	11	[0.77]	0.97	1.07
CMSeASY	6	[1.83]	1.23	1.08
CMSmuASY	6	[1.24]	0.63	0.56
D0eASY	12	[4.39]	[3.46]	1.38
D0muASY	10	[1.48]	[1.17]	0.35

Initial comparison





Opportunities at 8 TeV

- From 7 TeV to 8 TeV: **increase in parton luminosity**
- This increase grows with the mass of final state
  - At fixed M_X, PDF uncertainties from increased phase space increase only moderately
  - Higher impact in cross section ratios