PDFs, constraints and searches at the LHC

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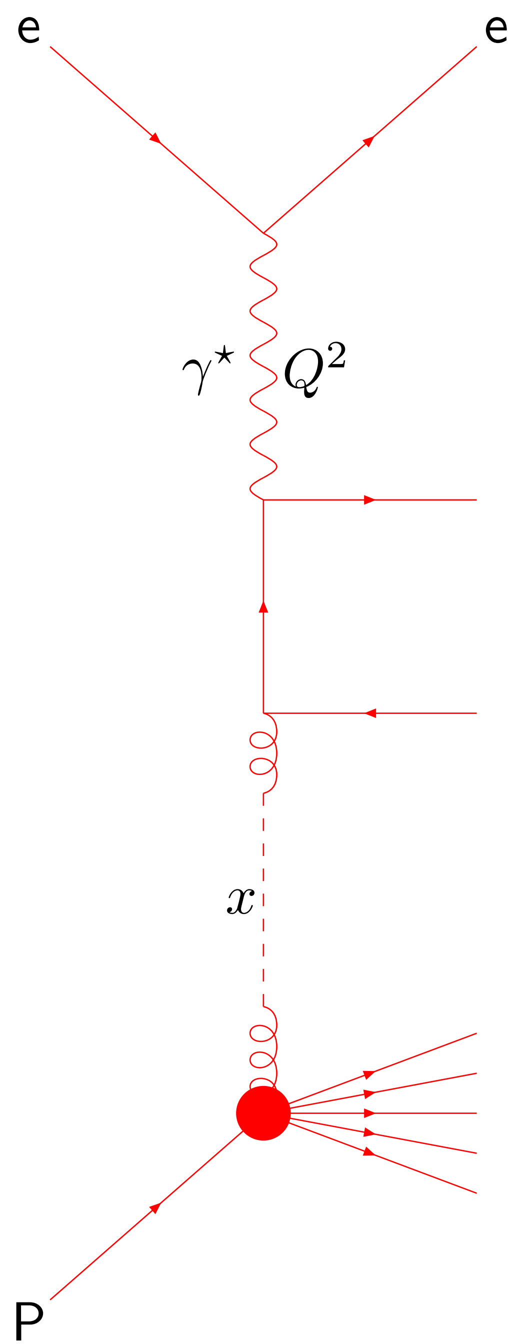
Strong force makes it difficult to perform analytic calculations of scattering processes involving hadronic particles.

The weakening of $\alpha_S(\mu^2)$ at higher scales $\longrightarrow$ the **Factorization Theorem**.

Hadron scattering with an electron factorizes.

Q^2 – Scale of scattering

$x = \frac{Q^2}{2m\nu}$ – Momentum fraction of Parton (ν=energy transfer)



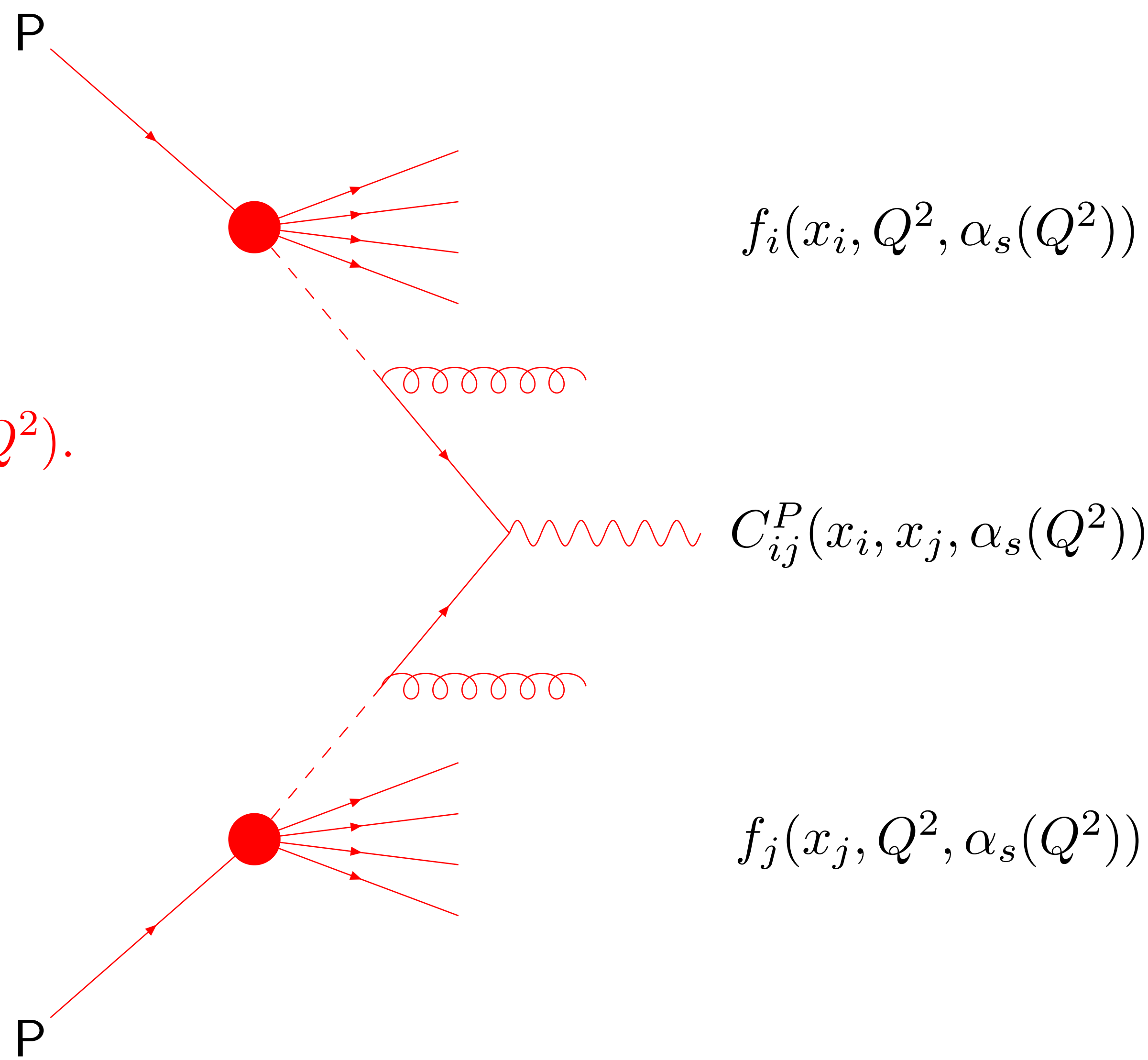
perturbative
calculable
coefficient function
$C_i^P(x, \alpha_s(Q^2))$

nonperturbative
incalculable
parton distribution
$f_i(x, Q^2, \alpha_s(Q^2))$

The coefficient functions $C_i^P(x, \alpha_s(Q^2))$ are process dependent (new physics) but are calculable as a power-series in $\alpha_s(Q^2)$.

$$C_i^P(x, \alpha_s(Q^2)) = \sum_k C_i^{P,k}(x) \alpha_s^k(Q^2).$$

Since the parton distributions $f_i(x, Q^2, \alpha_s(Q^2))$ are process-independent, i.e. **universal**, and evolution with scale is calculable, once they have been measured at one experiment, one can predict many other scattering processes.



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,

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

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.

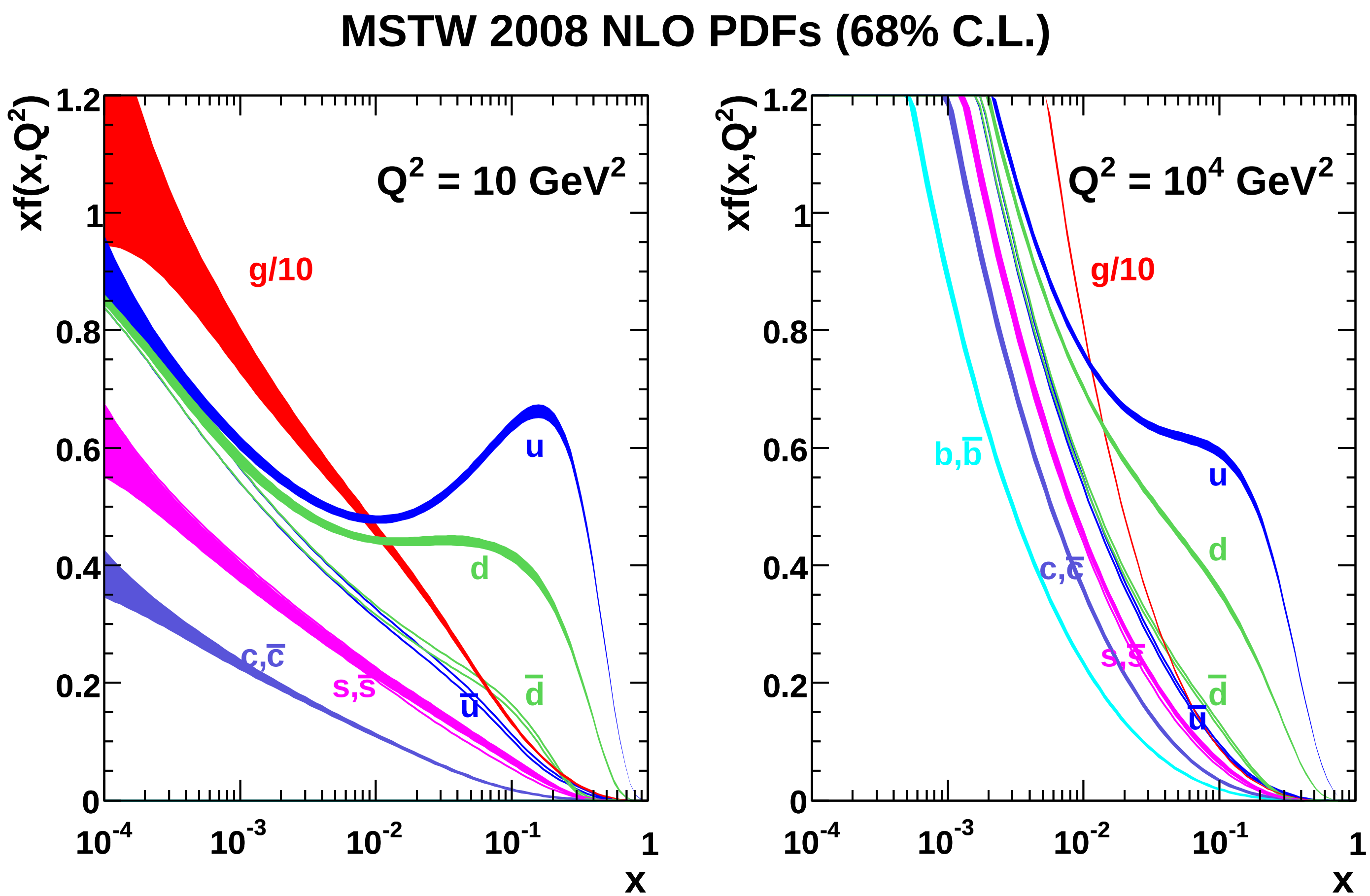
- Di-muon production in neutrino DIS – strange quarks and neutrino-antineutrino comparison $\rightarrow$ asymmetry . Only for $x > 0.01$.

- 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 – $x > 0.01$.

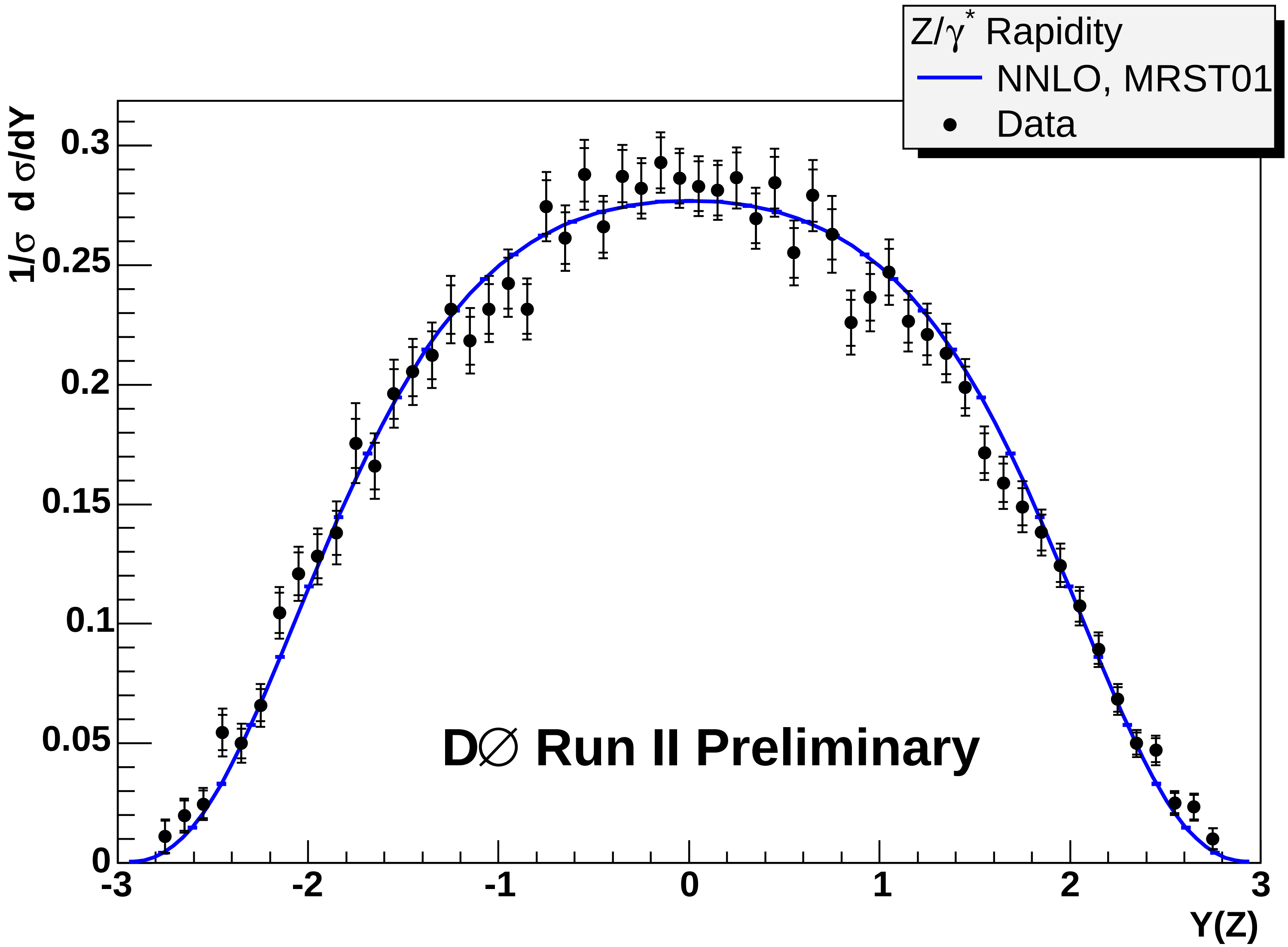
- W and Z production at colliders (Tevatron) – different quark contributions to DIS.

This procedure is generally successful and is part of a large-scale, ongoing project. Results in partons of the form shown.



Various choices of PDF – MSTW, CTEQ, NNPDF, *etc.*. All LHC cross-sections rely on our understanding of these partons.

Excellent predictive power – comparison of MRST prediction for Z rapidity distribution with preliminary data.



Interplay of LHC and pdfs/QCD

Make predictions for all processes, both SM and BSM, as accurately as possible given current experimental input and theoretical accuracy.

Check against well-understood processes, e.g. central rapidity W, Z production (luminosity monitor), lowish-E_T jets, ...

Compare with predictions with more uncertainty and lower confidence, e.g. high-E_T jets, high rapidity bosons or heavy quarks .....

Improve uncertainty on parton distributions by improved constraints, and check understanding of theoretical uncertainties, and determine where NNLO, electroweak corrections, resummations $etc.$ needed.

Make improved predictions for both background and signals with improved partons and surrounding theory.

Spot new physics from deviations in these predictions. As a nice by-product improve our understanding of the strong sector of the Standard Model considerably.

Remainder of talk describes this process in more detail.

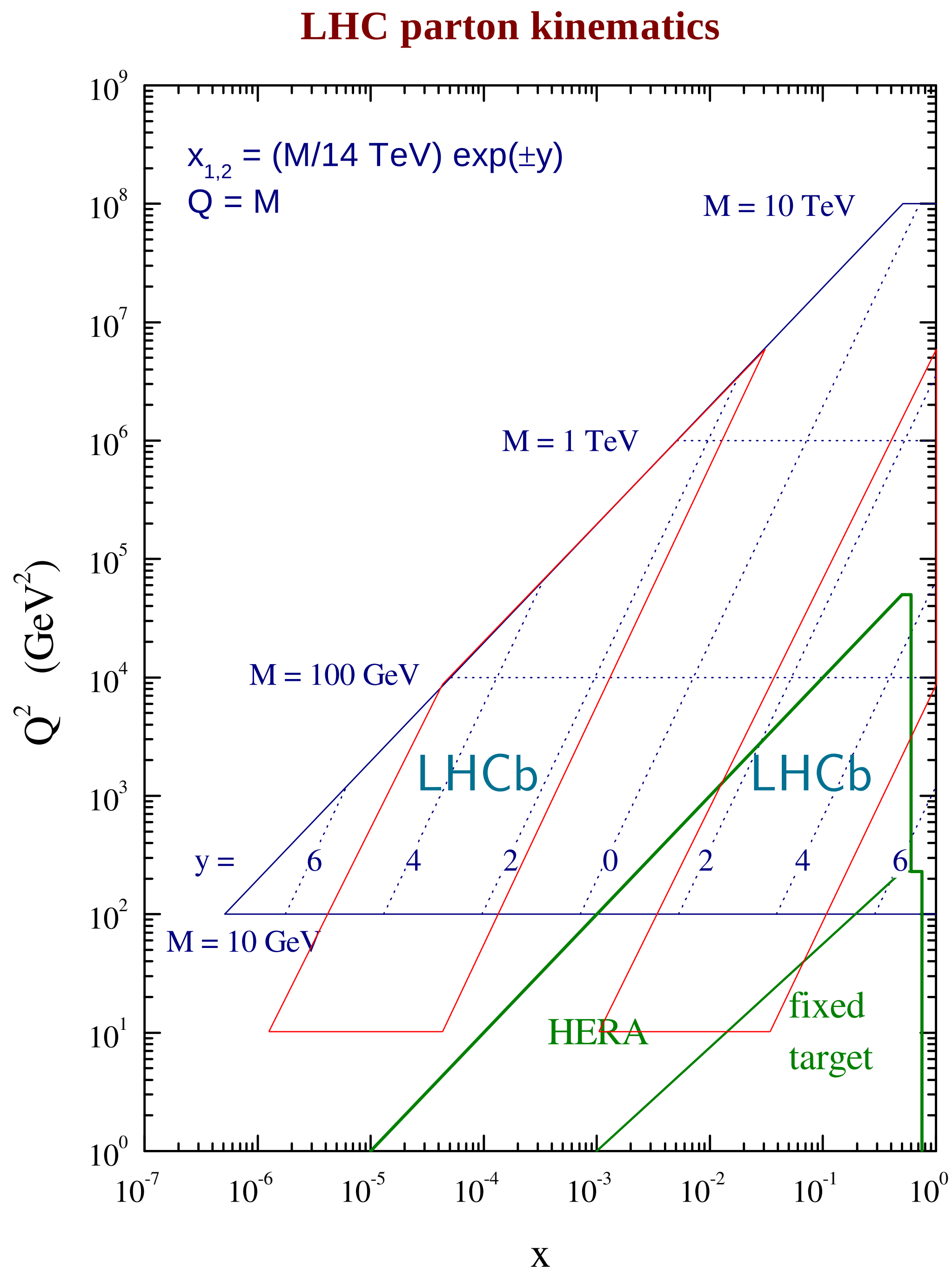
Predictions at the LHC

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.

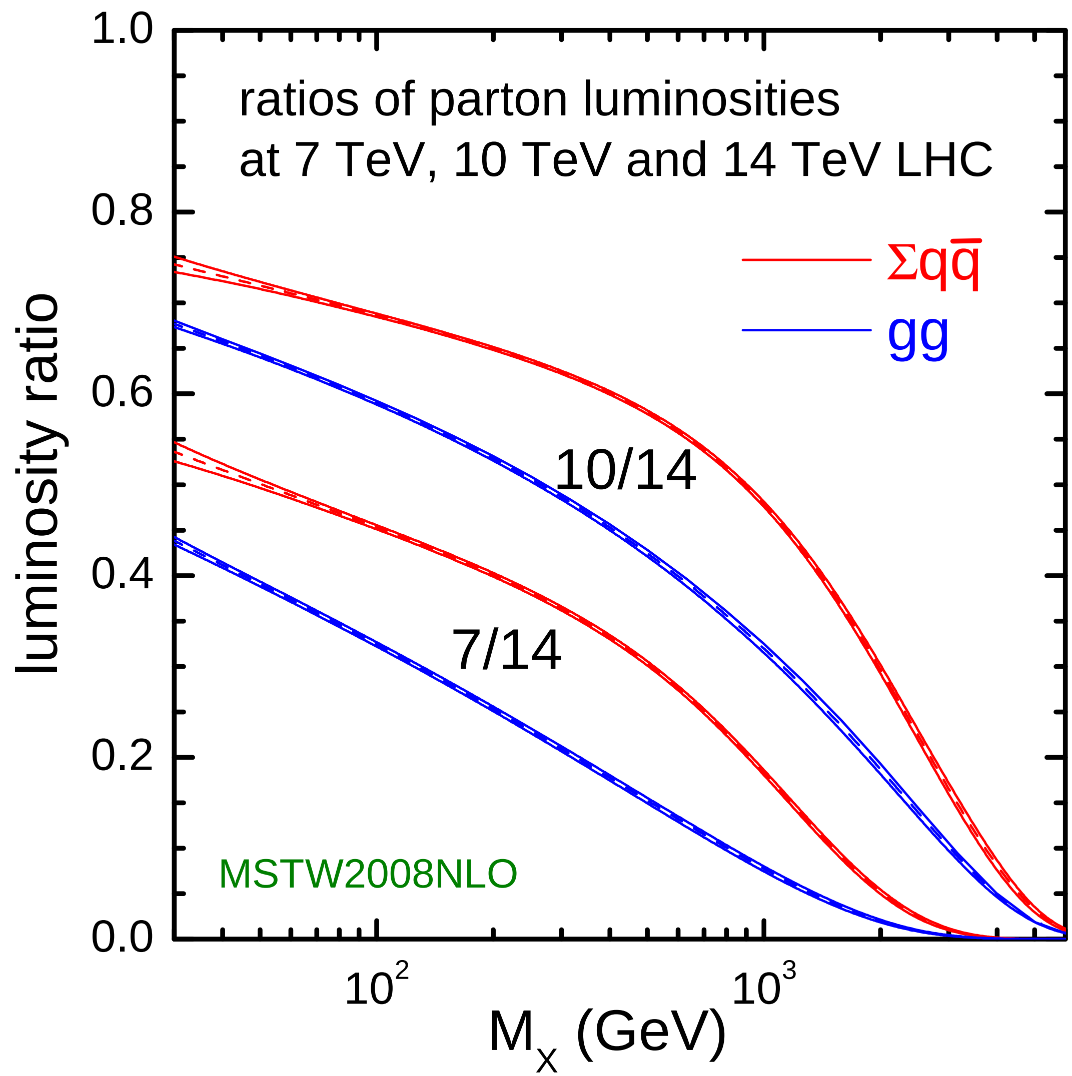


Initial Running

The LHC is currently running at 7 TeV rather than the full 14 TeV.

Reduces rapidity range by $\ln 2$.

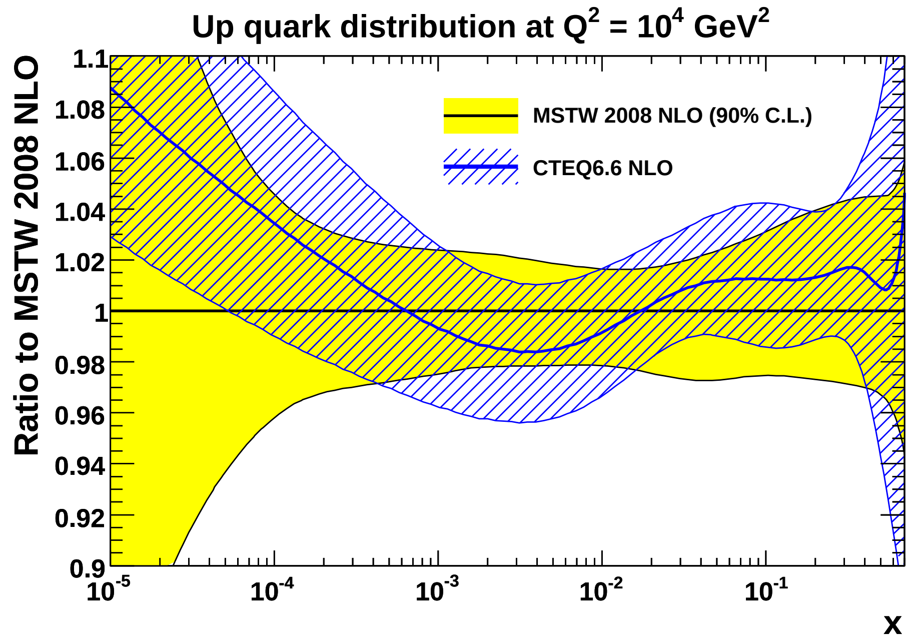
Roughly $30-50\%$ the full cross-sections for most standard model (including light Higgs) processes.

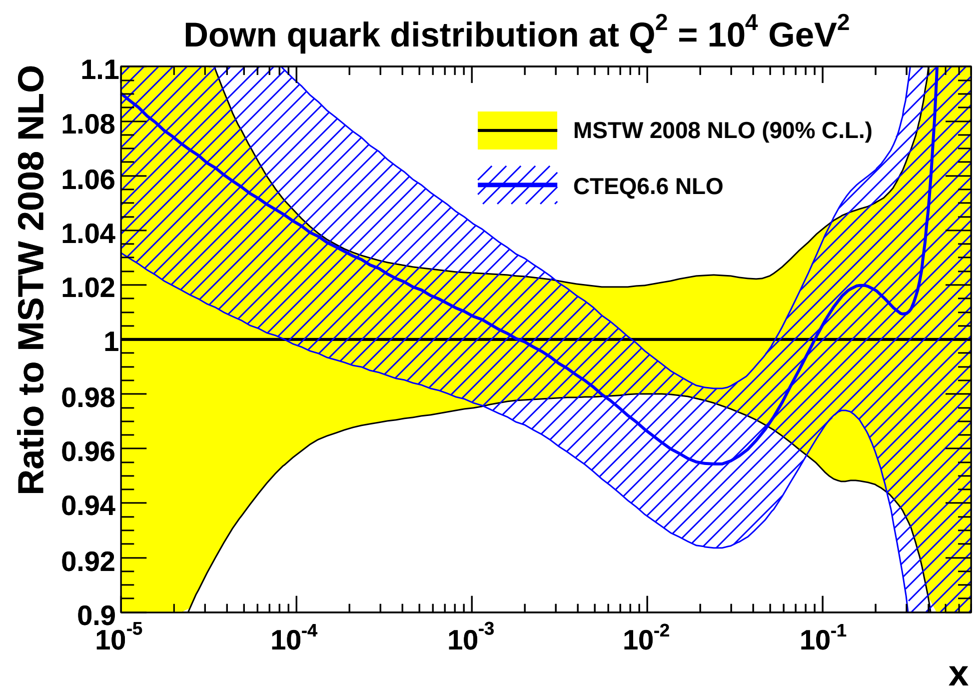


Uncertainty on MSTW u and d distributions, along with CTEQ6.6.

Reasonable agreement between groups.

Central rapidity $x = 0.006$ is ideal for uncertainty in W, Z (Higgs?) at the LHC.





Predictions (Watt) for W and Z cross-sections for LHC with common NLO QCD and vector boson width effects, and common branching ratios, and at 7TeV.

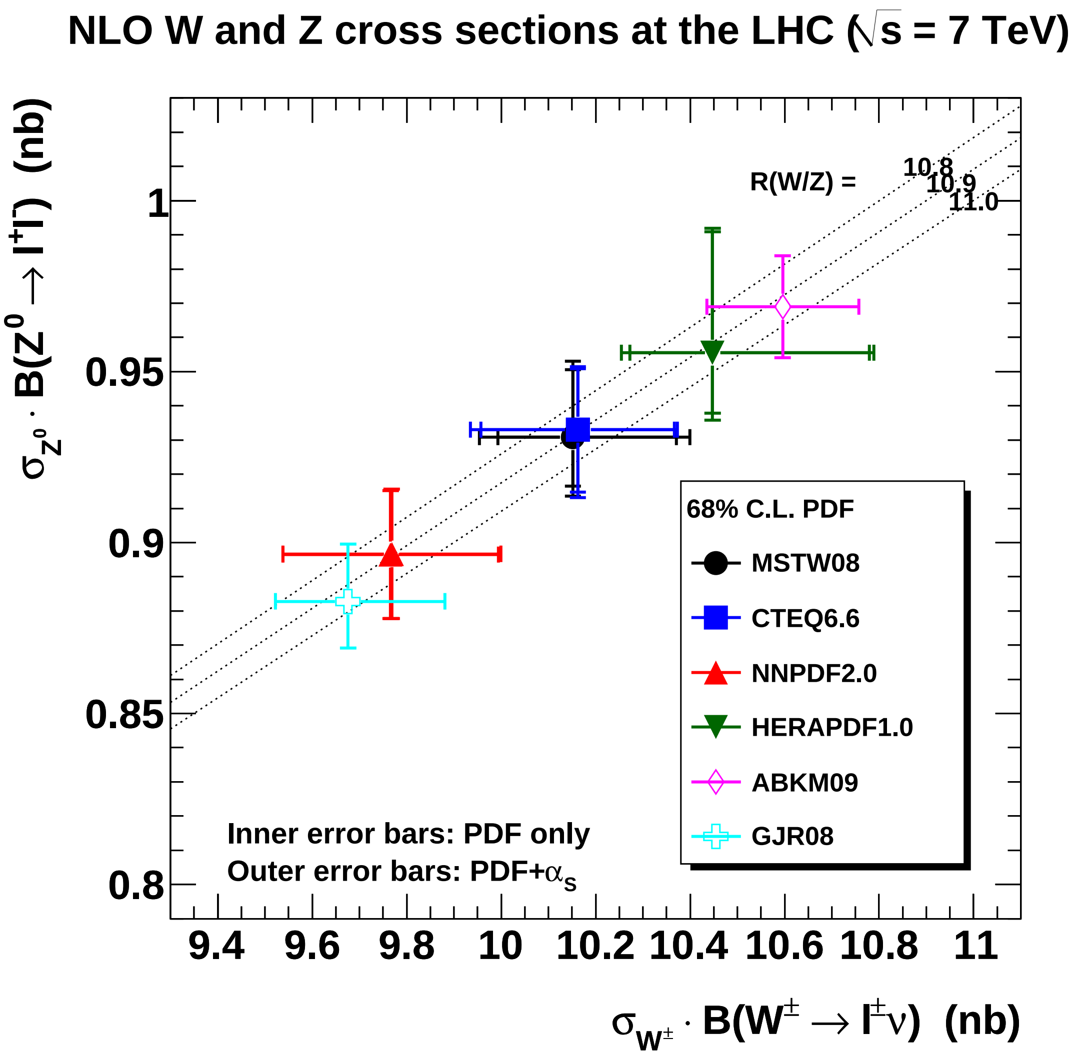
Good agreement at NLO for some PDFs.

In fact comparing all groups get significant discrepancies between them even for this benchmark process.

Can understand some of the systematic differences – see later.

Some difference in W/Z ratio.

Generally all fine?



W, Z total cross-sections best-case scenario.

W, Z uncertainty – more details

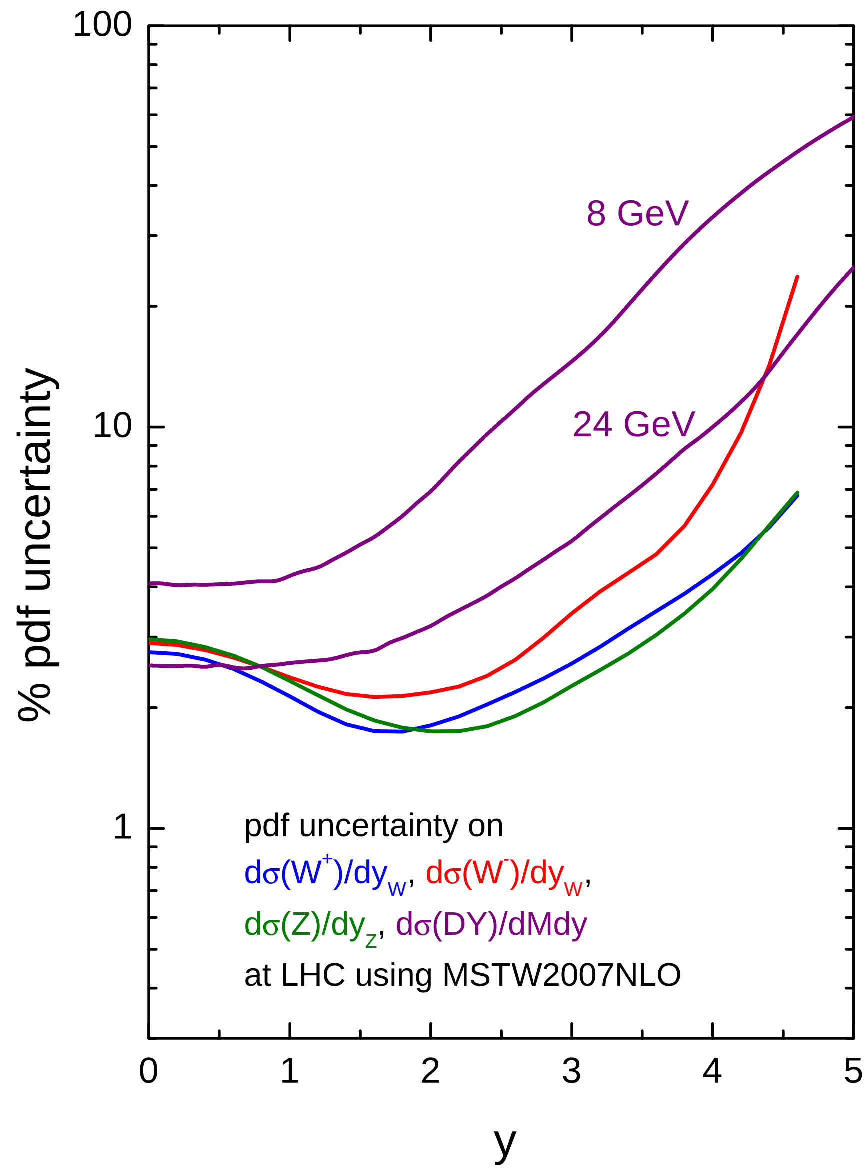
Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ grows at high rapidity.

Uncertainty on $\sigma(W^-)$ grows more quickly at very high y – depends on less well-known down quark.

Uncertainty on $\sigma(\gamma^\star)$ is greatest as y increases. Depends on partons at very small x.

Lots of interest in LHCb range.

Still only uncertainty from data with *perfect* framework.



Sources of Variations/Uncertainty

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.

Responsible for differences between groups for extraction of fixed-order PDFs.

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. New – CT10 include HERA combination and more Tevatron data. Little changes.

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

- HERAPDF1.0 – based entirely on HERA inclusive structure functions, neutral and charged current. Use combined data. PDFs at LO, NLO and now NNLO.

- 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 slight increase in quarks at low x (depending on procedure).

Determination of best fit and uncertainties

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

- 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 40 for 1 sigma for eigenvectors (no normalization uncertainties in CTEQ6.6).
- HERAPDF2.0 – 9 eigenvectors. Use "$\Delta\chi^2 = 1$". Additional model and parameterisation uncertainties.
- ABKM09 – 21 parton parameters. Use $\Delta\chi^2 = 1$. Also α_S, m_c, m_b.
- GJR08 – 20 parton parameters and α_S. Use $\Delta\chi^2 \approx 20$. Impose strong theory constraint on input form of PDFs.

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

Neural Network group (Ball *et al.*) limit parameterization dependence. Leads to alternative approach to "best fit" and uncertainties.

First part of approach, no longer perturb about best fit. Construct a set of Monte Carlo replicas $F_{i,p}^{art,k}$ of the original data set $F_{i,p}^{exp,(k)}$.

- REPLICAS FLUCTUATE ABOUT CENTRAL DATA:
$$F_{i,p}^{(art)(k)} = S_{p,N}^{(k)} F_{i,p}^{\rm exp}\left(1 + r_p^{(k)}\sigma_p^{\rm stat} + \sum_{j=1}^{N_{\rm sys}} r_{p,j}^{(k)}\sigma_{p,j}^{\rm sys}\right)$$

Where $r_p^{(k)}$ are random numbers following Gaussian distribution, and $S_{p,N}^{(k)}$ is the analogous normalization shift of the of the replica depending on $1 + r_{p,n}^{(k)}\sigma_p^{norm}$. Hence, include information about measurements and errors in distribution of $F_{i,p}^{art,(k)}$.

Fit to the data replicas obtaining PDF replicas $q_i^{(net)(k)}$ (follows Giele *et al.*)

Mean μ_O and deviation σ_O of observable O then given by

$$\mu_O = \frac{1}{N_{rep}}\sum_{1}^{N_{rep}} O[q_i^{(net)(k)}], \quad \sigma_O^2 = \frac{1}{N_{rep}}\sum_{1}^{N_{rep}}(O[q_i^{(net)(k)}] - \mu_O)^2.$$

Eliminates parameterisation dependence by using a neural net which undergoes a series of (mutations via genetic algorithm) to find the best fit. In effect is a much larger sets of parameters – ~ 37 per distribution.

However, does include pre-processing exponents as $x \to 1$ and $x \to 0$ to aid convergence of fit,

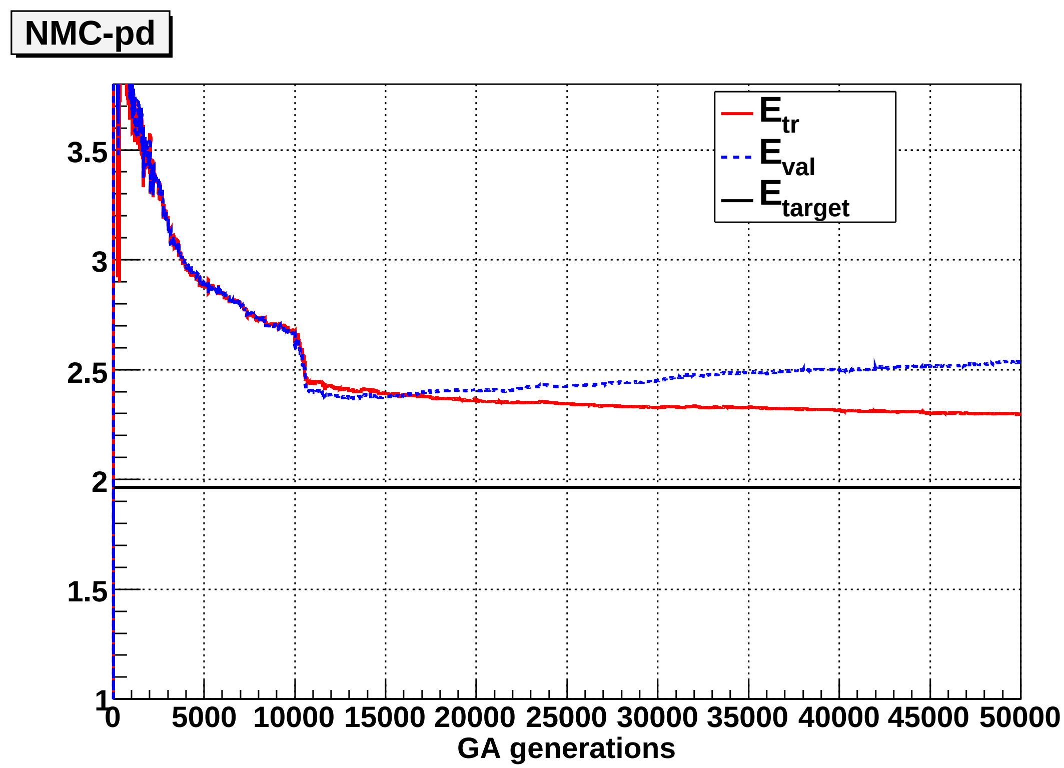
$$f(x, Q_0^2) = A(1-x)^m x^{-n} NN(x)$$

where n, m are in fairly narrow ranges, so overall behaviour guided at these extremes where data constraints vanish.

Split data sets randomly into equal size *training* and *validation* sets.

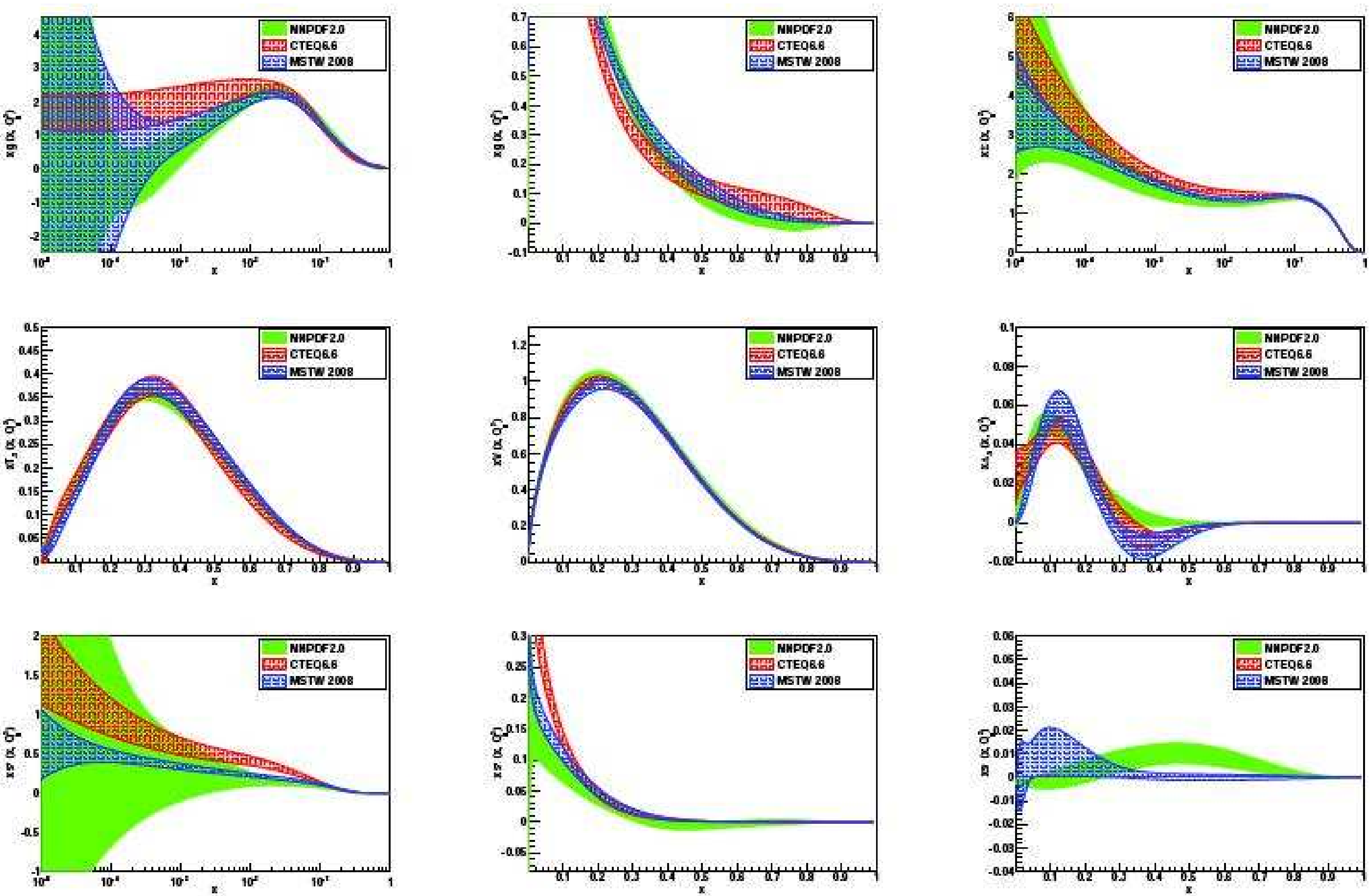
Fit until quality of fit to validation set starts to go up, even though training set still (hopefully slowly) improving.

Criterion for stopping the fit depends on different data sets.

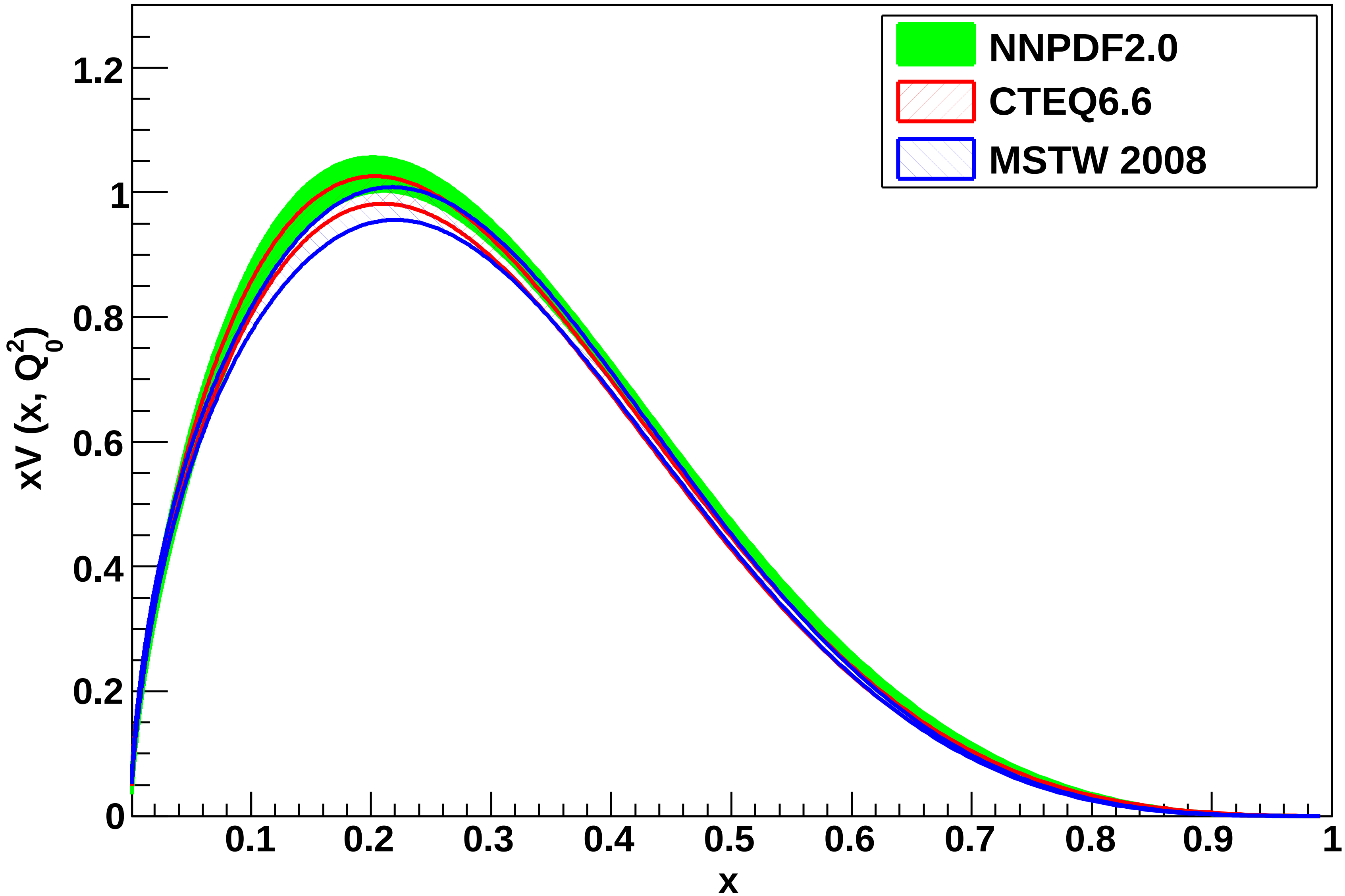


Uncertainty has depended on stopping criteria.

Also reductions due to inclusion of new data.

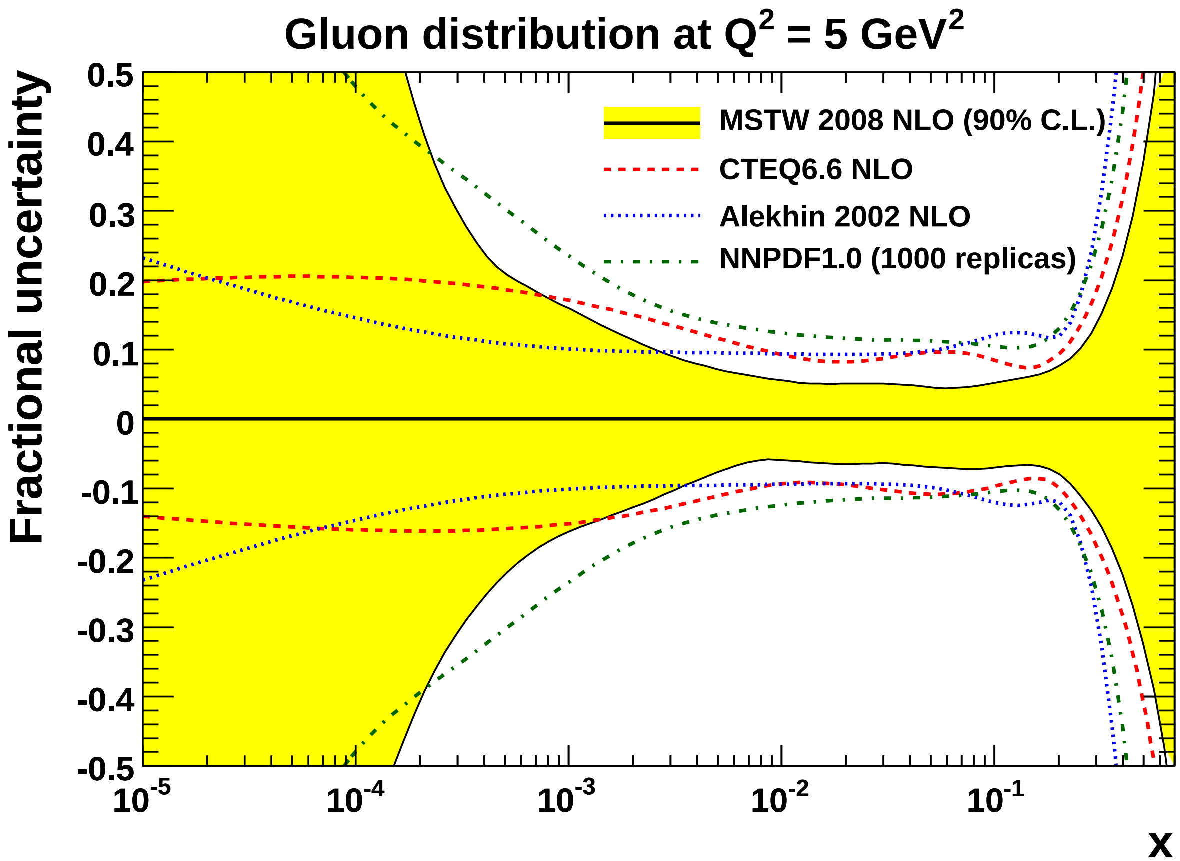


NNPDF uncertainties pretty similar to other groups, with some particular exceptions.



Uncertainties on, e.g. valence quarks not notably different to other groups at all.

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.

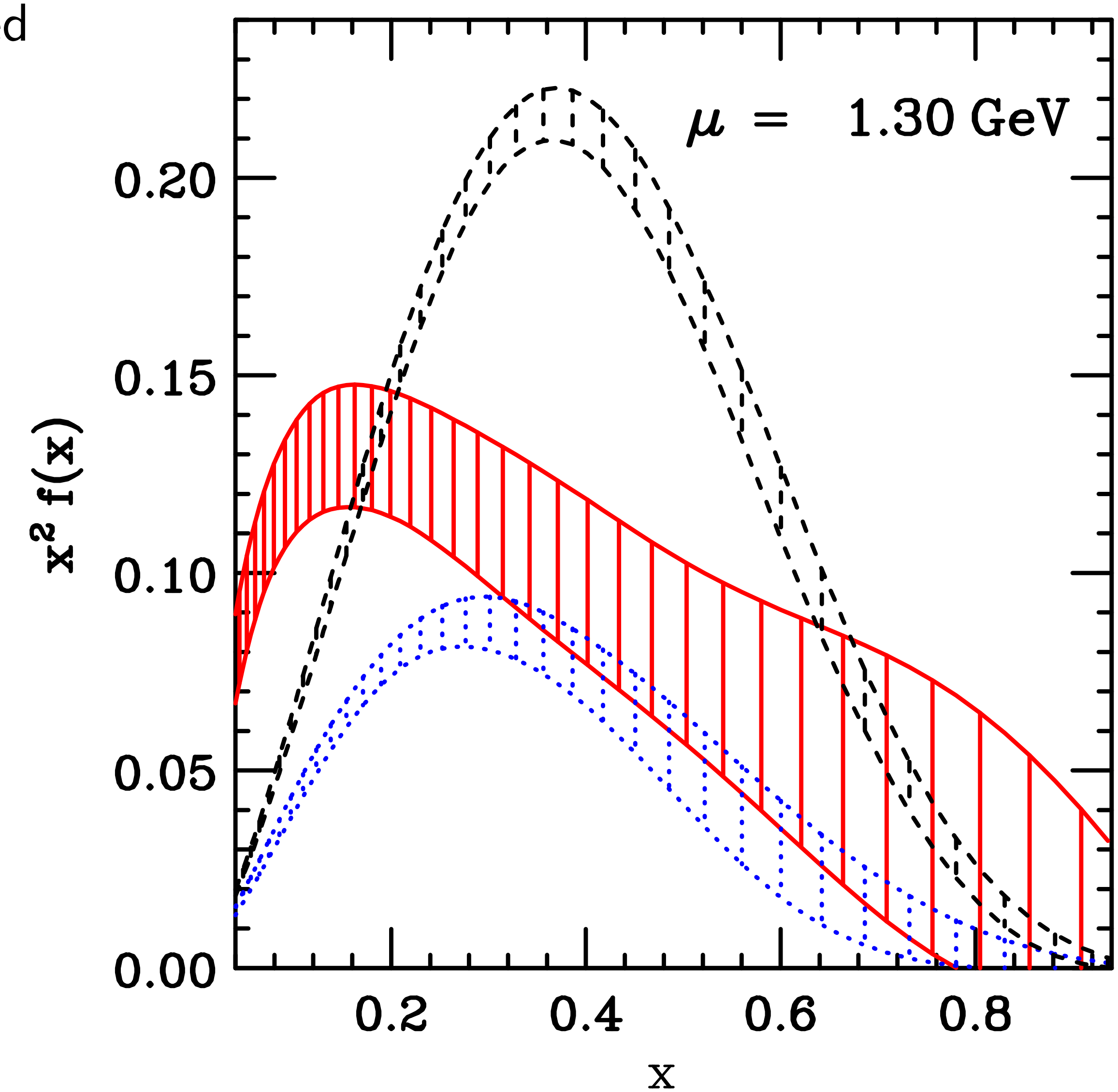
If $g(x) \propto x^{\lambda \pm \Delta\lambda}$ then $\Delta g(x) = \Delta\lambda \ln(1/x) * g(x)$.

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

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 $x \to 1$?



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).

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

Contain mass effects, but does not sum $\ln^n(Q^2/m_H^2)$ terms, and not calculated for many processes beyond LO. Still occasionally used, e.g. GJR and effectively ABKM.

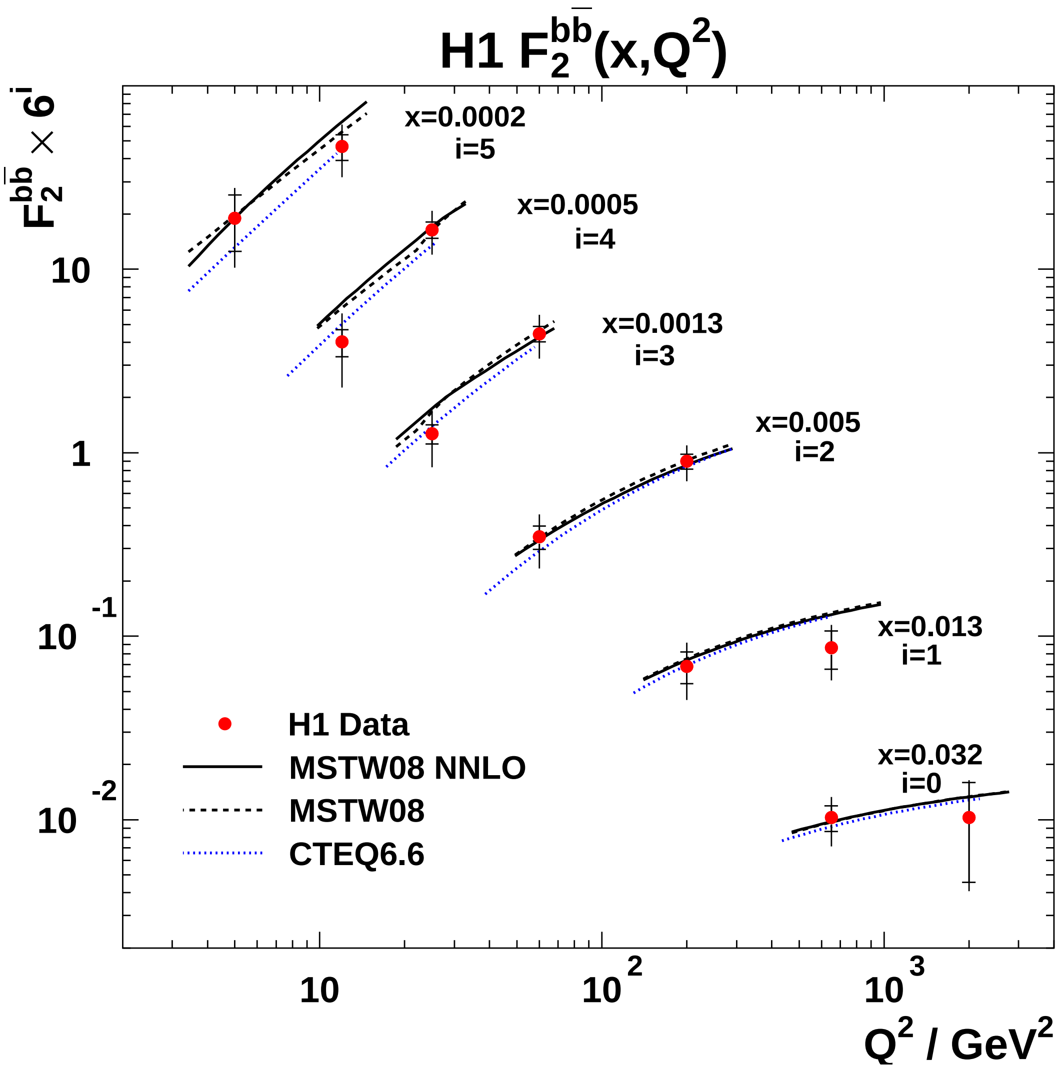
Alternative, at high scales $Q^2 \gg m_H^2$ heavy quarks like massless partons. Behave like up, down, strange. Sum $\ln(Q^2/m_H^2)$ terms via evolution. **Zero Mass Variable Flavour Number Scheme** (ZM-VFNS). Normal assumption in calculations. Ignores $\mathcal{O}(m_H^2/Q^2)$ corrections.

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

Need 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 regularly by HERA (default same as MSTW). NNPDF updating from ZM-VFNS very soon.

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

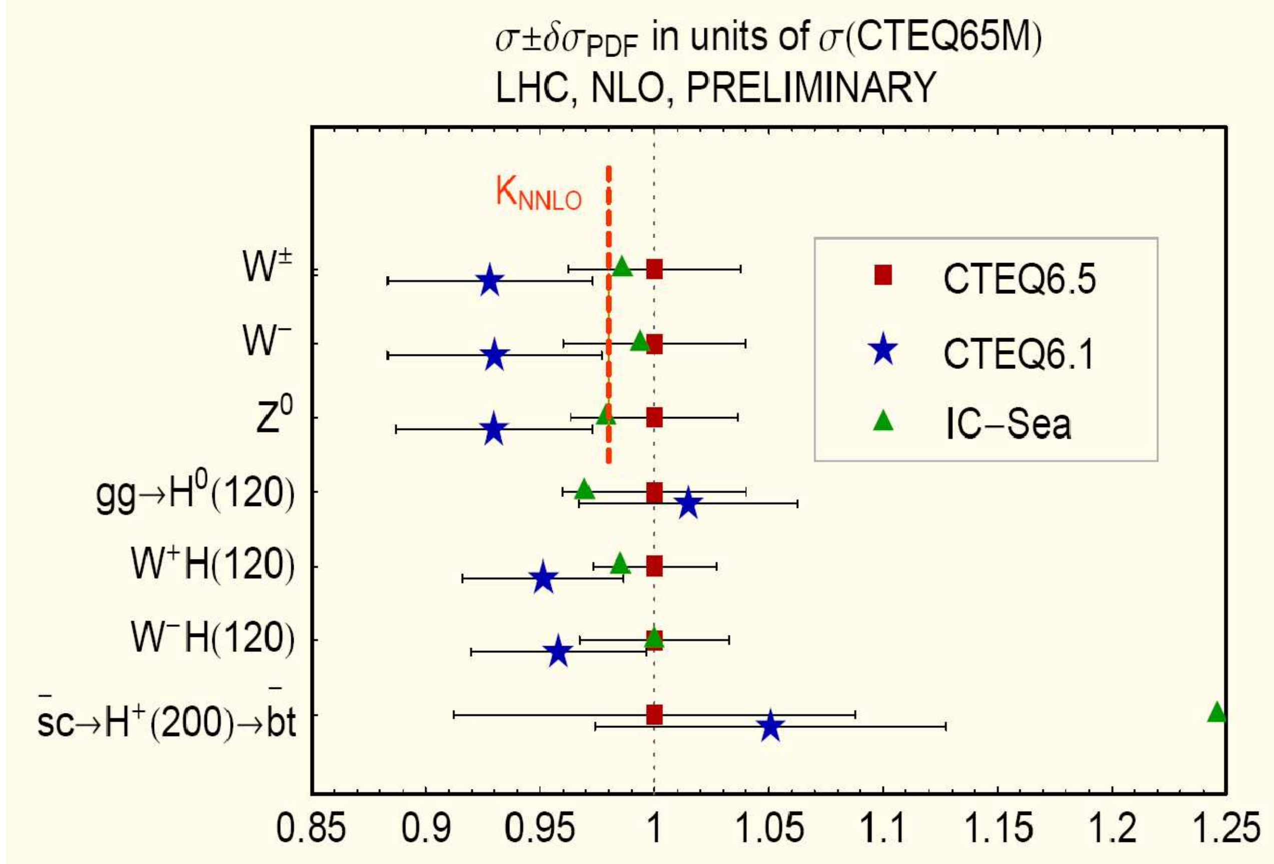
Various significant differences still exist as illustrated by comparison to most recent H1 data on bottom production.



Importance of using GM-VFNS instead of massless approach illustrated by CTEQ6.5.

Can be up to 8% error in PDFs. Much more than scheme uncertainty.

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



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	Tev		LHC	(14 TeV)
	σ_Z (nb)	σ_H(pb)	σ_Z (nb)	σ_H(pb)
MSTW08	7.207	0.7462	59.25	40.69
GMvar1	$+0.3\%$	-0.5%	$+1.1\%$	$+0.2\%$
GMvar2	$+0.7\%$	-1.1%	$+3.0\%$	$+1.5\%$
GMvar3	$+0.1\%$	-0.3%	$+1.1\%$	$+0.8\%$
GMvar4	$+0.0\%$	-0.1%	-0.4%	-0.2%
GMvar5	-0.1%	-0.1%	-0.5%	-0.3%
GMvar6	$+0.3\%$	-0.4%	$+1.6\%$	$+0.8\%$
GMvaropt	$+0.3\%$	-1.5%	$+2.0\%$	$+0.4\%$
ZM-VFNS	-0.7%	-1.2%	-3.0%	-3.1%
GMvarcc	$+0.0\%$	-0.1%	$+0.0\%$	-0.1%

Little more than 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.

Most variation in ZM-VFNS.

The values of the predicted cross-sections at NNLO.

PDF set	Tev σ_Z (nb)	σ_H(pb)	LHC (14 TeV) σ_Z (nb)	σ_H(pb)
MSTW08	7.448	0.9550	60.93	50.51
GMvar1	$+0.1\%$	-0.5%	$+0.1\%$	-0.2%
GMvar2	$+0.3\%$	-0.8%	$+0.5\%$	$+0.1\%$
GMvar3	$+0.4\%$	-0.1%	$+0.5\%$	$+0.7\%$
GMvar4	$+0.0\%$	-0.2%	$+0.1\%$	-0.1%
GMvar5	$+0.1\%$	-0.3%	-0.2%	-0.2%
GMvar6	$+0.1\%$	-0.9%	$+0.3\%$	-0.2%
GMvaropt	$+0.4\%$	-0.2%	$+0.6\%$	$+0.8\%$
GMvarmod	-0.2%	-0.4%	-1.4%	-1.0%
GMvarmod′	$+0.0\%$	-0.7%	$+0.0\%$	$+0.1\%$

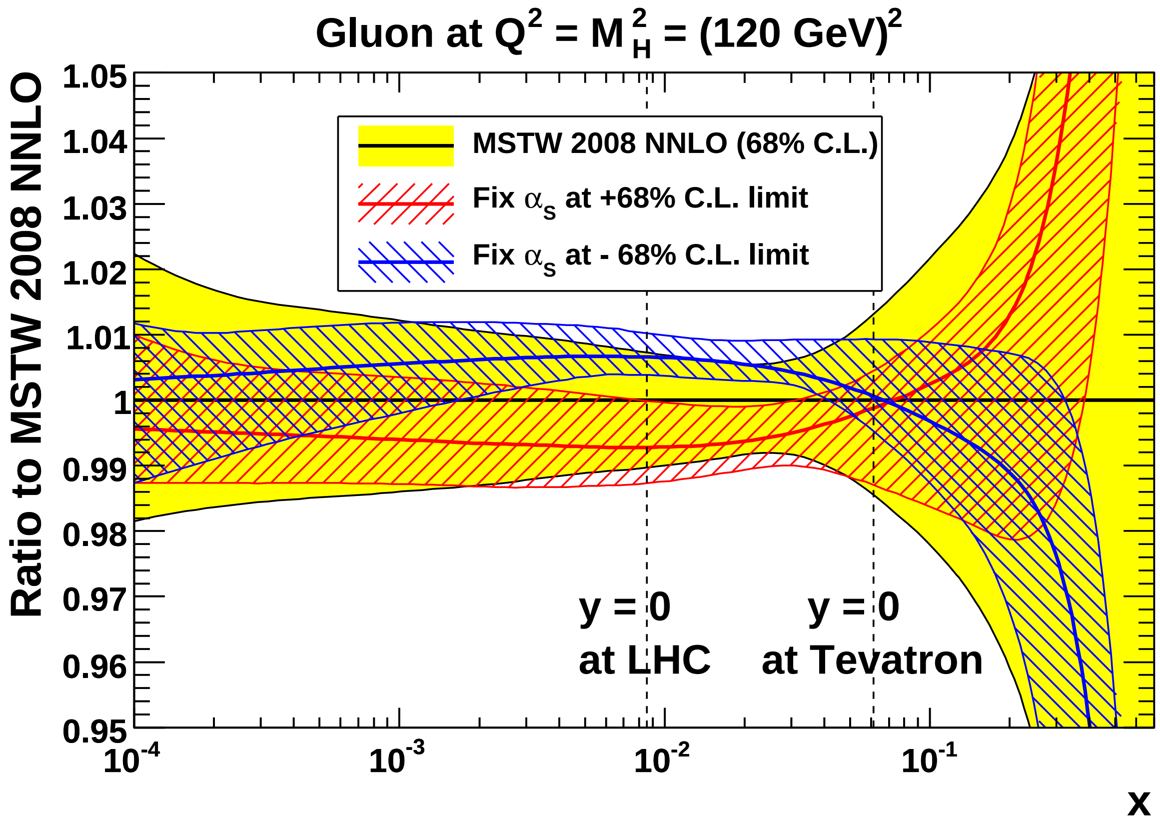
Maximum variations of order 1% at LHC. High-x gluon leads to 1% on σ_H at Tevatron.

Much improved stability compared to NLO.

PDF correlation with α_S.

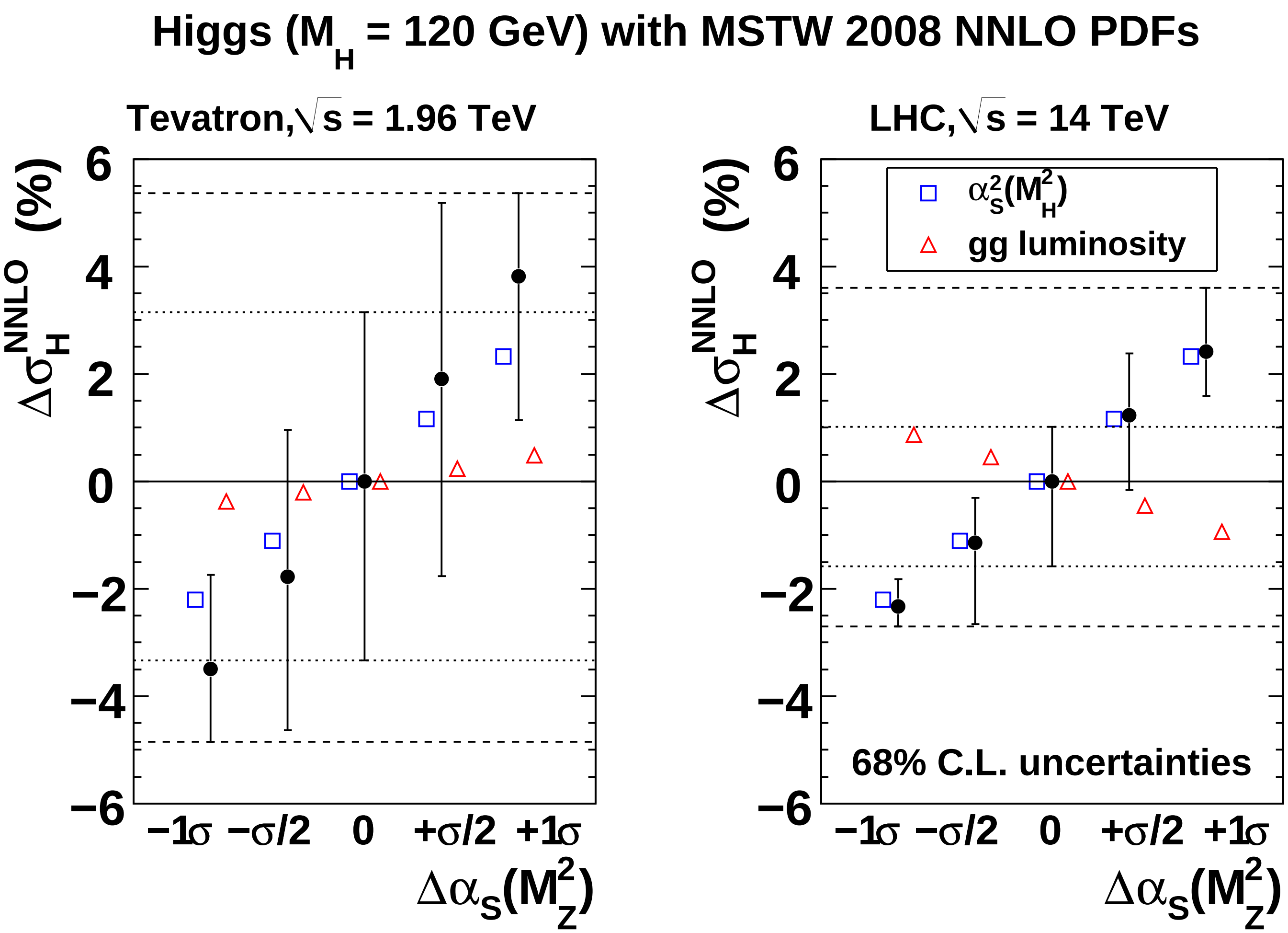
Can also look at PDF changes and uncertainties at different $\alpha_S(M_Z^2)$. Latter usually only for one fixed $\alpha_S(M_Z^2)$. Can be determined from fit, e.g. $\alpha_S(M_Z^2) = 0.1202^{+0.0012}_{-0.0015}$ at NLO and $\alpha_S(M_Z^2) = 0.1171^{+0.0014}_{-0.0014}$ at NNLO from MSTW.

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



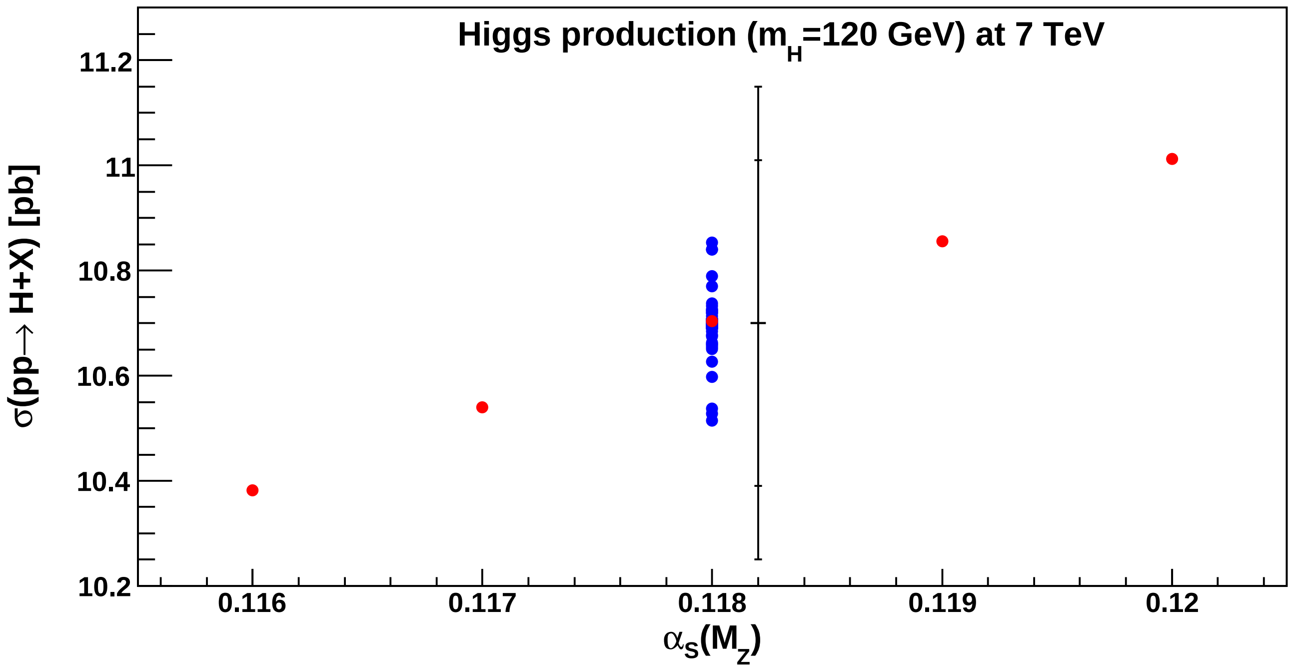
Expected gluon–$\alpha_S(M_Z^2)$ small–x anti-correlation $\rightarrow$ high-x correlation from sum rule.

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.

CTEQ have shown that up to Gaussian approx. for uncertainties (and some other caveats) α_S uncertainty accounted for by adding deviation from PDFs with upper and lower α_S limits (red) in quadrature with all other PDF eigenvectors (blue), seen below. ABKM and GJR similar procedure in practice, but not diagonalised.

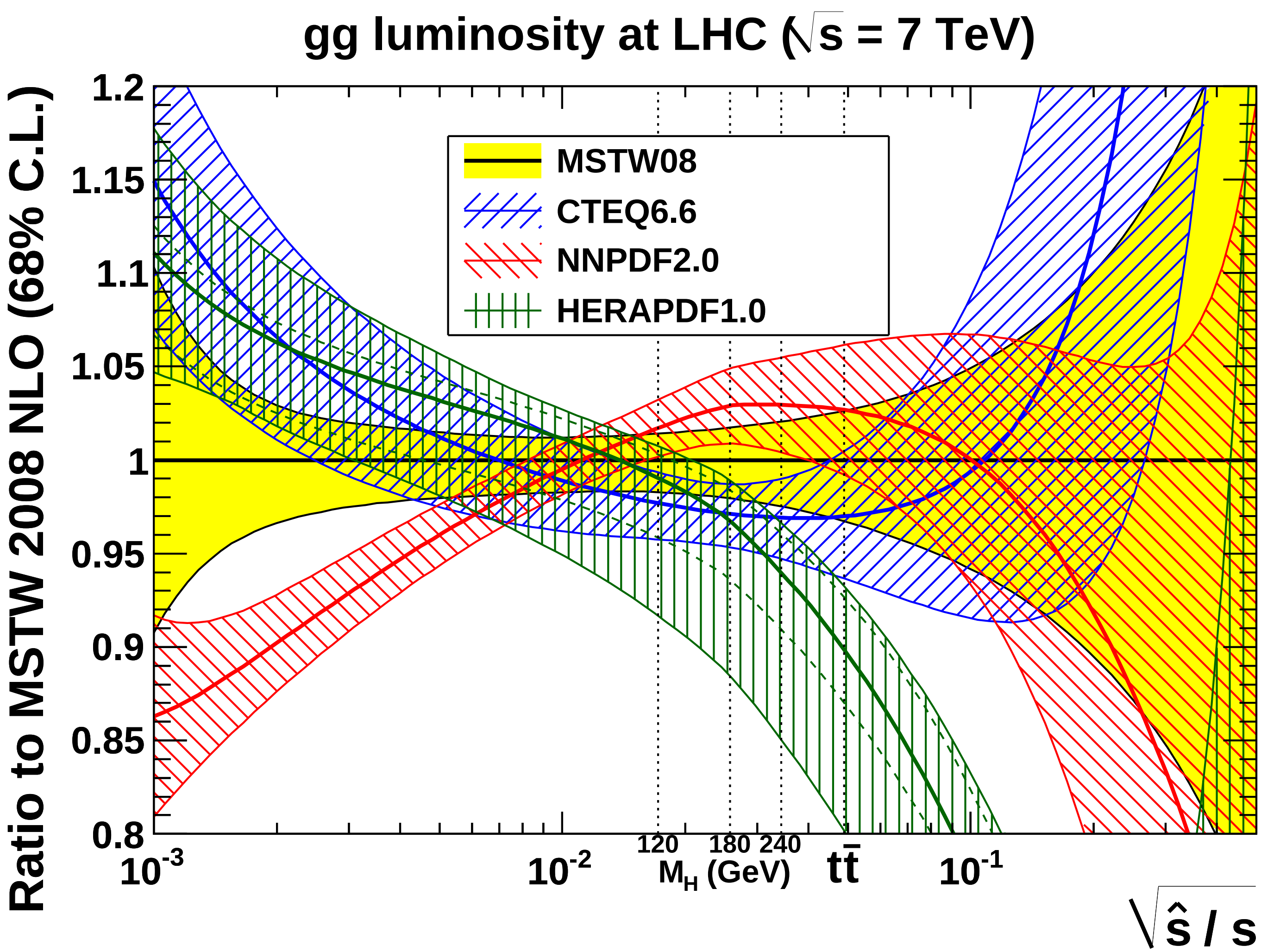


NNPDF advocate distributing PDF replicas according to probability of $\alpha_S(m_Z^2)$ taking that value based on some assumed central value and uncertainty, i.e.

$$N_{\rm rep}^{\alpha_S} \propto \exp\left(-\frac{(\alpha_S-\alpha_S^{(0)})^2}{2(\delta\alpha_S^{(68)})^2}\right),$$

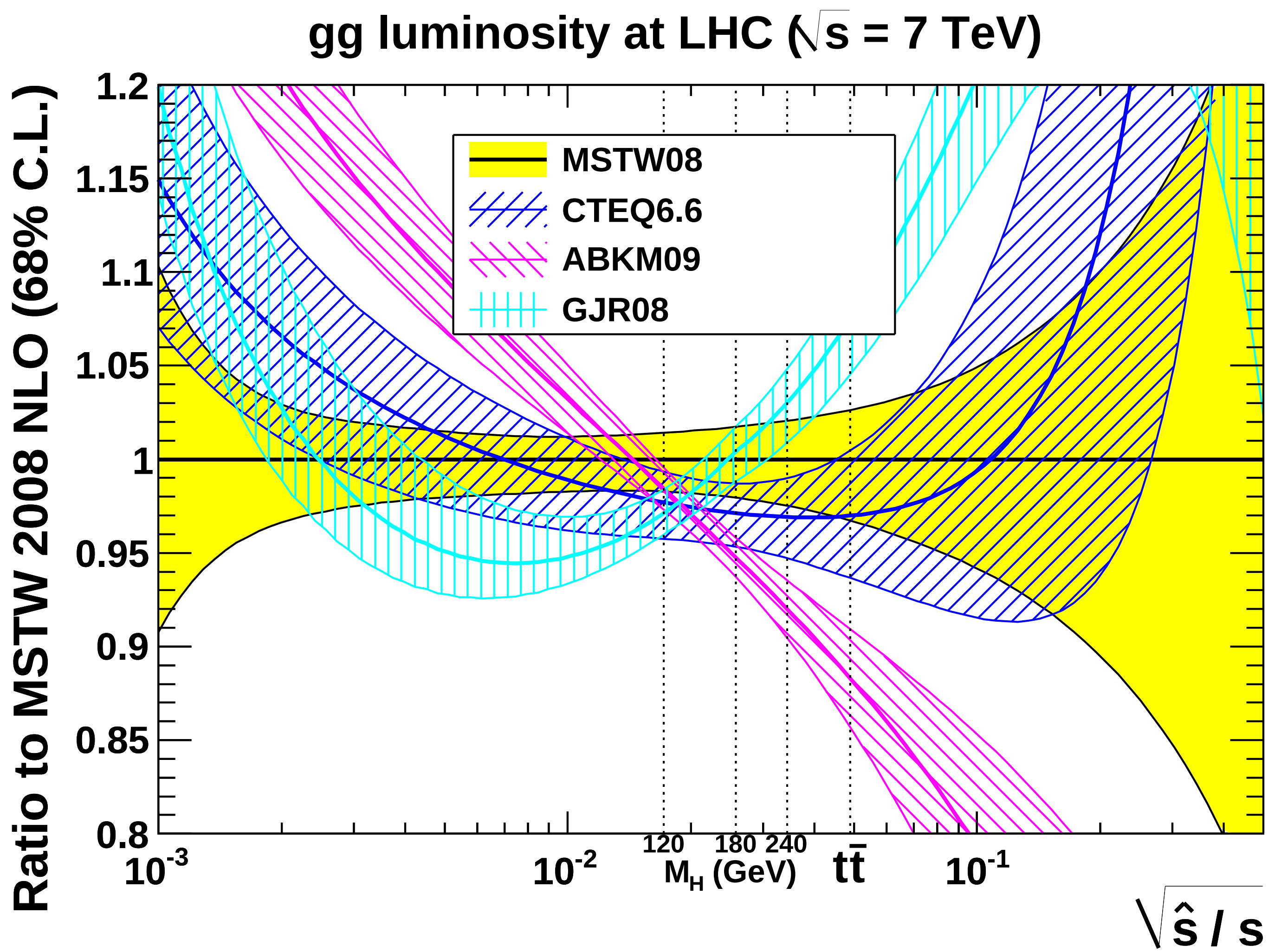
All lead to roughly same results Vicini *et al*.

Predictions by various groups - parton luminosities – NLO. Plots by G. Watt.

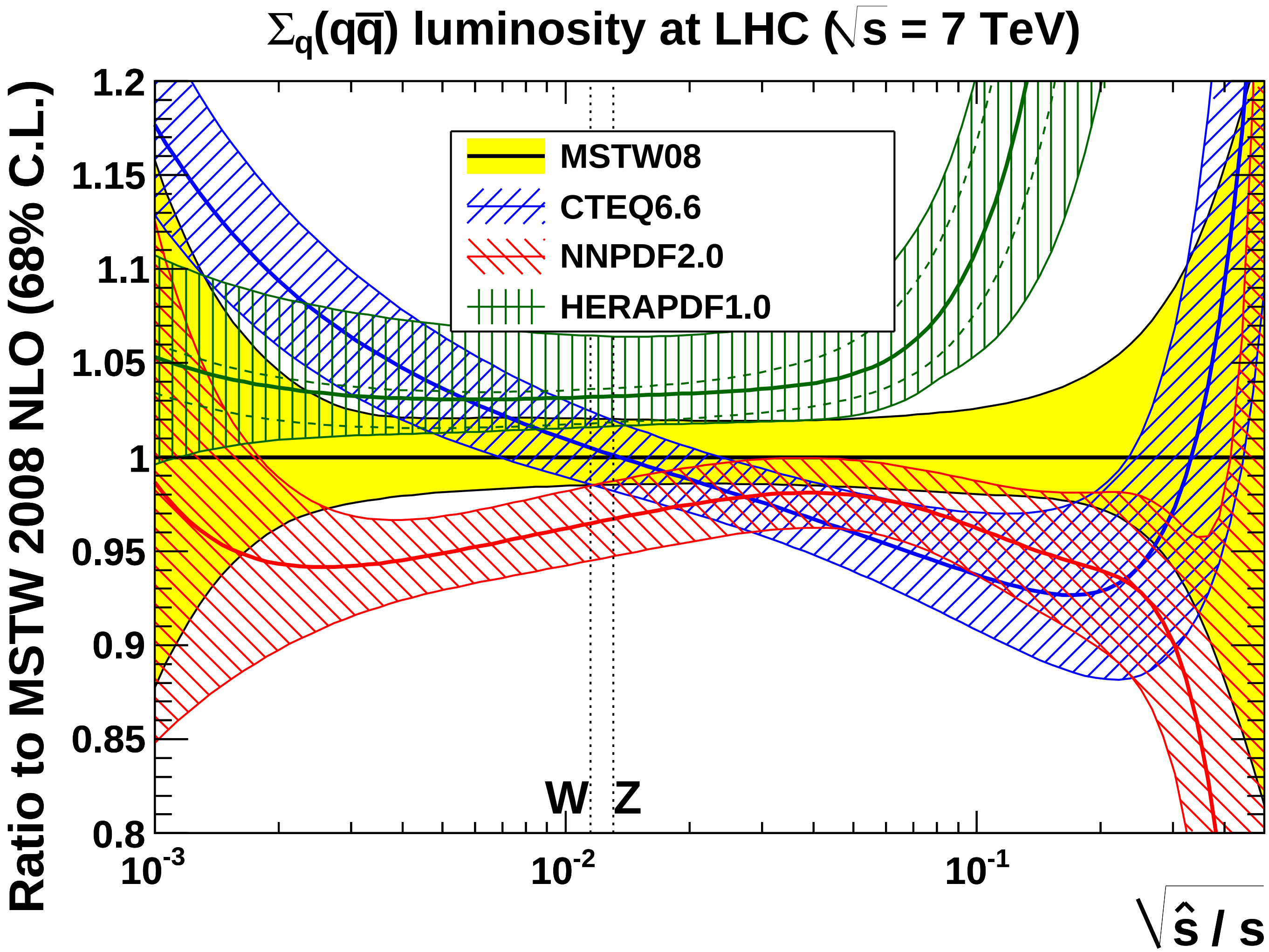


Cross-section for $t\bar{t}$ almost identical in PDF terms to $450\mathrm{GeV}$ Higgs.

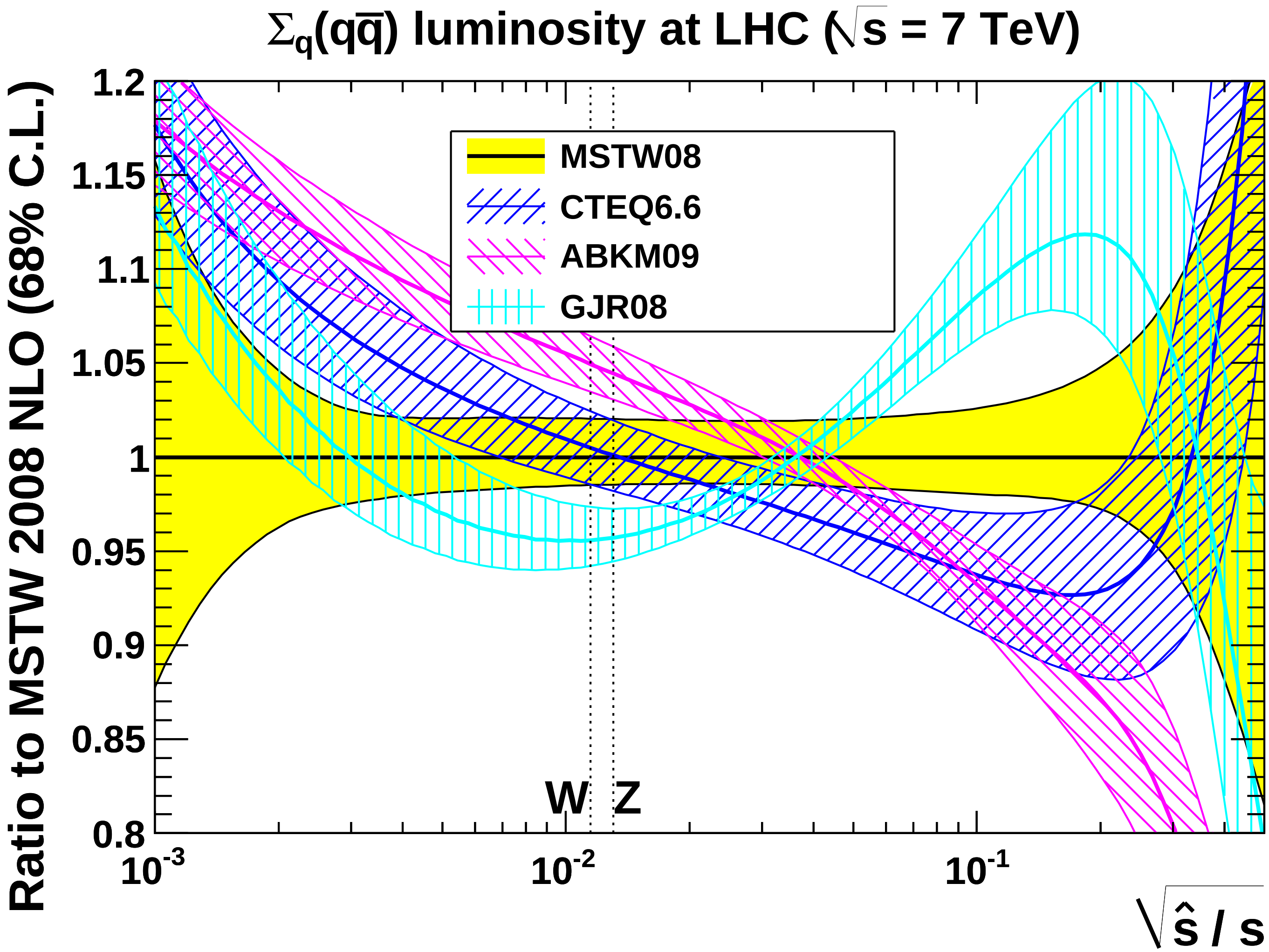
Also $H + t\bar{t}$ at $\sqrt{\hat{s}/s} \sim 0.1$.



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



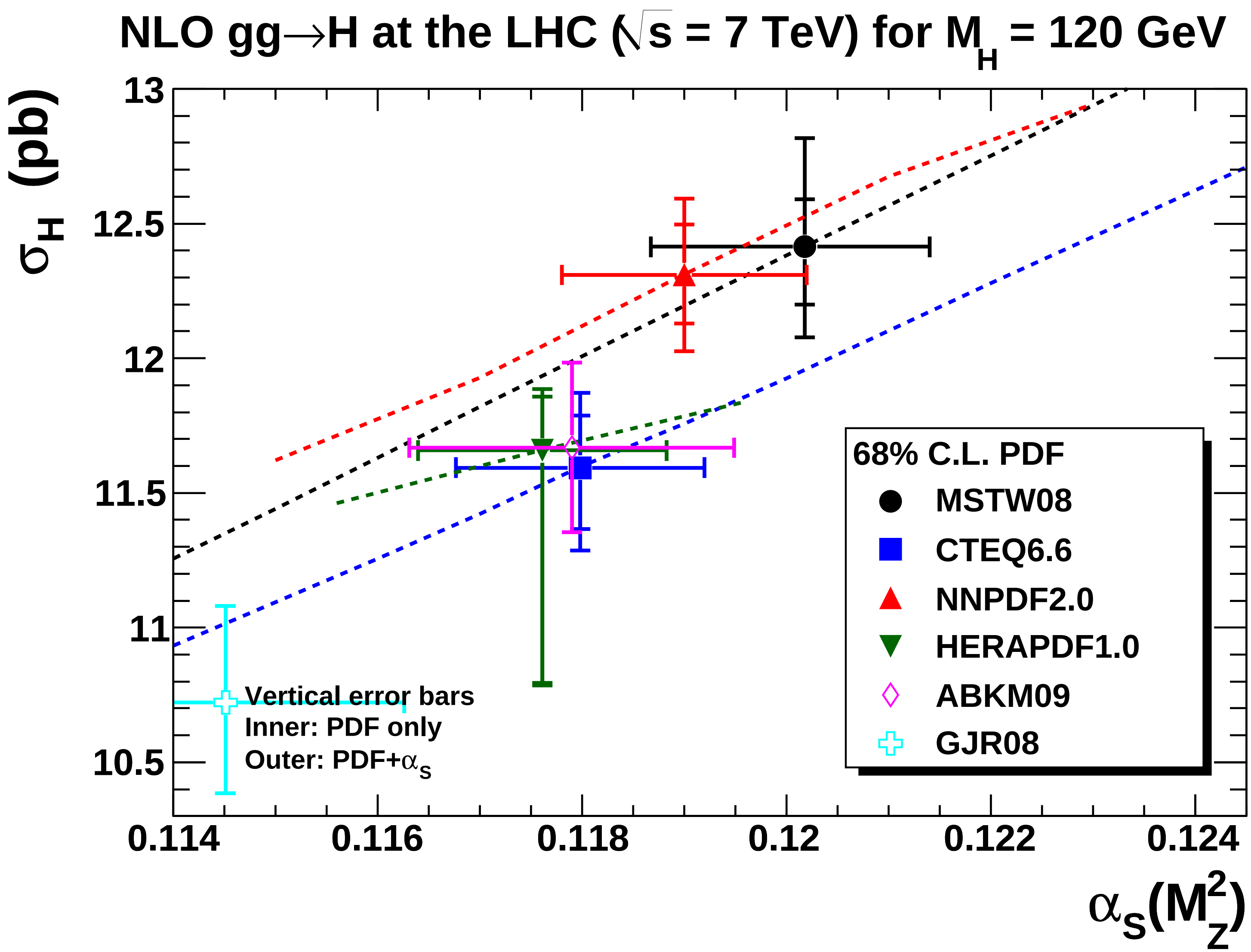
Many of the same general features for quark-antiquark luminosity. Some differences mainly at higher x.



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

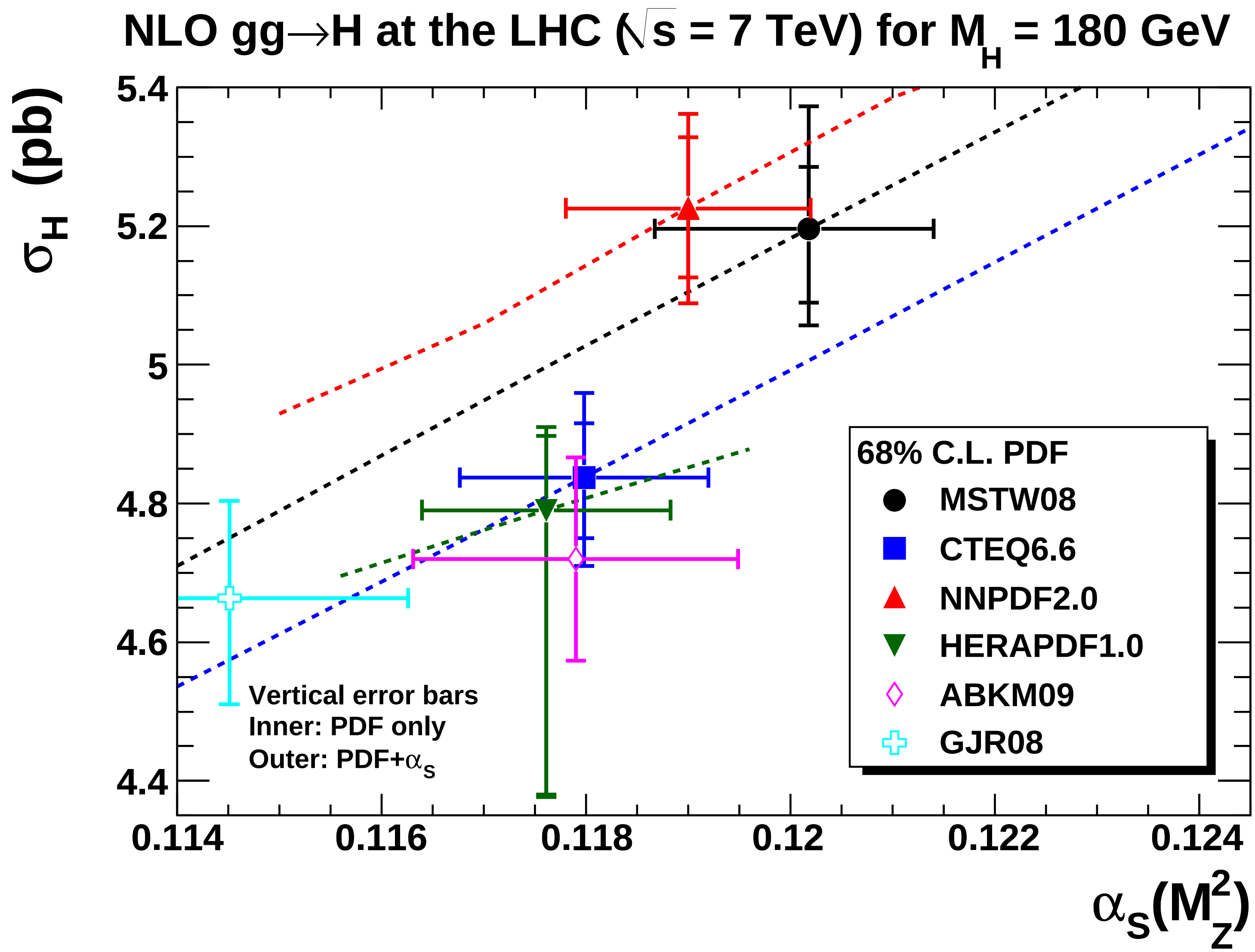
All plots and more at http://projects.hepforge.org/mstwpdf/pdf4lhc

Variations in Cross-Section Predictions – NLO

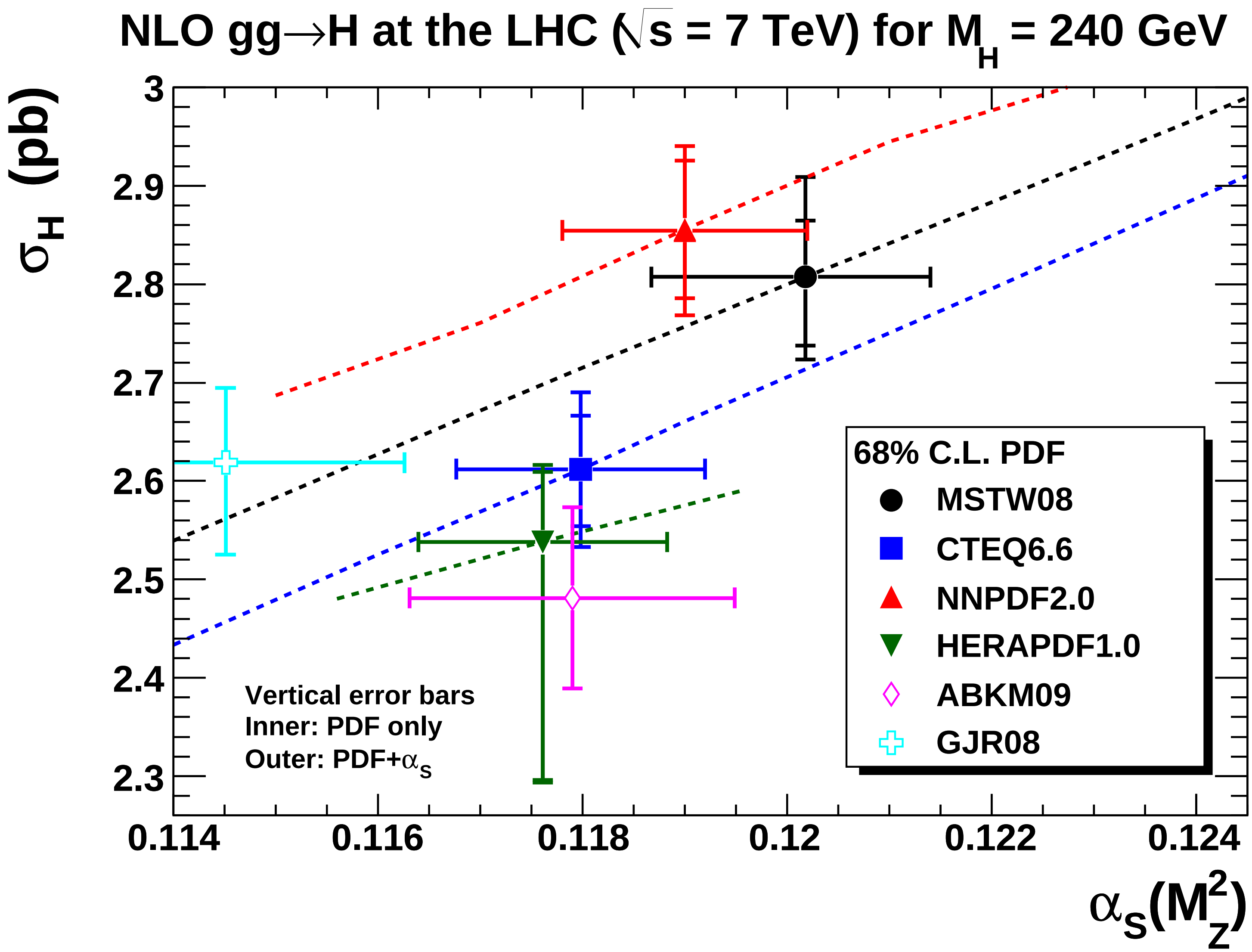


Dotted lines show how central PDF predictions vary with $\alpha_S(M_Z^2)$.

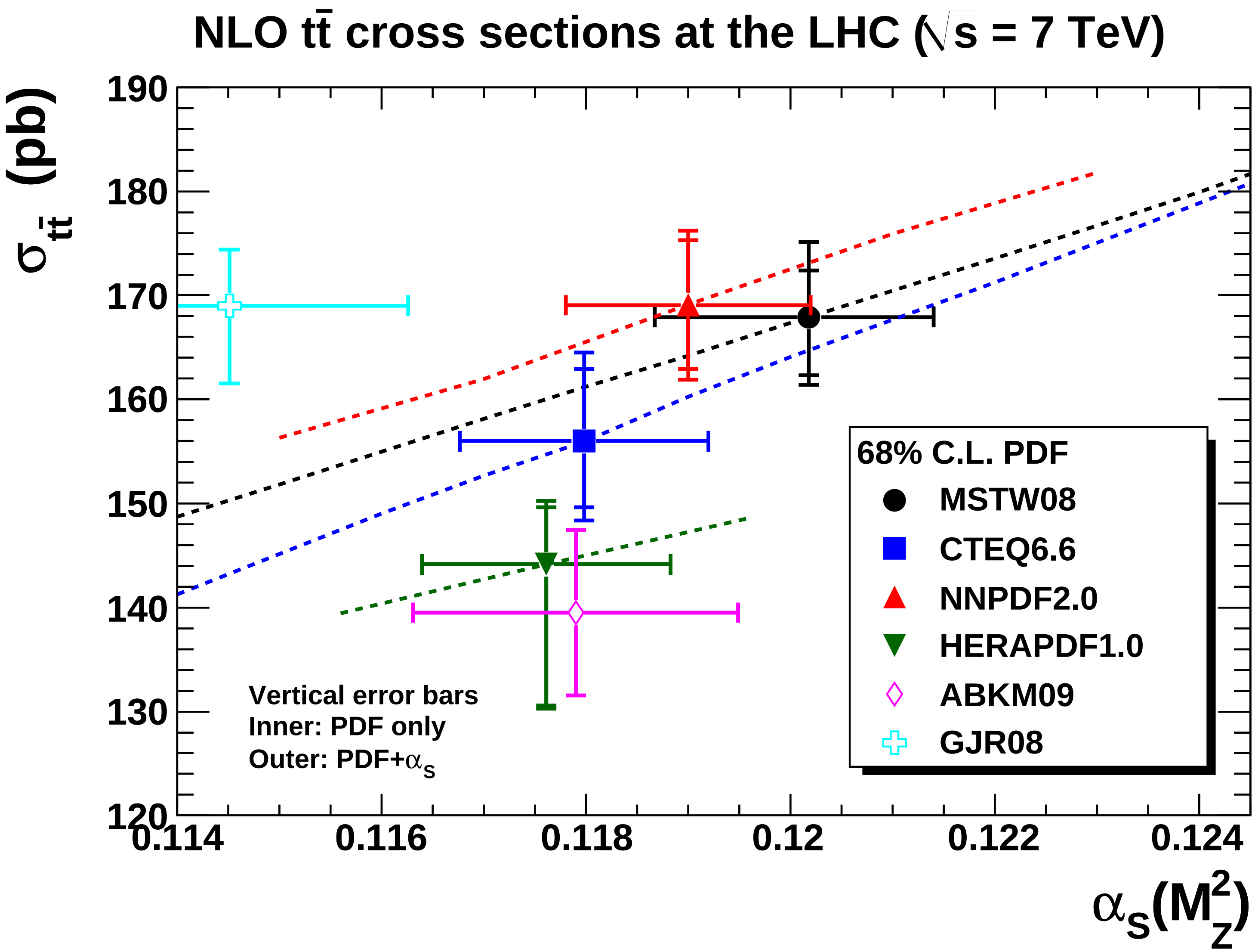
Again plots by G Watt using PDF4LHC benchmark criteria.



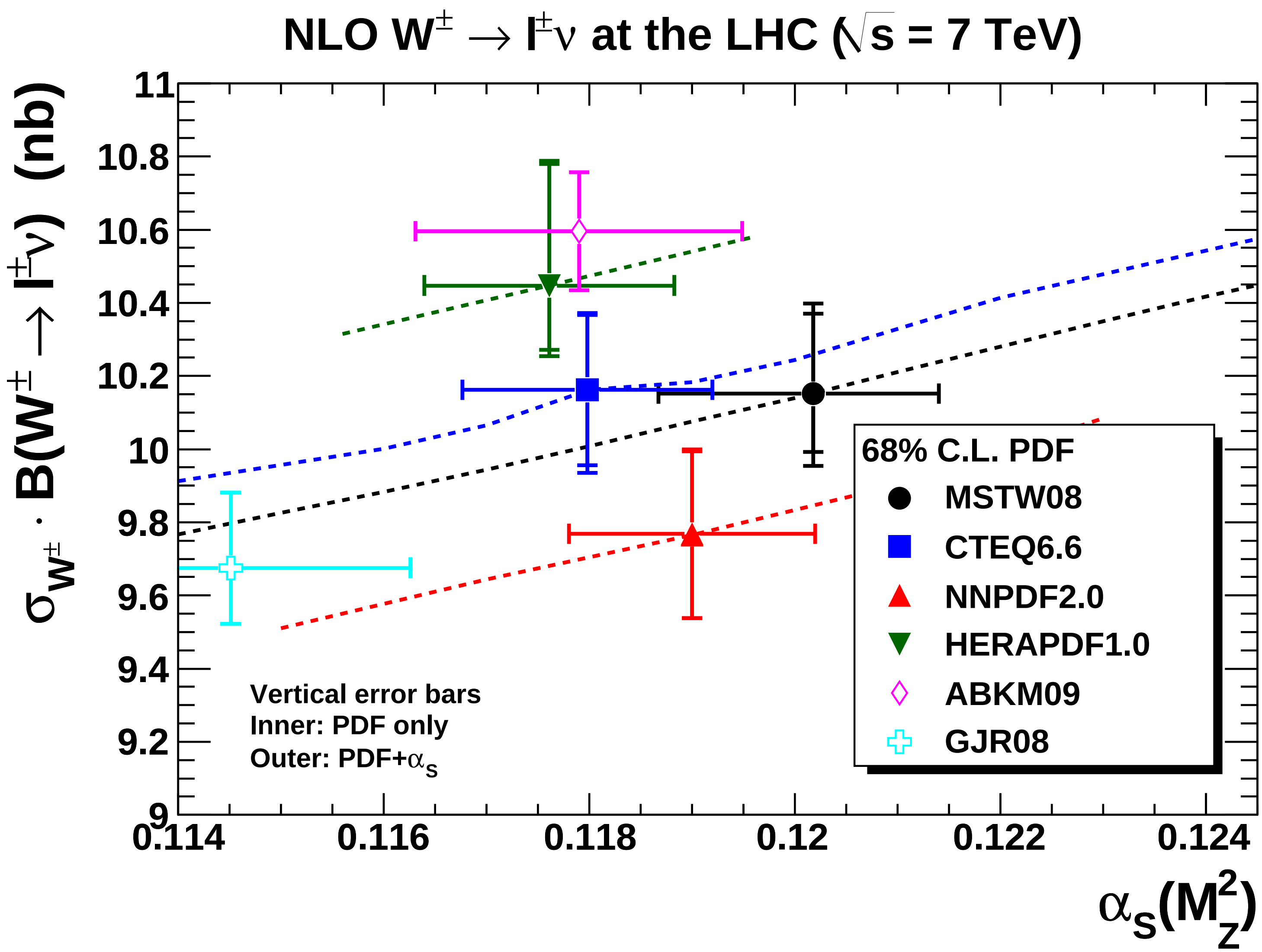
Clearly much more variation in predictions than uncertainties claimed by individual groups.



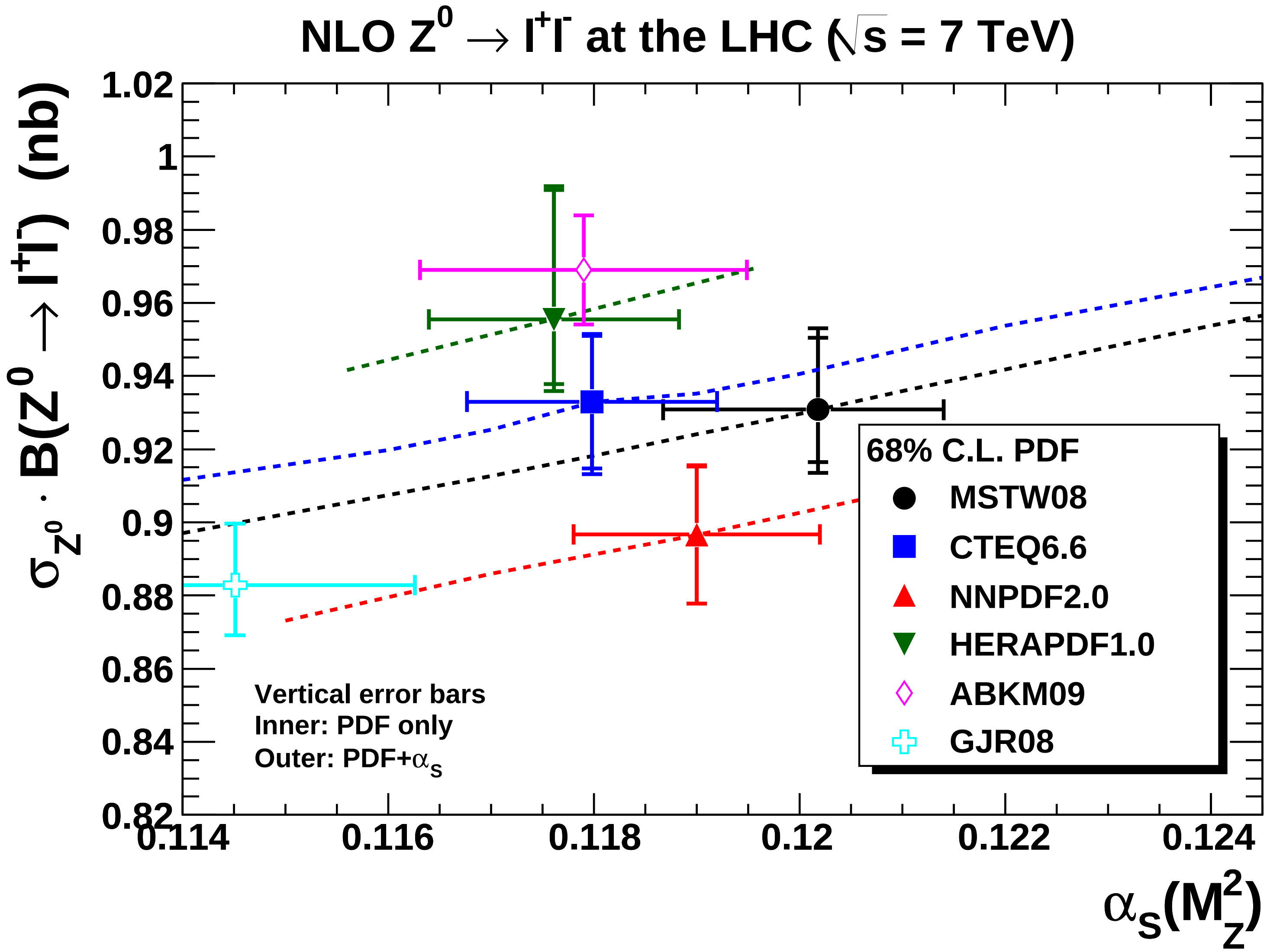
Excluding GJR08 amount of difference due to $\alpha_S(M_Z^2)$ variations $3 - 4\%$.



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

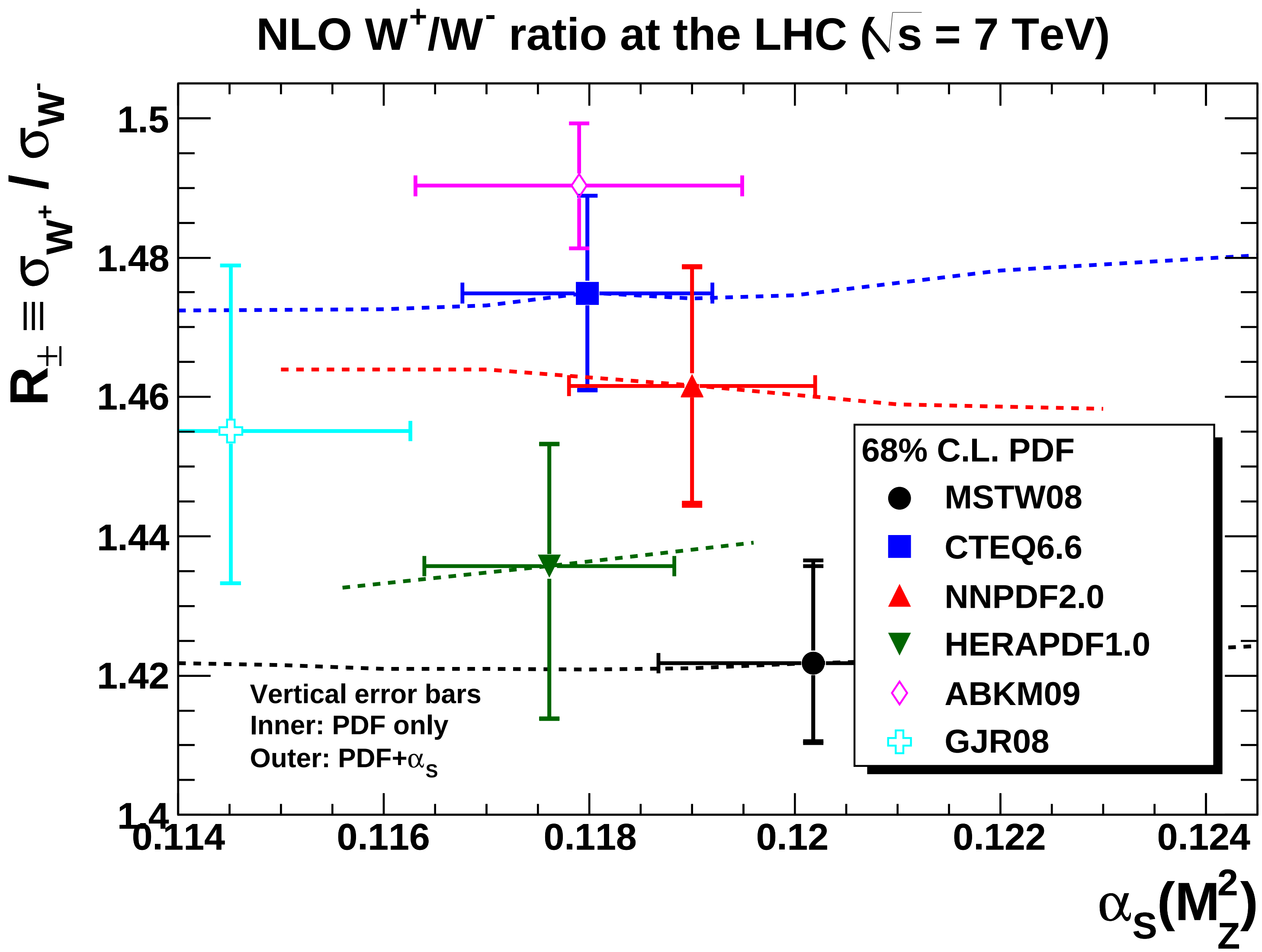


$W^+ + W^-$ cross-section. $\alpha_S(M_Z^2)$ dependence now more due to PDF variation with $\alpha_S(M_Z^2)$.



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

Deviations in predictions clearly much more than uncertainty claimed by each.

In some cases clear reason why central values differ, e.g. lack of some constraining data, though uncertainties then do not reflect true uncertainty.

Sometimes no good understanding, or due to difference in procedure which is simply a matter of disagreement, e.g. gluon parameterisation at small x affects predicted Higgs cross-section.

What is true uncertainty? Question posed to PDF4LHC group.

Interim recommendation take envelope of $global$ sets, MSTW, CTEQ, NNPDF (check other sets) and take central point as uncertainty.

Not very satisfactory, but not clear what would be an improvement, especially as a general rule.

Usually not a big disagreement, and factor of about 2 expansion of MSTW uncertainty.

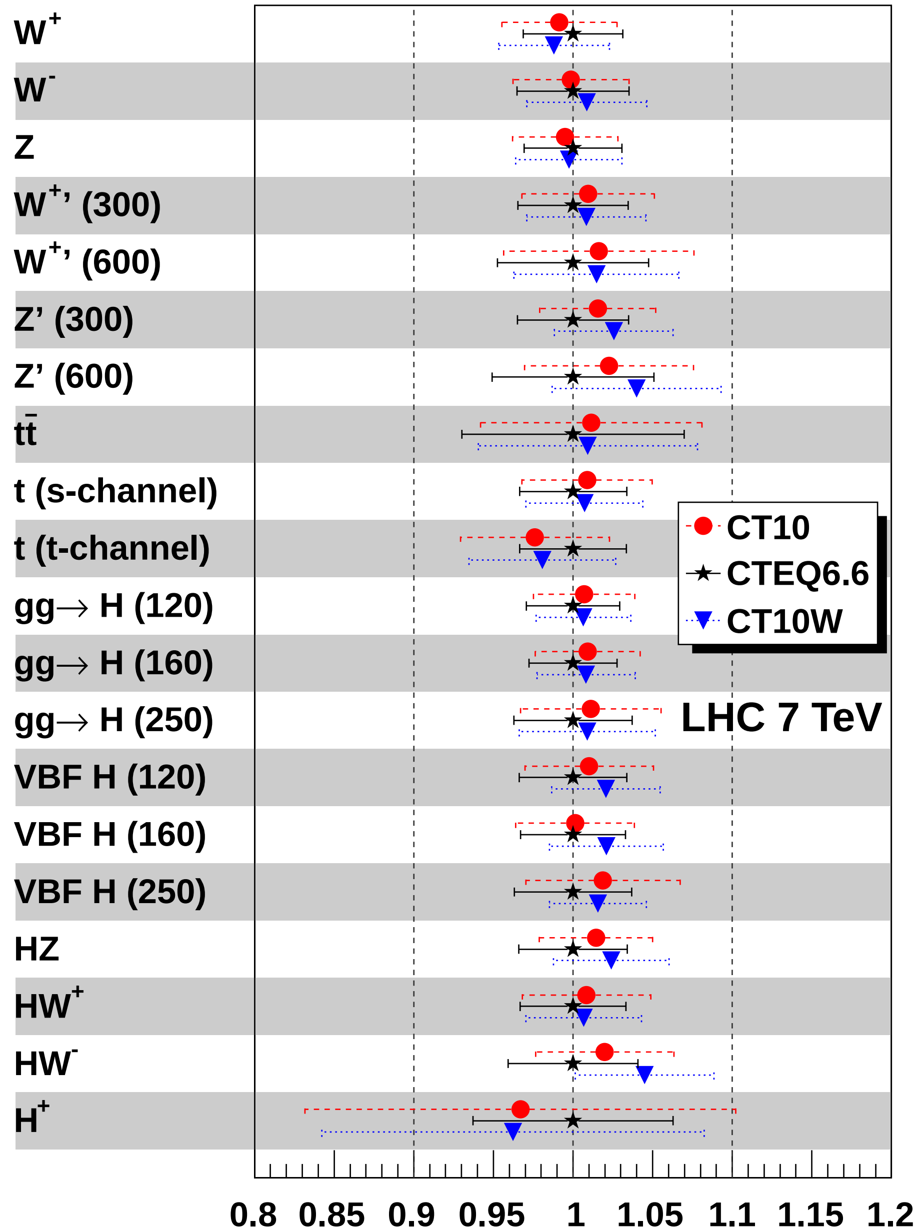
Very Recent Updates

MSTW find new combined HERA data lead to increase in W, Z by couple of $\%$. Less than 1% on Higgs (Tevatron and LHC).

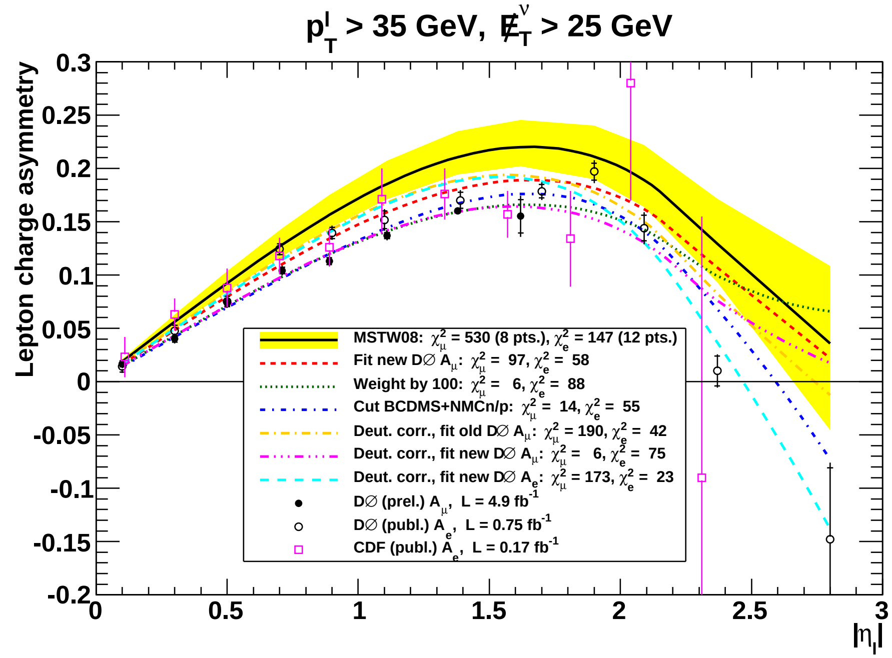
CT10 (right) find change in W, Z very small (probably countered by gluon parameterisation change).

Slight increase in Higgs, $t\bar{t}$ (again probably gluon shape).

NNPDF find prelim GM-VFNS fits bring them closer to MSTW,CTEQ for W, Z.



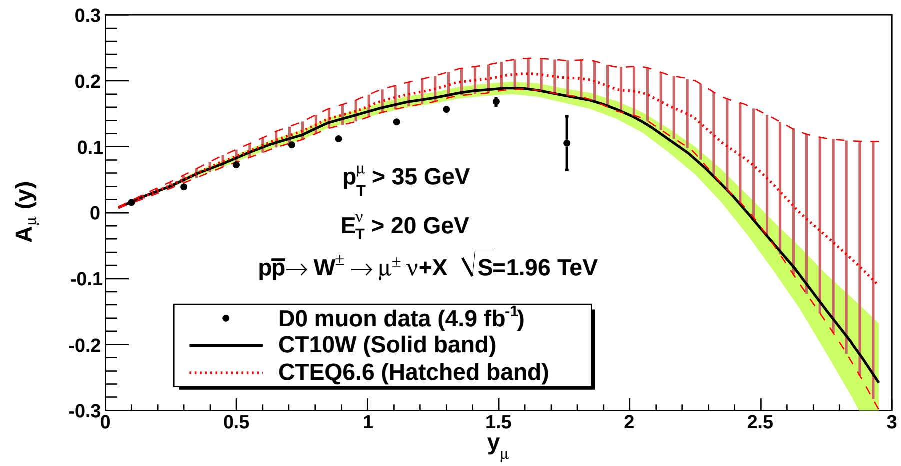
Both MSTW and CTEQ have difficulty fitting new D0 lepton asymmetry (particularly muon in different E_T bins) along with other data.



MSTW have considered cutting other data or investigating deuterium corrections.

No public sets yet.

CTEQ have alternative CT10W set where this has added weight.



Largely affects W, Z physics at high rapidity.

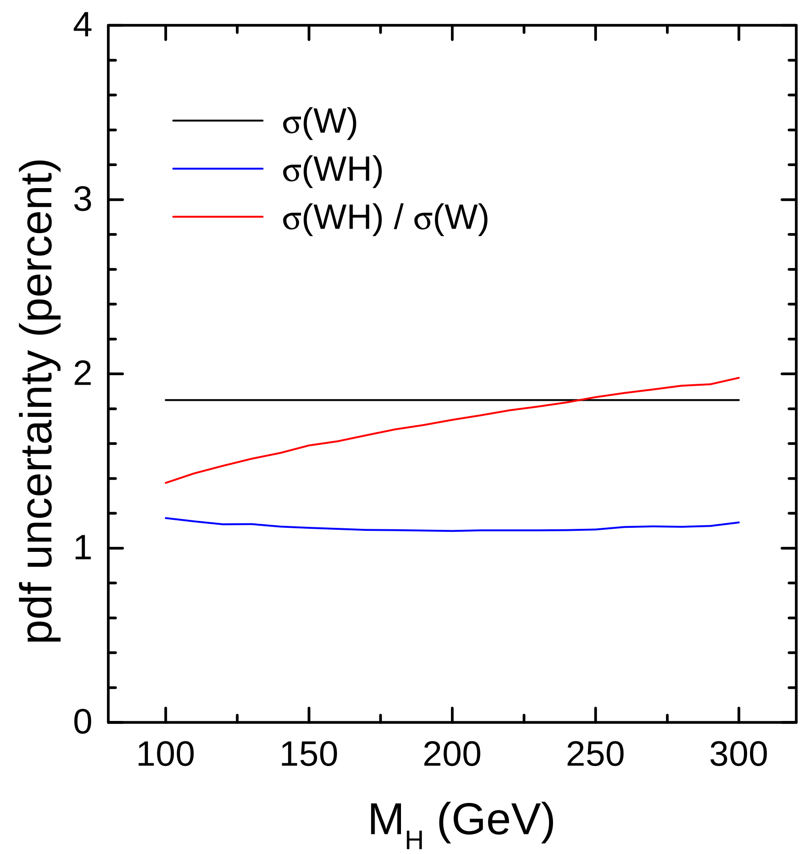
Could $\sigma(W)$ or $\sigma(Z)$ be used to calibrate other cross-sections, e.g. $\sigma(WH)$, $\sigma(Z')$?

$\sigma(WH)$ 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.

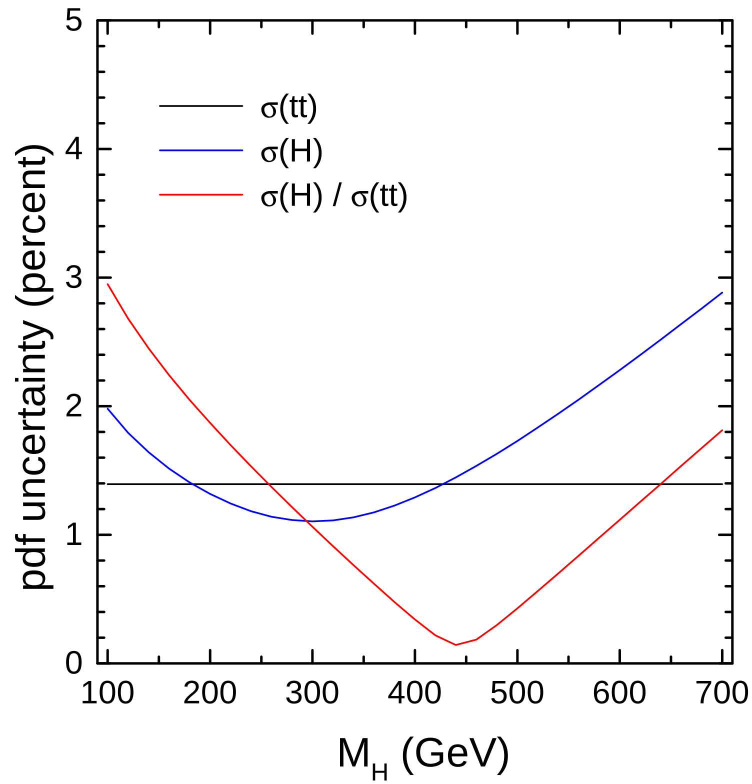
Partons in different regions of x are often anti-correlated rather than correlated, partially due to sum rules.

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.

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



Other sources of Uncertainty.

Also other sources which (mainly) lead to inaccuracies common to all fixed-order extractions.

- Standard higher orders (NNLO – may sets available here.)
- 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.
- QED and Weak (comparable to NNLO ?) $(\alpha_s^3 \sim \alpha)$. Sometime enhancements.

NNLO

NNLO splitting functions now complete. (Moch, Vermaseren and Vogt). Essentially full NNLO determination of partons now being performed (MSTW, ABKM,GJR,HERA), though heavy flavour not fully worked out in the fixed-flavour number scheme (FFNS) PDFs. Improve consistency of fit very slightly, and reduces α_S.

Surely this is best, i.e. most accurate.

Yes, but ...... only know some hard cross-sections at NNLO.

Processes with two strongly interacting particles largely completed

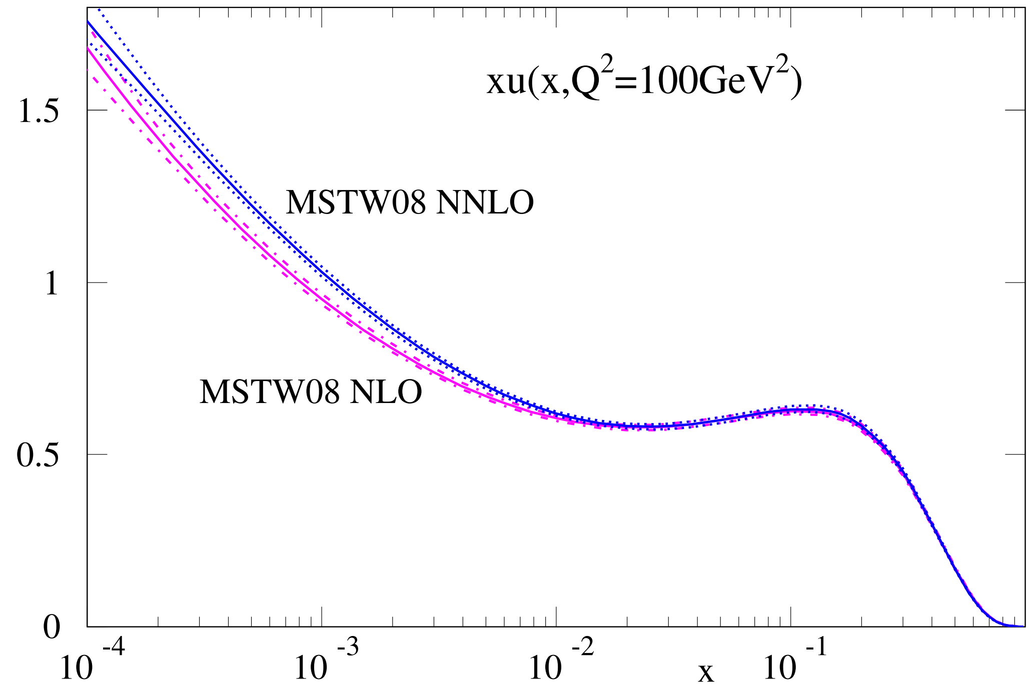
DIS coefficient functions and sum rules

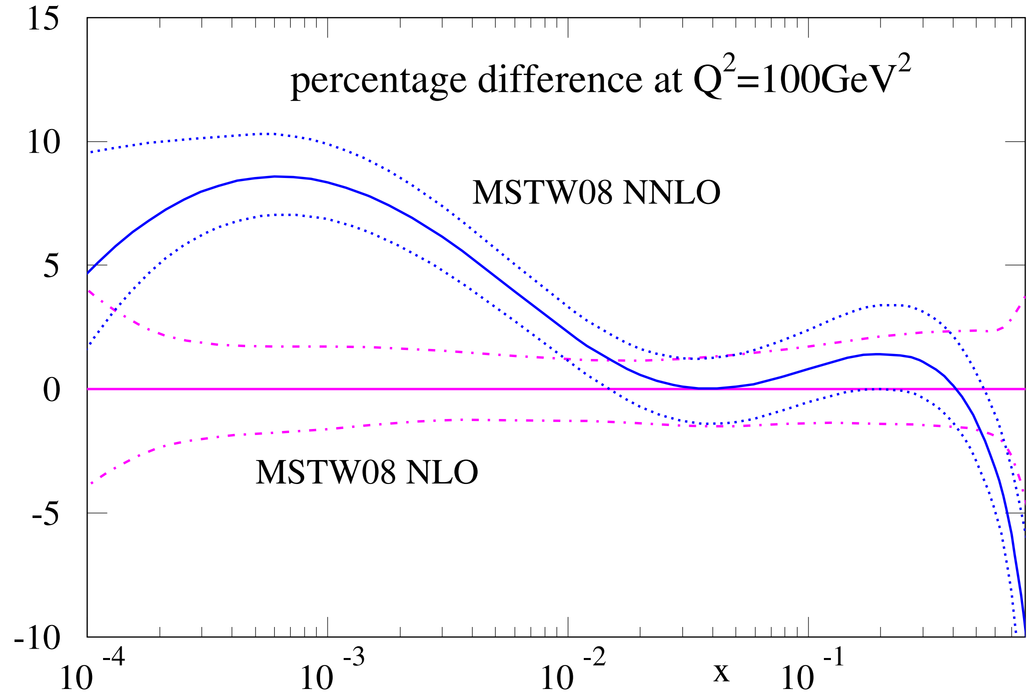
$pp(\bar{p}) \rightarrow \gamma^\star, W, Z$ (including rapidity dist.), H, A^0, WH, ZH.

But for many other final states NNLO not known. NLO still more appropriate.

Stability order-by-order.

Systematic difference between PDF defined at NLO and at NNLO.



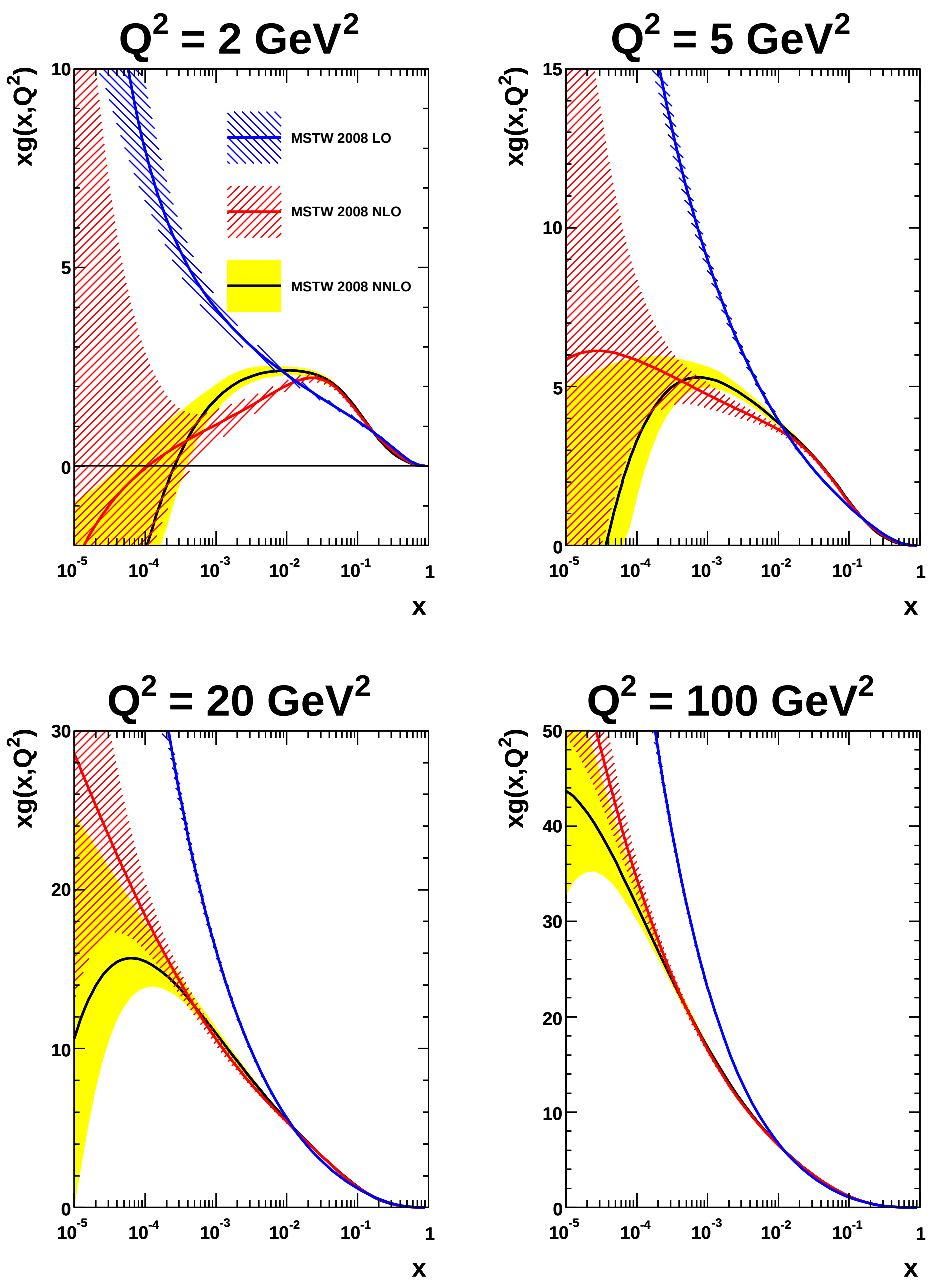


The gluon extracted from the global fit at LO, NLO and NNLO.

Additional and positive small-x contributions in P_{qg} at each order leads to smaller small-x gluon at each order.

Clearly poor stability.

OK for Higgs production, but only because different $\alpha_S(M_Z^2)$ at NLO and NNLO.



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.

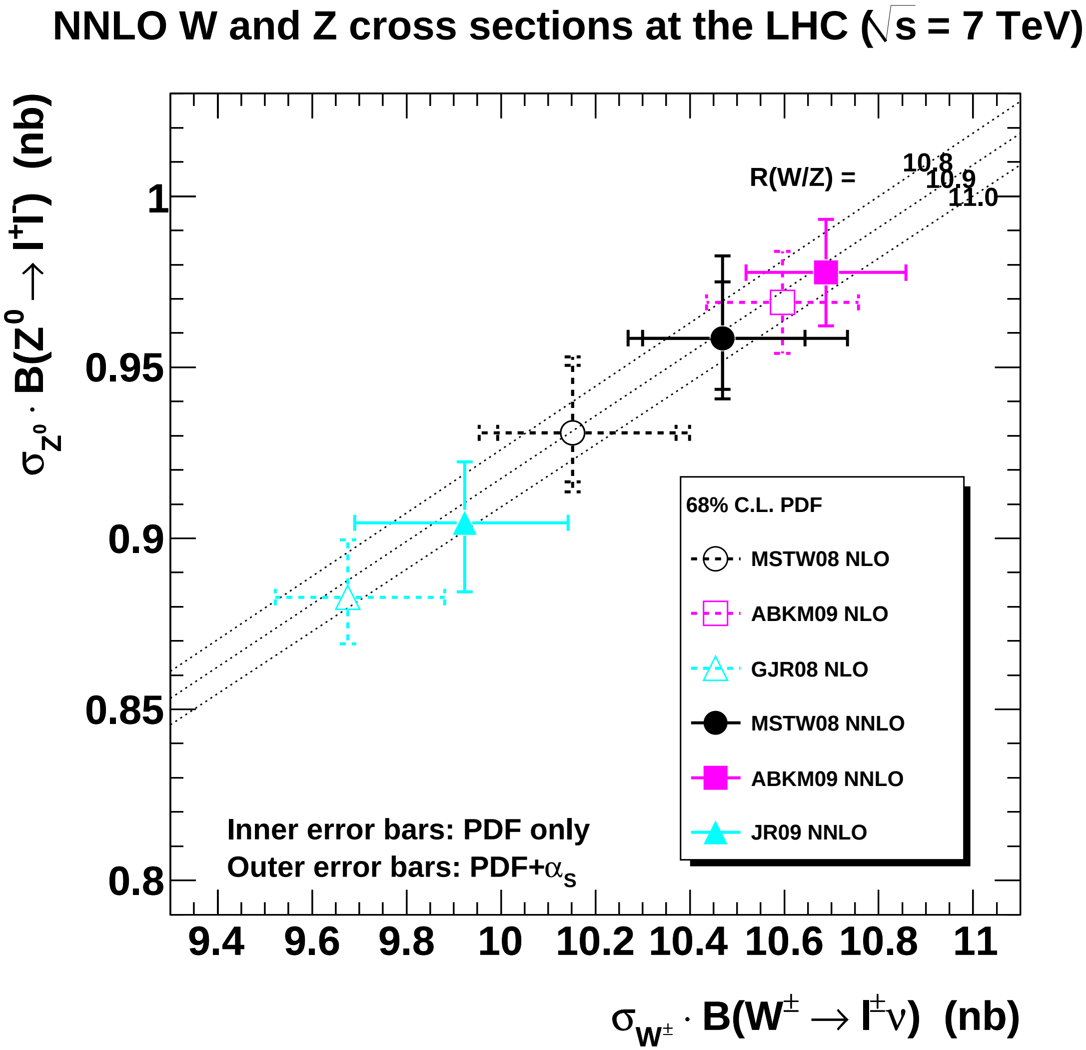
Consider percentage change from NLO to NNLO in MSTW08 predictions for best fit α_S compared to fixed $\alpha_S(M_Z^2) = 0.119$.

	$\sigma_{W(Z)}$ 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.

Differences in predictions at NNLO compared to NLO (Watt).

Note differences in heavy mass treatments between groups and for GJR and ABKM this component is same in NNLO extraction as in NNLO.



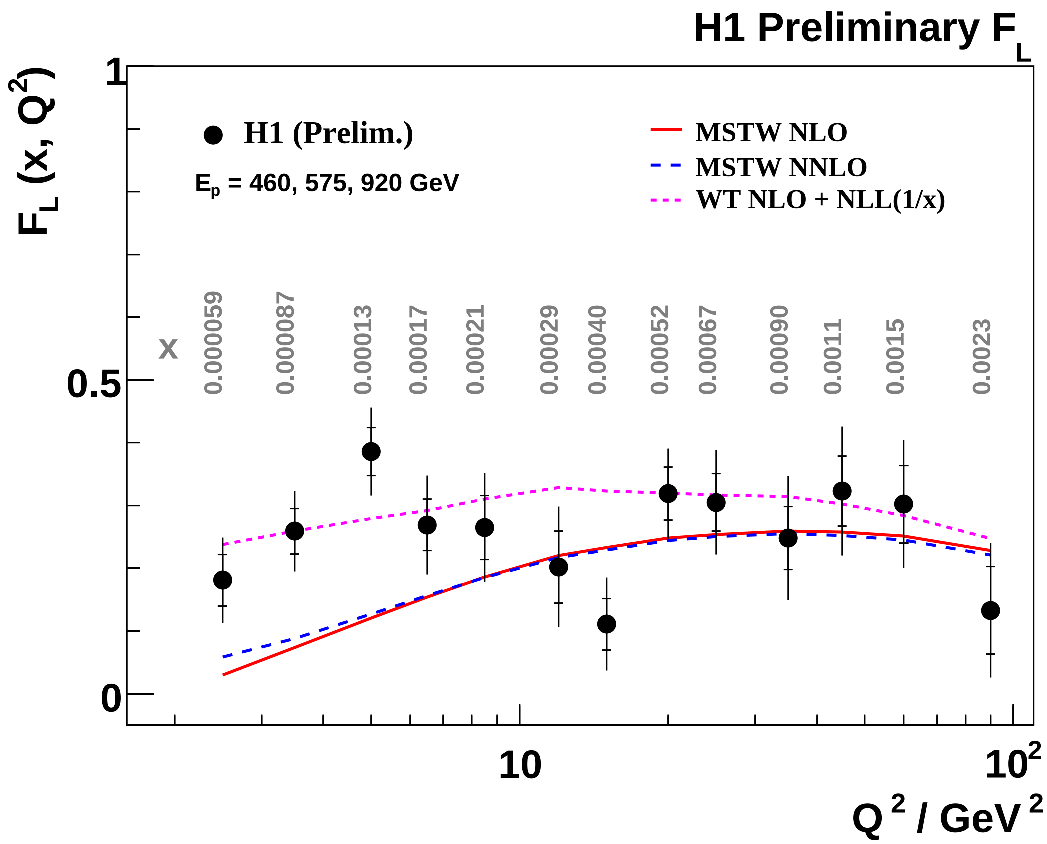
Small-x Theory

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. $P_{ij}(x, \alpha_s(Q^2)), C_i^P(x, \alpha_s(Q^2)) \sim \alpha_s^m(Q^2) \ln^{m-1}(1/x)$.

Summed using BFKL equation (and a lot of work – Altarelli-Ball-Forte, Ciafaloni-Colferai-Salam-Stasto and White-RT)

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.

Could possibly give a few percent effect on Higgs cross sections.



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.

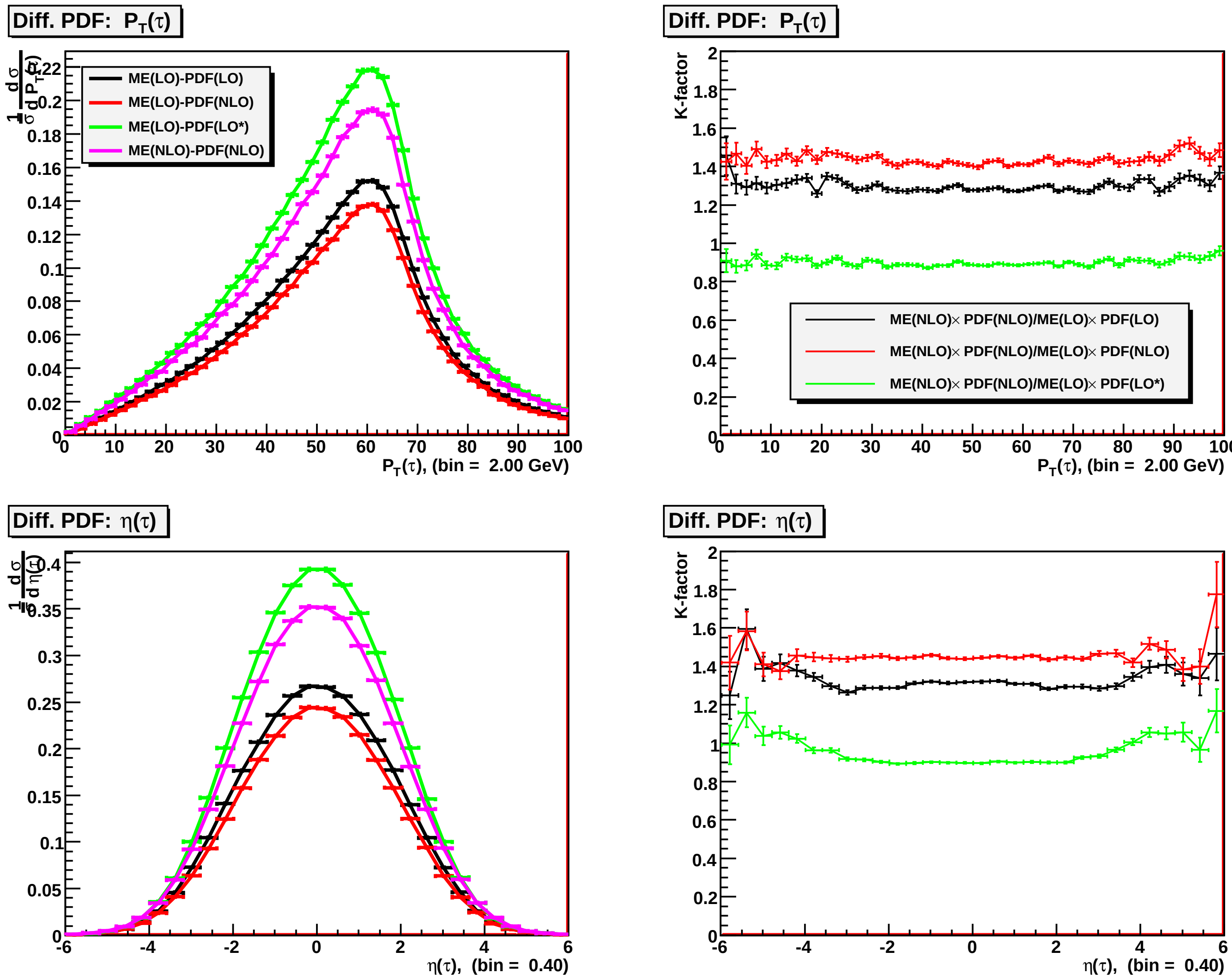
NLO corrections to cross-section usually positive $\rightarrow$ LO PDFs bigger by allowing momentum violation in global fits, using NLO α_S, fit LHC pseudo-data ......

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).

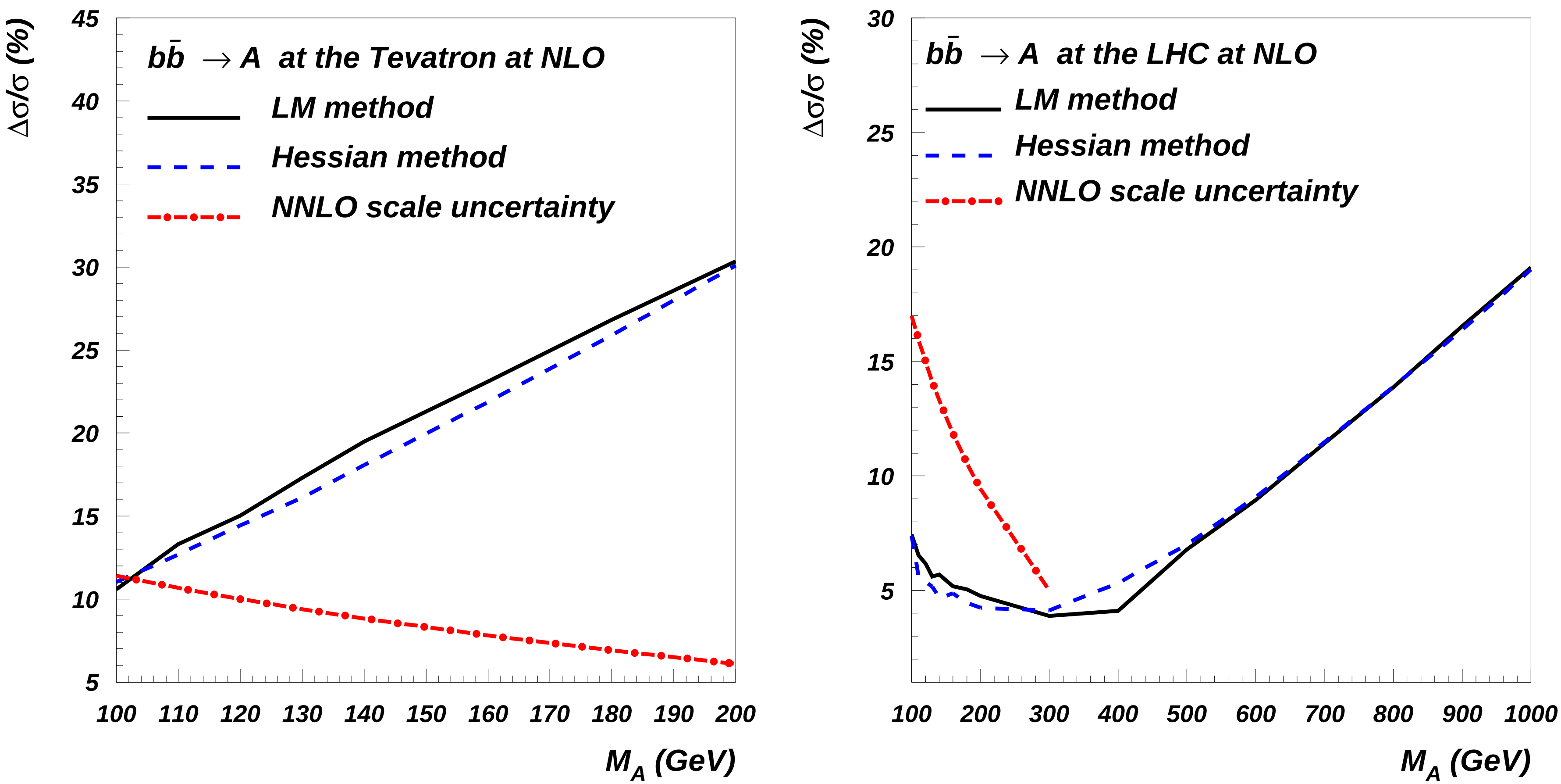


Results using LO* partons clearly best in normalization. NLO worst and problems with shape at low scales (i.e. small x).

Final Examples

Need to understand both heavy flavours and small-x physics for LHC.

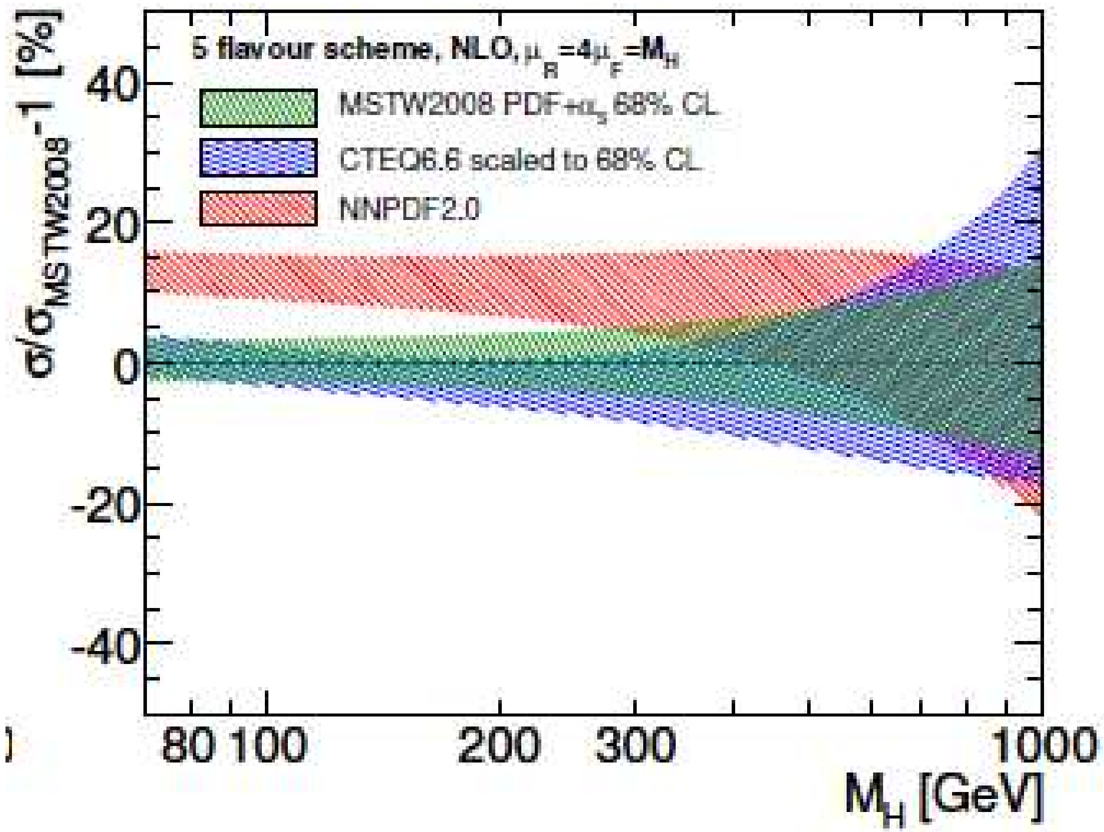
Production of supersymmetric Higgs depends on parton uncertainties (Belyaev, Pumplin, Tung and Yuan), heavy flavour procedure and theory corrections.



Another example, Warsinsky at recent Higgs-LHC working group meeting.

m_b values bring CTEQ and MSTW together but exaggerate NNPDF difference.

Couplings have assumed common mass value.



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.

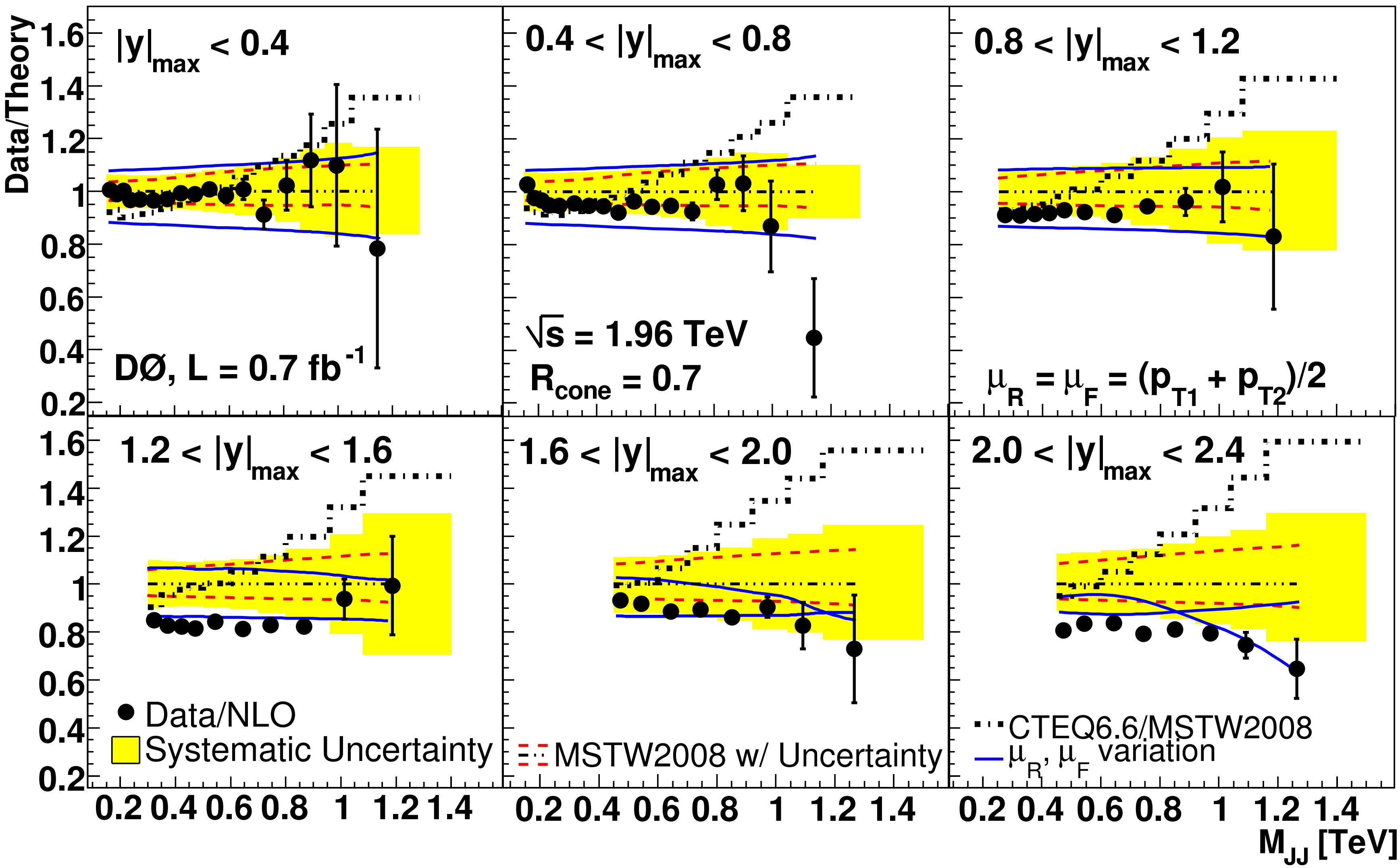
Various ways of looking at *experimental* uncertainties. Uncertainties $\sim 1-5\%$ for most LHC quantities. Ratios, e.g. W^+/W^- tight constraint on partons.

Effects from input assumptions e.g. selection of data fitted, cuts and input parameterisation can shift central values of predictions significantly. Also affect size of uncertainties. Want balance between freedom and sensible constraints.

Complete heavy flavour treatments essential in extraction and use of PDFs. α_S and PDFs heavily correlated.

Errors from higher orders/resummation potentially large. At LHC measurement at high rapidities, e.g. W, Z would be useful in testing understanding of QCD, and particularly quantities sensitive to low x at low scales, e.g. low mass Drell-Yan.

Extraction of PDFs from existing data and use for LHC far from a straightforward procedure. Lots of theoretical issues to consider for real precision. Relatively few cases where Standard Model discrepancies will not require some significant input from PDF physics to determine real significance.

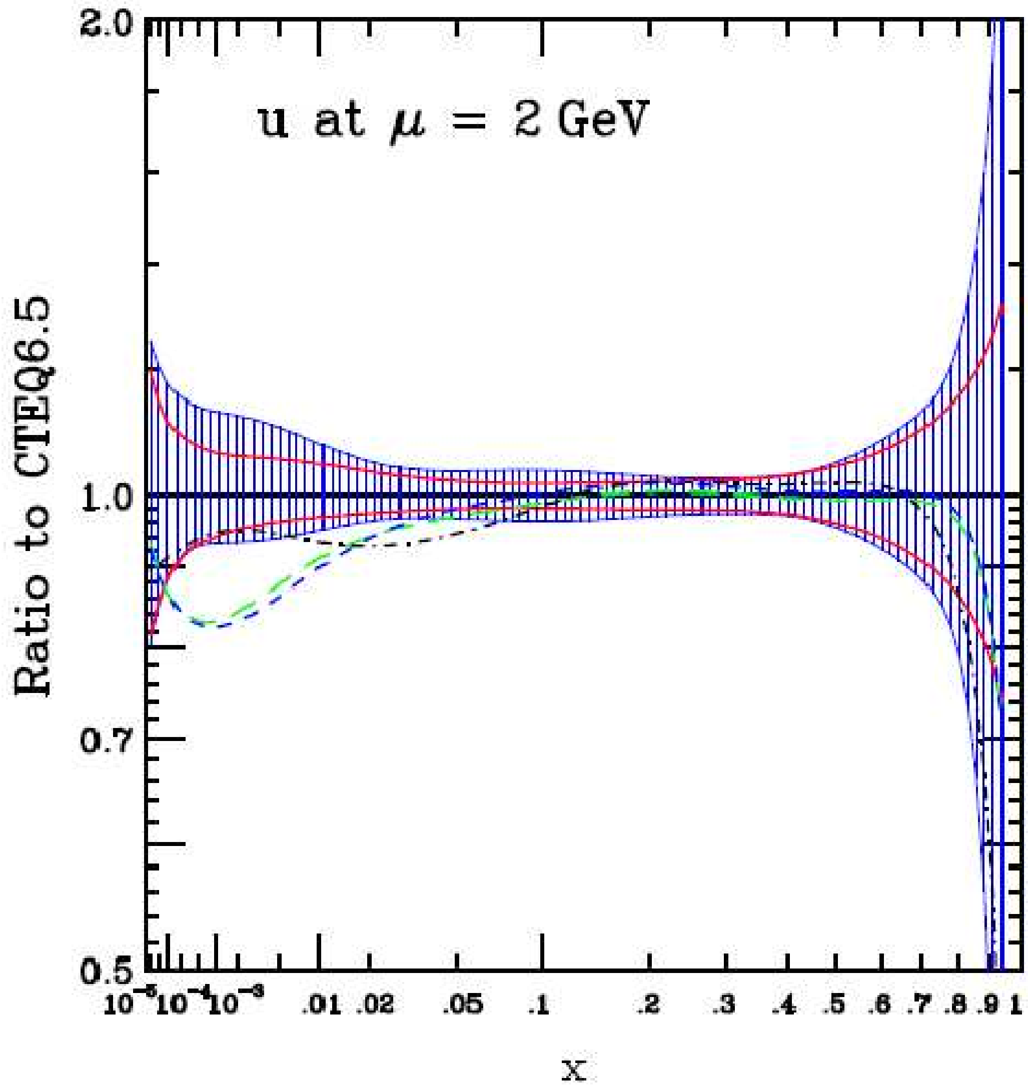


Very large high-x gluon not supported by very recent D0 dijet data.

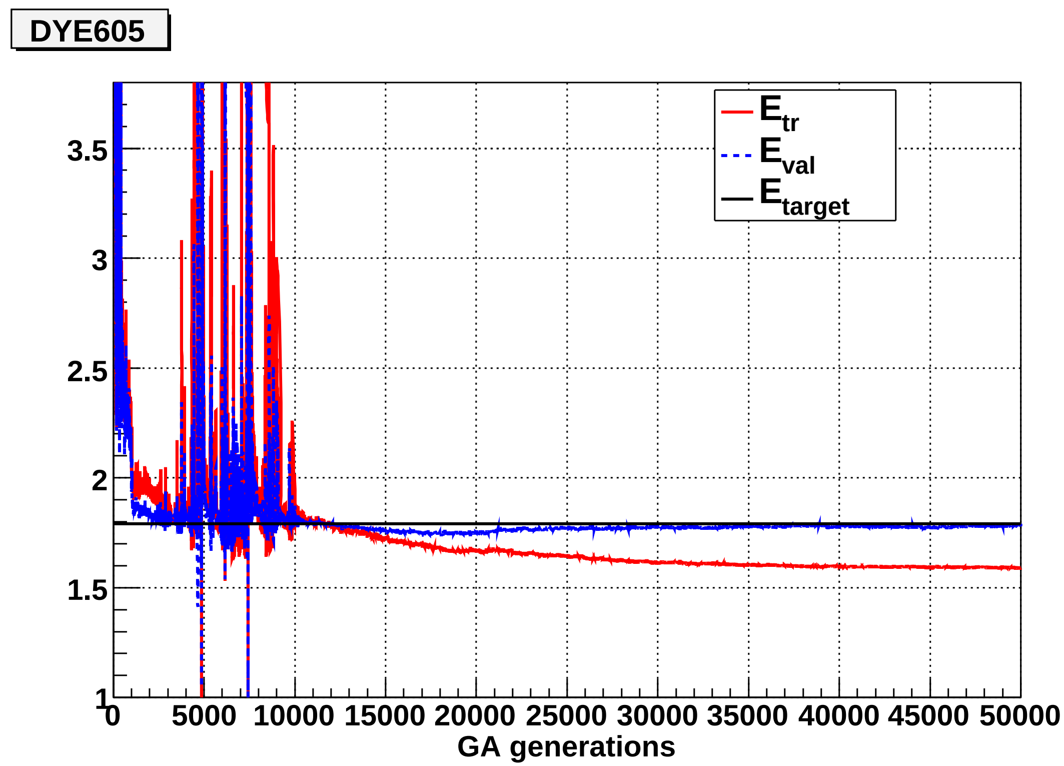
Importance of using GM-VFNS instead of massless approach illustrated by CTEQ6.5 up quark with uncertainties compared with previous versions, e.g. CTEQ6 in green.

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.



Difficult to know when fit to validation set has started increasing significantly for some sets.



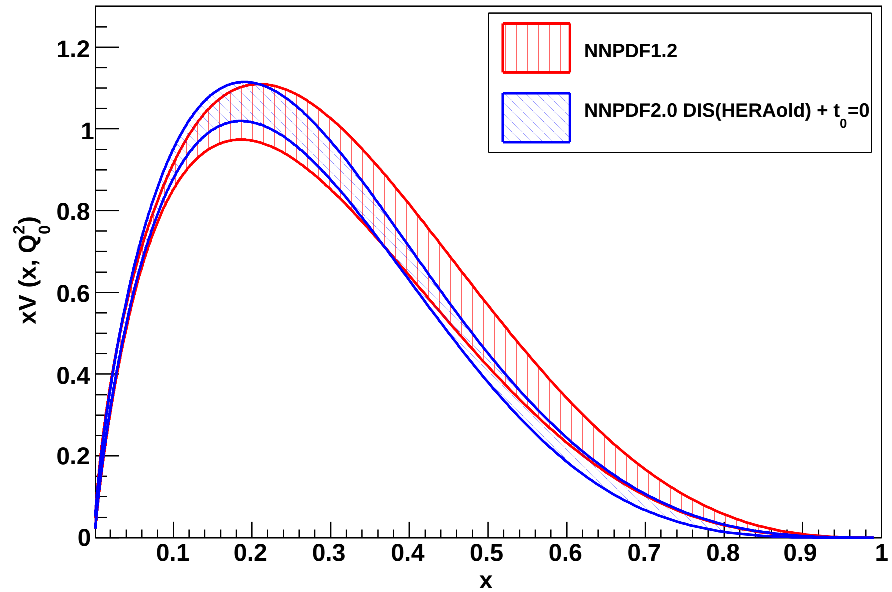
Weighted training in early stages according to a target (determined iteratively), so stopping for global fit more in line with individual sets.

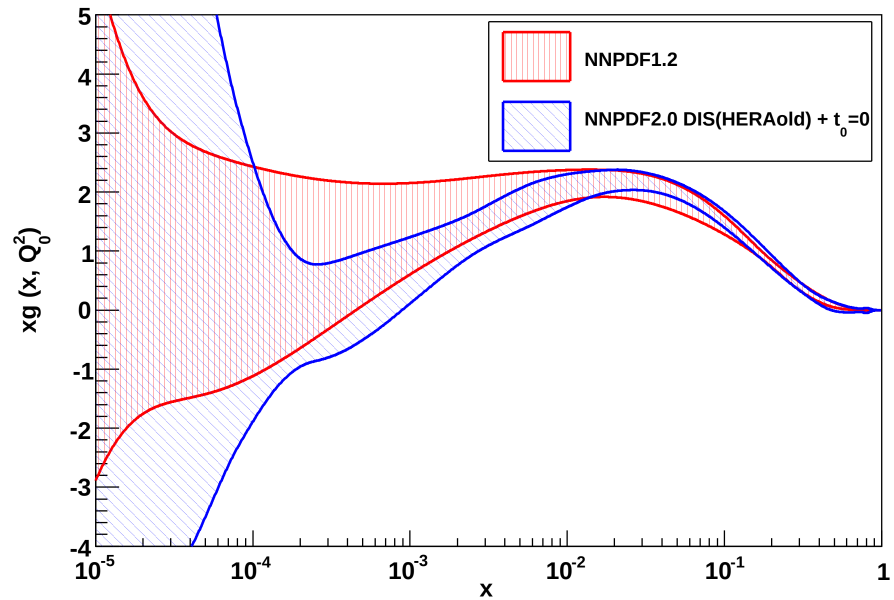
Criterion for increase in fit to validation sets relative to decrease in training sets made more strict.

Significant reductions (usually) in uncertainty in latest version, and changed central values, just due to change in stopping and fitting procedures.

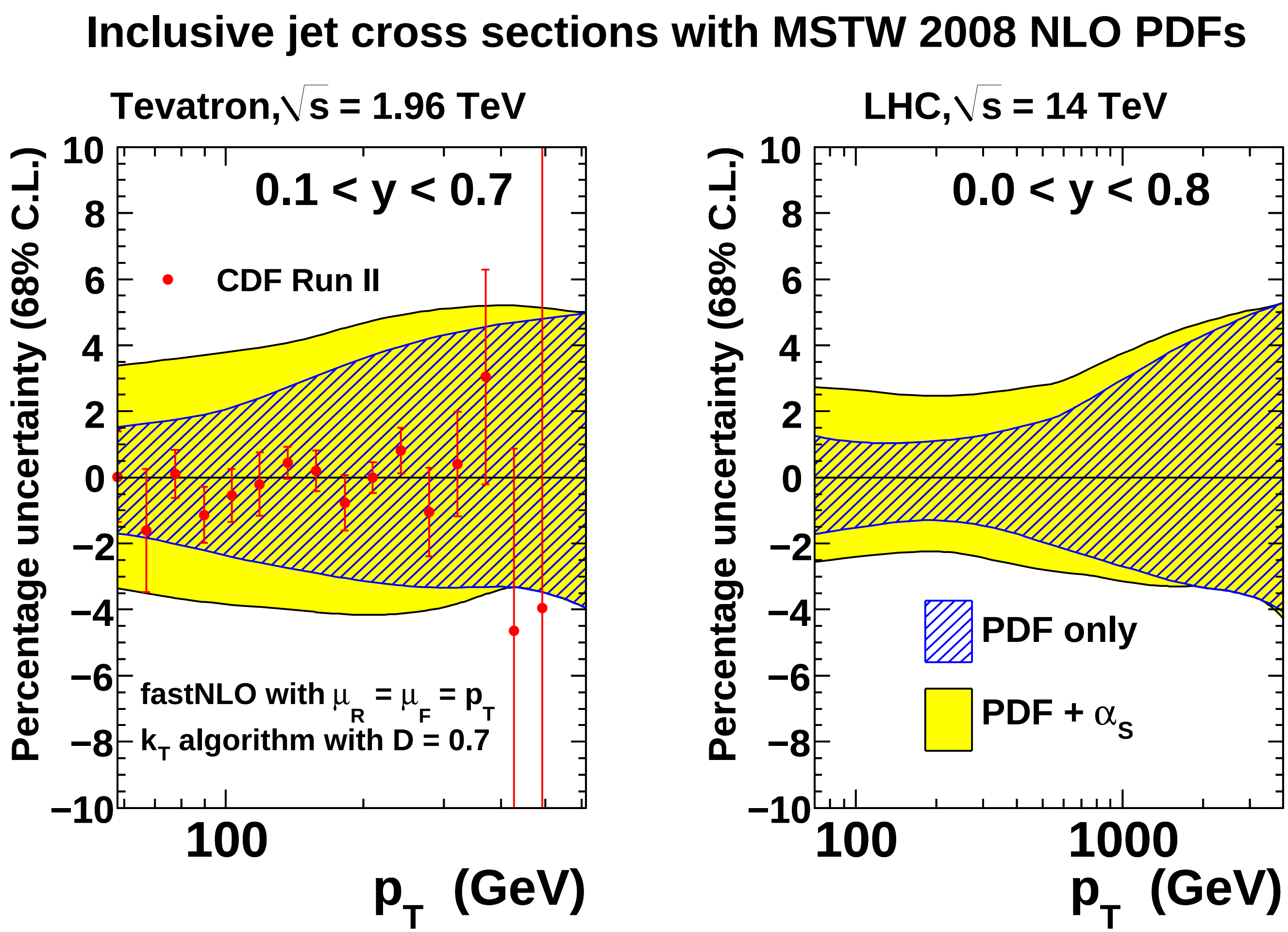
I would suggest uncertainty now more analogous to smaller "$\Delta\chi^2$", but actual value very difficult to ascertain. Fluctuations in error function (and χ^2) still arguably a bit larger than naively expected.

Is there a definitive set of stopping criteria?





Can also investigate uncertainties for inclusive jets at Tevatron and at LHC.



At lower p_T gluons dominate and α_S correlated. At higher p_T quarks become more important and high-x quarks anti-correlated to α_S so no additional α_S uncertainty.

NNLO

Default has long been NLO. Essentially well understood. Now starting to go further.

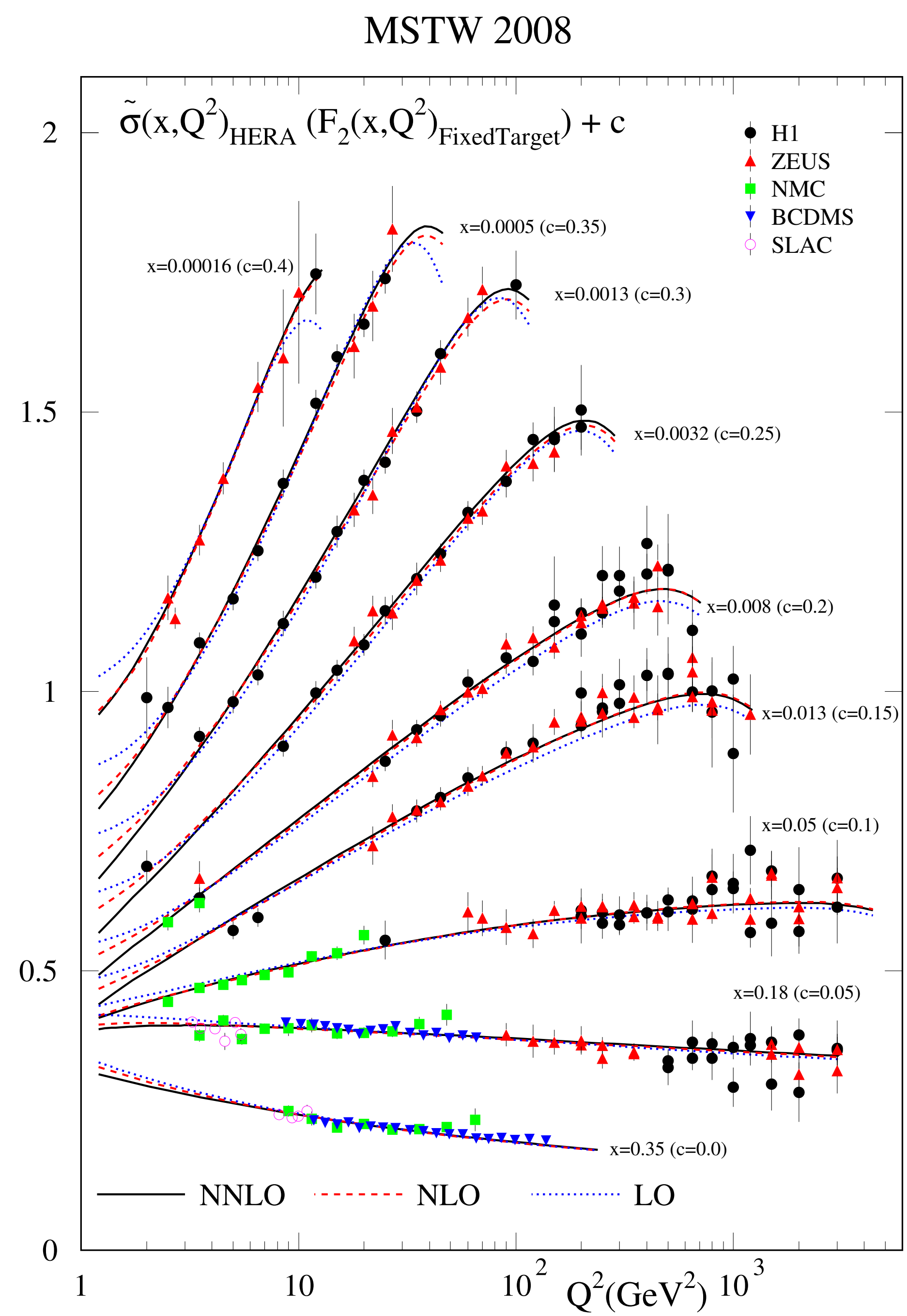
NNLO coefficient functions for structure functions know for many years.

Splitting functions now complete. (Moch, Vermaseren and Vogt). Improve consistency of fit very slightly (MSTW), and reduces α_S.

Fit to $F_2(x,Q^2)$ data.

Slope poor (too flat) at LO, ok at NLO and better at NNLO.

Some slight room for improvements.



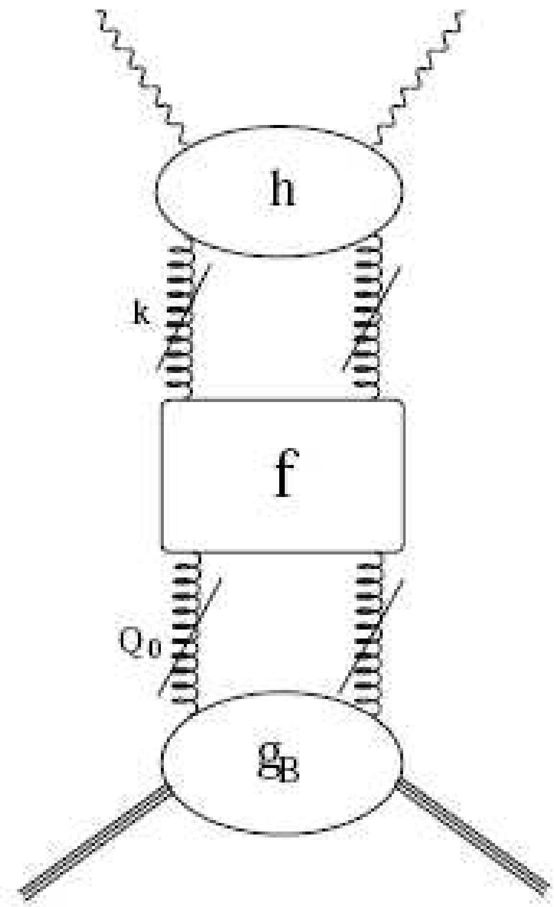
Small-x Theory

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.

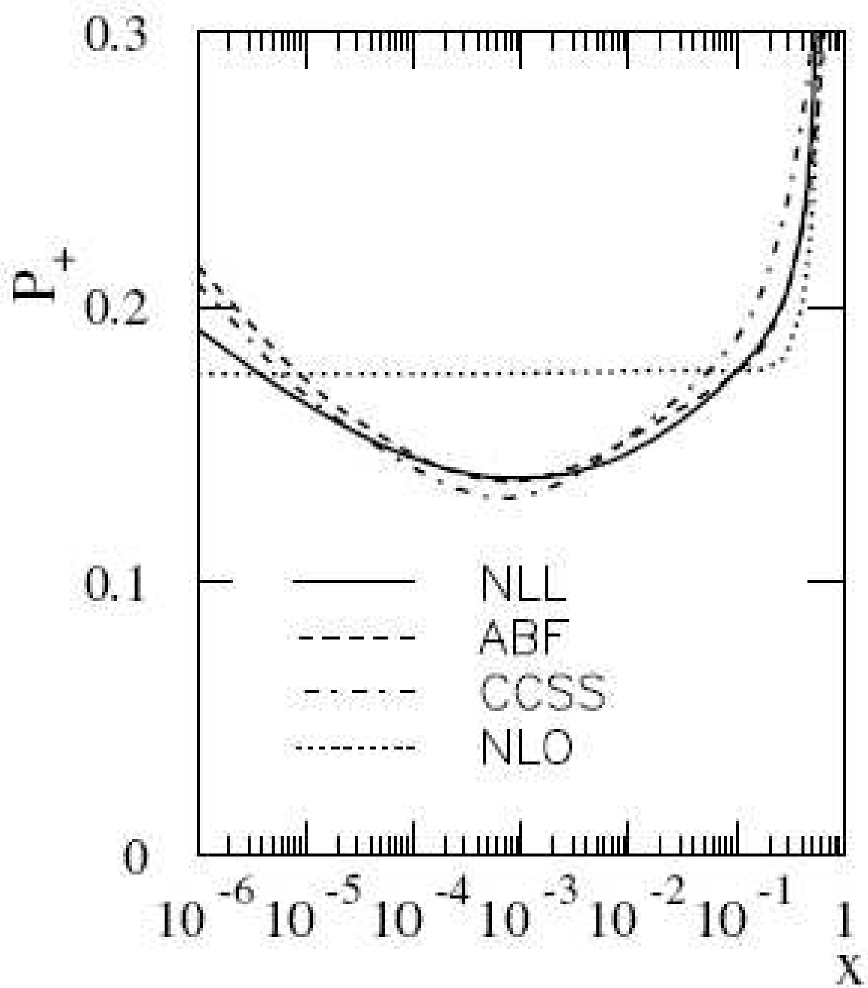
Good recent progress in incorporating $\ln(1/x)$ resummation Altarelli-Ball-Forte, Ciafaloni-Colferai-Salam-Stasto and White-RT.

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

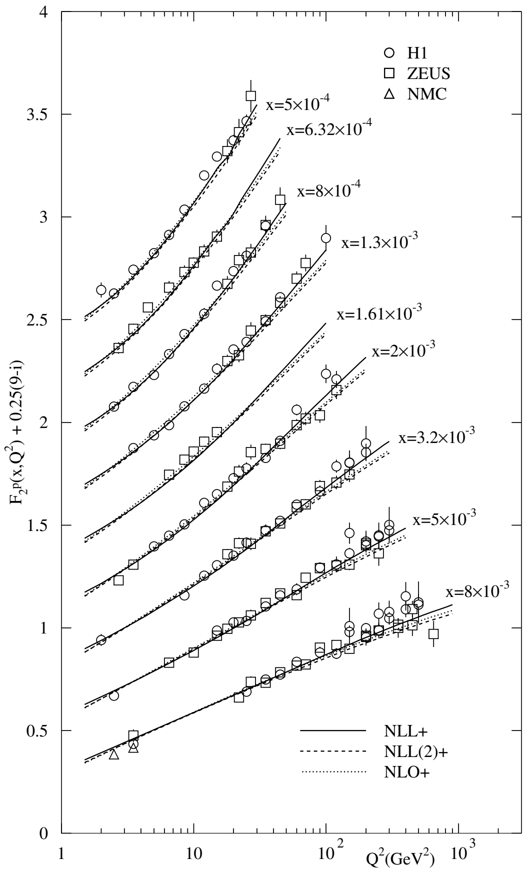
By 2008 very similar results coming from the competing procedures, despite some differences in technique.

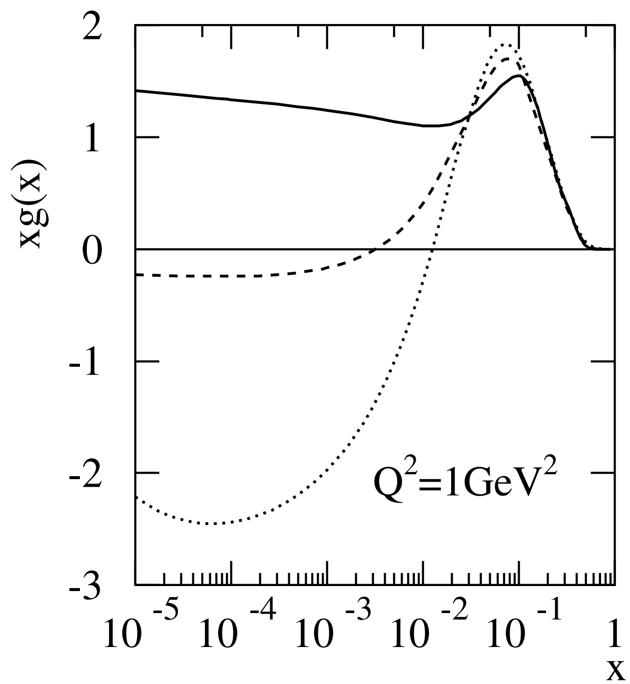
Full set of coefficient functions still to come in some cases, but splitting functions comparable.

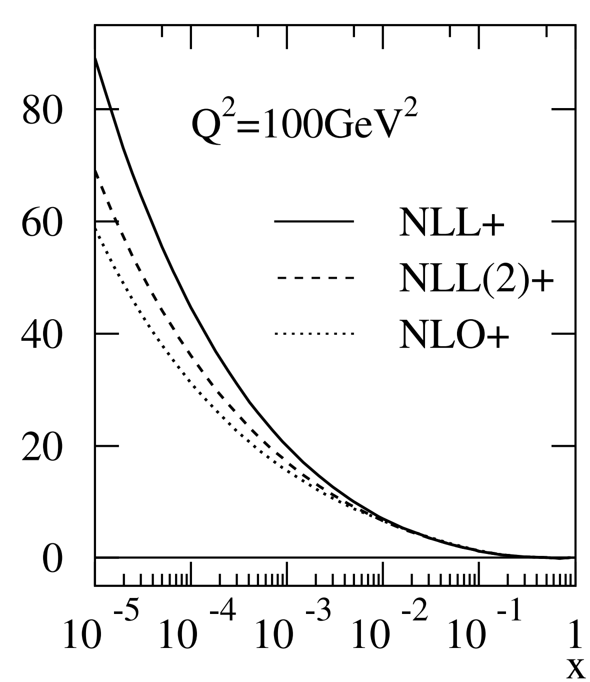
Note, in all cases NLO corrections lead to dip in functions below fixed order values until slower growth (running coupling effect) at very small x.



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





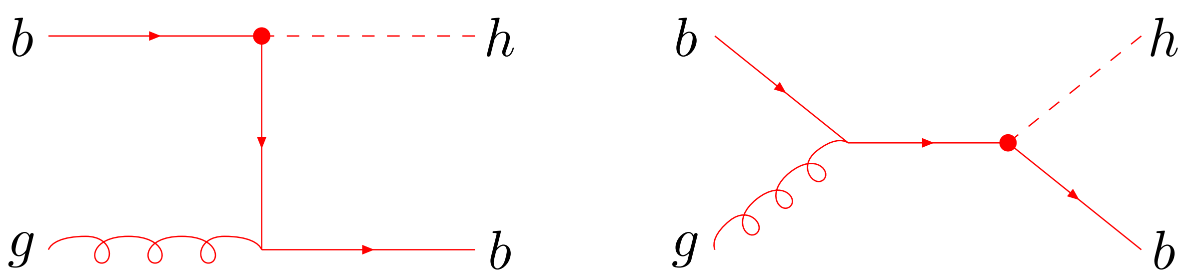


→ moderate improvement in fit to HERA data within global fit, and change in extracted gluon (more like quarks at low Q^2).

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

Final Example

Consider bottom production along with a Higgs boson.



In Standard Model tiny since Higgs-bottom coupling $g_{b\bar{b}h} = m_b/v$, (v Higgs vacuum expectation value.) $m_b = 4.5\mathrm{GeV}$, $v = 246\mathrm{GeV}$.

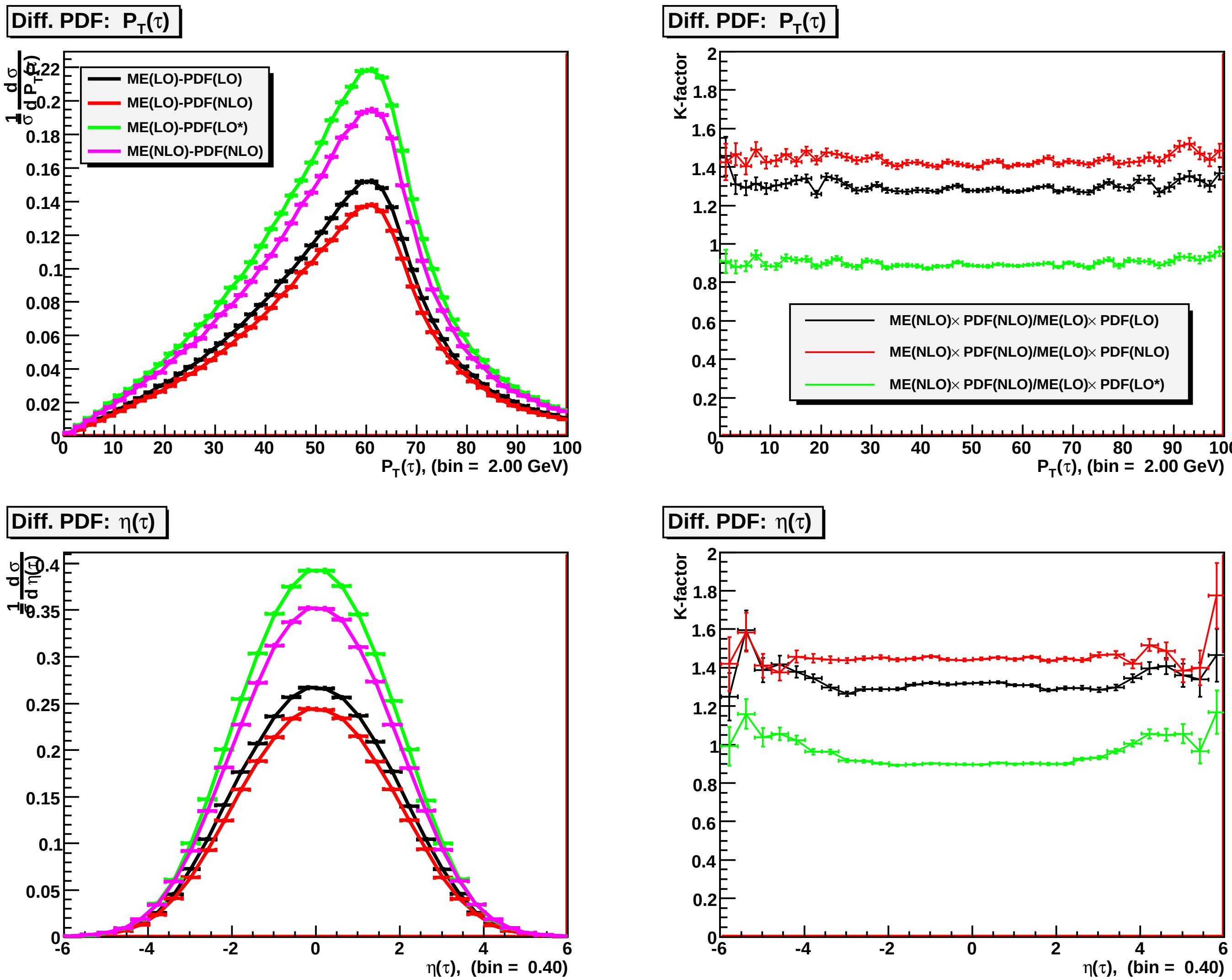
In Minimal Supersymmetric Standard Model two Higgs doublets coupling separately to d-type and u-type quarks. Expectation values v_d and v_u.

Ratio $\tan\beta = v_u/v_d \longrightarrow$ enhancement of Higgs-bottom coupling

$$g_{b\bar{b}h} \propto \frac{g^{SM}_{b\bar{b}h}}{\cos\beta}.$$

Bounds from LEP, $\tan\beta$ large $\rightarrow \cos\beta$ small. Enhancement of Higgs-bottom coupling.

Look at distributions for $b\bar{b}$ production (Shertsnev, RT).



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