PDF benchmarking with LHC data

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PDF4LHC Workshop 08/10/2012

Work in collaboration with R. Ball, S. Carrazza, L. del Debbio, S. Forte, N. Hartland, J. Huston, J. Gao, P. Nadolsky, and R. Thorne

PDF benchmarking

- Several groups provide **regular updates of their PDF sets**. These differ by the choice of dataset, statistical methodology, treatment of higher order corrections and of the strong coupling, heavy quarks ...
- Benchmarking exercises between PDF groups have been performed in the past, and have been instrumental for **understanding differences and similarities between PDF sets**, and lead to improved convergence of some of them
- In this talk: updated benchmarking of the most recent PDF sets

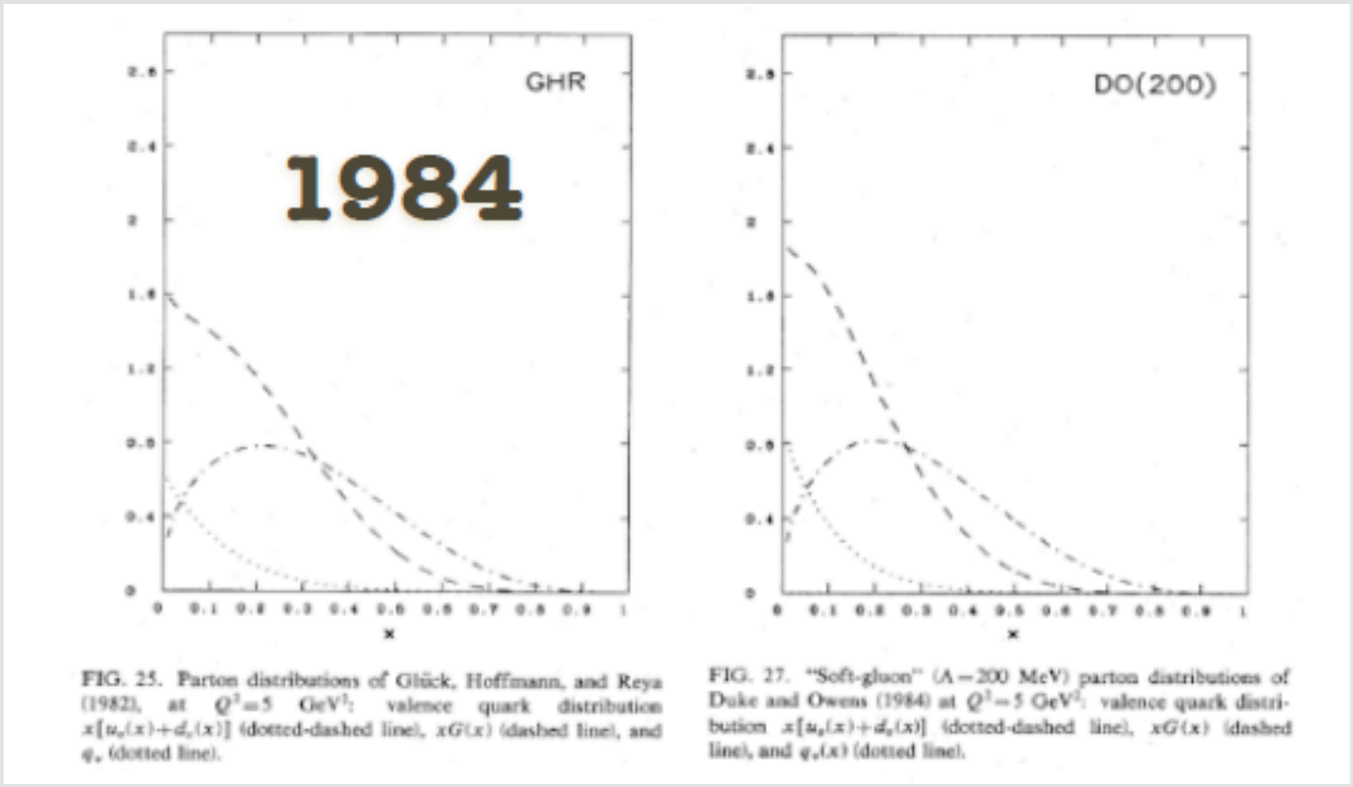
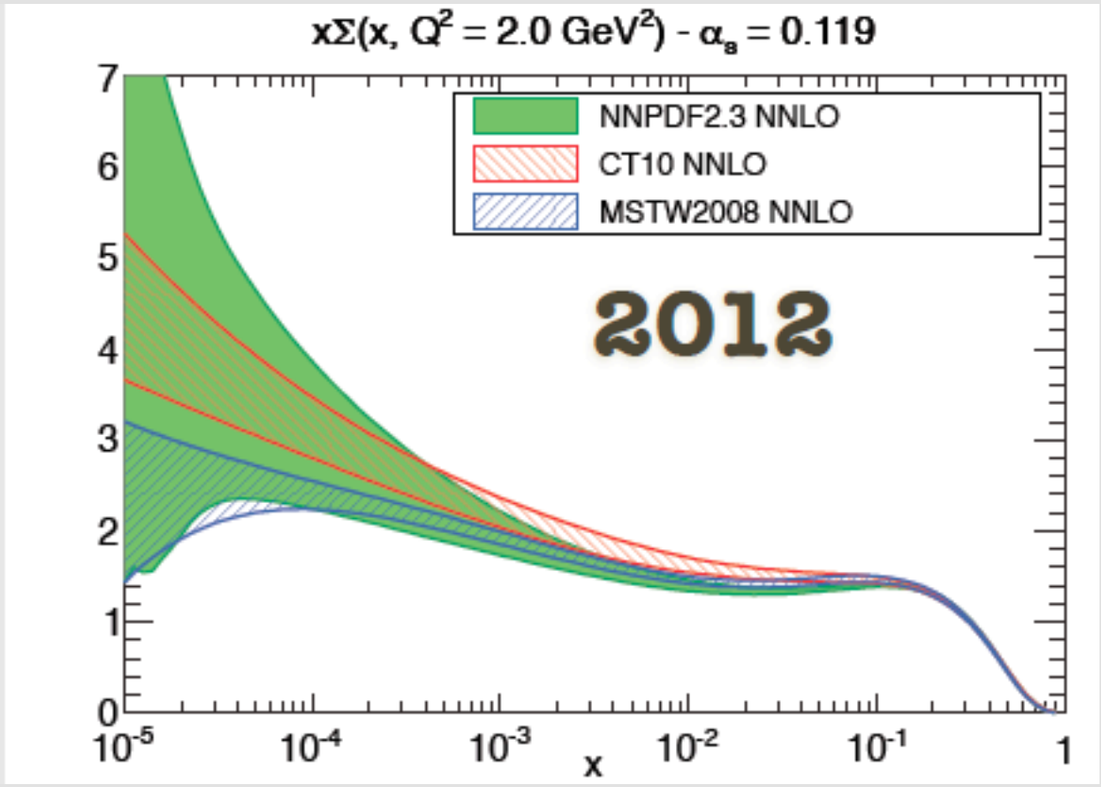


FIG. 25. Parton distributions of Glück, Hoffmann, and Reya (1982), at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and q_s (dotted line).

FIG. 27. "Soft-gluon" ($\Lambda=200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).



PDF benchmarking

Collaboration	Authors	arXiv
ABM	S. Alekhin, J. Blümlein, S. Moch	1105.5349, 1101.5261, 1107.3657, 0908.3128, 0908.2766, ...
CTEQ/TEA	M. Guzzi J. Huston, H.-L. Lai, P. Nadolsky, J. Pumplin, D. Stump, C.-P. Yuan	1108.5112, 1101.0561, 1007.2241, 1004.4624, 0910.4183, 0904.2424, 0802.0007, ...
GJR	M. Glück, P. Jimenez-Delgado, E. Reya	1003.3168, 0909.1711, 0810.4274, ...
HERAPDF	H1 and ZEUS Collaborations	1107.4193, 1006.4471, 0906.1108, ...
MSTW	A. Martin, J. Stirling, R. Thorne, G. Watt	1107.2624, 1006.2753, 0905.3531, 0901.0002, ...
NNPDF	R. D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, AG, N. P. Hartland, J. I. Latorre, J. Rojo, M. Ubiali	1110.2483, 1108.2758, 1107.2652, 1103.2369, 1102.3182, 1101.1300, 1005.0397, 1002.4407, 0912.2276, 0906.1958, ...

(A. Guffanti)

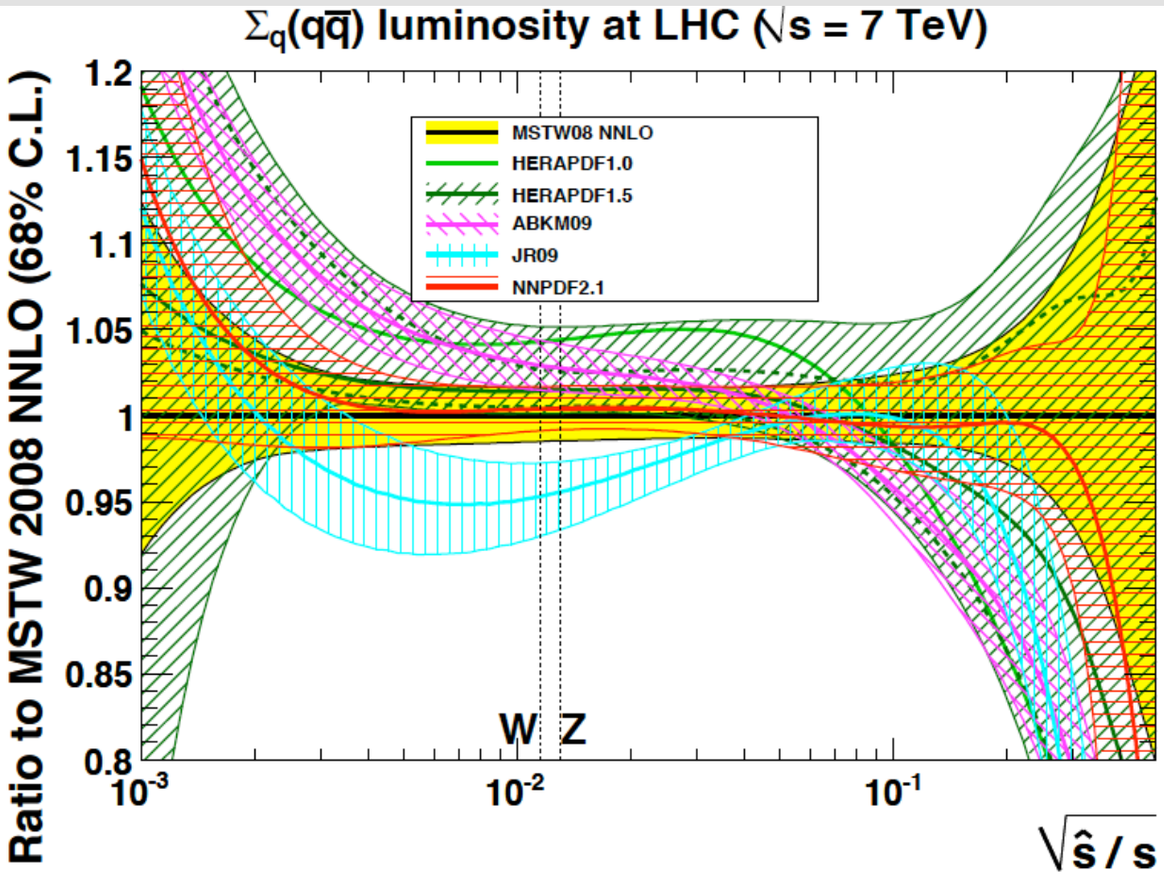
PDF benchmarking

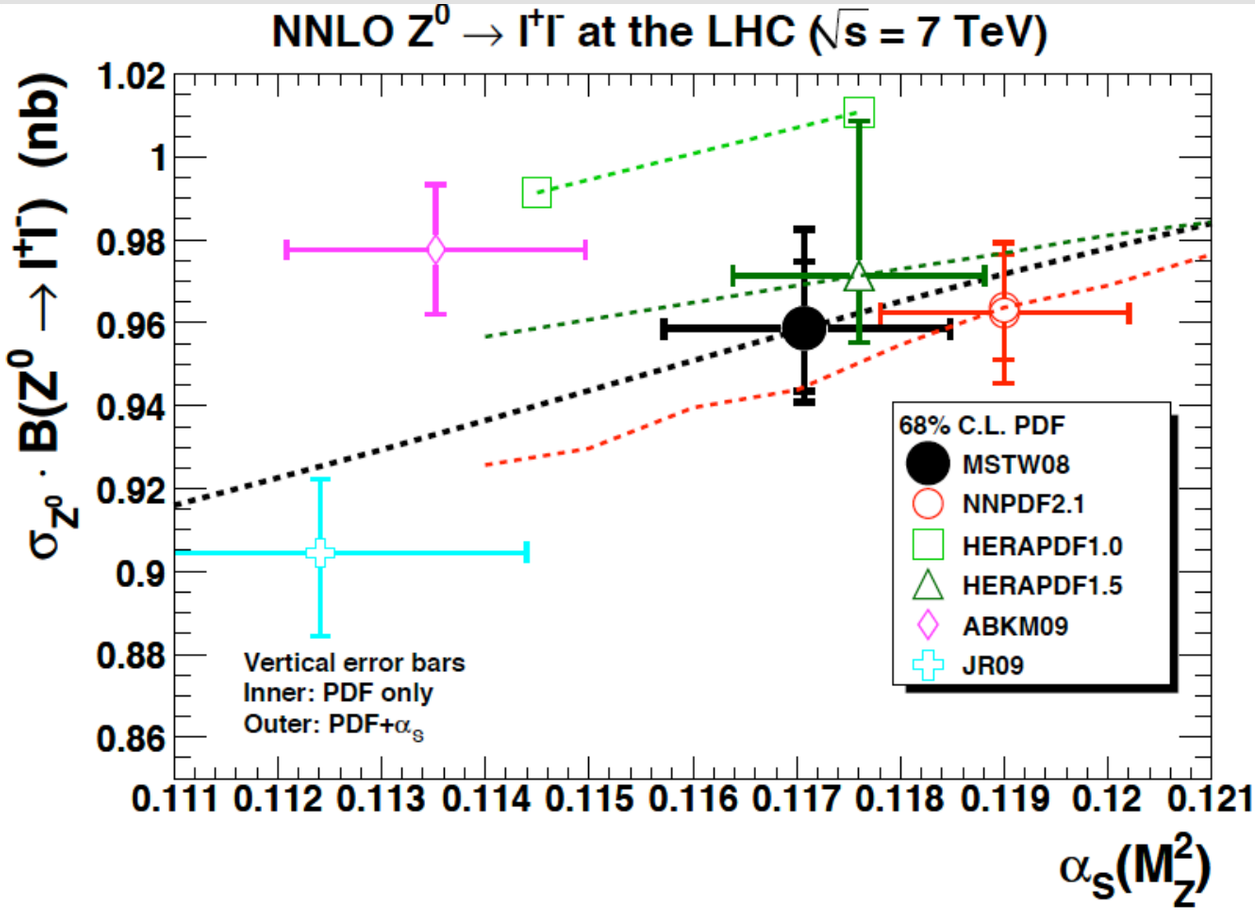
	DATASET	PERT. ORDER	HQ TREATMENT	α_s	PARAM.	UNCERT.
ABM11	DIS Drell-Yan	NLO NNLO	FFN (BMSN)	Fit (multiple values available)	6 indep. PDFs Polynomial (25 param.)	Hessian ($\Delta\chi^2$=1)
CT10	**Global**	LO NLO NNLO	GM-VFNS (S-ACOT)	External (multiple values available)	6 indep. PDFs Polynomial (26 param.)	Hessian ($\Delta\chi^2$=100)
JR09	DIS Drell-Yan Jets	NLO NNLO	FFN VFN	Fit	5 indep. PDFs Polynomial (15 param.)	Hessian ($\Delta\chi^2$=1)
HERAPDF1.5	DIS (HERA)	NLO NNLO	GM-VFNS (TR)	External (multiple values available)	5 indep. PDFs Polynomial (14 param.)	Hessian ($\Delta\chi^2$=1)
MSTW08	**Global**	LO NLO NNLO	GM-VFNS (TR)	Fit (multiple values available)	7 indep. PDFs Polynomial (20 param.)	Hessian ($\Delta\chi^2$~25)
NNPDF2.1/2.3	**Global**	LO NLO NNLO	GM-VFNS (FONLL)	External (multiple values available)	7 indep. PDFs Neural Nets (259 param.)	Monte Carlo

(A. Guffanti)

PDF benchmarking - 2010/2011

- **Systematic PDF benchmarking** studies using 2010/2011 PDFs by **G. Watt** (arxiv:1106.5788,1201.1295)
- Instrumental to understand in a systematic way common aspects and differences between PDF sets. Input to the current **PDF4LHC interim report** and **recommendations**





- Our aim is to update t**his benchmarking exercise** with **2012 NNLO PDFs** and with all the available (inclusive and differential) **LHC data**

PDF benchmarking

- Since last benchmark study new PDF sets have been released:
  - **NNPDF2.3**: inclusion of ATLAS, CMS and LHCb W,Z and jet data (arXiv:1207.1303)
  - **ABM11**: HERA-I data, running heavy quark masses, N_F=5 PDF sets for different values of α_S (arXiv:1202.2281)
  - **CT10 NNLO**: update of CT10 NLO with the same dataset (arXiv: 1206.3321)

- In addition, LHC **7 TeV differential distributions** with covariance matrix and **8 TeV inclusive cross sections** are also available
- Thus a **new detailed benchmarking exercise** is timely and useful for the community (*ie* as input for new PDF4LHC recommendations)

- **JR09** not included because PDF sets provided for single value of α_S = **0.1134**: not possible to **consistently compare** with all other PDF sets

PDF benchmarking

- We compare the **most updated NNLO PDFs** from NNPDF, CT, MSTW, ABM and HERAPDF collaborations
- We first compare **PDFs** and then **parton luminosities**
- We compute inclusive **benchmark cross sections** (including Higgs) and compare them with recent LHC 8 TeV data when available
- We compute also **differential distributions** for jets and W/Z production and compare them for LHC data with full the covariance matrix: **ATLAS W/Z** 2010 data, **ATLAS 2010 jets**, **CMS 2011 W electron asymmetry** and **LHCb 2010 W/Z** data
- Data/theory agreement is quantified by a χ^2 **estimator**

$$(\mathrm{cov})_{IJ} = \left(\sum_{l=1}^{N_c} \sigma_{I,l}\sigma_{J,l} + \delta_{IJ}\sigma_{I,s}^2\right) F_I F_J + \left(\sum_{n=1}^{N_a} \sigma_{I,n}\sigma_{J,n} + \sum_{n=1}^{N_r} \sigma_{I,n}\sigma_{J,n}\right) F_I F_J$$

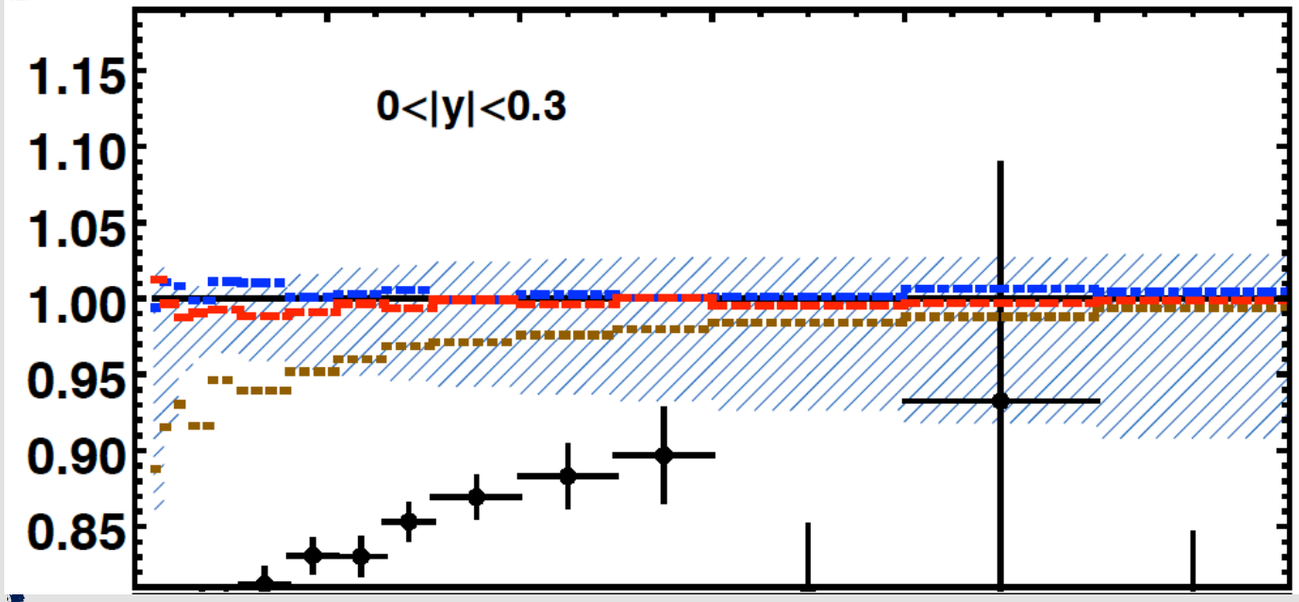
- In this talk we compare results consistently for common values of α_S **= 0.117** and α_S **= 0.119.** We only show NNLO. The complete set of plots, results for NLO and other α_S values available online in **HepForge:**

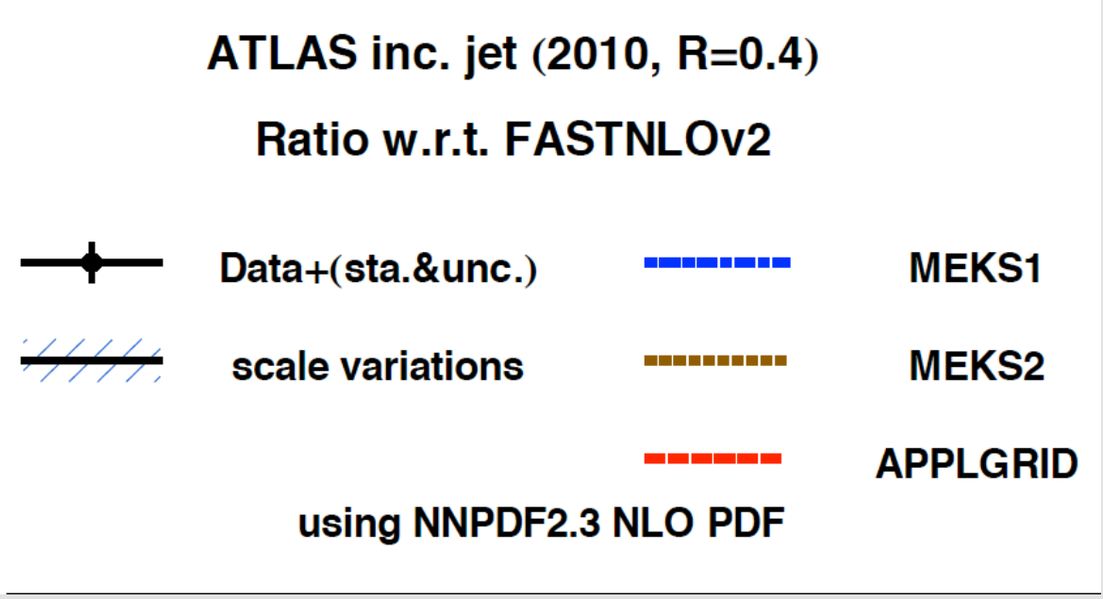
http://nnpdf.hepforge.org/html/pdfbench/catalog/

PDF benchmarking - Settings

- Theory predictions computed with the following codes, interfaced to **LHAPDF5.8.8**
  - **Vrap** for inclusive **electroweak** boson production at **NNLO**
  - **iHixs** for inclusive **Higgs** production in gluon fusion at **NNLO**
  - **Top++** for inclusive **top quark pair** production at **NNLO$_{approx}$+NNLL**
  - **MCFM** and **NLOjet++** interfaced through **APPLgrid** for **electroweak distributions** and **jet production** at **NLO.** Also **DYNNLO** for electroweak distributions at **NNLO**

- **Scale variations** non negligible for jet data. Dedicated **benchmark comparison of jet codes** in progress. Here we use **APPLgrid** settings (as in ATLAS 2010 jet paper)



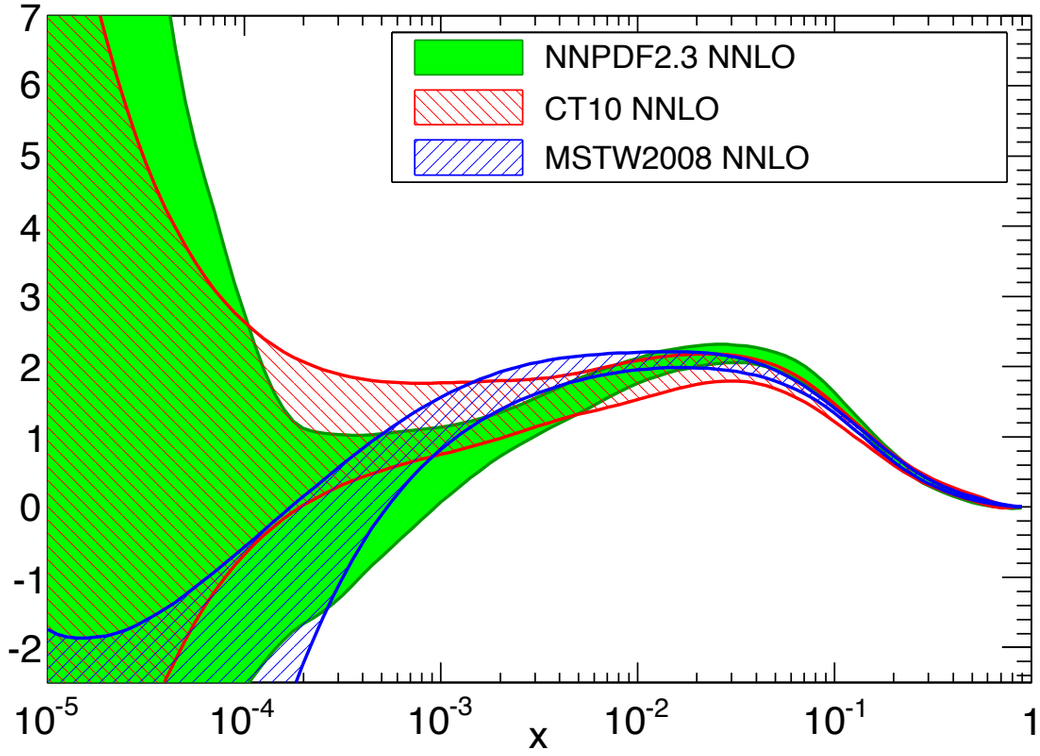


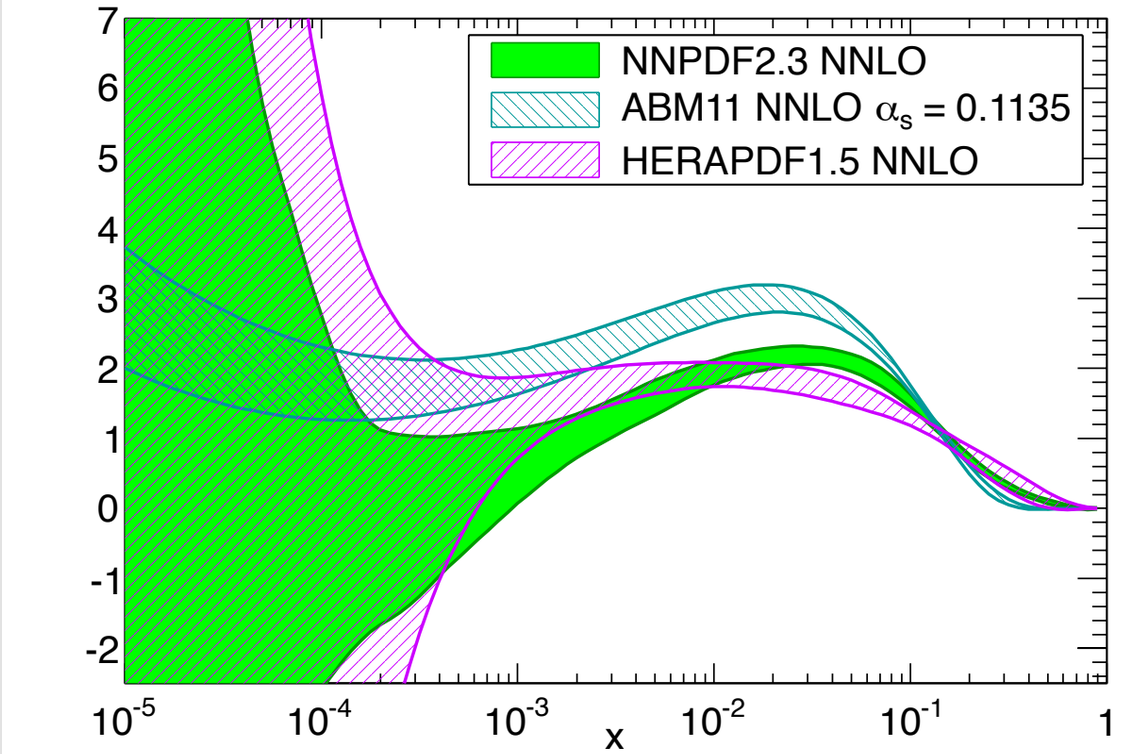
Parton Distributions and Parton Luminosities

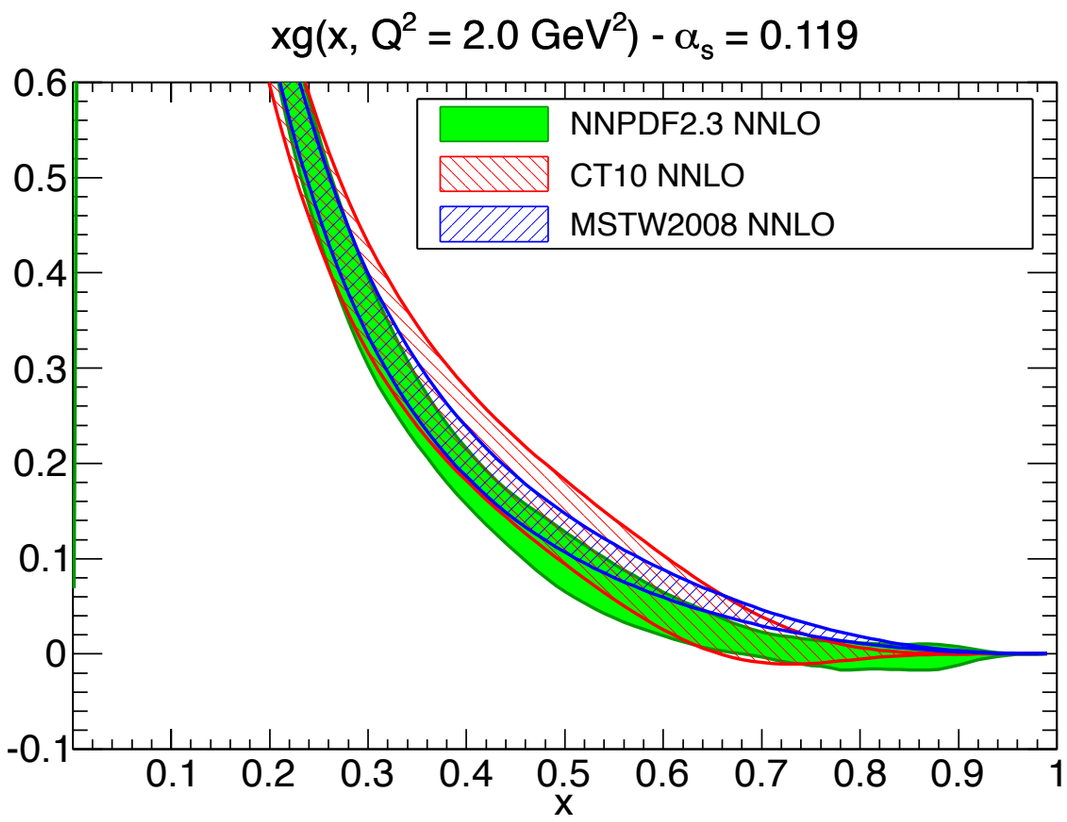
Juan Rojo

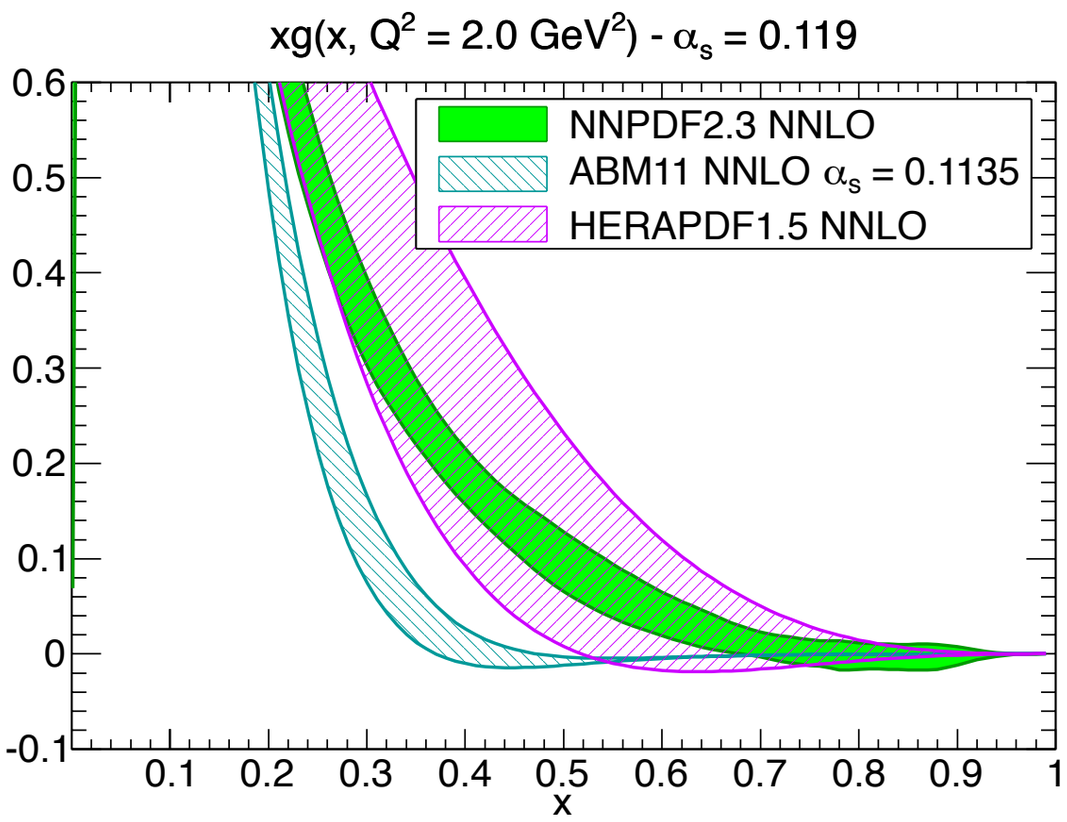
PDF4LHC Workshop, 08/09/2012

PDFs: Gluon

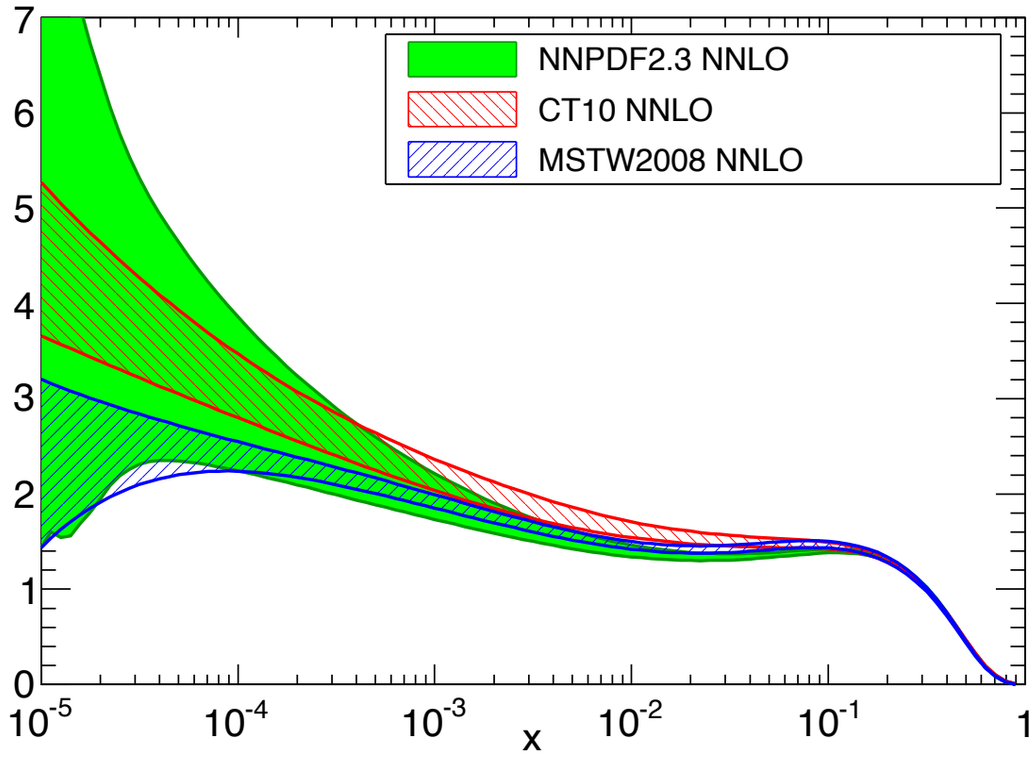

xg(x, Q² = 2.0 GeV²) - αs = 0.119
NNPDF2.3 NNLO
CT10 NNLO
MSTW2008 NNLO
x

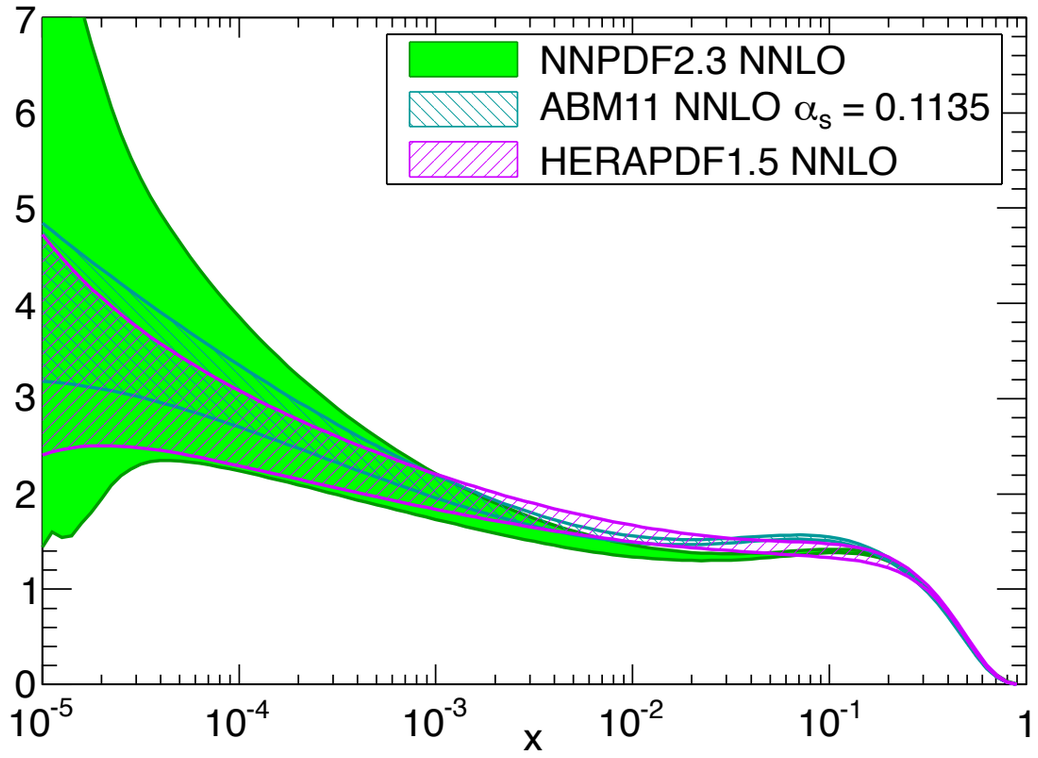

xg(x, Q² = 2.0 GeV²) - αs = 0.119
NNPDF2.3 NNLO
ABM11 NNLO αs = 0.1135
HERAPDF1.5 NNLO
x

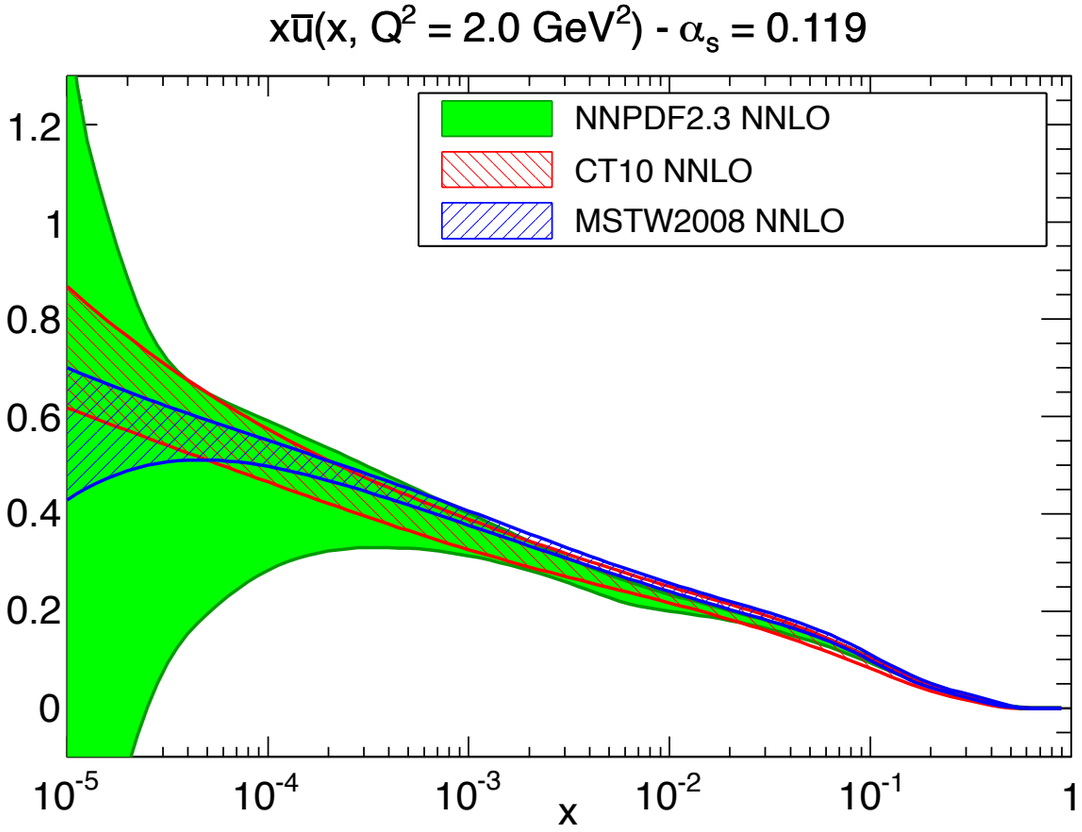

xg(x, Q² = 2.0 GeV²) - αs = 0.119
NNPDF2.3 NNLO
CT10 NNLO
MSTW2008 NNLO
x

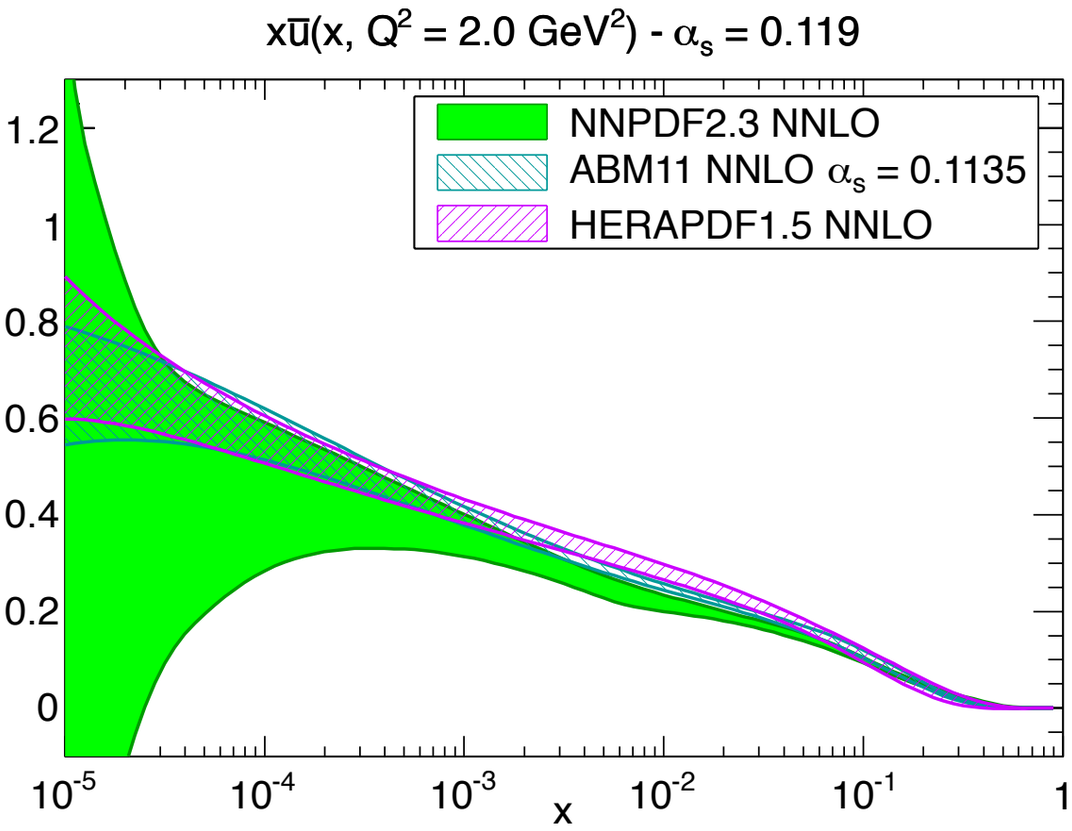

xg(x, Q² = 2.0 GeV²) - αs = 0.119
NNPDF2.3 NNLO
ABM11 NNLO αs = 0.1135
HERAPDF1.5 NNLO
x

PDFs: Sea Quarks

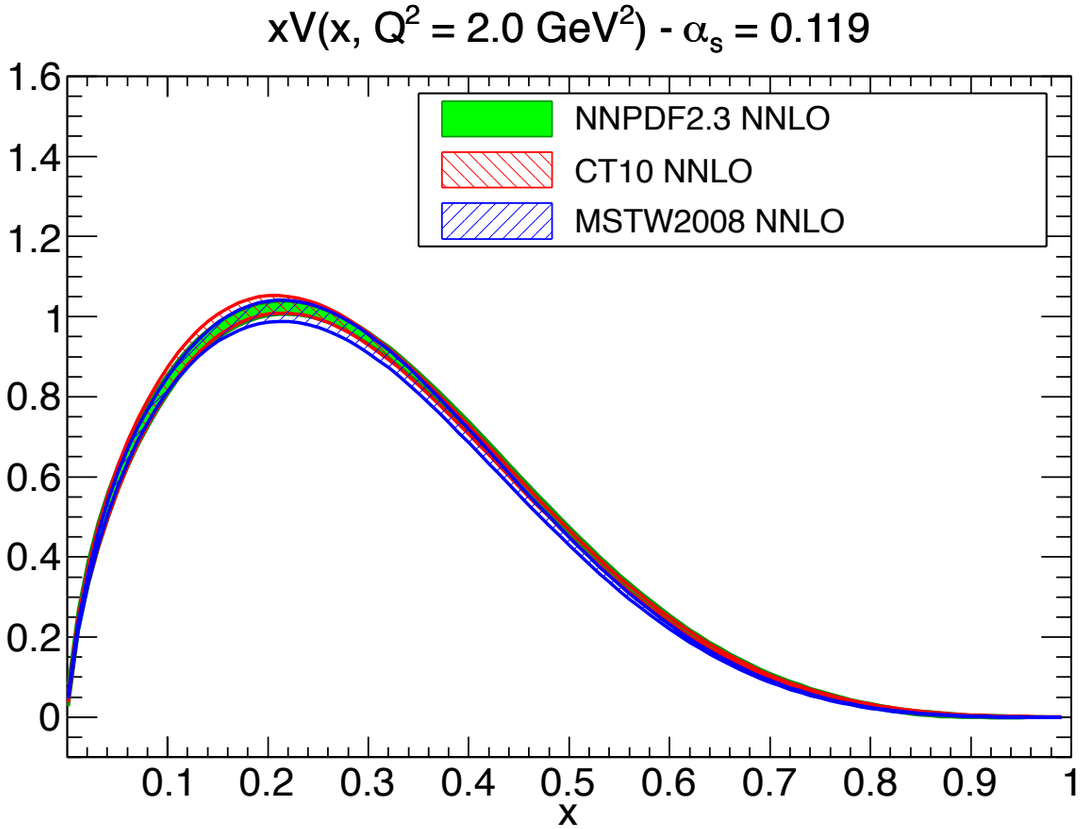


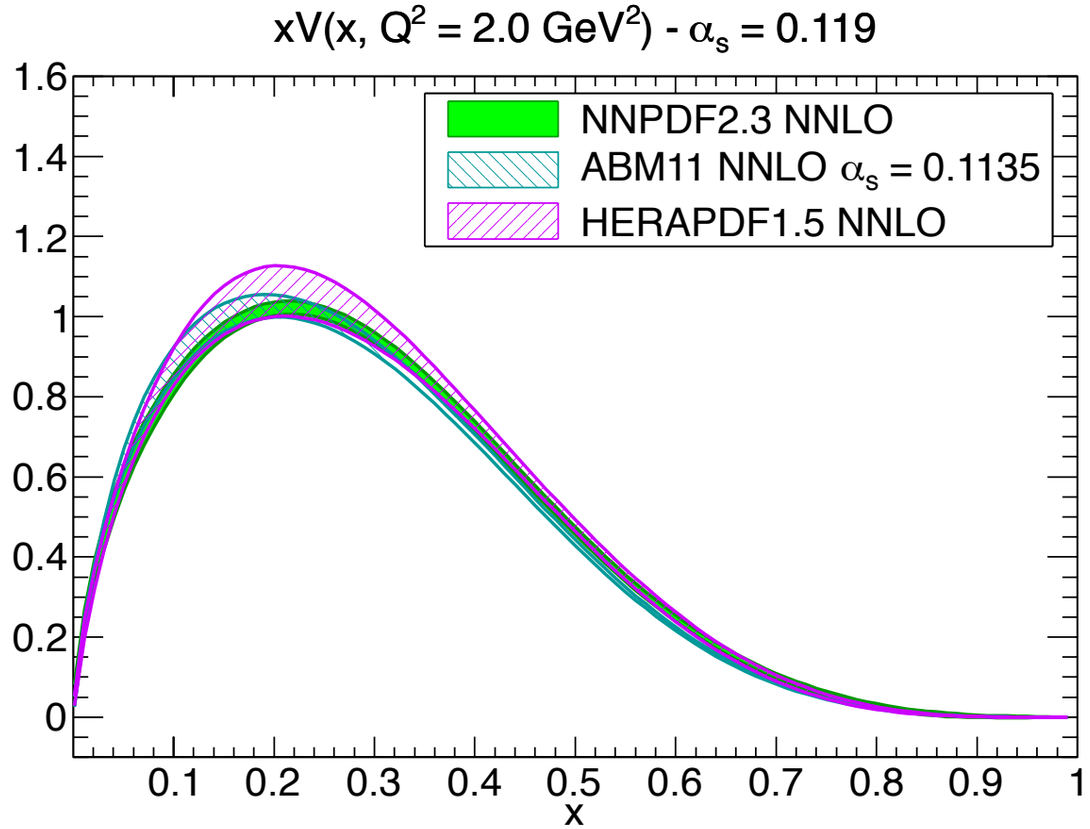


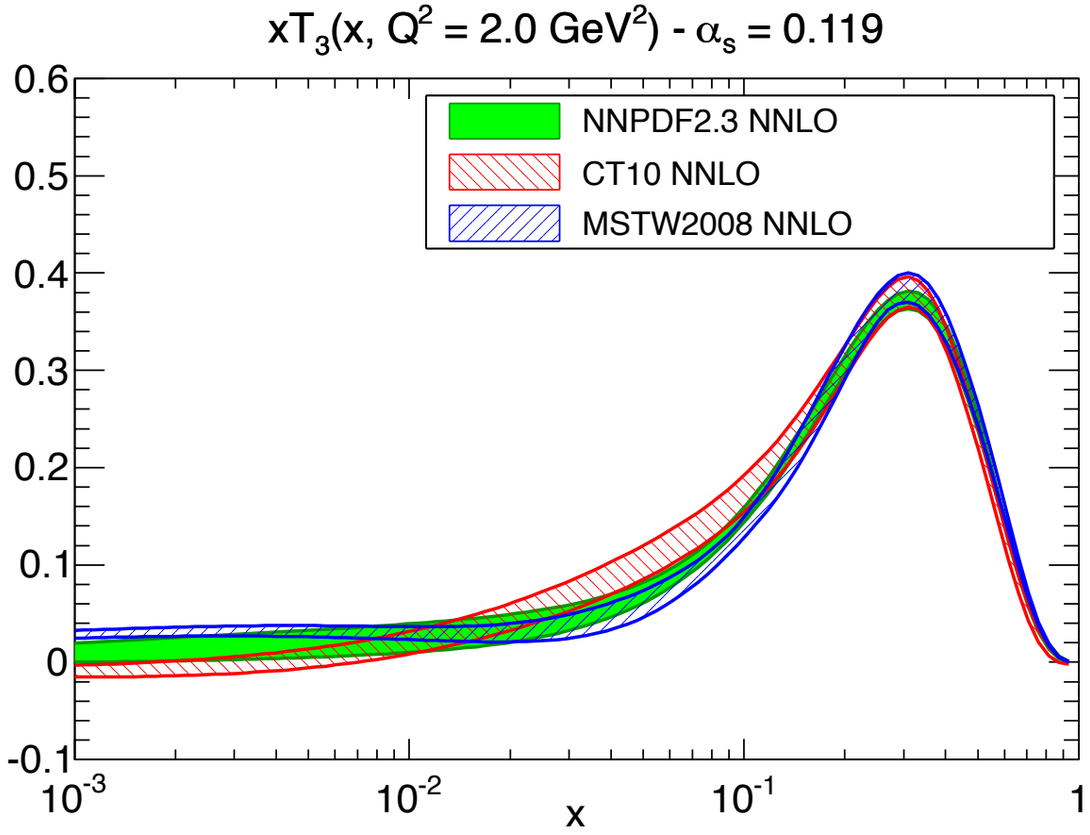


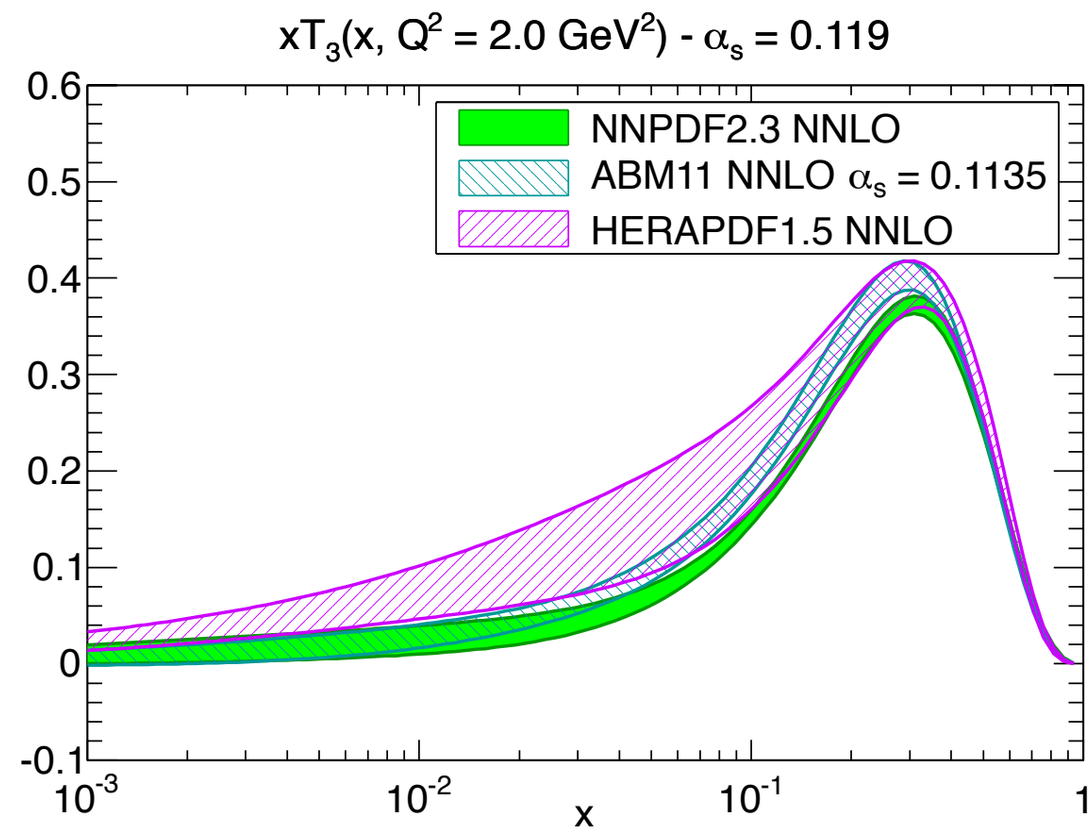


PDFs: Valence Quarks



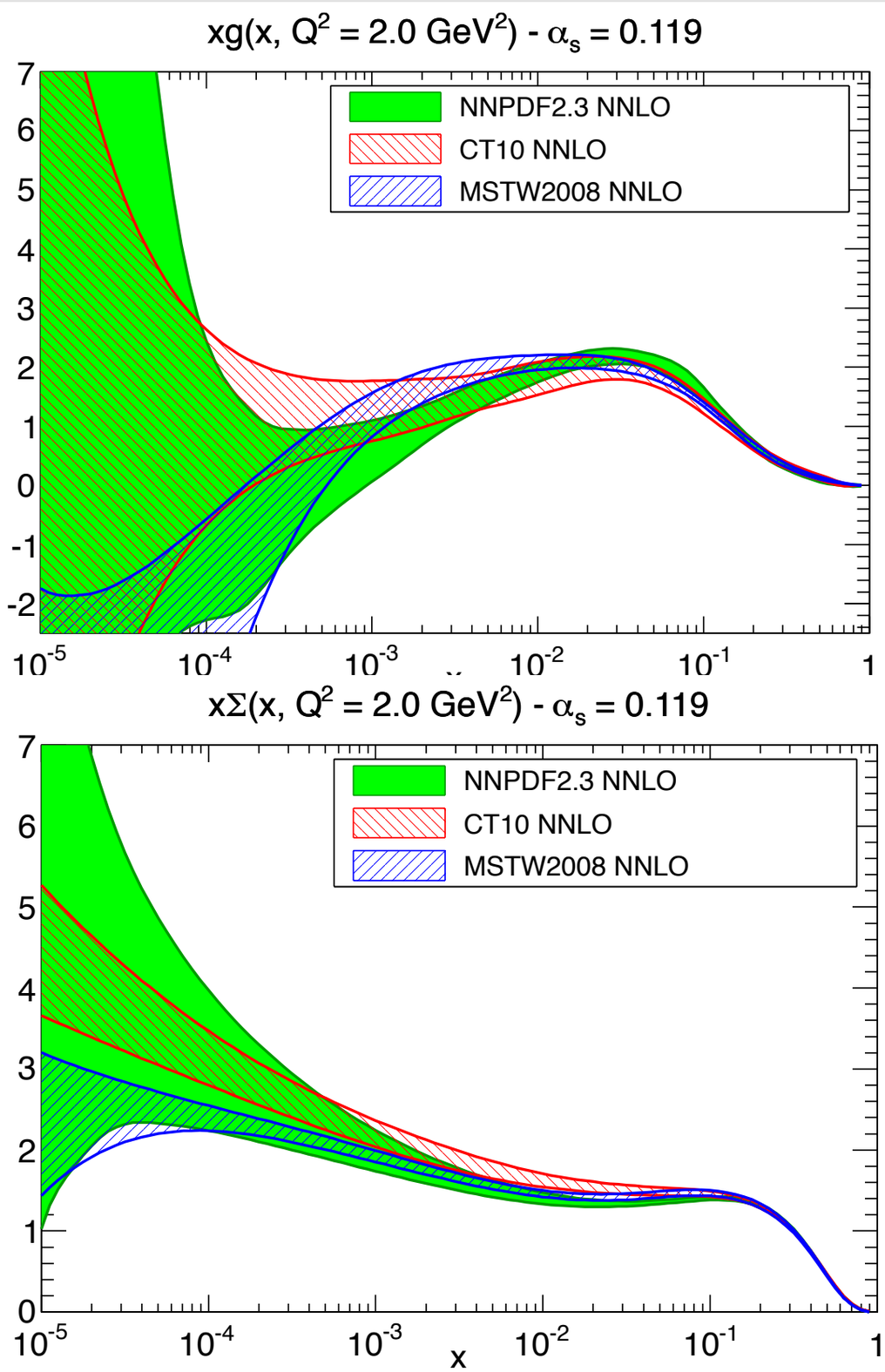


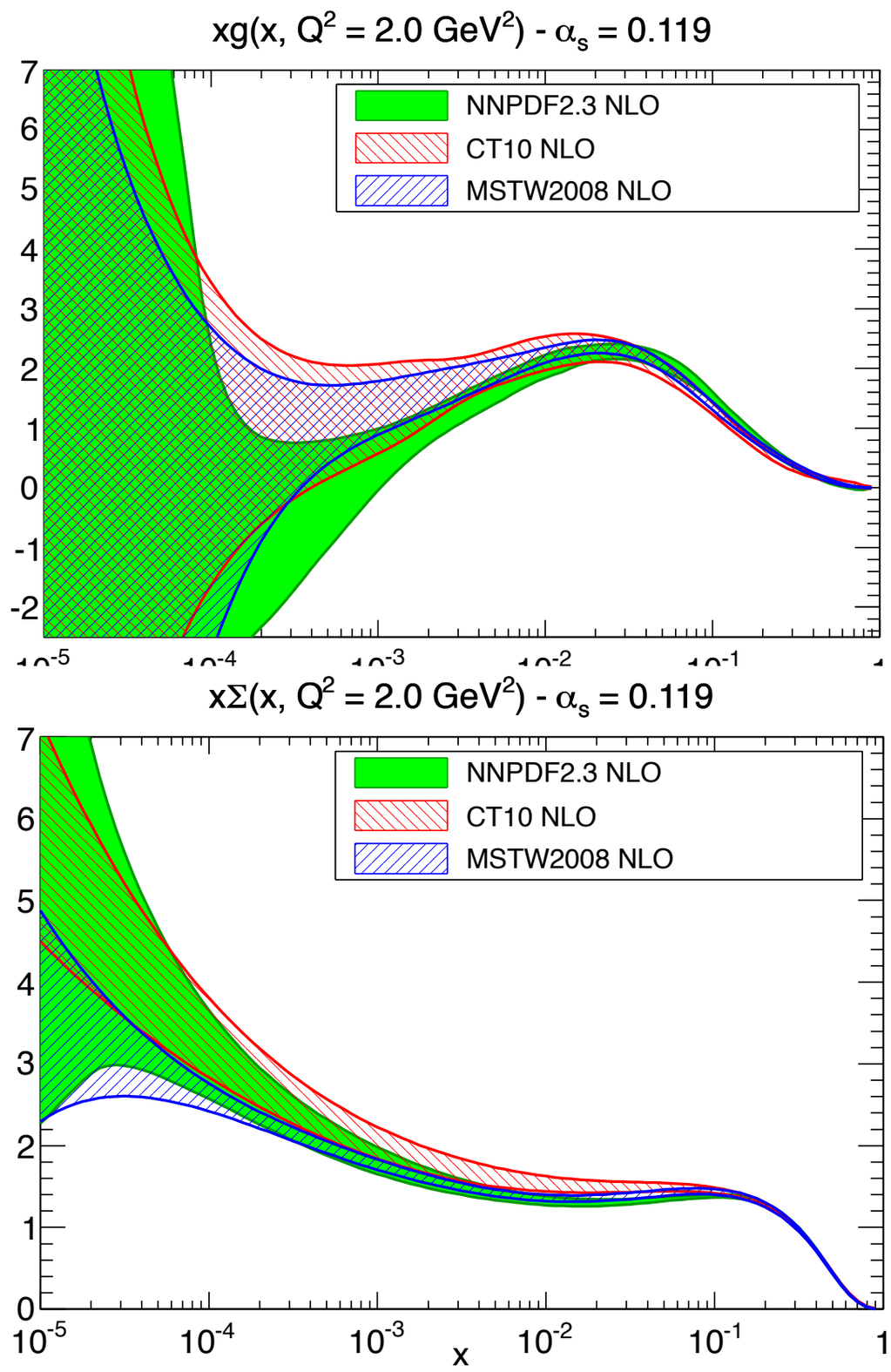




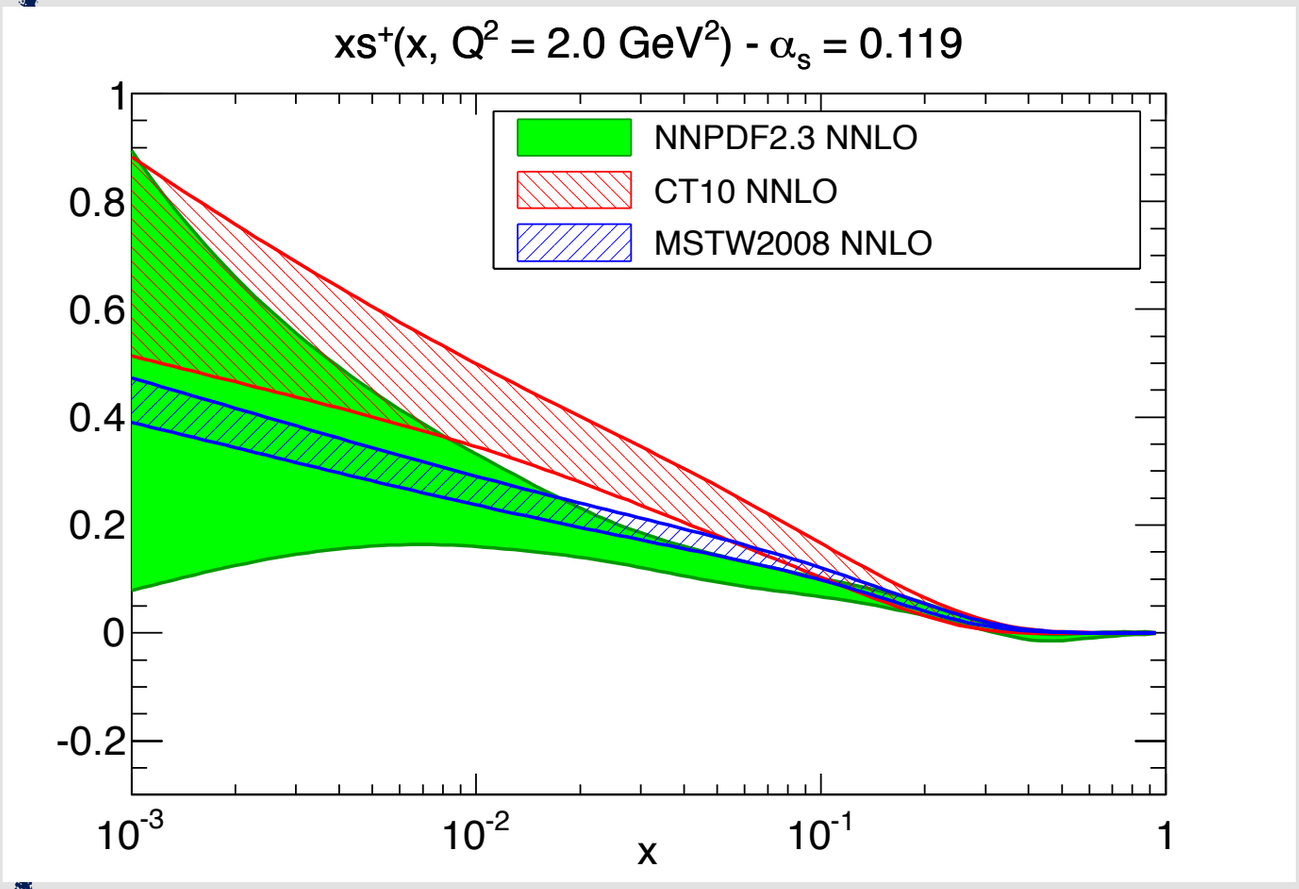
PDFs: NLO vs NNLO

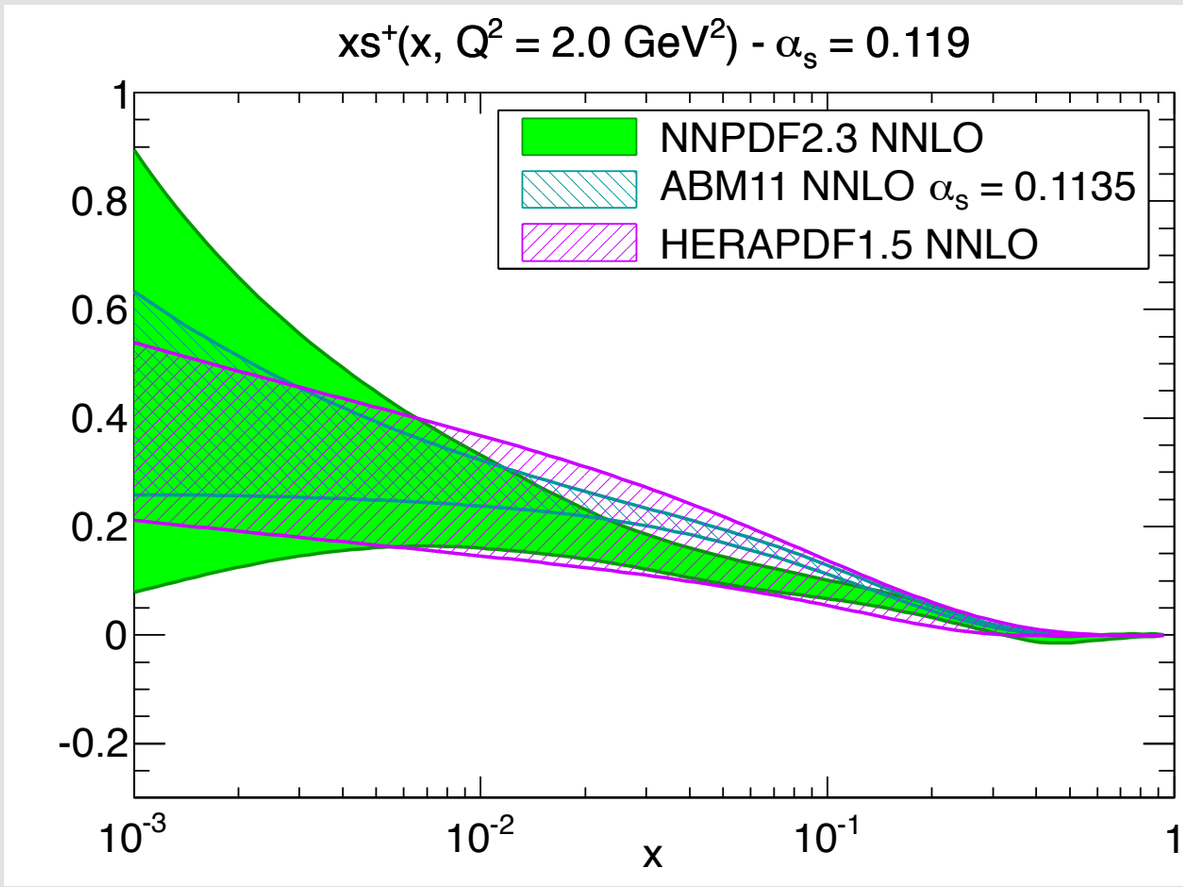
- Good **PDF stability** when going from **NLO to NNLO**





PDFs: Strangeness

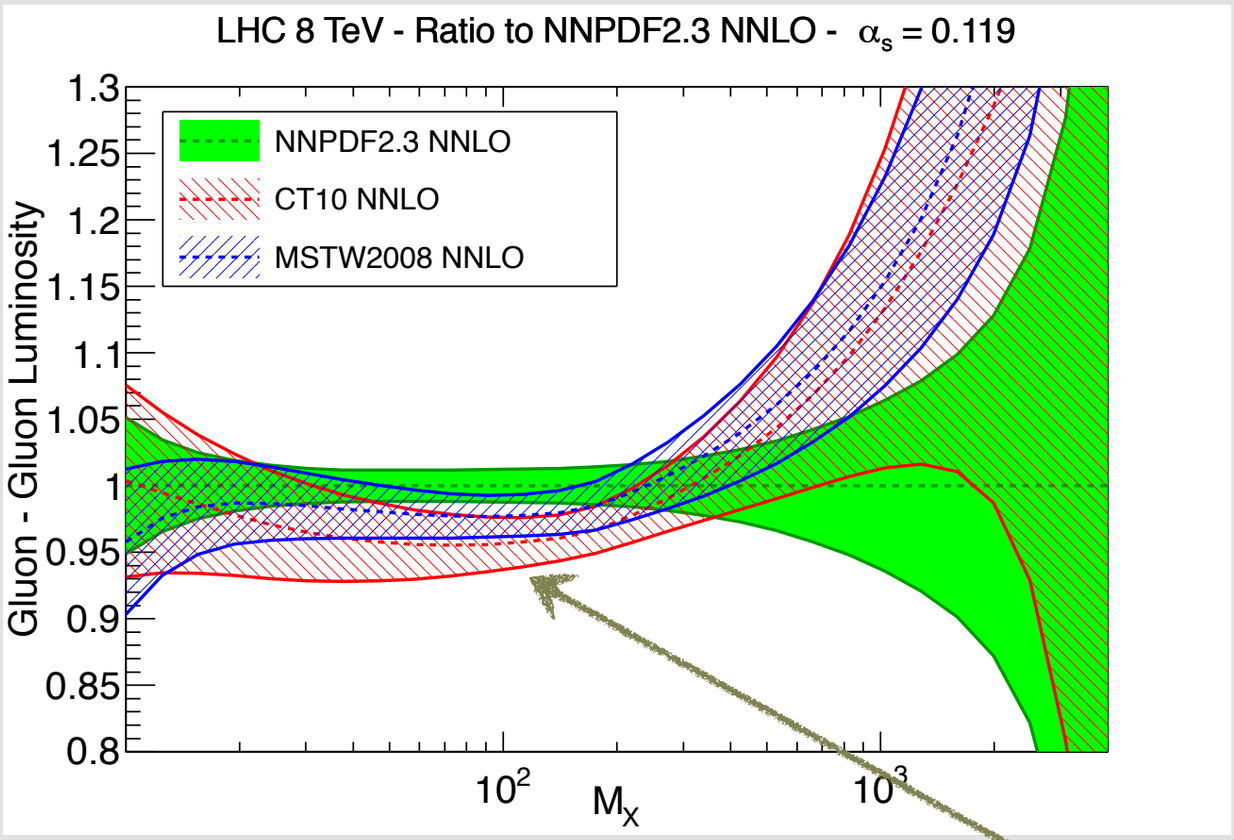


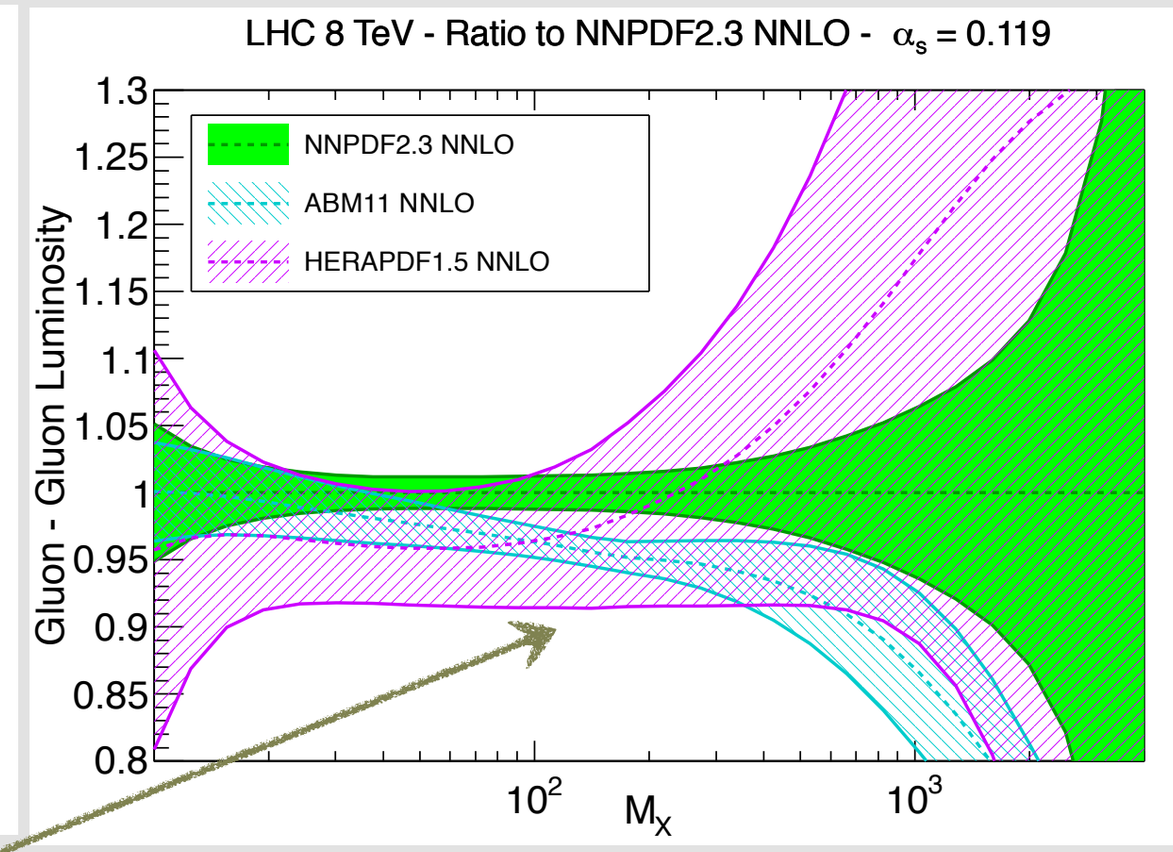


- Reasonable agreement for all PDF sets
- ATLAS W,Z data support **strange sea symmetric with non-strange sea**, but this leads to **poor description of NuTeV dimuon data** (also R. Thorne's talk at last PDF4LHC)
- NNPDF2.3 fits NuTeV and ATLAS data: **softer strangeness still favored**
- **Upcoming W+c data** will shed more light on strangeness

PDF Luminosities: Gluon-Gluon

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



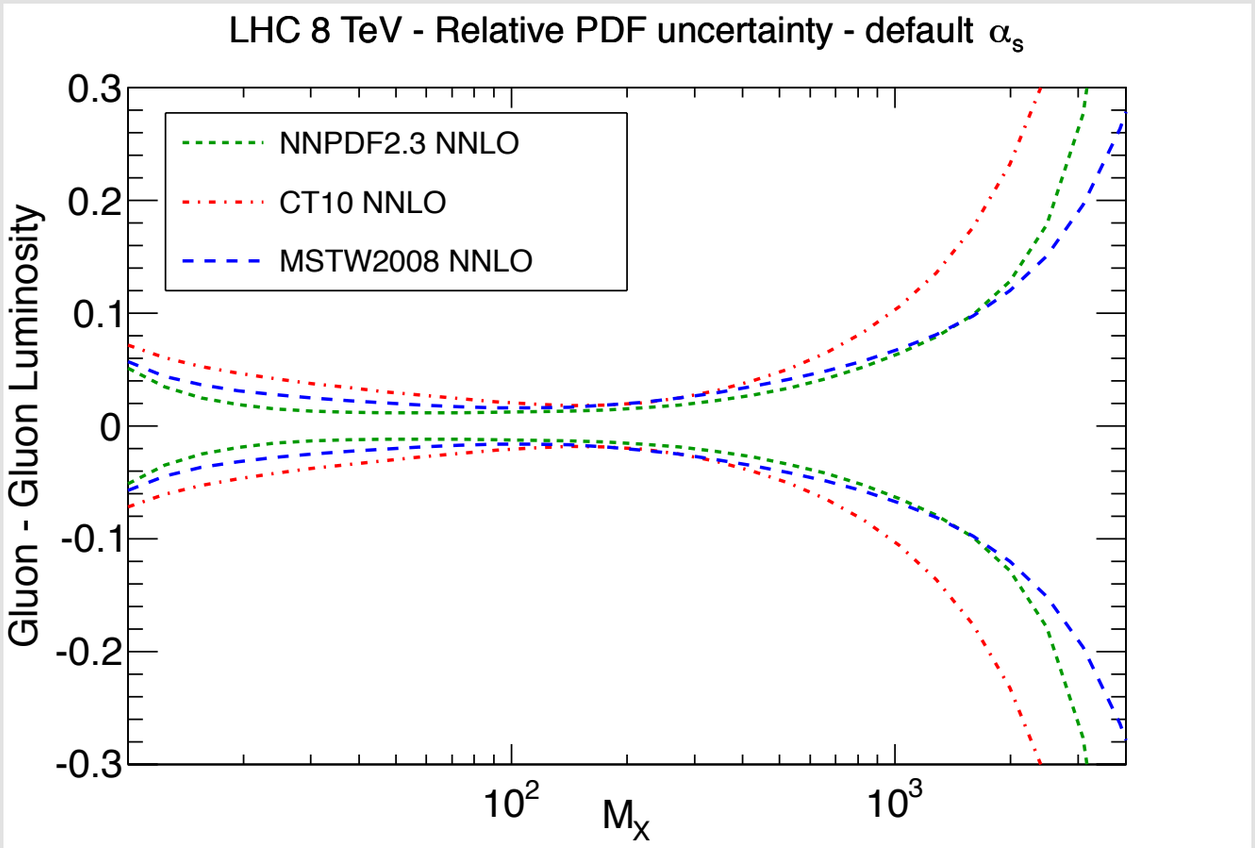


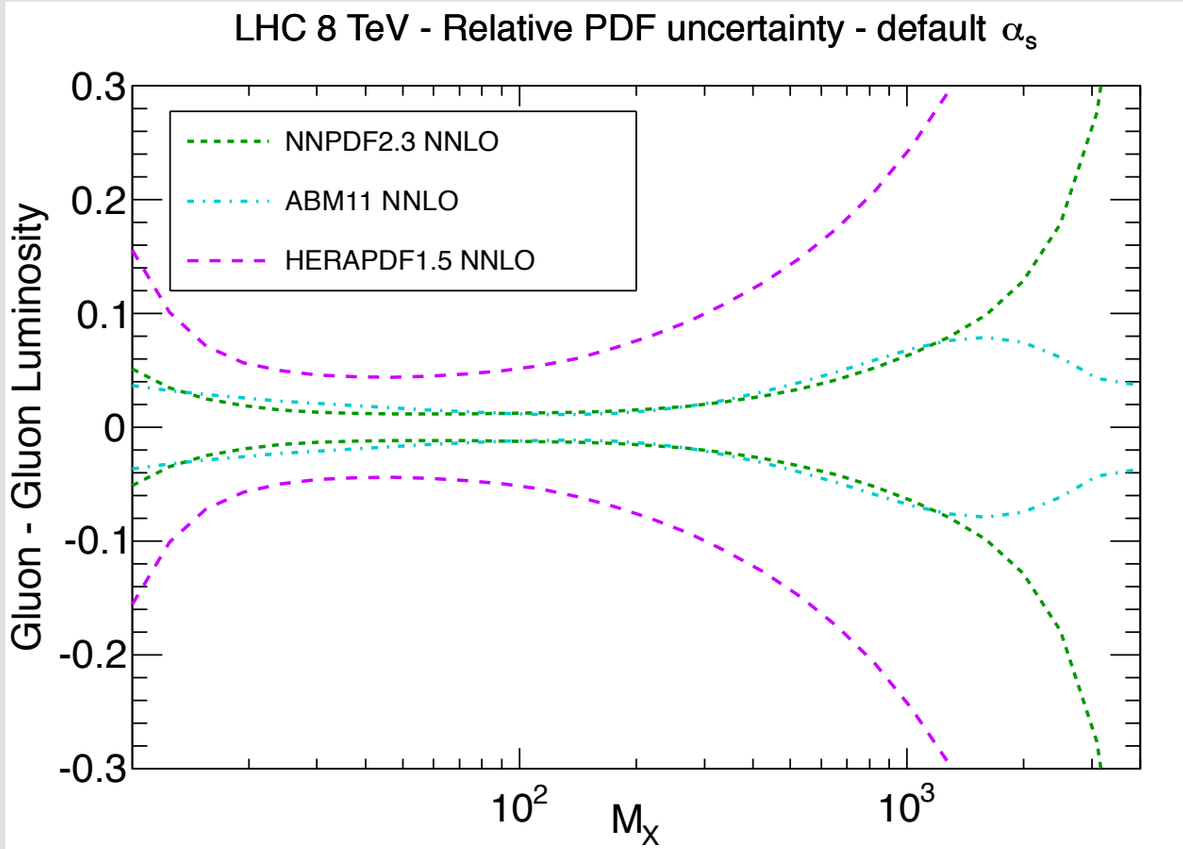
M_H=125 GeV

- **Good agreement** between **CT, MSTW, NNPDF** in the whole mass range
- ABM11 inconsistent with CT, MSTW, NNPDF except at low masses - but only for common α_S, much softer gluon luminosity if default α_s**=0.1134** were to be used
- HERAPDF1.5 consistent with MSTW with much **larger PDF uncertainties**

PDF Luminosities: Gluon-Gluon

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

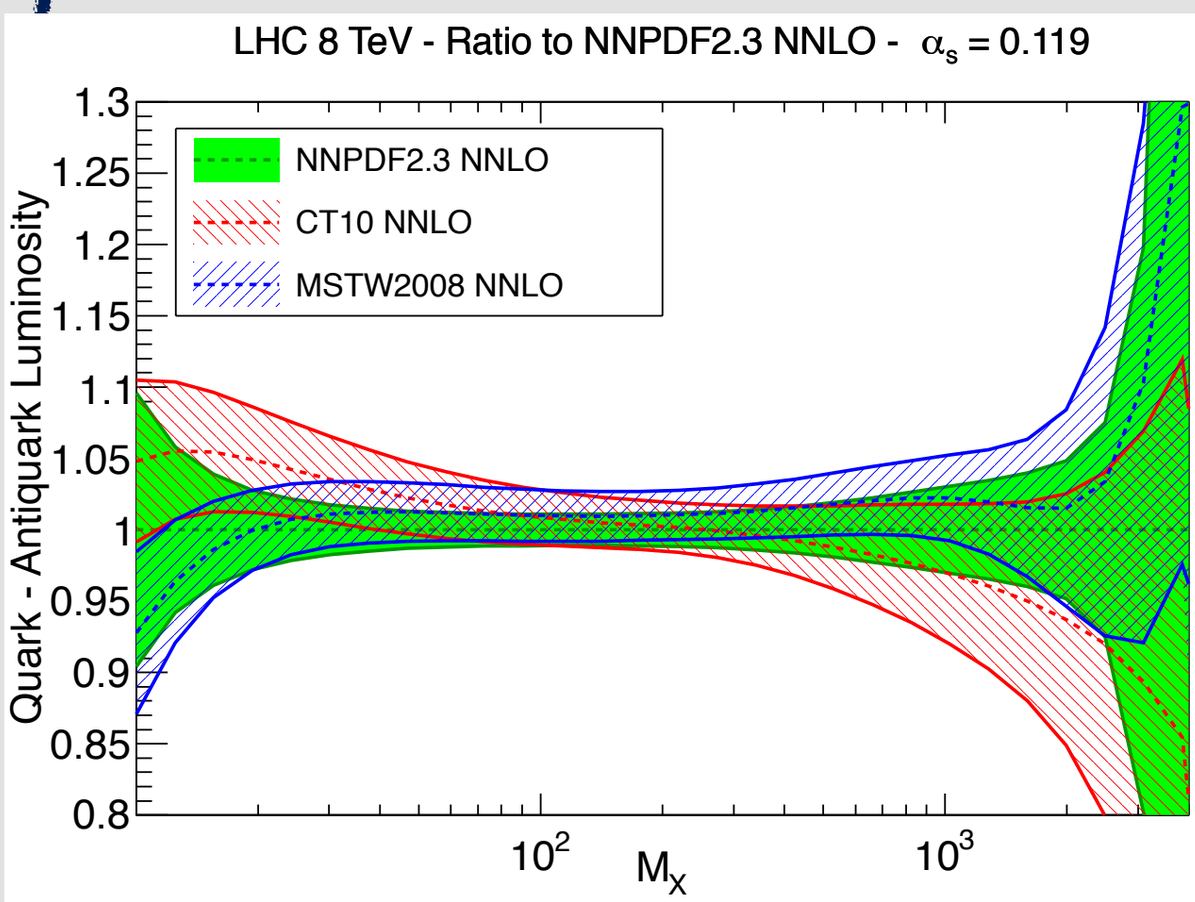


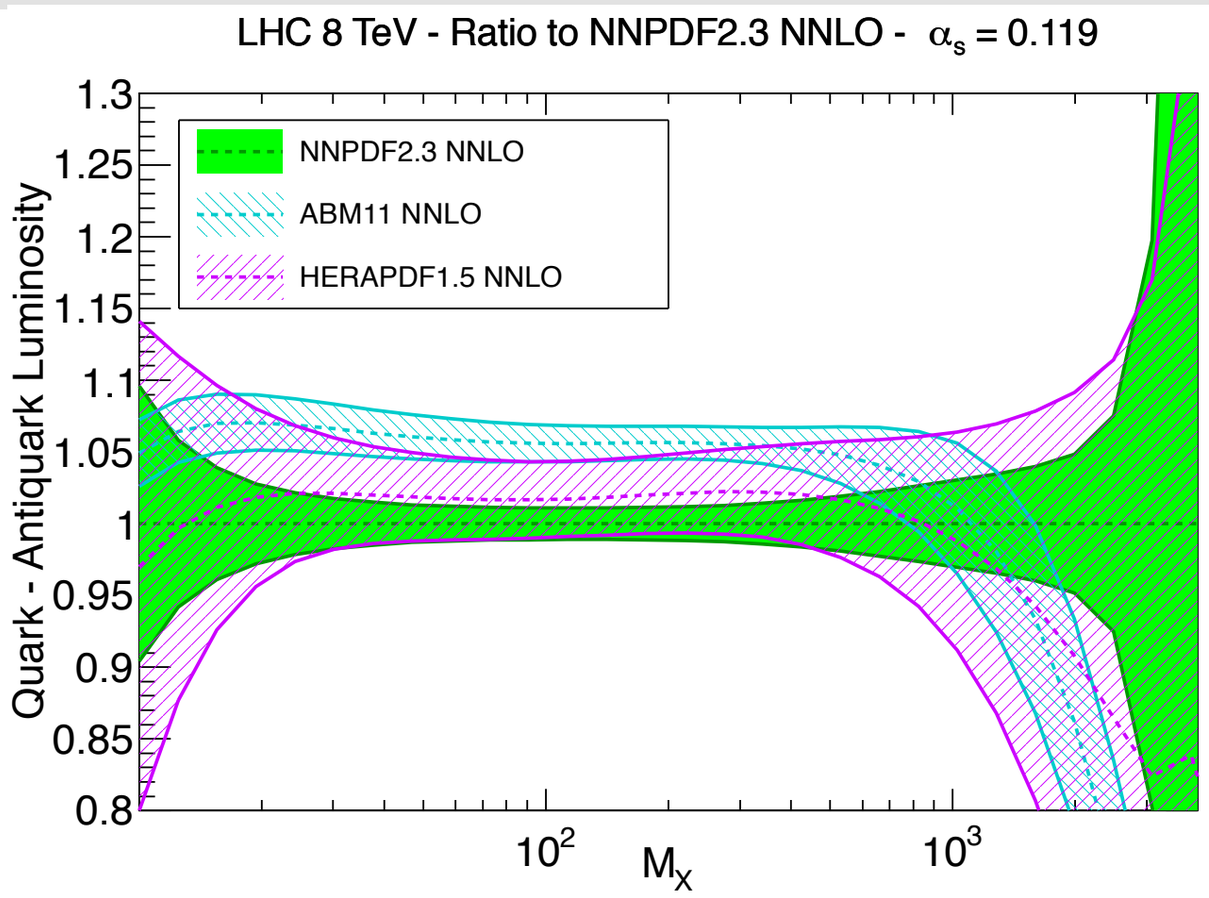


- Now we show the **relative PDF uncertainty** in the partonic luminosities
- Between **100 and 500 GeV**, PDF errors from CT/MSTW/NNPDF very similar
- ABM11 uncertainties **shrink** at large invariant masses (relevant for SUSY ...) as opposed to the other PDF sets

PDF Luminosities: Quark-AntiQuark

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



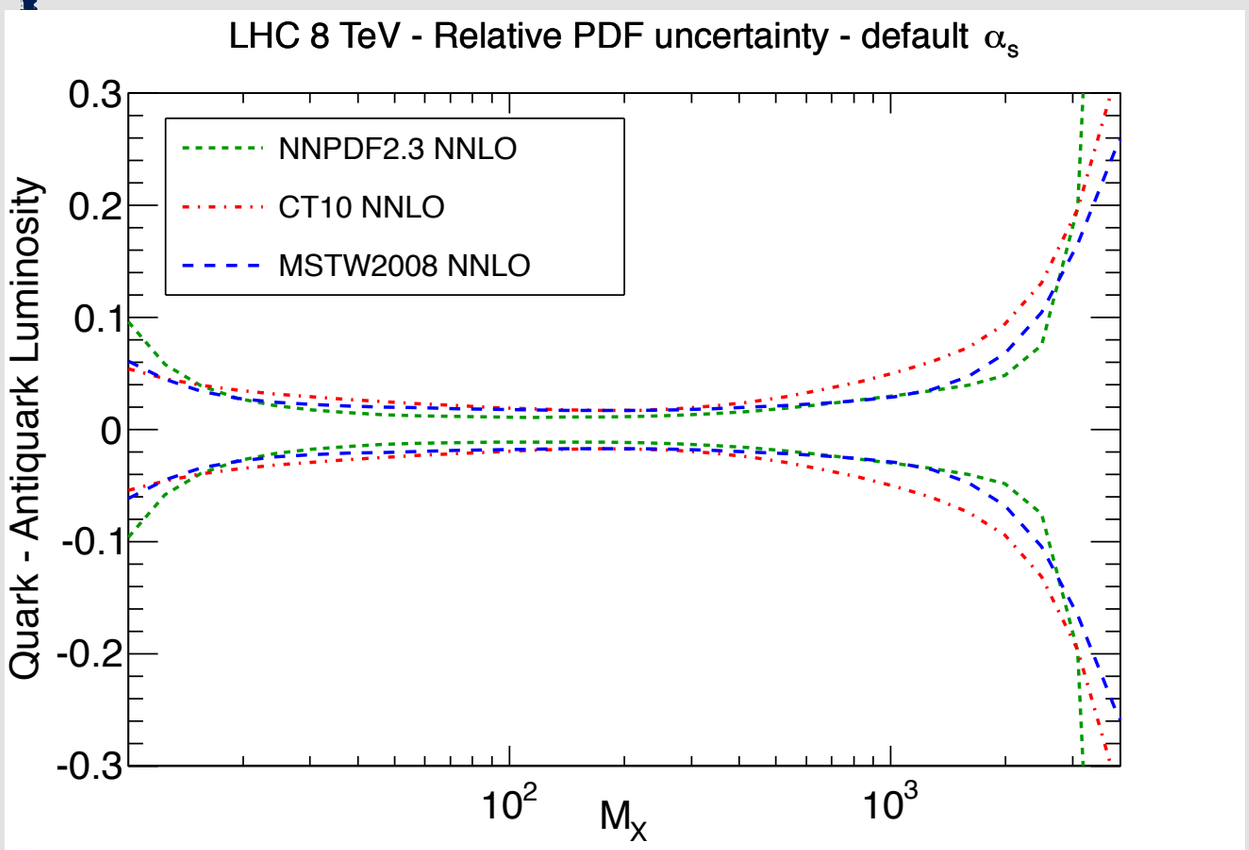


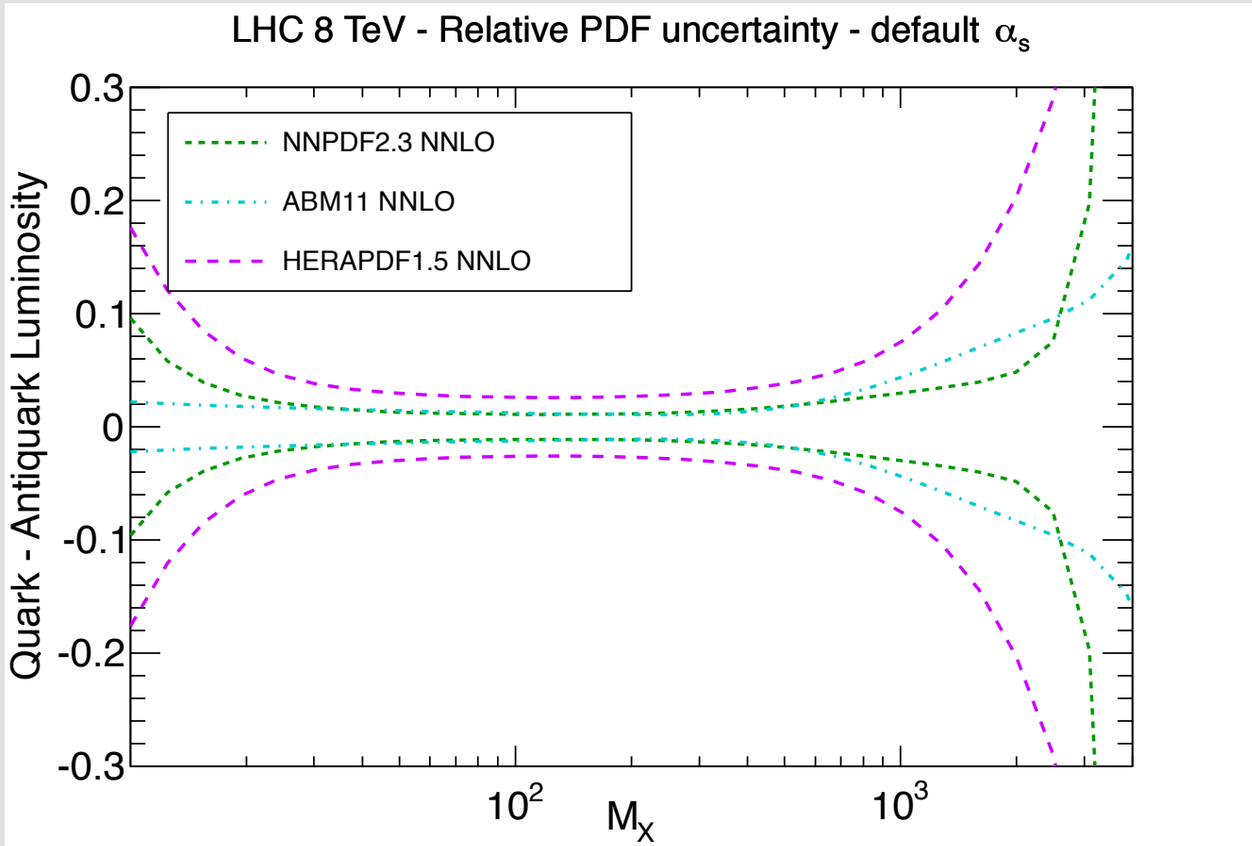
- **Good agreement** between NNPDF2.3, CT10 and MSTW08 in all the mass range. Also HERAPDF1.5 with somewhat larger uncertainties

- ABM11 **larger qqbar luminosity** below 1 TeV by a factor ~8% as compared to NNPDF2.3. Partly from use of FFN scheme.

PDF Luminosities: Quark-AntiQuark

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



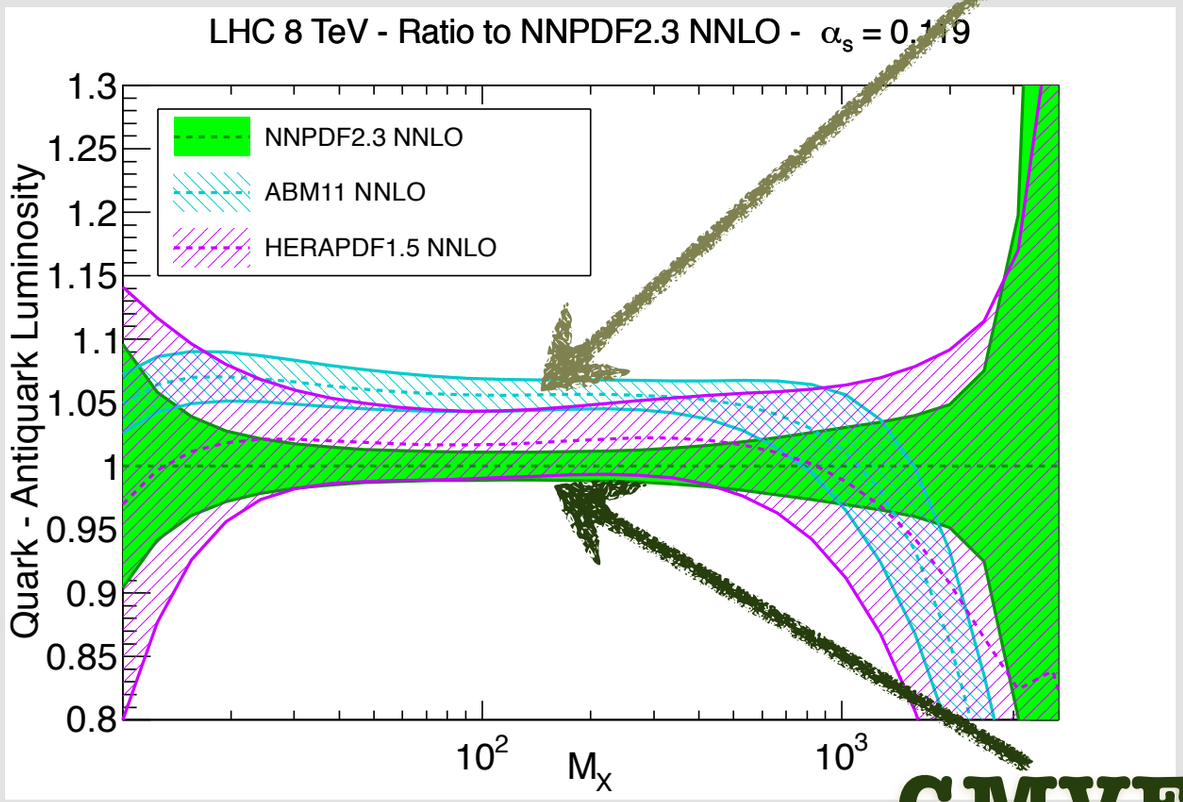


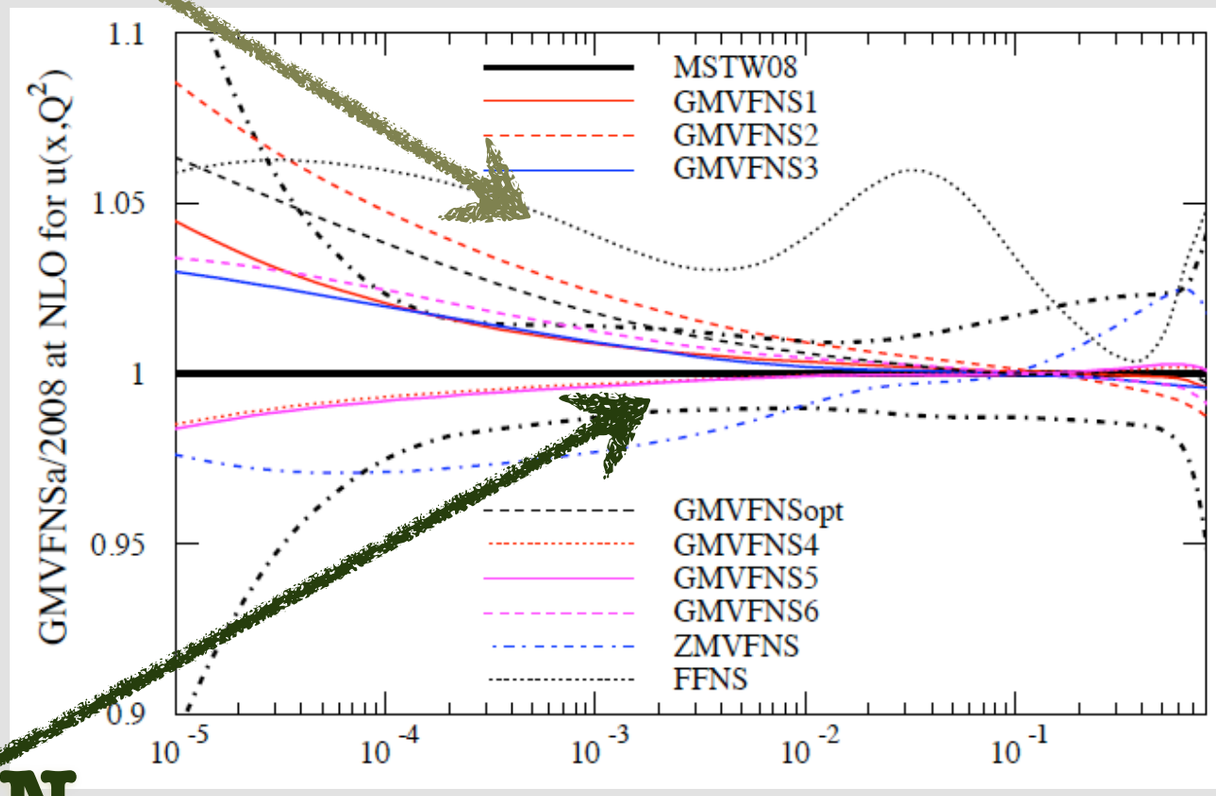
- Again, the **relative PDF uncertainty** in the partonic luminosities
- Between **100 and 500 GeV**, PDF errors from CT/HERAPDF/MSTW/NNPDF very similar

Heavy quark treatment

- Differences between ABM11 and other PDF sets partly arise from **different HQ treatment**: Fixed Flavor Number vs General Mass VFN schemes. R. Thorne PDF4LHC 24.09.2012, arXiv:1201.6180
- The FFN fit leads to a **harder small-x gluon**, and thus (via the momentum sum rule) a **softer large-x gluon**, and to a **harder quarks at small-x** at LHC scales through evolution
- Differences between various **GM-VFN** schemes much smaller that between **FFN** and **GM-VFN.** See also Les Houches heavy quark benchmark study.

FFN

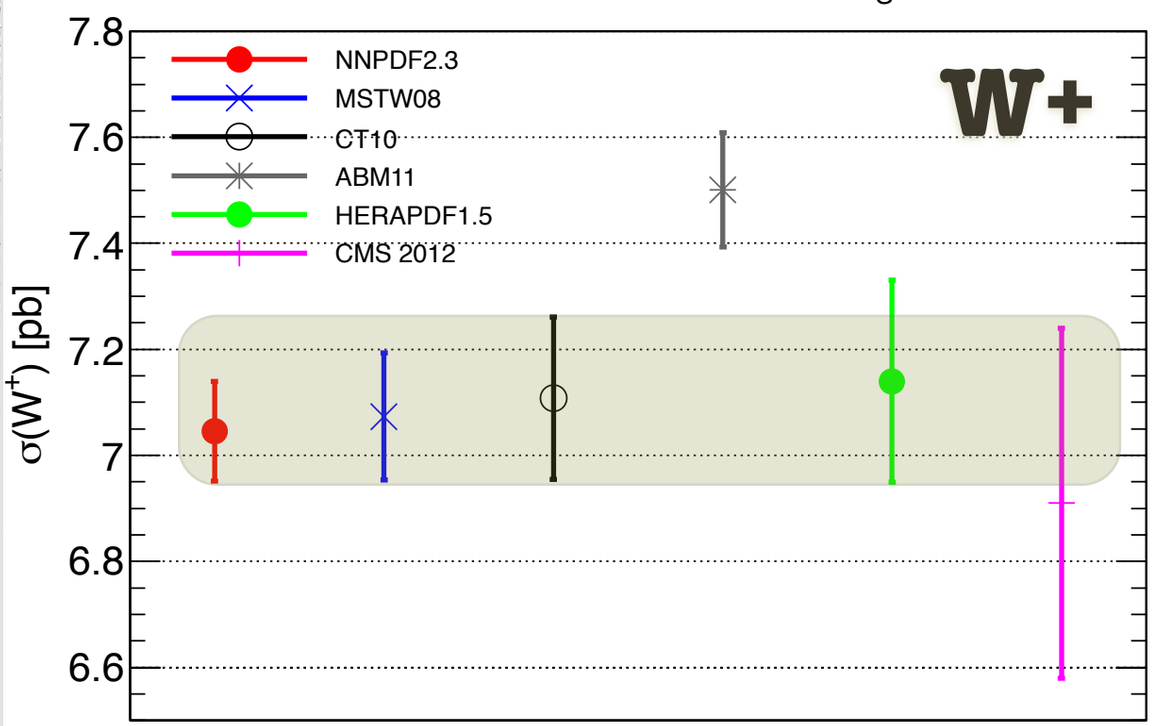


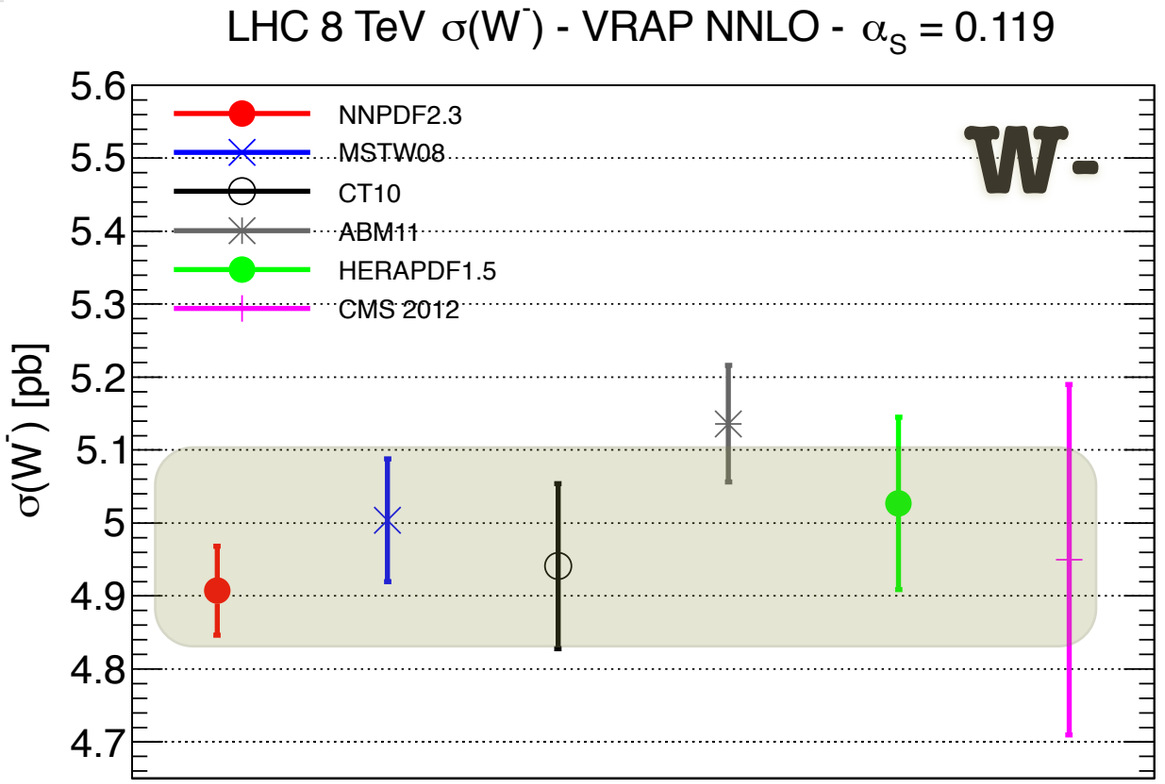


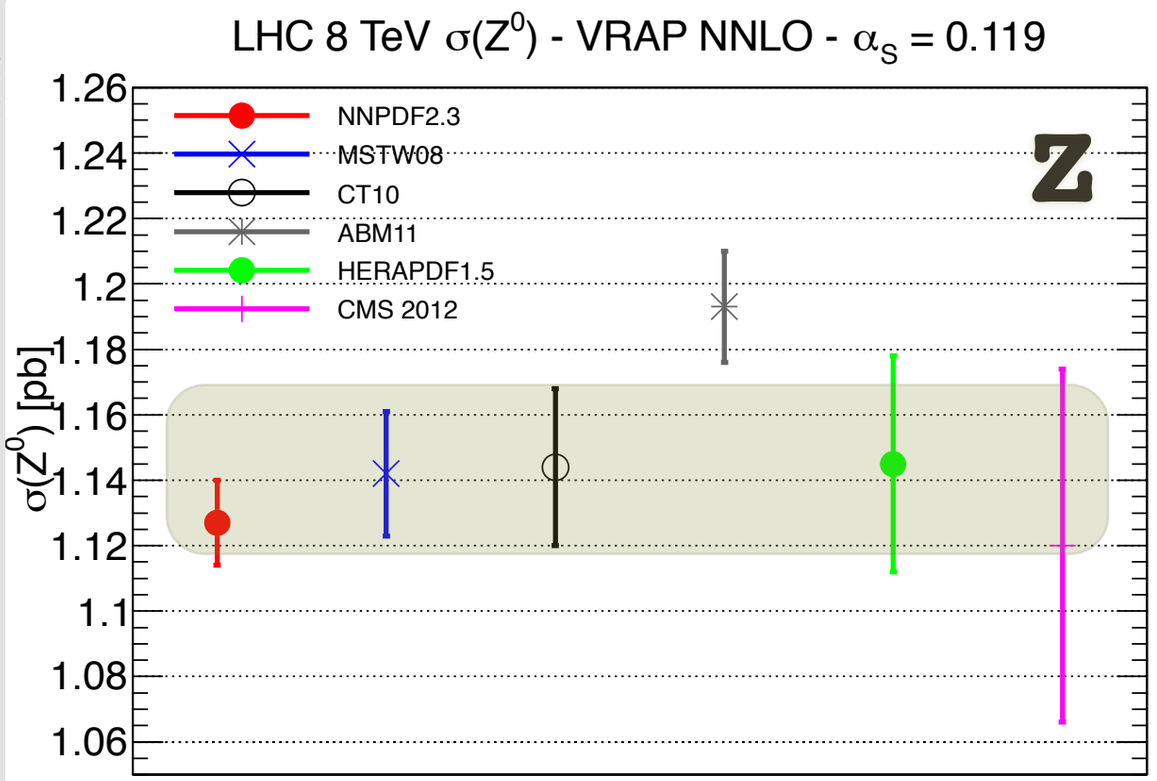
GMVFN

LHC 8 TeV Inclusive Cross Sections

Inclusive Cross Sections - W and Z

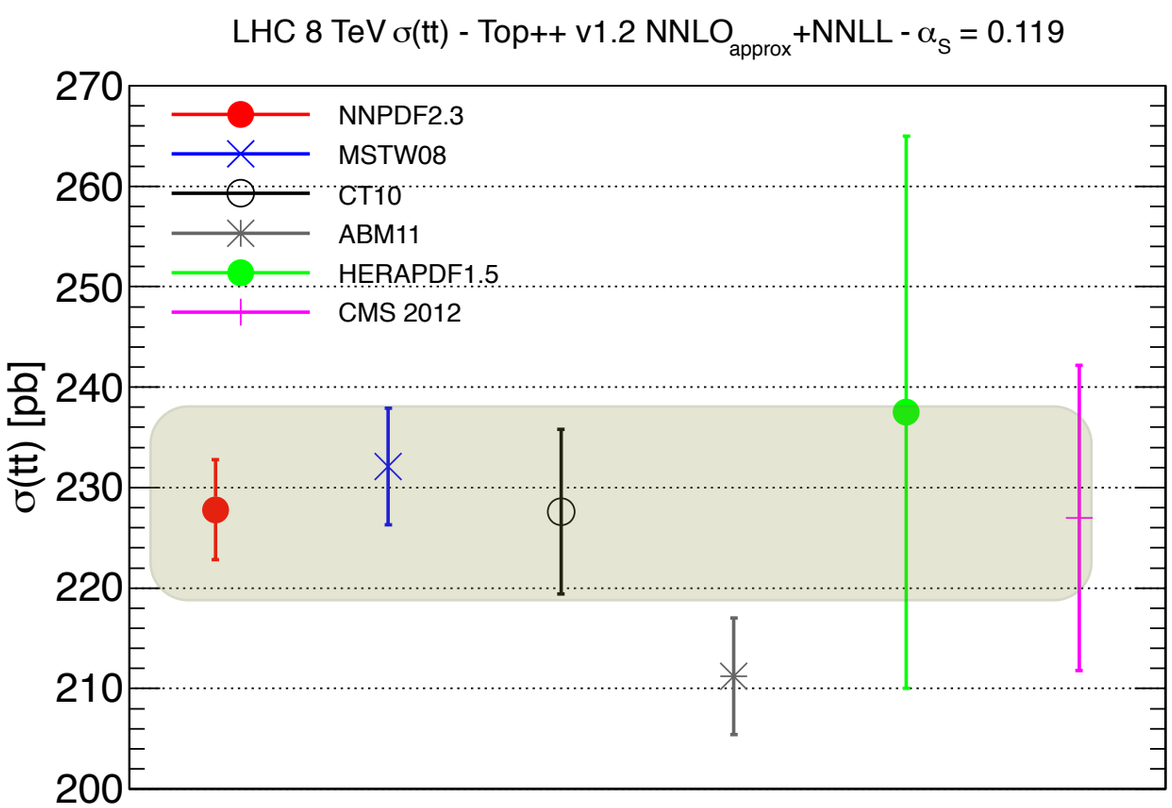


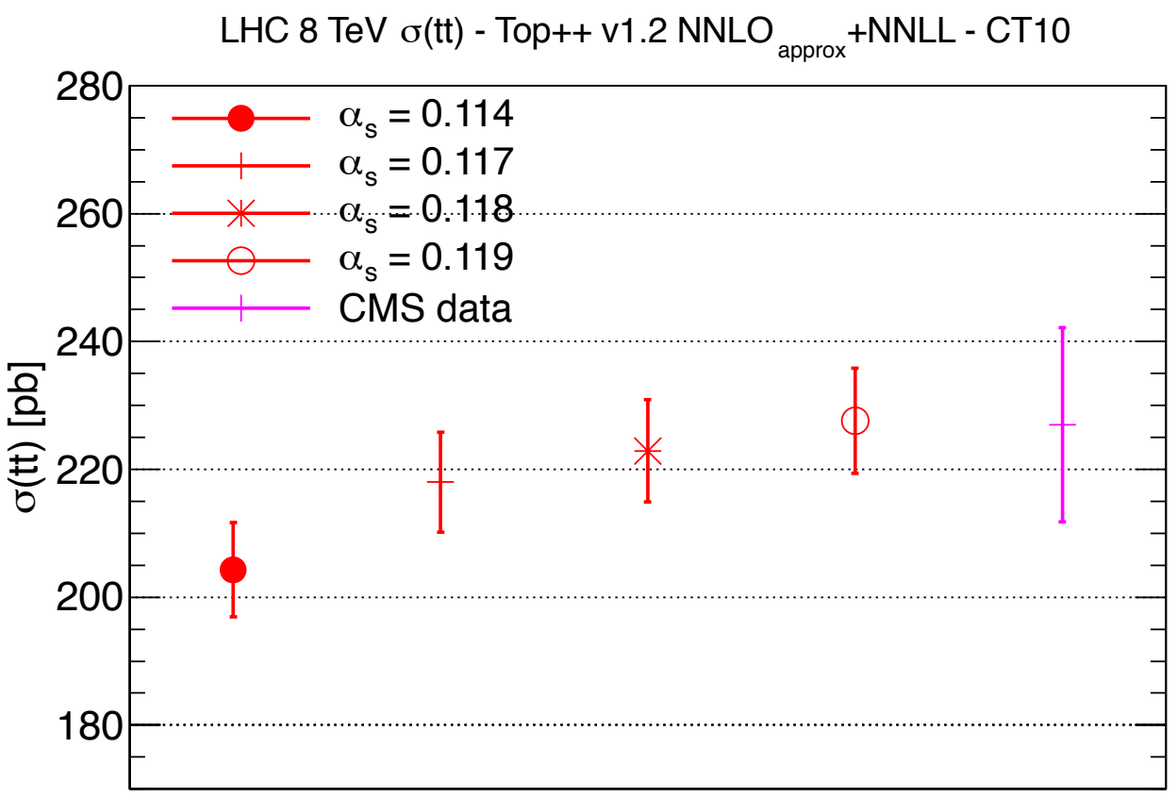




- **Good agreement between all sets** between them and with CMS 8 TeV data except ABM11 (larger cross sections)
- More stringent constraints from the 8 **TeV W,Z differential distributions with covariance matrix**

Inclusive Cross Sections - Top





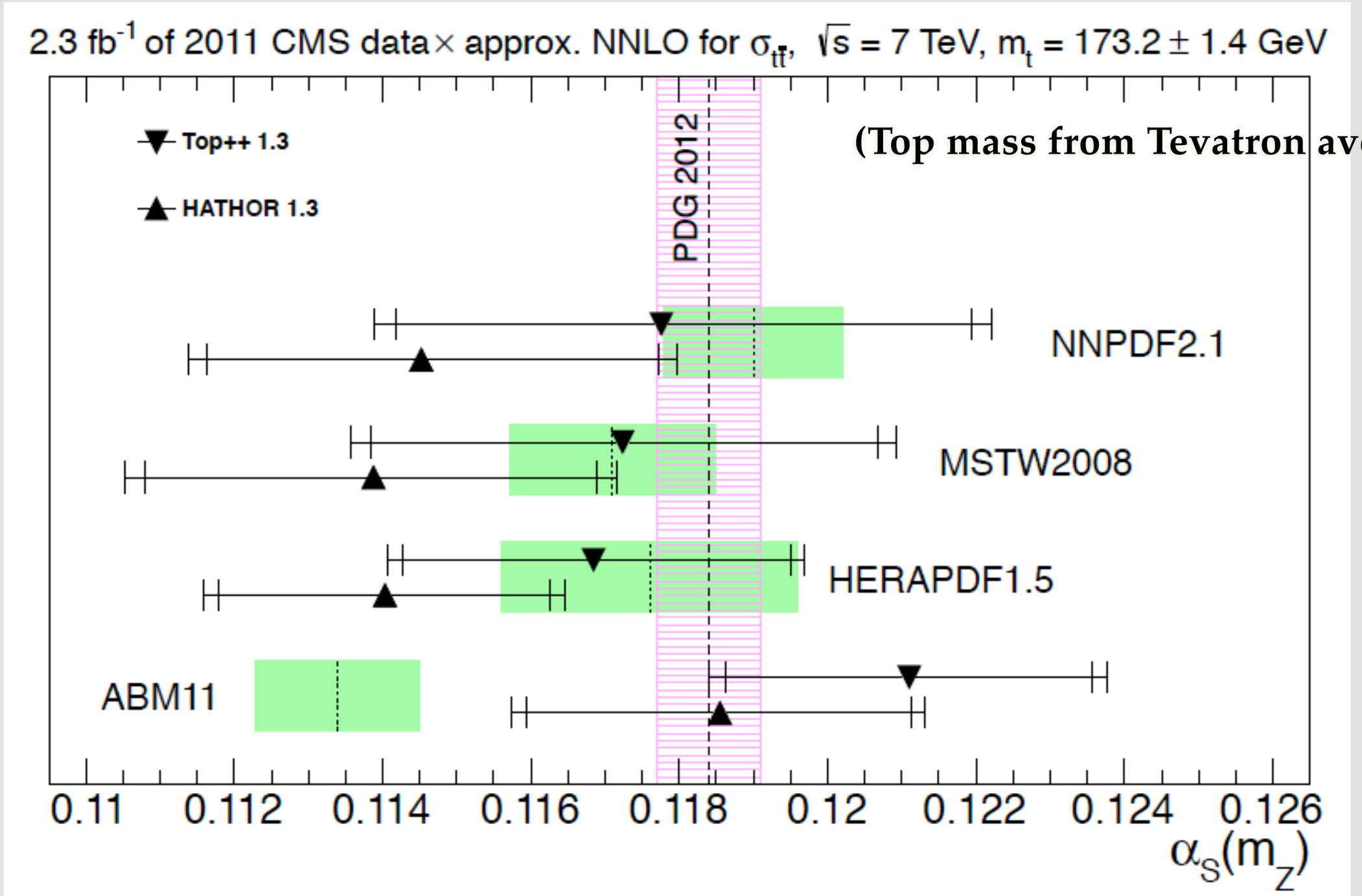
- Good agreement between all PDFs. ABM11 a bit lower, even for $\alpha_S = 0.119$. HERAPDF15 large uncertainties from unconstrained gluon

- LHC data **disfavor small values** of α_S. Sensitivity justifies **direct extraction from cross section** (CMS-TOP-12-022)
- More stringent constraints on PDFs from **top differential distributions** from ATLAS and CMS: direct constraints **on the gluon PDF**

- Also **cross section ratios** between 8 TeV and 7 TeV provide useful for PDF information

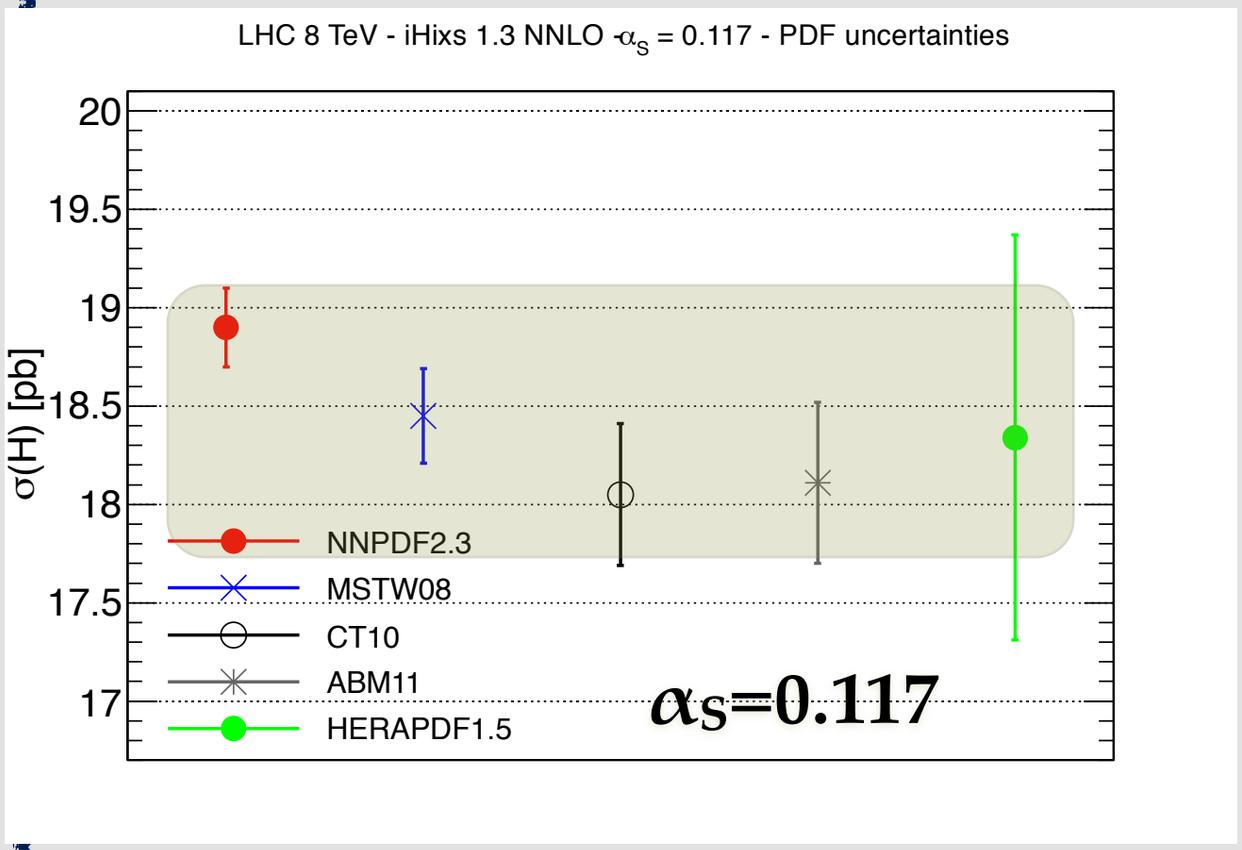
Inclusive Cross Sections - Top

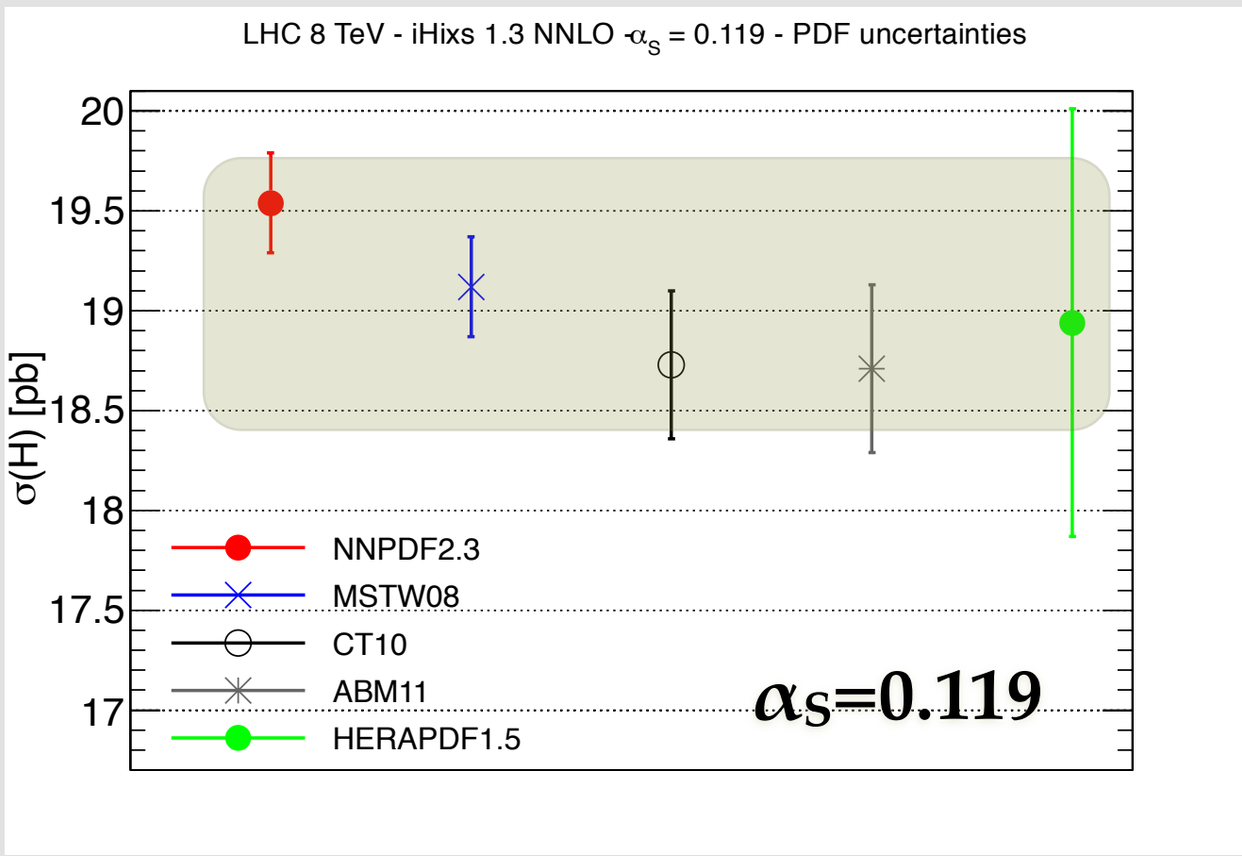
- LHC data **disfavor small values** of α_S. Sensitivity justifies **direct extraction from cross section** (CMS-TOP-12-022). NNPDF2.1, MSTW08 and HERAPDF **self-consistent**



NNLO PDFs and Higgs production

- **Higgs gluon fusion** computed with **iHixs** at NNLO with **$Q=M_H=125$ GeV**
- **Relative** differences between PDF sets (when compared at the same α_s) are unaffected when the common value of α_s is changed
- ABM11 similar to CT10, but much lower if default **$\alpha_s=0.1134$** used
- HERAPDF1.5 same central value as MSTW08, but **uncertainties factor 4 larger**





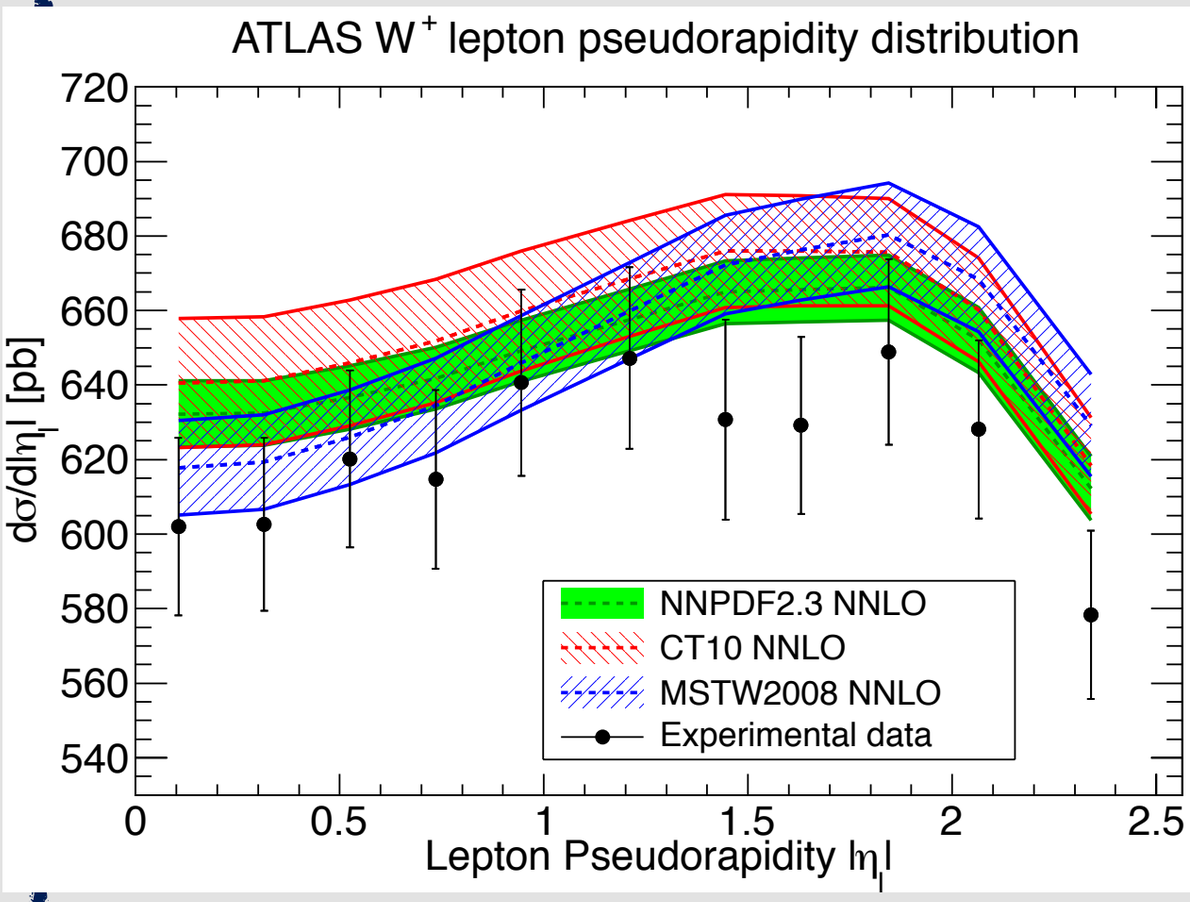
Jets and Electroweak Differential Distributions at LHC 7 TeV

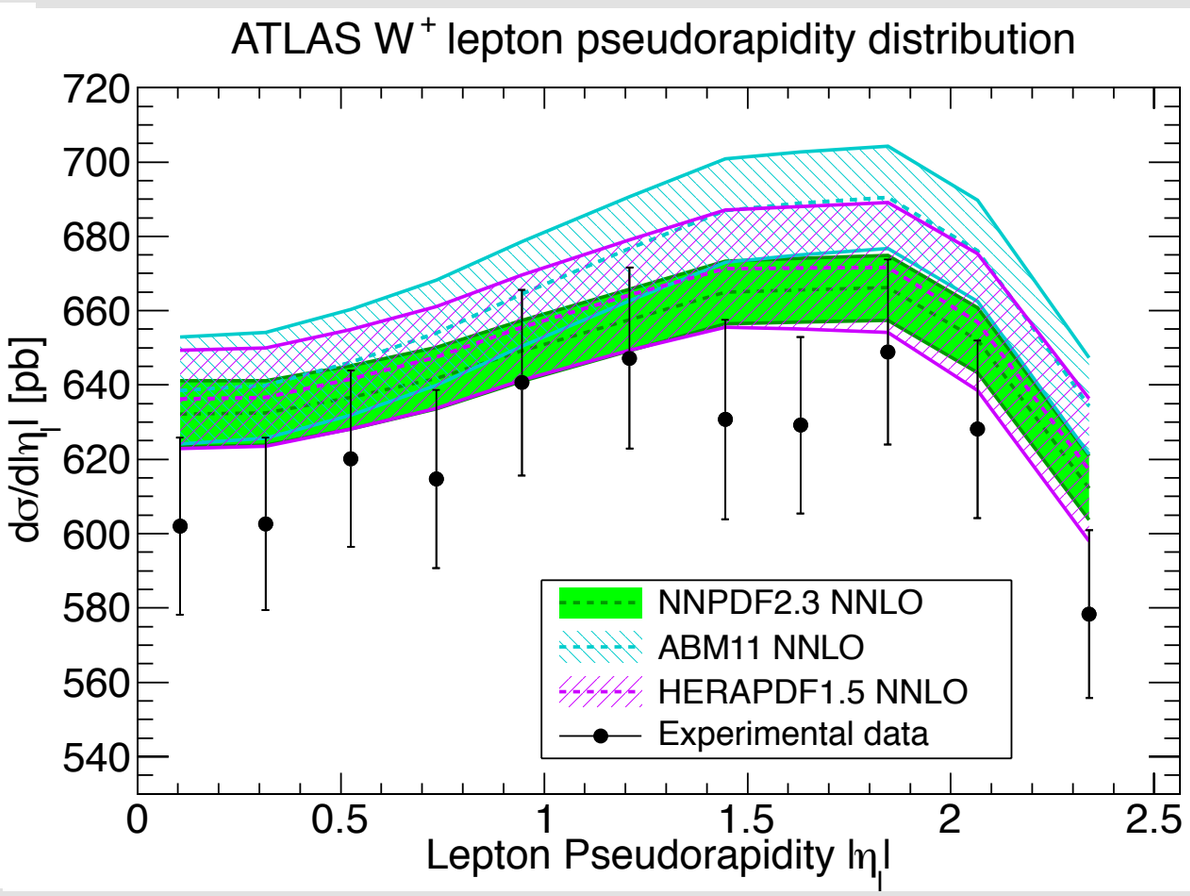
(NB: NNPDF2.3 already includes these datasets)

Juan Rojo

PDF4LHC Workshop, 08/09/2012

ATLAS 2010 W,Z distributions



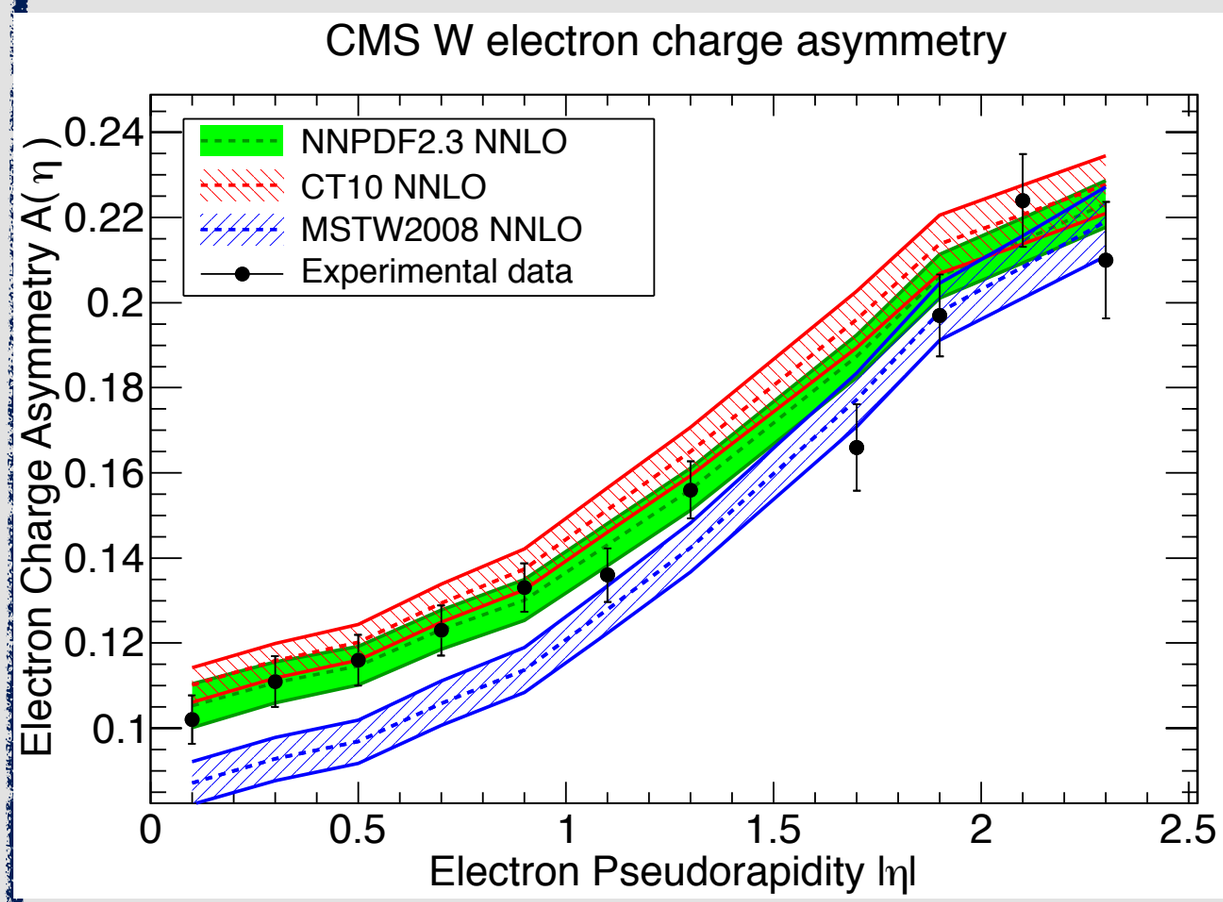


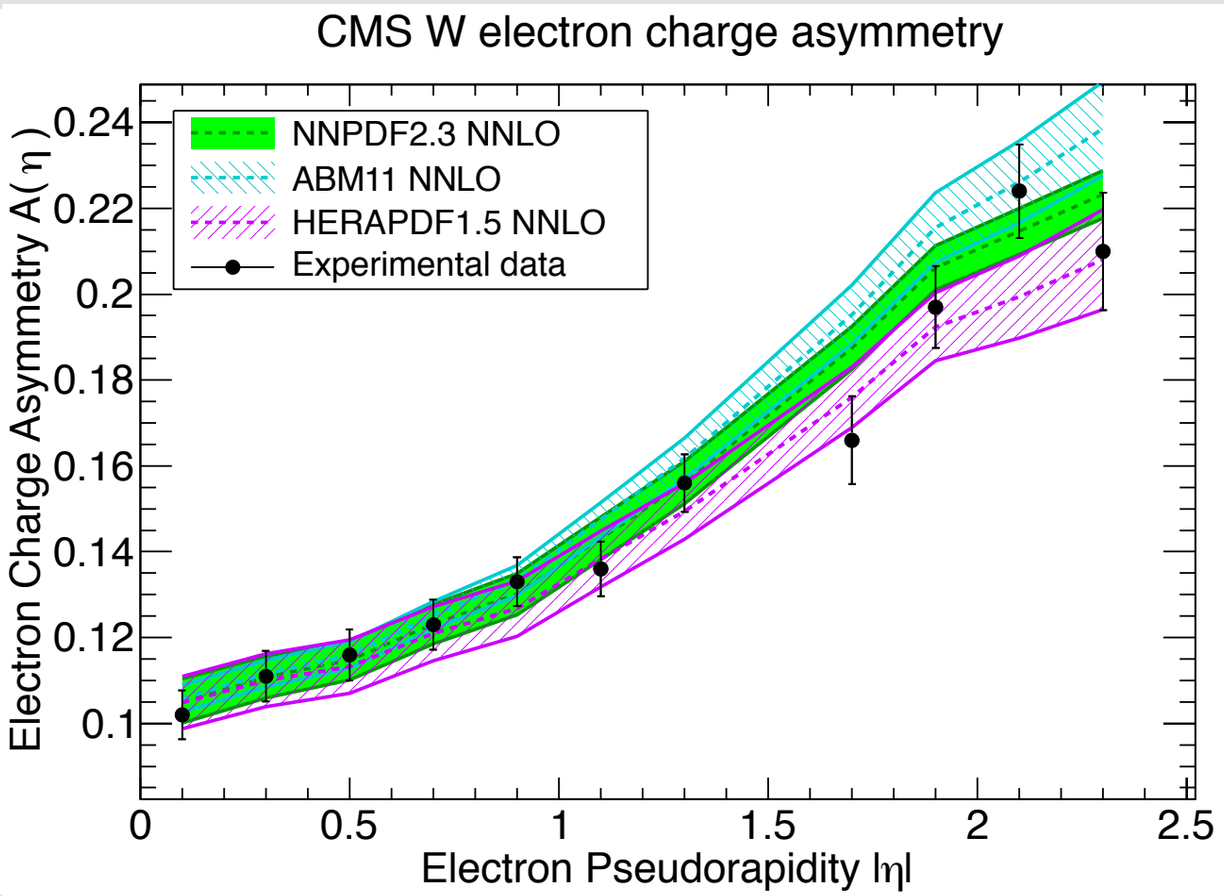
χ^2	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
ATLAS'10 W,Z	1.4	3.2	1.2	1.6	1.8

- **Sensitive to sea and valence quarks**: absolute normalization and flavor separation. Also handle on **strangeness**

- MSTW worse description. Problem understood due to not flexible enough parametrization for $\mathbf{u_V}$-$\mathbf{d_V}$, also nuclear corrections (R. Thorne, PDF4LHC)

CMS 2011 W electron asymmetry

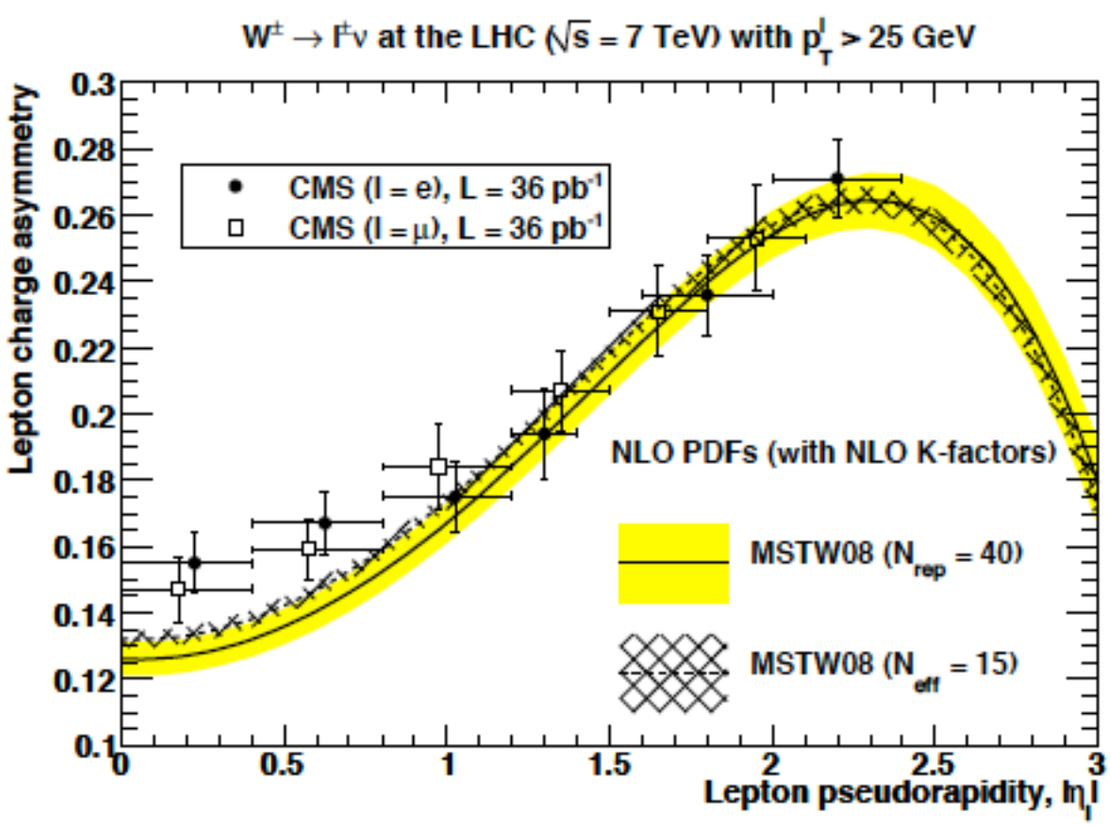


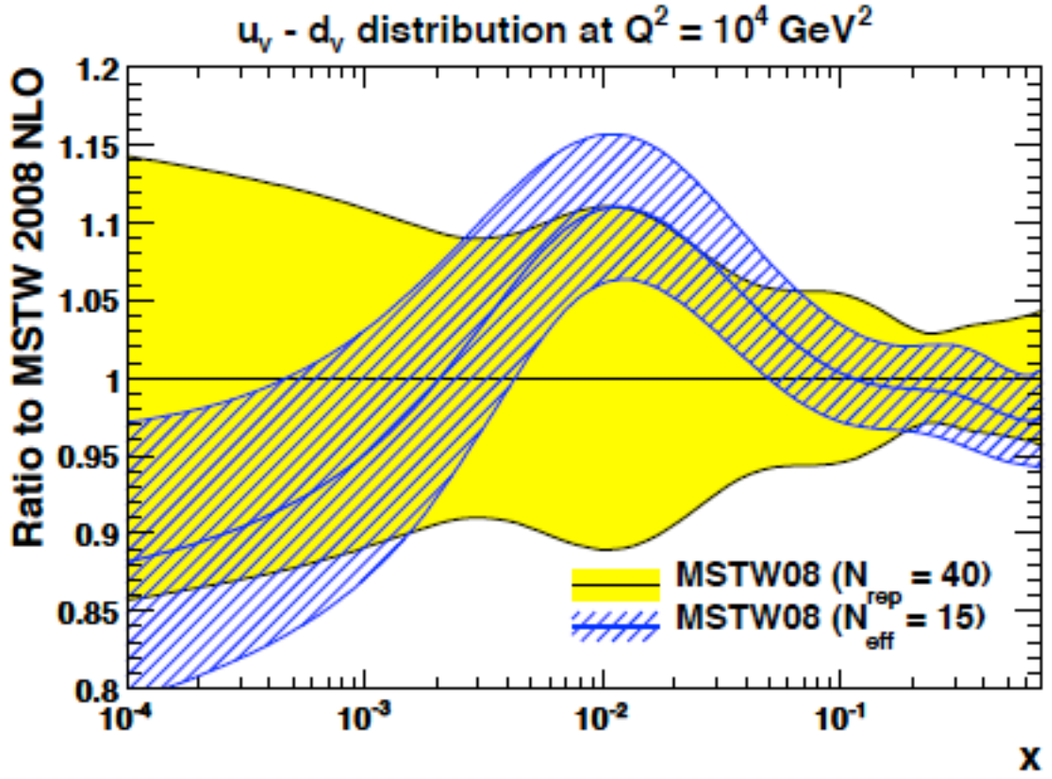


χ^2	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
CMS'11 Wasy	0.8	3.9	1.8	1.6	0.8

- W asymmetry direct probe of **light quark flavor separation**
- Also sensitive to strangeness: R. Plakakyte's PDF@CMS talk

MSTW08 and LHC W asymmetry



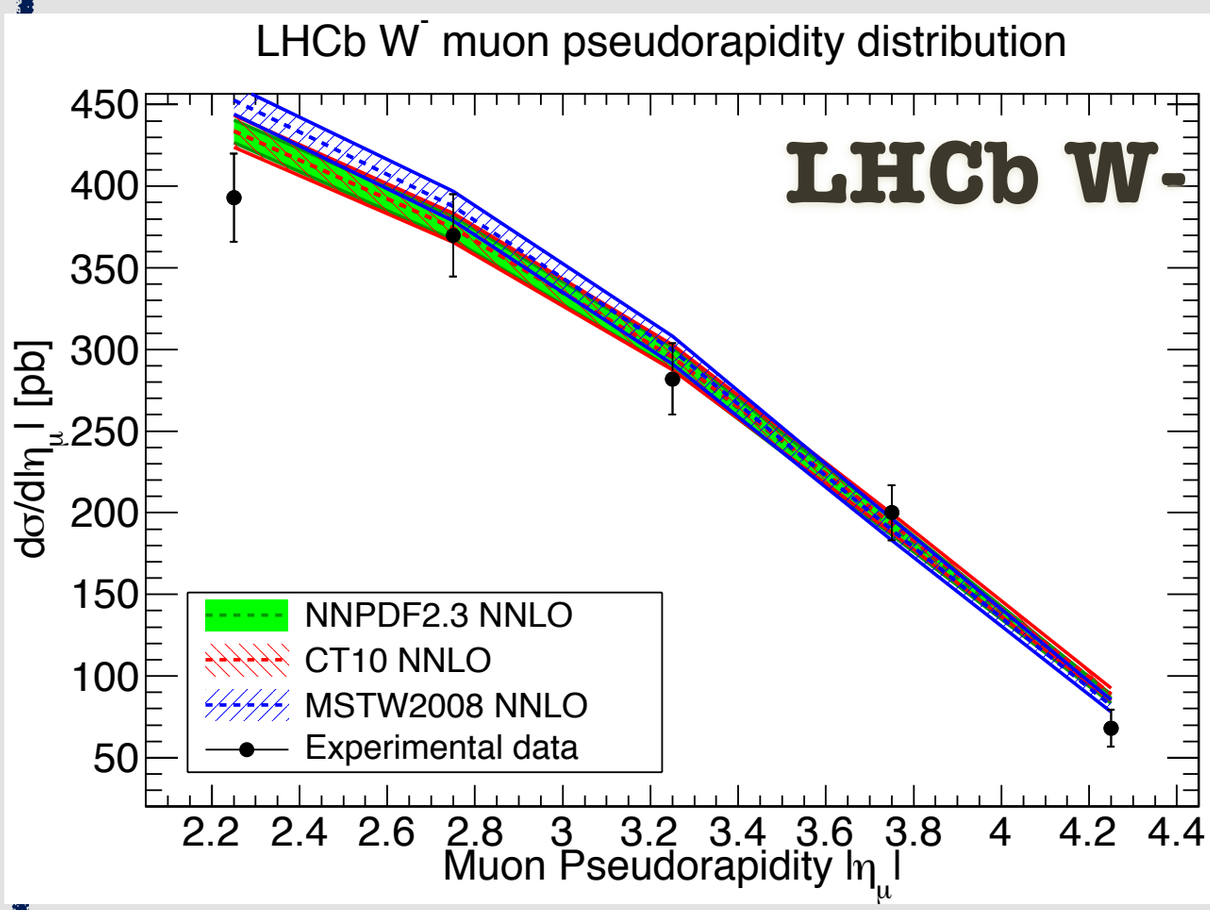


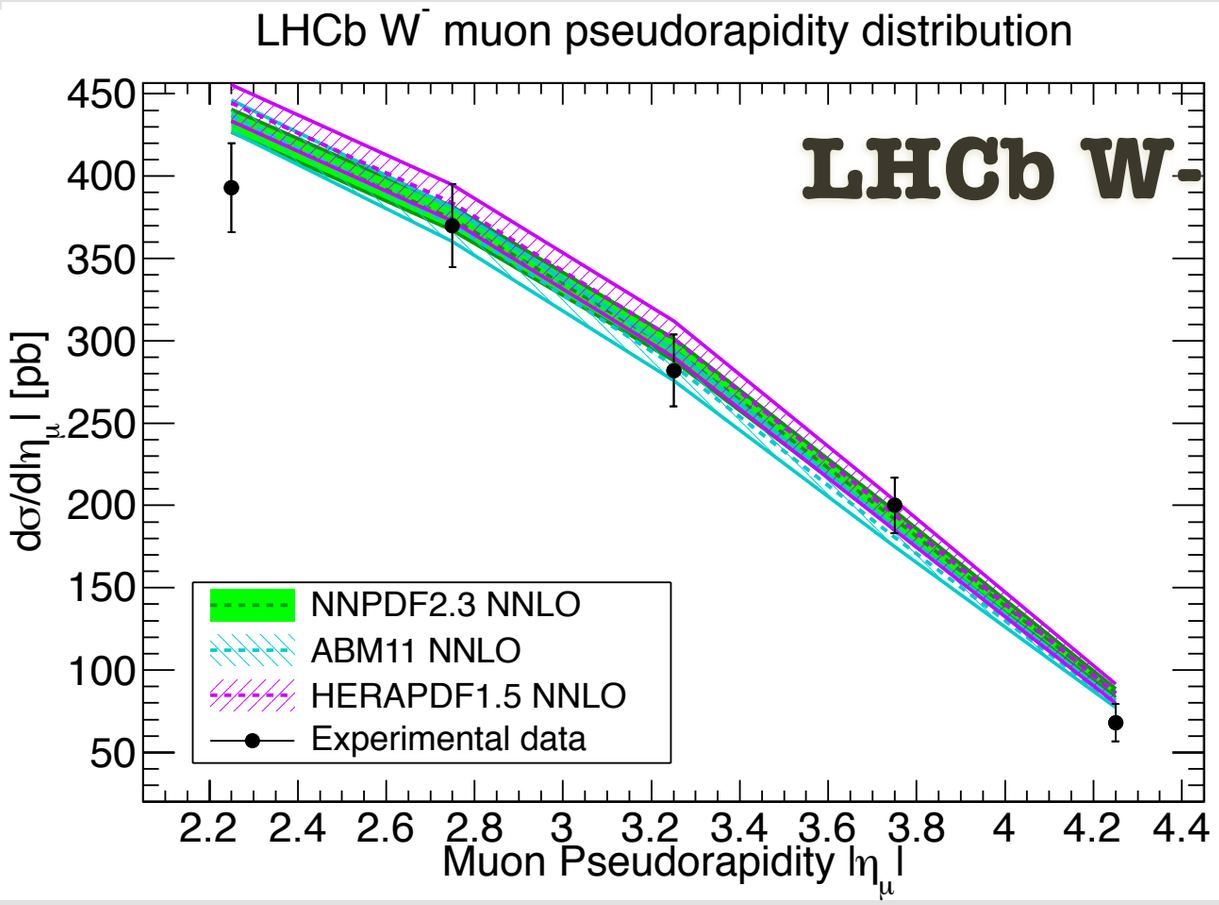
- Include CMS data by reweighting: $\chi^2/N_{\rm pts.} = 2.43 \to 1.32$.
- Reweighting shifts $u_v - d_v$ at $x \sim M_W/\sqrt{s} \sim 0.01$.

Including **LHC W asymmetry** data in MSTW08 improves substantially the fit quality. Shift in **near x=0.01 in the u_V-d_V difference.** arXiv:1205.4024

Extended parametrization + improved **deuteron corrections** also help. Tiny impact in inclusive cross sections.

LHCb 2010 W distributions

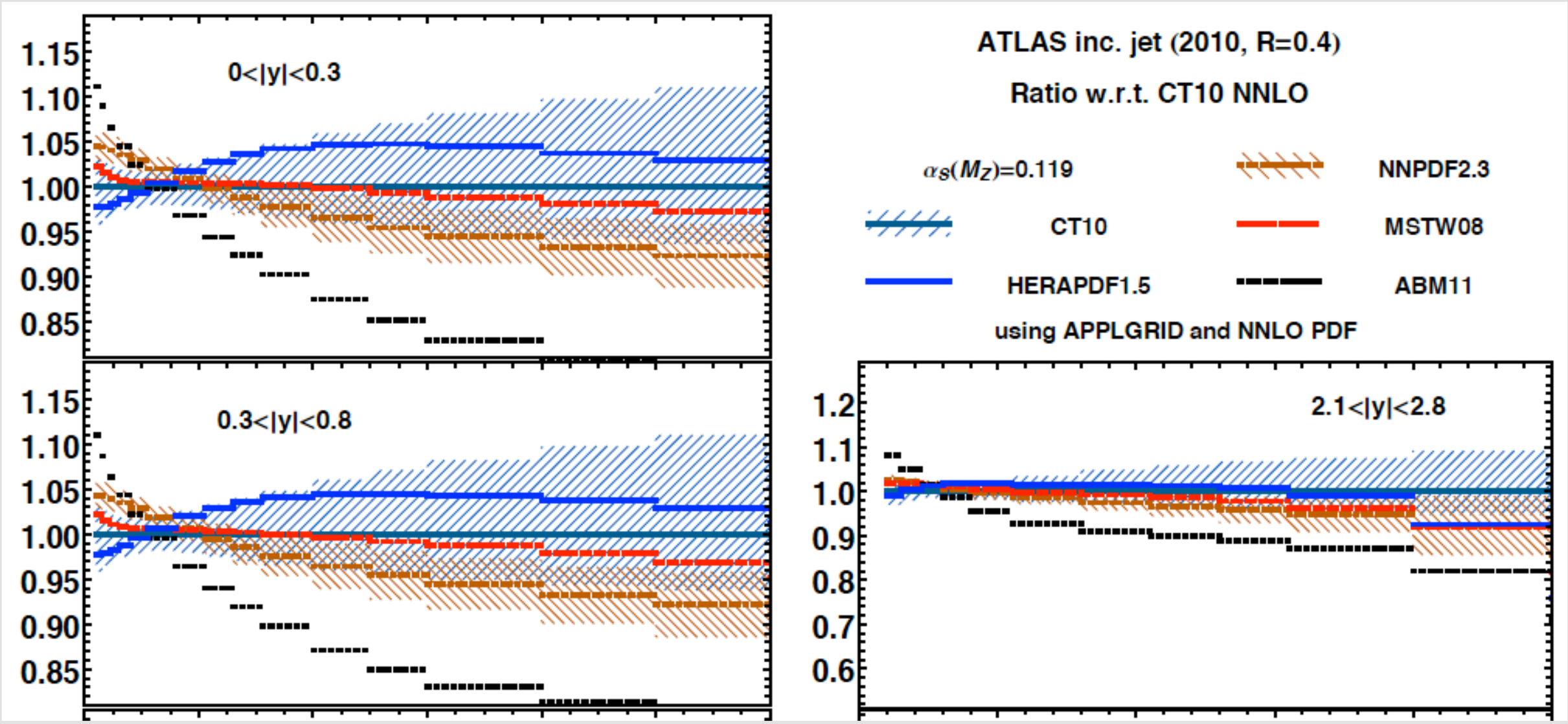




χ^2	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
LHCb'10 W	0.8	1.0	1.0	2.0	0.8

- LHCb forward data **unique probe of small-x PDFs**
- Moderate **discriminating power**. ABM11 worse description.
- LHCb Z data **cannot be used in PDF fits** in the present form, issues with the estimates of correlated systematics (R. McNulty)

ATLAS 2010 Jet Production



χ^2	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
ATLAS'10 Jets	0.9	0.9	1.0	1.0	1.0

- **Similar description** between all PDF sets. Visual data/theory comparisons not that informative without **quantitative χ^2 tests**
- Very moderate constraining power. To be improved with **5 fb^{-1} 2011 jet data**.

Impact of χ^2 definition

- When comparing χ^2 recall different definitions possible
- For example, one can use in the normalization term either the **experimental value** or a given **theory prediction (T_0 method),** which yields numerically smaller values
- Qualitative conclusions robust against χ^2 definitions. Other definitions also explored.

$$(\mathrm{cov})_{IJ} = \left(\sum_{l=1}^{N_c} \sigma_{I,l}\sigma_{J,l} + \delta_{IJ}\sigma_{I,s}^2\right) F_I F_J + \left(\sum_{n=1}^{N_a} \sigma_{I,n}\sigma_{J,n} + \sum_{n=1}^{N_r} \sigma_{I,n}\sigma_{J,n}\right) F_I F_J \quad \textbf{EXP}$$

$$(\mathrm{cov}_{\mathrm{t0}})_{IJ} = \left(\sum_{l=1}^{N_c} \sigma_{I,l}\sigma_{J,l} + \delta_{IJ}\sigma_{I,s}^2\right) F_I F_J + \left(\sum_{n=1}^{N_a} \sigma_{I,n}\sigma_{J,n} + \sum_{n=1}^{N_r} \sigma_{I,n}\sigma_{J,n}\right) F_I^{(0)} F_J^{(0)} \quad \textbf{T}_0$$

	NNLO $\alpha_s = 0.119$				
Dataset	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
ATLAS W, Z (EXP)	1.435	3.201	1.160	2.061	1.872
ATLAS W, Z (T0)	1.385	3.043	1.082	1.965	1.817
CMS W el asy (EXP)	0.813	3.862	1.772	1.614	0.814
CMS W el asy (T0)	0.813	3.862	1.772	1.614	0.814
LHCb W, Z (EXP)	0.831	1.050	0.966	1.970	0.784
LHCb W, Z (T0)	0.784	0.968	0.905	1.906	0.727
ATLAS jets (EXP)	0.937	0.935	1.016	0.959	1.011
ATLAS jets (T0)	0.812	0.802	0.879	0.892	0.855

Higgs Production: Combined PDF+ α_S Uncertainties

Juan Rojo

PDF4LHC Workshop, 08/09/2012

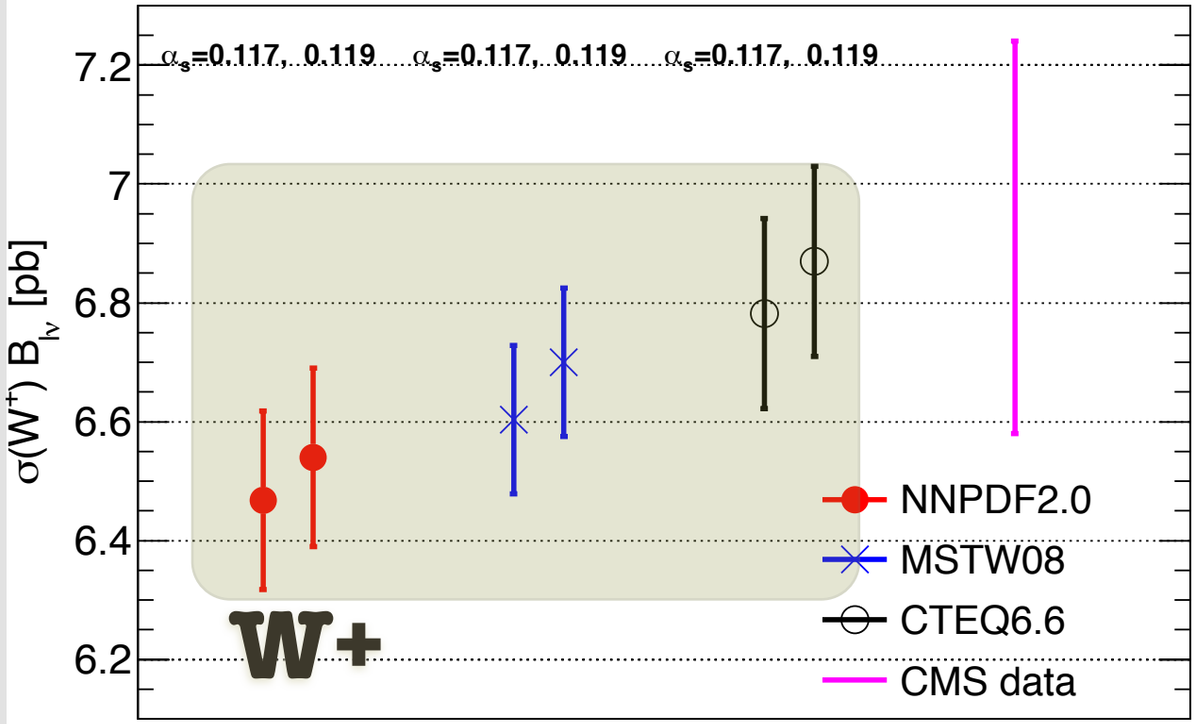
NNLO PDFs and Higgs production

- The **Higgs Cross Section Working Group** estimates **PDF+α_S** uncertainties using the current **PDF4LHC recommendations**. What would be the differences if the same prescription was upgraded to NNLO: Envelope of **NNPDF2.3, CT10, MSTW08**?

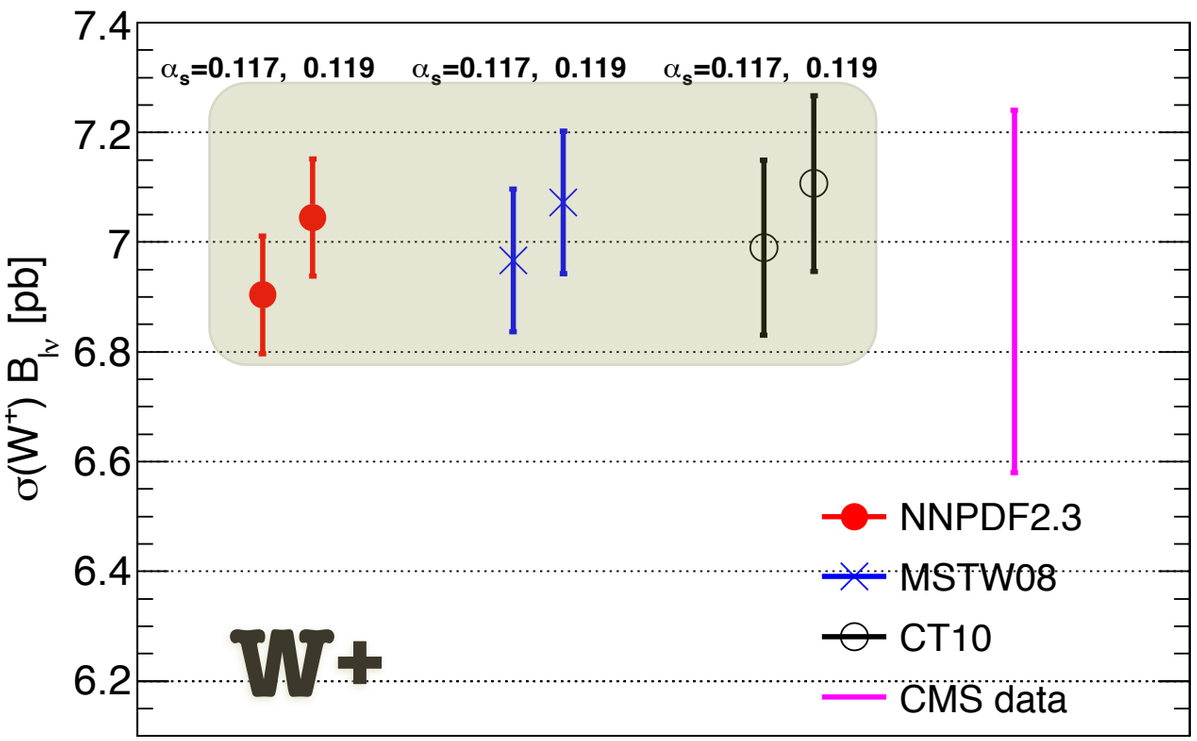
- Simplified toy calculation: **envelope** of cross sections including **PDF+α_S uncertainties** computed for α_S **=0.117** and **0.119.** PDF and α_S errors added in quadrature

- For most processes the envelope with NNLO PDFs leads to a **substantial improvement** with respect the original NLO envelope. Example: **W production**

LHC 8 TeV - VRAP NLO - 2010 PDFs - PDF +α_S



LHC 8 TeV - VRAP NNLO - 2012 PDFs - PDF + α_S



2010 NLO PDFs: $\Delta_{PDF+\alpha s}$ = 5.3%

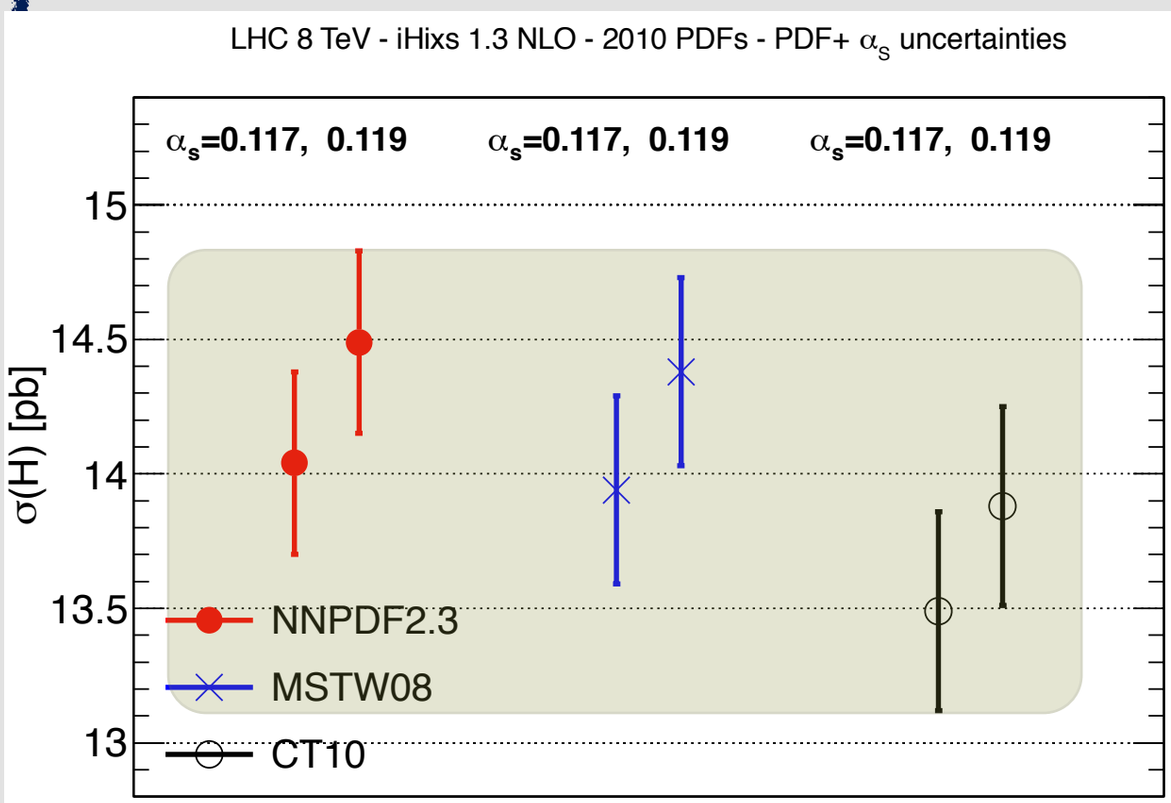
2012 NNLO PDFs: $\Delta_{PDF+\alpha s}$ = 3.3%

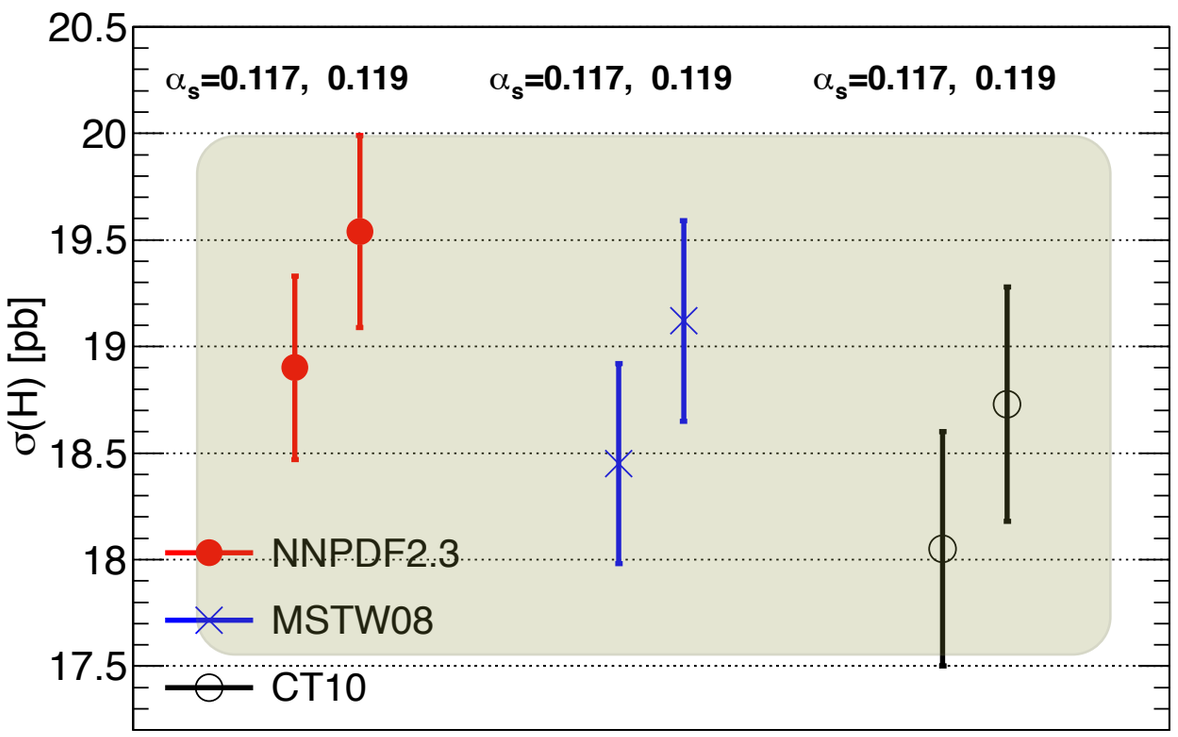
NNLO PDFs and Higgs production

- Simplified toy calculation: **envelope** of cross sections including **PDF+α_S uncertainties** computed for α_S **=0.117** and **0.119.** PDF and α_S errors in quadrature

- For a wide range of Higgs masses and most other processes (VBF, WH), NLO -> NNLO leads to substantial reduction of **PDF+α_S uncertainties ...**

- **...** except for the **ggF Higgs** with **M_H=125 GeV,** with a **slight increase** of **PDF+α_S** uncertainties by **10% :(**



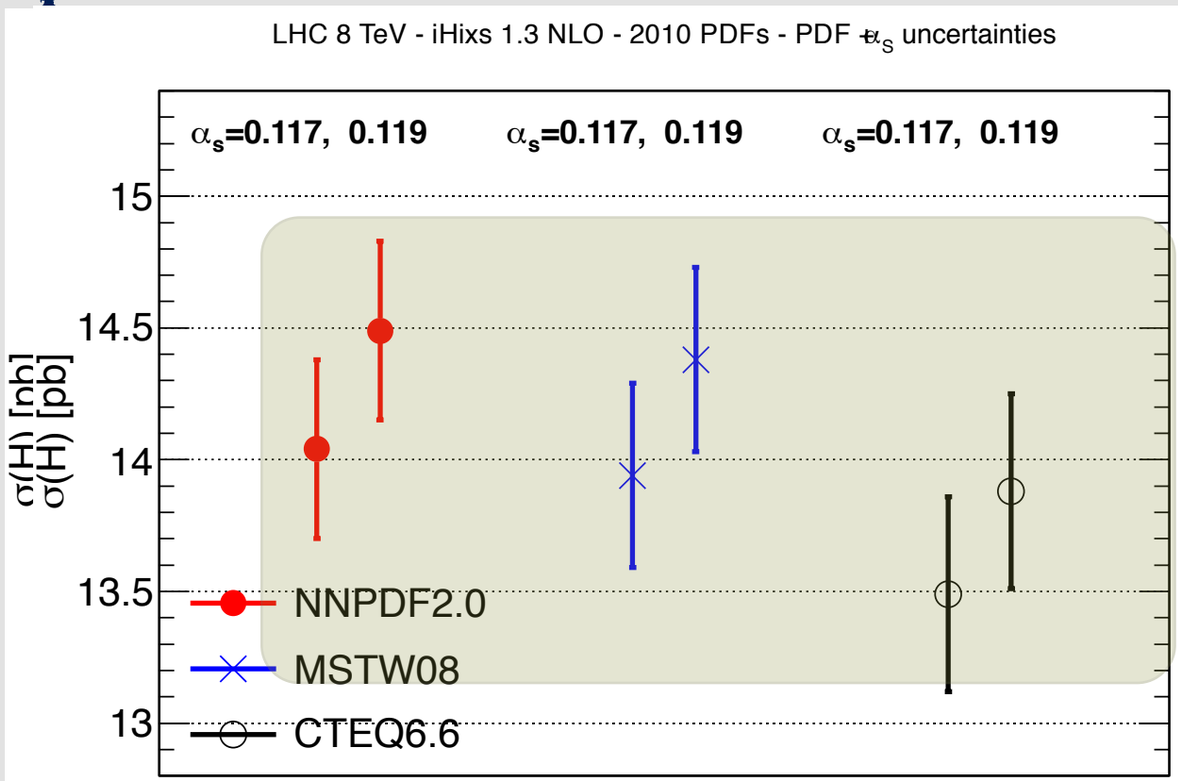


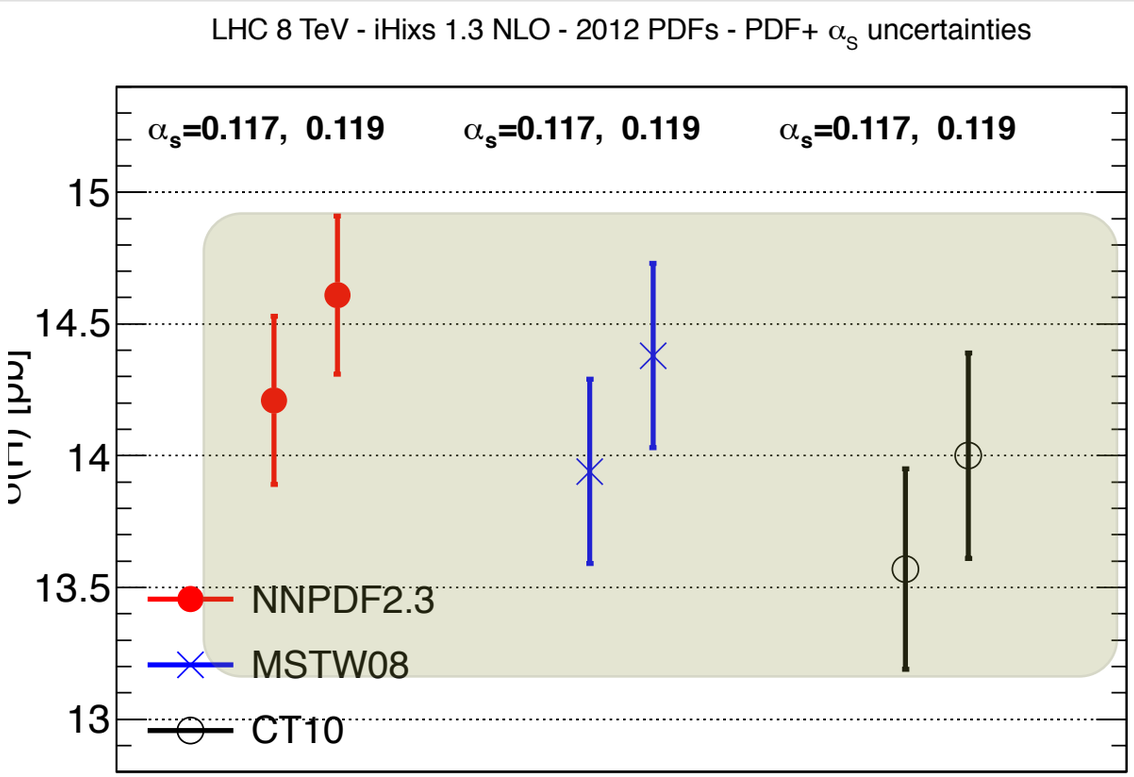
2010 NLO PDFs: $\Delta_{PDF+\alpha s}$ = 6.1%

2012 NNLO PDFs: $\Delta_{PDF+\alpha s}$ = 6.6%

NNLO PDFs and Higgs production

- Compare to the **PDF+α_S uncertainties** of the **NLO envelope** with 2010 and 2012 PDFs
- Good stability between **2010 and 2012 NLO PDFs**
- Robustness of PDF4LHC envelope: **a posteriori validation** of the original PDF4LHC recommendations





2010 NLO PDFs: $\Delta_{PDF+\alpha s} = 6.1\%$

2012 NLO PDFs: $\Delta_{PDF+\alpha s} = 6.1\%$

Summary

- We find **good agreement between CT10, MSTW08 and NNPDF2.3 NNLO sets** in most cases for PDFs, luminosities and physical cross sections

- ABM11 has **harder quarks and a softer large-x gluon** as compared CT/MSTW/NNPDF**.** Partly understood from use of FFN scheme. Larger differences if default α_S used.

- HERAPDF1.5 agrees with CT/MSTW/NNPDF on **central values**, but has **larger PDF uncertainties** (consistently due to reduced dataset). **No tension** between HERA-only fits and fits to a wider dataset observed.

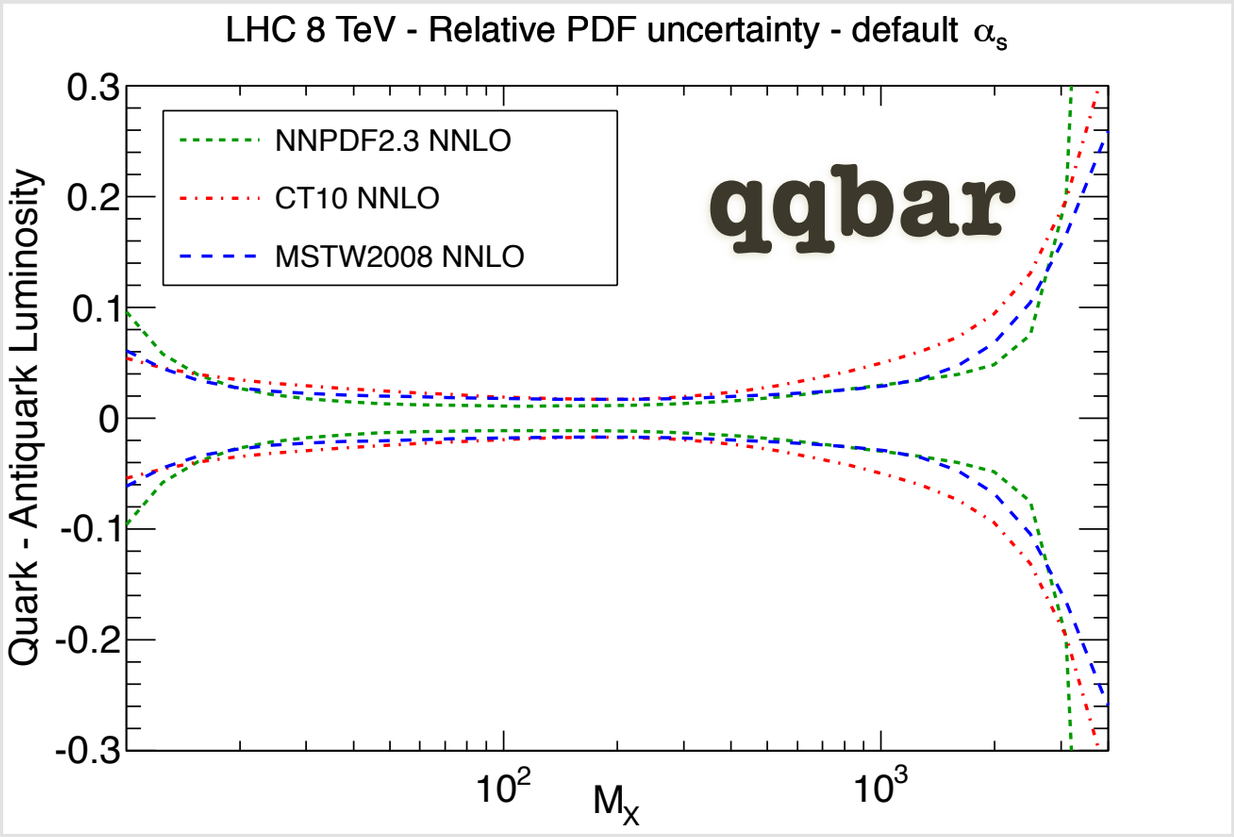
- We have compared all PDF sets to **available LHC 7 and 8 TeV data**, and for differential distributions made the **comparison quantitative** using a χ^2 estimator. LHC data already provides **important constraints on PDFs**, much more to come in next months/years!

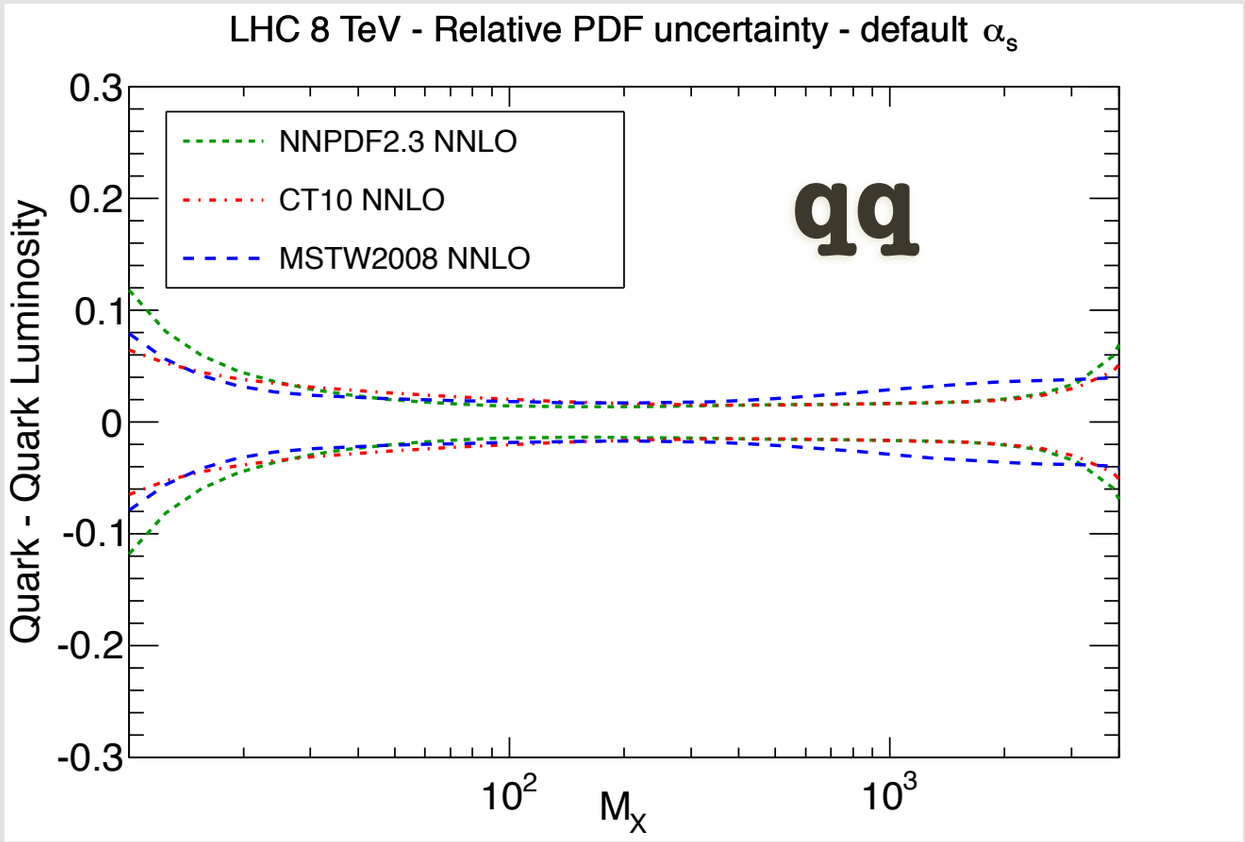
- An **NNLO update** of the current **PDF4LHC envelope** results in substantial improvement of the **PDF+α_S** uncertainties for a wide range of processes.

- For a **Higgs at M_H=125 GeV**, such **NNLO update** yields similar **PDF+α_S** uncertainties as in the current prescription.

Extra Material

Quark Luminosities



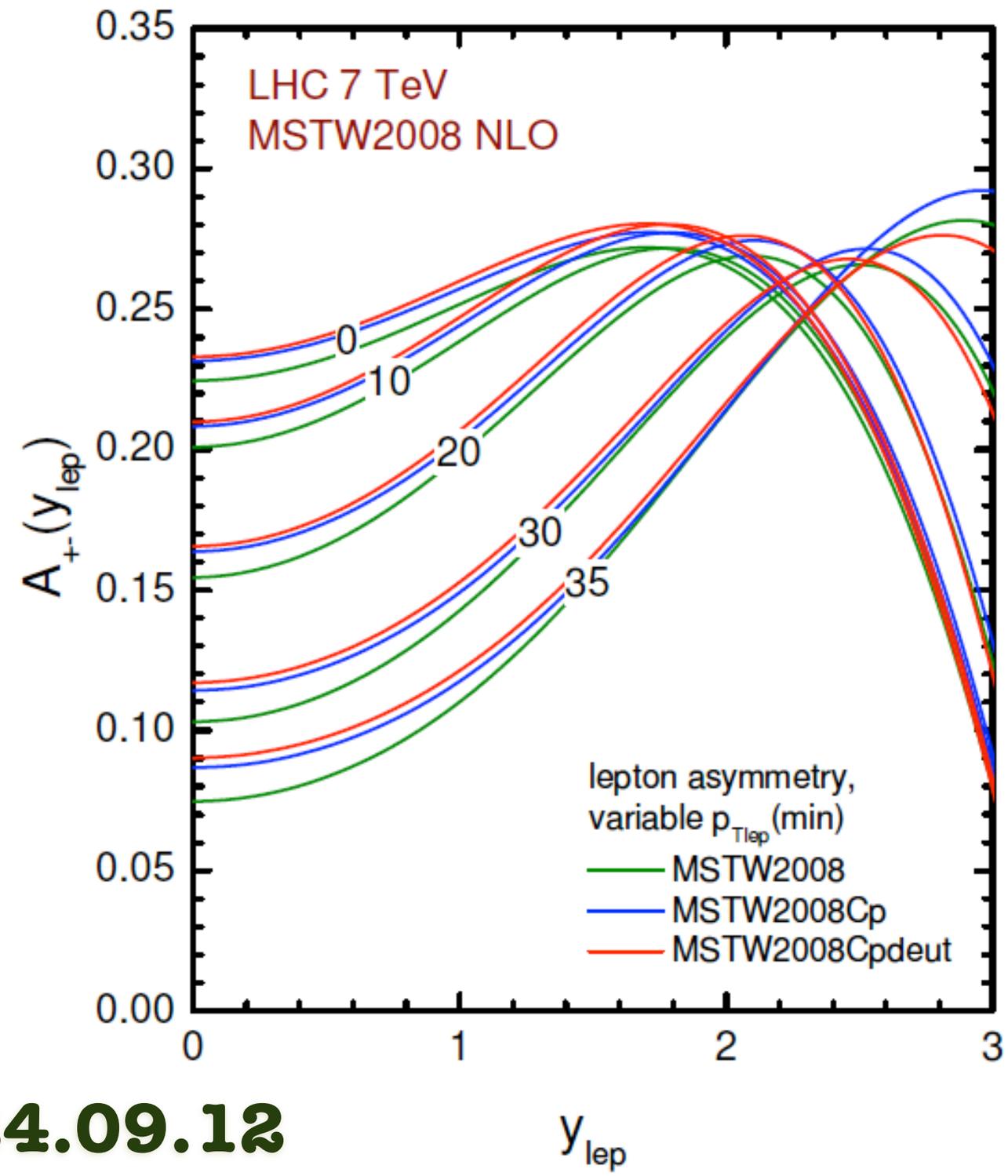


- **Quark-Antiquark luminosities** (relevant for SUSY, W', ...) have much larger uncertainties at large masses due to poorly known large-x antiquarks
- **Quark-Quark luminosities** (relevant for jets) better constrained at large masses

MSTW2008 and W asymmetry

Increases lepton asymmetry, but very preferentially for high p_T cut. (Curves made here with LO calculations).

Most of the effect already obtained for parameterisation extension, but some from deuterium study.



R. Thorne PDF4LHC 24.09.12

MSTW2008 and W asymmetry

Big change in high p_T cut asymmetry, but very specifically sensitive to $u_V(x,Q^2) - d_V(x,Q^2)$. What about other quantities? Other PDFs changed little. α_S free but tiny change. Expect little variation.

The % change in the cross sections ($M_H = 120\text{GeV}$).

	MSTWCp	MSTWCpdeut
W Tev	+0.6	+0.1
Z Tev	+0.8	+0.7
W^+ LHC (7TeV)	+0.7	+0.3
W^- LHC (7TeV)	-0.7	-0.4
Z LHC (7TeV)	+0.0	-0.1
W^+ LHC (14TeV)	+0.6	+0.3
W^- LHC (14TeV)	-0.6	-0.5
Z LHC (14TeV)	+0.1	-0.1
Higgs TeV	-0.5	-1.8
Higgs LHC (7TeV)	+0.2	-0.1
Higgs LHC (14TeV)	+0.1	+0.1

Extreme stability in total cross sections, all far inside uncertainties. Even $\sigma(W^+)/\sigma(W^-)$ barely more than 1%.

R. Thorne PDF4LHC 24.09.12