Parton Distributions and MSTW updates

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Thanks to Alan Martin, James Stirling, Graeme Watt

and Arnold Mathijssen and Ben Watt

Quick Introduction –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 $s = \bar{s}$.

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

Input partons very generally parameterised as

$$xf(x, Q_0^2) = (1-x)^\eta x^\delta \tilde{f}(x)$$

Evolve partons upwards using LO, NLO or increasingly 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.

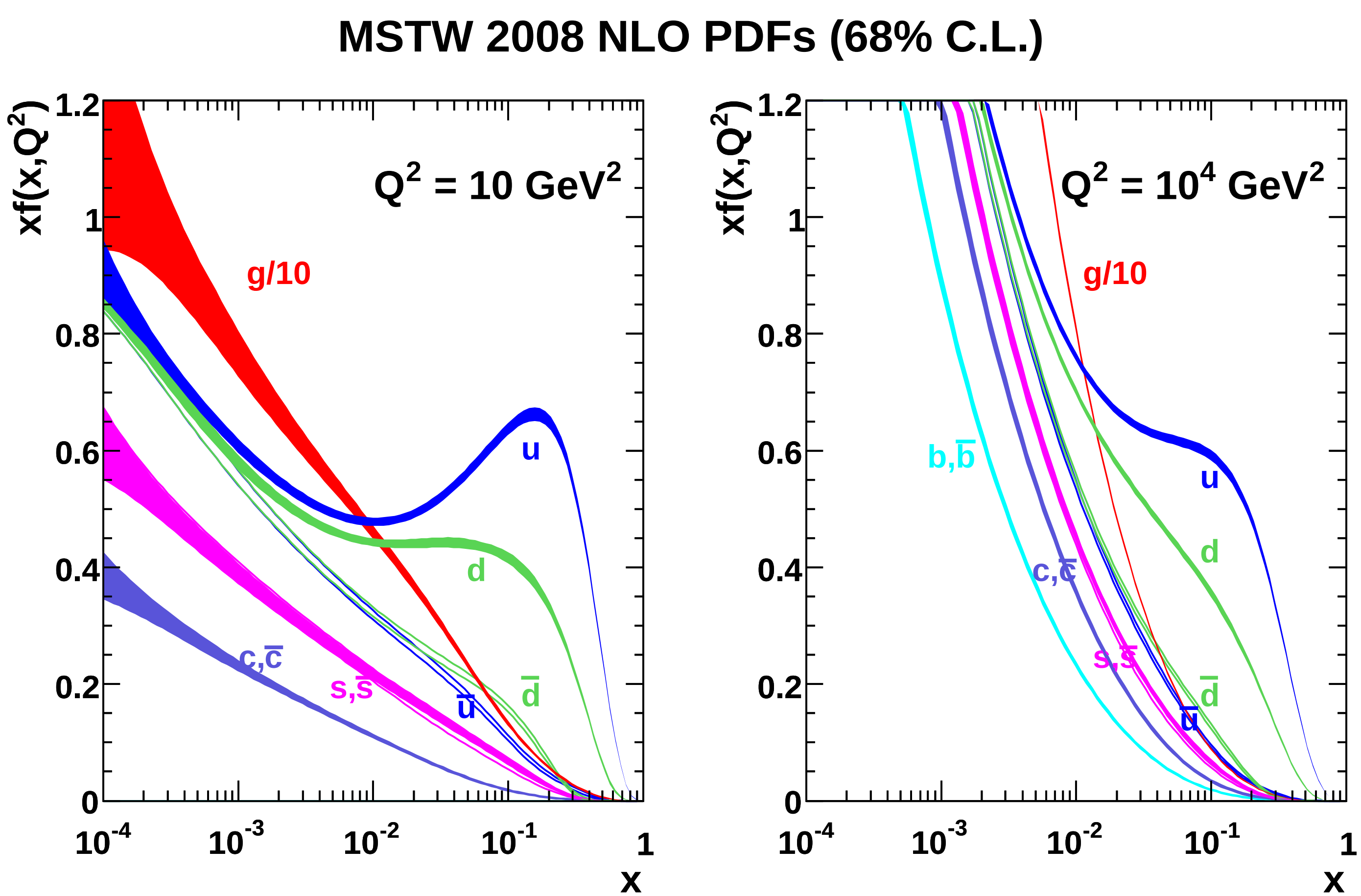
- Di-muon production in neutrino DIS – strange quarks and neutrino-antineutrino comparison $\rightarrow$ asymmetry . Only for $x > 0.01$.

- 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, LHC) – high-x gluon distribution – $x > 0.01$.

- W and Z production at colliders (Tevatron/LHC) – 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, AB(K)M, HERA, Jimenez-Delgado *et al etc.*. All LHC cross-sections rely on our understanding of these partons.

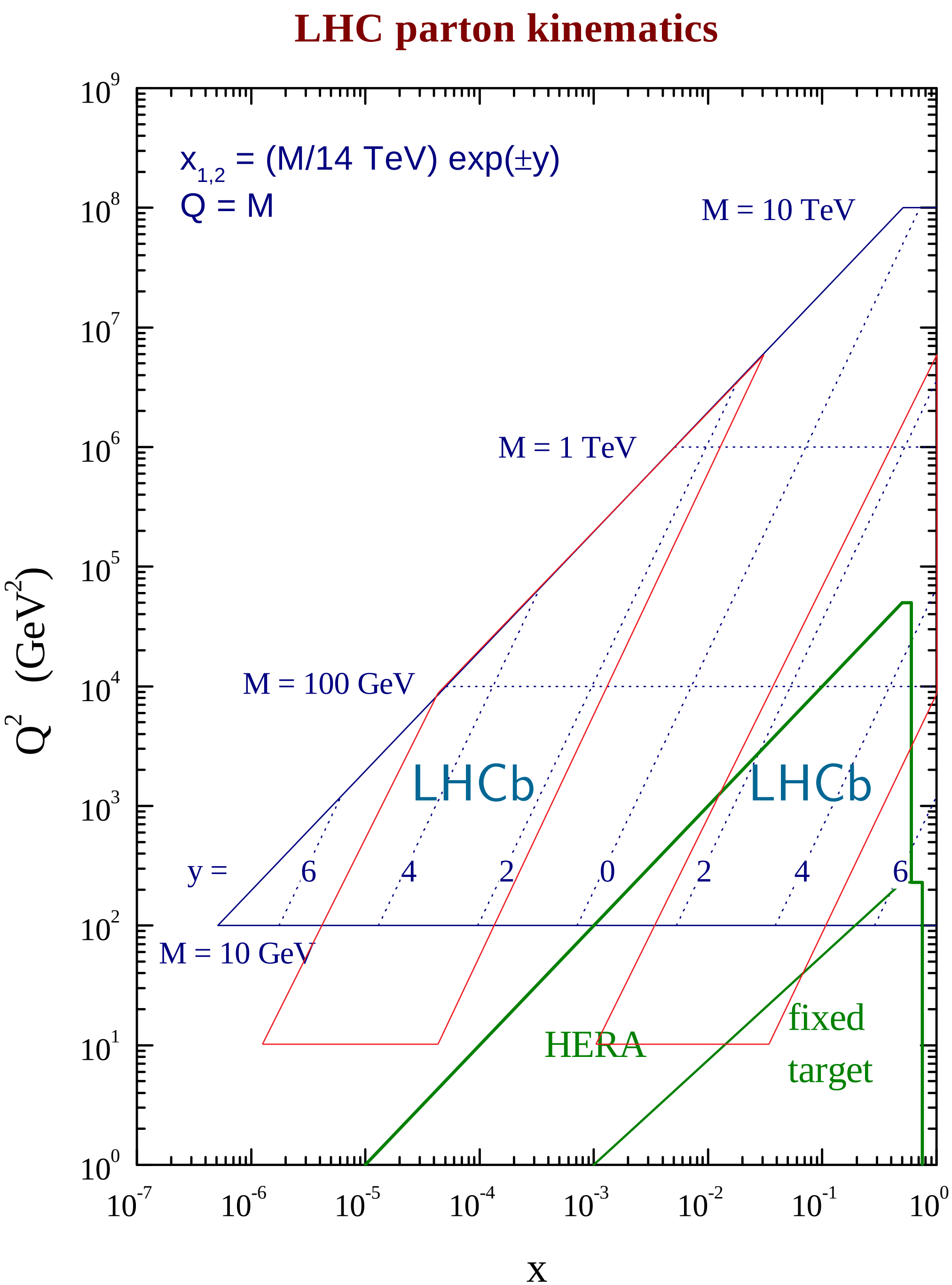
LHC **Physics**

The kinematic range for particle production at the LHC is shown.

$$x_{1,2} = x_0 \exp(\pm y), \quad x_0 = \frac{M}{\sqrt{s}}.$$

Smallish $x \sim 0.001 - 0.01$ parton distributions therefore vital for understanding the standard production processes at the LHC.

However, even smaller (and higher) x required when one moves away from zero rapidity, e.g. when calculating total cross-sections.

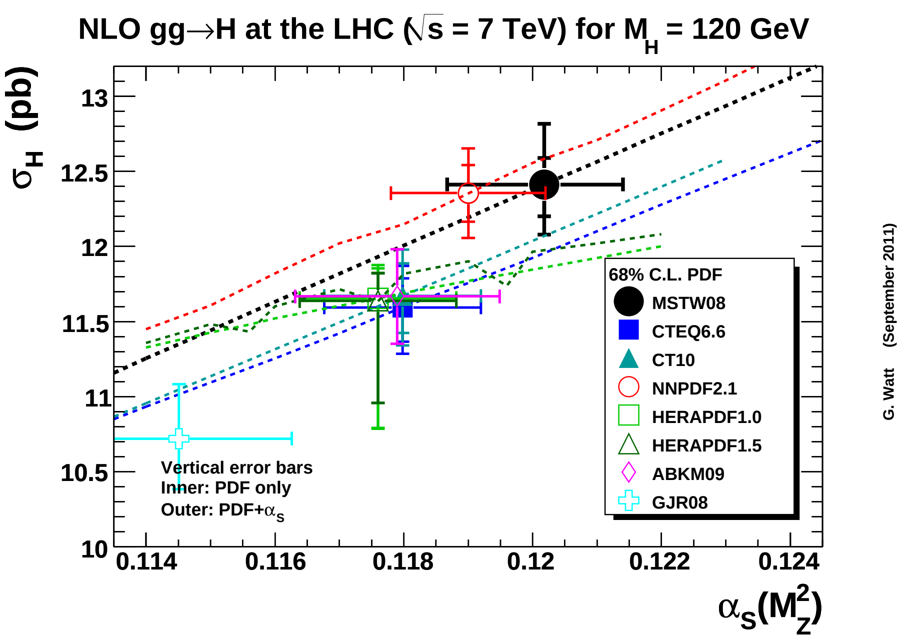


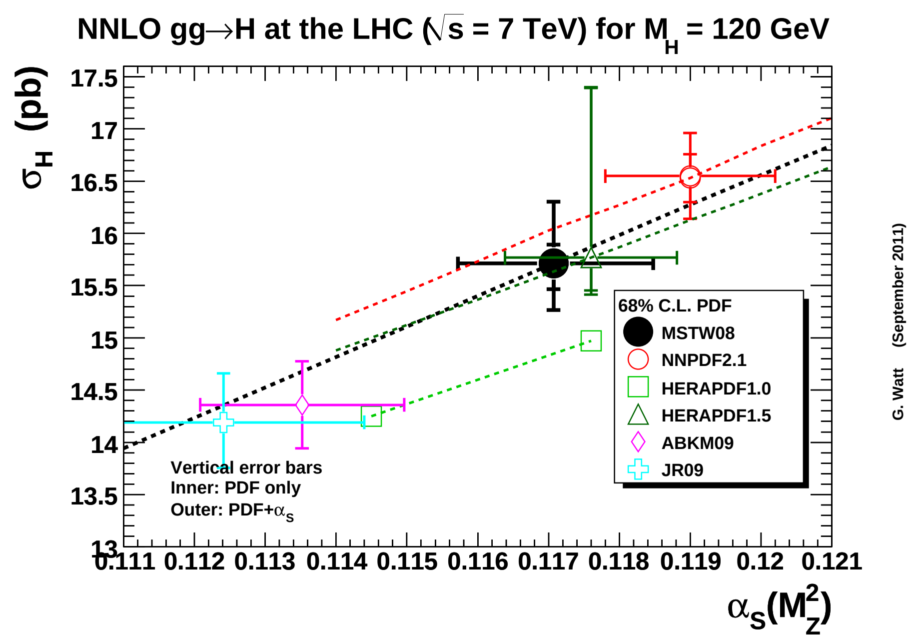
Different PDF sets.

- 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.
- CT10 PDFs at NLO. CT10 include HERA combination and more Tevatron data though also run I jet data. Not large changes from CTEQ6.6. CT10W gives higher weight to Tevatron asymmetry data. NNLO provisionally available.
- NNPDF2.3 – include all except HERA jet data (not strong constraint). NNPDF2.1 improves on NNPDF2.0 by better heavy flavour treatment. PDFs at NLO and recently NNLO and LO. Some LHC data included.
- HERAPDF1.5 – based on HERA I inclusive structure functions, neutral and charged current. Use combined data. PDFs at NLO and NNLO. Use some not yet published HERA II data.
- ABKM11 – fit to DIS and fixed target Drell-Yan data. PDFs at NLO and NNLO. Less conservative cuts at low W^2 than other groups – fit for higher twist corrections rather than attempt to avoid them.
- GJR08 – fit to DIS, fixed target Drell-Yan and Tevatron jet data (not at NNLO). PDFs at NLO and NNLO.

Variations in Higgs Cross-Section Predictions

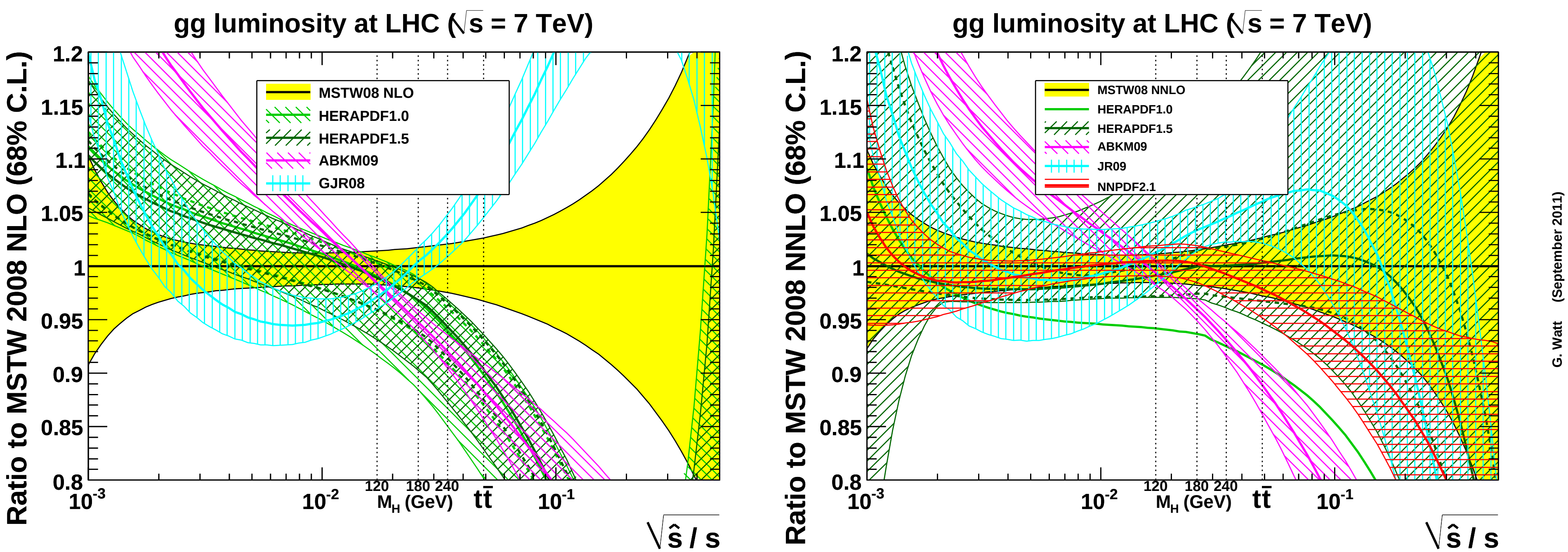
Dependent on gluon distributions.





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

Explained by parton luminosity differences.



Plots by Watt - Ringberg 2011. Luminosity differences for gluons largely the same at NNLO as at NLO, except for HERAPDF1.5 at large x.

Differences between different sets not likely to be due to theory choices which would diminish at higher orders, or approx. at NNLO which would change relative NLO and NNLO differences.

$\alpha_S(M_Z^2)$ at NLO and at NNLO

Also differences due to $\alpha_S(M_Z^2)$ values.

Note, converging on general agreement that the NNLO values of α_S are $0.0002-0.0003$ smaller than the NLO values of α_S.

MSTW08 – $\alpha_S(M_Z^2) = 0.1202 \rightarrow 0.1171$.

ABM11 – $\alpha_S(M_Z^2) = 0.1180 \rightarrow 0.1134$.

GJR/JR – $\alpha_S(M_Z^2) = 0.1145 \rightarrow 0.1124$.

NNPDF2.1 – $\alpha_S(M_Z^2) = 0.1191 \rightarrow 0.1173$.

CT10.1 – $\alpha_S(M_Z^2) = 0.1196 \rightarrow 0.1180$.

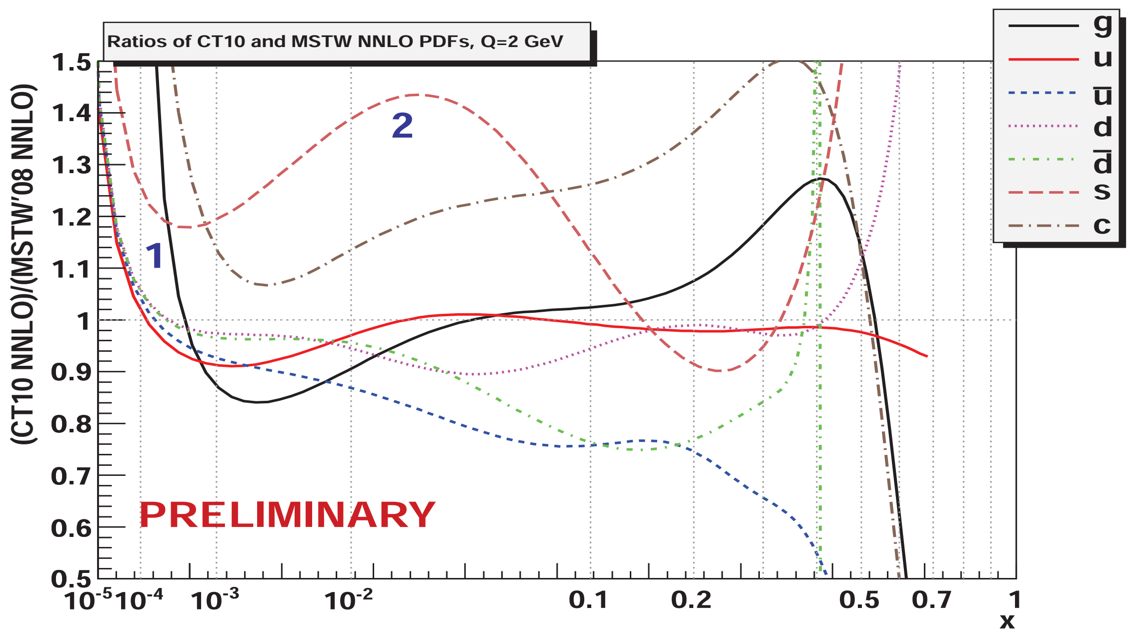
HERAPDF1.6 – $\alpha_S(M_Z^2) = 0.1202$ at NLO and general preference for ~ 0.1176 at NNLO.

Central values differ far more than NLO $\rightarrow$ NNLO trend.

Update for CT10.

CT10 at NNLO now available on group website. Publication imminent.

CT10 NNLO PDFs compared to MSTW NNLO



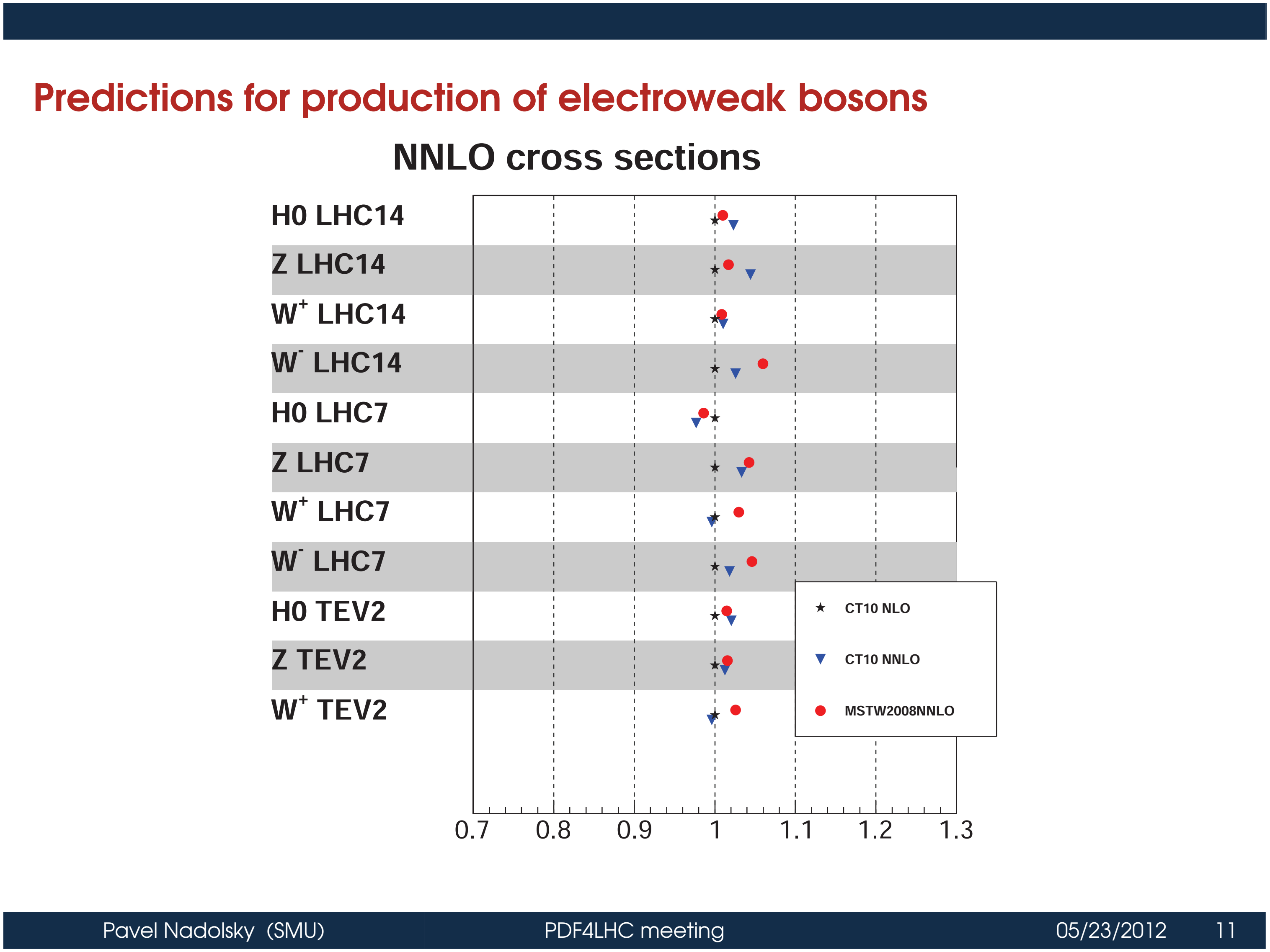
1. CT10 gluon and quarks are harder at $x \to 0$; $g(x, Q_0) > 0$ at $10^{-5} \le x \le 1$

2. The CT10 strange PDF is larger at $x \sim 10^{-3}$

Pavel Nadolsky (SMU) PDF4LHC meeting 05/23/2012 10

Some systematic differences to MSTW. Similar to at NLO

Predictions very similar



Except some difference on flavour separation (present at NLO).

Recent MSTW progress - Variety of topics - related in various ways.

- Results from Monte Carlo approach using MSTW PDFs arXiv:1205.4024.
- Comparison of MSTW PDFs with LHC data and implications.
- Study of strange quark in MSTW2008 fits and source of constraint.
- Investigation of parameterisation extension dependence. Related to deuterium corrections. Implication for LHC data.

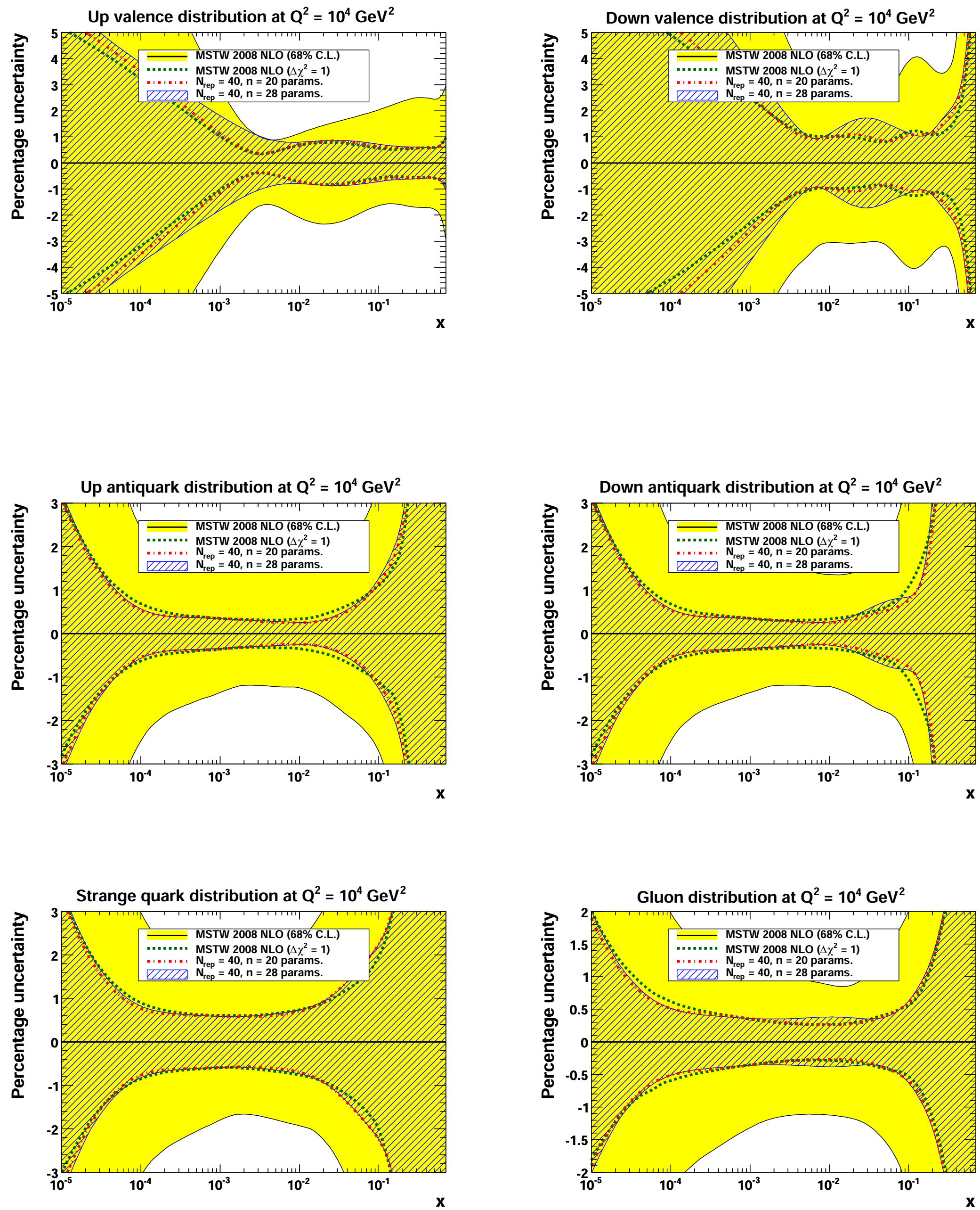
Monte Carlo Approach. (Graeme Watt + RT arXiv:1205.4024)

Generate replica data sets with central values shifted according to size of errors. Similar to NNPDF. Fit using standard technique.

Confirms same result as Hessian approach using $\Delta\chi^2 = 1$ (see previous HERA study).

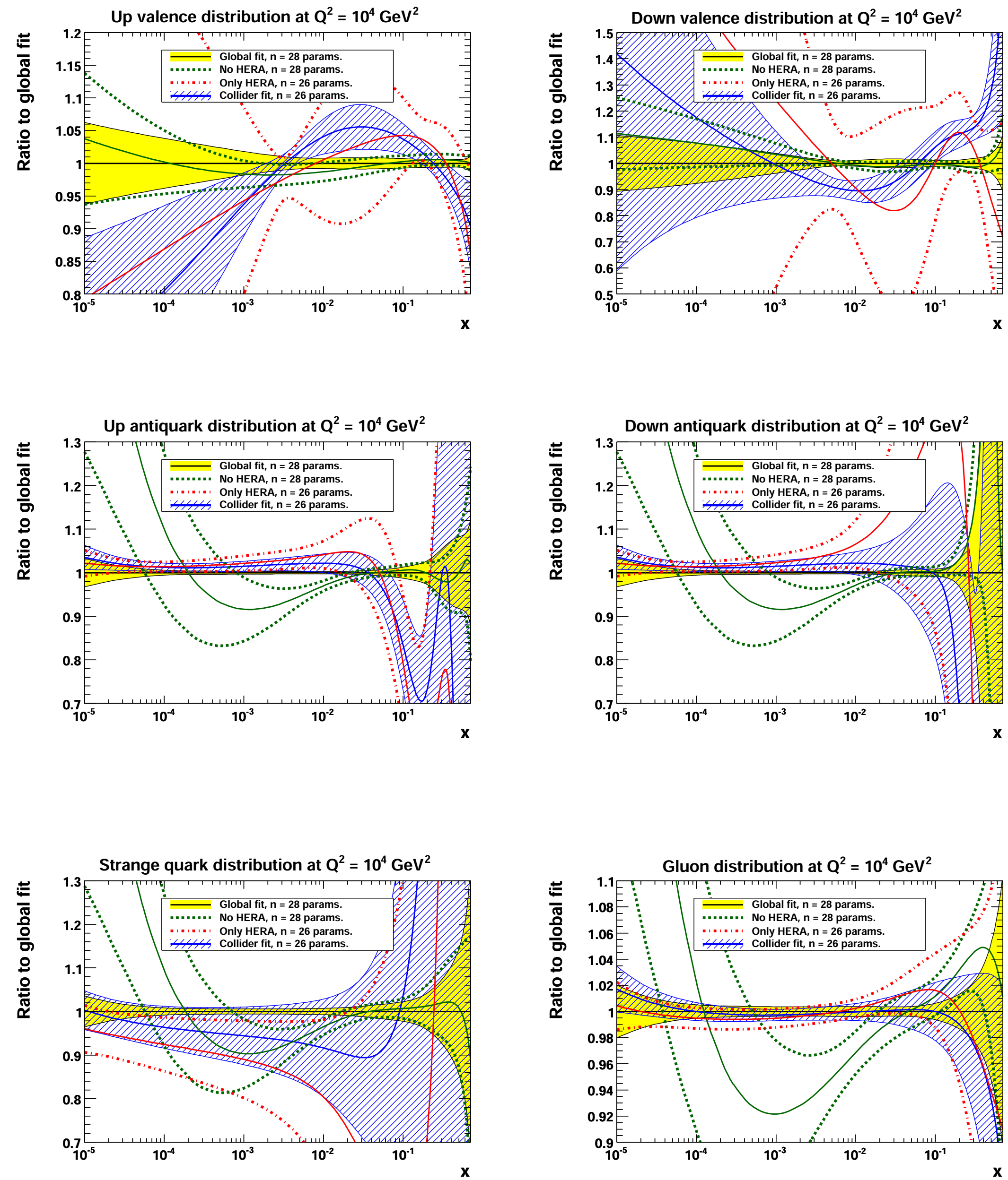
Can vary all 28 parameters rather than just 20 in eigenvectors.

Affects valence quarks at small ($x < 0.01$) mainly.



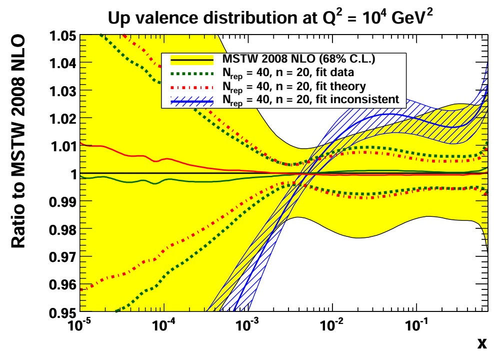
Fit to subsets of data.

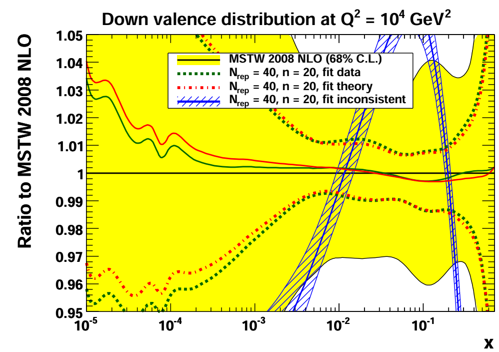
PDFs move by considerably more than $\Delta\chi^2 = 1$ uncertainties in many places.

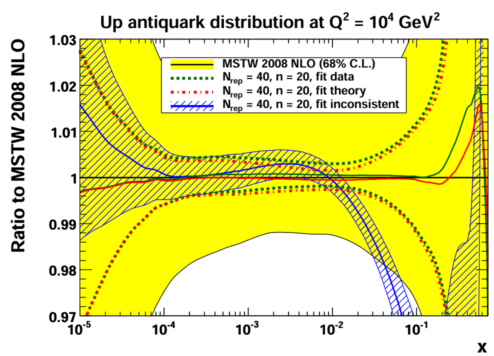


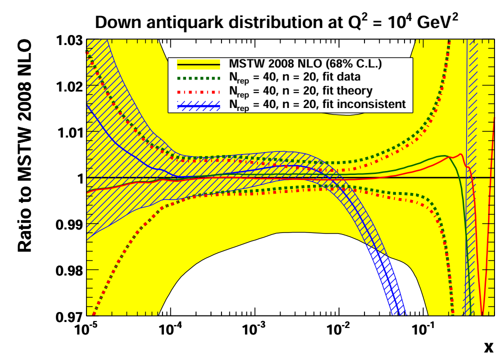
Can construct pseudodata from theory predictions and make "consistent" and "inconsistent" sets.

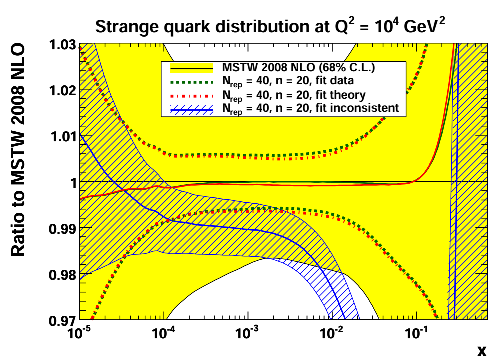
Fit to "inconsistent" sets same uncertainty as "consistent" sets and $\chi^2/N \sim 1$, but PDFs move many $\Delta\chi^2 = 1$ uncertainties.

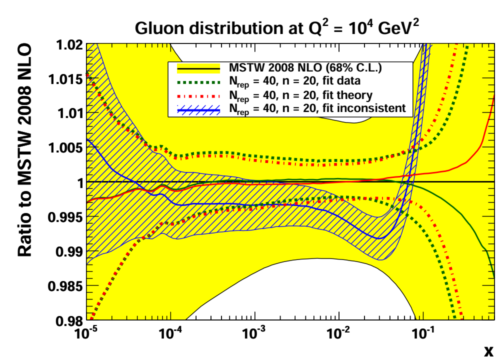




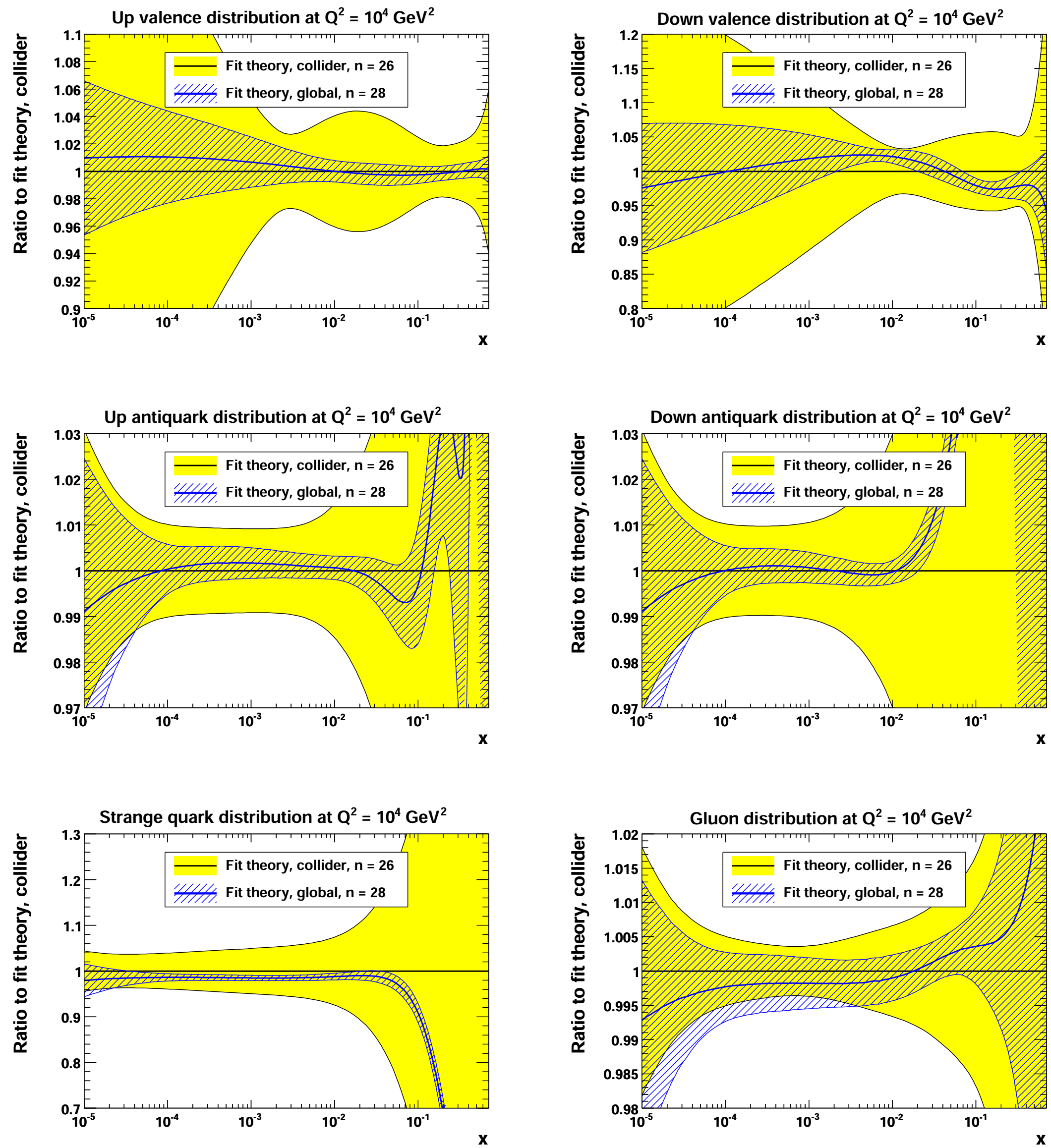




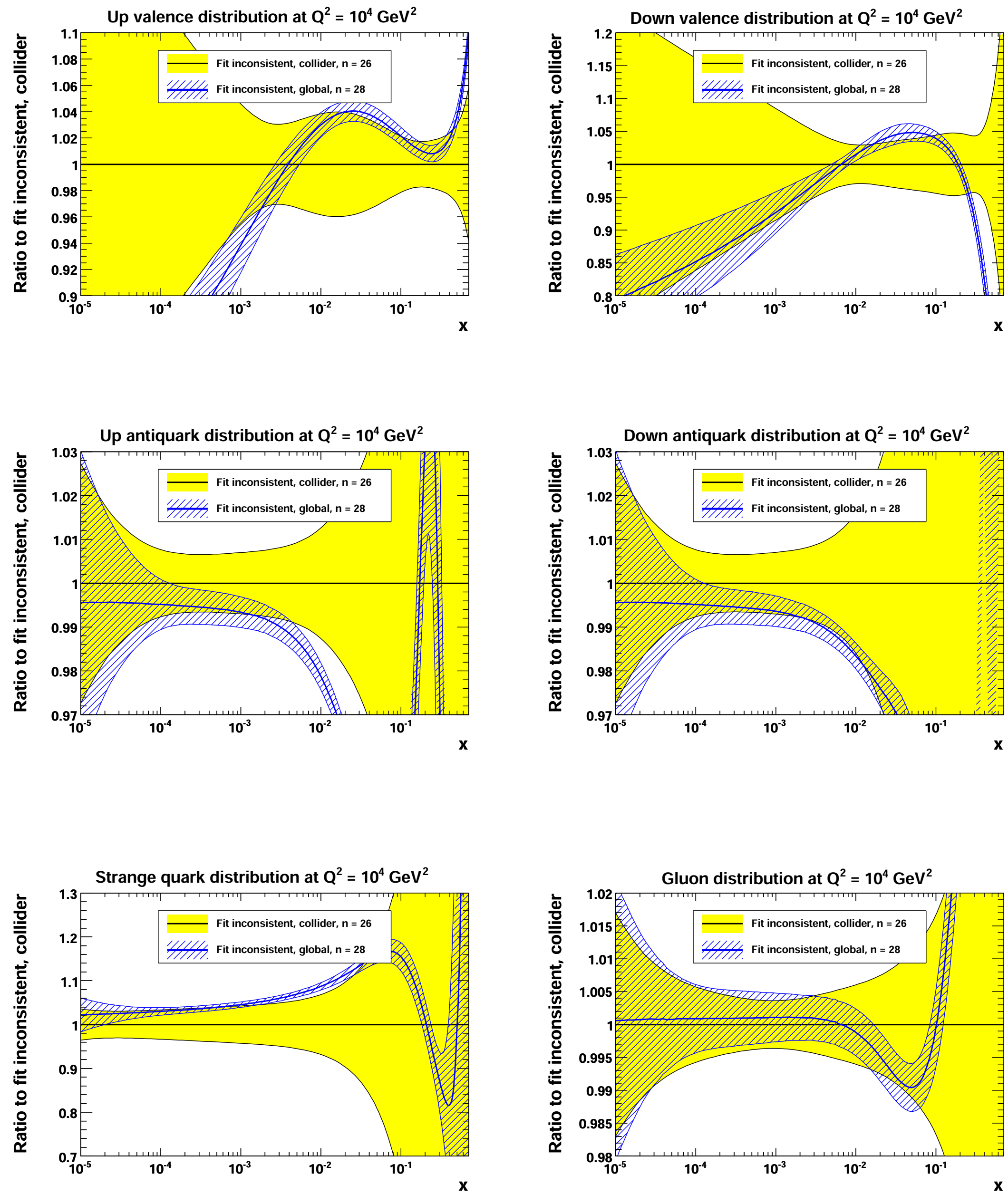




Change fit from “Collider only” to full set for “consistent” set. PDFs consistent but uncertainties much reduced.



For "inconsistent" pseudodata uncertainties reduce in same way but central values move far more than $\Delta\chi^2 = 1$ uncertainty.



Like real situation.

Maintain correctness of "dynamic tolerance" approach. Easiest in Hessian study with eigenvectors.

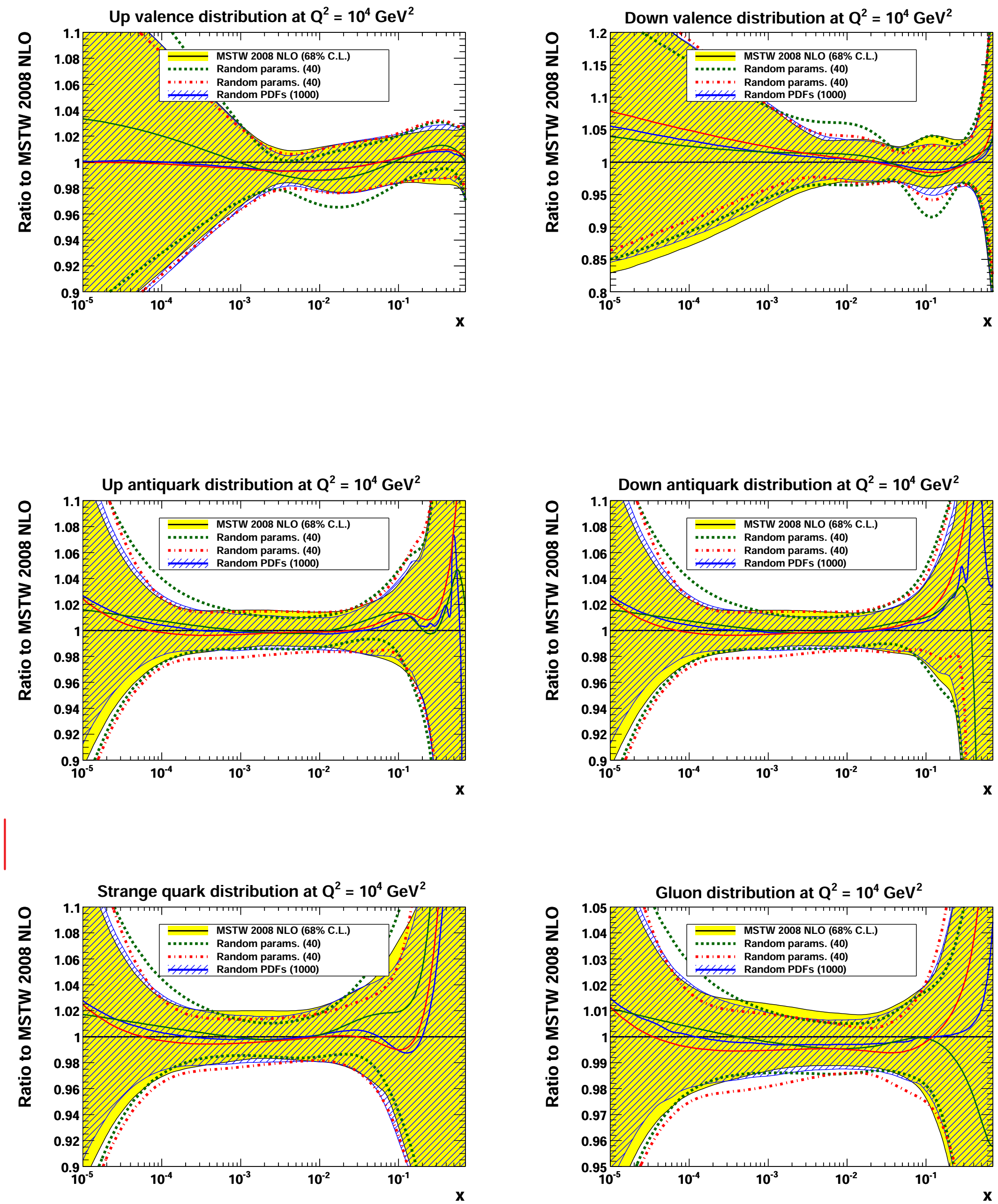
However, can generate "random" PDF sets directly from parameters and variation from eigenvectors.

$$a_i(\mathcal{S}_k) = a_i^0 + \sum_{j=1}^{n} e_{ij}\left(\pm t_j^{\pm}\right)|R_{jk}|$$

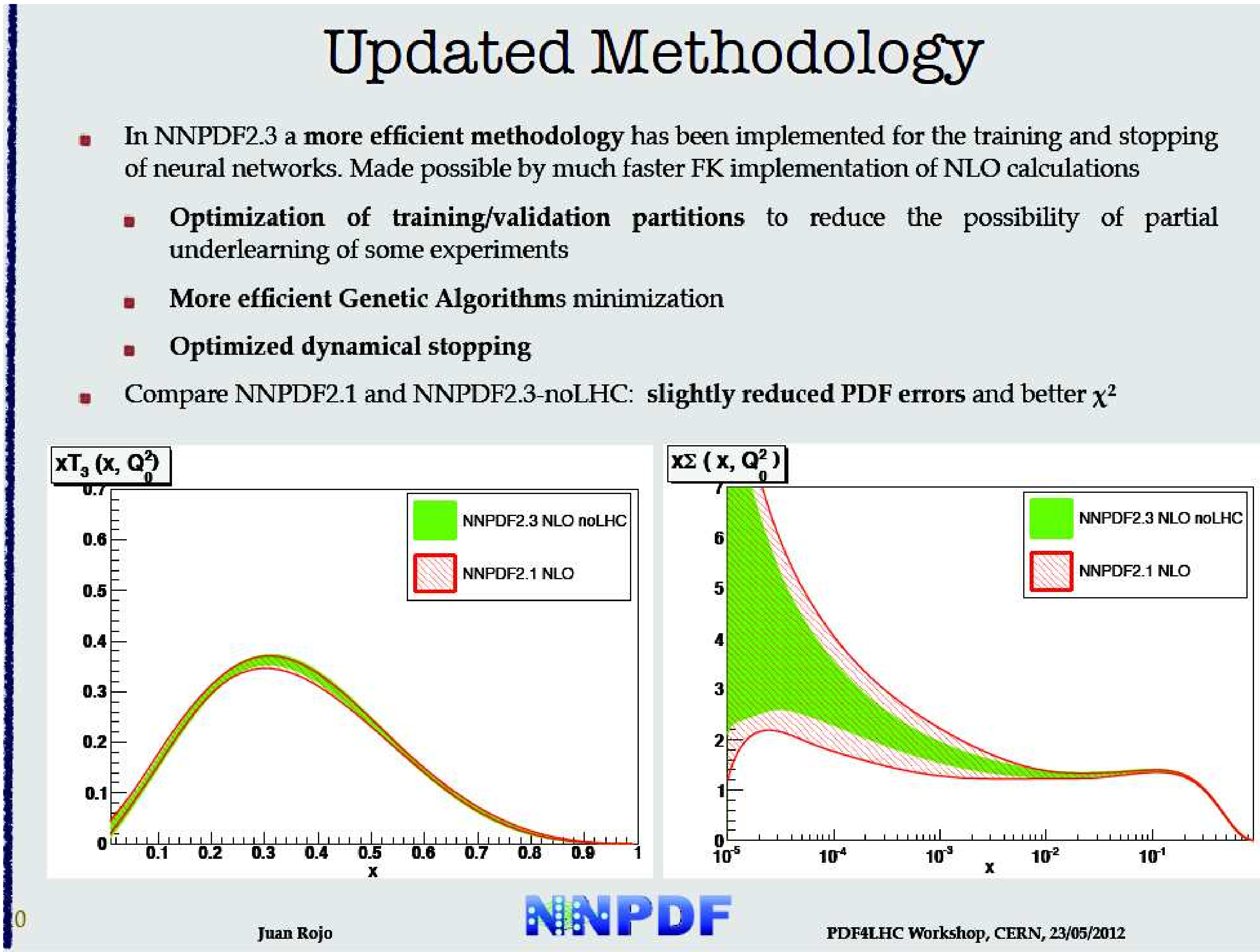
$(k = 1, \ldots, N_{\mathrm{pdf}})$. Or from eigenvectors directly (see LHCb study and De Lorenzi thesis). Far quicker.

$$F(\mathcal{S}_k) = F(S_0) + \sum_j \left[F(S_j^{\pm}) - F(S_0)\right]|R_{jk}|$$

Use in reweighting studies as NNPDF.



NNPDF2.2 replaced by NNPDF2.3. Include LHC data but methodology change affects uncertainty a little.



MSTW Comparison to LHC data.

Start with ATLAS jets. Use APPLGrid or FastNLO at NLO (Ben Watt) and correlated errors treated as multiplicative, as suggested.

Table 1: χ^2 per point (90 points)

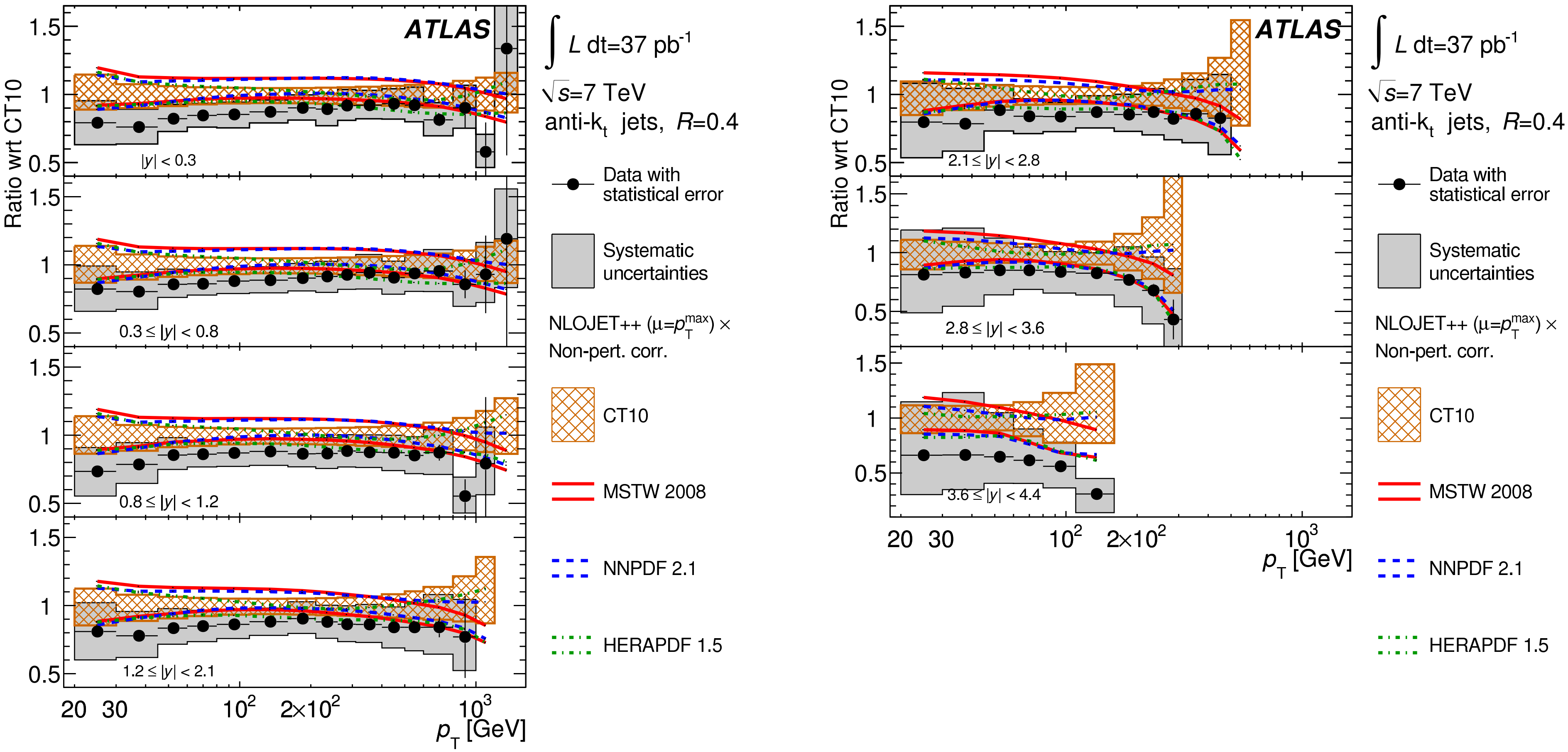
Scale	pT/2	pT	2pT
Inclusive (R=0.4)	0.580	0.548	0.522
Inclusive (R=0.6)	0.630	0.584	0.587
Dijet (R=0.4)	3.76	1.67	1.57
Dijet (R=0.6)	2.91	1.96	1.76

Table 2: Distribution of r_ks (Total 88)

	$\lvert r_k\rvert < 1$	$1 < \lvert r_k\rvert < 2$	$2 < \lvert r_k\rvert < 3$	$3 < \lvert r_k\rvert < 4$
Inclusive (R=0.4)	74	13	1	0
Inclusive (R=0.6)	71	16	1	0
Dijet (R=0.4)	61	25	2	0
Dijet (R=0.6)	55	25	8	0

MSTW fit very good, though numbers lower for inclusive data. Always close to, if not best, particularly for $R = 0.6$. Not huge variation in PDFs though.

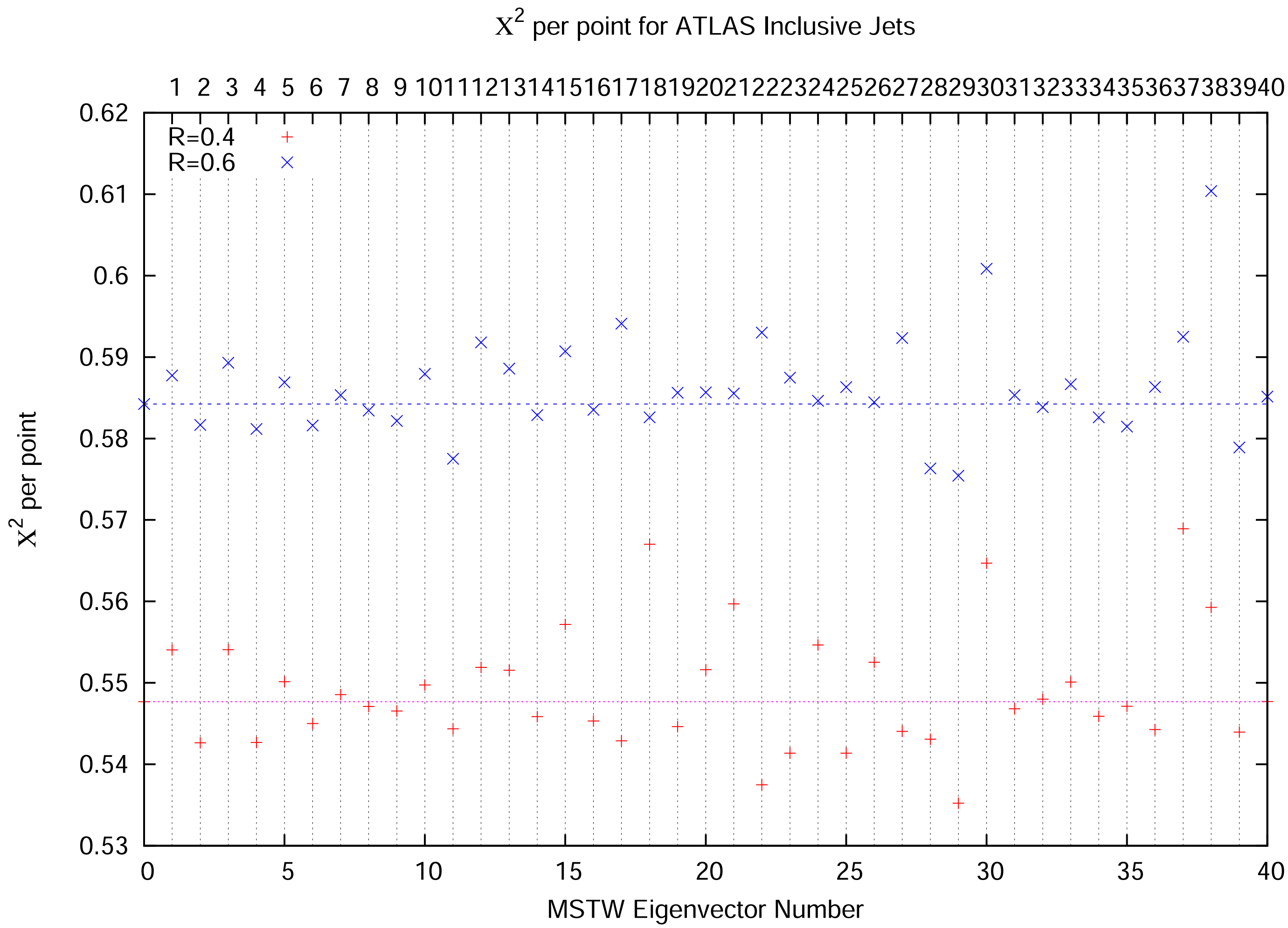
χ^2 per point about $0.7 - 0.8$ lower when multiplicative rather than additive (except $R = 0.6$ dijets) since data scales up relative to theory.



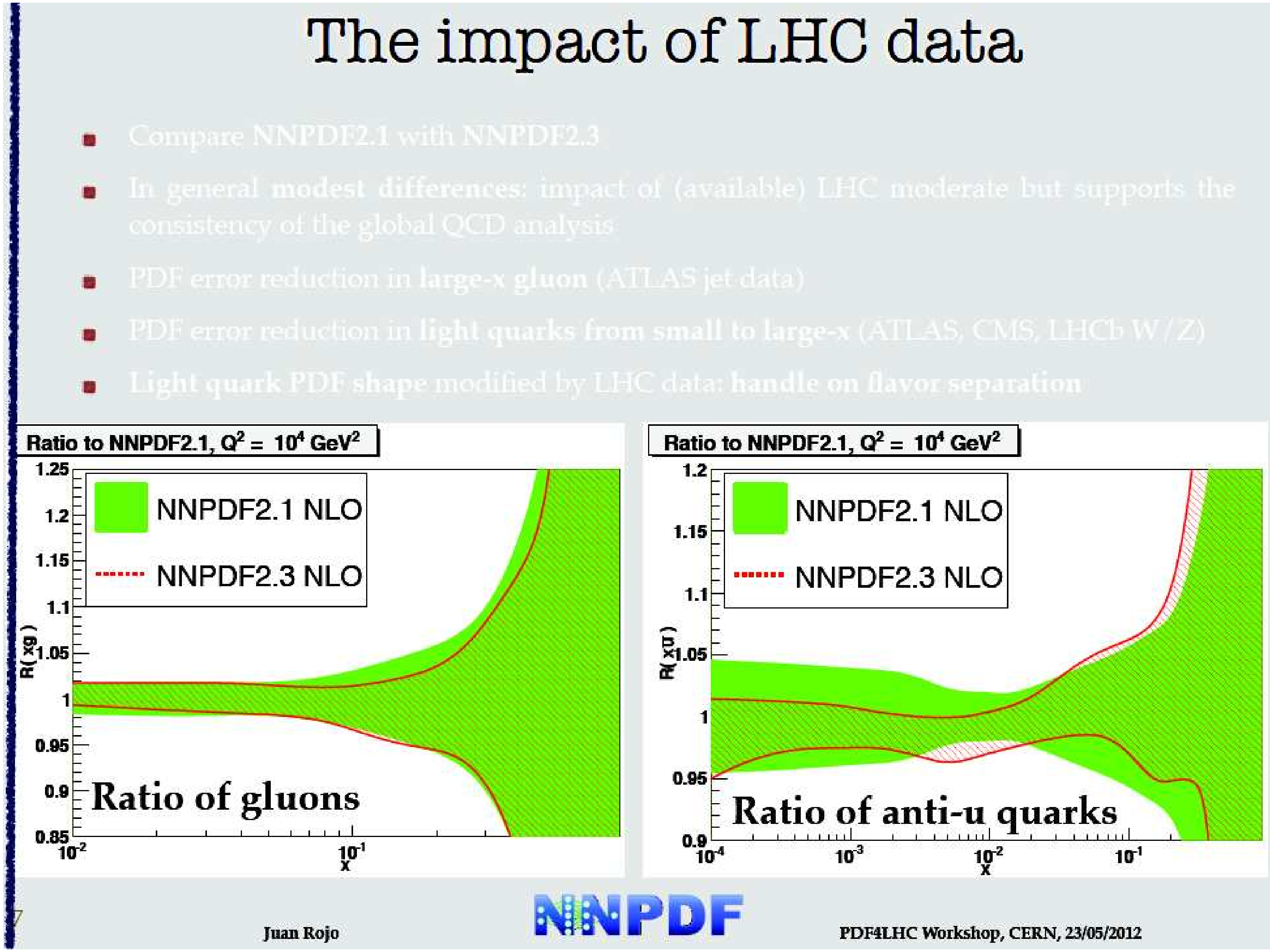
ATLAS
$\int L\,dt$=37 pb^{-1}
$\sqrt{s}$=7 TeV
anti-k$_t$ jets, R=0.4
Data with statistical error
Systematic uncertainties
NLOJET++ ($\mu=p_T^{max}$) × Non-pert. corr.
CT10
MSTW 2008
NNPDF 2.1
HERAPDF 1.5
Ratio wrt CT10
|y| < 0.3
0.3 ≤ |y| < 0.8
0.8 ≤ |y| < 1.2
1.2 ≤ |y| < 2.1
2.1 ≤ |y| < 2.8
2.8 ≤ |y| < 3.6
3.6 ≤ |y| < 4.4
p_T [GeV]

Can see how fit varies across eigenvectors.

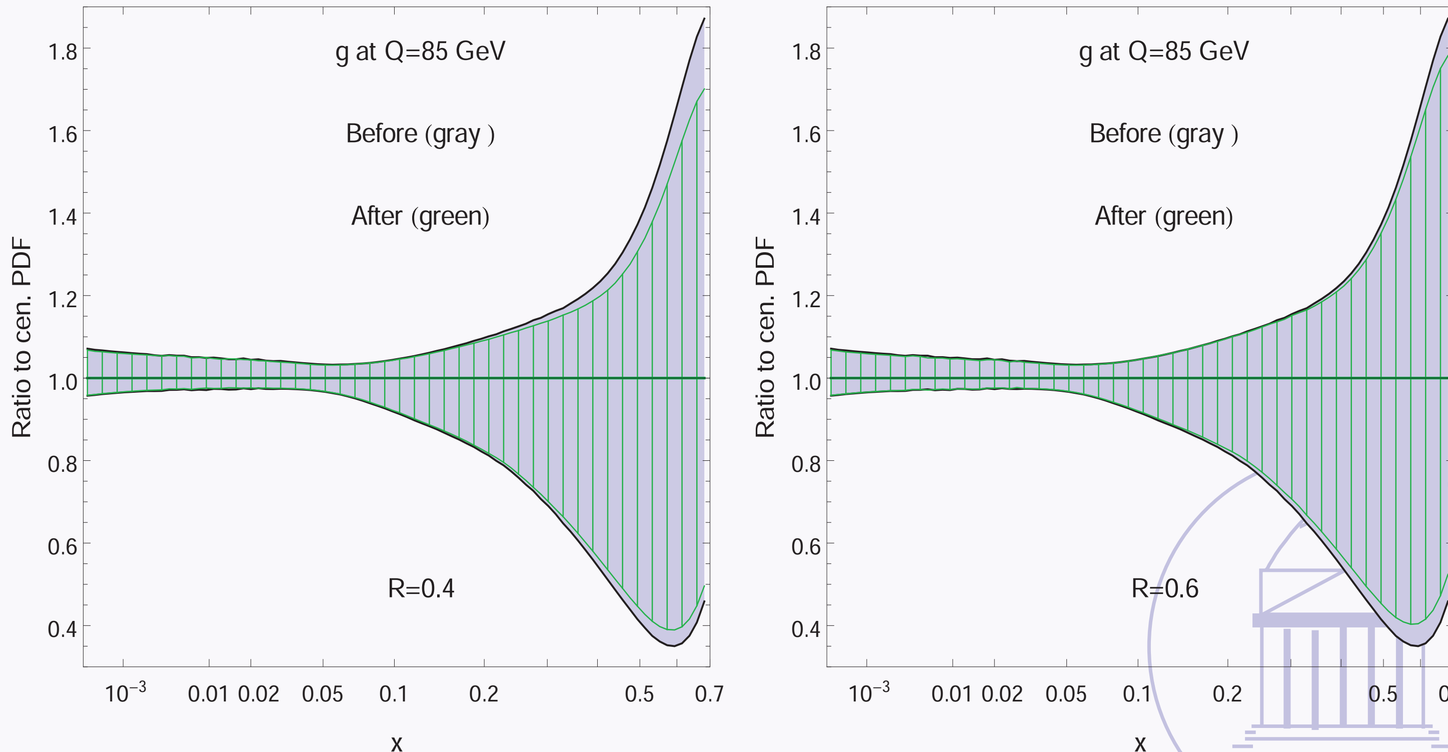
Clearly no pull with present data. (Eigenvector χ^2 variation lower than PDF variation.) Same conclusion with dijets.



Constraints from data - Jets.

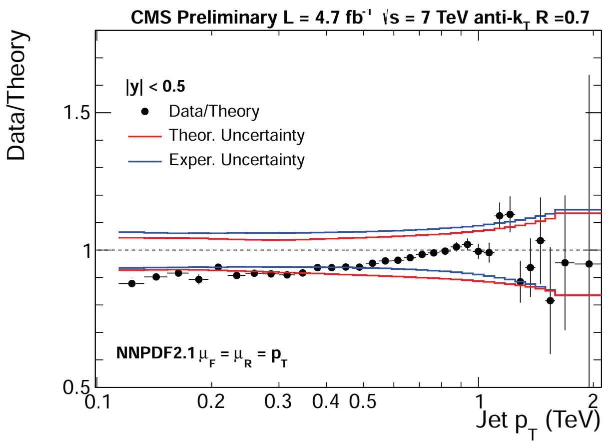


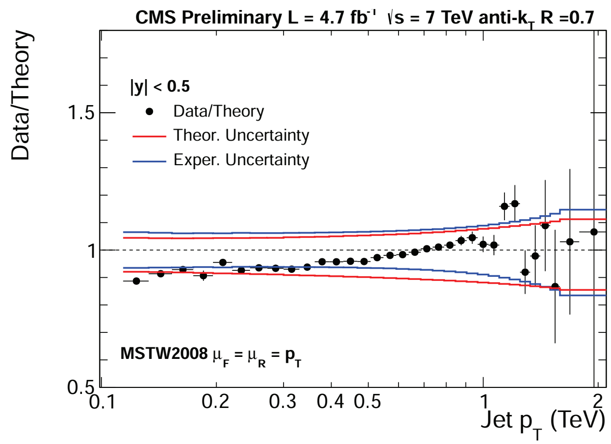
- CT10 NNLO fits before and after including the 2010 ATLAS jet data: no significant improvement in the error band (left: R=0.4, right: R=0.6).

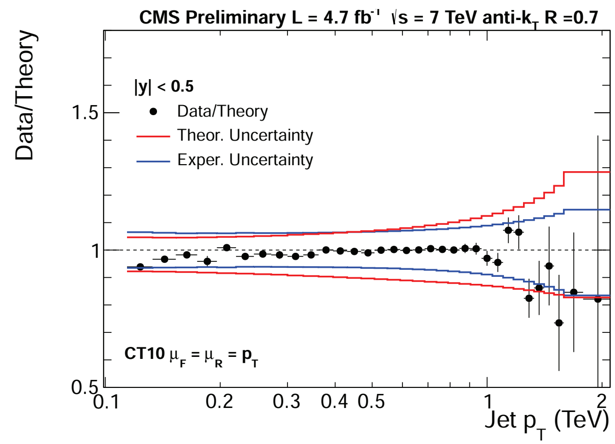


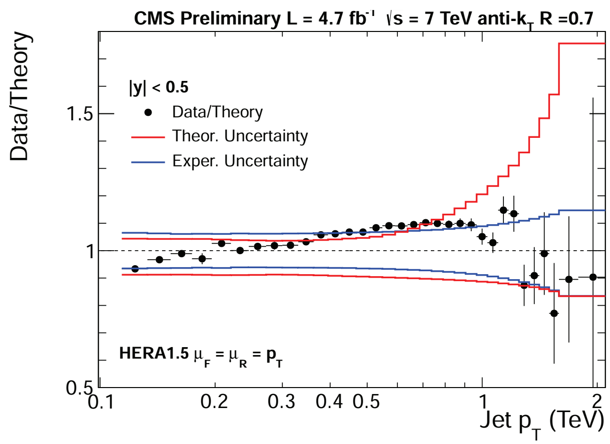
90% C.L. PDF uncertainties normalized to the central PDF

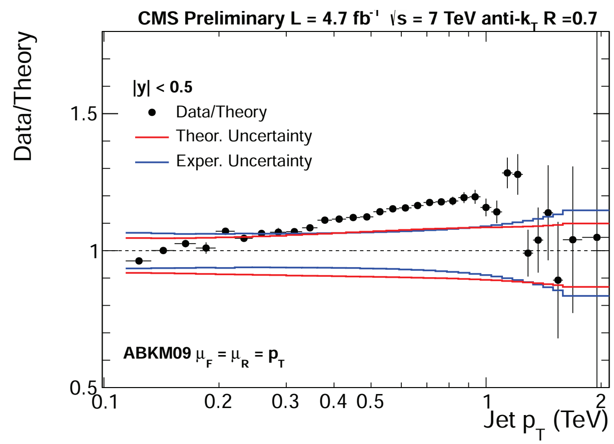
Will be interesting to see results from higher luminosity data. Looks more constraining.

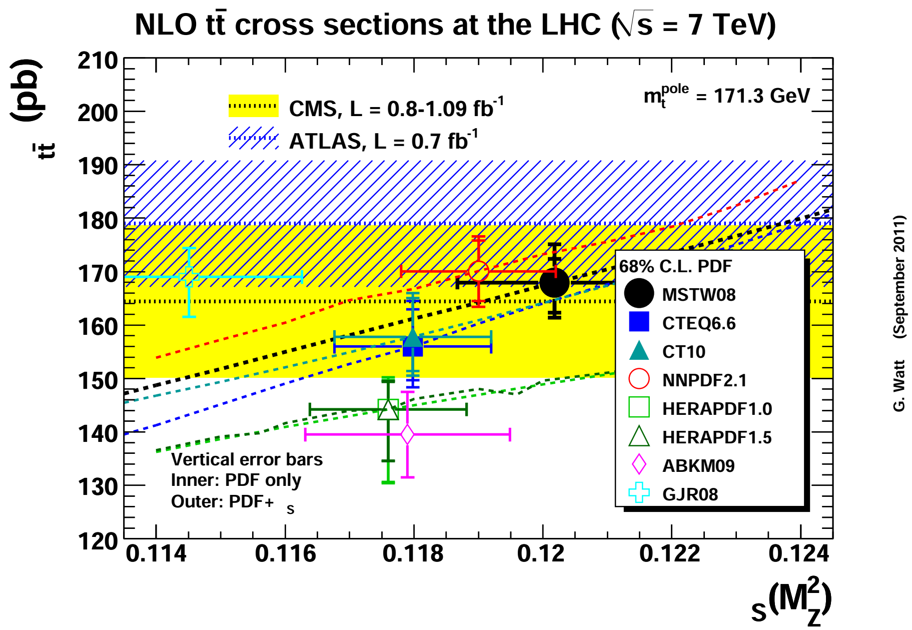


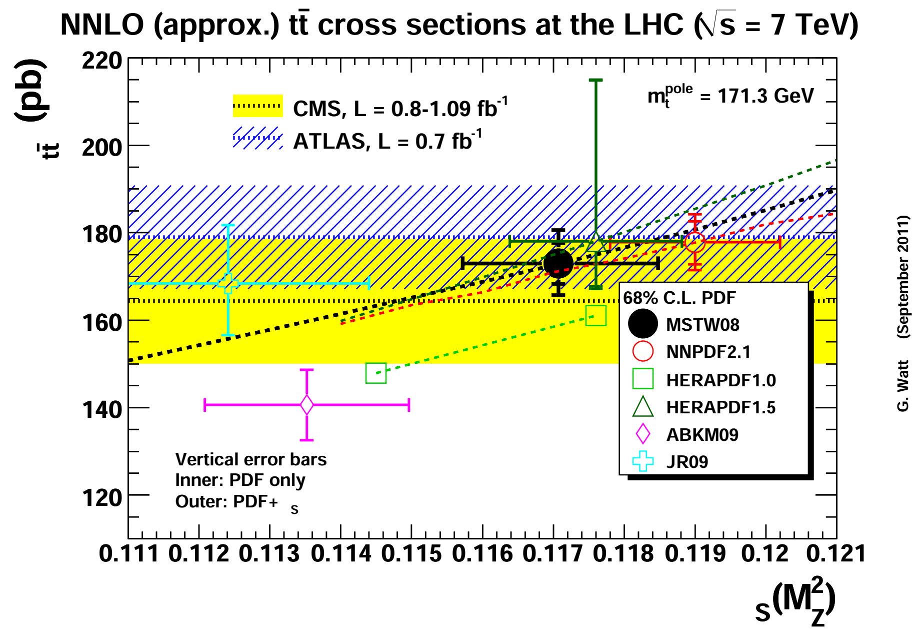









NLO tt̄ cross sections at the LHC (√s = 7 TeV)
tt̄ (pb)
CMS, L = 0.8-1.09 fb-1
ATLAS, L = 0.7 fb-1
m_t^pole = 171.3 GeV
68% C.L. PDF
MSTW08
CTEQ6.6
CT10
NNPDF2.1
HERAPDF1.0
HERAPDF1.5
ABKM09
GJR08
Vertical error bars
Inner: PDF only
Outer: PDF+ s
s(M_Z^2)
G. Watt (September 2011)


NNLO (approx.) tt̄ cross sections at the LHC (√s = 7 TeV)
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JR09
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Inner: PDF only
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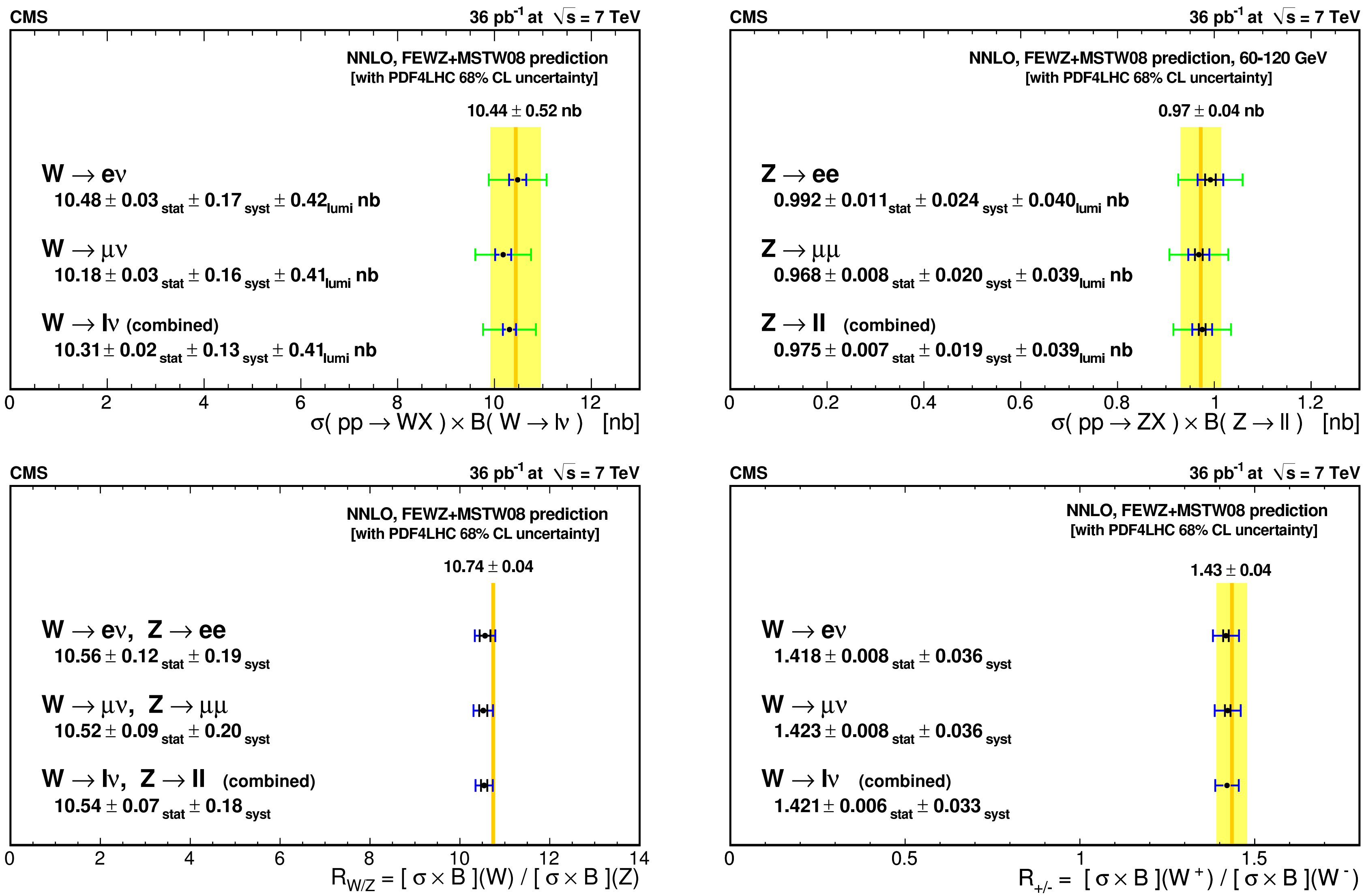
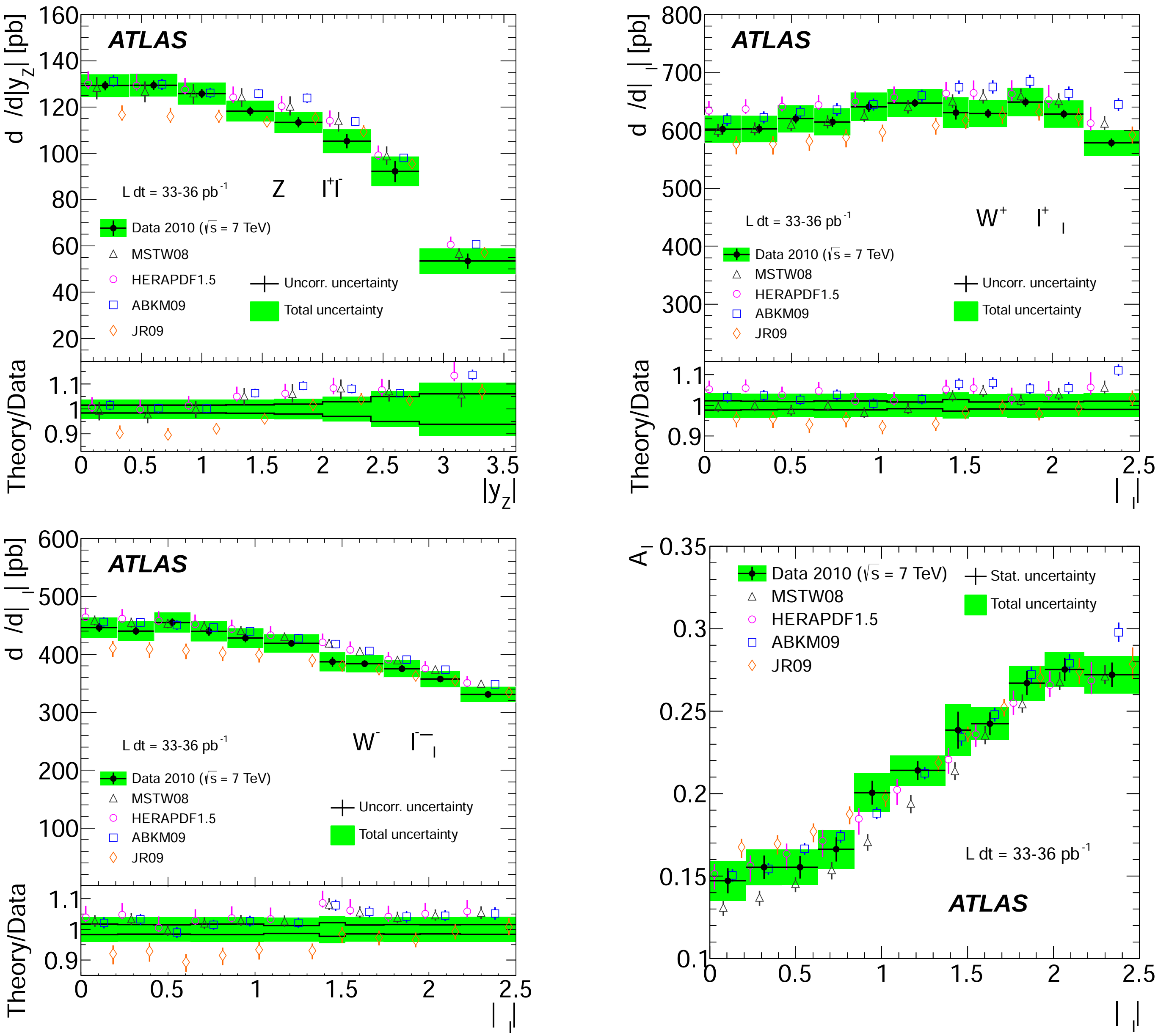
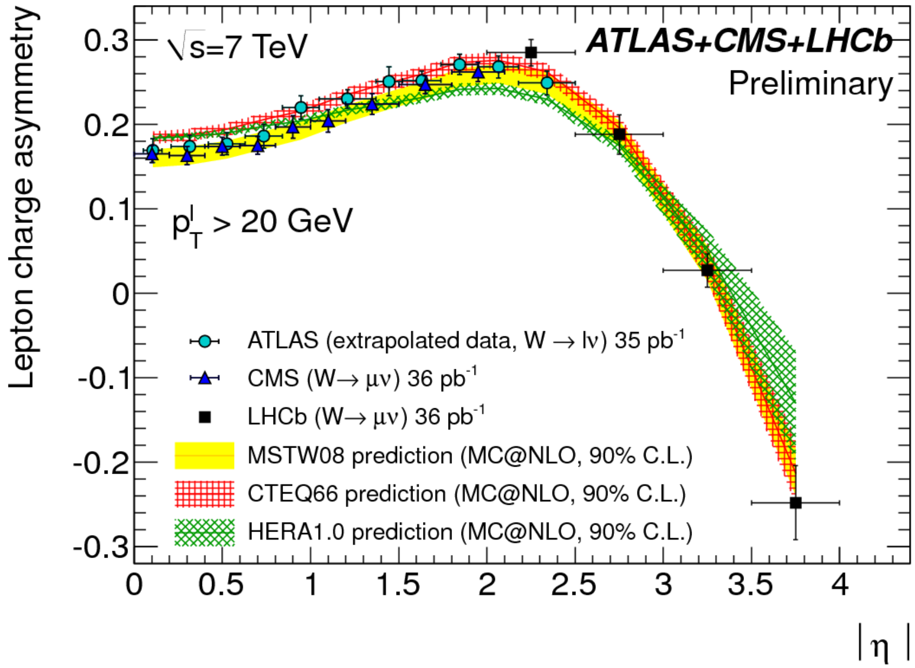
s(M_Z^2)
G. Watt (September 2011)

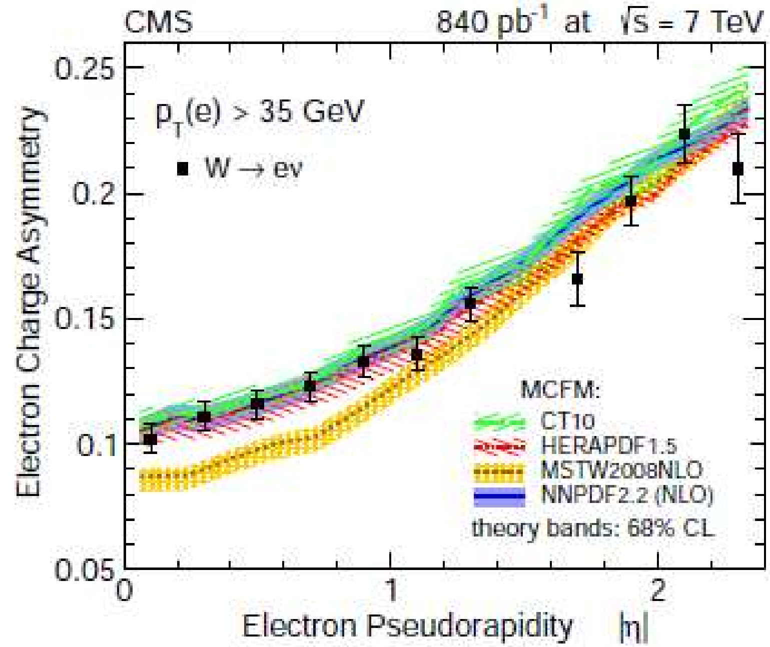
Comparison of MSTW2008 to total W, Z excellent.



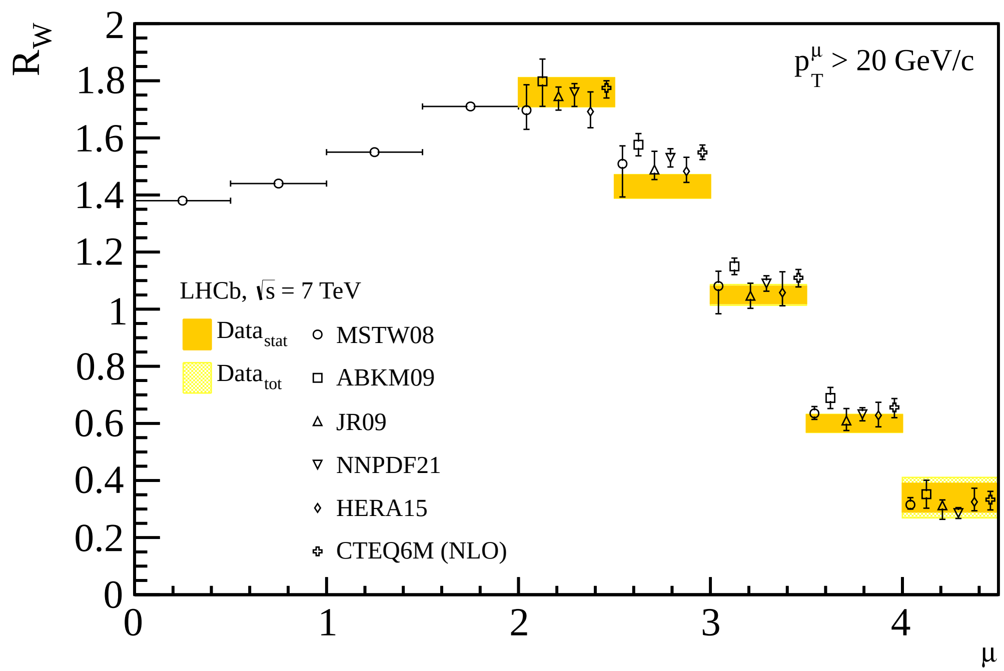
Also pretty good for inclusive distributions. Except some problems with asymmetry.





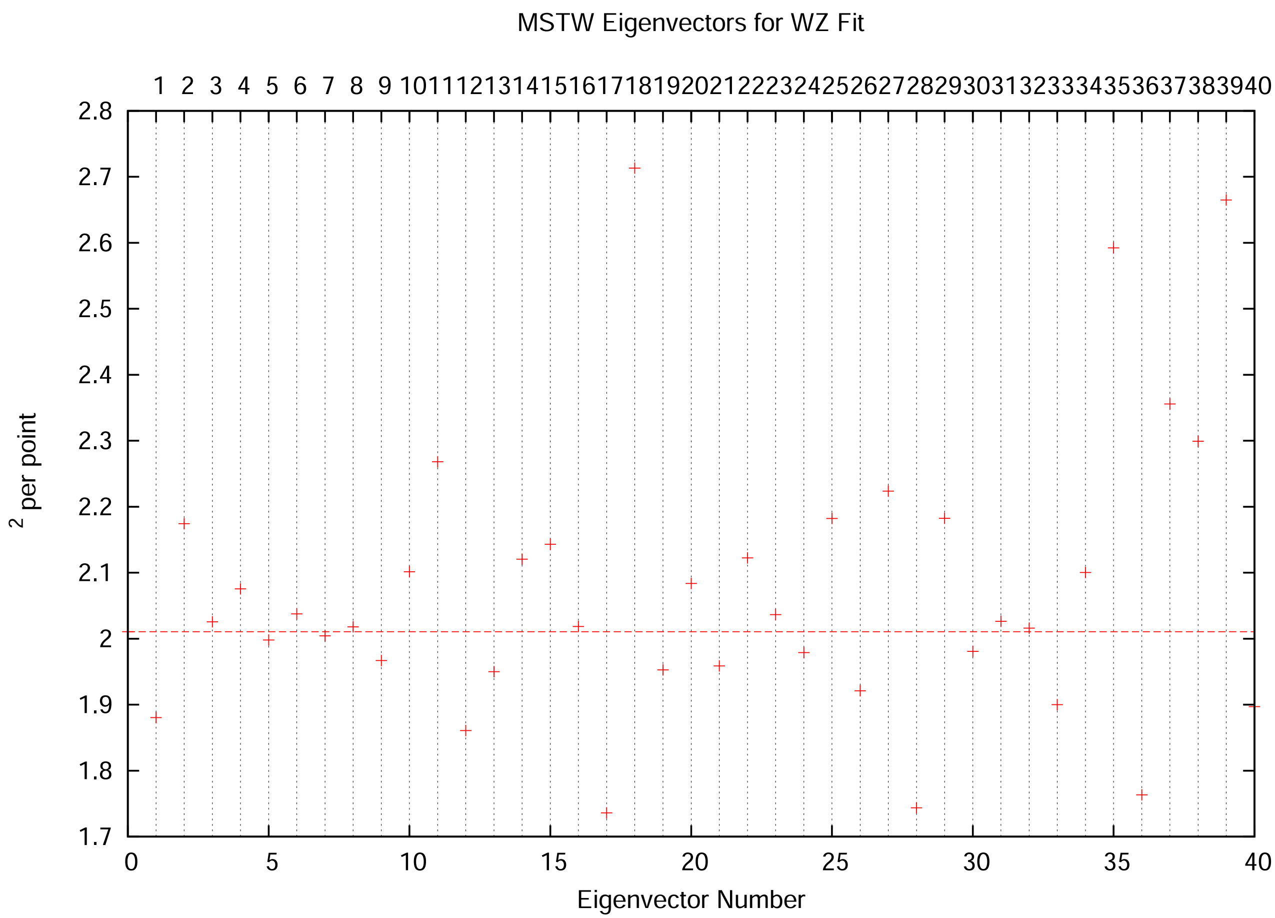


Similar for CMS data, though depends on p_T cut. Generally very good for LHCb. Correlated to WH and VBF.

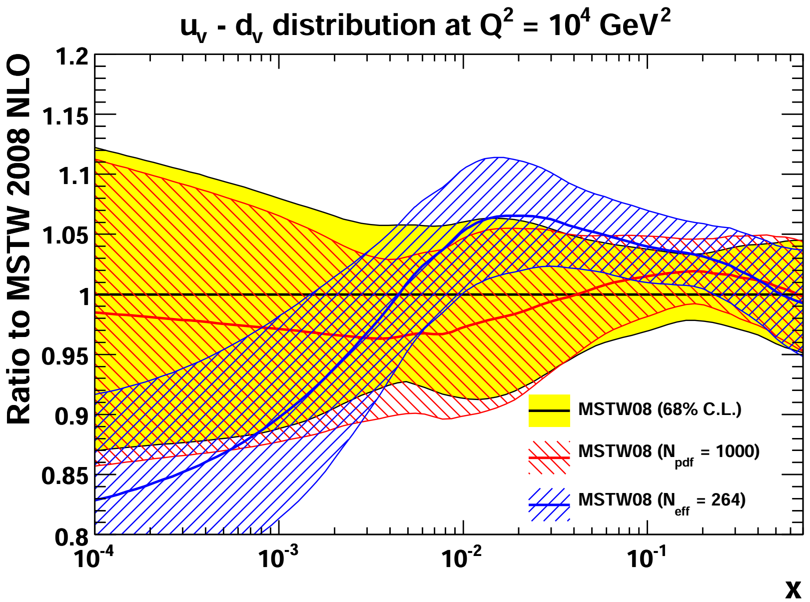


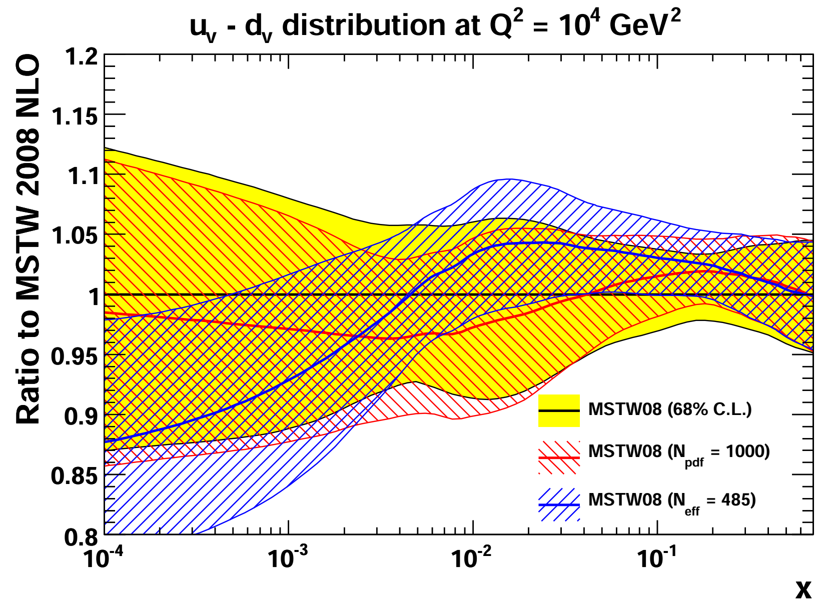
Calculate $\chi^2/N = 60/30$ for ATLAS W, Z data again at NLO using APPLGrid. Not best, but fairly close to any other set except CT10 which is best. Again look at eigenvectors.

Fit improves markedly in one direction with eigenvector 9, gluon, which alters common shape and normalisation, and 14 and 18 which alter d_V and u_V, i.e. affect asymmetry. Not much variation in strange normalisation.

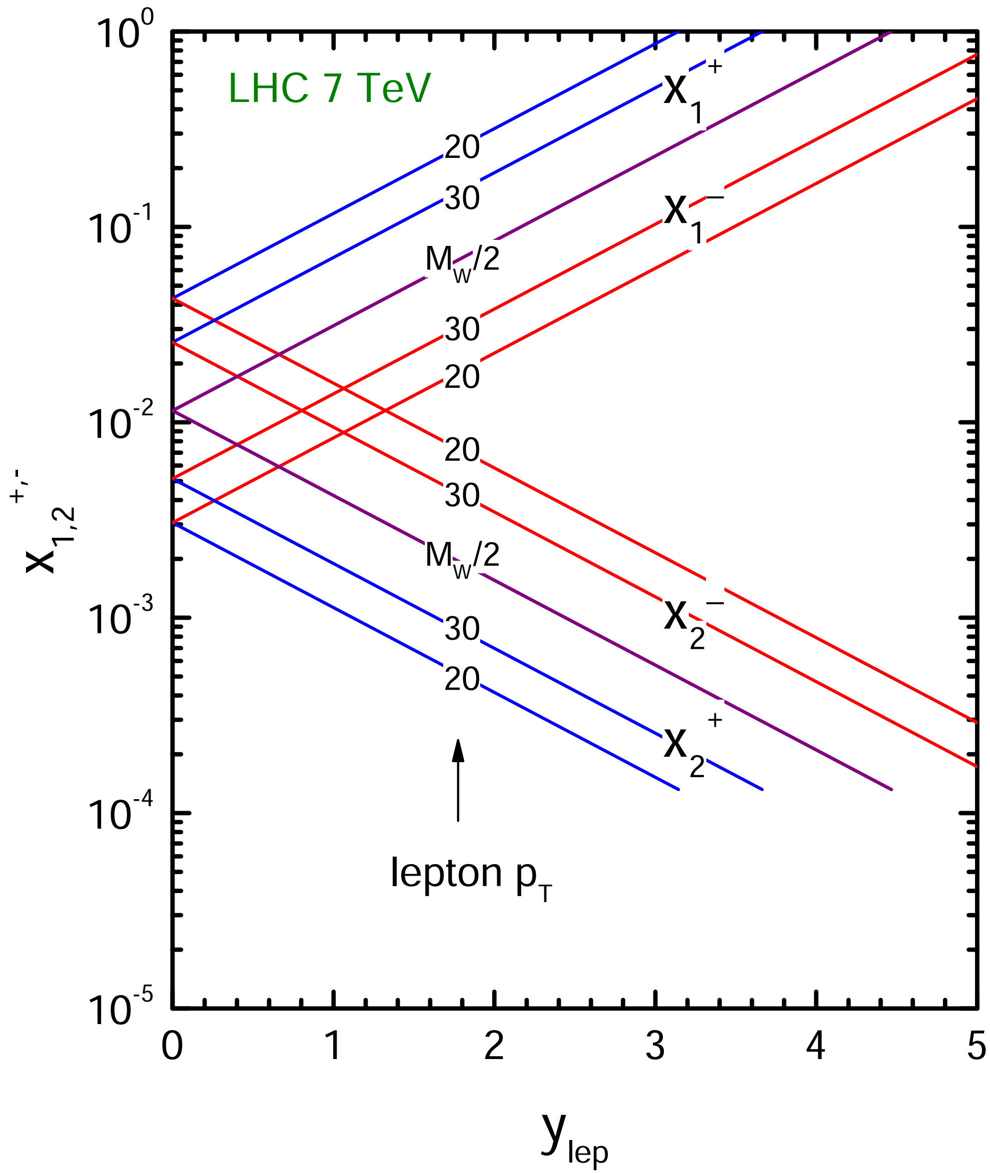


Asymmetry used by Graeme Watt in reweighting, and moves $u_V - d_V$ up around $x = 0.01$ - where parameterisation perhaps underestimates uncertainty. (ATLAS left, CMS $p_T > 25\text{GeV}$ right).



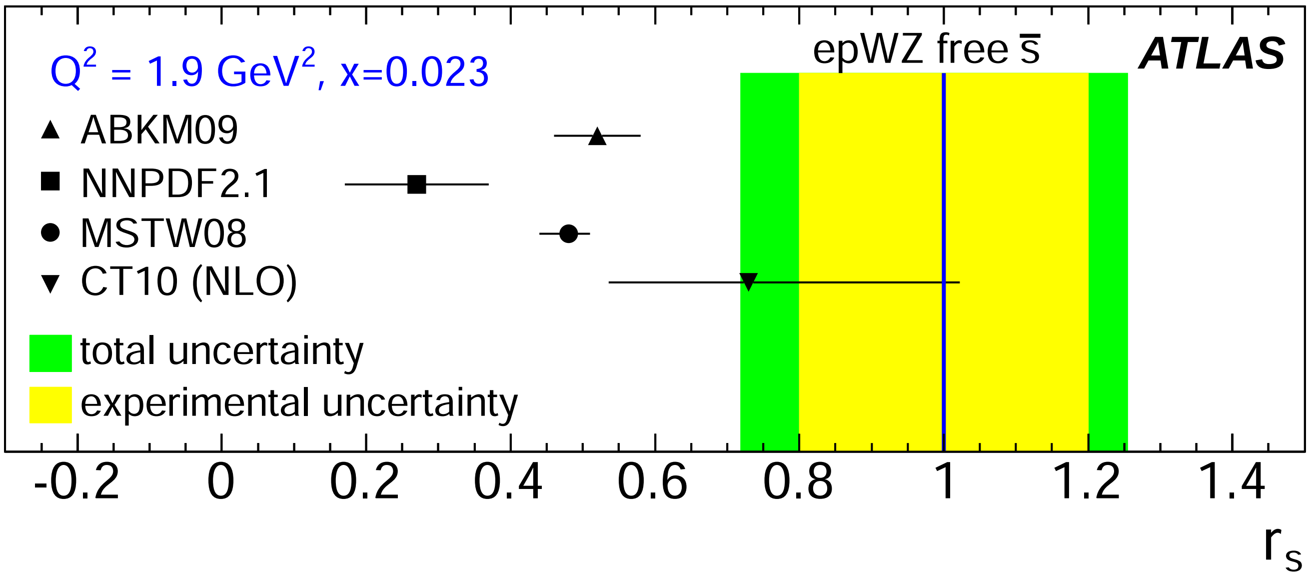


Fits with details of x values probed for different p_T cuts (Stirling).



Strange Quark

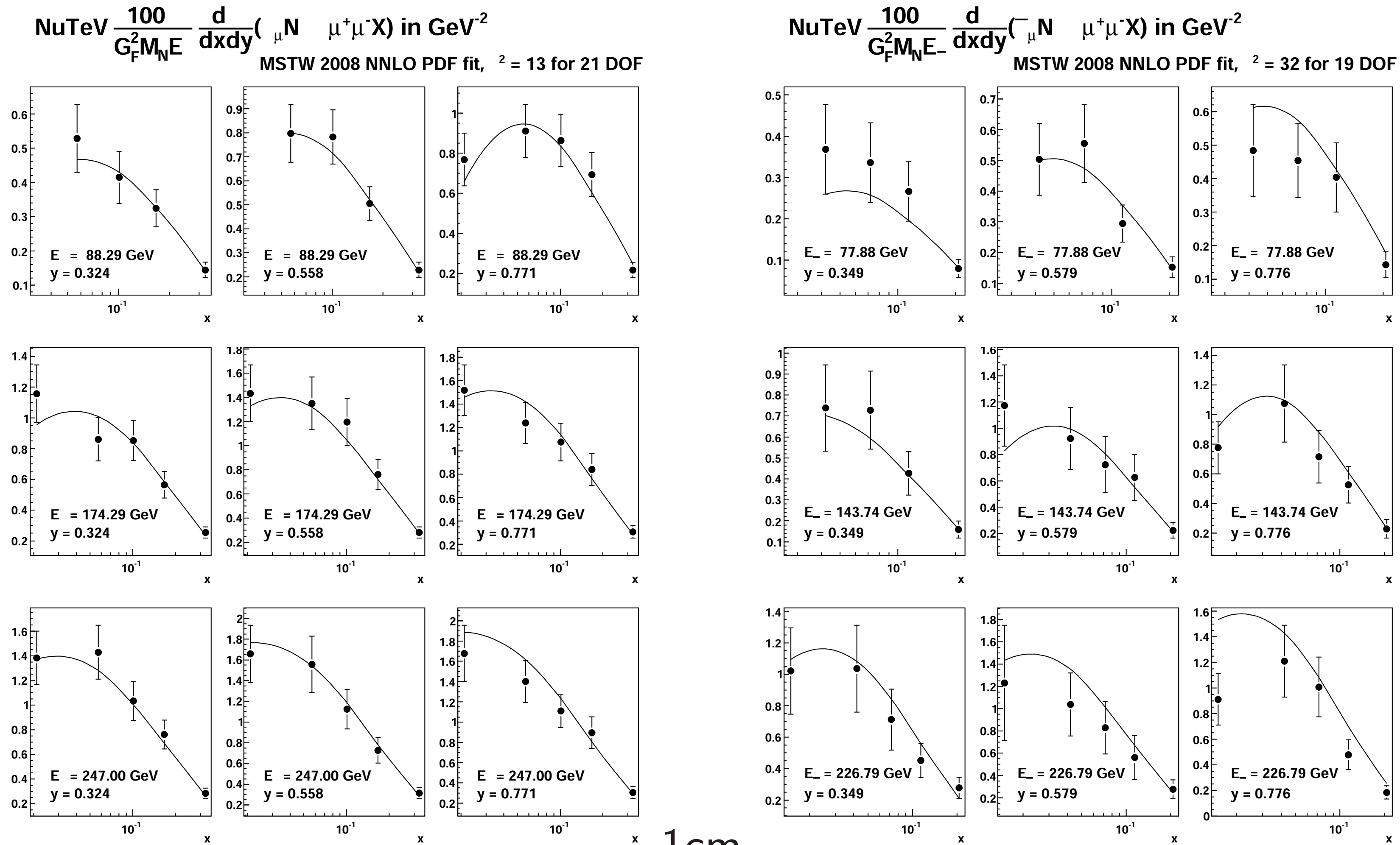
Recently suggested by ATLAS study that strange quark fraction at $x \sim 0.01$ much larger than generally suggested - though there is quite a lot of variation.



Mostly determined in many fits by dimuon data

$$\nu_\mu \rightarrow \mu^- + W^+, \qquad W^+ + s \rightarrow c$$

where the charm meson decays to a muon. From CCFR, NuTeV, the latter being more constraining.



1cm

Where $Q^2 = 2m_p yxE_\nu$. At $x \sim 0.02$ $Q^2 \sim 2-5\mathrm{GeV}^2$. Lowest x bin usually $Q^2 = 2-3\mathrm{GeV}^2$.

Nuclear corrections required. Can vary penalty free in MSTW fit.

Try various fits changing strange parameterisation. General form

$$s(x, Q_0^2) + \bar{s}(x, Q_0^2) = A(1-x)^\eta (1 + \epsilon x^{0.5} + \gamma x) x^\delta, \qquad Q_0^2 = 1\mathrm{GeV}^2.$$

where δ set equal to light sea. Fix ϵ and γ because the fit finds no improvement if left free. A leads to suppression and η slightly greater than for light sea.

Try raising strange at low x by setting A so that $s(x, Q_0^2) + \bar{s}(x, Q_0^2)$ is a third of the total sea at input at low x. Try 4 variations.

- $k\!=\!1$ where $k = (s + \bar{s})/(\bar{u} + \bar{d})$ - all other parameters fixed. Strange exactly $1/3$ of sea at input. $\Delta\chi^2 = -10$ for ATLAS, W,Z data.
- $k\!=\!1\,1p$ - η free. $\Delta\chi^2 = -11$ for ATLAS, W,Z data.
- $k\!=\!1\,2p$ - η, γ free. $\Delta\chi^2 = -10$ for ATLAS, W,Z data.
- $k\!=\!1\,3p$ - η, γ, ϵ free. $\Delta\chi^2 = -4$ for ATLAS, W,Z data.

$k = 1$ - $\Delta\chi^2 = 1200$. NuTeV dimuon χ^2 25 times worse. All nuclear data and Drell Yan data (E866 and Tevatron) much worse.

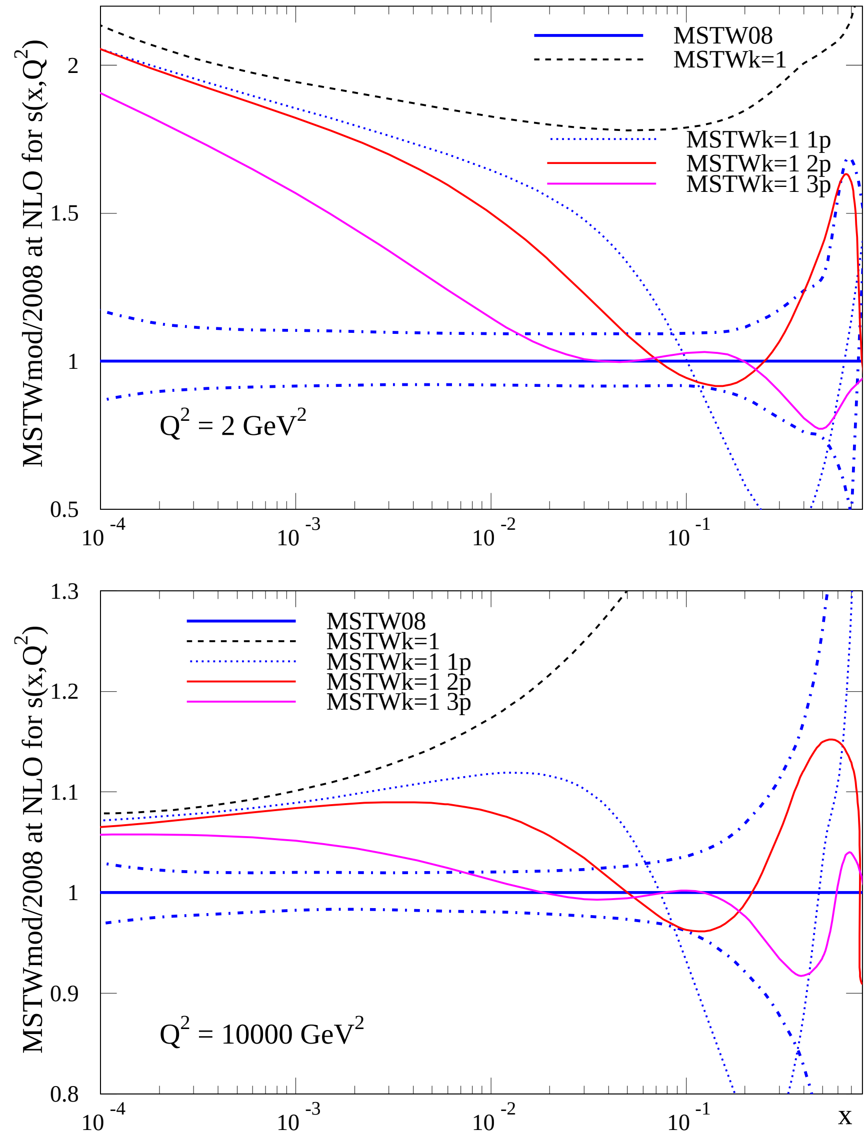
$k = 1\ 1p$ - $\Delta\chi^2 = 190$. NuTeV dimuon $\chi^2 120$ worse. Nuclear and Drell Yan data worse. Nuclear correction modified.

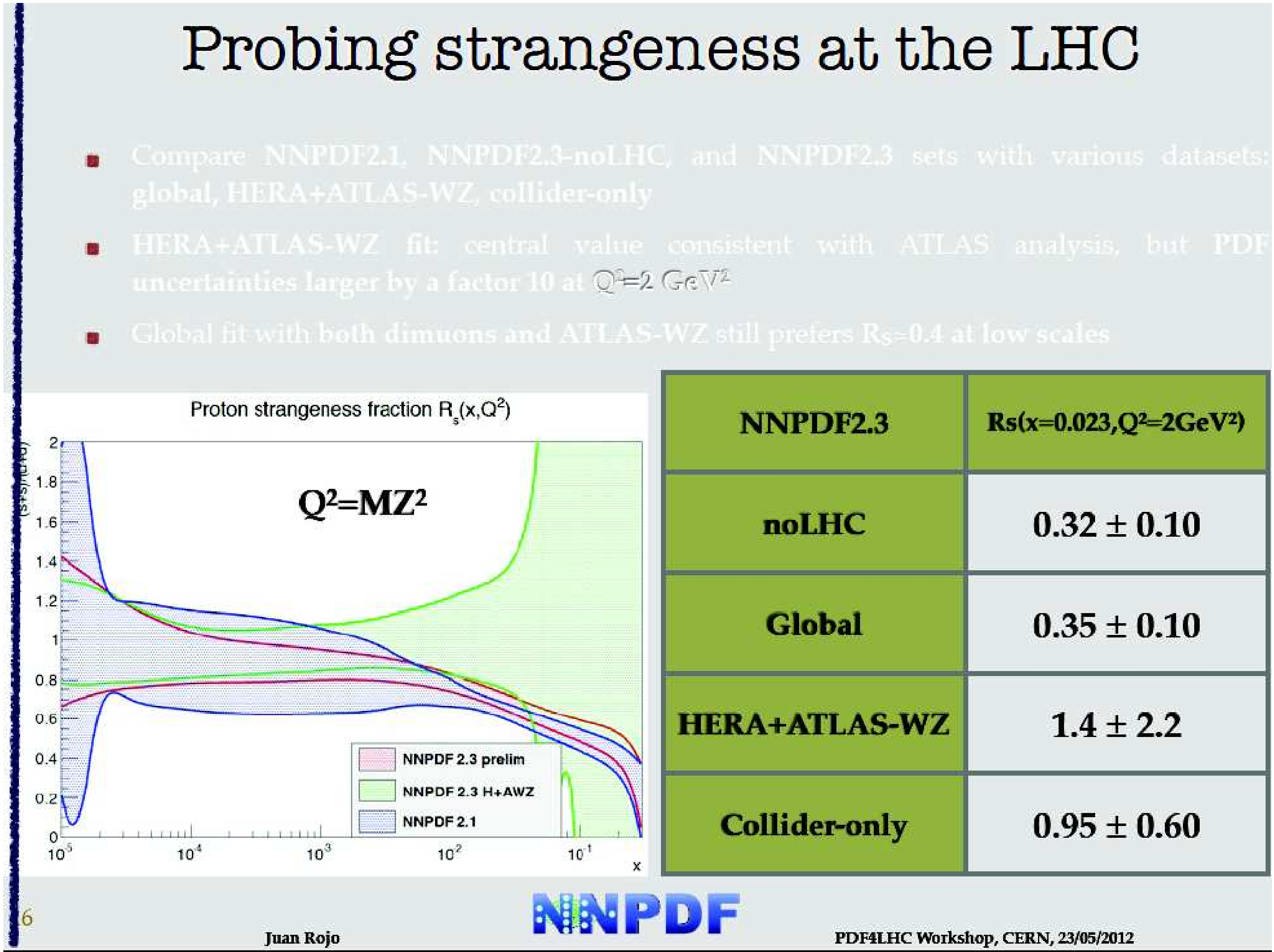
$k = 1\ 2p$ - $\Delta\chi^2 = 55$. NuTeV dimuon $\chi^2 42$ worse. Nuclear and Drell Yan data slightly worse. (Similar to CT10 strange)

$k = 1\ 3p$ - $\Delta\chi^2 = 43$. NuTeV dimuon $\chi^2 17$ worse. Nuclear and Drell Yan data slightly worse.

Does not resolve issues. Some pull from ATLAS data.

Much more from $W + c$ data (see Stirling and Vryonidou study).





NNPDF suggest larger error and some inconsistency in data in global fit. Similar conclusions from MSTW.

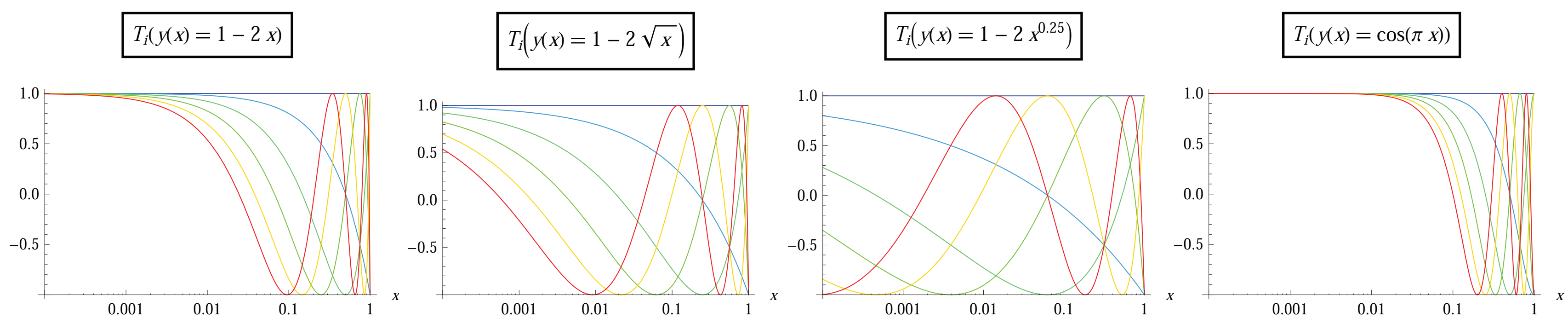
Investigation of Parameterisation Issues - with A. Mathijssen.

In the light of Monte Carlo studies investigate parameterisation dependence, initially concentrating on valence quarks.

Decide to use Chebyshev polynomials (looked at other possibilities)

$$xf(x,Q_0^2) = A(1-x)^{\eta}x^{\delta}(1+\sum_n a_n T_n(y))$$

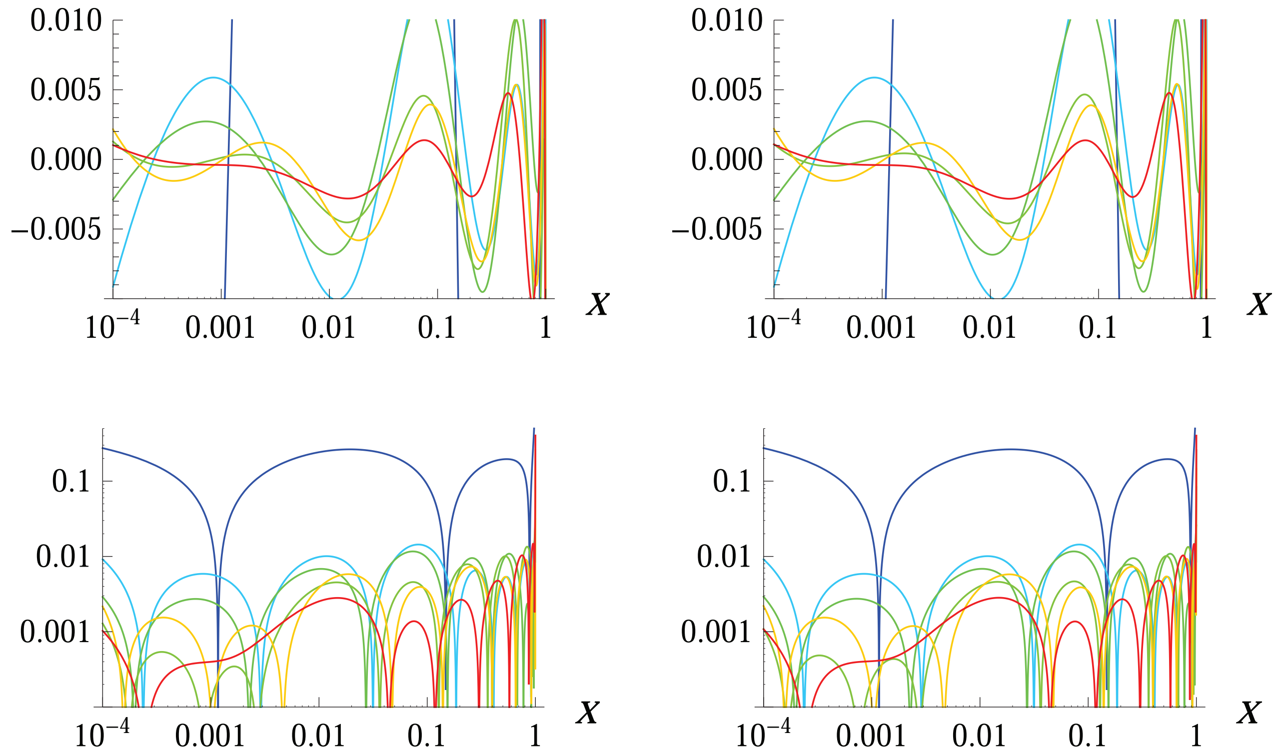
i.e. keep high and low x limits. Choose $y = 1-2\sqrt{x}$.



Same choice as in Pumplin study. Slightly different to Glazov, Moch and Radescu.

Fit to pseudodata for valence quark generated from very large order polynomial with smoothness constraints applied.

Distributed evenly in $\ln(1/x)$ with percentage error constant.



Percent deviation for full function - Chebyshev result on right. Order increase across the visible spectrum (i.e. dark blue to red).

2 terms in polynomial mainly $\leq 1\%$ deviation. 4 terms $\leq 0.5\%$ deviation except high x. After $5-6$ polynomials start fitting noise, i.e. χ^2 lower than true function.

Fits to data

Just applying to valence quarks $\Delta\chi^2 = -4$.

Significant change in $u_V(x), x \leq 0.03$

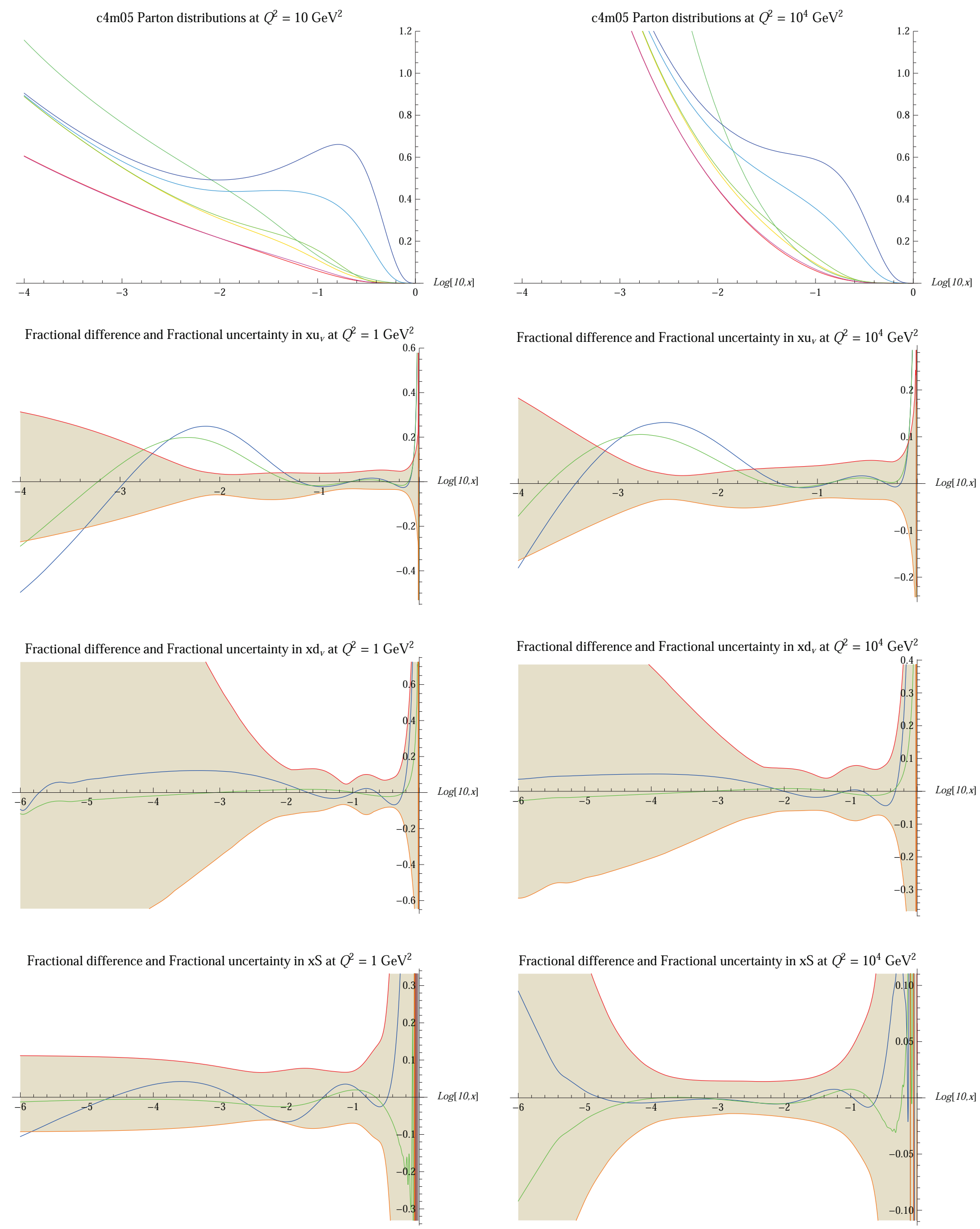
Similar to earlier conclusion adding x^2 term to parameterisation.

Applying also to sea and gluon $\Delta\chi^2 = -29$ (mainly BCDMS and Drell Yan data).

Still change significant only for $u_V(x), x \leq 0.03$.

Fits with requirement for fitting lepton asymmetry at LHC.

—— valence, —— valence + sea

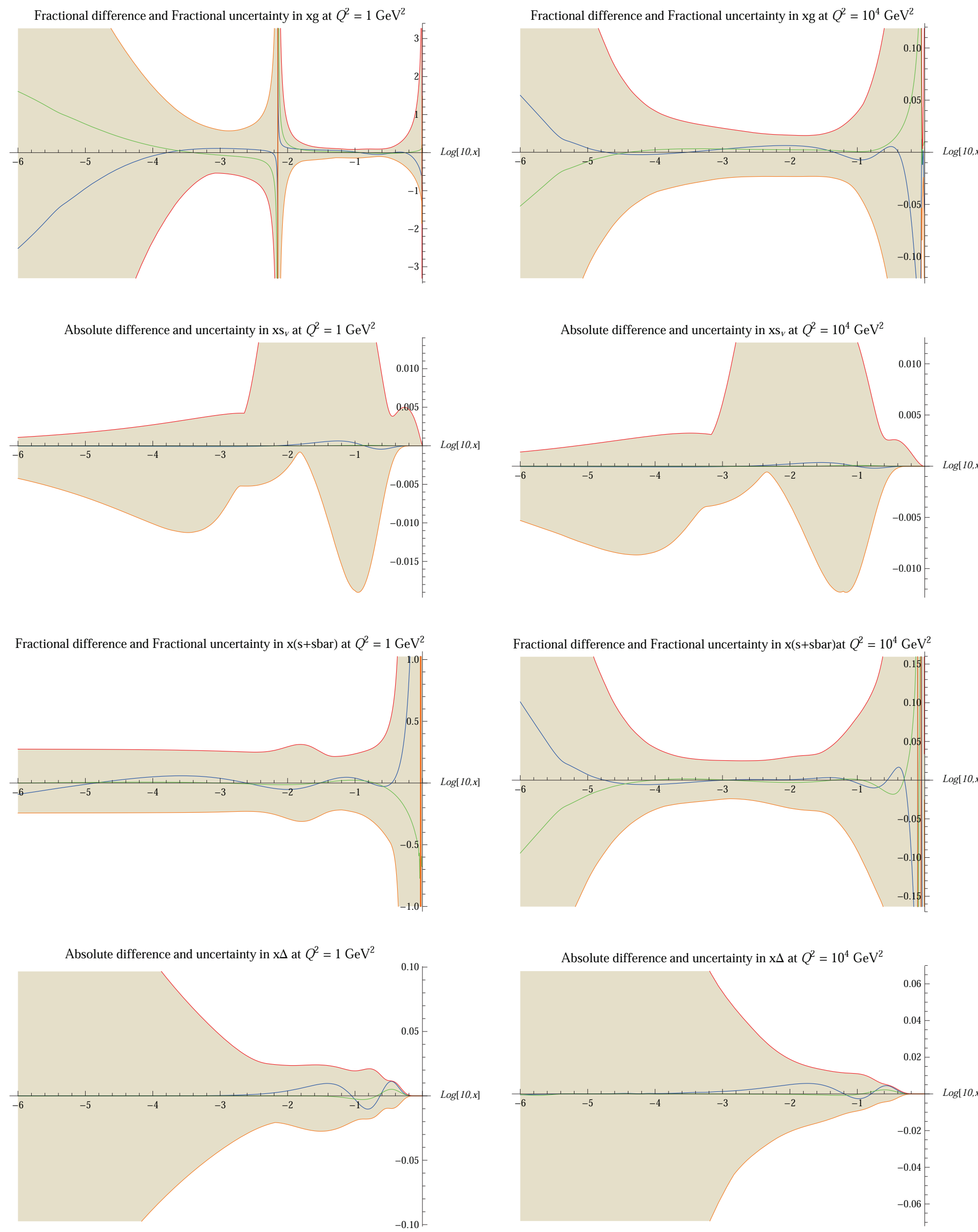


Little change in other PDFs.

Already 7 free parameters in the gluon. Sticking with two terms in Chebyshev polynomial leads to no change.

Take this a default - MSTW2008Cp (preliminary).

Prelim. study of uncertainties with 23 eigenvectors (one extra for valence quarks and sea). Little change except valence for $x \leq 0.03$, where significant increase.

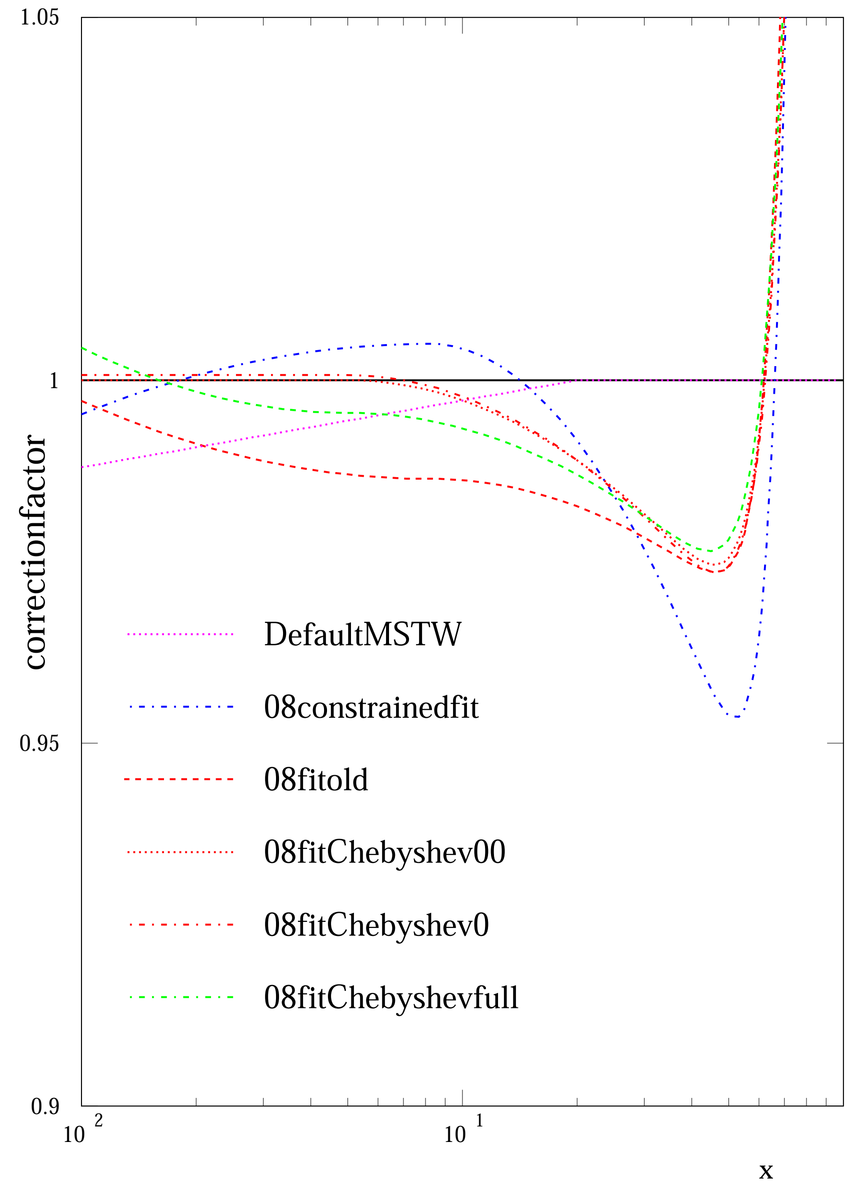


Given previous relationship between Tevatron asymmetry and deuterium corrections where partial success was noted revisit with extended parameterisation.

Default for MSTW some shadowing for $x < 0.01$.

Previously big improvement in fit, but "unusual" corrections.

Now improvement again but much more stable, and sensible for deuterium corrections. (No shadowing favoured though.)

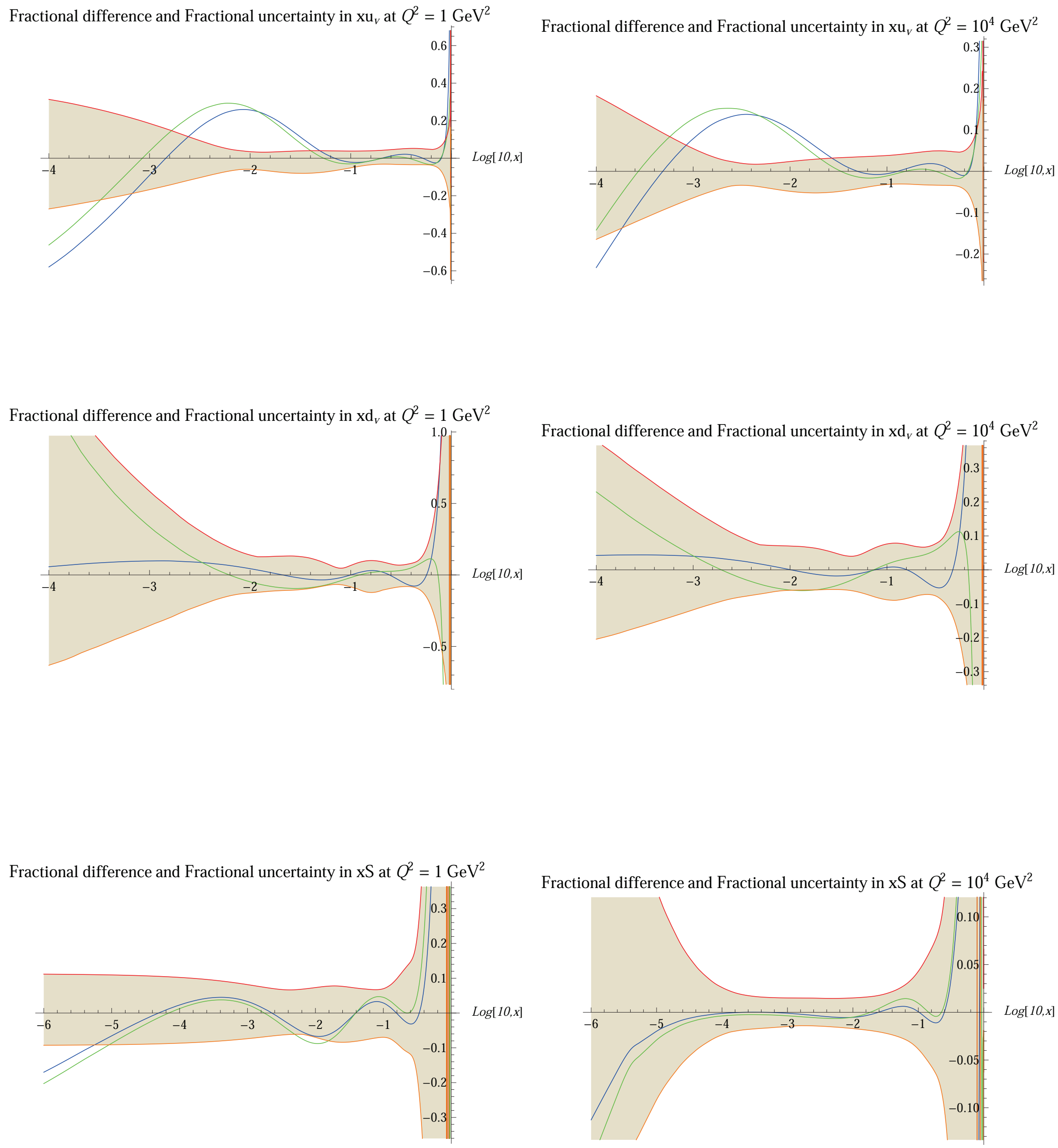


Now also get variation in $d_V(x)$ for higher x due to deuterium correction (seen before) and $x \leq 0.03$ due to parameterization and corrections.

Prelim. MSTW2008Cpdeut PDFs.

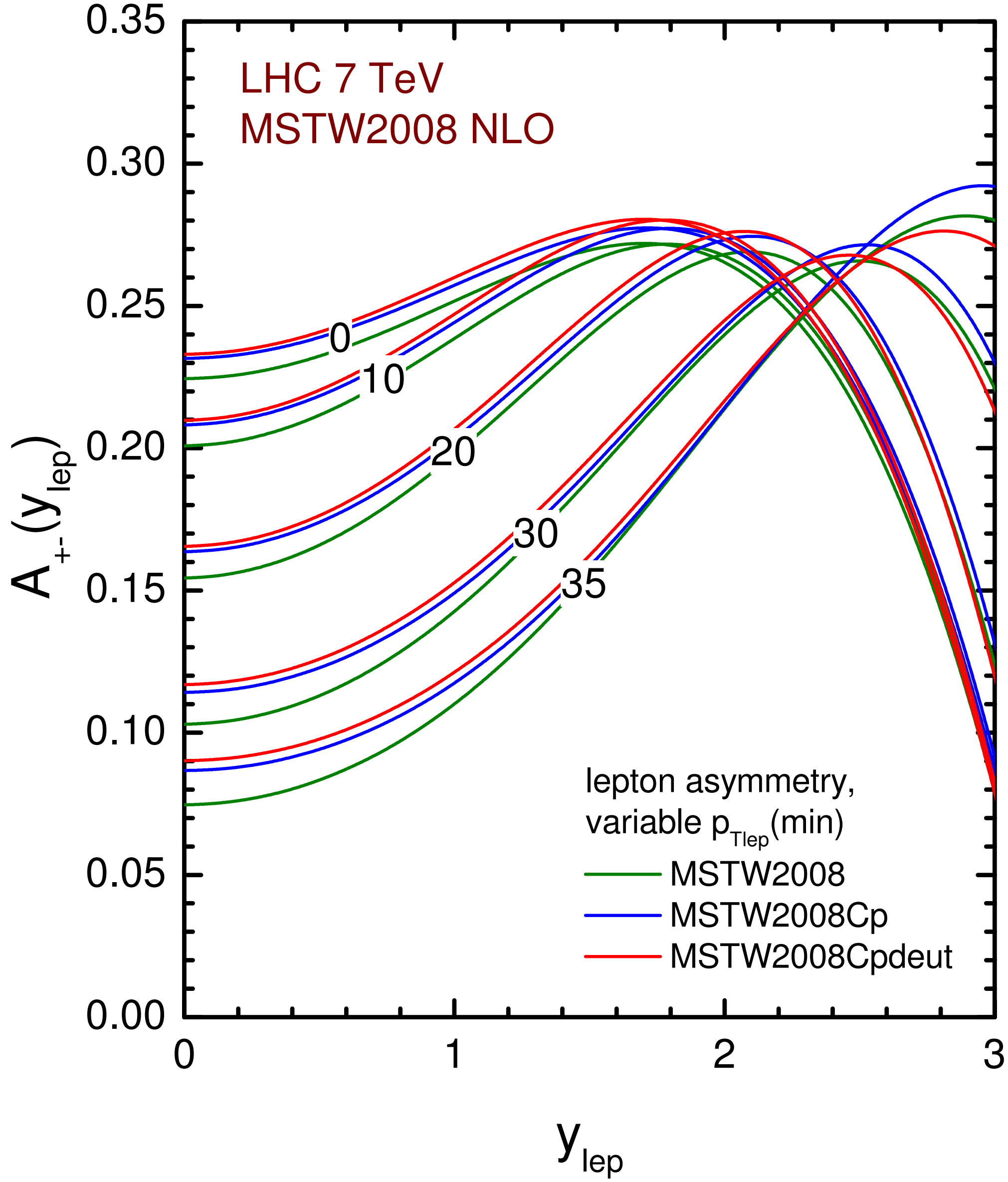
Fit to ATLAS W, Z rapidity data at NLO improves to $48/30$ for MSTWCp and 45/30 for MSTWCpeut.

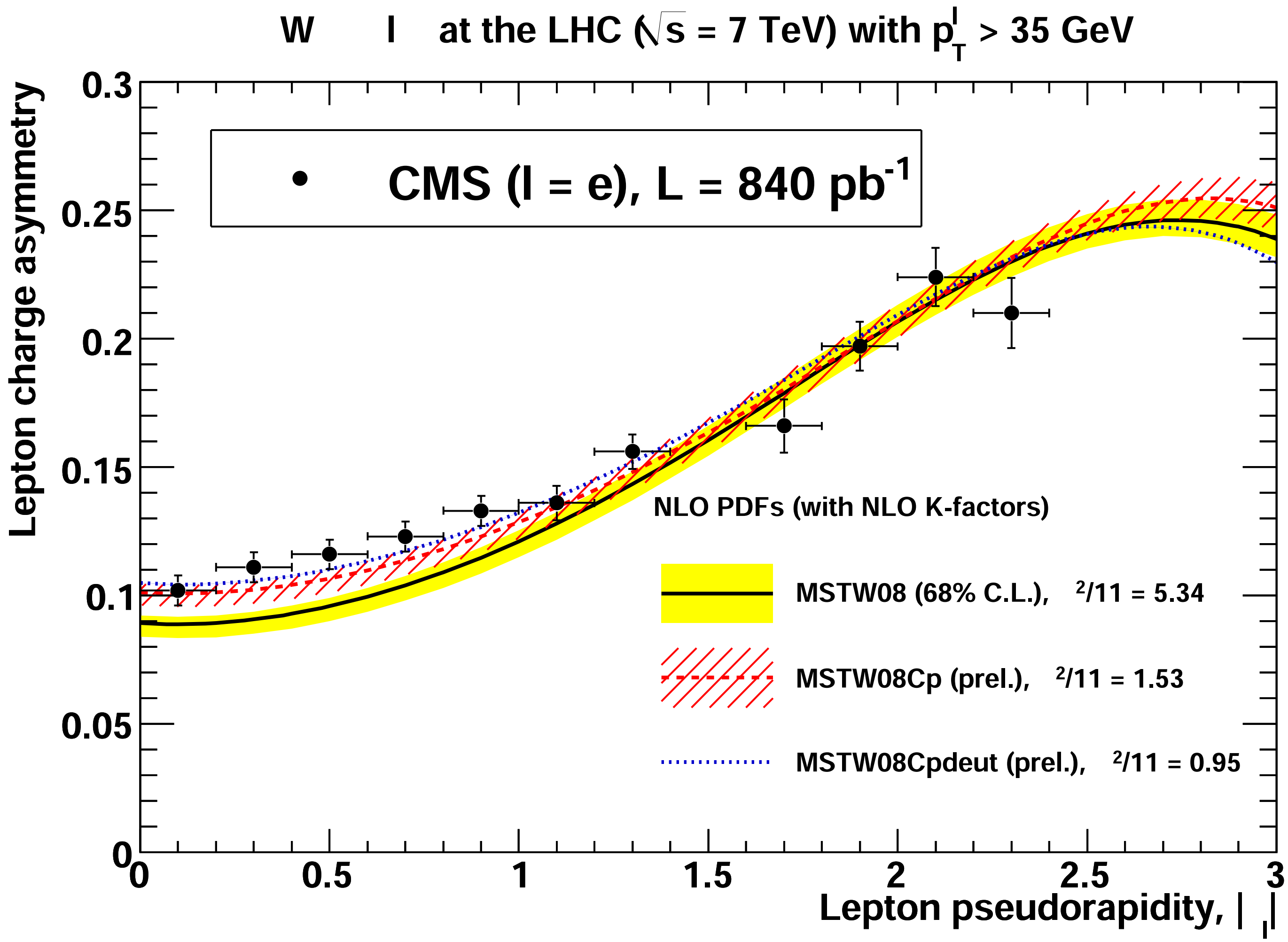
—— CP, —— CPdeut



Increases lepton asymmetry, but very preferentially for high p_T cut. (Curves made here with LO calculations).

Most of the effect already obtained for parameterisation extension, but some from deuterium study.





Prediction for $p_T > 35\mathrm{GeV}$ CMS asymmetry data using MCFM.

Note no change to data fit, just parameterisation and some from deuterium corrections.

Main deuterium effect absence of shadowing in default fit.

Big change in high p_T cut asymmetry, but very specifically sensitive to $u_V(x,Q^2) - d_V(x,Q^2)$. What about other quantities. Other PDFs changed little. α_S free but tiny change. Expect little variation.

The $\%$ change in the cross sections ($M_H = 120\mathrm{GeV}$).

	MSTWCp	MSTWCpdeut
W Tev	+0.6	+0.1
Z Tev	+0.8	+0.7
W^+ LHC (7TeV)	+0.7	+0.3
W^- LHC (7TeV)	-0.7	-0.4
Z LHC (7TeV)	+0.0	-0.1
W^+ LHC (14TeV)	+0.6	+0.3
W^- LHC (14TeV)	-0.6	-0.5
Z LHC (14TeV)	+0.1	-0.1
Higgs TeV	-0.5	-1.8
Higgs LHC (7TeV)	+0.2	-0.1
Higgs LHC (14TeV)	+0.1	+0.1

Extreme stability in total cross sections, all far inside uncertainties. Even $\sigma(W^+)/\sigma(W^-)$ barely more than 1%.

Impact on Cross Sections of combined HERA data - NNLO.

The values of the predicted cross-sections at NNLO for Z and a 120 GeV Higgs boson at the Tevatron and the LHC (latter for 14 TeV centre of mass energy).

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	0.9549	2.051	50.51
Comb HERA	$+2.1\%$	$+1.2\%$	$+0.9\%$	$+0.7\%$

For new global fits 2% effect on Z (and W) cross sections at Tevatron, but small change at LHC. Similar to, or less than $1-\sigma$ uncertainty in former case.

Maximum of $\sim 1\%$ for Higgs. Small effect.

GMVFNS variations – values of predicted cross-sections at NLO for Z and a 120 GeV H at Tevatron and LHC (latter for 14 TeV centre of mass energy).

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.

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.

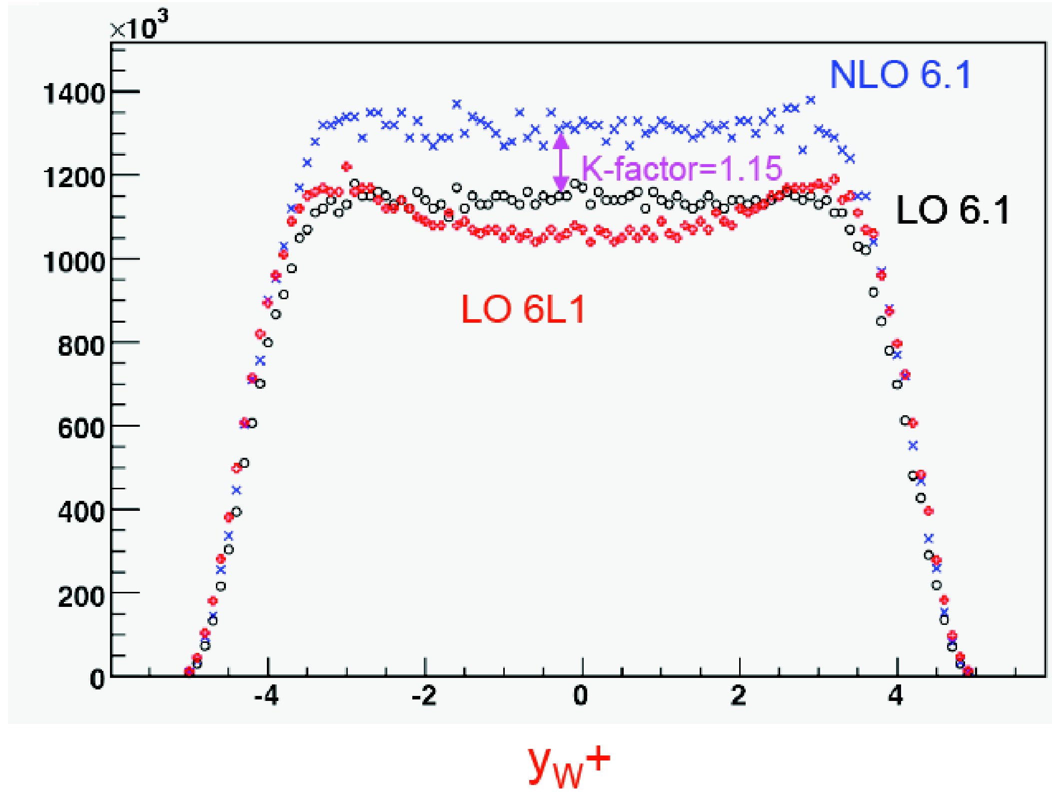
Model uncertainties can be $> 1\%$ from region at very small x and low Q^2. Can perhaps input more small-x knowledge here. Effect far smaller when $\mathcal{O}(\alpha_S^3)$ term falls with Q^2.

PDFs for LO Monte Carlo generators.

Noticed by CTEQ that for standard production processes at the LHC, e.g. W rapidity, that NLO PDFs used in a LO event generator give a better representation of the true (full NLO) shape than LO PDFs.

Led to the proposal that NLO partons should always be used.

W+ rapidity distribution at LHC



For example, the shape of the W+ rapidity distribution is significantly different than the NLO result if the LO pdf is used, but very similar if the NLO pdf is used.

Sometimes NLO partons better to use if only LO matrix elements are known. Can get significant problems with shape if LO partons used.

But can be completely wrong at small x using NLO partons due to $zero$-counting of $\ln(1/x)$ terms.

At LO compared to NLO (and higher orders) missing terms in $\ln(1-x)$ and $\ln(1/x)$ in coefficient functions and/or evolution.

$\rightarrow$ partons at LO bigger at $x \rightarrow 1$ and at $x \rightarrow 0$ in order to compensate.

From momentum sum rule not enough partons to go around – leads to bad global fit at LO – partially compensated by large $\alpha_S(M_Z^2)$.

Implies modified LO* PDFs. Relaxing momentum sum rule at LO could make LO partons rather more like NLO partons where they are normally too small but would still be bigger than NLO where necessary.

Also useful to use NLO definition of coupling constant. Because of quicker running at NLO couplings with same $\alpha_S(M_Z^2)$ very different at lower scales where DIS data exists.

Overall LO* PDFS enhanced.

NLO **Corrections**

NLO matrix elements often give large positive corrections.

- $1/z$ divergent terms in matrix elements.

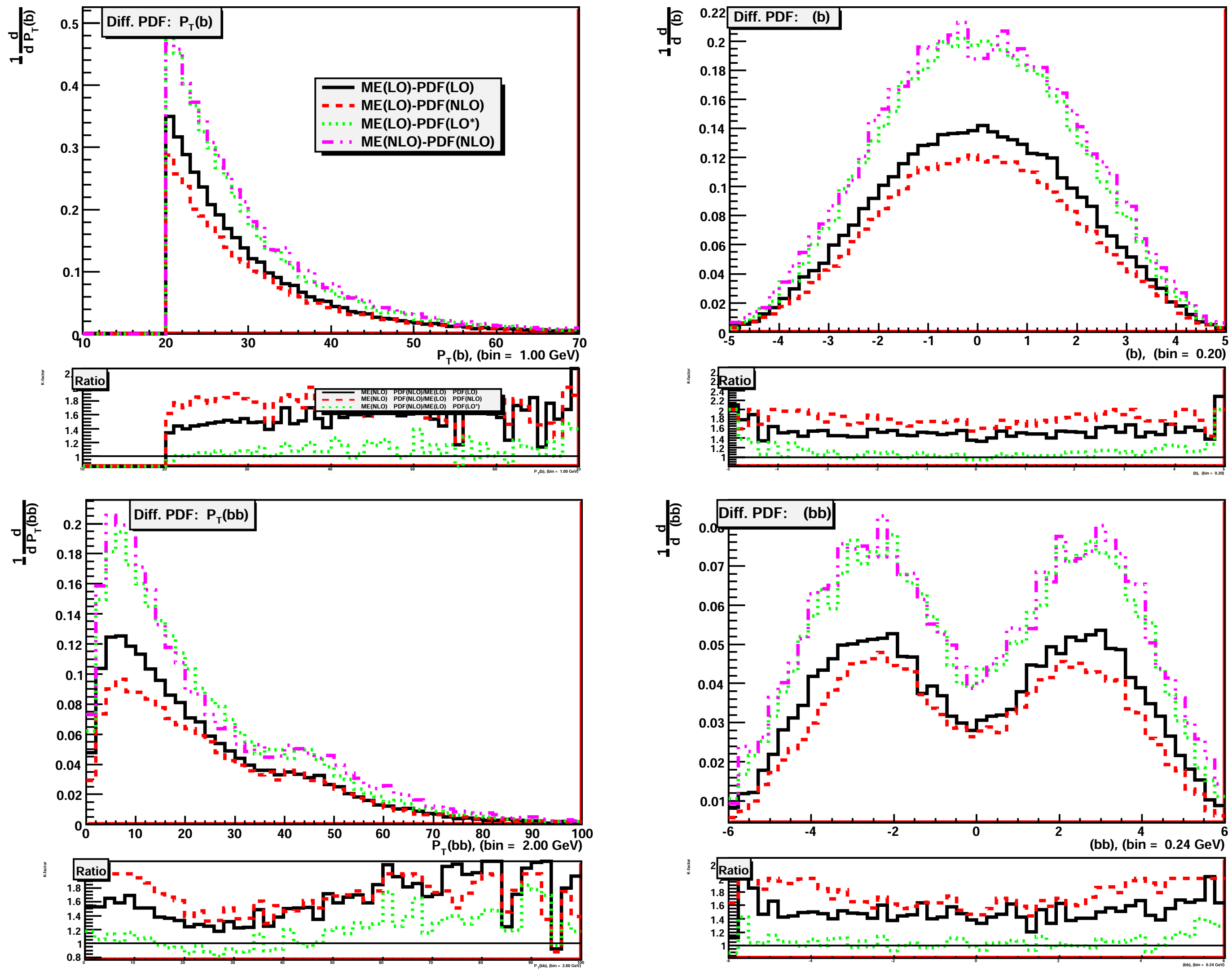
- Large corrections from soft-gluon emissions near the edge of phase space, i.e. large threshold corrections.

- Large correction from analytic continuation from space-like to time-like region, i.e. $1 + \alpha_S C_F/2$ factor in Drell-Yan production.

W, Z, Higgs and $t\bar{t}$, b-production and jet production (including $W + j$) all have NLO enhancements from at least one of these sources. In each case the enhancement of LO* partons compared to LO should compensate to some extent.

t-channel processes do not have these type of large corrections, and for e.g. single t or Higgs via vector boson fusion the NLO matrix-element correction is small. But these processes do not probe very small-x too much by the nature of processes.

Example, look at e.g. distributions for single b and $b\bar{b}$ pair (Shertsnev, RT).



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

Further developments - change of argument of coupling constant.

Monte Carlo generators use scale $p_t^2 = Q^2 * (1-z)$ for the coupling constant in initial state parton branching rather than the standard PDF choice of Q^2. Automatically incorporates leading log corrections at high z.

Need to freeze α_S at low scales.

Incorporated this scale in P_{qq} splitting function (by far most important effect at high z and x) in a parton number conserving manner - nonsinglet evolution still conserves number of valence quarks.

Quality of fit improves by ~ 50 units, mainly for high-x structure functions where resummation speeds evolution.

Allows $\alpha_S(M_Z^2)$ to lower to 0.115 - depends on regularisation.

Input partons now carry 117% momentum, but this now falls with Q^2 since modified coupling leads to increased branching of high-x quarks.

Overall change in partons LOMC compared to LO* very modest.

Similar sets by CTEQ. Based also (sometimes) on momentum violation in input and sometimes in this case fitting to pseudodata.

CTEQ modified LO pdf's (LO*)

- Include in LO* fit (weighted) pseudo-data for characteristic LHC processes produced using CTEQ6.6 NLO pdf's with NLO matrix elements (using MCFM), along with full CTEQ6.6 dataset (2794 points)
  - low mass bB
    - fix low x gluon for UE
  - tT over full mass range
    - higher x gluon
  - W^+, W^-, Z^0 rapidity distributions
    - quark distributions
  - gg->H (120 GeV) rapidity distribution

Choices

- Use of 2-loop or 1-loop α_s
  - Herwig preference for 2-loop
  - Pythia preference for 1-loop
- Fixed momentum sum rule, or not
  - re-arrange momentum within proton and/or add extra momentum
  - extra momentum appreciated by some of pseudo-data sets but not others and may lose some useful correlations
- Fix pseudo-data normalizations to K-factors expected from higher order corrections, or let float
- Scale variation within reasonable range for fine-tuning of agreement with pseudo-data
  - for example, let vector boson scale vary from 0.5 m_B to 2.0 m_B
- Will provide pdf's with several of these options for user

Recently by NNPDF. Find little evidence for improvement in fit in LO* treatment.

Recent thoughts and issues.

DØ II $p\bar{p}$ incl. jets [56]	193 / 110	114 / 110	123 / 110
CDF II $p\bar{p}$ incl. jets [54]	143 / 76	56 / 76	54 / 76
CDF II $W \to \ell\nu$ asym. [48]	50 / 22	29 / 22	30 / 22
DØ II $W \to \ell\nu$ asym. [49]	23 / 10	25 / 10	25 / 10
DØ II Z rap. [53]	25 / 28	19 / 28	17 / 28
CDF II Z rap. [52]	52 / 29	49 / 29	50 / 29
All data sets	**3066 / 2598**	**2543 / 2699**	**2480 / 2615**

Initial MRSTLO*(*) PDFs based on fit to data in MRST2006 fit. Run I Tevatron jet data. Fit well at LO due to LO quark being harder than NLO quark.

More recent jet data softer. Difficult to fit at LO.

Resummations, e.g. as in running of coupling effectively in DIS-type scheme. In $\overline{MS}$ in coefficient functions.

Interplay between resummation and higher twist/renormalons. From experience difficult to disentangle at and beyond about N^{3}LO. However beyond NNLO does not affect data below $W^2 = 15\mathrm{GeV}^2$ cut for MSTW.

So much more Monte Carlo generation with NLO matrix element these days. LO* not so important.

Conclusions

Investigating best PDFs from global fits, and reasons for variations between groups.

Monte Carlo study shows that fits to real data behave more like those to "inconsistent" than "consistent" pseudodata. Imply parameterisation limitations small except for small-x valence quarks. Maintain Hessian approach with tolerance, but Monte Carlo approach to using PDFs is straightforward.

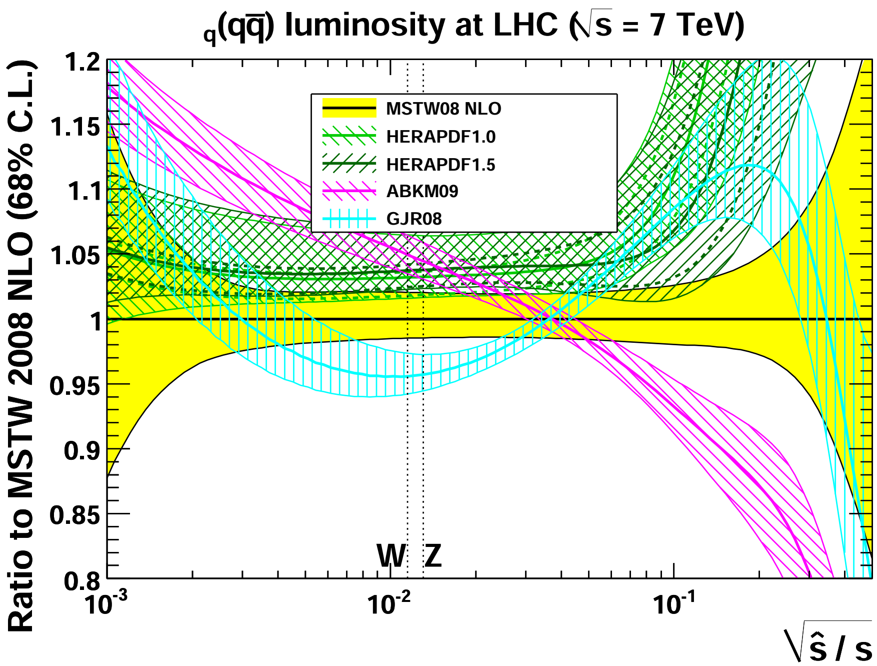
MSTW08 fits current LHC data as well, or better than other sets, with exception of (particularly high-p_T) lepton asymmetry. In the main need more data for constraints.

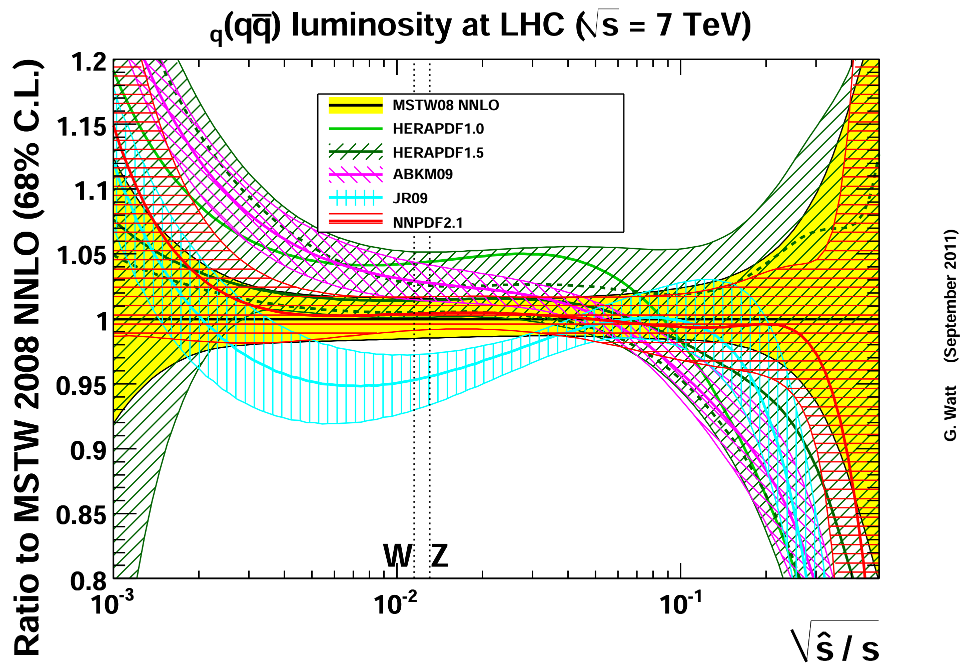
Studies suggest it is very difficult to raise strange quark fraction at input for $x \sim 0.01$ without spoiling fit.

Studies of parameterisation dependence suggest ~ 4 terms in polynomial about the maximum needed. Backs up conclusion that in MSTW fits the only need for an extended parameterisation is for small-x valence quarks. Automatically improves comparison to LHC lepton asymmetry data. Total cross sections practically unchanged.

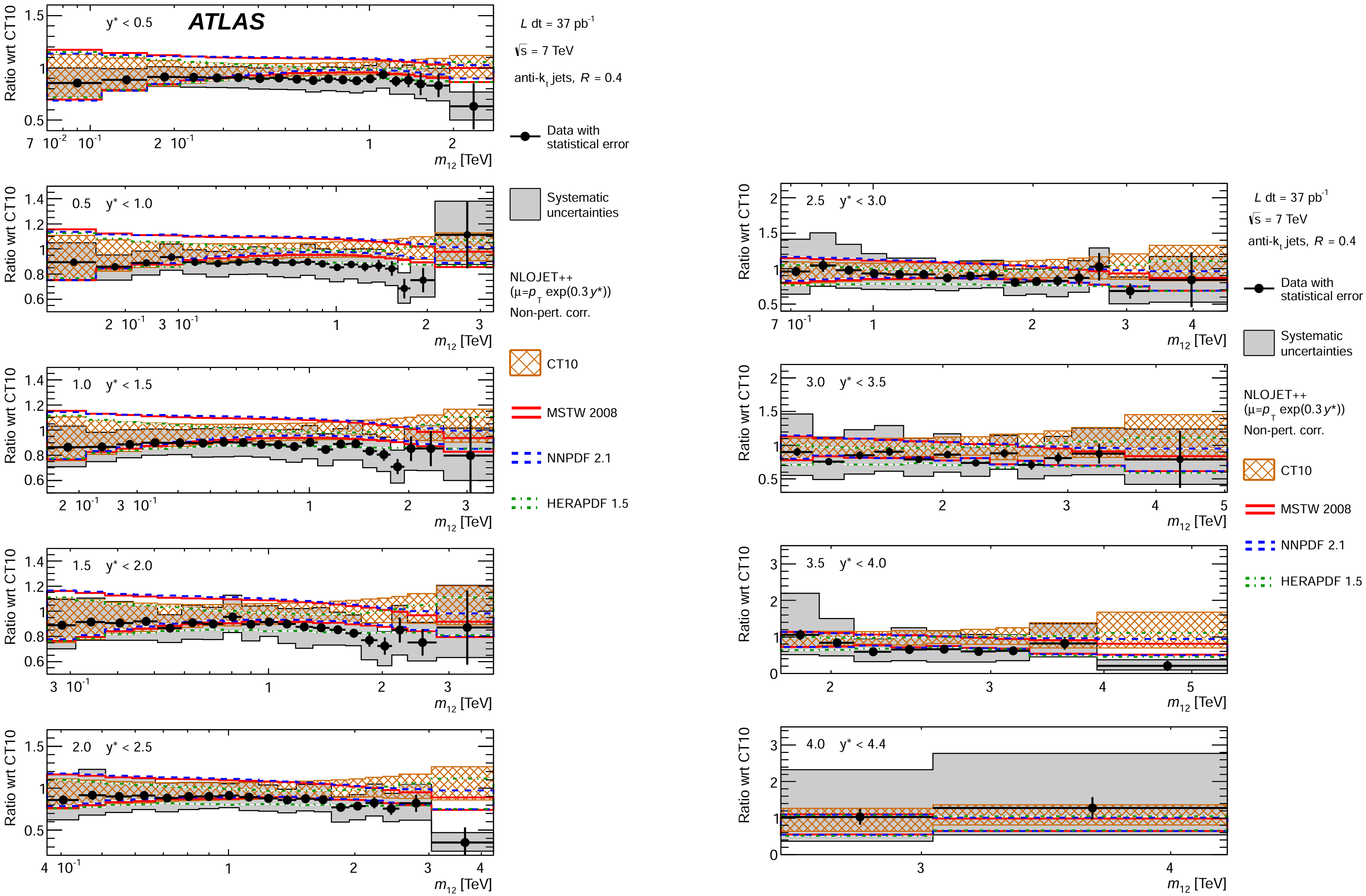
No recent updates on LO* PDFs or PDFs for Monte Carlo generators. A few issues to consider before doing this.

Backup Slides



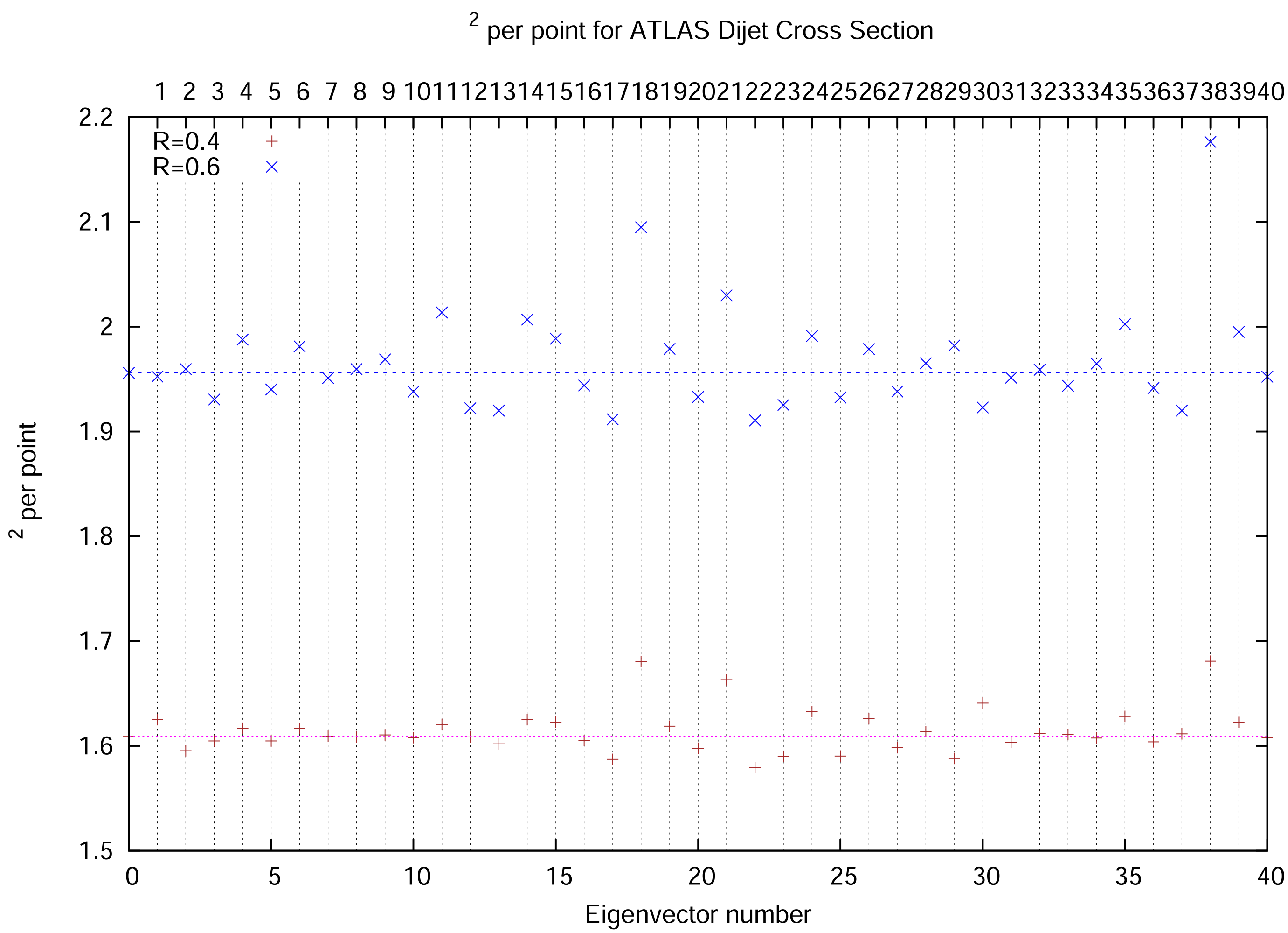


Plots by Watt - Ringberg 2011. Luminosity differences for the quarks also largely the same at NNLO as at NLO, except for HERAPDF1.5 again.


ATLAS
∫ L dt = 37 pb-1
√s = 7 TeV
anti-kt jets, R = 0.4
Data with statistical error
Systematic uncertainties
NLOJET++ (μ=pT exp(0.3 y*))
Non-pert. corr.
CT10
MSTW 2008
NNPDF 2.1
HERAPDF 1.5
y* < 0.5
0.5 ≤ y* < 1.0
1.0 ≤ y* < 1.5
1.5 ≤ y* < 2.0
2.0 ≤ y* < 2.5
2.5 ≤ y* < 3.0
3.0 ≤ y* < 3.5
3.5 ≤ y* < 4.0
4.0 ≤ y* < 4.4
Ratio wrt CT10
m12 [TeV]

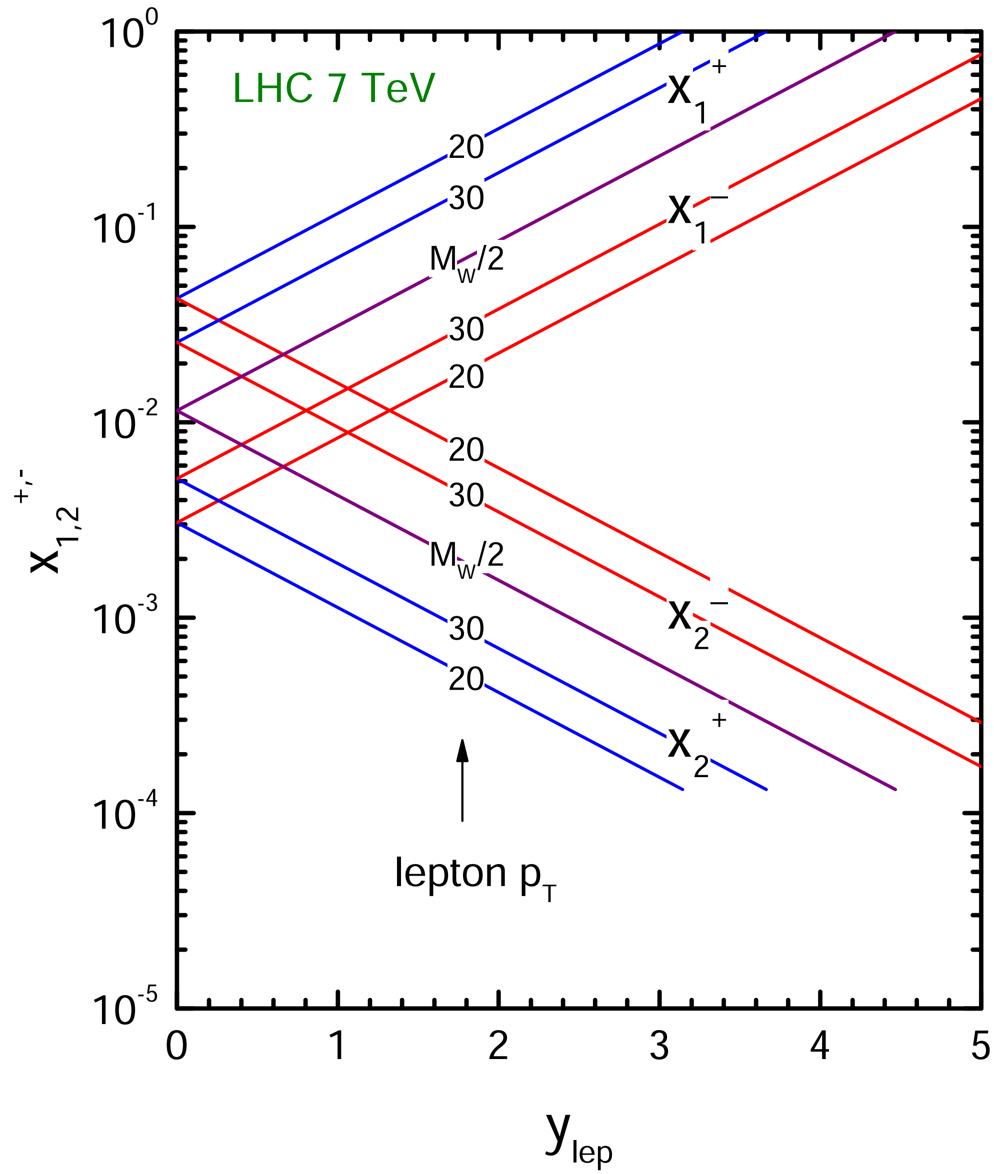
Same conclusion with dijets.

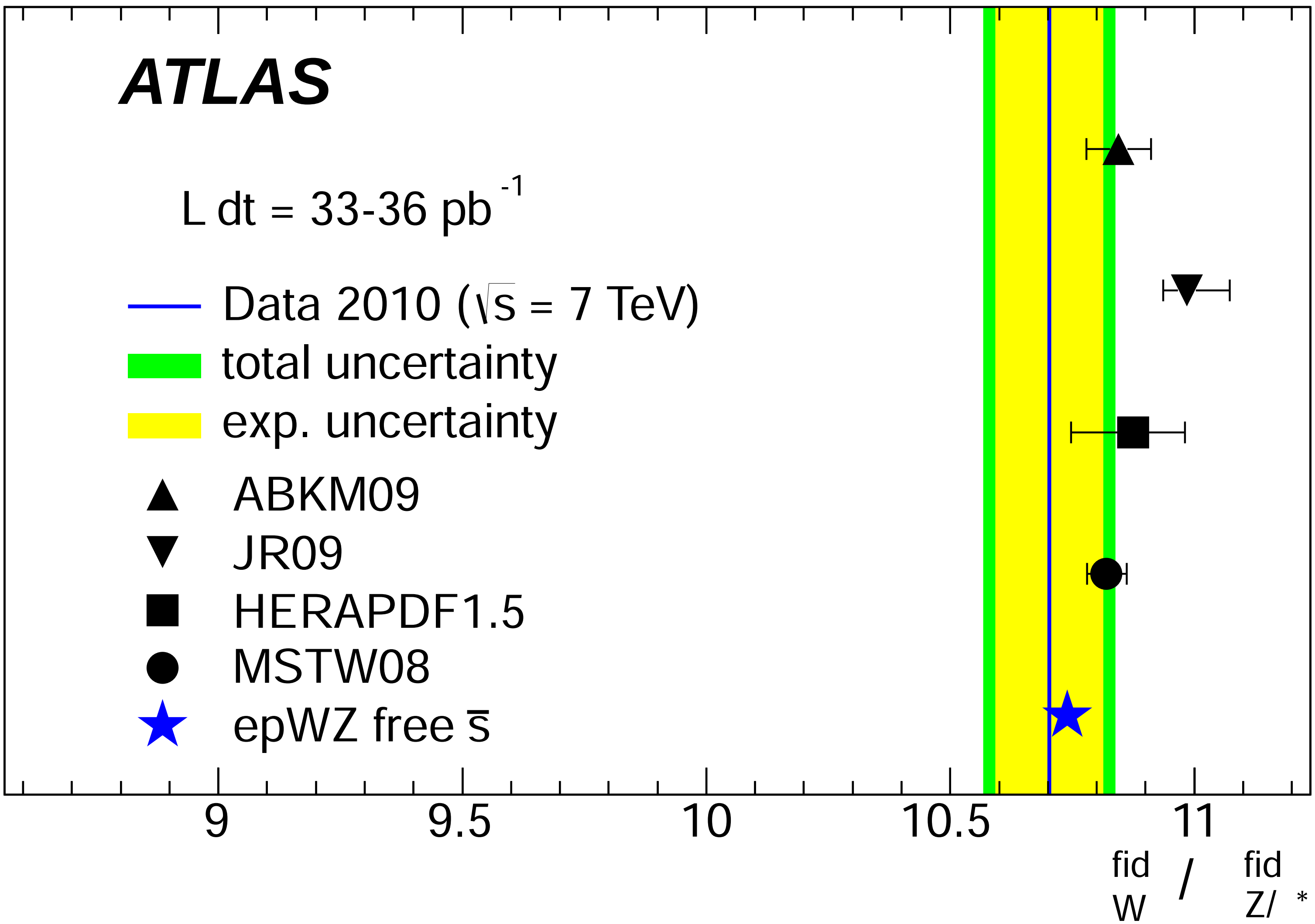
Overall result similar using NNLO PDFs with NLO cross sections. Approx NNLO in FastNLO has unusual features and fit bad (previously noticed).



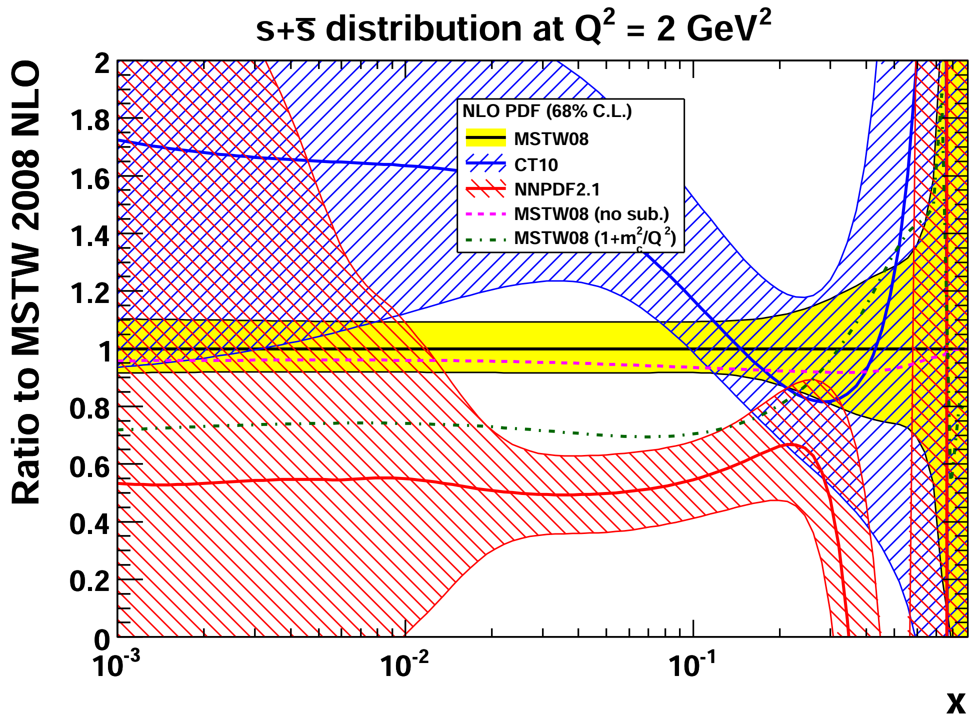
Fits with details of x values probed for different p_T cuts (Stirling).

$y = 3, p_T = 20\text{GeV} \rightarrow x_1 \sim 0.06$.



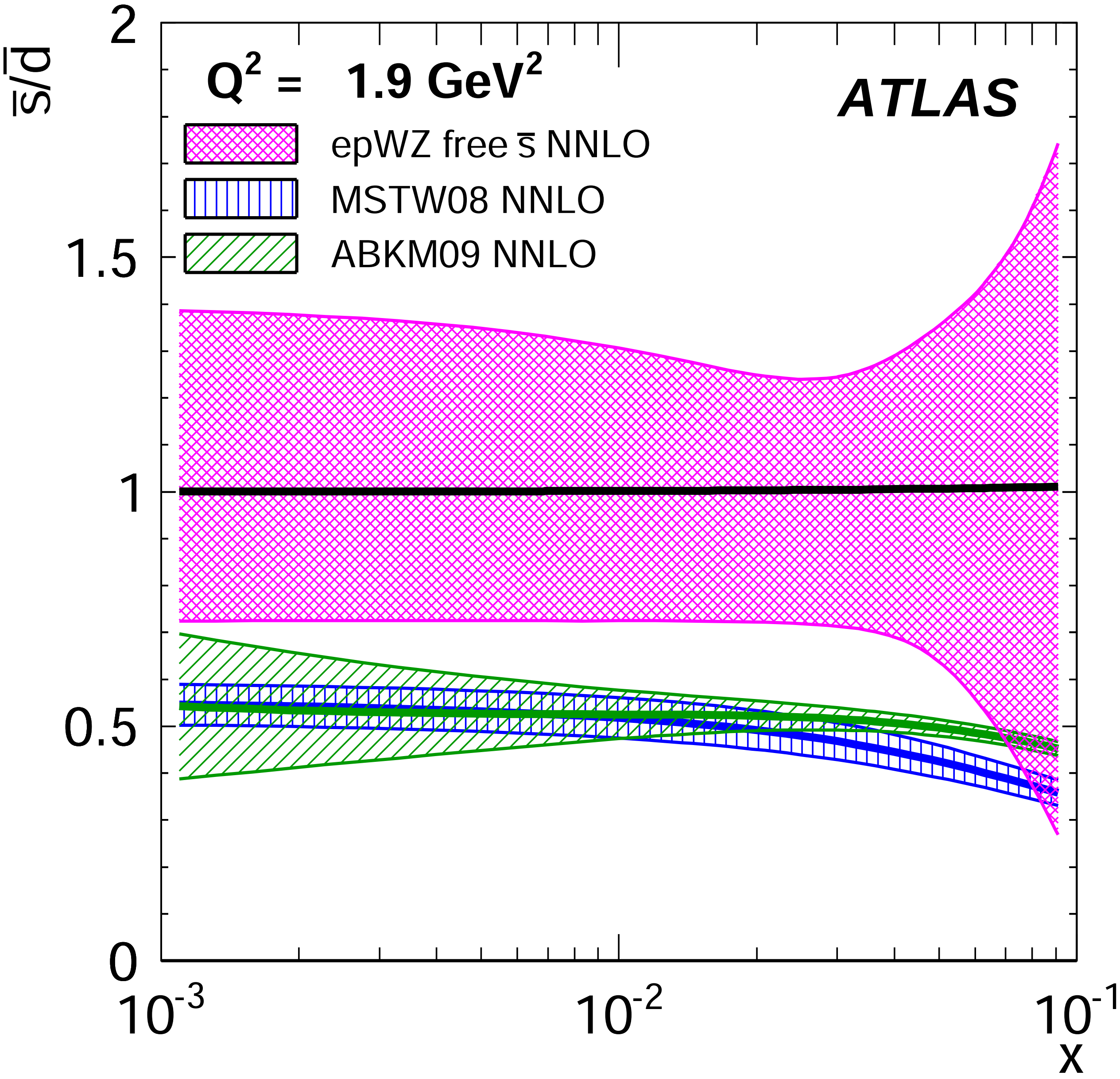

ATLAS
L dt = 33-36 pb -1
Data 2010 (√s = 7 TeV)
total uncertainty
exp. uncertainty
ABKM09
JR09
HERAPDF1.5
MSTW08
epWZ free s̄
9
9.5
10
10.5
11
fid W / fid Z/ *

Significant variation in PDFs (ABM similar to MSTW). Maybe partially explained by Q^2 cuts (MSTW $2\mathrm{GeV}^2$, NNPDF $3\mathrm{GeV}^2$, CT10 $4\mathrm{GeV}^2$). Strange almost unchanged if MSTW cut $5\mathrm{GeV}^2$.



Factor of $(1+m_c^2/Q^2)$ in NNPDF2.1 lowers MSTW a little - cuts different.

Correction of contribution from initial state charm quarks/subtraction from gluon ($\sigma \propto s+(1-y)^2\bar{c}, y=0.3-0.7$) to be consistent with acceptance corrections moves MSTW down very slightly (smaller $y \rightarrow$ smaller charm). Plot by G. Watt.

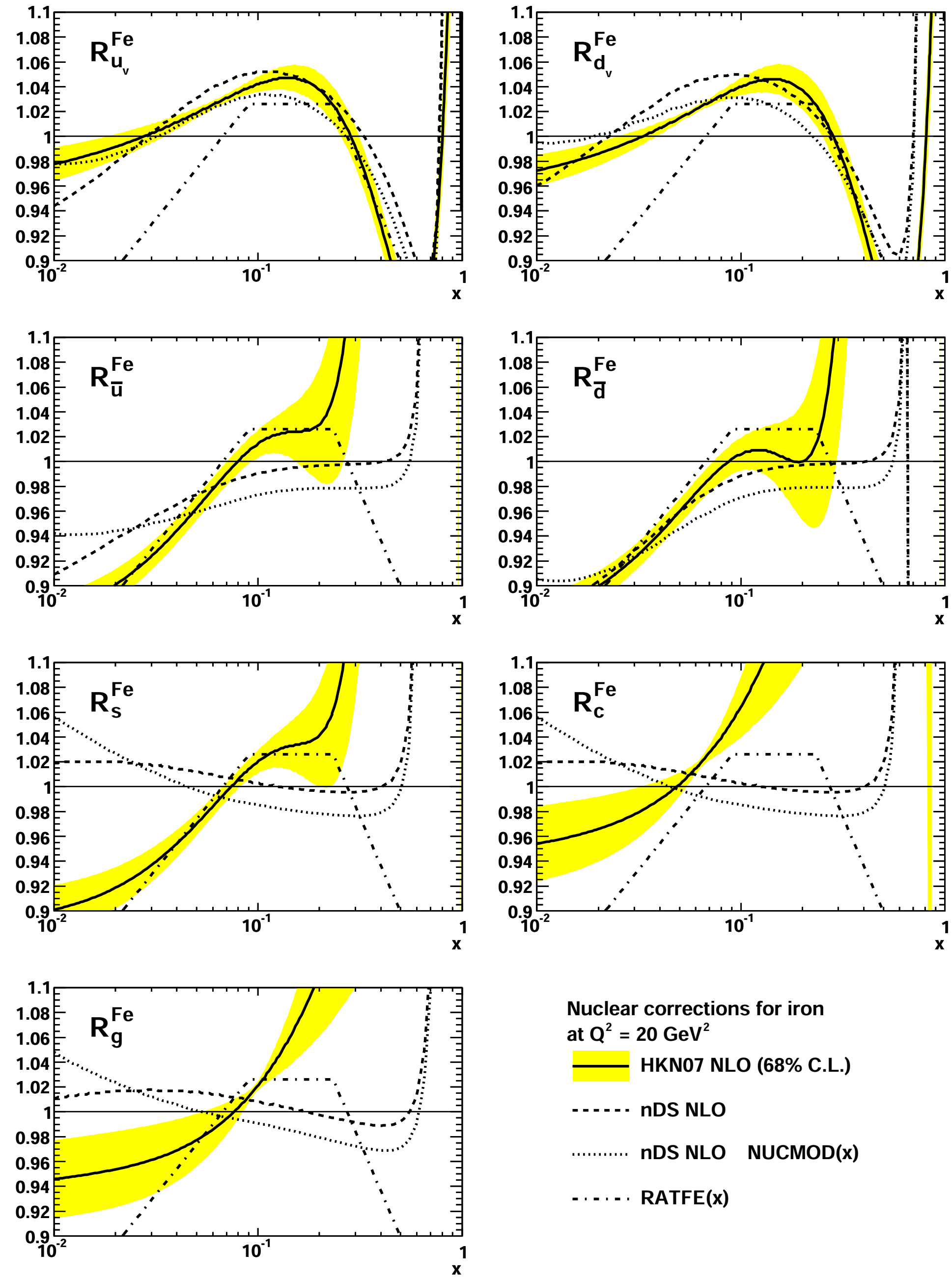


$\bar{s}/\bar{d}$
$Q^2 = 1.9\ GeV^2$
ATLAS
epWZ free $\bar{s}$ NNLO
MSTW08 NNLO
ABKM09 NNLO
2
1.5
1
0.5
0
10^{-3}
10^{-2}
10^{-1}
x

Requires use of nuclear corrections.

Can vary by $\sim 10\%$ at $x \sim 0.01$. A little more at low Q^2.

MSTW allow no penalty variation in nuclear corrections with three parameters (normalisation, low x shape and high x shape).



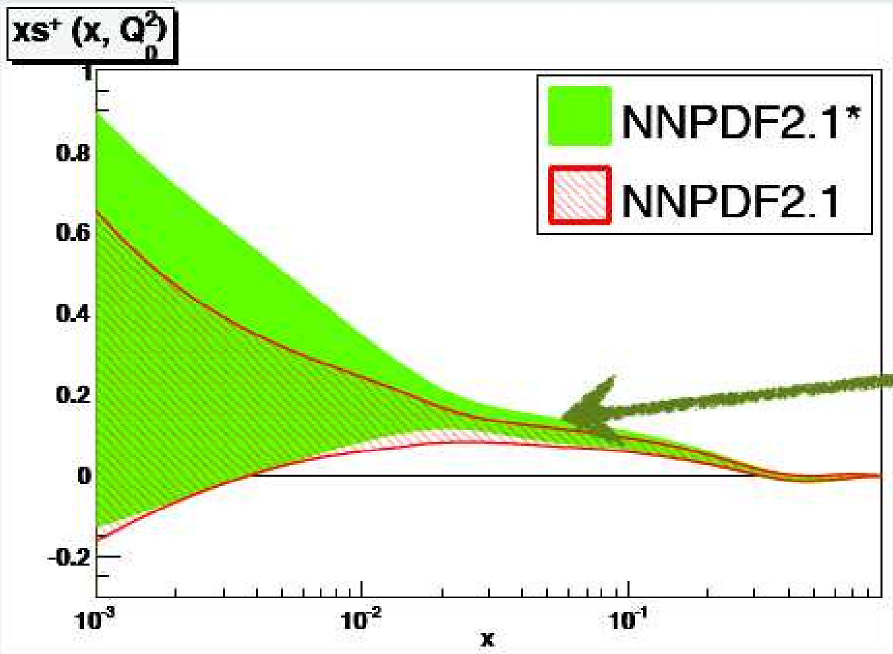
Strangeness

- Updated **minor inconsistency** on the treatment of **neutrino charm production cross section** (related to the definition of F_L in the massive scheme)

$$\tilde{\sigma}^{\nu(\bar{\nu}),c}(x,y,Q^2) \equiv \frac{1}{E_\nu}\frac{d^2\sigma^{\nu(\bar{\nu}),c}}{dx\,dy}(x,y,Q^2)$$
$$= \frac{G_F^2 M_N}{2\pi(1+Q^2/M_W^2)^2}\left[\left(\left(Y_+ - \frac{2M_N^2x^2y^2}{Q^2} - y^2\right)\left(1+\frac{m_c^2}{Q^2}\right) + y^2\right) F_{2,c}^{\nu(\bar{\nu})}(x,Q^2)\right.$$

Required in Improved ZM scheme
Not present for FONLL GM-VFN

- Marginal effect, **localized** for **strangeness** only around **x=0.03 (less than half-sigma shift)**
- Negligible impact for collider phenomenology (except maybe W+c)



Slightly **enhanced strangeness** near x=0.0
Improve **agreement** with MSTW08

Juan Rojo PDF4LHC Workshop, CERN, 23/05/2012

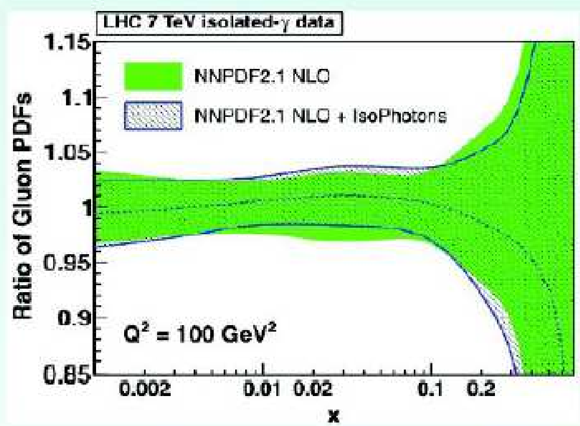
3.3) Observables : prompt photons

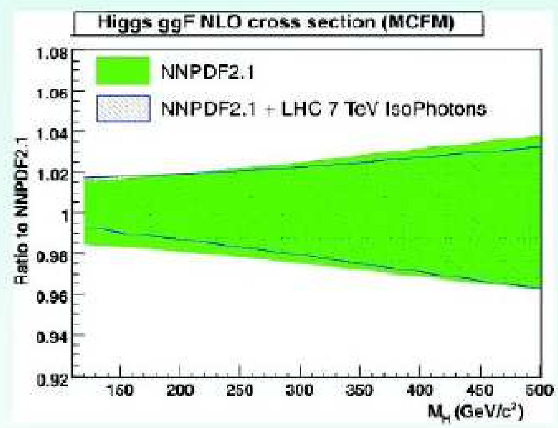
System	Collab./experiment (collider) [Ref.]	$\sqrt{s}$ (TeV)	$\lvert y_\gamma \rvert$ range	E_T^γ range (GeV)	x range	Data points	Isolation radius, had. energy
p–p	ATLAS (LHC) [34]	7.	<0.6	15–100	5×10^{-3}–0.05	8	$R = 0.4$, $E_h < 5$ GeV
p–p	ATLAS (LHC) [34]	7.	0.6–1.37	15–100	3×10^{-3}–0.1	8	$R = 0.4$, $E_h < 5$ GeV
p–p	ATLAS (LHC) [34]	7.	1.52–1.81	15–100	2×10^{-3}–0.1	8	$R = 0.4$, $E_h < 5$ GeV
p–p	ATLAS (LHC) [35]	7.	<0.6	45–400	5×10^{-3}–0.1	8	$R = 0.4$, $E_h < 4$ GeV
p–p	ATLAS (LHC) [35]	7.	0.6–1.37	45–400	5×10^{-3}–0.2	8	$R = 0.4$, $E_h < 4$ GeV
p–p	ATLAS (LHC) [35]	7.	1.52–1.81	45–400	2×10^{-3}–0.3	8	$R = 0.4$, $E_h < 4$ GeV
p–p	ATLAS (LHC) [35]	7.	1.81–2.37	45–400	2×10^{-3}–0.5	8	$R = 0.4$, $E_h < 4$ GeV
p–p	CMS (LHC) [37]	7.	<1.45	21–300	5×10^{-3}–0.1	11	$R = 0.4$, $E_h < 5$ GeV
p–p	CMS (LHC) [36]	7.	<0.9	25–400	5×10^{-3}–0.2	15	$R = 0.4$, $E_h < 5$ GeV
p–p	CMS (LHC) [36]	7.	0.9–1.44	25–400	2×10^{-3}–0.3	15	$R = 0.4$, $E_h < 5$ GeV
p–p	CMS (LHC) [36]	7.	1.57–2.1	25–400	10^{-3}–0.4	15	$R = 0.4$, $E_h < 5$ GeV
p–p	CMS (LHC) [36]	7.	2.1–2.5	25–400	10^{-3}–0.5	15	$R = 0.4$, $E_h < 5$ GeV
p–p	CMS (LHC) [38]	2.76	<1.45	20–80	10^{-3}–0.05	6	$R = 0.4$, $E_h < 5$ GeV

- Large list of measurements provided by LHC collaborations.
- Impact of isolated photons on the gluon PDF for x=0.01 - 0.1.

- Isolated γ production directly sensitive to *g(x)*: D. D'Enteria, J. Rojo NPB 860 (2012) 311

NNPDF Reweighing





CMS Experiment at the LHC, CERN

23/05/2012

M. Gouzevitch. Report on CMS PDF forum

8

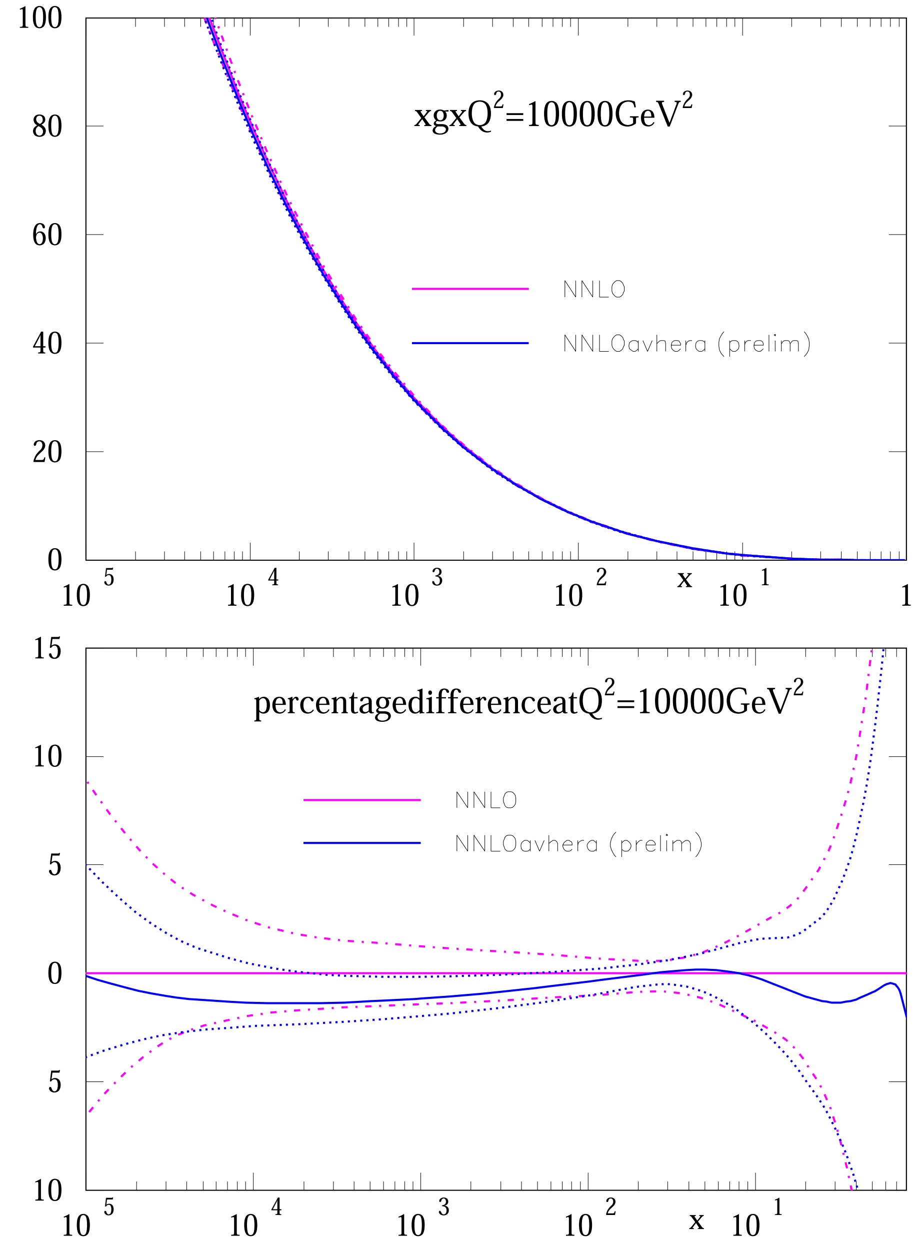
Comparison of gluon from fit using combined HERA data to MSTW2008 NNLO versions with $1-\sigma$, uncertainty shown.

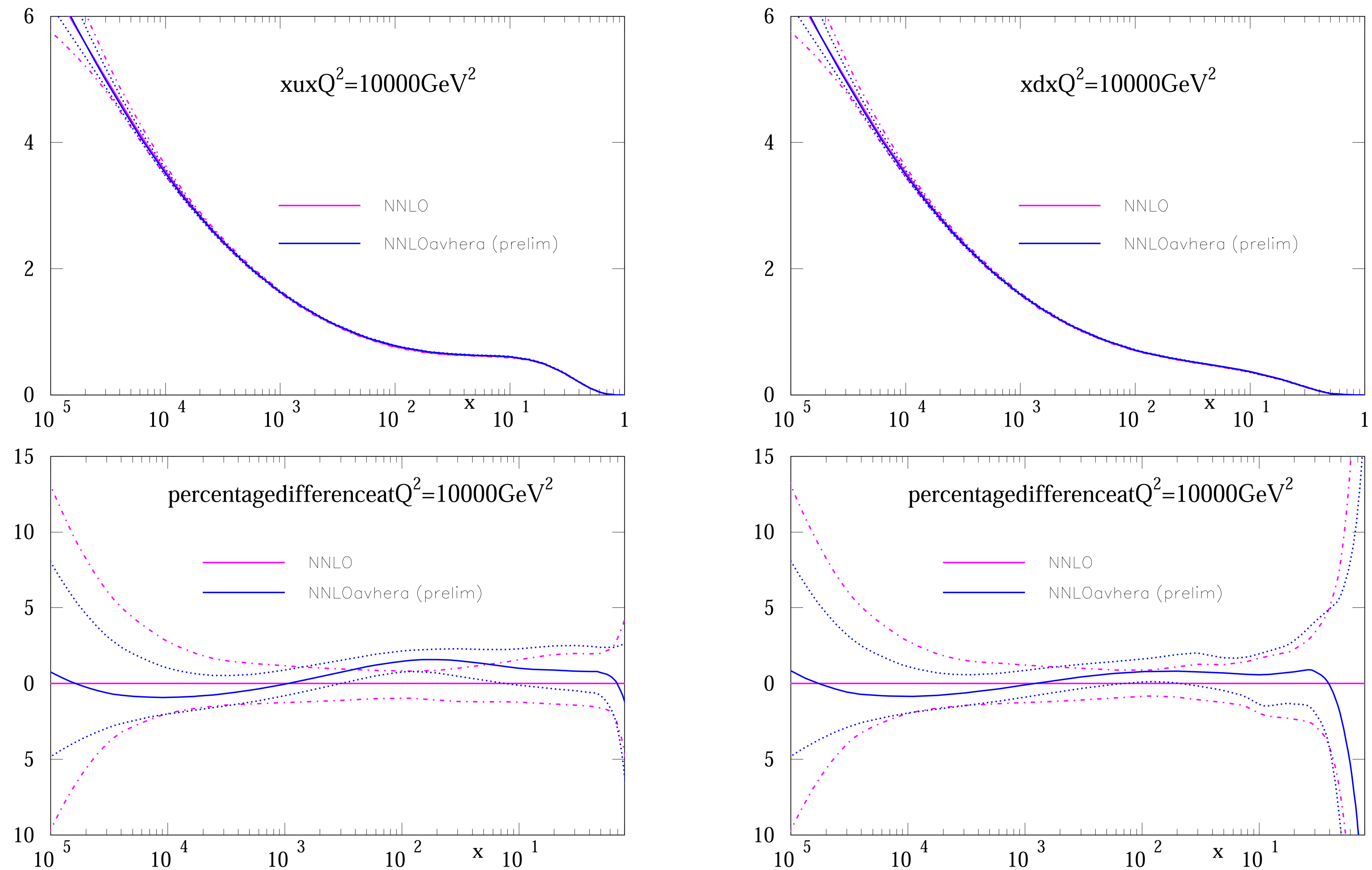
Slight difference in details of normalisation treatment compared to previous versions, still preliminary. First times showed uncertainty.

Value of $\alpha_S(M_Z^2)$ moves slightly, $0.1171 \rightarrow 0.1178$.

Changes always within $1-\sigma$, and really less due to correlations with α_S.

Uncertainty slightly smaller, especially at very small x.





Most dramatic change for up quark at about $x = 0.01$.

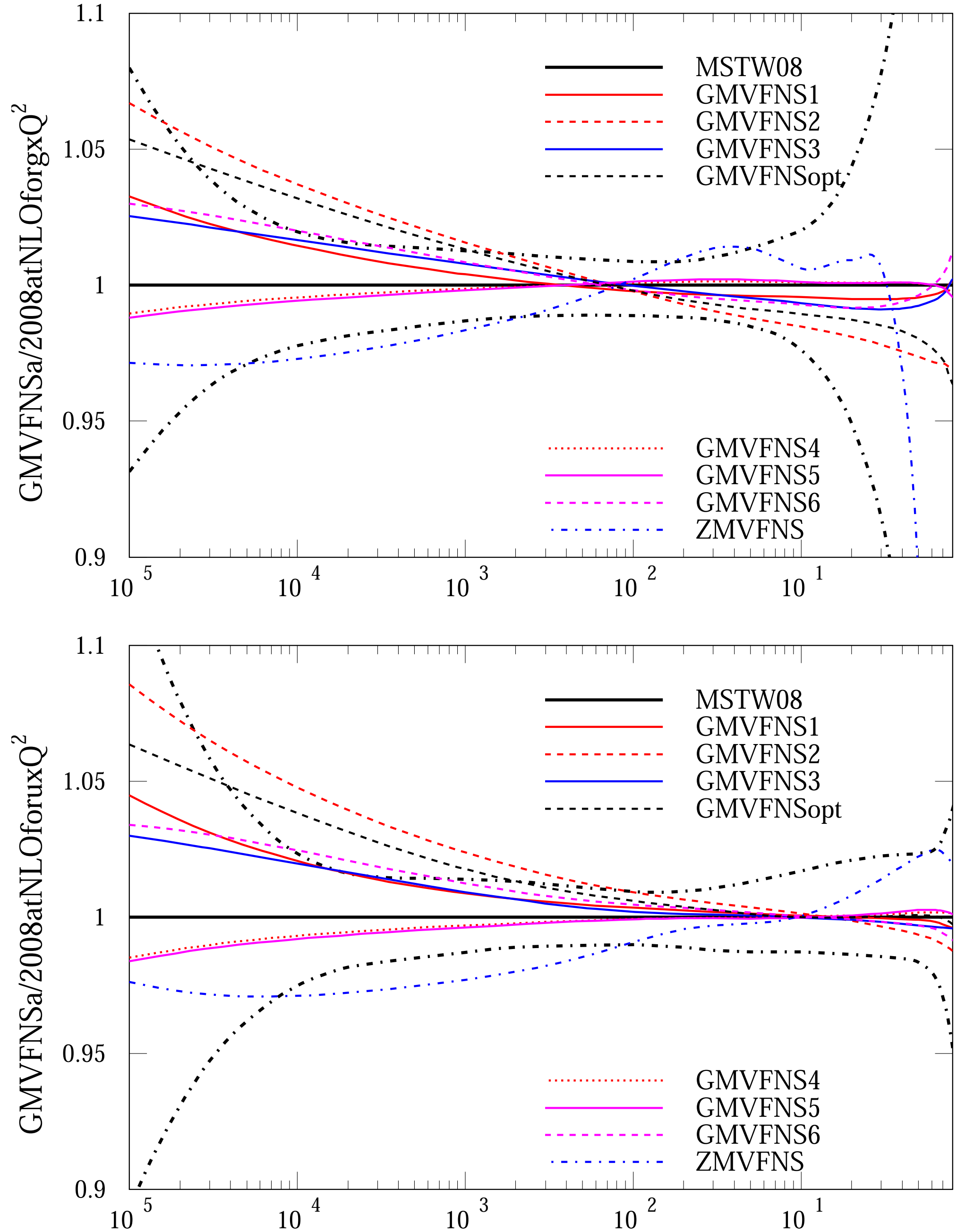
Variations in partons extracted from global fit due to different choices of GM-VFNS at NLO.

Initial χ^2 can change by 250.

Converges to at most about 15 of original.

Better fit for GMVFNS1, GMVFNS3 and GMVFNS6.

Some changes in PDFs large compared to one-sigma *uncertainty*.



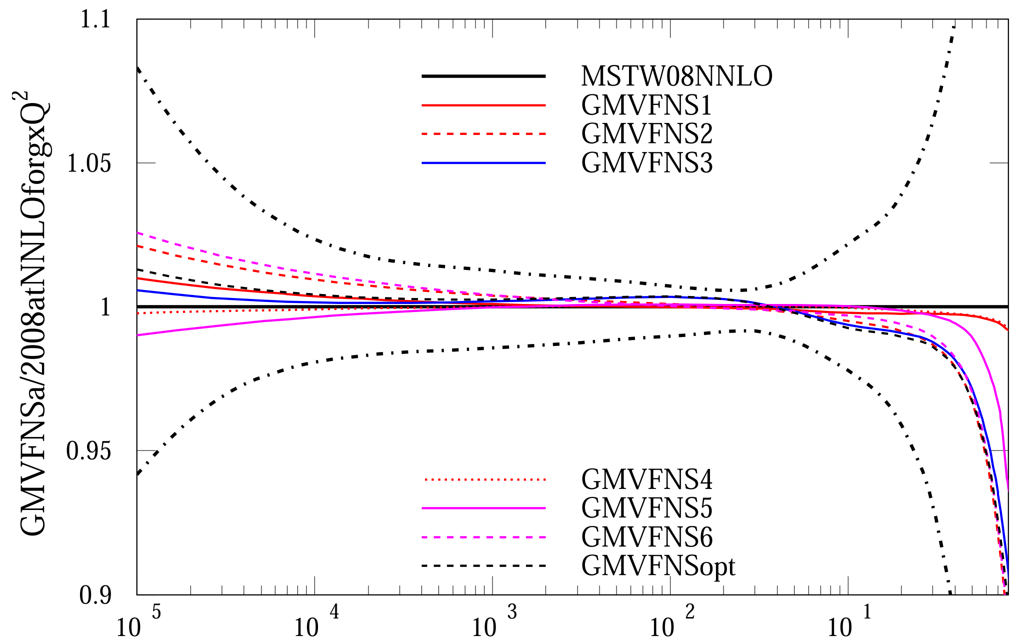
Variations in partons extracted from global fit due to different choices of GM-VFNS at NNLO.

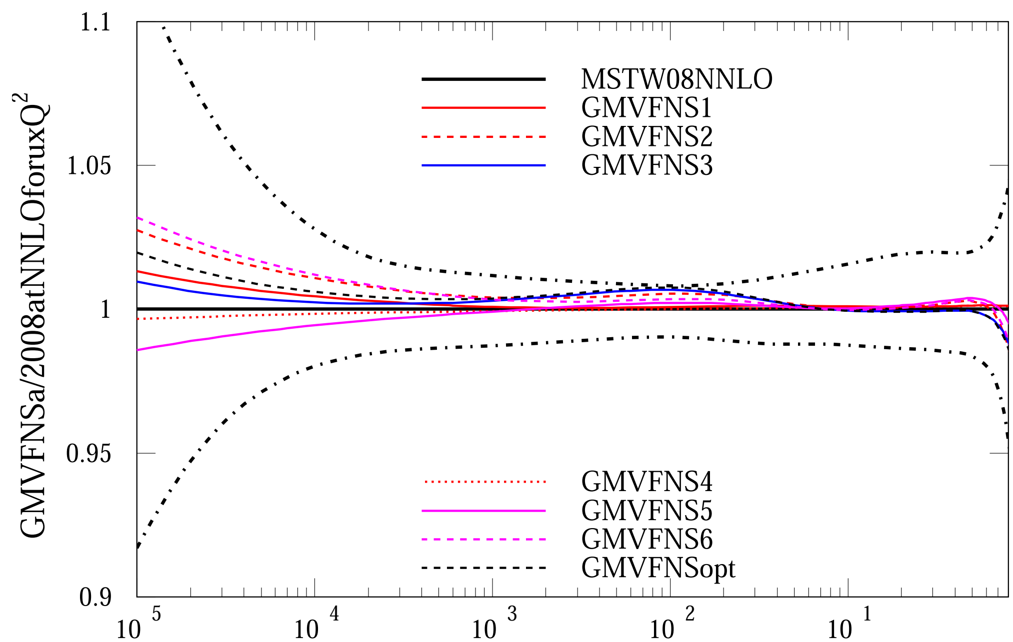
Initial changes in $\chi^2 < 20$.

Converge to about 10. None a marked improvement.

At worst changes approach *uncertainty*.

Biggest variation in high-x gluon, which has large uncertainty.





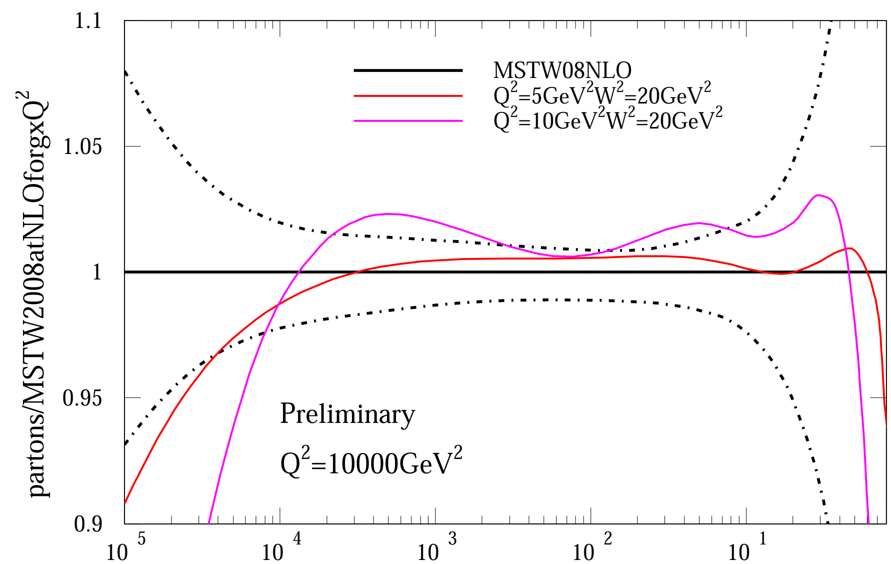
Investigation to stability under changes in cuts.

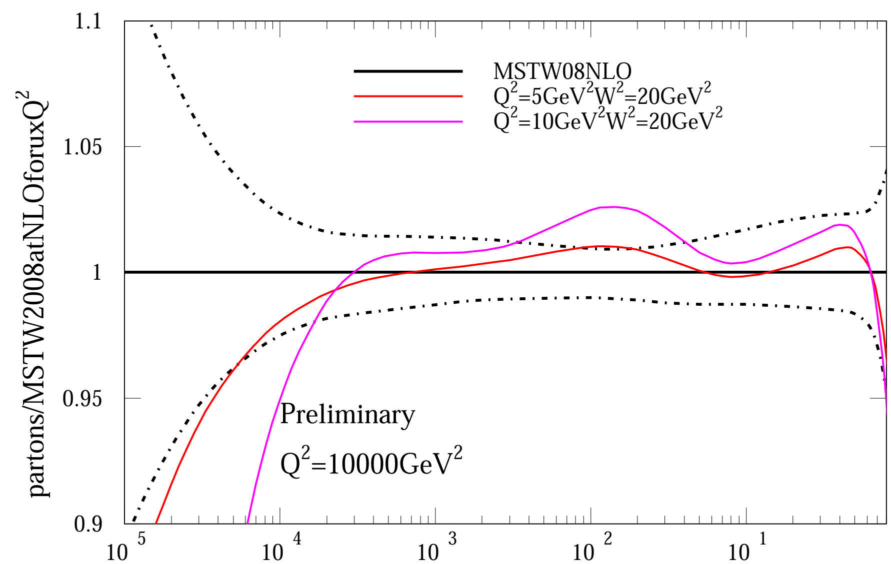
Raise $W^2_{\rm cut}$ to $20{\rm GeV}^2$, but no real changes.

Also raise $Q^2_{\rm cut}$ to $5{\rm GeV}^2$ and then $10{\rm GeV}^2$.

At NLO some movement just outside default error bands at general x.

Find $\alpha_S(M_Z^2) = 0.1202 \rightarrow 0.1193 \rightarrow 0.1175$, though for $Q^2 = 10{\rm GeV}^2$ cut error has roughly doubled to about 0.0025.

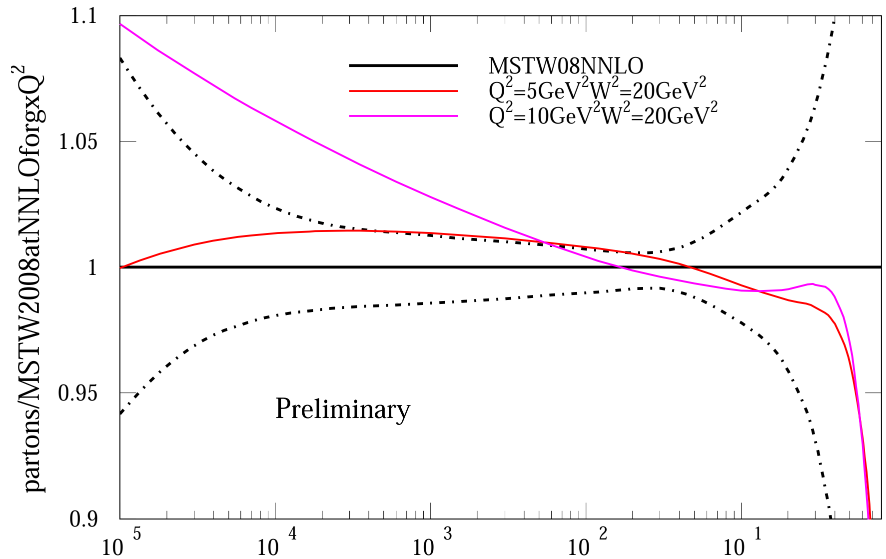


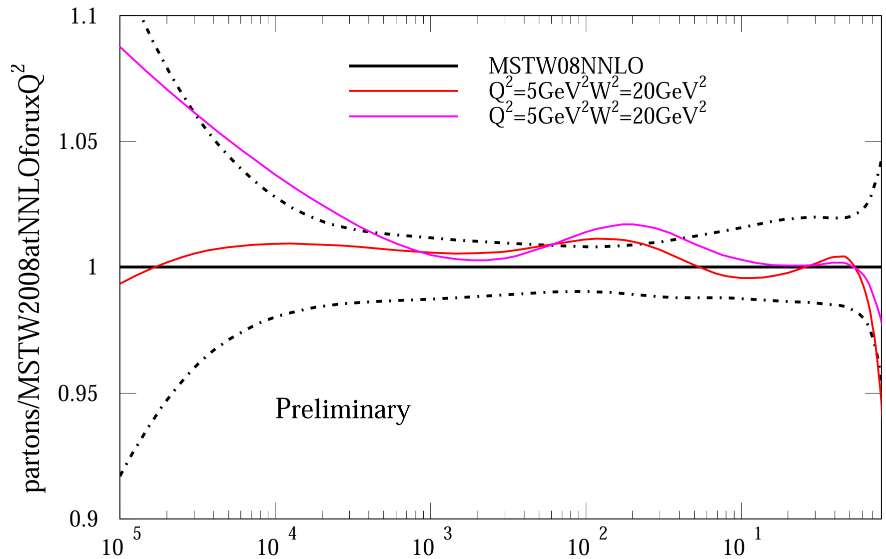


At NNLO most movement outside default error bands at low x, where constraint vanishes as Q^2 cut raises.

For $Q^2_{\rm cut} = 10{\rm GeV}^2$ no points below $x = 0.0001$, and little lever arm for evolution constraint for a bit higher.

Find $\alpha_S(M_Z^2) = 0.1171 \rightarrow 0.1171 \rightarrow 0.1164$, i.e. no change of significance.





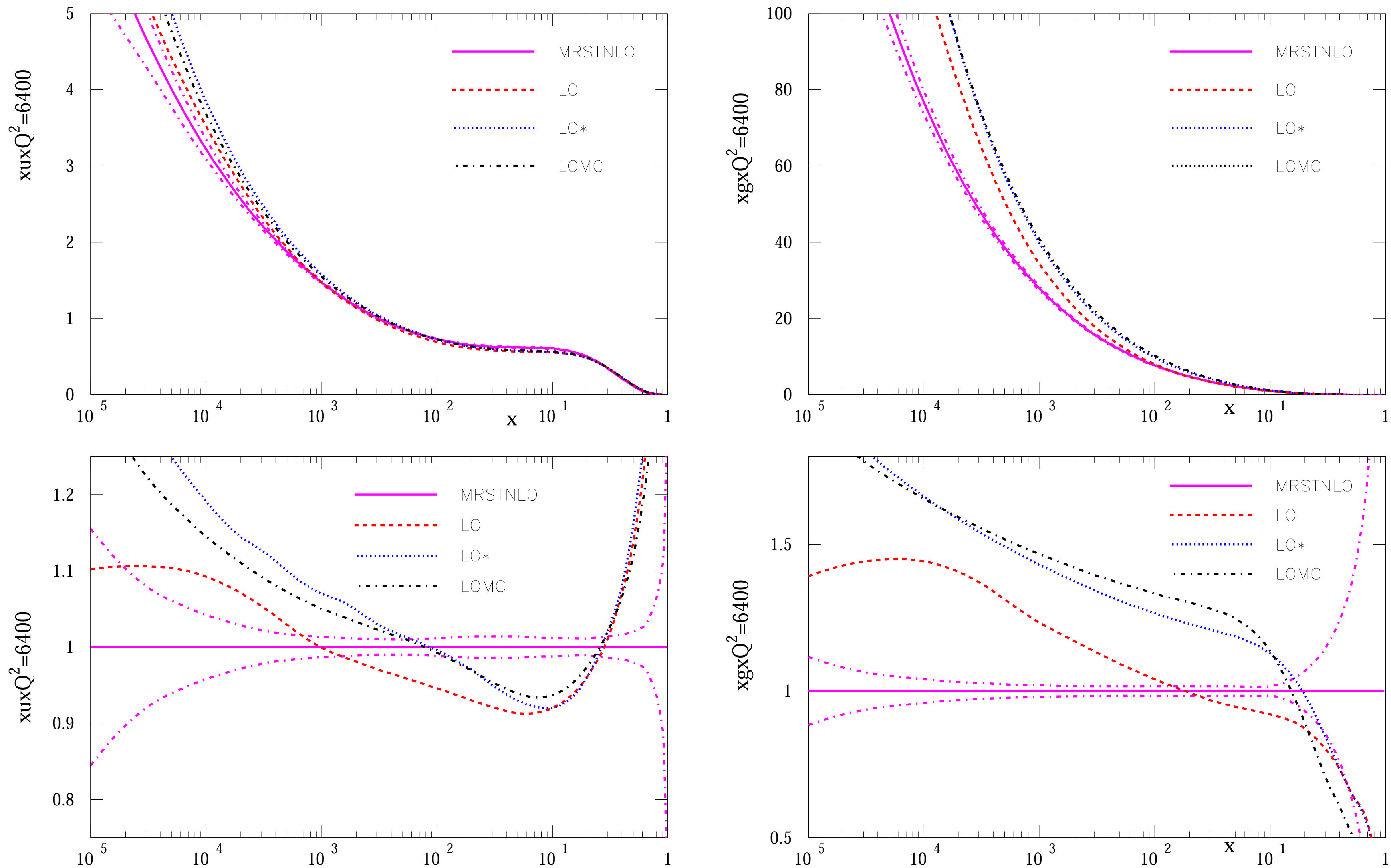
The % change in the cross sections after cuts ($M_H = 165\mathrm{GeV}$).

	NLO $Q^2_{\mathrm{cut}}=5\mathrm{GeV}^2$	NLO $Q^2_{\mathrm{cut}}=10\mathrm{GeV}^2$	NNLO $Q^2_{\mathrm{cut}}=5\mathrm{GeV}^2$	NNLO $Q^2_{\mathrm{cut}}=10\mathrm{GeV}^2$
W Tev	0.0	-2.4	-0.7	-0.4
Z Tev	0.0	-0.8	-0.4	0.0
W LHC (7TeV)	-0.2	-0.1	-0.2	-0.2
Z LHC (7TeV)	-0.2	-0.3	-0.4	-0.5
W LHC (14TeV)	-0.6	-1.1	0.3	0.8
Z LHC (14TeV)	-0.6	-1.5	0.2	0.4
Higgs TeV	-1.1	-1.5	-1.2	-3.2
Higgs LHC (7TeV)	-0.8	-2.5	0.4	-1.8
Higgs LHC (14TeV)	-0.9	-1.9	1.0	-0.8

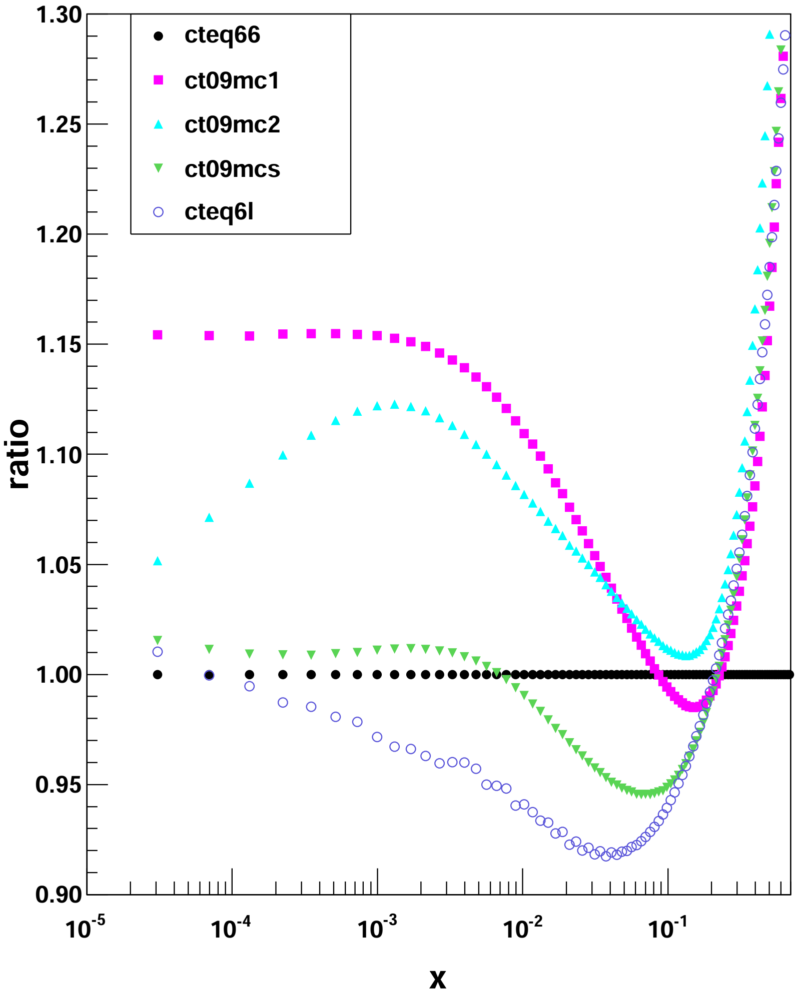
More variation at NLO than at NNLO, i.e. 7 changes of $> 1\%$ compared to 4.

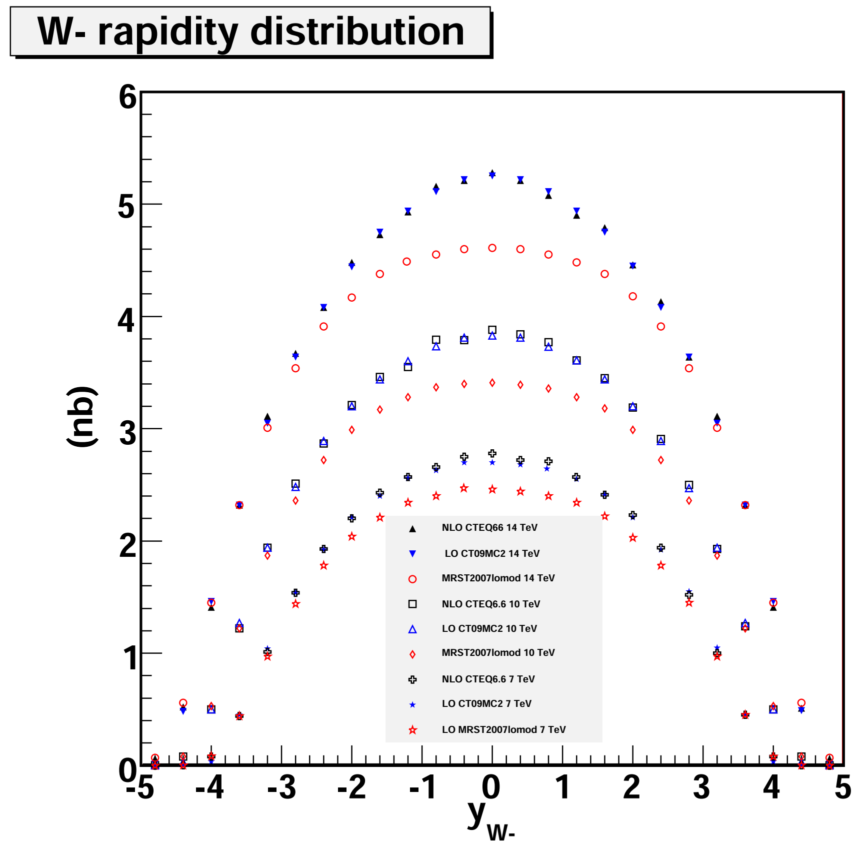
However, both small, and changes with change in Q^2_{cut} slow. Does not suggest significant higher twist or problem with default cuts.

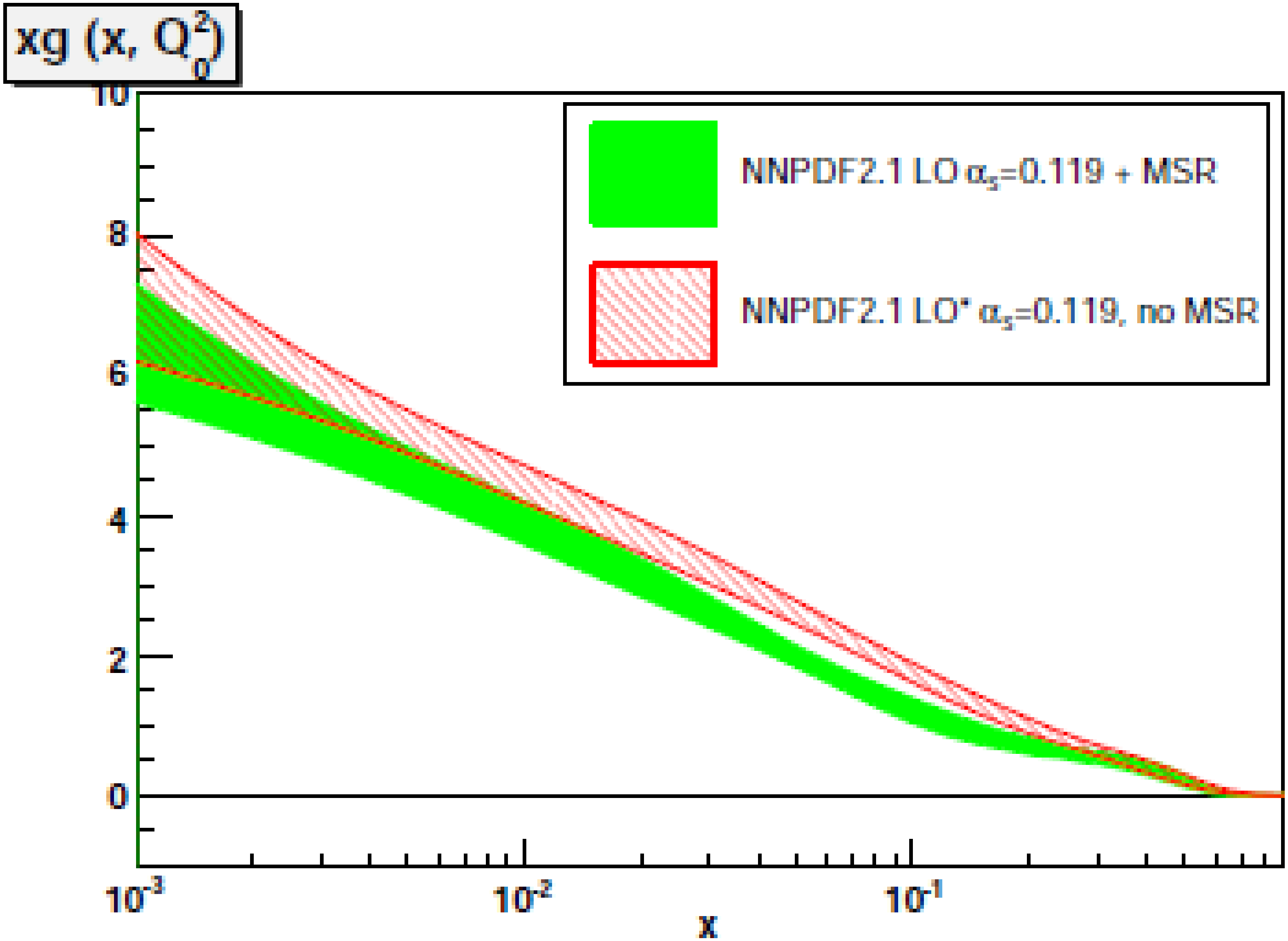
Partons rather insensitive to change. LOMC far more similar to LO* than to LO and NLO.



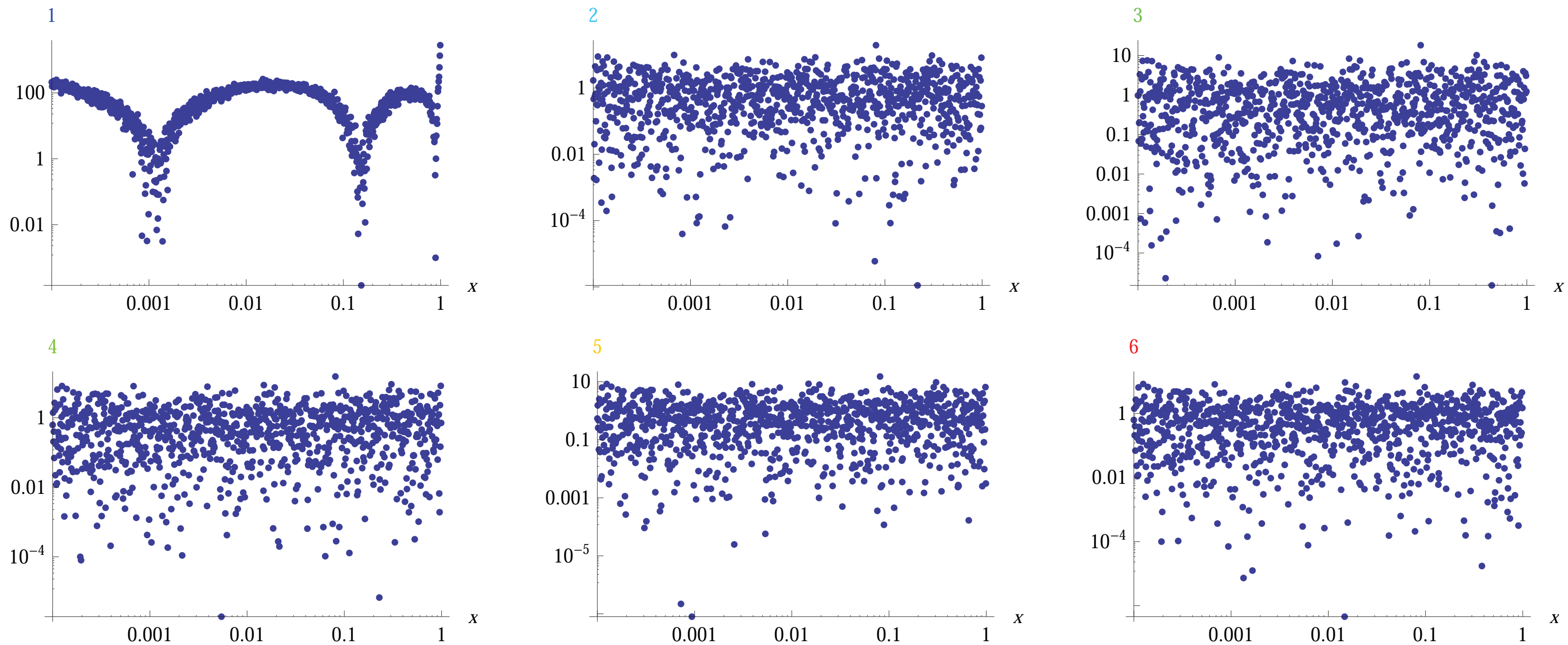
Q value: 85 GeV, for parton: u






xg (x, Q_0^2)
NNPDF2.1 LO α_s=0.119 + MSR
NNPDF2.1 LO* α_s=0.119, no MSR
10
8
6
4
2
0
10^{-3}
10^{-2}
10^{-1}
x

Contributions to χ^2.

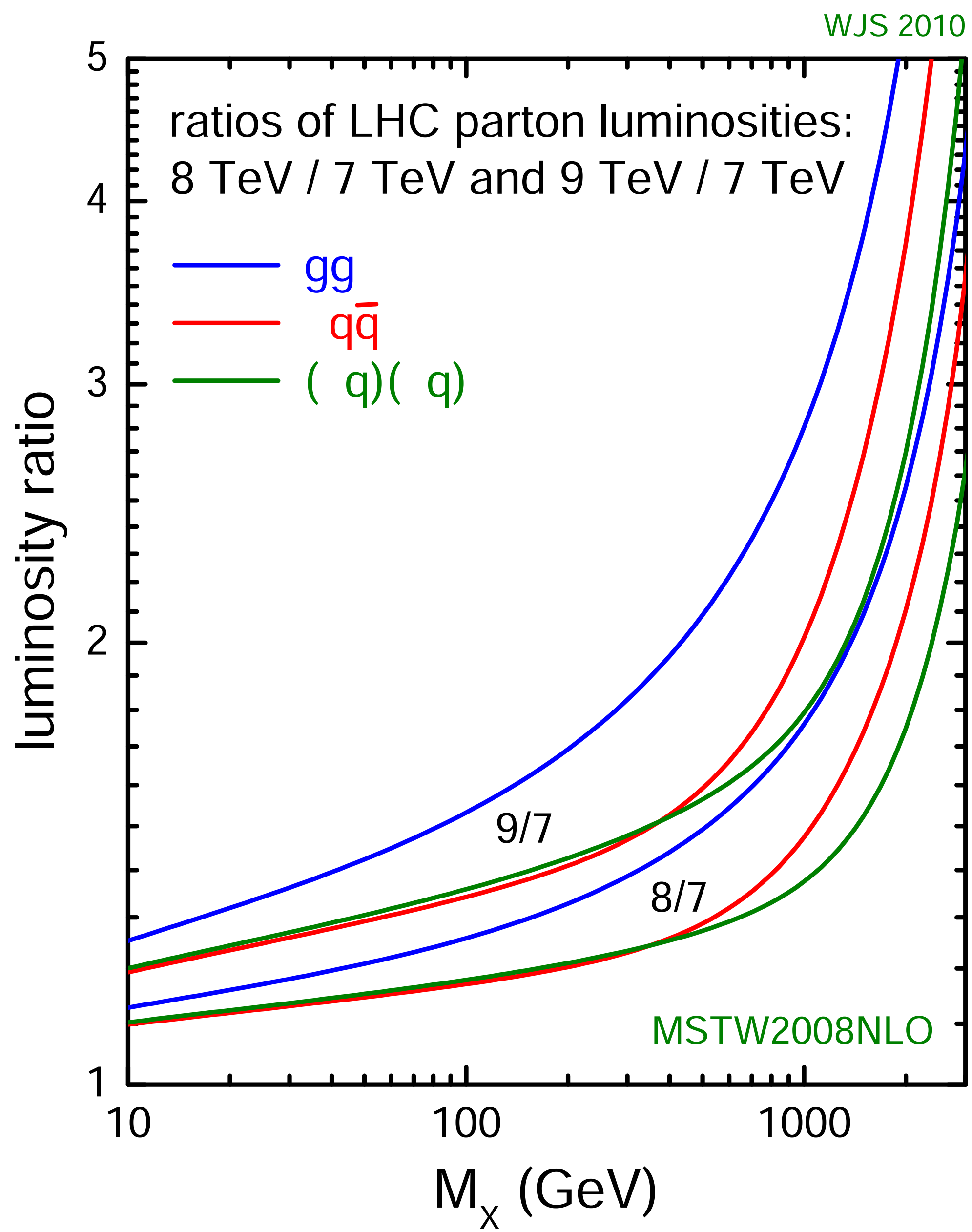


After $5 - 6$ polynomials start fitting noise, i.e. χ^2 lower than real function.

Conclude 4 parameters fine. (Note first 2 just re-expression of standard MSTW parameterisation.)

What are the advantages of running at $8\mathrm{TeV}$?

Limited for quark dominated processes up to $m_X > 1\mathrm{TeV}$, but more for gluon dominated processes for $M_X > 200 - 300\mathrm{GeV}$.



What about running at $14\mathrm{TeV}$ and $33\mathrm{TeV}$?