Parton Distribution Functions at the LHC

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CERN, Geneva, Switzerland
Antwerp University, Belgium
UC Davis, California, USA

PDF4LHC

Contents(*)

- Introduction: PDFs & PDF4LHC
- Processes @ LHC with sensitivity to PDFs
  - Jet Cross sections
  - Prompt Photon production
  - Drell Yan Production
  - W, Z production, W asymmetries
  - Top Production
- Outlook and Summary

(*) Disclaimer: NOT a technical talk on PDFs, uncertainties, TH issues…

PDF4LHC

PDF4LHC

UCL HEP Home
PDF4LHC Home

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Recommendation
Meetings
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Hypernews

- A forum for discussions on PDFs, created as a spin off of the HERALHC workshops (2008). Mandate:
  - Uncertainties on the PDFs for LHC x-section estimates
  - Usage of LHC data for including in PDF fits
  - Recommendations…

PDFs are a very dynamic and constantly developing field, reacting to new data, eg from HERA, Tevatron, the LHC…

Steering Committee

Michiel Botje (NIKHEF)
Jonathan Butterworth (University College London)
Joël Feltesse (CEA/Saclay and Hamburg University)
Stefano Forte (Milan University)
Sasha Glazov (DESY)
Joey Huston (Michigan State University)
Ronan McNulty (University College Dublin (UCD) Dept. Experimental Physics)
Albert de Roeck (CERN)
Amanda Sarkar (University of Oxford)
Torbjörn Sjöstrand (CERN and Lund University)
Robert Thorne (University College London)

Previous meetings:

- 4 Jul 2011, DESY Hamburg - Agenda on Indico
- 7 Mar 2011, CERN - Agenda on Indico
- 29 Nov 2010, DESY - Agenda on Indico
- 26 Sep - 1 Oct 2010 at *QCD at the LHC*, ECT Trento - Agenda on Indico
- 4 Jul 2010, CERN - Agenda on Indico
- **Special meeting for PDF4LHC cross section benchmarking:**
  26 March 2010, CERN - Agenda on Indico
  Detailed results available at the PDF4LHC wiki.
- 29 Jan 2010, CERN - Agenda on Indico
- 23 Oct 2009, DESY Hamburg (as part of PDF School 2009) - Agenda on Indico
- 6-7 Aug 2009, CERN (as part of the CERN SM/BSM workshop) - Agenda on Indico
- 29 May 2009, CERN - Agenda on Indico
- 4 Sep 2008, CERN - Agenda on Indico
- 14 Jul 2008, CERN - Agenda on Indico
- Session at HERA-LHC workshop, 26-30 May 2008, CERN - Agenda on Indico
- 22-23 February 2008, CERN - Agenda on Indico

http://www.hep.ucl.ac.uk/pdf4lhc/
Next meeting 28/11 CERN (LPCC)

PDFs for the LHC

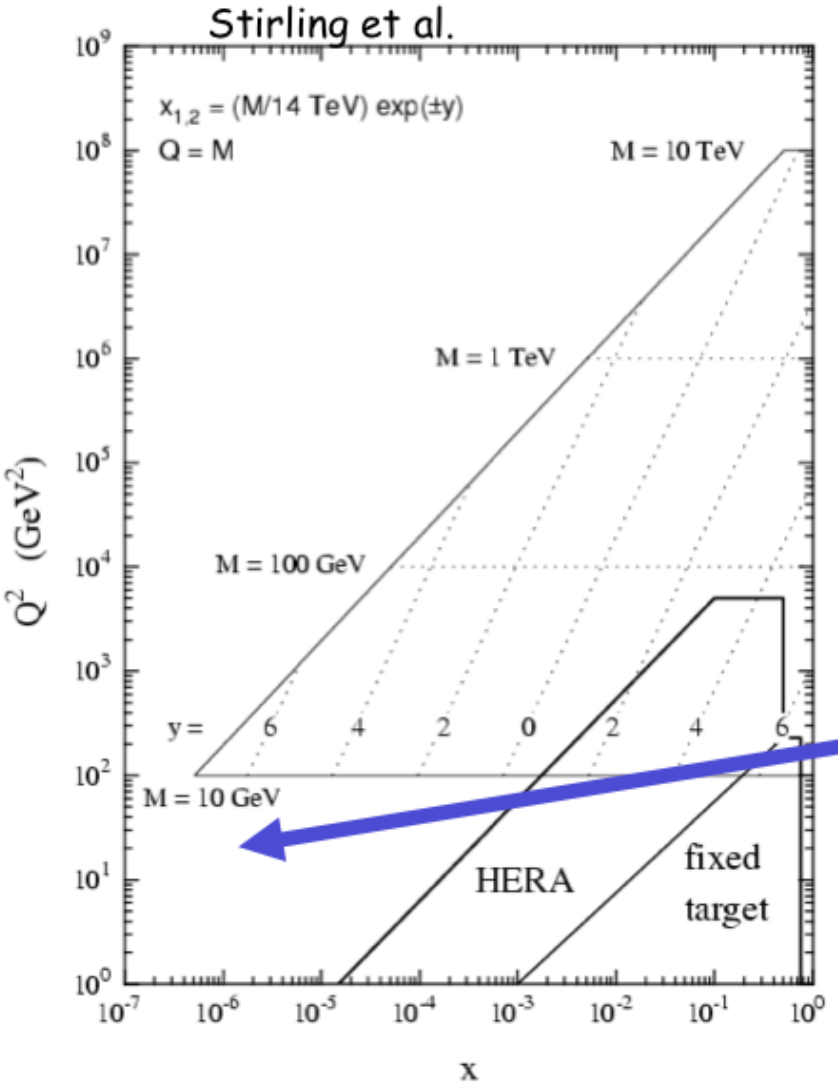
Recent versions

	MSTW08	CTEQ6.6/CT10	NNPDF2.1	HERAPDF1.0/1.5	ABKM09/ABM11	GJR08/JR09
PDF order:	LO NLO NNLO	LO NLO NNLO	LO NLO NNLO	NLO NNLO	NLO NNLO	NLO NNLO
HERA DIS	yes	yes	yes	yes	yes	yes
Fixed target DIS	yes	yes	yes	no	yes	yes
Fixed target DY	yes	yes	yes	no	yes	yes
Tevatron W,Z	yes	yes	yes	no	no	no
Tevatron jets	yes	yes	yes	no	no	yes
HF scheme	RT GMVF	SACOT	FONLL	RT	BMSN FFNS	FFNS
α_s (NLO)	0.120	0.118	0.119	0.1176	0.118	0.1135
α_s (NNLO)	0.1171	0.118	0.1174	0.1176	0.1135	0.1124

Most PDF families based on χ^2 minimization of fits to data
NNPDF based on neural net instead of starting parameterizations, and replicas

All PDF families now deliver NNLO sets (CT not public yet)
However there are many differences in details in the PDFs!

PDFs and the LHC



LHC kinematics coverage compared to other experiments:

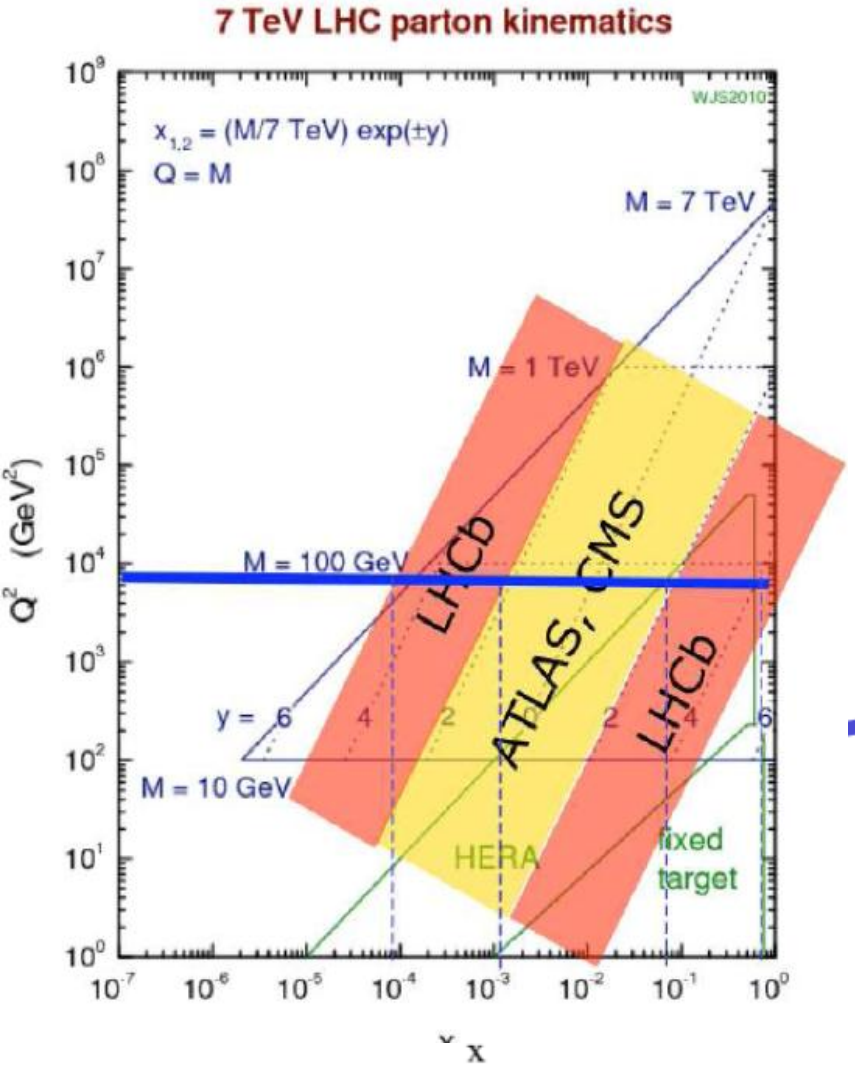
Extension to small x and large Q^2

Processes: (2005)

$p(p_1) + p(p_2) \rightarrow \text{jet} + \gamma + \text{X}$	Prompt photons
$p(p_1) + p(p_2) \rightarrow l\bar{l} + \text{X}$	Drell-Yan
$p(p_1) + p(p_2) \rightarrow \text{jet}_1 + \text{jet}_2 + \text{X}$	Jets
$p(p_1) + p(p_2) \rightarrow \text{Q} + \bar{\text{Q}} + \text{X}$	Heavy Flavours
$p(p_1) + p(p_2) \rightarrow W/Z + \text{X}$	W,Z production

If rapidities below 5 and masses below 10 GeV can be covered ⇒ x down to 10^{-6}-10^{-7}

PDFs and the LHC



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$p(p_1) + p(p_2) \to \text{jet} + \gamma + \text{X}$	Prompt photons
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$p(p_1) + p(p_2) \to W/Z + \text{X}$	W,Z production

If rapidities below 5 and masses below 10 GeV can be covered ⇒ x down to 10^{-6}-10^{-7}

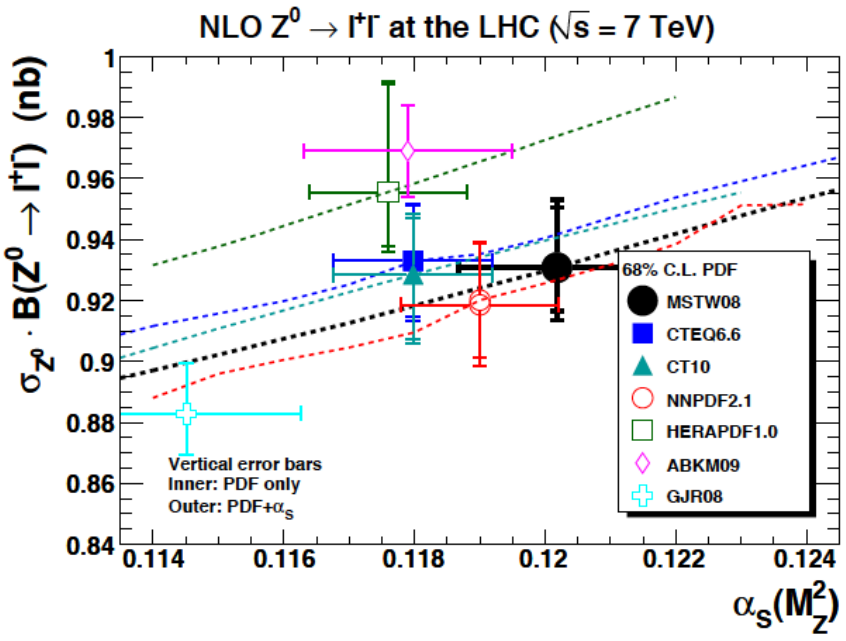
Further processes @ LHC
- W+c, Z+b, W/Z+jets
- Top production

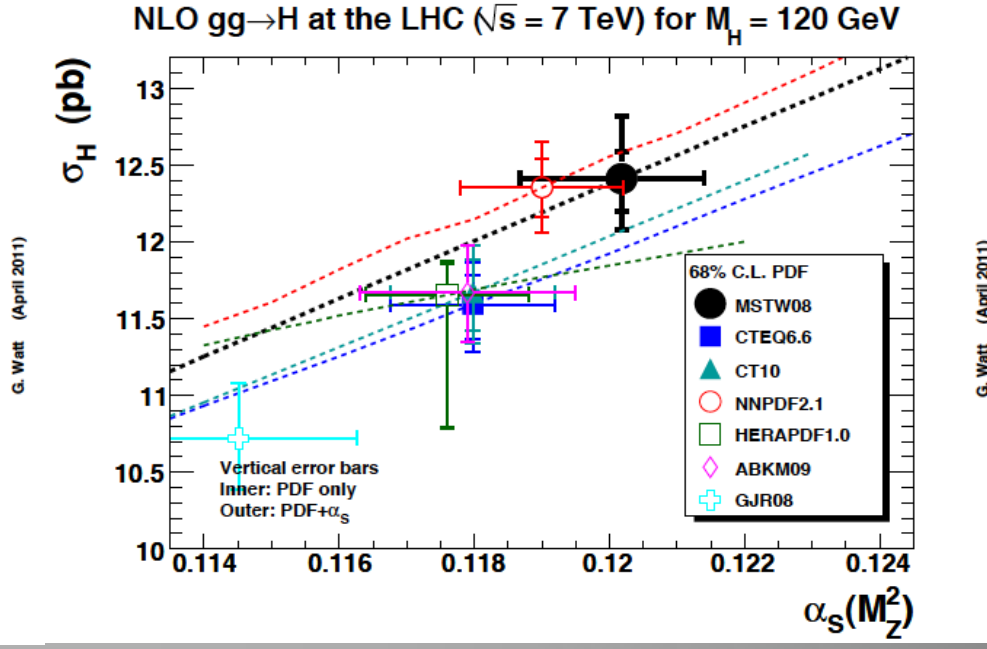
PDF Benchmark Studies

The PDF4LHC Working Group Interim Report arXiv:1101.0536

Sergey Alekhin[1,2], Simone Alioli[1], Richard D. Ball[3], Valerio Bertone[4], Johannes Blümlein[1], Michiel Botje[5], Jon Butterworth[6], Francesco Cerutti[7], Amanda Cooper-Sarkar[8], Albert de Roeck[9], Luigi Del Debbio[3], Joel Feltesse[10], Stefano Forte[11], Alexander Glazov[12], Alberto Guffanti[4], Claire Gwenlan[8], Joey Huston[13], Pedro Jimenez-Delgado[14], Hung-Liang Lai[15], José I. Latorre[7], Ronan McNulty[16], Pavel Nadolsky[17], Sven Olaf Moch[1], Jon Pumplin[13], Voica Radescu[18], Juan Rojo[11], Torbjörn Sjöstrand[19], W.J. Stirling[20], Daniel Stump[13], Robert S. Thorne[6], Maria Ubiali[21], Alessandro Vicini[11], Graeme Watt[22], C.-P. Yuan[13]

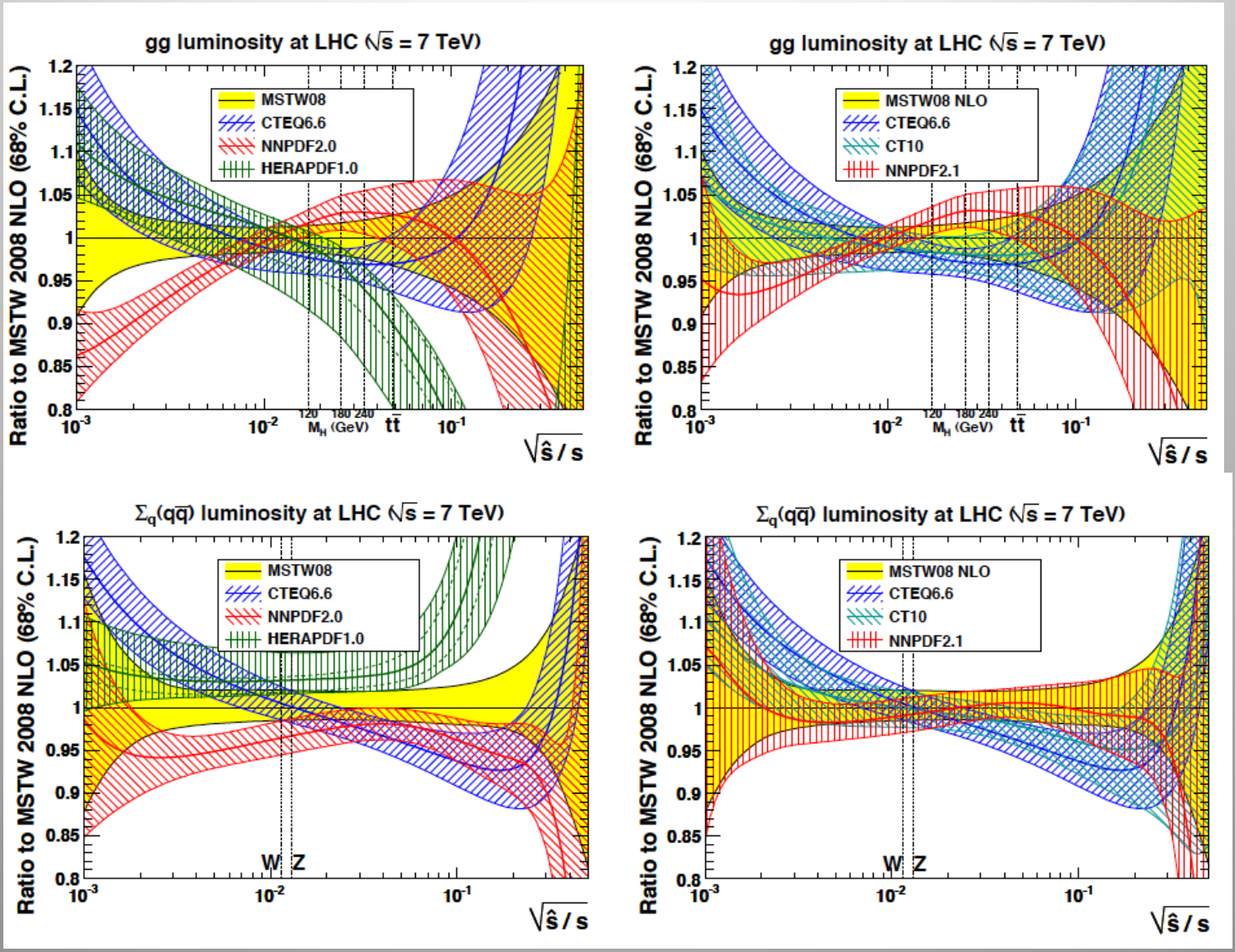
Recent updates in
G. Watt arXiv:1106.5788





End 2010: pragmatic recommendation to use for the uncertainty the error envelope of MSTW08, CTEQ6.6 and NNPDF2.0 (arXiv:1101.0538).
But of course ALL PDFs should be used for PDF comparisons/studies!!

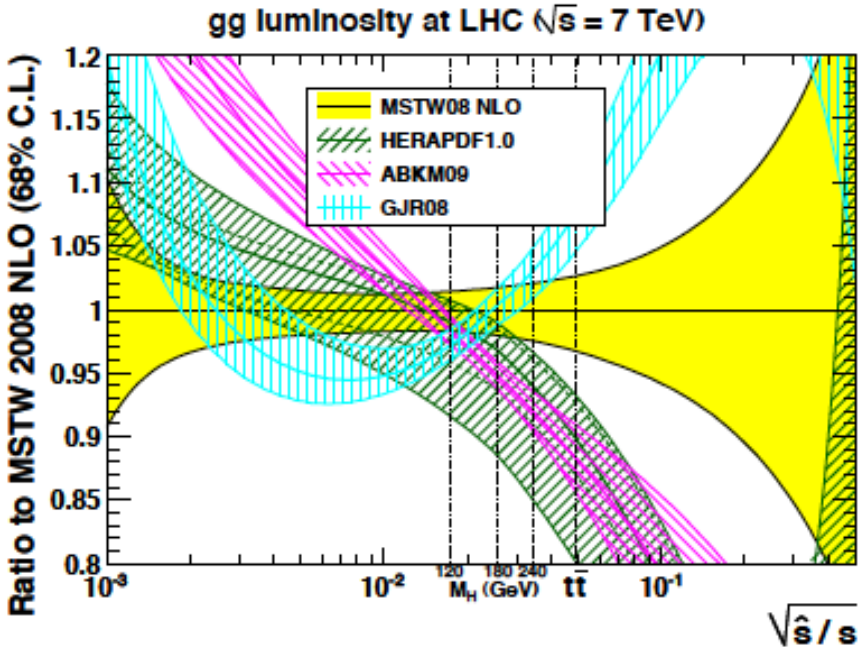
Recent NLO PDF Updates

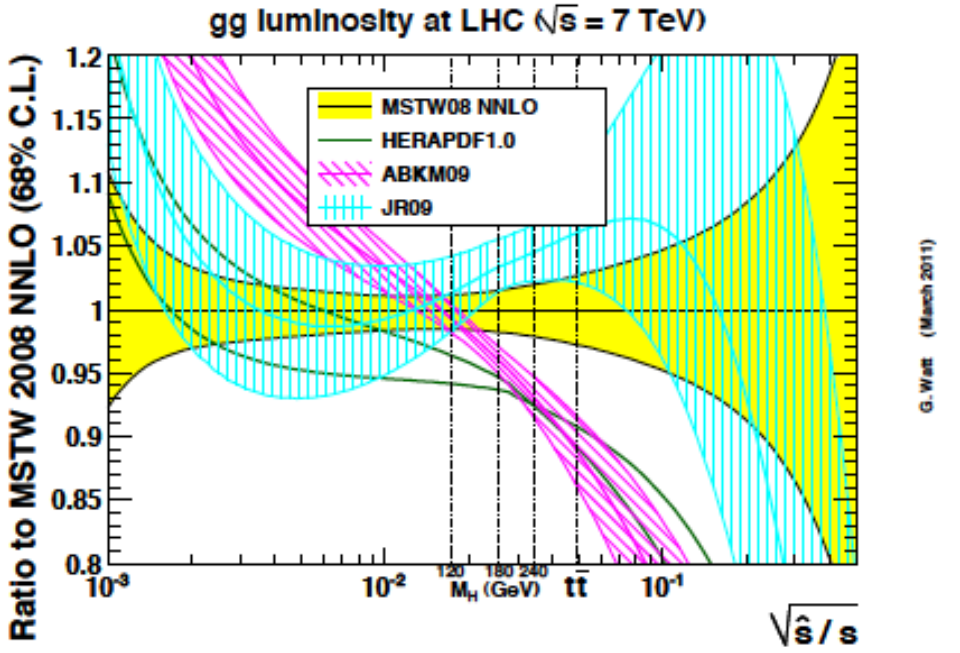


MSTW, CT (fka CTEQ) and NNPDF are converging somewhat

NNLO PDF Comparisons

April 2011

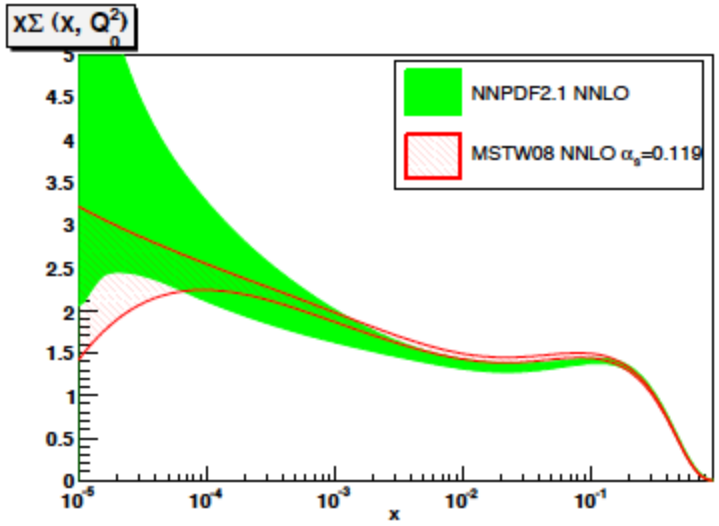


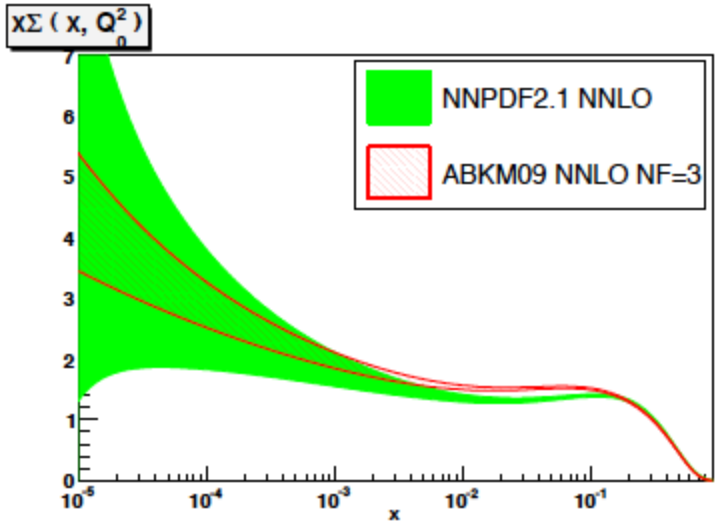


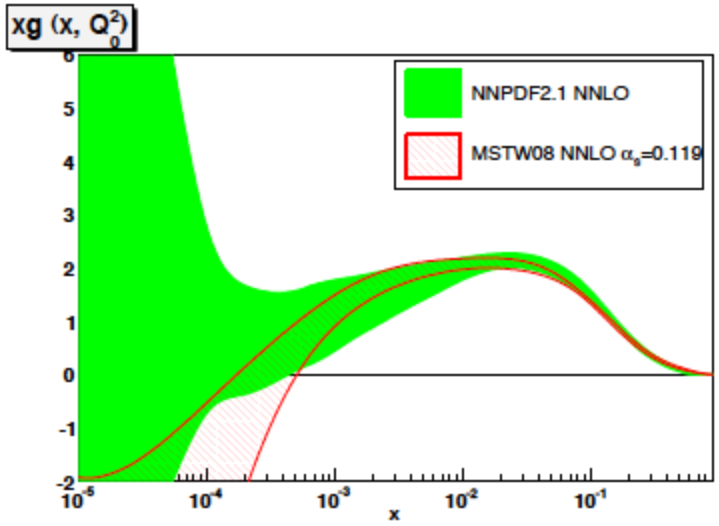
Since then: Also the NNPDF and CT have now NNLO PDF sets

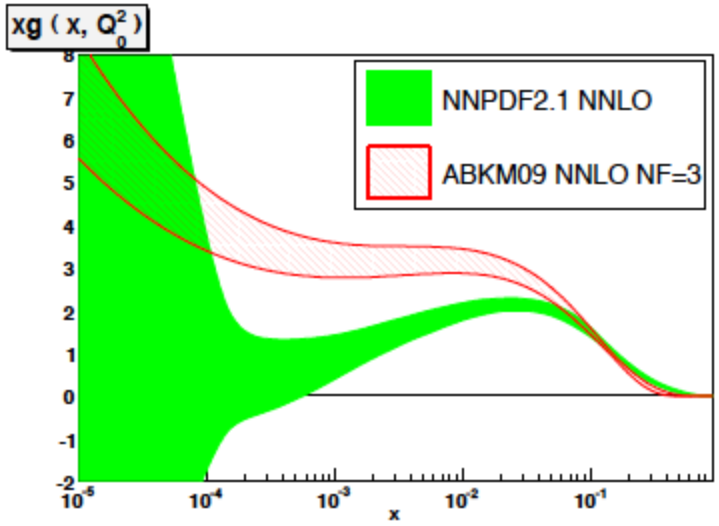
NNLO PDF Comparisons

Comparison of NNLO NNPDF2.1 with MSTW and ABKM at low scale

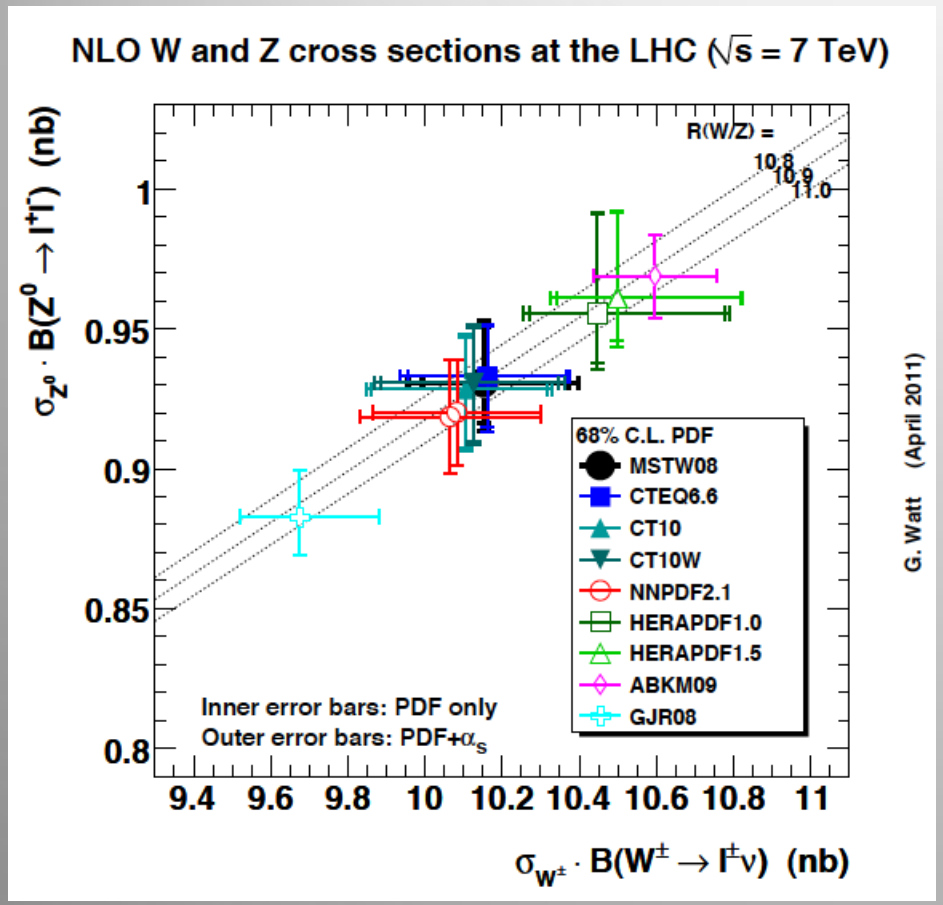


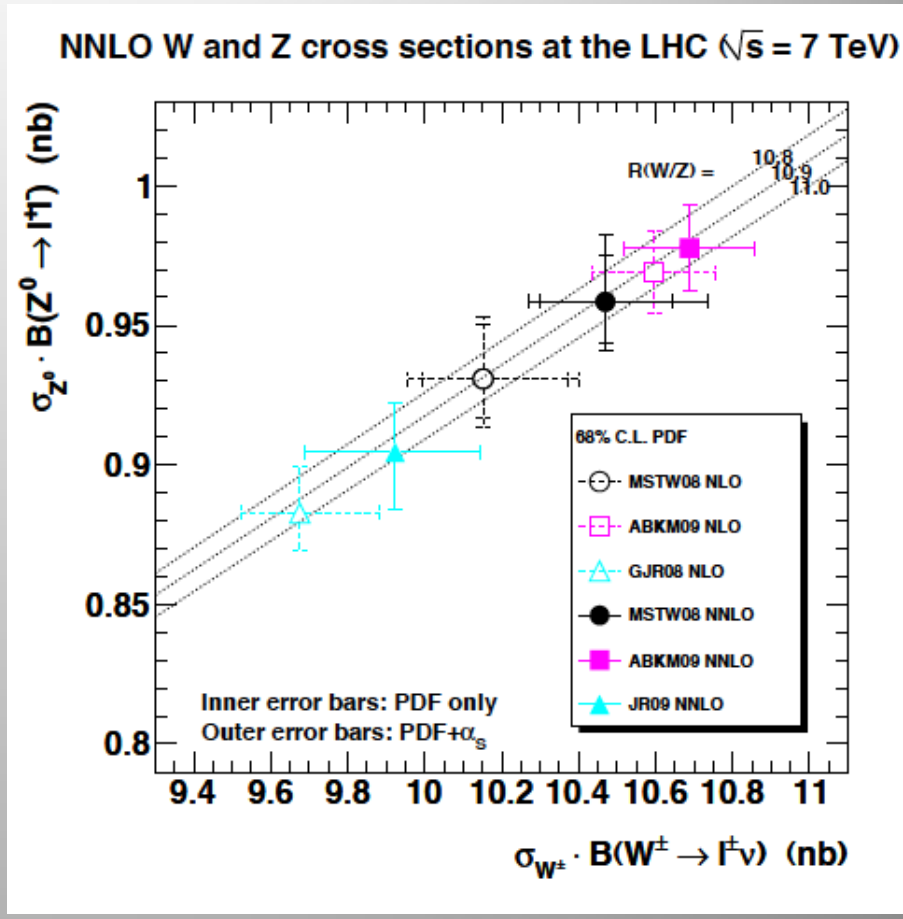






W and Z Cross Sections

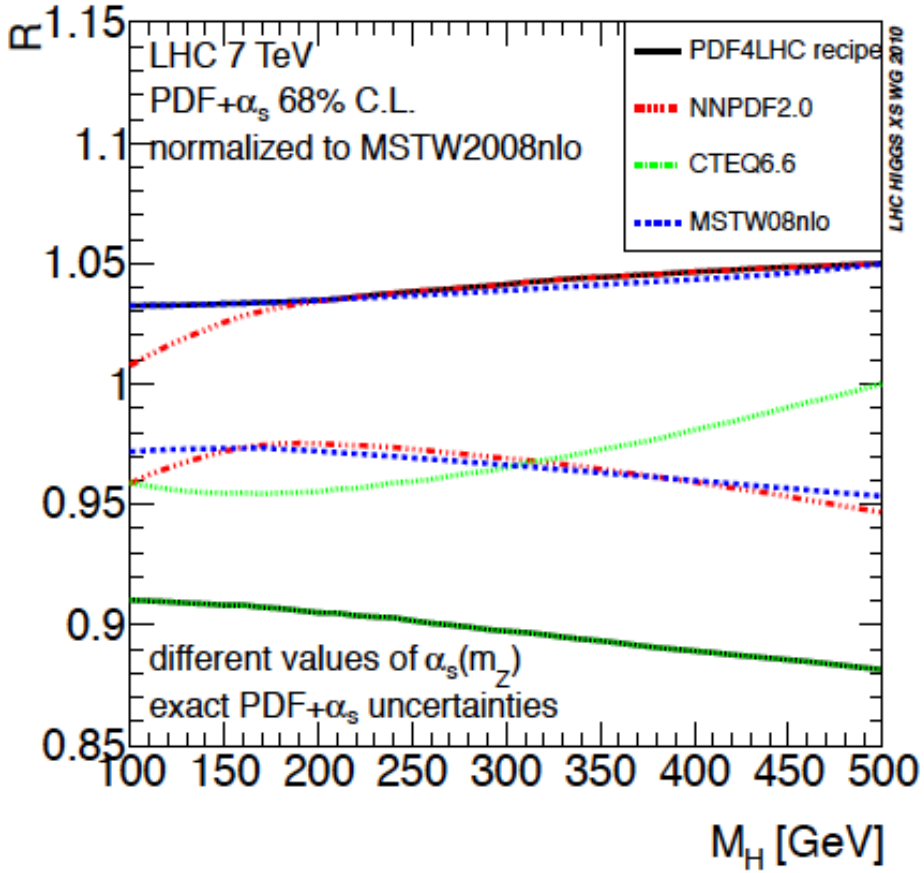




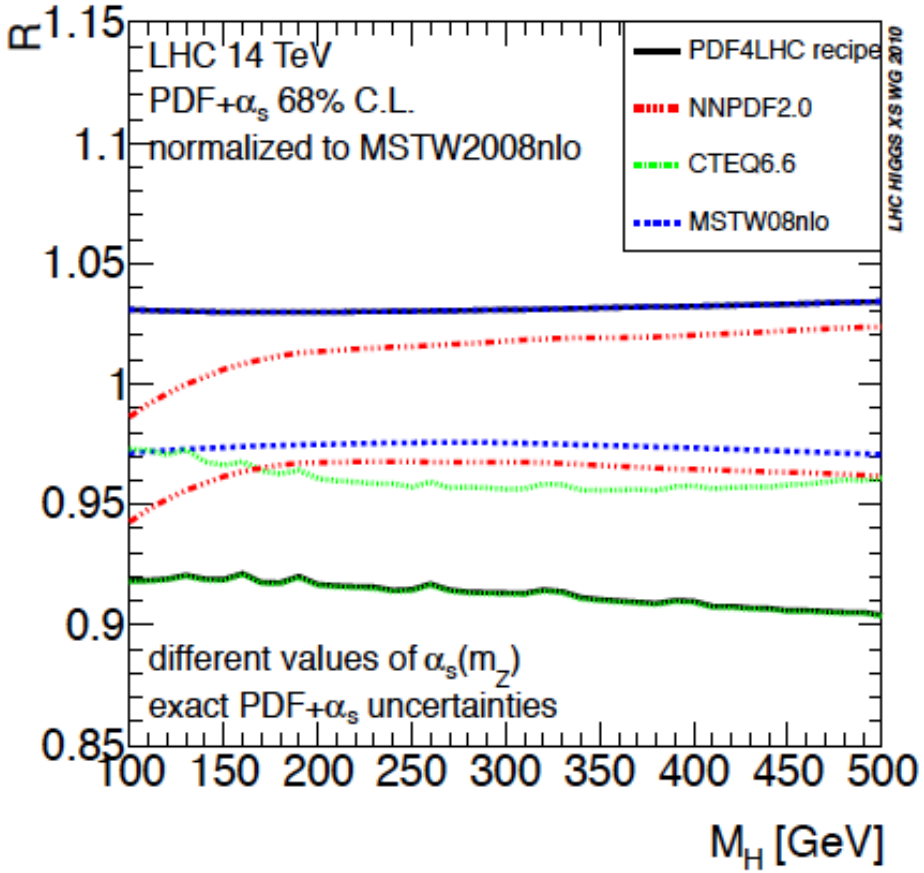
Much more comparisons in G. Watt, arXiv:1106.5788
and on http://projects.hepforge.org/mstwpdf/pdf4lhc

Higgs Cross Section Uncertainty

The Handbook of the LHC Higgs cross sections arXiv:1101.0593



ArXiv:1101.0593



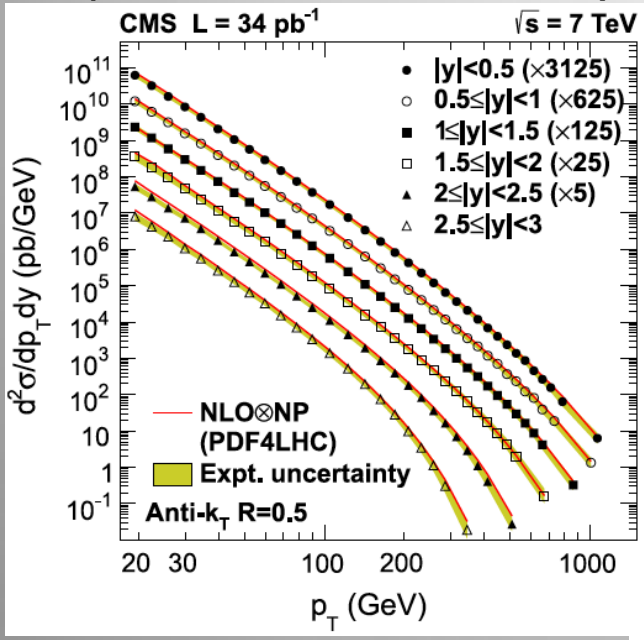
Combined PDF+α_s uncertainty using the PDF4LHC prescription

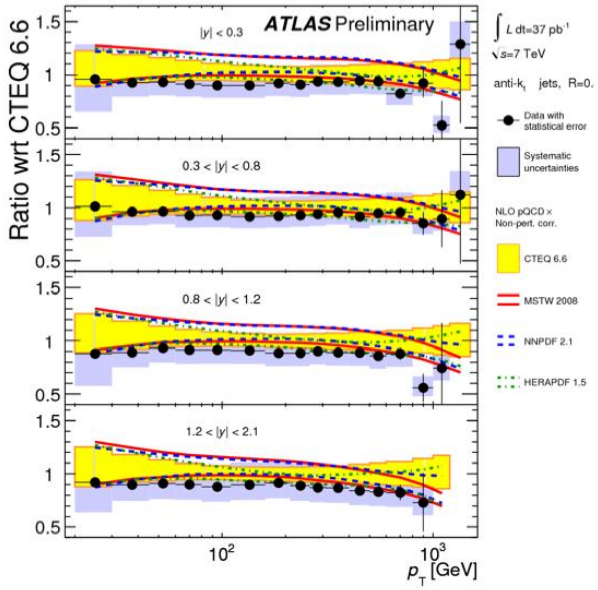
LHC Data for PDFs

Jet Production Data

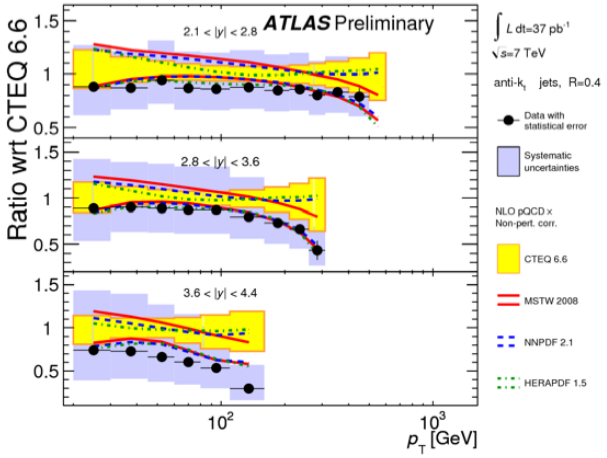
CMS and ATLAS results for incl. jet/dijet cross sections on 2010 data

Phys. Rev. Lett. 107, 132001 (2011)



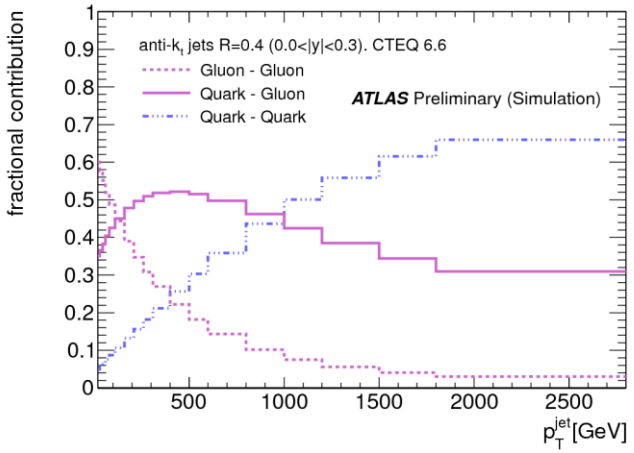


arXiv:1109.5141



Agreement pQCD/data tested to about 20%

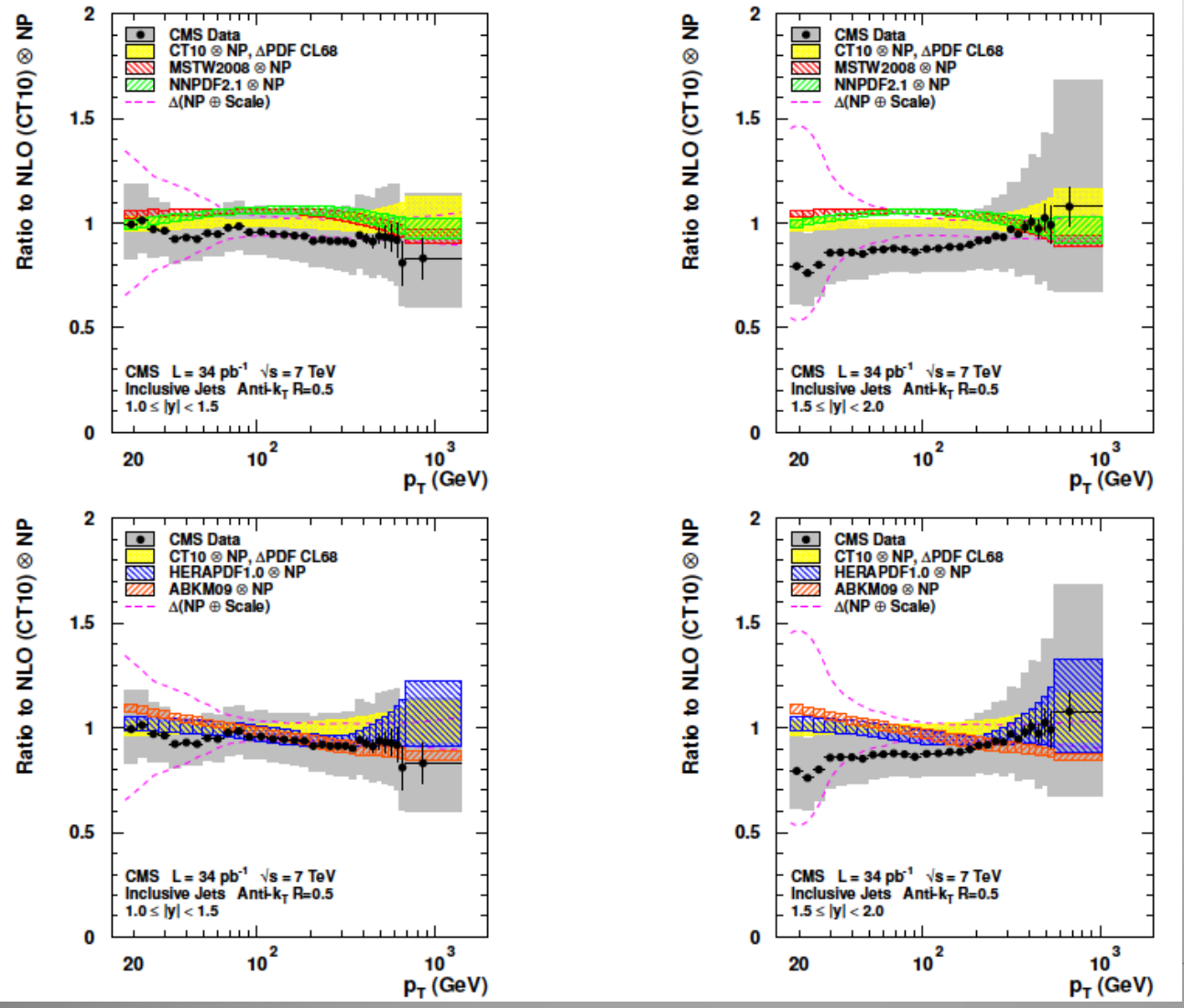
Jet Energy scale is the most important systematics



dijets sensitive to qq, qg or gg depending on jet kinematics

Jet Production PDF Studies

K. Rabbertz CMS-NOTE-2011-004

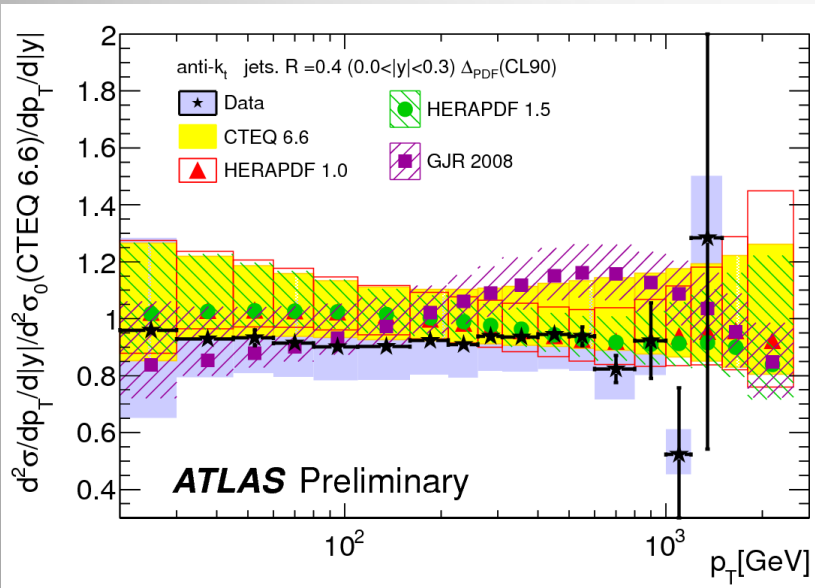


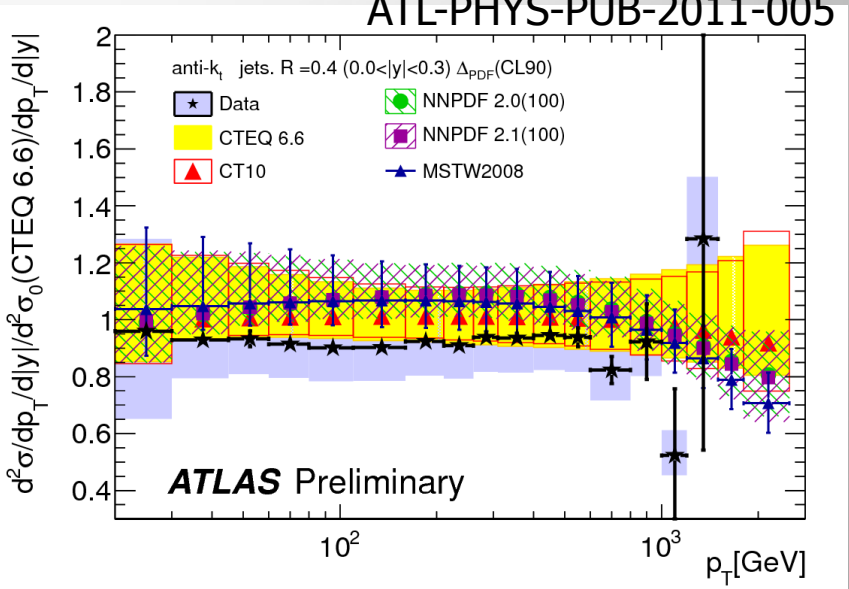
Systematic study of all PDFs compared to CMS jet data

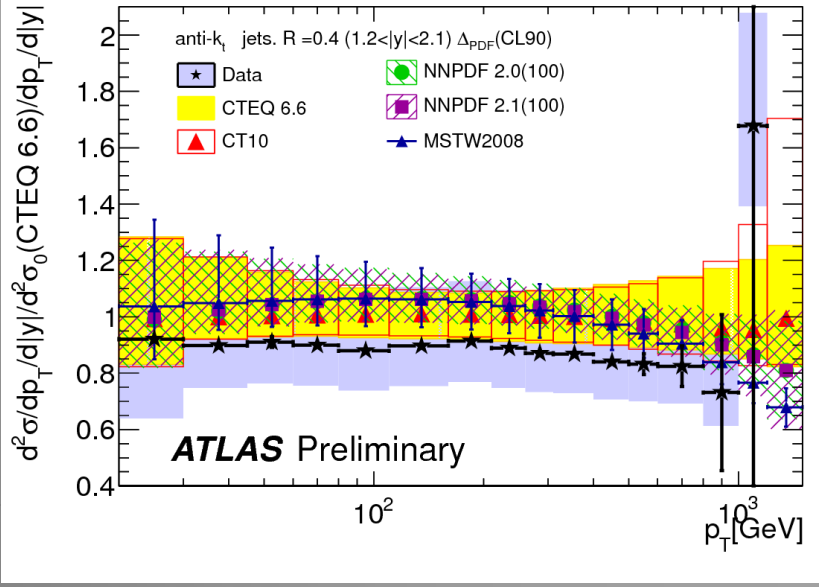
No clear preference for a particular set yet, but some differences found

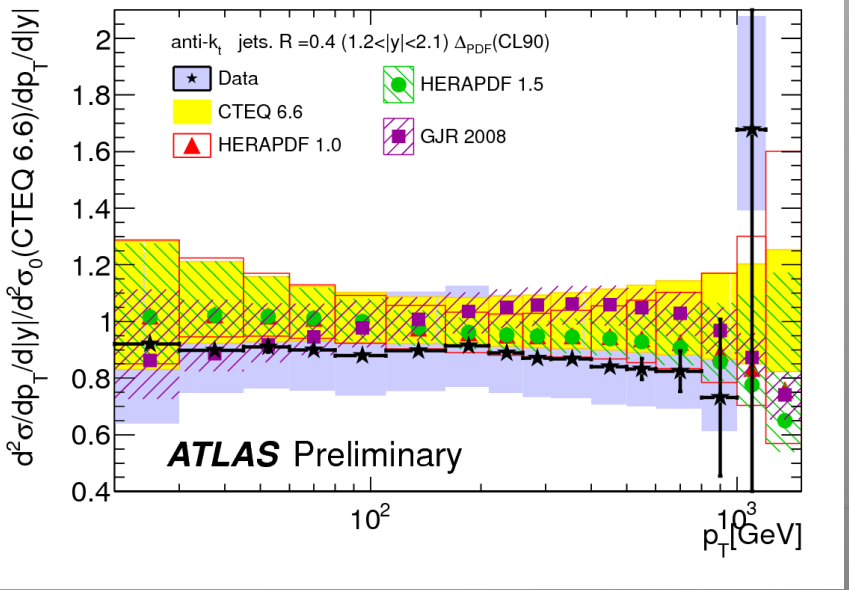
Jet Production PDF Studies

ATL-PHYS-PUB-2011-005



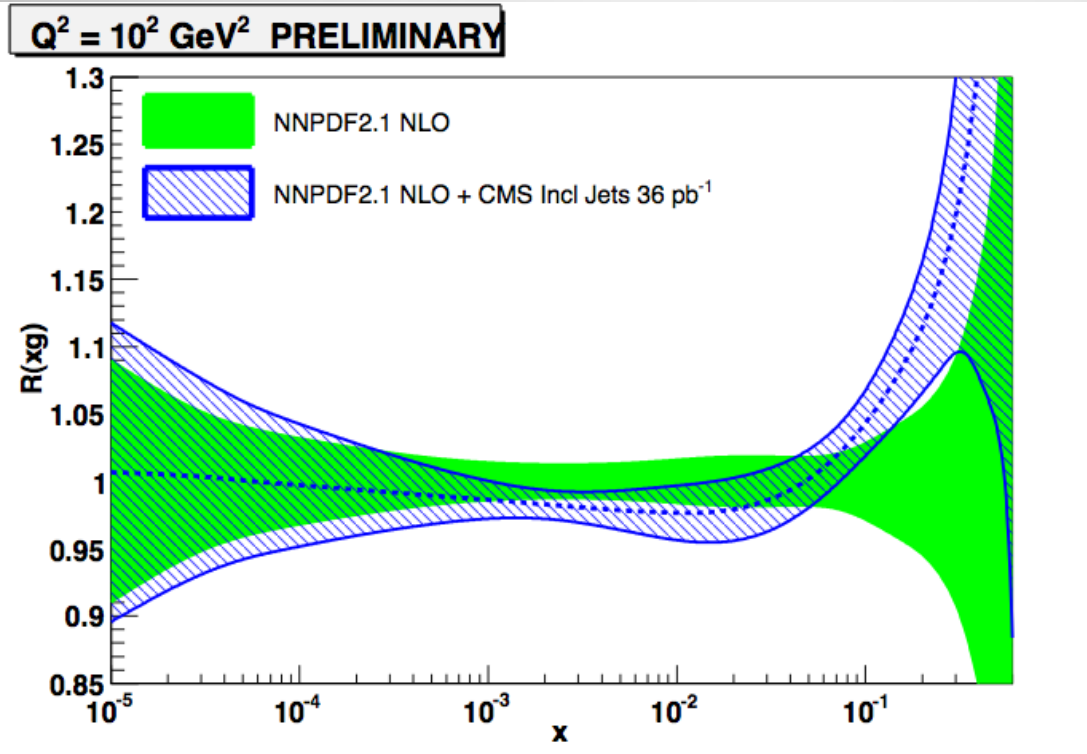






Impact of jet data on PDF-fits

Vanilla NNPDF2.1: No LHC data included



NEW

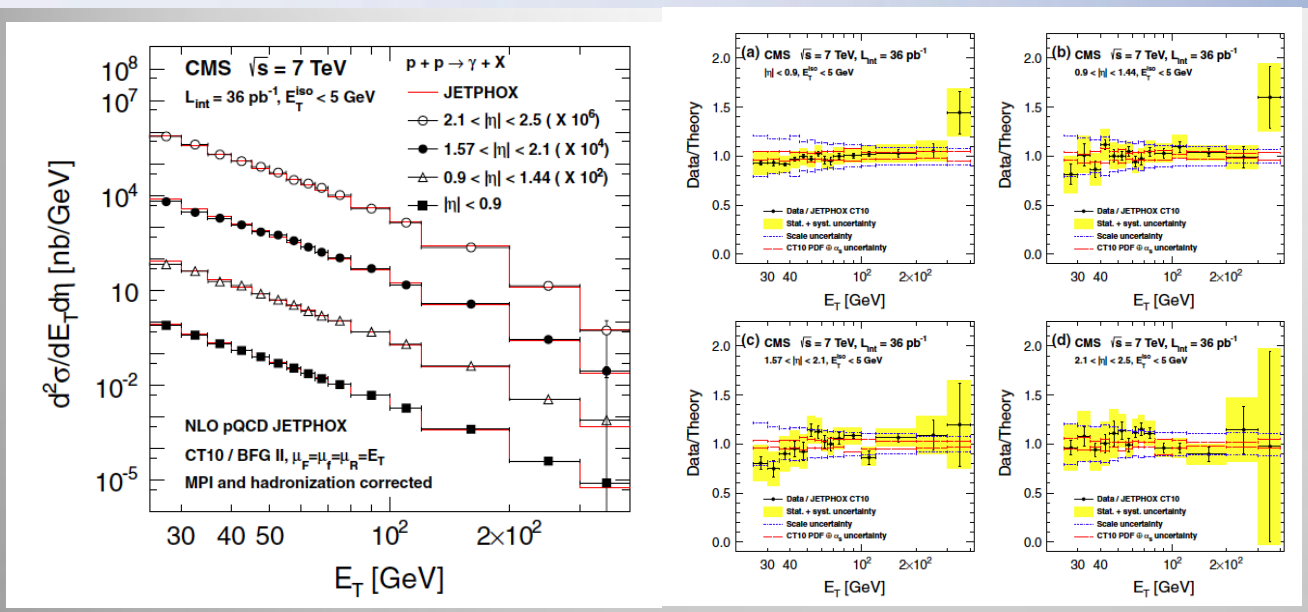
NNPDF preliminary:
S. Forte, J. Rojo et al.

A real promise for the future, ie with 2011 jet data

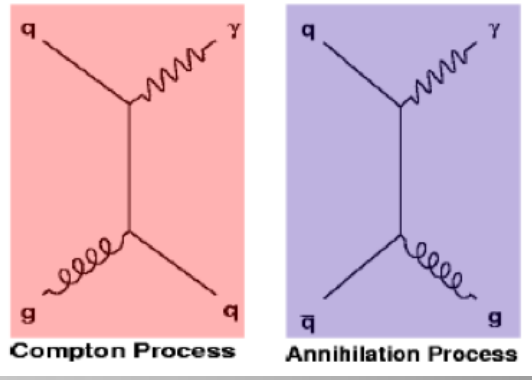
Note that data generally dominated by systematics: important to minimize

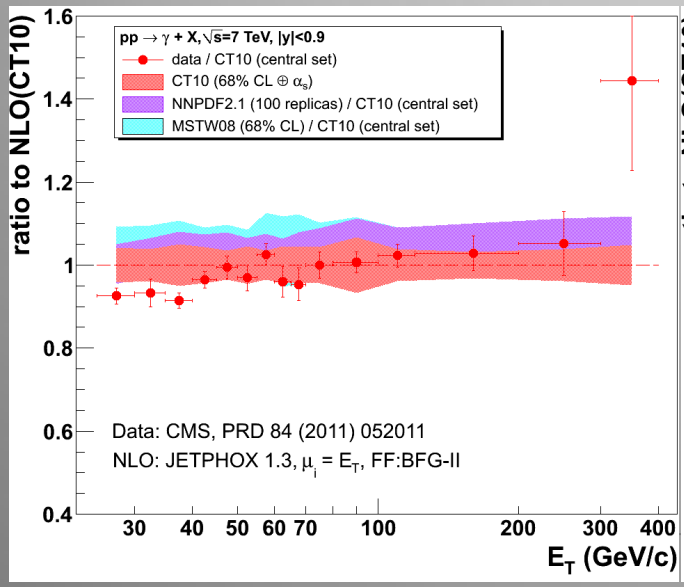
- Experiments: please publish also error correlation matrices
- Other TH issues: scale choices, using fixed NLO or Powheg,…

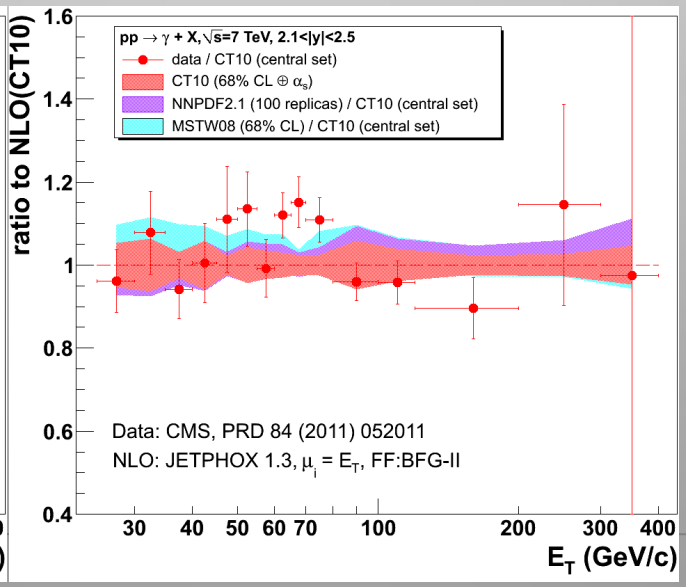
Prompt Photons for PDFs



ATLAS: arXiv:1108.0253
CMS: PRD 84 052011 (2011)



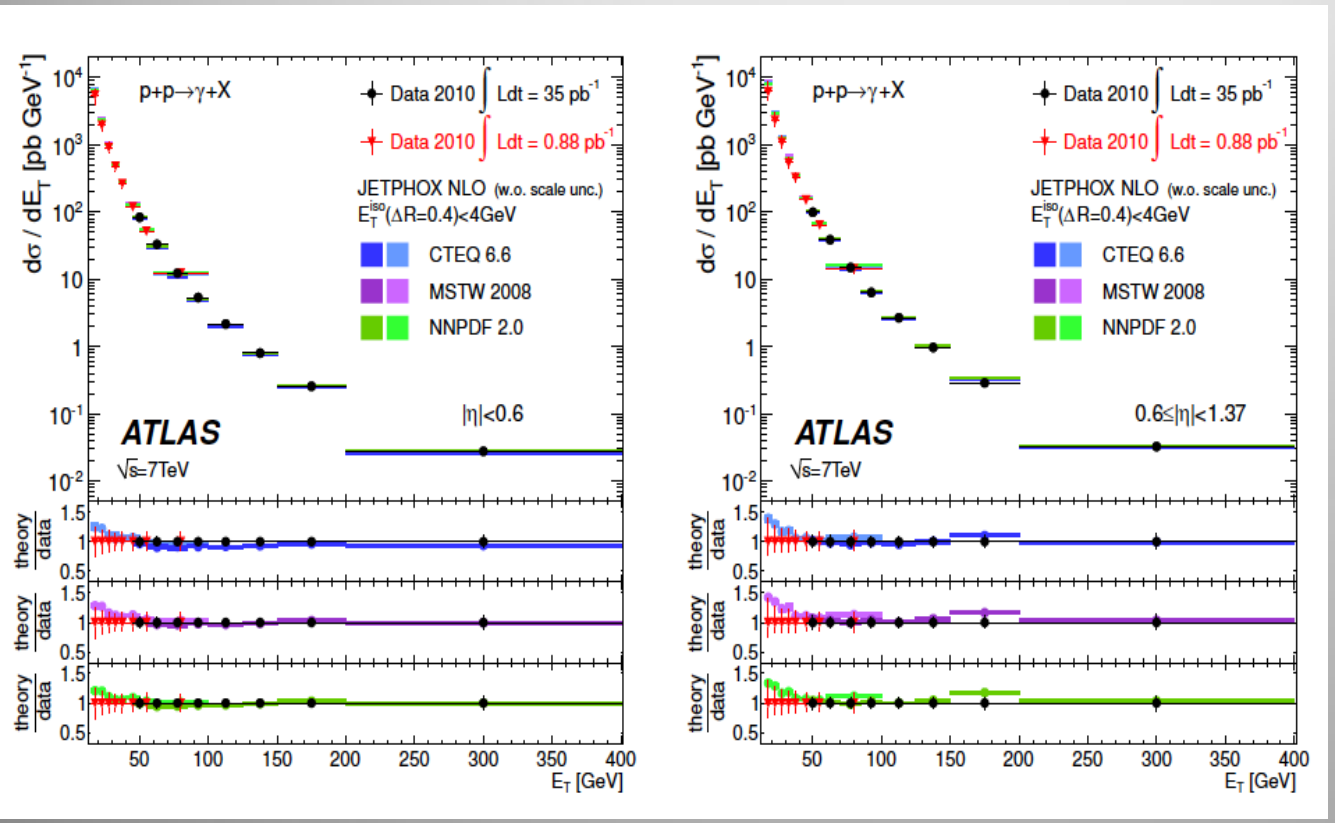




Results from prompt photon production in CMS and ATLAS

General good agreement with PQCD

Photon Studies



Comparison with different PDF families

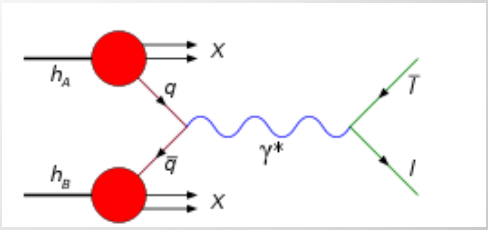
Next step: Include the photon data in PDF fits

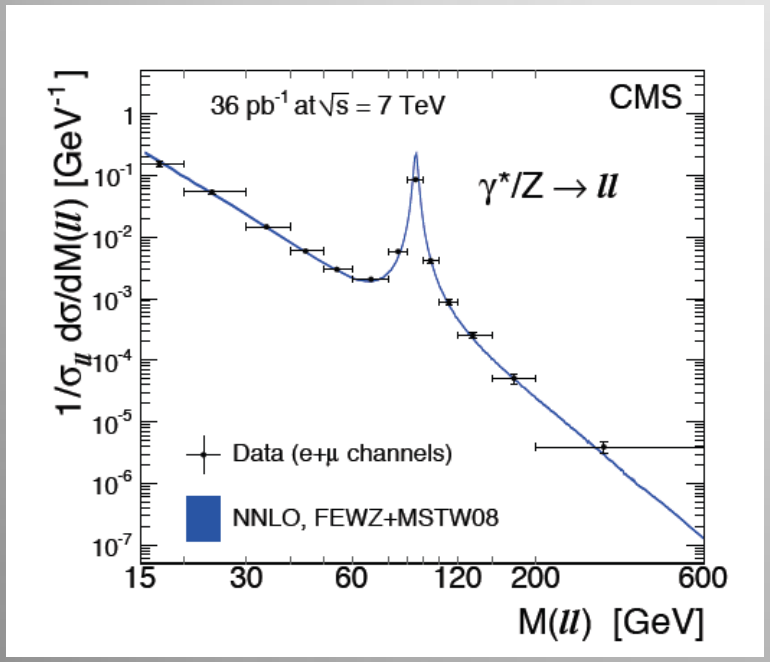
Eg. D. d'Enterria et al., (reweighting) EPS2011

Drell-Yan Data

Recent CMS measurements

arXiv:1108.0566





Invariant mass bin (GeV)	Cross section (pb)			R (10^{-3})
	CT10	CTEQ66	MSTW2008	MSTW2008
15–20	787	811	819	812
20–30	476	483	499	494
30–40	135	137	142	141
40–50	53	54	56	55
50–60	27	27	29	28
60–76	32	32	33	33
76–86	56	57	58	58
86–96	822	825	852	844
96–106	51	51	53	52
106–120	12	12	13	13
120–150	6.7	6.7	7.0	6.9
150–200	2.6	2.6	2.7	2.7
200–600	1.3	1.3	1.3	1.3

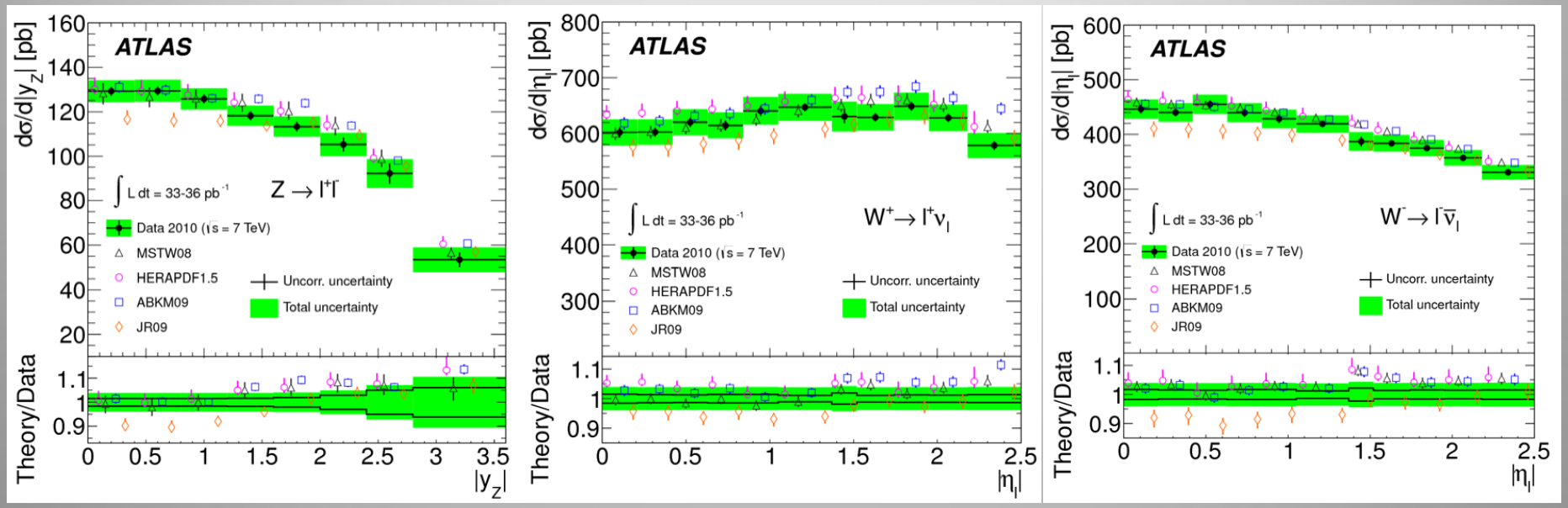
Presently the experimental uncertainties ~ 10% on the data

From the PDF constraints point of view:
Drell-Yan measurements at low M_{ll} values would be useful (small x data)

W & Z Production

LHC is a W/Z factory: precise measurements of the cross sections and differential cross sections

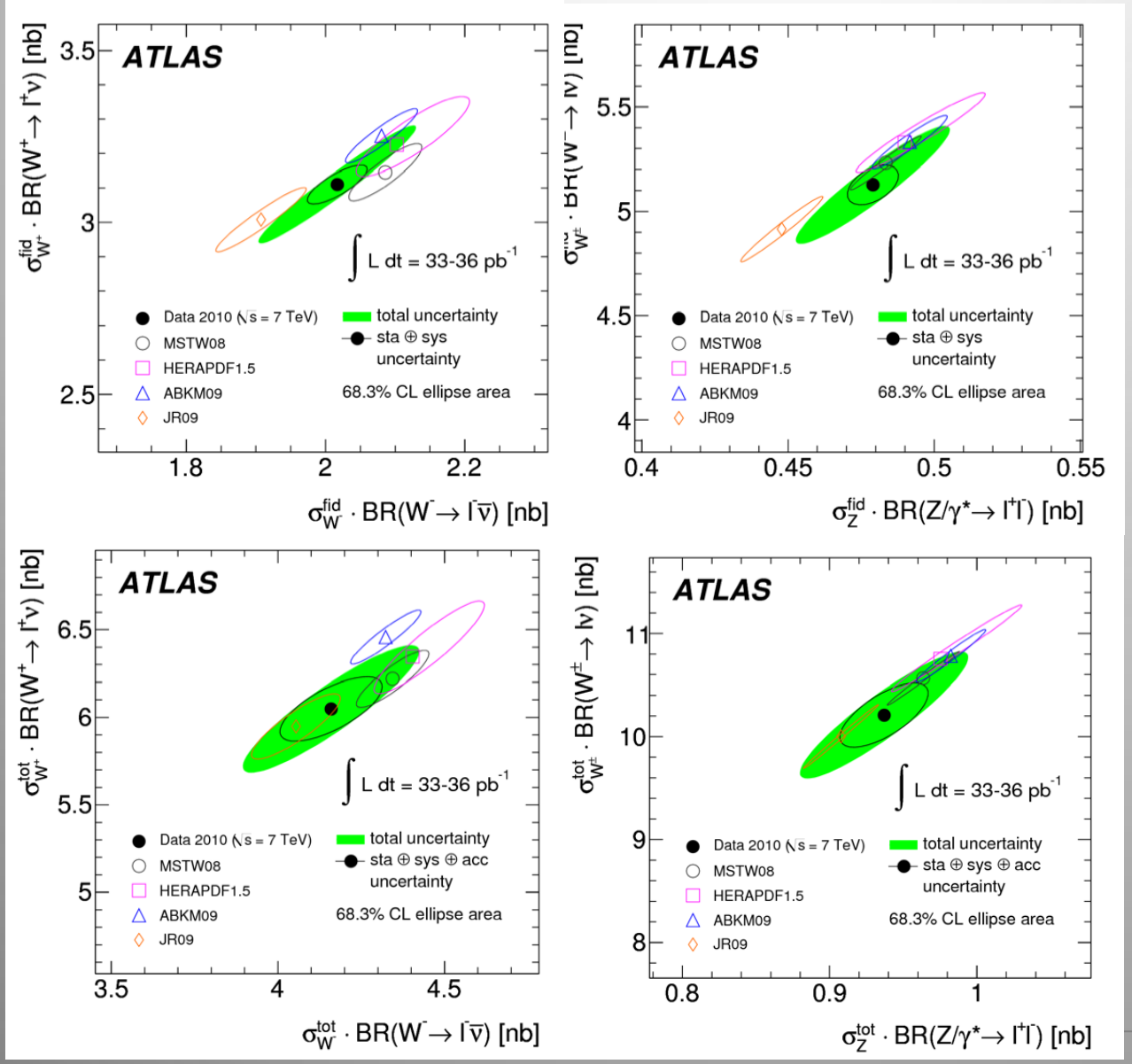
arXiv:1109.5141



For the PDF studies

Differential data on rapidity is becoming very constraining on both shapes and on and normalization of the predictions

PDF Correlations

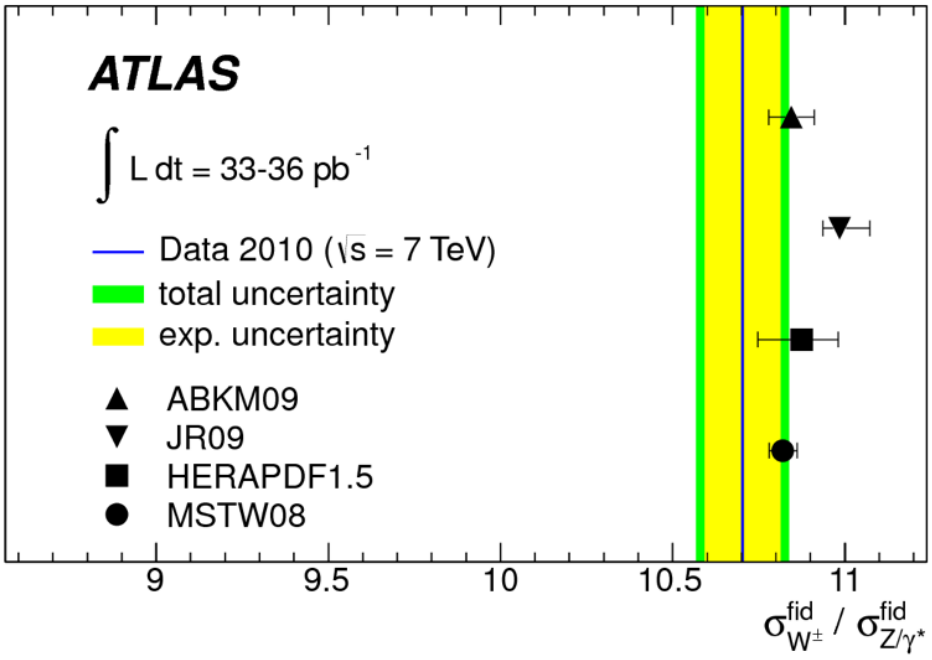


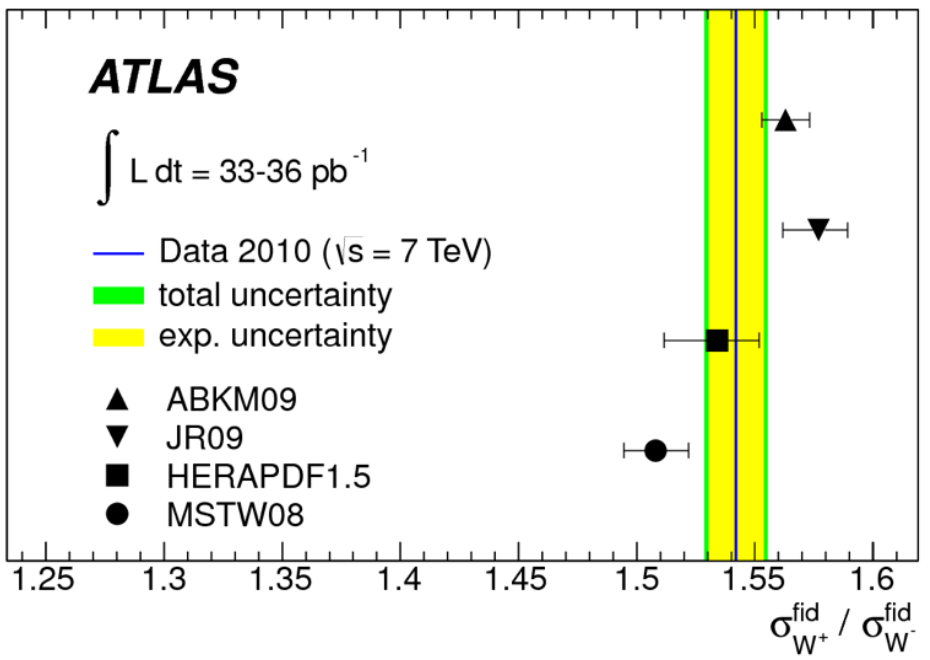
Compare the Z and W cross sections, and W^+ and W^- cross sections, with PDF predictions at NNLO

Some PDFs clearly deviate from the measurements

PDF Correlations

Ratios of measurements within the fiducial volume…

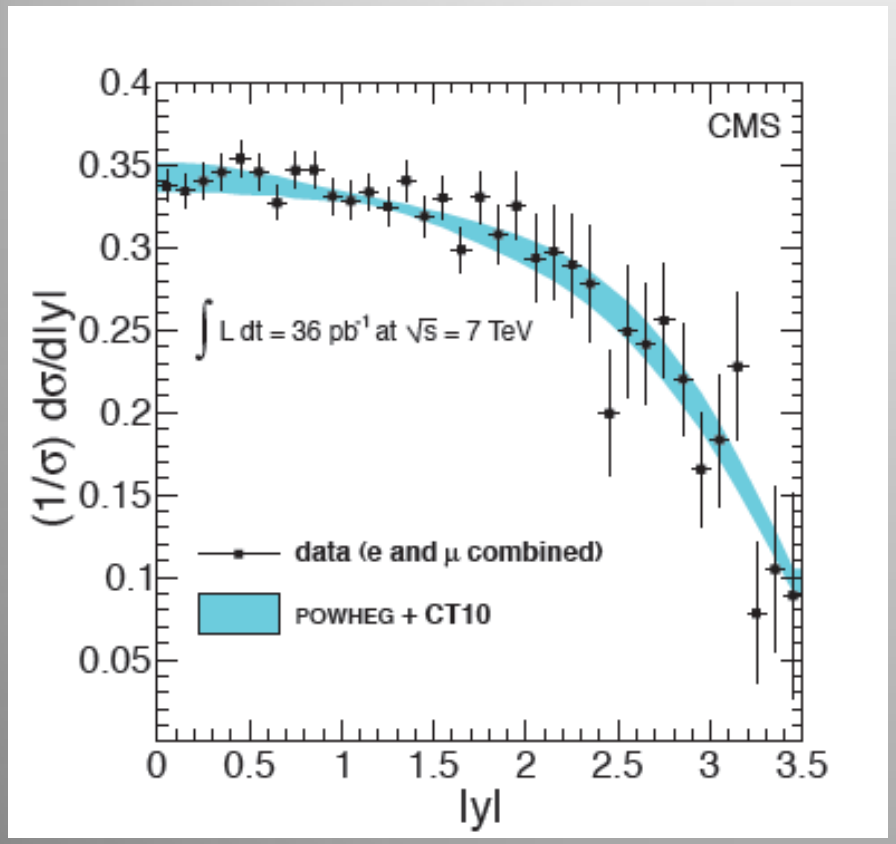




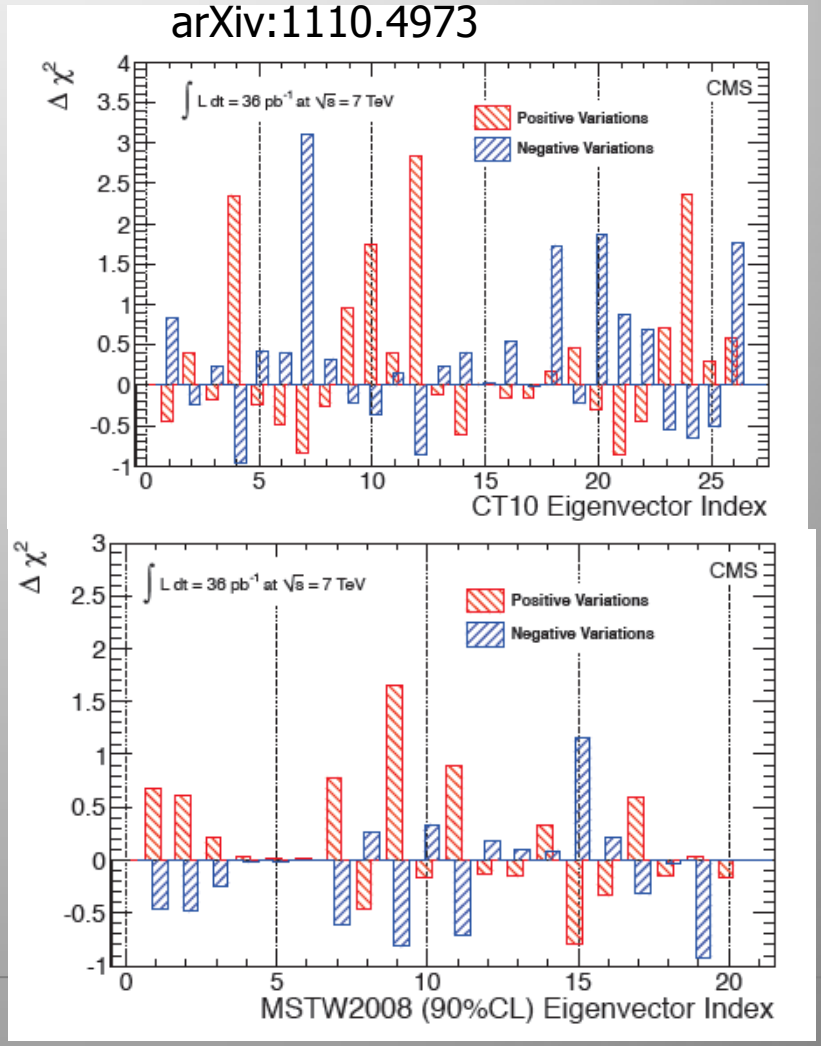
Similar conclusion: some PDFs clearly deviate from the measurements

Z Differential Distributions

CMS eigenvector analysis from dσ/dy distributions of the Z
→ Check the changeχ^2 by changing the parameters by +/-1σ

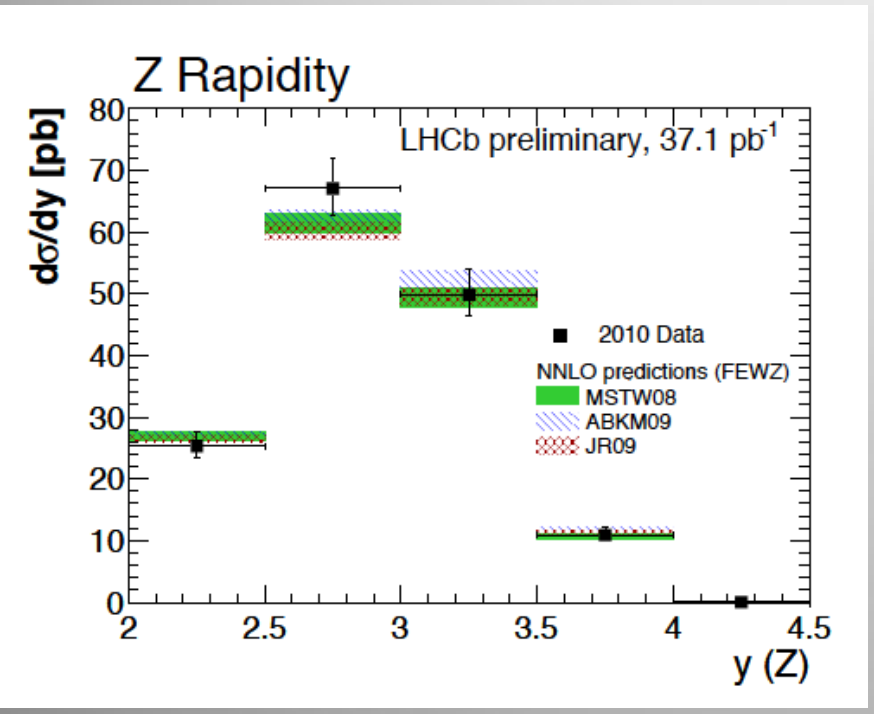


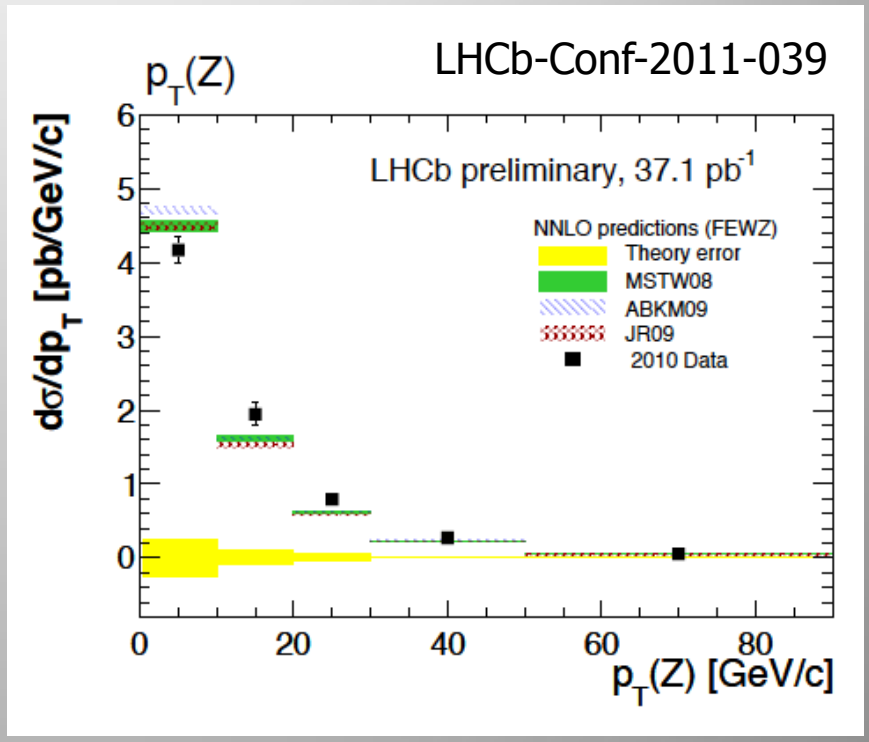
arXiv:1110.4973



LHCb: Forward Z Measurements

Provides complementary information to CMS and ATLAS

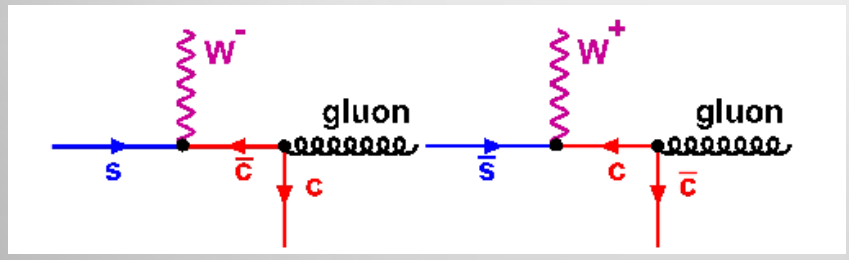




W+c-quark Production

CMS-EWK-11-013

Sensitive to strangeness content of the proton



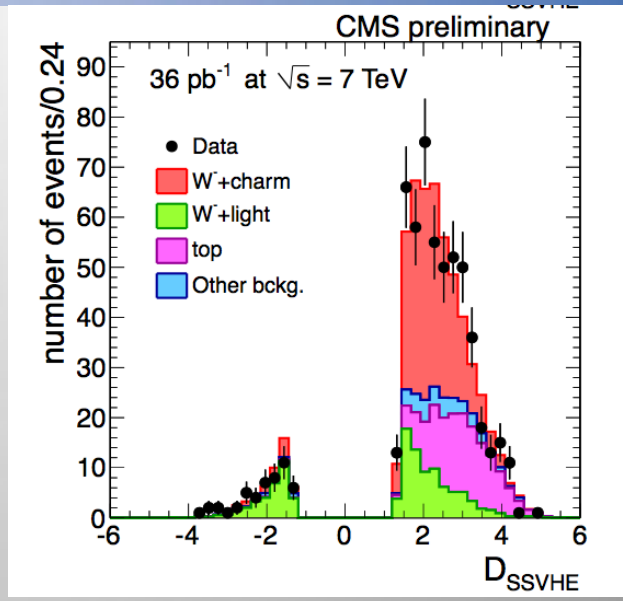
Measure W+/W- ratio and ratio to 'all jets'

$$R_c^{\pm}(p_T^{jet} > 20, |\eta^{jet}| < 2.1) = 0.92 \pm 0.19\ (stat.)$$

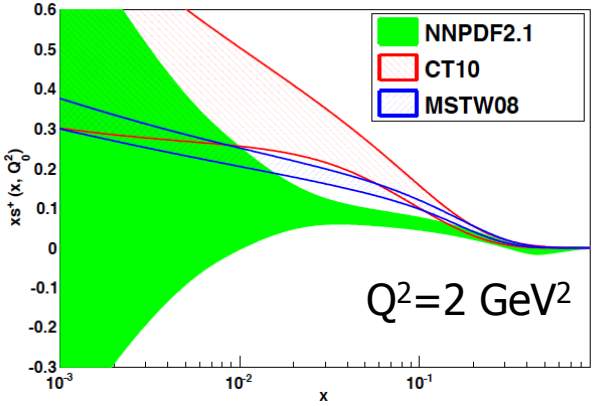
$$R_c(p_T^{jet} > 20, |\eta^{jet}| < 2.1) = \frac{N(W^+ + charm) + N(W^- + charm)}{\epsilon_c\, N(W + jets)}$$

$$R_c = 0.13 \pm 0.02$$

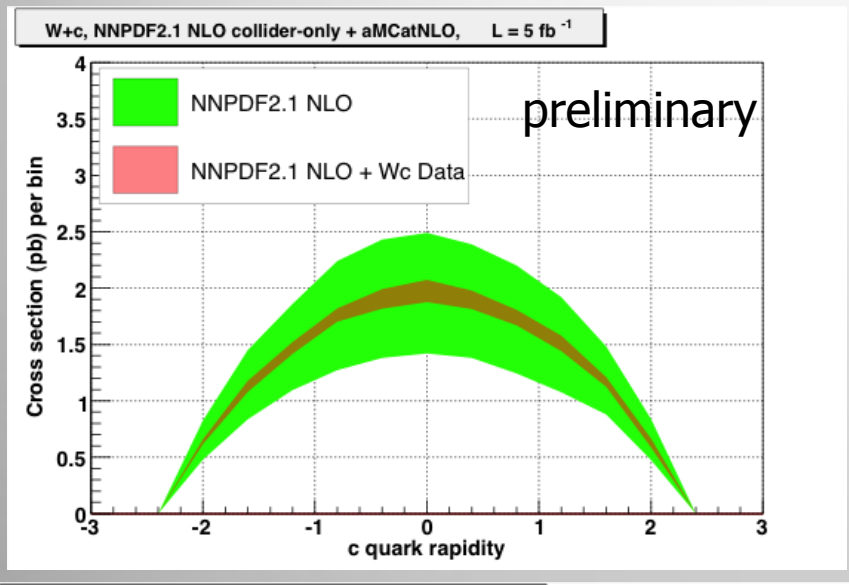
Ratio	MCFM (CT10)	MCFM (MSTW08)	MCFM (NNPDF21)
$R_c^{\pm}$	$0.915^{+0.006}_{-0.006}$	$0.881^{+0.022}_{-0.032}$	0.902 ± 0.008
R_c	$0.125^{+0.013}_{-0.007}$	$0.118^{+0.002}_{-0.002}$	0.103 ± 0.005

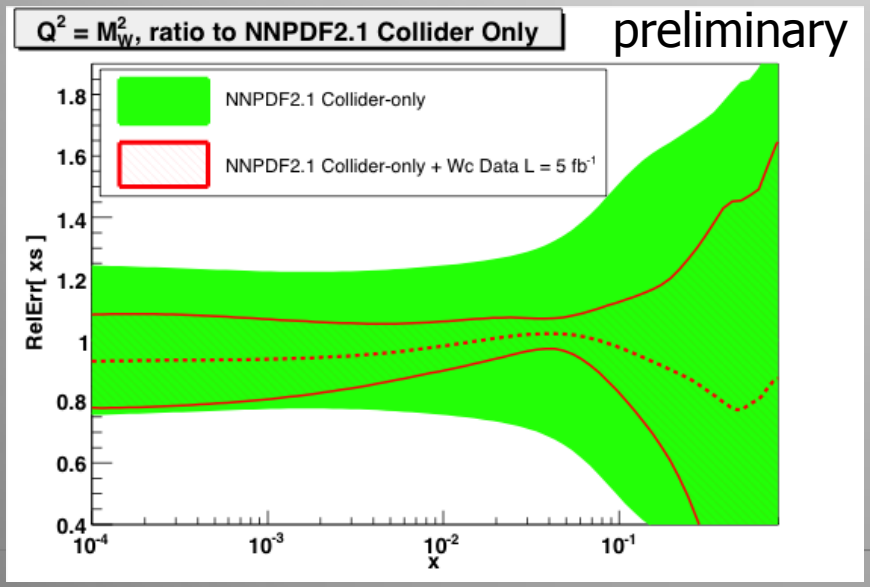


Present uncertainties



W+c Impact on PDFs





Preliminary:
Frixione, Mangano and Rojo

Charm rapidity with "Collider only" PDFs, without and with including 5fb^{-1} of CMS W+c data

NEW

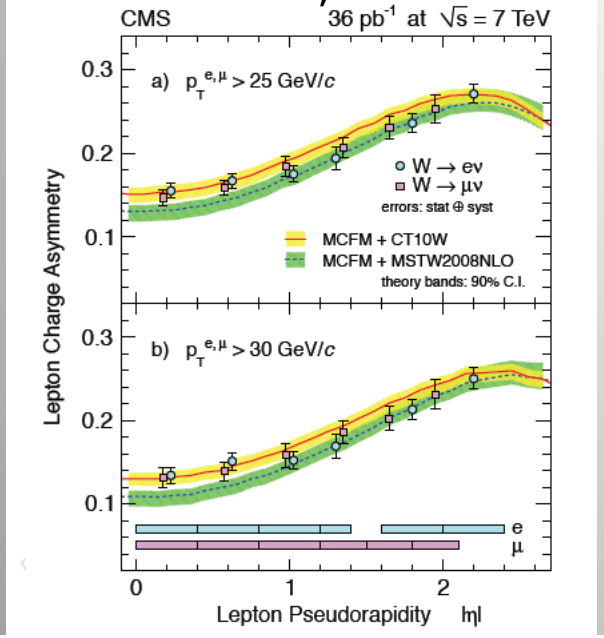
Impact on strangeness

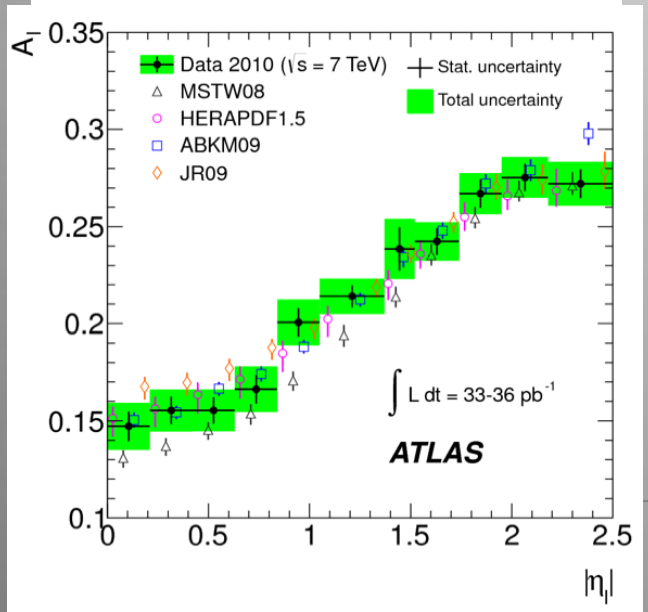
In future also expect Zb measurements to contribute

More at the LHCC EWK/PDF Workshop 28-30 Nov @ CERN

W-Asymmetry Measurements

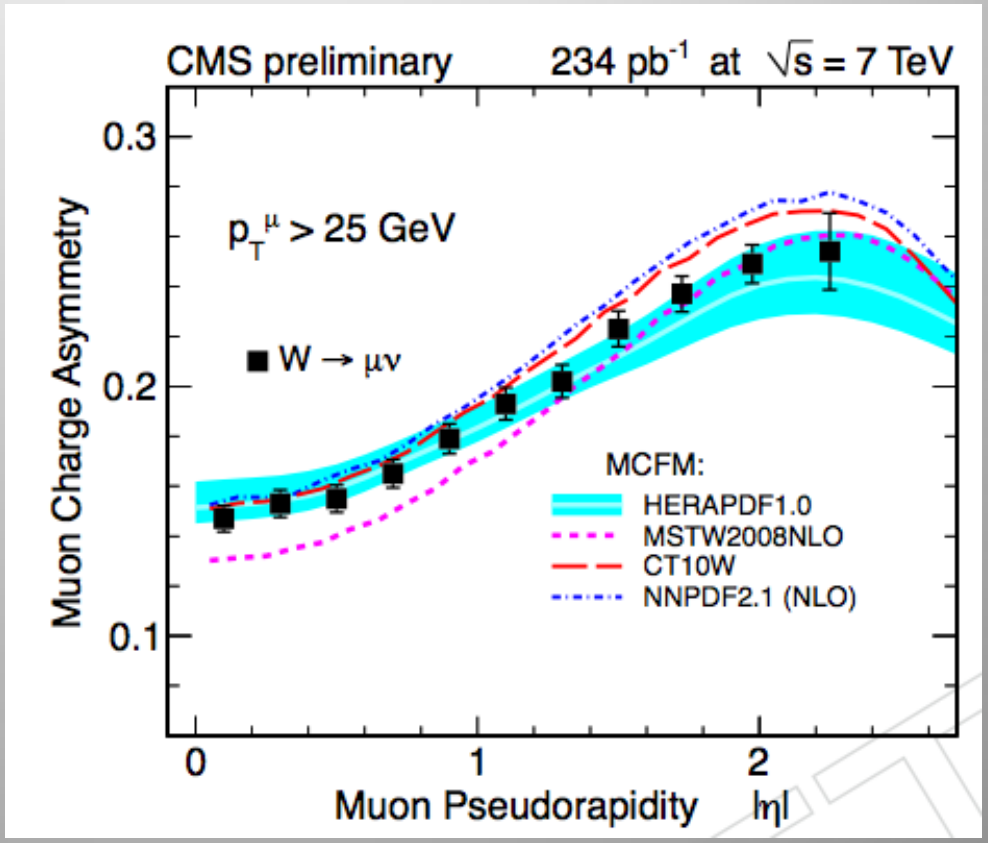
JHEP 1104:050,2011.





$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

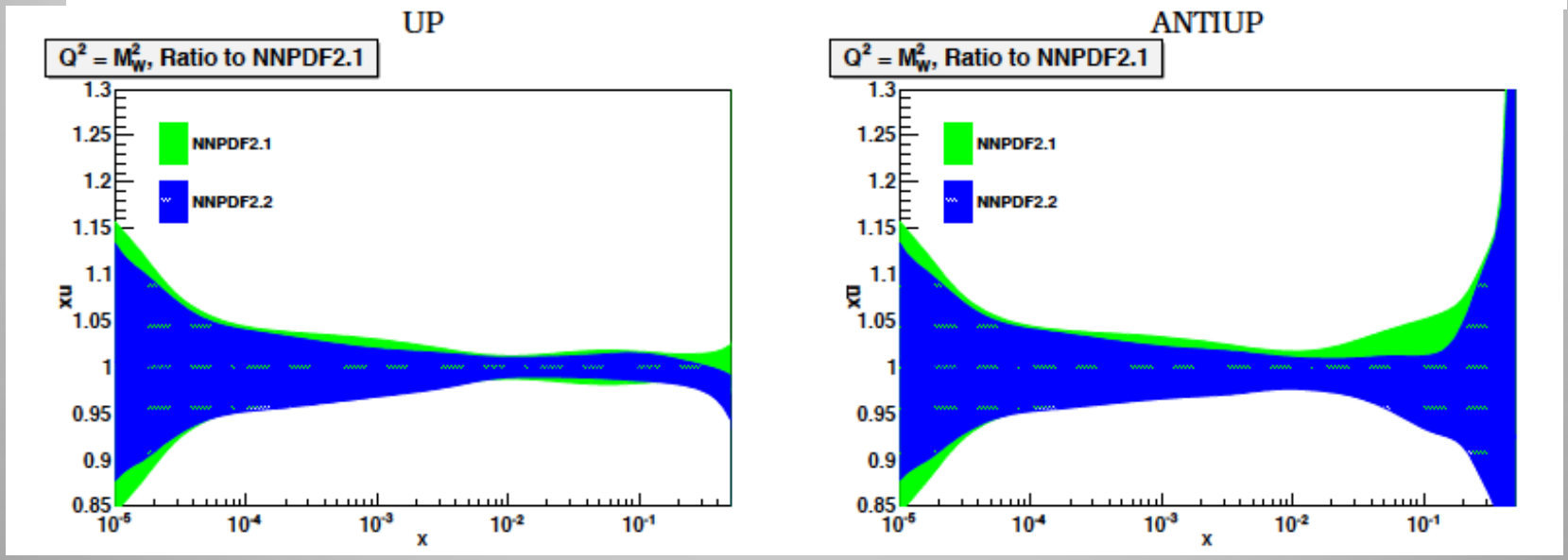
CMS-EWK-11-005

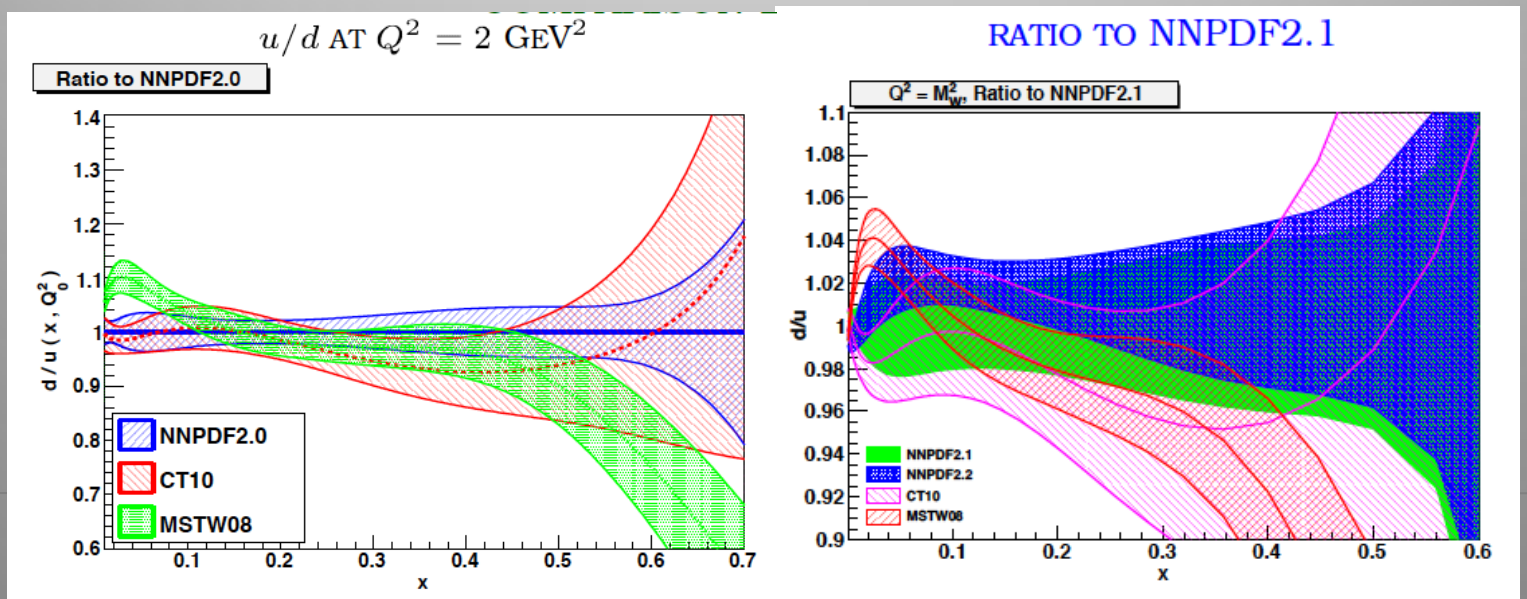


Probably the most sensitive LHC-PDF variable to date

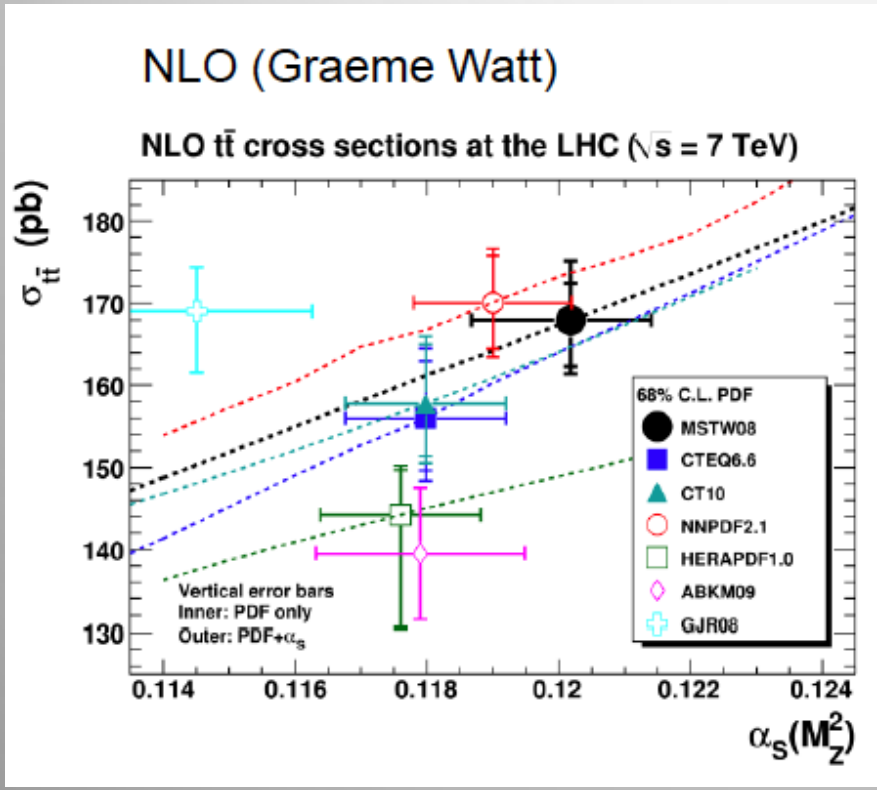
Impact of the Asymmetry Data

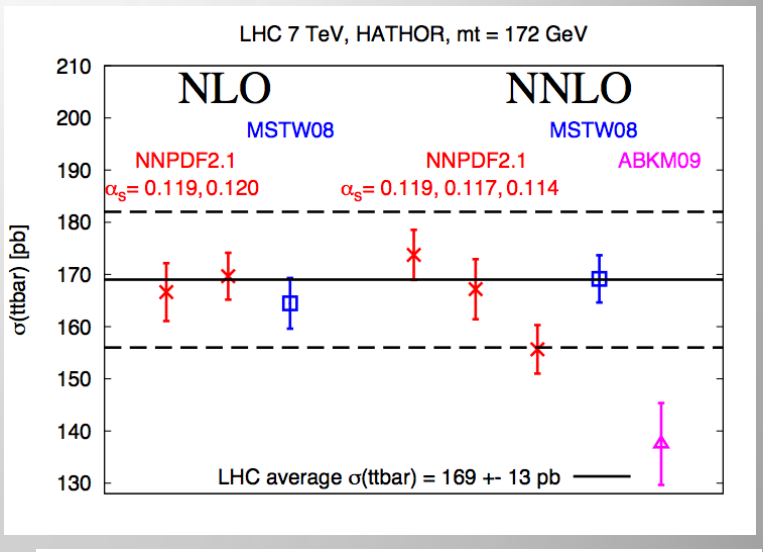
Including D0, CMS and ATLAS (2010) asymmetry data in the PDF

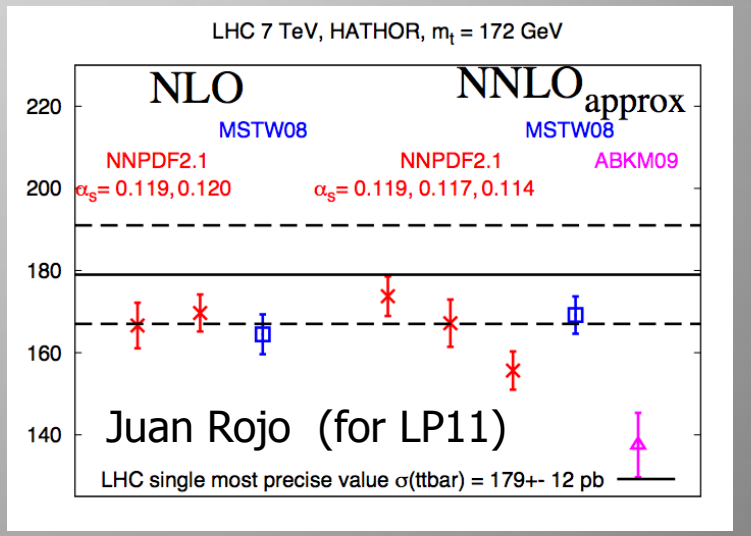




Top quark Production and PDFs







- Starting to have sensitivity to PDFs
- ttbar to Z ratios are anti-correlated in PDFs

Best measurement of the top cross section has ~7% uncertainty

Challenges Ahead

- PDF4LHC created after the HERALHC workshops. At the time there were 3-4 PDF groups. Since then we have:
  - New PDF families have been established. All now with NNLO PDF sets.
  - HERA dominates today the information to PDFs via precision measurements on F2 and FL
  - LHC 2010 data already counts. 2011 and future data will become important for PDF fits.
  - PDF4LHC and TH need to follow on these developments
- Points of focus for the near future/Wish list
  - Flavor information from the LHC data (Z,W, photon+ HF)
  - Z,W Rapidity, P_T distributions, precision asymmetries
  - High x gluons (top, prompt photon, precision jets data …)
  - Low mass/high mass Drell-Yan data?
  - Combination of QCD and EWK fits…
  - Further TH developments for PDFs

Summary

- These are exciting times for PDF studies: understanding the structure of the proton
  - HERA DIS data analysis will be finalized soon
  - LHC at the brink of differentiating between PDFs. Starting to add critical input to the PDF determination
- Dedicated PDF optimal measurements in the experiments will require a special effort, but it is worthwhile.
  - Special effort on the systematics for certain measurements, eg dijets
- We should of course make sure we do not 'PDF-fit away' new physics in the LHC data…

- Many thanks to J Butterworth, A. Cooper-Sarkar, S. Forte, J. Huston, K. Kousouris, R. McNulty, K. Rabbertz, R. Thorne

Backup

Different PDF sets

- MSTW08 – fit all previous types of data. Most up-to-date Tevatron jet data. Not most recent HERA combination of data. PDFs at LO, NLO and NNLO.
- CT10 – very similar. PDFs at NLO. CT10 include HERA combination and more Tevatron data though also run I jet data. Not large changes from CTEQ6.6. CT10W gives higher weight to Tevatron asymmetry data.
- NNPDF2.1 – include all except HERA jet data (not strong constraint). NNPDF2.1 improves on NNPDF2.0 by better heavy flavour treatment. PDFs at NLO and very recently NNLO and LO .
- HERAPDF1.0 – based on HERA inclusive structure functions, neutral and charged current. Use combined data. PDFs at NLO and (without uncertainties) NNLO.
- ABKM09 – fit to DIS and fixed target Drell-Yan data. PDFs at NLO and NNLO. Less conservative cuts at low W^2 than other groups – fit for higher twist corrections rather than attempt to avoid them.
- GJR08 – fit to DIS, fixed target Drell-Yan and Tevatron jet data (not at NNLO). PDFs at NLO and NNLO.

Various groups have provided preliminary updates or illustrations of variations due to inclusion of new data. Includes ...

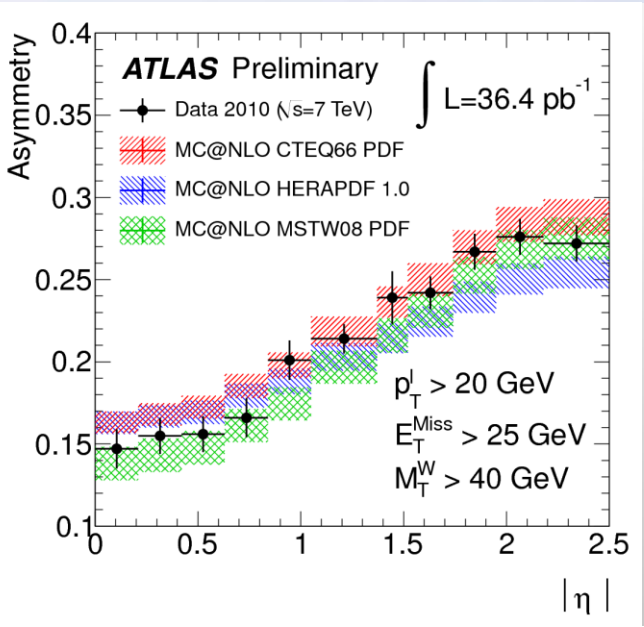
HERAPDF have *preliminary* version HERAPDF1.5 with grids available at NLO and NNLO, both with uncertainties. However, based on as yet unpublished combined run II data and no official publication. Also versions 1.6 and 1.7 including combinations including HERA jet data, prelim. combined charm data, lower beam energy data.

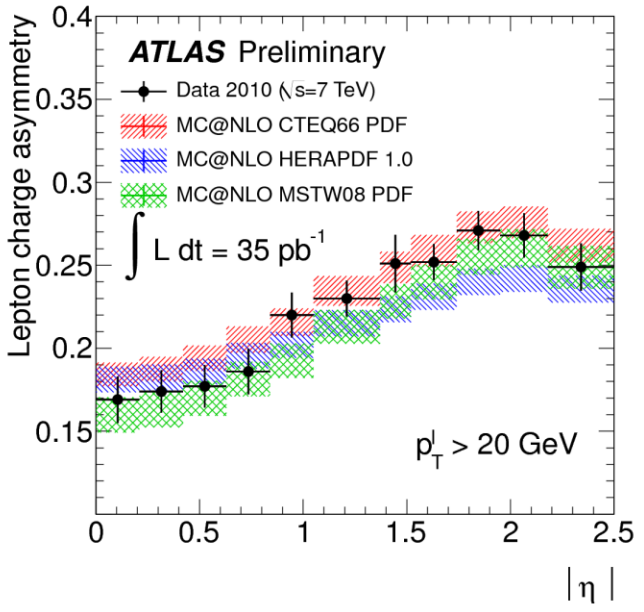
MSTW have prelim. sets fit to combined HERA data, and looking at deuterium corrections – in DIS proceedings.

ABM have versions including combined HERA data and including a variety of Tevatron jet data sets – again see DIS proceedings.

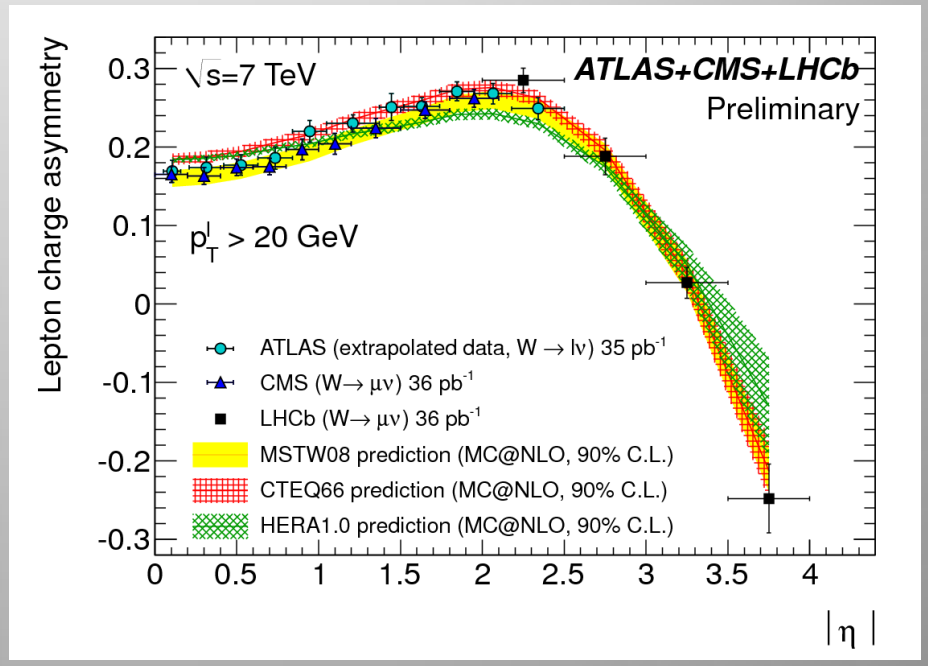
Lots of other reports, e.g. sets for fits to Collider data only (NNPDF, MSTW), ...

W- Asymmetry combined plot





Extrapolation of ATLAS data to a larger fiducial volume, not using an Etmiss and MTW cut to allow comparison of the experiments
Not to be used for fits…



Experiments all agree well

Determination of best fit and uncertainties

All but NNPDF minimise χ^2 and expand about best fit.

- MSTW08 – 28 parameters, 20 eigenvectors. Due to incompatibility of different sets and (perhaps to some extent) parameterisation inflexibility (little direct evidence for this) have inflated $\Delta\chi^2$ of $5 - 20$ for eigenvectors.
- CT10 – 26 eigenvectors, and some fixed parameters. Inflated $\Delta\chi^2$ of ~ 40 for 1-sigma for eigenvectors.
- HERAPDF2.0 – 10 eigenvectors. Use "$\Delta\chi^2 = 1$". Additional model and parameterisation uncertainties.
- ABKM09 – 21 parton parameters. Use $\Delta\chi^2 = 1$. Also α_S, m_c, m_b.
- GJR08 – 20 parton parameters (8 fixed for uncertainty) and α_S. Use $\Delta\chi^2 \approx 20$. Impose strong constraint on input form of PDFs.

Perhaps surprisingly all get rather similar uncertainties for PDFs cross-sections, though don't all mean the same.