Parton Distributions
and
Heavy Quark Production at the LHC

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- introduction and overview
- PDFs
- LHC benchmarks
- summary

(with thanks to Graeme Watt for many of the plots)

Heavy Particles at the LHC, ETH Zürich, January 2011

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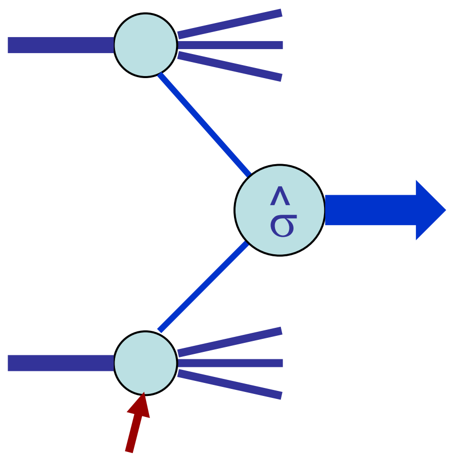
introduction and overview

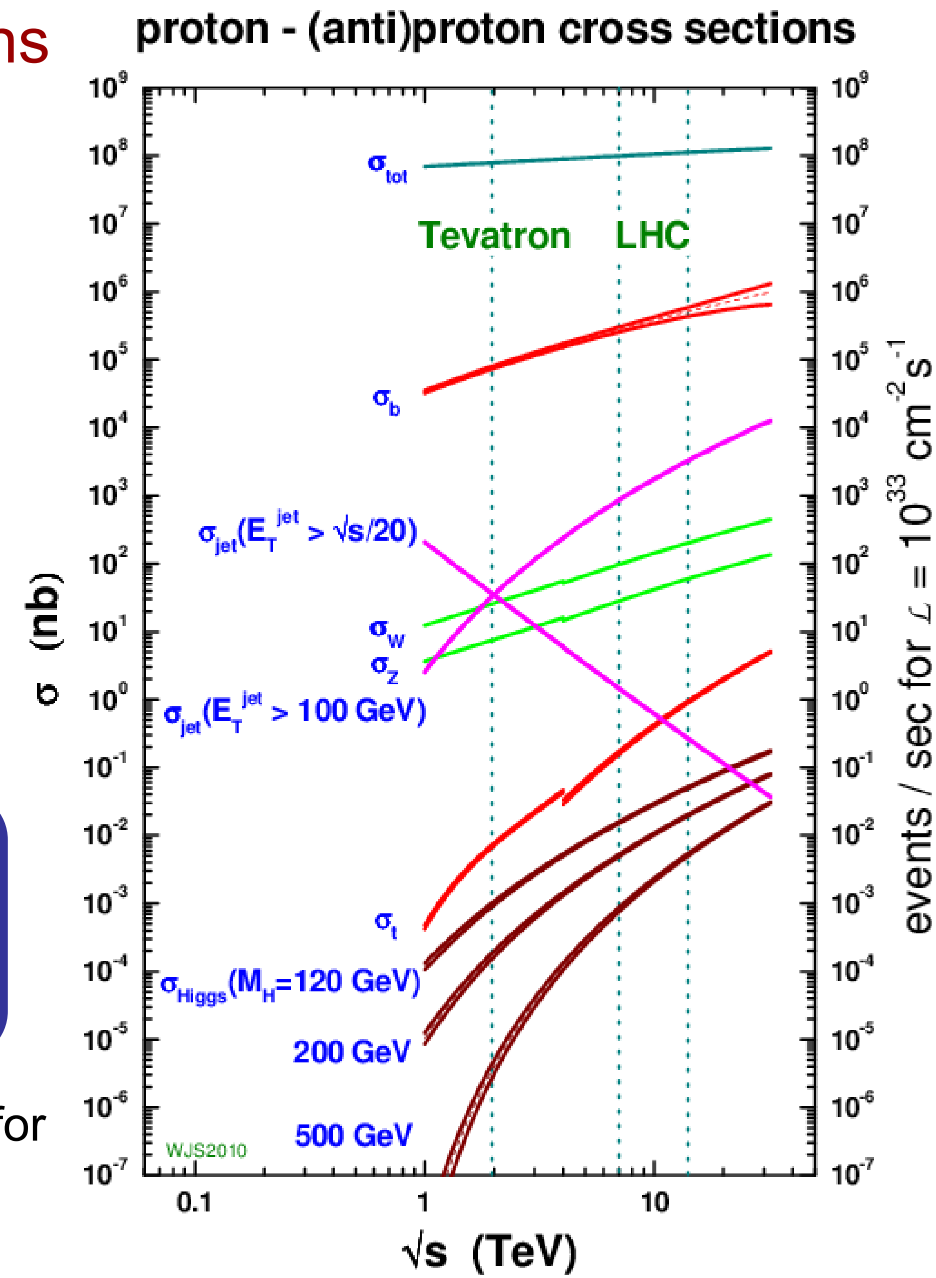
hard scattering formalism for hadron collider cross sections



parton distribution functions

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)$$
$$\times\ \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

... this is the QCD **factorization theorem** for hard-scattering (short-distance) inclusive processes, e.g. *W*,*t*,*H*, ... production



precision phenomenology at LHC

- *Benchmarking*
  - inclusive SM quantities (V, jets, top,…), calculated to the highest precision available (e.g. NNLO, NNLL, etc)
  - tools needed: robust jet algorithms, kinematics, decays included, PDFs, …
  - theory uncertainty in predictions:

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

what do these mean?!

- *Backgrounds*
  - new physics generally results in some combination of multijets, multileptons, missing E_T
  - therefore, we need to know SM cross sections {V,VV,bb,tt,H,…} + jets to high precision → `wish lists'
  - ratios can be useful

Note: $V = \gamma^*, Z, W^\pm$

top quark production at hadron colliders

$$\hat{\sigma}^{q\bar{q}\to Q\bar{Q}} = \frac{\pi\alpha_S^2\beta\rho}{27M_Q^2}(2+\rho)$$

$$\hat{\sigma}^{gg\to Q\bar{Q}} = \frac{\pi\alpha_S^2\beta\rho}{192M_Q^2}[\frac{1}{\beta}(\rho^2+16\rho+16)\log\frac{1+\beta}{1-\beta}-28-31\rho],$$

where $\rho = 4M_Q^2/\hat{s}$, $\beta = \sqrt{1-\rho}$.

NLO known, but awaits full NNLO pQCD calculation (see talks by Czakon and Ferroglia); NNLO & N^nLL "soft+virtual" fixed order and resummed approximations exist, see for example talks by

Neubert (based on Ahrens, Ferroglia, Neubert, Pecjak, Yang, arXiv:1003.5827 etc.)

Schwinn (based on Beneke, Falgari, Schwinn, arXiv:1007.5414 etc.)

and by Pozzorini, Papadopoulos and Melnikov (NLO QCD corrections to production and decay, importance of selection cuts, spin correlations etc.)

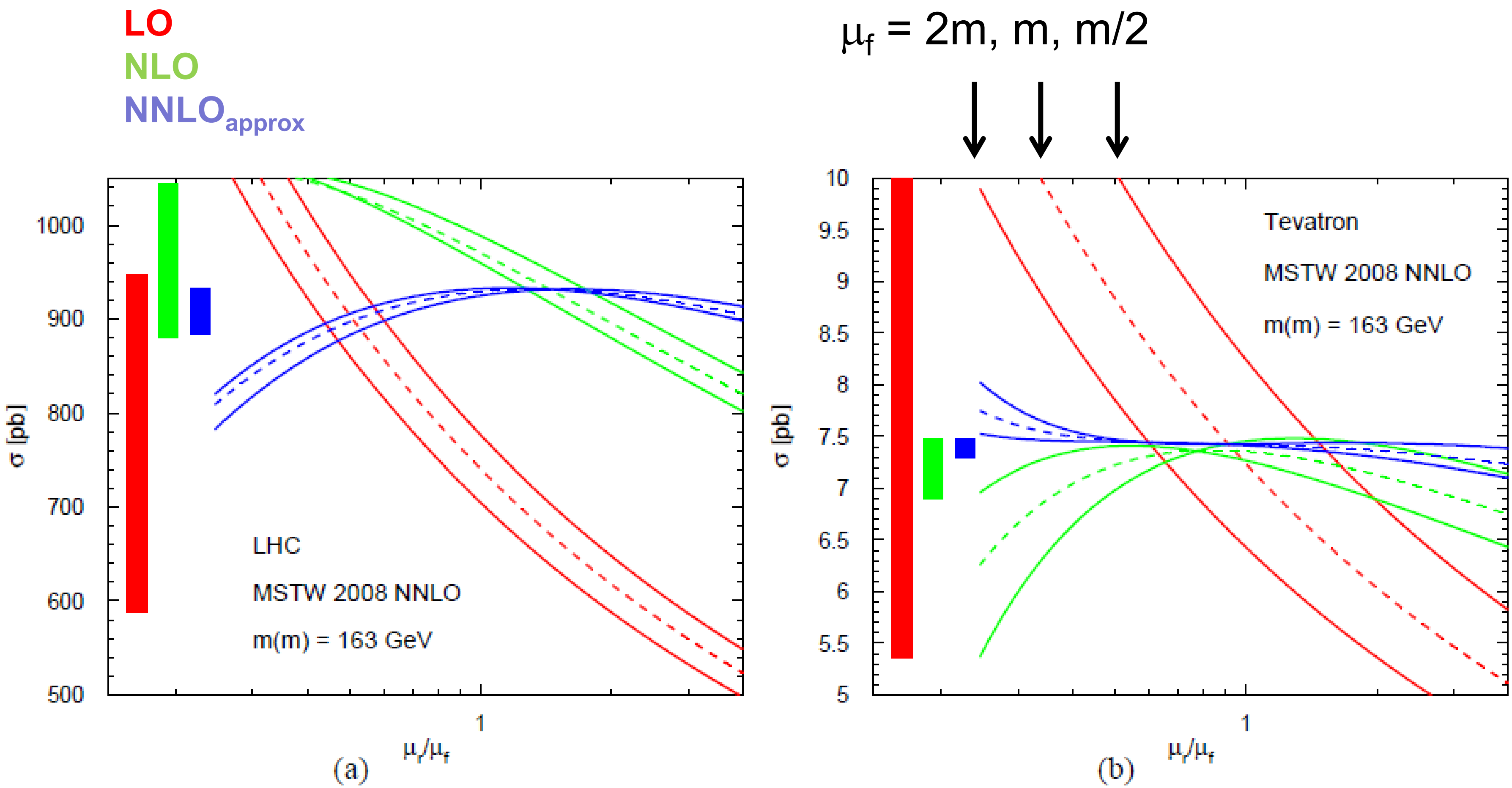
also

$\text{NNLO}_{\text{approx}}$: Moch & Uwer; Langenfeld, Moch & Uwer (threshold enhancement due to soft gluons, Coulomb corrections, scale dependencies, MSbar mass, ...) arXiv:0906.5273 etc.

$\text{NNLO}_{\text{approx}}$: Kidonakis & Vogt (soft gluon contributions inc. kinematics-dependent soft anomalous dimension matrices, …) arXiv:0805.3844

NLL: Cacciari, Frixione, Mangano, Nason, Ridolfi (NLO + resummed next-to-leading threshold logarithms) arXiv:0804.2800

...



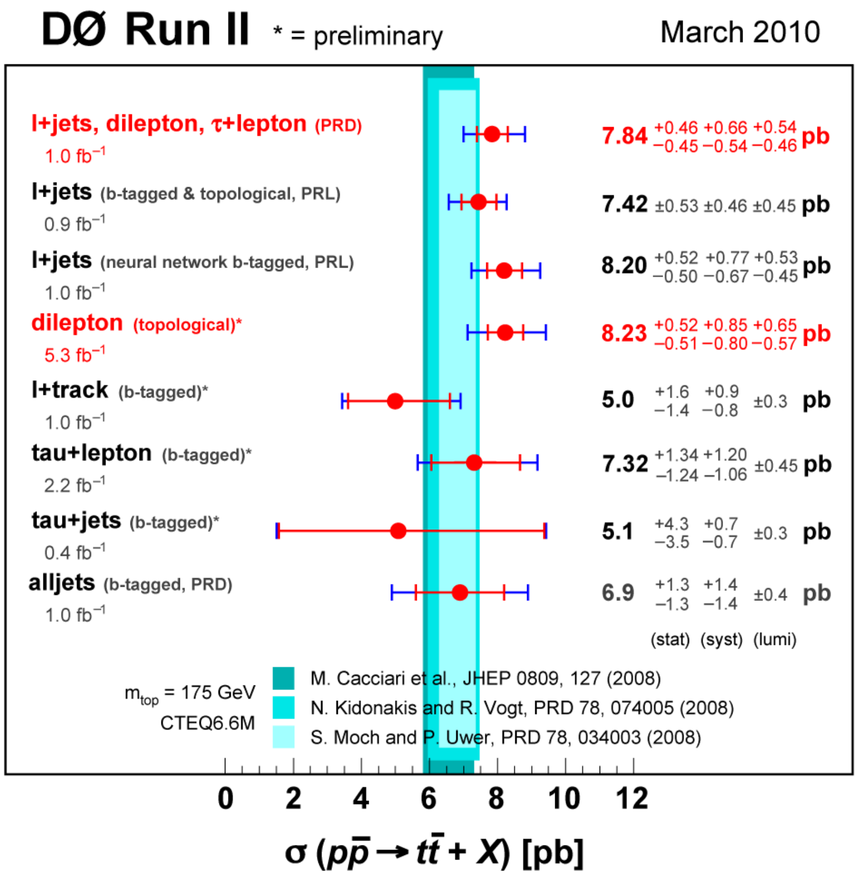
Langenfeld, Moch, Uwer, arXiv:0906.5273

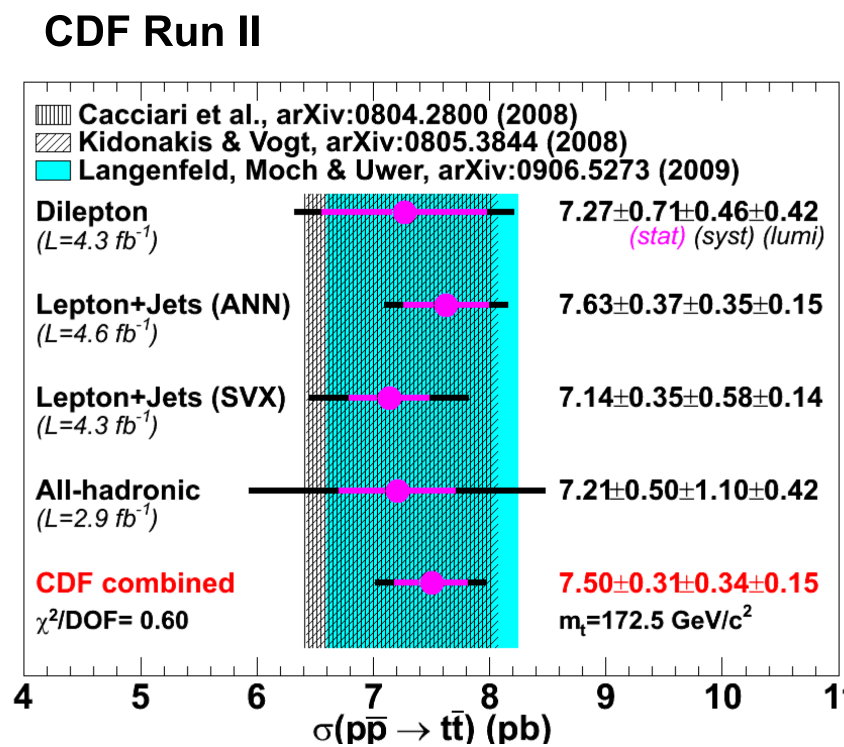
Total top-pair production cross-section

$\sigma_{t\bar{t}}$(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$_{\rm app}(\beta)$	$7.10^{+0.0+0.36}_{-0.26,-0.26}$	162^{+2+9}_{-3-9}	407^{+9+17}_{-5-18}	895^{+24+31}_{-6-33}
NNLO$_{\rm app}(\beta)$ + 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$_{\rm app}(\beta)$ + 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 $\Delta\sigma^{\rm NLO}_{\rm soft}(\mu_s)$
  $\Rightarrow \tilde{\mu}_s = 85/146$ 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: $\sim 3\%$

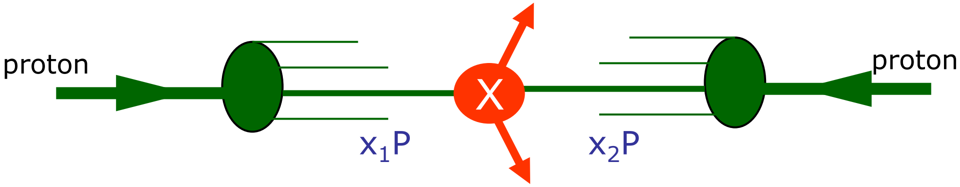

DØ Run II
* = preliminary
March 2010
l+jets, dilepton, τ+lepton (PRD)
1.0 fb⁻¹
7.84 +0.46 −0.45 +0.66 −0.54 +0.54 −0.46 pb
l+jets (b-tagged & topological, PRL)
0.9 fb⁻¹
7.42 ±0.53 ±0.46 ±0.45 pb
l+jets (neural network b-tagged, PRL)
1.0 fb⁻¹
8.20 +0.52 −0.50 +0.77 −0.67 +0.53 −0.45 pb
dilepton (topological)*
5.3 fb⁻¹
8.23 +0.52 −0.51 +0.85 −0.80 +0.65 −0.57 pb
l+track (b-tagged)*
1.0 fb⁻¹
5.0 +1.6 −1.4 +0.9 −0.8 ±0.3 pb
tau+lepton (b-tagged)*
2.2 fb⁻¹
7.32 +1.34 −1.24 +1.20 −1.06 ±0.45 pb
tau+jets (b-tagged)*
0.4 fb⁻¹
5.1 +4.3 −3.5 +0.7 −0.7 ±0.3 pb
alljets (b-tagged, PRD)
1.0 fb⁻¹
6.9 +1.3 −1.3 +1.4 −1.4 ±0.4 pb
(stat) (syst) (lumi)
m_top = 175 GeV
CTEQ6.6M
M. Cacciari et al., JHEP 0809, 127 (2008)
N. Kidonakis and R. Vogt, PRD 78, 074005 (2008)
S. Moch and P. Uwer, PRD 78, 034003 (2008)
0 2 4 6 8 10 12
σ (pp̄ → tt̄ + X) [pb]


CDF Run II
Cacciari et al., arXiv:0804.2800 (2008)
Kidonakis & Vogt, arXiv:0805.3844 (2008)
Langenfeld, Moch & Uwer, arXiv:0906.5273 (2009)
Dilepton
(L=4.3 fb⁻¹)
7.27±0.71±0.46±0.42
(stat) (syst) (lumi)
Lepton+Jets (ANN)
(L=4.6 fb⁻¹)
7.63±0.37±0.35±0.15
Lepton+Jets (SVX)
(L=4.3 fb⁻¹)
7.14±0.35±0.58±0.14
All-hadronic
(L=2.9 fb⁻¹)
7.21±0.50±1.10±0.42
CDF combined
χ²/DOF= 0.60
7.50±0.31±0.34±0.15
m_t=172.5 GeV/c²
4 5 6 7 8 9 10 11
σ(pp̄ → tt̄) (pb)

2

parton distribution functions

Parton Distribution Functions

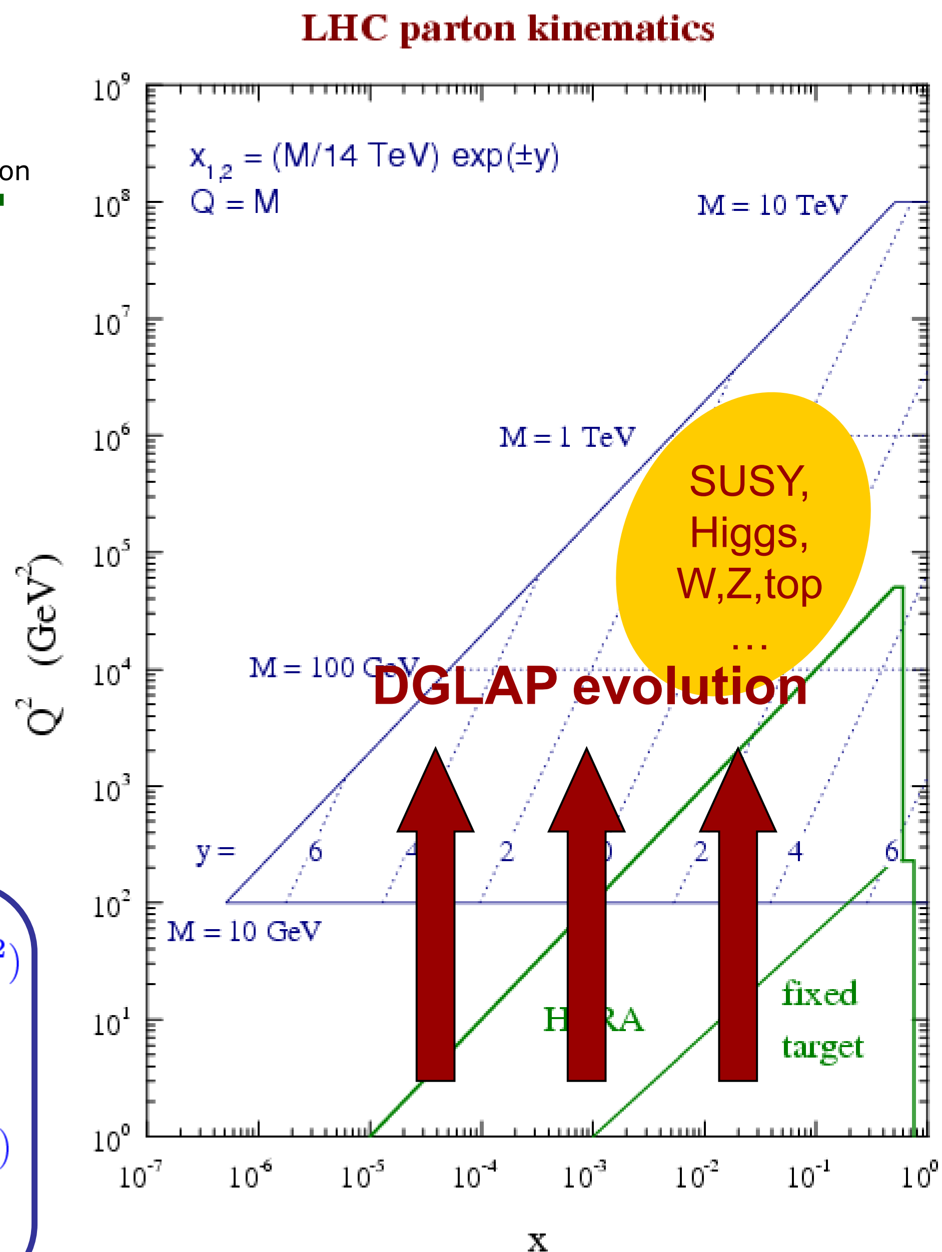


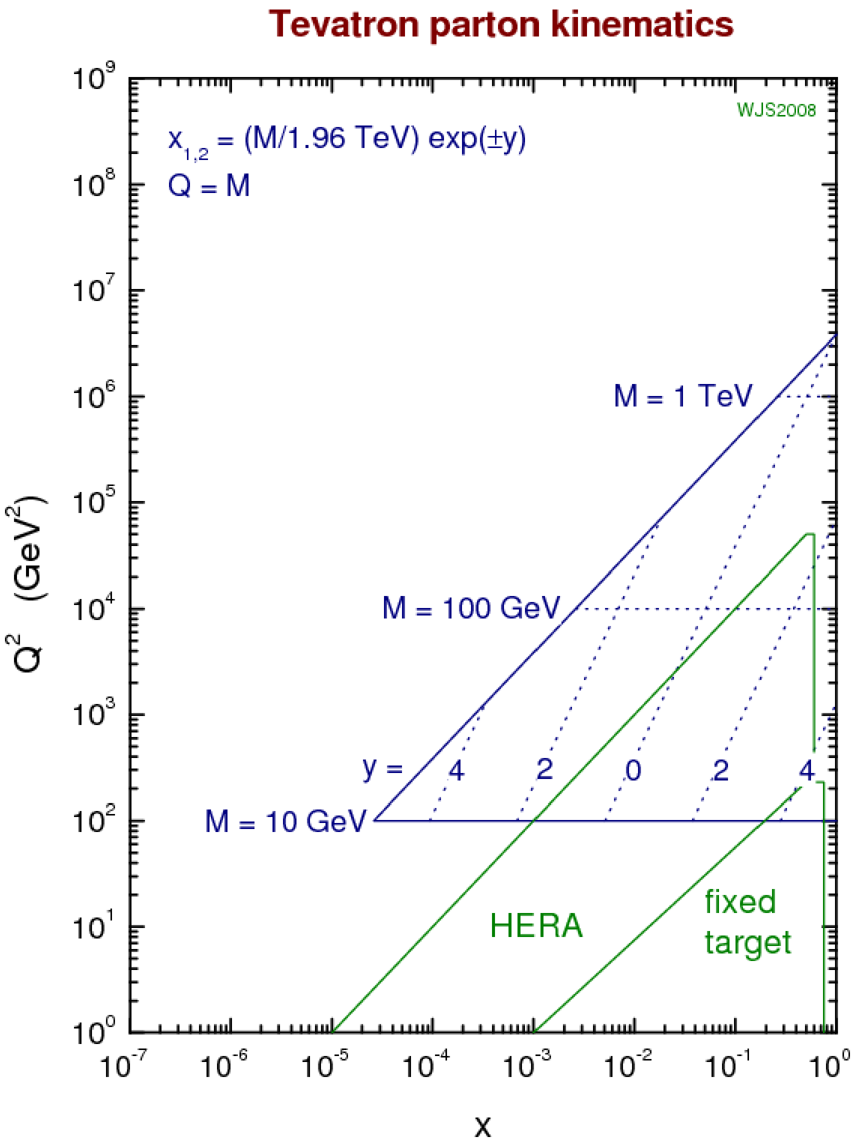
momentum fractions x_1 and x_2 determined by mass and rapidity of **X**

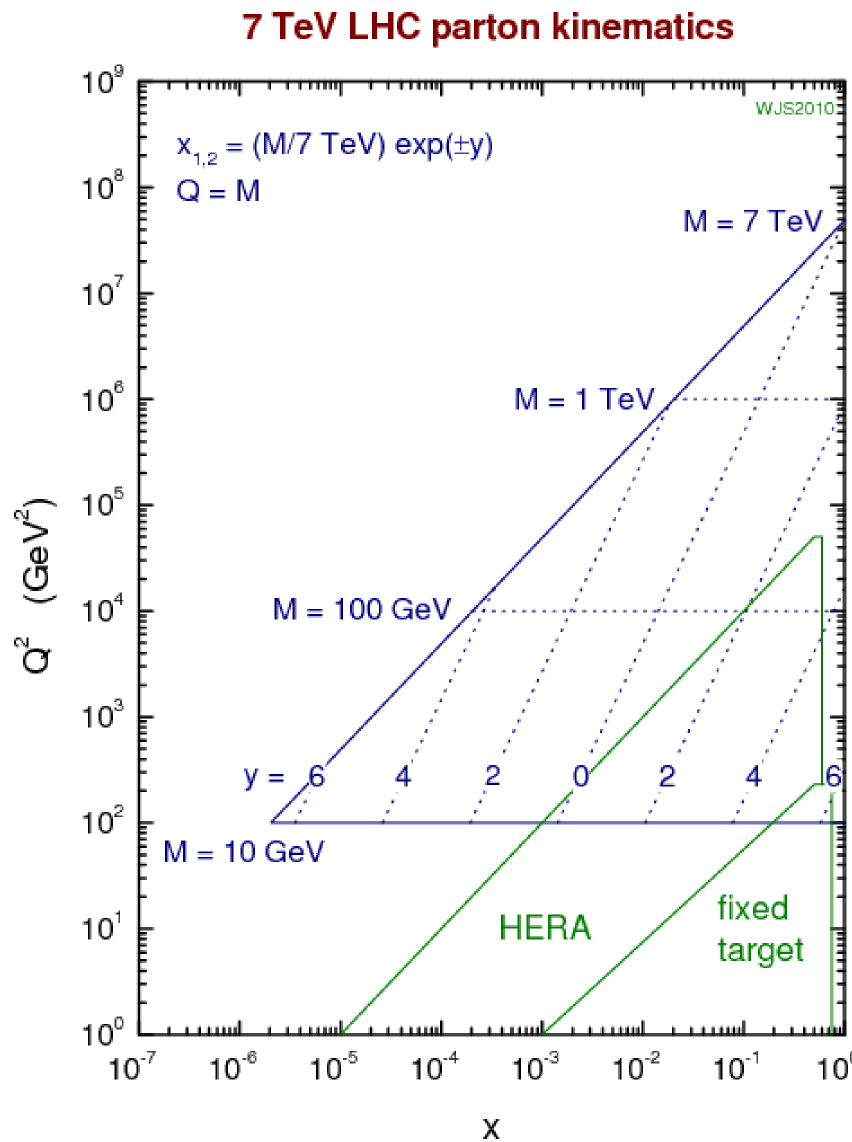
x dependence of $f_i(x,Q^2)$ determined by 'global fit' to deep inelastic scattering and other data, Q^2 dependence determined by **DGLAP** equations:

$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{q_iq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2) + P_{q_ig}(y,\alpha_S)\, g(\frac{x}{y},Q^2)\right\}$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{gq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2) + P_{gg}(y,\alpha_S)\, g(\frac{x}{y},Q^2)\right\}$$




Tevatron parton kinematics
WJS2008
$x_{1,2}$ = (M/1.96 TeV) exp(±y)
Q = M
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 4 2 0 2 4
HERA
fixed target
Q^2 (GeV^2)
x


7 TeV LHC parton kinematics
WJS2010
$x_{1,2}$ = (M/7 TeV) exp(±y)
Q = M
M = 7 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 2 4 6
HERA
fixed target
Q^2 (GeV^2)
x

the PDF industry

- many groups now extracting PDFs from 'global' data analyses (ABKM, CTEQ, GJR, HERAPDF, MSTW, NNPDF, …)

- broad agreement, but differences due to
  - choice of data sets (including cuts and corrections)
  - treatment of data errors
  - treatment of heavy quarks (s,c,b)
  - order of perturbation theory
  - parameterisation at Q_0
  - theoretical assumptions (if any) about:
    - flavour symmetries
    - $x \rightarrow 0, 1$ behaviour
    - …

HERA-DIS
FT-DIS
Drell-Yan
Tevatron jets
Tevatron W,Z
other

recent global or quasi-global PDF fits

PDFs	**authors**	**arXiv**
ABKM	S. Alekhin, J. Blümlein, S. Klein, S. Moch, and others	1011.6259, 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	0909.1711, 0810.4274, …
HERAPDF	H1 and ZEUS collaborations	1006.4471, 0906.1108, …
MSTW	A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt	1006.2753, 0905.3531, 0901.0002, …
NNPDF	R. Ball, L. Del Debbio, S. Forte, A. Guffanti, J. Latorre, J. Rojo, M. Ubiali, and others	1012.0836, 1005.0397, 1002.4407, 0912.2276, 0906.1958, …
…		

	MSTW08	CTEQ6.6X	NNPDF2.0	HERAPDF1.0	ABKM09X	GJR08
HERA DIS	✓	✓	✓*	✓*	✓	✓
F-T DIS	✓	✓	✓	✘	✓	✓
F-T DY	✓	✓	✓	✘	✓	✓
TEV W,Z	✓	✓+	✓	✘	✘	✘
TEV jets	✓	✓+	✓	✘	✘	✓
GM-VFNS	✓	✓	✘	✓	✓	✘
NNLO	✓	✘	✘	✘	✓	✓

+ Run 1 only

* includes new combined H1-ZEUS data → few% increase in quarks at low x

X new (July 2010) ABKM and CTEQ updates: ABKM includes new combined H1-ZEUS data + new small-x parametrisation + partial NNLO HQ corrections; CT10 includes new combined H1-ZEUS data + Run 2 jet data + extended gluon parametrisation + … → more like MSTW08

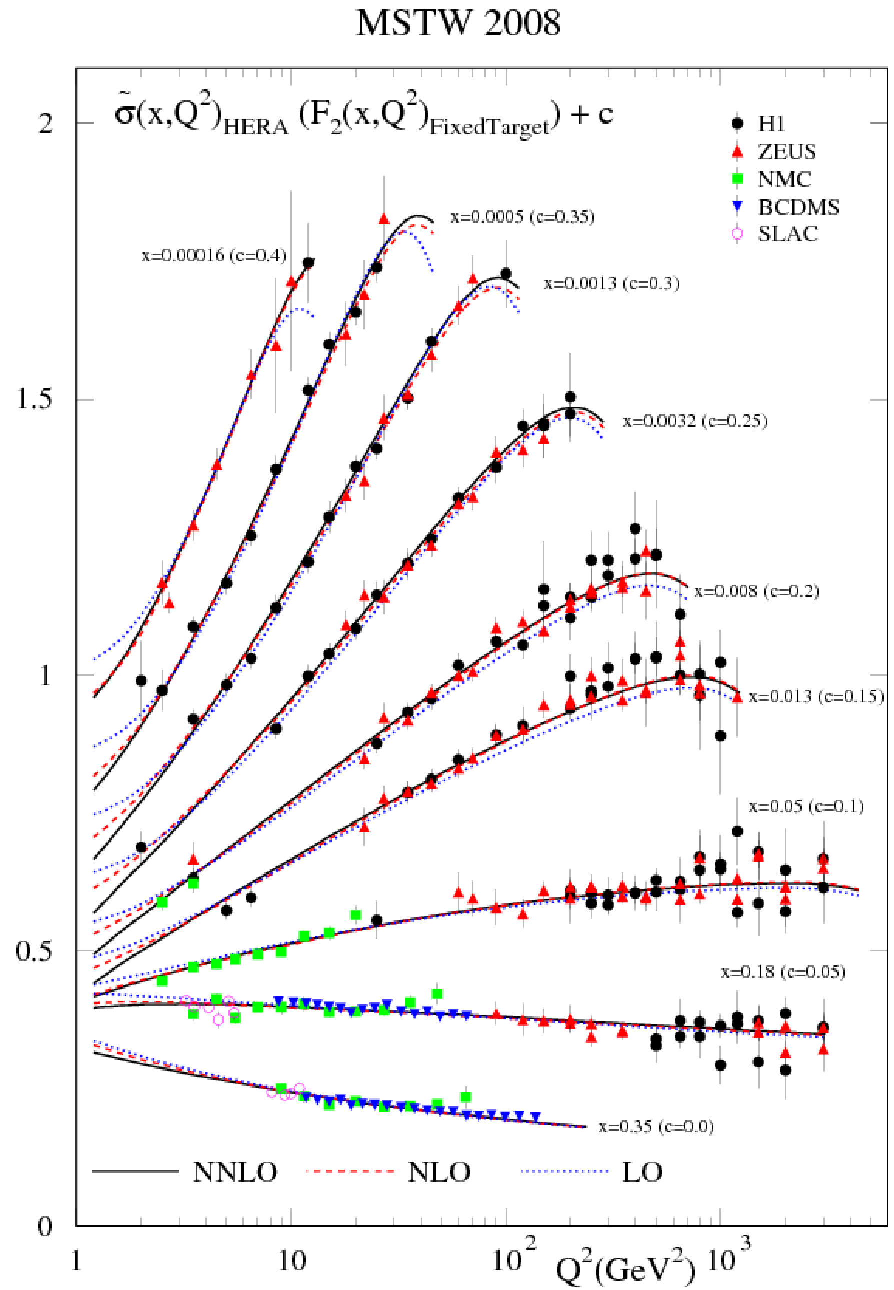
LO *vs* NLO *vs* NNLO?

in the MSTW2008 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.



impact of Tevatron jet data on fits

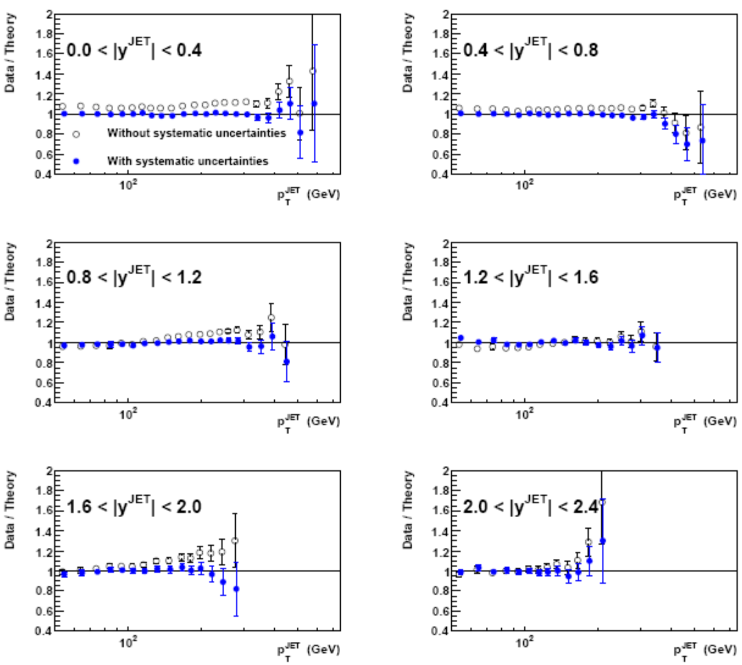
- a distinguishing feature of PDF sets is whether they use (MRST/MSTW, CTEQ, NNPDF, GJR,…) or do not use (HERAPDF, ABKM, …) Tevatron jet data in the fit: the impact is on the *high-x gluon*

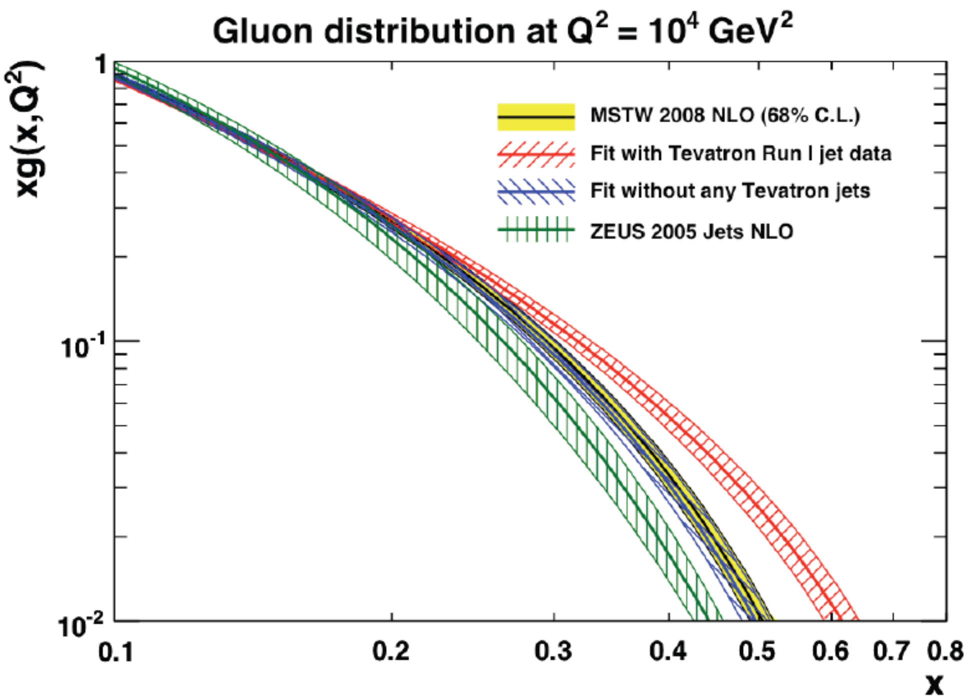
  (Note: Run II data requires slightly softer gluon than Run I data)

- the (still) missing ingredient is the full NNLO pQCD correction to the cross section, but not expected to have much impact in practice [Kidonakis, Owens (2001)]

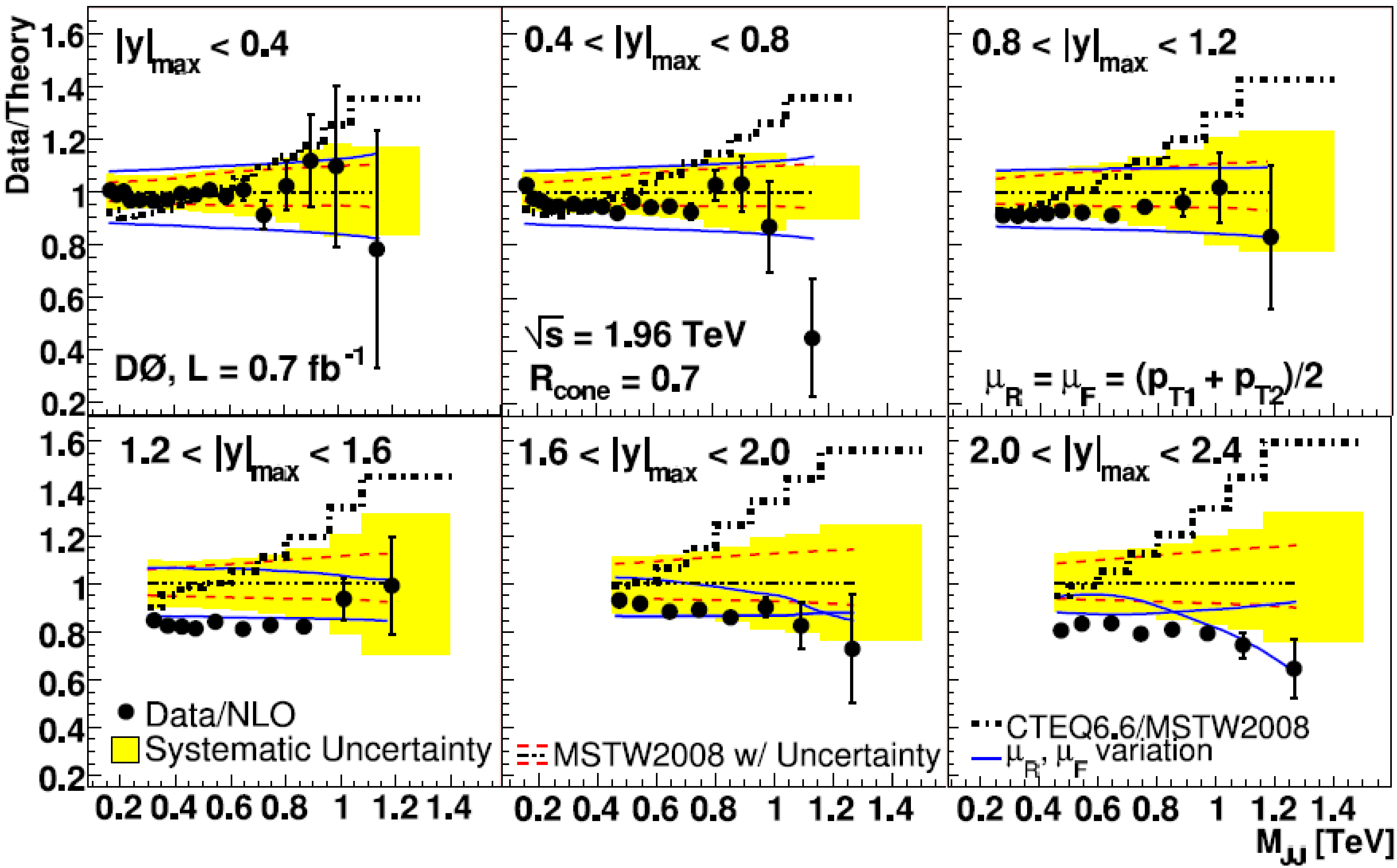
DØ Run II inclusive jet data (cone, R = 0.7)

MSTW 2008 NLO PDF fit ($\mu_R = \mu_F = p_T^{JET}$), χ^2 = 114 for 110 pts.





dijet mass distribution from D0



D0 collaboration: arXiv:1002.4594

PDF uncertainties

- all groups produce 'PDFs with errors'
- typically, 20-40 'error' sets based on a 'best fit' set to reflect $\pm 1\sigma$ variation of all the parameters* $\{A_i, a_i, \ldots, \alpha_S\}$ inherent in the fit
- these reflect the uncertainties on the data used in the global fit (e.g. $\delta F_2 \approx \pm 3\% \rightarrow \delta u \approx \pm 3\%$)
- however, there are also systematic PDF uncertainties reflecting theoretical assumptions/prejudices in the way the global fit is set up and performed

* e.g. $f_i(x, Q_0^2) = A_i x^{a_i}[1 + b_i\sqrt{x} + c_i x](1-x)^{d_i}$

PDF uncertainties (contd.)

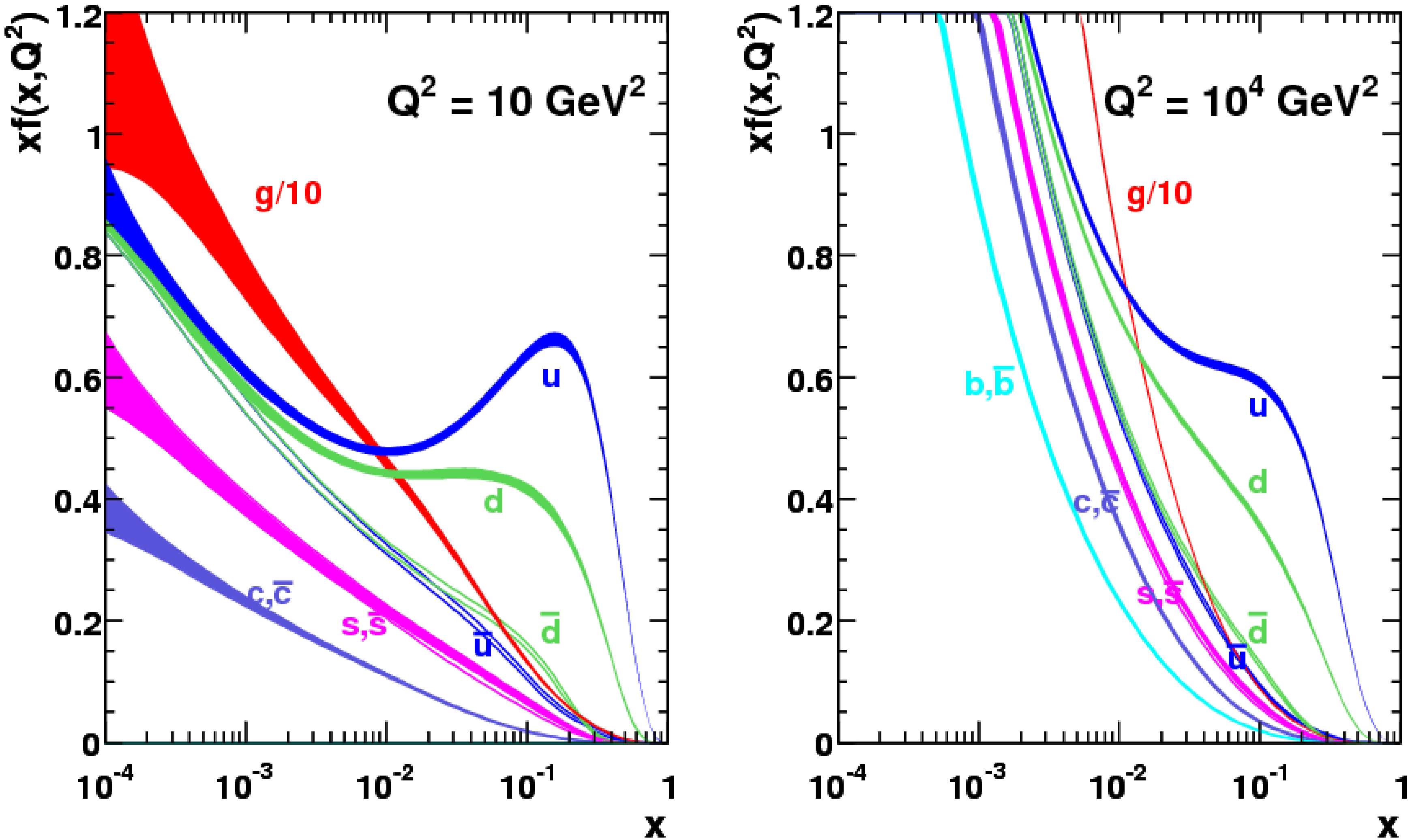
- NNPDF create many replicas of data and obtain PDF replicas in each case by fitting to training set and comparing to validation set → uncertainty determined by spread of replicas. Direct relationship to χ^2 in global fit not trivial.

- NNPDF and MSTW (due to extra parameters) have more complicated shape for gluon at smaller x and bigger small-x uncertainty, ditto for CTEQ at large x

- different theory assumptions in strange quark PDF leads to vastly different uncertainties — e.g. MSTW small, NNPDF large; feeds into other 'light' quarks

- perhaps surprisingly, all get rather similar uncertainties for PDFs and predicted cross sections — see later

MSTW 2008 NLO PDFs (68% C.L.)



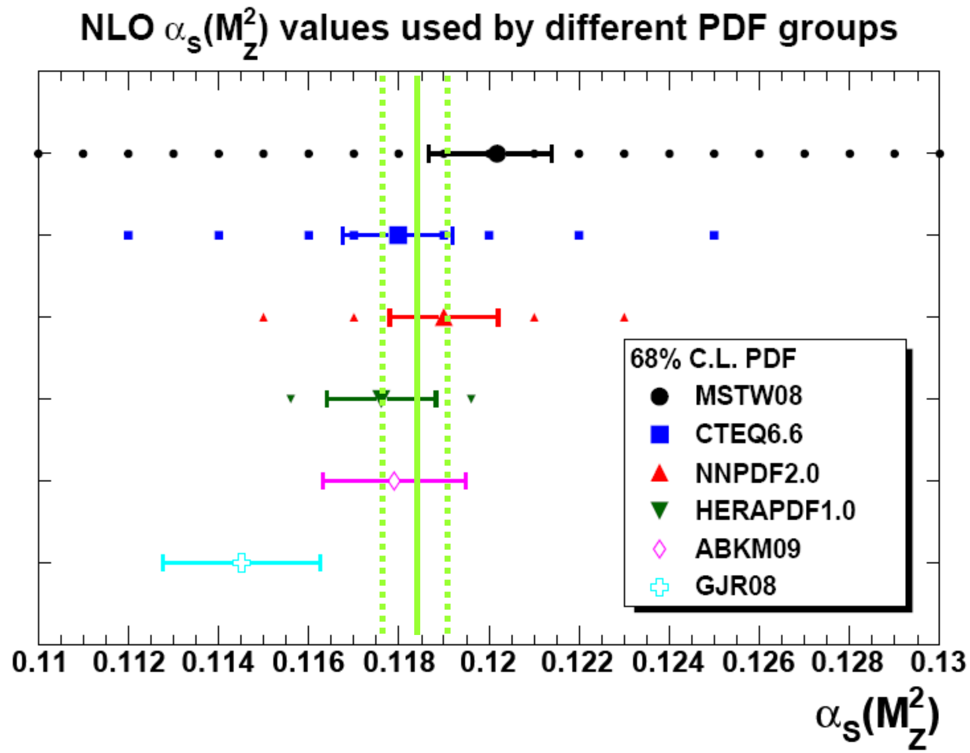
MSTW = Martin, S, Thorne, Watt

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

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

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

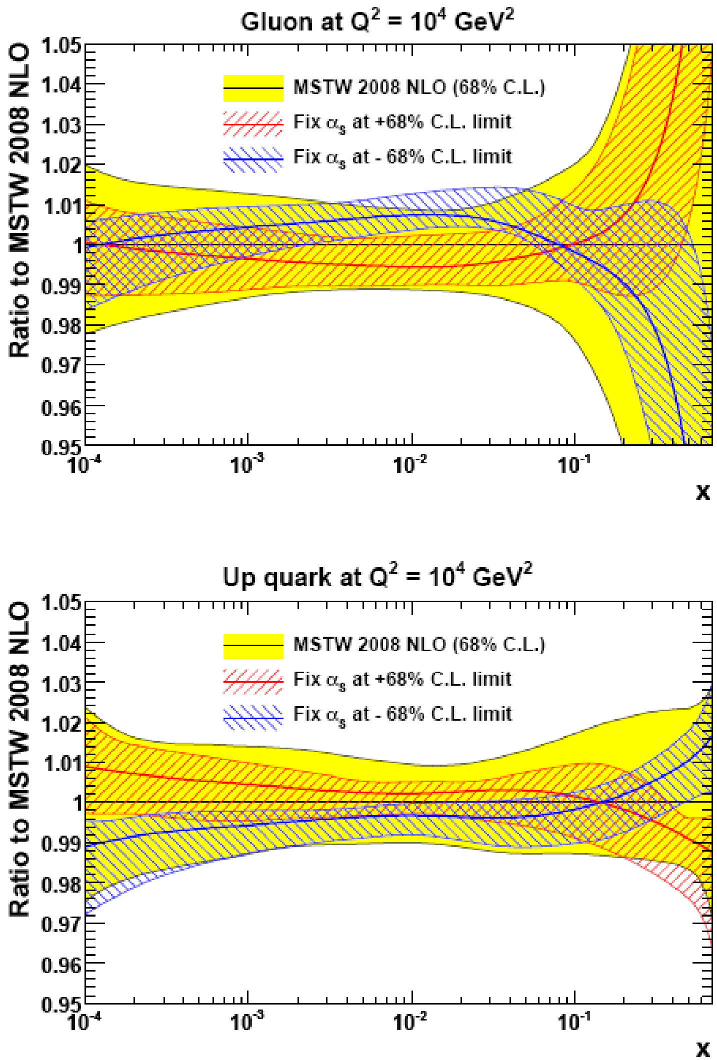


- CTEQ, NNPDF, HERAPDF choose standard values and uncertainties
- world average (PDG 2009)

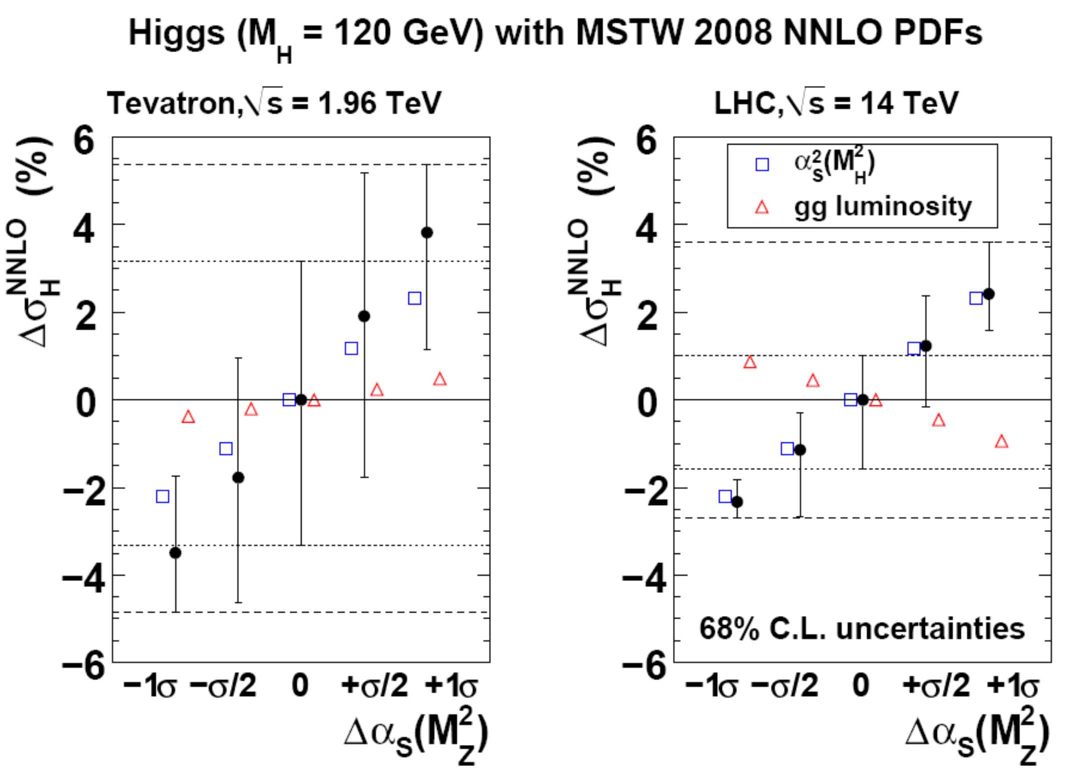
$$\alpha_S^{\overline{MS}}(M_Z^2) = 0.1184 \pm 0.0007$$

- 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 ~ $(\alpha_S)^n$ (e.g. top, Higgs)



MSTW: arXiv:0905.3531

3

LHC benchmark cross sections

LHC benchmark study for Standard Model cross sections at 7 TeV LHC

arXiv:1101.0536v1 [hep-ph] 3 Jan 2011

The PDF4LHC Working Group Interim Report

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Abstract

This document is intended as a study of benchmark cross sections at the LHC (at 7 TeV) at NLO using modern PDFs currently available from the 6 PDF fitting groups that have participated in this exercise. It also contains a succinct user guide to the computation of PDFs, uncertainties and correlations using available PDF sets.

A companion note provides an interim summary of the current recommendations of the PDF4LHC working group for the use of parton distribution functions (PDFs) and of PDF uncertainties at the LHC, for cross section and cross section uncertainty calculations.

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:

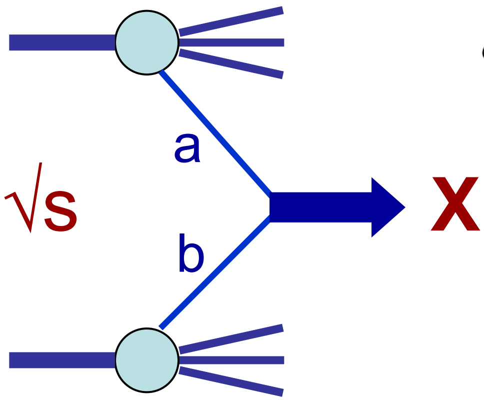
m_{top}= 171.3 GeV

zero width approximation, no branching ratios

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

parton luminosity functions

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



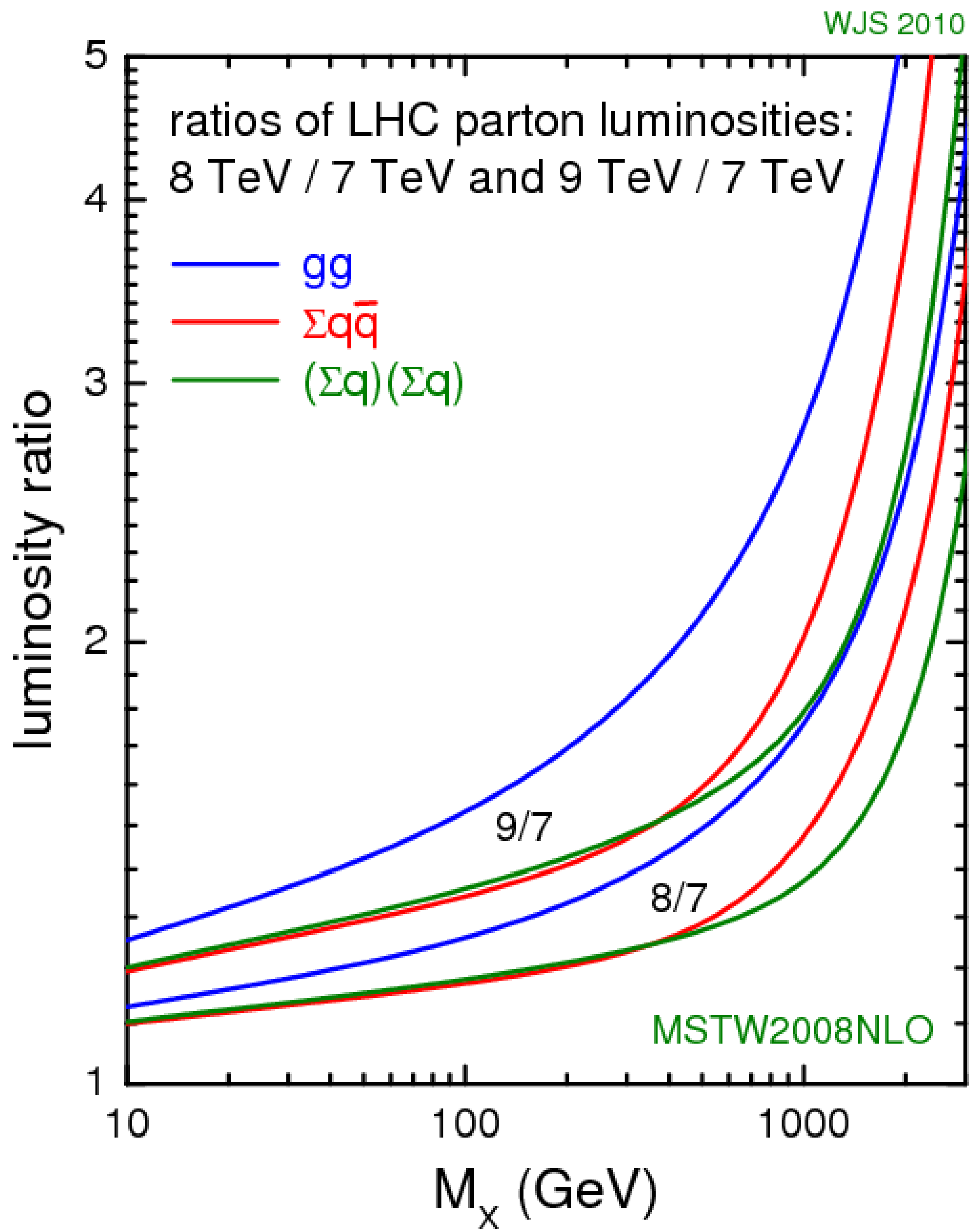
$$\hat{\sigma}_{ab\to X} = C_X \delta(\hat{s} - M_X^2)$$

$$\sigma_X = \int_0^1 dx_a dx_b \, f_a(x_a, M_X^2) f_b(x_b, M_X^2) \, C_X \, \delta(x_a x_b - \tau)$$

$$\equiv C_X \left[\frac{1}{s} \frac{\partial \mathcal{L}_{ab}}{\partial \tau} \right] \qquad (\tau = M_X^2/s)$$

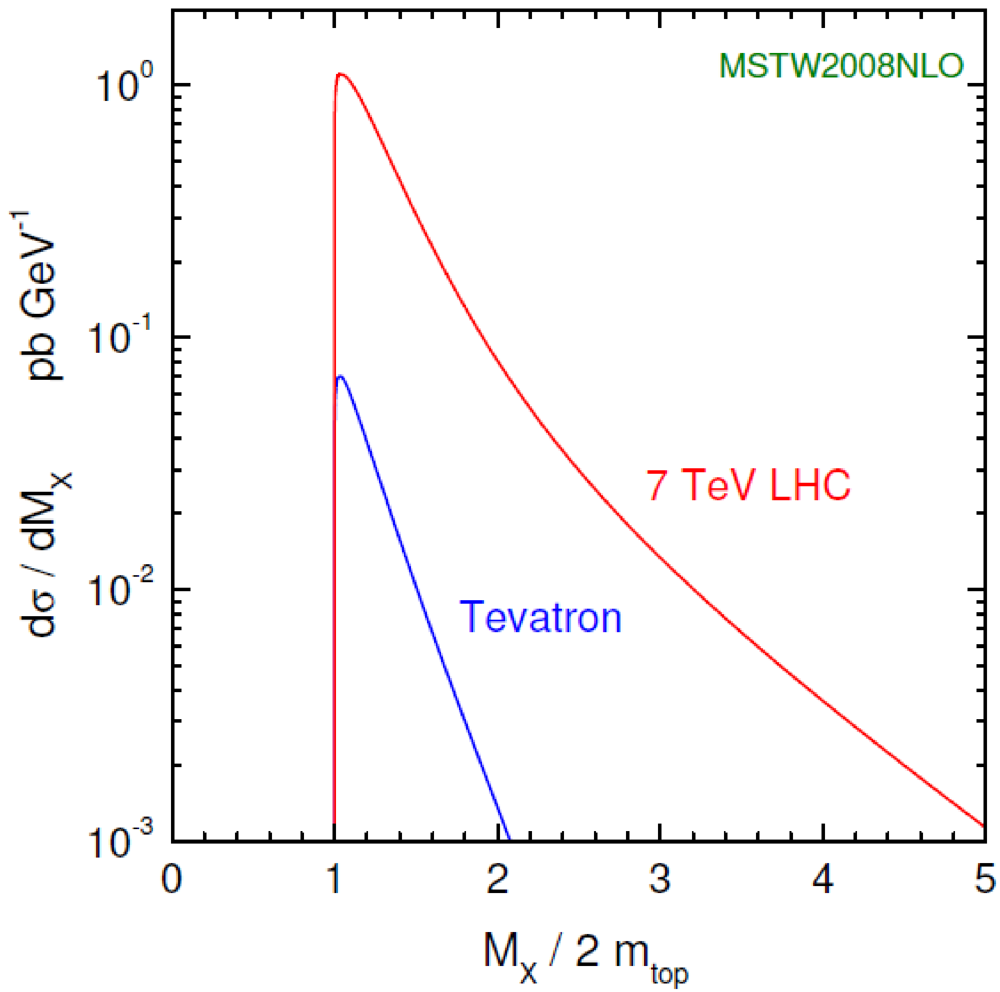
$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_0^1 dx_a dx_b \, f_a(x_a, M_X^2) f_b(x_b, M_X^2) \, \delta(x_a x_b - \tau)$$

- 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

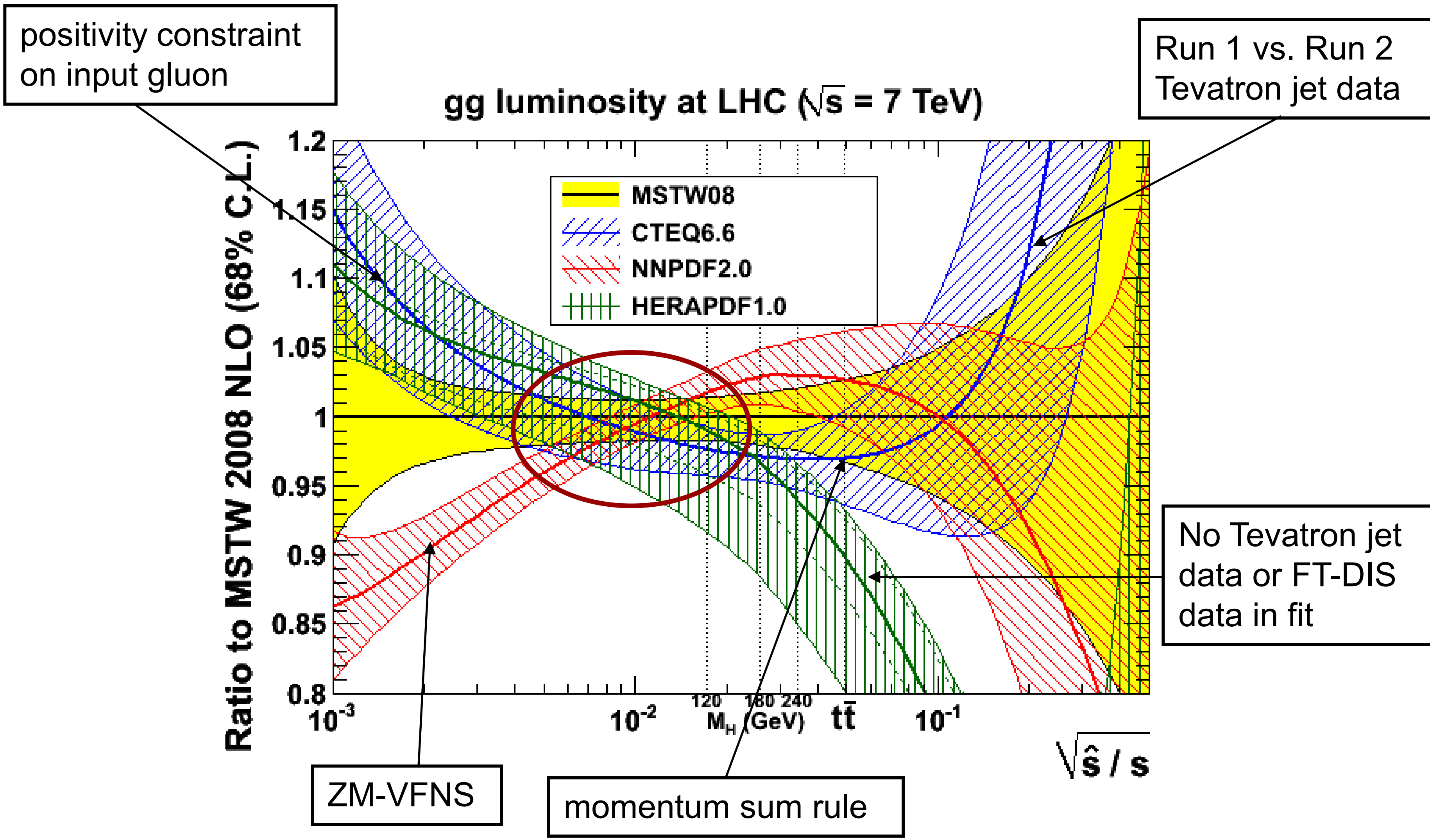


e.g.
gg→H,QQ̄
qq̄→VH
qq→qqH

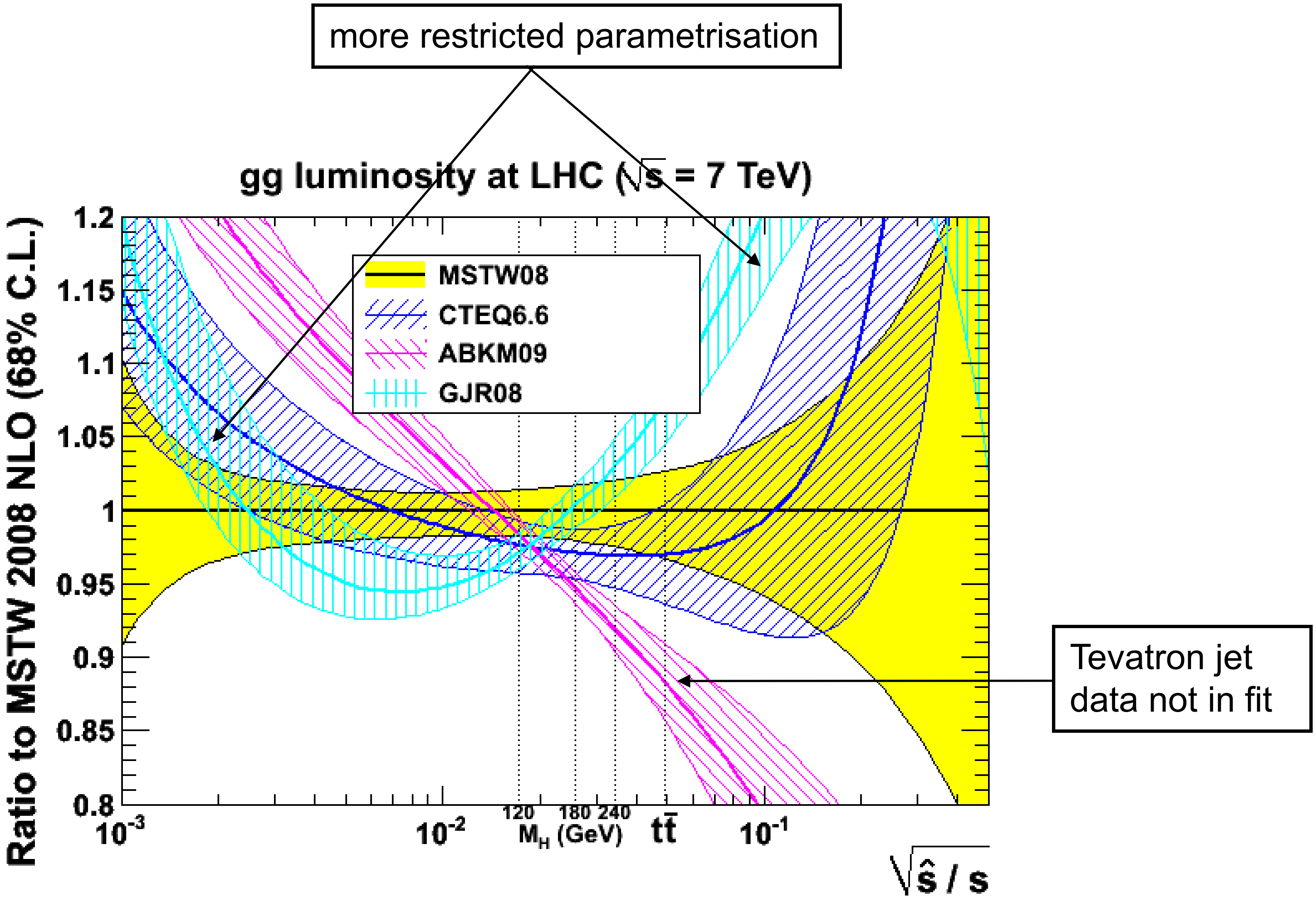
final-state total invariant mass distribution in top production at LHC and Tevatron



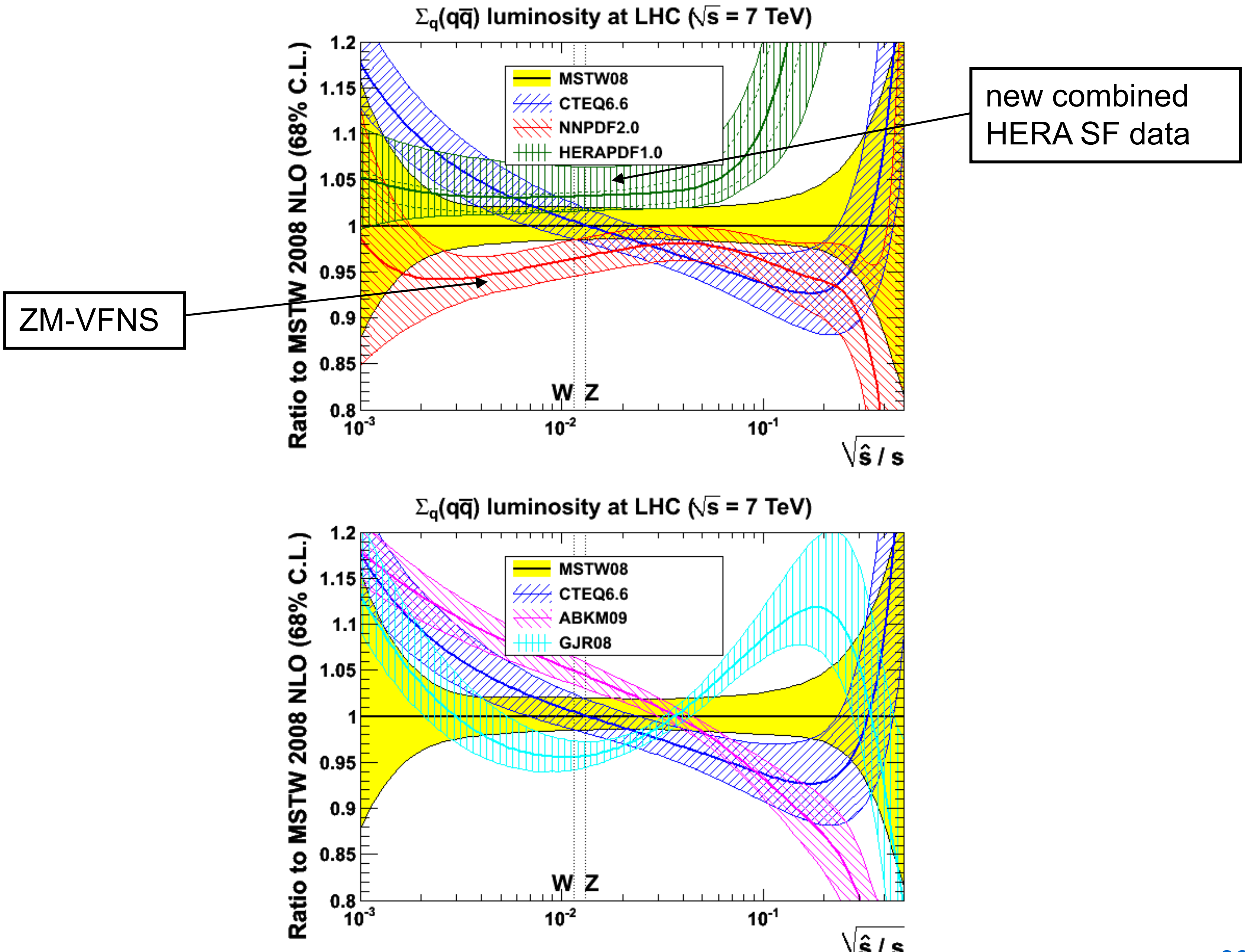
parton luminosity comparisons



Luminosity and cross section plots from Graeme Watt (MSTW, in preparation), available at projects.hepforge.org/mstwpdf/pdf4lhc

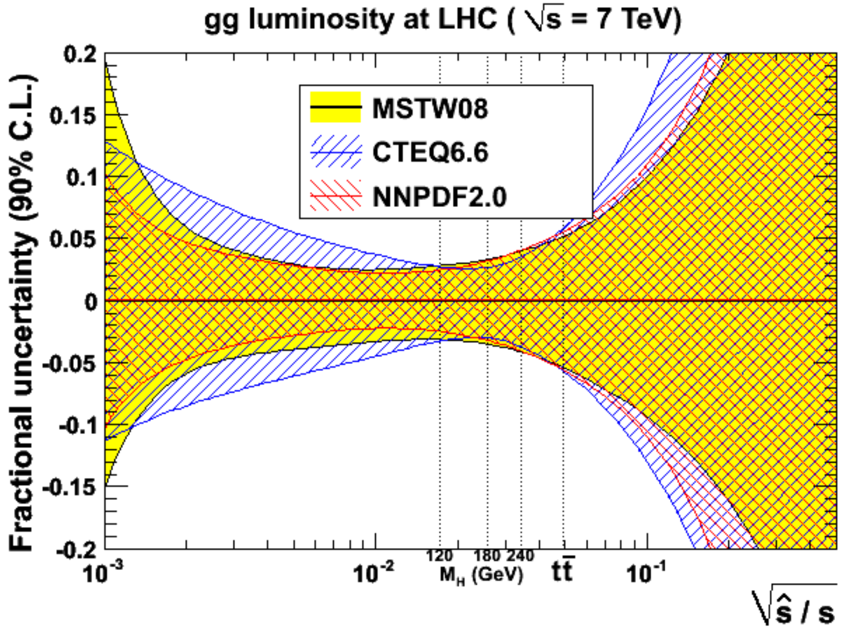


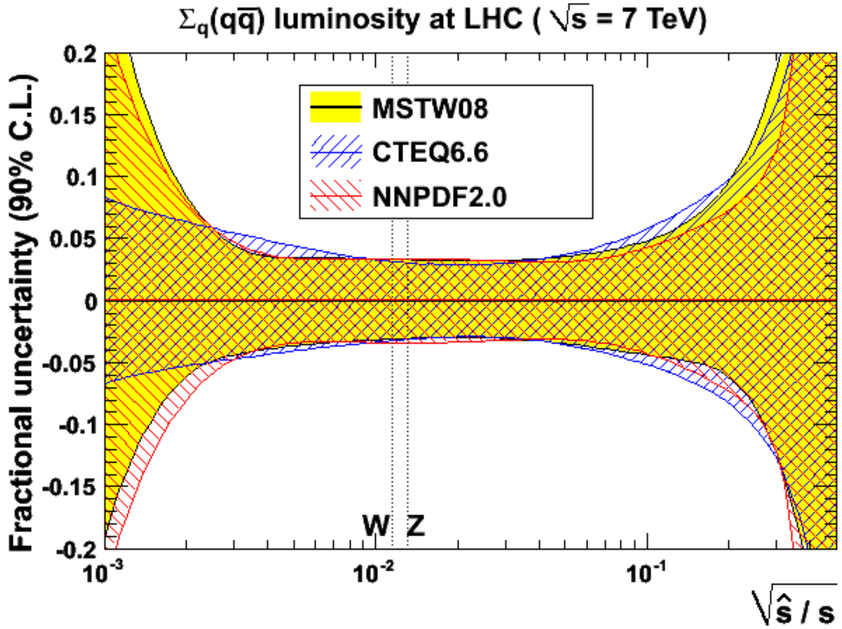
more restricted parametrisation
gg luminosity at LHC (√s = 7 TeV)
MSTW08
CTEQ6.6
ABKM09
GJR08
Ratio to MSTW 2008 NLO (68% C.L.)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
10^-3
10^-2
120 180 240
M_H (GeV)
tt̄
10^-1
√ŝ / s
Tevatron jet data not in fit



$\Sigma_q(q\bar{q})$ luminosity at LHC ($\sqrt{s}$ = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
new combined HERA SF data
ZM-VFNS
W Z
$\sqrt{\hat{s}/s}$
$\Sigma_q(q\bar{q})$ luminosity at LHC ($\sqrt{s}$ = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
ABKM09
GJR08
W Z
$\sqrt{\hat{s}/s}$

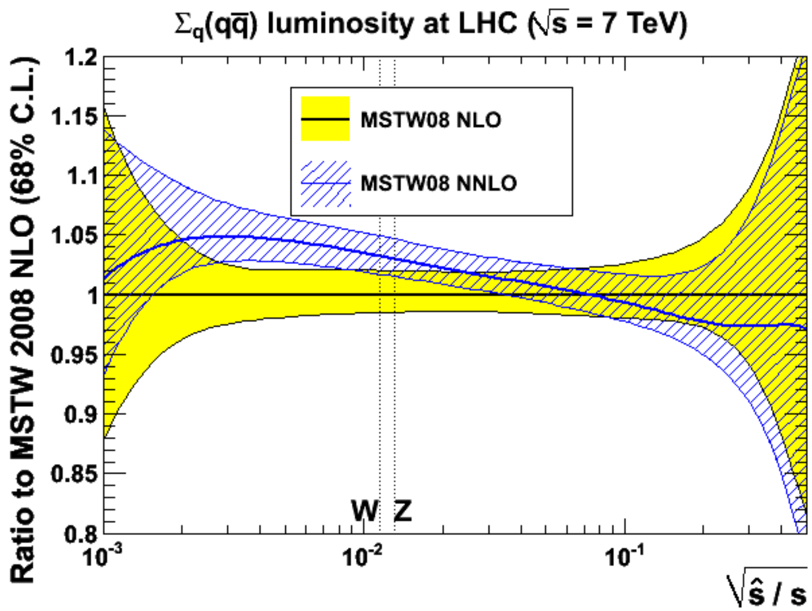
fractional uncertainty comparisons

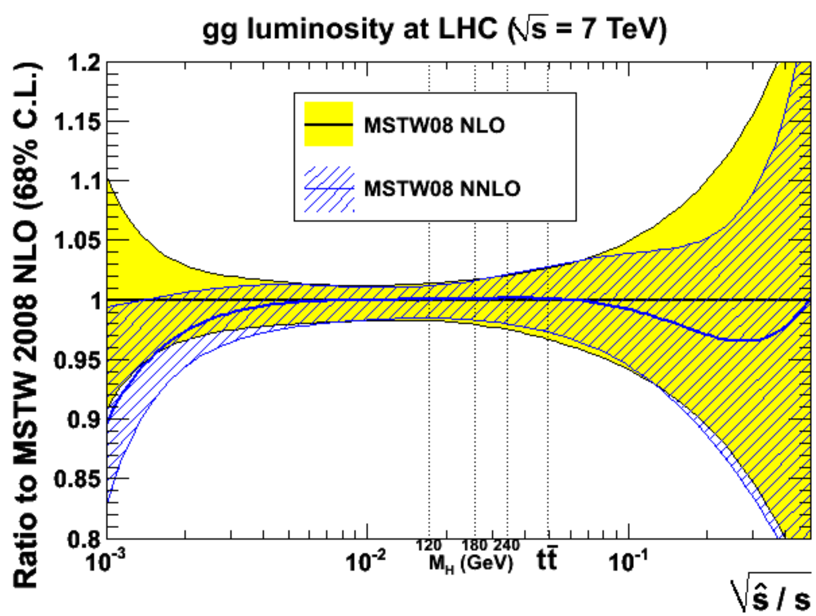




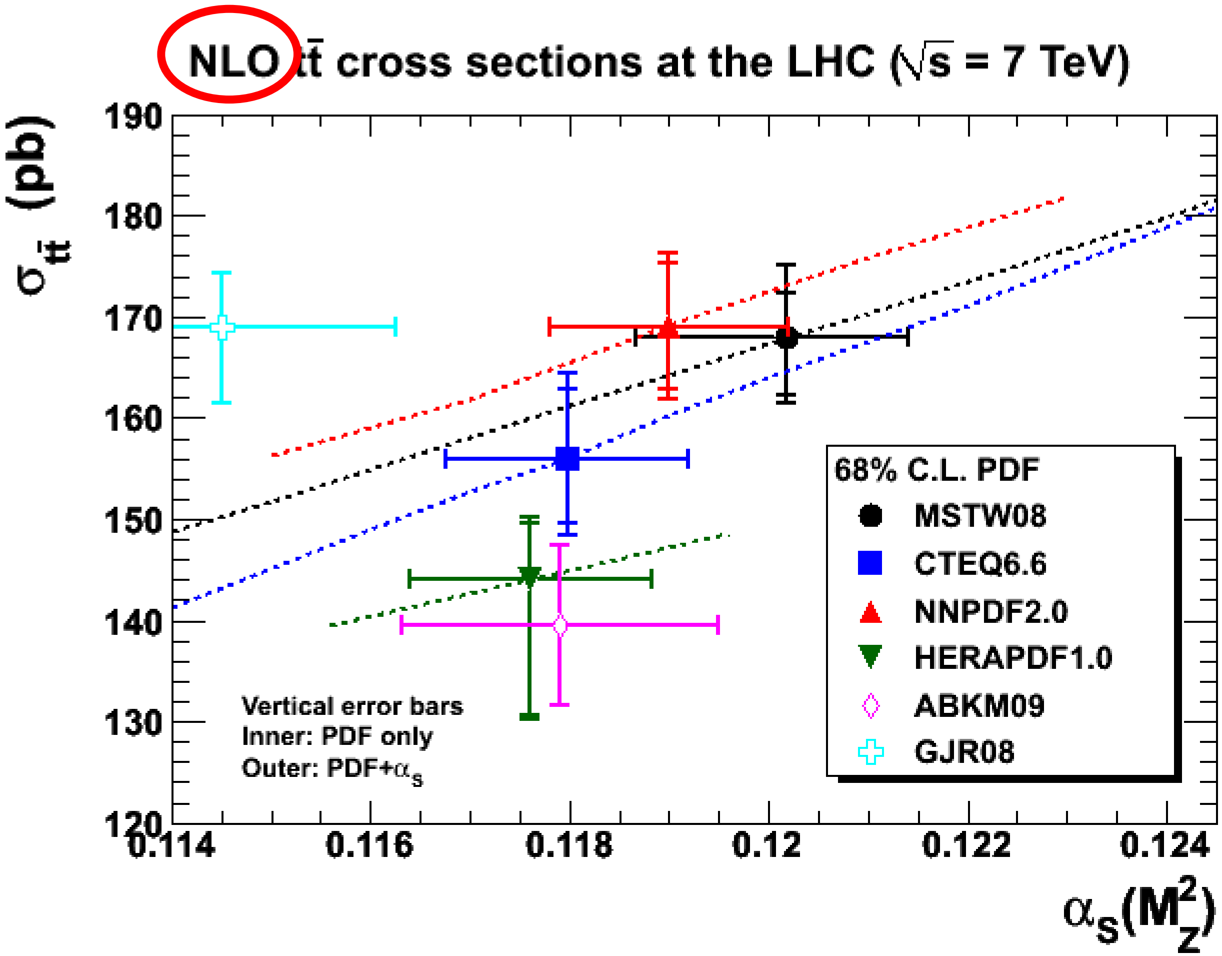
remarkably similar considering the different definitions of PDF uncertainties used by the 3 groups!

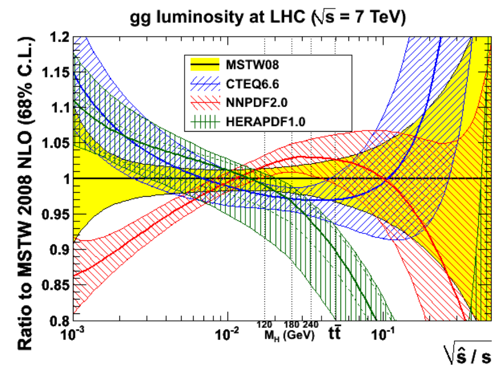
NLO and NNLO parton luminosity comparisons

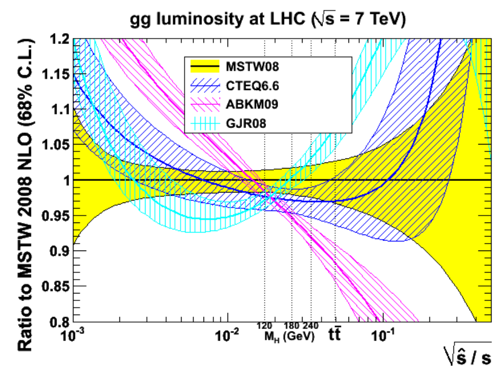




benchmark top cross sections







G. Watt: projects.hepforge.org/mstwpdf/pdf4lhc

benchmark NLO top cross sections at 7 TeV LHC

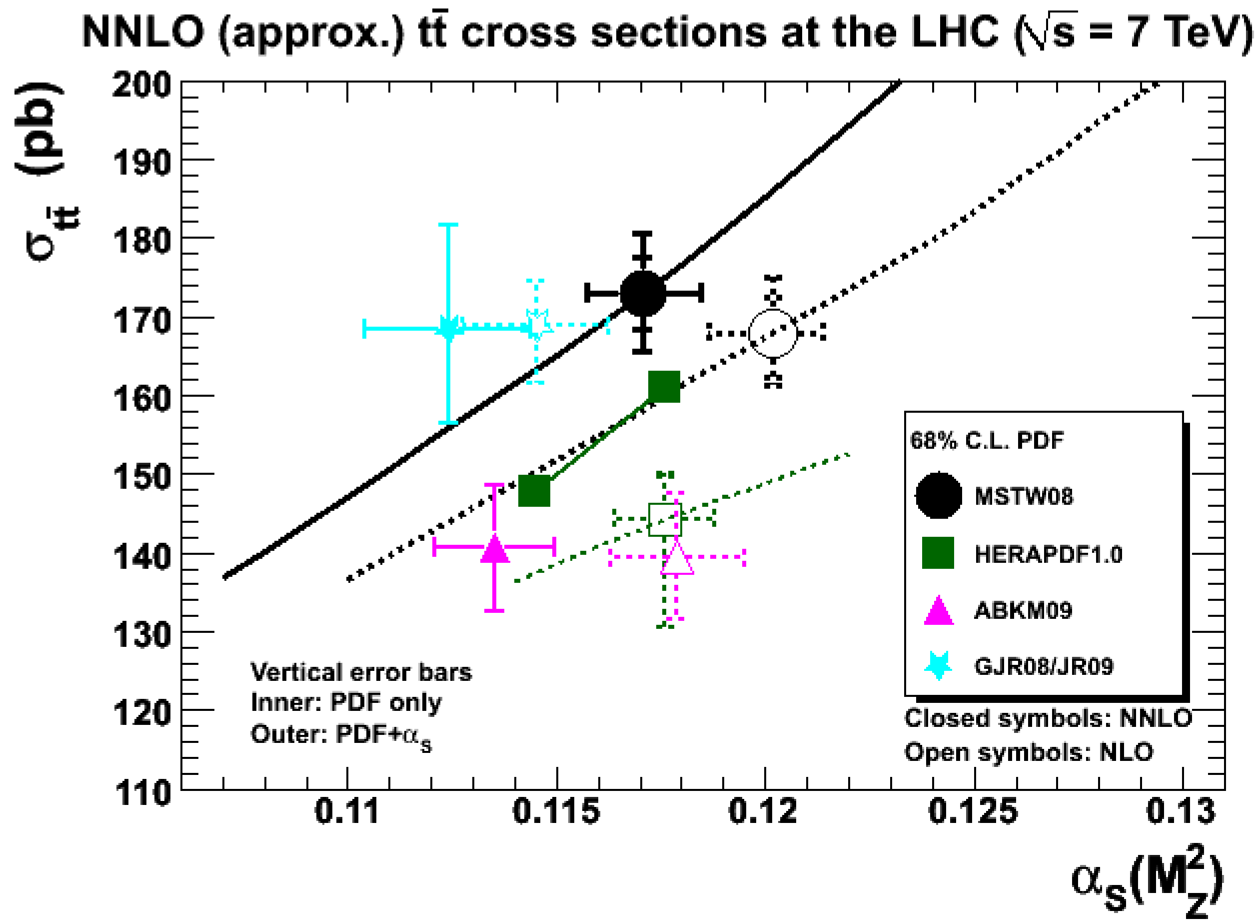
	σ (pb)	$\delta\sigma$ (pb)	comment
ABKM09	139.55	7.96	combined PDF and α_s
CTEQ6.6	156.2	8.06	combined PDF and α_s *
GJR08	169	6	PDF only
HERAPDF1.0	147.31	+5.18 -13.76	combined PDF and α_s**
MSTW08	168.1	+7.2-6.0	combined PDF and α_s***
NNPDF2.0	169	7	combined PDF and α_s ****

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)

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

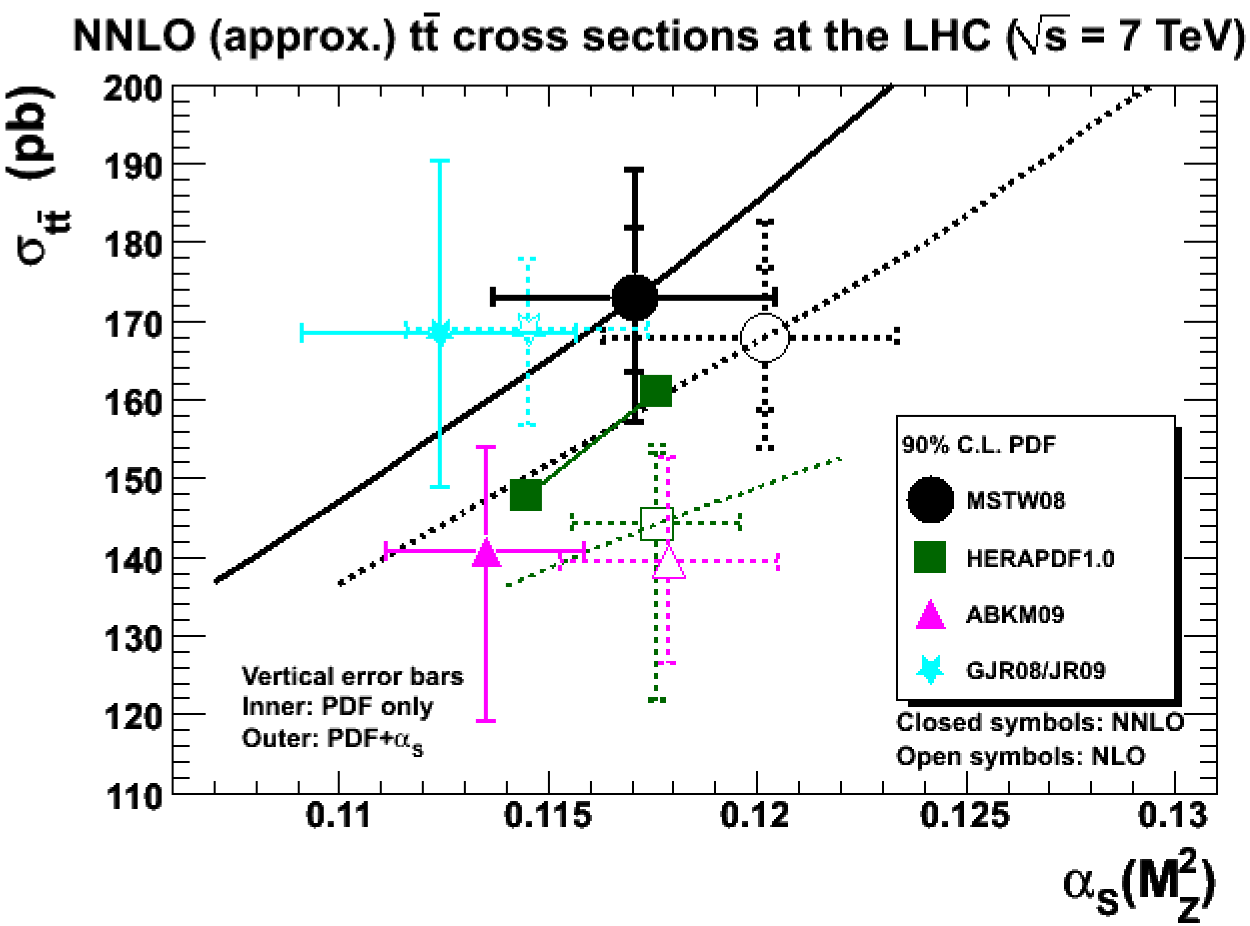
... and at NNLO



$NNLO_{approx}$: Hathor (Langenfeld, Moch, Uwer, arXiv:0906.5273)

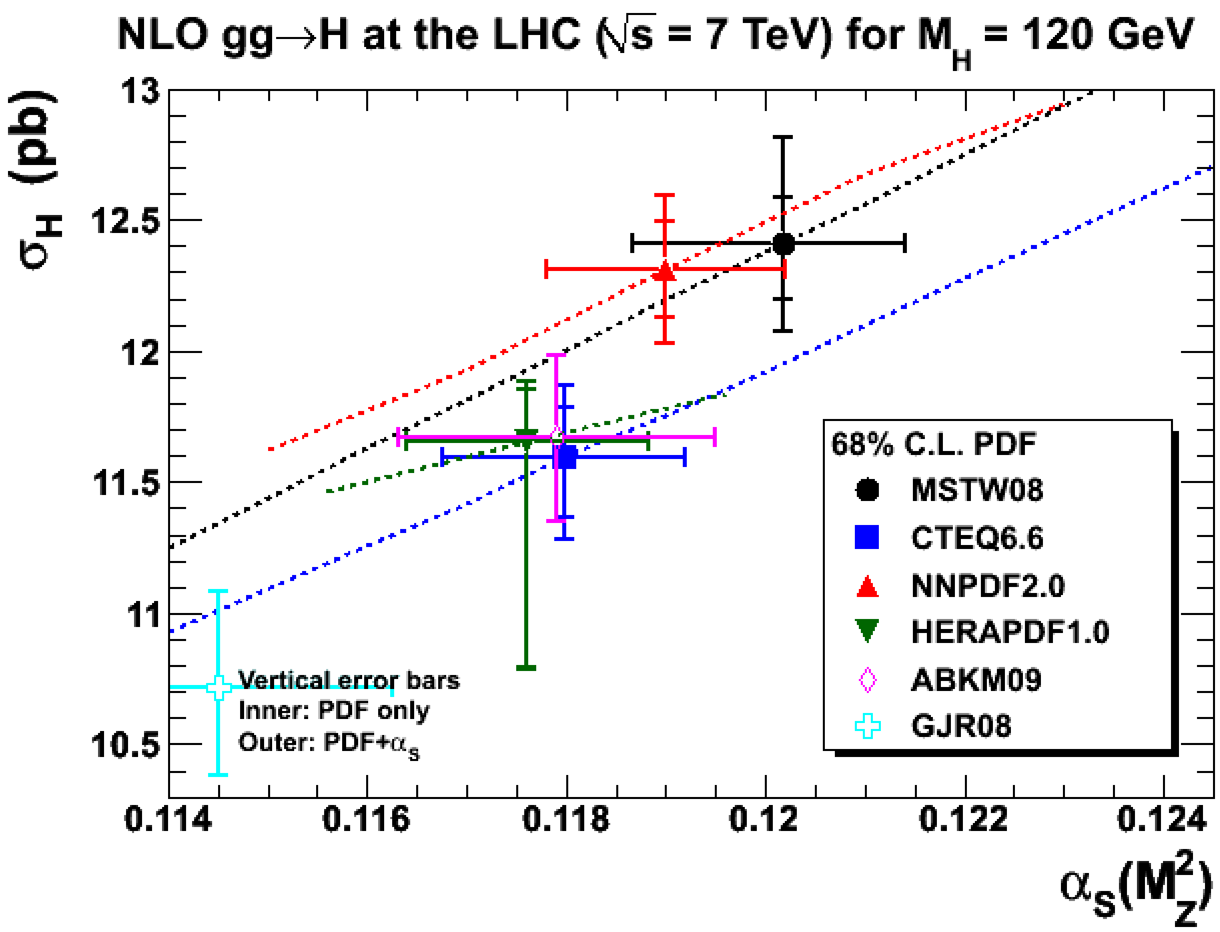
plot from Graeme Watt

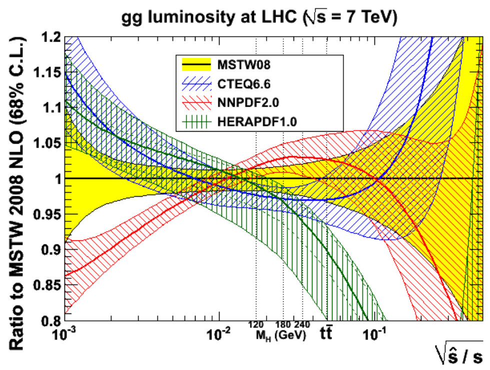
... and with 90%cl PDF uncertainties

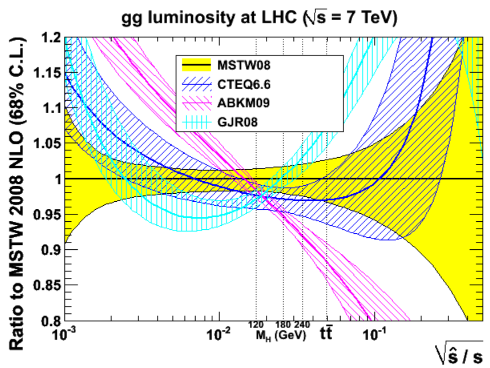


plot from Graeme Watt

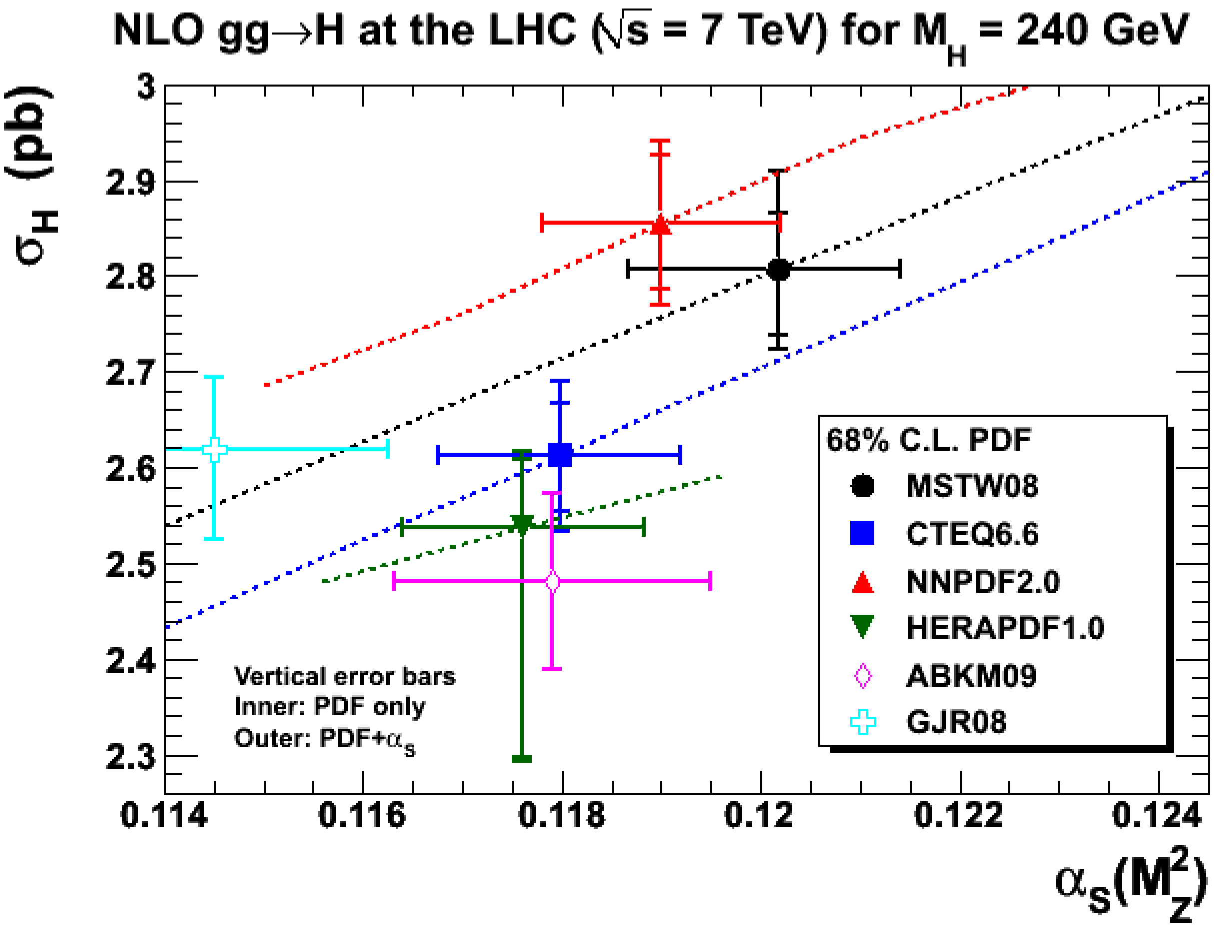
benchmark Higgs cross sections

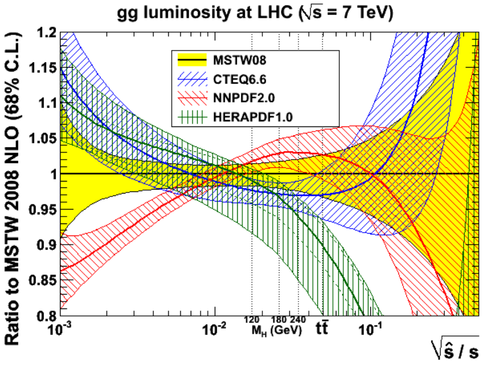


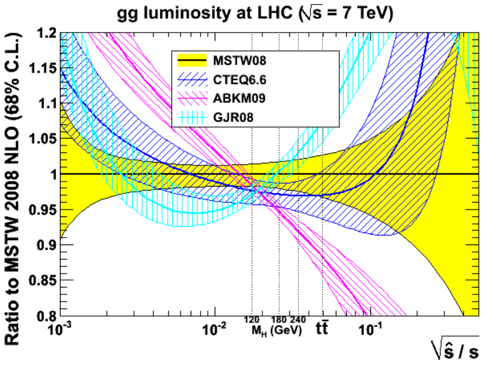




G. Watt: projects.hepforge.org/mstwpdf/pdf4lhc







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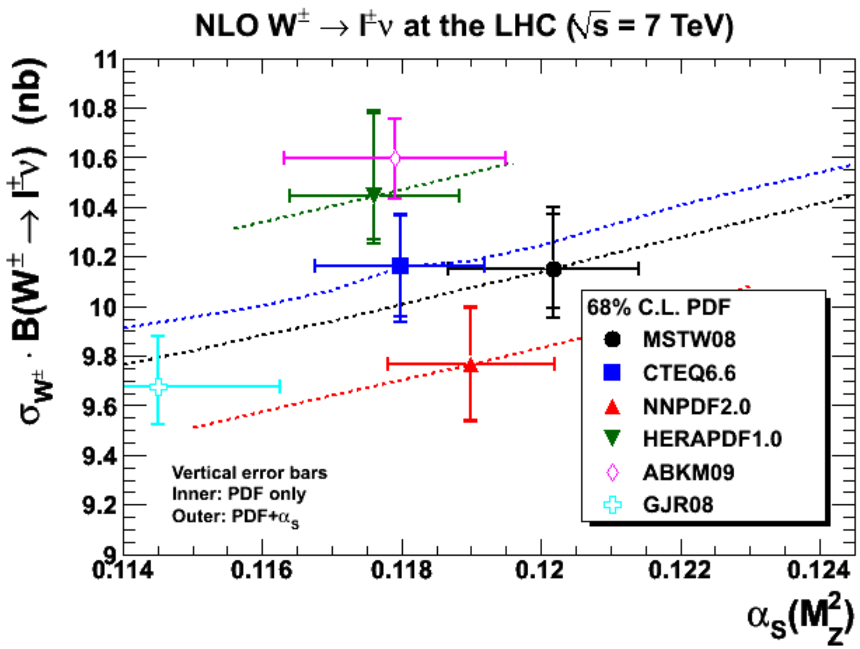
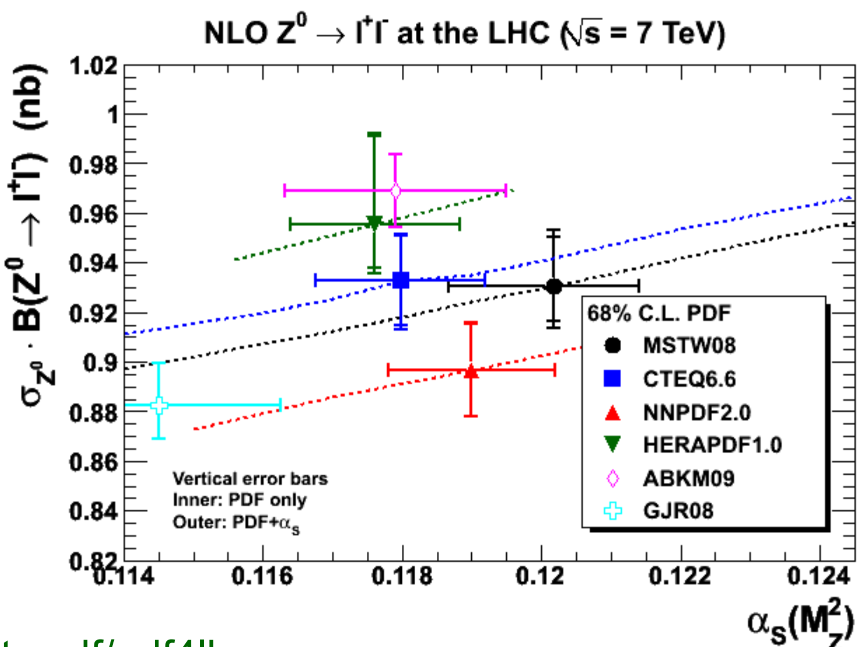
cf. benchmark W,Z cross sections





G. Watt: projects.hepforge.org/mstwpdf/pdf4lhc

summary

- the PDF dependence of the 7 TeV LHC top cross section has been studied: NLO benchmark “68% cl” predictions from the various groups span the range 131-175 pb (122-182 pb at “90% cl”) ! ... driven by differences in the gluon distribution at large x
- this is *much* larger than the estimated scale dependence/UHO uncertainty (using approx. NNLO or NNLL etc.)
- however, uncertainties in the Individual predictions are in the ± 6-8 pb range
- corresponding predictions for a light Higgs boson are more similar, as are top predictions at 14 TeV
- corresponding predictions for a heavier quark or similar coloured object: (gg → Q Qbar, squark pairs etc) would be even more different
- therefore, an experimental measurement of the top quark cross section at LHC will be very important for discriminating between PDF sets
- a similar benchmarking study for the Tevatron would be interesting (CDF: σ_{top} = 7.50 ± 0.48 pb [6%]) ... although expect *much* better agreement between different PDF sets