C T E Q

CTEQ-TEA Update

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September 26, 2012 @

PDF4LHC Meeting

Outline

- Much has been said in Joey Huston's talk, such as benchmark studies.

- CT10 NNLO and CT12 BLO/NLO PDFs

- Some comparisons to data

Two sets of CT NNLO error PDFs

1. CT10 NNLO eigenvector set

Available at http://hep.pa.msu.edu/cteq/public/ct10_2012.html**; is being submitted to LHAPDF; main focus of this talk**

Complements the CT10/CT10W NLO PDF sets *(Lai et al., PRD82, 074024 (2010))*

- **Includes only "pre-LHC" CT10 data.** Can be used to predict LHC cross sections based on pre-LHC experimental inputs
- Same input parameters, functional forms for input PDFs as in the CT10 NLO PDFs
  - $\alpha_s(M_Z) = 0.118 \pm 0.002$, $m_c^{pole} = 1.3$ GeV, $m_b^{pole} = 4.75$ GeV
  - Simpler assumptions about the PDF flavor composition at $\mu_0 = m_c^{pole} = 1.3$ GeV, *e.g.*, $\bar{u}(x)/\bar{d}(x) \to 1$ as $x \to 0$

Two sets of CT NNLO error PDFs

2. CT12 NLO and NNLO eigenvector sets

To be released within a few months

- Include LHC W and Z rapidity data, ATLAS and CMS jet data, HERA'2011 F_L data
- Updated α_s, m_c, m_b values
- Flexible $\bar{d}/\bar{u}$ ratio at $x \to 1$, updated $(s+\bar{s})/(\bar{u}+\bar{d})$ at $x \lesssim 10^{-2}$
  - Constrained by the LHC W/Z rapidity distributions

The CT10-NNLO global analysis of QCD

Parametrization of PDFs at Q = 1.3 GeV, with 25 parameter values to be chosen; there are from 4 to 6 parameters for each parton type.

Many data sets, for short distance interactions.

Perturbative QCD, using NNLO approximations wherever available.

Taking account of ***experimental errors***, statistical and systematic.

(Not so strong on systematic ***theoretical errors***.)

Heavy flavor mass effects are included using the ***S-ACOT-χ*** factorization formalism (extended to NNLO).

28 data sets used for the CT10-NNLO global analysis

CT10-NNLO Table	Ndp	Chi^2	Nsy	
1/ 159 HERA1X0	579	617.	114	Combined HERA1 NC+CC DIS (2009)
2/ 101 BcdF2pCor	339	392.	5	BCDMS collaboration
3/ 102 BcdF2dCor	251	291.	5	BCDMS collaboration
4/ 103 NmcF2pCor	201	333.	11	NMC collaboration
5/ 104 NmcRatCor	123	151.	5	NMC collaboration
6/ 108 cdhswf2	85	70.5	0	P Berge et al Z Phys C49 187 (1991)
7/ 109 cdhswf3	96	77.9	0	P Berge et al Z Phys C49 187 (1991)
8/ 110 ccfrf2.mi	69	67.8	5	Yang&Bodek model-independent
9/ 111 ccfrf3.md	86	34.8	0	Shaevitz&Seligman model-dependent processed by SK
10/ 201 e605	119	95.7	0	DY Q^3 dSig/dQ dy proton on heavy target
11/ 203 e866f	15	9.7	0	E866 experiment: pd / 2pp
12/ 225 cdfLasy	11	13.4		W production: decay lepton asymmetry CDF Run-1
13/ 140 HN+67F2c	8	9.3	0	H1 neutral current charm
14/ 143 HN+90X0c	10	16.3	8	H1 neutral current charm
15/ 156 ZN+67F2c	18	13.4	0	ZEUS neutral current charm
16/ 157 ZN+80F2c	27	16.7	0	ZEUS neutral current charm
17/ 124 NuTvNuChXN	38	29.6	0	NuTev Neutrino Dimuon Reduced xSec
18/ 125 NuTvNbChXN	33	28.4	0	NuTev Neutrino Dimuon Reduced xSec
19/ 126 CcfrNuChXN	40	48.0	0	Ccfr Neutrino Dimuon Reduced xSec
20/ 127 CcfrNbChXN	38	26.4	0	Ccfr Neutrino Dimuon Reduced xSec
21/ 204 e866ppxf	184	234.	0	E866 experiment: DY pp: Q^3 dSig/dQ dxf
22/ 260 ZyD02a	28	15.6	6	Z rapidity dist. (D0 TeV II-a)
23/ 261 ZyCDF2	29	46.5	6	Z rapidity dist. (CDF TeV II)
24/ 227 cdfLasy2	11	11.4	0	W production: decay lepton asymmetry CDF Run-2
25/ 231 d02Easy1	12	26.0	0	W production: decay elec asymmetry D0 Run-2 Pt>25
26/ 234 d02Masy1	9	14.8	0	W production: decay muon asymmetry D0 Run-2 Pt>20
27/ 504 cdf2jtCor2	72	101.	24	(run II: cor.err; ptmin & ptmax)
28/ 514 d02jtCor2	110	114.	23	(run II: cor.err; ptmin & ptmax)

CT10 NNLO PDFs

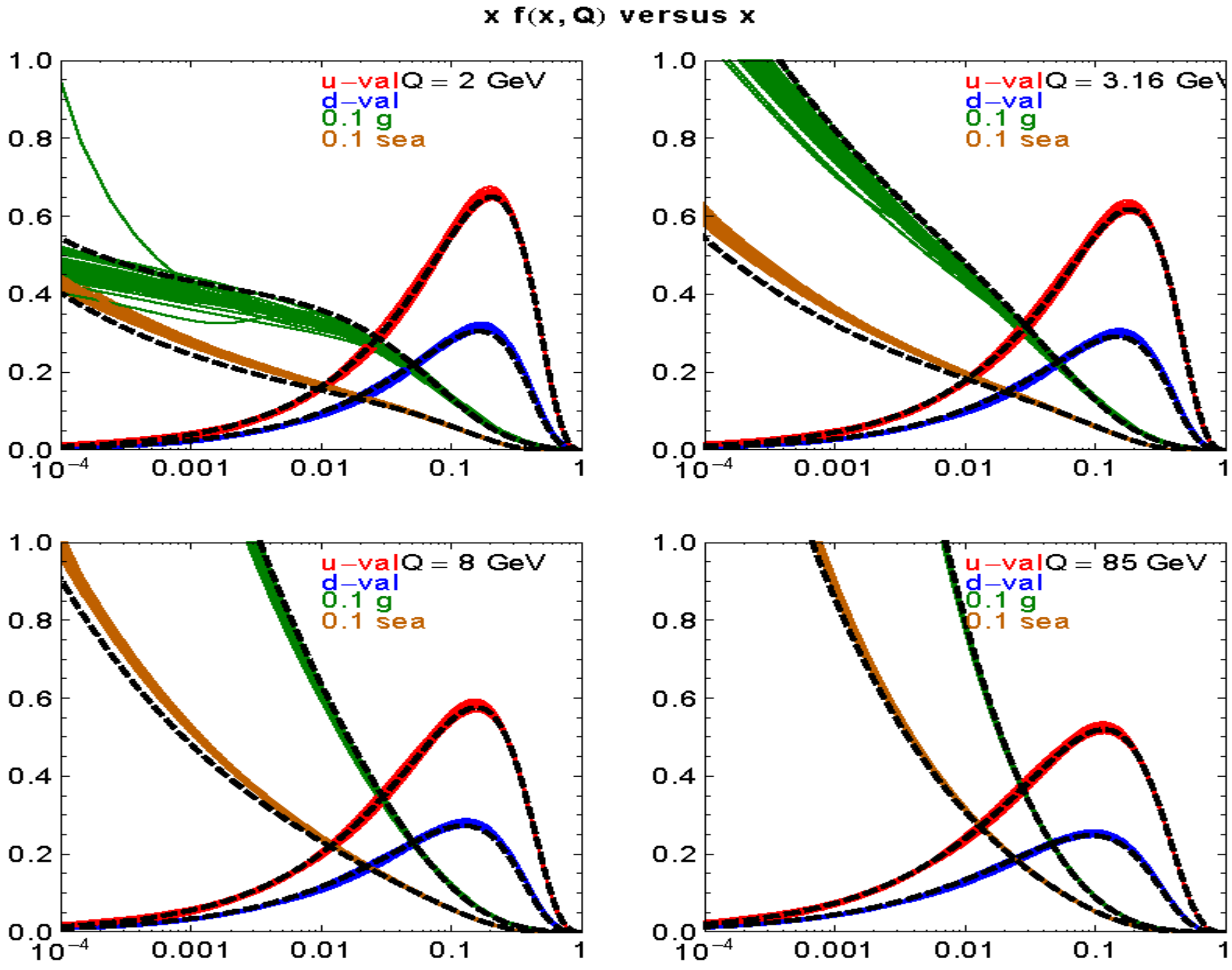
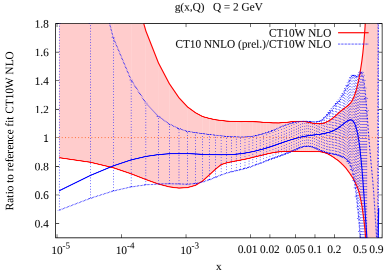
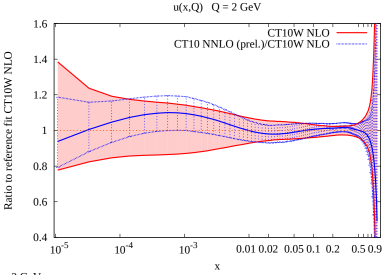
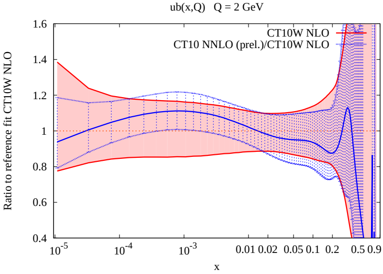


Figure 3: CT10-NNLO parton distribution functions. These figures show the *alternate fits* for the CT10-NNLO analysis. Each graph shows $x\,u_{\text{valence}} = x(u - \overline{u}), x\,d_{\text{valence}} = x(d - \overline{d}), 0.10\,x\,g$ and $0.10\,x\,\overline{q}$sea as functions of x for a fixed value of Q. The values of Q are $2, 3.16, 8, 85$ GeV. Sea $= 2(\overline{d} + \overline{u} + \overline{s})$. The dashed curves are the central NLO fit, CT10.

CT10 NNLO error PDFs (compared to CT10W NLO)







Experimental "Errors" (or, Uncertainties)

An experiment publishes N measurements,

$\{M_i \,;\, i = 1,2,3,\ldots,N\}$.

Each measurement has several parts,

$M_i = \{D_i \,;\, \sigma_{0i} \,;\, \{\sigma_{1i}, \sigma_{2i}, \sigma_{3i}, \ldots\}\}$

= {central value; SD of statistical error; SDs of correlated systematic errors};

that is,

$$D_i = True_i + \sigma_{0i}\, r_{0i} + \sum_{k=1}^{Nsy} \sigma_{ki}\, r_k$$

…where r_{0i} and $\{r_k\}$ are random variables (gaussian?)

Define $$\chi^2 = \sum_i \left(D_i - \sum_k \sigma_{ki} r_k - T_i\right)^2 / \sigma_{0i}^2 + \sum_k r_k^2$$

…and minimize with respect to both the normalized systematic shifts $\{r_k\}$ and the theory parameters.

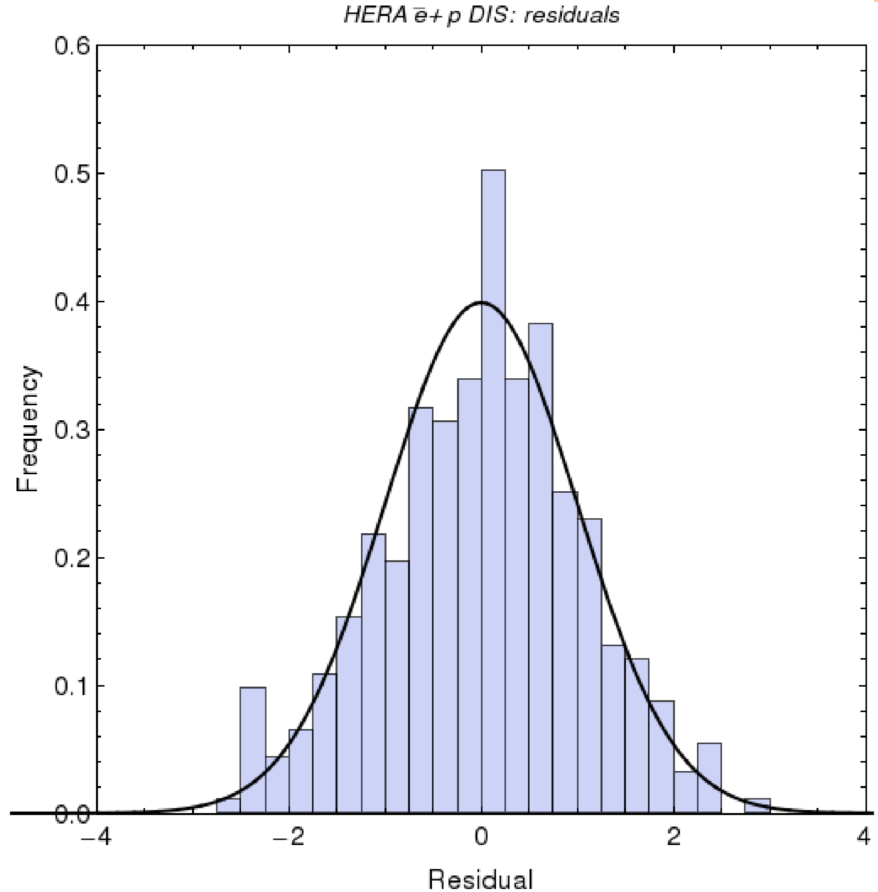
"Histogram of Residuals"

We define the *residual* by

$$\text{Residual}_{\,i} = \frac{sD_i - T_i}{\sigma_{0i}}$$

(i = 1, 2, 3, ..., NDP)

For good agreement between data and theory , the residuals should have a Gaussian distribution with mean = 0 and standard deviation = 1.



Theory = CT10-NNLO, i.e., ***the central fit***;
sData = Data ***MINUS*** the optimized systematic errors;
Black curve = ideal Gaussian distribution

HERA : $\bar{e}$ P → $\bar{e}$ X

HERA Combined Data:

e± p deep inelastic scattering

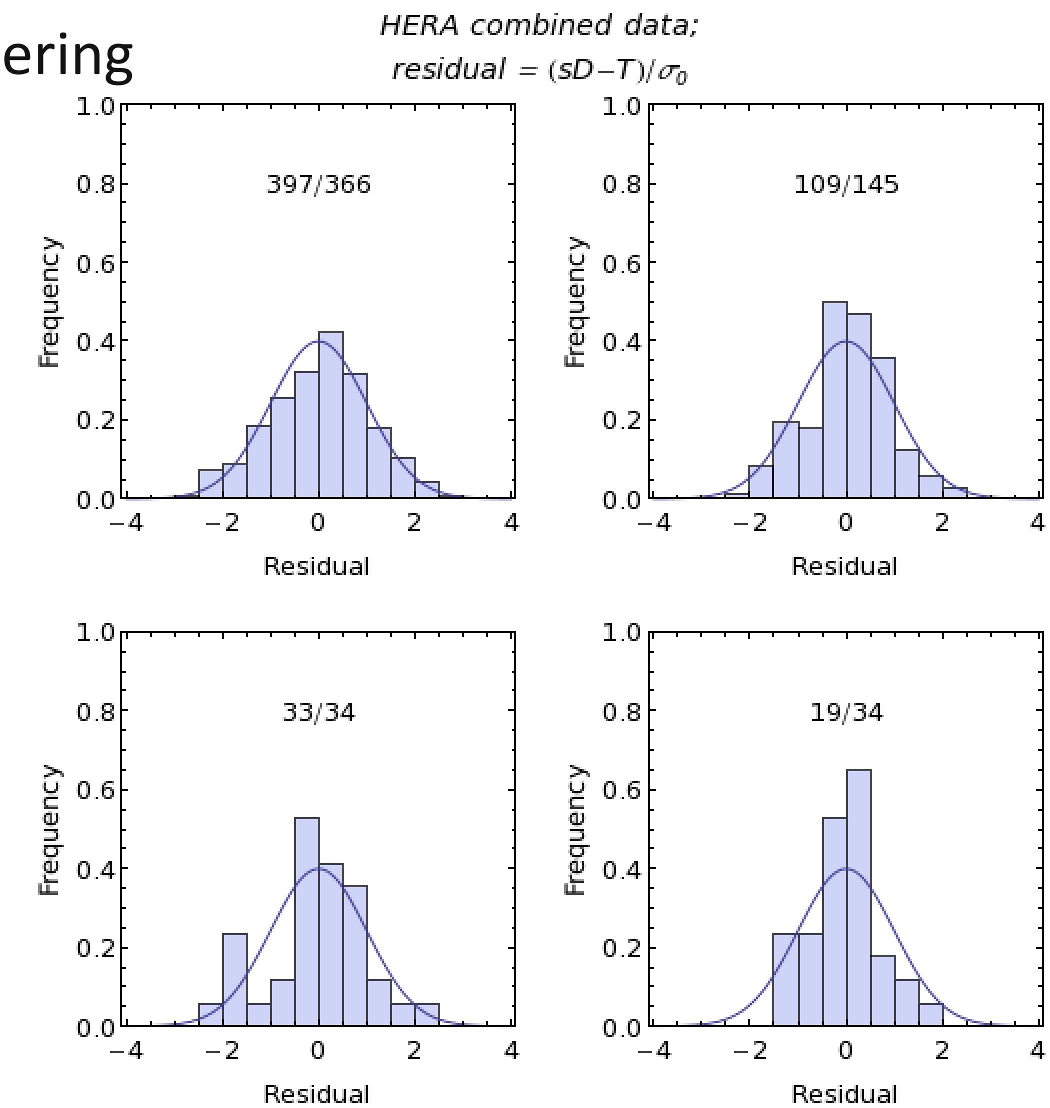
e+ p , NC DIS
$\chi 2$ /N = 397/366

e- p , NC DIS
$\chi 2$ /N =109/145

e+ p , CC DIS
$\chi 2$ /N =33/34

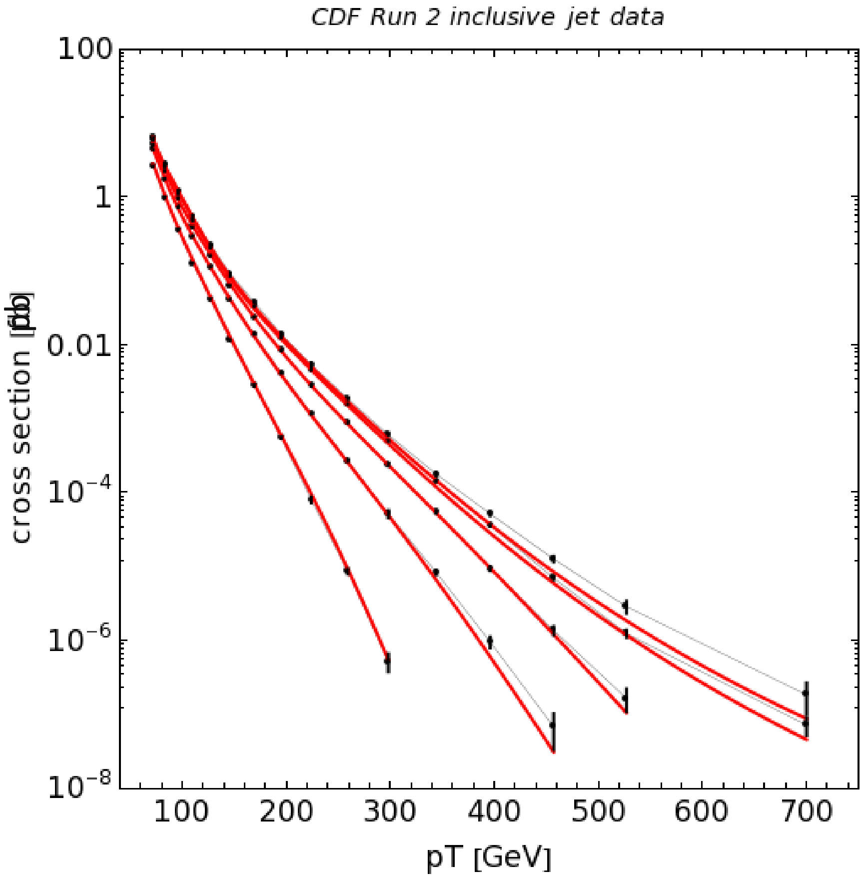
e- p , CC DIS
$\chi 2$ /N = 19/34

The CT10-NNLO central fit

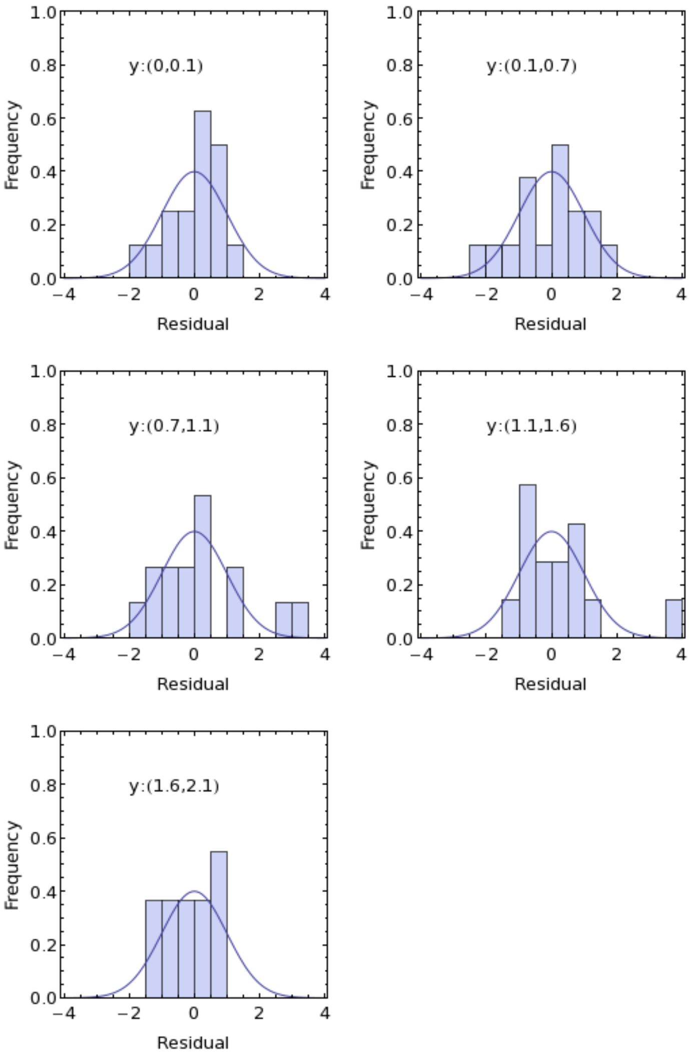


$(N_{dp}, N_{sy}) = (579, 114)$

Inclusive Jet Production in Run 2 at the Tevatron Collider - CDF

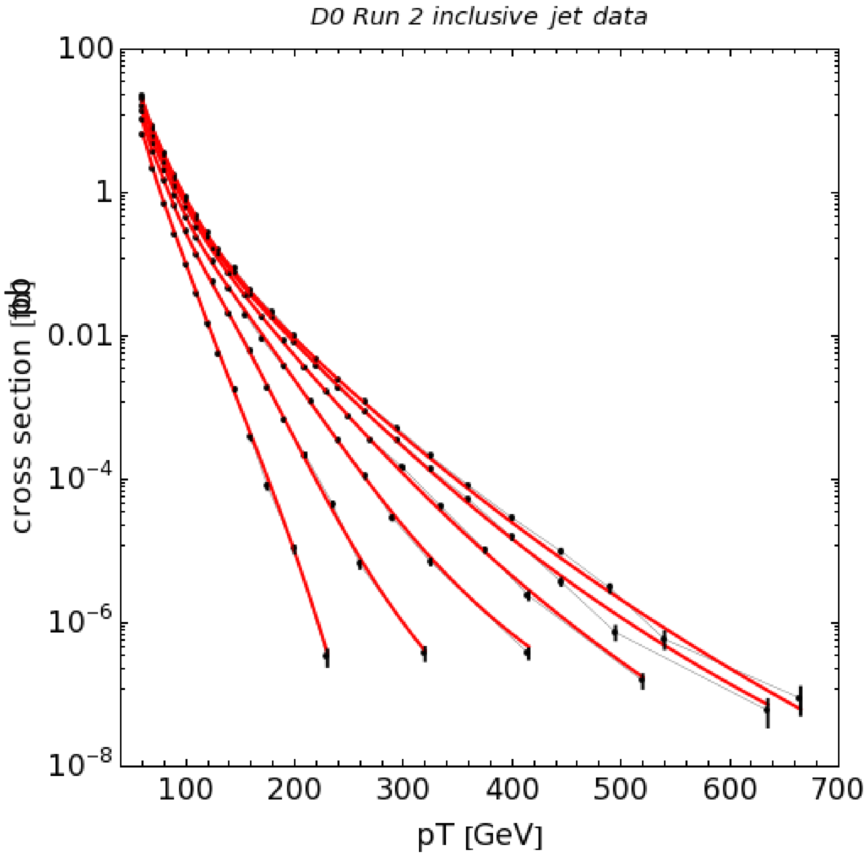


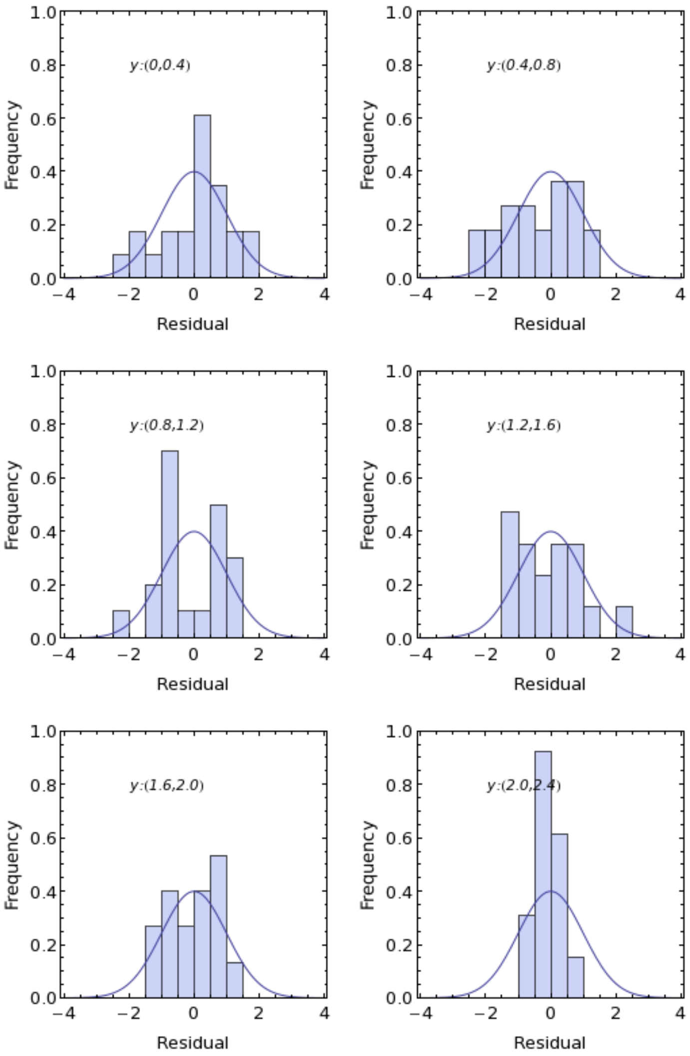
The red curves are the theoretical calculations with CT10-NNLO PDFs, i.e., **the central fit**.



$(N_{dp}, N_{sy}) = (72, 25)$

Inclusive Jet Production in Run 2 at the Tevatron Collider – D0

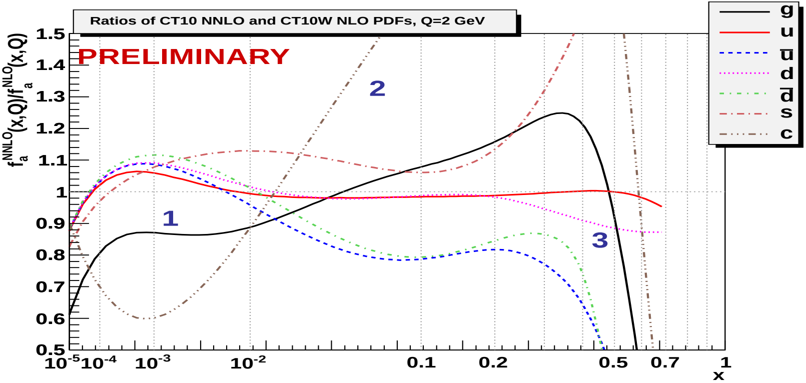




The red curves are the theoretical calculations with CT10-NNLO PDFs, i.e., **<u>the central fit</u>**.

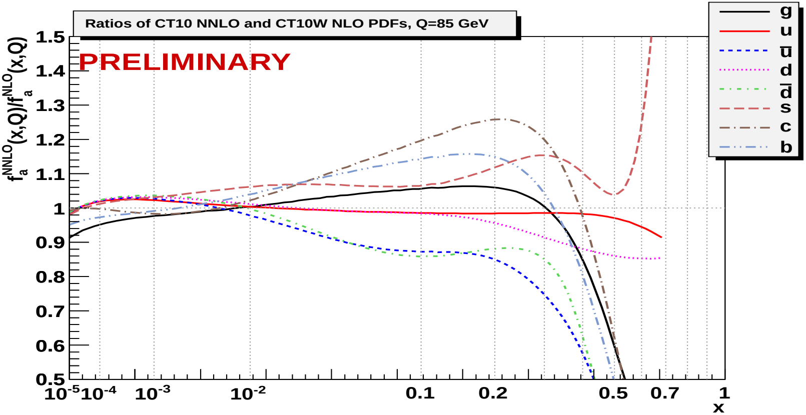
$(N_{dp}, N_{sy}) = (110; 23)$

CT10 NNLO central PDFs, as ratios to NLO, Q=2 GeV



1. At $x < 10^{-2}$, $\mathcal{O}(\alpha_s^2)$ evolution suppresses $g(x,Q)$, increases $q(x,Q)$
2. $c(x,Q)$ and $b(x,Q)$ change as a result of the $\mathcal{O}(\alpha_s^2)$ GM VFN scheme
3. In large x region, $g(x,Q)$ and $d(x,Q)$ are reduced by not including Run-1 inclusive jet data, revised EW couplings, alternative treatment of correlated systematic errors, scale choices.

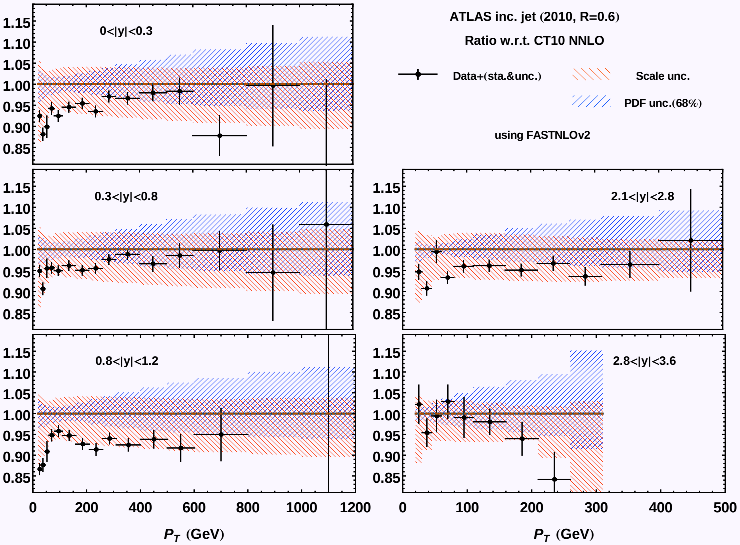
CT10 NNLO central PDFs, as ratios to NLO, Q=85 GeV



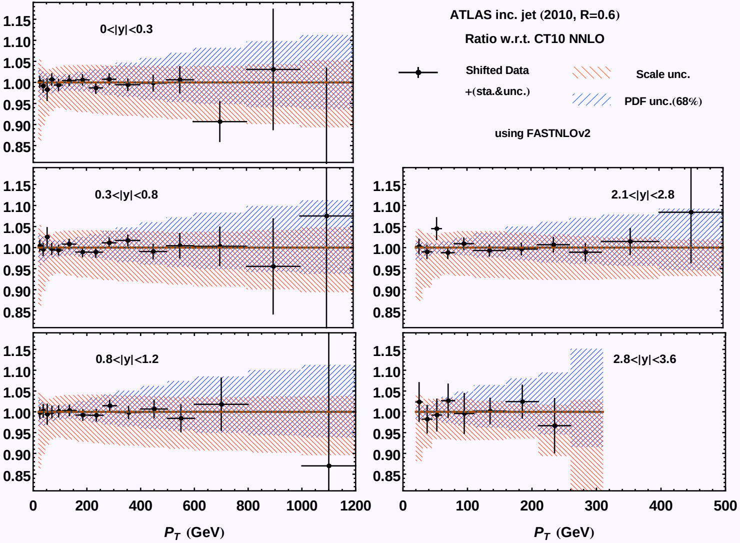
At $x > 0.1$, $d(x,Q)$, $\bar{u}(x,Q)$ and $\bar{d}(x,Q)$ are reduced.

$g(x,Q)$ is also reduced in large x region.

Comparison of CT10 predictions with unshifted ATLAS jet data:

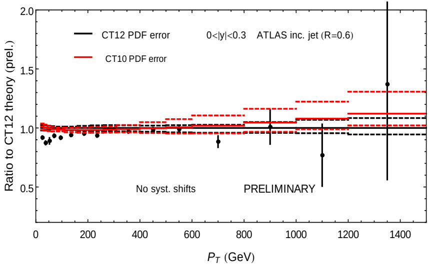


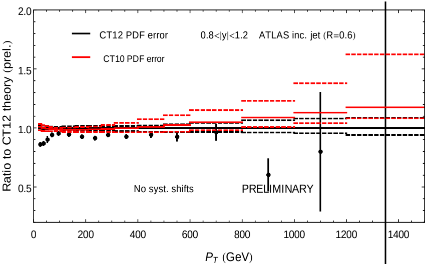
Comparison of CT10 predictions with shifted ATLAS jet data:

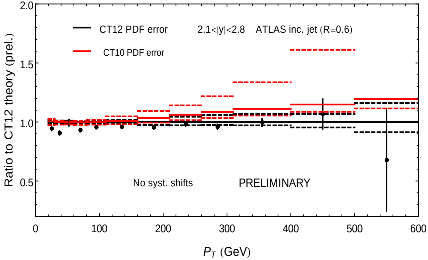


CT12 NLO predictions for LHC jet production

ATLAS single-inclusive jet production *(arXiv:1112.6297)*; FastNLO 2; R=0.6; $\chi^2/N_{d.o.f} = 0.72\,(0.98)$ for CT12 NLO (CT10 NLO)

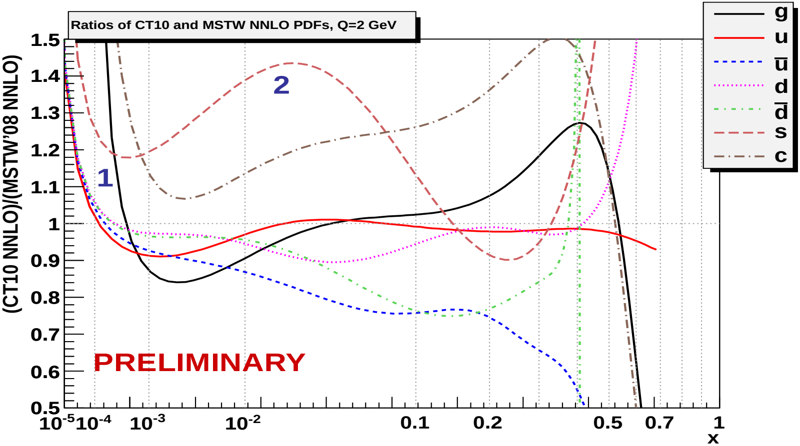






CT10 NNLO and CT12 PDFs (black lines) predict smaller jet cross sections at large p_T, as a result of reduced $g(x, Q)$ in large x region.

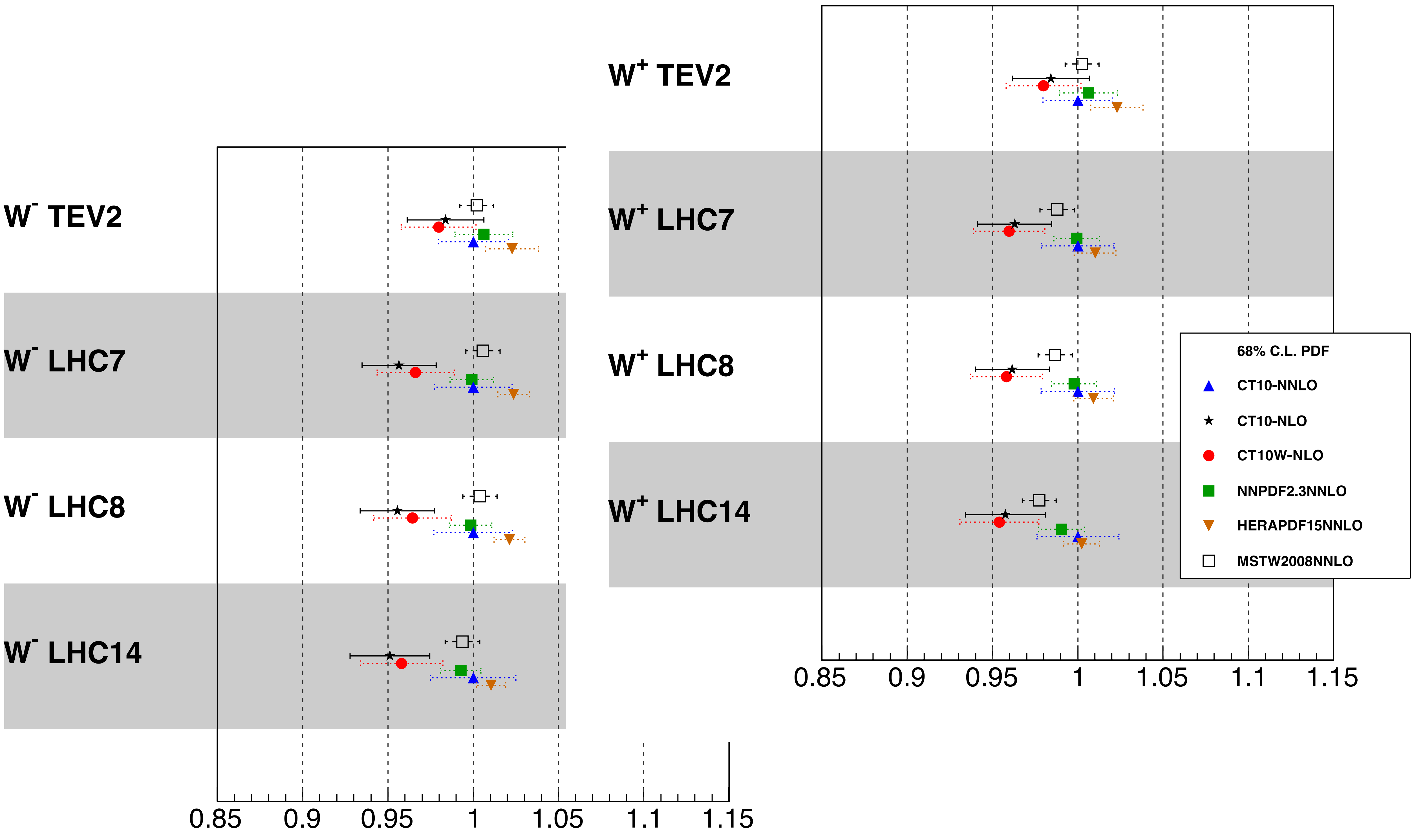
CT10 NNLO PDFs compared to MSTW NNLO



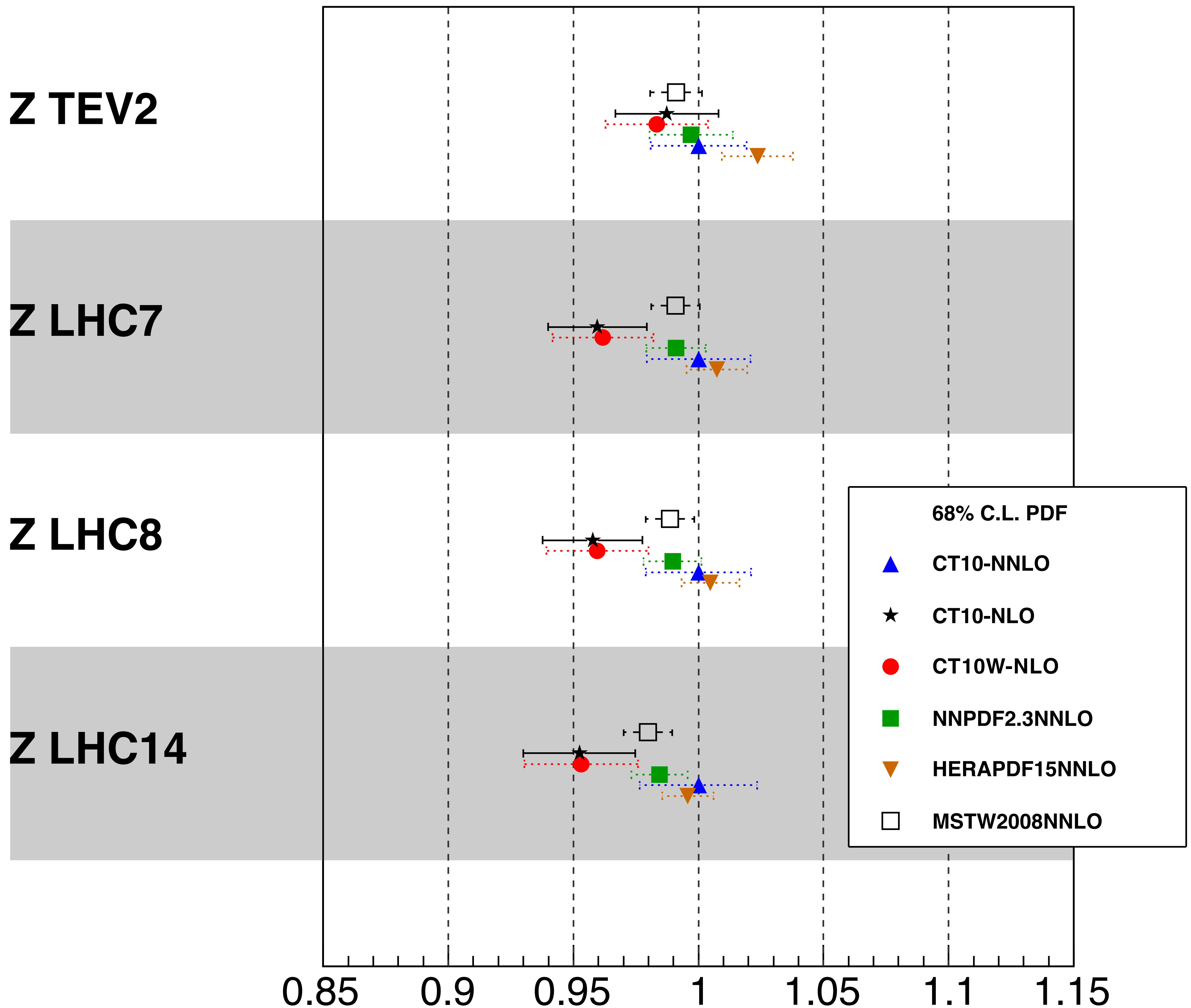
1. CT10 gluon and quarks are harder at $x \to 0$; $g(x, Q_0) > 0$ at $10^{-5} \leq x \leq 1$

2. The CT10 strange PDF is larger at $x \sim 10^{-3}$

CT10-NNLO compared with other PDFs for W boson production (NNLO)

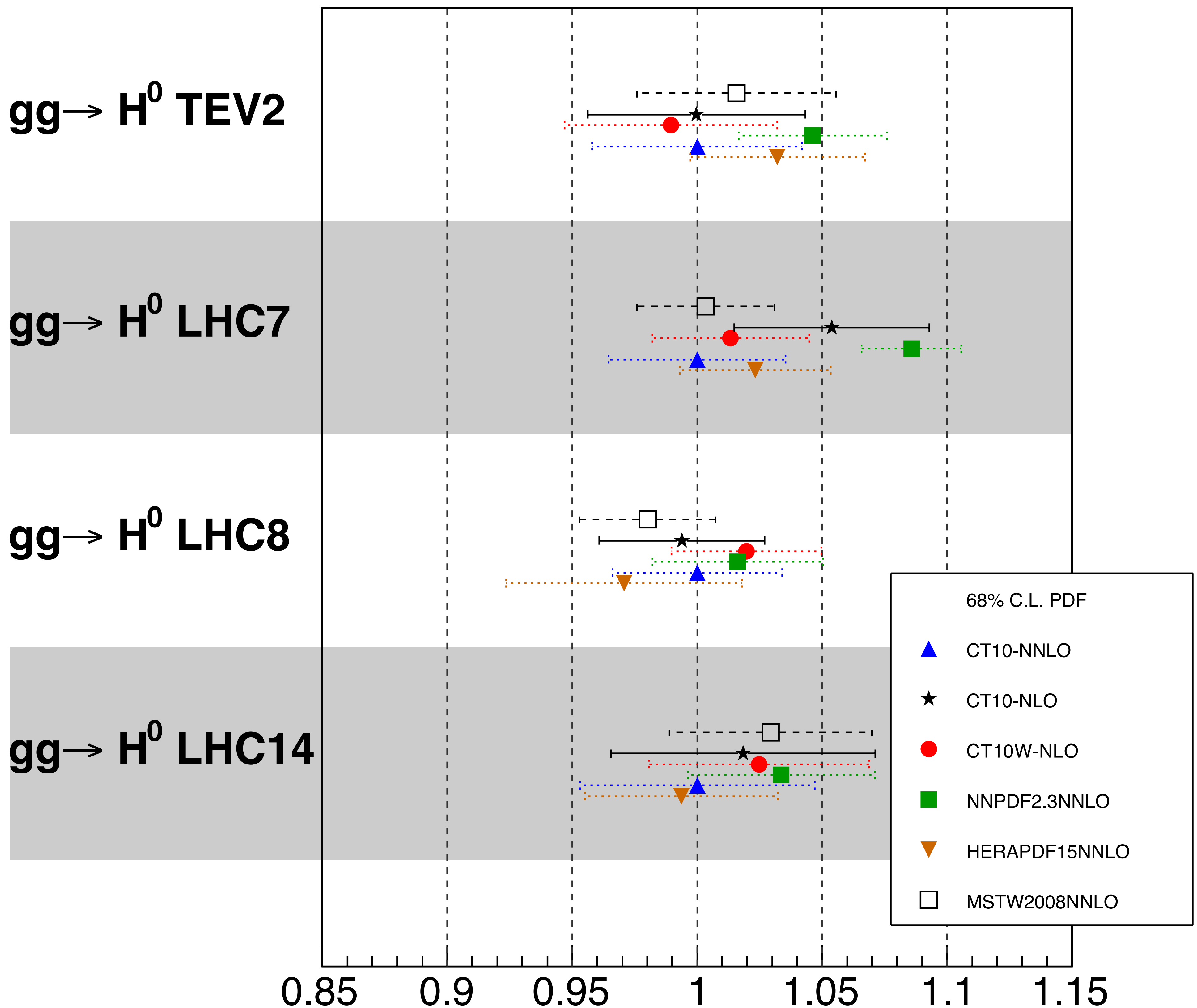


CT10-NNLO compared with other PDFs for Z boson production (NNLO)



CT10-NNLO compared with other PDFs

Use HNNLO1.3



NNLO cross section and PDF induced uncertainty for gg->H (using ResBos2 program)

$$\Delta\sigma_{\mathrm{PDF}} = \frac{1}{2}\sqrt{\sum_{i=1}^{d}\left(\sigma_i^{(+)} - \sigma_i^{(-)}\right)^2}.$$

arXiv:1205.4311 [hep-ph]

M=125 GeV

	CTEQ6.6	CT10 NLO	CT10W NLO	CT10 NNLO	MSTW2008NNLO	NNPDF2.3NNLO
Tevatron	$0.77 \pm 6.9\%$	$0.77 \pm 6.9\%$	$0.76 \pm 7.0\%$	$0.77 \pm 6.9\%$	$0.78 \pm 6.4\%$	$0.80 \pm 4.6\%$
LHC 7 TeV	$12.80 \pm 6.1\%$	$13.33 \pm 6.1\%$	$12.82 \pm 5.1\%$	$12.65 \pm 5.8\%$	$12.69 \pm 4.5\%$	$13.73 \pm 3.0\%$
LHC 8 TeV	$16.31 \pm 5.5\%$	$16.53 \pm 5.5\%$	$16.95 \pm 4.8\%$	$16.63 \pm 5.6\%$	$16.30 \pm 4.5\%$	$16.90 \pm 5.5\%$
LHC 14 TeV	$42.39 \pm 8.5\%$	$42.64 \pm 8.5\%$	$42.91 \pm 7.1\%$	$41.87 \pm 7.7\%$	$43.10 \pm 6.4\%$	$43.28 \pm 5.9\%$

TABLE II: The total cross sections (in pb) for Higgs boson production via $g + g \to H + X$ at the Tevatron (1.96 TeV) and LHC (7 TeV, 8 TeV and 14 TeV) by using different PDF sets in ResBos2. The PDF induced uncertainties are estimated at 90% confidence-level, and expressed in the form of percentages.

Uncertainties of cross sections for gg->H (using ResBos2 program)

$$\Delta\sigma_{\alpha_s} = \frac{1}{2}\sqrt{[\sigma_0(A_{-2}) - \sigma_0(A_2)]^2}.$$

(at 90% CL, with the range of 0.116 to 0.120)

$$(\Delta\sigma)^2 = (\Delta\sigma_{\rm PDF})^2 + (\Delta\sigma_{\alpha_s})^2 .$$

M=125 GeV

CT10-NNLO	σ_0	$\Delta\sigma_{\rm PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma = \sqrt{(\Delta\sigma_{\rm PDF})^2 + (\Delta\sigma_{\alpha_s})^2}$
Tevatron	0.77	±6.9%	±1.8%	±7.1%
LHC 7 TeV	12.65	±5.8%	±2.5%	±6.3%
LHC 8 TeV	16.63	±5.6%	±3.5%	±6.6%
LHC 14 TeV	41.87	±7.7%	±5.3%	±9.3%

Total NNLO cross section for gg->H (comparing various codes)

	m_H (GeV)	ResBos2	ResBos	HNNLO (NNLO)	HqT2 (NNLL+NLO)
Tevatron	115	$0.98^{+9.2\%}_{-6.1\%}$	$0.91^{+15.7\%}_{-6.9\%}$	$0.96^{+13.6\%}_{-13.7\%}$	$0.97^{+14.2\%}_{-13.8\%}$
	120	$0.87^{+9.2\%}_{-6.9\%}$	$0.80^{+15.8\%}_{-6.6\%}$	$0.84^{+13.4\%}_{-13.7\%}$	$0.85^{+13.9\%}_{-13.8\%}$
	125	$0.77^{+9.1\%}_{-6.5\%}$	$0.71^{+15.9\%}_{-6.5\%}$	$0.75^{+13.5\%}_{-14.2\%}$	$0.75^{+13.8\%}_{-13.8\%}$
	130	$0.68^{+10.3\%}_{-5.9\%}$	$0.63^{+15.9\%}_{-6.4\%}$	$0.66^{+14.5\%}_{-13.1\%}$	$0.67^{+13.9\%}_{-13.8\%}$
LHC 7 TeV	115	$15.11^{+7.8\%}_{-5.8\%}$	$14.21^{+8.3\%}_{-5.9\%}$	$15.16^{+9.0\%}_{-10.7\%}$	$15.19^{+10.8\%}_{-10.4\%}$
	120	$13.89^{+7.8\%}_{-5.7\%}$	$13.06^{+8.4\%}_{-5.8\%}$	$13.80^{+10.6\%}_{-10.5\%}$	$13.94^{+10.2\%}_{-10.4\%}$
	125	$12.80^{+7.7\%}_{-5.5\%}$	$12.03^{+8.5\%}_{-5.6\%}$	$12.72^{+10.2\%}_{-10.6\%}$	$12.83^{+10.7\%}_{-10.4\%}$
	130	$11.83^{+7.7\%}_{-5.4\%}$	$11.12^{+8.6\%}_{-5.5\%}$	$11.75^{+10.8\%}_{-10.7\%}$	$11.84^{+9.9\%}_{-10.4\%}$
LHC 8 TeV	115	$19.15^{+7.5\%}_{-6.5\%}$	$17.58^{+8.1\%}_{-7.1\%}$	$19.05^{+9.9\%}_{-9.2\%}$	$19.25^{+10.8\%}_{-9.8\%}$
	120	$17.65^{+7.5\%}_{-6.5\%}$	$16.21^{+8.1\%}_{-7.1\%}$	$17.59^{+9.7\%}_{-9.9\%}$	$17.76^{+9.8\%}_{-10.1\%}$
	125	$16.31^{+7.5\%}_{-6.4\%}$	$14.98^{+8.1\%}_{-7.0\%}$	$16.26^{+10.2\%}_{-10.4\%}$	$16.39^{+9.8\%}_{-10.1\%}$
	130	$15.11^{+7.5\%}_{-6.4\%}$	$13.89^{+8.1\%}_{-7.0\%}$	$15.07^{+10.9\%}_{-10.6\%}$	$15.17^{+10.3\%}_{-10.1\%}$
LHC 14 TeV	115	$48.84^{+7.6\%}_{-5.7\%}$	$46.03^{+10.0\%}_{-5.3\%}$	$49.24^{+9.4\%}_{-9.8\%}$	$48.90^{+9.0\%}_{-9.8\%}$
	120	$45.45^{+7.5\%}_{-5.5\%}$	$42.84^{+9.8\%}_{-5.2\%}$	$45.57^{+10.4\%}_{-9.5\%}$	$45.52^{+10.3\%}_{-8.4\%}$
	125	$42.39^{+7.4\%}_{-5.4\%}$	$39.96^{+9.6\%}_{-5.0\%}$	$42.61^{+9.6\%}_{-9.7\%}$	$42.57^{+9.7\%}_{-8.8\%}$
	130	$39.65^{+7.3\%}_{-5.2\%}$	$37.38^{+9.4\%}_{-4.8\%}$	$39.93^{+11.1\%}_{-9.8\%}$	$39.75^{+9.7\%}_{-8.9\%}$

TABLE I: The ResBos2, ResBos, HNNLO and HqT2 predictions on the total cross sections (in pb) for Higgs boson production via $g+g \to H+X$ at the Tevatron (1.96 TeV) and LHC (7 TeV, 8 TeV and 14 TeV). The upper (lower) uncertainties, expressed in the form of percentages, are obtained by dividing (multiplying) the canonical scale by a factor of two.

Transverse momentum distribution of Higgs boson via gg->H

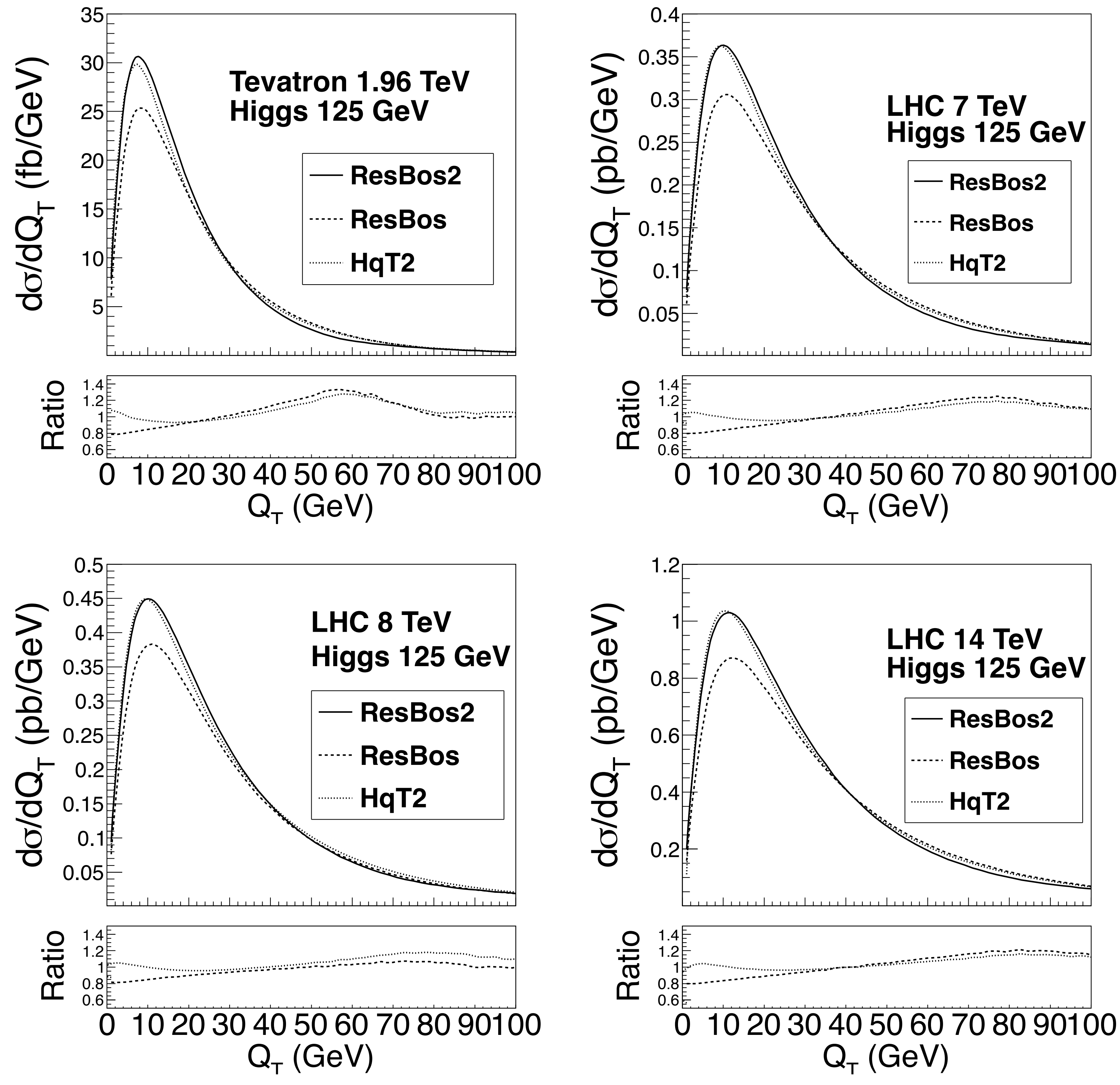
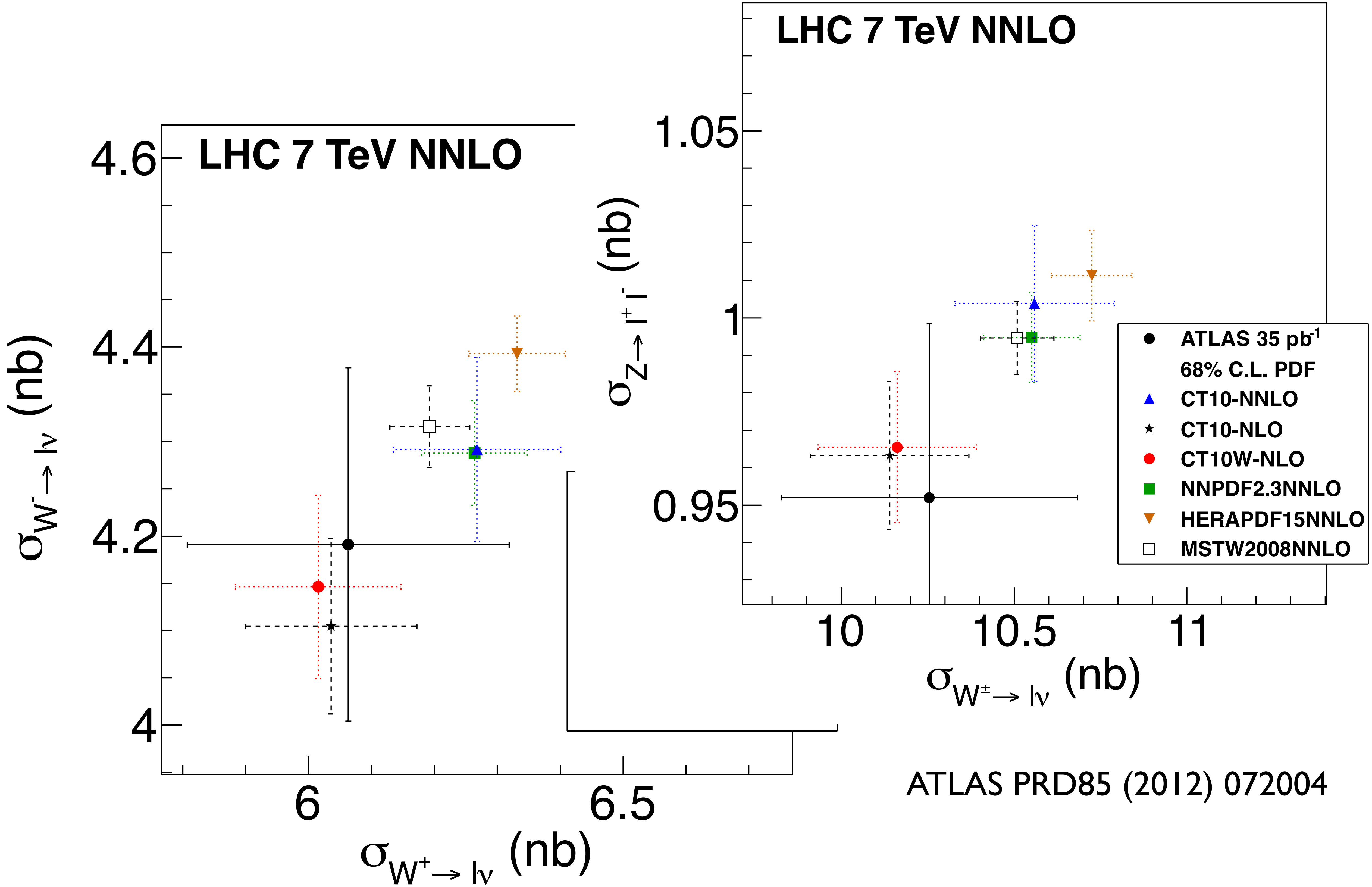


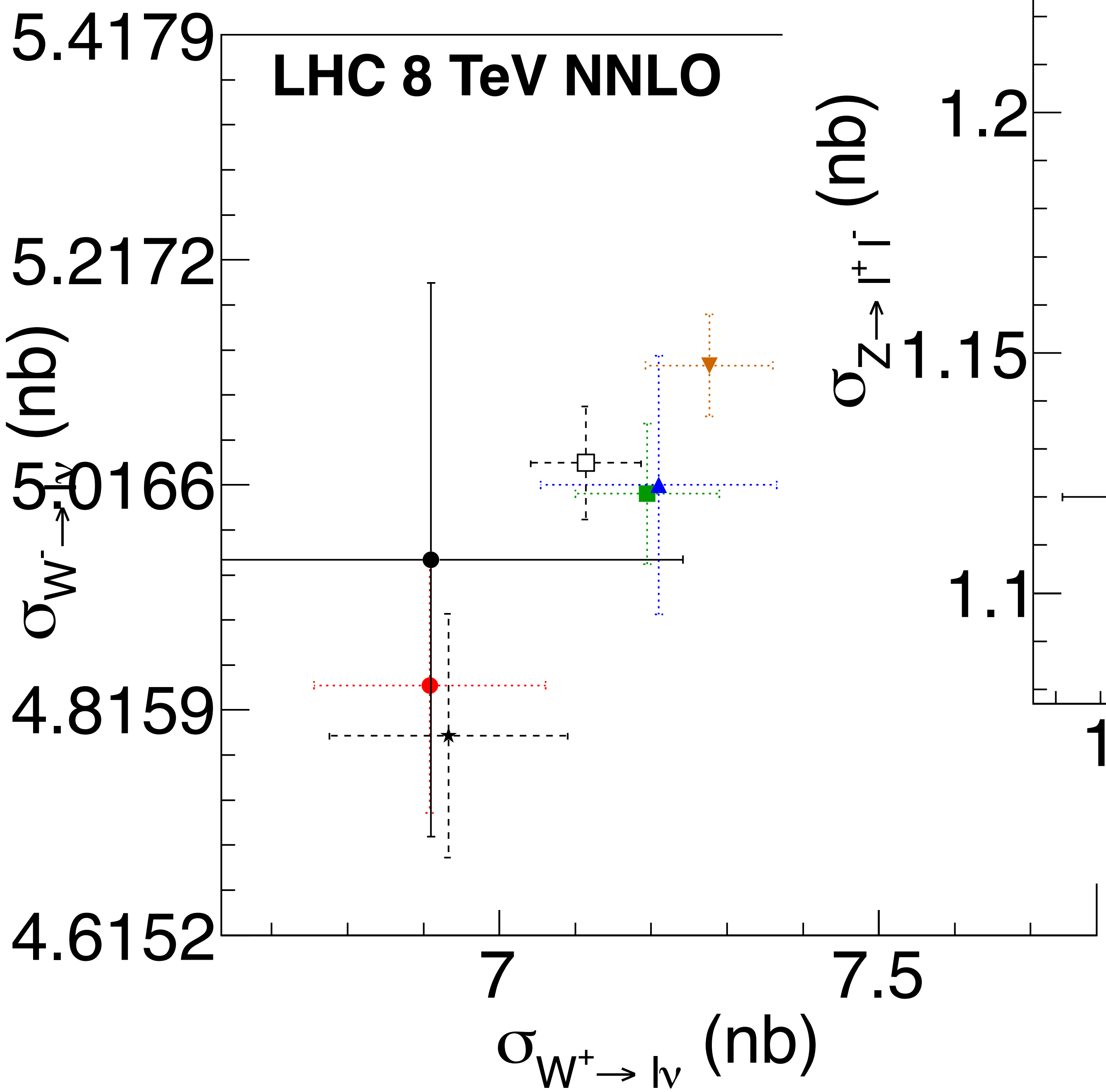
FIG. 1: The different theoretical predictions on the transverse momentum distributions for the Higgs boson production at the Tevatron (1.96 TeV) and the LHC (7 TeV, 8 TeV and 14 TeV). In the bottom of each plot, the ratios to ResBos2 predictions are also shown.

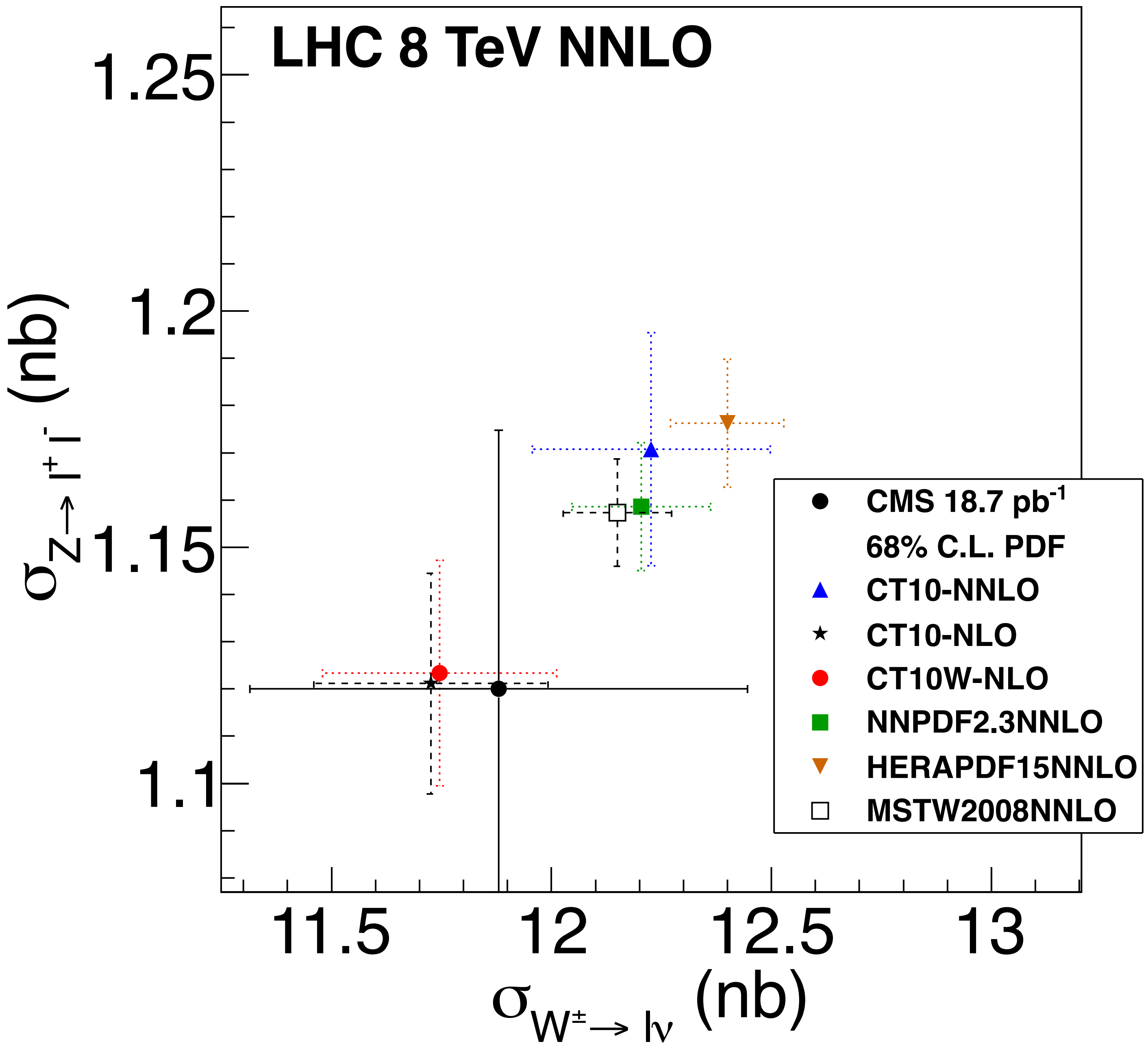
Comparison between Z and W NNLO cross sections (7 TeV)



ATLAS PRD85 (2012) 072004

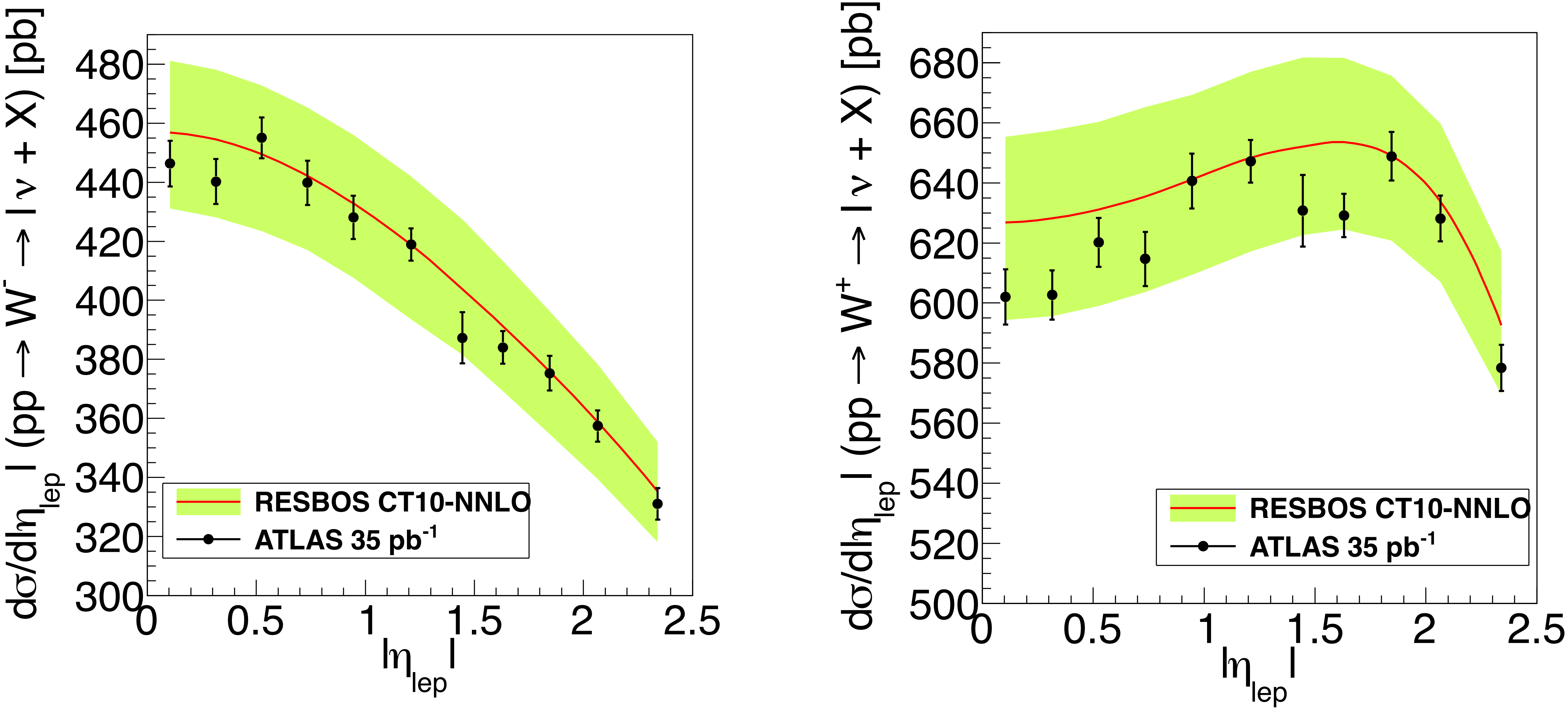
Comparison between Z and W NNLO cross sections (8 TeV)





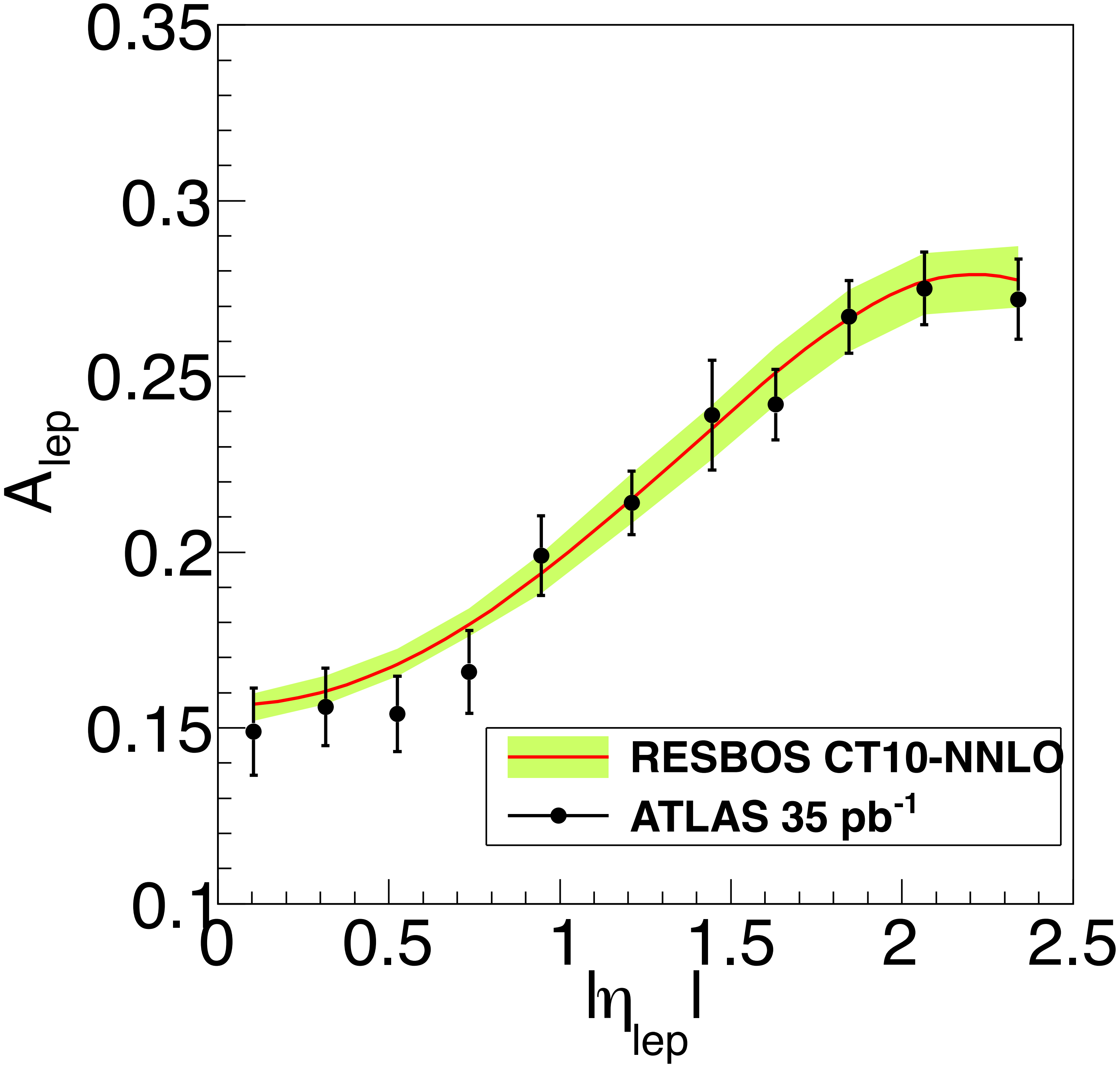
CMS-PAS-SMP-12-011(2012)

ResBos predictions for W-lepton rapidity distribution using CT10-NNLO



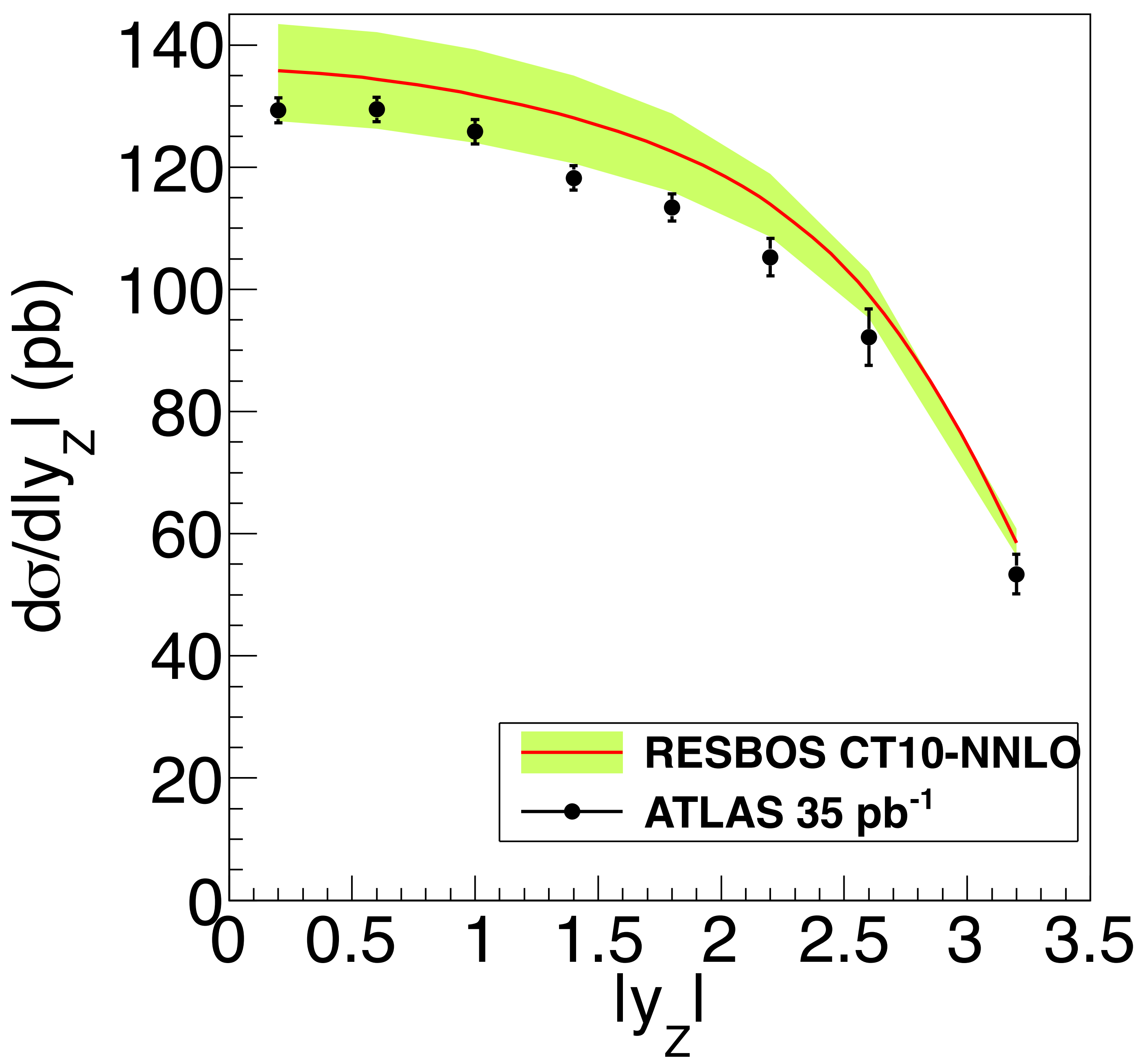
ATLAS Collaboration, PRD85 (2012) 072004

ResBos predictions for W-lepton charge asymmetry using CT10-NNLO



ATLAS Collaboration, PRD85 (2012) 072004

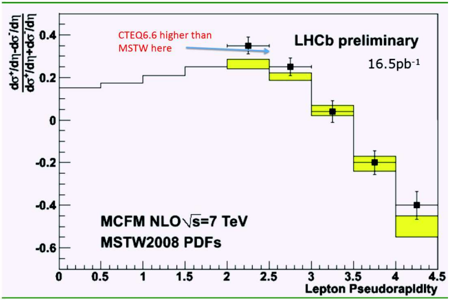
ResBos predictions for Z rapidity distribution using CT10-NNLO

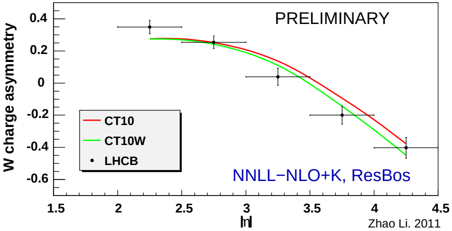


ATLAS Collaboration, PRD85 (2012) 072004

CT10(W) vs. A_ℓ: LHC-B

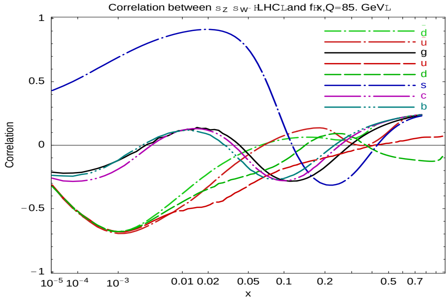
LHCb asymmetry measurement; from PDF4LHC Mar 7



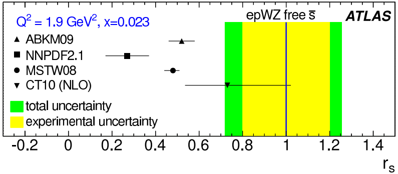


LHC-B marginally prefers CT10W

Strangeness in CT12 PDFs and LHC W/Z cross sections



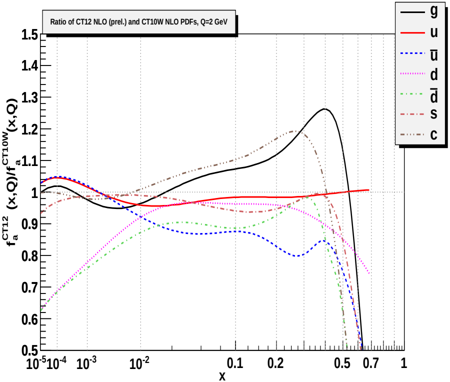
In 2008, our CTEQ6.6 PDF correlation analysis pointed out the sensitivity of ratios σ_W/σ_Z at the LHC to the strangeness PDF, with implications to EW precision measurements *(Nadolsky, Lai, Cao, Huston, Pumplin, Tung, Yuan, PRD, 78 (2008) 013004)*.

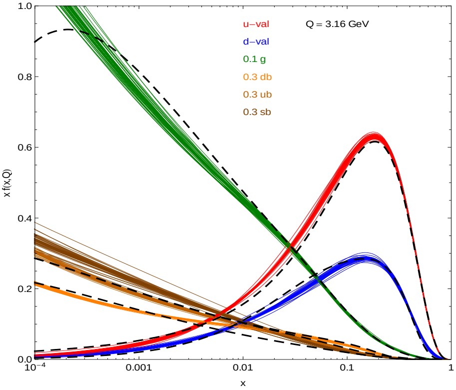


The ATLAS analysis (arXiv:1203.4051) of W and Z production suggests that $\bar{s}(x,Q)/\bar{d}(x,Q) = 1.00^{+0.25}_{-0.28}$ at $x = 0.023$ and $Q^2 = 1.9$ GeV^2

What is the impact of LHC W and Z data on CT12 PDFs?

Small-x limits of $\bar{d}(x,Q)/\bar{u}(x,Q)$ and $\bar{s}(x,Q)/\bar{u}(x,Q)$ in the CT12 analysis (PRELIMINARY)





The CT12 analysis explores the possibility of $\lim_{x\to 0} \bar{d}/\bar{u} \neq 1$. Some "unbiased" CT12 candidate fits have $\bar{s}(x,Q)/\bar{u}(x,Q) > 1$ at $x < 10^{-3}$.

We would like to better understand the flavor decomposition at small x before releasing the CT12 PDFs.

Conclusions

- The CT10 NNLO PDF analysis (based on pre-LHC data only) is released. It is based on a new streamlined implementation of heavy-quark DIS contributions at two loops *(Guzzi et al., arXiv:1108.5112).*

- The CT12 NLO and NNLO analysis (in progress) will include latest LHC data on W, Z, and jet production. Possible impact on $SU(3)$ properties of quark sea at $x < 10^{-3}$.

- Several factors that are comparable to NNLO contributions (treatment of percentage corr. syst. errors, choices of scales, electroweak radiative contributions, ...) have been thoroughly examined in this analysis

- We use a specific choice to evaluate these factors in the CT12 (N)NLO fits. The uncertainty associated with this choice need to be examined in the future