PDF systematics in M_W and $\sin\theta_W$ precision measurements

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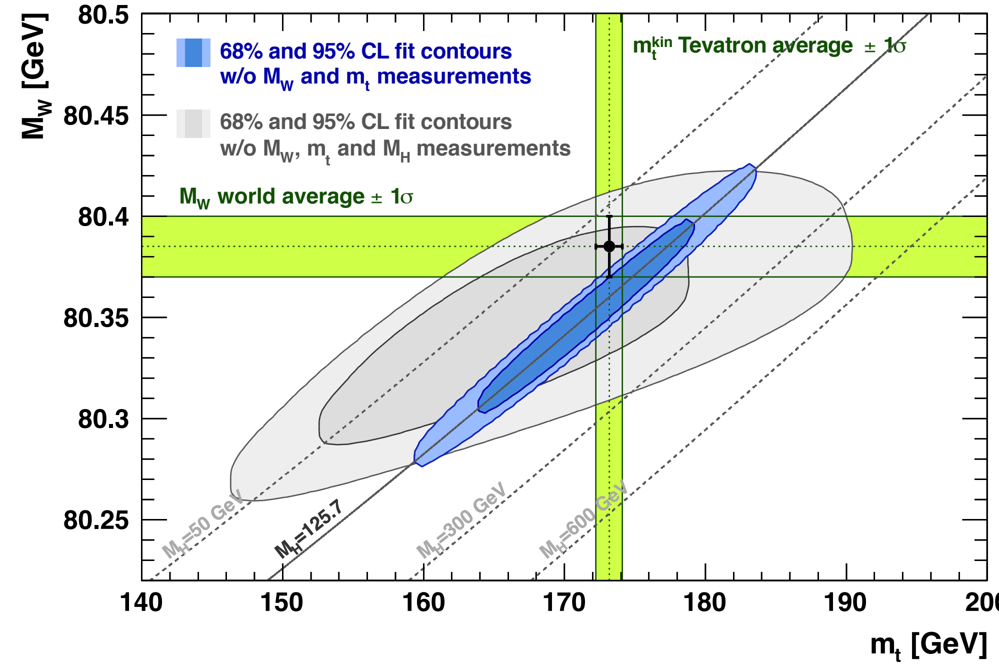
Motivations

- SM precision tests possibly leading to tensions that might point to BSM physics

→precision measurement of M_W and of $\sin\theta_W$



- measurement of differential cross sections and asymmetries in CC, NC Drell-Yan processes

→crucial role of proton PDFs
need to study all the available observables and investigate all possible correlations among them to cancel common systematic effects

CC-DY: lepton-pair transverse mass
lepton transverse momentum M_W, Γ_W

jacobian peak: control of the lineshape at the per mille level

NC-DY: invariant mass A_FB asymmetry $\sin^2\theta_W$

possible thanks to the PDF unbalance in forward (backward) region between qqbar and qbarq initiated processes

Impact of theoretical uncertainties on EW precision measurements

- extraction of masses and couplings is based on a template fit procedure:
  - best theoretical prediction for a distribution computed with different $M_W(\sin\theta_W)$ (template)
  - each template is compared to the data
  - measured $M_W(\sin\theta_W)$= $M_W(\sin\theta_W)$ of the template that maximizes the agreement with the data

- theoretical systematics = uncertainties/ambiguities that affect the evaluation of the templates (PDFs, scales, non-perturbative, different prescriptions, ...)

Focusing on PDFs

- different PDF replicas (or different PDF sets) yields in general a distortion of the template shapes to be compared with data → direct impact on the measured value of the observable

- Questions:

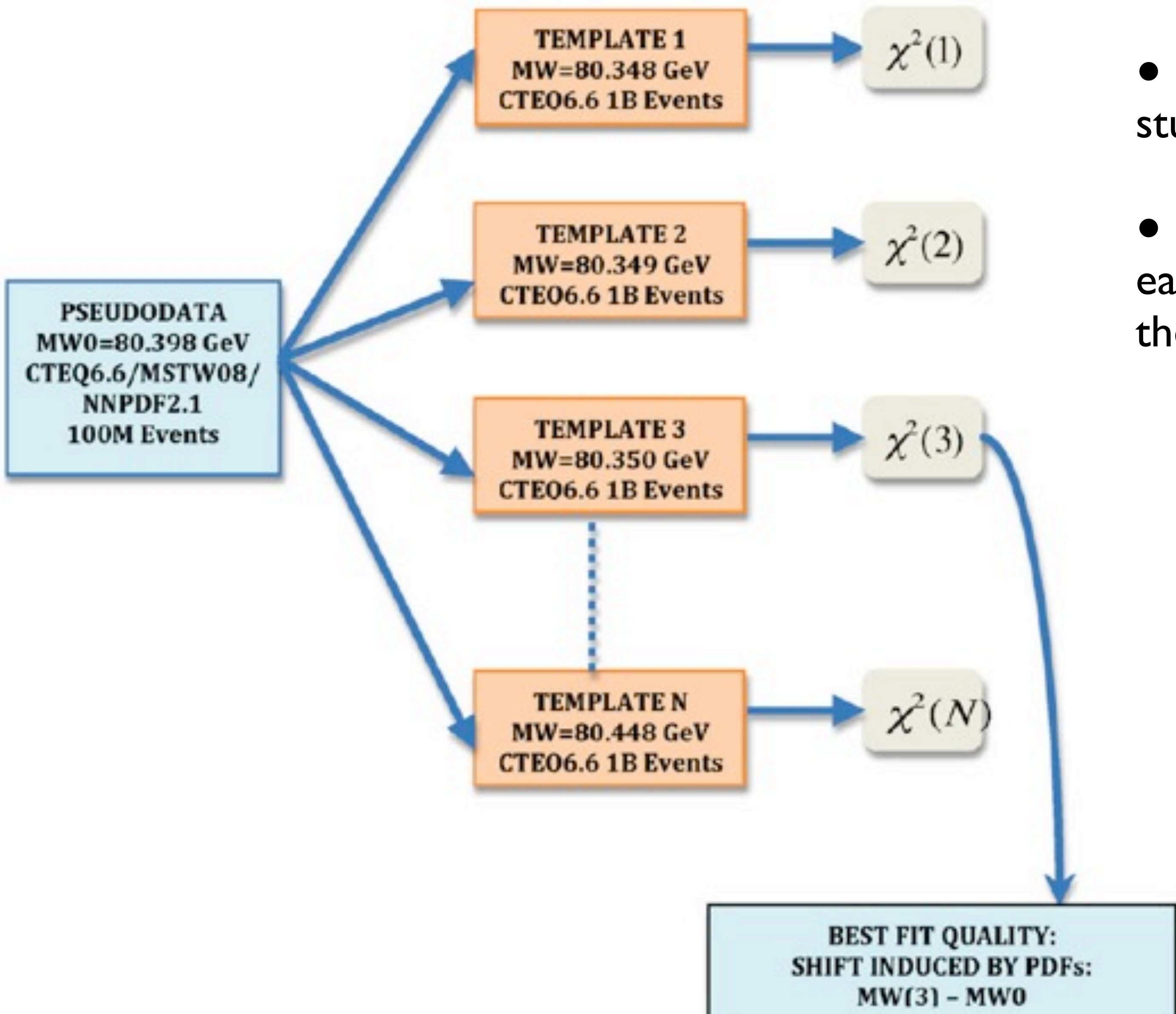
  - are PDFs a limiting factor (i.e., forbid a precision measurement)?

  - can we better constrain PDFs with LHC data and reduce their impact on precision measurements?
    → reweighting technique for a quick estimate of the role of new available data

  - can we exploit correlations (w.r.t. PDFs) between all the available EW observables?
    → e.g., can we build ratios of observables with reduced PDF uncertainty still sensitive to the EW parameters?

Estimate of the error on MW induced by the PDFs (Bozzi, Rojo, Vicini 1104.2056)

- each PDF replica is used to generate a set of pseudodata (100M events) with a fixed value M_{W0}
- a very accurate (1B events) set of template distributions has been prepared with a reference (CTEQ6.6) PDF replica
- when pseudodata generated with the reference replica are fitted, the nominal value M_{W0} is found (sanity check)
- same code (DYNNLO) used to generate both pseudodata and templates → only effect probed is the PDF one



- M_W shift = distance between the PDF replica under study and the reference replica

- PDF error = combination of different M_W results from each replica, according to the formulae recommended by the PDF collaborations

Hessian: CTEQ, MSTW

$$\sigma_X^2 = \frac{1}{4}\sum_{k=1}^{N}[X(S_k^+) - X(S_k^-)]^2$$

Montecarlo: NNPDF

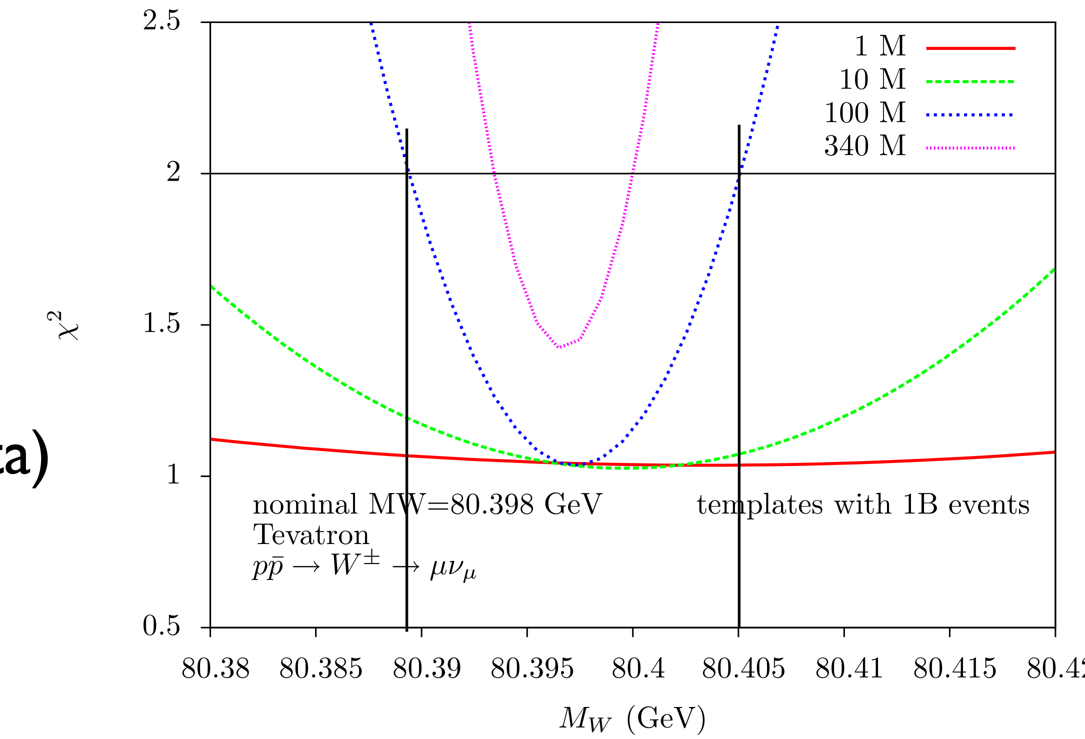
$$\sigma_X^2 = \frac{1}{N_{\rm rep}-1}\sum_{i}^{N_{\rm rep}}[X^i - X]^2$$

Comments on the template-fitting procedure

- Fit pseudo-data computed in the same approximation and with the same parameters of the templates: the fit should exactly find the nominal value M_{W0} used to generate the pseudo-data (reduced χ^2~1)

- The accuracy of the fit depends on the error associated to each bin of the pseudo-data

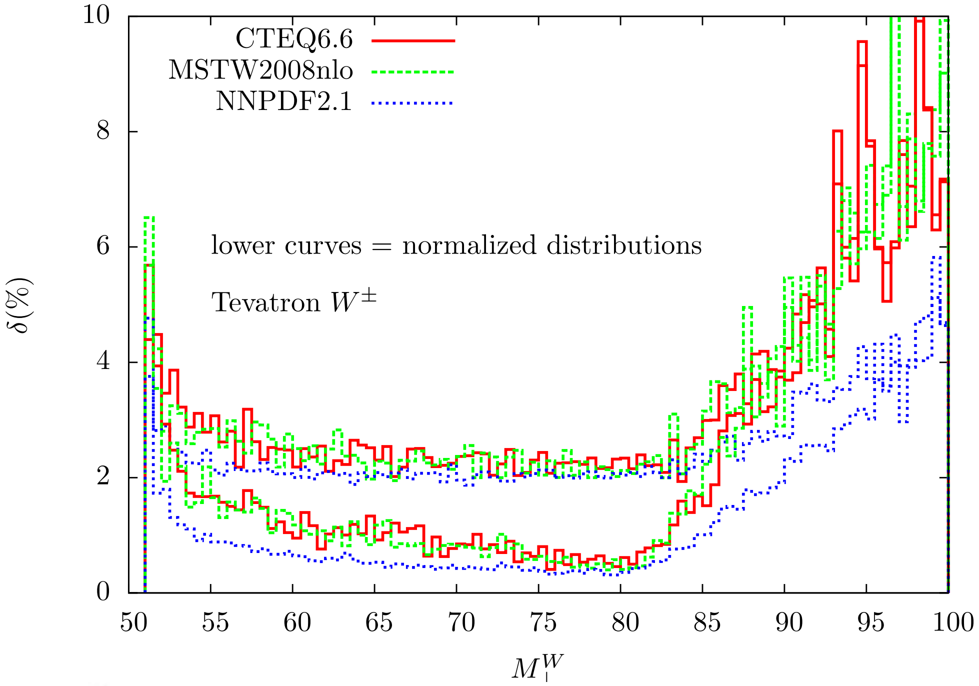
- In the validation test, the $\Delta\chi^2$ =1 MW points fix the 68% C.L. interval associated to the estimate of the preferred MW (→ choice of 100M for pseudodata)



- When the pseudodata have a shape different than the one of the templates, the reduced χ^2 is never close to one because the distributions are "by construction" different

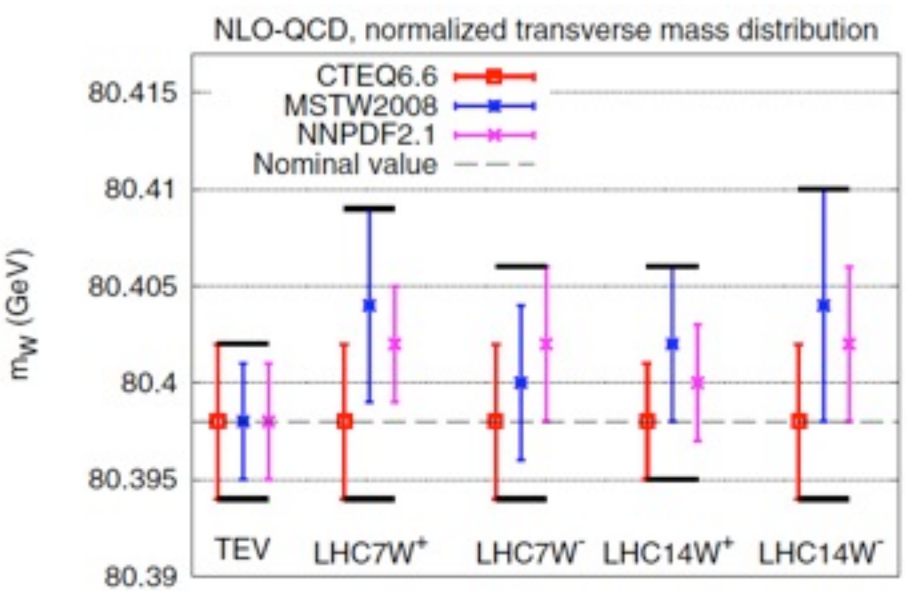
- When the shapes compared are sensibly different, the fitter is pulled towards values very different than the nominal one: the fitter tries to compensate the shape difference, with a large adjustment of MW

PDF effect on M_W from transverse mass distribution



- transverse mass normalized distributions: reduced sensitivity to PDFs
- plot shows ratio of (non-)normalized distributions w.r.t. to central PDF set
- templates and pseudodata computed with same generator and exp. setup: <u>in first approximation the PDF effects factorize w.r.t. all other theoretical and experimental factors</u>

	CTEQ6.6		MSTW2008		NNPDF2.1		
	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$\delta^{\rm tot}_{\rm pdf}$
Tevatron, $W^\pm$	80.398 ± 0.004	1.42	80.398 ± 0.003	1.42	80.398 ± 0.003	1.30	4
LHC 7 TeV W^+	80.398 ± 0.004	1.22	80.404 ± 0.005	1.55	80.402 ± 0.003	1.35	8
LHC 7 TeV W^-	80.398 ± 0.004	1.22	80.400 ± 0.004	1.19	80.402 ± 0.004	1.78	6
LHC 14 TeV W^+	80.398 ± 0.003	1.34	80.402 ± 0.004	1.48	80.400 ± 0.003	1.41	6
LHC 14 TeV W^-	80.398 ± 0.004	1.44	80.404 ± 0.006	1.38	80.402 ± 0.004	1.57	8



- accuracy of the templates is essential: highly demanding computing task!
- for the transverse mass distribution, a fixed order NLO-QCD analysis is sufficient to assess this PDF uncertainty
- if confirmed, the PDF error is moderate at the Tevatron, but also at the LHC, <u>even before the use of the LHC data</u>

Inclusion of LHC data via reweighting (NNPDF)

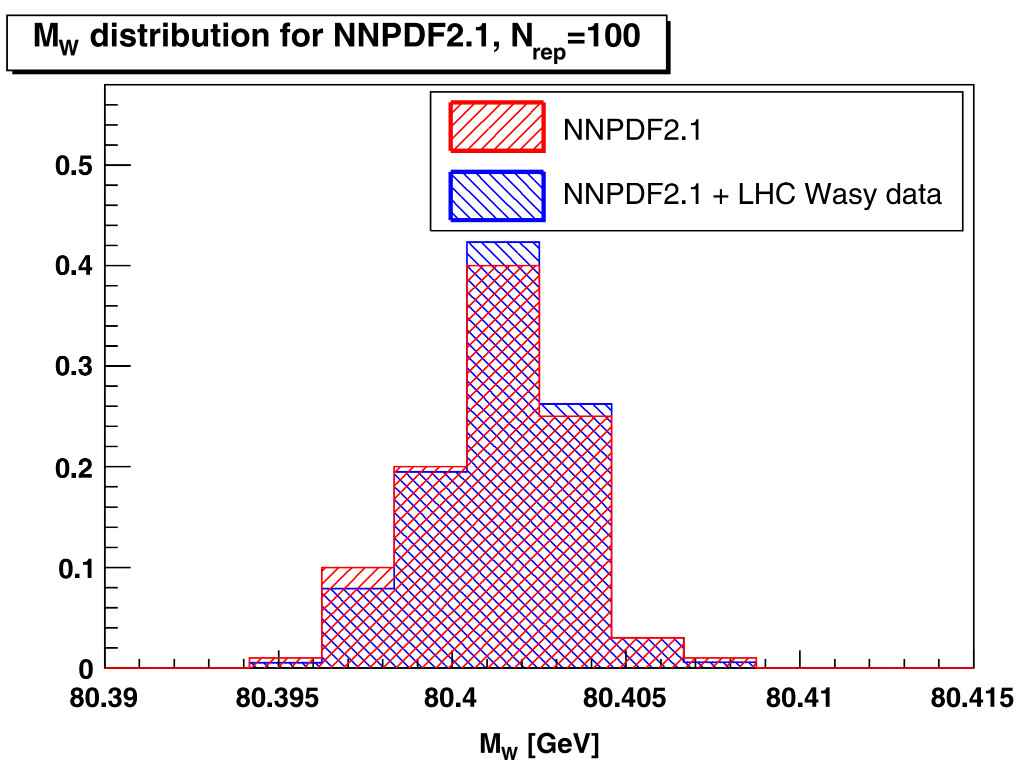
- existing PDF replicas can be favored/disfavored by comparison with new LHC data

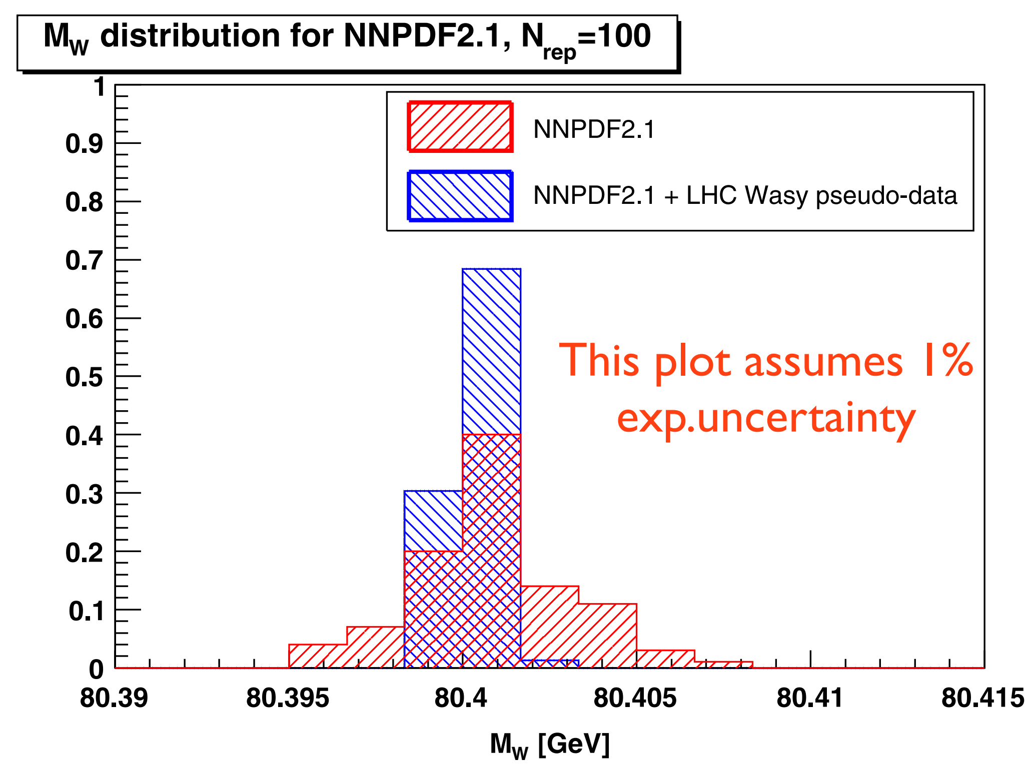
→ associate a weight to each replica based on how well it describes new data

$$w_k \propto \chi_k^{n-1} e^{-\frac{1}{2}\chi_k^2}$$

where the χ^2 is computed from the new data set containing *n* points

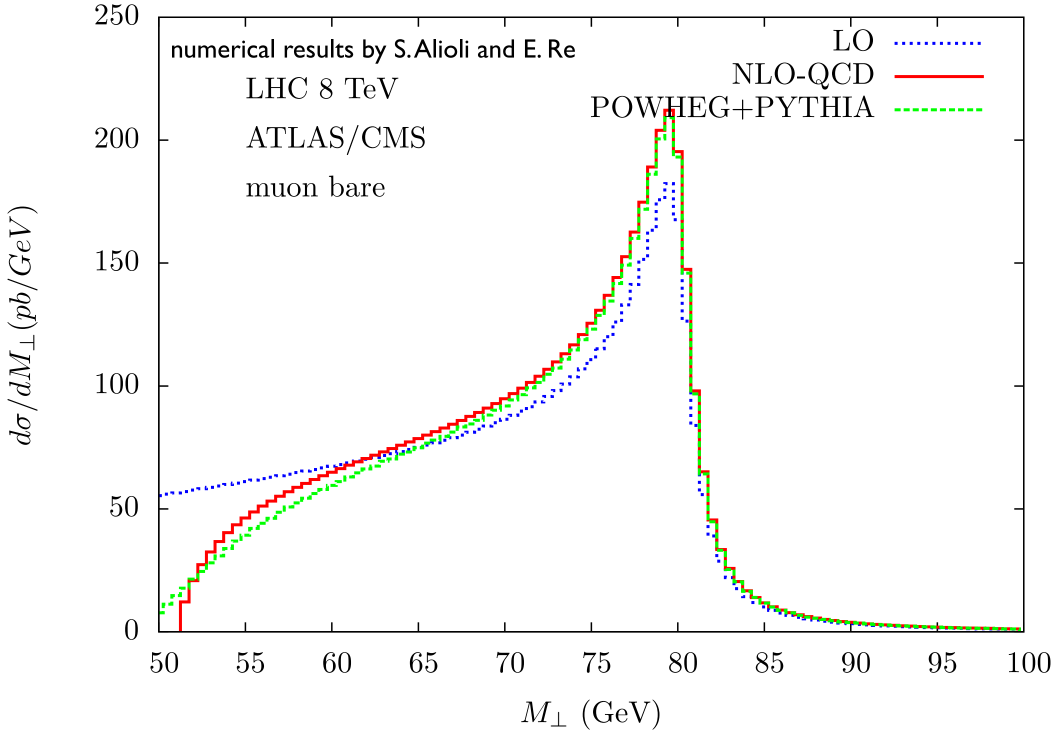
- this weight is then used in the evaluation of the PDF spread on any other observable (like M_W)

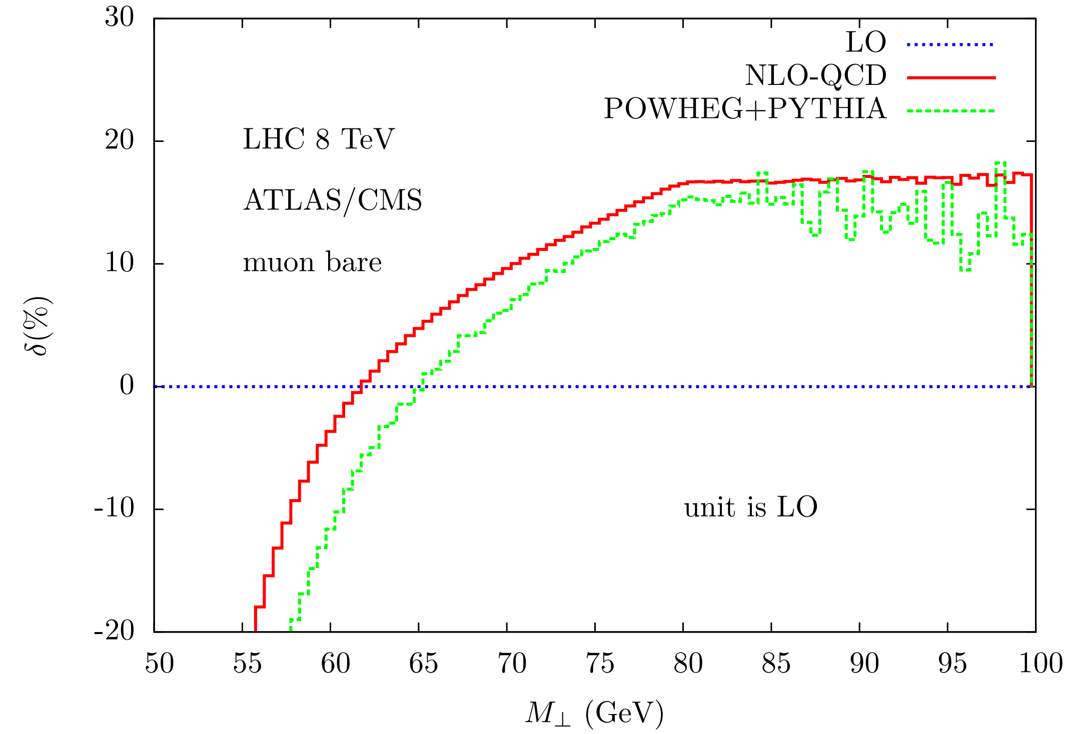




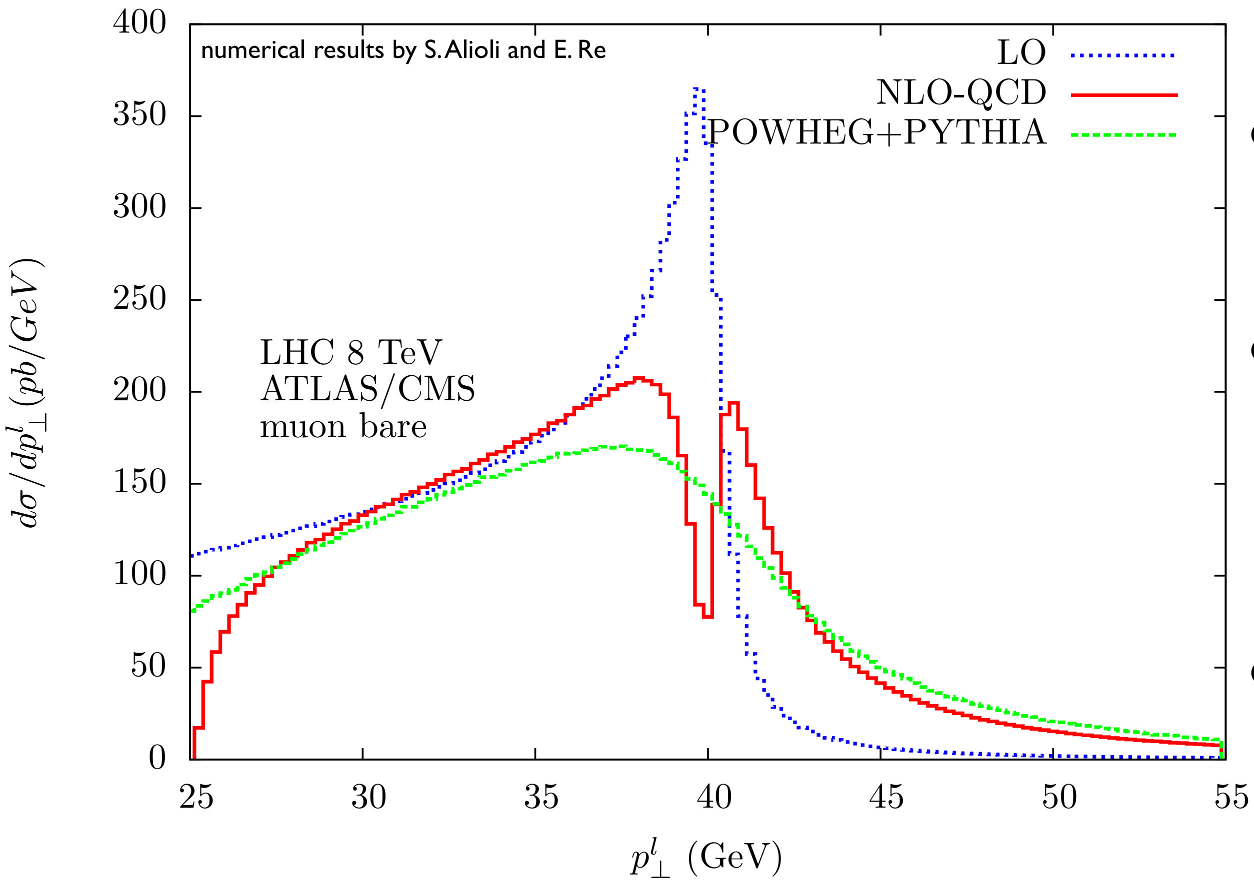
more details about the evaluation of weights with multiple data sets in arXiv:1108.1758 (NNPDF)

Transverse mass vs. lepton p_T (1)





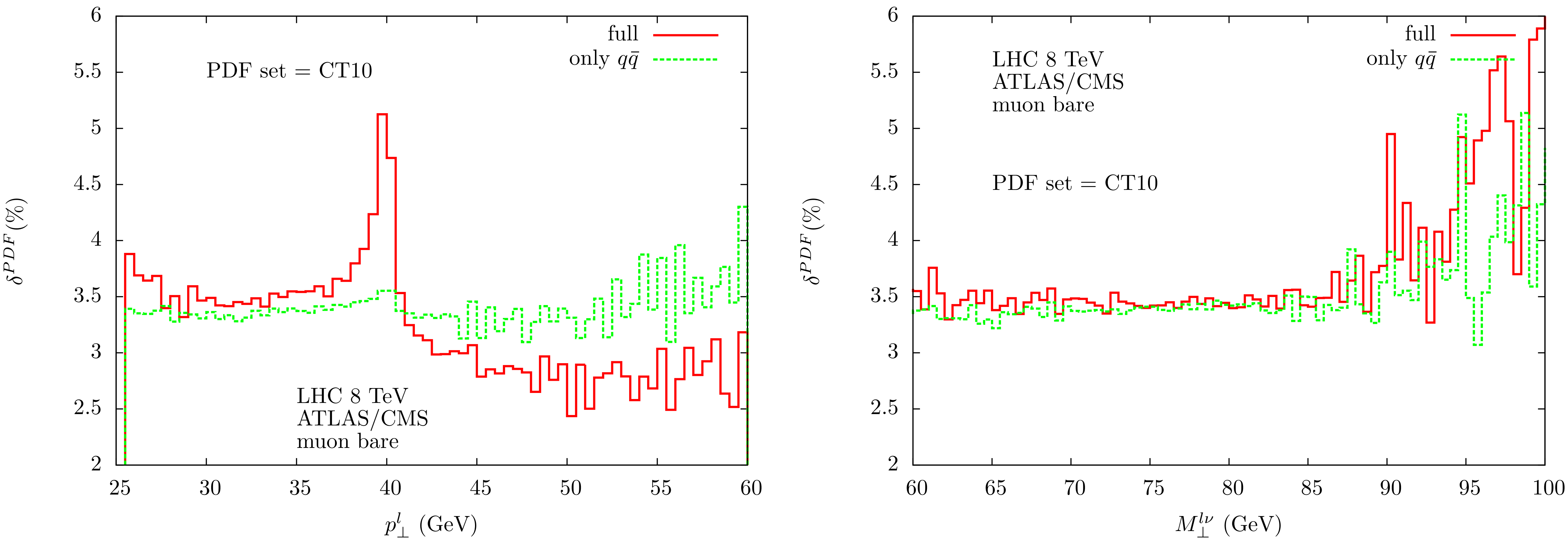
- similar shapes, K-factor quite flat (in relevant region), PS/NLO between -5% and 0 (in relevant region)



- LO: only the W decay generates the lepton pt, with Gamma_W smearing effect in the right tail
- NLO-QCD: lepton pt receives contributions from W recoil against QCD radiation (singular at $p_{TW} \to 0$)
  → resummation needed!
- matching with shower smears the distribution

Transverse mass vs. lepton p_T (2)

- at NLO-QCD gluon-quark subprocesses yield an important contribution
  → the gluon PDF uncertainty is more pronounced than in the transverse mass case



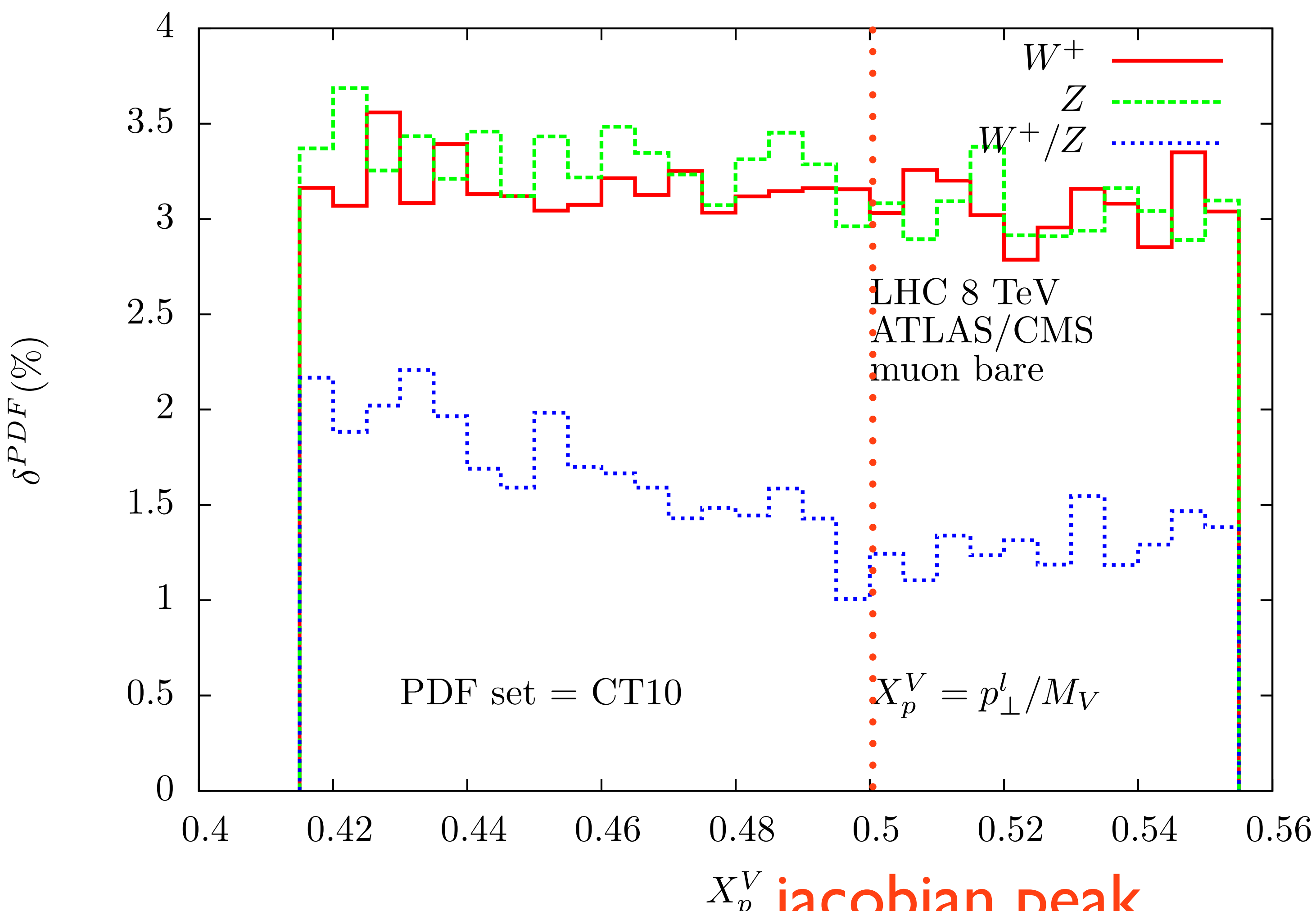
(Bozzi, Ferrera, Vicini: (very) preliminary!)

caveat: 1) the above uncertainties have been computed with DYNNLO at NLO-QCD
2) only the full process has a well defined physical meaning

PDF effect on M_W from lepton p_T

a (very!) preliminary study with DYqT shows that it is possible to partially reduce the PDF uncertainty (e.g. of the quark-gluon luminosity) by studying appropriate ratios of observables which should preserve the sensitivity to MW (in progress)

(Bozzi, Ferrera, Vicini: (very) preliminary!)



jacobian peak

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

DYqT @ NLL+LO QCD accuracy

- W^+ (lepton p_T) distribution sensitive to M_W

- Z (lepton p_T) distribution weakly sensitive to M_W, but probes similar *x*-ranges

Reduction of the PDF uncertainty on M_W

Two possible strategies (similar in their physical content):

1) correlations

use a large set of observables including also data NOT sensitive to M_W to exploit the possible PDF correlations with the observables that ARE sensitive to M_W
(e.g. building ratios that implement some cancellations)

2) improve PDFs

- ideally a new fit that includes at differential level all the new LHC measurements;

in practice, we need to understand which measurements can be most useful to reduce specifically the uncertainties affecting M_W

- in the short term, we can test the validity of our guesses by applying a reweighting procedure to existing PDFs, checking that a significant reduction of the error is achieved

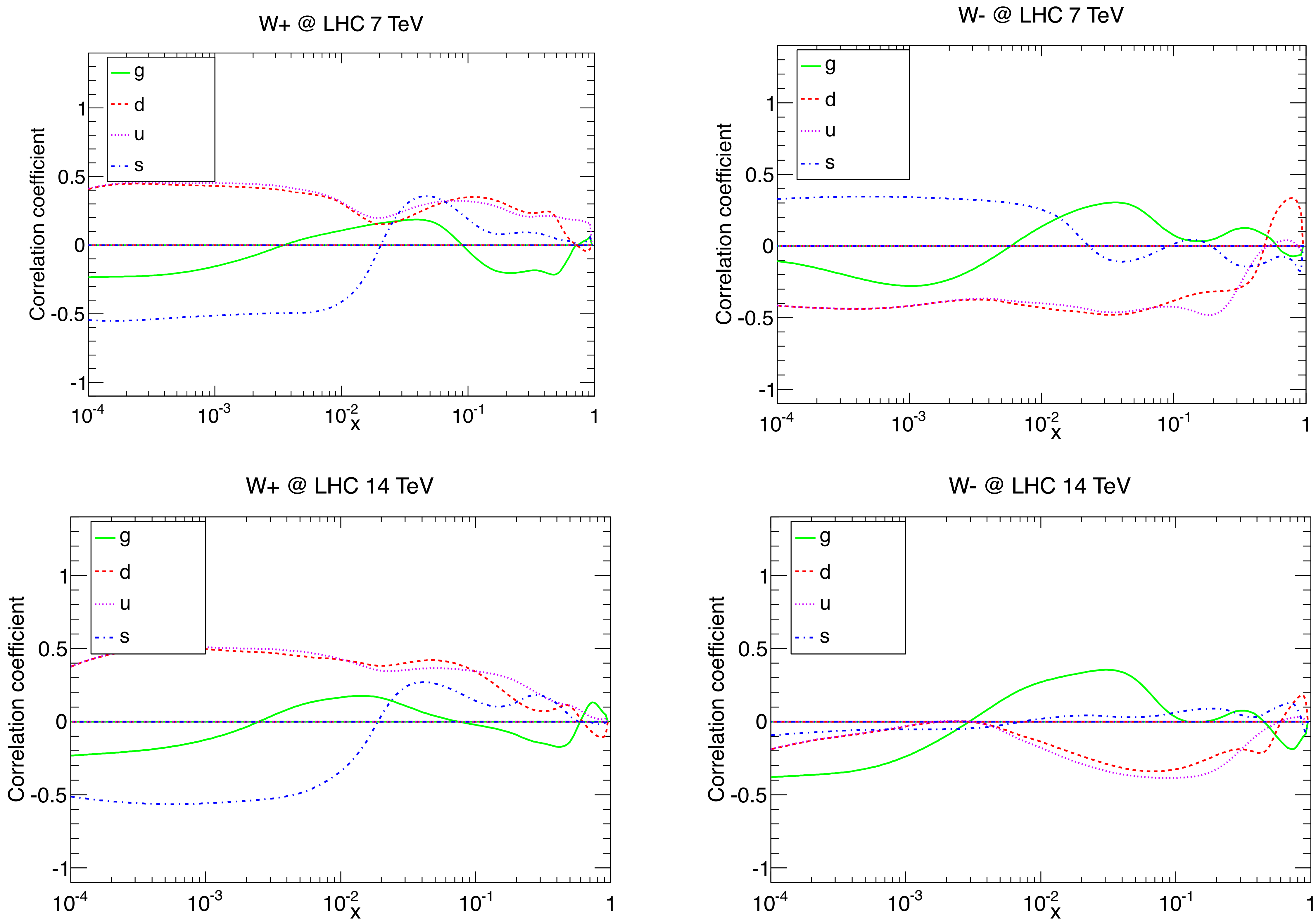
in the long term, the relevant data can be included in a full global fit

In both cases, one needs to analyze at differential level

- which parton luminosities are responsible for the PDF uncertainty on M_W
- which ranges of *x* and of the final state invariant mass are probed

$$\sigma(P_1,P_2;m_H) = \sum_{a,b}\int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1,M_F) f_{h_2,b}(x_2,M_F)\, \hat{\sigma}_{ab}(x_1P_1,x_2P_2,\alpha_s(\mu),M_F)$$

M_W - PDFs correlation



Large absolute value → large sensitivity

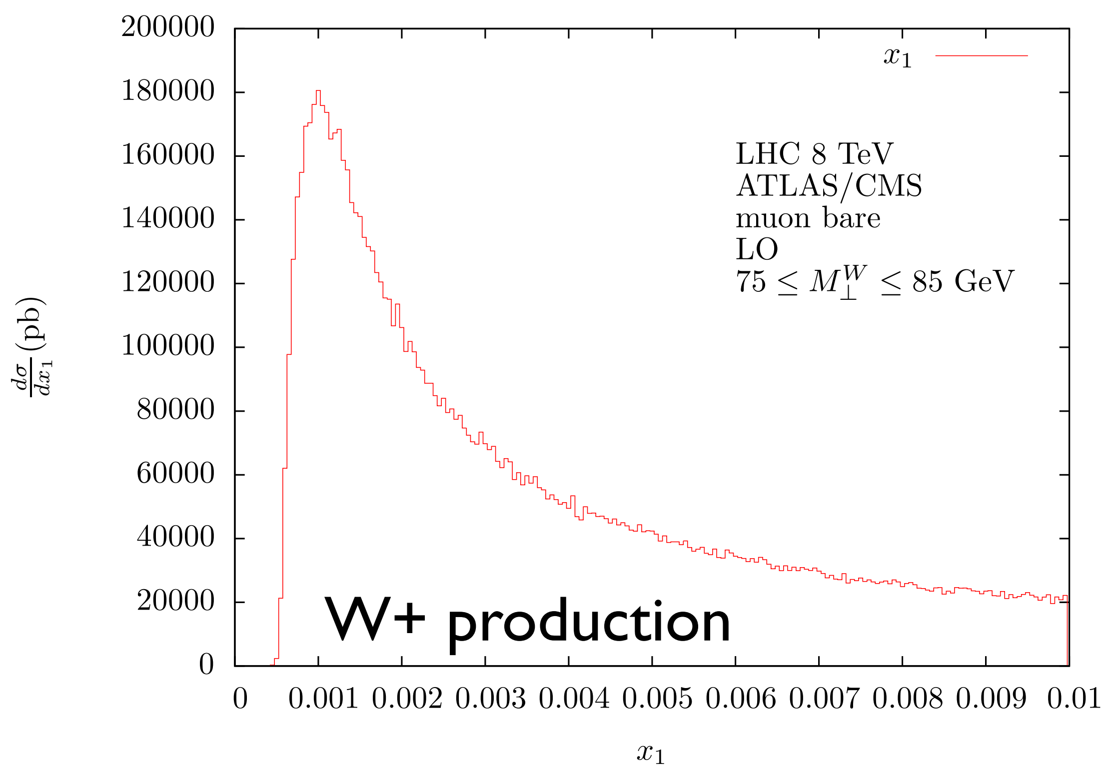
No clear region of maximal sensitivity (gluon seems less important w.r.t. quarks)

Which observables can help?

- Contribution of different parton luminosities
(LO total cross section @LHC 8 TeV, with ATLAS/CMS central cuts)

W+ production		W- production	
u-dbar	79.5%	d-ubar	71.5%
c-sbar	16.1%	s-cbar	24.0%
u-sbar	3.3%	d-cbar	2.5%
c-dbar	1.1%	s-ubar	2.0%

- Distribution of partonic *x* in a range relevant for M_W measurement



- W charge asymmetry
- W+charm production
- NC-DY invariant mass and inv. mass A_{FB}

with cuts selecting the relevant *x* range

Impact of PDF uncertainties on $\sin^2\theta_W$ measurement: A_{FB} in NC-DY

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

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

$$\cos\theta^* = f \frac{2}{M(l^+l^-)\sqrt{M^2(l^+l^-) + p_t^2(l^+l^-)}} [p^+(l^-)p^-(l+) - p^-(l^-)p^+(l^+)]$$

$$p^\pm = \frac{1}{\sqrt{2}}(E \pm p_z) \qquad f = \frac{|p_z(l^+l^-)|}{p_z(l^+l^-)}$$

- At Y_Z=0, A_{FB} is exactly zero: LHC is a symmetric collider (pp) and the asymmetry of q-qbar and qbar-q initiated processes cancels

- At large Y_Z, the different weight of q-qbar and qbar-q initiated processes leaves a residual asymmetry: the <u>larger</u> Y_Z, the <u>more pronounced</u> A_{FB}

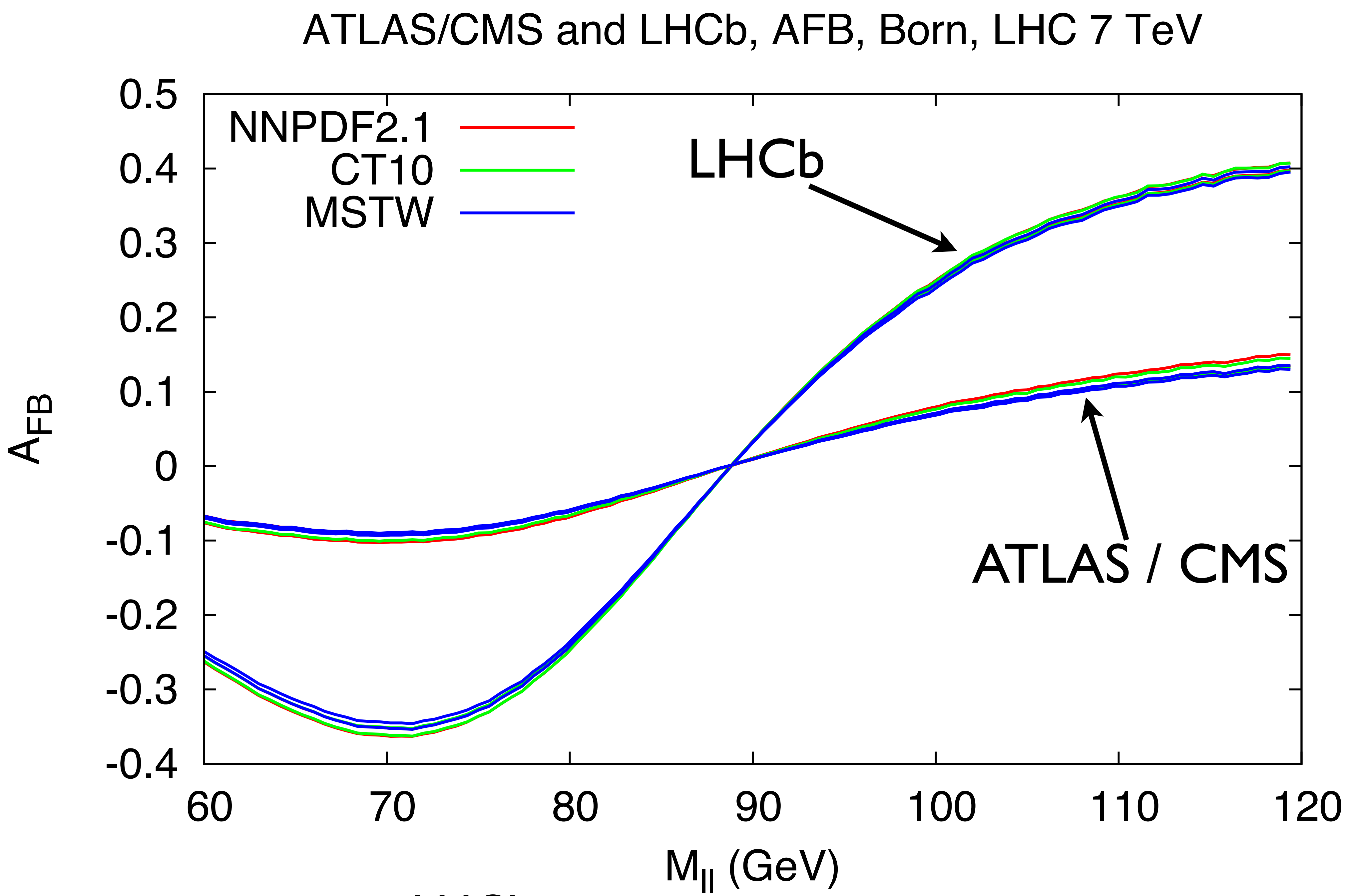
- The asymmetry is due to the difference between <u>valence</u> and <u>sea</u> components of the quark densities

A_{FB} @ ATLAS/CMS/LHCb

acceptance cuts: $p_\perp^l > 25\,\mathrm{GeV}$

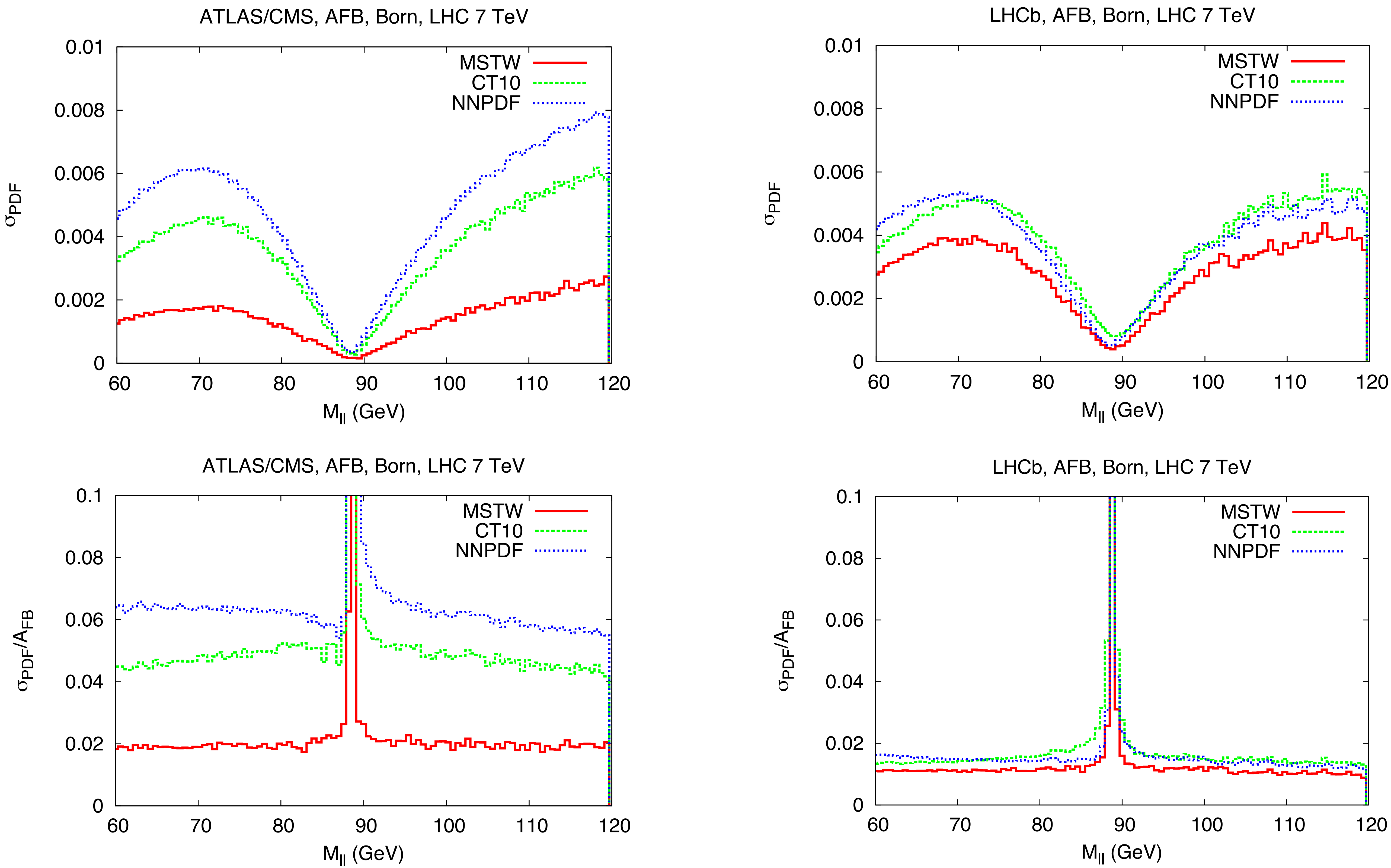
ATLAS / CMS $|\eta_l| < 2.5$

LHCb $2.0 < \eta_l < 4.5$



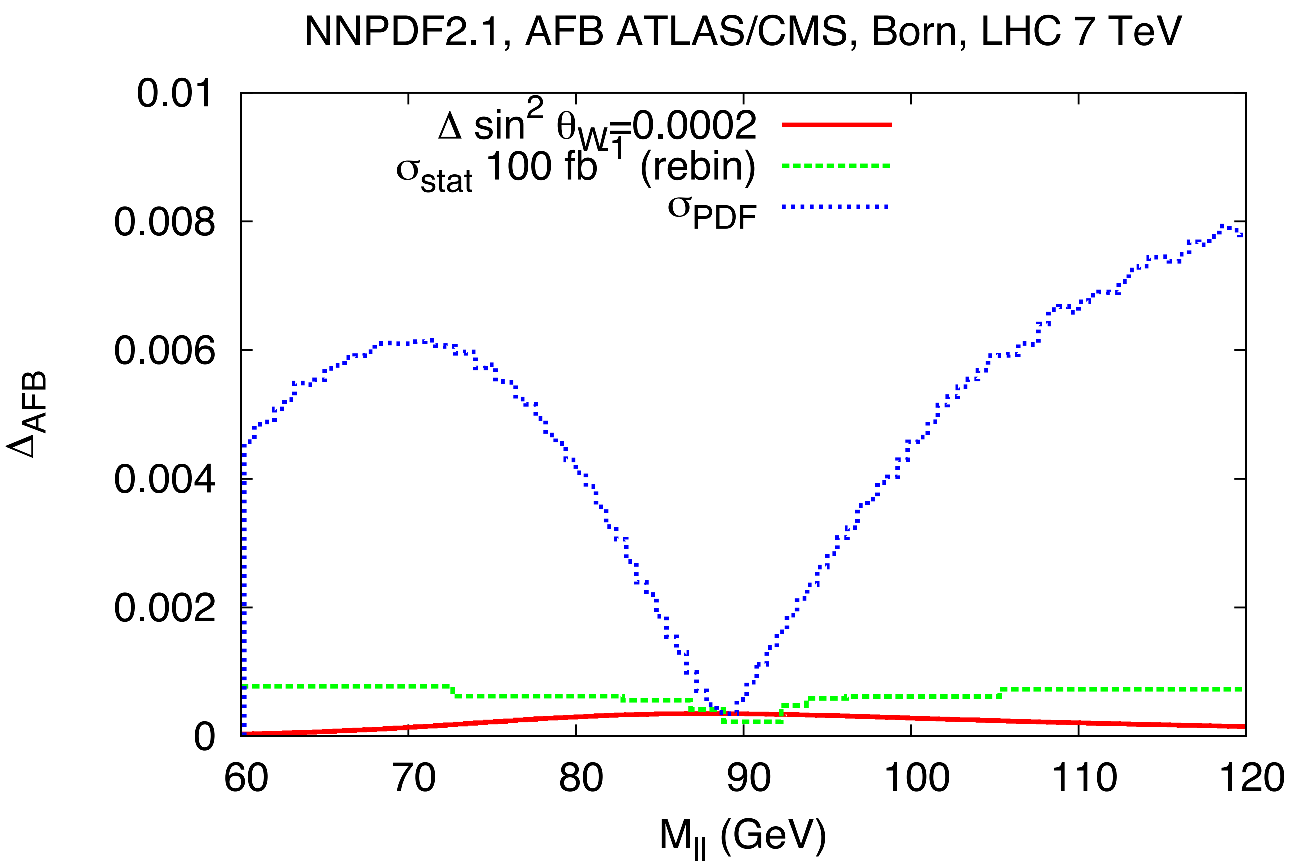
- stronger asymmetry at LHCb
- A_{FB} vanishes for $M_{ll} \approx 88.5$ GeV
- region of maximal sensitivity to $\sin^2\theta_W$ around M_Z, where A_{FB} is still small

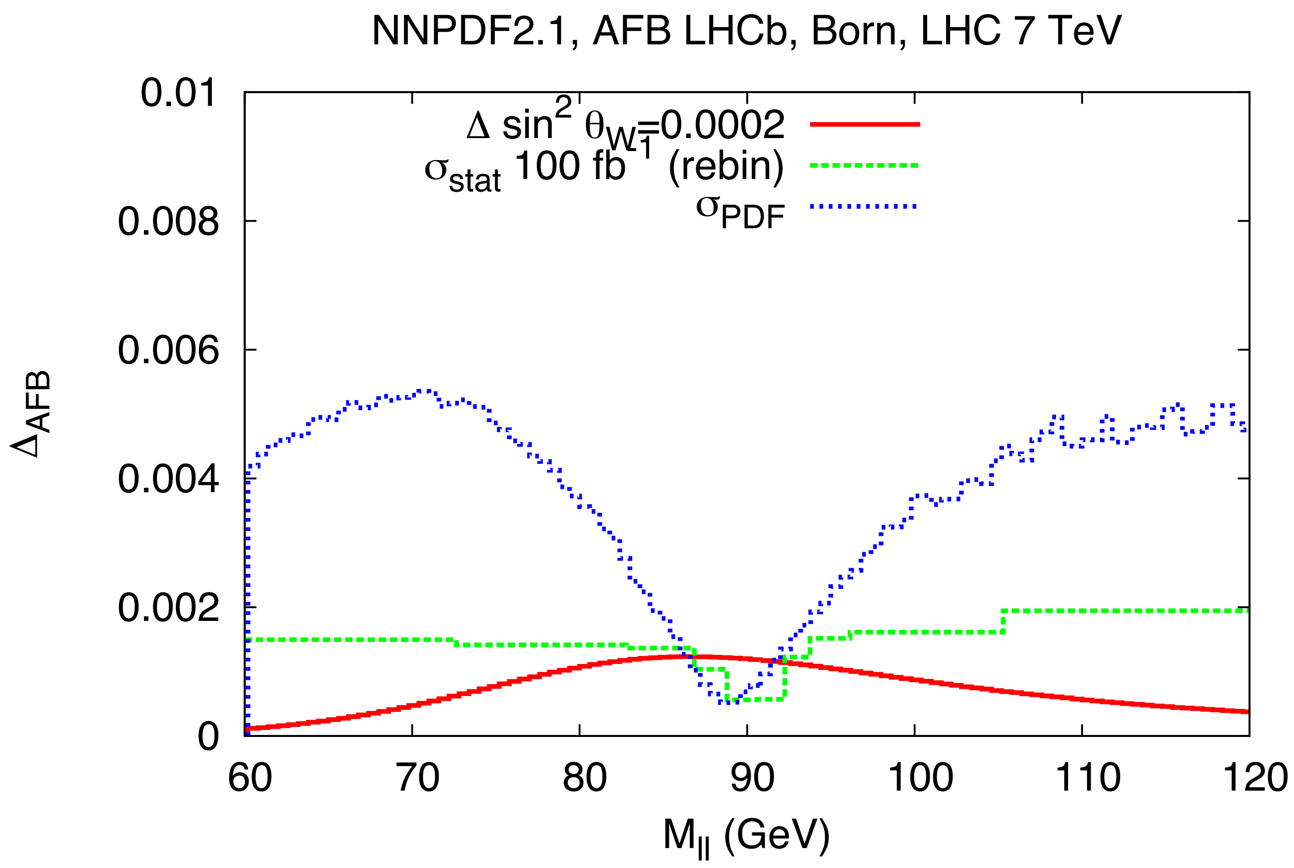
PDF uncertainties on A_{FB}: absolute and relative spread



The relative error is almost constant for all invariant masses (below 120 GeV)

Summary of uncertainties on A_{FB}

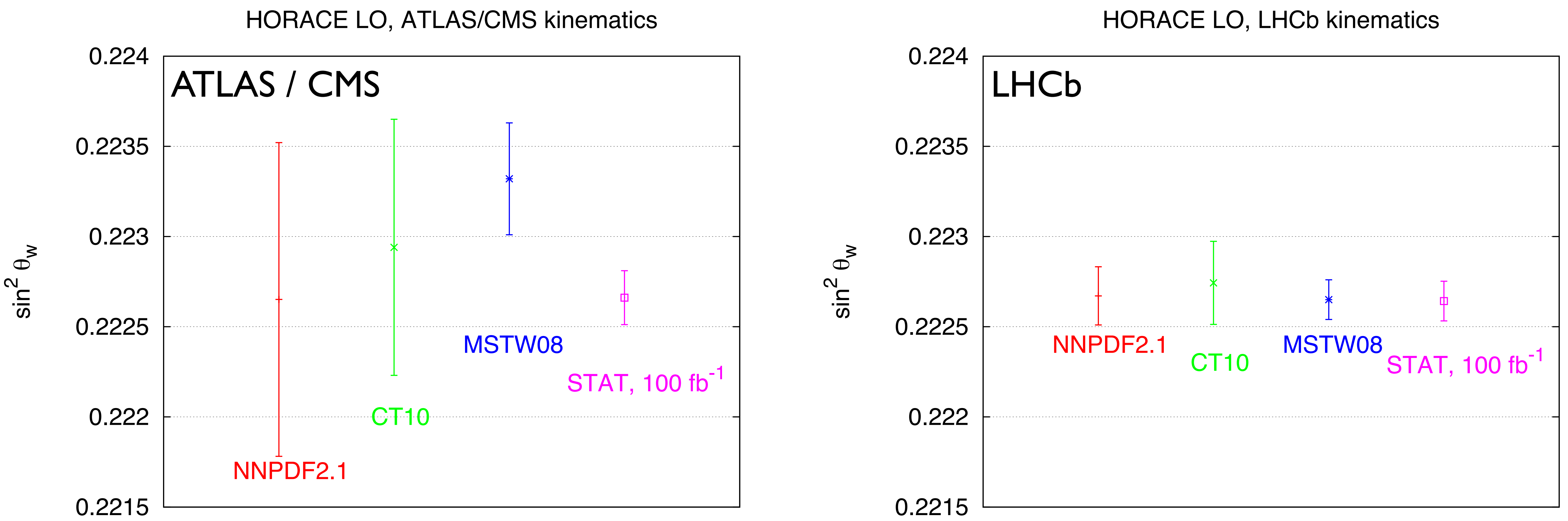




- the PDF uncertainty dominates over the statistical one (after rebinning)
- at LHCb the larger asymmetry implies a stronger sensitivity to $\sin^2\theta_W$

Impact of PDF uncertainties on $\sin^2\theta_W$ measurement

- template fit procedure: find the preferred $\sin^2\theta_W$ associated to each replica



- spread of central values: (max-min)

$$\Delta \sin^2\theta_W = 0.0007 \quad \text{ATLAS/CMS}$$
$$\Delta \sin^2\theta_W = 0.0001 \quad \text{LHCb}$$

- envelope of PDF unc. bands: (max-min)

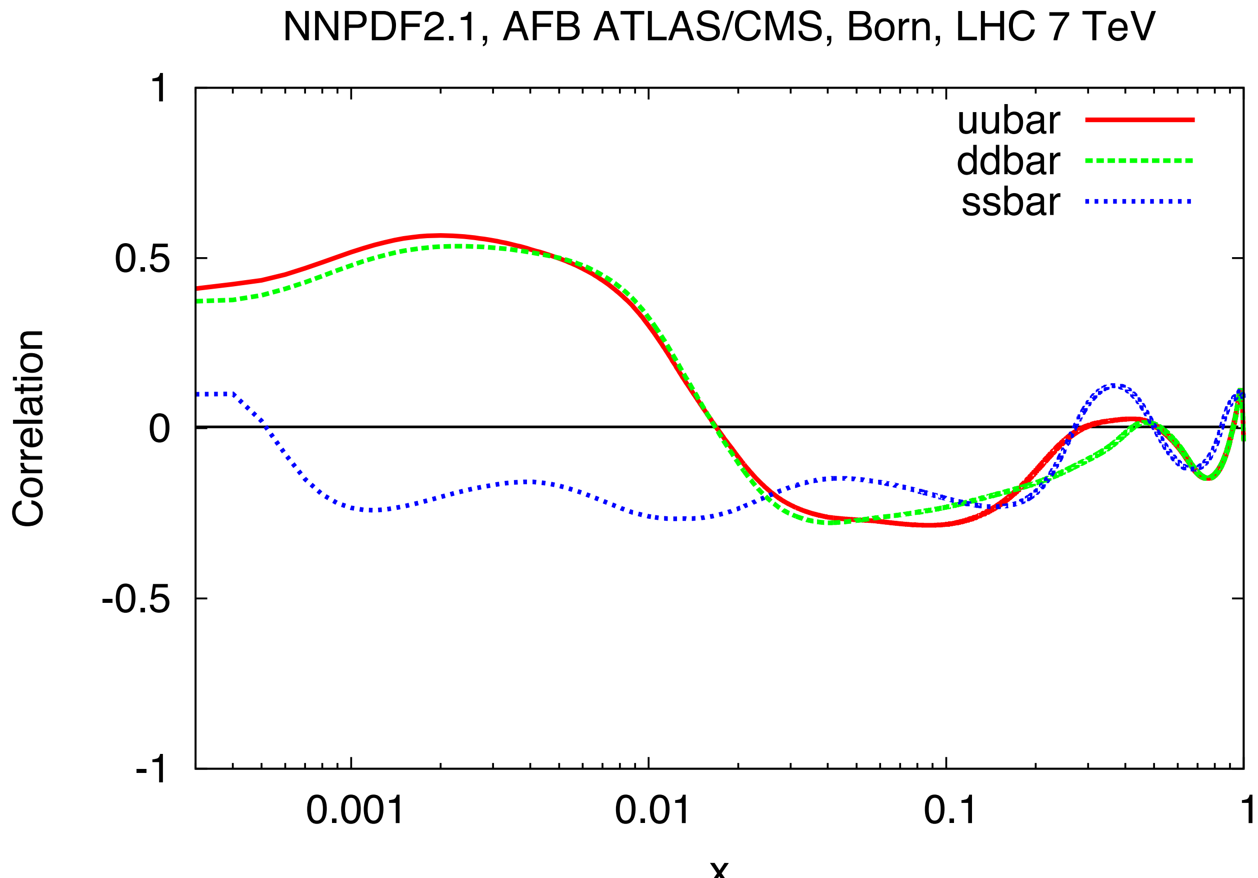
$$\delta \sin^2\theta_W = 0.0019 \quad \text{ATLAS/CMS}$$
$$\delta \sin^2\theta_W = 0.0005 \quad \text{LHCb}$$

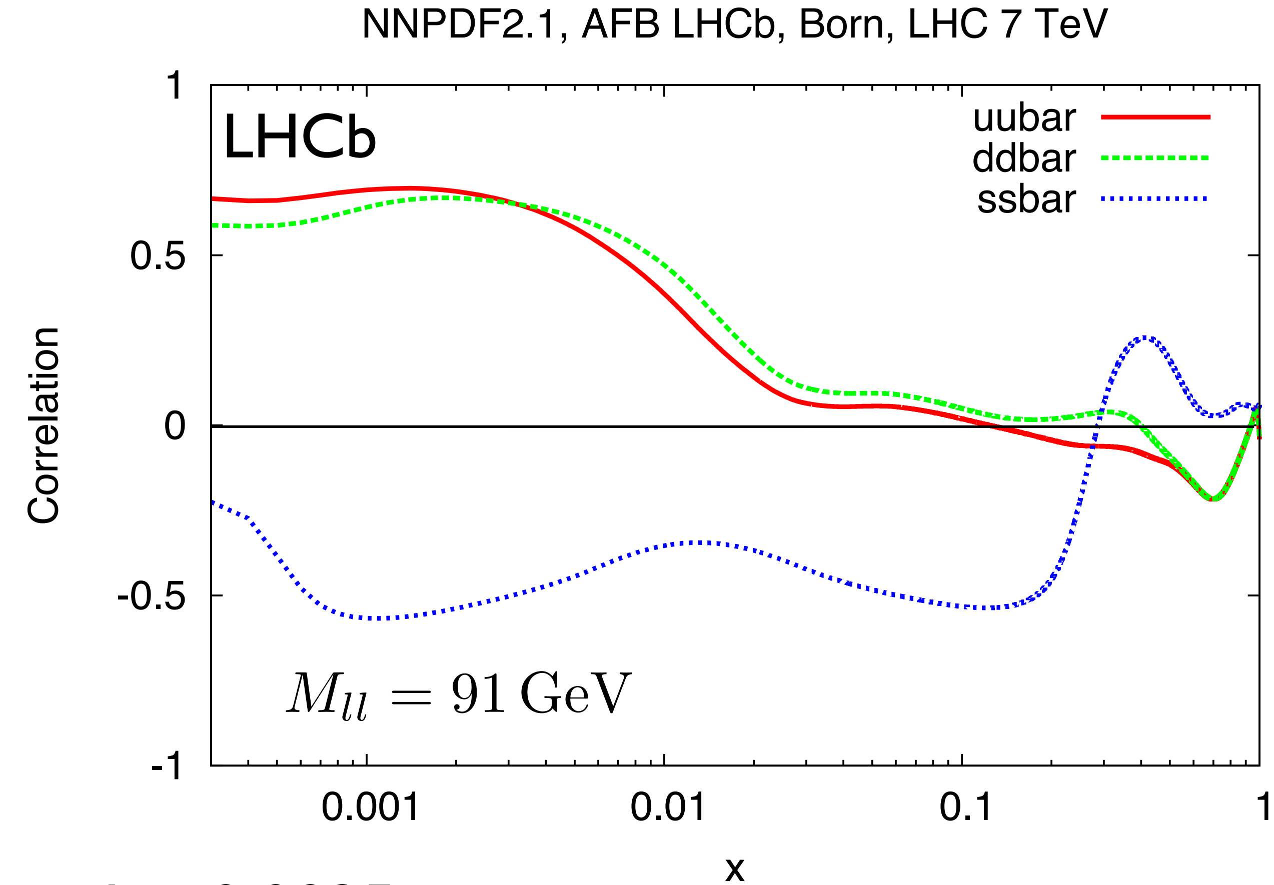
- statistical unc.(100fb-1):

$$\delta \sin^2\theta_W = 0.00015 \quad \text{ATLAS/CMS, LHCb}$$

Correlation of A_{FB} with parton luminosities

$$\rho\left[A_{FB}(M_{ll}^2),\ q(x)\bar{q}(\tau/x)\right] = \frac{\langle A_{FB}(M_{ll}^2)\ q(x)\bar{q}(\tau/x)\rangle_{rep} - \langle A_{FB}(M_{ll}^2)\rangle_{rep}\langle q(x)\bar{q}(\tau/x)\rangle_{rep}}{\sigma_{PDF}^{A_{FB}}\ \sigma_{PDF}^{q\bar{q}}}$$





- At ATLAS/CMS the *x* distribution is peaked around x=0.0025
  At LHCb the x_1 and x_2 distributions are peaked around x_1=0.2 , x_2=0.0006
- The asymmetry is mostly due to the role of the valence component of quarks: valence quarks boost the event to large rapidities ➔ positive correlation with (u-ubar, d-dbar)
- The s-sbar and sbar-s processes are (almost) identical: (almost) cancel in the numerator but are present in the denominator of AFB and reduce the asymmetry ➔ s-sbar is anti-correlated

➔ A precise measurement might help to constrain the up and down densities

Conclusions and outlook

- Template-fit technique
  - clear procedure to assess the impact of PDFs on precision EW measurements
  - quickly very demanding (CPU time), especially when QCD corrections are included
  - intrinsic uncertainty

- M_W from W transverse mass
  - LO and NLO-QCD analyses are both feasible
  - QCD corrections are moderate, fixed order simulation code is sufficient

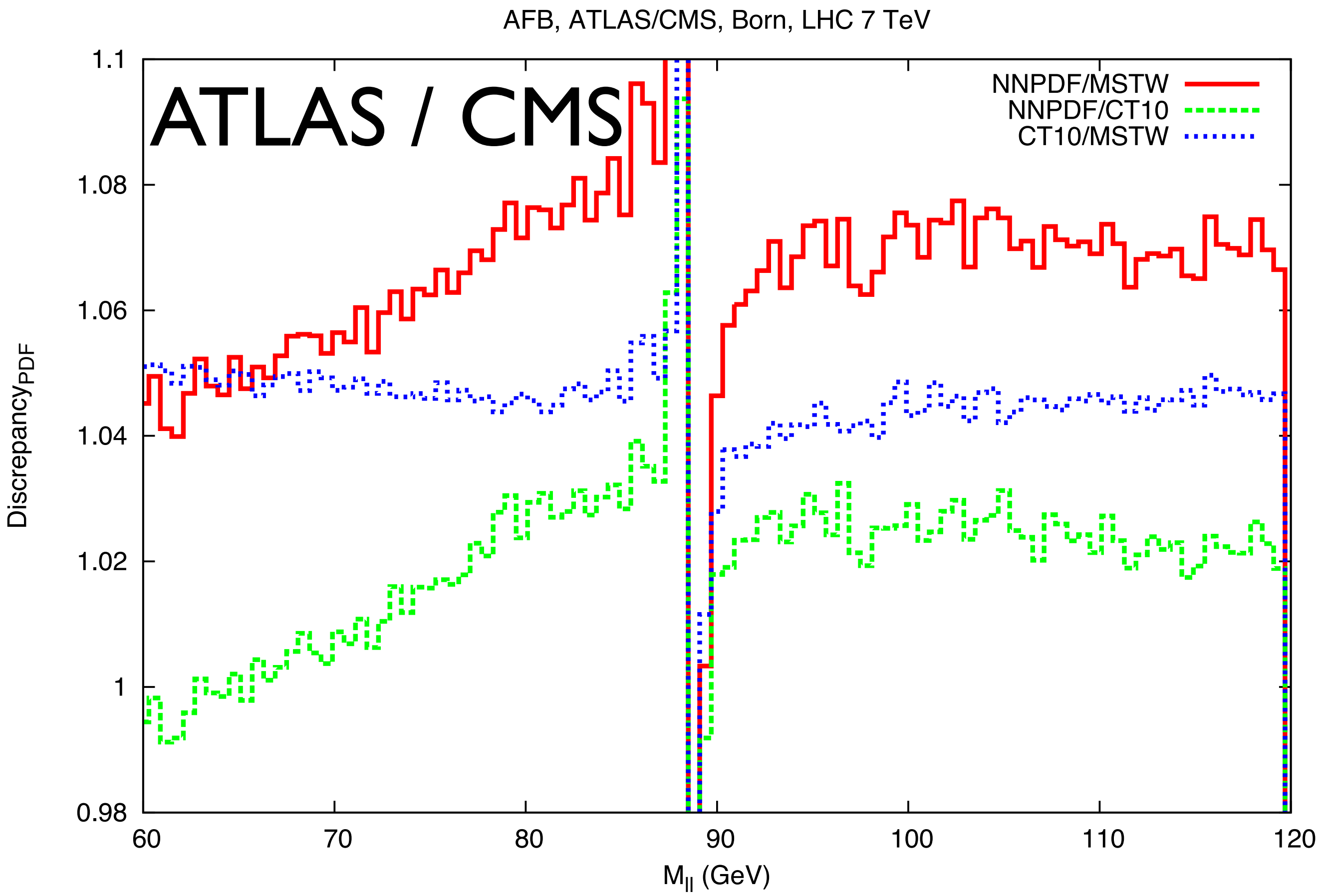
- M_W from lepton pt
  - LO study not realistic, NLO-QCD shows instabilities at the jacobian peak
  - → need to use a resummed calculation (DYqT), technically challenging (in progress)

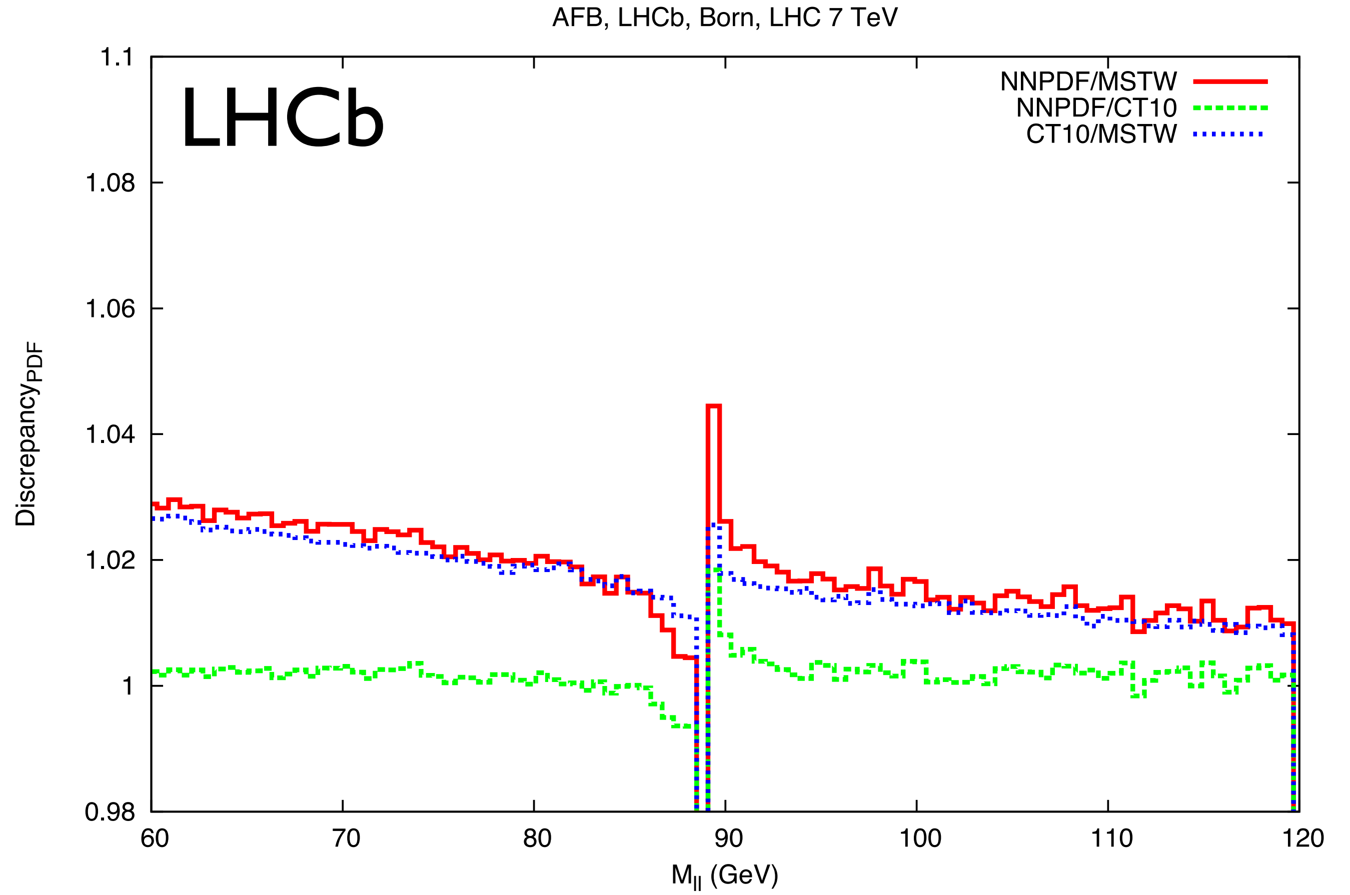
- $\sin\theta_W$ from A_{FB} asymmetry
  - LO analysis is feasible, LHCb can be competitive with LEP, larger uncertainty at ATLAS/CMS
  - NLO-QCD study (in progress) shows severe simulation problems (MC fluctuations)

- Need
  - build ratios of observables in order to reduce PDF uncertainty
  - systematic study of correlations between parton luminosities and all available observables: useful indication of relevant data (not only DY) are relevant to reduce the PDF impact
  - a lot of CPU-time!

Back-up slides

A_{FB}: comparison of the central values

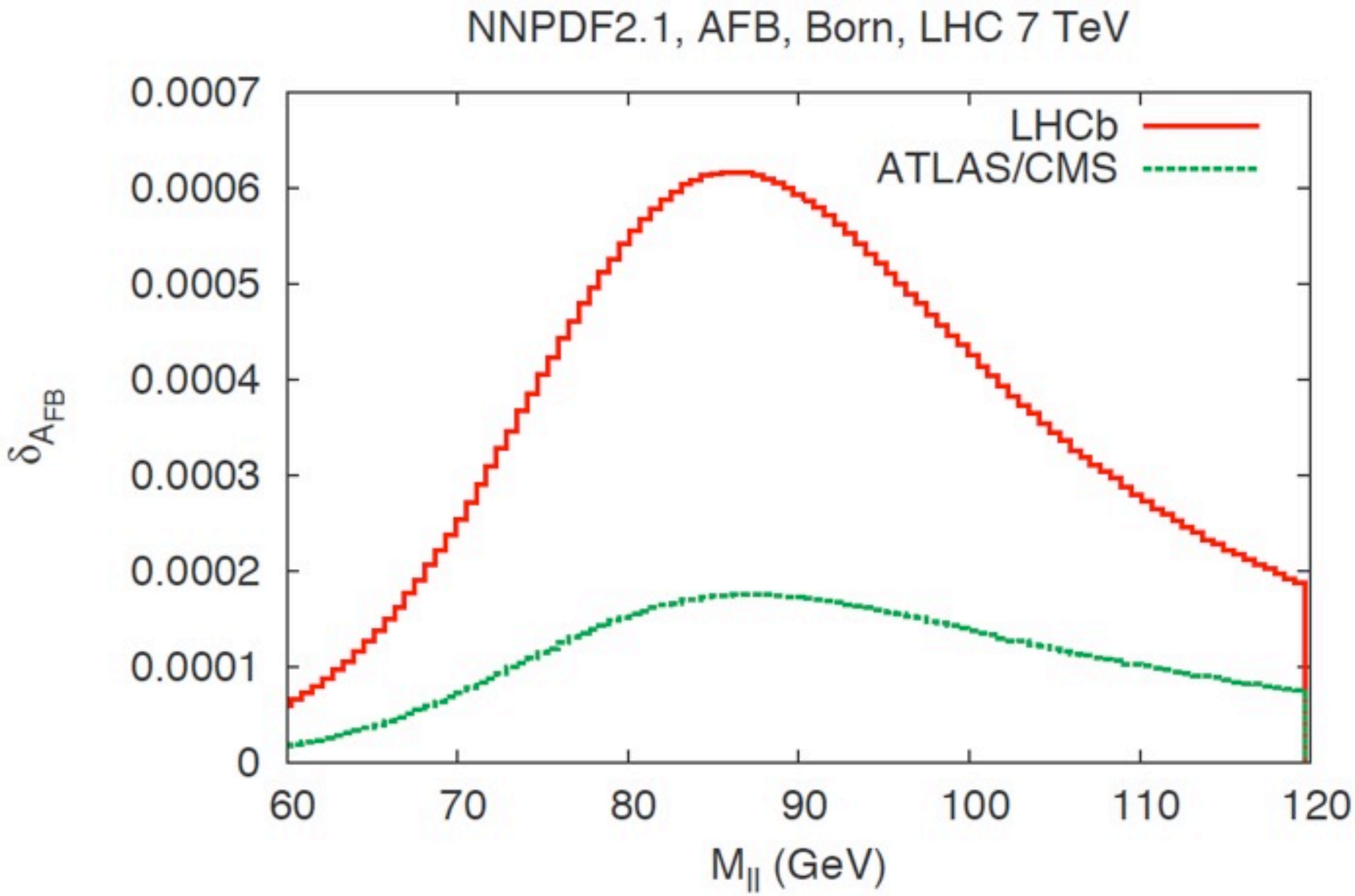




- The ratio probes the absolute value of A_{FB} (A_{FB} changes sign below 88.5 GeV)

- Larger spread of the central predictions at ATLAS / CMS with respect to LHCb

Sensitivity of A_{FB} to a variation of $\sin^2\theta_W$



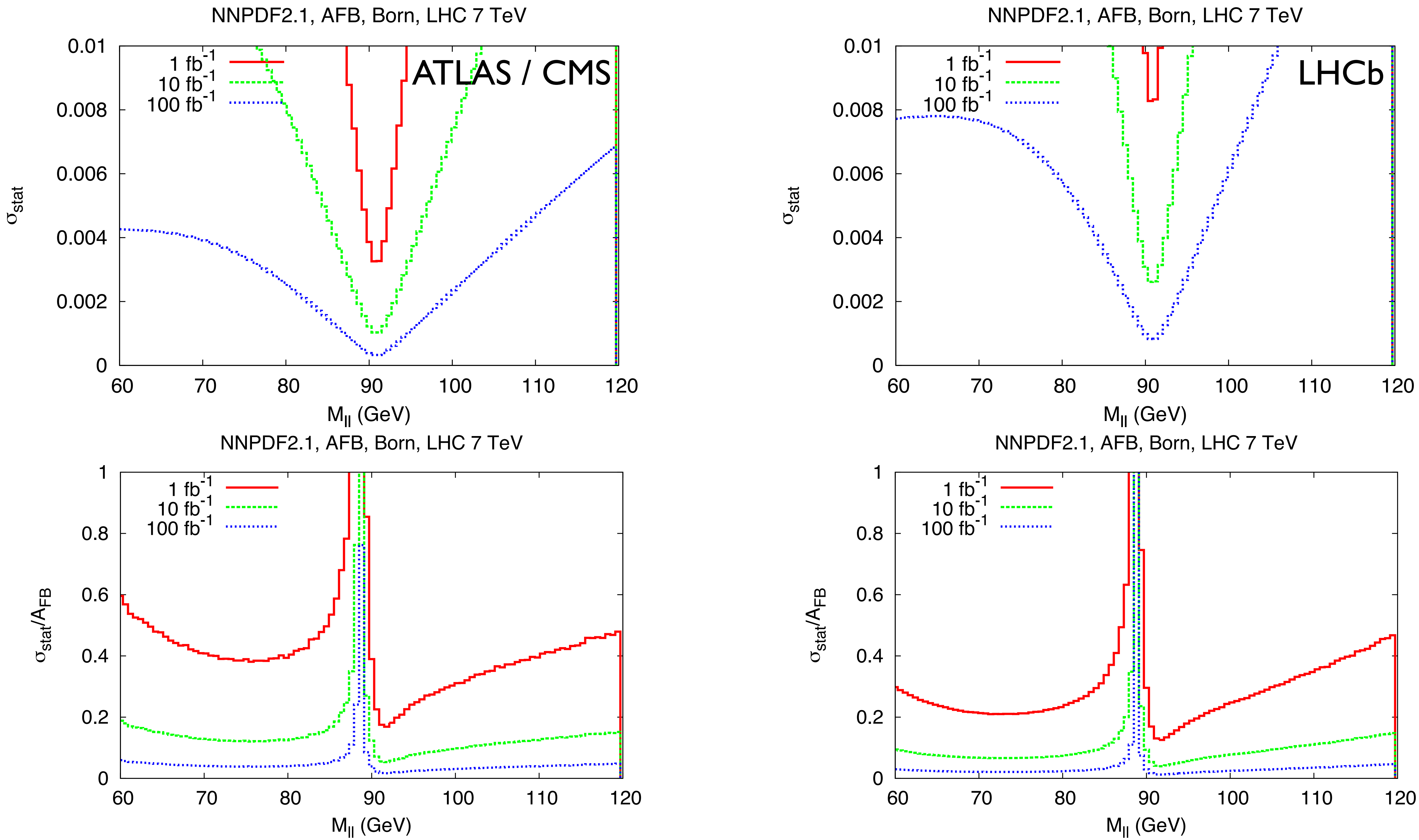
$$\delta A_{FB} = A_{FB}(\sin^2\theta_W + \delta\sin^2\theta_W) - A_{FB}(\sin^2\theta_W - \delta\sin^2\theta_W)$$

$$\delta\sin^2\theta_W = 0.0001$$

best PDG value $\sin^2\theta_{eff}^{lep} = 0.23146 \pm 0.00012$

can we measure A_{FB} with an accuracy of few parts in 10^{-4} , to extract $\sin^2\theta_W$?

Statistical uncertainty on A_{FB}



- The relative error is not constant for all invariant masses

➔ a rebinning procedure can considerably reduce the impact of the statistical error on the measurement of $\sin^2\theta_W$

Impact on $\sin^2\theta_W$ of the PDF uncertainty on A_{FB}

- for each member/replica $\xrightarrow{\text{template fit}}$ preferred $\sin^2\theta_W$ value
- the set of preferred values is then combined according to PDF recipes

- the average NNPDF2.1 value coincides with the nominal value used in the templates

Impact on $\sin^2\theta_W$ of the statistical uncertainty on A_{FB}

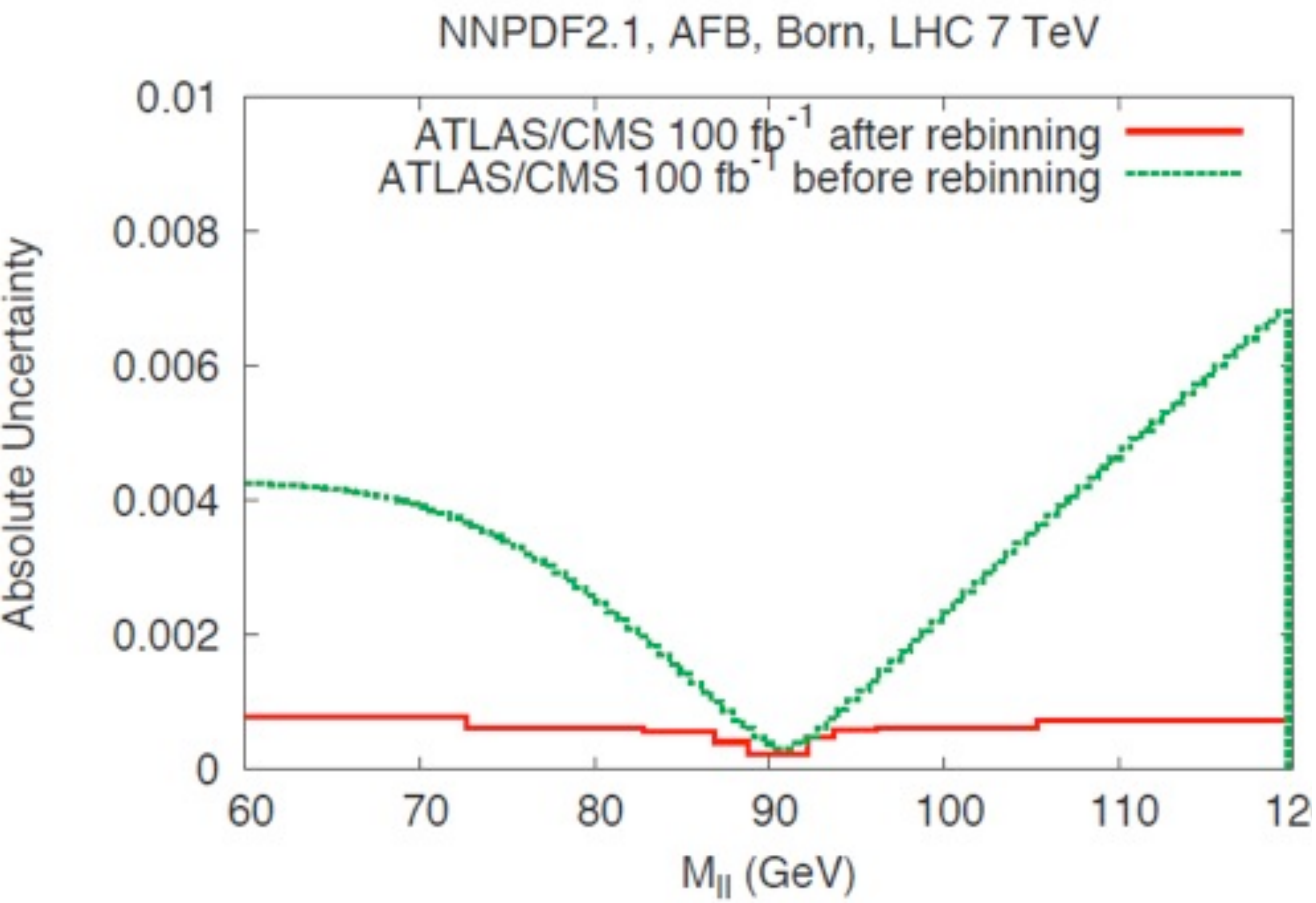
- 100 pseudo-experiments with NNPDF2.1,
 assuming a luminosity and adding to each bin gaussianly distributed fluctuations
 (propagation of the error from the F and B distributions to A_{FB})

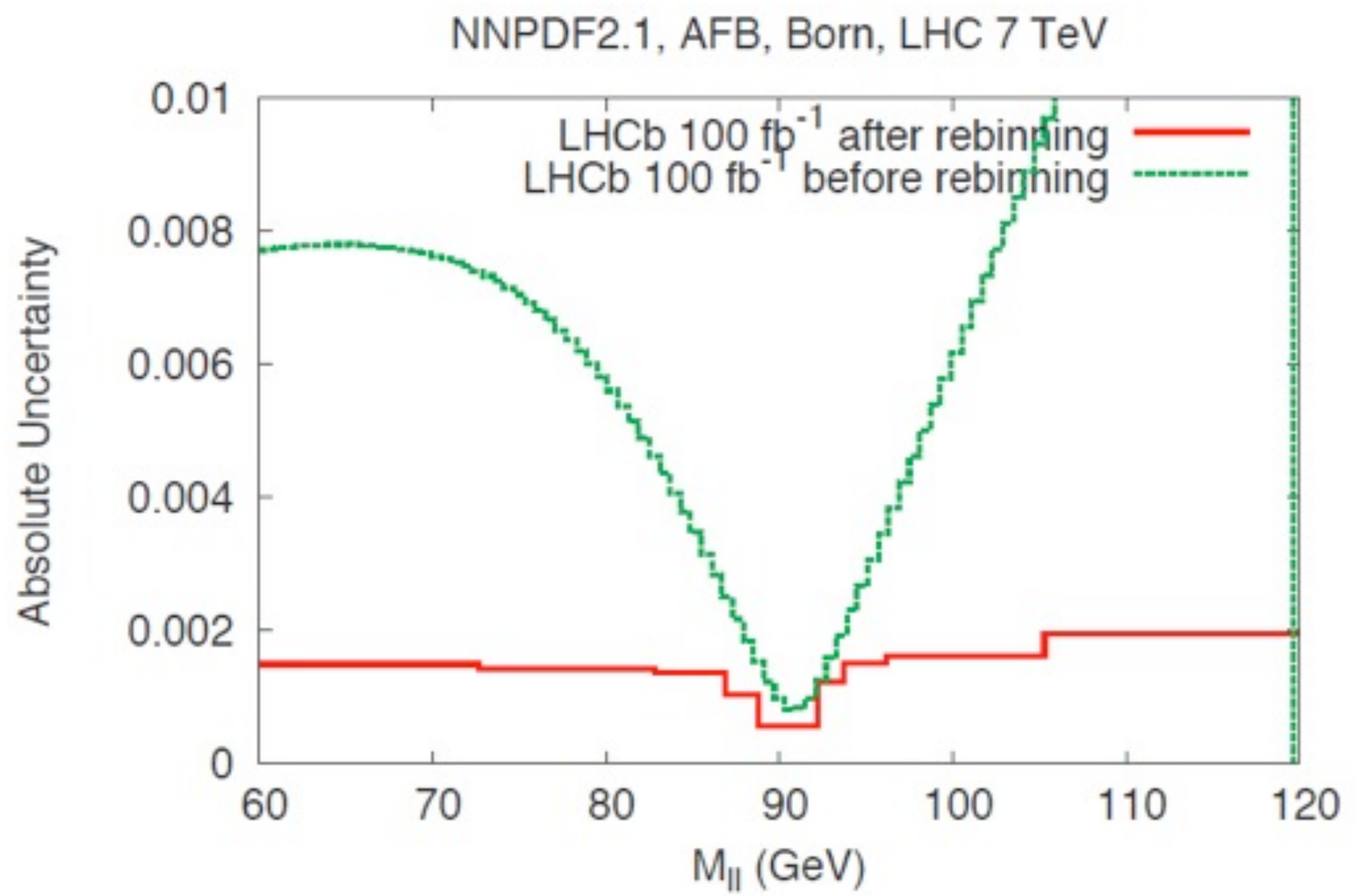
- for each pseudo-experiment $\xrightarrow{\text{template fit}}$ preferred $\sin^2\theta_W$ value

- statistical combination of the 100 results

Reducing the statistical uncertainty on A_{FB}

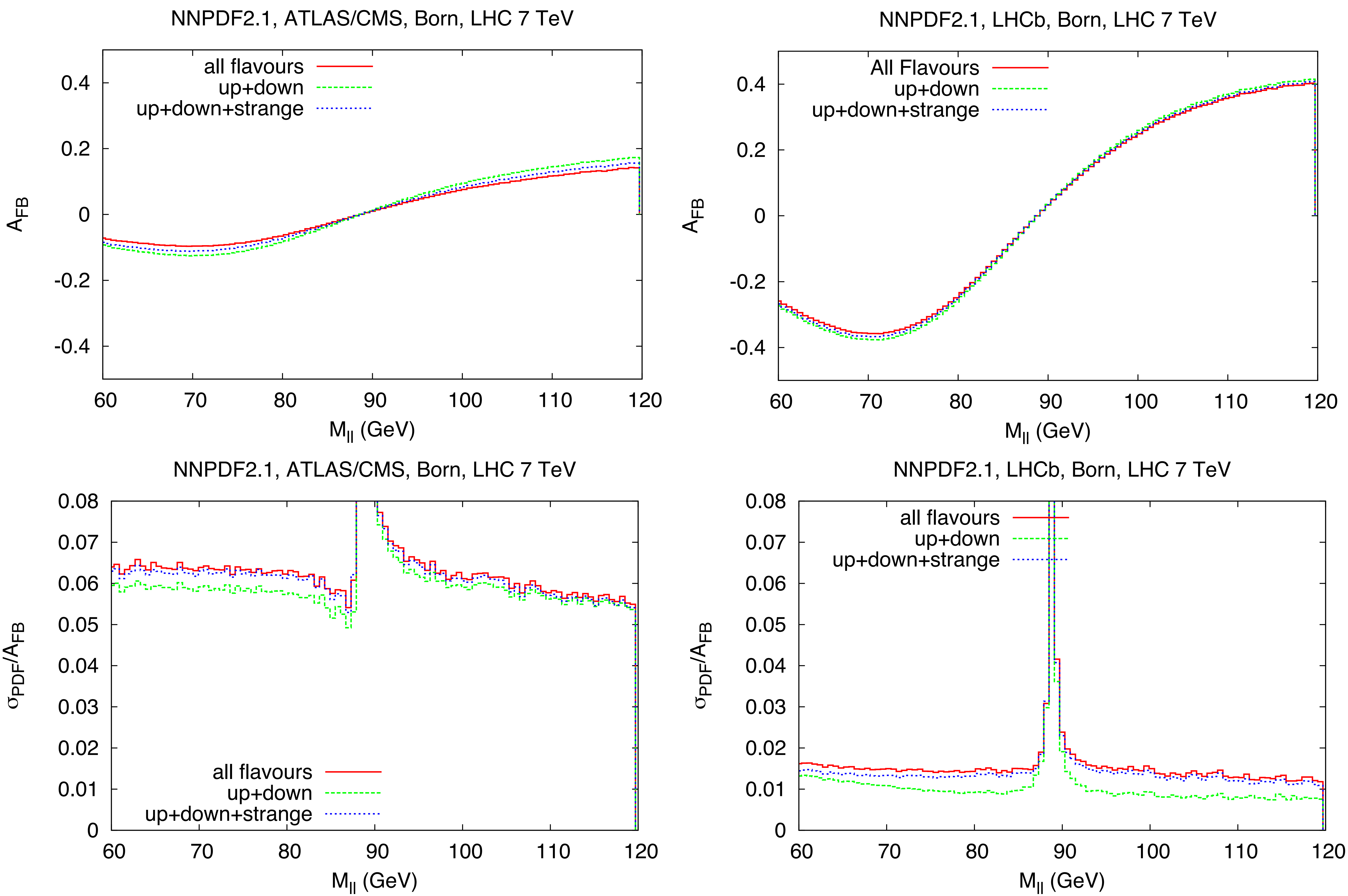
- Out of the Z resonance lower # of events ➔ larger bins to reduce the fluctuations



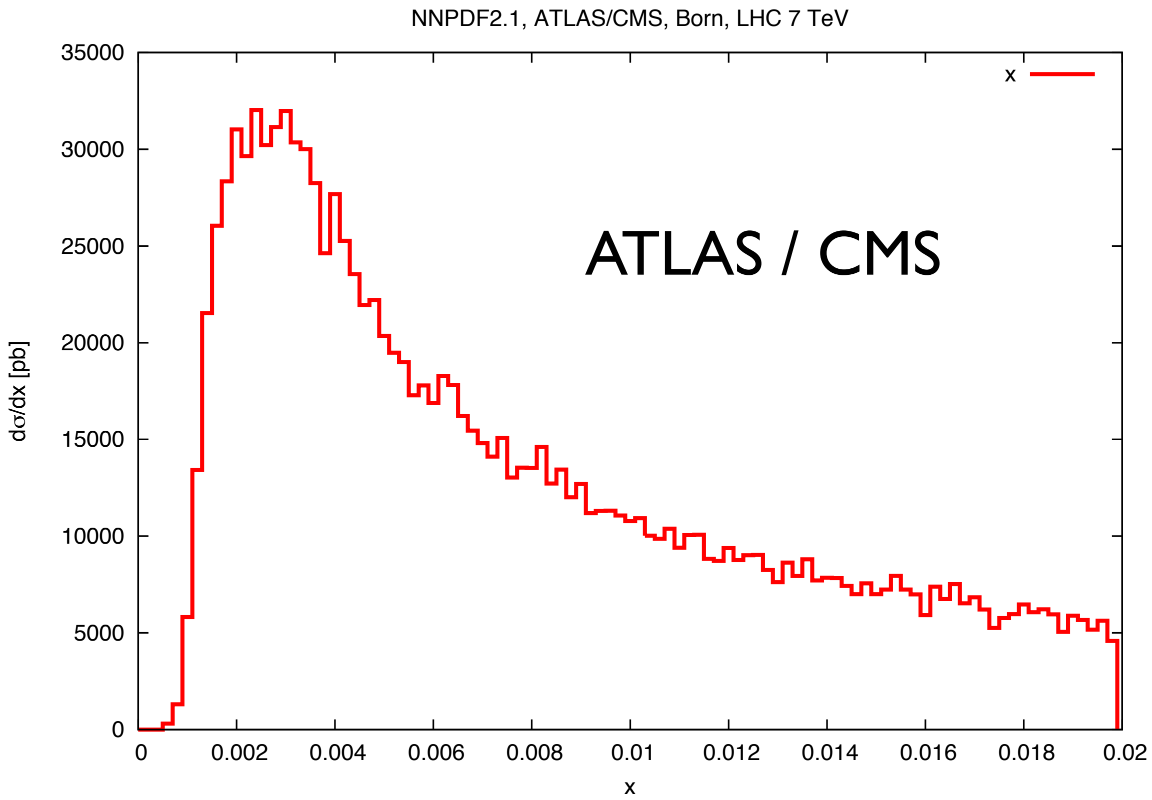


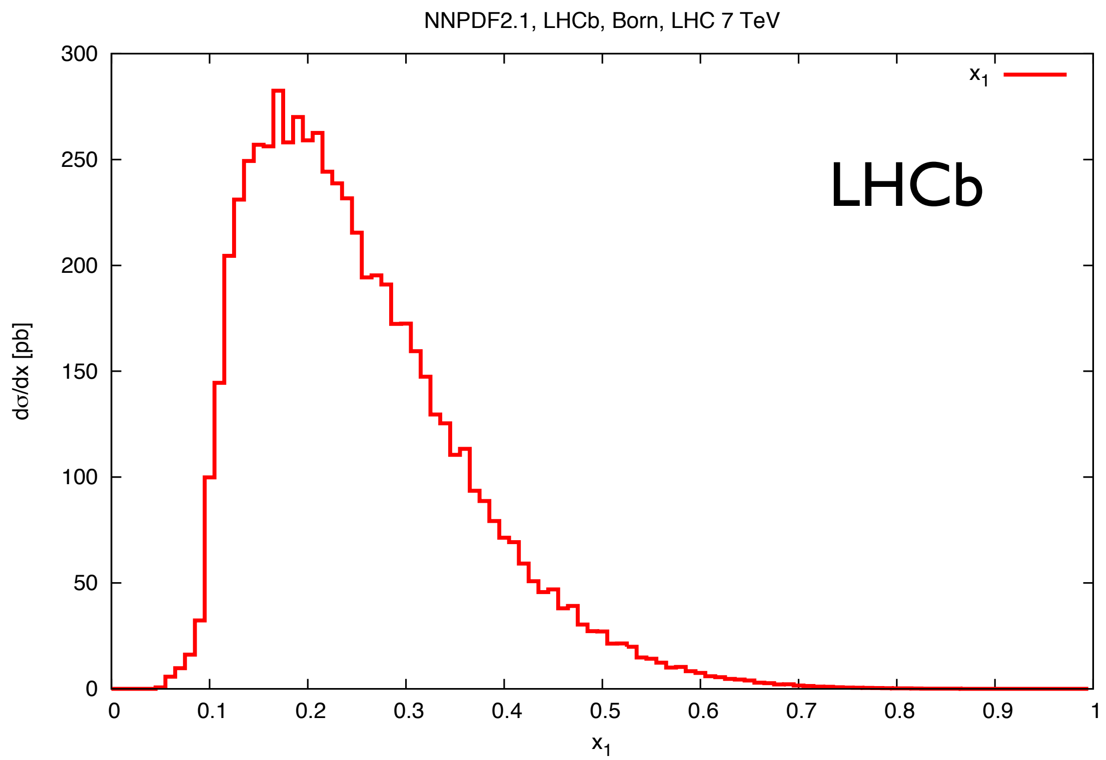
- bins chosen to preserve the asymmetry

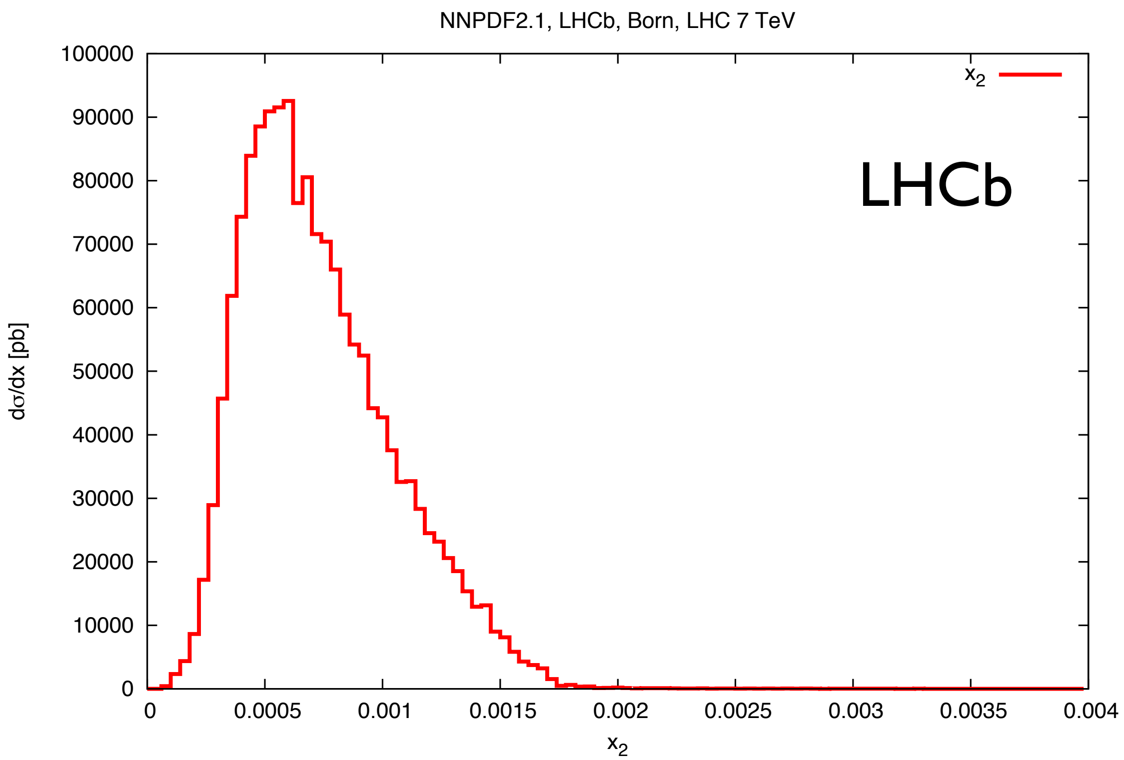
The role of s,c,b quarks



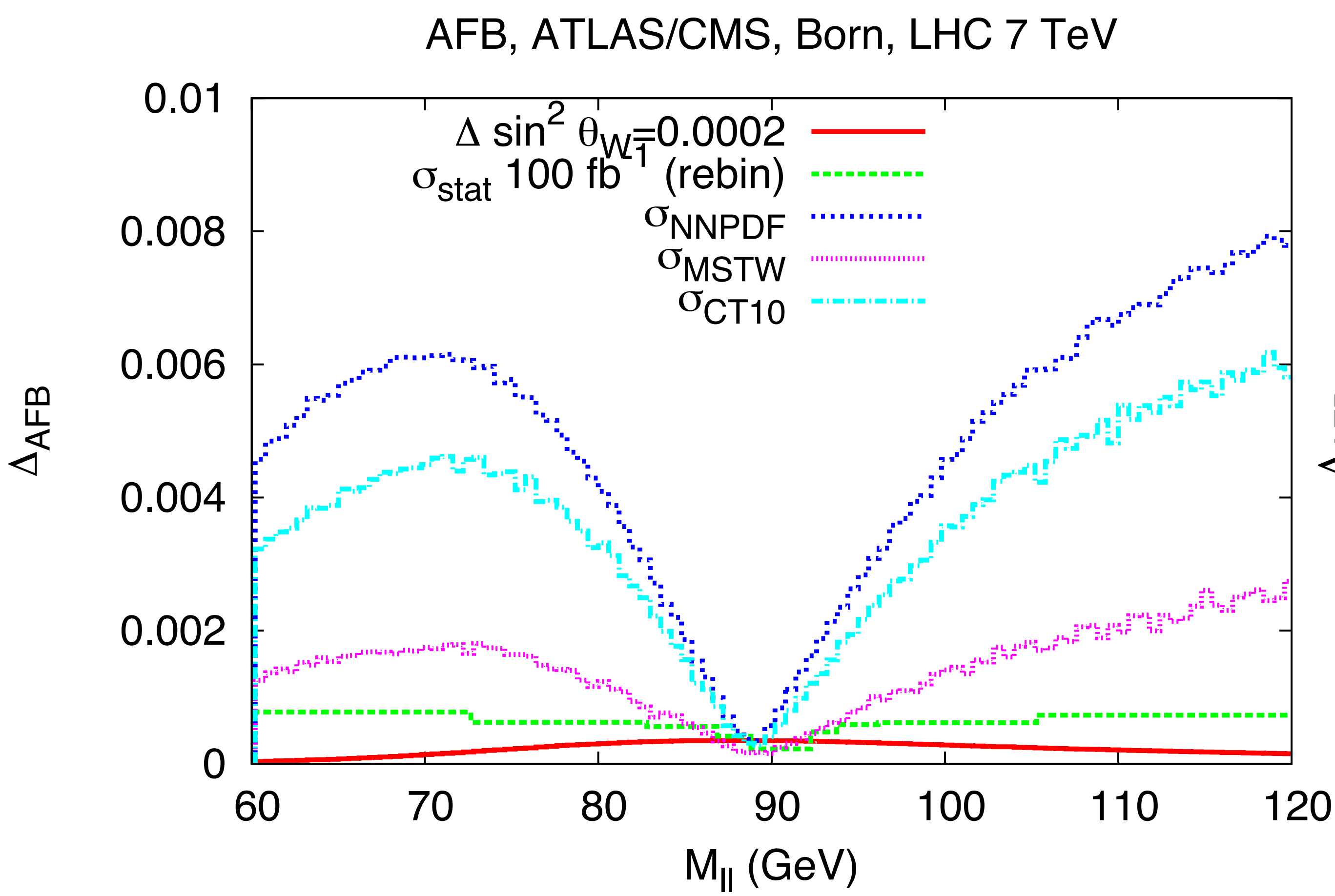
The momentum fraction distributions at ATLAS/CMS and at LHCb

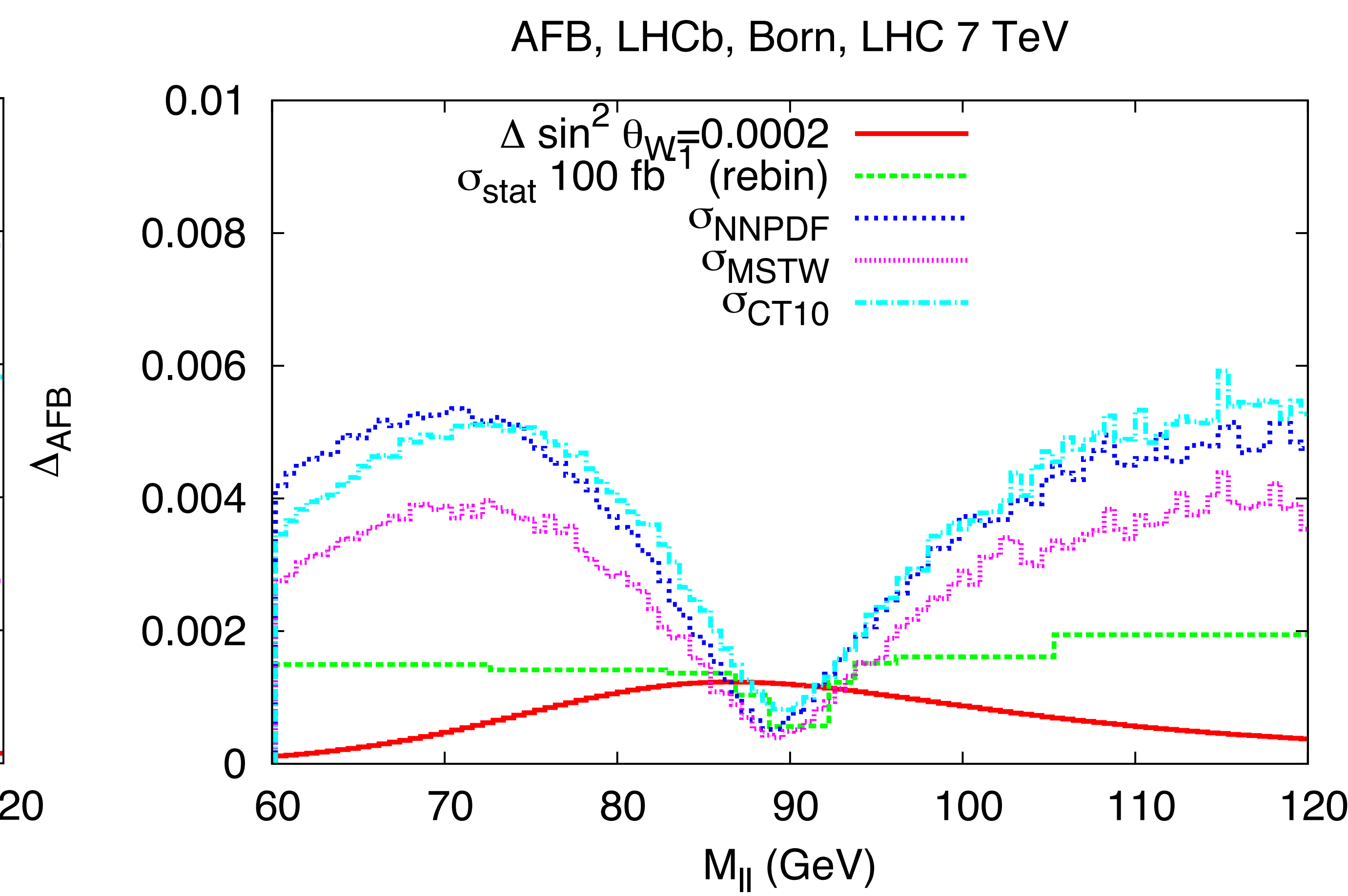






Summary of the uncertainties on A_{FB} all PDF sets





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