Parton Distributions and the Higgs Cross-section

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Obtaining PDF sets – General procedure.

Start parton evolution at low scale $Q_0^2 \sim 1\mathrm{GeV}^2$. In principle 11 different partons to consider.

$$u, \bar{u}, \quad d, \bar{d}, \quad s, \bar{s}, \quad c, \bar{c}, \quad b, \bar{b}, \quad g$$

$m_c, m_b \gg \Lambda_{\mathrm{QCD}}$ so heavy parton distributions determined perturbatively. Leaves 7 independent combinations, or 6 if we assume $s = \bar{s}$ (just started not to).

$$u_V = u - \bar{u}, \quad d_V = d - \bar{d}, \quad \mathrm{sea} = 2 * (\bar{u} + \bar{d} + \bar{s}), \quad s + \bar{s} \quad \bar{d} - \bar{u}, \quad g.$$

Input partons parameterised as, e.g. MSTW, – much more general form for NNPDF, but same limits as $x \rightarrow, 0, 1$.

$$xf(x, Q_0^2) = (1-x)^{\eta}(1 + \epsilon x^{0.5} + \gamma x)x^{\delta}.$$

Evolve partons upwards using LO, NLO (or NNLO) DGLAP equations.

$$\frac{df_i(x, Q^2, \alpha_s(Q^2))}{d \ln Q^2} = \sum_j P_{ij}(x, \alpha_s(Q^2)) \otimes f_j(x, Q^2, \alpha_s(Q^2))$$

Fit data for scales above $2 - 5\mathrm{GeV}^2$. Need many different types for full determination.

- Lepton-proton collider HERA – (DIS) $\rightarrow$ small-x quarks (best below $x \sim 0.05$). Also gluons from evolution (same x), and now $F_L(x, Q^2)$. Also, jets $\rightarrow$ moderate-x gluon.Charged current data some limited info on flavour separation. Heavy flavour structure functions – gluon and charm, bottom distributions and masses.

- Fixed target DIS – higher x – leptons (BCDMS, NMC, ...) $\rightarrow$ up quark (proton) or down quark (deuterium) and neutrinos (CHORUS, NuTeV, CCFR) $\rightarrow$ valence or singlet combinations.

- Di-muon production in neutrino DIS – strange quarks and neutrino-antineutrino comparison $\rightarrow$ asymmetry . Only for $x > 0.01$.

- Drell-Yan production of dileptons – quark-antiquark annihilation (E605, E866) – high-x sea quarks. Deuterium target – $\bar{u}/\bar{d}$ asymmetry.

- High-p_T jets at colliders (Tevatron) – high-x gluon distribution – $x > 0.01$.

- W and Z production at colliders (Tevatron) – different quark contributions to DIS.

Different PDF sets

- MSTW08 – fit all previous types of data. Most up-to-date Tevatron jet data. Not most recent HERA combination of data. PDFs at LO, NLO and NNLO.

- CTEQ6.6 – very similar. Not quite as up-to-date on Tevatron data. PDFs at NLO.

- NNPDF2.0 – include all above except HERA jet data (not strongest constraint) and heavy flavour structure functions. Include HERA combined data. PDFs at NLO.

- HERAPDF2.0 – based entirely on HERA inclusive structure functions, neutral and charged current. Use combined data. PDFs at LO, NLO.

- ABKM09 – fit to DIS and fixed target Drell-Yan data. PDFs at NLO and NNLO.

- GJR08 – fit to DIS, fixed target Drell-Yan and Tevatron jet data. PDFs at NLO and NNLO.

Use of HERA combined data instead of original data $\rightarrow 1-2.5\%$ increase in quarks at low x (depending on procedure), similar on $\alpha_S(M_Z^2)$ if free (MSTW prelim.), and somewhat less on gluon. More stable at NNLO (MSTW prelim.).

Determination of best fit and uncertainties

All but NNPDF minimise χ^2 and define eigenvectors of parameter combinations expanding about best fit.

NNPDF create many replicas of data and obtain PDF replicas in each case by fitting to training set and comparing to validation set.

- MSTW08 – 20 eigenvectors. Due to incompatibility of different sets and (perhaps to some extent) parameterisation inflexibility (little direct evidence for this) have inflated $\Delta\chi^2$ of $5 - 20$ for eigenvectors.

- CTEQ6.6 – 22 eigenvectors. Inflated $\Delta\chi^2$ of 50 for 1 sigma for eigenvectors (no normalization uncertainties in CTEQ6.6).

- NNPDF2.0 – uncertainty determined by spread of replicas. Direct relationship to $\Delta\chi^2$ in global fit not trivial.

- HERAPDF2.0 – 9 eigenvectors. Use "$\Delta\chi^2 = 1$". Additional model and parameterisation uncertainties.

- ABKM09 – 21 parton parameters. Use $\Delta\chi^2 = 1$.

- GJR08 – 12 parton parameters. Use $\Delta\chi^2 \approx 20$. Impose strong theory constraint on input form of PDFs.

Perhaps surprisingly all get rather similar uncertainties for PDFs and predicted cross-sections.

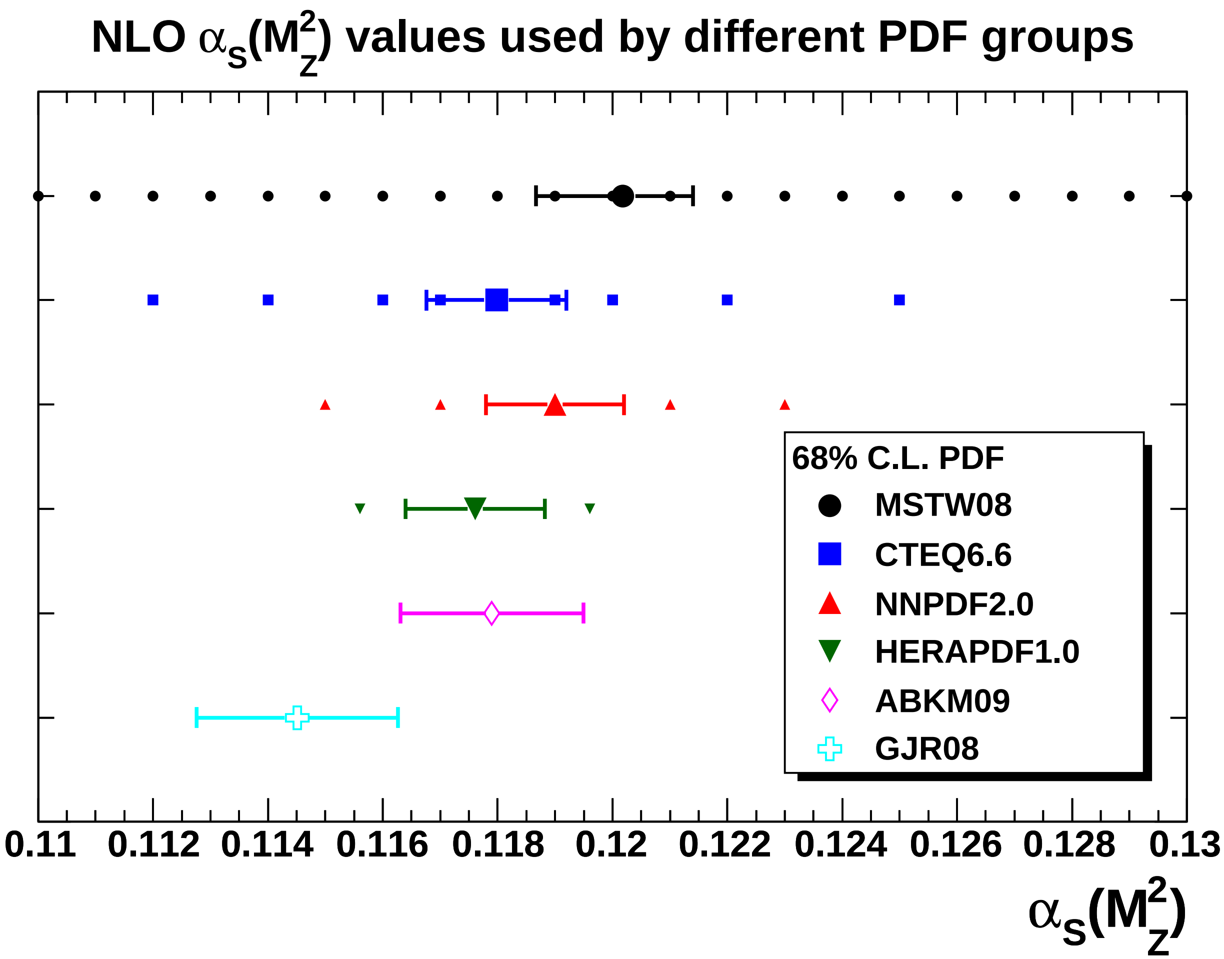
Some exceptions (more details later)

NNPDF and due to extra parameters MSTW have more complicated shape for gluon at smaller x and bigger small-x uncertainty.

Choice of parameterisation leads to bigger very high-x gluon uncertainty for CTEQ.

Different theory assumptions in strange leads to vastly different uncertainties – MSTW small $\rightarrow$ NNPDF large. Feeds into other "light" quarks.

Choices of $\alpha_S(M_Z^2)$



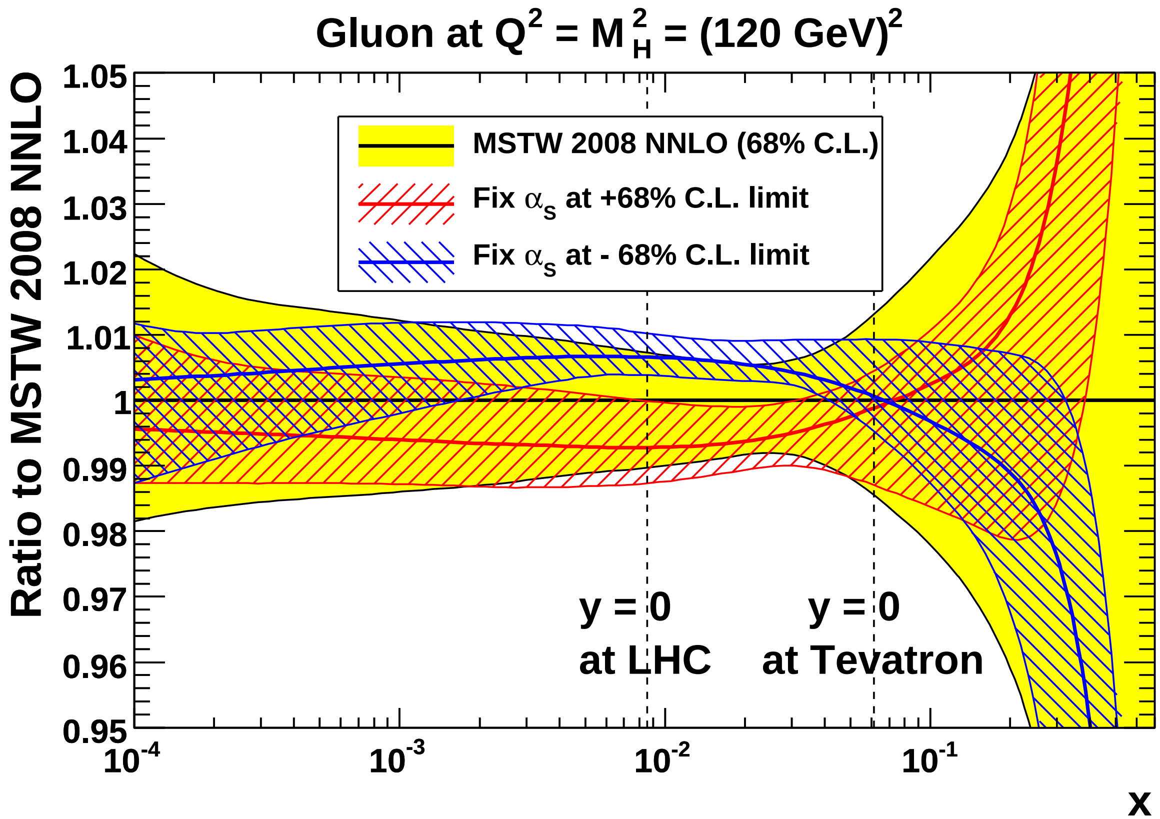
$\alpha_S(m_Z^2)$ values and uncertainty determined by fit for MSTW08, ABKM09 and GJR08.In each case NNLO value about $0.003 - 0.004$ lower than NLO value.

Others pick *standard* values and uncertainties.

PDF correlation with α_S.

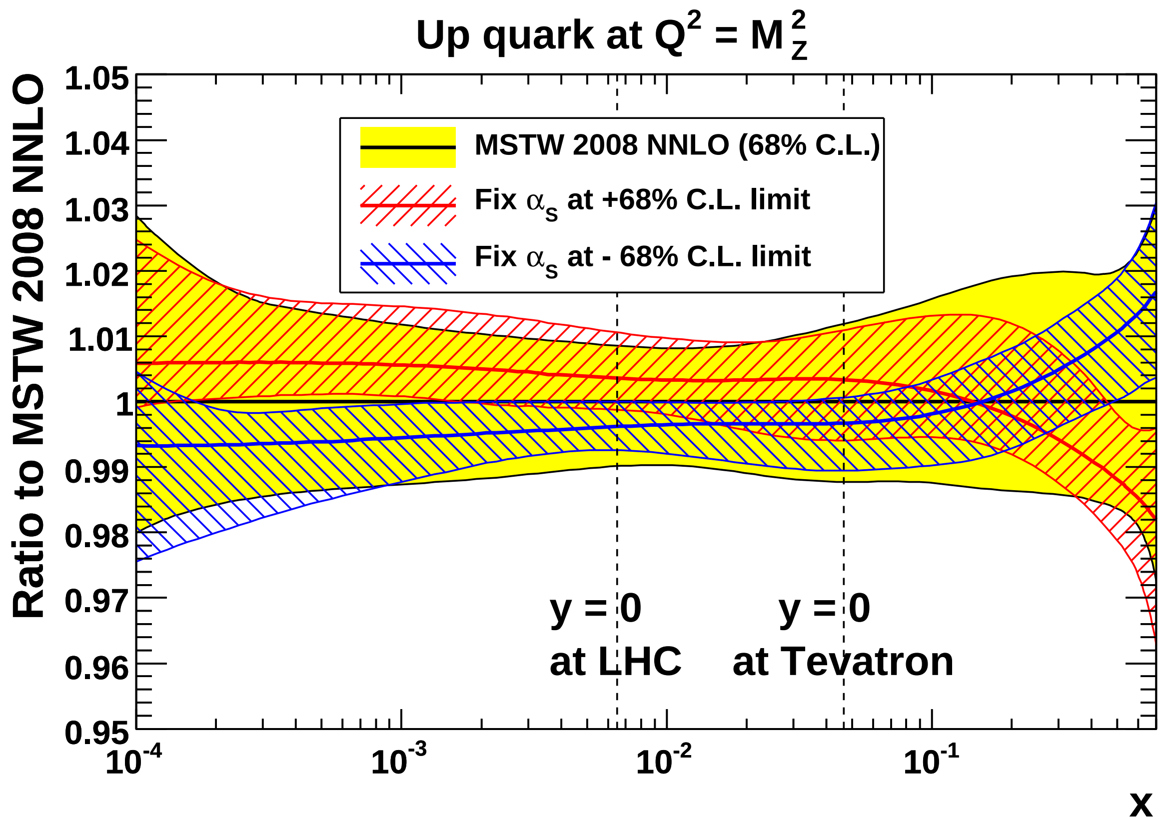
Can also look at PDF changes and uncertainties at different $\alpha_S(M_Z^2)$. Latter usually only for one fixed $\alpha_S(M_Z^2)$. Can be determined from fit, e.g. $\alpha_S(M_Z^2) = 0.1202^{+0.0012}_{-0.0015}$ at NLO and $\alpha_S(M_Z^2) = 0.1171^{+0.0014}_{-0.0014}$ at NNLO from MSTW.

PDF uncertainties reduced since quality of fit already worse than best fit.



Expected gluon–$\alpha_S(M_Z^2)$ small–x anti-correlation $\rightarrow$ high-x correlation from sum rule.

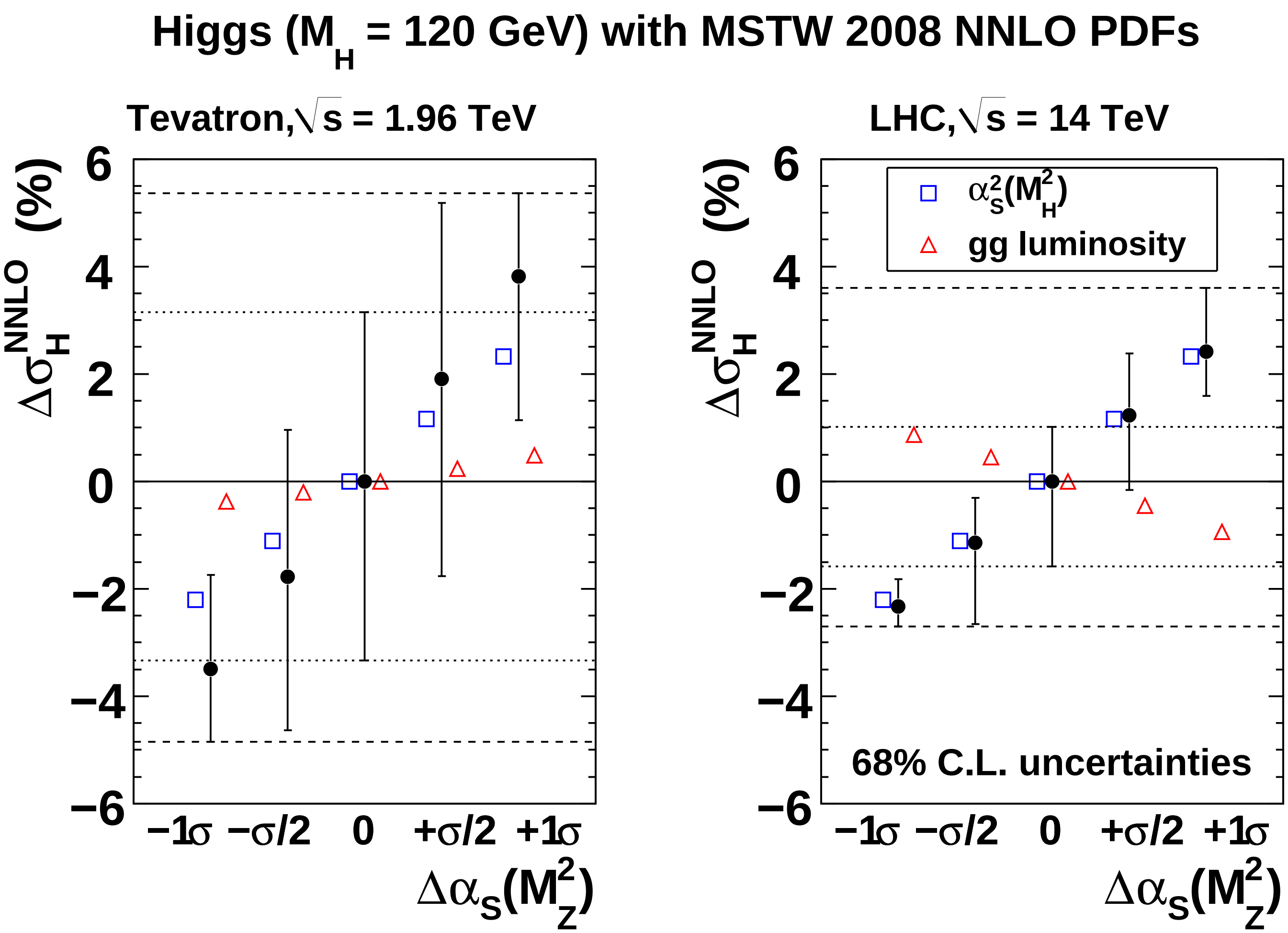
Gluon feeds into evolution of quarks, but change in $\alpha_S(M_Z^2)$ just outweighs gluon change, i.e. larger $\alpha_S(M_Z^2) \rightarrow$ slightly more evolution.



Strong anti-correlation at high-x due to evolution and positive coefficient functions.

Quarks roughly opposite to gluons.

NNLO predictions for Higgs ($120\mathrm{GeV}$) production for different allowed $\alpha_S(M_Z^2)$ values and their uncertainties.



Increases by a factor of $2-3$ (up more than down) at LHC. Direct $\alpha_S(M_Z^2)$ dependence mitigated somewhat by anti-correlated small-x gluon (asymmetry feature of *minor* problems in fit to HERA data). At Tevatron intrinsic gluon uncertainty dominates.

Consideration of NNLO

Very good evidence that one should use NNLO if possible rather than NLO – many physical cross-sections, particularly $gg \to H$, not very convergent.

Fewer PDF sets available, can study differences between them better at NLO, but for central prediction need NNLO.

Related to issue of use and uncertainty of $\alpha_S(M_Z^2)$. Noted systematic change in value form fit as one goes from NLO to NNLO. Also highlighted in stability of predictions.

Consider percentage change from NLO to NNLO in MSTW08 predictions for best fit α_S compared to fixed $\alpha_S(M_Z^2) = 0.119$.

	$\sigma_{W(Z)}$ 7TeV	$\sigma_{W(Z)}$ 14TeV	σ_H 7TeV	σ_H 7TeV
MSTW08 best fit α_S	3.0	2.6	25	24
MSTW08 $\alpha_S = 0.119$	5.3	5.0	32	30

$\alpha_S(M_Z^2)$ is not a physical quantity. In (nearly) all PDF related quantities (and many others) shows tendency to decrease from order to order. Noticeable if one has fit at NNLO. Any settling on, or near common $\alpha_S(M_Z^2)$ **has** to take this into account.

Note that like α_S the PDFs are systematically different at NNLO compared to NLO. At high scales more so for quarks than gluon.

Heavy Quarks – Essential to treat these correctly. Two distinct regimes:

Near threshold $Q^2 \sim m_H^2$ massive quarks not partons. Created in final state. Described using **Fixed Flavour Number Scheme** (FFNS).

$$F(x,Q^2) = C_k^{FF}(Q^2/m_H^2) \otimes f_k^{n_f}(Q^2)$$

Does not sum $\ln^n(Q^2/m_H^2)$ terms, and not calculated for many processes beyond LO. Still occasionally used. Sometimes final state details in this scheme only.

Alternative, at high scales $Q^2 \gg m_H^2$ heavy quarks like massless partons. Behave like up, down, strange. Sum $\ln(Q^2/m_H^2)$ terms via evolution. **Zero Mass Variable Flavour Number Scheme** (ZM-VFNS). Normal assumption in calculations. Ignores $\mathcal{O}(m_H^2/Q^2)$ corrections.

$$F(x,Q^2) = C_j^{ZMVF} \otimes f_j^{n_f+1}(Q^2).$$

Can devise a **General Mass Variable Flavour Number Scheme** (GM-VFNS) interpolating between the two well-defined limits of $Q^2 \leq m_H^2$ and $Q^2 \gg m_H^2$. Used by MRST/MSTW and more recently (as default) by CTEQ, and now also more regularly by H1,ZEUS.

General result, evolution at small x quicker using ZM-VFNS than using GM-VFNS which is quicker than using FFNS.

$\rightarrow$ small-x gluon and consequently light quarks smaller in ZM-VFNS than GM-VFNS and largest in FFNS.

Details follow, but to summarise

- Small-x quarks can be up to 8% smaller at electroweak scale in ZM-VFNS than in GM-VFNS – CTEQ, similar for MSTW. Slightly smaller effect in gluon. Similar size effects in LHC cross-sections. (Only twice PDF change for distinct rapidity.)

- Various definitions of GM-VFNS possible. Versions used by MSTW (RT) and CTEQ (ACOT) have converged somewhat.

- Variation in vaguely $sensible$ definitions of GM-VFNS lead to changes of maximum 3% in LHC cross-sections – MSTW study.

- Use of ZM-VFNS gives about 0.0015 lower value of $\alpha_S(M_Z^2)$. Basis of existing CTEQ study on $\alpha_S(M_Z^2)$ dependence.

Related issue. Can be $1-2\%$ variation in predicted cross-sections from variations in charm mass of 0.15GeV. Perhaps more like 1% at 7TeV.

Different PDF sets

- MSTW08 – use definition of GM-VFNS at LO, NLO and NNLO. (Have done since MRST98, but details changed in 2006 – pre-2006 NNLO prescription incomplete).

- CTEQ6.6 – use GM-VFNS at NLO as default. Only used as special case in pre-CTEQ6.5 sets.

- NNPDF2.0 – currently use ZM-VFNS. Have version of GM-VFNS bench-marked along with MSTW and CTEQ ready to use.

- HERAPDF2.0 – use same GM-VFNS as MSTW.

- ABKM09 – perform fit using FFNS. Claim insensitivity to using GM-VFNS. Currently heavy quark treatment same at NNLO as at NLO.

- GJR08 – use FFNS, again same at NNLO as at NLO.

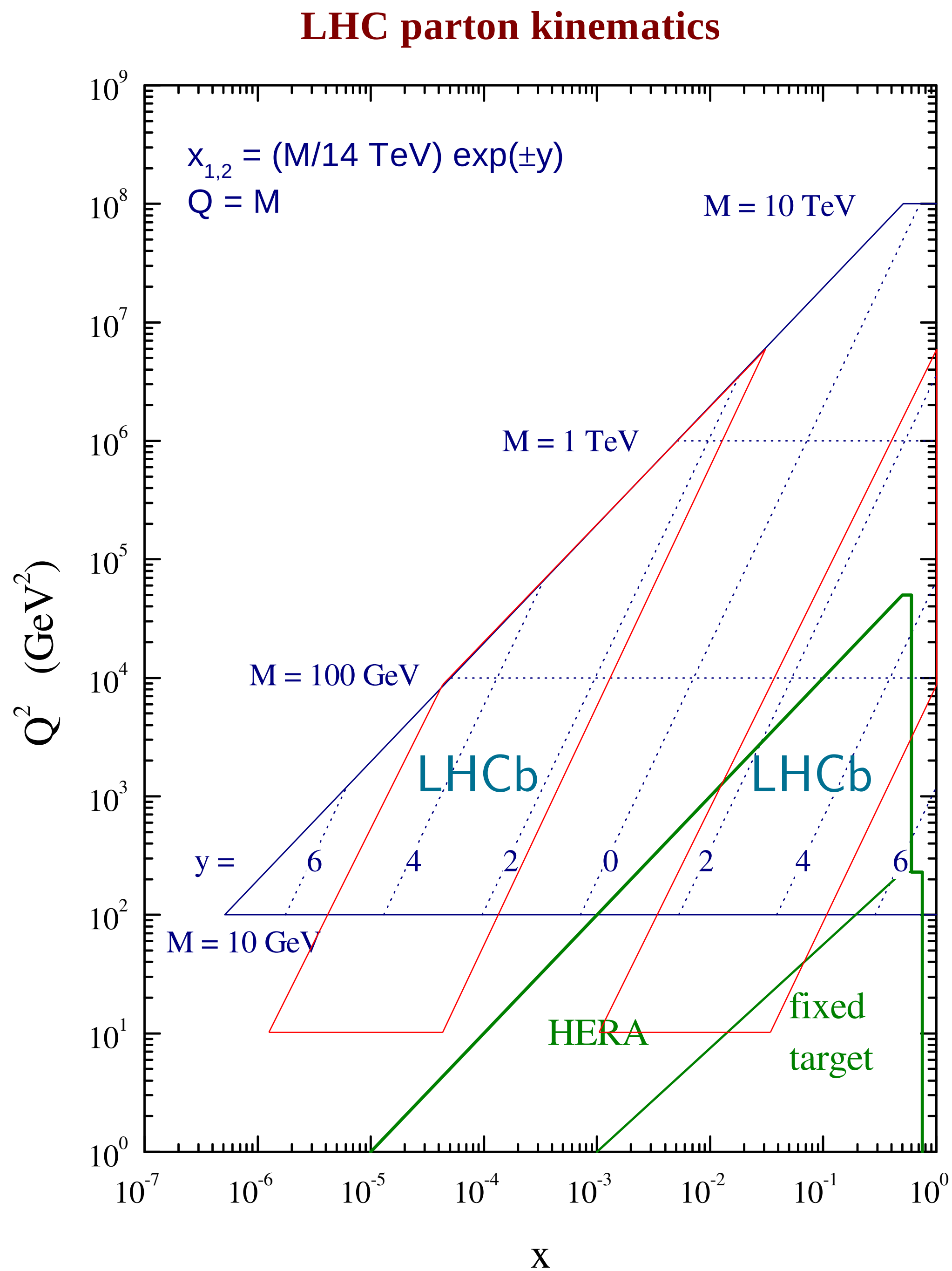
Predictions at the LHC

New kinematic regime.

PDFs mainly extrapolated via evolution rather than measured directly.

High scale and small-x parton distributions are vital for understanding processes at the LHC.

More discrepancy at values of x away from this.

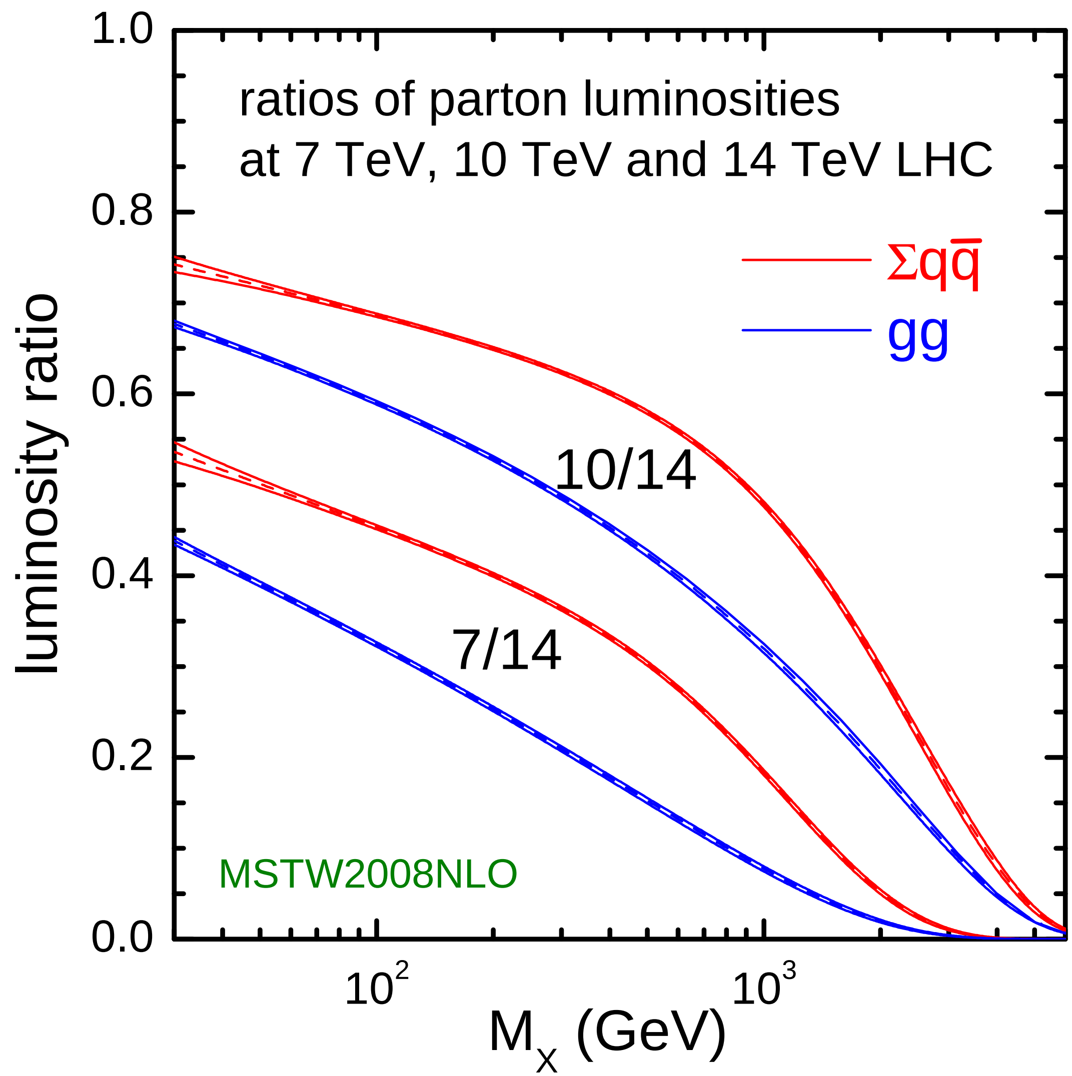


Initial Running

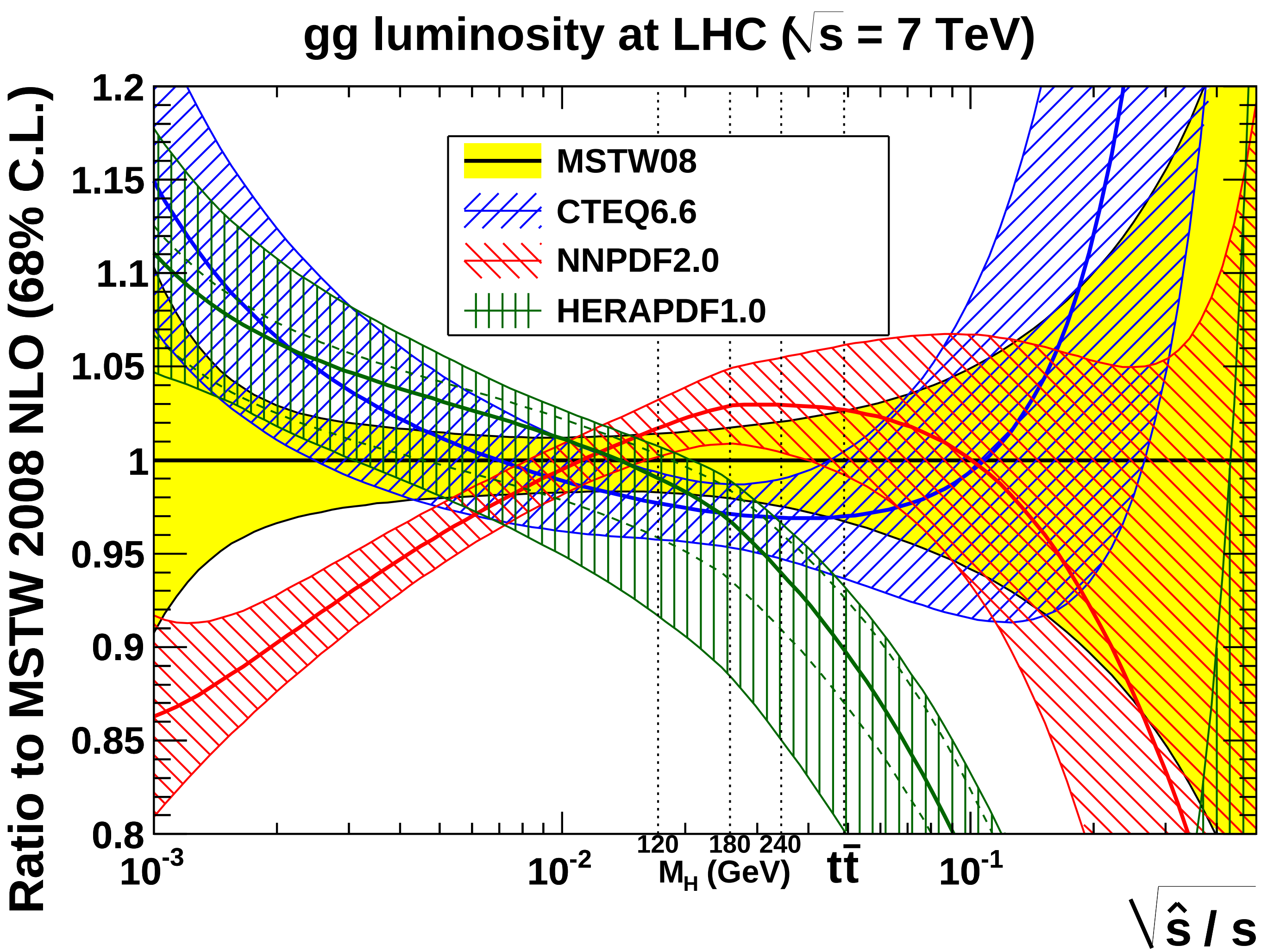
Of course, will be starting the LHC running at 7 TeV rather than the full 14 TeV.

Reduces rapidity range by $\ln 2$.

Roughly $30-50\%$ the full cross-sections for most standard model (including light Higgs) processes.

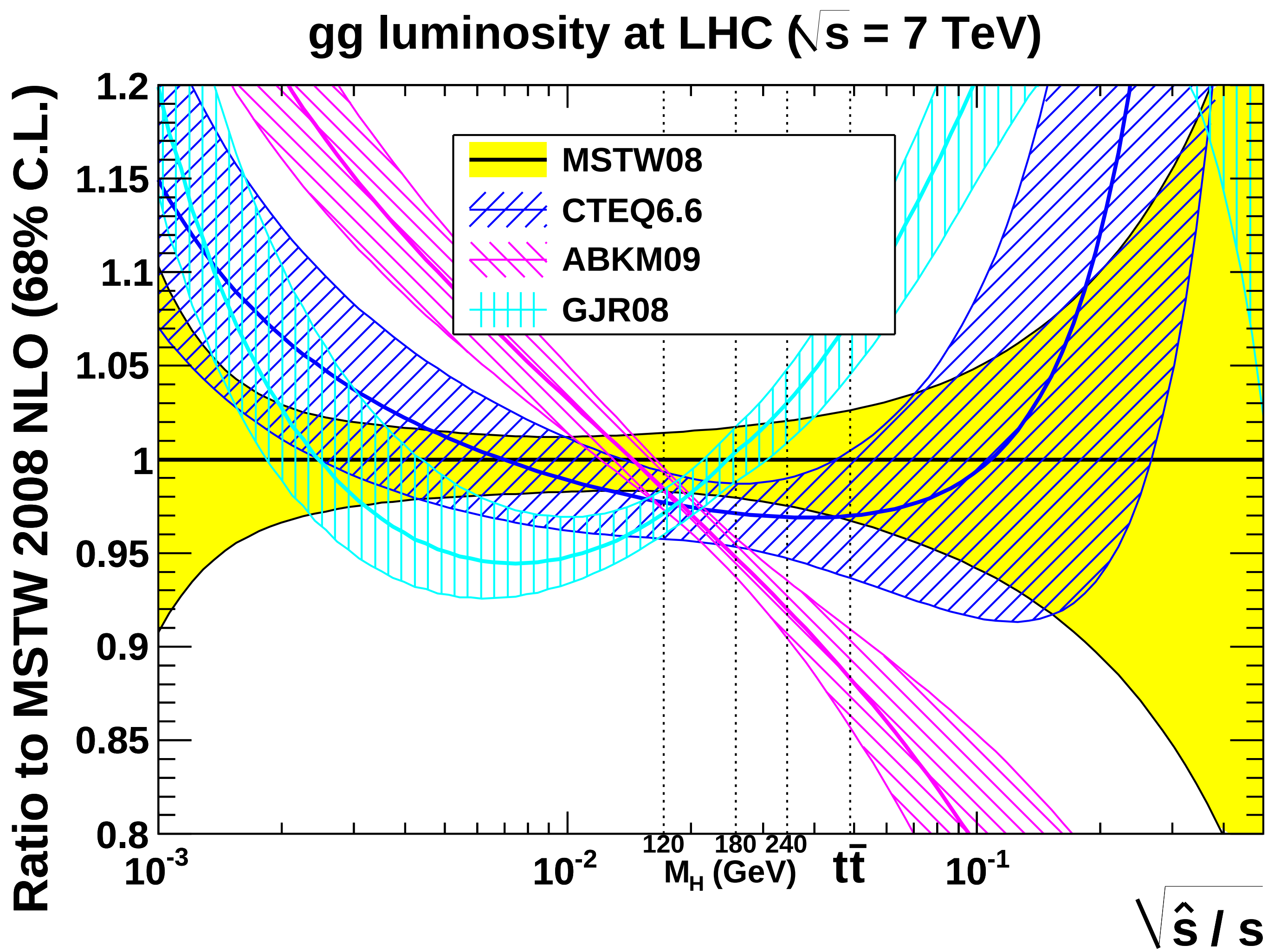


Predictions by variousgroups - parton luminosities – NLO. Plots by G. Watt.

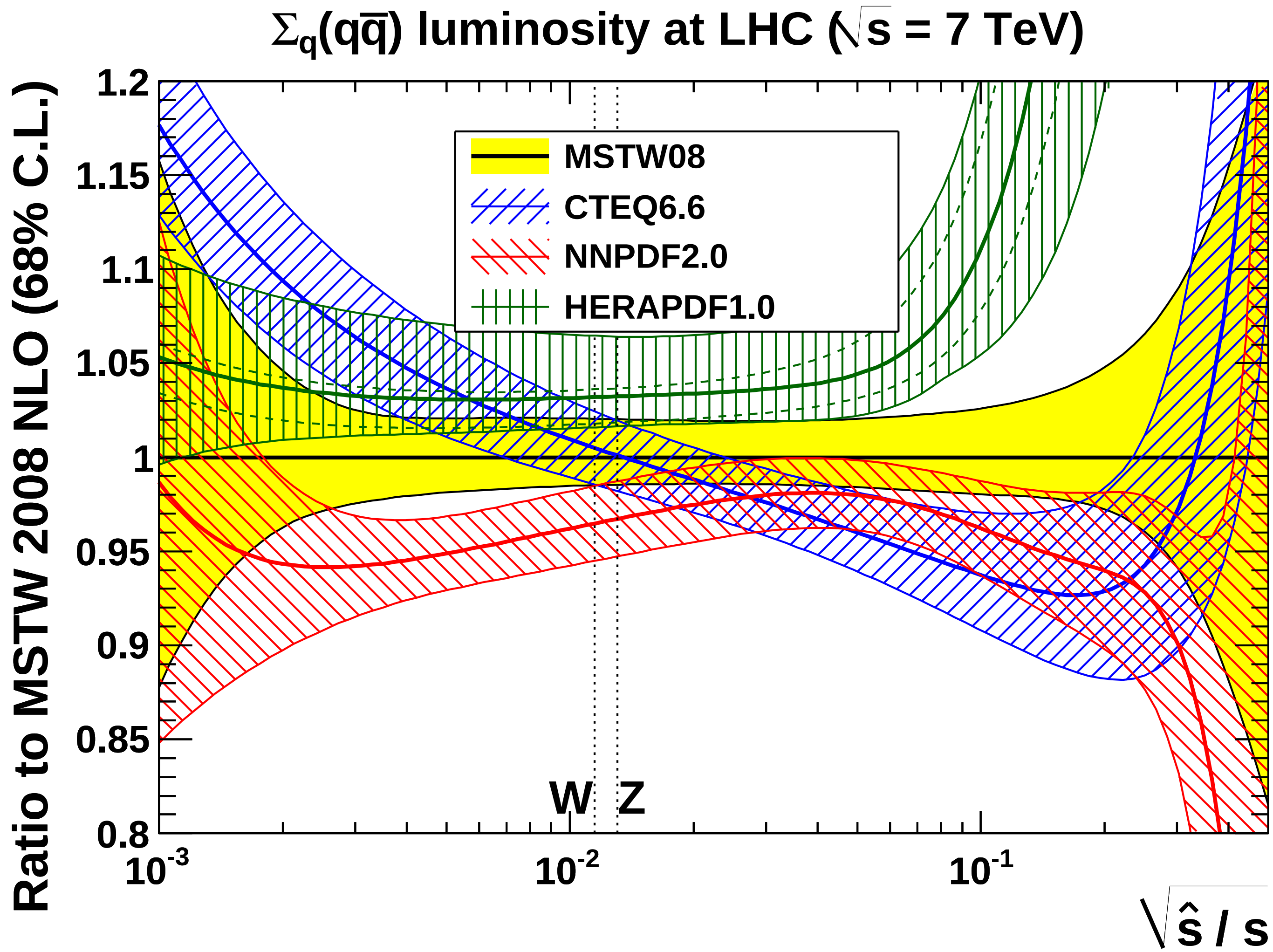


Cross-section for $t\bar{t}$ almost identical in PDF terms to $450\mathrm{GeV}$ Higgs.

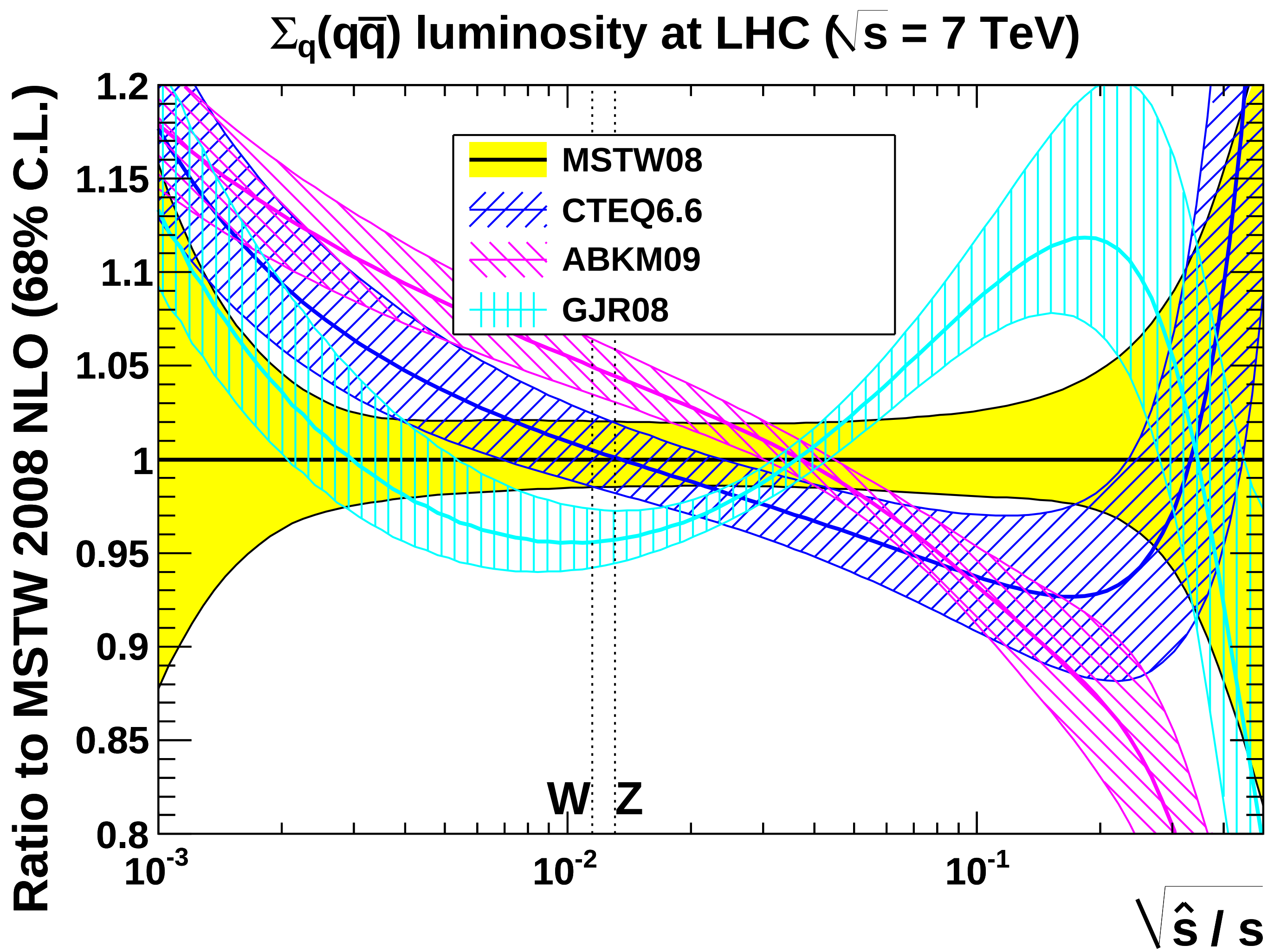
Also $H + t\bar{t}$ at $\sqrt{\hat{s}/s} \sim 0.1$.



Clearly some distinct variation between groups. Much can be understood in terms of previous differences in approaches.



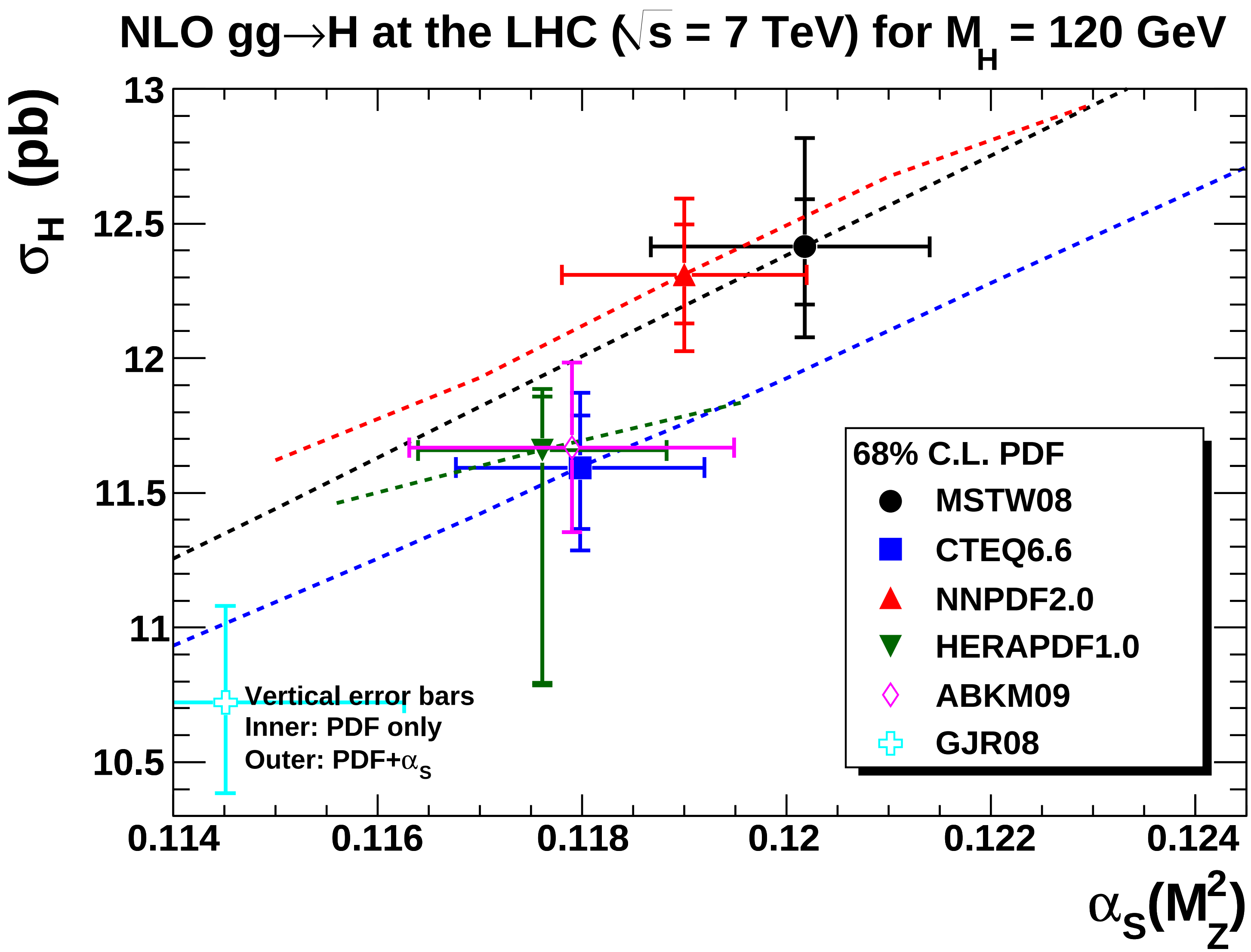
Many of the same general features for quark-antiquark luminosity. Some differences mainly at higher x.



Canonical example W, Z production, but higher $\hat{s}/s$ relevant for WH or vector boson fusion.

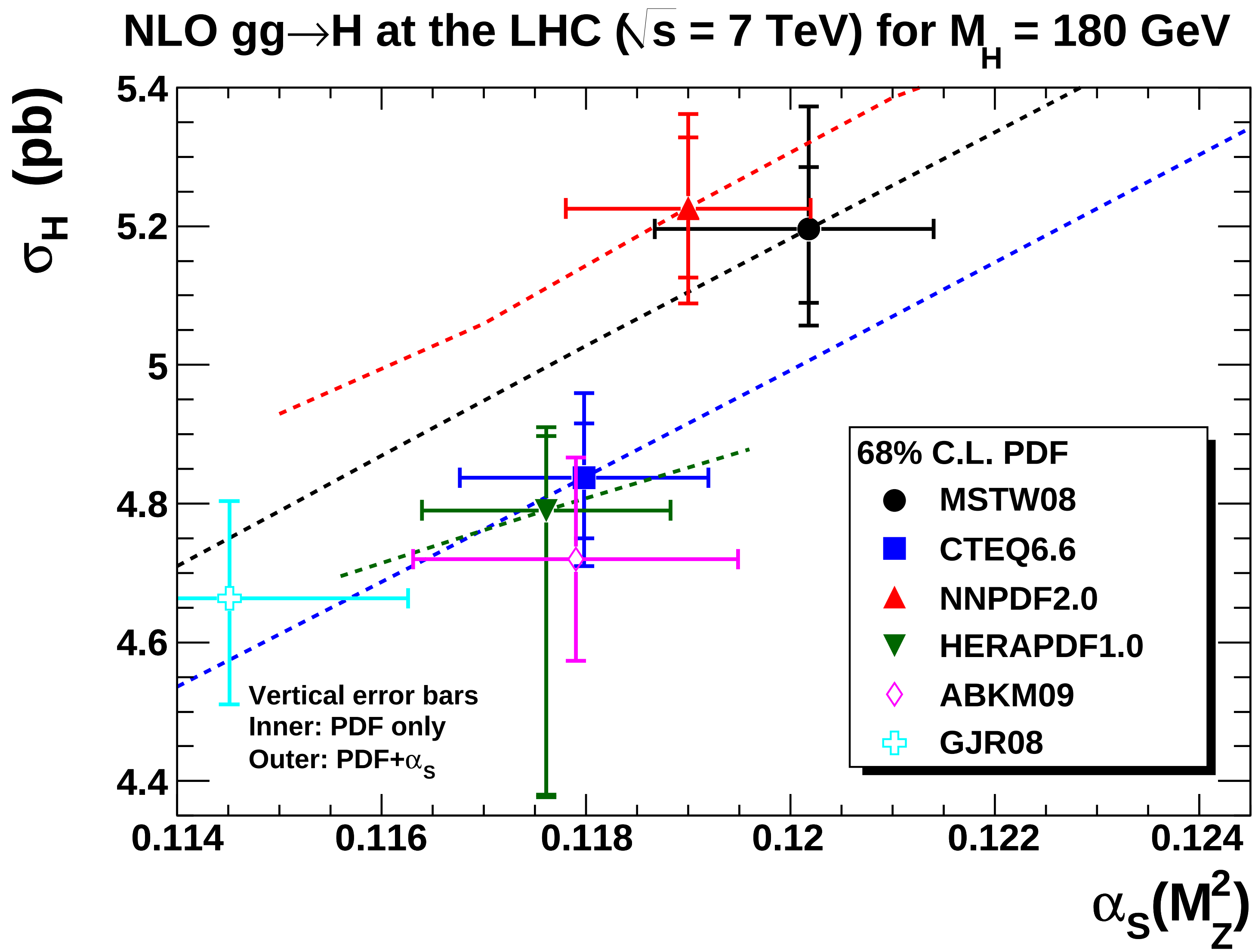
All plots and more at http://projects.hepforge.org/mstwpdf/pdf4lhc

Variations in Cross-Section Predictions – NLO

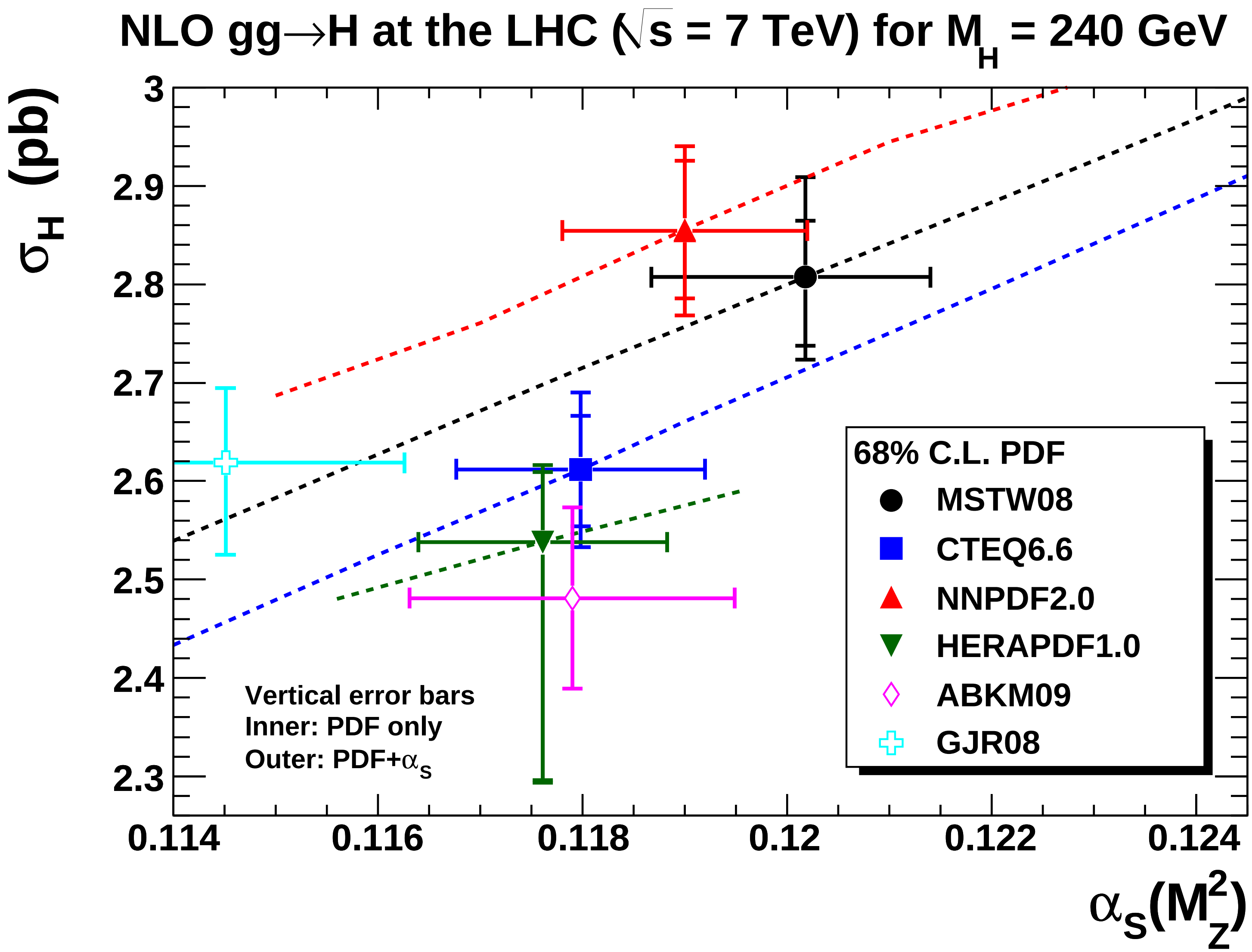


Dotted lines show how central PDF predictions vary with $\alpha_S(M_Z^2)$.

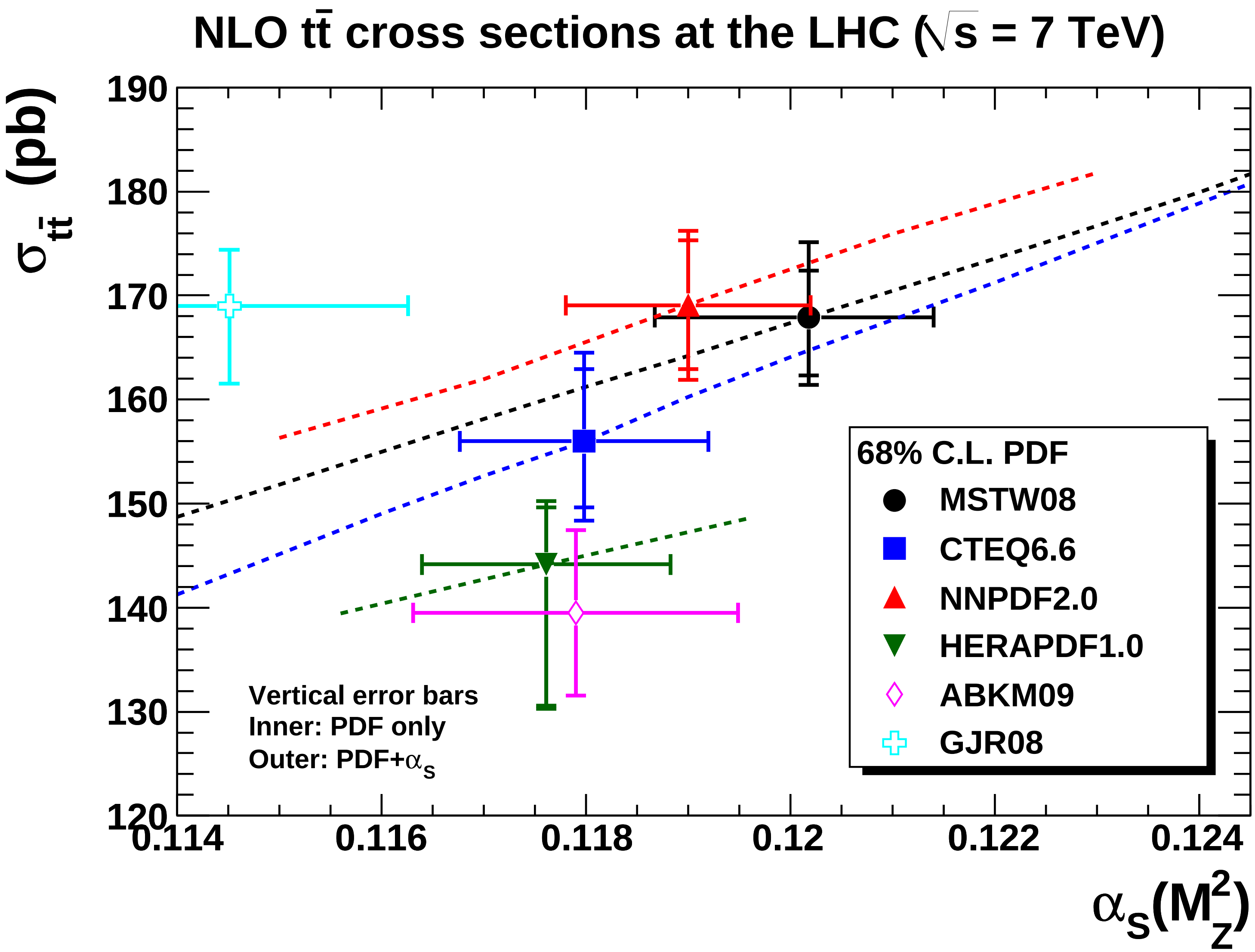
Again plots by G Watt using PDF4LHC benchmark criteria.



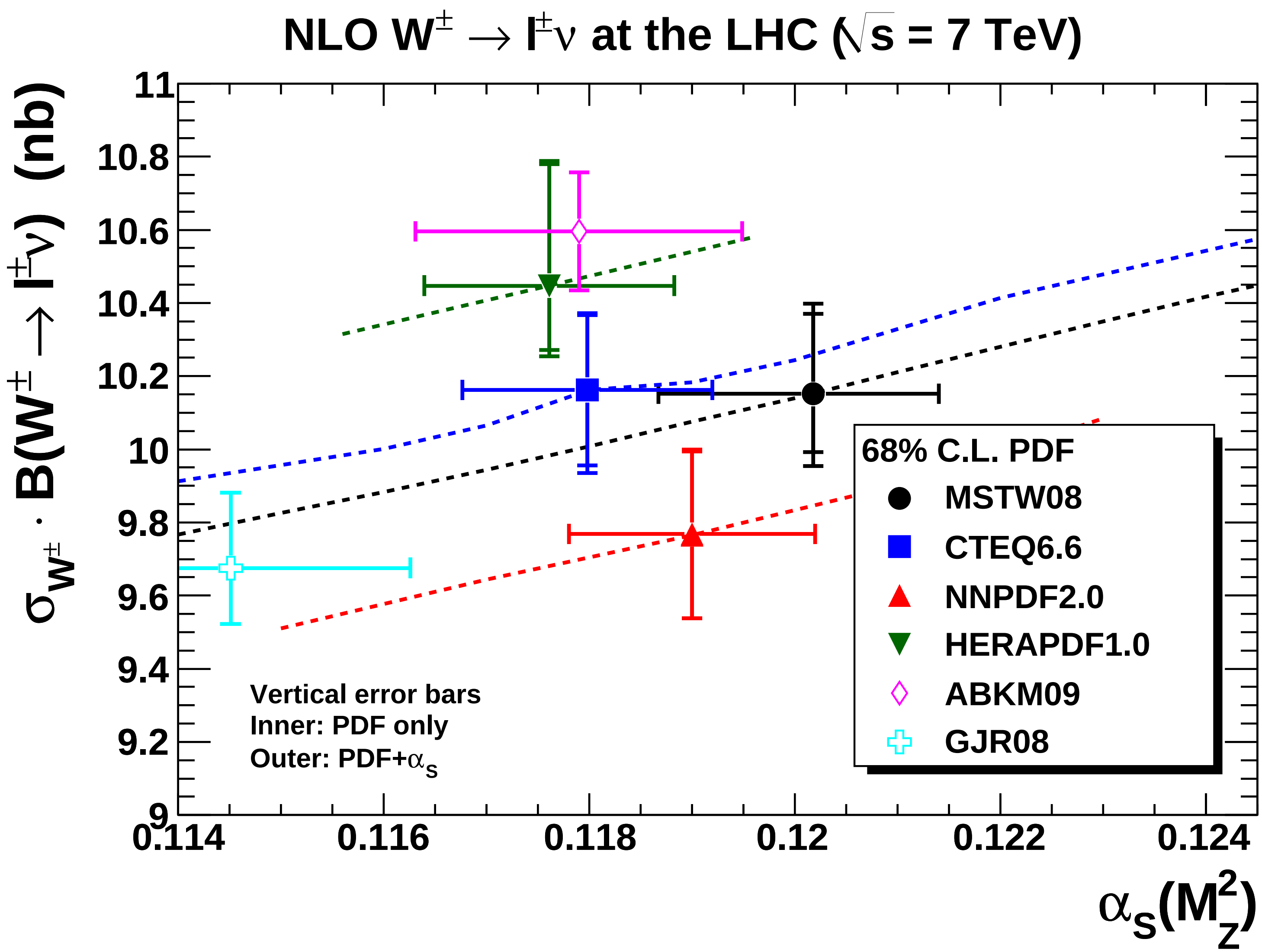
Clearly much more variation in predictions than uncertainties claimed by individual groups.



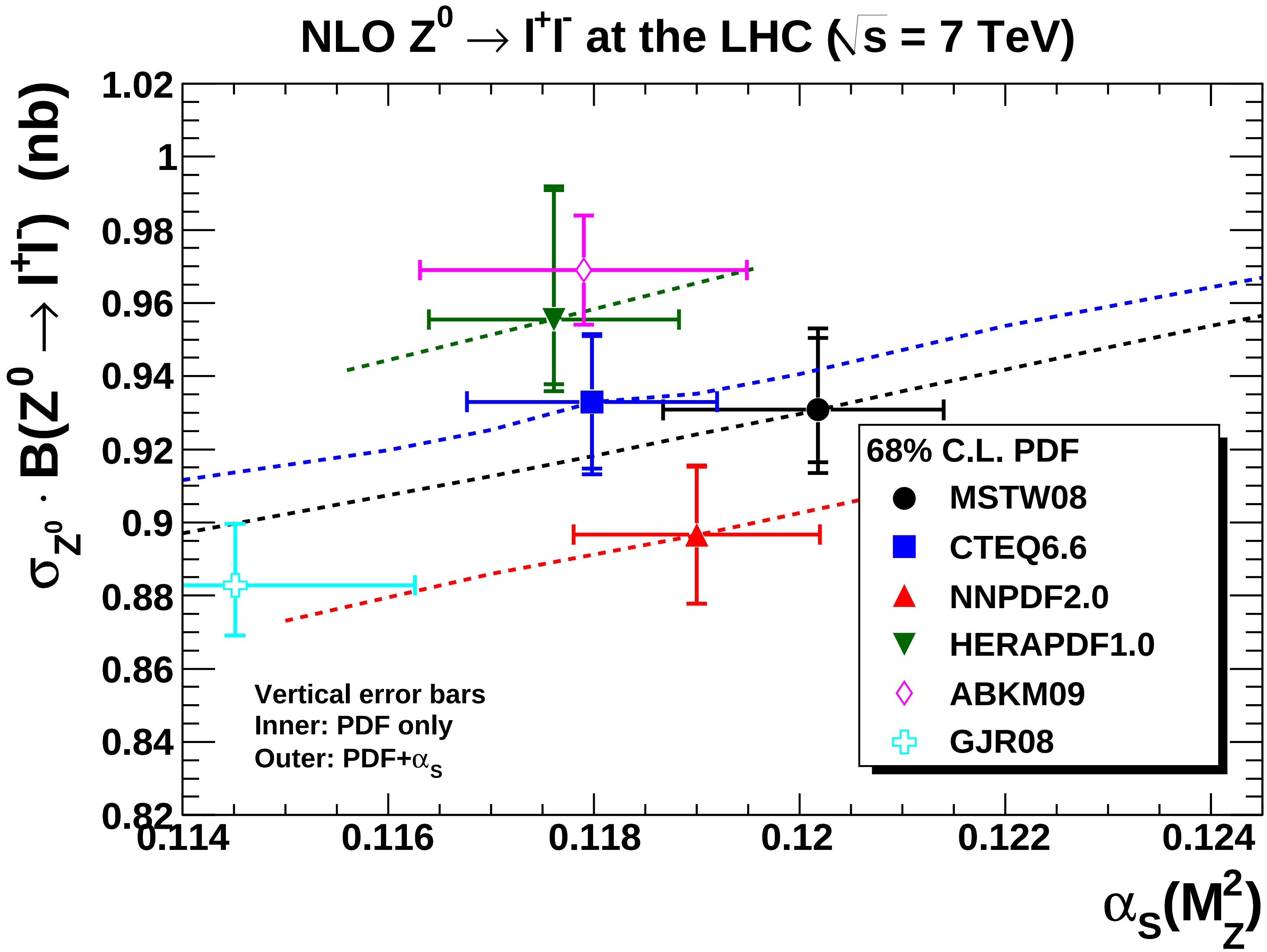
Excluding GJR08 amount of difference due to $\alpha_S(M_Z^2)$ variations $3-4\%$.



CTEQ6.6 now heading back towards MSTW08 and NNPDF2.0.

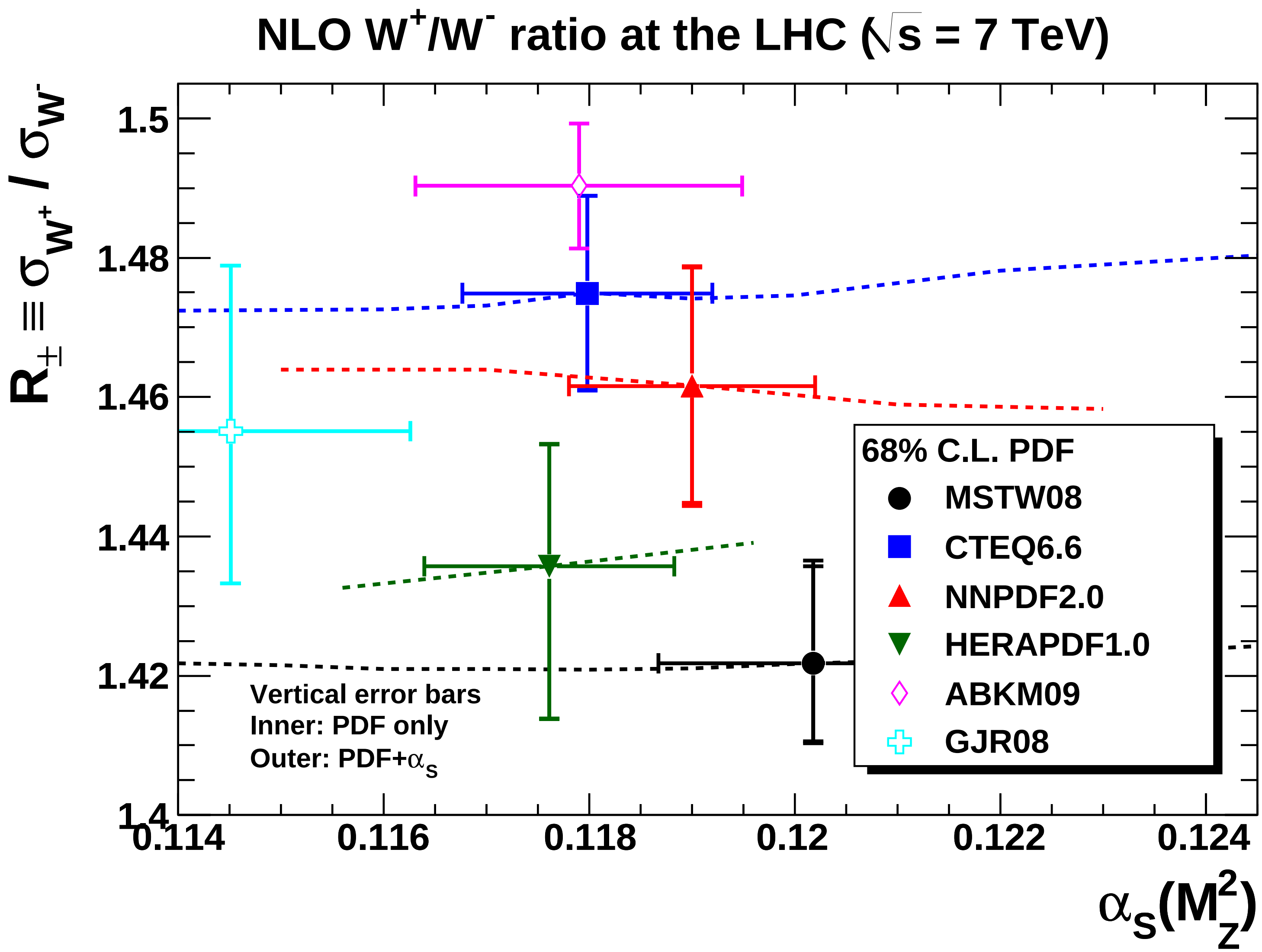


$W^+ + W^-$ cross-section. $\alpha_S(M_Z^2)$ dependence now more due to PDF variation with $\alpha_S(M_Z^2)$.



Again variations somewhat bigger than individual uncertainties.

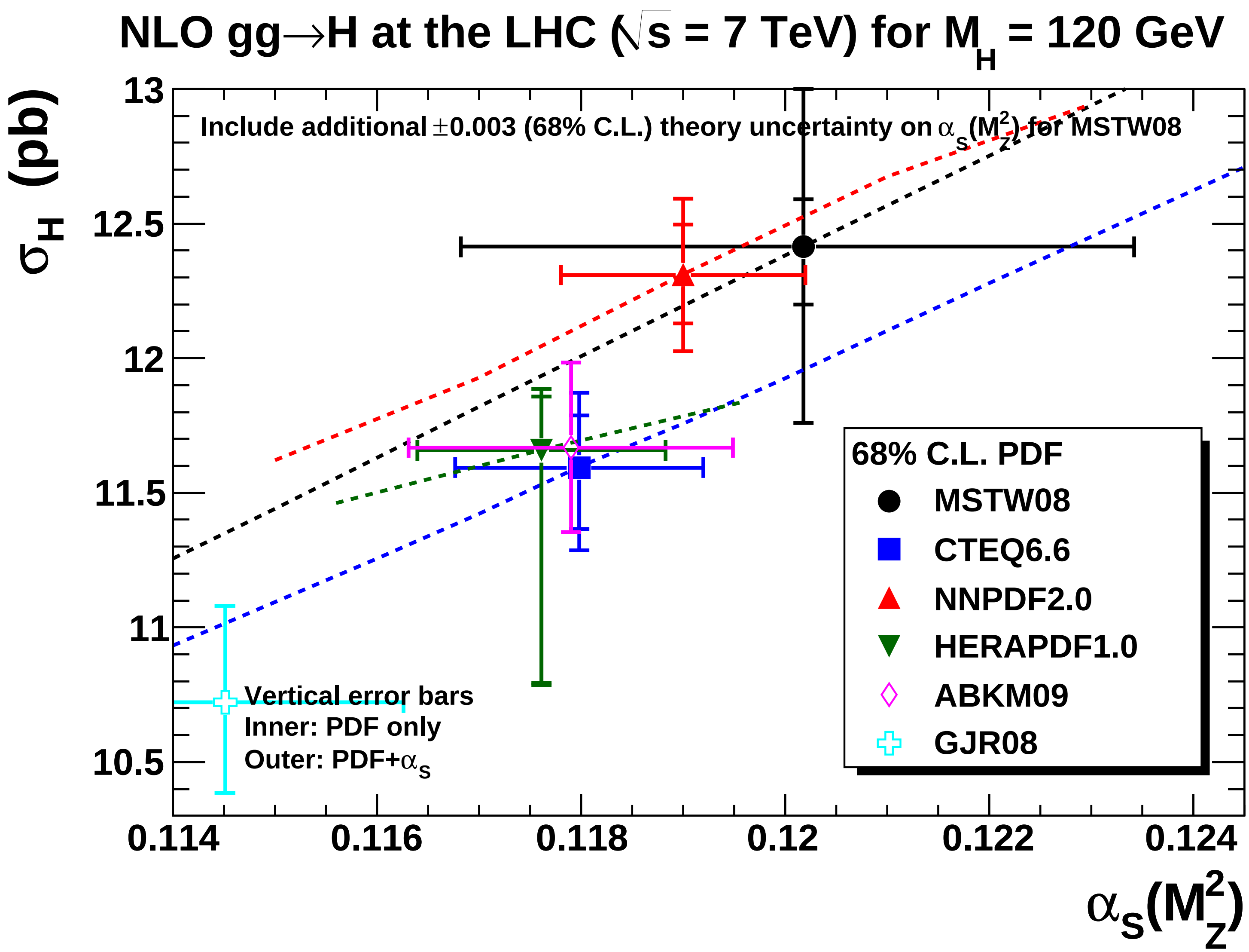
Roughly similar variation for $\hat{s}$ up to a few times higher.



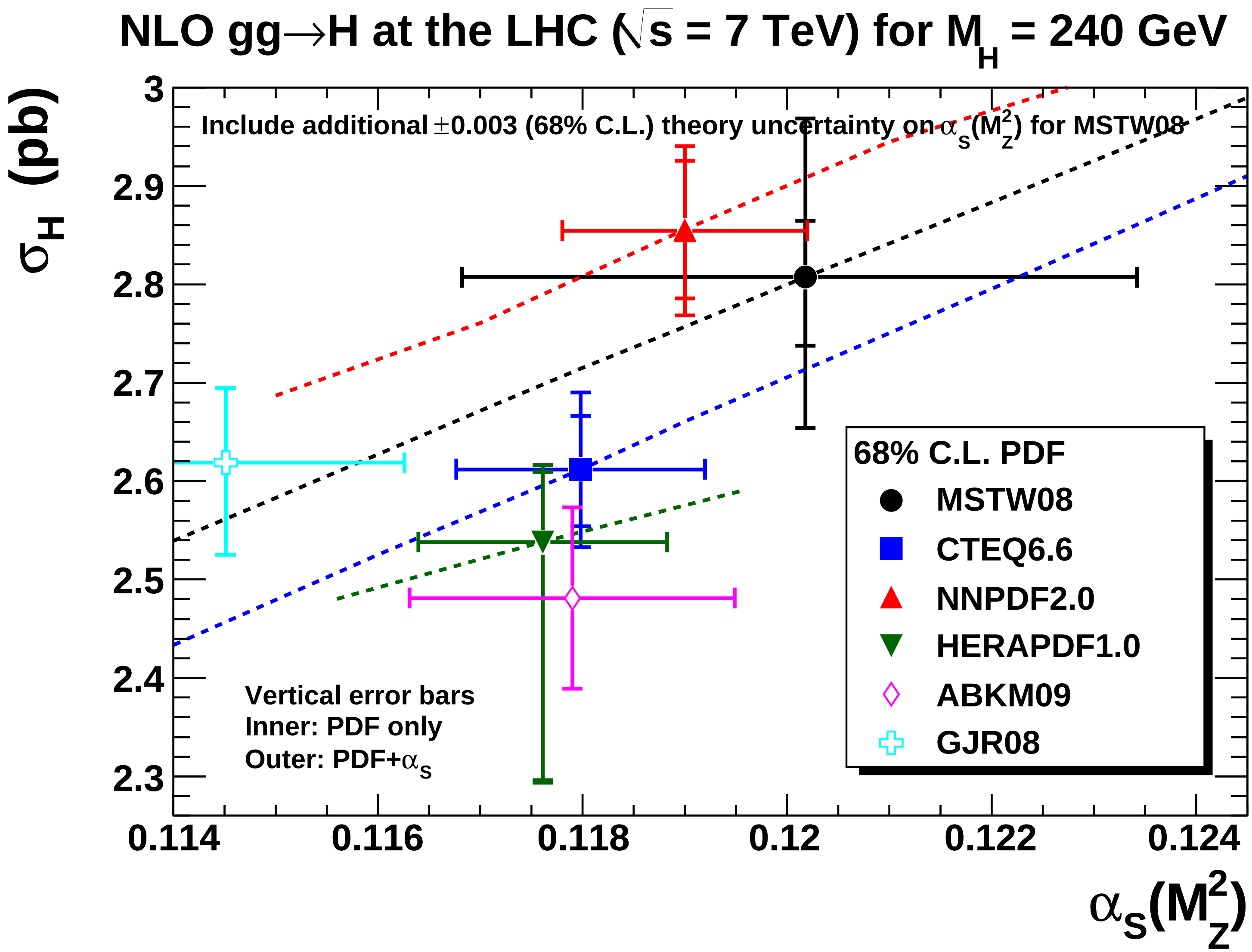
Quite a variation in ratio. Shows variations in flavour and quark-antiquark decompositions.

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

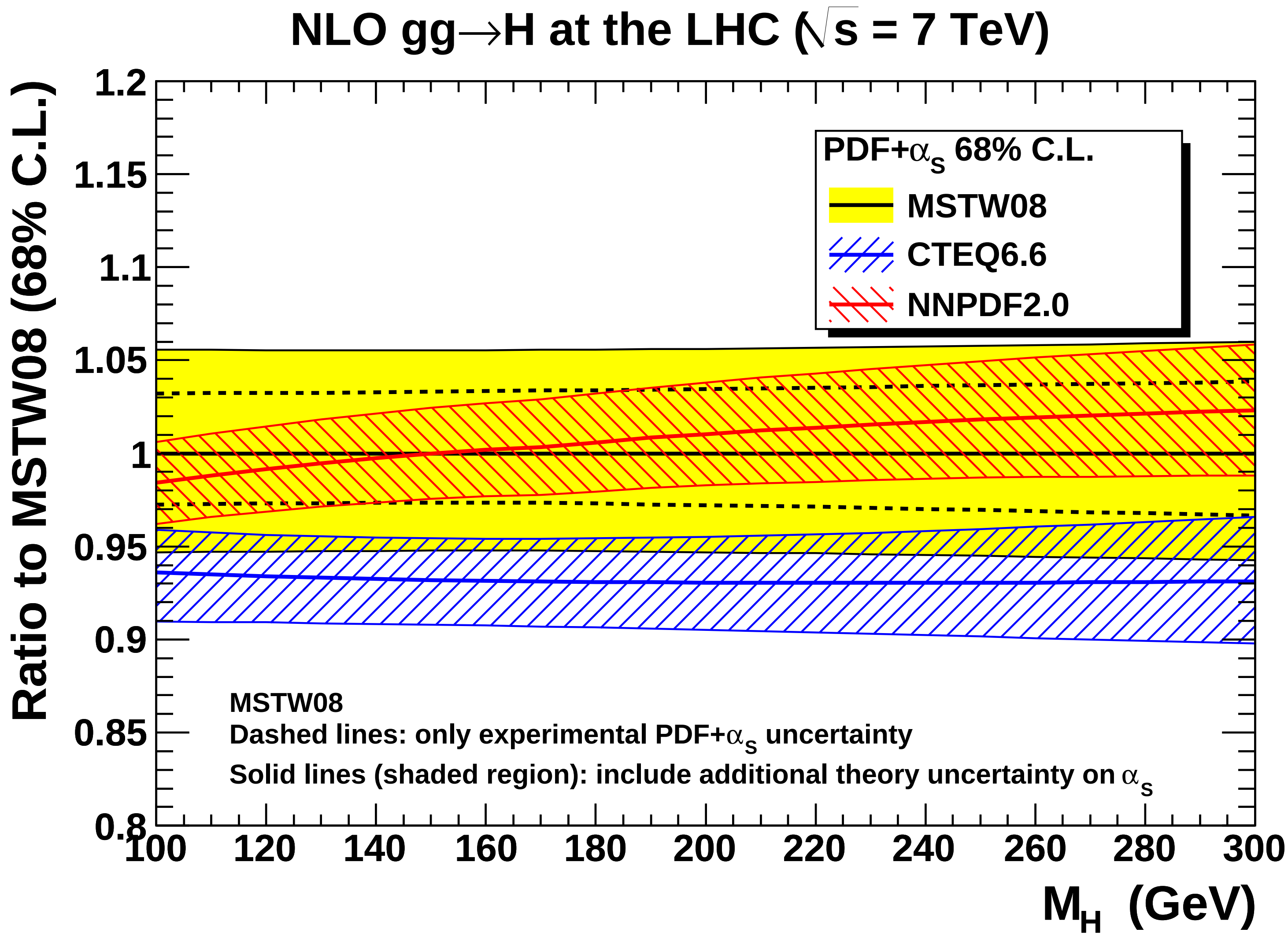
Variations in Cross-Section Predictions – extra uncertanty at NLO



Uncertainty in prediction now includes an additional $\alpha_S(M_Z^2) \pm 0.003$ theory uncertainty added in quadrature with original uncertainties.



Even with this extra uncertainty MSTW doesn't completely span range of predictions, certainly at 68% confidence level.



Same calculations shown as ratio for MSTW, CTEQ6.6 and NNPDF2.0 for continuous Higgs mass.

Sources of Uncertainty - Variation

It is vital to consider theoretical/assumption-dependent uncertainties:

- Methods of determining "best fit" and uncertainties.
- Underlying assumptions in procedure, e.g. parameterisations and data used.
- Treatment of heavy flavours.
- PDF and α_S correlations.

Considered to some extent above, can explain some of the observed differences.

More details after conclusion.

Theoretical Uncertainties

Other sources not considered even by looking at variations between groups.

- Standard higher orders (NNLO)
- QED and Weak (comparable to NNLO ?) ($\alpha_s^3 \sim \alpha$). Sometime enhancements.
- Resummations, e.g. small x ($\alpha_s^n \ln^{n-1}(1/x)$), or large x ($\alpha_s^n \ln^{2n-1}(1-x)$)
- low Q^2 (higher twist), saturation

Lead to differences in current partons, and to corrections in predicted cross-sections.

Would be much the same for each group though.

Most obviously important NNLO, already considered to some extent.

Some more info in back-up slides on others, mainly small-resummations.

Conclusions

One can determine the parton distributions and predict cross-sections at the LHC, and the fit quality using NLO or NNLO QCD is fairly good.

NNLO is strongly desirable if possible. Fewer PDFs and uncertainties available.

Various ways of looking at uncertainties due to errors on data. Uncertainties due to PDFS naively rather small – $\sim 2-5\%$ for most LHC quantities.

Effects from input assumptions e.g. selection of data, cuts, input parameterisation, treatment of heavy flavour, choice of α_S, can shift central predictions significantly.

Some shifts have well-understood origins, particularly some of the most extreme. Some are more difficult to tie down.

α_S and PDFs correlated. Differences in predictions reduced if common value taken – MSTW/CTEQ difference halved but still 2σ. Not clear what common value is best to take. We argue very strongly it is order dependent. Groups also have (different) prescriptions for including α_S uncertainty. Linked to "best-fit" value for some.

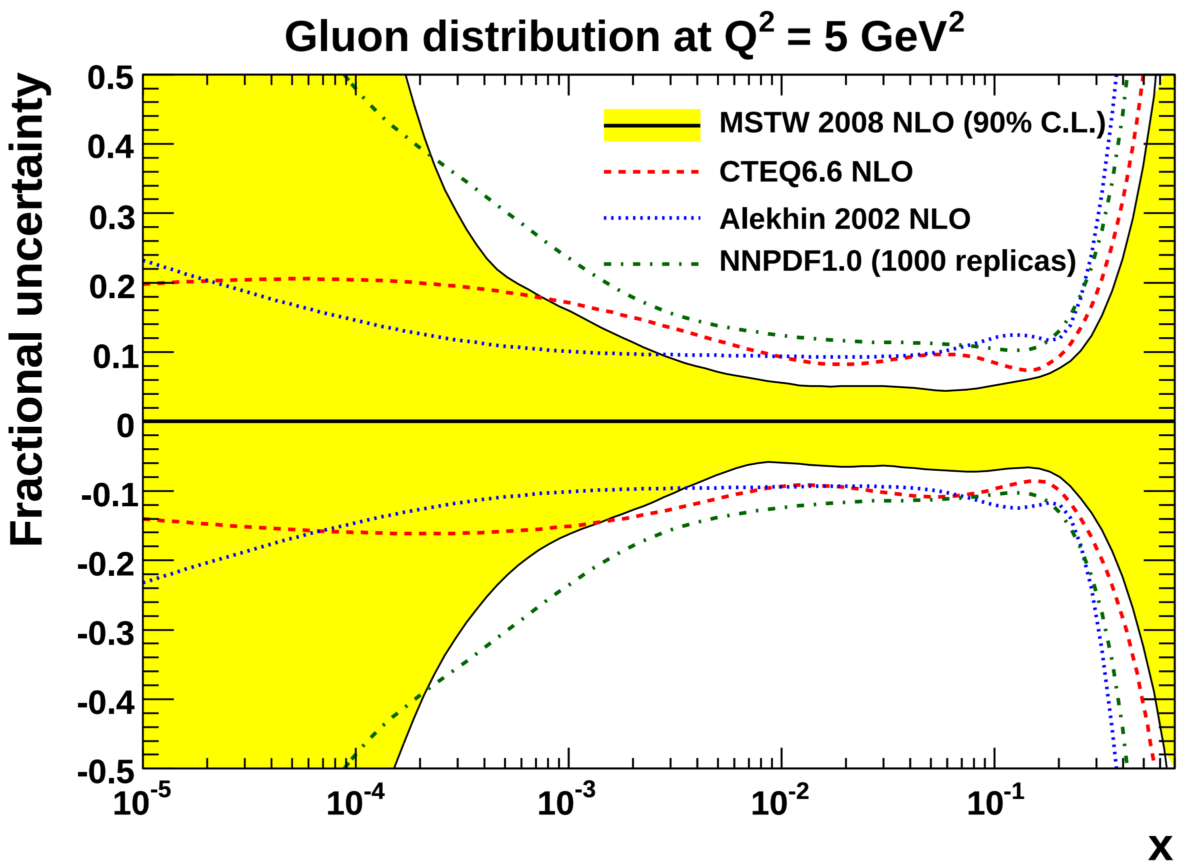
Studies suggest naive uncertainties should be about doubled to take account of the "not very well-understood" effects. For $gg \rightarrow H$ similar to span of MSTW08, CTEQ6.6 and NNPDF. Very conservative approach indeed – look at span of all sets.

Errors from higher orders/resummation and other theoretical sources potentially significant – back to NNLO again. Direct measurement of $F_L(x,Q^2)$ at HERA now testing small-x resummation, for example.

Generally same systematic type of effect for all PDFs.

At LHC early measurements, e.g. W,Z and jets would be useful in testing understanding of QCD (Standard Model).

Gluon Parameterisation - small x – different parameterisations lead to very different uncertainty for small x gluon.



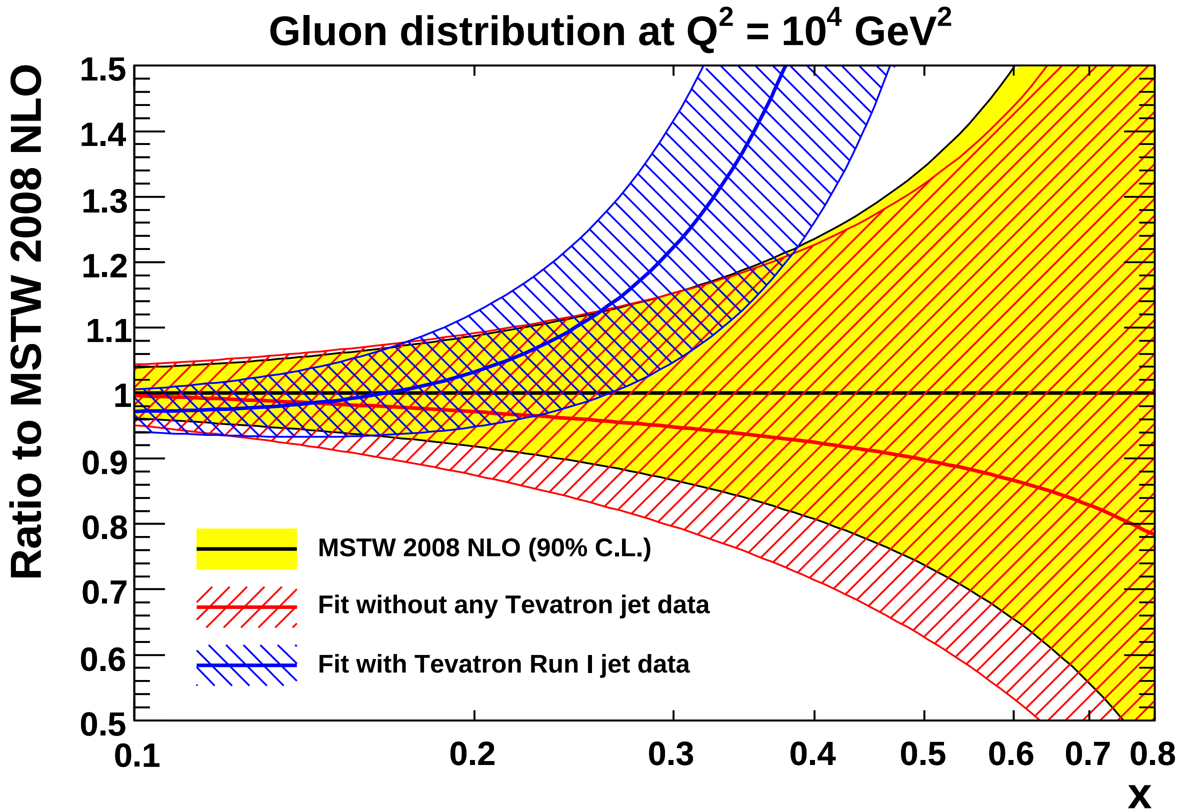
Most assume single power x^{λ} at input $\rightarrow$ limited uncertainty. If input at low Q^2 λ positive and small-x input gluon *fine-tuned* to ~ 0. Artificially small uncertainty.

If $g(x) \propto x^{\lambda \pm \Delta\lambda}$ then $\Delta g(x) = \Delta\lambda \ln(1/x) * g(x)$.

MRST/MSTW and NNPDF more flexible (can be negative) $\rightarrow$ rapid expansion of uncertainty where data runs out.

Gluon Distribution - large x.

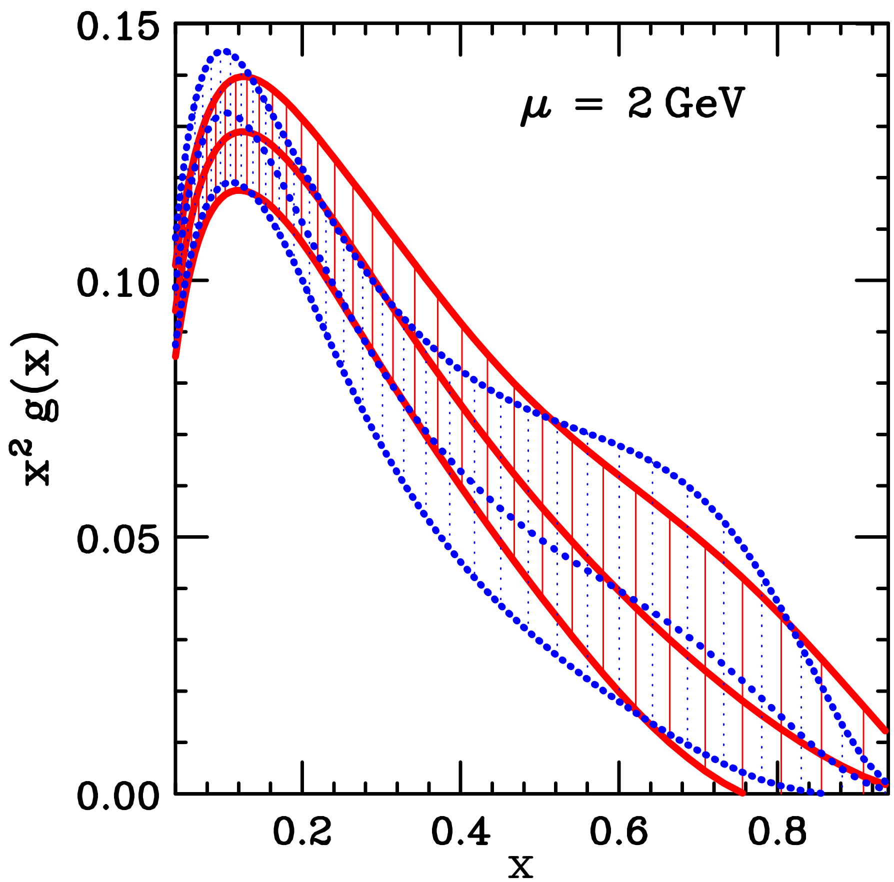
Constrained indirectly, but quite accurately, by DIS data, and directly by Tevatron high-p_T jets, now **Run I** and **Run II** available. *Slightly* confusing picture.

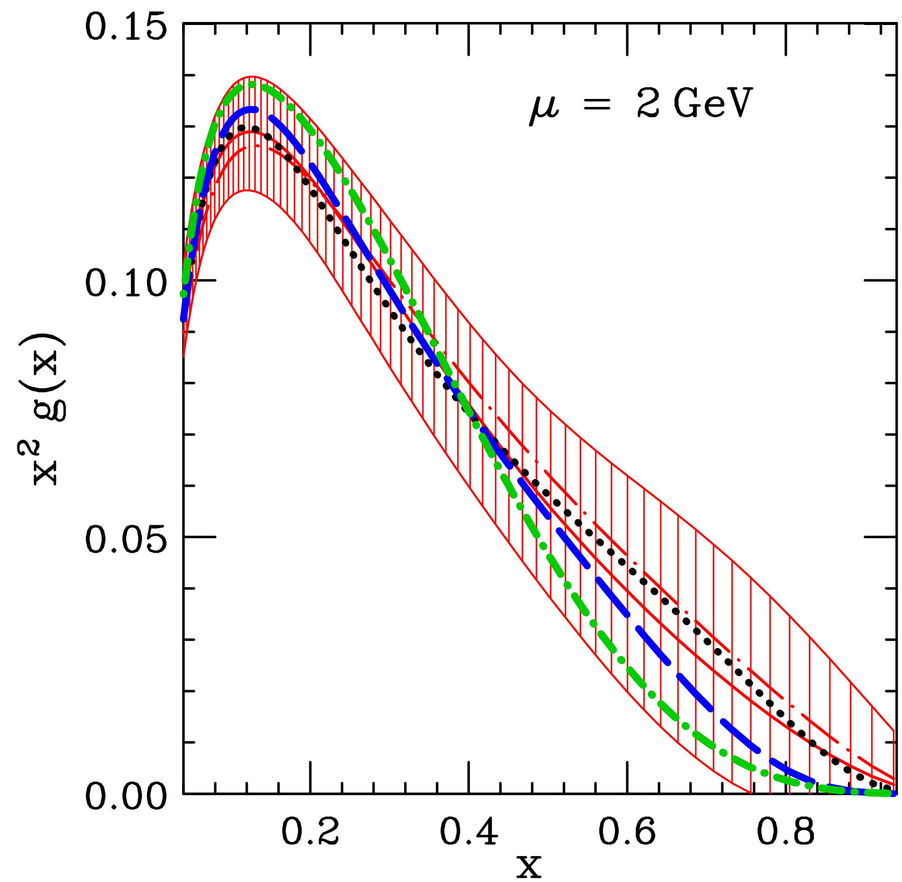


Only fit by MSTW and CTEQ (now also NNPDF. Former found gluon much softer for **Run II**. Fits not very consistent between runs.

CTEQ find more compatibility between **Run I** and **Run II** fits. Fit with both sets → little change – red CT09G, blue CTEQ6.6 (left).

Partially less strict with "consistency", partially difference in parameterisation, partially effectively *higher weight* to jet data in global fit.



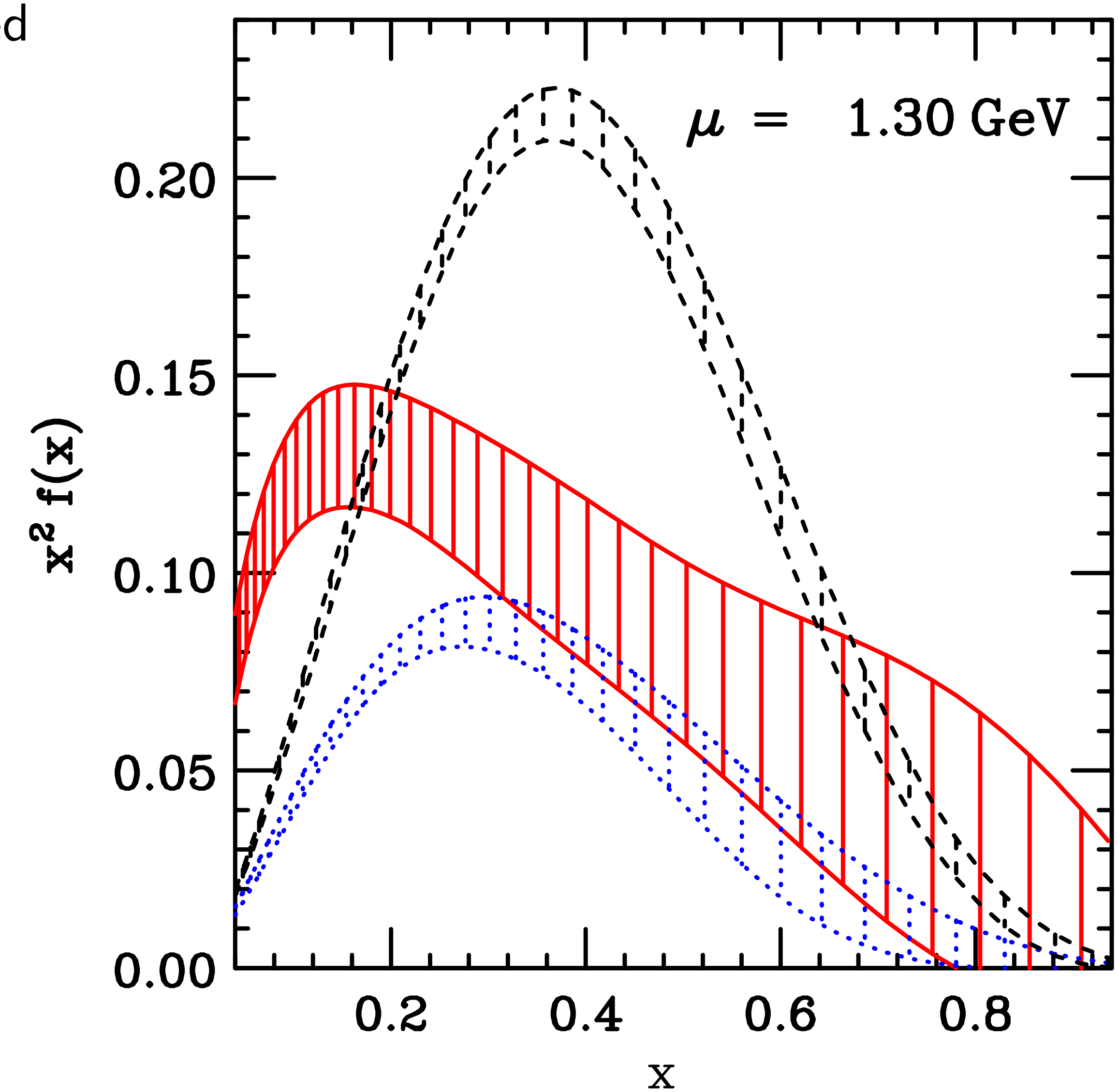


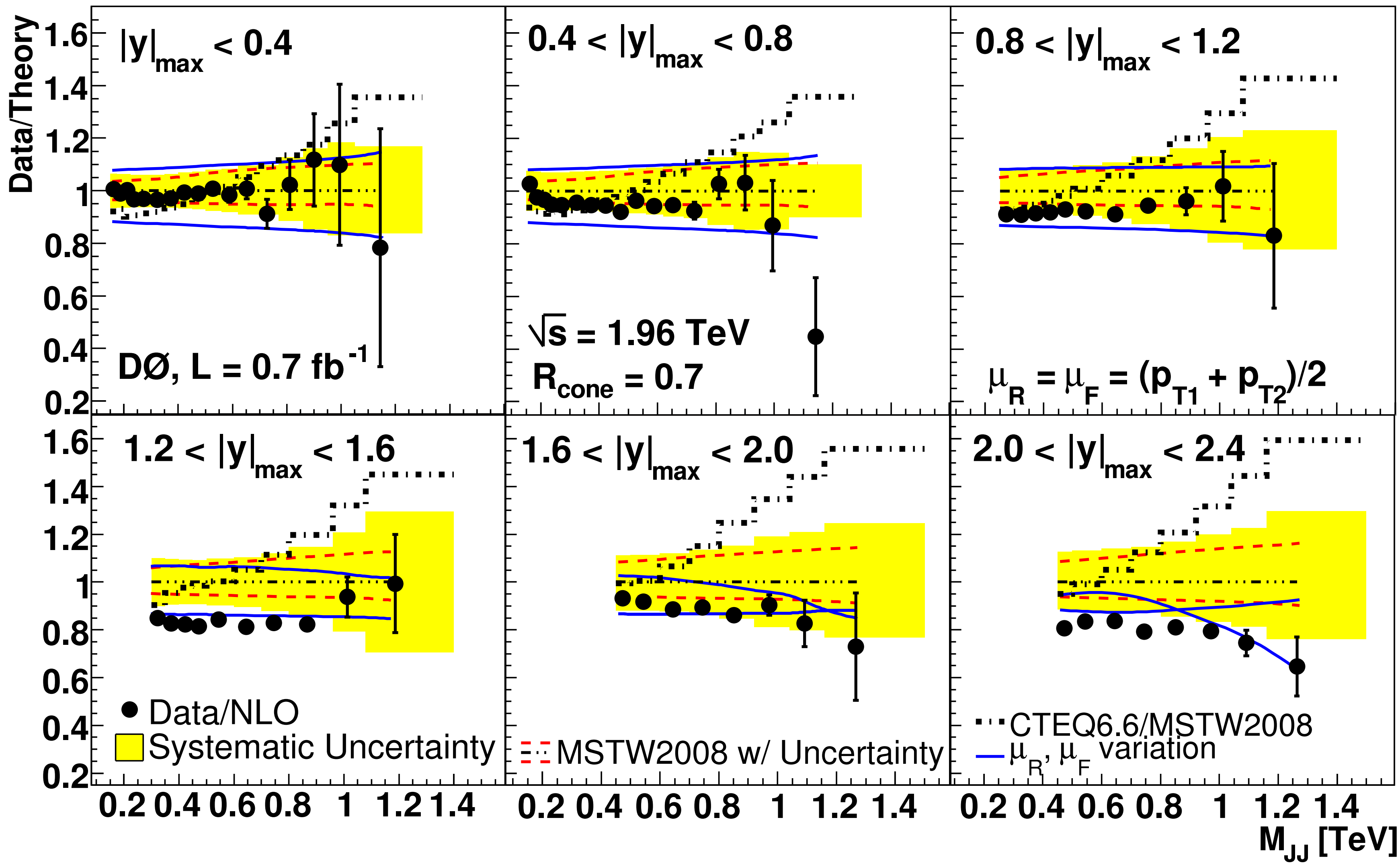
When fit to **Run II** data only and same procedure as MSTW blue (right) similar to MSTW green (right).

Generally high-x PDFs parameterised so will behave like $(1-x)^\eta$ as $x \to 1$. More flexibility in CTEQ.

Very hard high-x gluon distribution (more-so even than NNPDF uncertainties).

However, is gluon, which is radiated from quarks, harder than the up valence distribution for $x \to 1$?





Very large high-x gluon not supported by very recent D0 dijet data.

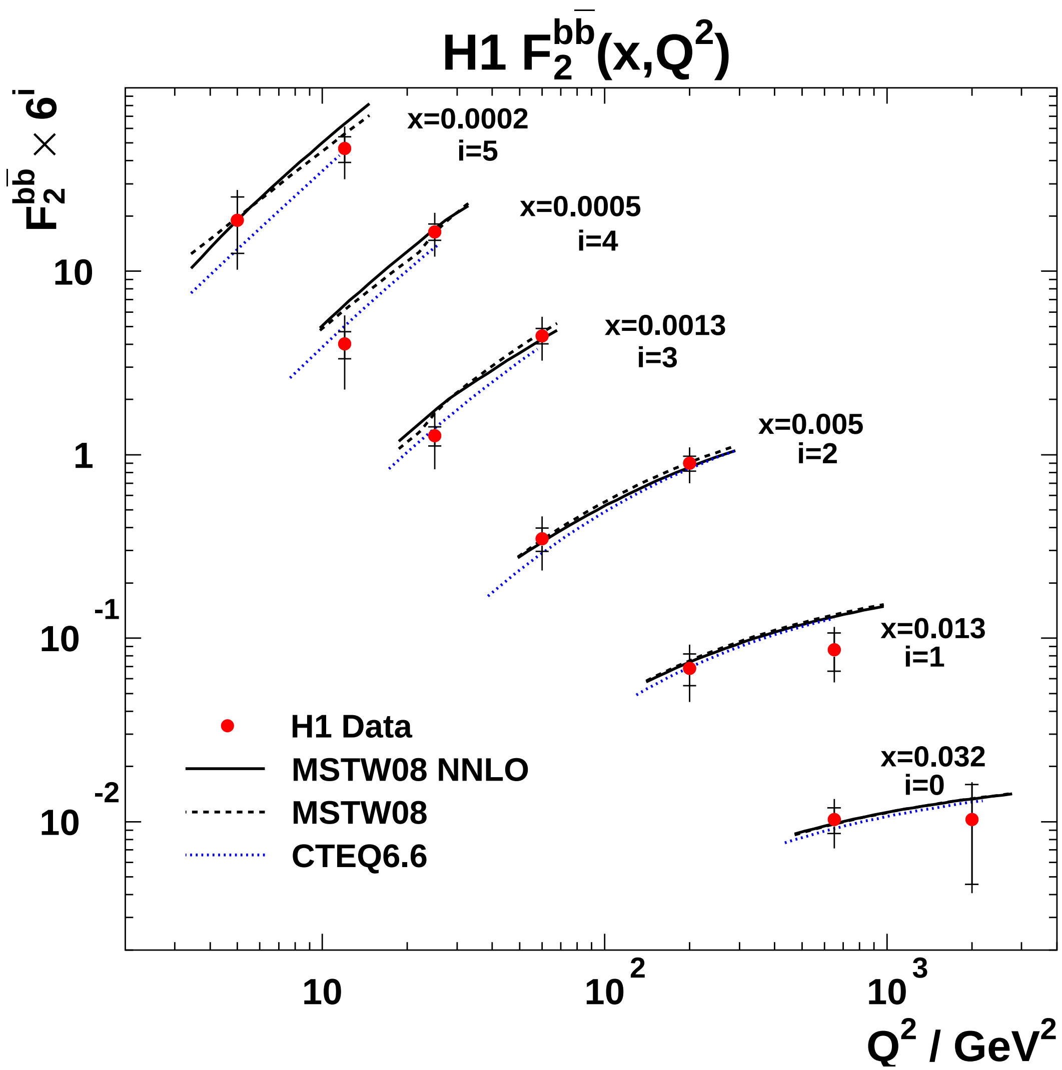
Heavy Flavours – GM-VFNS variations.

Various definitions possible. Versions used by MSTW (RT) and CTEQ (ACOT) have converged somewhat.

Freedom in choices and consistency of kinematic limits (heavy quark pair produced in final state) introduced in RT scheme.

Simplest choice in heavy flavour coefficient function now commonly based on ACOT(χ) prescription, i.e. scaling variable x replaced by $\chi \equiv x(1+4m_H^2/Q^2)$. (Two variations.)

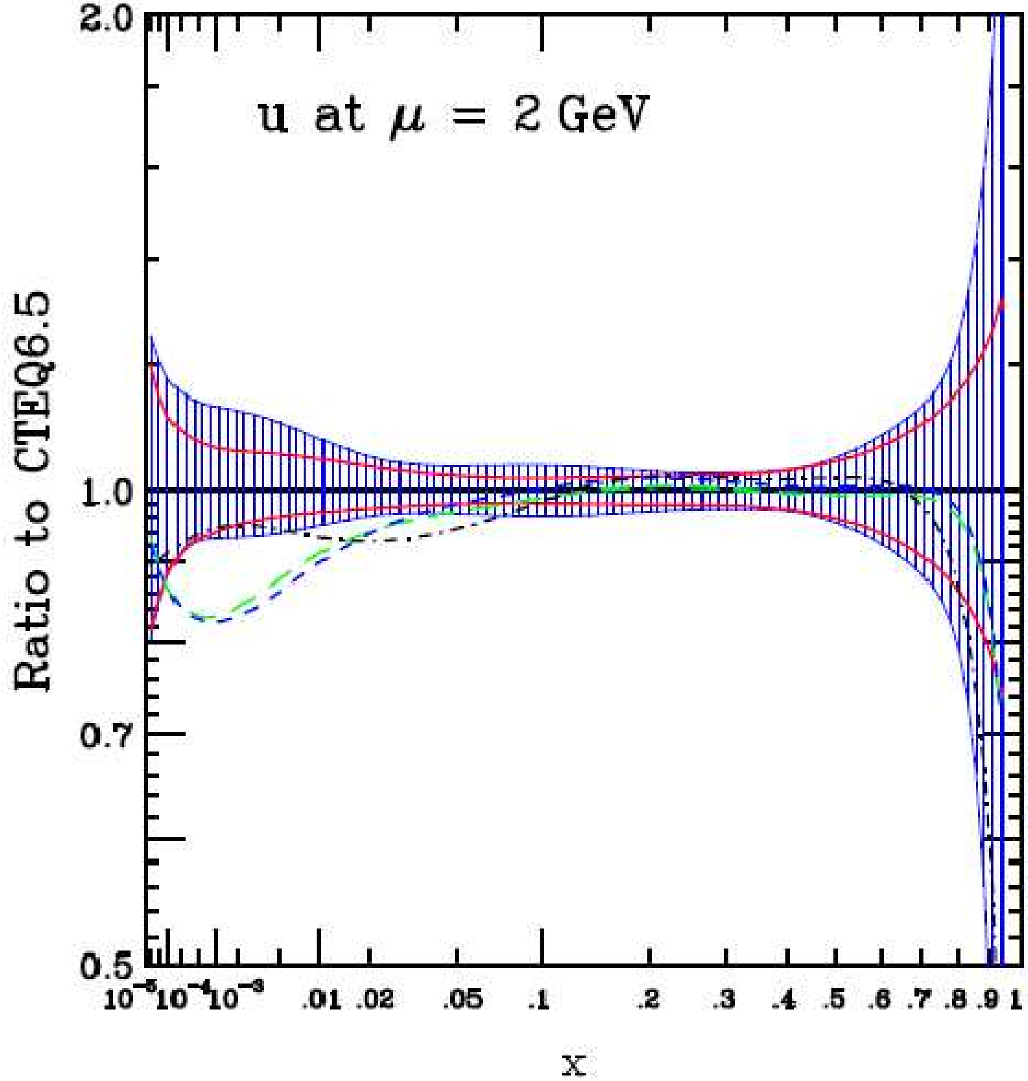
Various significant differences still exist as illustrated by comparison to most recent H1 data on bottom production.



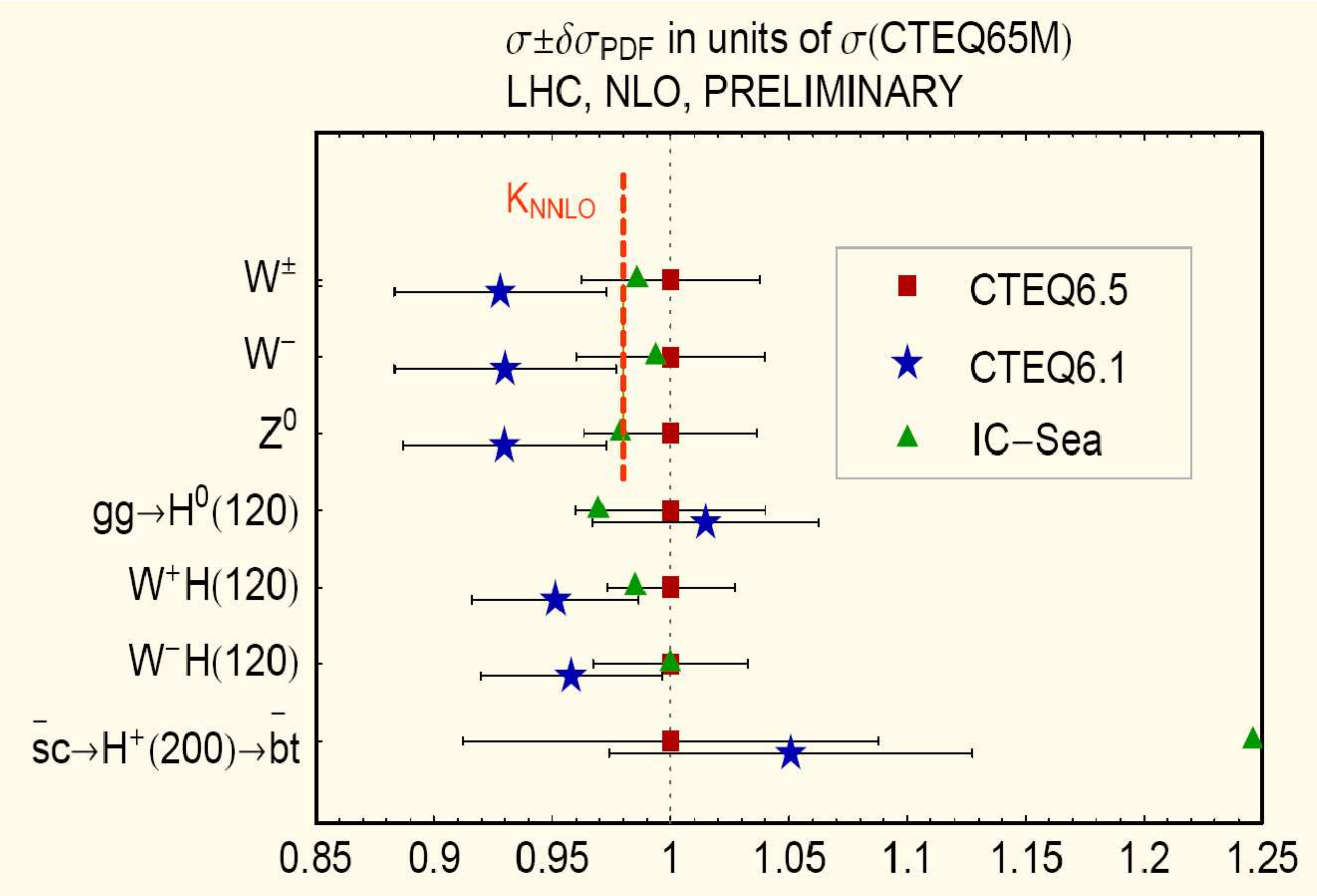
Importance of using GM-VFNS instead of massless approach illustrated by CTEQ6.5 up quark with uncertainties compared with previous versions, e.g. CTEQ6 in green.

Can be $> 8\%$ error in PDFs. Much more than scheme uncertainty.

MRST in dash-dot line. Reasonable agreement. Already used heavy flavour treatment in default sets.



Leads to large change in predictions using CTEQ partons at LHC of $5 - 10\%$.



Note effects of *intrinsic charm* in final case.

The values of the predicted cross-sections at NLO for Z and a 120 GeV Higgs boson at the Tevatron and the LHC (latter for 14 TeV) as GM-VFNS altered.

PDF set	$B_{l^+l^-} \cdot \sigma_Z$(nb) TeV	σ_H(pb)TeV	$B_{l^+l^-} \cdot \sigma_Z$(nb) LHC	σ_H(pb) LHC
MSTW08	0.2426	0.7462	2.001	40.69
GMvar1	0.2433	0.7428	2.023	40.76
GMvar2	0.2444	0.7383	2.061	41.29
GMvar3	0.2429	0.7438	2.024	41.03
GMvar4	0.2425	0.7457	1.993	40.60
GMvar5	0.2423	0.7454	1.991	40.56
GMvar6	0.2434	0.7431	2.032	41.00
GMvarcc	0.2427	0.7451	2.001	40.65

At most 1% variation at Tevatron in σ_Z.

Up to $+3\%$ and -0.5% variation in σ_Z at the LHC. About half as much in σ_H due to higher average x sampled.

Remember 8% from ZMVFNS to GMVFNS in CTEQ6 (6% for completed NNLO GMVFNS in MRST06).

The values of the predicted cross-sections at NNLO. σ_H calculated using Harlander, Kilgore code.

PDF set	$B_{l^+l^-} \cdot \sigma_Z$(nb) TeV	σ_H(pb)TeV	$B_{l^+l^-} \cdot \sigma_Z$(nb) LHC	σ_H(pb) LHC
MSTW08	0.2507	0.9550	2.051	50.51
GMvar1	0.2509	0.9505	2.054	50.39
GMvar2	0.2514	0.9478	2.061	50.55
GMvar3	0.2516	0.9539	2.062	50.88
GMvar4	0.2507	0.9534	2.050	50.45
GMvar5	0.2509	0.9519	2.046	50.37
GMvar6	0.2509	0.9462	2.057	50.38
GMvarmod	0.2501	0.9511	2.022	50.03
GMvarmod'	0.2508	0.9482	2.052	50.57

Other than from model dependence maximum variations of order 0.5% at LHC. High-x gluon leads to 1% on σ_H at Tevatron.

Model uncertainties can be $> 1\%$ from region at very small x and low Q^2. Can perhaps input more small-x knowledge here. Effect far smaller when $\mathcal{O}(\alpha_S^3)$ term falls with Q^2.

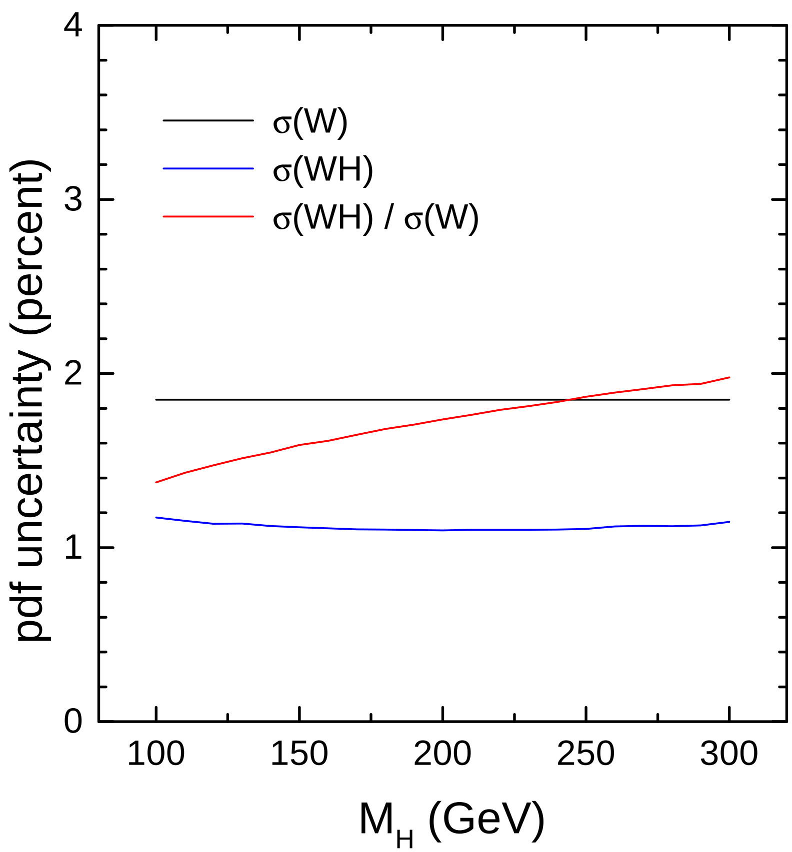
Could $\sigma(W)$ or $\sigma(Z)$ be used to calibrate other cross-sections, e.g. $\sigma(WH)$, $\sigma(Z')$?

$\sigma(WH)$ more precisely predicted because it samples quark pdfs at higher x, and scale, than $\sigma(W)$.

However, ratio shows no improvement in uncertainty, and can be worse.

Partons in different regions of x are often anti-correlated rather than correlated, partially due to sum rules.

pdf uncertainties on W, WH cross sections at LHC (MRST2001E)



No obvious advantage in using $\sigma(t\bar{t})$ as a calibration SM cross-section, except maybe for very particular, and rather large, M_H.

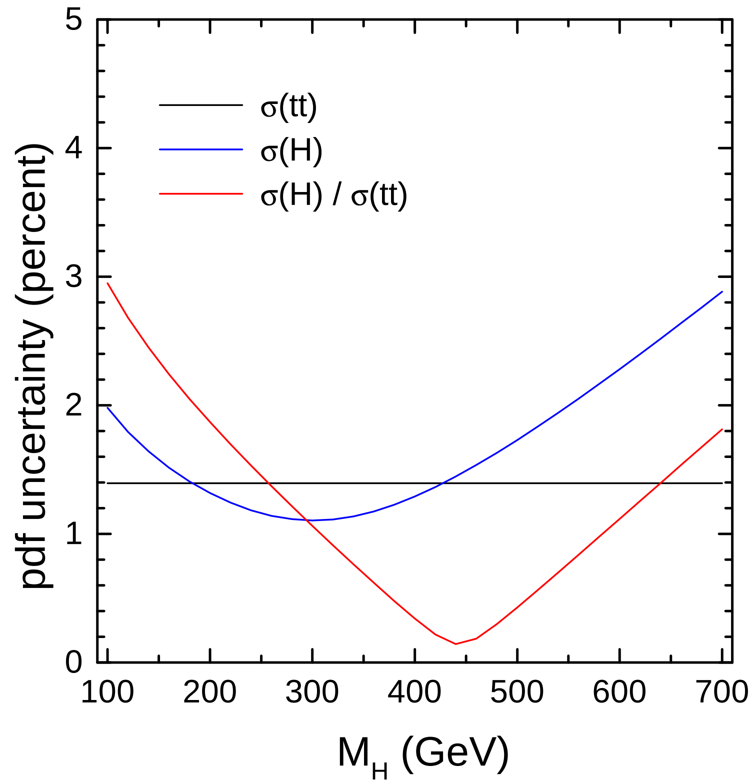
However, a light (SM or MSSM) Higgs dominantly produced via $gg \to H$ and the cross-section has small pdf uncertainty because $g(x)$ at small x is well constrained by HERA DIS data.

Current best (MRST) estimate, for $M_H = 120$ GeV: $\delta\sigma_H^{\rm NLO}(\text{expt pdf}) = \pm 2-3\%$ with less sensitivity to small x than $\sigma(W)$.

Much smaller than the uncertainty from higher-order corrections, for example, Catani et al,

$\delta\sigma_H^{\rm NNLL}(\text{scale variation}) = \pm 8\%$

pdf uncertainties on top, (gg→) H
cross sections at LHC (MRST2001E)

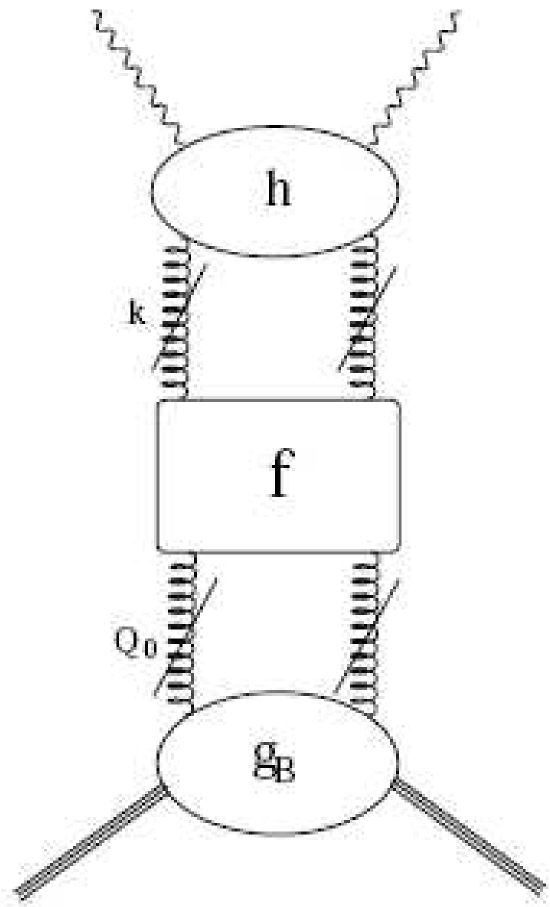


Small-x Theory

Reason for this instability – at each order in α_S each splitting function and coefficient function obtains an extra power of $\ln(1/x)$ (some accidental zeros in P_{gg}), i.e. $P_{ij}(x,\alpha_s(Q^2)), C_i^P(x,\alpha_s(Q^2)) \sim \alpha_s^m(Q^2)\ln^{m-1}(1/x)$.

BFKL equation for high-energy limit

$$f(k^2,x) = f_I(Q_0^2) + \int_x^1 \frac{dx'}{x'}\bar{\alpha}_S \int_0^\infty \frac{dq^2}{q^2} K(q^2,k^2) f(q^2,x),$$



where $f(k^2,x)$ is the unintegrated gluon distribution $g(x,Q^2) = \int_0^{Q^2}(dk^2/k^2) f(x,k^2)$, and $K(q^2,k^2)$ is a calculated kernel known to NLO.

Physical structure functions obtained from

$$\sigma(Q^2,x) = \int (dk^2/k^2)\, h(k^2/Q^2) f(k^2,x)$$

where $h(k^2/Q^2)$ is a calculable impact factor.

The global fits usually assume that this is unimportant in practice, and proceed regardless.

Fits work well at small x, but could improve.

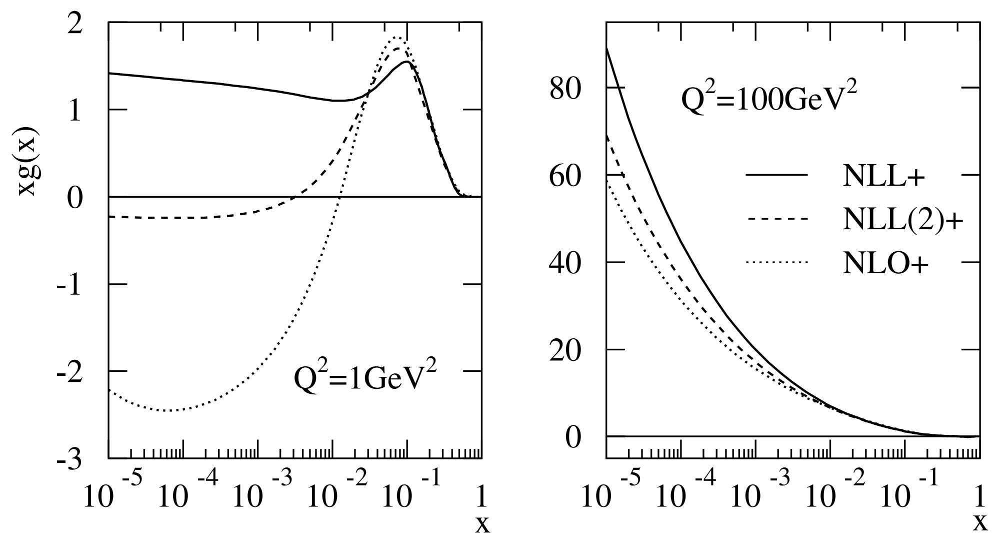
Good recent progress in incorporating $\ln(1/x)$ resummation Altarelli-Ball-Forte, Ciafaloni-Colferai-Salam-Stasto and White-RT.

Include running coupling effects and variety (depending on group) of other corrections

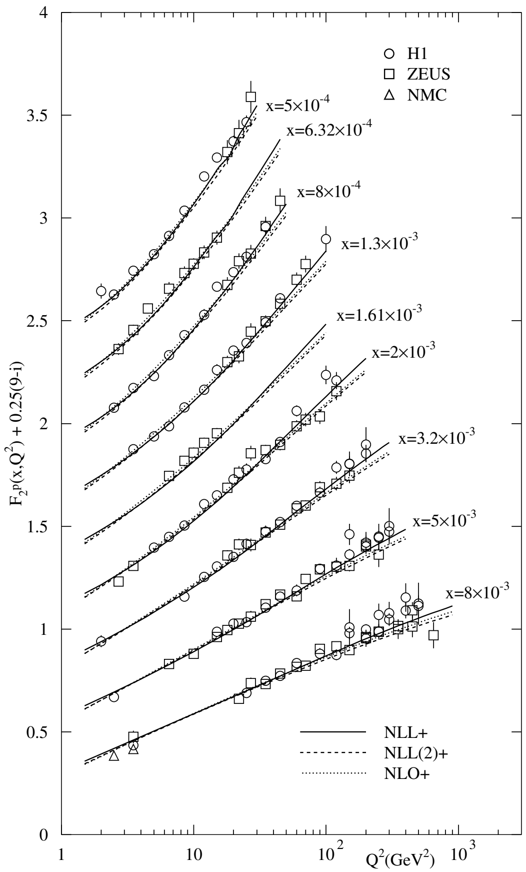
By 2008 very similar results coming from the competing procedures, despite some differences in technique.

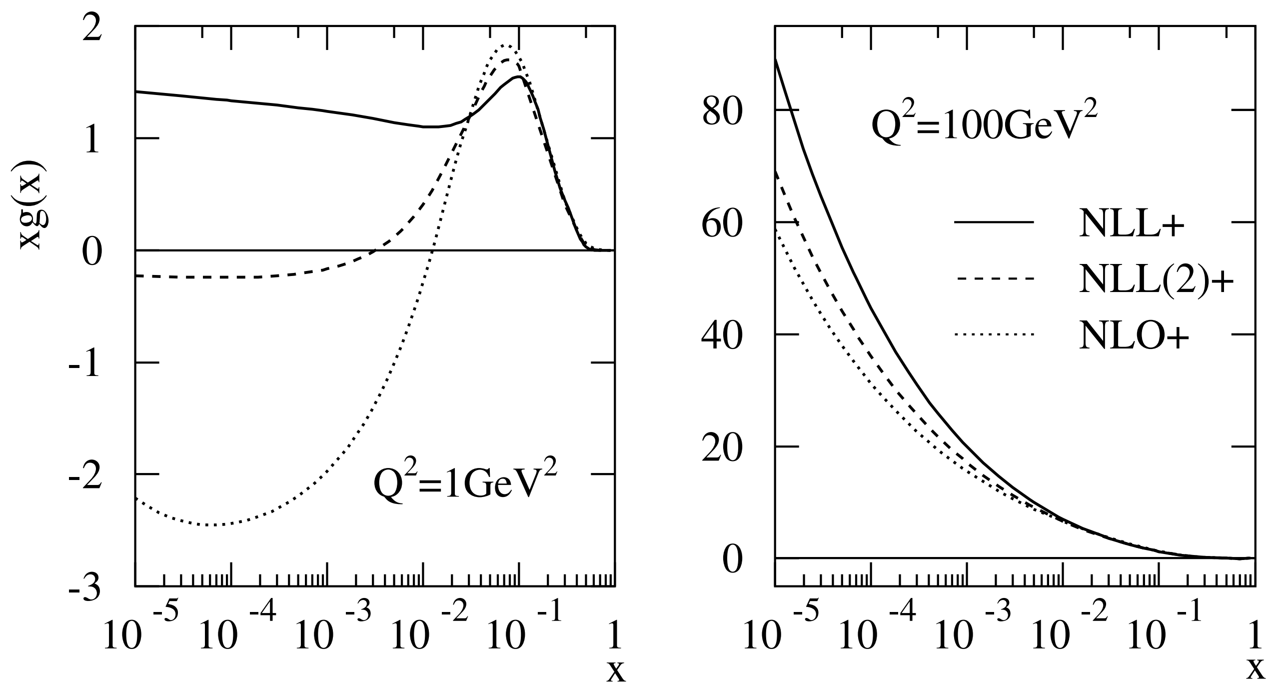
Full set of coefficient functions still to come in some cases, but splitting functions comparable.

Note, in all cases NLO corrections lead to dip in functions below fixed order values until slower growth (running coupling effect) at very small x.



A fit to data with NLO plus NLO resummation, with heavy quarks included (White,RT) performed.

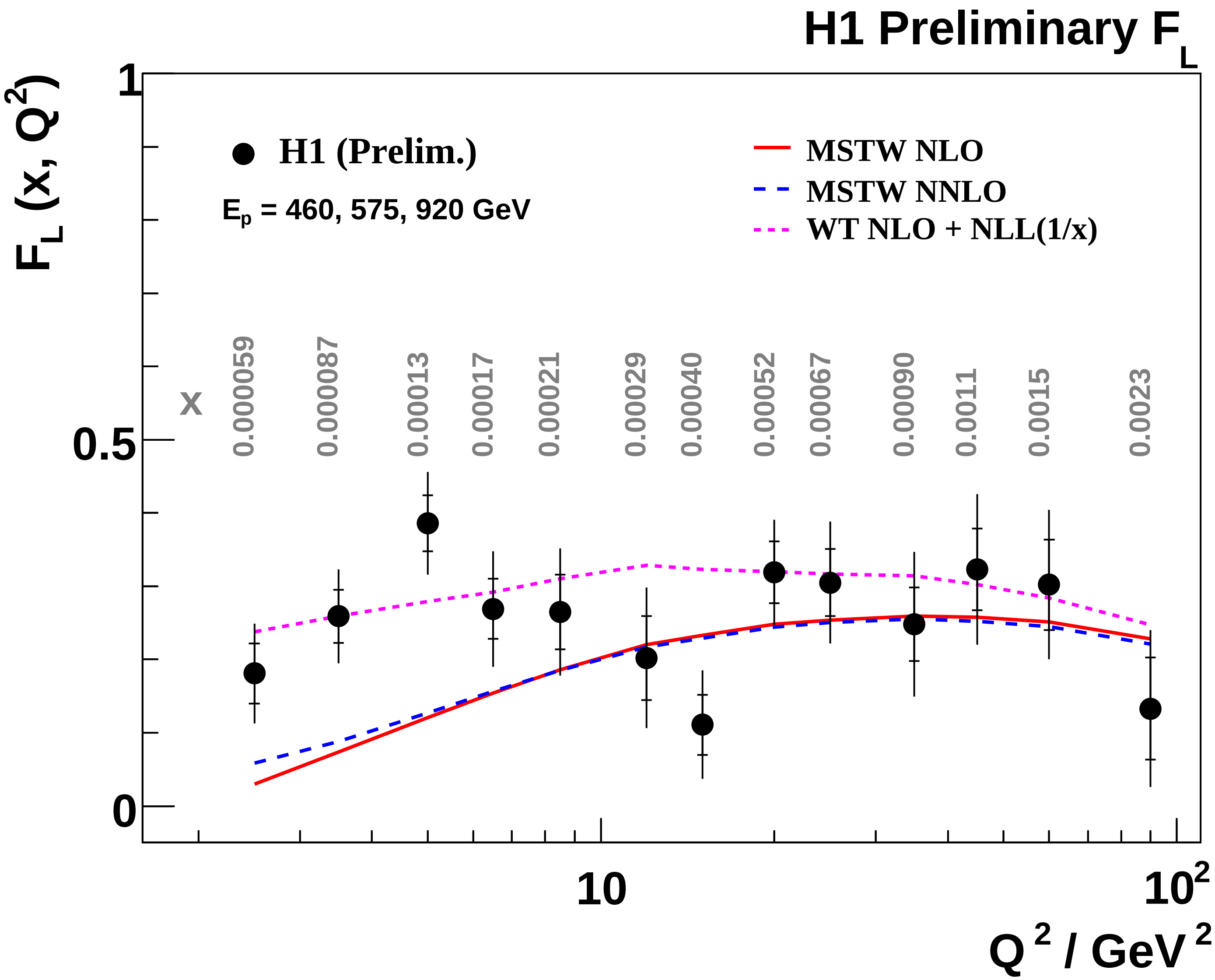




→ moderate improvement in fit to HERA data within global fit, and change in extracted gluon (more like quarks at low Q^2).

Together with indications from Drell Yan resummation calculations (Marzani, Ball) few percent effect quite possible.

Comparison to H1 prelim data on $F_L(x, Q^2)$ at low Q^2, only within White-RT approach, suggests resummations may be important.



Other possible (sometimes related) explanations.

PDFs for LO Monte Carlo generators.

Often need to use generators which calculate only at LO in QCD.

LO matrix elements + LO PDFs often very inaccurate.

Using NLO PDFS suggested – sometimes better, sometimes even worse (particularly small x, important for underlying event *etc*).

Leads to introduction of new type of LO* PDF.

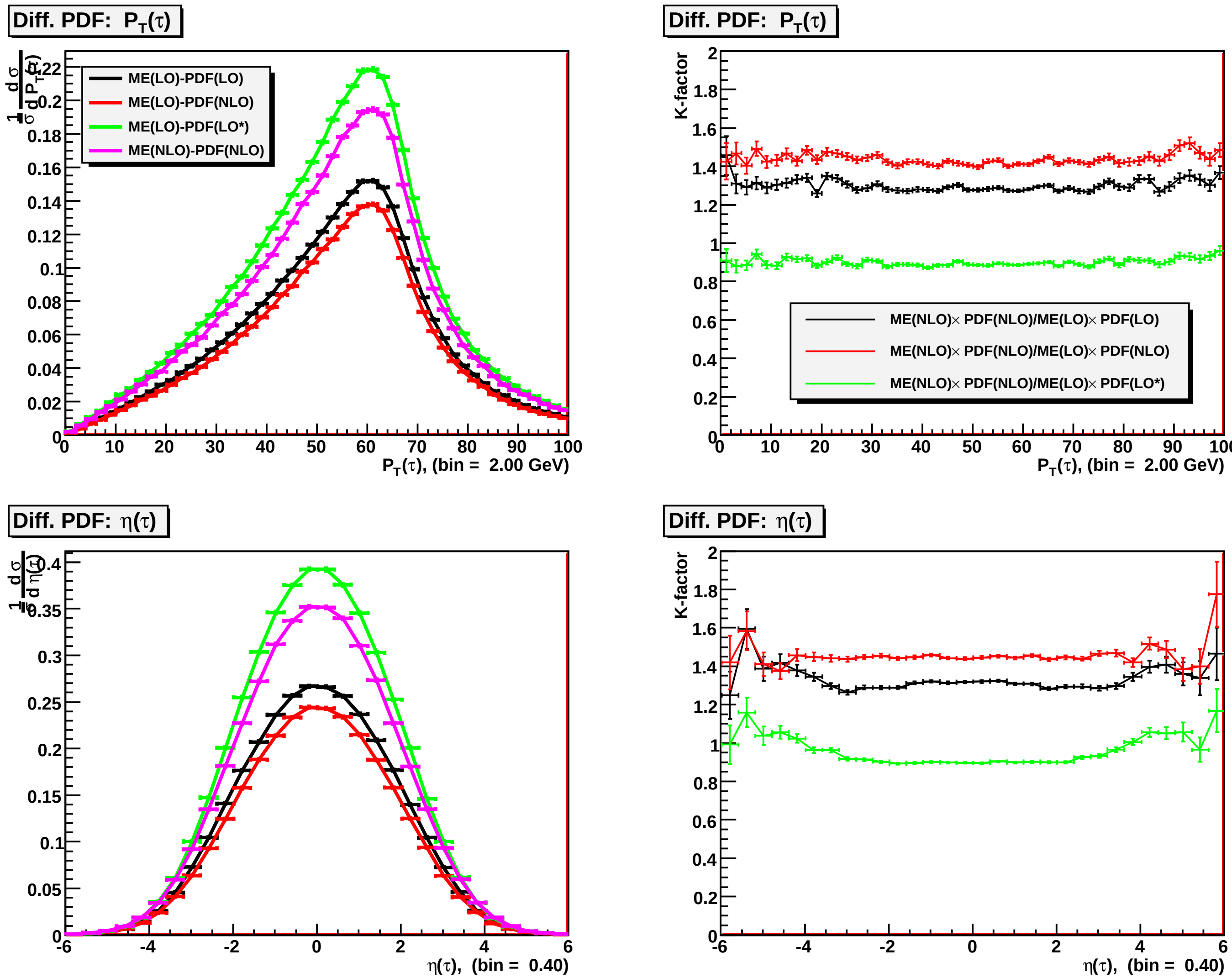
NLO corrections to cross-section usually positive $\rightarrow$ LO PDFs bigger by allowing momentum violation in global fits, using NLO α_S, fit LHC pseudo-data ......

Can also make evolution more "Monte Carlo like", e.g. change of scale in coupling.

LO* PDFs from MRST/MSTW followed by ones from CTEQ based on similar general principles.

Also work on fits using Monte Carlo generators directly (Jung *et al*).

Look at e.g. distributions for Higgs decaying to taus (Shertsnev, RT).



Results using LO* partons clearly best in normalization. NLO worst and problems with shape at low scales (i.e. small x).