Parton Distributions and Higgs Production at the LHC

James Stirling
Cambridge University

- introduction: overview and recent developments
- LHC Higgs cross sections and correlations
- summary

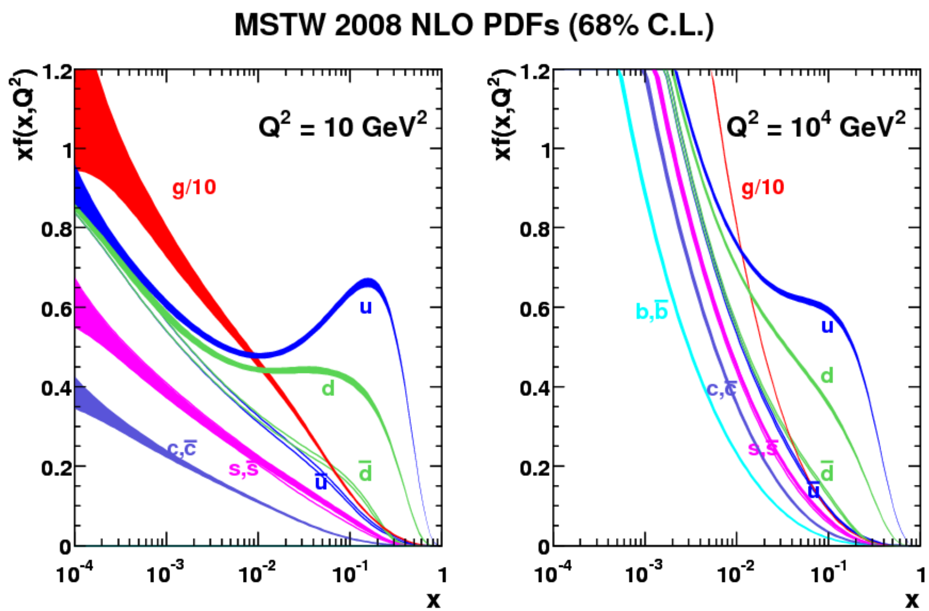
1

Introduction: overview and recent developments

parton distribution functions

$$f_{i/A}(x, Q^2)$$

- introduced by Feynman (1969) in the *parton model*, to explain Bjorken scaling in deep inelastic scattering data; interpretation as probability distributions
- according to the QCD *factorisation theorem* for inclusive hard scattering processes, universal distributions containing long-distance structure of hadrons; related to parton model distributions at leading order, but with logarithmic scaling violations (DGLAP)



- obtained by fitting a wide variety of high-precision deep inelastic and other hadron collider data ('global PDF fits')
- key ingredients for LHC phenomenology

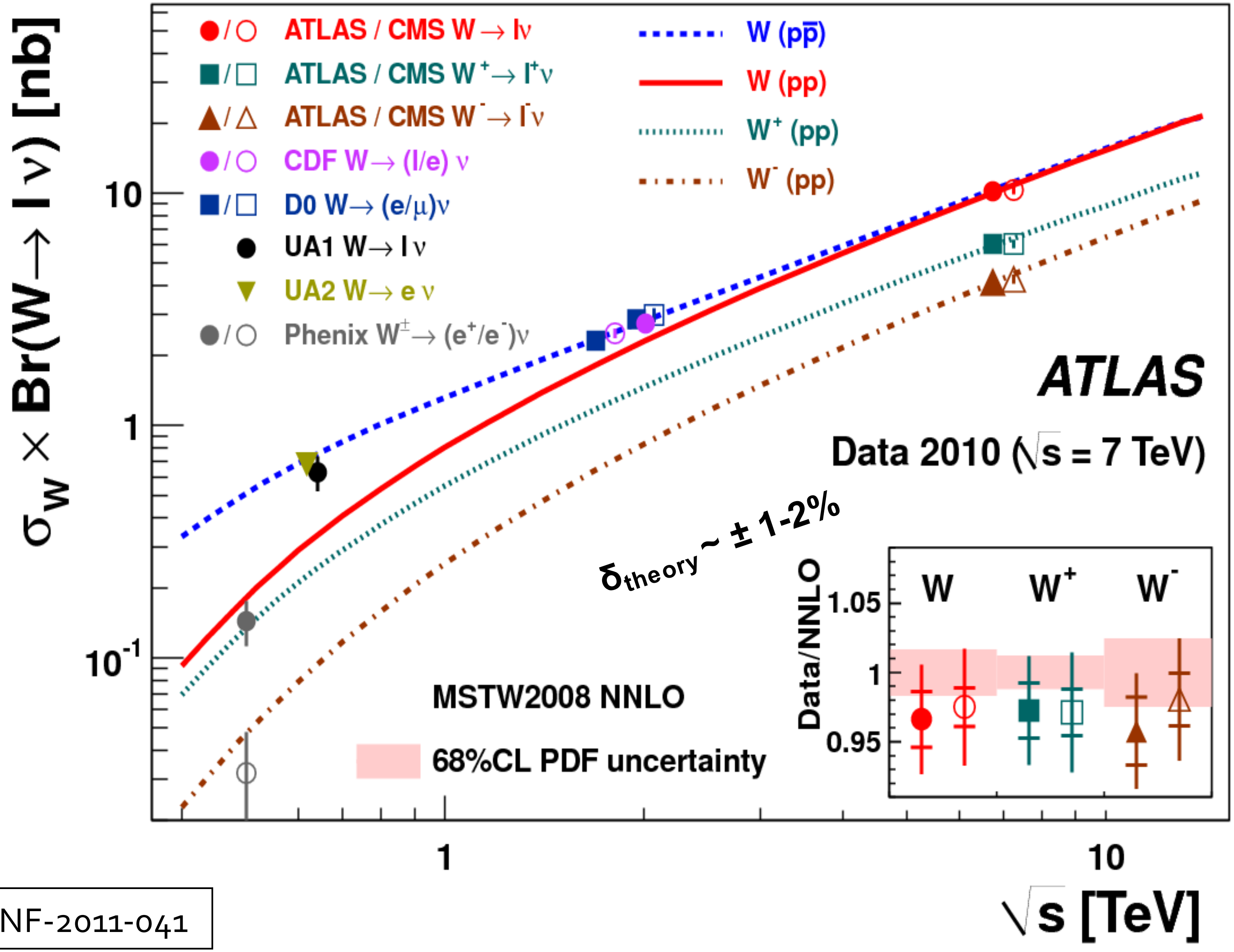
precision phenomenology at LHC

- *Benchmarking → precision predictions*
  - inclusive SM quantities ($V=(\gamma^*,W,Z)$, jets, top,…), calculated to the highest precision available (e.g. NNLO, NNLL, etc) and compared with exptl. measurements
  - tools needed: robust jet algorithms, kinematics, decays included, PDFs, …
  - theory uncertainty in predictions:

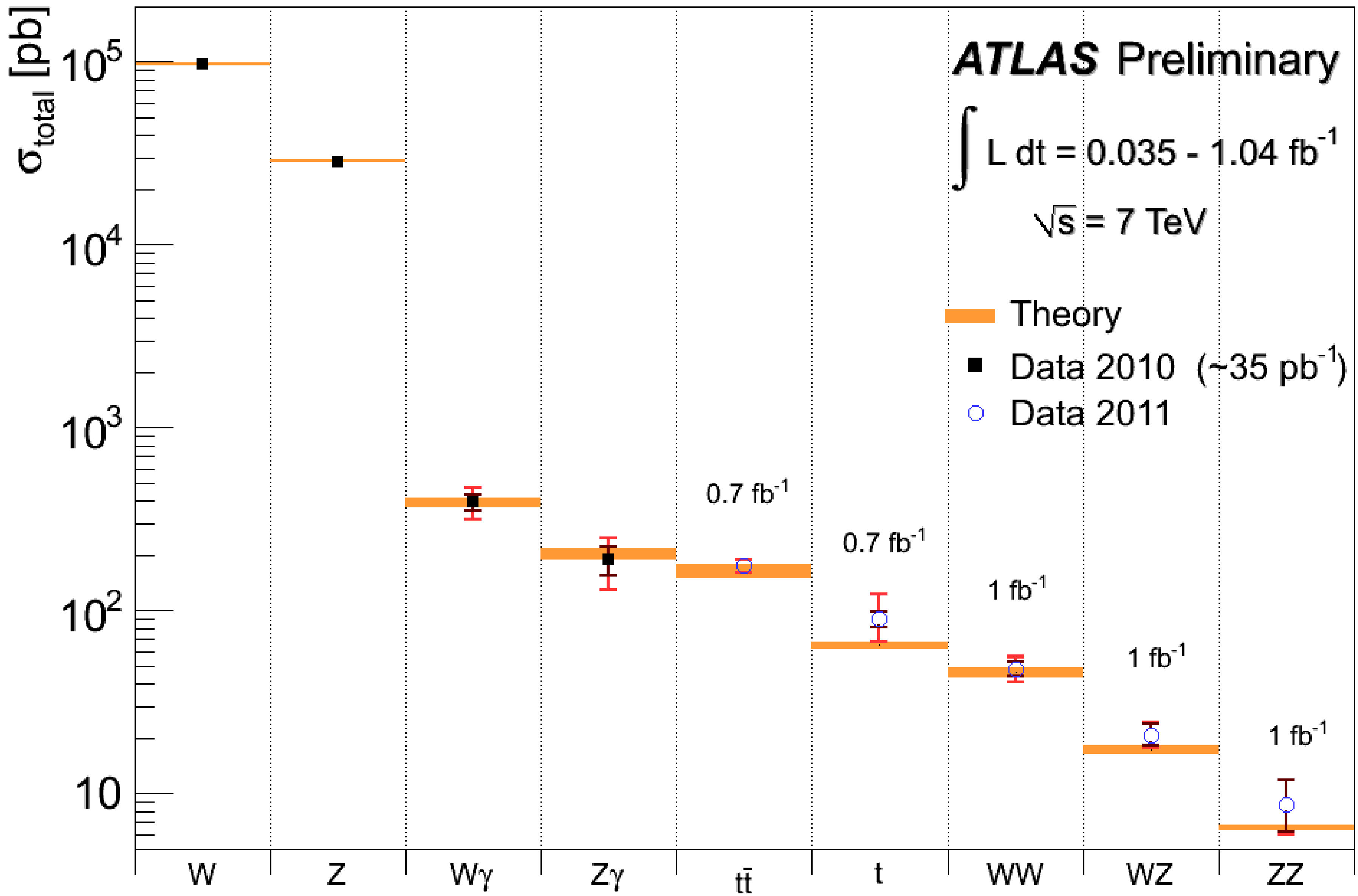
$$\delta\sigma_{th} = \delta\sigma_{UHO} \oplus \delta\sigma_{PDF} \oplus \delta\sigma_{param} \oplus \ldots$$

  - such comparisons give confidence in the calculation of SM backgrounds, e.g. {V,VV,bb,tt,H,…} + jets

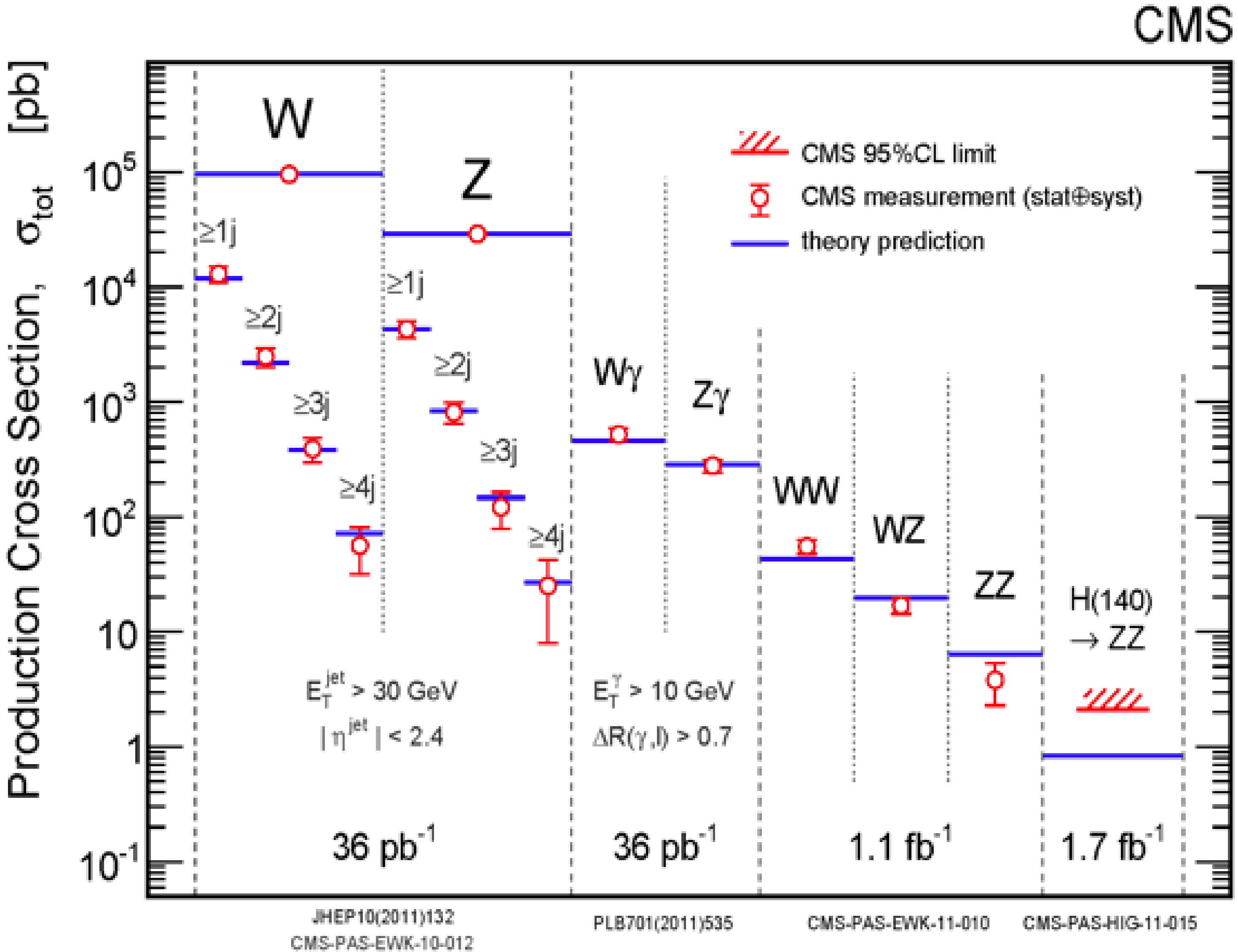
W cross section measurements



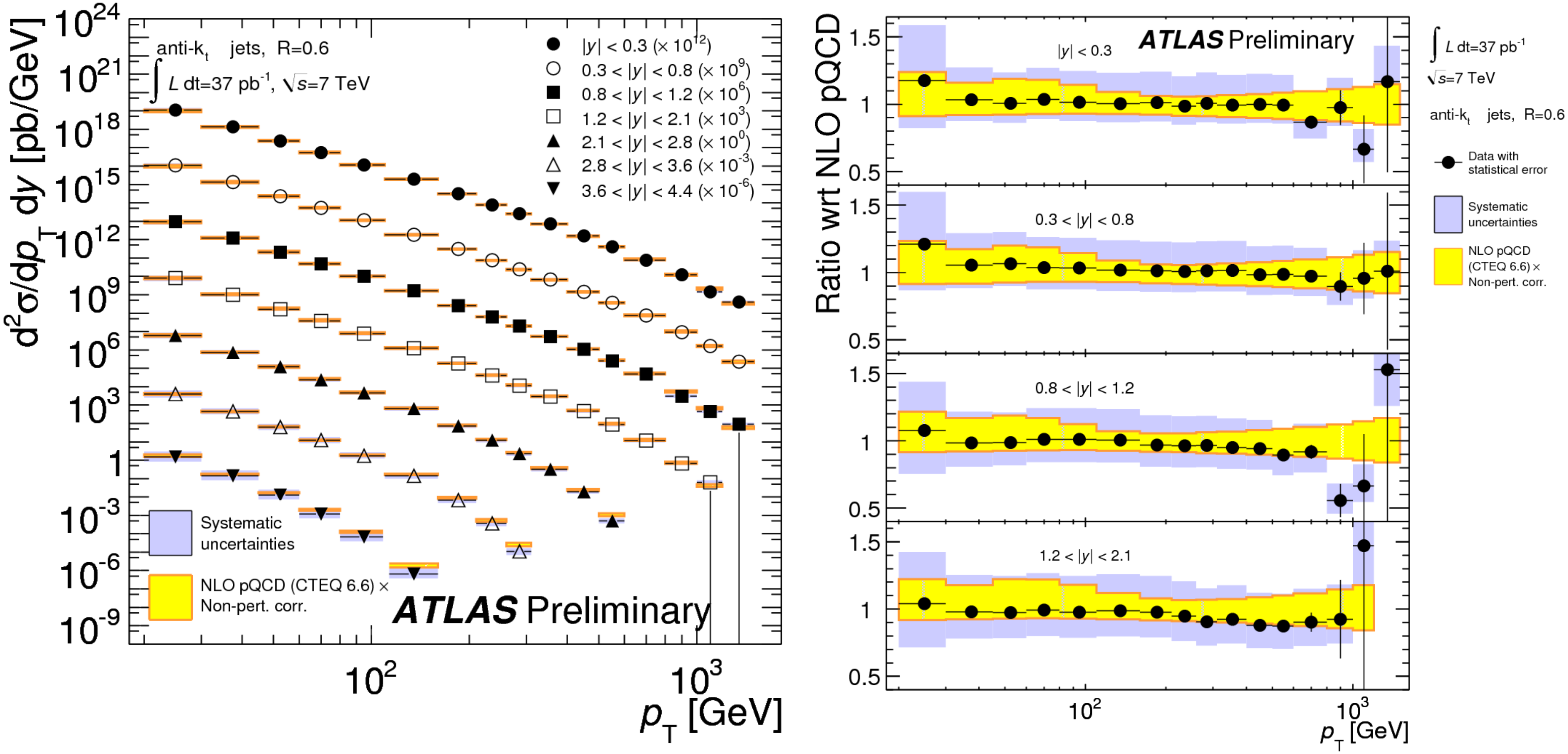
ATLAS-CONF-2011-041



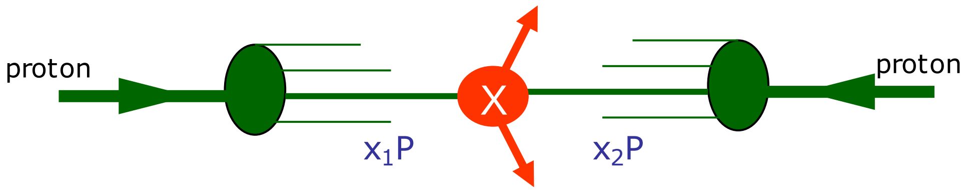
ATLAS Preliminary
$\int L\,dt = 0.035 - 1.04\ \mathrm{fb}^{-1}$
$\sqrt{s} = 7$ TeV
Theory
Data 2010 (~35 pb^{-1})
Data 2011
σ_{total} [pb]
10^5
10^4
10^3
10^2
10
0.7 fb^{-1}
0.7 fb^{-1}
1 fb^{-1}
1 fb^{-1}
1 fb^{-1}
W
Z
Wγ
Zγ
$t\bar{t}$
t
WW
WZ
ZZ

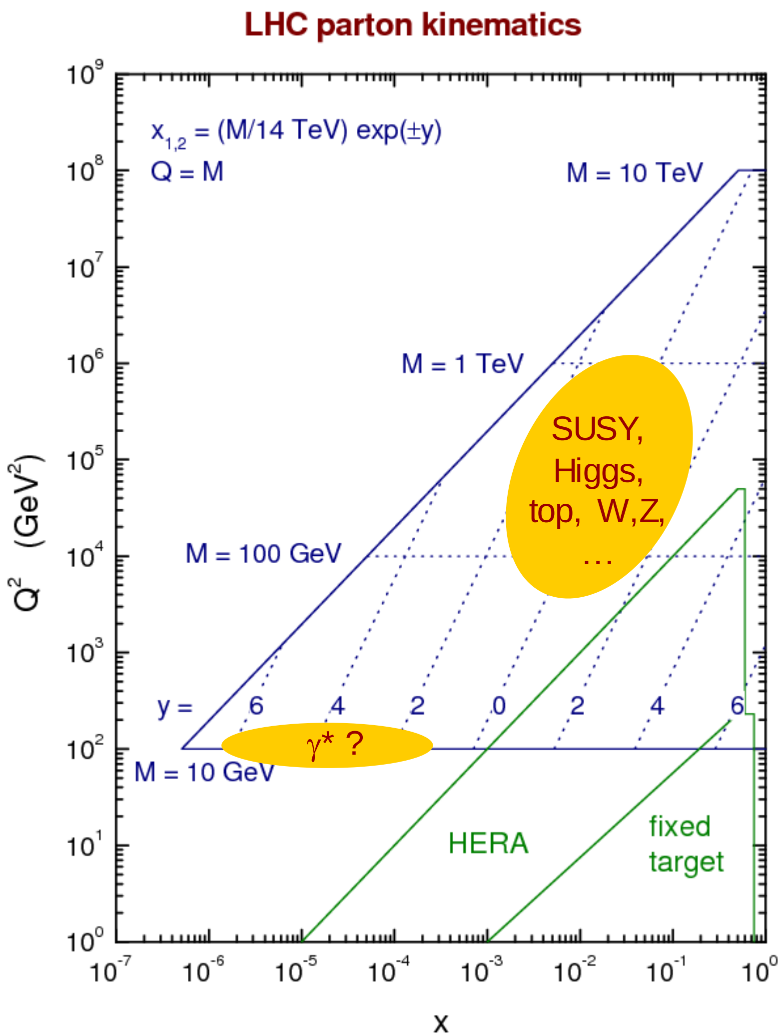

CMS
Production Cross Section, σtot [pb]
W
Z
≥1j
≥2j
≥3j
≥4j
Wγ
Zγ
WW
WZ
ZZ
H(140) → ZZ
CMS 95%CL limit
CMS measurement (stat⊕syst)
theory prediction
E_T^jet > 30 GeV
|η^jet| < 2.4
E_T^γ > 10 GeV
ΔR(γ,l) > 0.7
36 pb-1
36 pb-1
1.1 fb-1
1.7 fb-1
JHEP10(2011)132
CMS-PAS-EWK-10-012
PLB701(2011)535
CMS-PAS-EWK-11-010
CMS-PAS-HIG-11-015

inclusive jet cross section

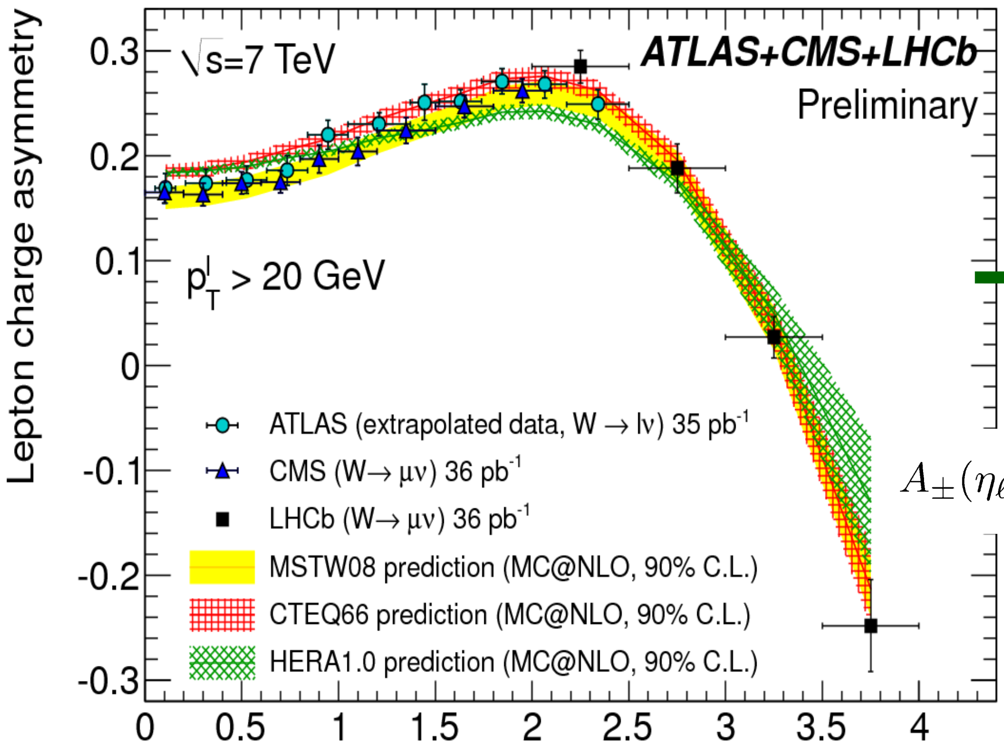


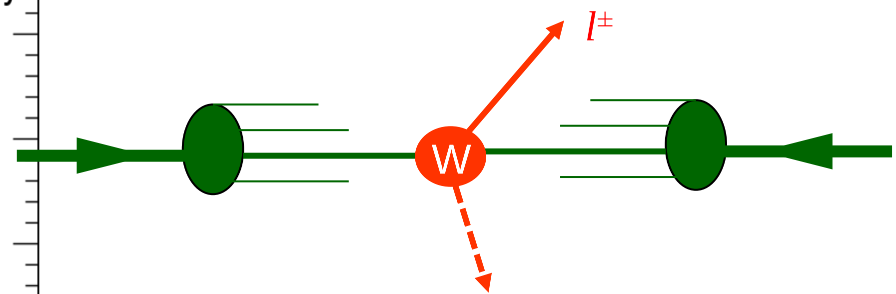
- *PDF fitting*
  - LHC can in principle provide complementary (and new?) information on PDFs, particularly from well measured, generally inclusive, Standard Candle cross sections (W,Z,jets,tt,…)
  - the process has already started...





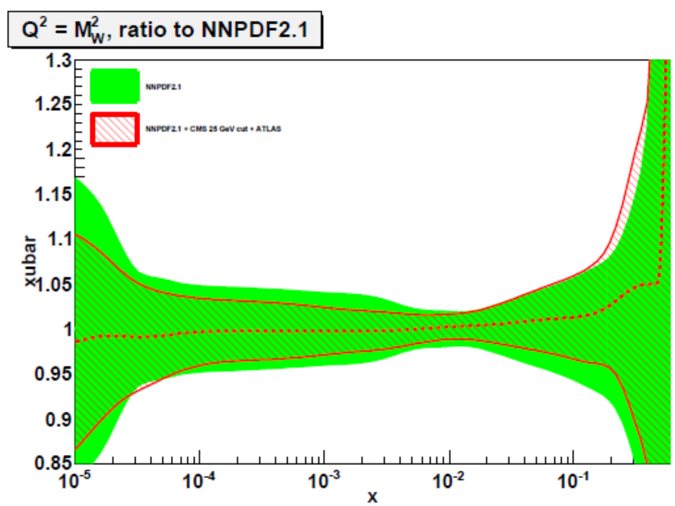
W rapidity asymmetry

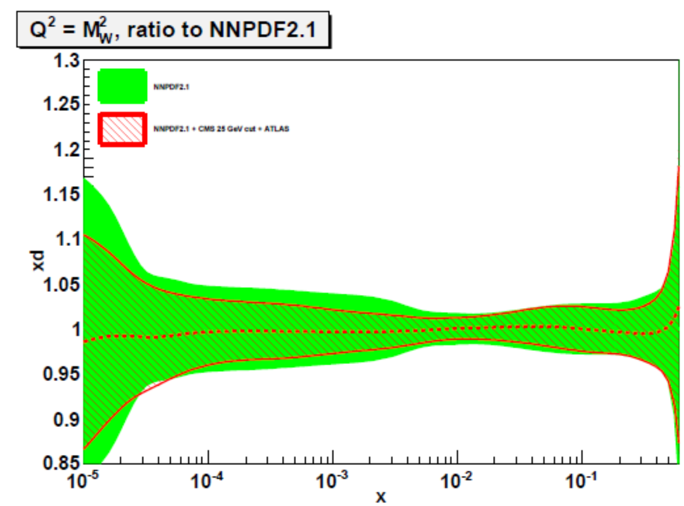




$$A_\pm(\eta_\ell) \approx \frac{S(x_1)u_V(x_2) - d_V(x_1)S(x_2)}{S(x_1)u_V(x_2) + d_V(x_1)S(x_2) + 2S(x_1)S(x_2)}.$$

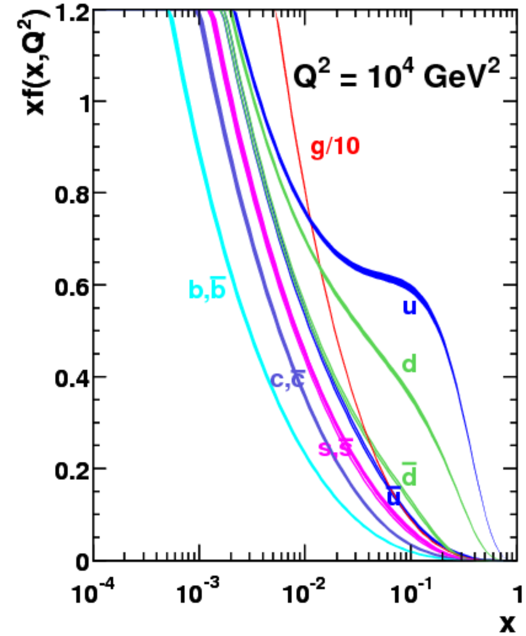
impact of LHC W asymmetry on NNPDF ubar and d PDFs

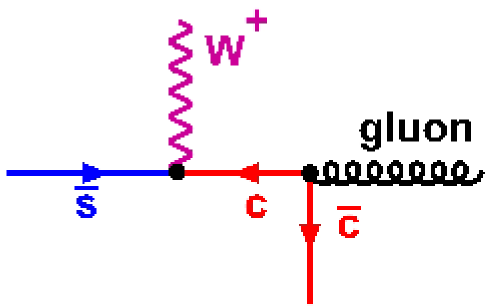




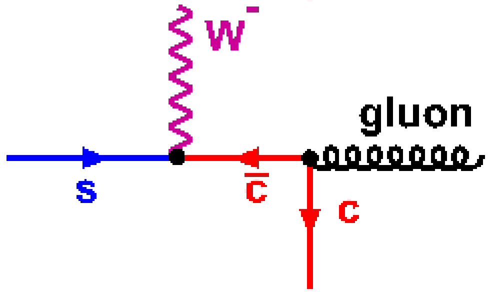
probing heavy quark pdfs

take advantage of (a) qg dominates W,Z + jet production, (b) heavy quark suppression becomes weaker at high Q^2, small x, (c) ability to tag c,b jets





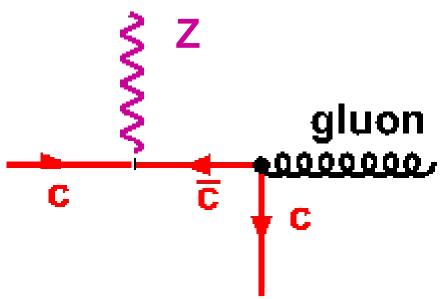
CMS: "W production in association with c jets"
(CMS-PAS-EWK-11-013)



$$R_c^{\pm} \equiv \sigma(W^+\bar{c})/\sigma(W^-c) \text{ and } R_c \equiv \sigma(W+c)/\sigma(W+jets)$$

$$R_c^{\pm} = 0.92 \pm 0.19\,(stat.) \pm 0.04\,(syst.)$$ ← sbar / s

$$R_c = 0.143 \pm 0.015\,(stat.) \pm 0.024\,(syst.)$$ ← sbar + s

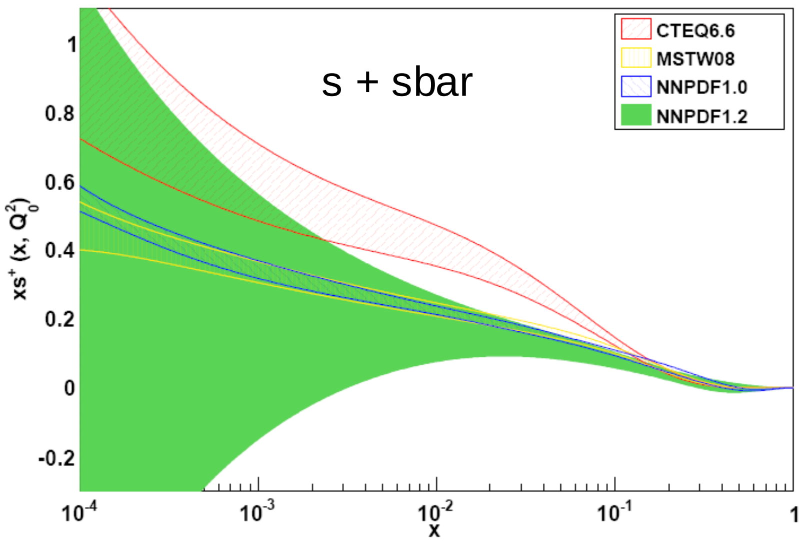


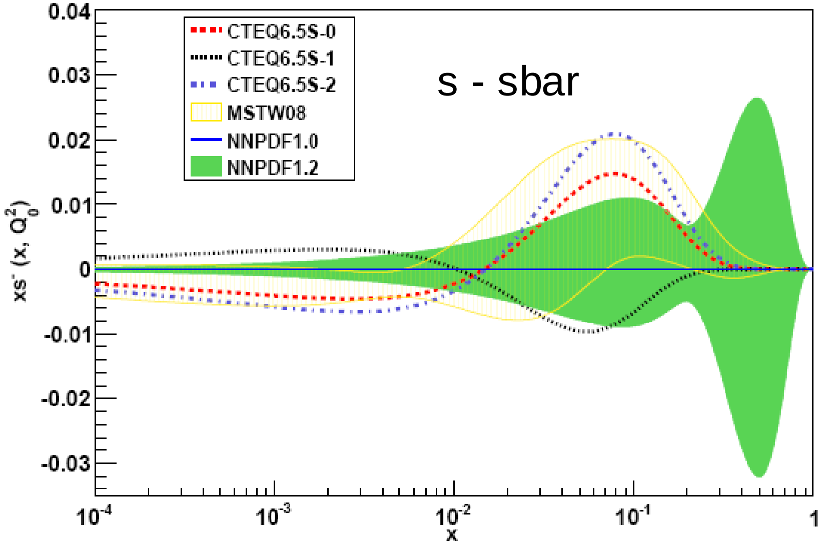
Ratio	MCFM (CT10)	MCFM (MSTW08)	MCFM (NNPDF21)
$R_c^{\pm}$	$0.915^{+0.006}_{-0.006}$	$0.881^{+0.022}_{-0.032}$	0.902 ± 0.008
R_c	$0.125^{+0.013}_{-0.007}$	$0.118^{+0.002}_{-0.002}$	0.103 ± 0.005

differences at level of exptl. systematic error!

Also: Z + c as a measure of charm pdf

strange quarks in NNPDF, MSTW, CTEQ



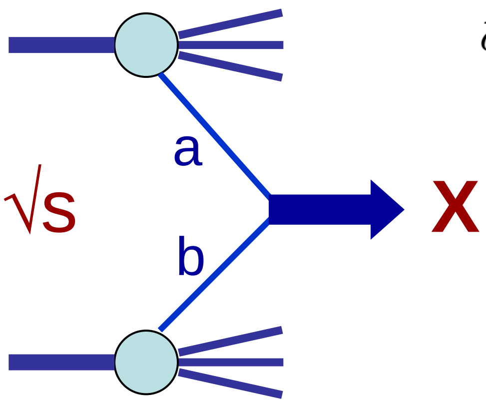


<u>Note:</u>

MSTW: assume u,d,s quarks have same x^δ behaviour as $x \to 0$

parton luminosity functions

- a quick and easy way to assess the mass and collider energy dependence of production cross sections, and to compare different PDF sets



$$
\begin{aligned}
\hat{\sigma}_{ab\to X} &= C_X \delta(\hat{s} - M_X^2) \\
\sigma_X &= \int_0^1 dx_a dx_b\, f_a(x_a, M_X^2) f_b(x_b, M_X^2)\, C_X\, \delta(x_a x_b - \tau) \\
&\equiv C_X \left[\frac{1}{s} \frac{\partial \mathcal{L}_{ab}}{\partial \tau} \right] \qquad\qquad (\tau = M_X^2/s) \\
\frac{\partial \mathcal{L}_{ab}}{\partial \tau} &= \int_0^1 dx_a dx_b\, f_a(x_a, M_X^2) f_b(x_b, M_X^2)\, \delta(x_a x_b - \tau)
\end{aligned}
$$

- i.e. all the mass and energy dependence is contained in the **X**-independent parton luminosity function in [ ]
- useful combinations are $ab = gg, \sum_q q\bar{q}, \ldots$
- and also useful for assessing the uncertainty on cross sections due to uncertainties in the PDFs

The PDF4LHC Working Group Interim Report

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]

[1] Deutsches Elektronen-Synchrotron, DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[2] Institute for High Energy Physics, IHEP, Pobeda 1, 142281 Protvino, Russia
[3] School of Physics and Astronomy, University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland
[4] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg i. B., Germany
[5] NIKHEF, Science Park, Amsterdam, The Netherlands
[6] Department of Physics and Astronomy, University College, London, WC1E 6BT, UK
[7] Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain
[8] Department of Physics, Oxford University, Denys Wilkinson Bldg, Keble Rd, Oxford, OX1 3RH, UK
[9] CERN, CH–1211 Genève 23, Switzerland; Antwerp University, B–2610 Wilrijk, Belgium; University of California Davis, CA, USA
[10] CEA, DSM/IRFU, CE-Saclay, Gif-sur-Yvetee, France
[11] Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy
[12] Deutsches Elektronensynchrotron DESY Notkestraße 85 D–22607 Hamburg, Germany
[13] Physics and Astronomy Department, Michigan State University, East Lansing, MI 48824, USA
[14] Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland
[15] Taipei Municipal University of Education, Taipei, Taiwan
[16] School of Physics, University College Dublin Science Centre North, UCD Belfeld, Dublin 4, Ireland
[17] Department of Physics, Southern Methodist University, Dallas, TX 75275-0175, USA
[18] Physikalisches Institut, Universität Heidelberg Philosophenweg 12, D–69120 Heidelberg, Germany
[19] Department of Astronomy and Theoretical Physics, Lund University, Sölvegatan 14A, S-223 62 Lund, Sweden
[20] Cavendish Laboratory, University of Cambridge, CB3 OHE, UK
[21] Institut für Theoretische Teilchenhysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany
[22] Theory Group, Physics Department, CERN, CH-1211 Geneva 23, Switzerland

benchmark cross sections at 7 TeV from 6 fitting groups

CERN–2011–002
17 February 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2011

Chapter 8: Parton Distribution Functions (*S. Forte et al.)*

See also ....

CERN-PH-TH/2011-149
28th June 2011

Parton distribution function dependence of benchmark Standard Model total cross sections at the 7 TeV LHC

G. Watt

Theory Group, Physics Department, CERN, CH-1211 Geneva 23, Switzerland

E-mail: Graeme.Watt@cern.ch

Abstract: We compare predictions for the W, Z, $gg \to H$ and $t\bar{t}$ total cross sections at the Large Hadron Collider (LHC), for a centre-of-mass energy of 7 TeV, using the most recent publicly available next-to-leading order and next-to-next-to-leading order parton distribution functions (PDFs) from all PDF fitting groups. In particular, we focus on the dependence on the different values of the strong coupling, $\alpha_S(M_Z^2)$, used by each group. We also perform a comparison of the relevant quark–antiquark and gluon–gluon luminosity functions. We make some comments on the recent PDF4LHC recommendations. Finally, we discuss the comparison of data and theory for W and Z cross sections at the LHC.

Keywords: Hadronic Colliders, Standard Model, Deep Inelastic Scattering, Parton Model

ArXiv ePrint: 1106.5788

and many plots at ...
http://projects.hepforge.org/mstwpdf/pdf4lhc/

recent global or quasi-global PDF fits

PDFs	authors	arXiv
ABKM	S. Alekhin, J. Blümlein, S. Klein, S. Moch, and others	1105.5349, 1007.3657, 0908.3128, 0908.2766, …
CTEQ	H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. Nadolsky, J. Pumplin, C.-P. Yuan, and others	1007.2241, 1004.4624, 0910.4183, 0904.2424, 0802.0007, …
GJR	M. Glück, P. Jimenez-Delgado, E. Reya, and others	1006.5890, 0909.1711, 0810.4274, …
HERAPDF	H1 and ZEUS collaborations	1012.1438,1006.4471, 0906.1108, …
MSTW	A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt	1007.2624, 1006.2753, 0905.3531, 0901.0002, …
NNPDF	R. Ball, L. Del Debbio, S. Forte, A. Guffanti, J. Latorre, J. Rojo, M. Ubiali, and others	1108.1758, 1107.2652, 1102.3182, 1101.1300, 1012.0836, 1005.0397, 1002.4407, …

2010 (shown at the January 2011 Heavy Quarks meeting)

	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08/JR09
HERA DIS	✓	✓	✓	✓	✓	✓
F-T DIS	✓	✓	✓	✘	✓	✓
F-T DY	✓	✓	✓	✘	✓	✓
TEV W,Z	✓	✓	✓	✘	✘	✘
TEV jets	✓	✓	✓	✘	✘	✓/✘
GM-VFNS	✓	✓	✘	✓	✘	✘
NNLO	✓	✘	✘	✘	✓	✓

January 2012

	MSTW08	CT10	NNPDF2.1	HERAPDF1.5	ABKM09	GJR08/JR09
HERA DIS	✓	✓	✓	✓	✓	✓
F-T DIS	✓	✓	✓	✘	✓	✓
F-T DY	✓	✓	✓	✘	✓	✓
TEV W,Z	✓	✓	✓	✘	✘	✘
TEV jets	✓	✓	✓	✘	✘	✓/✘
GM-VFNS	✓	✓	✓	✓	✘	✘
NNLO	✓	✘	✓	✓	✓	✓

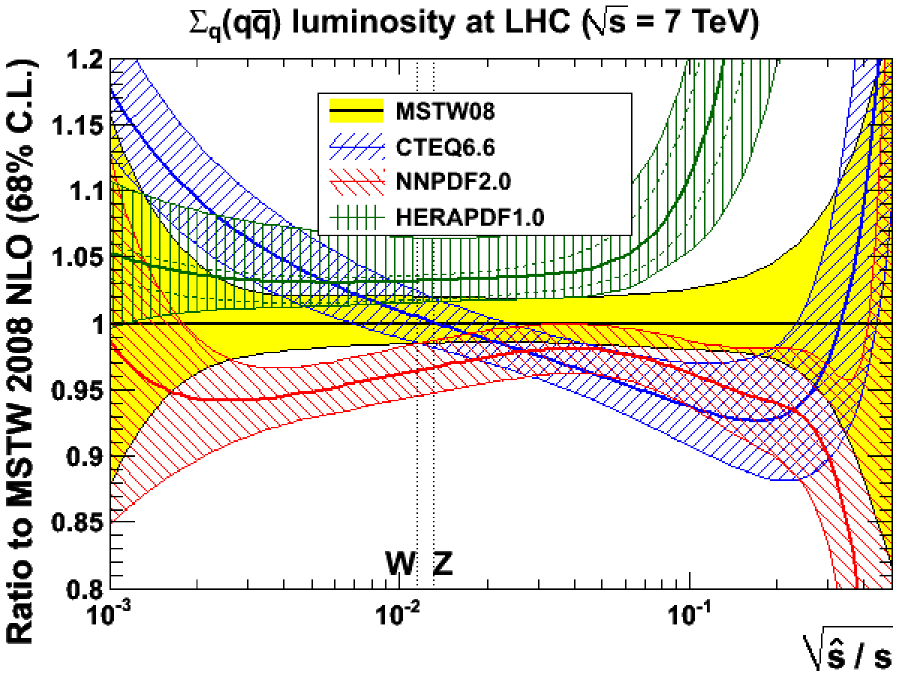
– all available in LHAPDF V5.8.6 (August 2011)

Note:

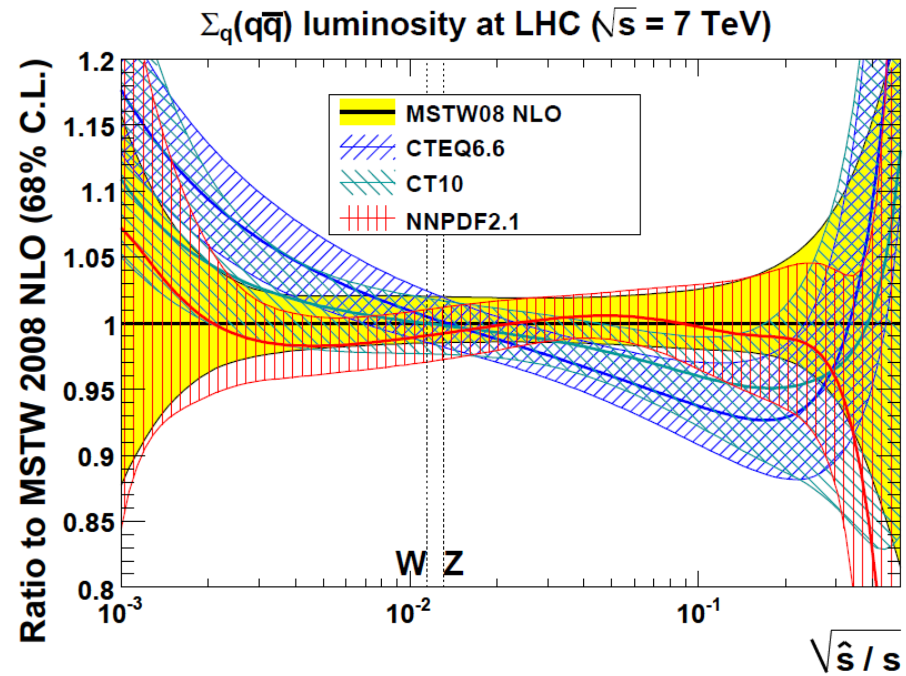
- not 'true' NNLO fits when collider inclusive jet data are included, since NNLO pQCD corrections not yet known
- all except CTEQ/CT now have publicly available NNLO sets
- PDF groups may also have 'internal' unpublished sets (e.g. CT-NNLO, HERAPDF1.6/7, ABM10, ...)
- convergence and broad agreement (see below), but still differences for example due to
  - choice of data sets (including cuts, corrections and weighting) and treatment of data errors
  - definition of 'PDF uncertainties'
  - treatment of heavy quarks (s,c,b), FFNS, ZM-VFNS, GM-VFNS,
  - treatment of α_S (fitted or fixed)
  - parametric form at Q_0
  - (hidden) theoretical assumptions (if any) about flavour symmetries, $x \to 0,1$ behaviour, etc.
  - ...

convergence of pdfs!

plots from Graeme Watt



2010



2011

... although still some differences with ABKM, GJR, HERAPDF

Note: NPDF2.0→2.1: ZM-VFNS → GM-VFNS (FONLL) → larger PDFs at small x
CTEQ6.6→CT10: Tevatron Run II jets + extended parametrisation + ...

PDFs and $\alpha_S(M_Z^2)$

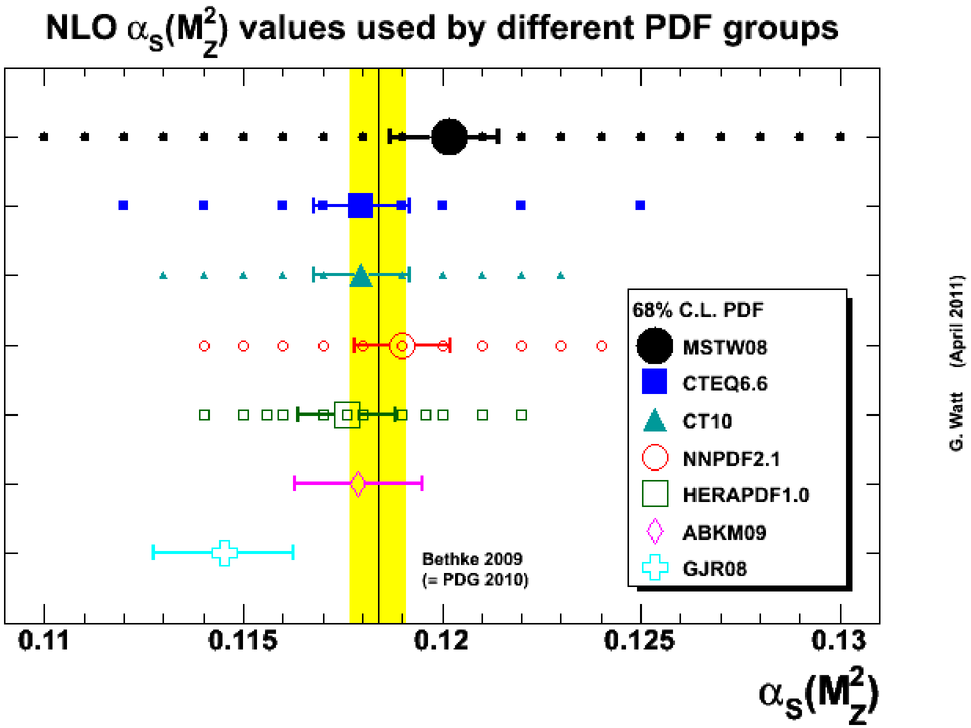
- MSTW08, ABKM09 and GJR08: $\alpha_S(M_Z^2)$ values and uncertainty determined by global fit
- NNLO value about 0.003 – 0.004 lower than NLO value, e.g. for MSTW08

$$\alpha_S^{\overline{MS},NLO}(M_Z^2) = 0.1202^{+0.012}_{-0.015}$$

$$\alpha_S^{\overline{MS},NNLO}(M_Z^2) = 0.1171^{+0.014}_{-0.014}$$

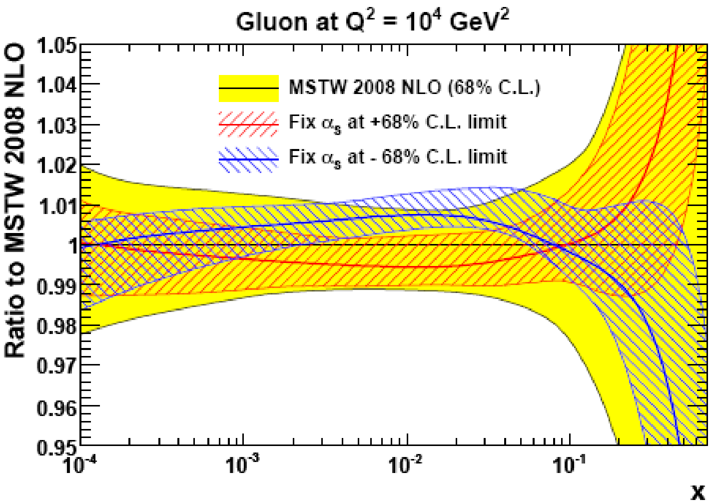
- CTEQ/CT10, NNPDF, HERAPDF choose standard values and uncertainties
- world average (Bethke 2009)

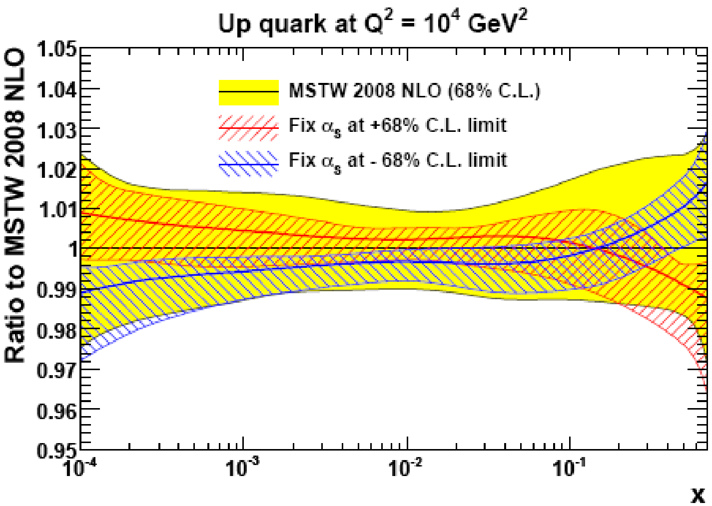
$$\alpha_S^{\overline{MS}}(M_Z^2) = 0.1184 \pm 0.0007$$



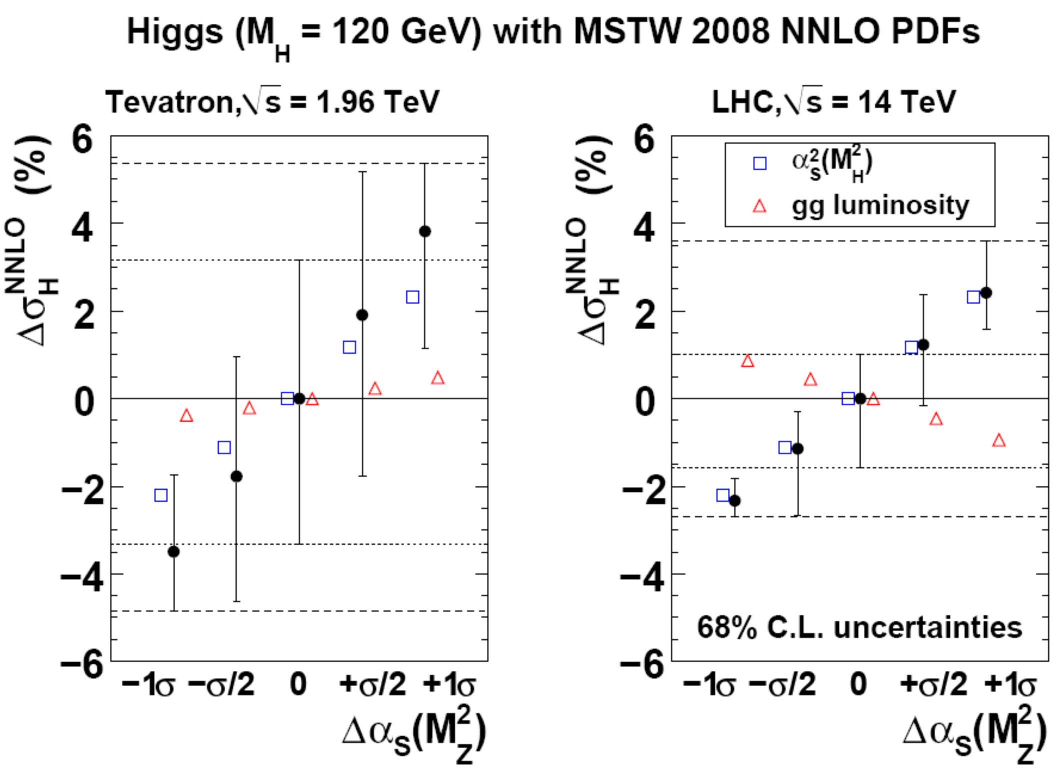
- note that the PDFs and α_S are correlated!
- e.g. gluon – α_S anticorrelation at small x and quark – α_S anticorrelation at large x

α_S - PDF correlations



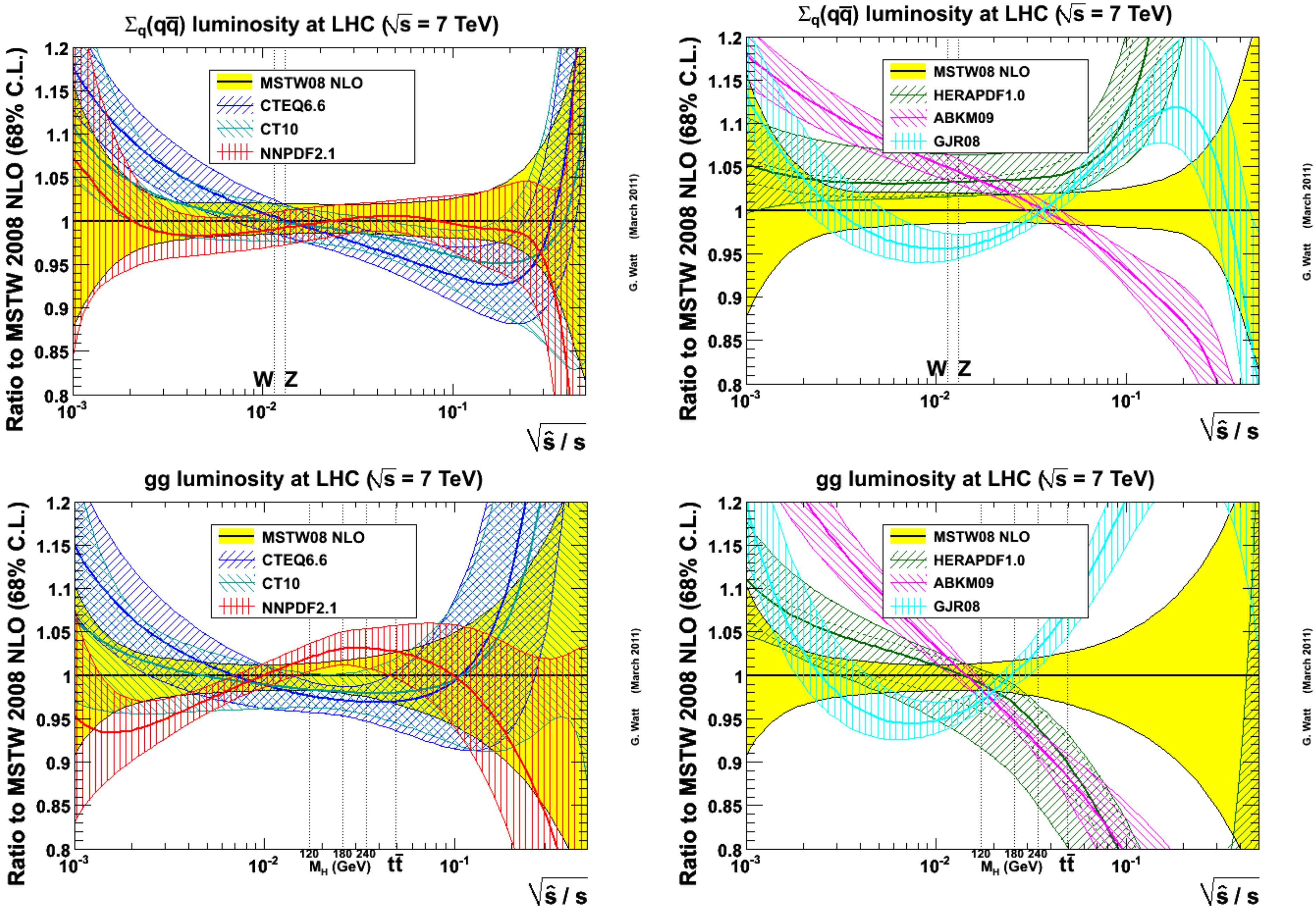


- care needed when assessing impact of varying α_S on cross sections $\sim (\alpha_S)^n$ (e.g. top, Higgs)

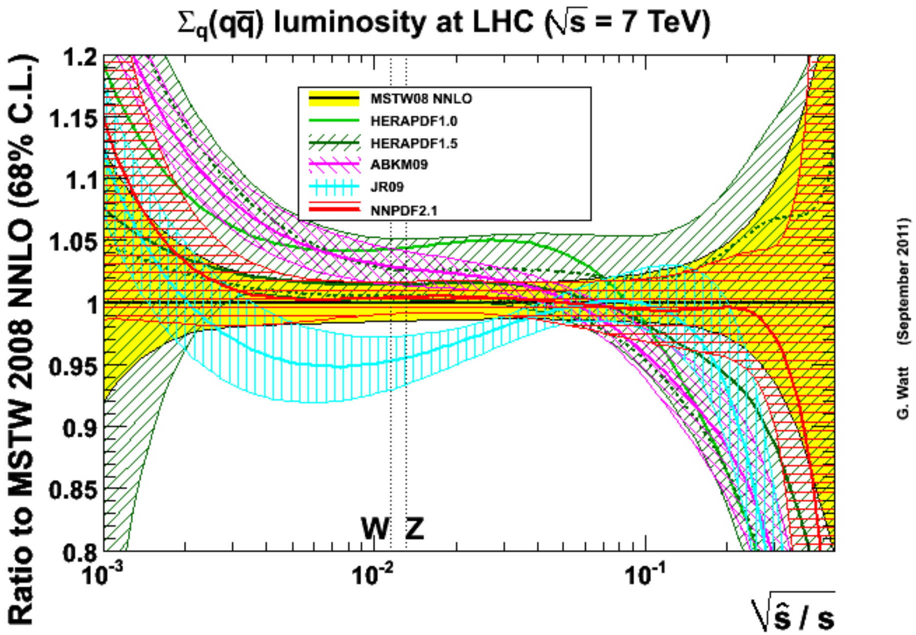


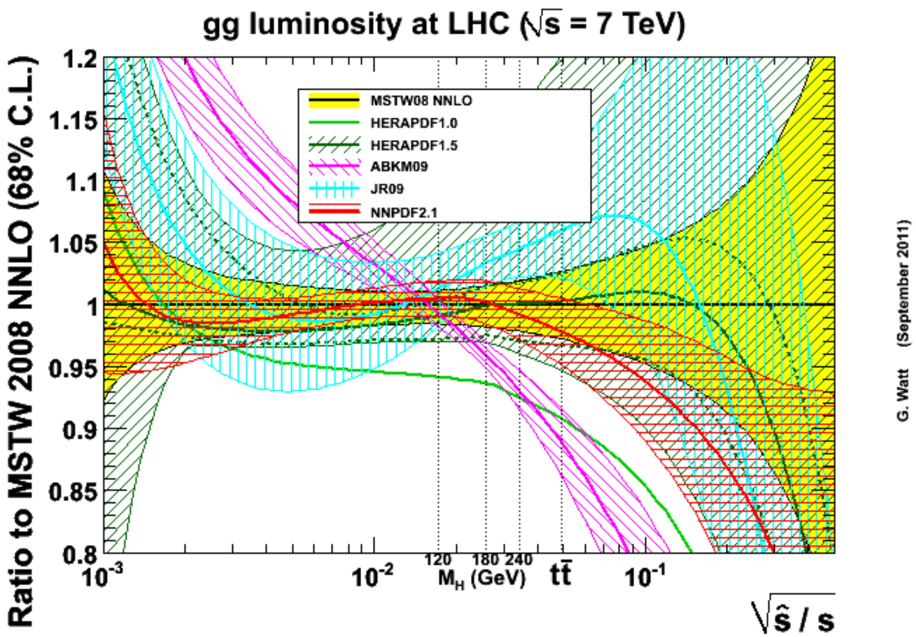
MSTW: arXiv:0905.3531

comparison of NLO parton luminosity functions at 7 TeV LHC



comparison of NNLO parton luminosity functions at 7 TeV LHC





The ‘PDF4LHC recommendation’* for combining best fits and uncertainties from different PDF sets into a single prediction

NLO

“For the calculation of uncertainties at the LHC, use the envelope provided by the central values and PDF+α_s errors from the MSTW08, CTEQ6.6, and NNPDF2.0 PDFs, using each group’s prescriptions for combining the two types of errors. We propose this definition of an envelope because the deviations between the predictions can sometimes be as large as their uncertainties. As a central value, use the midpoint of this envelope. We follow the PDF4LHC prescription and recommend that a 68% CL uncertainty envelope be calculated and the α_s variation suggested is consistent with this. Note that the CTEQ6.6 set has uncertainties and α_s variations provided only at 90% CL and thus their uncertainties should be reduced by a factor of 1.645 for 68% CL. Within the quadratic approximation, this procedure is exact.”

NNLO

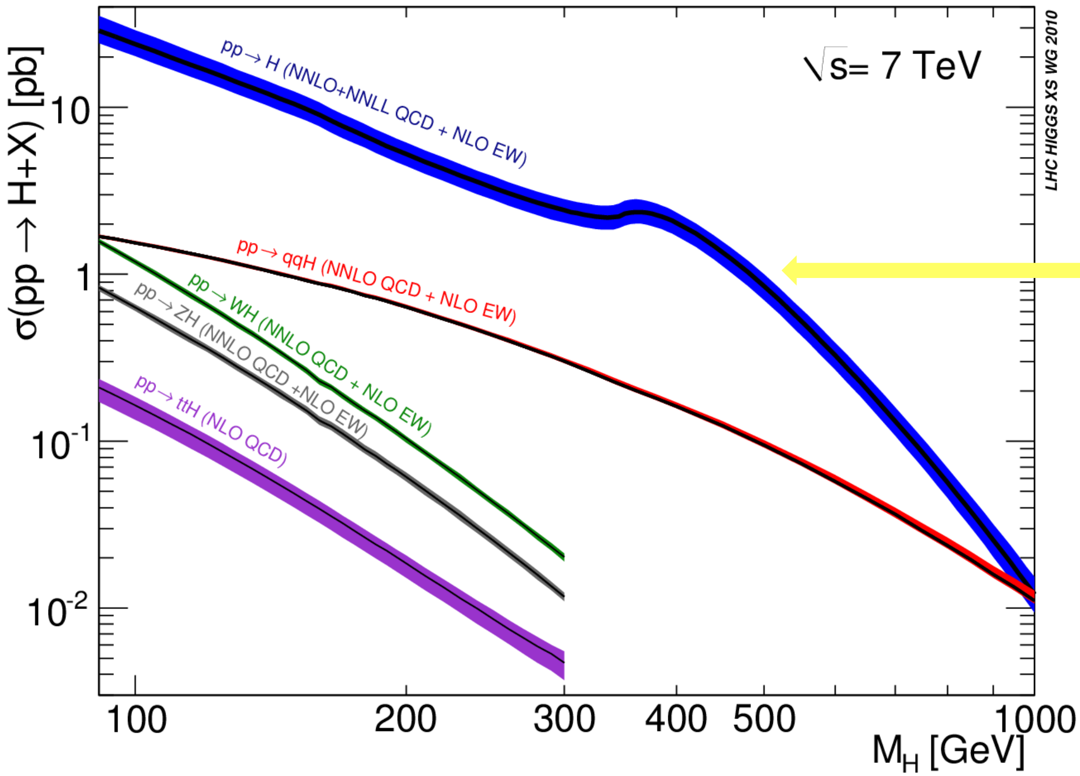
“As a central value, use the MSTW08 prediction. As an uncertainty, take the same percentage uncertainty on this NNLO prediction as found using the NLO uncertainty prescription given above.”

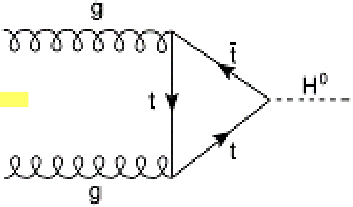
2011 update: CTEQ6.6 → CT10, NNPDF2.0 → NNPDF2.1

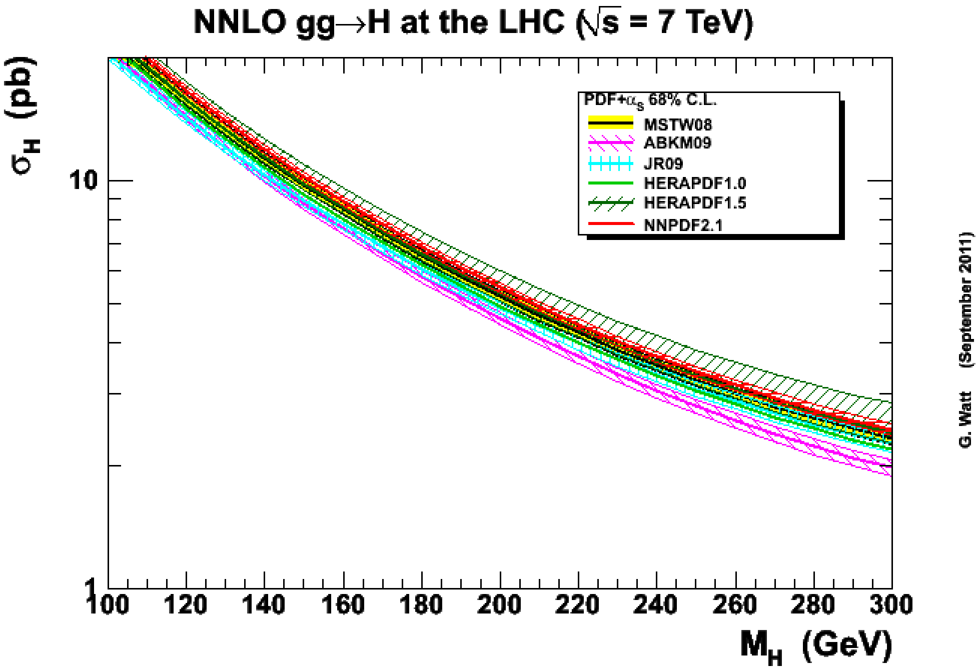
*S. Forte, J. Huston, K. Mazumdar, R.S. Thorne and A. Vicini, Section 8, in Report of the LHC Higgs Cross Section Working Group, arXiv:1101.0593

2

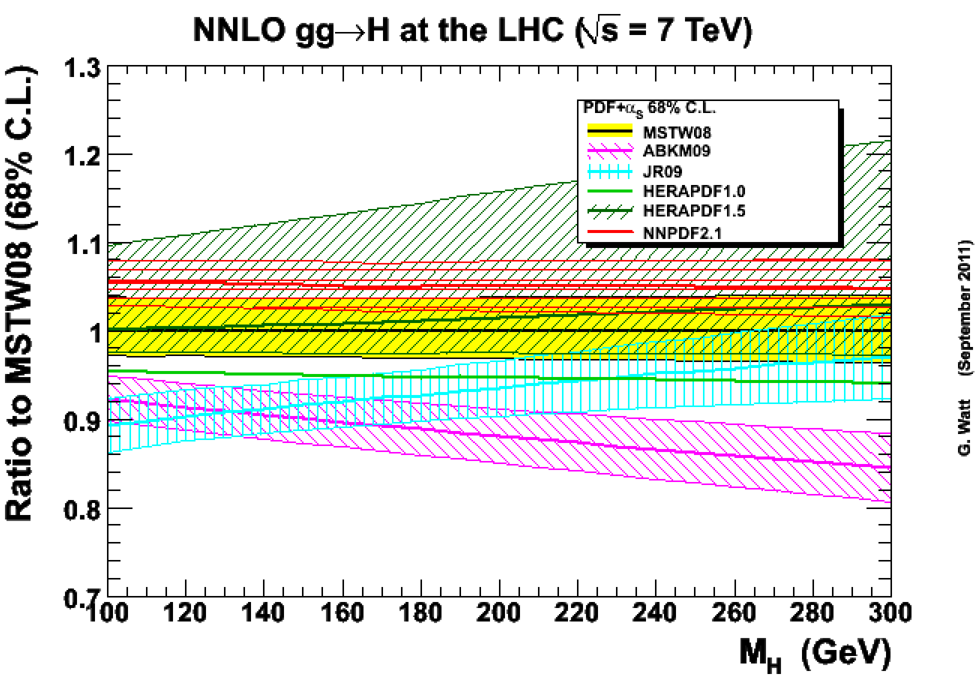
Higgs cross sections



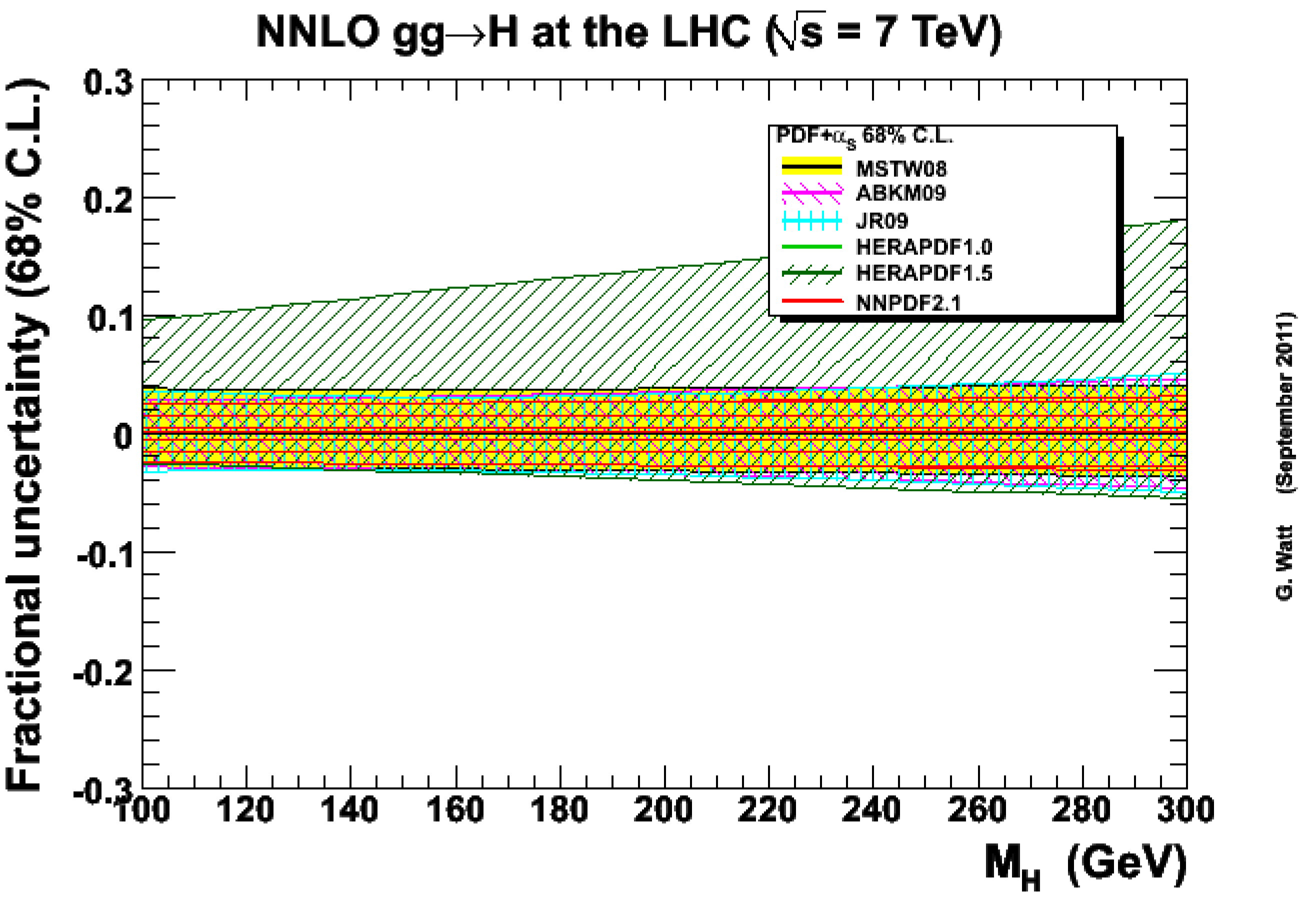




NNLO gg→H at the LHC (√s = 7 TeV)
σ_H (pb)
PDF+α_S 68% C.L.
MSTW08
ABKM09
JR09
HERAPDF1.0
HERAPDF1.5
NNPDF2.1
M_H (GeV)
G. Watt (September 2011)

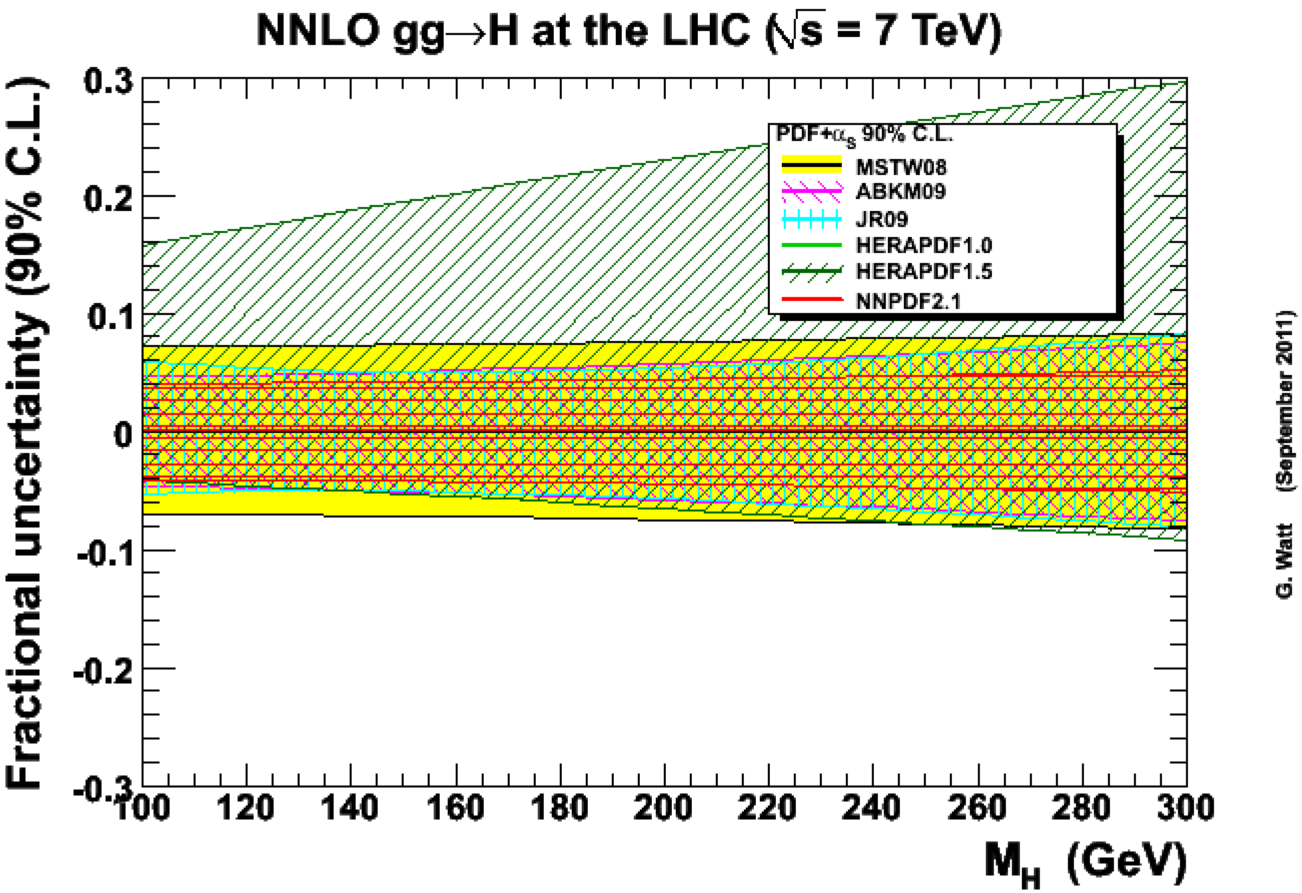


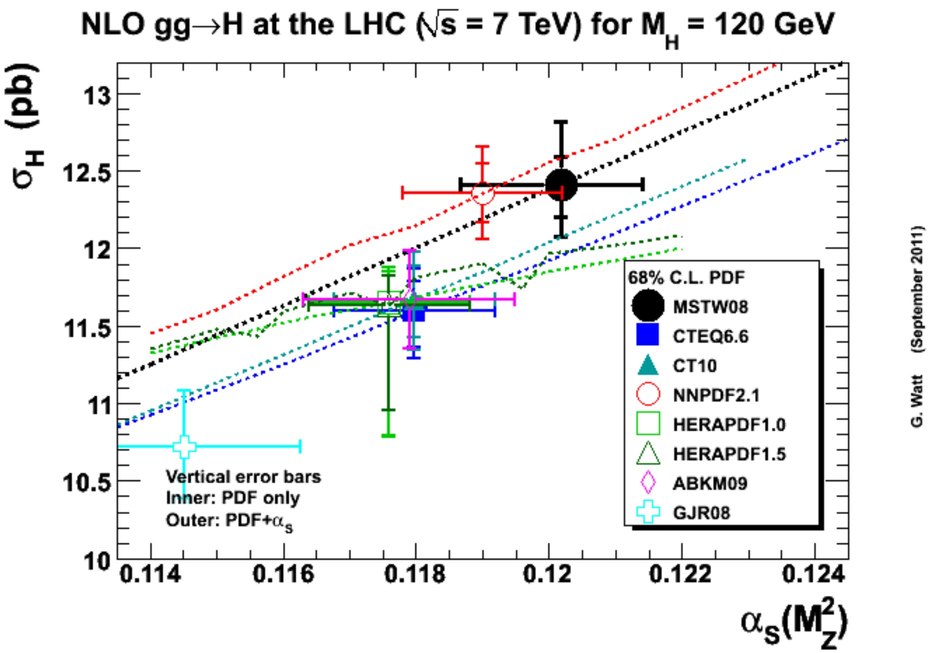
NNLO gg→H at the LHC (√s = 7 TeV)
Ratio to MSTW08 (68% C.L.)
PDF+α_S 68% C.L.
MSTW08
ABKM09
JR09
HERAPDF1.0
HERAPDF1.5
NNPDF2.1
M_H (GeV)
G. Watt (September 2011)

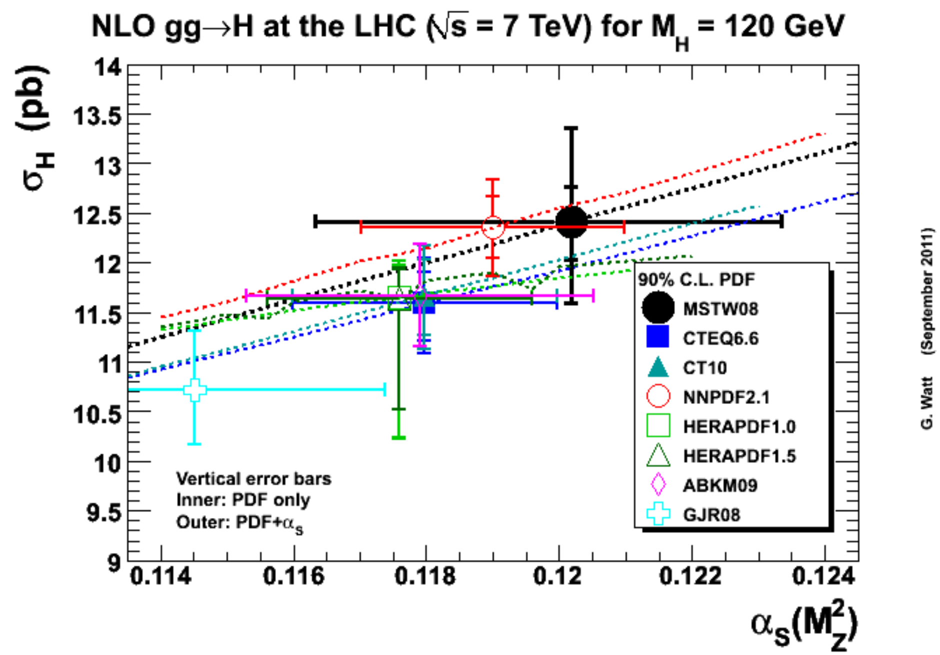


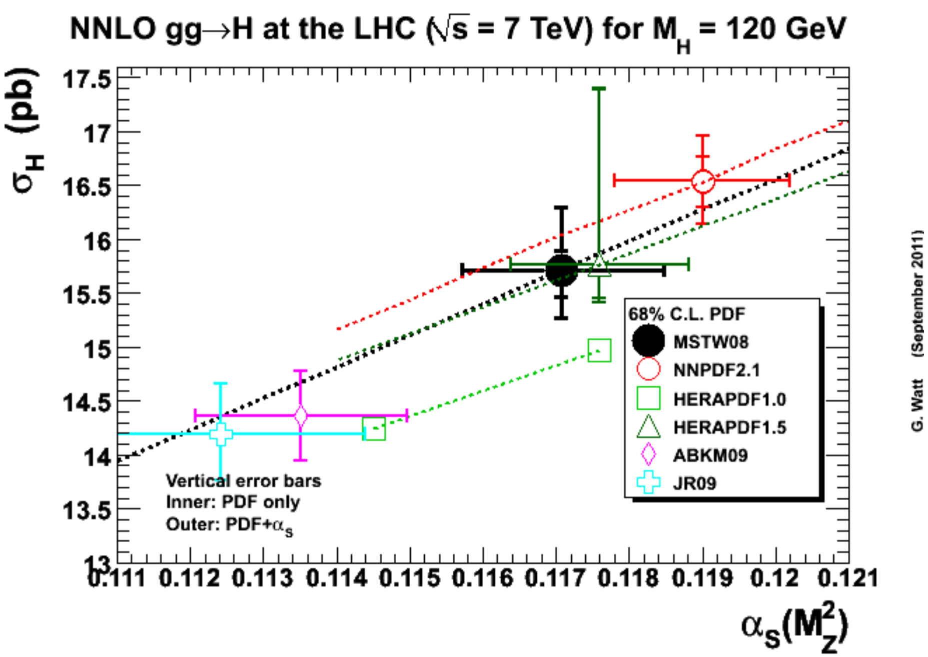
- with the exception of HERAPDF1.5, the uncertainties are very similar, in the ±3-4% range for light M_H

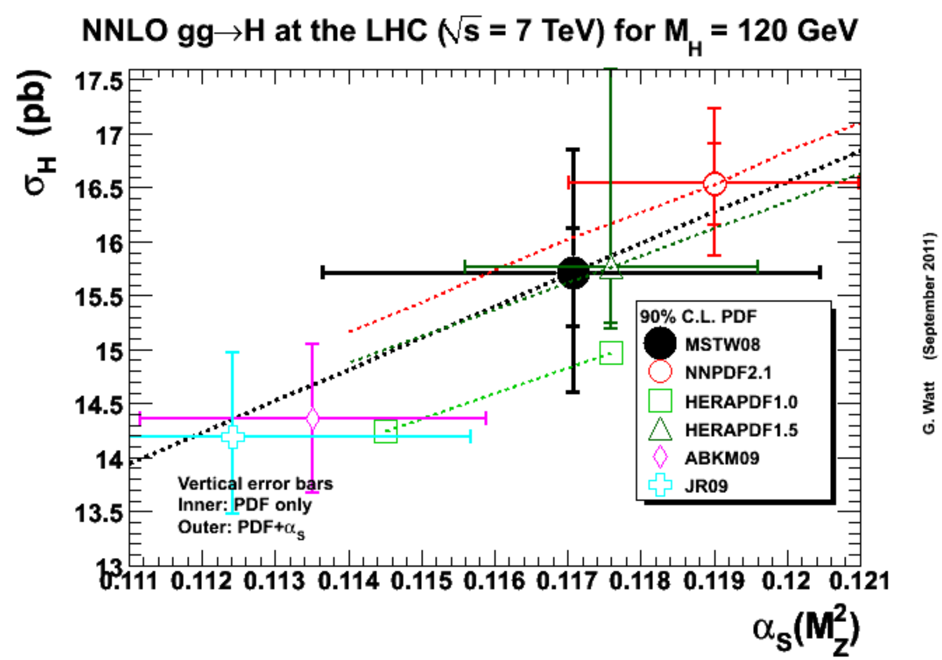
- the same but with 90% C.L.

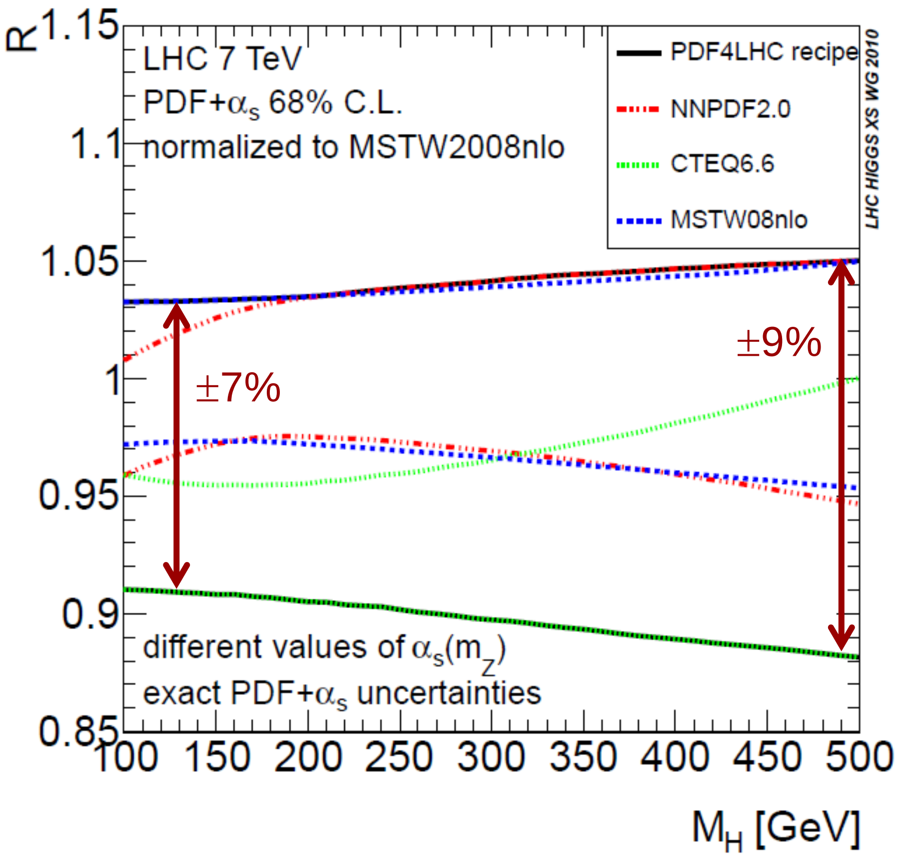


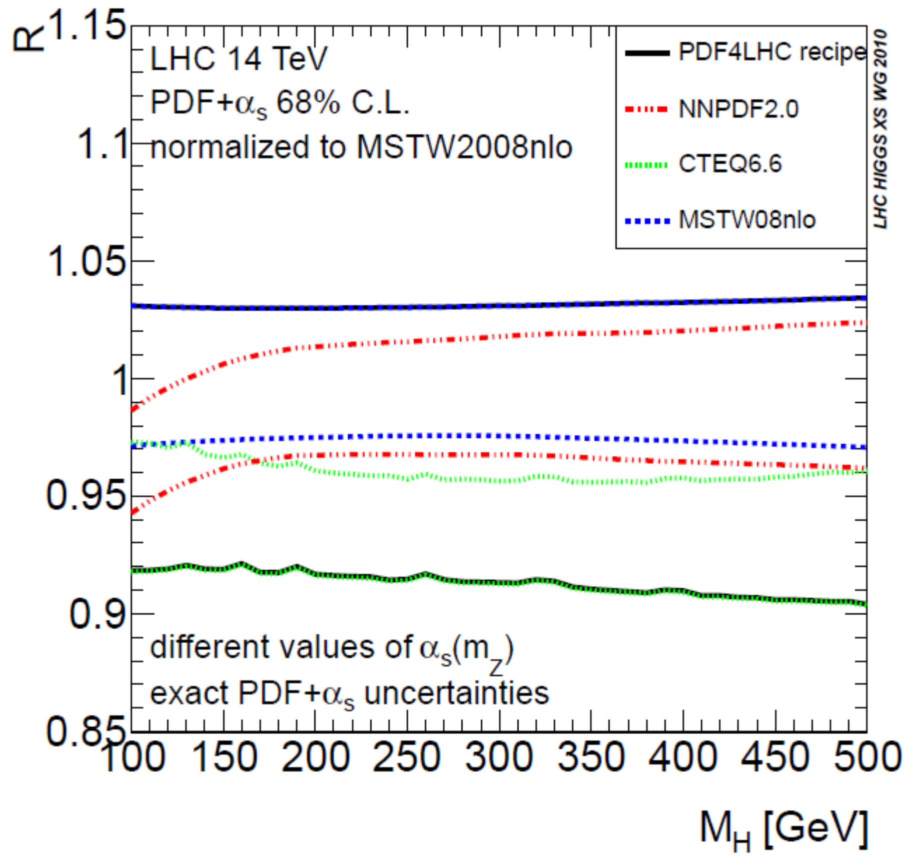

NLO gg→H at the LHC (√s = 7 TeV) for M_H = 120 GeV
σ_H (pb)
α_S(M_Z^2)
68% C.L. PDF
MSTW08
CTEQ6.6
CT10
NNPDF2.1
HERAPDF1.0
HERAPDF1.5
ABKM09
GJR08
Vertical error bars
Inner: PDF only
Outer: PDF+α_S
G. Watt (September 2011)


NLO gg→H at the LHC (√s = 7 TeV) for M_H = 120 GeV
σ_H (pb)
α_S(M_Z^2)
90% C.L. PDF
MSTW08
CTEQ6.6
CT10
NNPDF2.1
HERAPDF1.0
HERAPDF1.5
ABKM09
GJR08
Vertical error bars
Inner: PDF only
Outer: PDF+α_S
G. Watt (September 2011)

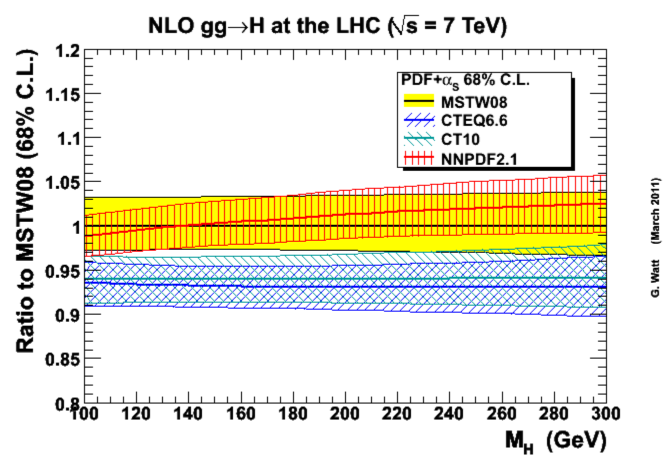

NNLO gg→H at the LHC (√s = 7 TeV) for M_H = 120 GeV
σ_H (pb)
α_S(M_Z^2)
68% C.L. PDF
MSTW08
NNPDF2.1
HERAPDF1.0
HERAPDF1.5
ABKM09
JR09
Vertical error bars
Inner: PDF only
Outer: PDF+α_S
G. Watt (September 2011)


NNLO gg→H at the LHC (√s = 7 TeV) for M_H = 120 GeV
σ_H (pb)
α_S(M_Z^2)
90% C.L. PDF
MSTW08
NNPDF2.1
HERAPDF1.0
HERAPDF1.5
ABKM09
JR09
Vertical error bars
Inner: PDF only
Outer: PDF+α_S
G. Watt (September 2011)

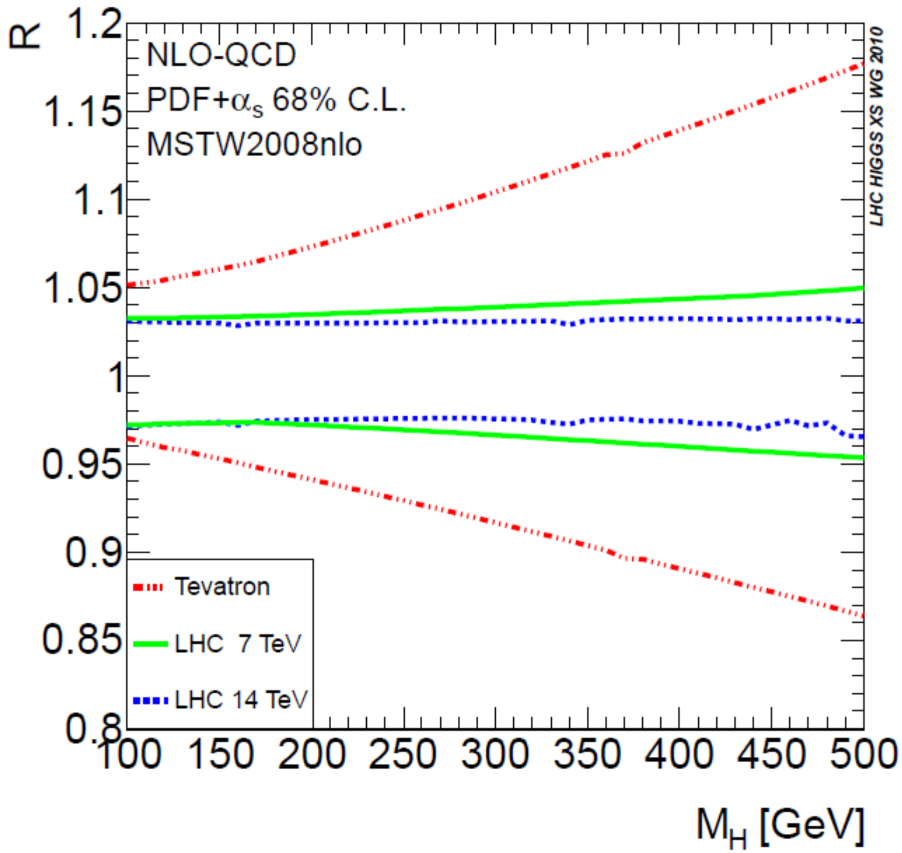


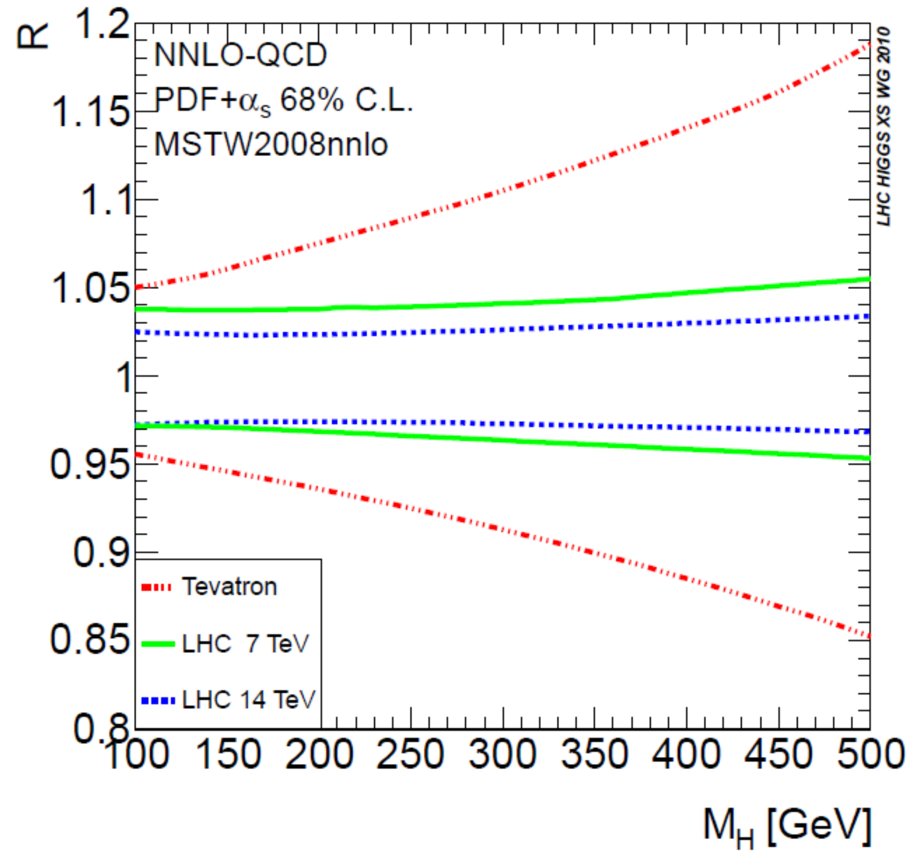


largely unchanged by NNPDF2.0→2.1 and CTEQ6.6→CT10

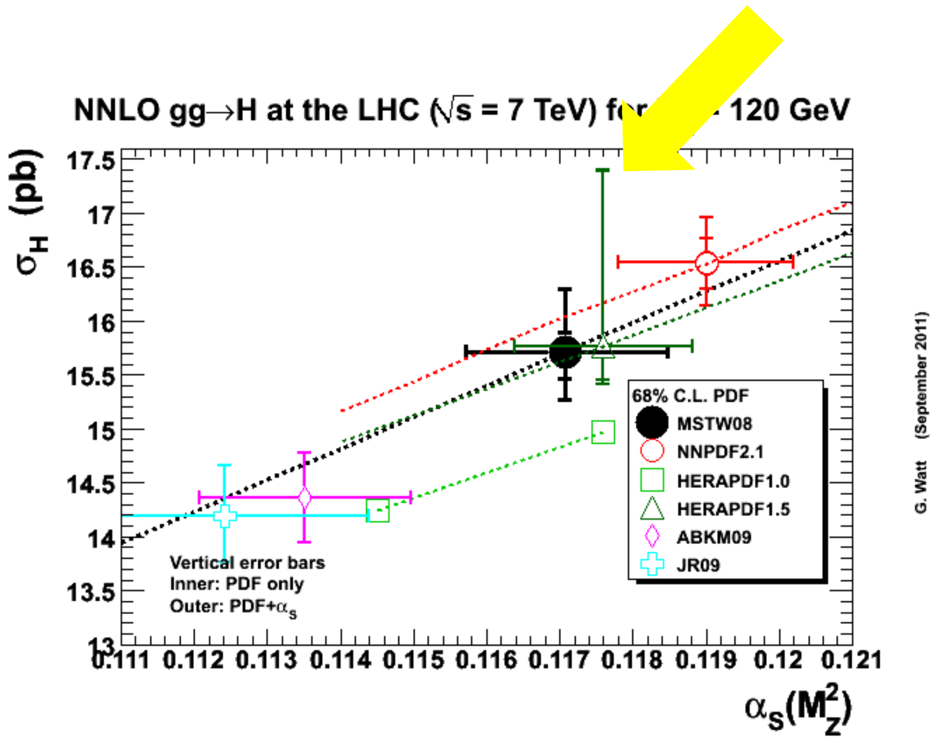


PDF + α_S uncertainties: Tevatron *vs.* LHC

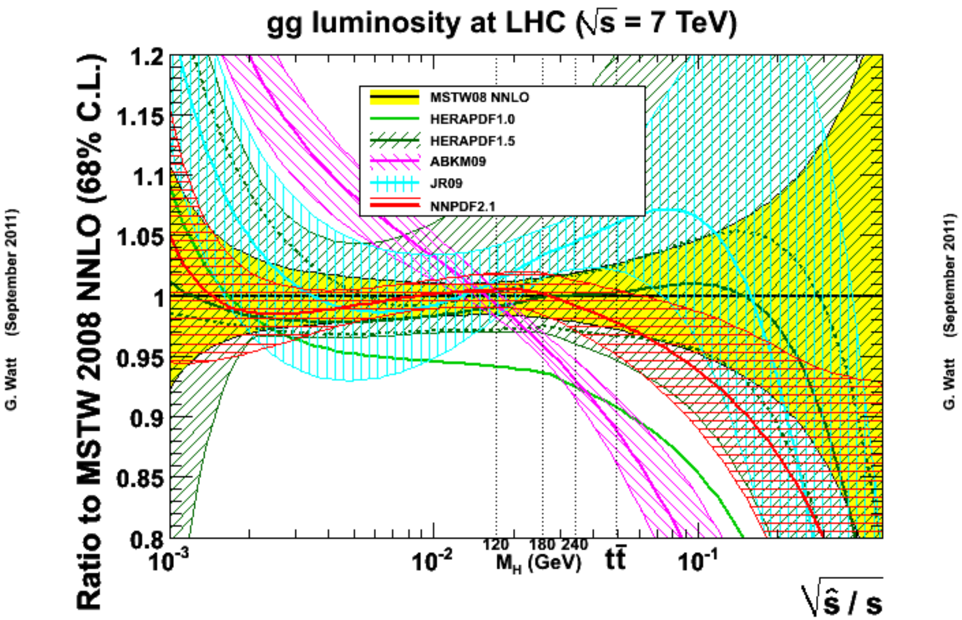




recall

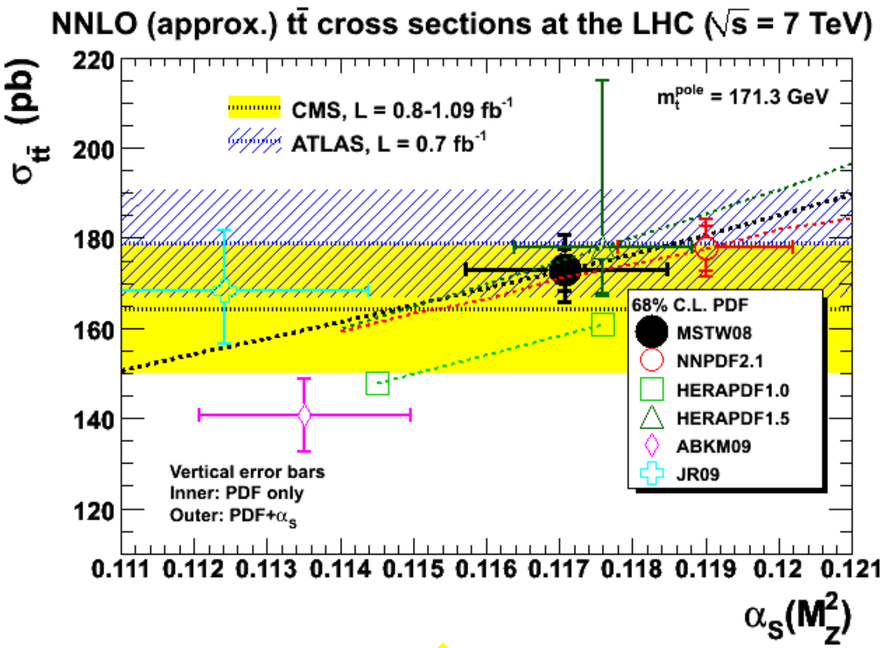


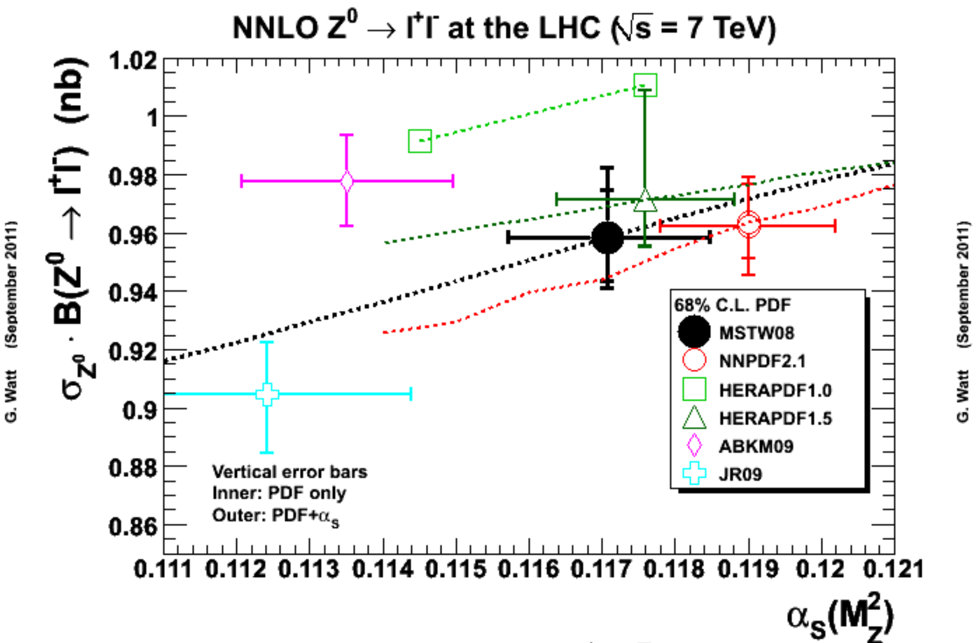
NNLO gg→H at the LHC (√s = 7 TeV) for 120 GeV
σ_H (pb)
α_S(M_Z^2)
68% C.L. PDF
MSTW08
NNPDF2.1
HERAPDF1.0
HERAPDF1.5
ABKM09
JR09
Vertical error bars
Inner: PDF only
Outer: PDF+α_S
G. Watt (September 2011)



gg luminosity at LHC (√s = 7 TeV)
Ratio to MSTW 2008 NNLO (68% C.L.)
MSTW08 NNLO
HERAPDF1.0
HERAPDF1.5
ABKM09
JR09
NNPDF2.1
120 180 240
M_H (GeV)
tt̄
√ŝ / s
G. Watt (September 2011)

- the relatively high upper limit of the HERAPDF1.5 prediction is visible in other SM cross sections

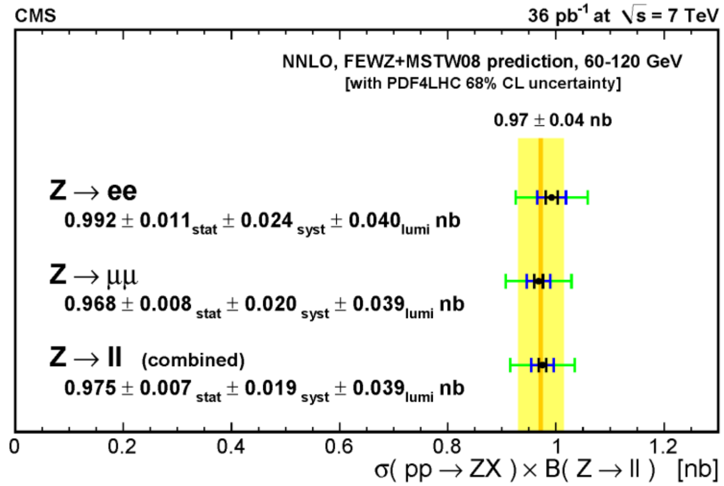


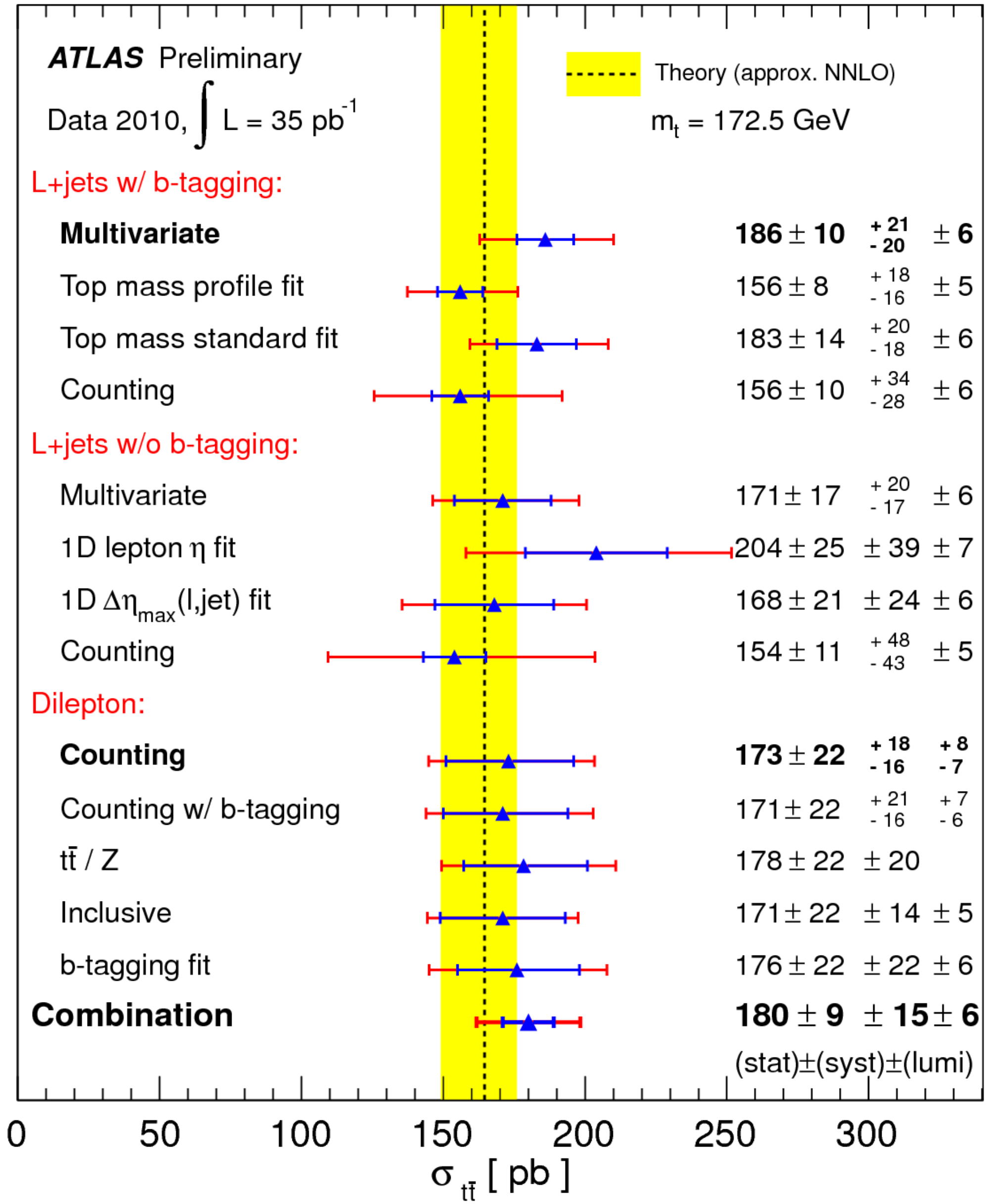


<u>Note</u>:

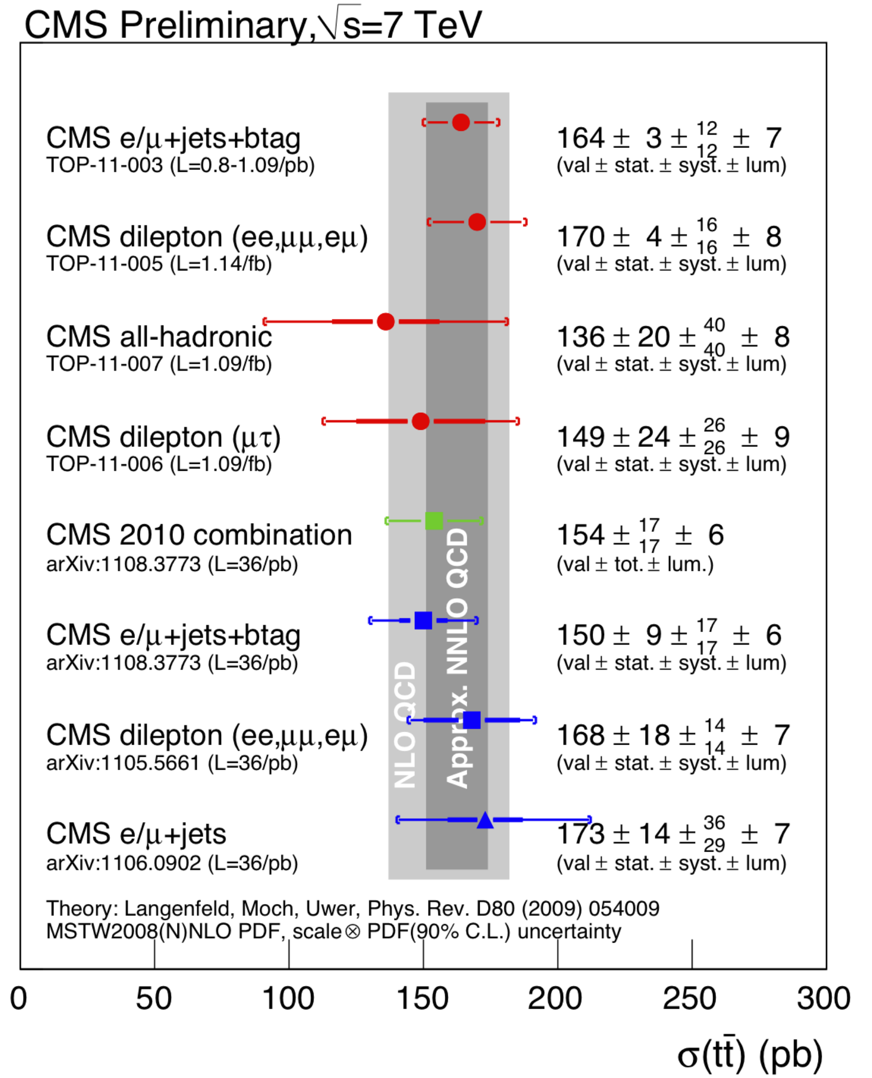
– these are calculated for m_t = 171.3 GeV (PDG2010); the PDG2011 value is 172.9±0.6±0.9 GeV

– $\delta\sigma_{top}$ (pb) $\approx$ -5 δm_{top} (GeV)





ATLAS Preliminary
Data 2010, ∫ L = 35 pb^{-1}
Theory (approx. NNLO)
m_t = 172.5 GeV
L+jets w/ b-tagging:
Multivariate 186 ± 10 +21 -20 ± 6
Top mass profile fit 156 ± 8 +18 -16 ± 5
Top mass standard fit 183 ± 14 +20 -18 ± 6
Counting 156 ± 10 +34 -28 ± 6
L+jets w/o b-tagging:
Multivariate 171 ± 17 +20 -17 ± 6
1D lepton η fit 204 ± 25 ± 39 ± 7
1D $\Delta\eta_{max}$(l,jet) fit 168 ± 21 ± 24 ± 6
Counting 154 ± 11 +48 -43 ± 5
Dilepton:
Counting 173 ± 22 +18 -16 +8 -7
Counting w/ b-tagging 171 ± 22 +21 -16 +7 -6
$t\bar{t}$ / Z 178 ± 22 ± 20
Inclusive 171 ± 22 ± 14 ± 5
b-tagging fit 176 ± 22 ± 22 ± 6
Combination 180 ± 9 ± 15 ± 6
(stat)±(syst)±(lumi)
0 50 100 150 200 250 300
$\sigma_{t\bar{t}}$ [pb]



CMS Preliminary, $\sqrt{s}$=7 TeV
CMS e/μ+jets+btag 164 ± 3 ± $^{12}_{12}$ ± 7
TOP-11-003 (L=0.8-1.09/pb) (val ± stat. ± syst. ± lum)
CMS dilepton (ee,μμ,eμ) 170 ± 4 ± $^{16}_{16}$ ± 8
TOP-11-005 (L=1.14/fb) (val ± stat. ± syst. ± lum)
CMS all-hadronic 136 ± 20 ± $^{40}_{40}$ ± 8
TOP-11-007 (L=1.09/fb) (val ± stat. ± syst. ± lum)
CMS dilepton (μτ) 149 ± 24 ± $^{26}_{26}$ ± 9
TOP-11-006 (L=1.09/fb) (val ± stat. ± syst. ± lum)
CMS 2010 combination 154 ± $^{17}_{17}$ ± 6
arXiv:1108.3773 (L=36/pb) (val ± tot. ± lum.)
CMS e/μ+jets+btag 150 ± 9 ± $^{17}_{17}$ ± 6
arXiv:1108.3773 (L=36/pb) (val ± stat. ± syst. ± lum)
CMS dilepton (ee,μμ,eμ) 168 ± 18 ± $^{14}_{14}$ ± 7
arXiv:1105.5661 (L=36/pb) (val ± stat. ± syst. ± lum)
CMS e/μ+jets 173 ± 14 ± $^{36}_{29}$ ± 7
arXiv:1106.0902 (L=36/pb) (val ± stat. ± syst. ± lum)
NLO QCD
Approx. NNLO QCD
Theory: Langenfeld, Moch, Uwer, Phys. Rev. D80 (2009) 054009
MSTW2008(N)NLO PDF, scale ⊗ PDF(90% C.L.) uncertainty
0 50 100 150 200 250 300
$\sigma(t\bar{t})$ (pb)

from “Handbook of LHC Higgs cross sections: 1. Inclusive observables”

Table 13: Total inclusive cross section at 7 TeV for WH and ZH production at NNLO QCD + NLO EW. The first error indicates the uncertainty from the renormalization and factorization scale variation, the second from the PDF+α_s variation.

M_H [GeV]	σ(WH) [pb]	Scale [%]	PDF4LHC [%]	σ(ZH) [pb]	Scale [%]	PDF4LHC [%]
90	1.640	+0.3 −0.8	±3.0	0.8597	+0.9 −1.0	±3.0
95	1.392	+0.1 −0.9	±3.2	0.7348	+1.0 −1.1	±3.6
100	1.186	+0.6 −0.5	±3.4	0.6313	+1.1 −1.2	±3.4
105	1.018	+0.3 −0.8	±3.5	0.5449	+1.3 −1.6	±3.7
110	0.8754	+0.3 −0.7	±3.8	0.4721	+1.2 −1.2	±4.1
115	0.7546	+0.4 −0.8	±3.9	0.4107	+1.3 −1.2	±4.2
120	0.6561	+0.4 −0.7	±3.4	0.3598	+1.5 −1.2	±3.5
125	0.5729	+0.2 −0.8	±3.5	0.3158	+1.4 −1.6	±3.5
130	0.5008	+0.3 −0.8	±3.5	0.2778	+1.5 −1.4	±3.7
135	0.4390	+0.7 −0.4	±3.4	0.2453	+1.7 −1.4	±3.6
140	0.3857	+0.5 −0.5	±3.5	0.2172	+1.5 −1.6	±3.7
145	0.3406	+0.2 −0.8	±3.8	0.1930	+1.8 −1.8	±4.0
150	0.3001	+0.4 −0.8	±3.3	0.1713	+1.8 −1.6	±3.6
155	0.2646	+0.5 −0.8	±3.5	0.1525	+2.1 −1.6	±3.6
160	0.2291	+0.5 −0.7	±3.8	0.1334	+2.0 −1.7	±4.0
165	0.2107	+0.5 −0.7	±3.6	0.1233	+2.1 −1.7	±4.1
170	0.1883	+0.5 −0.7	±3.8	0.1106	+2.2 −1.9	±4.2
175	0.1689	+0.3 −1.1	±3.8	0.09950	+2.1 −1.9	±4.1
180	0.1521	+0.6 −0.6	±3.5	0.08917	+2.2 −1.9	±3.8
185	0.1387	+0.4 −0.9	±3.5	0.08139	+2.3 −2.0	±3.8
190	0.1253	+0.5 −0.7	±3.7	0.07366	+2.2 −2.1	±3.9
195	0.1138	+0.7 −0.6	±3.7	0.06699	+2.3 −1.9	±4.0
200	0.1032	+0.4 −1.0	±3.8	0.06096	+2.3 −1.9	±4.1
210	0.08557	+0.5 −0.7	±3.7	0.05068	+2.1 −2.0	±4.2
220	0.07142	+0.3 −0.9	±3.7	0.04235	+2.2 −1.9	±4.2
230	0.06006	+0.7 −0.7	±4.5	0.03560	+2.1 −1.9	±4.8
240	0.05075	+0.5 −0.7	±4.0	0.02999	+1.9 −1.8	±4.4
250	0.04308	+0.5 −0.7	±4.0	0.02540	+2.0 −1.6	±4.2
260	0.03674	+0.8 −0.7	±4.0	0.02158	+1.8 −1.7	±4.5
270	0.03146	+0.6 −0.9	±3.8	0.01839	+1.7 −1.7	±4.3
280	0.02700	+0.4 −1.0	±4.4	0.01575	+1.6 −1.3	±4.9
290	0.02333	+0.7 −0.8	±4.2	0.01355	+1.5 −1.3	±4.5
300	0.02018	+0.6 −0.9	±4.5	0.01169	+1.4 −1.2	±5.0

NNLO WH, ZH
7 TeV LHC

±3-4%

correlations between Higgs and other cross sections at 7 TeV LHC

a simple example: $\sigma_{gg\rightarrow H}$ vs. σ_{top}

a more detailed study will appear (this week?) in the second LHC-Higgs working group Yellow Report

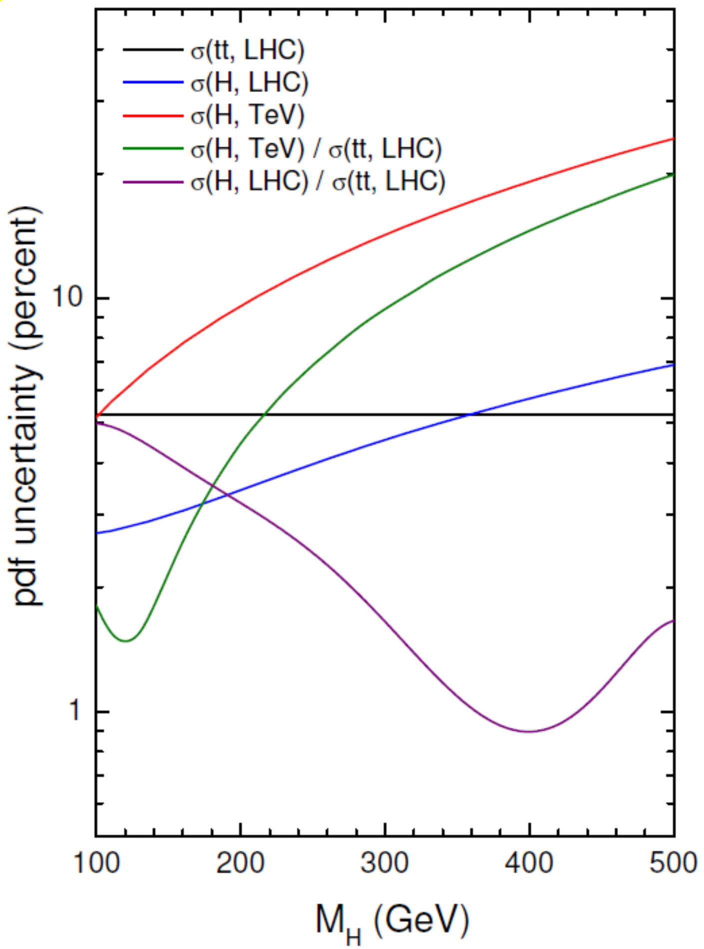
Define the degree of correlation:

$$\rho\,(X,Y) \equiv \cos\varphi = \frac{\sum_i (X_i - X_0)(Y_i - Y_0)}{\sqrt{\sum_i (X_i - X_0)^2 \sum_i (Y_i - Y_0)^2}}.$$

for two (e.g. cross section) quantities X and Y, using a particular PDF set "0" with its uncertainty sets "i":

ρ = 0, +1(-1) for uncorrelated, completely (anti-)correlated quantities

90% cl MSTW2008 pdf uncertainties on NLO top, (gg→) Higgs cross sections at 7 TeV LHC and Tevatron



- sets used: MSTW2008, CT10, GJR08, ABKM09, HERAPDF1.5*, NNPDF2.1*
- four Higgs production mechanisms studied (ggH, VBF, WH, ttH) and many other SM (W, Z, t, b,...) processes
- results presented for the individual PDF sets and for the PDF4LHC average (defined here with CT10, MSTW2008, NNPDF2.1)
- α_S variation can be omitted or included (small changes in most cases)

* requires modified definition of ρ because of the way that the uncertainties are defined for these sets

PDF4LHC average correlations Higgs *vs.* Higgs and Higgs *vs.* other SM

strong correlation:

tt *vs*. ggH_{heavy}, ttH_{light}

WZ *vs.* WH

tb vs. WH_{light}

- same PDFs, similar x

weak correlation:

ttH *vs.* WH

- different PDFs, different x -0.2

anticorrelation:

W, Wγ *vs.* ttH

- hi/lo x

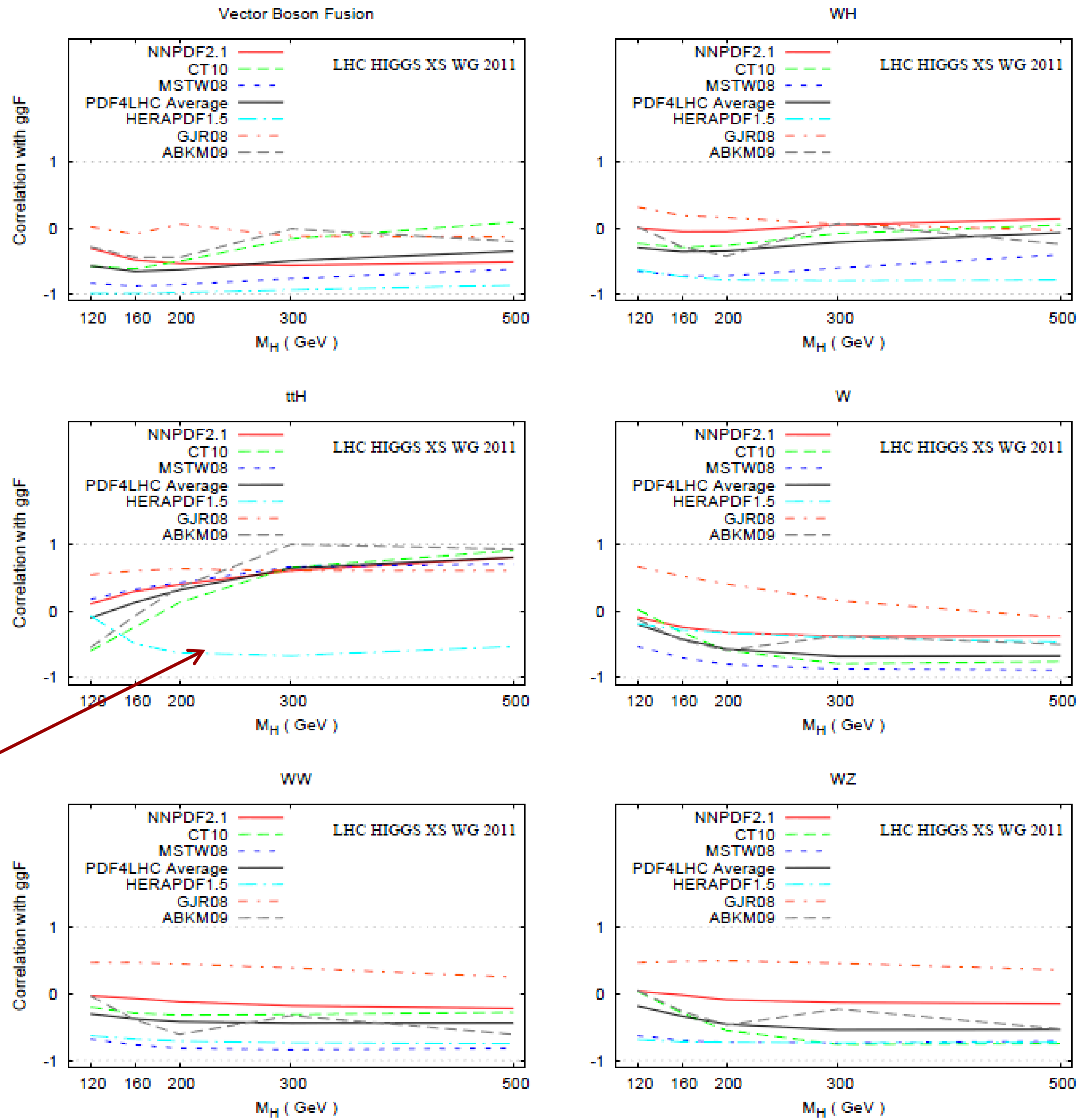
120 GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	-0.6	-0.2	-0.2
VBF	-0.6	1	0.6	-0.4
WH	-0.2	0.6	1	-0.2
$t\bar{t}H$	-0.2	-0.4	-0.2	1
W	-0.2	0.6	0.8	-0.6
WW	-0.4	0.8	1	-0.2
WZ	-0.2	0.4	0.8	-0.4
$W\gamma$	0	0.6	0.8	-0.6
$Wb\bar{b}$	-0.2	0.6	1	-0.2
$t\bar{t}$	0.2	-0.4	-0.4	1
$t\bar{b}$	-0.4	0.6	1	-0.2
$t(\to\bar{b})q$	0.4	0	0	0

160 GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	-0.6	-0.4	0.2
VBF	-0.6	1	0.6	-0.2
WH	-0.4	0.6	1	0
$t\bar{t}H$	0.2	-0.2	0	1
W	-0.4	0.4	0.6	-0.4
WW	-0.4	0.6	0.8	-0.2
WZ	-0.4	0.4	0.8	-0.2
$W\gamma$	-0.4	0.6	0.6	-0.6
$Wb\bar{b}$	-0.2	0.6	0.8	-0.2
$t\bar{t}$	0.4	-0.4	-0.2	0.8
$t\bar{b}$	-0.4	0.6	1	0
$t(\to\bar{b})q$	0.6	0	0	0

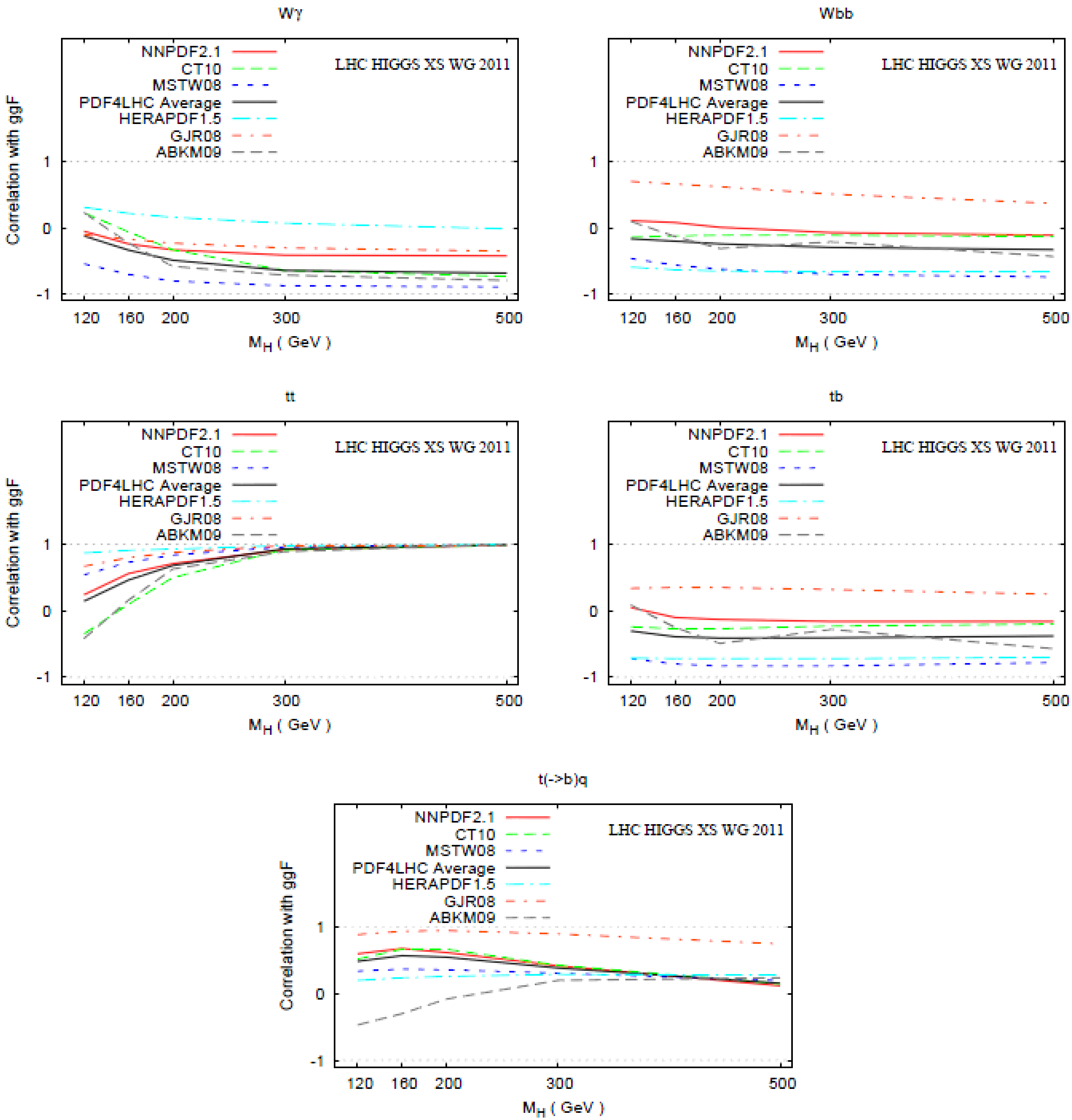
200 GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	-0.6	-0.4	0.4
VBF	-0.6	1	0.6	-0.2
WH	-0.4	0.6	1	0
$t\bar{t}H$	0.4	-0.2	0	1
W	-0.6	0.4	0.6	-0.4
WW	-0.4	0.6	0.8	-0.2
WZ	-0.4	0.4	0.8	-0.2
$W\gamma$	-0.4	0.4	0.6	-0.6
$Wb\bar{b}$	-0.2	0.6	0.8	-0.2
$t\bar{t}$	0.6	-0.4	-0.2	0.8
$t\bar{b}$	-0.4	0.6	0.8	0
$t(\to\bar{b})q$	0.6	-0.2	0	0

300 GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	-0.4	-0.2	0.6
VBF	-0.4	1	0.4	-0.2
WH	-0.2	0.4	1	0.2
$t\bar{t}H$	0.6	-0.2	0.2	1
W	-0.6	0.4	0.4	-0.6
WW	-0.4	0.6	0.8	-0.2
WZ	-0.6	0.4	0.6	-0.4
$W\gamma$	-0.6	0.4	0.4	-0.6
$Wb\bar{b}$	-0.2	0.4	0.8	-0.2
$t\bar{t}$	1	-0.4	0	0.8
$t\bar{b}$	-0.4	0.4	0.8	-0.2
$t(\to\bar{b})q$	0.4	-0.2	0	-0.2

500 GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	-0.4	0	0.8
VBF	-0.4	1	0.4	-0.2
WH	0	0.4	1	0
$t\bar{t}H$	0.8	-0.2	0	1
W	-0.6	0.4	0.2	-0.6
WW	-0.4	0.6	0.6	-0.4
WZ	-0.6	0.4	0.6	-0.4
$W\gamma$	-0.6	0.4	0.2	-0.6
$Wb\bar{b}$	-0.4	0.4	0.6	-0.4
$t\bar{t}$	1	-0.4	0	0.8
$t\bar{b}$	-0.4	0.4	0.8	-0.2
$t(\to\bar{b})q$	0.2	-0.2	0	-0.2

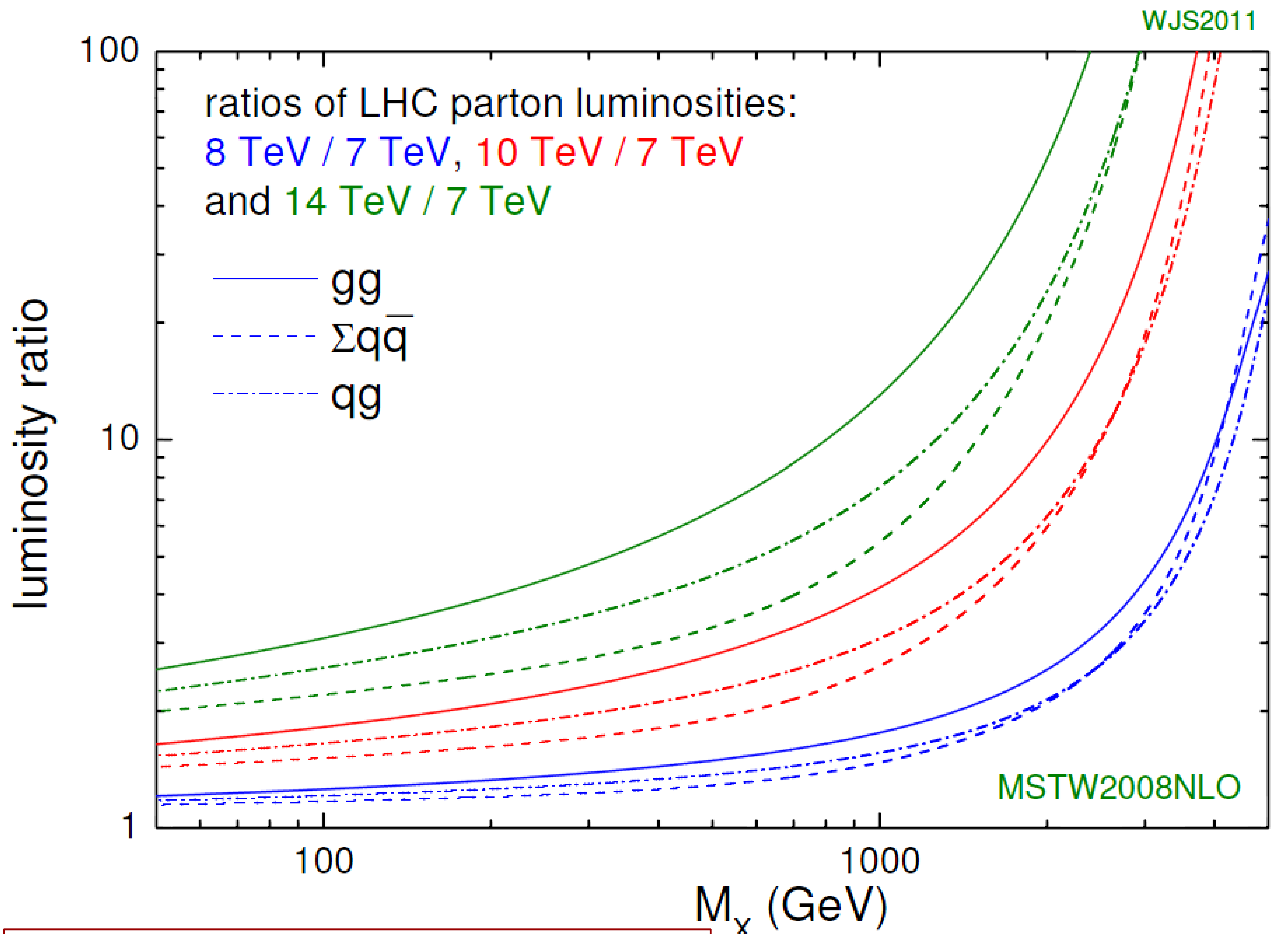

Vector Boson Fusion
WH
ttH
W
WW
WZ
NNPDF2.1
CT10
MSTW08
PDF4LHC Average
HERAPDF1.5
GJR08
ABKM09
LHC HIGGS XS WG 2011
Correlation with ggF
M_H (GeV)
120 160 200 300 500
1 0 -1

Note!

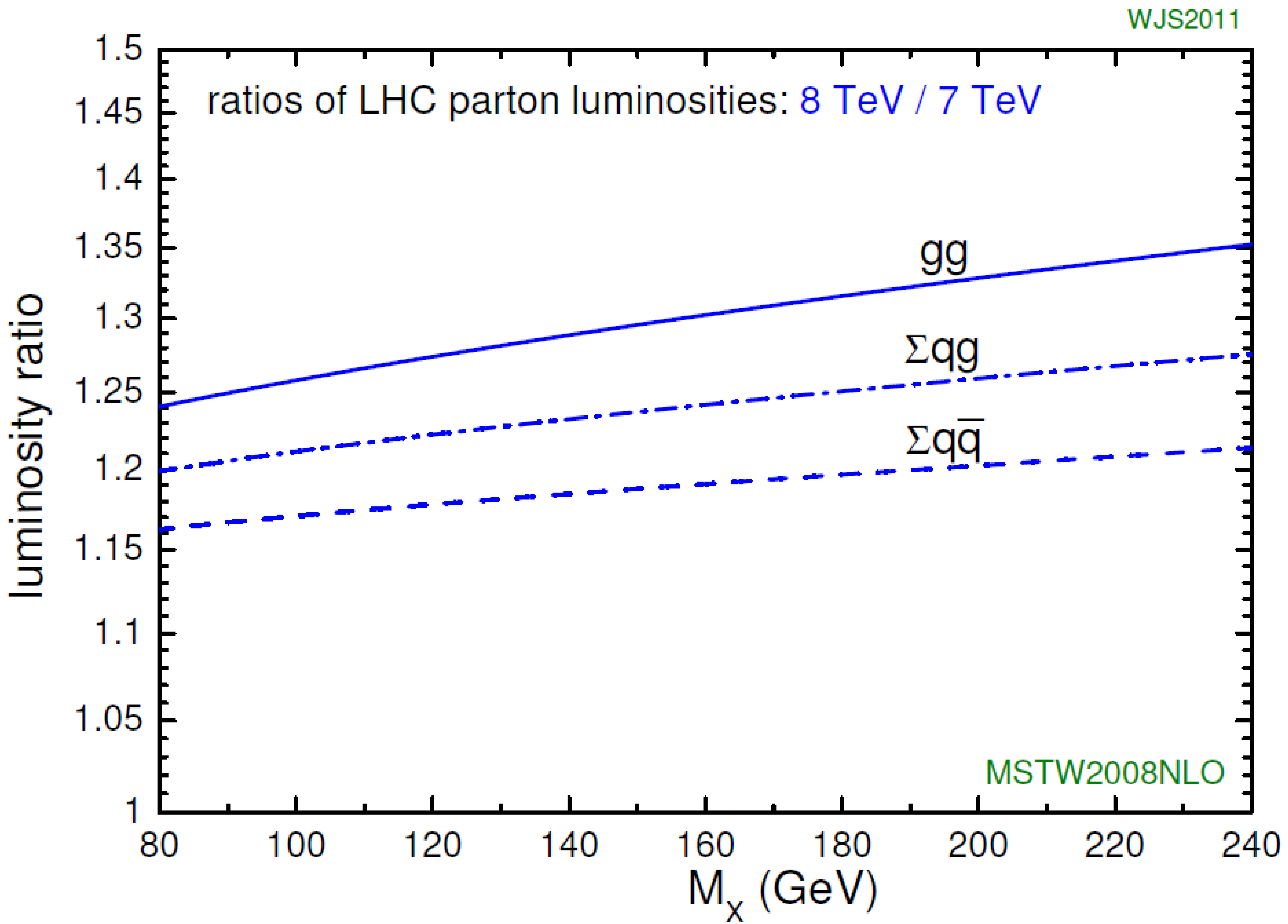

Wγ
Wbb
tt
tb
t(->b)q
NNPDF2.1
CT10
MSTW08
PDF4LHC Average
HERAPDF1.5
GJR08
ABKM09
LHC HIGGS XS WG 2011
Correlation with ggF
1
0
-1
120
160
200
300
500
M_H (GeV)

summary

- knowledge of PDFs continues to improve
- the 'global fit' sets (MSTW, CT, NNPDF) are becoming more similar; origin of residual differences largely understood
- sets fitted without Tevatron jets (HERAPDF, GJR, ABKM) tend to give smaller high-x gluons → visible differences in LHC cross section predictions (e.g. top)
- *PDF4LHC Workshops have provided an extremely valuable forum for understanding and comparing PDFs*
- PDF dependence of 7 TeV LHC cross sections and correlations has been studied; fitting to LHC data has already begun
- for $gg \to H$ with $M_H \sim 125$ GeV, combined PDF+α_S uncertainty is ~ ±7%; uncertainty increases with M_H and is similar for NLO and NNLO
- for $q\bar{q} \to WH, ZH$ with $M_H \sim 125$ GeV, combined PDF+α_S uncertainty is ~ ±3.5%, slightly anticorrelated with $gg \to H$ ($\rho = -0.2$)



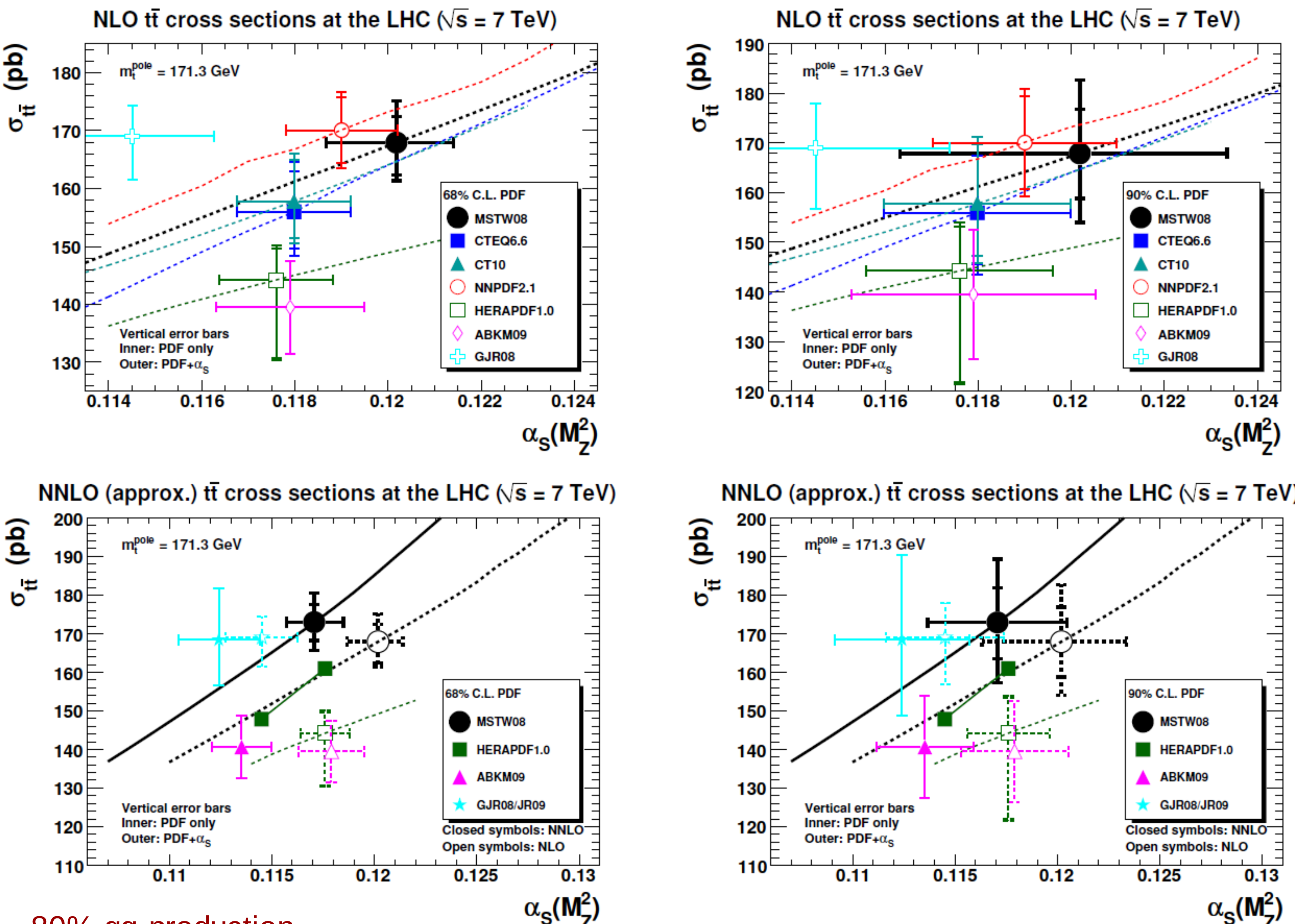
$r_{gg}(8/7) = 1.28$ for $M_X = 125$ GeV, cf. $r_Z(8/7) = 1.17$


WJS2011
ratios of LHC parton luminosities: 8 TeV / 7 TeV
gg
Σqg
Σq$\bar{q}$
MSTW2008NLO
luminosity ratio
M_X (GeV)
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
80
100
120
140
160
180
200
220
240

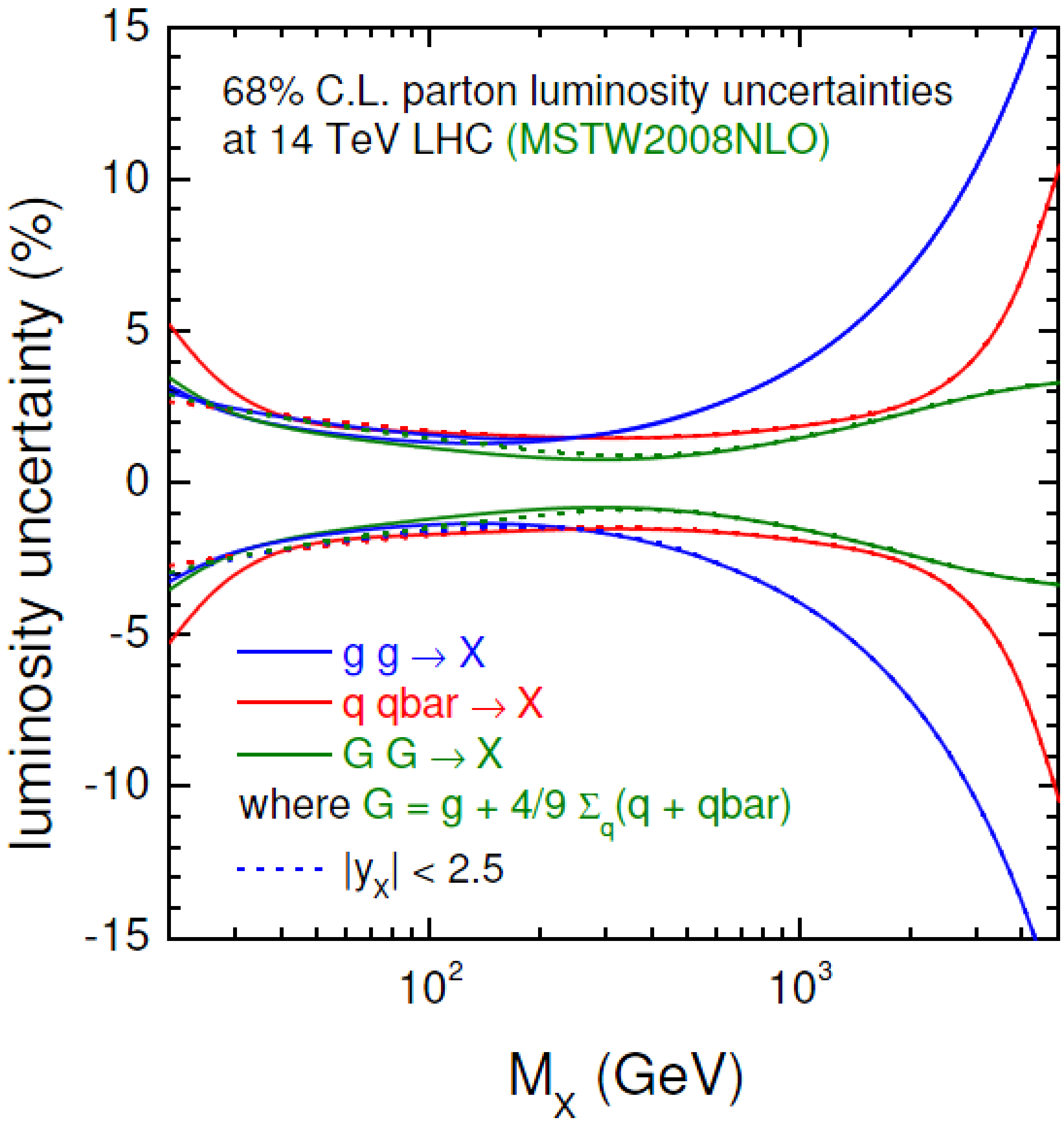
extra slides

7 TeV LHC top cross section predictions

plots from G. Watt



Note: ~80% gg production


68% C.L. parton luminosity uncertainties
at 14 TeV LHC (MSTW2008NLO)
g g → X
q qbar → X
G G → X
where G = g + 4/9 Σq(q + qbar)
|yX| < 2.5
luminosity uncertainty (%)
MX (GeV)
15
10
5
0
-5
-10
-15
10^2
10^3

Total top-pair production cross-section

$\sigma_{t\bar{t}}$(pb)	Tevatron	LHC7	LHC10	LHC14
NLO	$6.50^{+0.32+0.33}_{-0.70-0.24}$	150^{+18+8}_{-19-8}	380^{+44+17}_{-46-17}	842^{+97+30}_{-97-32}
NLO+NLL	$6.57^{+0.52+0.33}_{-0.30-0.24}$	151^{+23+8}_{-12-9}	382^{+60+17}_{-32-18}	$848^{+136+30}_{-75-32}$
NLO+NNLL	$6.77^{+0.27+0.35}_{-0.48-0.25}$	155^{+4+8}_{-9-9}	390^{+14+17}_{-26-18}	858^{+35+31}_{-64-33}
NNLO$_{\text{app}}(\beta)$	$7.10^{+0.0+0.36}_{-0.26,-0.26}$	162^{+2+9}_{-3-9}	407^{+9+17}_{-5-18}	895^{+24+31}_{-6-33}
NNLO$_{\text{app}}(\beta)$ + NNLL	$7.13^{+0.22+0.36}_{-0.24-0.26}$	162^{+4+9}_{-1-9}	405^{+14+17}_{-2-18}	892^{+38+31}_{-3-33}
NNLO$_{\text{app}}(\beta)$ + NNLL+BS	$7.14^{+0.14+0.36}_{-0.22-0.26}$	162^{+4+9}_{-1-9}	407^{+14+17}_{-2-18}	896^{+38+31}_{-3-33}

($m_t = 173.1$ GeV, $\tilde{\mu}_f = mt$, MSTW08NNLO) (Beneke, Falgari, Klein, CS preliminary)

- Resummation in momentum space using fixed μ_s from minimising $\Delta\sigma^{\text{NLO}}_{\text{soft}}(\mu_s)$
  $\Rightarrow \tilde{\mu}_s = 85/146$ GeV for Tevatron/LHC7: no big scale hierarchy
- vary μ_s, μ_h, μ_f from $0.5\tilde{\mu} < \mu < 2\tilde{\mu}$, add uncertainties in quadrature
- (N)NLL includes (N)LO Coulomb resummation
- BS: include bound-state contributions below threshold
- Preliminary estimate of uncertainty from $\alpha_s^2 C^{(2)}$ terms: $\sim 3\%$

benchmark NLO top cross sections at 7 TeV LHC

	σ (pb)	$\delta\sigma$ (pb)	comment
ABKM09	139.55	7.96	combined PDF and α_s
CTEQ6.6	156.2	8.06	combined PDF and α_s *
GJR08	169	6	PDF only
HERAPDF1.0	147.31	+5.18 -13.76	combined PDF and α_s**
MSTW08	168.1	+7.2-6.0	combined PDF and α_s***
NNPDF2.0	169	7	combined PDF and α_s ****

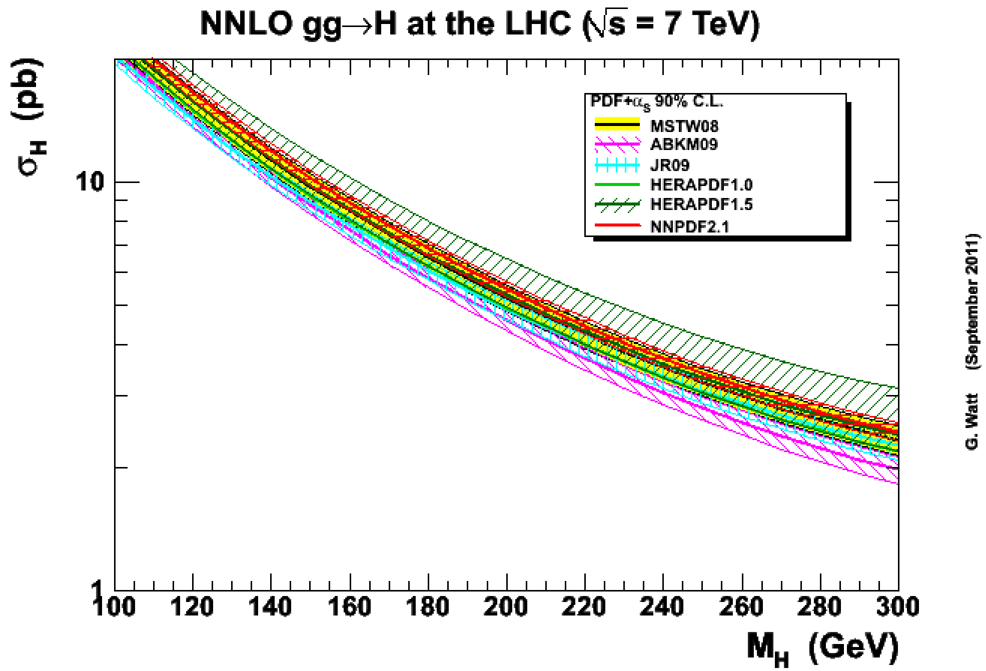
m_{top}= 171.3 GeV*
zero width approximation,
no branching ratios
68% cl uncertainties
scales $\mu_F = \mu_R = m_{top}$

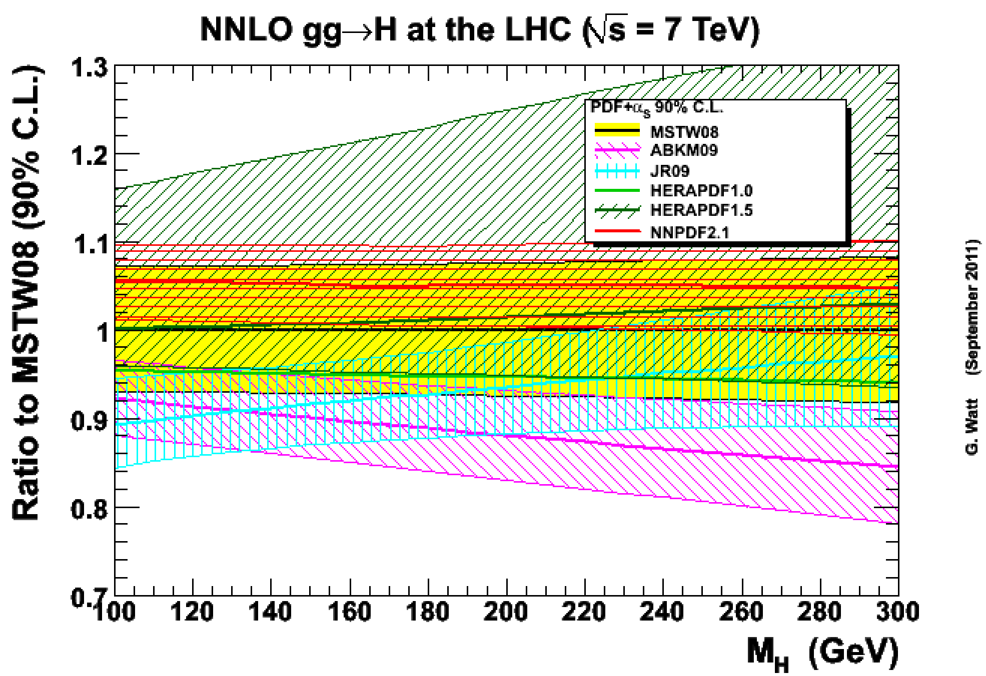
* ±6.63 (PDF) ±4.59 (α_s)
** expt.+model+param.+α_s , see report for details
*** +4.7-5.6 (PDF) +3.8-4.6 (α_s)
**** ±6 (PDF) ±4 (α_s)

Note: $\delta\sigma_{top}$ (pb) $\approx$ -5 δm_{top} (GeV)

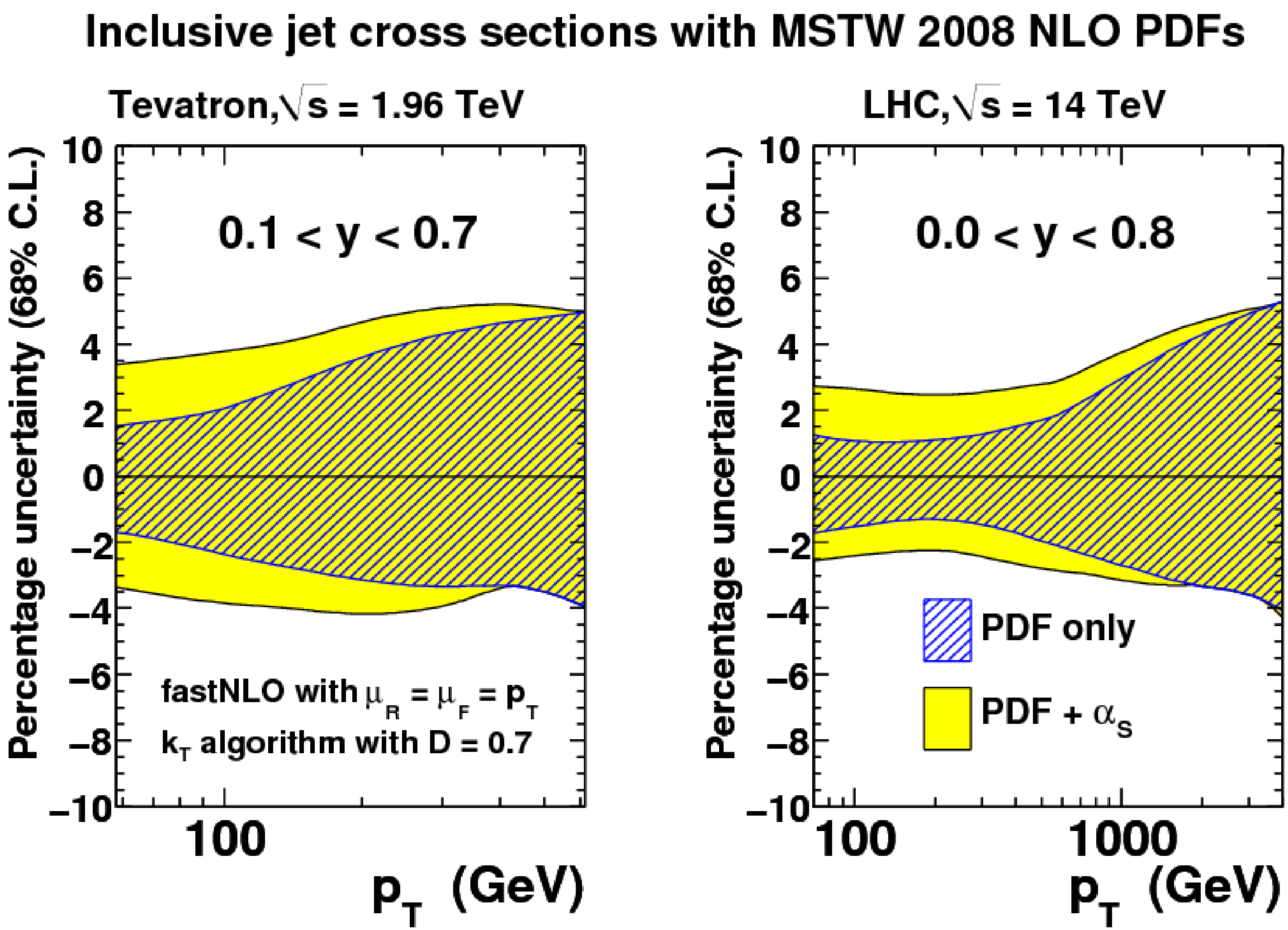
*PDG2011 value is 172.9±0.6±0.9 GeV

PDF4LHC Working Group Interim Report, arXiv:1101.0536 (January 2011)


NNLO gg→H at the LHC (√s = 7 TeV)
σ_H (pb)
M_H (GeV)
PDF+α_s 90% C.L.
MSTW08
ABKM09
JR09
HERAPDF1.0
HERAPDF1.5
NNPDF2.1
G. Watt (September 2011)


NNLO gg→H at the LHC (√s = 7 TeV)
Ratio to MSTW08 (90% C.L.)
M_H (GeV)
PDF+α_s 90% C.L.
MSTW08
ABKM09
JR09
HERAPDF1.0
HERAPDF1.5
NNPDF2.1
G. Watt (September 2011)

PDF + α_S uncertainties in jet cross sections



A benchmarking exercise was carried out to which all PDF groups were invited to participate. This exercise considered only the-then most up to date published versions/most commonly used of NLO PDFs from 6 groups: ABKM09 [2], [3], CTEQ6.6 [4], GJR08 [7], HERAPDF1.0 [8], MSTW08 [9], NNPDF2.0 [10]. The benchmark cross sections were evaluated at NLO at both 7 and 14 TeV. We report here primarily on the 7 TeV results.

All of the benchmark processes were to be calculated with the following settings:

1. at NLO in the $\overline{MS}$ scheme
2. all calculation done in a the 5-flavor quark ZM-VFNS scheme, though each group uses a different treatment of heavy quarks
3. at a center-of-mass energy of 7 TeV
4. for the central value predictions, and for $\pm 68\%$ and $\pm 90\%$ c.l. PDF uncertainties
5. with and without the α_s uncertainties, with the prescription for combining the PDF and α_s errors to be specified
6. repeating the calculation with a central value of $\alpha_s(m_Z)$ of 0.119.

To provide some standardization, a gzipped version of MCFM5.7 [25] was prepared by John Campbell, using the specified parameters and exact input files for each process. It was allowable for other codes to be used, but they had to be checked against the MCFM output values.

includes ttbar total production cross section with:

m_{top}= 171.3 GeV

zero width approximation, no branching ratios

scales $\mu_F = \mu_R = m_{top}$

data sets used in MSTW fit

Data set	$N_{\text{pts.}}$
H1 MB 99 e^+p NC	8
H1 MB 97 e^+p NC	64
H1 low Q^2 96–97 e^+p NC	80
H1 high Q^2 98–99 e^-p NC	126
H1 high Q^2 99–00 e^+p NC	147
ZEUS SVX 95 e^+p NC	30
ZEUS 96–97 e^+p NC	144
ZEUS 98–99 e^-p NC	92
ZEUS 99–00 e^+p NC	90
H1 99–00 e^+p CC	28
ZEUS 99–00 e^+p CC	30
H1/ZEUS $e^{\pm}p$ F_2^{charm}	83
H1 99–00 e^+p incl. jets	24
ZEUS 96–97 e^+p incl. jets	30
ZEUS 98–00 $e^{\pm}p$ incl. jets	30
DØ II $p\bar{p}$ incl. jets	110
CDF II $p\bar{p}$ incl. jets	76
CDF II $W \to l\nu$ asym.	22
DØ II $W \to l\nu$ asym.	10
DØ II Z rap.	28
CDF II Z rap.	29

Data set	$N_{\text{pts.}}$
BCDMS μp F_2	163
BCDMS μd F_2	151
NMC μp F_2	123
NMC μd F_2	123
NMC $\mu n/\mu p$	148
E665 μp F_2	53
E665 μd F_2	53
SLAC ep F_2	37
SLAC ed F_2	38
NMC/BCDMS/SLAC F_L	31
E866/NuSea pp DY	184
E866/NuSea pd/pp DY	15
NuTeV νN F_2	53
CHORUS νN F_2	42
NuTeV νN xF_3	45
CHORUS νN xF_3	33
CCFR $\nu N \to \mu\mu X$	86
NuTeV $\nu N \to \mu\mu X$	84
All data sets	**2743**

- Red = New w.r.t. MRST 2006 fit.

MSTW input parametrisation

At input scale $Q_0^2 = 1\ \mathrm{GeV}^2$:

$$xu_v = A_u\, x^{\eta_1}(1-x)^{\eta_2}(1+\epsilon_u\sqrt{x}+\gamma_u\, x)$$
$$xd_v = A_d\, x^{\eta_3}(1-x)^{\eta_4}(1+\epsilon_d\sqrt{x}+\gamma_d\, x)$$
$$xS = A_S\, x^{\delta_S}(1-x)^{\eta_S}(1+\epsilon_S\sqrt{x}+\gamma_S\, x)$$
$$x\bar{d} - x\bar{u} = A_\Delta\, x^{\eta_\Delta}(1-x)^{\eta_S+2}(1+\gamma_\Delta\, x+\delta_\Delta\, x^2)$$
$$xg = A_g\, x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g\, x) + A_{g'}\, x^{\delta_{g'}}(1-x)^{\eta_{g'}}$$
$$xs + x\bar{s} = A_+\, x^{\delta_S}(1-x)^{\eta_+}(1+\epsilon_S\sqrt{x}+\gamma_S\, x)$$
$$xs - x\bar{s} = A_-\, x^{\delta_-}(1-x)^{\eta_-}(1-x/x_0)$$

Note: 20 parameters allowed to go free for eigenvector PDF sets, *cf.* 15 for MRST sets

which data sets determine which partons?

Process	Subprocess	Partons	x range
$\ell^\pm \{p,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu}) N \to \mu^-(\mu^+) X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \to e^\pm X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu} X$	$W^+ \{d, s\} \to \{u, c\}$	d, s	$x \gtrsim 0.01$
$e^\pm p \to e^\pm c\bar{c} X$	$\gamma^* c \to c,\ \gamma^* g \to c\bar{c}$	$c,\ g$	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^\pm \to \ell^\pm \nu) X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-) X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

LO *vs* NLO *vs* NNLO?

in the MSTW 2008 fit

χ^2_{global} /dof = 3066/2598 (LO)
2543/2699 (NLO)
2480/2615 (NNLO)

LO evolution too slow at small x;
NNLO fit marginally better than NLO

Note:
- an important ingredient missing in the full NNLO global PDF fit is the NNLO correction to the Tevatron high E_T jet cross section
- LO can be improved (e.g. LO*) for MCs by adding K-factors, relaxing momentum conservation, etc.