PDF systematics for Higgs cross sections and coupling determinations

Graeme Watt

Institut für Theoretische Physik, Universität Zürich

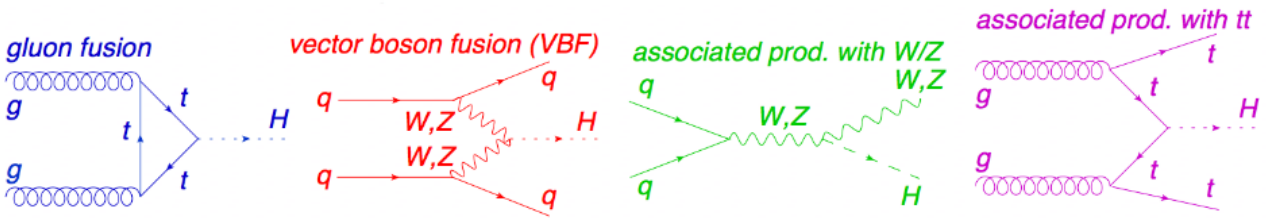
PDF4LHC Meeting
CERN, Geneva, 17th April 2013

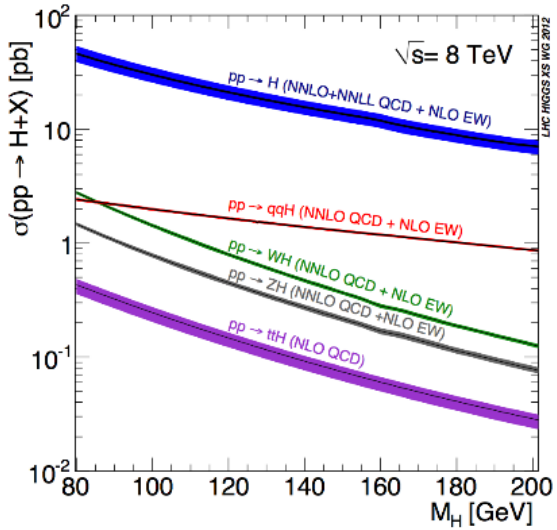
Partly based on material prepared for review article with S. Forte
[to appear in Ann. Rev. Nucl. Part. Sci. **63**, arXiv:1301.6754]

Higgs production at the LHC with $\sqrt{s} = 8$ TeV

- Higgs physics has moved on from discovery to precision studies.
- Theoretical σ_{SM} needed to extract signal strength $\mu = \sigma/\sigma_{\mathrm{SM}}$.

Higgs production





Main production mode via loops. Theory uncertainty $O(10\%)$

Access to top-quark, W and Z couplings via production cross section

CERN Seminar, 15 April 2013 *ATLAS* Higgs 5

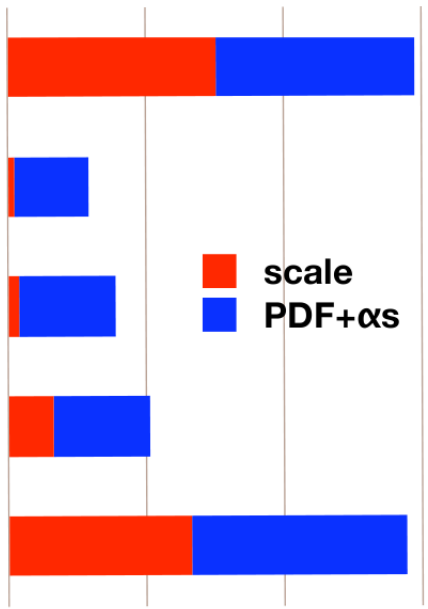
Breakdown of theoretical QCD uncertainties for Higgs

Higgs production at 125 GeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- Model testing requires assessment of theoretical uncertainties
  - uncertainties from scale variation and PDF+strong coupling

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



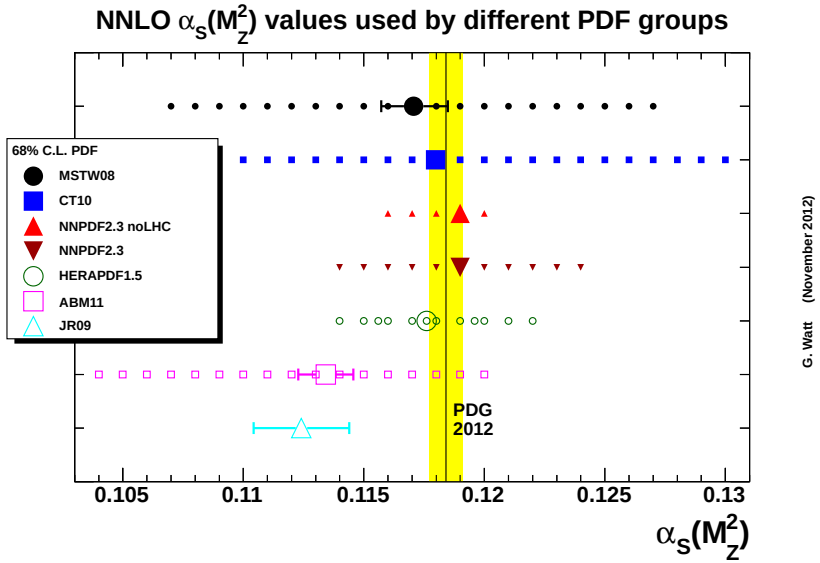
Perturbative QCD: Status - John Campbell, Fermilab ICHEP2012 30

Ongoing work towards $gg \to H$ at N^{3}LO

- Worry about TH uncertainties when $\gtrsim$ EXP uncertainties.
- Worry about PDF($+\alpha_S$) uncertainties when $\gtrsim$ scale variation.

- Perturbative expansion for $gg \to H$ is only slowly convergent.
- Experiments currently use prediction with NNLO QCD and soft-gluon resummation up to NNLL [Catani *et al.*, `hep-ph/0306211`].
- Progress towards N^{3}LO [e.g. Anastasiou *et al.*, `arXiv:1302.4379`].
- Recent work on constructing approximate N^{3}LO by combining soft-gluon and high-energy resummation [Ball *et al.*, `arXiv:1303.3590`].
- PDF($+\alpha_S$) uncertainties may eventually become dominant.
- Would we need N^{3}LO PDFs to calculate $gg \to H$ at N^{3}LO?
  - In principle, yes.
  - In practice, N^{3}LO corrections to typical processes included in PDF fits likely to be much smaller than other (usually neglected) theoretical uncertainties, e.g. difference between NLO PDFs and NNLO PDFs is already generally small.

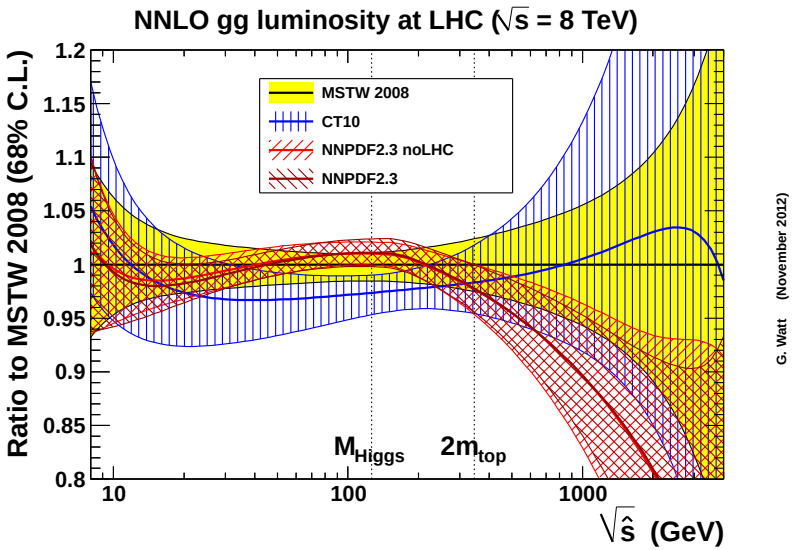
Default values of $\alpha_S(M_Z^2)$ used by different fitting groups

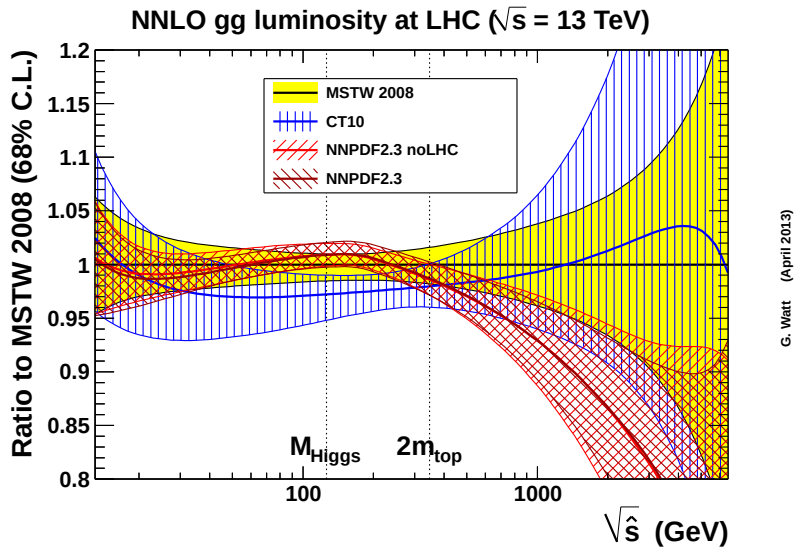


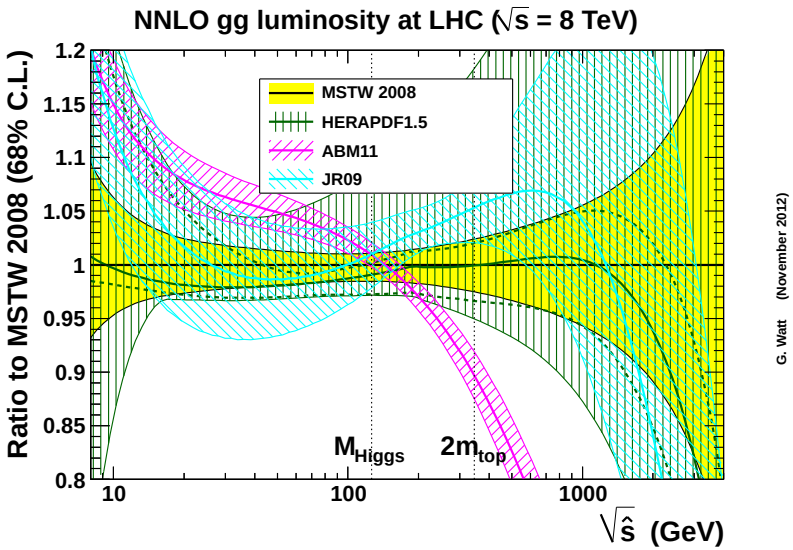
- $\alpha_S(M_Z^2)$ for MSTW08, ABKM09 and JR09 fitted.
- $\alpha_S(M_Z^2)$ for other groups applied as an external constraint.
- Smaller symbols indicate alternative $\alpha_S(M_Z^2)$ values.

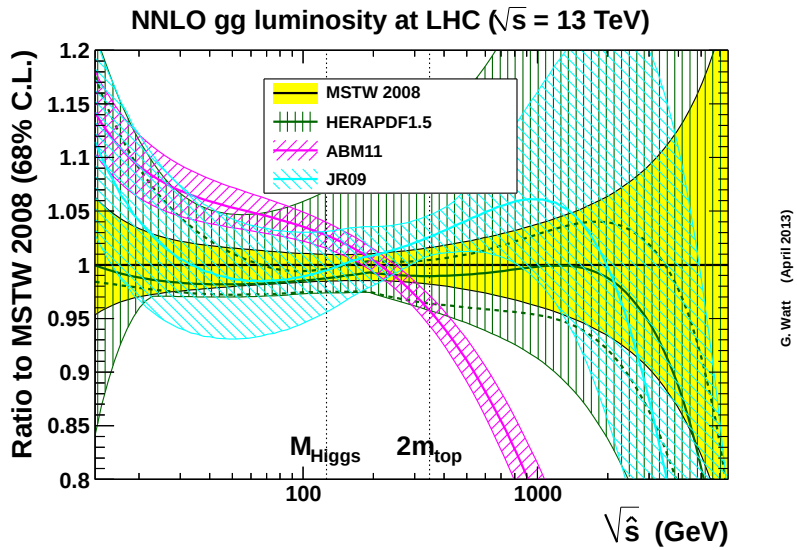
- PDG 2012 [Bethke, Dissertori, Salam]: $\alpha_S(M_Z^2) = 0.1184 \pm 0.0007$.
- Alternative [Pich, arXiv:1303.2262]: $\alpha_S(M_Z^2) = 0.1186 \pm 0.0007$.
- Z decay and DIS [Altarelli, arXiv:1303.6065]: 0.1174 ± 0.0016.
- If choose $\alpha_S(M_Z^2) = 0.119$ for NNPDF2.3 (historical default value), then envelope of MSTW08, CT10 and NNPDF2.3 implicitly spans $\alpha_S(M_Z^2) \approx 0.118 \pm 0.001$.
  $\Rightarrow$ Don't need to include α_S uncertainties explicitly.

Ratio of NNLO gluon-gluon luminosity functions

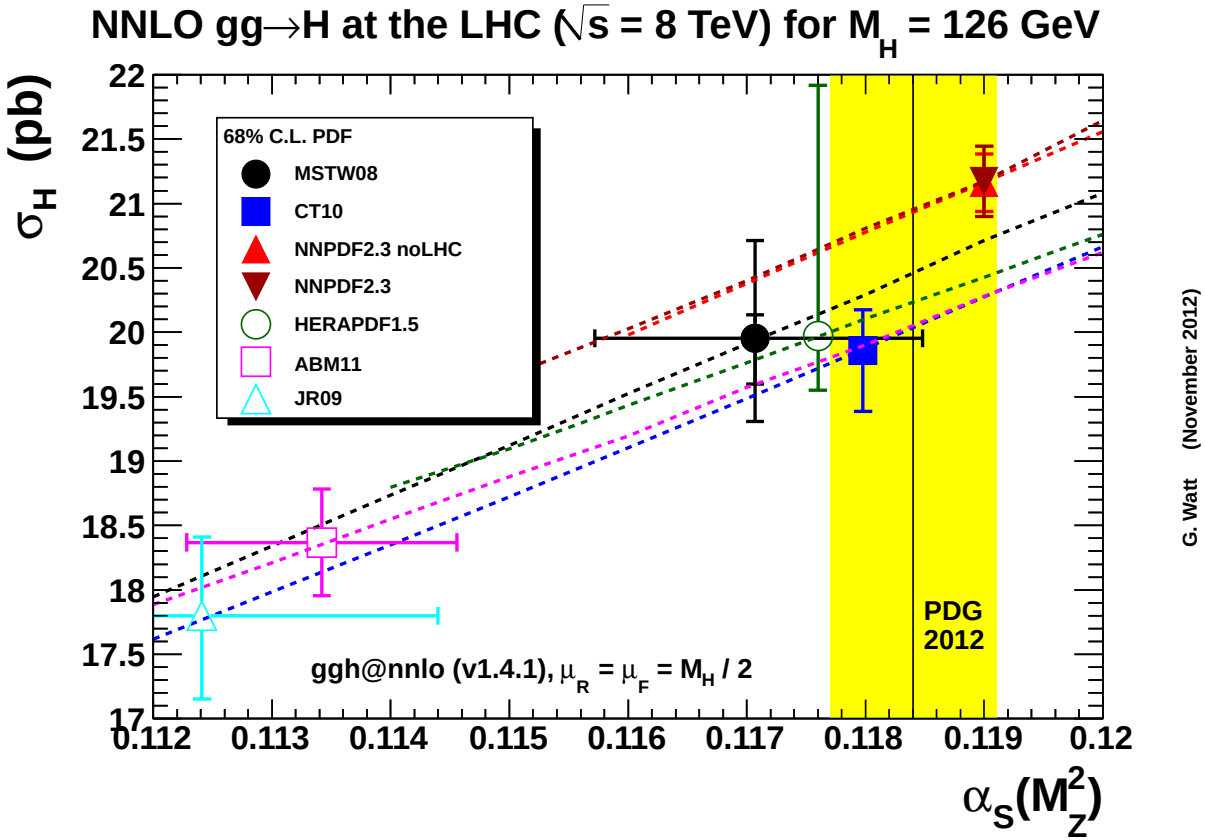








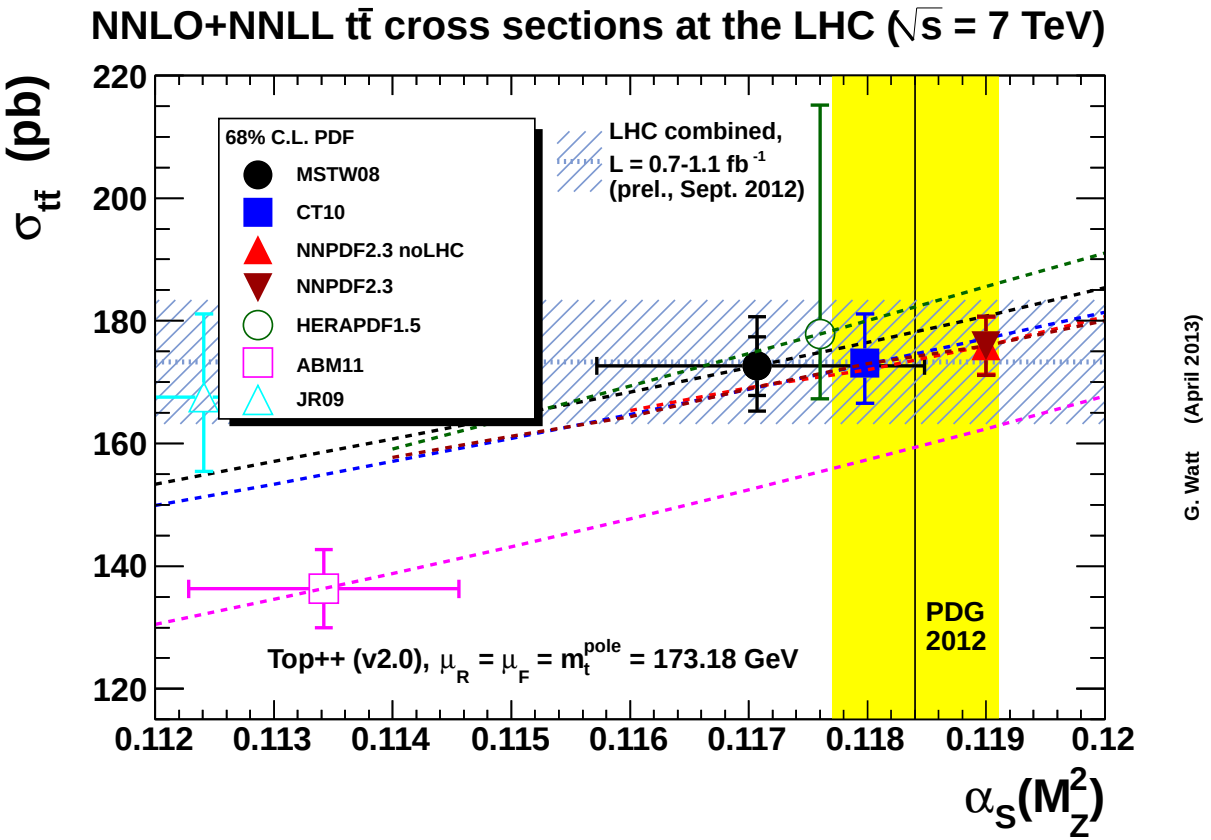
$gg \to H$ total cross sections versus $\alpha_S(M_Z^2)$ [arXiv:1301.6754]



- **MSTW08**: PDF+α_S uncertainties (outer error bars) much larger than PDF-only uncertainties (inner error bars).
- Reasonable agreement comparing at common $\alpha_S(M_Z^2)$, with CT10/NNPDF2.3 giving the minimum/maximum prediction.

$t\bar{t}$ total cross sections versus $\alpha_S(M_Z^2)$ [update of arXiv:1301.6754]

- Exact NNLO QCD now known for all partonic channels, including dominant gg [Czakon, Fiedler, Mitov, arXiv:1303.6254].

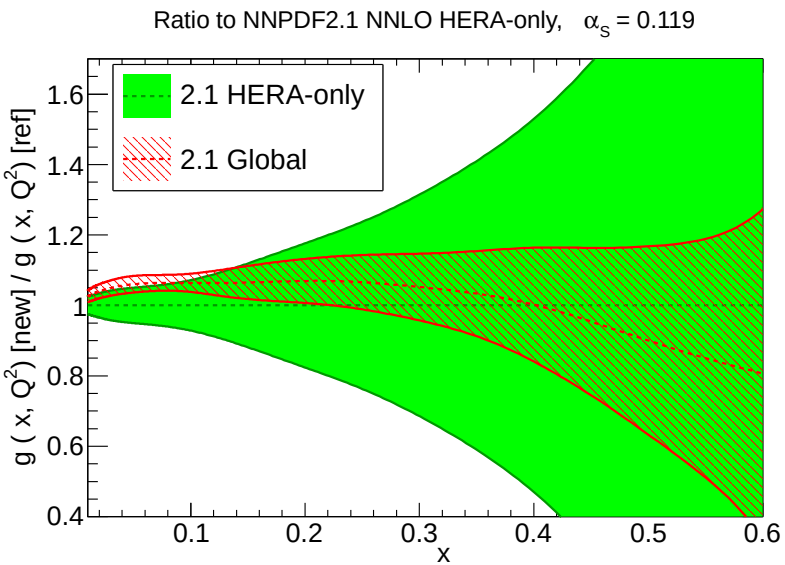


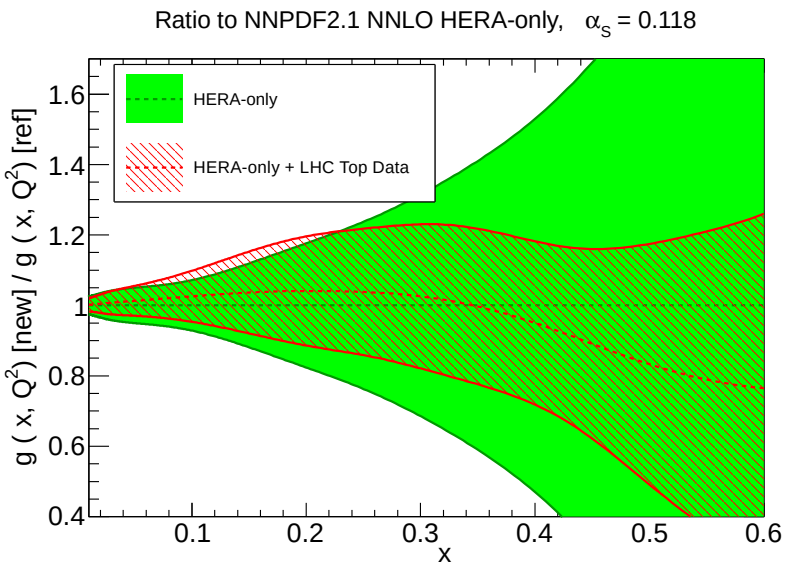
LHC data: $\sigma_{t\bar{t}} = 173.3 \pm 2.3(\text{stat.}) \pm 7.6(\text{syst.}) \pm 6.3(\text{lumi.})\ \text{pb} = 173.3 \pm 10.1\ \text{pb}$

ABM11: $\sigma_{t\bar{t}} = 136.3 \pm 6.4(\text{PDF}+\alpha_S)^{+3.5}_{-4.2}(\text{scales})^{+4.1}_{-3.9}(m_t)\ \text{pb} = 136.3^{+8.3}_{-8.6}\ \text{pb}$

Constraints on the gluon distribution from $t\bar{t}$ production

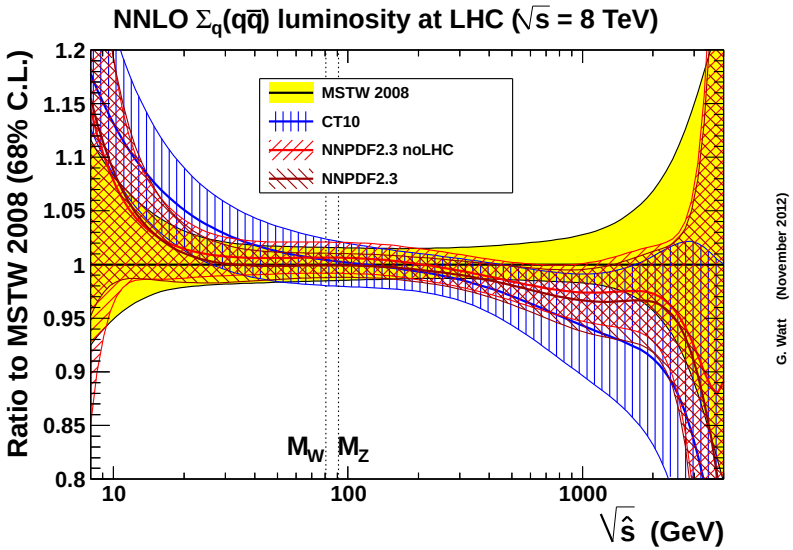
- LHC $\sigma_{t\bar{t}}$ is first NNLO observable to provide a direct gluon constraint [Czakon, Mangano, Mitov, Rojo, arXiv:1303.7215].

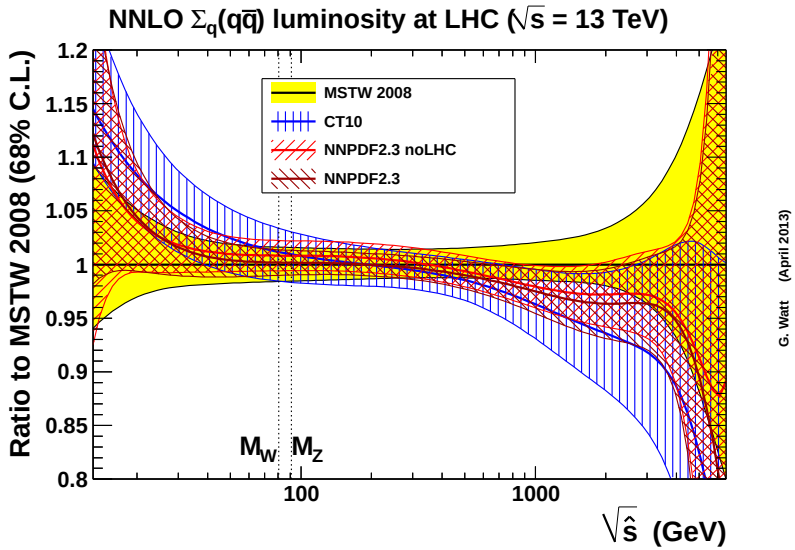


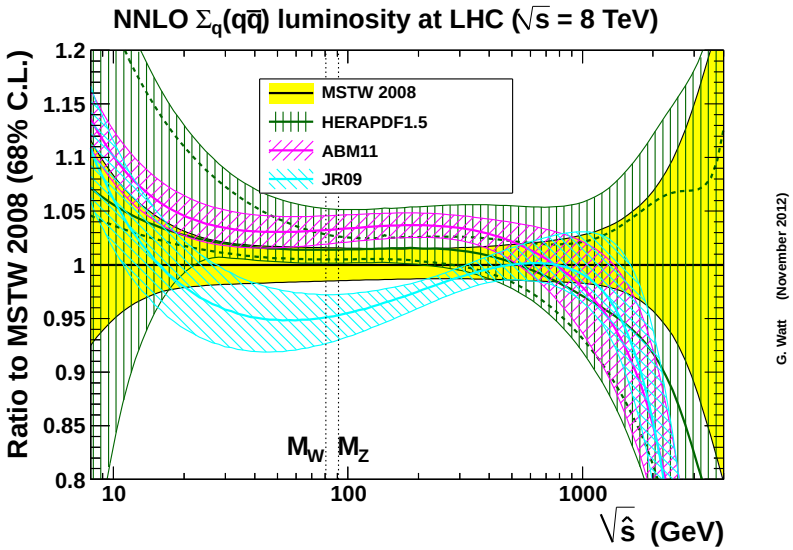


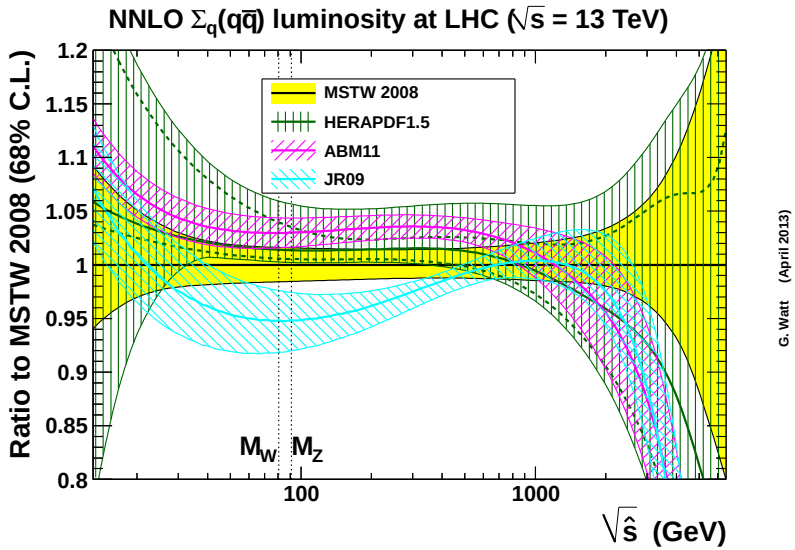
- Consistent picture emerging between NNLO $\sigma_{t\bar{t}}$ at LHC, PDF sets that use a GM-VFNS for heavy quarks in DIS, PDF sets including Tevatron jet data, and the world average value of α_S.
- Other differences in the treatment of DIS data in the ABM11 fit (e.g. F_L, correlated errors, higher-twist) are less relevant.

Ratio of NNLO quark-antiquark luminosity functions

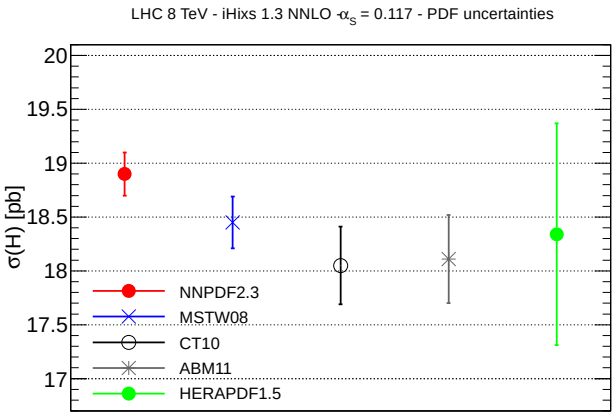




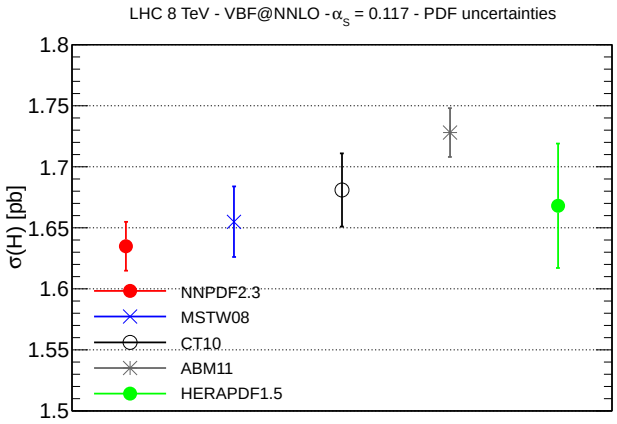




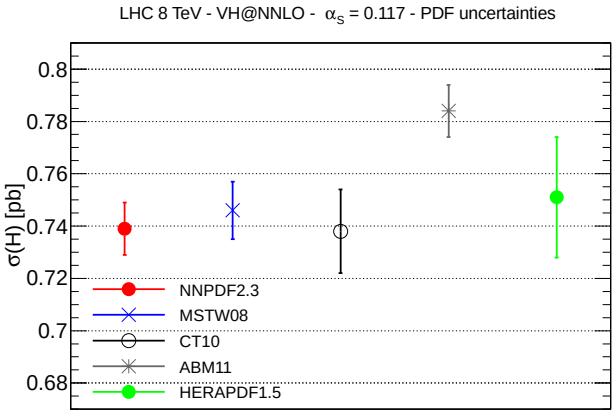
Other Higgs production channels [Ball *et al.*, arXiv:1211.5142]



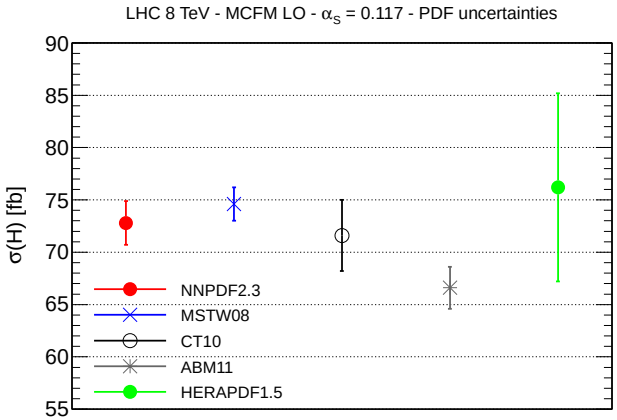
$gg \to H \Rightarrow gg$ luminosity



VBF $\Rightarrow qq$ luminosity



$WH \Rightarrow q\bar{q}$ luminosity



$t\bar{t}H \Rightarrow gg$ luminosity

Combination of results from different groups

Current PDF4LHC recommendation uses midpoint and envelope of PDF+α_S uncertainties with PDF sets from **MSTW**, CT and NNPDF.

Problems [more discussion in arXiv:1106.5788]

- Potential double-counting of α_S uncertainties if central prediction of each group each has different $\alpha_S(M_Z^2)$.
- Lack of statistical interpretation: what is the underlying probability distribution using the midpoint and envelope?
- How to calculate the PDF correlation between two observables if the uncertainty is defined using an envelope?

Proposal for statistical combination [S. Forte, arXiv:1011.5247]

Combined probability density $P(f)$ that a given observable has value f is simply (relative weights need not be equal):

$$P(f) = \frac{1}{3}\left[P_{\mathrm{MSTW}}(f) + P_{\mathrm{CT}}(f) + P_{\mathrm{NNPDF}}(f)\right].$$

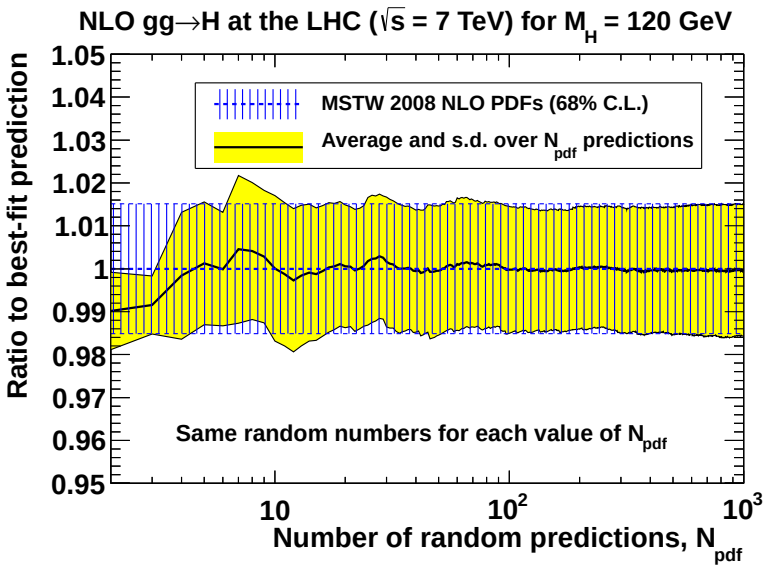
Generating random predictions for MSTW and CT

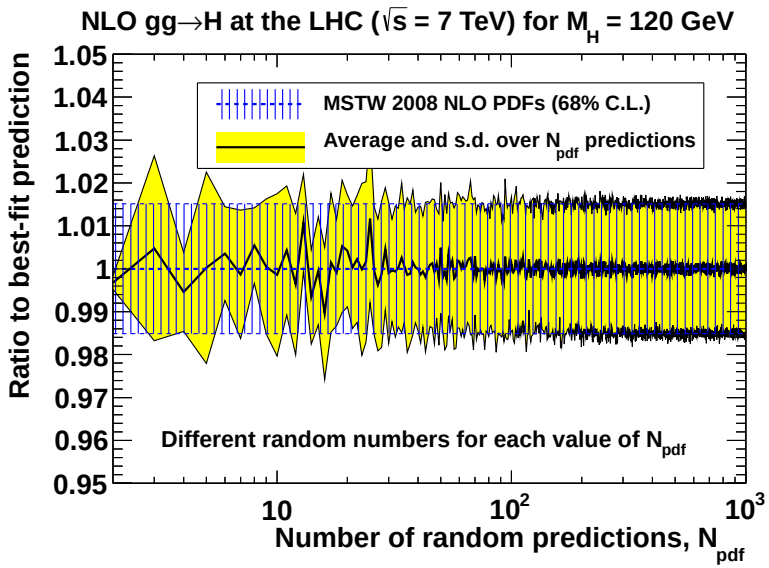
[G.W., Thorne, arXiv:1205.4024, http://mstwpdf.hepforge.org/random/]

- Build $N_{\rm pdf}$ random values of observable F according to:

$$F_k = F(S_0) + \frac{1}{2}\sum_{j=1}^{n}\left|F(S_j^+) - F(S_j^-)\right| R_{jk} \qquad (k = 1, \ldots, N_{\rm pdf}),$$

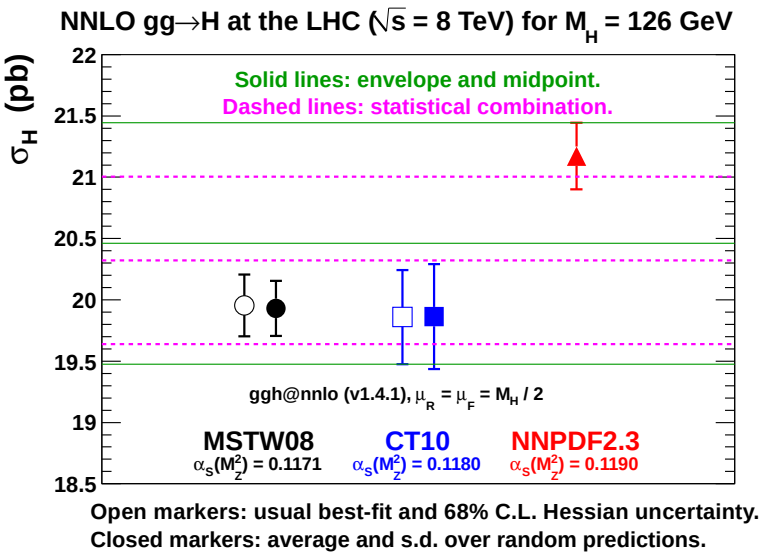
where R_{jk} is a Gaussian-distributed random number.

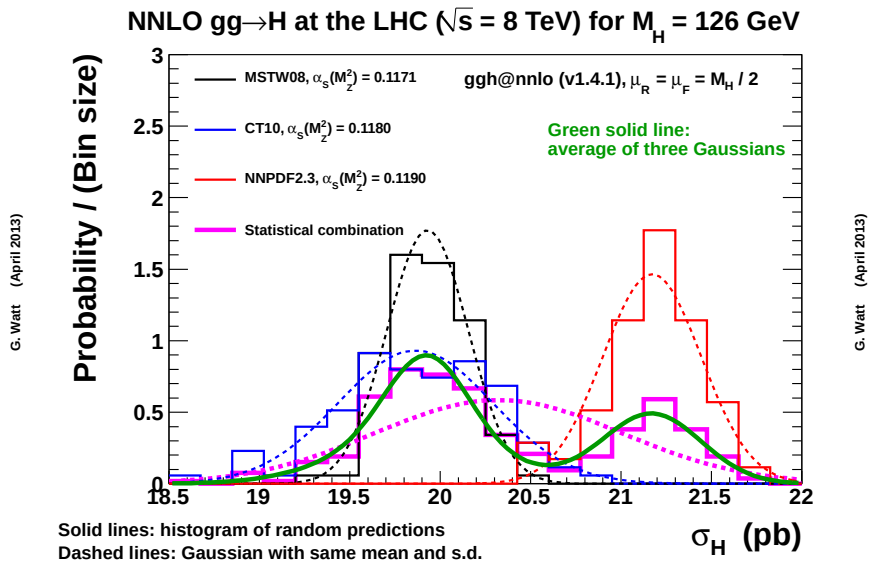




Statistical combination from different PDF groups

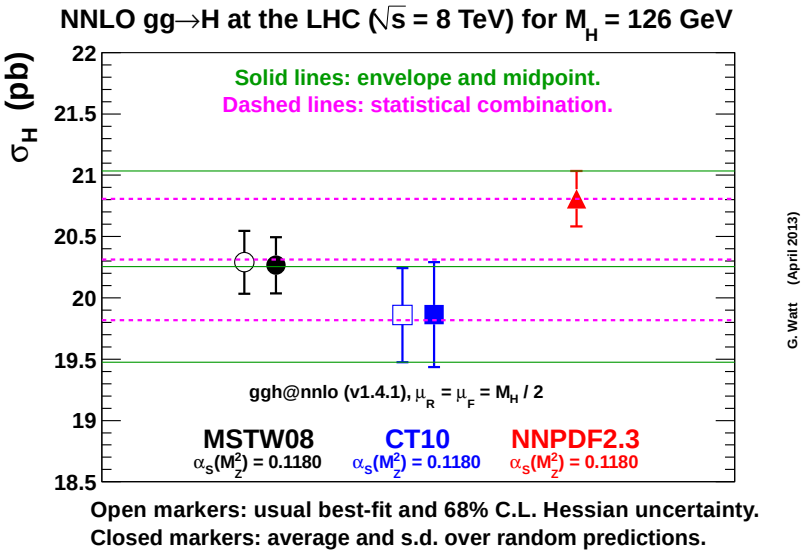
[Forte, G.W., arXiv:1301.6754; + work in progress for LHC Higgs XS WG]

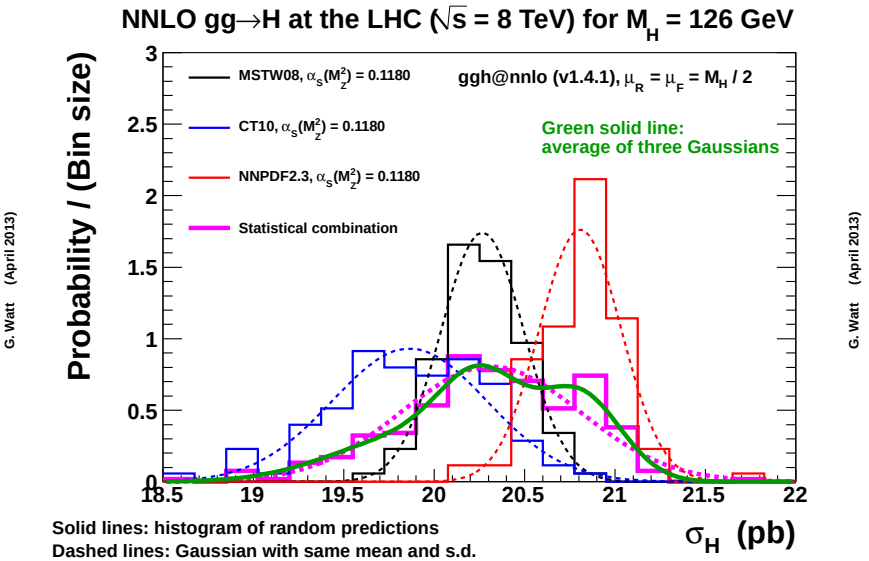




- Statistical combination gives smaller uncertainties than envelope. Each group gives 1–2%, envelope 4.8%, combination 3.4%.
- Outlying groups influence the combination less than the envelope.
- Bimodal feature of combined probability density partly explained by lower/higher $\alpha_S(M_Z^2) = 0.1171/0.1190$ for **MSTW**/NNPDF.
- No explicit α_S uncertainties included here, i.e. PDF-only.

Statistical combination from different PDF groups





- Combined probability density closer to Gaussian distribution with common $\alpha_S(M_Z^2) = 0.118$ for all three PDF groups.
- Each group gives 1–2%, envelope 3.8%, combination 2.4%.
- Suggestion for shape of combined probability density:
  - Construct three Gaussian distributions with mean and standard deviation given by central prediction and PDF($+\alpha_S$) uncertainty of each PDF group (**MSTW**, CT, NNPDF).
  - Combined probability density given by single Gaussian having same mean and standard deviation as probability density obtained from statistical combination of three Gaussians.

Summary

- Consistent picture of $gg \to H$ predictions emerging between:
  - Exact NNLO calculation of $\sigma_{t\bar{t}}$ at LHC [arXiv:1303.6254].
  - PDF sets that use a GM-VFNS for heavy quarks in DIS.
  - PDF sets that use Tevatron jet data to constrain high-x gluon.
  - The world average value of the strong coupling $\alpha_S(M_Z^2) \approx 0.118$.
- PDF uncertainties on $gg \to H$ already 1–2% per group.
- Larger uncertainties come from recipes used for including α_S uncertainties and combining predictions from different groups.
- Value of $\alpha_S(M_Z^2)$ crucial for $gg \to H$. It is important to continue extracting α_S from PDF fits, but when making precision predictions better to decouple $\alpha_S(M_Z^2)$ from PDF fits.
- Ideally, all sources of experimental and theoretical uncertainty should be consistently accounted for within one PDF set, so that combination of multiple PDF sets would be unnecessary.
- Expect some convergence between groups with inclusion of new LHC observables in PDF fits ($\to$ talk by J. Rojo).