MSTW PDFs and impact of PDFs on cross sections at Tevatron and LHC

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Introduction

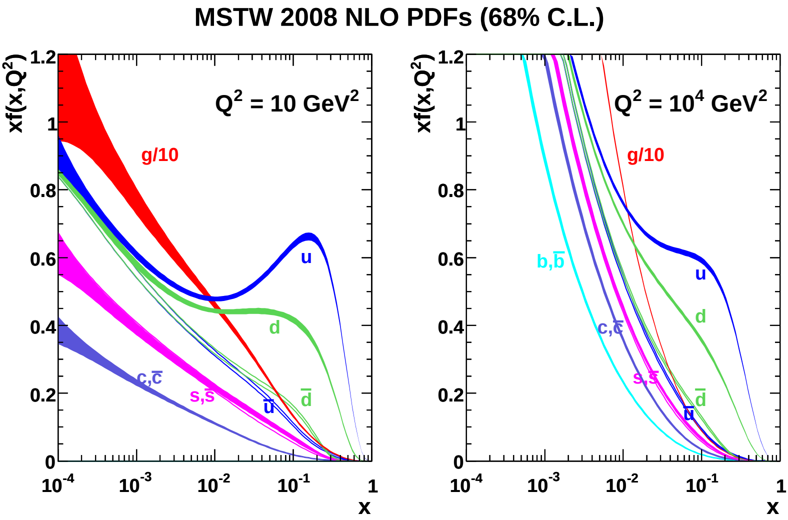
Talk mostly based on two recent papers (with some updates):

- G. Watt,
  "*Parton distribution function dependence of benchmark Standard Model total cross sections at the 7 TeV LHC*"
  [JHEP **09** (2011) 069, arXiv:1106.5788]
- R. S. Thorne and G. Watt,
  "*PDF dependence of Higgs cross sections at the Tevatron and LHC: response to recent criticism*"
  [JHEP **08** (2011) 100, arXiv:1106.5789]

"Impact of PDFs on cross sections at Tevatron and LHC"

PDFs $\Rightarrow$ cross sections at the Tevatron and LHC.
Cross sections at the Tevatron and LHC $\Rightarrow$ PDFs.

MSTW 2008 PDFs [http://projects.hepforge.org/mstwpdf/]



MSTW 2008 PDFs [http://projects.hepforge.org/mstwpdf/]

A. D. **M**artin, W. J. **S**tirling, R. S. **T**horne, G. **W**att

- "*Parton distributions for the LHC*"
  [Eur. Phys. J. C **63** (2009) 189, arXiv:0901.0002]
- "*Uncertainties on α_S in global PDF analyses and implications for predicted hadronic cross sections*"
  [Eur. Phys. J. C **64** (2009) 653, arXiv:0905.3531]
- "*Heavy-quark mass dependence in global PDF analyses and 3- and 4-flavour parton distributions*"
  [Eur. Phys. J. C **70** (2010) 51, arXiv:1007.2624]
- "*The effects of combined HERA and recent Tevatron $W \to \ell\nu$ charge asymmetry data on the MSTW PDFs*"
  [DIS 2010 proceedings, arXiv:1006.2753]

Data sets fitted in MSTW 2008 NLO analysis [arXiv:0901.0002]

Data set	χ^2 / $N_{\rm pts.}$
H1 MB 99 e^+p NC	9 / 8
H1 MB 97 e^+p NC	42 / 64
H1 low Q^2 96–97 e^+p NC	44 / 80
H1 high Q^2 98–99 e^-p NC	122 / 126
H1 high Q^2 99–00 e^+p NC	131 / 147
ZEUS SVX 95 e^+p NC	35 / 30
ZEUS 96–97 e^+p NC	86 / 144
ZEUS 98–99 e^-p NC	54 / 92
ZEUS 99–00 e^+p NC	63 / 90
H1 99–00 e^+p CC	29 / 28
ZEUS 99–00 e^+p CC	38 / 30
H1/ZEUS $e^\pm p$ $F_2^{\rm charm}$	107 / 83
H1 99–00 e^+p incl. jets	19 / 24
ZEUS 96–97 e^+p incl. jets	30 / 30
ZEUS 98–00 $e^\pm p$ incl. jets	17 / 30
DØ II $p\bar{p}$ incl. jets	114 / 110
CDF II $p\bar{p}$ incl. jets	56 / 76
CDF II $W \to l\nu$ asym.	29 / 22
DØ II $W \to l\nu$ asym.	25 / 10
DØ II Z rap.	19 / 28
CDF II Z rap.	49 / 29

Data set	χ^2 / $N_{\rm pts.}$
BCDMS μp F_2	182 / 163
BCDMS μd F_2	190 / 151
NMC μp F_2	121 / 123
NMC μd F_2	102 / 123
NMC $\mu n/\mu p$	130 / 148
E665 μp F_2	57 / 53
E665 μd F_2	53 / 53
SLAC ep F_2	30 / 37
SLAC ed F_2	30 / 38
NMC/BCDMS/SLAC F_L	38 / 31
E866/NuSea pp DY	228 / 184
E866/NuSea pd/pp DY	14 / 15
NuTeV νN F_2	49 / 53
CHORUS νN F_2	26 / 42
NuTeV νN xF_3	40 / 45
CHORUS νN xF_3	31 / 33
CCFR $\nu N \to \mu\mu X$	66 / 86
NuTeV $\nu N \to \mu\mu X$	39 / 40
All data sets	**2543 / 2699**

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

Input parameterisation in MSTW 2008 NLO fit

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

$$
\begin{aligned}
xu_v &= A_u\, x^{\eta_1}(1-x)^{\eta_2}(1+\epsilon_u\,\sqrt{x}+\gamma_u\,x)\\
xd_v &= A_d\, x^{\eta_3}(1-x)^{\eta_4}(1+\epsilon_d\,\sqrt{x}+\gamma_d\,x)\\
xS &= A_S\, x^{\delta_S}(1-x)^{\eta_S}(1+\epsilon_S\,\sqrt{x}+\gamma_S\,x)\\
x(\bar{d}-\bar{u}) &= A_\Delta\, x^{\eta_\Delta}(1-x)^{\eta_S+2}(1+\gamma_\Delta\,x+\delta_\Delta\,x^2)\\
xg &= A_g\, x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\,\sqrt{x}+\gamma_g\,x)+A_{g'}\,x^{\delta_{g'}}(1-x)^{\eta_{g'}}\\
x(s+\bar{s}) &= A_+\, x^{\delta_S}\,(1-x)^{\eta_+}(1+\epsilon_S\,\sqrt{x}+\gamma_S\,x)\\
x(s-\bar{s}) &= A_-\, x^{0.2}(1-x)^{\eta_-}(1-x/x_0)
\end{aligned}
$$

- A_u, A_d, A_g and x_0 are determined from sum rules.
- 28 parameters allowed to go free to find best fit,
  20 parameters allowed to go free for error propagation.

Compare to input parameterisation in HERAPDF fits

Input parameterisation ($Q_0^2 = 1.9$ GeV^2) in HERAPDF1.0/1.5

$$xu_v = A_{u_v}\, x^{B_{qv}}(1-x)^{C_{u_v}}(1+E_{u_v}\, x^2)$$

$$xd_v = A_{d_v}\, x^{B_{qv}}(1-x)^{C_{d_v}}$$

$$x\bar{u} = A_{\bar{q}}\, x^{B_{\bar{q}}}(1-x)^{C_{\bar{u}}}$$

$$x\bar{d} = A_{\bar{q}}\, x^{B_{\bar{q}}}(1-x)^{C_{\bar{d}}}$$

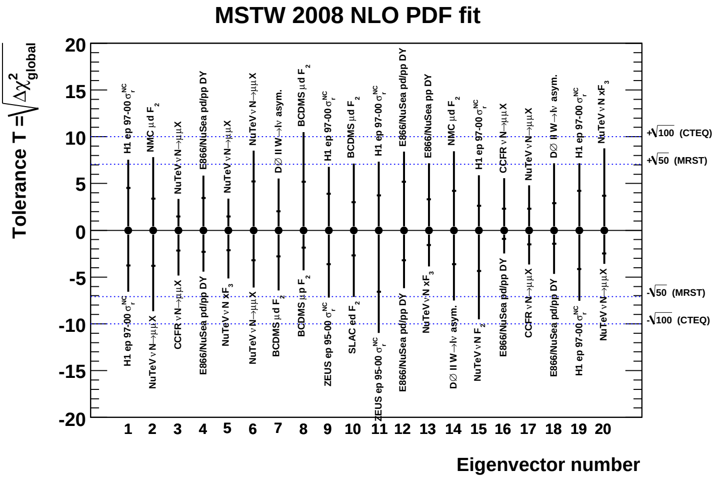
$$x\bar{s} = 0.45\, x\bar{d}$$

$$xs = x\bar{s}$$

$$xg = A_g\, x^{B_g}(1-x)^{C_g}$$

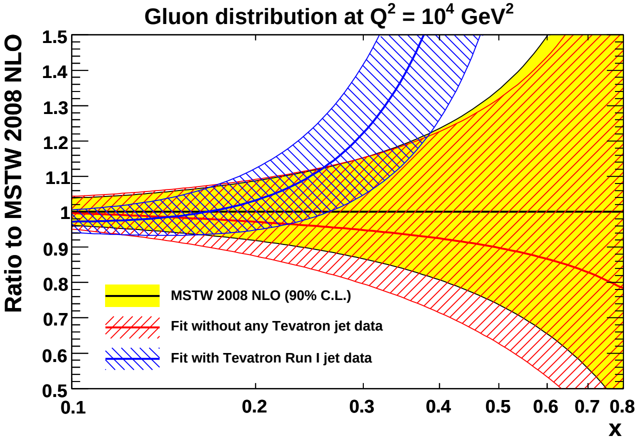
- 10 parameters for central fit and "experimental" uncertainties, additional "model" and "parameterisation" uncertainties.
- 4 more params. for HERAPDF1.5 NNLO (2 for g, 1 each for u_v, d_v).

Dynamic tolerance: different for each eigenvector



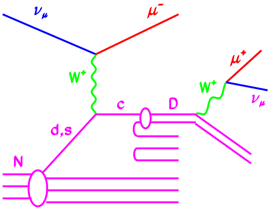
- Outer (inner) error bars give tolerance for 90% (68%) C.L.

Impact of Tevatron Run II jet data on high-x gluon



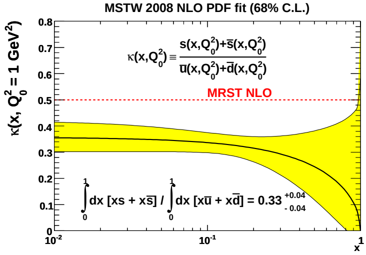
- Run II jet data prefer **softer** gluon at high x than Run I.

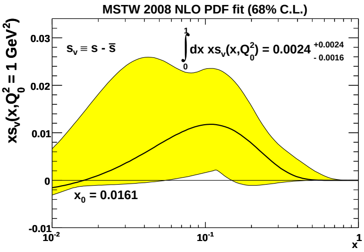
NuTeV/CCFR dimuon cross sections and strangeness



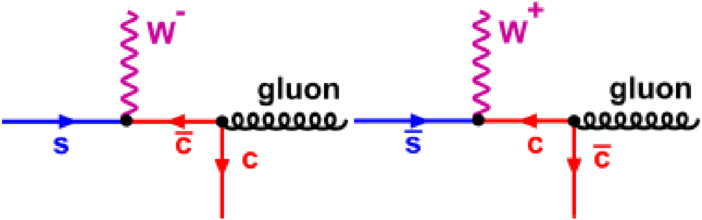
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y}(\nu_\mu N \to \mu^+\mu^- X) = B_c\,\mathcal{A}\,\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y}(\nu_\mu N \to \mu^- c\, X)$$
$$\propto |V_{cs}|^2 \xi s(\xi, Q^2) + |V_{cd}|^2 \ldots$$

- ν_μ and $\bar{\nu}_\mu$ cross sections constrain s and $\bar{s}$.



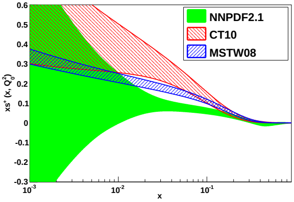


W+charm as a probe of strangeness [CMS PAS EWK-11-013]



- Dominant $\bar{s}\,\mathbf{g} \to W^+\,\bar{c}$ and $s\,\mathbf{g} \to W^-\,c$.
- 5% from $\bar{d}\,\mathbf{g} \to W^+\,\bar{c}$, 15% from $d\,\mathbf{g} \to W^-\,c$.

$x(s+\bar{s})(x, Q^2 = 2\ \mathrm{GeV}^2)$:

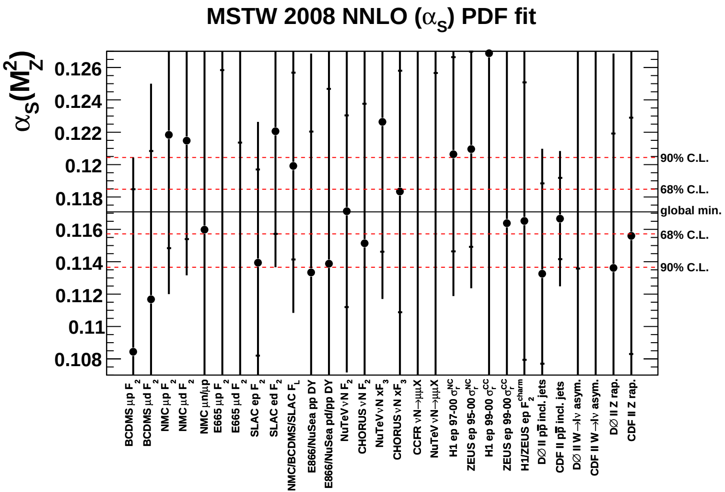


$$R_c^\pm \equiv \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)} = 0.92 \pm 0.19(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$$

$$R_c \equiv \frac{\sigma(W + c)}{\sigma(W + \mathrm{jets})} = 0.143 \pm 0.015(\mathrm{stat.}) \pm 0.024(\mathrm{syst.})$$

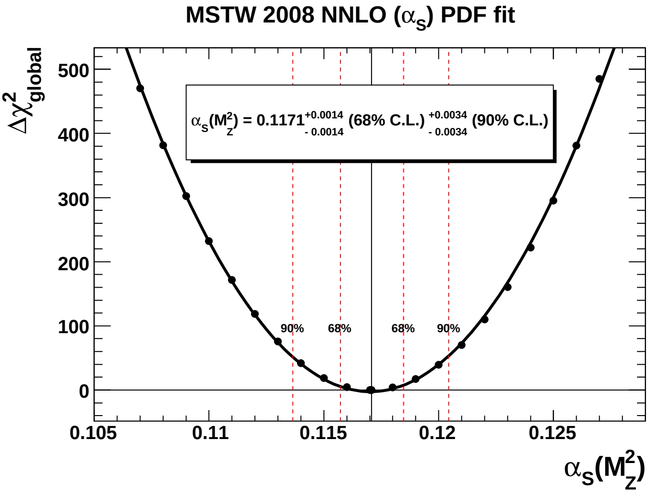
Ratio	MCFM (MSTW08)	MCFM (CT10)	MCFM (NNPDF2.1)
$R_c^\pm$	$0.881^{+0.022}_{-0.032}$	$0.915^{+0.006}_{-0.006}$	0.902 ± 0.008
R_c	$0.118^{+0.002}_{-0.002}$	$0.125^{+0.013}_{-0.007}$	0.103 ± 0.005

Dependence on strong coupling $\alpha_S(M_Z^2)$ [MSTW, arXiv:0905.3531]



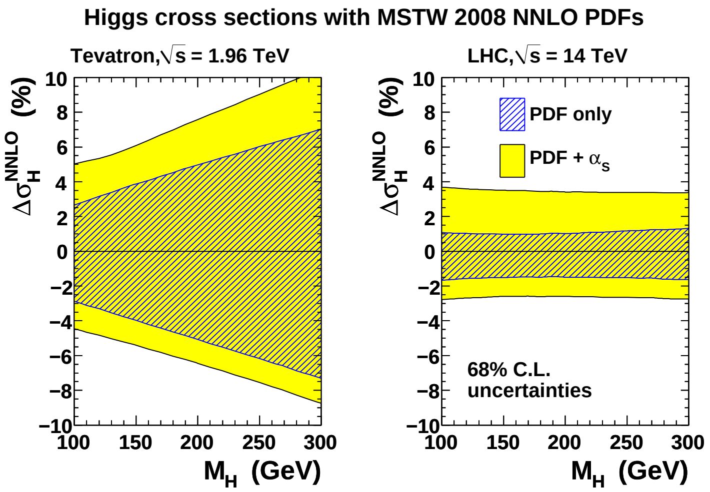
- **Experimental error** on best-fit $\alpha_S(M_Z^2)$ using same method applied to determine the tolerance for each eigenvector.

$\Delta\chi^2_{\rm global}$ as a function of $\alpha_S(M_Z^2)$ for the NNLO global fit



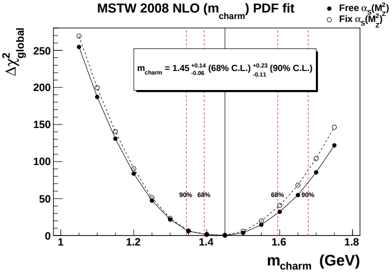
- Additional theory uncertainty ($\lesssim |\mathrm{NNLO} - \mathrm{NLO}| = 0.003$).
- cf. $\alpha_S(M_Z^2) = 0.1184 \pm 0.0007$ [S. Bethke, arXiv:0908.1135].

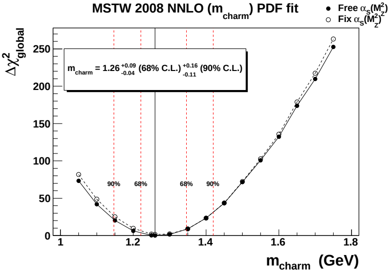
Impact of α_S on SM Higgs uncertainty versus M_H



- Enhanced "PDF+α_S" uncertainty compared to "PDF only".

Heavy-quark mass dependence [MSTW, arXiv:1007.2624]





Impact of (pole-mass) $m_{c,b}$ variation on LHC cross sections

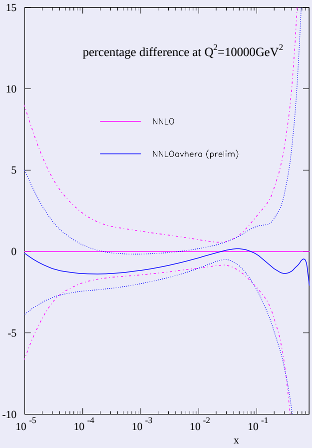
- Vary $m_c = 1.40 \pm 0.15$ GeV $\Rightarrow$ just over 1% change in $\sigma_{W,Z}$.
- Vary $m_b = 4.75 \pm 0.25$ GeV $\Rightarrow$ negligible change (0.1%).

LHC, $\sqrt{s} = 7$ TeV	σ_W	σ_Z	σ_H
PDF only uncertainty	$+1.7\%$ -1.6%	$+1.7\%$ -1.5%	$+1.1\%$ -1.6%
PDF+α_S uncertainty	$+2.5\%$ -1.9%	$+2.5\%$ -1.9%	$+3.7\%$ -2.9%
PDF+α_S+$m_{c,b}$ uncertainty	$+2.7\%$ -2.2%	$+2.9\%$ -2.4%	$+3.7\%$ -2.9%

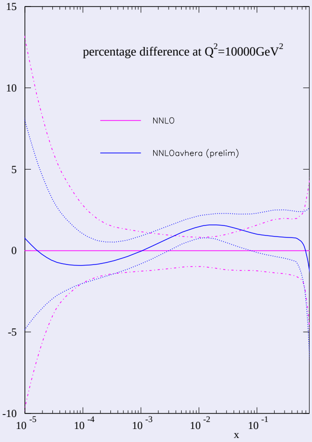
- Only slight increase in uncertainty on $\sigma_{W,Z}$, no impact on σ_H.

Impact of combined HERA I data [arXiv:0911.0884] (R. Thorne)

Gluon distribution

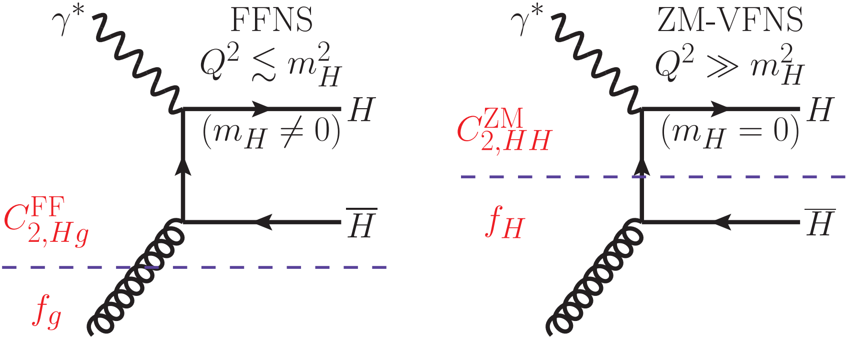


Up quark distribution



- Changes not large enough to warrant an immediate update.

Heavy quark contribution to DIS structure function F_2



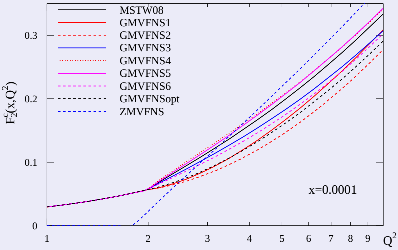
Fixed flavour number scheme

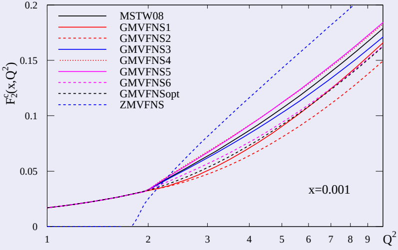
Zero-mass variable flavour number scheme

- **G**eneral-**m**ass **v**ariable **f**lavour **n**umber **s**cheme (**GM-VFNS**) interpolates between two well-defined regions ($H \equiv c, b$): **FFNS** for $Q^2 \leq m_H^2$, **ZM-VFNS** for $Q^2 \gg m_H^2$.
- Ambiguous up to $\mathcal{O}(m_H^2/Q^2)$ terms $\Rightarrow$ theory uncertainty.

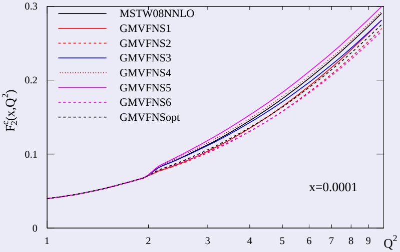
Impact of GM-VFNS variations [R. Thorne, arXiv:1006.5925]

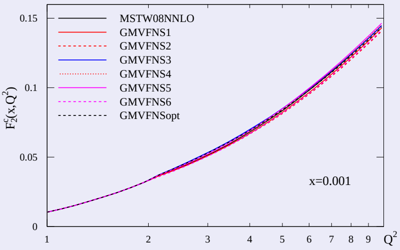
$F_2^{\rm charm}$ at NLO (fixed PDFs)





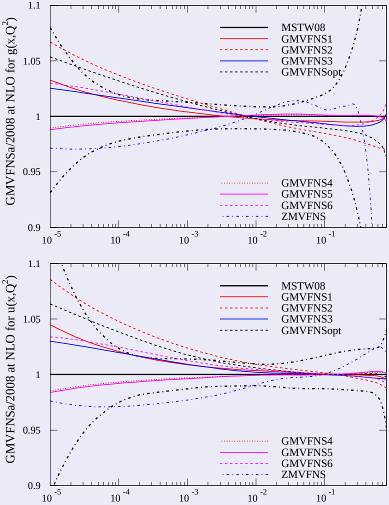
$F_2^{\rm charm}$ at NNLO (fixed PDFs)



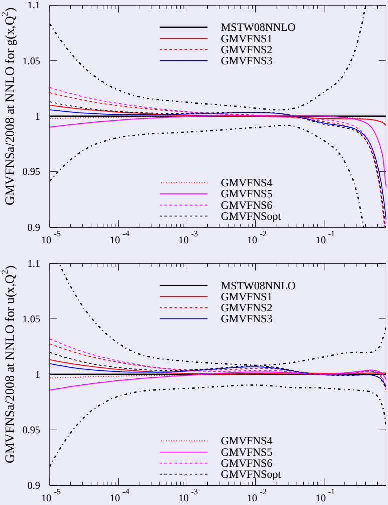


Impact of GM-VFNS variations [R. Thorne, arXiv:1006.5925]

Effect on g and u at NLO



Effect on g and u at NNLO



Background and motivation for benchmark exercise

- Various fitting groups currently produce PDF sets: **MSTW**, CT, NNPDF, HERAPDF, AB(K)M, (G)JR.
- Quantifying and understanding differences *between* groups is as (or more) important as continued improvements *within* groups.
- Recent work initiated by activities of *LHC Higgs Cross Section Working Group* and *PDF4LHC Working Group*.
- Use most recent public NLO PDFs from all fitting groups to calculate LHC benchmark processes: $W^{\pm}$, Z^0, $t\bar{t}$, $gg \to H$.
  Aims:
  - Establish degree of compatibility and identify outliers.
  - Compare cross sections at *same* α_S values.
  - To what extent are differences in predictions due to different α_S values used by each group, rather than differences in PDFs?
- Results initially presented in talk by **G.W.** at PDF4LHC meeting at CERN on 26th March 2010 and formed basis for subsequent *PDF4LHC Interim Report* [arXiv:1101.0536].
- Subsequent update and extension to NNLO [G.W., arXiv:1106.5788].

Status of PDFs from different groups in March 2010

- Consider only *public* sets, where "public" ≡ available in LHAPDF.
- Then LHAPDF V5.8.2 (released 18th March 2010).
- Highlight major differences in data and theory between groups:

	MSTW08	**CTEQ6.6**	**NNPDF2.0**	HERAPDF1.0	ABKM09	GJR08/JR09
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✗	✔	✔
Fixed-target DY	✔	✔	✔	✗	✔	✔
Tevatron W,Z	✔	✔	✔	✗	✗	✗
Tevatron jets	✔	✔	✔	✗	✗	✔
GM-VFNS	✔	✔	✗	✔	✗	✗
NNLO	✔	✗	✗	✗	✔	✔

- "Global" ≡ includes all five main categories of data.
- GJR08 *almost* global but restrictive "dynamical" parameterisation.
- *Three* groups with **NLO** global fits, but only *one* at **NNLO**. Approx. NNLO for jets, massive $\mathcal{O}(\alpha_S^3)$ NC and $\mathcal{O}(\alpha_S^2)$ CC DIS.
- CTEQ6.6 only uses Tevatron Run I data, not Run II.
- NNPDF2.0 inadequate through use of ZM-VFNS for DIS.

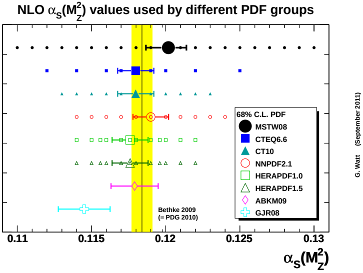
Status of PDFs from different groups in September 2011

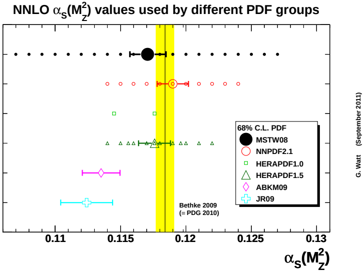
- Now LHAPDF V5.8.6 (released 2nd August 2011).
- Highlight major differences in data and theory between groups:

	MSTW08	**CT10**	**NNPDF2.1**	HERAPDF1.5	ABKM09	GJR08/JR09
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✗	✔	✔
Fixed-target DY	✔	✔	✔	✗	✔	✔
Tevatron W,Z	✔	✔	✔	✗	✗	✗
Tevatron jets	✔	✔	✔	✗	✗	✔
GM-VFNS	✔	✔	✔	✔	✗	✗
NNLO	✔	✗	✔	✔	✔	✔

- CT10 uses both Tevatron Run I and Run II data.
- Only CT10, NNPDF2.1 and HERAPDF use *combined* HERA I.
- Only HERAPDF1.5 uses preliminary *combined* HERA II data.
- NNPDF2.0 (ZM-VFNS) $\rightarrow$ NNPDF2.1 (GM-VFNS), now allowing meaningful comparison to other NLO global fits.
- NNPDF2.1 and HERAPDF1.5 now provided at NNLO.

Default values of $\alpha_S(M_Z^2)$ used by different fitting groups

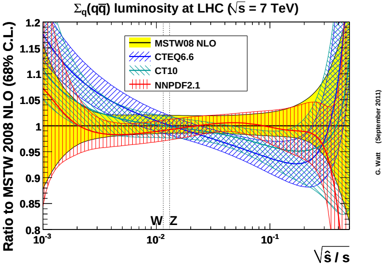


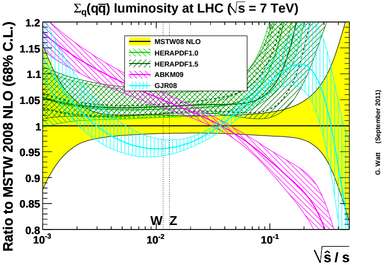


- $\alpha_S(M_Z^2)$ for MSTW08, ABKM09 and GJR08/JR09 fitted.
- $\alpha_S(M_Z^2)$ for other groups applied as an external constraint.
- Smaller symbols indicate alternative $\alpha_S(M_Z^2)$ values provided.
- Fitted NLO $\alpha_S(M_Z^2)$ always larger than NNLO $\alpha_S(M_Z^2)$: attempt by fit to mimic missing higher-order corrections.

Ratio of NLO quark–antiquark luminosity functions

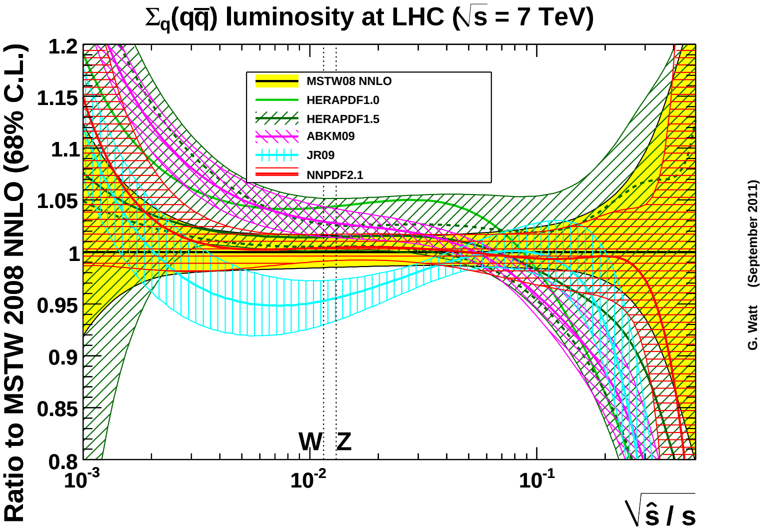
$$\frac{\partial \mathcal{L}_{\Sigma_q(q\bar{q})}}{\partial \hat{s}} = \frac{1}{s}\int_\tau^1 \frac{\mathrm{d}x}{x} \sum_{q=d,u,s,c,b} \left[q(x,\hat{s})\bar{q}(\tau/x,\hat{s}) + (q \leftrightarrow \bar{q})\right], \quad \tau \equiv \frac{\hat{s}}{s}$$





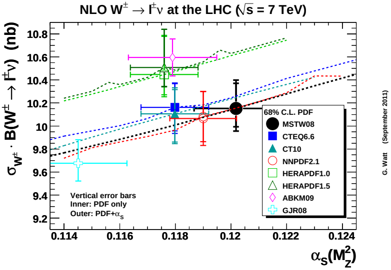
- Relevant values of $\sqrt{\hat{s}} = M_{W,Z}$ are indicated: good agreement for global fits (left), but more variation for other sets (right).

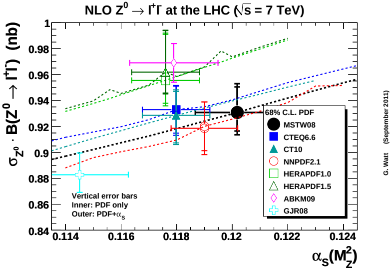
Ratio of NNLO quark–antiquark luminosity functions



- NNLO trend between groups similar to NLO (apart from HERAPDF).

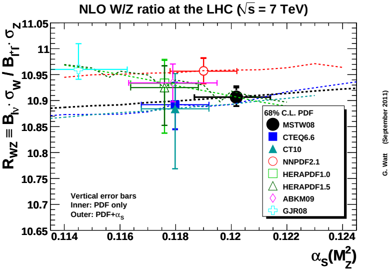
NLO $W^{\pm}$ and Z^0 total cross sections versus $\alpha_S(M_Z^2)$



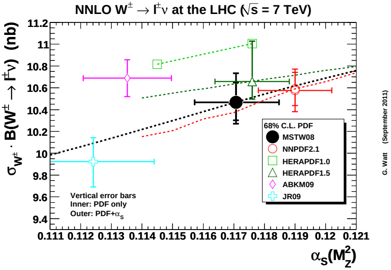


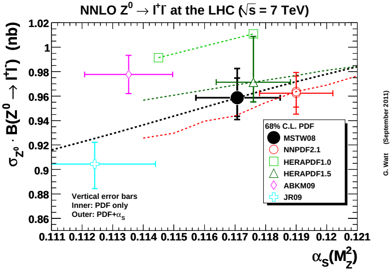
- Global fits in good agreement for $\sigma_{W^{\pm}}$ and σ_{Z^0} (left plots).
- Small PDF uncertainties in predictions for W/Z ratio:

$$\frac{\sigma_{W^+} + \sigma_{W^-}}{\sigma_{Z^0}} \sim \frac{u(x_1) + d(x_1)}{0.29\, u(\tilde{x}_1) + 0.37\, d(\tilde{x}_1)}$$

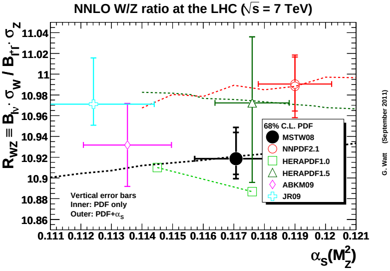


NNLO $W^{\pm}$ and Z^0 total cross sections versus $\alpha_S(M_Z^2)$

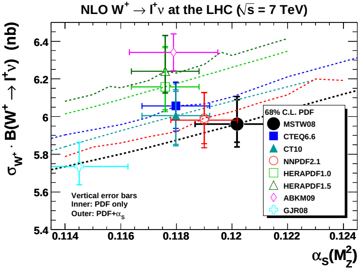


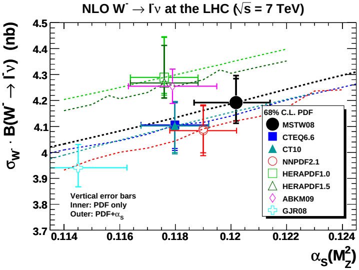


- HERAPDF1.5 closer to global fits at NNLO for $\sigma_{W^{\pm}}$ and σ_{Z^0} (left plots).
- W/Z ratio insensitive to NNLO corrections (and α_S):



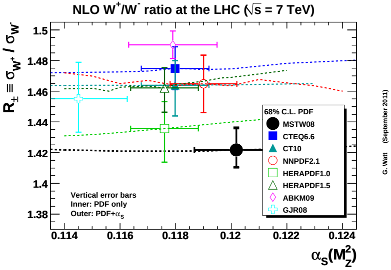
NLO W^+ and W^- total cross sections versus $\alpha_S(M_Z^2)$



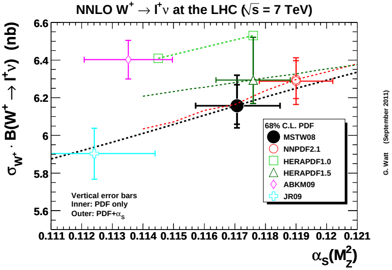


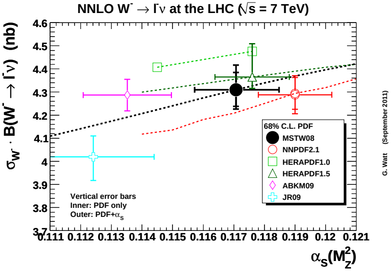
- Slightly more spread in separate σ_{W^+} and σ_{W^-}.
- Reflected in W^+/W^- ratio:

$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \sim \frac{u(x_1)\bar{d}(x_2)}{d(x_1)\bar{u}(x_2)} \sim \frac{u(x_1)}{d(x_1)}$$

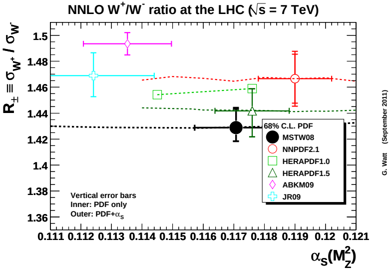


NNLO W^+ and W^- total cross sections versus $\alpha_S(M_Z^2)$



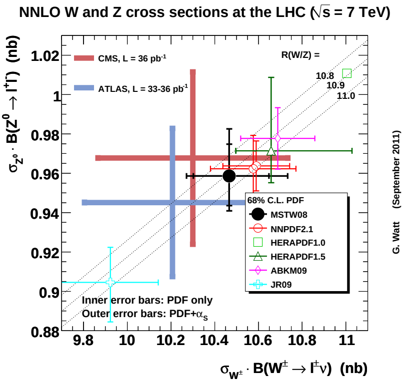


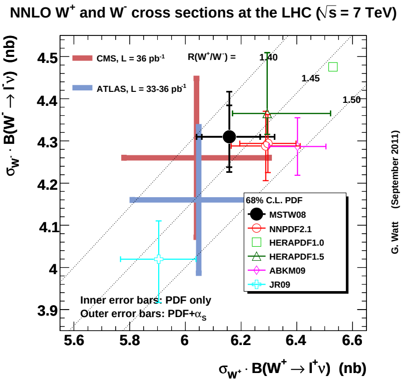
- HERAPDF1.5 closer to global fits at NNLO for σ_{W^+} and σ_{W^-} (left plots).
- W^+/W^- ratio insensitive to NNLO corrections (and α_S):



NNLO $W^{\pm}$ vs. Z^0 and W^+ vs. W^- total cross sections

- Consolidate two cross section measurements (and their ratio).

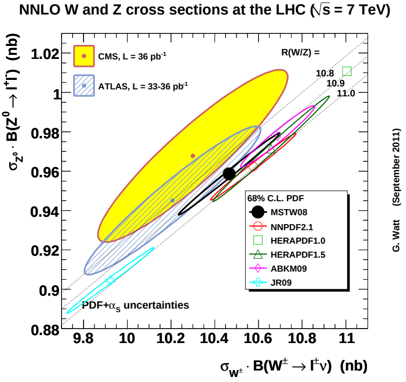


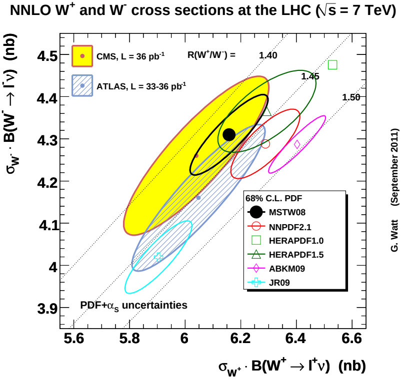


- Luminosity uncertainty of 3.4% (ATLAS) or 4% (CMS).
- Know correlation of both data and theory (from PDFs).

NNLO $W^{\pm}$ vs. Z^0 and W^+ vs. W^- total cross sections

- Correlation of ellipse ⇔ uncertainty in ratio of cross sections.

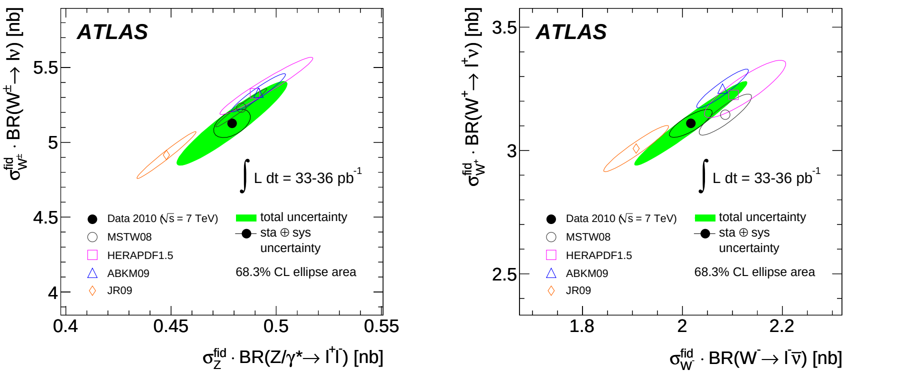




- Largest uncertainty in ATLAS/CMS total cross-section **ratios** from acceptance calculation ⇒ compare to theory **within** acceptance.

NNLO $W^\pm$ vs. Z^0 and W^+ vs. W^- fiducial cross sections

[http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-06/]

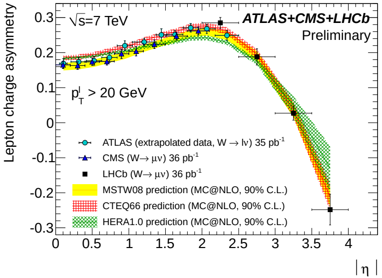


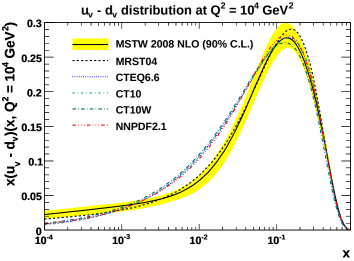
- **NNLO** comparisons now possible using FEWZ or DYNNLO codes.

$W^\pm \to \ell^\pm \nu$ charge asymmetry at the LHC

$$A_W(y_W) = \frac{\mathrm{d}\sigma(W^+)/\mathrm{d}y_W - \mathrm{d}\sigma(W^-)/\mathrm{d}y_W}{\mathrm{d}\sigma(W^+)/\mathrm{d}y_W + \mathrm{d}\sigma(W^-)/\mathrm{d}y_W} \approx \frac{u_v(x_1) - d_v(x_1)}{u(x_1) + d(x_1)}$$

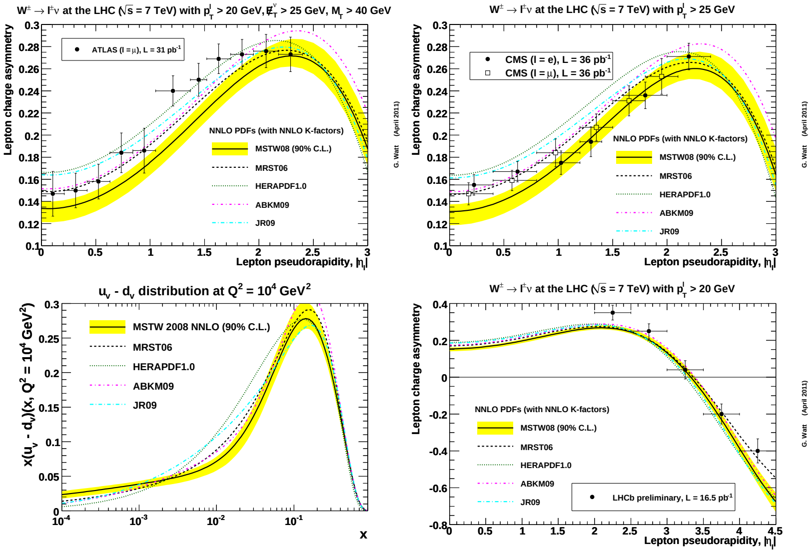
$$A_\ell(\eta_\ell) = \frac{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell - \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell}{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell + \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell} \equiv A_W(y_W) \otimes (W^\pm \to \ell^\pm \nu)$$





- First PDF constraint from LHC data (→ NNPDF2.2).
- **MSTW08** has input $xu_v \propto x^{0.29\pm0.02}$ and $xd_v \propto x^{0.97\pm0.11}$. Many other groups **assume** equal powers ⇒ potential bias.

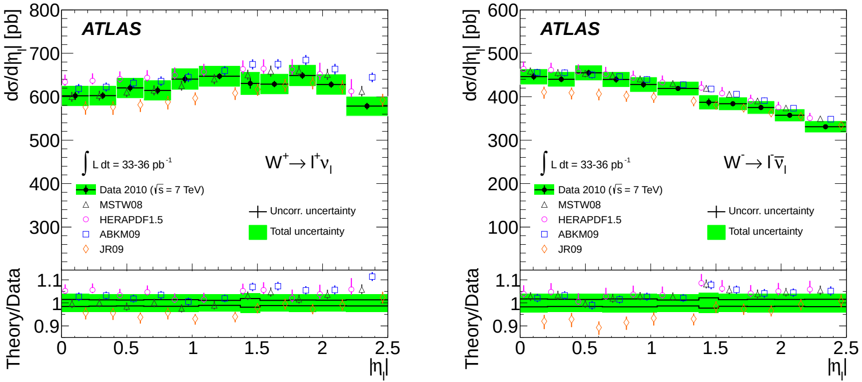
NNLO comparisons to data from ATLAS, CMS and LHCb



- Wide spread in predictions using different NNLO PDF sets.

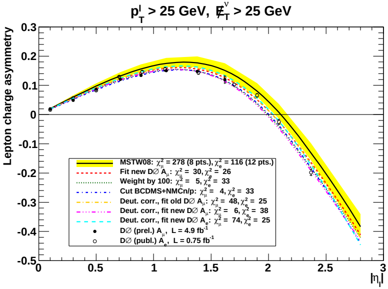
Differential cross sections: $\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell$ and $\mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell$

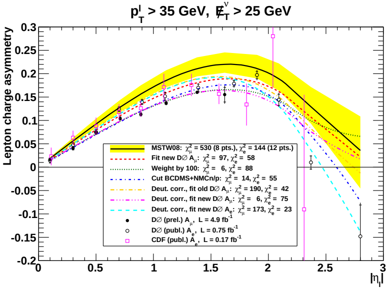
[http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-06/]



- ATLAS provide differential cross sections for W^+ and W^- with information on correlated systematic uncertainties.
  $\Rightarrow$ Potentially more useful for PDF fits than simply $A_\ell(\eta_\ell)$.

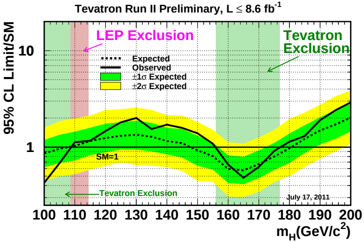
$W^{\pm} \to \ell^{\pm}\nu$ charge asymmetry at the Tevatron



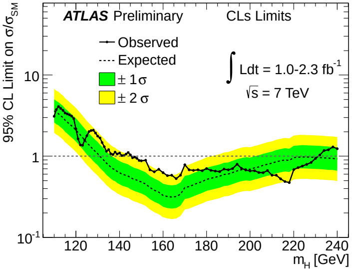


- Outstanding issues to be resolved concerning Tevatron data, particularly when split up into p_T^ℓ bins [MSTW, arXiv:1006.2753].
- **Current plan:** consider only inclusive p_T^ℓ bin, try to fit nuclear effects in deuteron structure functions simultaneously with PDFs.

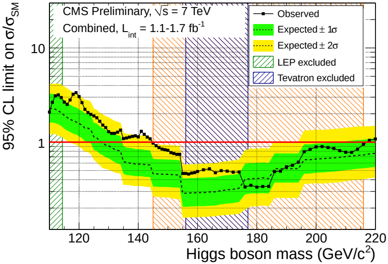
Exclusion limits at 95% C.L. for SM Higgs boson



[TEVNPHWG, arXiv:1107.5518]



	M_H (GeV)	$x \sim M_H/\sqrt{s}$
Tevatron	156 – 177	0.08 – 0.09
ATLAS	146 – 232	0.02 – 0.03
	256 – 282	0.04 – 0.04
	296 – 466	0.04 – 0.07
CMS	145 – 216	0.02 – 0.03
	226 – 288	0.03 – 0.04
	310 – 340	0.04 – 0.05

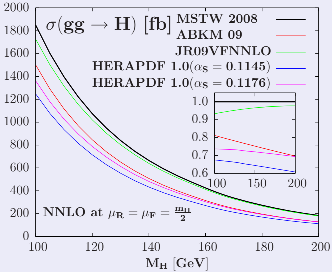


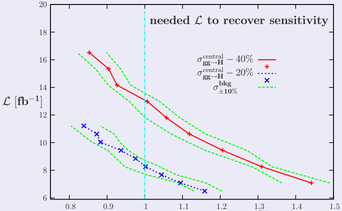
- $\sigma_{\rm SM}$ uses **MSTW 2008** PDFs.

Tevatron Higgs exclusion limits: a critical appraisal

[Baglio, Djouadi, Ferrag, Godbole, arXiv:1101.1832]

Phys. Lett. B **699** (2011) 368





Tevatron Higgs exclusion limits: a critical appraisal

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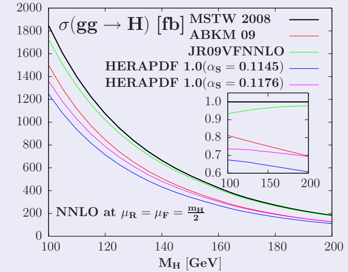
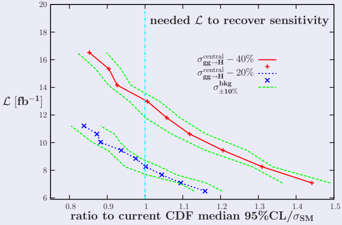
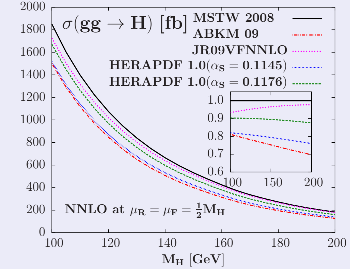
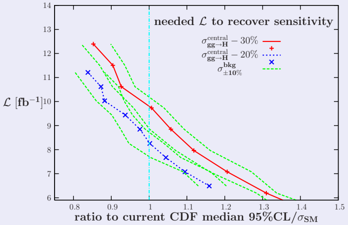
Phys. Lett. B **699** (2011) 368



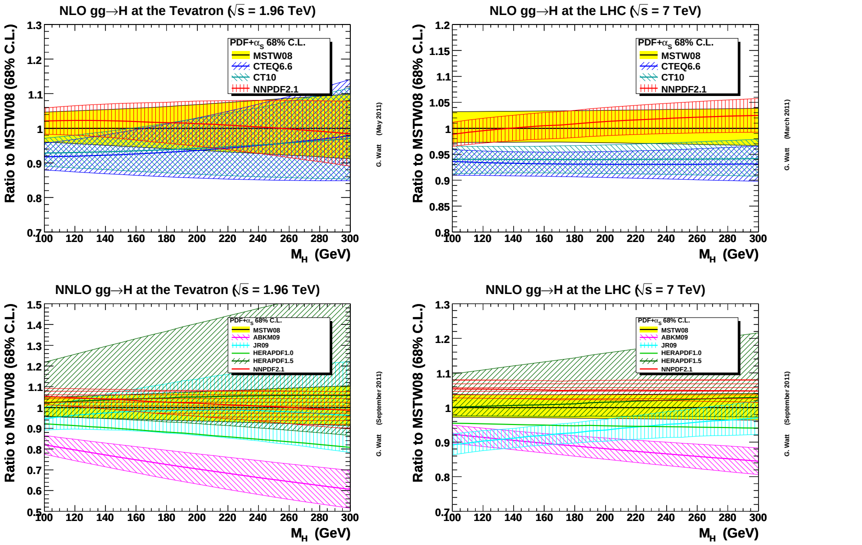


Erratum-ibid. B **702** (2011) 105



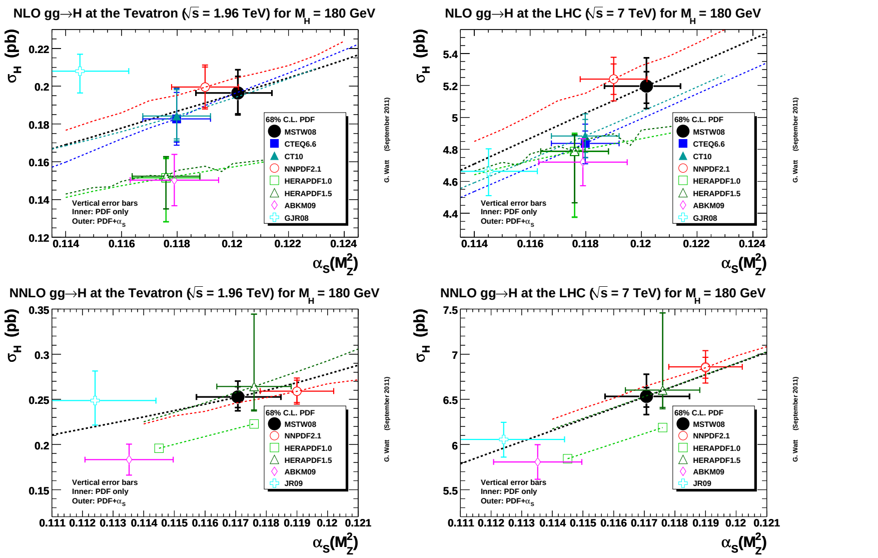


$gg \to H$ total cross sections versus SM Higgs mass M_H



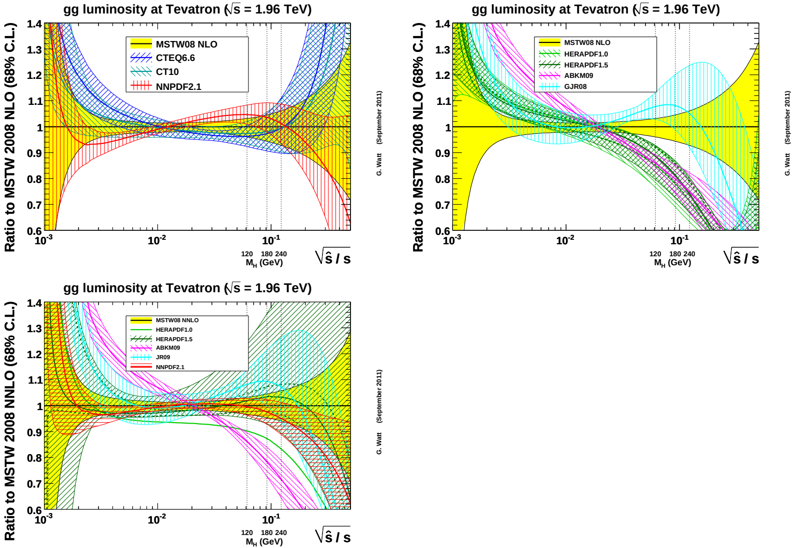
- HERAPDF1.5 and NNPDF2.1 results agree with **MSTW08**.

$gg \to H$ total cross sections versus $\alpha_S(M_Z^2)$



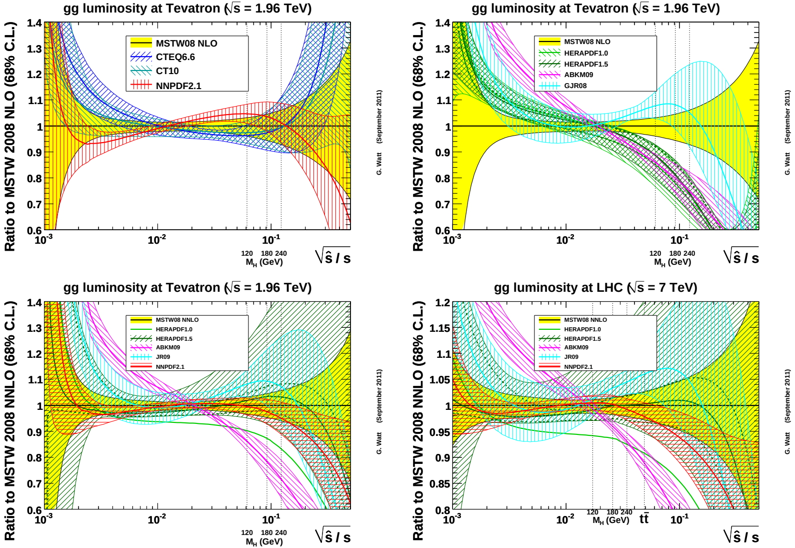
- $\alpha_S(M_Z^2)$ values can only *partly* explain low σ_H for ABKM09.

Ratio of gluon–gluon luminosity functions



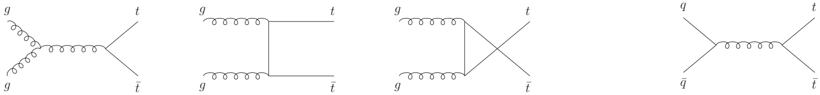
- Relevant values of $\sqrt{\hat{s}} = M_H$ are indicated.

Ratio of gluon–gluon luminosity functions



- Relevant values of $\sqrt{\hat{s}} = M_H, 2m_t$ are indicated.

Top-pair production at the Tevatron and LHC

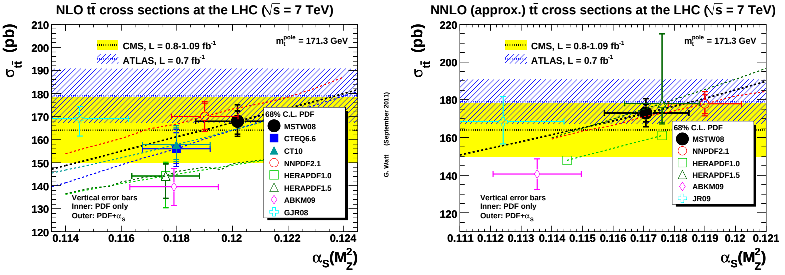


- $\sim$80% of $\sigma_{t\bar{t}}^{\rm NLO}$ from gg at LHC (7 TeV), cf. $\sim$15% at Tevatron.
- Compare NLO and various NNLO approximations for total $\sigma_{t\bar{t}}$ (pb) for $m_t = 173$ GeV [Kidonakis, Pecjak, arXiv:1108.6063]:

Calculation	Tevatron	LHC (7 TeV)
NLO	$6.74^{+0.36\,+0.37}_{-0.76\,-0.24}$	$160^{+20\,+8}_{-21\,-9}$
Aliev *et al.* [arXiv:1007.1327]	$7.13^{+0.31\,+0.36}_{-0.39\,-0.26}$	$164^{+3\,+9}_{-9\,-9}$
Kidonakis [arXiv:1009.4935]	$7.08^{+0.00\,+0.36}_{-0.24\,-0.24}$	$163^{+7\,+9}_{-5\,-9}$
Ahrens *et al.* [arXiv:1105.5824]	$6.65^{+0.08\,+0.33}_{-0.41\,-0.24}$	$156^{+8\,+8}_{-9\,-9}$

- First uncertainty is perturbative ($\mu_{R,F}$ variation etc.). Second uncertainty is the MSTW08 PDF error at 90% C.L.

$t\bar{t}$ total cross sections versus $\alpha_S(M_Z^2)$ at the LHC



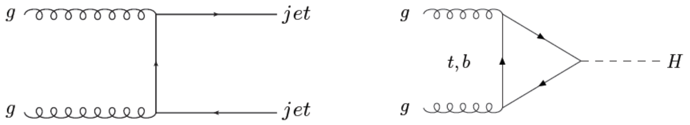
- NNLO (approx.) using HATHOR code [Aliev *et al.*, arXiv:1007.1327].
- Compare to single most precise current LHC measurements.
  - **CMS:** $\sigma_{t\bar{t}} = 164 \pm 3(\mathrm{stat.}) \pm 12(\mathrm{syst.}) \pm 7(\mathrm{lumi.})$ pb (e/μ+jets+b-tag) [CMS PAS TOP-11-003]
  - **ATLAS:** $\sigma_{t\bar{t}} = 179.0 \pm 9.8(\text{stat.+syst.}) \pm 6.6(\mathrm{lumi.})$ pb (using kinematic information of lepton+jets events) [ATLAS-CONF-2011-121]
- Tevatron: $m_t = 173.2 \pm 0.9$ GeV [TEVEWWG, arXiv:1107.5255]. Increasing m_t by 2 GeV decreases predicted $\sigma_{t\bar{t}}$ at LHC by 6%.

Jets as a discriminator of the high-x gluon distribution

JETS

PV: Any PDF should reproduce jet data if being used for Higgs

Closest observable to Higgs in terms of Luminosity, kinematics and power of coupling!



[D. de Florian, talk at "Higgs Hunting 2011", Orsay, France, 28th July 2011]

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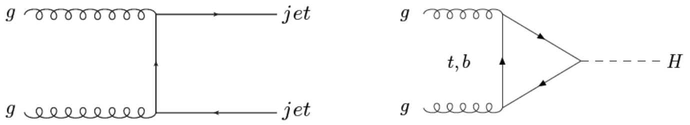
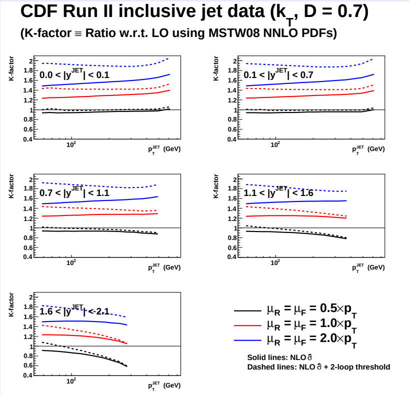


[D. de Florian, talk at "Higgs Hunting 2011", Orsay, France, 28th July 2011]

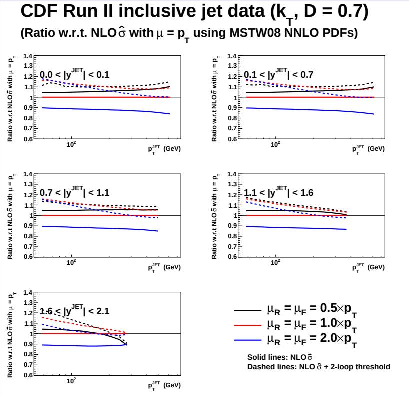
- **Problem:** NNLO $\hat{\sigma}$ unknown, approximate with NLO $\hat{\sigma}$ and 2-loop threshold corrections [Kidonakis, Owens, hep-ph/0007268].
- Jet cross sections calculated with FASTNLO [Kluge, Rabbertz, Wobisch, hep-ph/0609285]: includes 2-loop threshold corrections.
- Take different scale choices $\mu_R = \mu_F = \mu = \{p_T/2, p_T, 2p_T\}$ as some indication of the theoretical uncertainty.

Scale dependence and size of 2-loop threshold corrections

Ratio w.r.t. LO for different μ

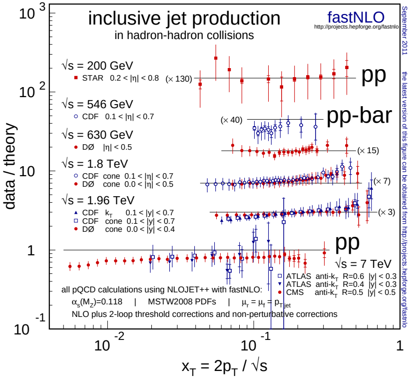


Ratio w.r.t. NLO with $\mu = p_T$

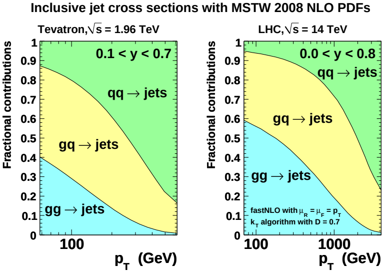


- K-factor with $\mu = p_T$ more uniform across $|y_{\rm JET}|$ bins than $\mu = p_T/2$.
- Scale dependence stabilised by inclusion of 2-loop threshold corrections.
- Lack of exact NNLO should **not** prevent use of jet data in PDF fits.

Inclusive jet production at the Tevatron and LHC



[M. Wobisch *et al.*, arXiv:1109.1310]



[MSTW, arXiv:0905.3531]

- Quarks constrained by other data ⇒ jets constrain gluon.

- **LHC jets**: generally lower x_T, no correlated systematics.
- Current best constraint on high-x gluon from **Tevatron jets**.

Treatment of correlated systematic uncertainties

- Important to account for *correlated* systematic uncertainties of experimental data points [CTEQ6, hep-ph/0201195]:

$$\chi^2 = \sum_{i=1}^{N_{\rm pts.}} \left(\frac{\hat{D}_i - T_i}{\sigma_i^{\rm uncorr.}} \right)^2 + \sum_{k=1}^{N_{\rm corr.}} {r_k}^2, \qquad (1)$$

where $\hat{D}_i \equiv D_i - \sum_{k=1}^{N_{\rm corr.}} r_k \, \sigma_{k,i}^{\rm corr.}$ are *shifted* data points.

- Trade-off between systematic shifts r_k and fitted parameters.
- More traditional form (with hidden systematic shifts):

$$\chi^2 = \sum_{i=1}^{N_{\rm pts.}} \sum_{j=1}^{N_{\rm pts.}} (D_i - T_i) \left(V^{-1}\right)_{ij} (D_j - T_j), \qquad (2)$$

where $V_{ij} = \delta_{ij} \, (\sigma_i^{\rm uncorr.})^2 + \sum_{k=1}^{N_{\rm corr.}} \sigma_{k,i}^{\rm corr.} \, \sigma_{k,j}^{\rm corr.}$.

- χ^2 definition similar to Eq. (1) used by **MSTW** and CTEQ.
  χ^2 definition similar to Eq. (2) used by ABKM and NNPDF.

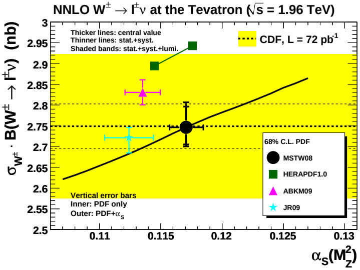
Description of CDF II inclusive jet (k_T) data [hep-ex/0701051]

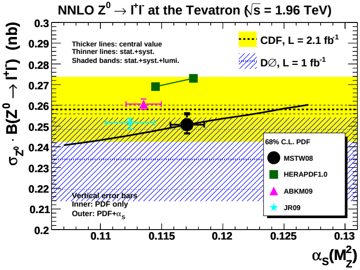
- Values of $\chi^2/N_{\rm pts.}$ for different NNLO PDFs and scale choices:

NNLO PDF	$\alpha_S(M_Z^2)$	$\mu = p_T/2$	$\mu = p_T$	$\mu = 2p_T$
MSTW08	0.1171	1.39 (+0.35)	0.69 (−0.45)	0.97 (−*1.30*)
NNPDF2.1	0.1190	0.68 (−0.77)	0.71 (−*2.02*)	0.71 (−**3.46**)
HERAPDF1.0	0.1145	2.37 (−*2.65*)	1.48 (−**3.64**)	1.29 (−**4.12**)
HERAPDF1.0	0.1176	2.24 (−0.48)	1.13 (−*1.60*)	1.09 (−*2.23*)
HERAPDF1.5	0.1176	1.61 (+*1.22*)	0.77 (+0.30)	1.06 (−0.39)
ABKM09	0.1135	1.53 (−**4.27**)	1.23 (−**5.05**)	1.44 (−**5.65**)
JR09	0.1124	0.75 (+0.13)	1.26 (−0.61)	2.20 (−*1.22*)

- Numbers in brackets are the systematic shift ("$-r_{\rm lumi.}$") for the 5.8% luminosity uncertainty.
- Highlight in *italics* if $|r_{\rm lumi.}| \in [1,3]$ and in **bold** if $|r_{\rm lumi.}| > 3$.
- Optimal χ^2 for ABKM09 requires data to be normalised downwards by $\sim$30%, i.e. 5-σ luminosity shift.

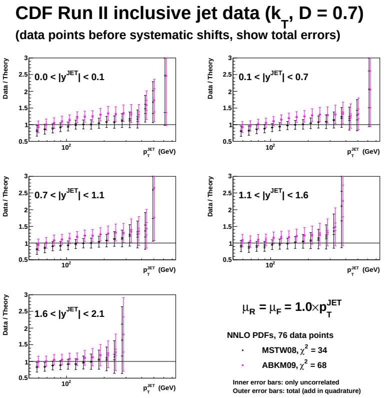
Description of Tevatron W/Z total cross sections

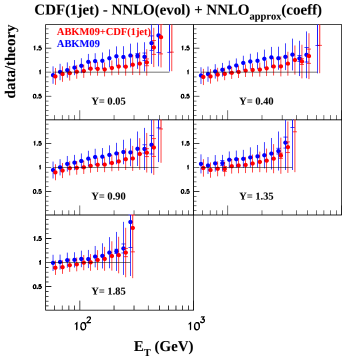




- CDF/DØ measurements of W/Z cross sections are dominated by $\sim$ 6% luminosity uncertainty (common to jet cross sections).
- All NNLO PDFs in good agreement with W/Z cross sections.
- Can use Tevatron W/Z cross sections as a luminosity monitor: demand agreement with theory prediction to effectively remove normalisation uncertainty from jet cross sections.
- Done automatically in **MSTW08** fit by fitting CDF $\mathrm{d}\sigma_Z/\mathrm{d}y_Z$.

Data/theory ratio for MSTW08 and ABKM09





[ABM, arXiv:1105.5349]

- ABM studies: data lie above theory even after refitting. But still 15% increase in σ_H ($M_H = 165$ GeV) at Tevatron.
- Would be interesting to see impact of Tevatron jet data on ABKM09 fit with *constrained* CDF/DØ normalisation.

Description of CDF II inclusive jet (k_T) data [hep-ex/0701051]

- More realistic χ^2 computation without complication of including W/Z data: simply constrain $|r_{\rm lumi.}| < 1$.
- Values of $\chi^2/N_{\rm pts.}$ for different NNLO PDFs and scale choices:

NNLO PDF	$\alpha_S(M_Z^2)$	$\mu = p_T/2$	$\mu = p_T$	$\mu = 2p_T$
MSTW08	0.1171	1.39	**0.69**	0.97
NNPDF2.1	0.1190	**0.68**	**0.81**	1.29
HERAPDF1.0	0.1145	2.64	2.15	2.20
HERAPDF1.0	0.1176	2.24	1.17	1.23
HERAPDF1.5	0.1176	1.61	**0.77**	1.06
ABKM09	0.1135	2.55	2.76	3.41
JR09	0.1124	**0.75**	1.26	2.21

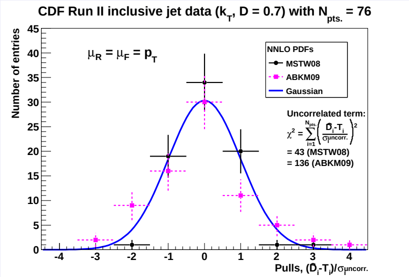
- Highlight in **bold** if $\chi^2/N_{\rm pts.} < 0.83$, i.e. 90% C.L. region.

Distribution of pulls and systematic shifts

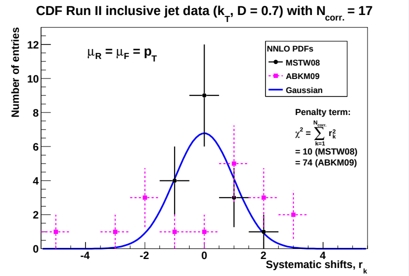
$$\chi^2 = \sum_{i=1}^{N_{\rm pts.}} \left(\frac{\hat{D}_i - T_i}{\sigma_i^{\rm uncorr.}}\right)^2 + \sum_{k=1}^{N_{\rm corr.}} r_k^{\ 2}$$

- Plot distribution of χ^2 contributions from each of two terms:

Pulls, $(\hat{D}_i - T_i)/\sigma_i^{\rm uncorr.}$



Systematic shifts, r_k



- **MSTW08**: both distributions follow Gaussian behaviour.
- ABKM09: broader tail for pulls, non-Gaussian systematic shifts.

Treatment of F_L correction for NMC data

- Recent claim that bulk of **MSTW**/ABKM difference explained by F_L for NMC data [Alekhin, Blümlein, Moch, arXiv:1101.5261].

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2} \simeq \frac{4\pi\alpha^2}{x\,Q^4}\left[1 - y + \frac{y^2/2}{1 + R(x,Q^2)}\right] F_2(x,Q^2)$$

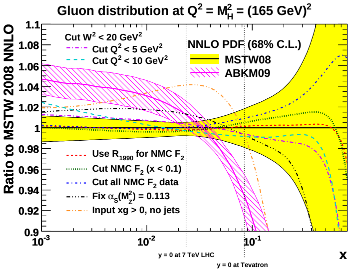
- ABKM fit NMC cross sections, **MSTW** fit NMC F_2 corrected for $R = \sigma_L/\sigma_T \simeq F_L/(F_2 - F_L)$, where [NMC, hep-ph/9610231]:

$$R(x,Q^2) = \begin{cases} R_{\rm NMC}(x) & \text{if } x < 0.12 \\ R_{1990}(x,Q^2) & \text{if } x > 0.12 \end{cases}.$$

ABKM09	**MSTW08**
Fit NMC cross section	Fit NMC F_2
$Q^2 \geq 2.5\ \mathrm{GeV}^2$, $W^2 \geq 3.24\ \mathrm{GeV}^2$	$Q^2 \geq 2\ \mathrm{GeV}^2$, $W^2 \geq 15\ \mathrm{GeV}^2$
Fit empirical higher-twist	Neglect higher-twist
Separated beam energies	Averaged beam energies
Correlated systematics	Neglect correlations
3 input gluon parameters	7 input gluon parameters
No jet data	Tevatron jet data

Effect of NMC F_L treatment on $\alpha_S(M_Z^2)$ and σ_H

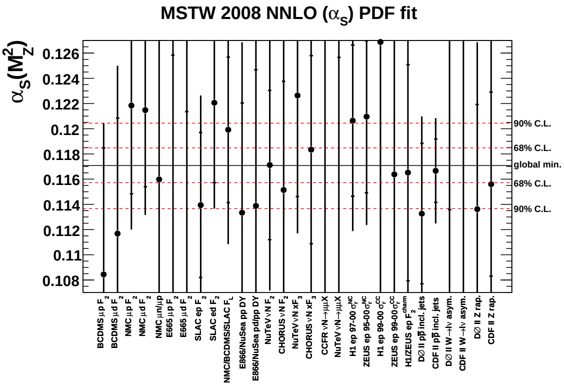
NNLO PDF	$\alpha_S(M_Z^2)$	σ_H at Tevatron	σ_H at 7 TeV LHC
MSTW08	**0.1171**	**0.342 pb**	**7.91 pb**
Use R_{1990} for NMC F_2	0.1167	-0.7%	-0.9%
Cut NMC F_2 ($x < 0.1$)	0.1162	-1.2%	-2.1%
Cut all NMC F_2 data	0.1158	-0.7%	-2.1%
Cut $Q^2 < 5$ GeV^2, $W^2 < 20$ GeV^2	0.1171	-1.2%	$+0.4\%$
Cut $Q^2 < 10$ GeV^2, $W^2 < 20$ GeV^2	0.1164	-3.0%	-1.7%
Fix $\alpha_S(M_Z^2)$	0.1130	-11%	-7.6%
Input $xg > 0$, no jets	0.1139	-17%	-4.9%
ABKM09	0.1135	-26%	-11%



- α_S and σ_H insensitive to treatment of NMC F_L.
- Similar stability found by NNPDF [arXiv:1102.3182], but using a fixed $\alpha_S(M_Z^2)$.
- **Conclusion:** jets stabilise fit (lessen sensitivity to details).

Common lore that DIS-only fits prefer low α_S. Is it true?

ABKM09: $\alpha_S(M_Z^2) = 0.1135 \pm 0.0014$, cf. **MSTW08:** 0.1171 ± 0.0014.

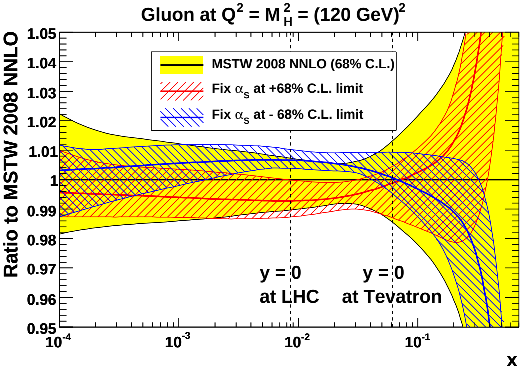


[MSTW, arXiv:0905.3531]

- **Answer:** Not all DIS data sets prefer low $\alpha_S(M_Z^2)$ values.
- True only for BCDMS, and for E665 and SLAC *ep* data.
- NMC, SLAC *ed* and HERA data prefer high $\alpha_S(M_Z^2)$ values.

Correlation between α_S and gluon distribution

- Known that α_S is **anticorrelated** with low-x gluon through scaling violations of HERA data: $\partial F_2/\partial \ln(Q^2) \sim \alpha_S\, g$. Then α_S is **correlated** with high-x gluon through *momentum sum rule*.



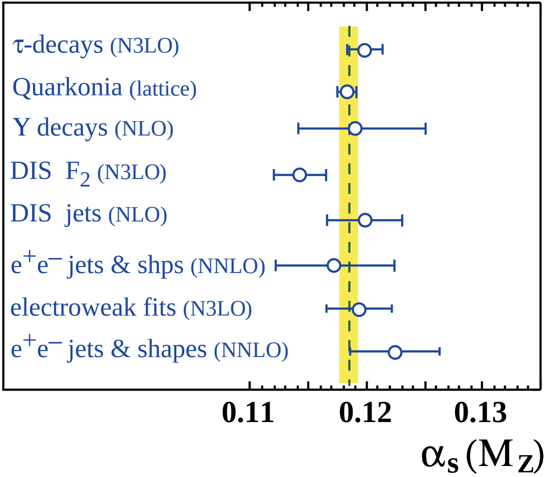
- **MSTW08:** $\alpha_S(M_Z^2) = 0.1171 \pm 0.0014$ [arXiv:0905.3531].
- Positive input gluon: $\alpha_S(M_Z^2) = 0.1157$, but $\Delta\chi^2_{\rm global} = 63$.

What is α_S from only DIS in the MSTW08 NNLO fit?

[Studies prompted by question from G. Altarelli, December 2010]

- **Global fit**: $\alpha_S(M_Z^2) = 0.1171 \pm 0.0014$ [arXiv:0905.3531].
- **DIS-only fit** gives $\alpha_S(M_Z^2) = 0.1104$ (BCDMS-dominated), but input $xg < 0$ for $x > 0.4$ due to lack of data constraint. $\Rightarrow F_2^{\mathrm{charm}} < 0$ and $\chi^2/N_{\mathrm{pts.}} \sim 10$ for Tevatron jets.
- DIS-only fit fixing high-x gluon parameters gives $\alpha_S(M_Z^2) = 0.1172$.
- DIS-only fit without BCDMS gives $\alpha_S(M_Z^2) = 0.1193$.
- Global fit without BCDMS gives $\alpha_S(M_Z^2) = 0.1181$.
- **Conclusion:** Tevatron jet data vital to pin down high-x gluon, giving smaller low-x gluon and therefore larger α_S in the global fit compared to a DIS-only fit, at the expense of some deterioration in the fit quality of the BCDMS data.

Input values to world average $\alpha_S(M_Z^2)$ [S. Bethke, arXiv:0908.1135]



- "DIS F_2" from BBG06 [Blümlein, Böttcher, Guffanti, hep-ph/0607200].
- Non-singlet analysis: free of assumptions on gluon (in principle).

Non-singlet QCD analysis of DIS data [BBG06, hep-ph/0607200]

Order	$\alpha_S(M_Z^2)$ (expt.)
NLO	$0.1148^{+0.0019}_{-0.0019}$
NNLO	$0.1134^{+0.0019}_{-0.0021}$
NNNLO	$0.1141^{+0.0020}_{-0.0022}$

- Fit F_2^p and F_2^d for $x > 0.3$ (neglect singlet contribution), and $F_2^{\rm NS}$.
- But singlet makes up about: 10% of F_2^p at $x = 0.3$, 2% of F_2^p at $x = 0.5$.

- **Exercise:** perform MSTW08 NNLO DIS-only fit to F_2^p and F_2^d for $x > 0.3$ (282 points, 160 from BCDMS).
  $\Rightarrow$ $\alpha_S(M_Z^2) = 0.1103\ (0.1130)$ without (with) singlet included.
  (Lower than BBG06 due to lack of $y > 0.3$ cut on BCDMS.)
- **Conclusion:** low value of $\alpha_S(M_Z^2)$ found by BBG06 due to (i) dominance of BCDMS data and (ii) neglect of singlet.
- Closest possible to reliable extraction of $\alpha_S(M_Z^2)$ from DIS is MSTW08 NNLO combined analysis of DIS, DY and jet data:

$$\alpha_S(M_Z^2) = 0.1171 \quad \pm 0.0014\ (68\%\ \text{C.L.}) \quad \pm 0.0034\ (90\%\ \text{C.L.})$$

Summary

- **MSTW08** still fairly current: no immediate update planned.
- The LHC is starting to provide useful input data for PDF fits.
- Now reasonably good agreement between *global* fits from **MSTW08**, CT10 and NNPDF2.1, all using GM-VFNS.
- More variation with other PDF sets using more limited data sets and/or restrictive input PDF parameterisations.
- (But HERAPDF1.5 NNLO is surprisingly close to **MSTW08**.)
- Tevatron jet data are important to pin down the high-x gluon, with indirect effect on the value of $\alpha_S(M_Z^2)$ extracted.