PDF uncertainties and the W boson mass at hadron colliders

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Based on: G. Bozzi, J. Rojo, A. Vicini, ***arXiv:1104.7215****,*
and G. Bozzi, G. Ferrera, A. Vicini, in preparation

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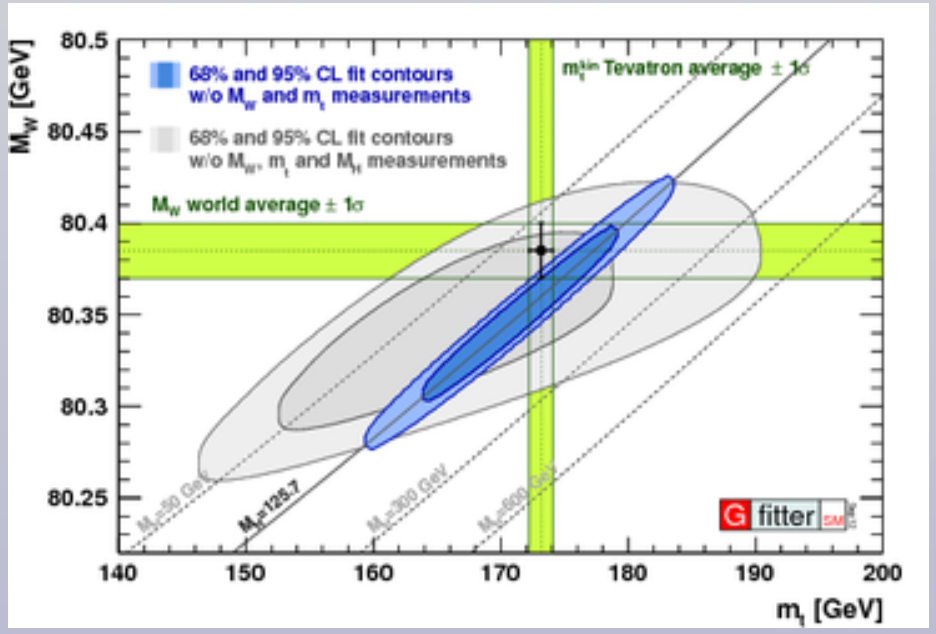
W mass at hadron colliders

- **The W mass** measurement is one of the legacy analysis of the Tevatron
- **LEP-like precision**, dominated by **theory systematics,** in particular **Parton Distributions**
- Stringent tests on the **consistency of the Standard Model**, indirect bounds on the Higgs boson mass

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

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

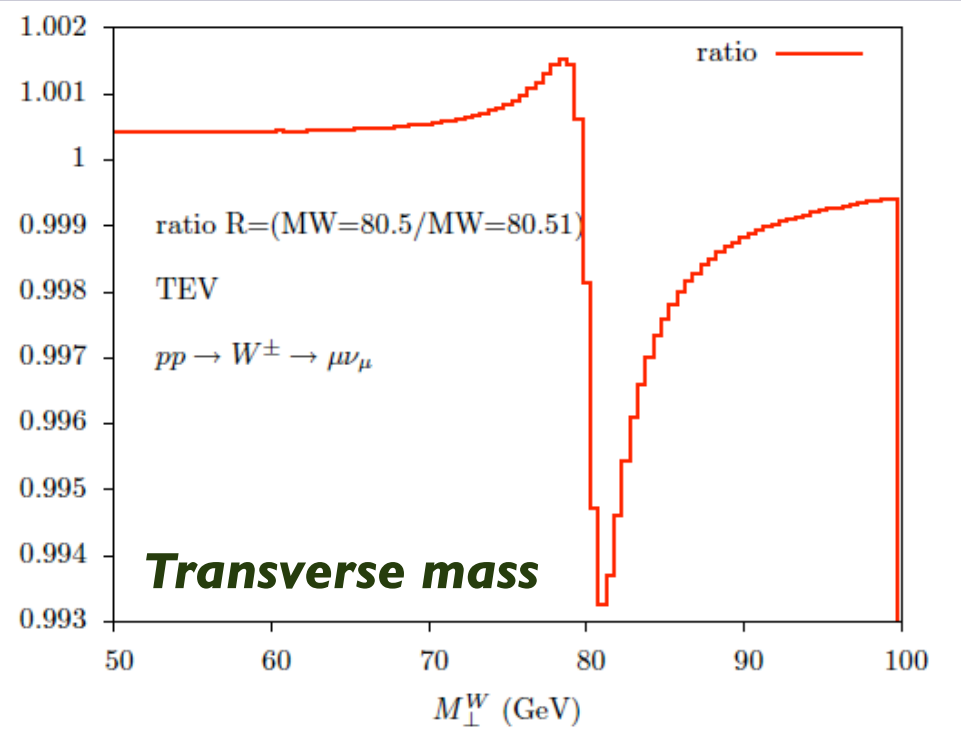


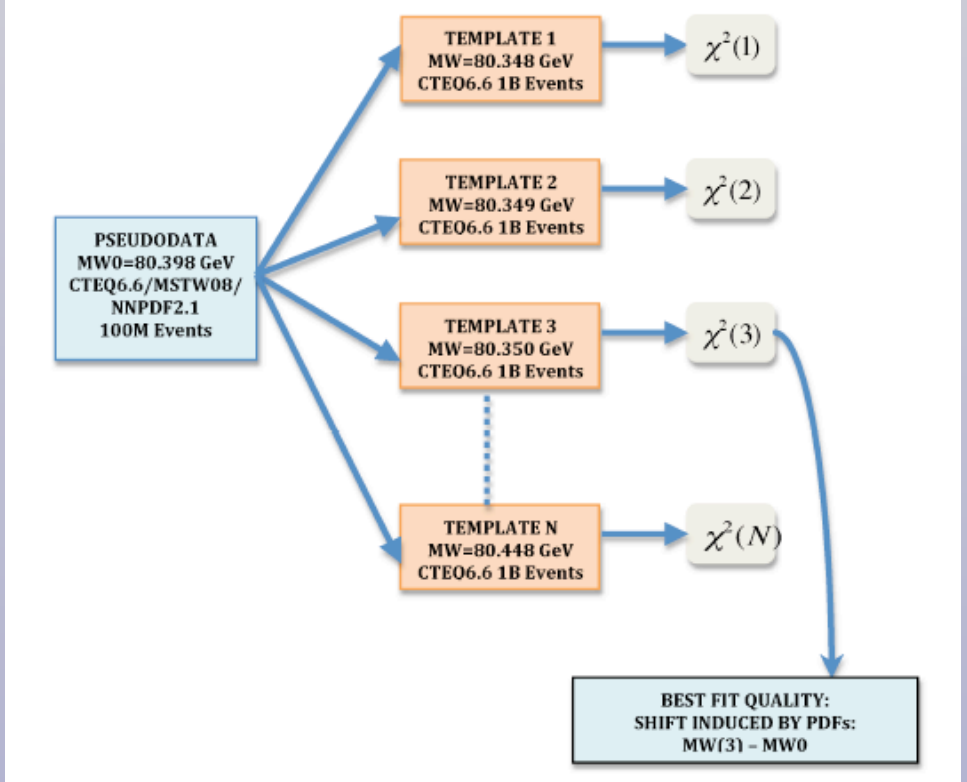
Is it feasible to achieve the **same precision/improve at the LHC**? Not everyone agrees, see for example **Krasny et al, arXiv:1004.2597:**

$\Delta M_W \leq 10$ MeV/c^2 at the LHC: a forlorn hope? †

W determination at the LHC

- The shape of various distributions in W production ($p_{W,T}$, $M_{W,T}$) are very sensitive to value of M_W
- At the Tevatron, a variation of 10 **MeV** in the mass leads to a variation of 7 **permille** in the distribution: Need to control **experimental and theory systematics** at similar degree of accuracy to obtain a competitive determination
- **Statistics** not an issue at the LHC: one can use **only muons or electrons**
- At the LHC **W+ different from W-**: provide two independent and complementary determinations, then **average**

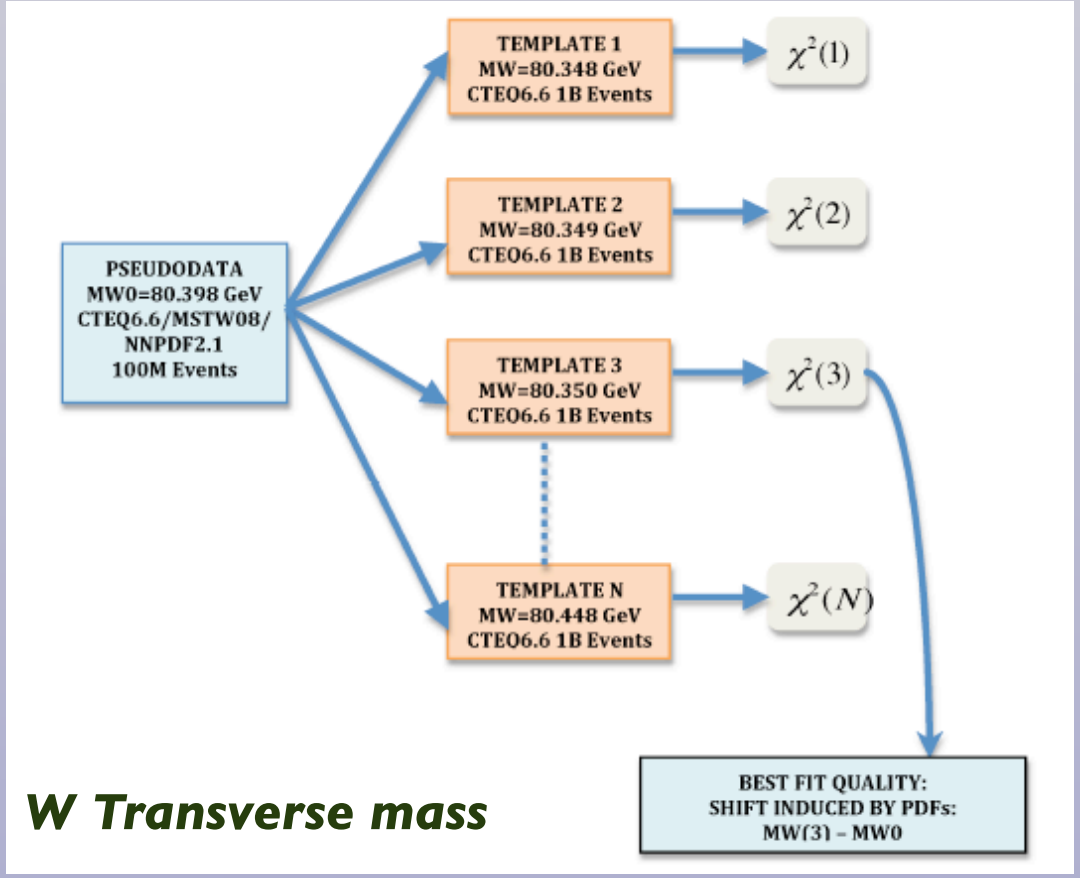




G. Bozzi, J. Rojo and A. Vicini, ``The Impact of PDF uncertainties on the measurement of the W boson mass at the Tevatron and the LHC," Phys. Rev. D83, 113008 (2011)

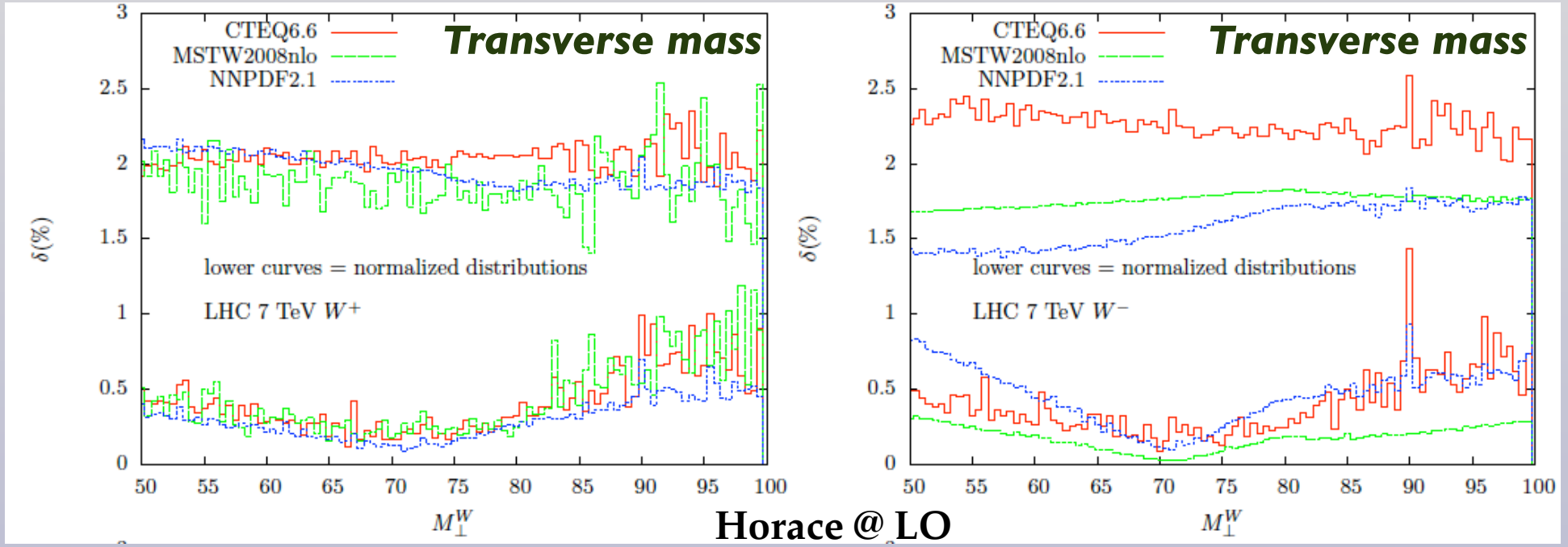
W determination at the LHC

- They key ingredient of the W mass determination is the construction of **templates** for various differential distributions, using the most accurate theory, for a large number of MW values
- Then we **fit experimental data and find the template** that leads to the same agreement
- The procedure is repeated for all **theoretical uncertainties**: PDF variations, scale uncertainties, model parameters....
- An alternative possibility is take the **Z distributions from data** and provide templates for the **W/Z ratios**

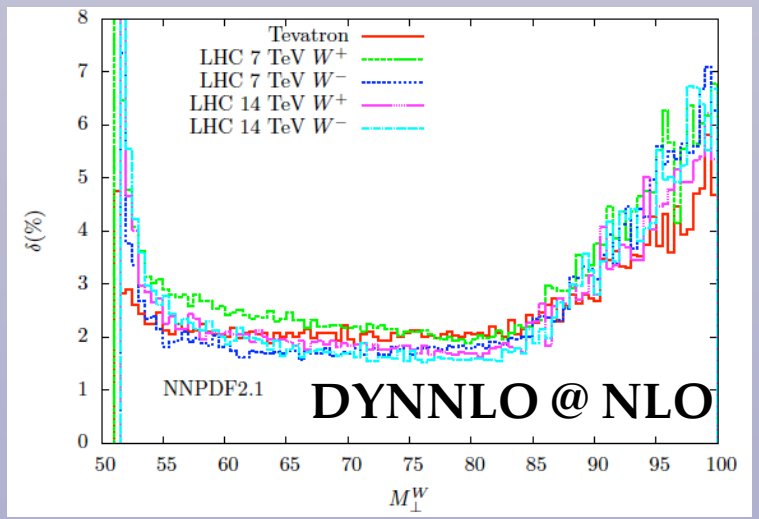


W determination at the LHC

The templates for the **differential W transverse mass distributions** should be normalized to reduce PDF uncertainties



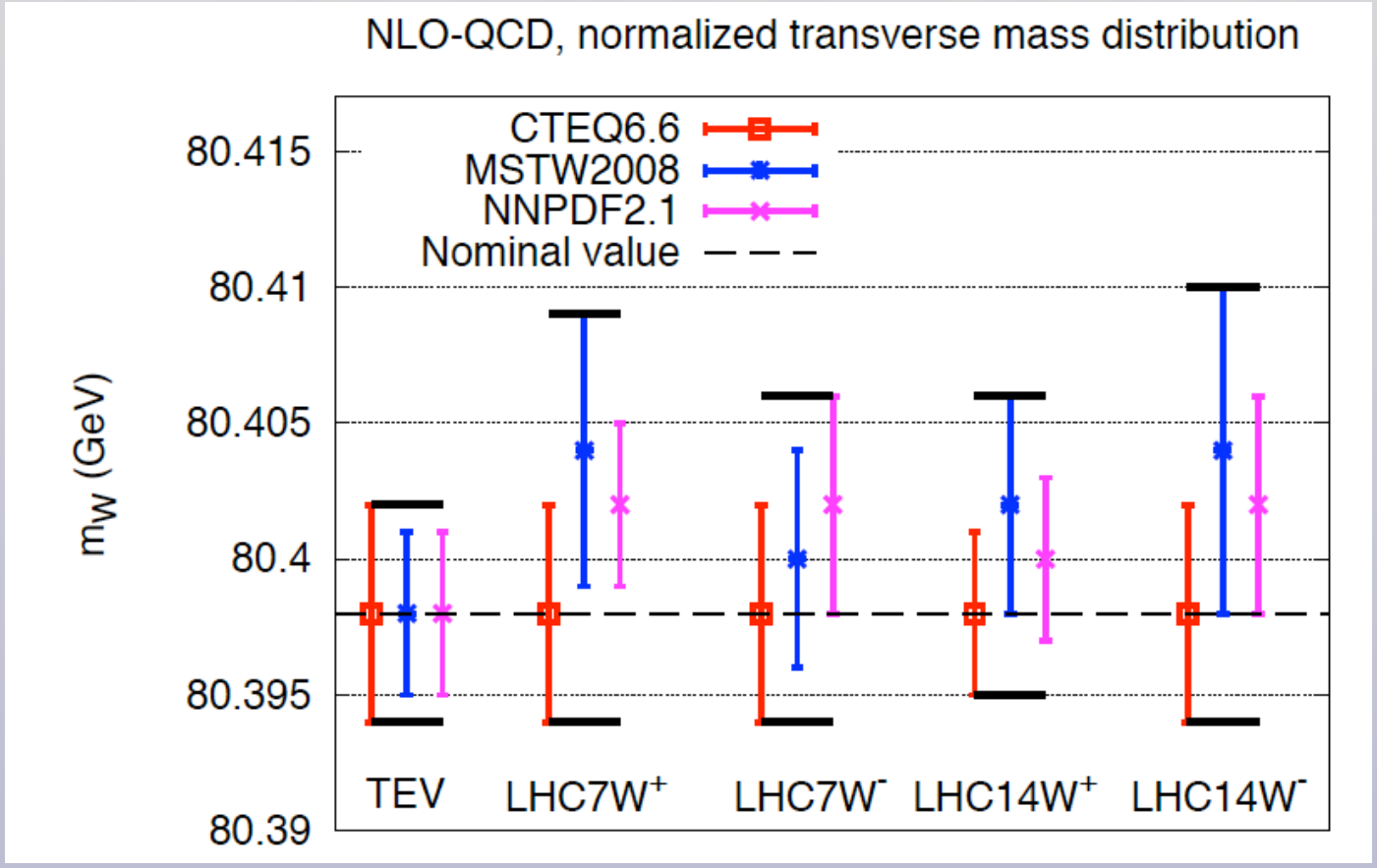
Horace @ LO



- The dependence on MW in the templates arises from the **shape of the distribution**, not on the **absolute normalization**
- Using normalized distributions in the template fits **reduces substantially PDF uncertainties**, wo removing MW sensitivity
- PDF uncertainties very **similar at Tevatron and at the LHC** at various collider energies

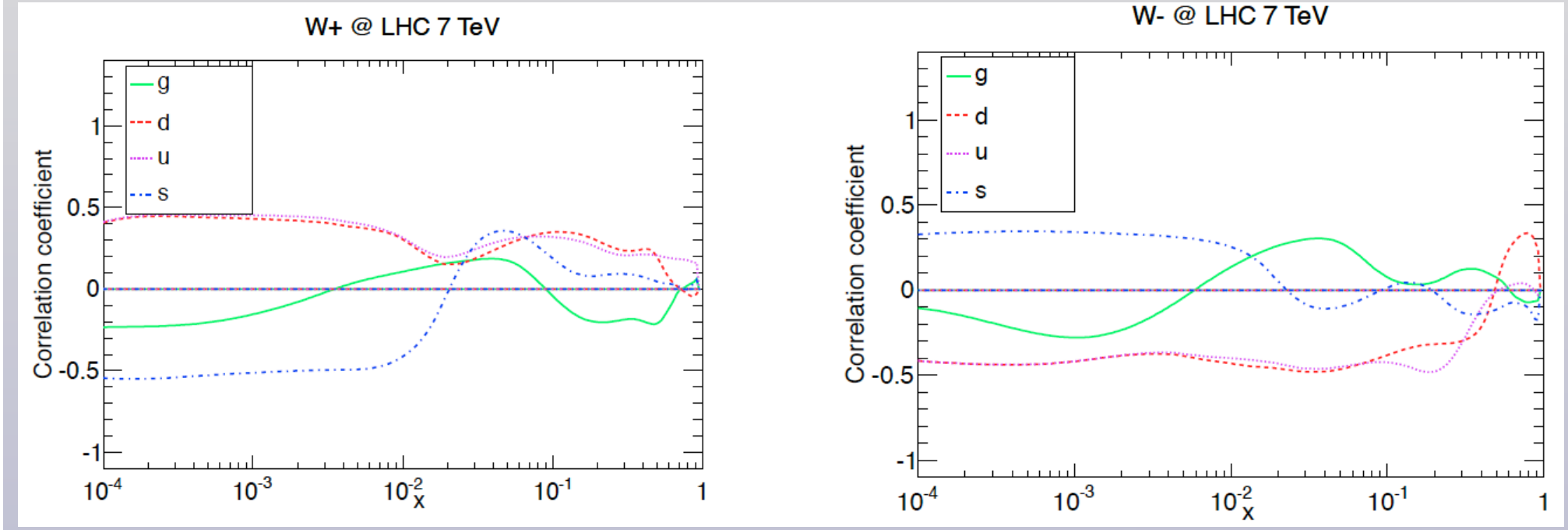
W determination at the LHC

NB: only PDFs pre-LHC considered in this study



- To provide a **conservative estimate of PDF errors**, we use the **PDF4LHC prescription**: combine in envelope **NNPDF, CT and MSTW**
- We found that a **20 MeV** uncertainty at the LHC was a reasonable estimate. No huge increase of PDF errors from Tevatron to LHC as claimed in the literature
- Our study based on **parton level templates**, but checked that **simple detector-like smearing** did not modify our results qualitatively.
- Variations in αs and in the **heavy quark masses** explicitly shown to be negligible

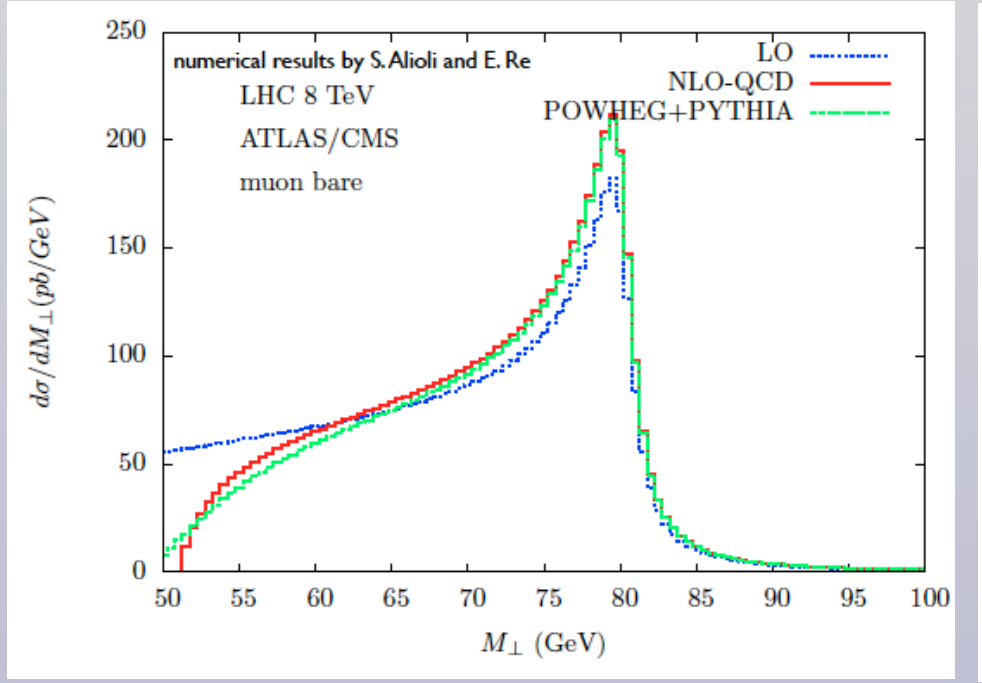
Correlation between PDFs and M_W



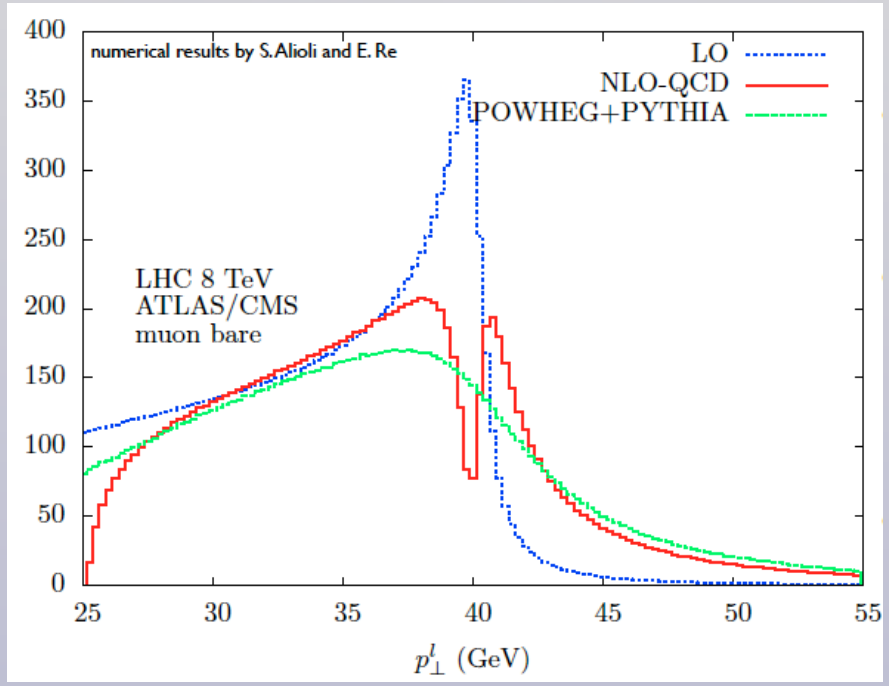
- **Smooth dependence of M_W** for all quark flavors and a broad range of Bjorken-x
- Sensitivity to the gluon PDF typically **smaller** than that of the quarks
- To **reduce PDF uncertainties on M_W** we need to better constrain **all quarks and antiquarks** in widest possible range of Bjorken-x

Transverse mass vs lepton p_T templates

Transverse mass



lepton p_t

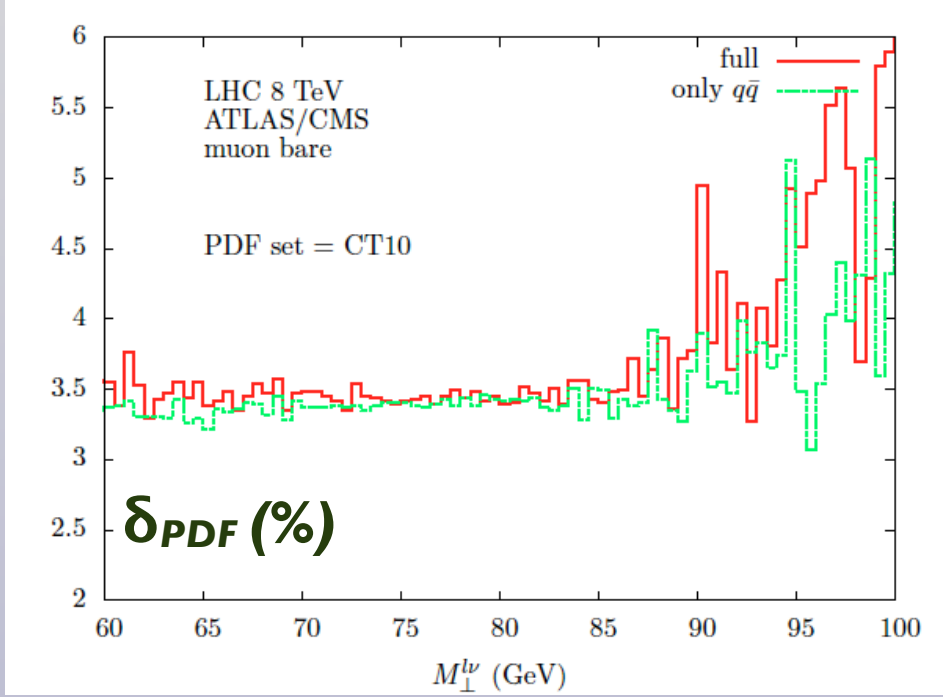


- **Transverse mass distribution** more stable wrt higher order QCD corrections
- **Lepton p_T distribution** depends strongly on QCD corrections (W p_T vanishes at Born), resummation of the W p_T spectrum required
- Accurate **modeling of QCD effects** crucial in M_W determinations from the lepton p_T distributions

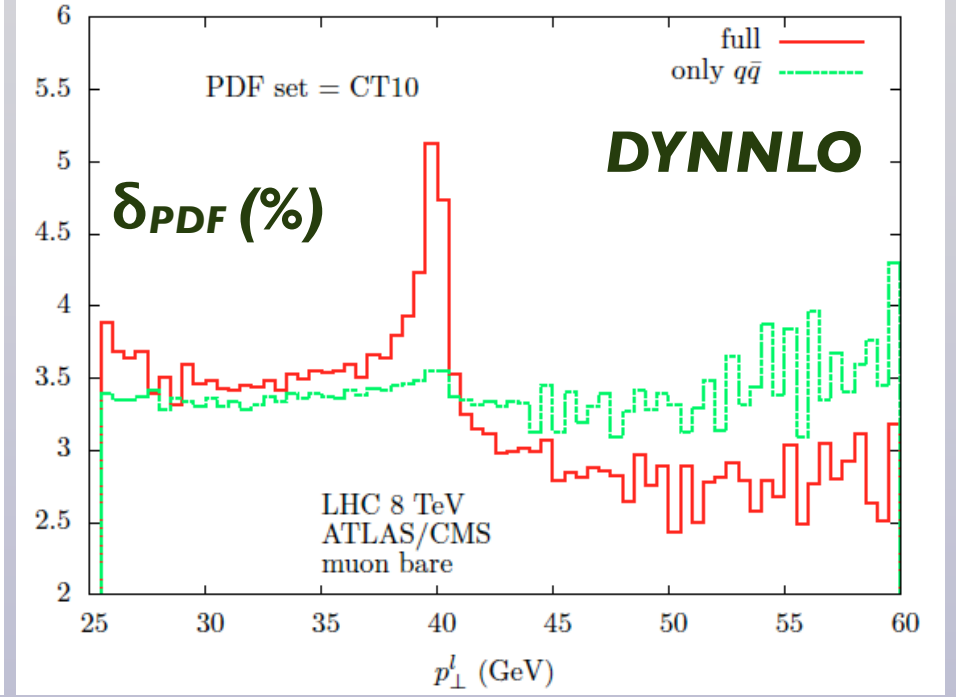
Results for M_W determination from the lepton p_T based on Bozzi, Ferrera, Vicini, in preparation

Transverse mass vs lepton p_T templates

Transverse mass



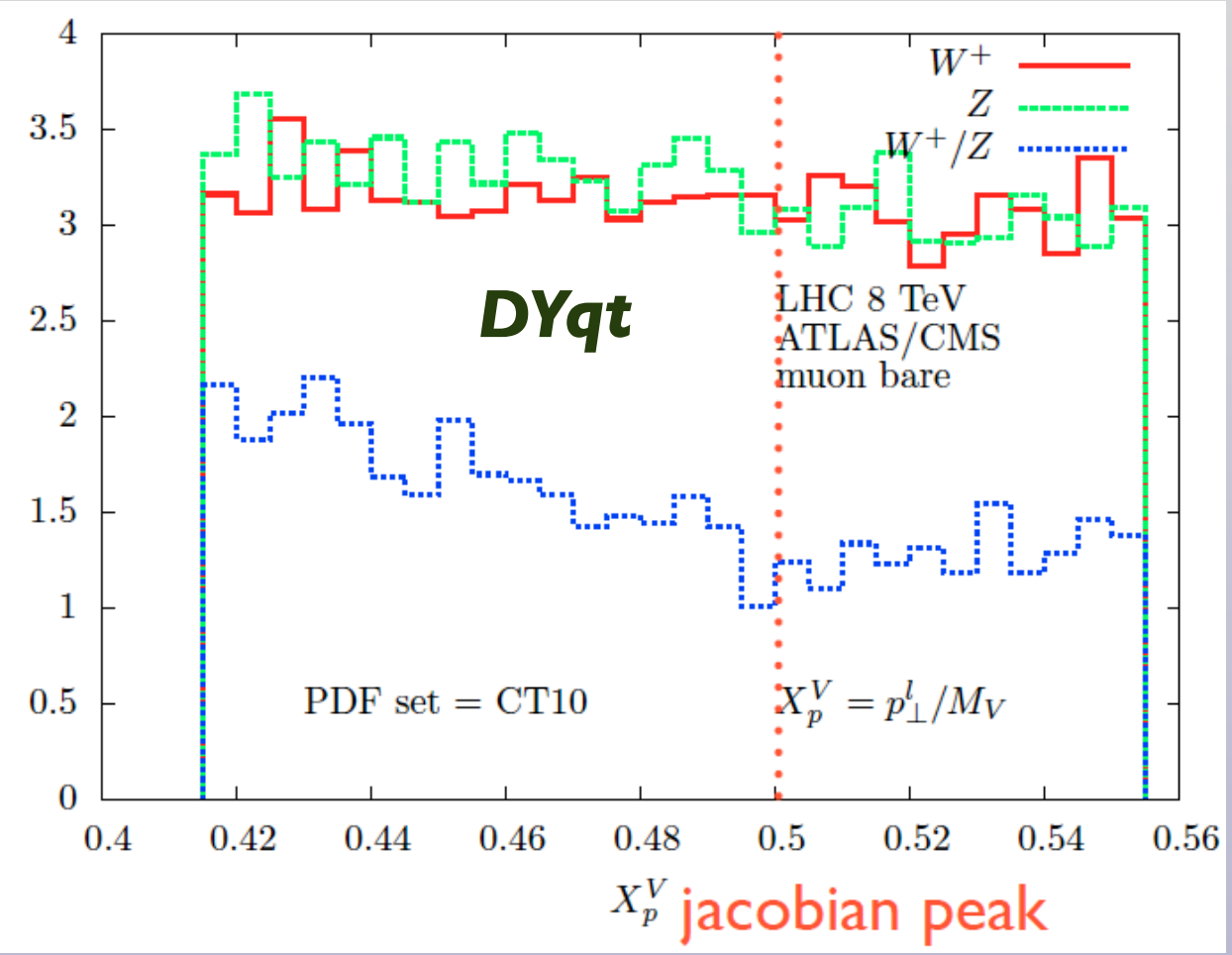
lepton p_t



- **Transverse mass distribution** dominated by **q-qbar scattering** (recall correlation plots)
- **Lepton p_T distribution** substantial contribution from **gluon PDF uncertainties** (due to the substantial NLO QCD corrections), in particular near Jacobian peak

W mass from lepton p_T templates

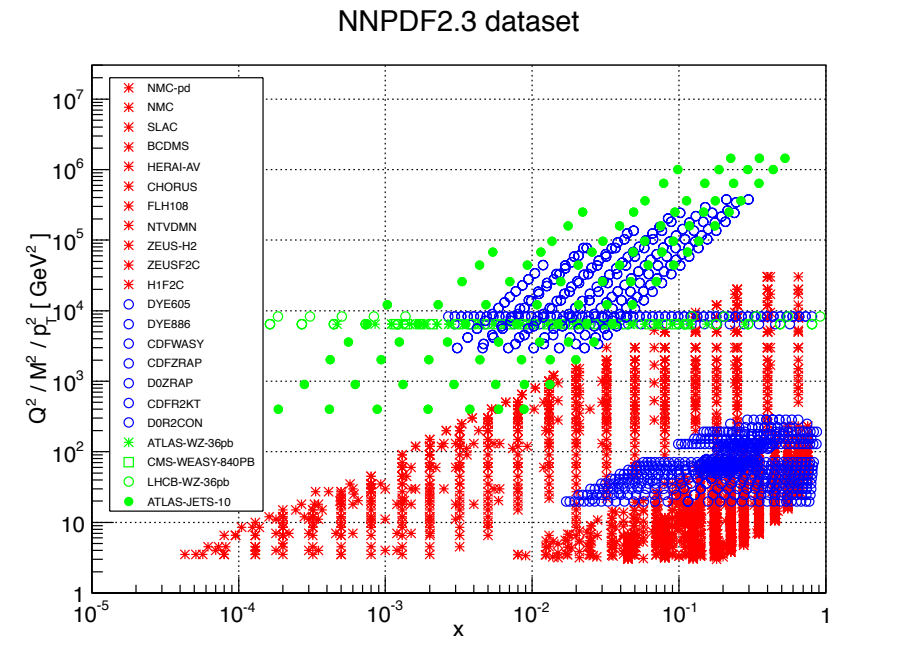
δ_{PDF} (%)



$$\frac{d\sigma}{dX_p^V}$$

- **Lepton p_T distribution** substantial contribution from **gluon PDF uncertainties** (due to the substantial NLO QCD corrections), in particular near Jacobian peak
- These effects can be reduced by taking ratios of observables that **cancel PDF uncertainties** without losing sensitivity to **M_W**

Improving PDFs with LHC data

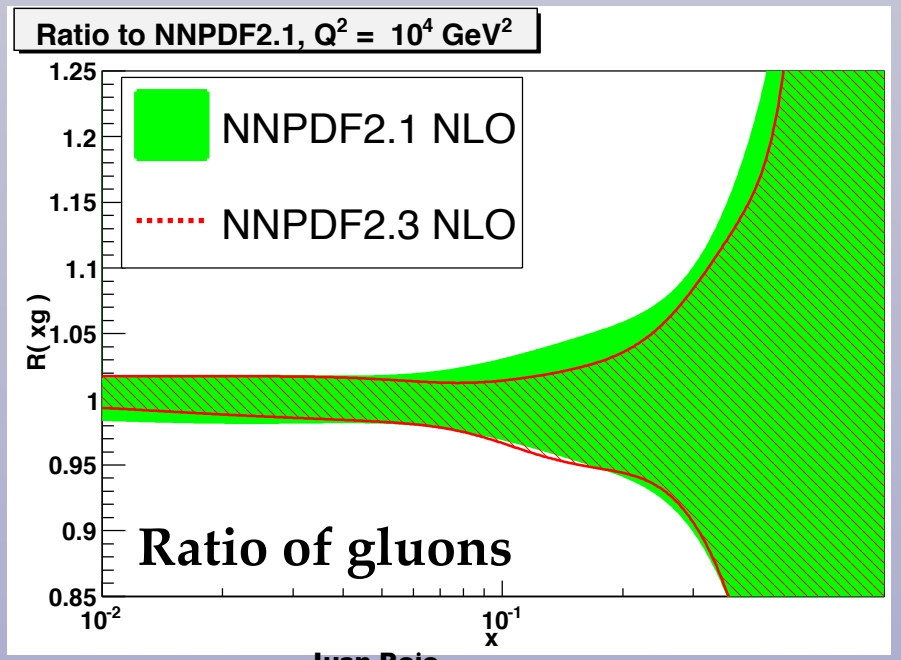


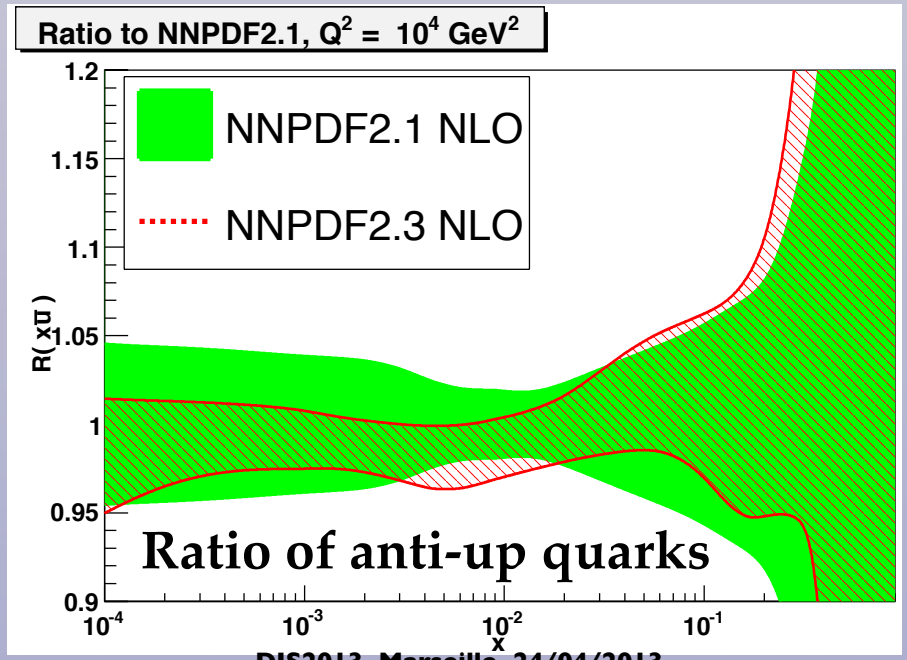
LHC data already part of the **NNPDF2.3 global PDF analysis**

The **inclusive jet data** constrains large-x gluon

The **W and Z production** data from **CMS, ATLAS and LHCb** constrain medium-x antiquarks

PDFs with LHC data are more reliable for determination of M_W because of **reduced uncertainties for W production kinematics**





PDF whishlist at the LHC

Traditional

- Inclusive jets and dijets, central and forward: **large-x quarks and gluons**
- Inclusive W and Z production and asymmetries: **quark flavor separation, strangeness**

New @ LHC

- Isolated photons, photons+jets: **medium-x gluons**
- W production with charm quarks: **direct handle on strangeness**
- W and Z production at high p_T: **medium and small-x gluon**
- Off resonance Drell-Yan and W production at high mass: **quarks at large-x**
- Low mass Drell-Yan production: **small-x gluon**
- Top quark cross-sections and differential distributions: **large-x gluon**

Speculative

- Z+charm: **intrinsic charm PDF**
- Single top production: **gluon and bottom PDFs**
- Charmonium production: **small-x gluon**
- Open heavy quark production: **gluon and intrinsic heavy flavor**

Relevant for M_W

Relevant for M_W

Relevant for M_W

Relevant for M_W

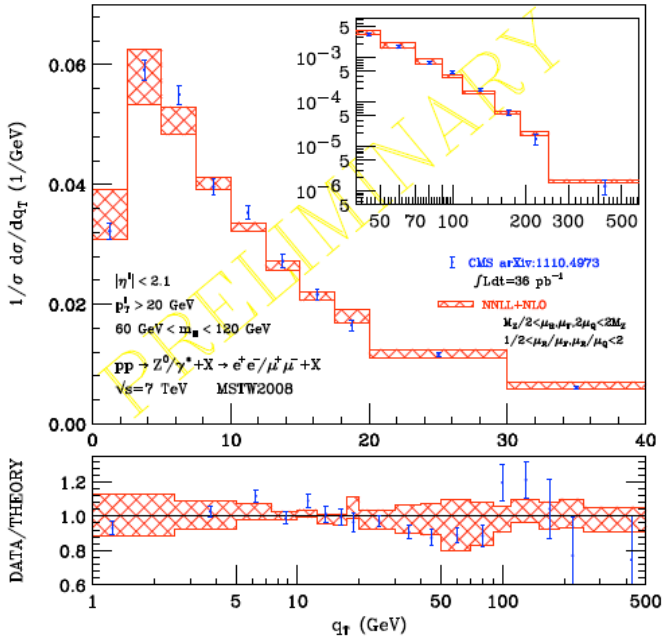
Relevant for M_W

Predicting the W/Z bosons p_T

- To model the **Higgs transverse momentum at the LHC**, one can **reweight the exclusive hadron NLO+PS distributions** from say POWHEG with the most **reliable perturbative calculations, NLO+NNLL**

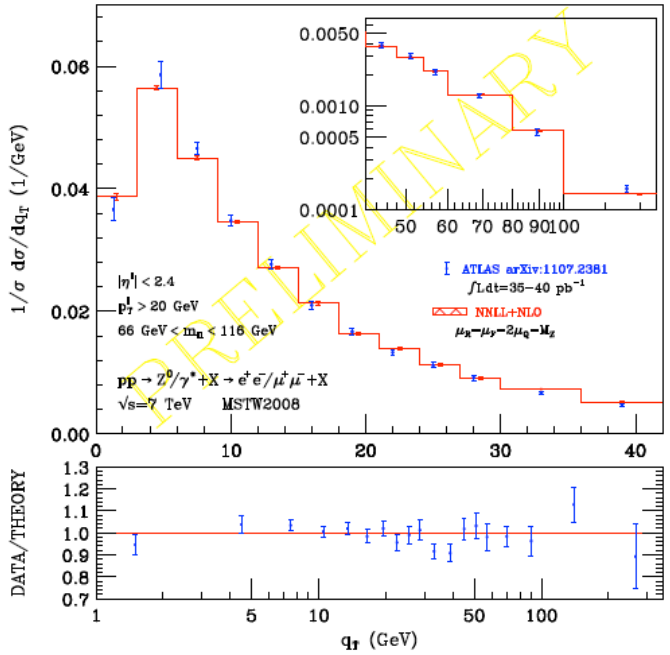
- The same approach is possible **for W/Z production**. The **DYqt code**, based on DYNNLO, allows to compute the **W and Z p_T** with NLO+NNLL precision

- An **excellent description of the LHC data** obtained even at very small p_T **without the need of non-perturbative modeling**



CMS data for the Z q_T spectrum compared with NNLL+NLO result. Scale variation:

$1/2 \leq \{\mu_F/m_Z, \mu_R/m_Z, \mu_F/\mu_R, 2Q/m_Z, Q/\mu_R\} \leq 2$



ATLAS data for the Z q_T spectrum compared with NNLL+NLO result.

G. Ferrera, Moriond 2012

NNPDFs with QED corrections

- **Photon-initiated diagrams** are required for consistent electroweak precision calculations, including **W production**
- The **DGLAP QCD evolution equations** can be modified to account for **QED corrections,** introducing a **photon PDF**
- Then the global PDF analysis is repeated, and we study
  - The **modifications on the proton and neutron PDFs due to QED corrections**
  - The size of the **photon PDF** allowed by experimental data
  - Violation of **isospin symmetry** (connection with nuclear models)

$$Q^2\frac{\partial}{\partial Q^2}\gamma(x,Q^2)=\frac{\alpha(Q^2)}{2\pi}\int_x^1\frac{d\xi}{\xi}\left\{P_{\gamma\gamma}(\xi)e_\Sigma^2\gamma\left(\frac{x}{\xi},Q^2\right)+P_{\gamma q}(\xi)\sum_j e_j^2 q_j\left(\frac{x}{\xi},Q^2\right)\right\}$$

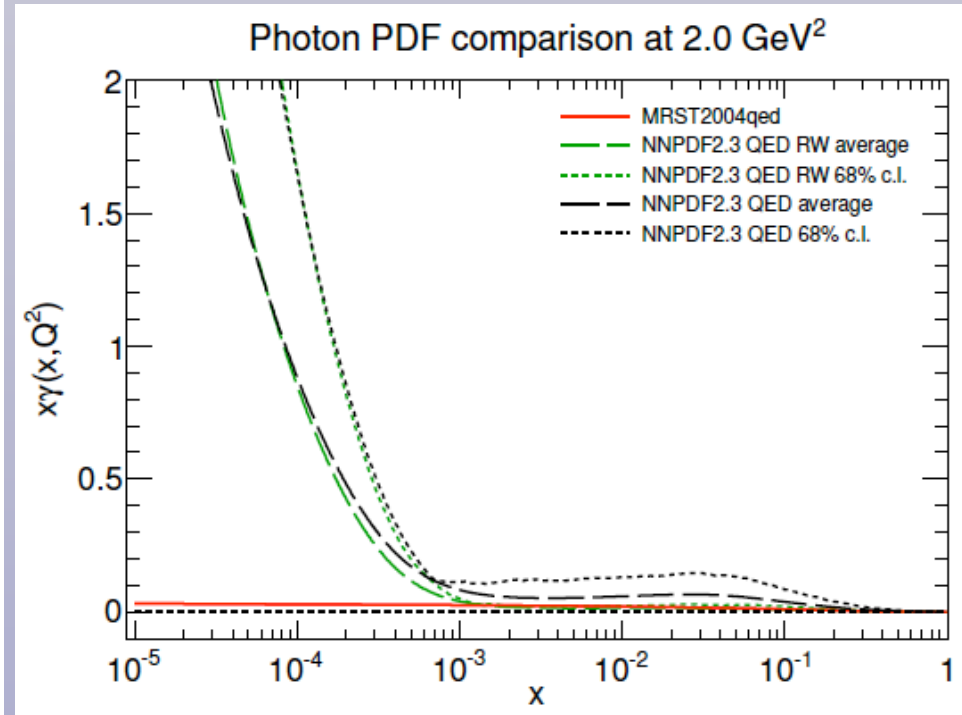
$$Q^2\frac{\partial}{\partial Q^2}q_i(x,Q^2)=\frac{\alpha(Q^2)}{2\pi}\int_x^1\frac{d\xi}{\xi}\left\{P_{q\gamma}(\xi)e_i^2\gamma\left(\frac{x}{\xi},Q^2\right)+P_{qq}(\xi)e_i^2 q_i\left(\frac{x}{\xi},Q^2\right)\right\}$$

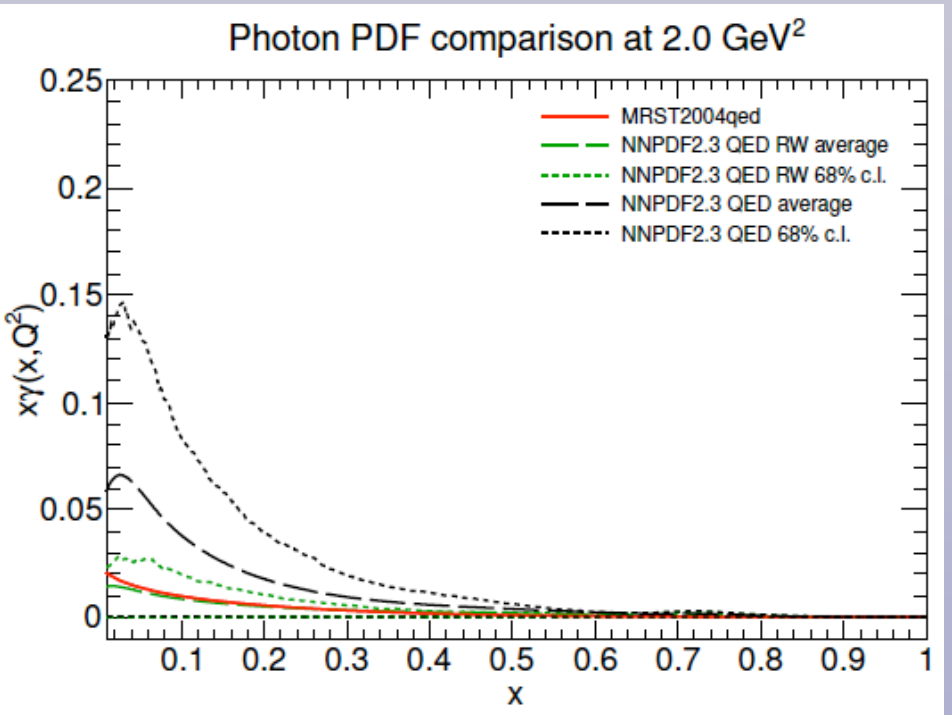
- As opposed to MRST2004QED, where a model was used for the photon PDF, in NNPDF we parametrize the photon with **a neural network with 37 parameters**, to be **extracted from data**

NNPDFs with QED corrections

- The **NNPDF2.3 QED** is essentially ready, will be made public in upcoming LHAPDF release
  - **Impact on QED** on **quarks and gluons small**, well below PDF uncertainties
  - Experimental DIS data leave room for a substantial **photon PDF:** large uncertainties. We have constrained the photon PDF with precise **LHC W and Z data**, both near Jacobian peak and at large invariant masses

    See Stefano Carrazza's talk for more details
- Work in progress: study the impact of the **NNPDF2.3 QED photon** on **W mass determinations**



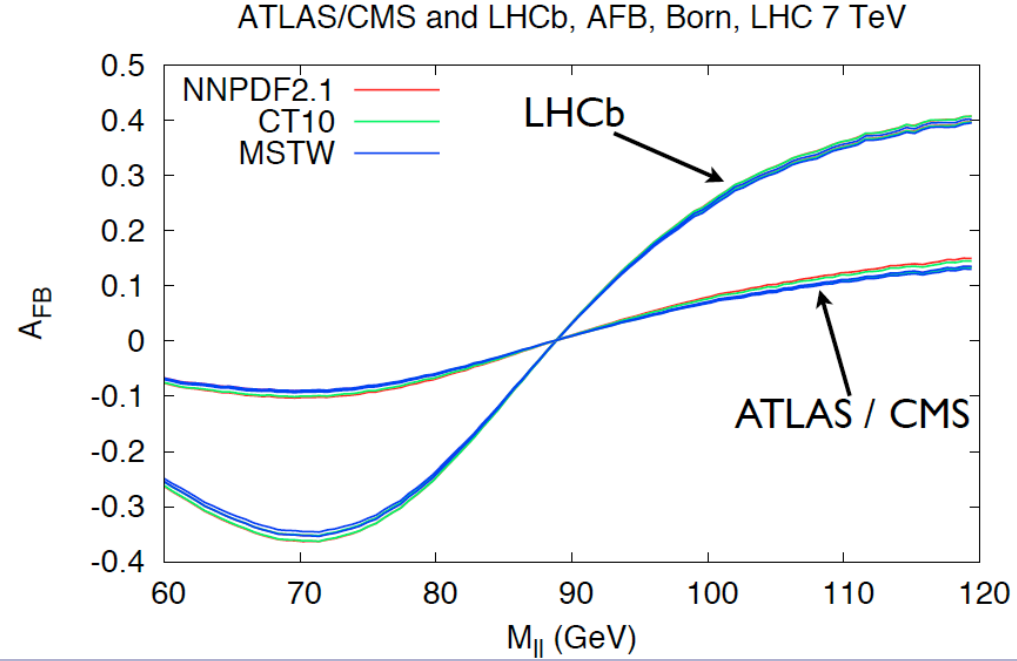


PDF uncertainties in A_{FB}

- The **Forward-Backward Asymmetry in Z production** at the LHC can be used to extract the **effective lepton mixing angle $\sin^2\theta^{eff}_l$**
- The **role of PDF uncertainties** in the determination of **$\sin^2\theta^{eff}_l$** can be studied with the same template techniques as in the W mass determination
- The **LHCb kinematics** are specially sensitive to **A_{FB}**

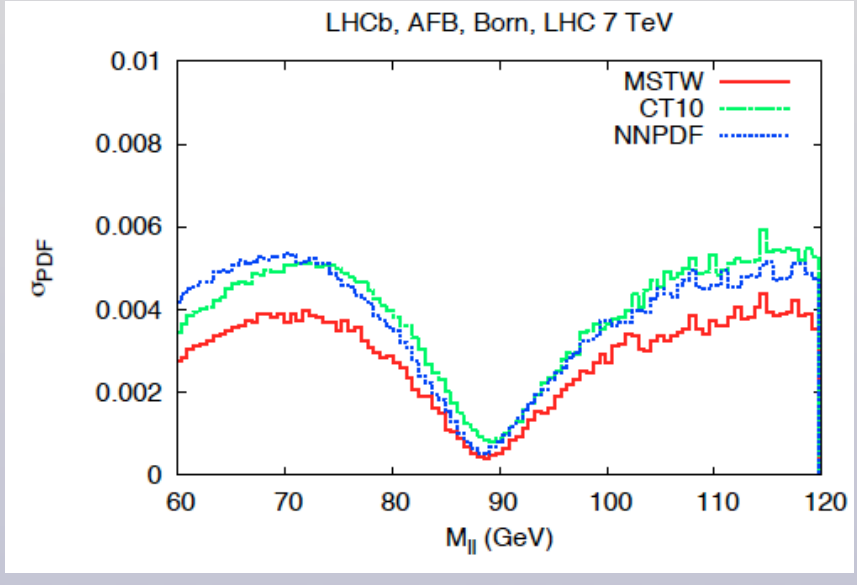
$$A_{FB}(M_{l^+l^-}) = \frac{F(M_{l^+l^-}) - B(M_{l^+l^-})}{F(M_{l^+l^-}) + B(M_{l^+l^-})}$$

$$B(M_{l^+l^-}) = \int_{-1}^{0} \frac{d\sigma}{d\cos\theta^*} d\cos\theta^* \qquad F(M_{l^+l^-}) = \int_{0}^{1} \frac{d\sigma}{d\cos\theta^*} d\cos\theta^*$$

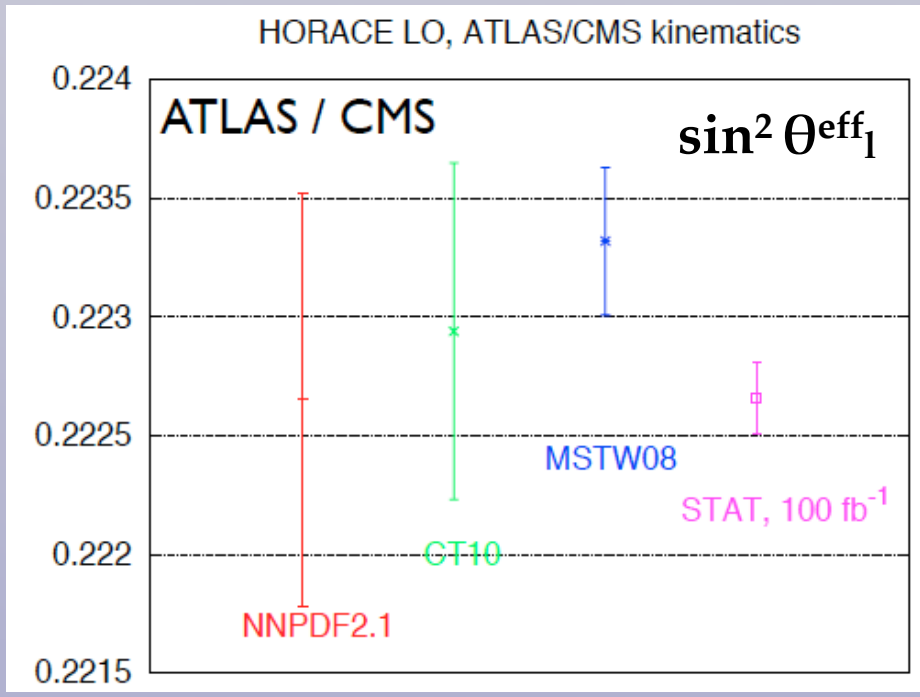


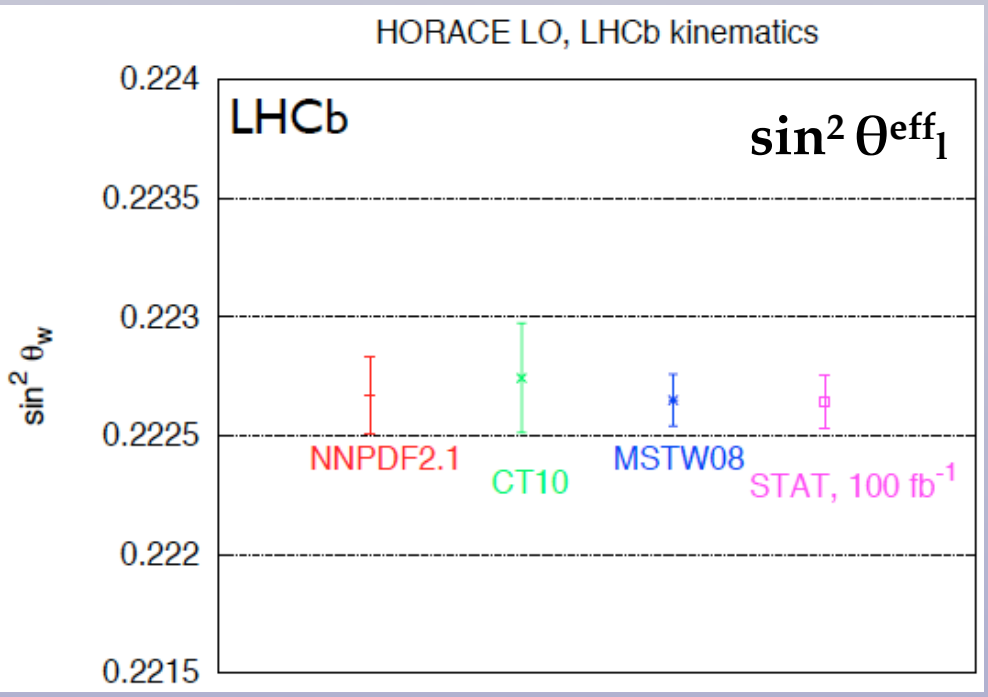
A_{FB} results based on Rojo, Rottoli, Vicini, in preparation

PDF uncertainties in A_{FB}



- PDF uncertainties minimal near Z peak, but A_{FB} close to zero in this region
- A template fit determination suggest that pre-LHC PDFs can lead to a reliable determination of $\mathbf{sin^2\,\theta^{eff}_l}$ at LHCb, but need PDFs with LHC data for ATLAS/CMS kinematics





Summary

- **The W mass** is a very important measurement at hadron colliders: provide **stringent test of SM consistency** and **sets bounds on many BSM scenarios**
- **Theoretical uncertainties** now dominant for W mass measurements at the Tevatron, will be crucial to carefully assess them at the LHC, but **no huge difference expected**
- **Initial study based on transverse mass templates:** PDF uncertainties reduce substantially if **normalized templates** are used in the W mass fit, **without affecting the sensitivity to M_W**
- PDF errors to M_W@ LHC not larger than **20 MeV** level, to be improved soon with LHC data
- Ongoing studies based on **lepton p_T templates**, crucial to control **higher order QCD corrections** and reduce **gluon PDF uncertainties**
- Both the **W mass measurement**, as many **other important LHC analysis**, such as the Forward-Backward asymmetry, will benefit from **improved PDFs** thanks to LHC data
- **NNPDF2.3 with QED corrections** will soon allow to consistently include **QED effects in NC and CC Drell-Yan** with an up-to-date PDF set, and provide an important ingredient for robust M_W determinations at hadron colliders

EXTRA MATERIAL