# MSTW Parton Distributions – Status

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**New data included.**

NuTeV and CHORUS data on $F_2^{\nu,\bar{\nu}}(x,Q^2)$ and $F_3^{\nu,\bar{\nu}}(x,Q^2)$ replacing CCFR.

NuTeV and CCFR dimuon data included directly. Leads to a direct constraint on $s(x,Q^2)+\bar{s}(x,Q^2)$ and on $s(x,Q^2)-\bar{s}(x,Q^2)$. Affects other partons.

CDFII lepton asymmetry data in two different $E_T$ bins – $25\mathrm{GeV} < E_T < 35\mathrm{GeV}$ and $35\mathrm{GeV} < E_T < 45\mathrm{GeV}$. D0II data for $E_T > 20\mathrm{GeV}$.

CDFII (prel) and D0II data on $d\,\sigma(Z)/d\,y$ for $0 < y < 3$.

HERA inclusive jet data (in DIS).

New CDFII and D0II high-$E_T$ jet data.

Direct high-$x$ data on $F_L(x,Q^2)$.

All published charm structure function data.

Would like averaged HERA structure function data. (Systematics currently meaningless?)

**Major changes in theory.**

Implementation of updated heavy flavour VFNS, particularly at NNLO. Already use in MRST06 NNLO distributions, but not in official NLO sets. (Already used a general VFNS since 1998 but change in details.)

Inclusion of NNLO corrections (Anastasiou, Dixon, Melnikov, Petriello) Drell-Yan ( $W, Z$ and $\gamma^*$) data using Vrap and FEWZ.

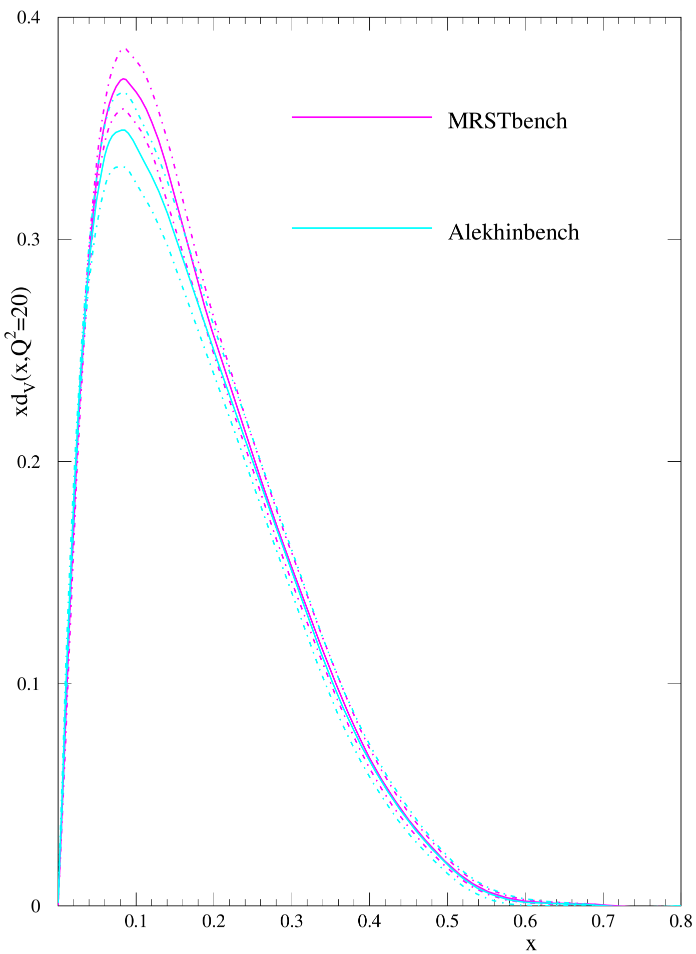
Change in definition of $\alpha_S$ – same as QCDNUM, Pegasus. No $\Lambda_{QCD}$ parameter.

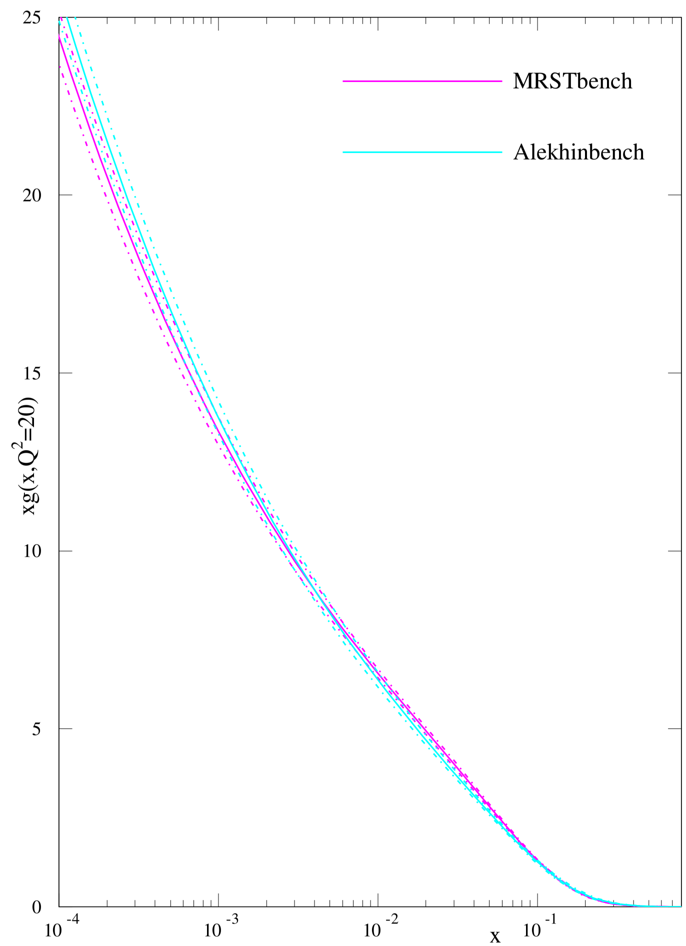
Improved nuclear corrections, De Florian and Sassot obtained from NLO partons.

Implementation of fastNLO – fast perturbative QCD calculations Kluge, Rabbertz, Wobisch. Allows easy inclusion of new jet data from both Tevatron and HERA.

Change in means of obtaining uncertainties. Still diagonalise covariance matrix of parameters and use 20 (previously 15) orthogonal eigenvectors. Tolerance now determined differently.

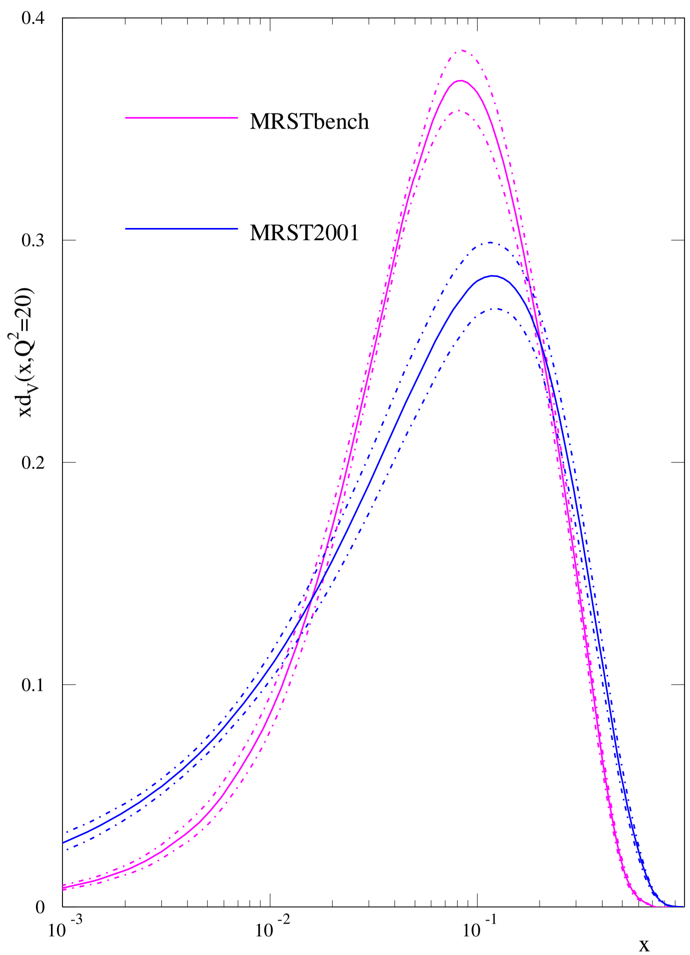
**Treatment of errors.** – exercise for $HERA-LHC$ meeting. Fit structure function data from H1, ZEUS, NMC and BCDMS, for $Q^2 > 9\mathrm{GeV}^2$ using $ZM-VFNS$. Very conservative fit. Safe partons?

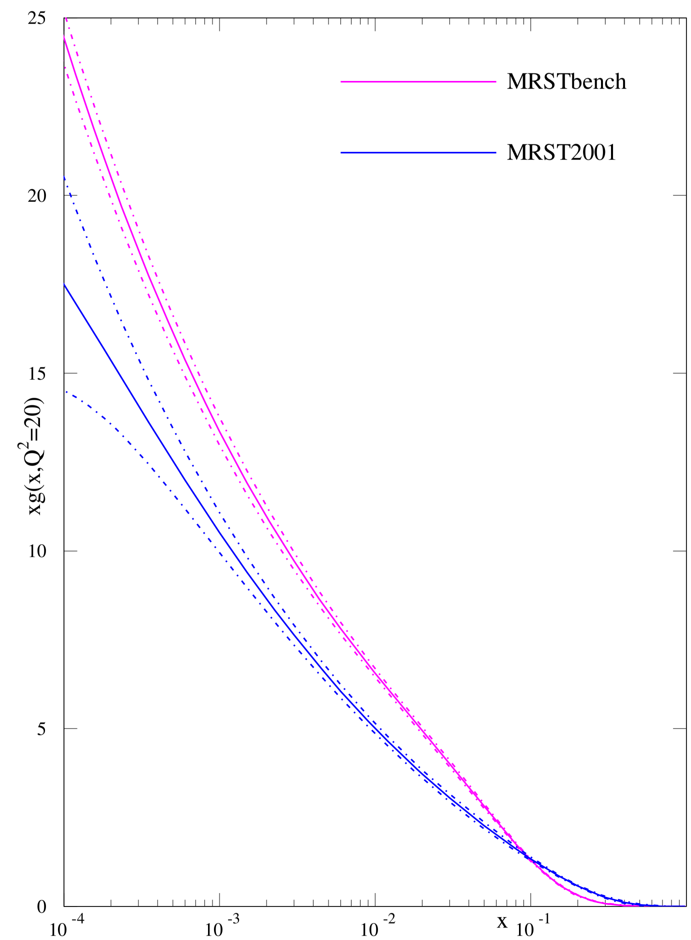



Compare rigorous treatment of all systematic errors (Alekhin) with simple quadratures approach (MRST), both with $\Delta\chi^2 = 1$. $\rightarrow$ some difference in central values (other possible reasons) and similar errors.

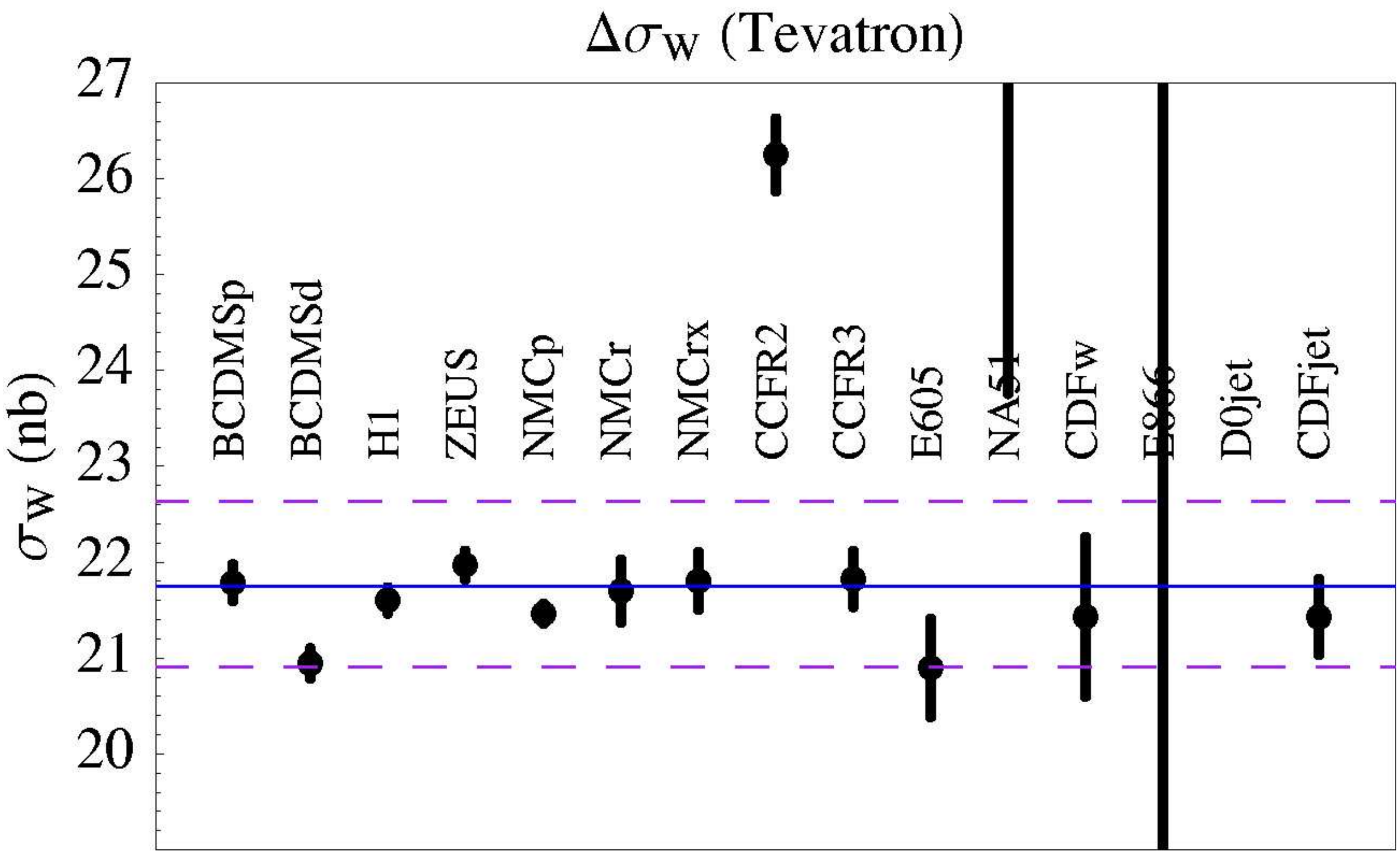
However, how do partons from very conservative, structure function only data compare to global partons? Compare to MRST01 partons with uncertainty from $\Delta\chi^2 = 50$. Enormous difference in central values. Errors similar. Moreover $\alpha_S(M_Z^2) = 0.1110 \pm 0.0015$ compared to $\alpha_S(M_Z^2) = 0.119 \pm 0.002$.



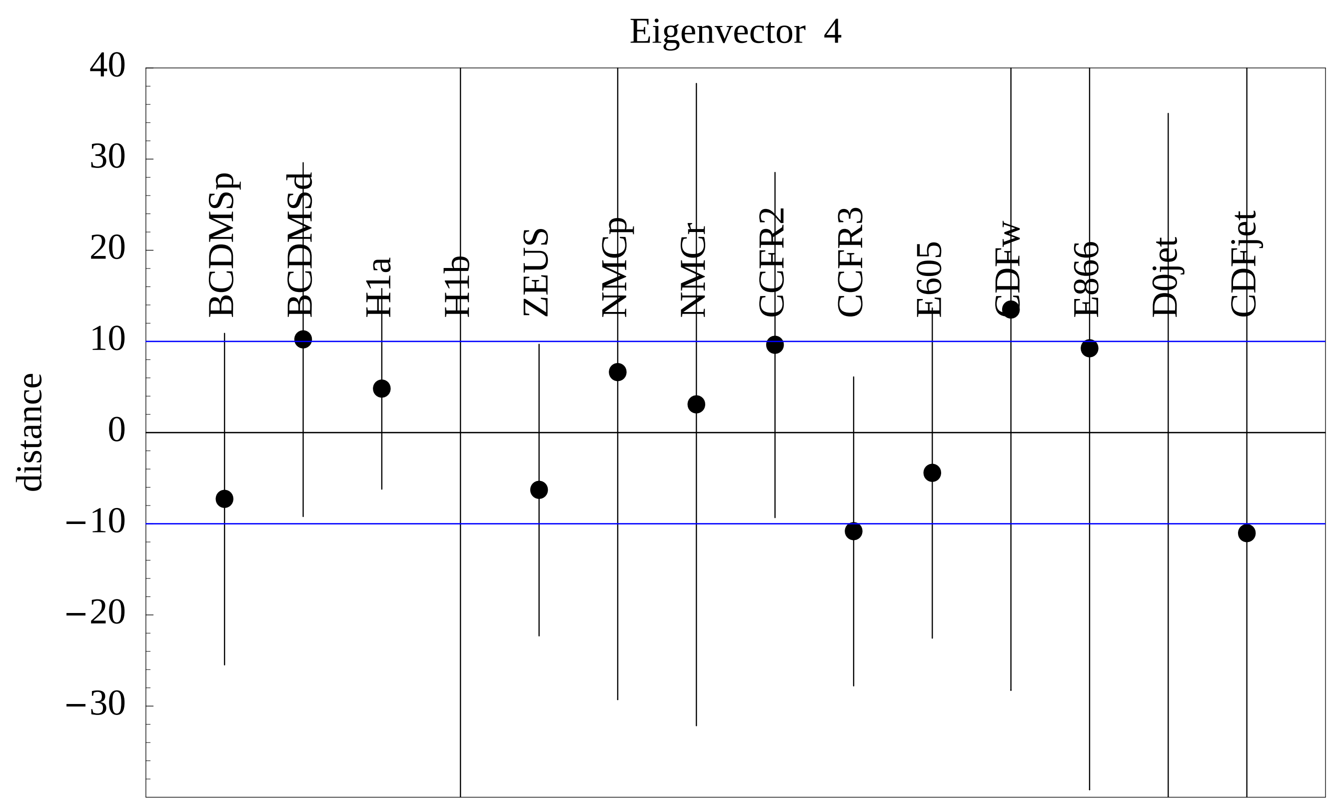

Conclude that fit using small sample of data sets and standard $\Delta\chi^2 = 1$ not a good way of proceeding. (Monte Carlo approach different alternative).

The inappropriateness of using $\Delta\chi^2 = 1$ when including a large number of sometimes conflicting data sets is shown by examining the best value of $\sigma_W$ and its uncertainty using $\Delta\chi^2 = 1$ for individual data sets as obtained by CTEQ using Lagrange Multiplier technique.



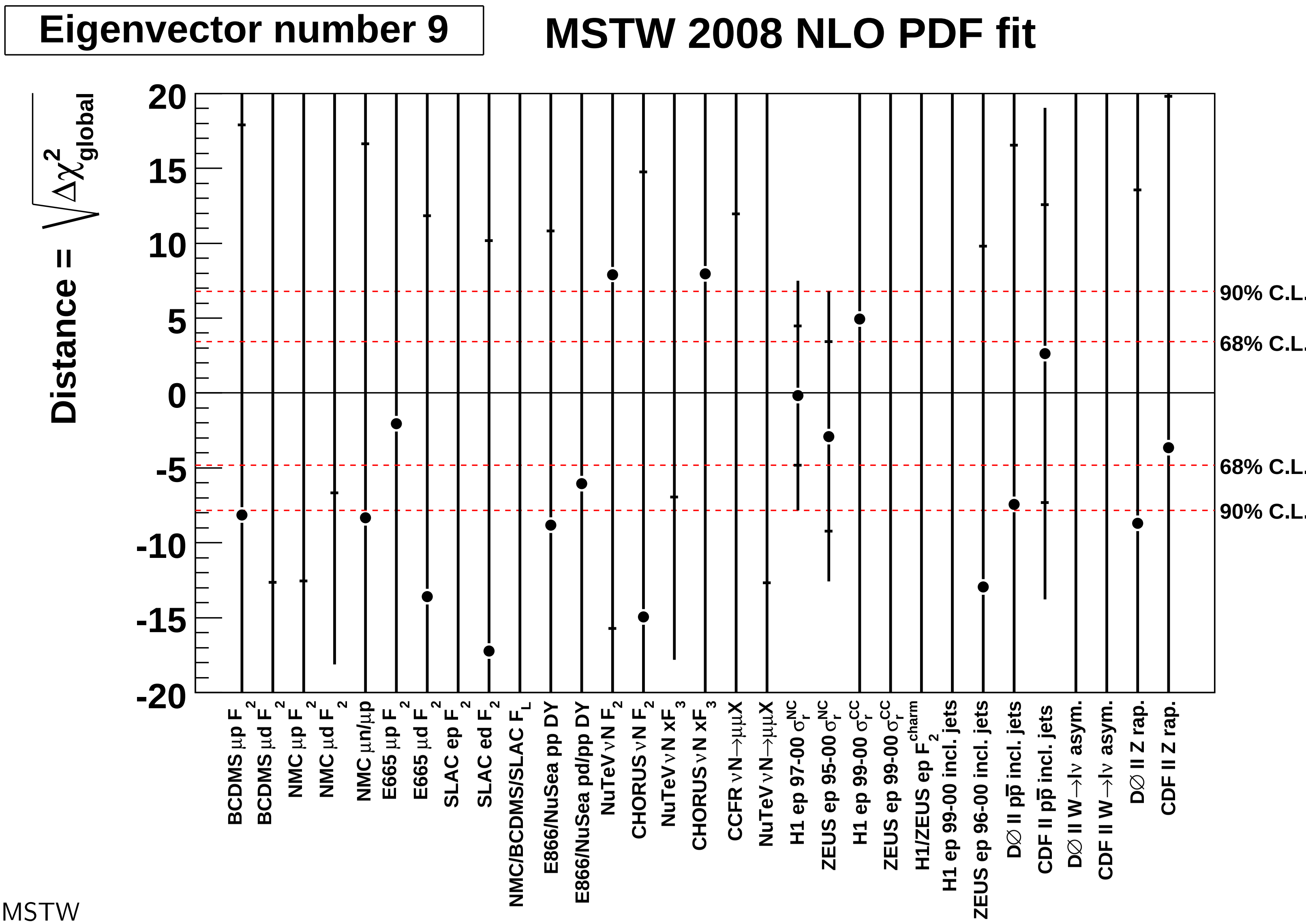
Alternative reasoning, allow $\Delta\chi^2$ to take a value such that every data set remains roughly within its $90\%$ confidence limit compared to the $\chi^2$ at best global fit.

These limits shown for CTEQ6 eigenvector 4 as function of $T = \sqrt{\Delta\chi^2}$. Some sets somewhat outside $90\%$ confidence limits for $T = 10$

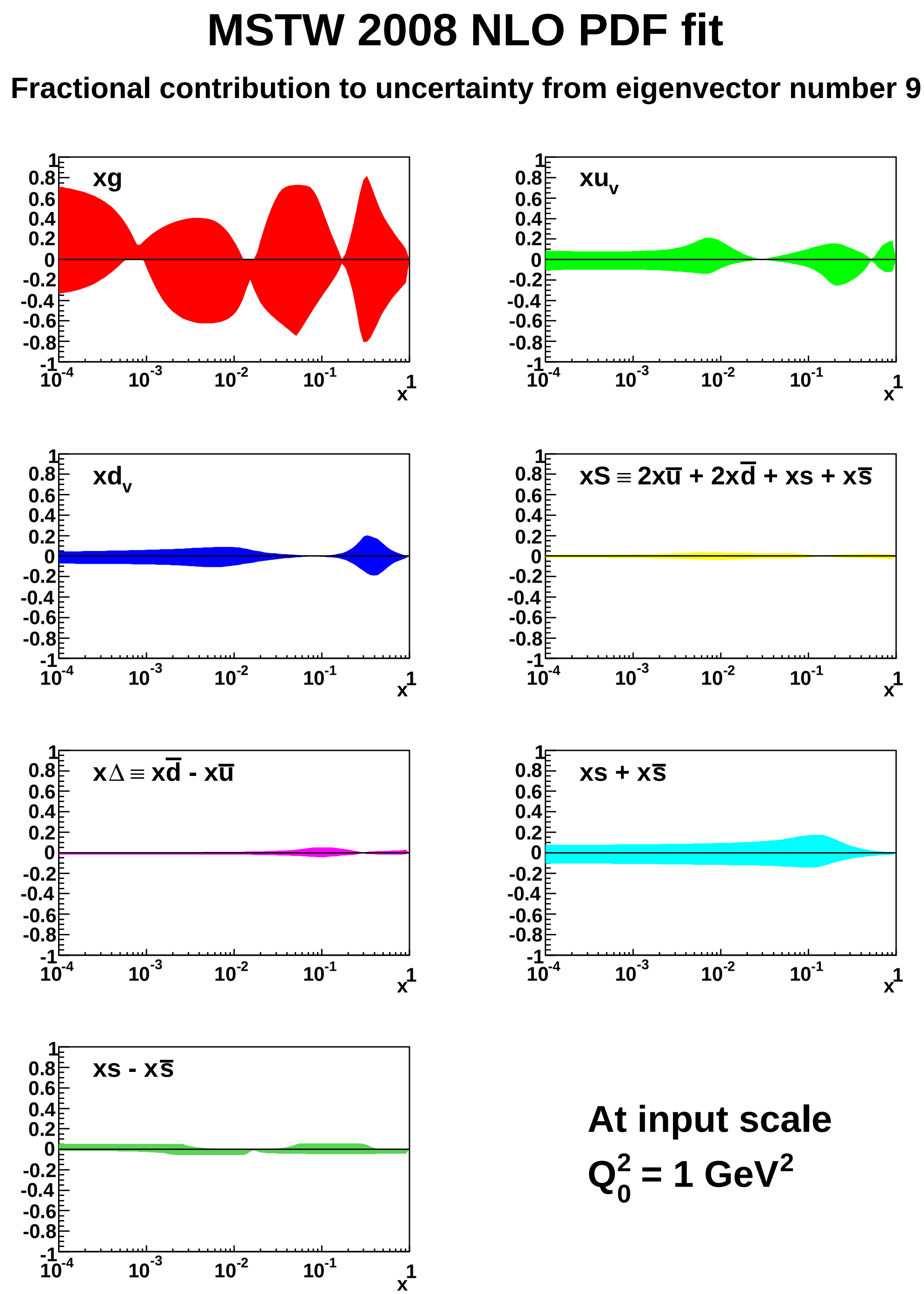



Using similar sort of reasoning MRST used $\Delta\chi^2 \sim 50$ for $90\%$ confidence level on partons. Still same basic idea but more sophisticated.

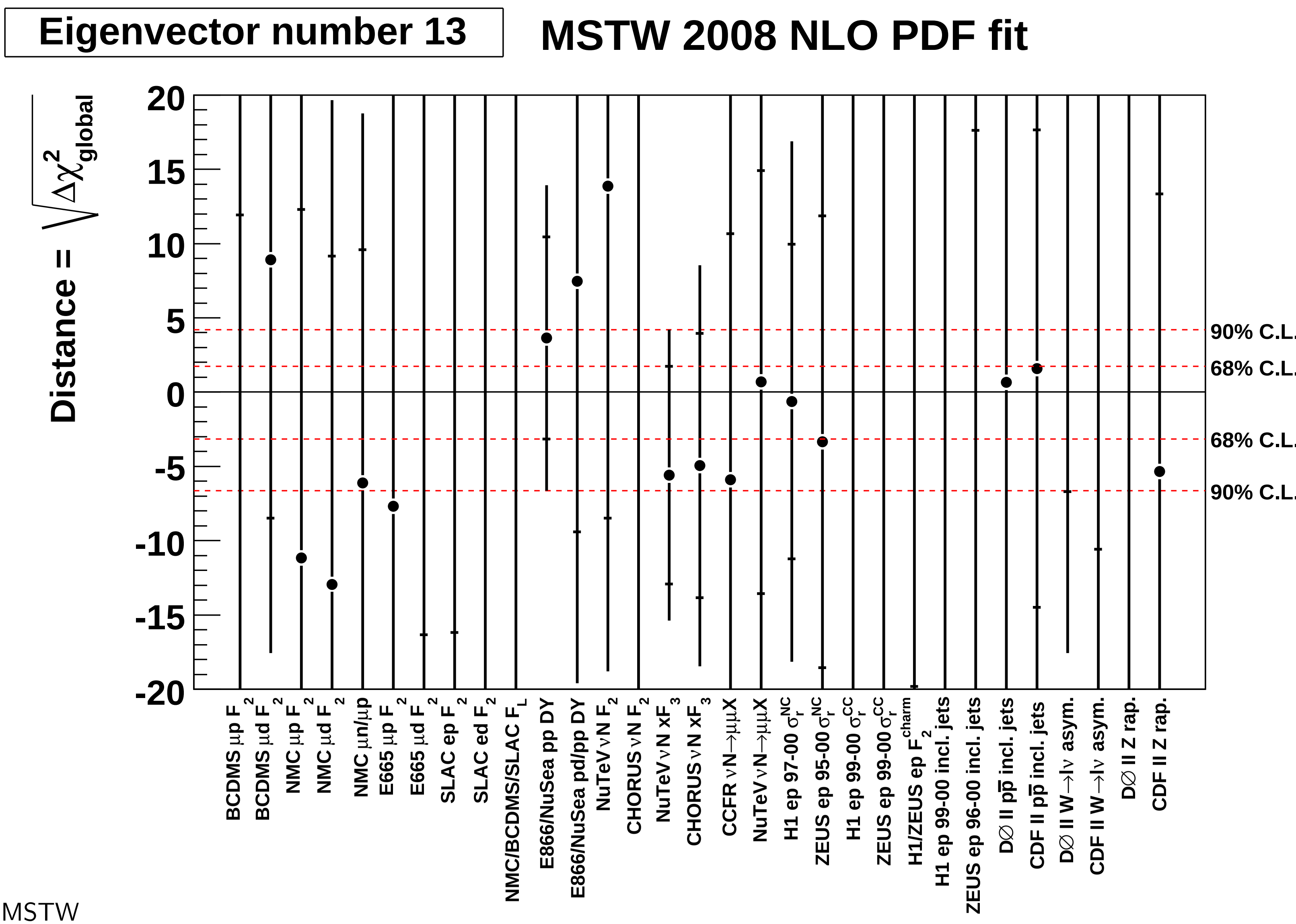
Examine variation in $\chi^2$ for each data set for an eigenvector as function of $\Delta\chi^2$ for global fit. Eigenvector 9 constrained most by H1 and ZEUS data on $F_2^p(x, Q^2)$. 90% confidence limit determining by ZEUS in $up$ direction and H1 in $down$ direction. Both $\Delta\chi^2 \approx 50$.



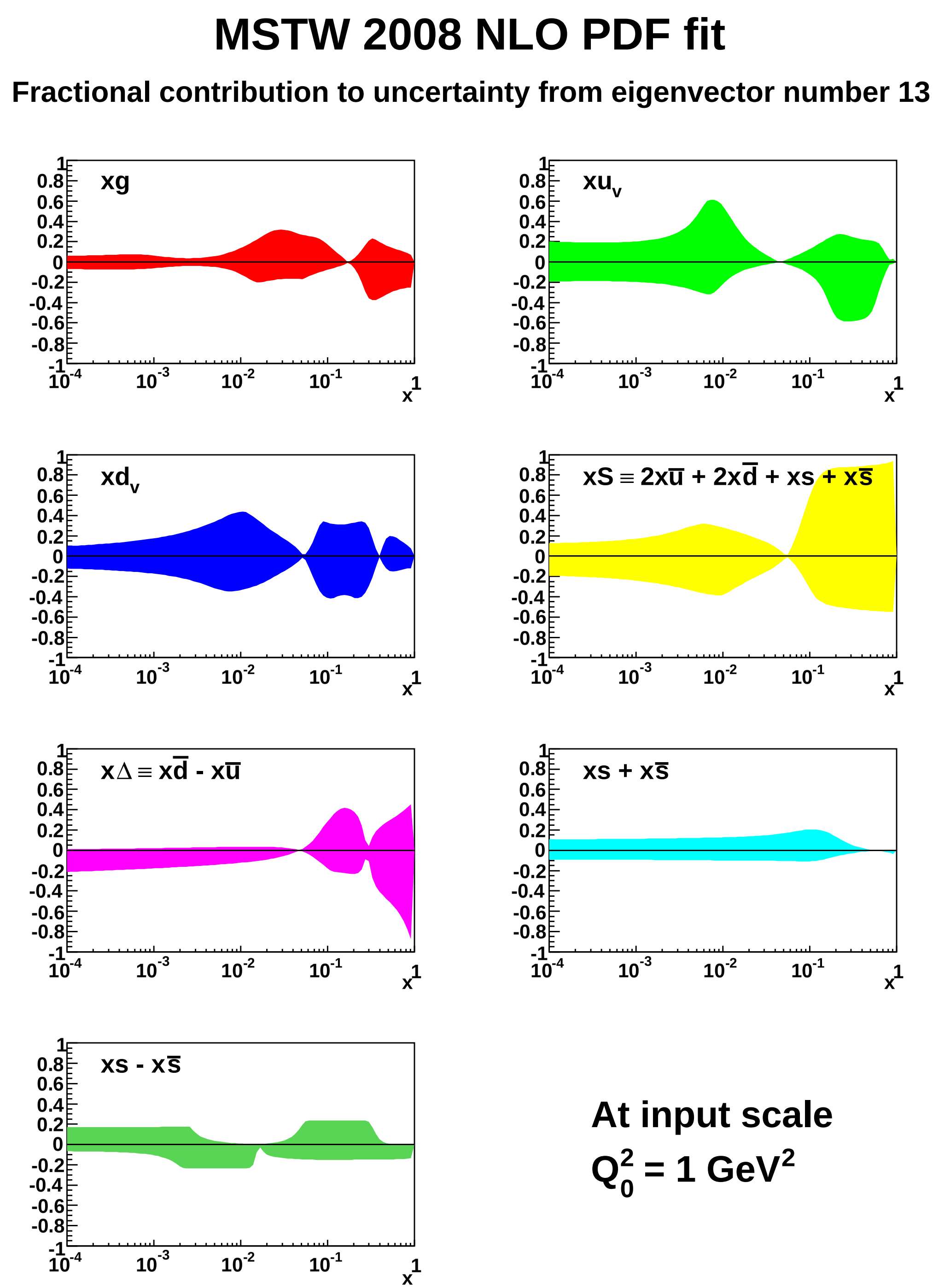
Not surprising this eigenvector contributes most to the gluon uncertainty.



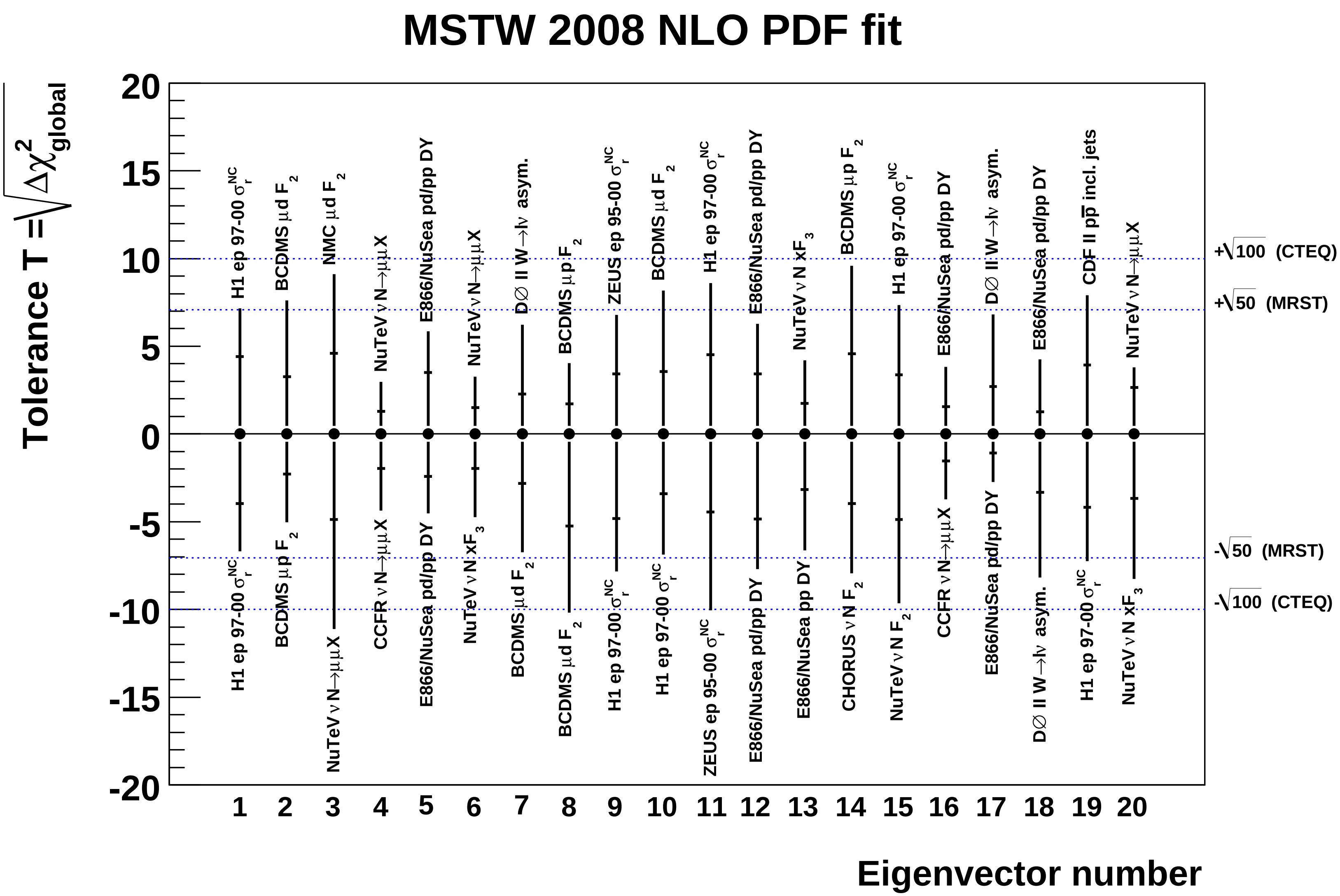
As another example number 13 constrained in one direction by E866 Drell-Yan data and in the other direction by NuTeV $F_3^p(x, Q^2)$ data . In this case the best fits for the two sets are highly inconsistent. $\Delta\chi^2 = 100$ well outside $90\%$ confidence level for each.



This eigenvector contributes most to the high-$x$ sea quark uncertainty.



Approach repeated for all $20$ eigenvectors to determine uncertainty on each. On average $\Delta\chi^2 = 40$, but large variations, and asymmetries.



## CCFR/NuTeV **dimuon cross-sections and strange quarks**

$$\frac{d\sigma}{dxdy}(\nu_\mu(\bar{\nu}_\mu)N \to \mu^+\mu^- X) = B_c \mathcal{N} \mathcal{A} \frac{d\sigma}{dxdy}(\nu_\mu s(\bar{\nu}_\mu \bar{s}) \to c\mu^-(\bar{c}\mu^+)X),$$

$B_c =$ semileptonic branching fraction

$\mathcal{N} =$ nuclear correction

$\mathcal{A} =$ acceptance correction.

$\nu_\mu$ and $\bar{\nu}_\mu$ cross-sections probe $s$ and $\bar{s}$ (small mixing with $d$ and $\bar{d}$).

Have previously indirectly used CCFR data to parameterise strange according to $s(x,Q_0^2) = \bar{s}(x,Q_0^2) = \kappa/2[\bar{u}(x,Q_0^2) + \bar{d}(x,Q_0^2)]$, where $\kappa \approx 0.5$

Now make definitions at input

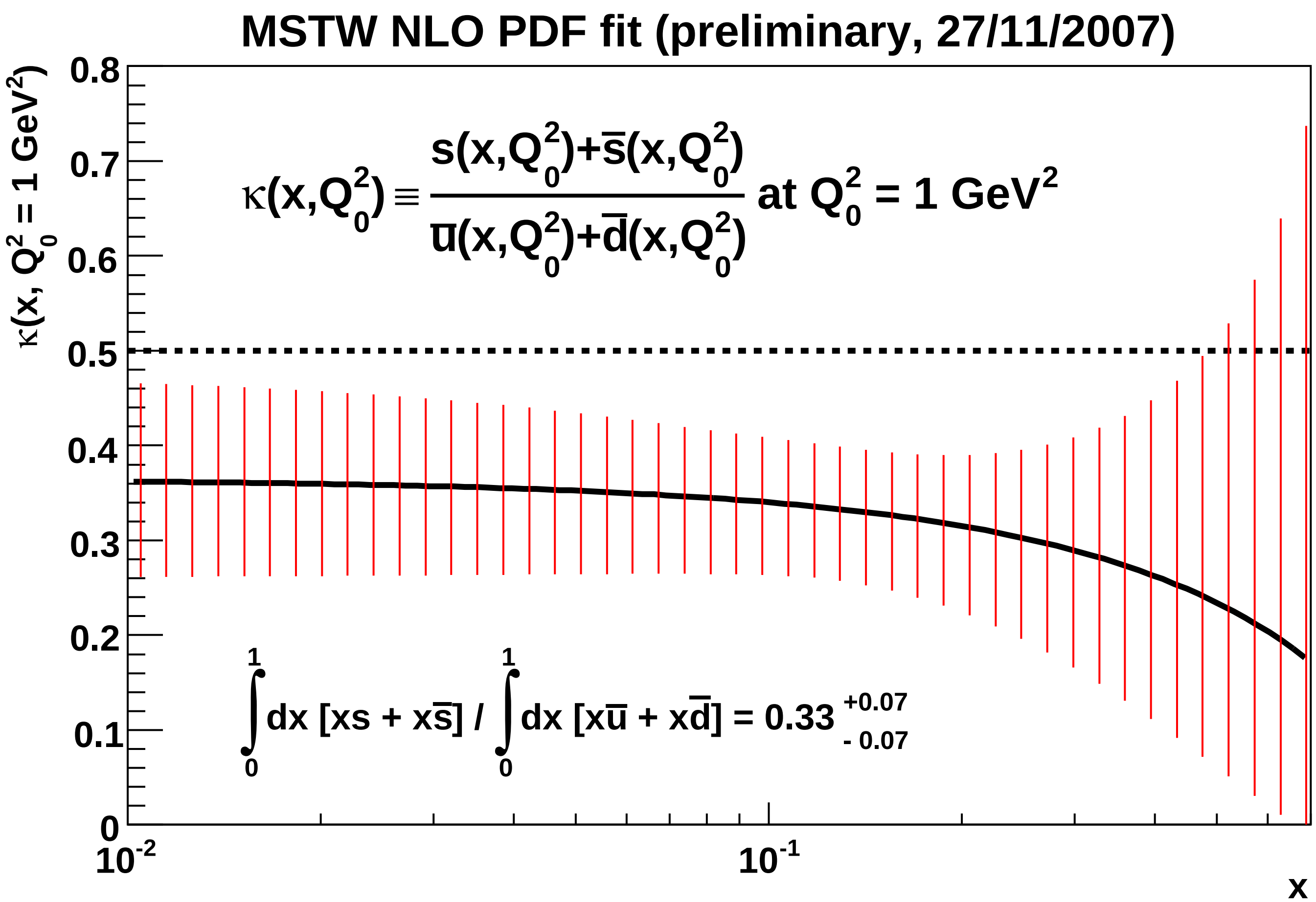
$$s^+(x,Q_0^2) \equiv s(x,Q_0^2) + \bar{s}(x,Q_0^2) = A_+(1-x)^{\eta_+} S(x,Q_0^2)$$

$$s^-(x,Q_0^2) \equiv s(x,Q_0^2) - \bar{s}(x,Q_0^2) = A_-(1-x)^{\eta_-} x^{-1+\delta_-}(1-x/x_0)$$

where $S(x,Q_0^2)$ is the total sea distribution, and $x_0$ is determined by zero strangeness of proton. In practice $\delta_-$ fixed $\to 4$ new eigenvectors.

Find reduced ratio of strange to non-strange sea compared to previous default $\kappa = 0.5$.

Suppression at high $x$, i.e. low $W^2$. Effect of $m_s$?

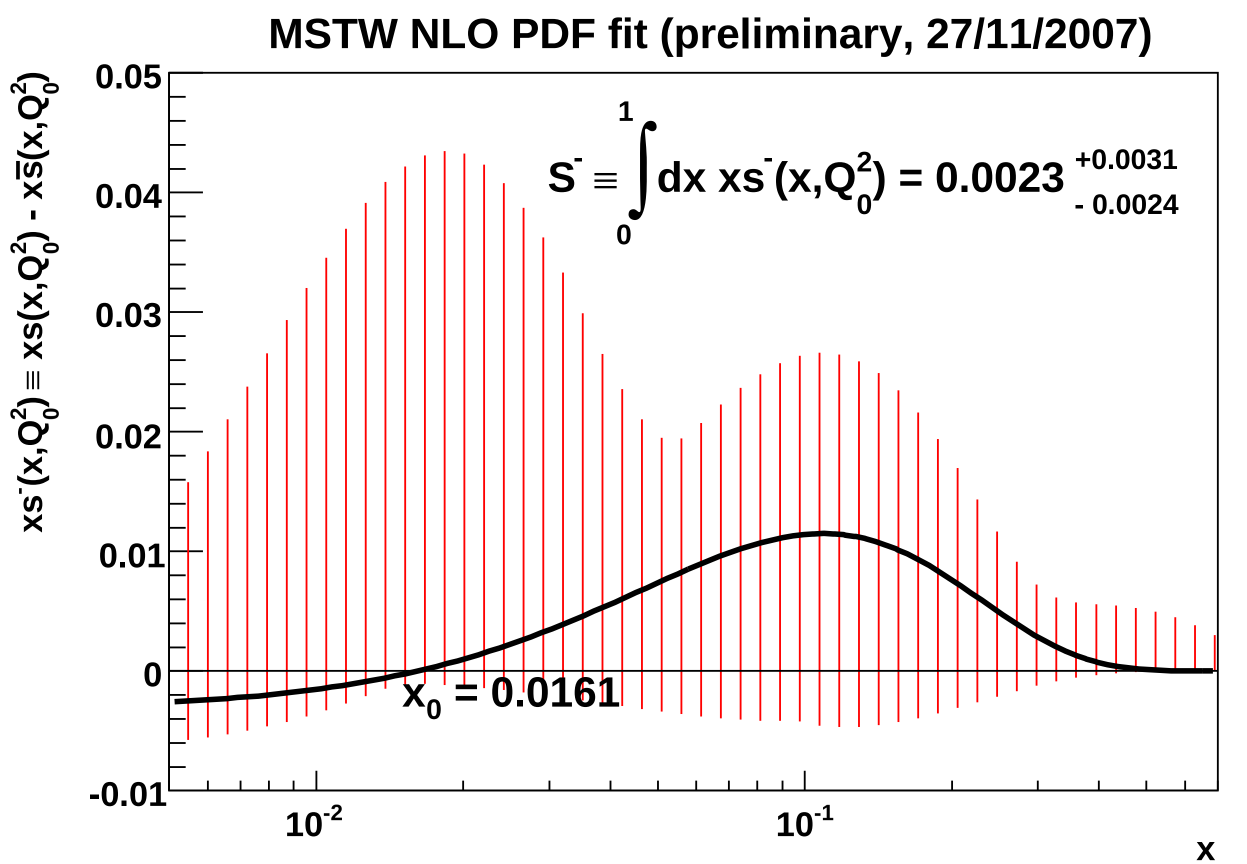



Suppression at *nonperturbative* $Q_0^2 = 1\text{GeV}^2$ now $\sim 0.3$, i.e. value in hadronization models (probability to generate $\bar{s}s$ compared to $\bar{u}u, \bar{d}d$). Similar at NNLO.

Strange sea asymmetry $xs(x,Q_0^2) - x\bar{s}(x,Q_0^2)$ constrained by dimuon data for $0.01 \geq x \geq 0.2$.

Positive, with central value $0.0023 \pm 0.0025$ (roughly $90\%$ confident limit). Nonzero value not huge significance. At $Q^2 = 10\mathrm{GeV}^2$ asymmetry of $0.0017 \pm 0.002$.

Need $S^- \sim 0.0068$ to bring NuTeV $\sin^2\theta_W$ in line with world average.



Direct determination of strange affects uncertainties on partons other than strange.

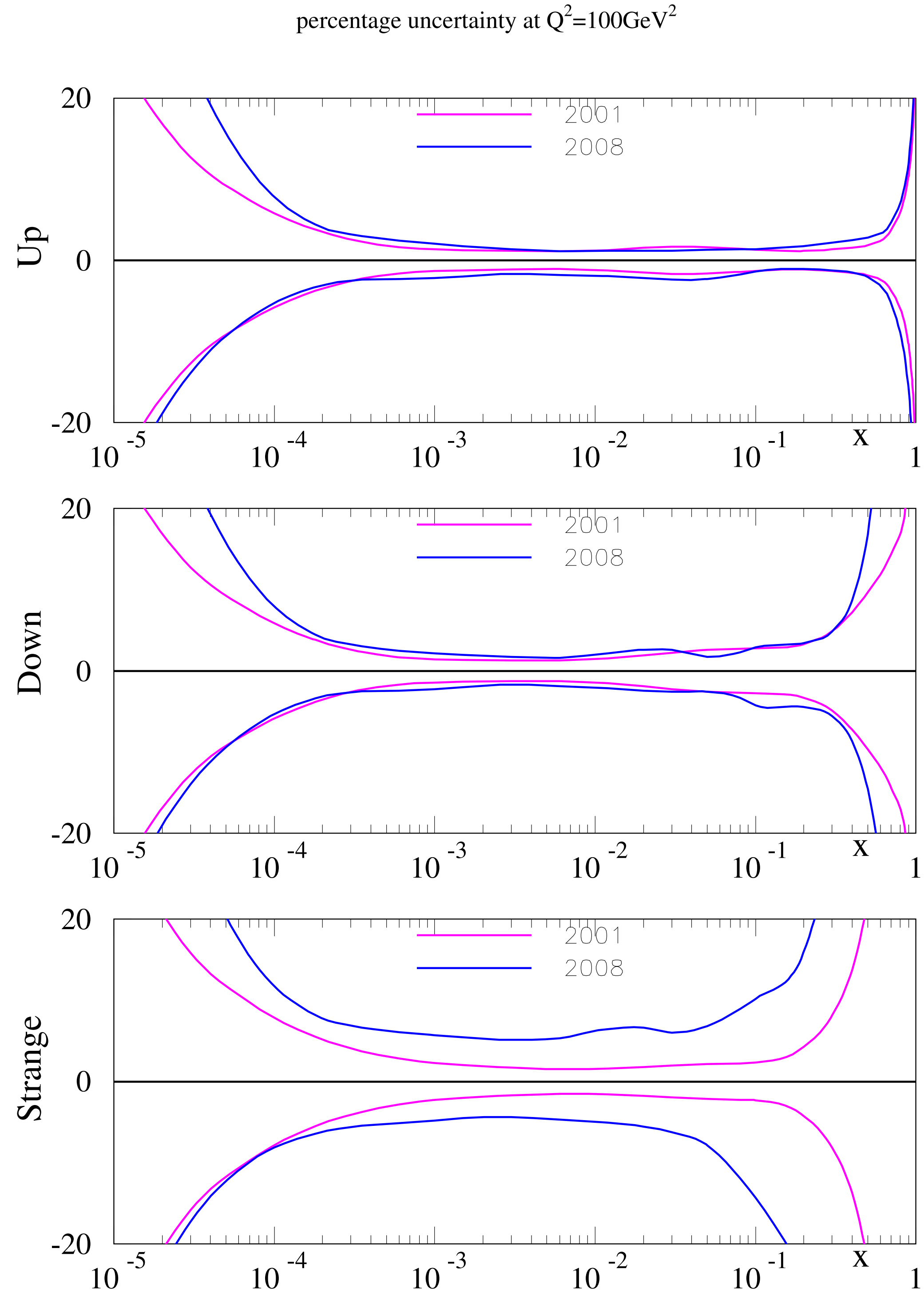
Previously for us (and everyone else) strange a fixed proportion of total sea in global fit.

Genuine *larger* uncertainty on $s(x)$– feeds into that on $\bar{u}$ and $\bar{d}$ quarks.

Low $x$ data on $F_2(x, Q^2)$ constrains sum $4/9(u + \bar{u}) + 1/9(d + \bar{d} + s + \bar{s})$.

Changes in fraction of $s + \bar{s}$ affects size of $\bar{u}$ and $\bar{d}$ at input.

The size of the uncertainty on the small $x$ anti-quarks increases – $\sim 1.5\% \rightarrow \sim 2 - 2.5\%$, despite additional constraints on quarks in new fit.



# Lepton asymmetry

Comparison of fits to CDF data.

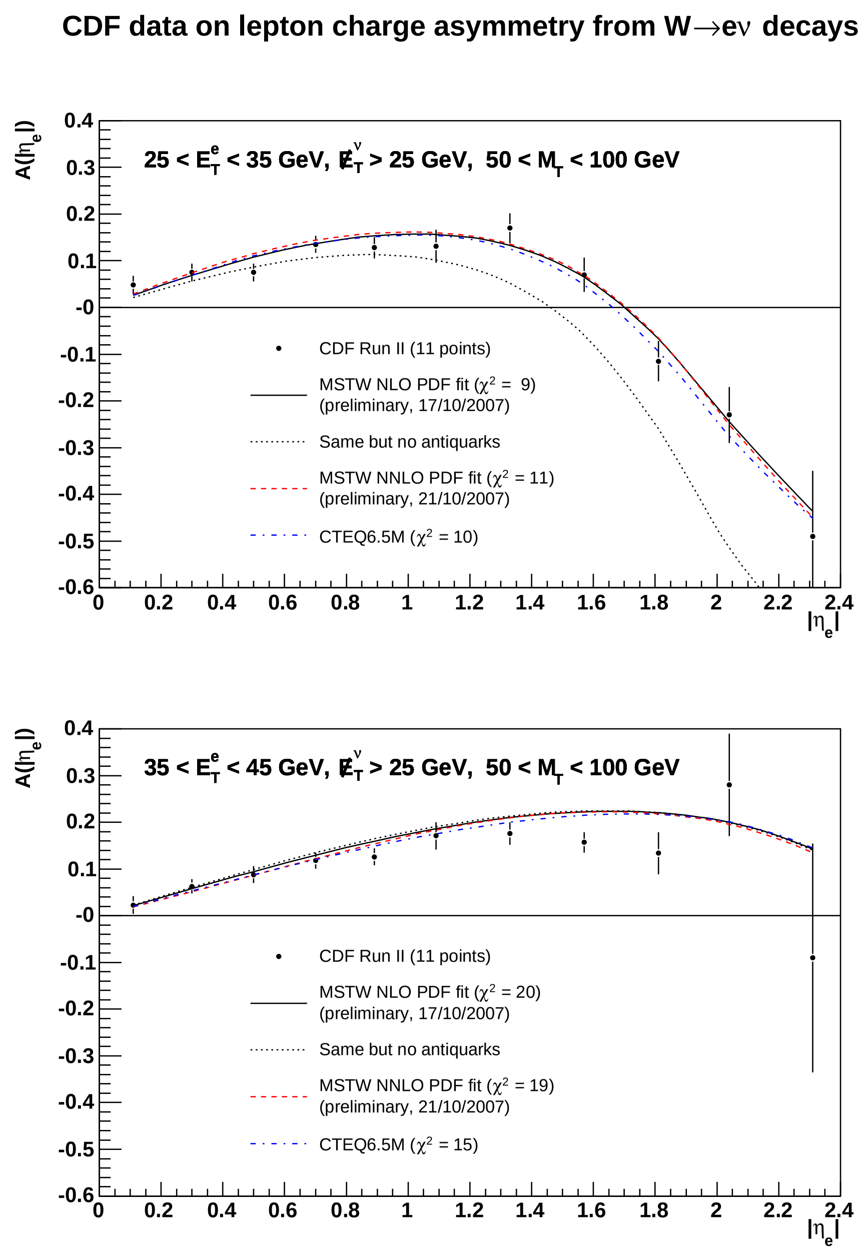
$$A_W(y) \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)},$$

At low $E_T$ antiquark contribution in $l^+$ enhanced by $\cos\theta^* = \sqrt{1 - 4E_T^2/M_W^2}$ dependence in $W$ decay distribution.

Some tension with other data sensitive to $d(x, Q^2)$ and $\bar{d}(x, Q^2)$.

CTEQ seems to be slightly better shape for some reason.

New CDF data does influence $d(x, Q^2)$ in MSTW fit. Similar for D0 but issues with detector corrections for muons.



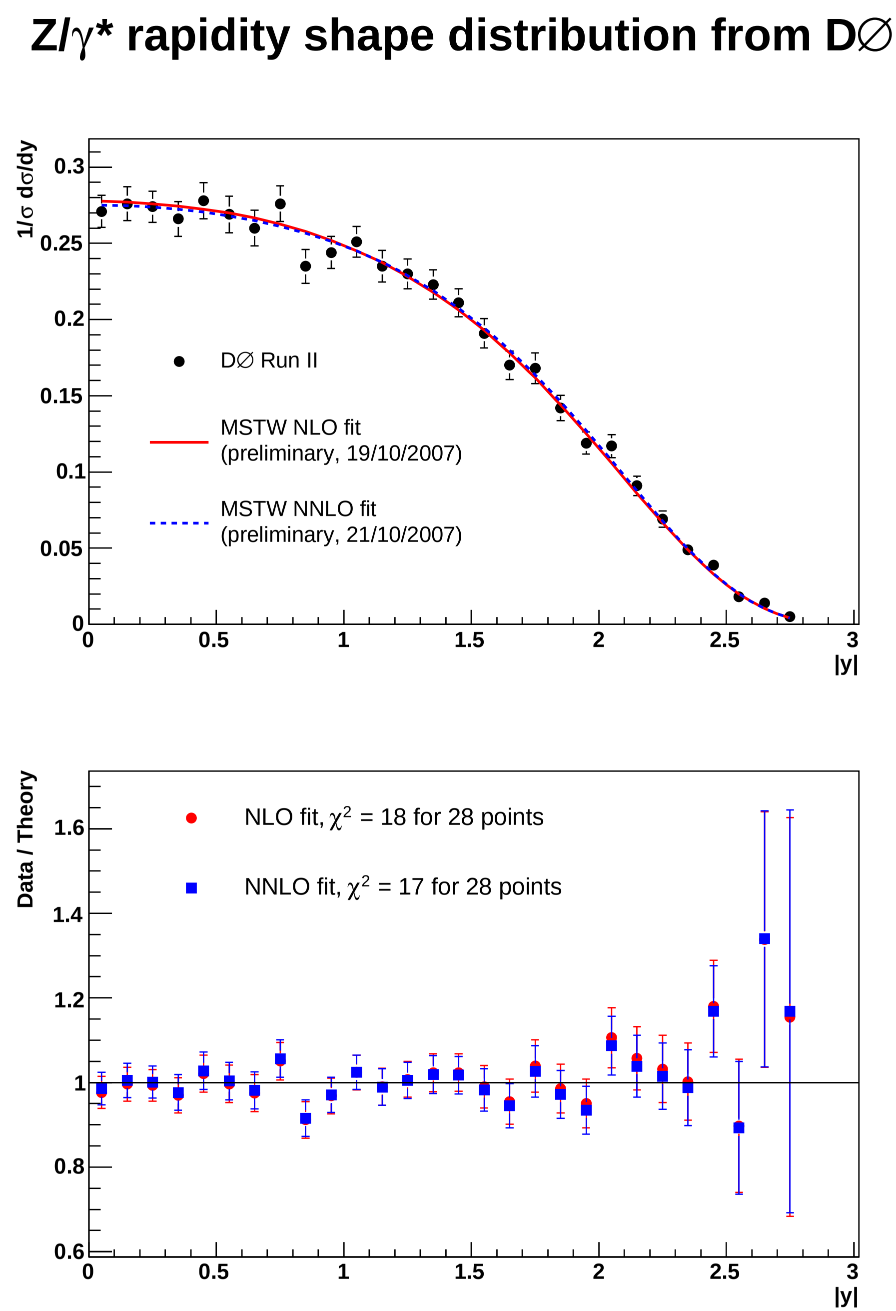
## $Z$-**rapidity data**.

Look at $Z$-rapidity data using NNLO coefficient functions.

$$\frac{d\sigma(Z)}{dy} \propto 0.37u(x_1)\bar{u}(x_2)+0.54d(x_1)\bar{d}(x_2)$$

Sensitive to the down quark as well as the better constrained up quark.

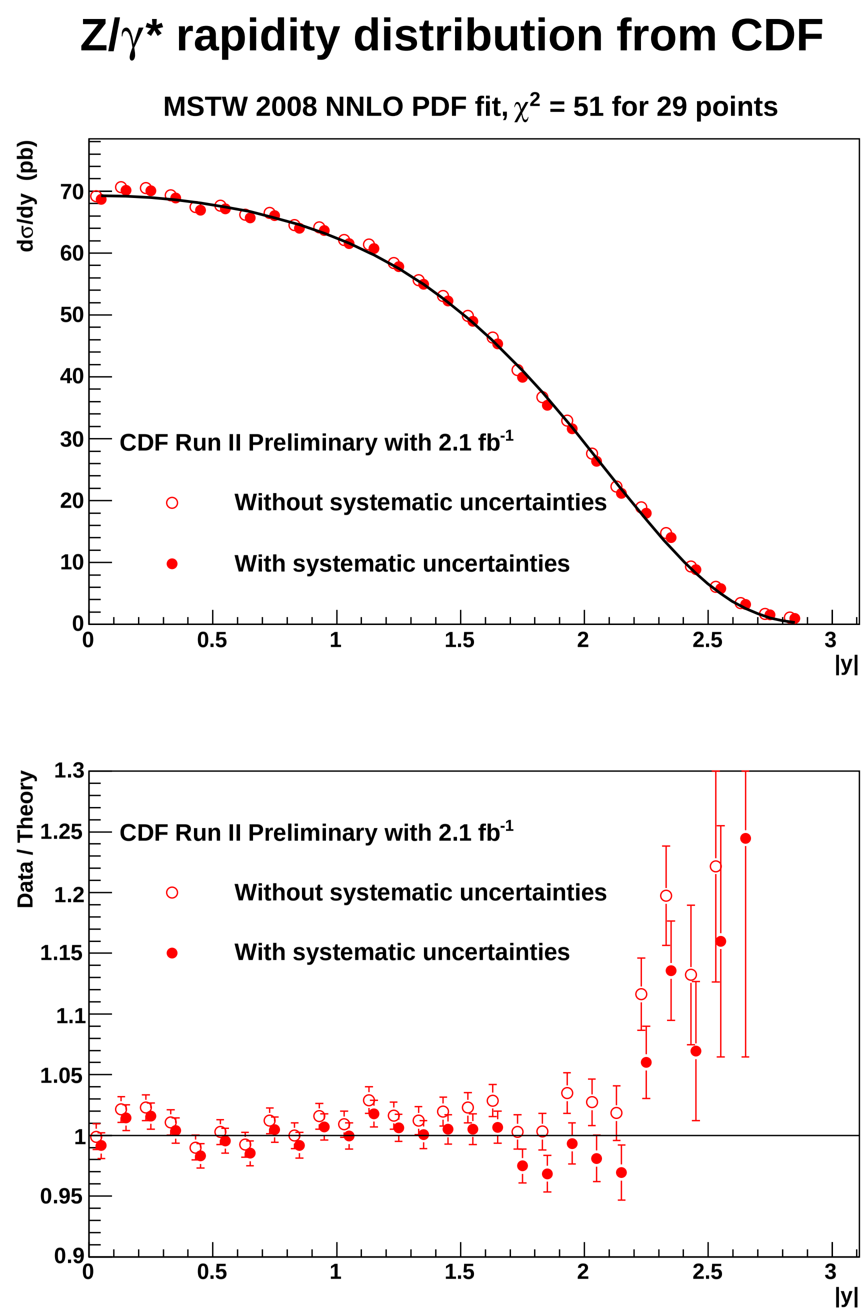
D0 data with $0.4fb^{-1}$ automatically fit well by MRST04 partons, easily accommodated in MSTW fit.



CDF data (preliminary) with $1 fb^{-1}$ more precise. Poor fit with existing MRST partons.

Improves a little in refit and constrains $d(x,Q^2)$. Pulls in opposite direction to $W$-asymmetry. (Latter stronger effect.)

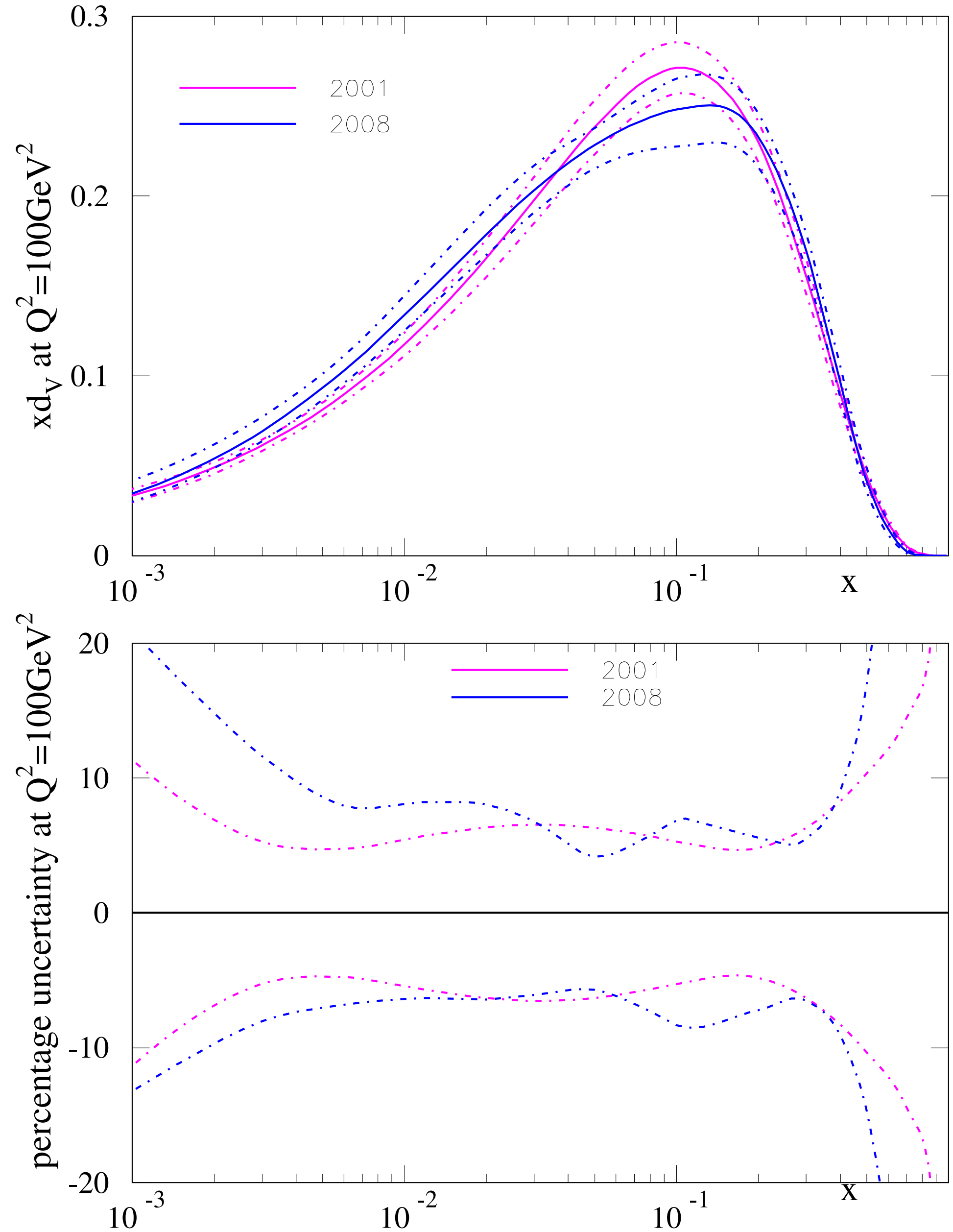
Highest rapidity points likely to move down slightly due to acceptance corrections.



Overall $d_V(x,Q^2)$ now chooses a different type of shape.

Mainly changed by new *Tevatron* $W$-asymmetry data and new neutrino structure function data.

Uncertainty growing more quickly as $x \to 0$ and $x \to 1$ than before due to better parameterisation in determining uncertainty eigenvectors.



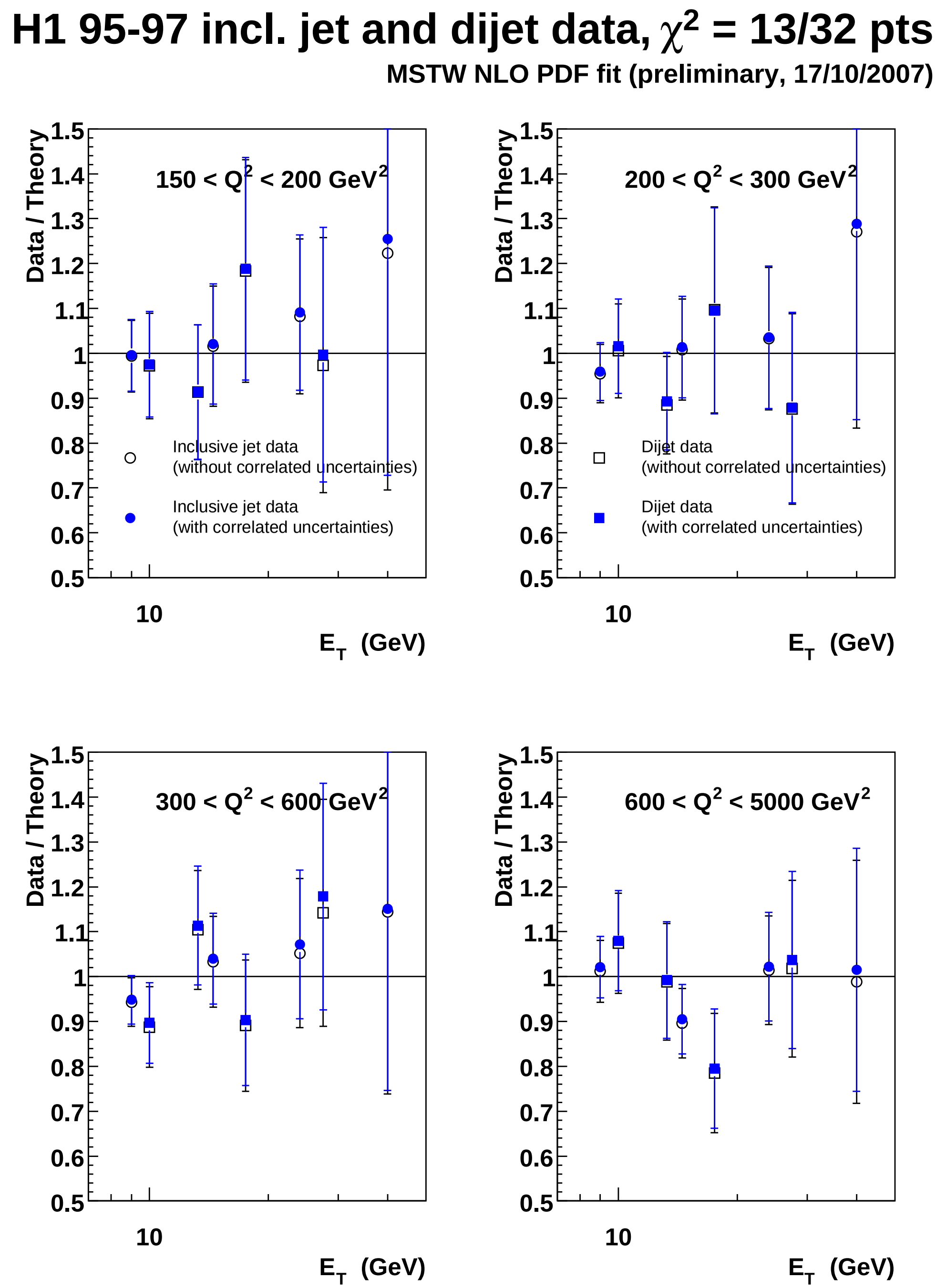
# Jet data and the gluon.

Also now include HERA inclusive and dijet DIS data using fastNLO.

Fit generally excellent. Correlated systematic uncertainties have little effect in this case.

At NNLO do not know cross-section. Leave out of NNLO fit.

Comparison to data using NNLO partons and NLO cross-sections very good.

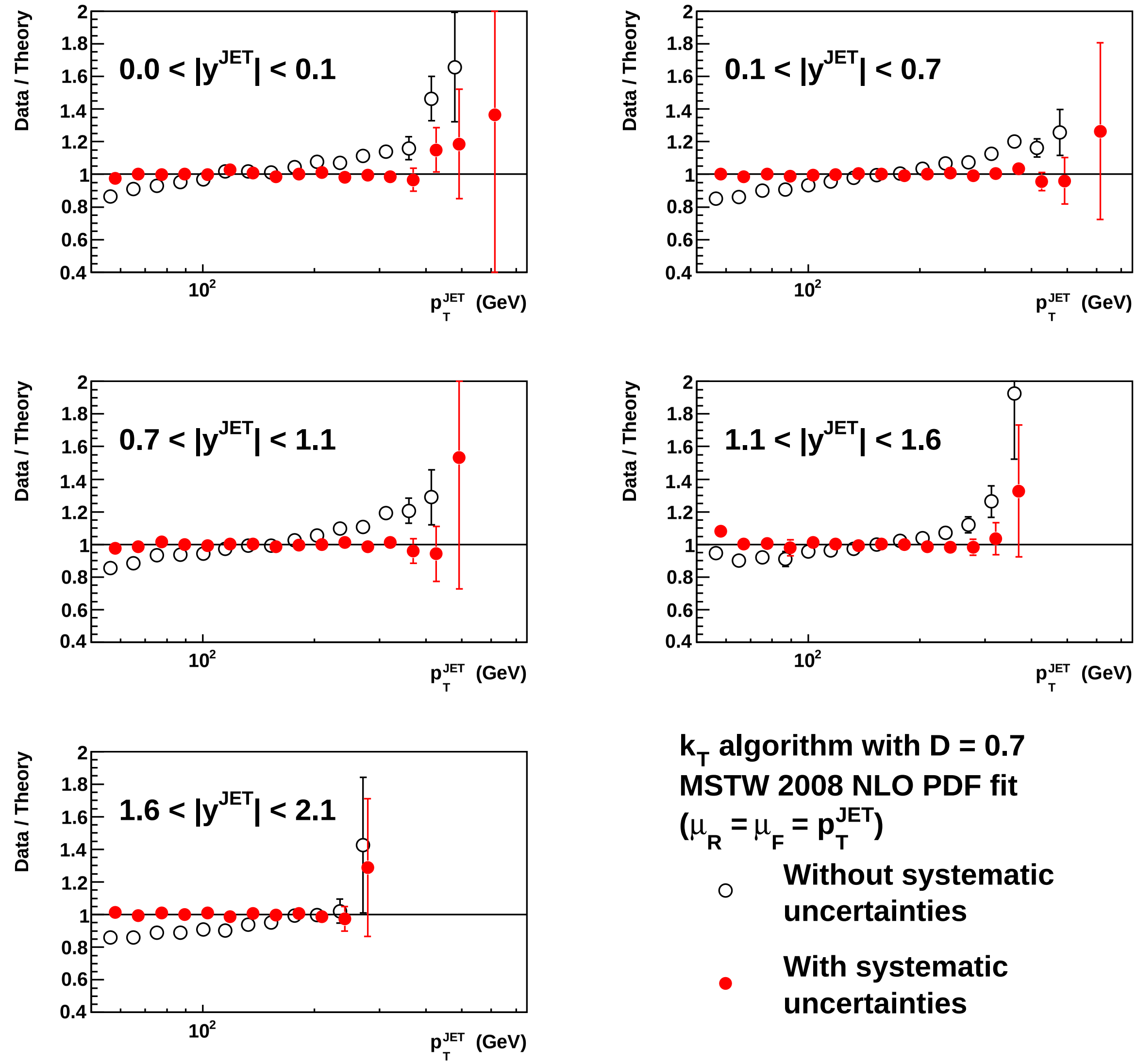


Include CDF Run II inclusive jet data in different rapidity bins using $k_T$ jet algorithm (mid-point cone algorithm data seems very similar – not published).

Very good fit – $\chi^2 = 55/76$.

Full use of correlated systematic errors required for any sensible result.

## CDF Run II inclusive jet data, $\chi^2$ = 55 for 76 pts.

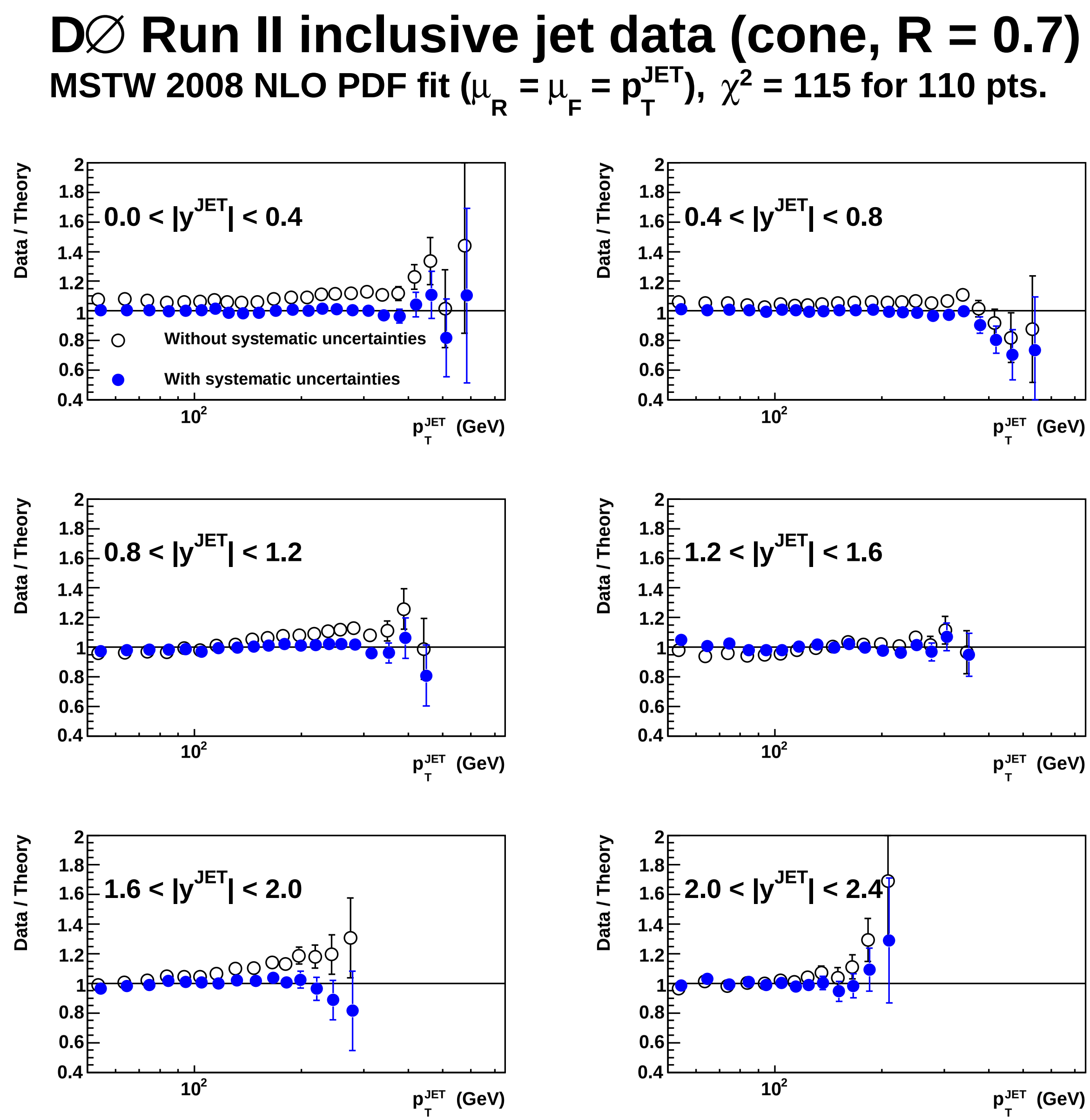


Also include very recent D0 Run II inclusive jet data in different rapidity bins using mid-point cone algorithm jet algorithm.

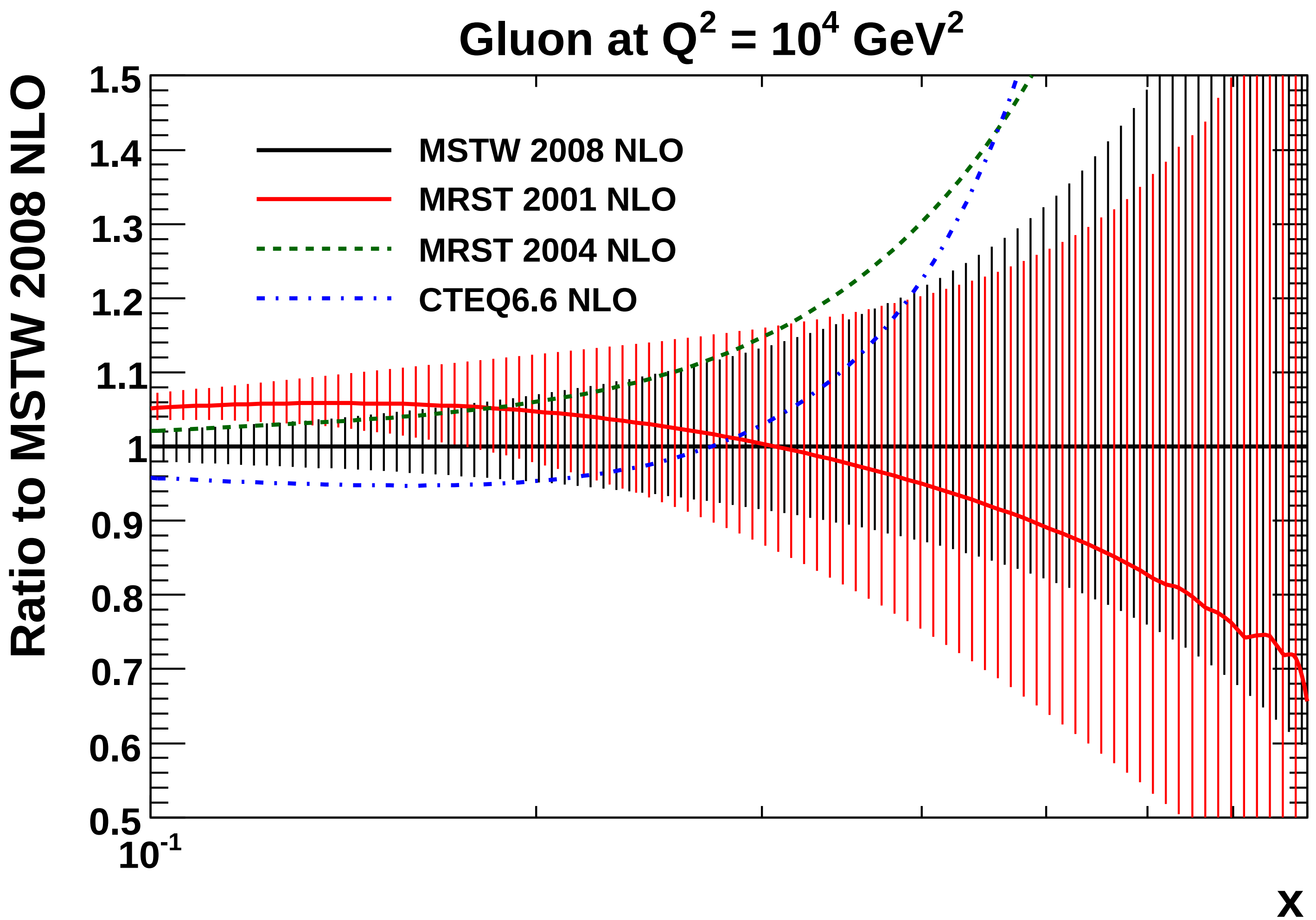
Again very good fit – $\chi^2 = 115/110$.

use $\mu = p_T$ rather than previous default $\mu = p_T/2$. Latter gives smaller NLO correction for low $y$, but dangerously large corrections for higher $y$ (noticed by D0).

Both CDF and D0 jet data softer at high $p_T$ than before.

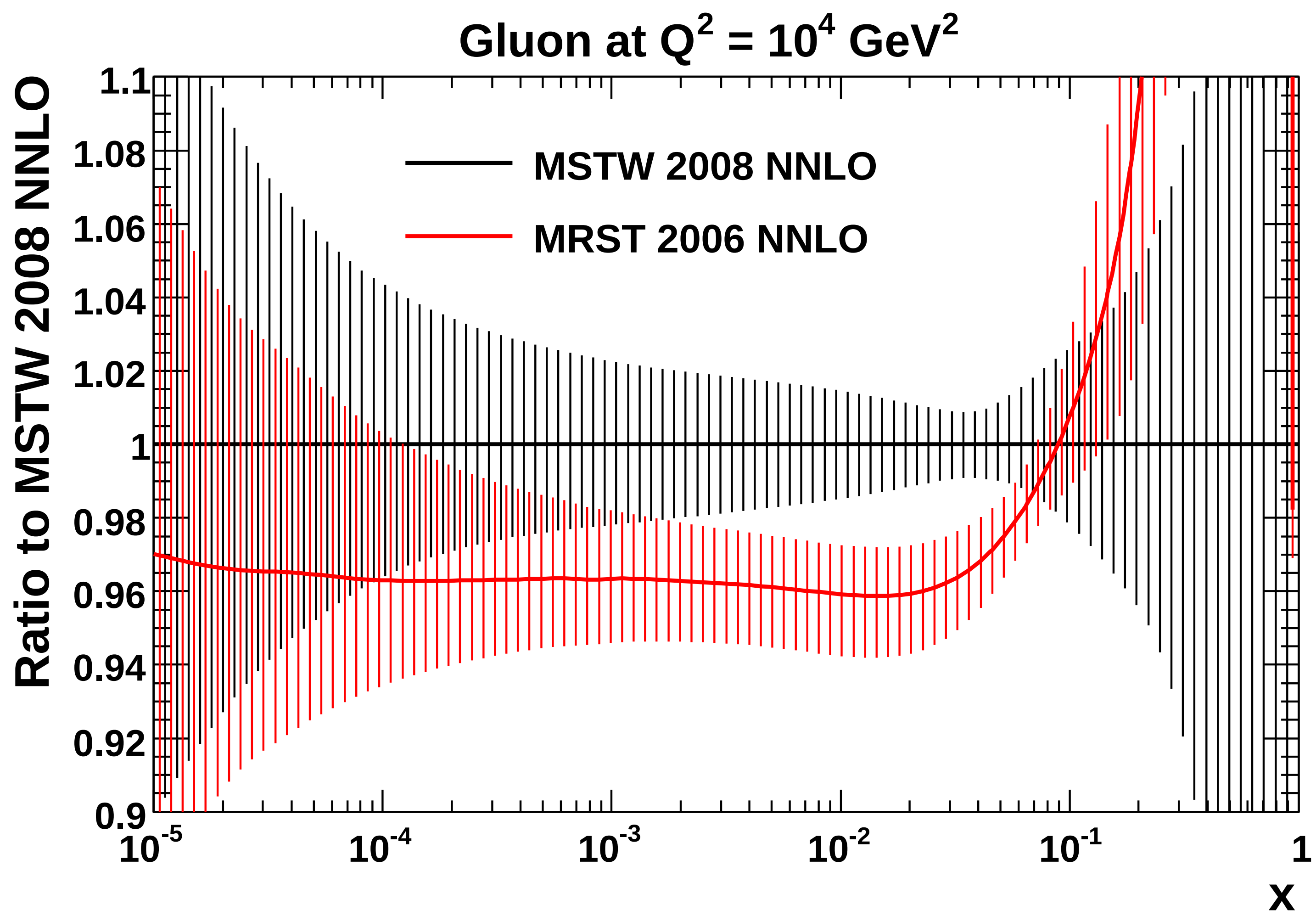


Results in softer gluon at high-$x$ than MRST2004 and CTEQ6.6 which fit run I data well.




Slightly harder than MRST2001 gluon, which did not fit run I data very well. Marginally smaller uncertainty, but now one more free gluon parameter in eigenvectors.

Smaller high-$x$ gluon (and slightly smaller $\alpha_S$) results in larger small-$x$ gluon – now shown at NNLO.

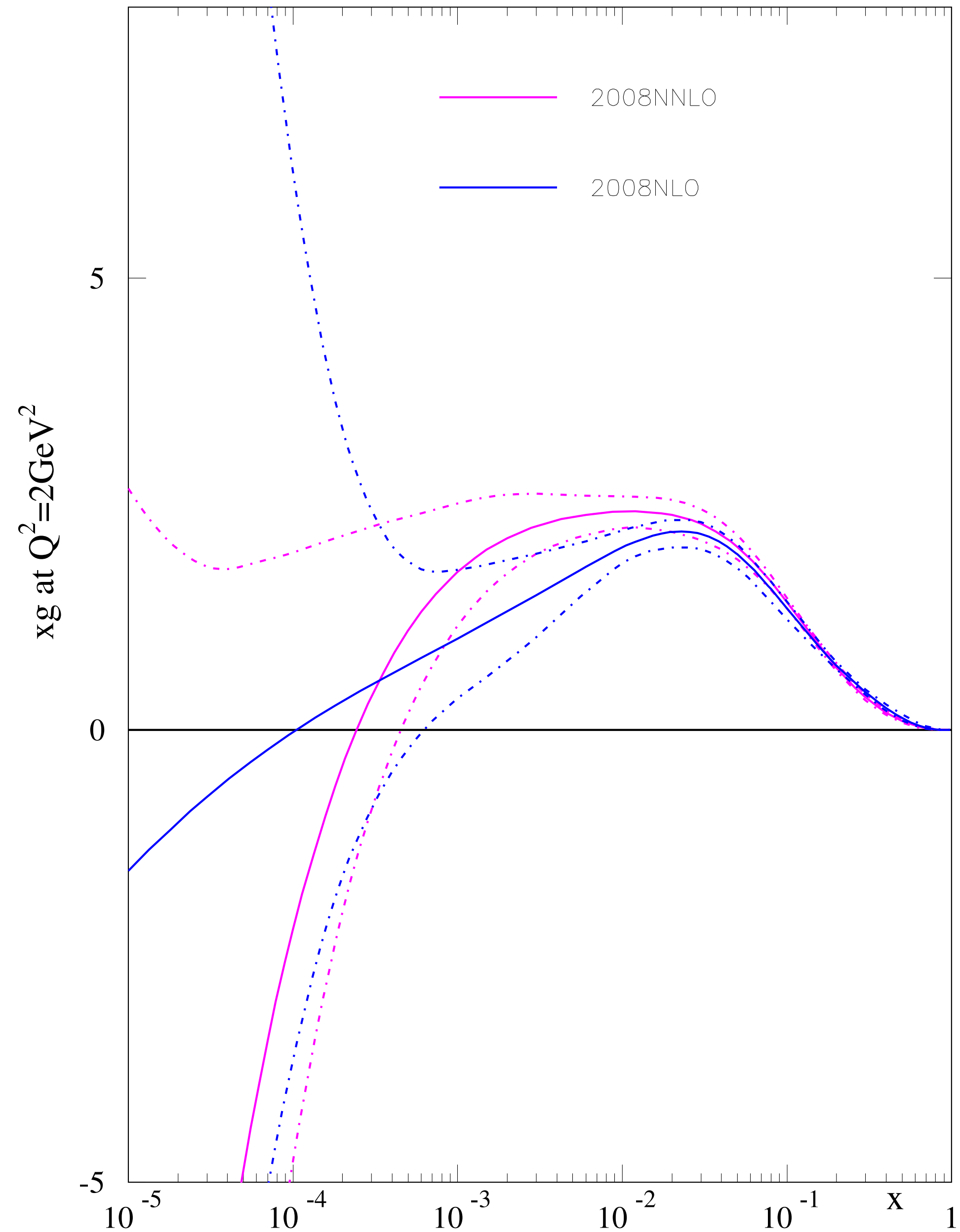



Larger small-$x$ uncertainty due to extrat free parameter.

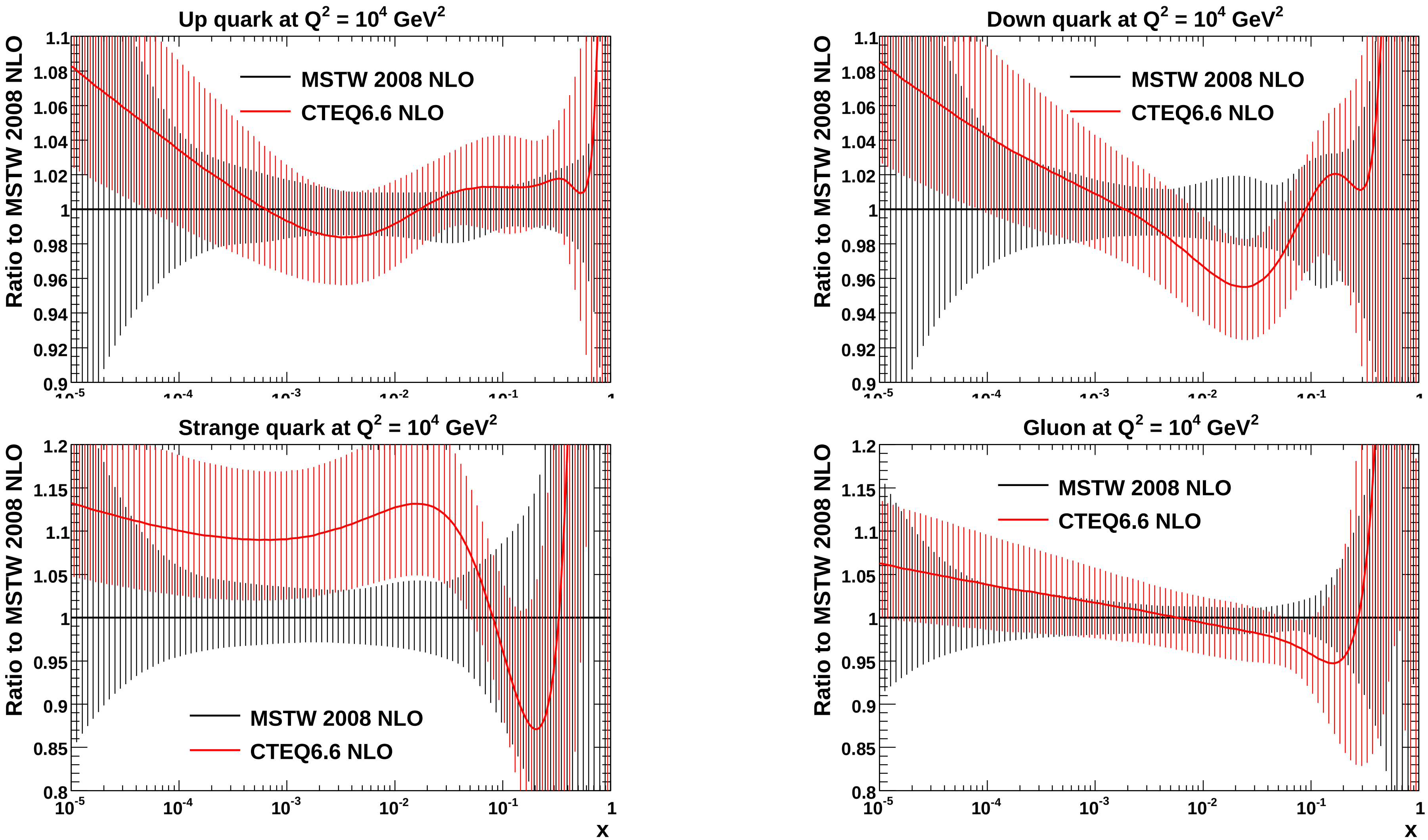
Comparison of gluon distributions at NLO and NNLO at $Q^2 = 2\text{GeV}^2$. General result that NNLO becomes more negative at very low $x$, still true.

Uncertainty on gluon also extremely large at $x \sim 10^{-5}$. Positivity well within uncertainties.

Less constraint on NNLO gluon on negativity (see later).



# Comparison to CTEQ6.6 at NLO.




CTEQ strange now larger at small-$x$.

CTEQ gluon larger at high-$x$ (run I jets) and small-$x$ (input parameterization). Feeds into quark shape.

**Predictions for W and Z cross-sections** for LHC and Tevatron (in brackets) with common fixed order QCD and vector boson width effects, and common branching ratios.

| | $B_{l\nu} \cdot \sigma_W$ (nb) | $B_{l^+l^-} \cdot \sigma_Z$ (nb) |
|---|---|---|
| MSTW 2008 NLO (prel.) | 20.45 (2.650) | 1.965 (0.2425) |
| MSTW 2008 NNLO (prel.) | 21.44 (2.739) | 2.043 (0.2512) |

| Ratio to MSTW 2008 (prel.) | $\sigma_W$ | $\sigma_Z$ |
|---|---|---|
| MRST 2006 NLO (unpublished) | 1.002 (0.995) | 1.009 (1.001) |
| MRST 2006 NNLO | 0.995 (1.004) | 1.001 (1.010) |
| MRST 2004 NLO | 0.974 (0.990) | 0.982 (1.000) |
| MRST 2004 NNLO | 0.936 (0.991) | 0.940 (1.003) |
| CTEQ6.6 NLO | 1.019 (0.978) | 1.022 (0.987) |

Increases from MRST2006 compared to MRST2004 due to changes due to improved (NLO) or completed (NNLO) heavy flavour prescription.

Virtually no change from MRST2006 → MRST2008. Not guaranteed to be true for all quantities.

Consistent with CTEQ6.6, but systematic differences mirror shape of gluon/quarks.

# $F_L(x,Q^2)$

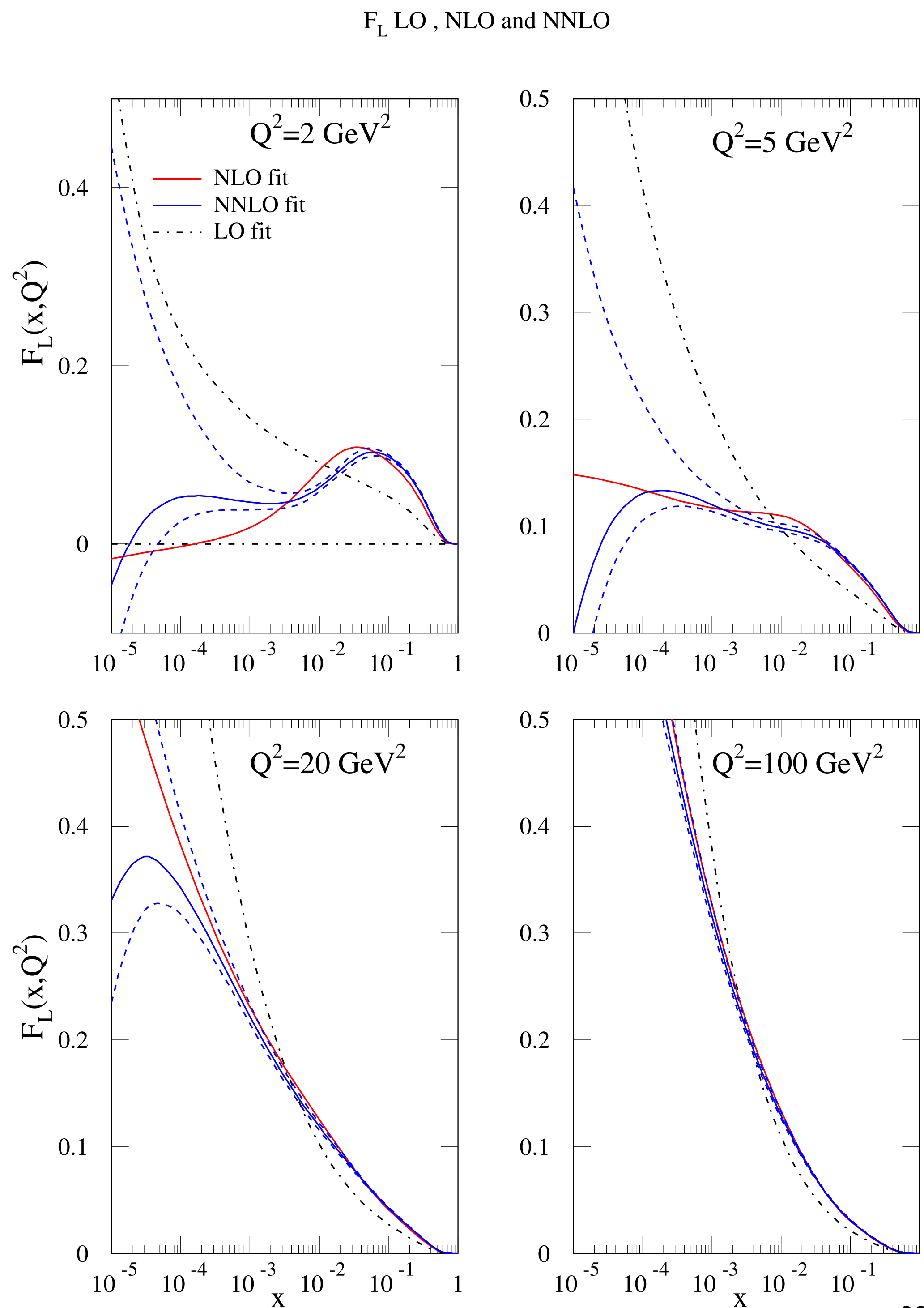
$F_L(x,Q^2)$ predicted from the MSTW global fit at LO, NLO and NNLO (prelim).

NNLO coefficient function compensates decrease in NNLO gluon.

$F_L(x,Q^2)$ prediction more stable than for gluon at small $x$.

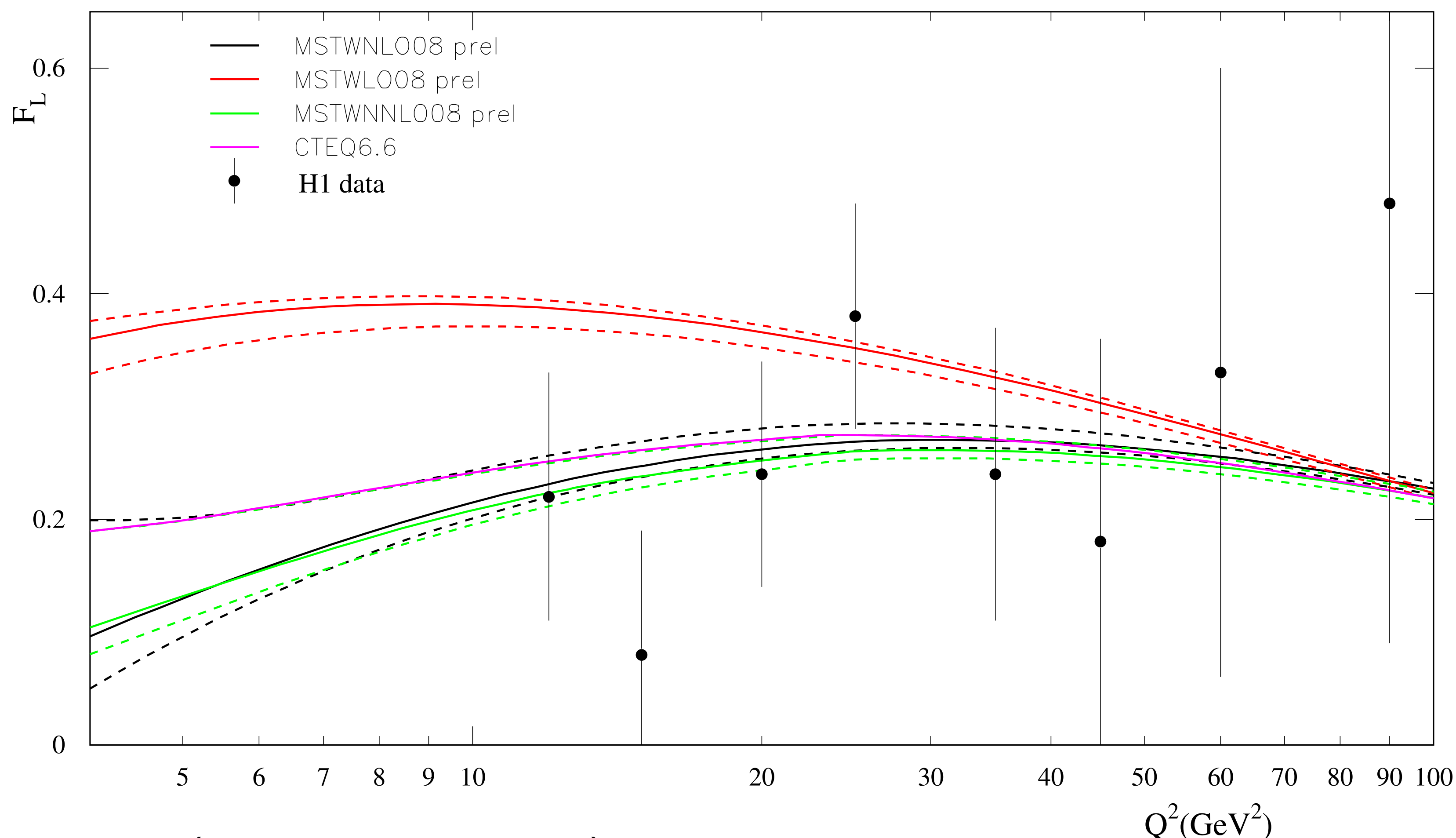
However, current default negative at both NLO and NNLO at lowest $x$ and $Q^2$ – delicate balance between gluon and NNLO coefficient function. However, enormous uncertainty here.

Significantly negative NNLO gluon can give sensible $F_L(x,Q^2)$.



Look at variations in predictions for HERA range of measurement. Use $x = Q^2/35420$.

Comparison of different $F_L$ predictions

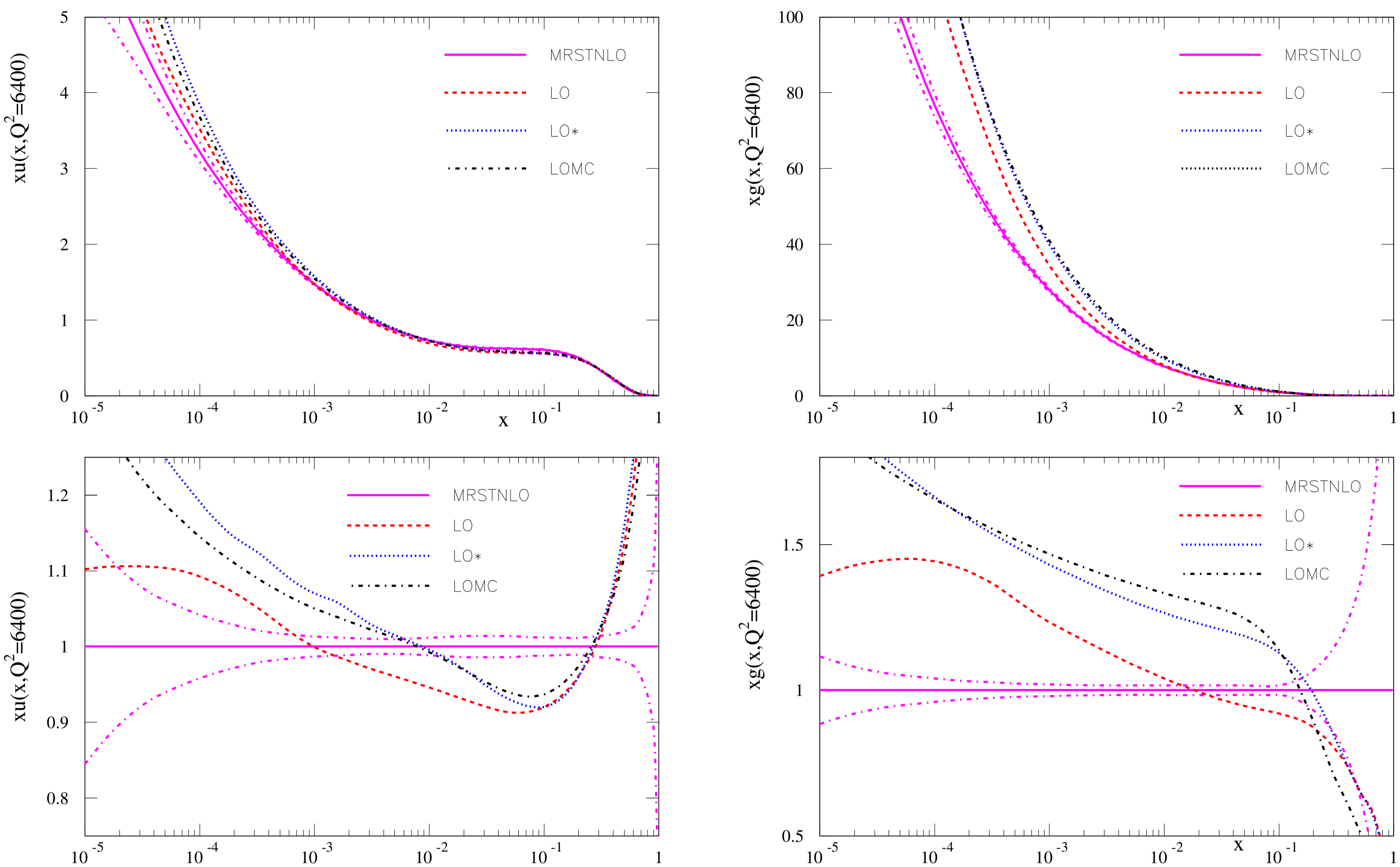



CTEQ6.6 curve (Nadolsky and Tung) at NLO, though uses different ordering definition $\rightarrow$ slight comparative increase. Within MSTW uncertainties.

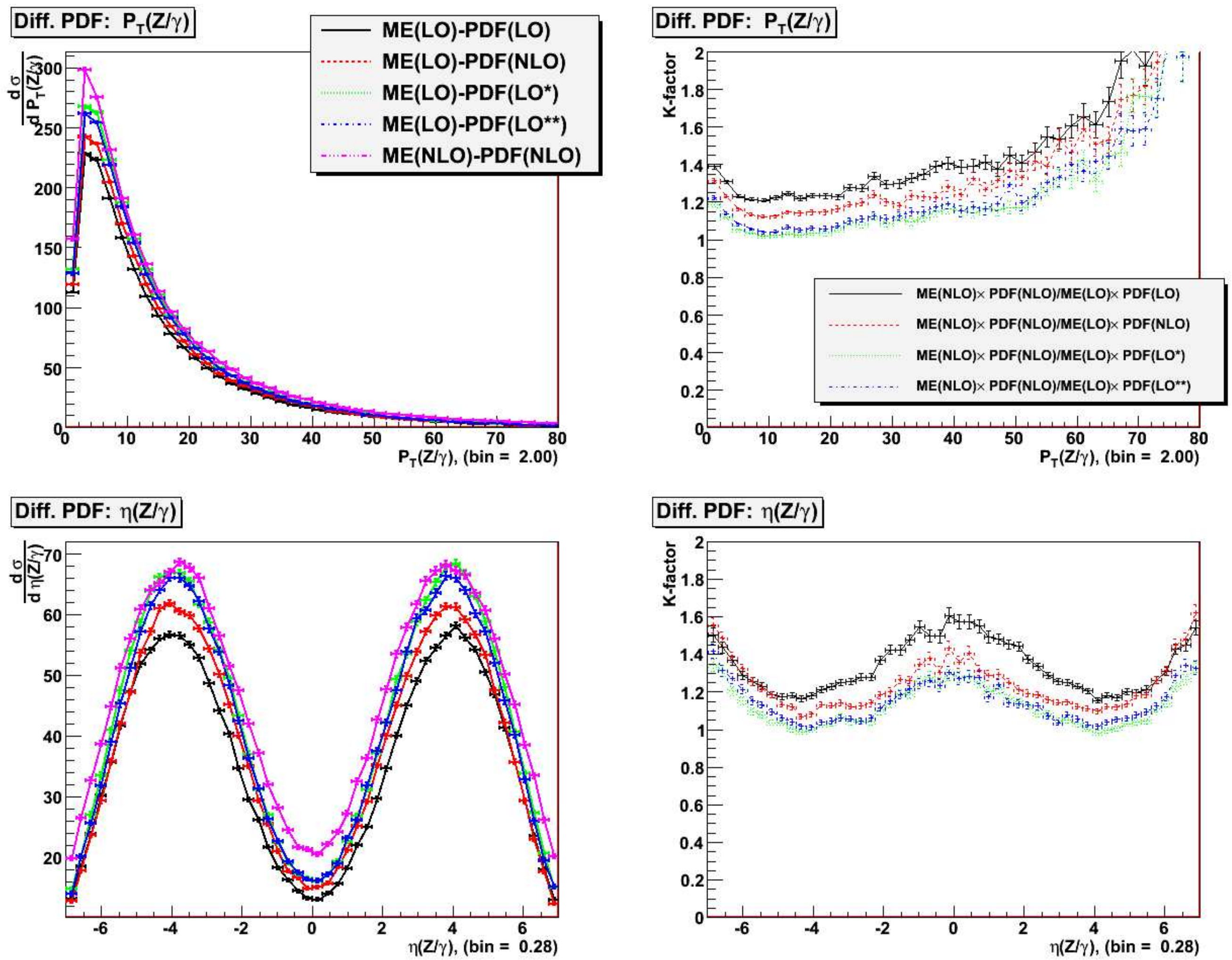
Not too much variation between NLO and NNLO until lower $Q^2$ and $x$.

**Modified LO partons for use in LO Monte Carlos** – work with A Sherstnev. Enhancement of LO* partons from momentum violation (plus use of NLO coupling) leads to best match to full NLO predictions except for $t$-channel processes, where all corrections are small anyway.

Recently updated by using Monte Carlo inspired choice of scale $k_T^2 = (1-z)/zQ^2$ in $P_{qq}$ splitting function. Automatically includes leading-log high-$z$ resummations. Partons rather insensitive to change.



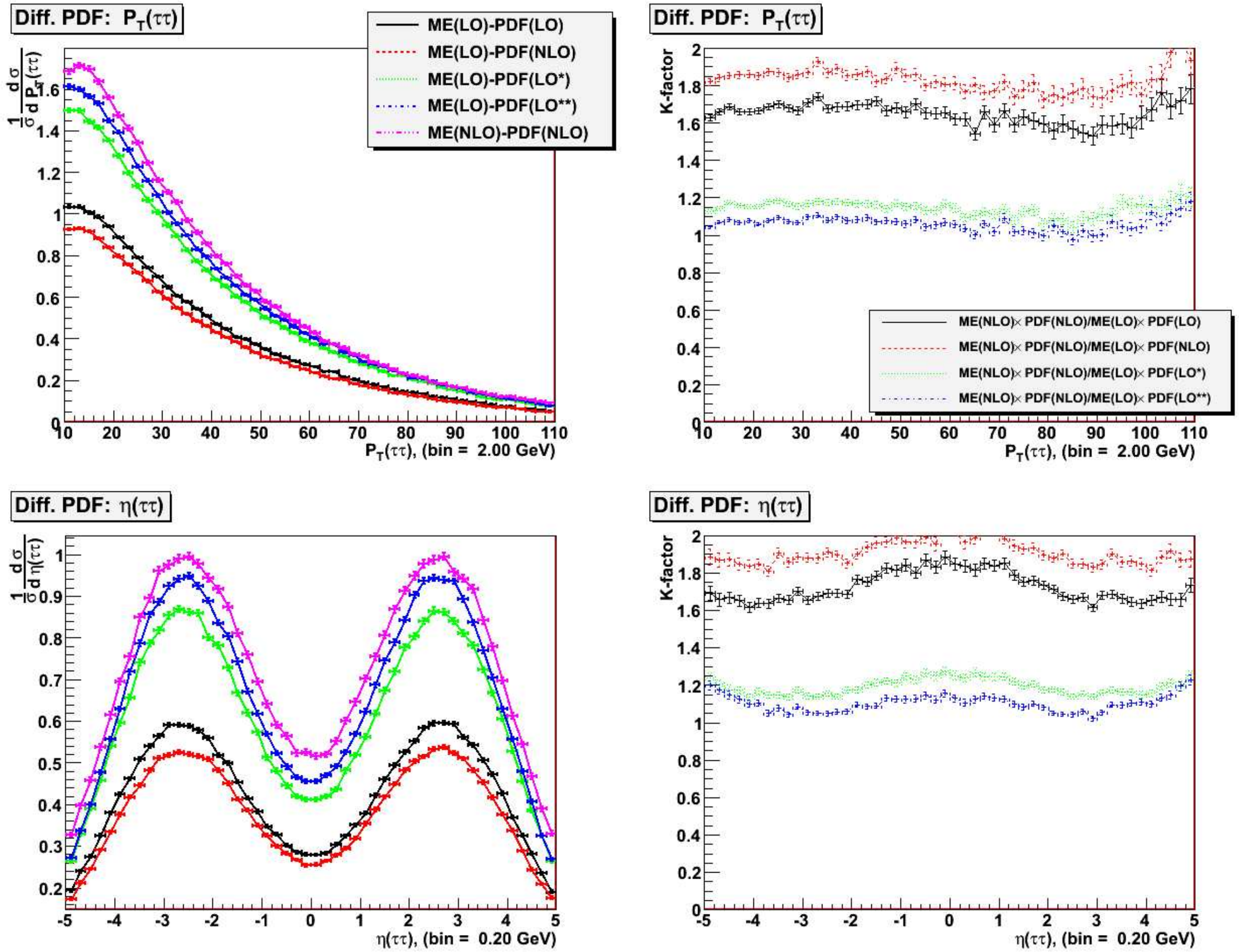
Look at distributions.




Results using LO** partons extremely similar to those using LO* partons for $Z$ production.

Very similar for $W$ production.

Look at gluon dominated quantity




Results using LO** partons extremely similar to those using LO* partons for Higgs production from gluon-gluon fusion.

Very similar for $b\bar{b}$ production.

Consider instead single top production with $t \rightarrow \mu + \nu + b$ production at the LHC. Now a $t$-channel process.

NLO(ME)$\otimes$ NLO(pdf)$= 259pb$.

LO(ME)$\otimes$ LO(pdf)$= 238pb$.

LO(ME)$\otimes$ NLO(pdf)$= 270pb$.

LO(ME)$\otimes$ LO*(pdf)$= 298b$.

LO(ME)$\otimes$ LO*(pdf)$= 288b$.

LO** slightly better than LO*. Similar for other $t$-channel process vector boson production of Higgs + two jets using NLO code VBFNLO (Zeppenfeld *et al*).

NLO(ME)$\otimes$ NLO(pdf)$= 4.52pb$.

LO(ME)$\otimes$ LO(pdf)$= 4.26pb$.

LO(ME)$\otimes$ NLO(pdf)$= 4.65pb$.

LO(ME)$\otimes$ LO*(pdf)$= 4.95pb$.

LO(ME)$\otimes$ LO**(pdf)$= 4.85pb$.

## Conclusions

Inclusion of a lot of new data. Dimuon data fitted directly. Important constraint on strange, and weak evidence for strangeness momentum asymmetry. New uncertainties on $s + \bar{s}$ feed into other partons.

Tevatron $W, Z$ data important constraint on quarks – constraining for $d_V$ and to some extent $\bar{d}$. Slightly different shape for $d_V(x, Q^2)$.

HERA and Tevatron jets now fit using fastNLO. Works well and fit good. New run II CDF and D0 jet data included in fit. Smaller high-$x$ gluon. larger small-$x$ gluon.

Change in best fit values of $\alpha_S(M_Z^2)$. Using $m_c = 1.4\mathrm{GeV}$ at NLO $0.1203$ compared to $0.121$ in unofficial MRST06 set. At NNLO $0.1169$ compared to $0.119$ in MRST06 set. At NNLO change in partons due coupling alone comparable to uncertainty.

Have full updated NLO and NNLO partons for LHC complete with experimental uncertainties. Different algorithm for uncertainties – similar results. To be certified very soon. Theoretical uncertainties require more work.

New HERA data on $F_L(x, Q^2)$ published so far in good agreement with predictions. Further data will help determine small-$x$ dynamics and "averaged" HERA structure function data help determine uncertainties on quarks and gluon.

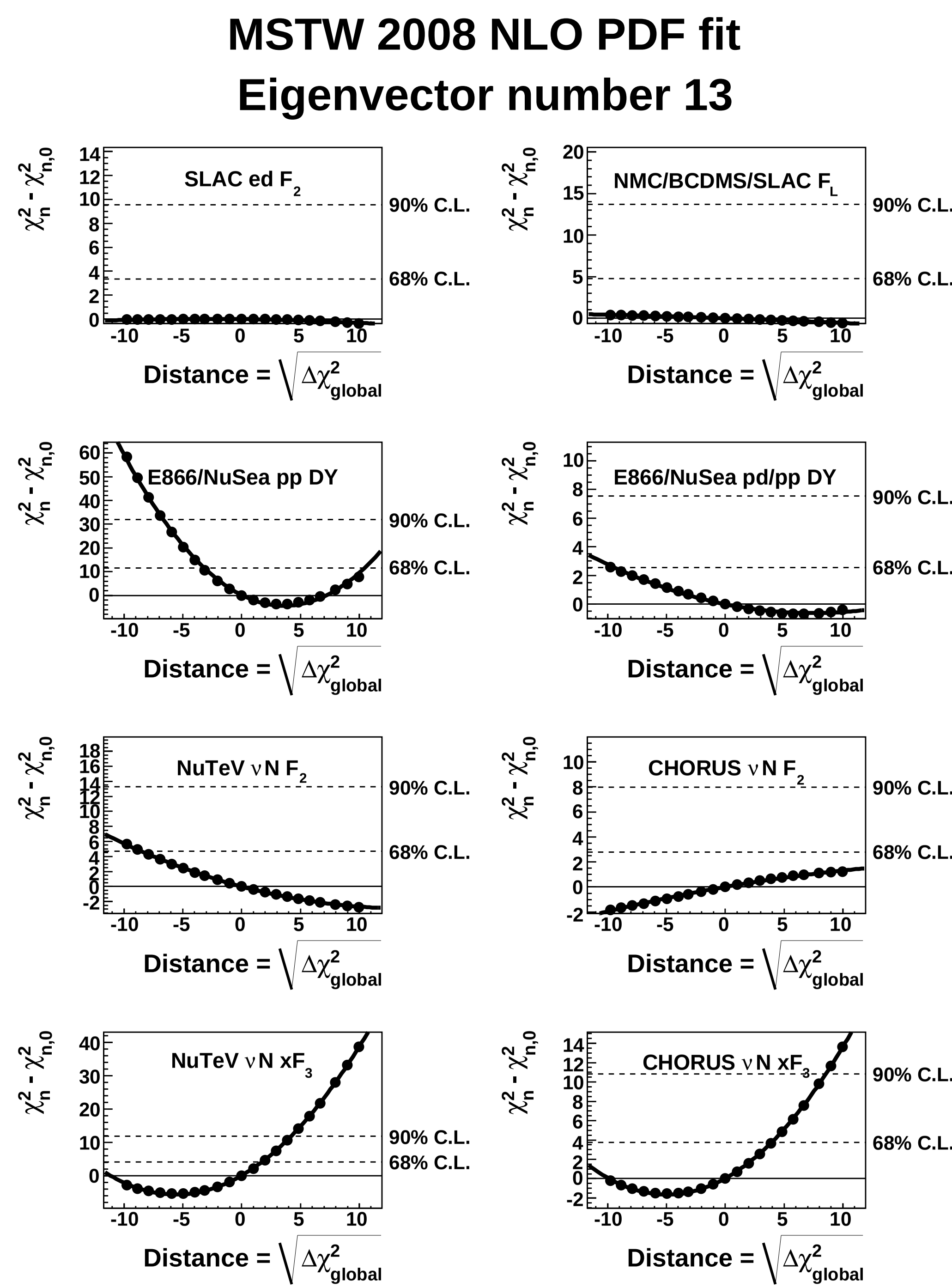
Neither standard LO and NLO partons ideal for LO generators. Comparison with processes where NLO known suggests modified LO* partons, usually provides most reliable results. Further change to coupling in LO** leads to slight further improvement. Now available on LHAPDF. In lhapdf-5.4.0 available as

MRST2007lomod.LHgrid – LO*

MRSTMCal.LHgrid – LO**

Structure of the proton incredibly well-constrained by lots of different data sets. Still lots to test/check at LHC and quite a few uncertain realms for predictions. Plenty of scope for surprises.

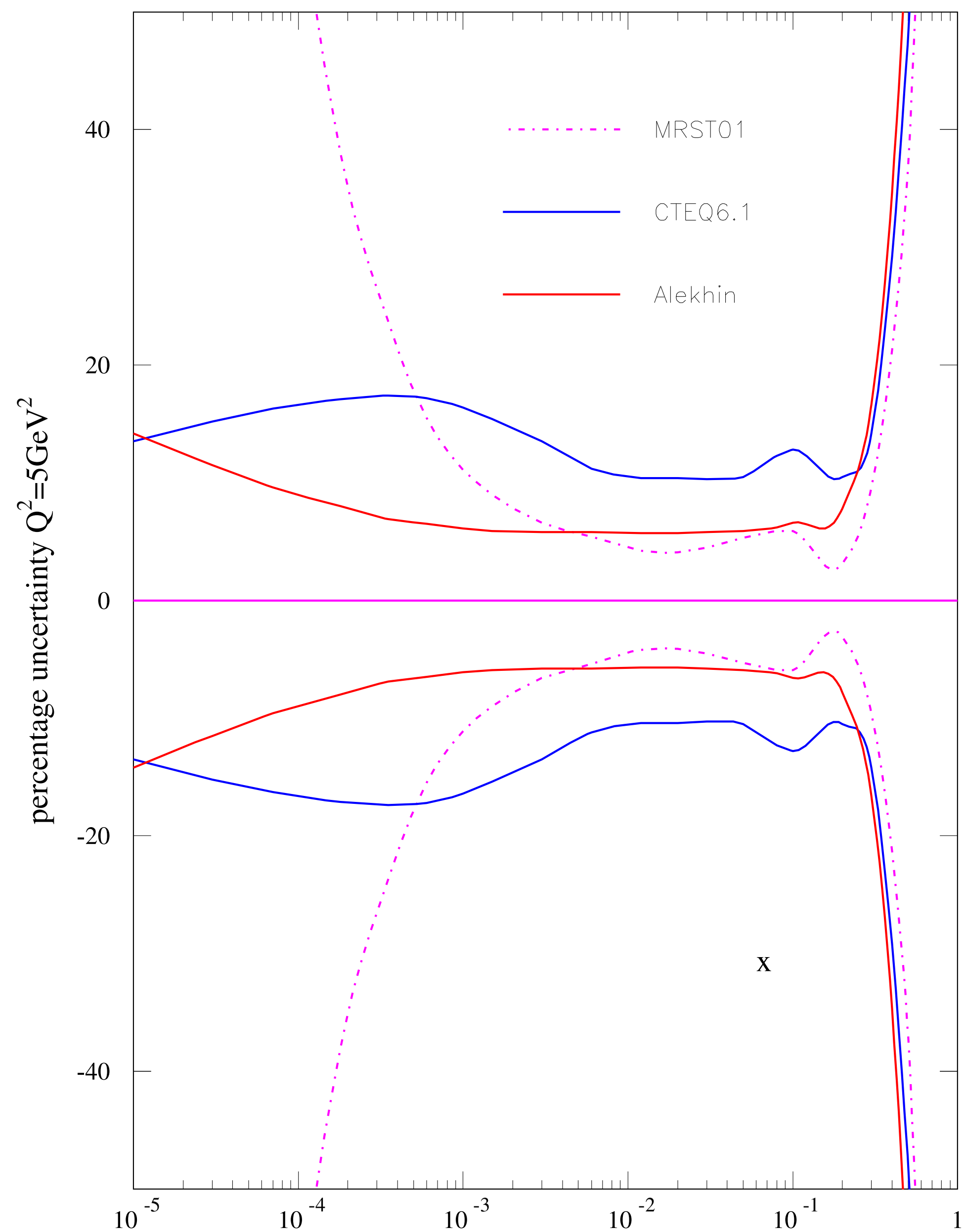
Variation in $\chi^2$ for single data set as function of increase in global $\chi^2$ for eigenvector13.



MRST uncertainty blows up for very small $x$, whereas Alekhin (and ZEUS and H1) gets slowly bigger, and CTEQ saturates (or even decreases).

Related to input forms and scales.

($Neck$ in MRST gluon cured in MSTW).



MRST (MSTW) parameterise at $Q_0^2 = 1\mathrm{GeV}^2$ but allow negative and positive small $x$ contributions. Very flexible. Represent true uncertainty at low $x$?

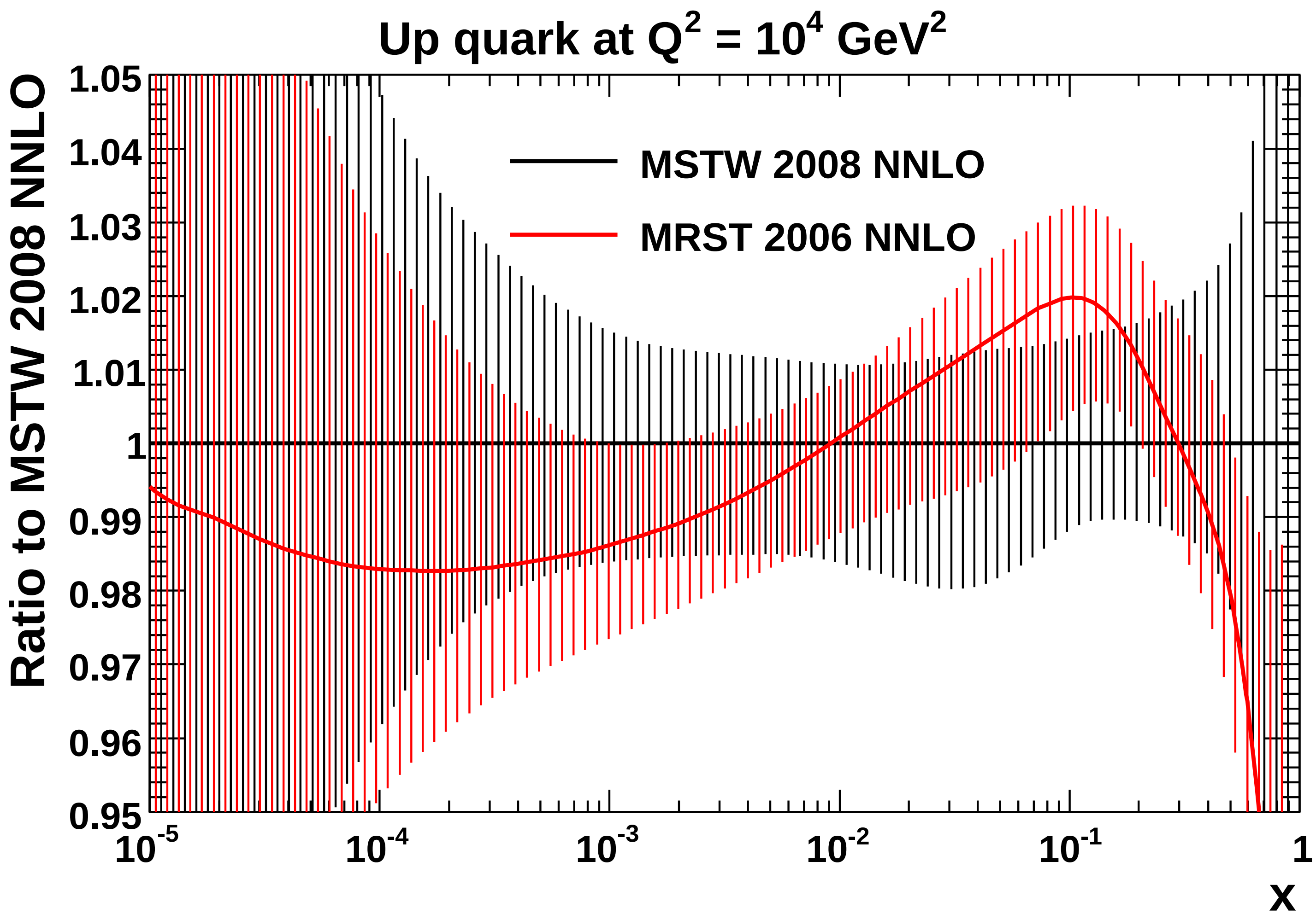
Alekhin and ZEUS gluons input at higher scale – behave like $x^{-\lambda}$ at small $x$. Uncertainty due to uncertainty in one parameter.

CTEQ gluons input at $Q_0^2 = 1.69\mathrm{GeV}^2$. Behave like $x^{\lambda}$ at small $x$ where $\lambda$ large and positive. Input gluon valence-like.

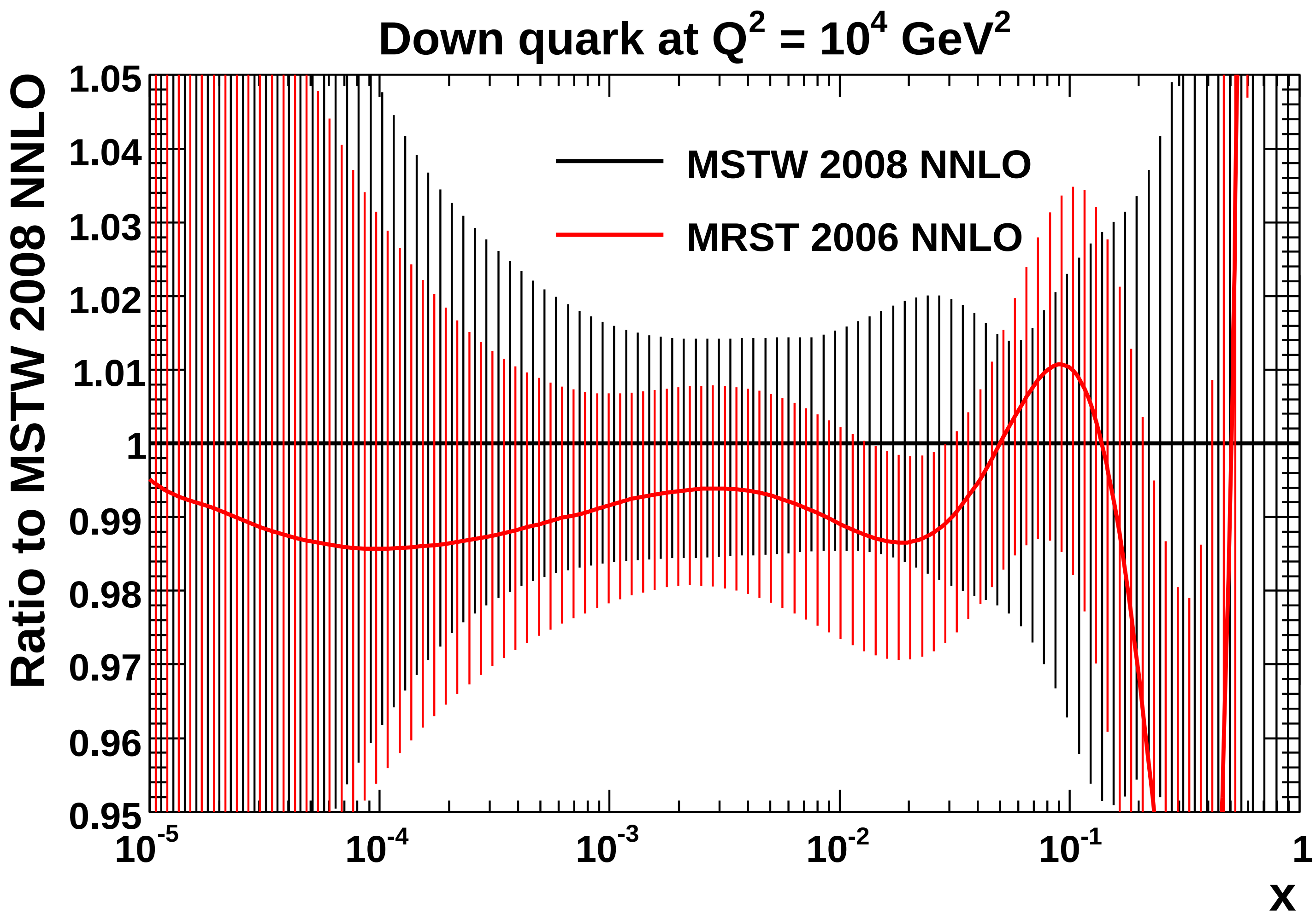
Requires fine tuning. Evolving backwards from steep gluon at higher scale valence-like gluon only exists for very narrow range of $Q^2$ (if at all).

Small $x$ input gluon tiny – very small absolute error. At higher $Q^2$ all uncertainty due to evolution driven by higher $x$, well-determined gluon. Very small $x$ gluon no more uncertain than at $x = 0.01 - 0.001$.

Change in shape in $u(x, Q^2)$ between MRST2006 and MRST2008 at NNLO at $x > 0.05$ mainly due to smaller $\alpha_S$ giving smaller coefficient function corrections to structure functions.

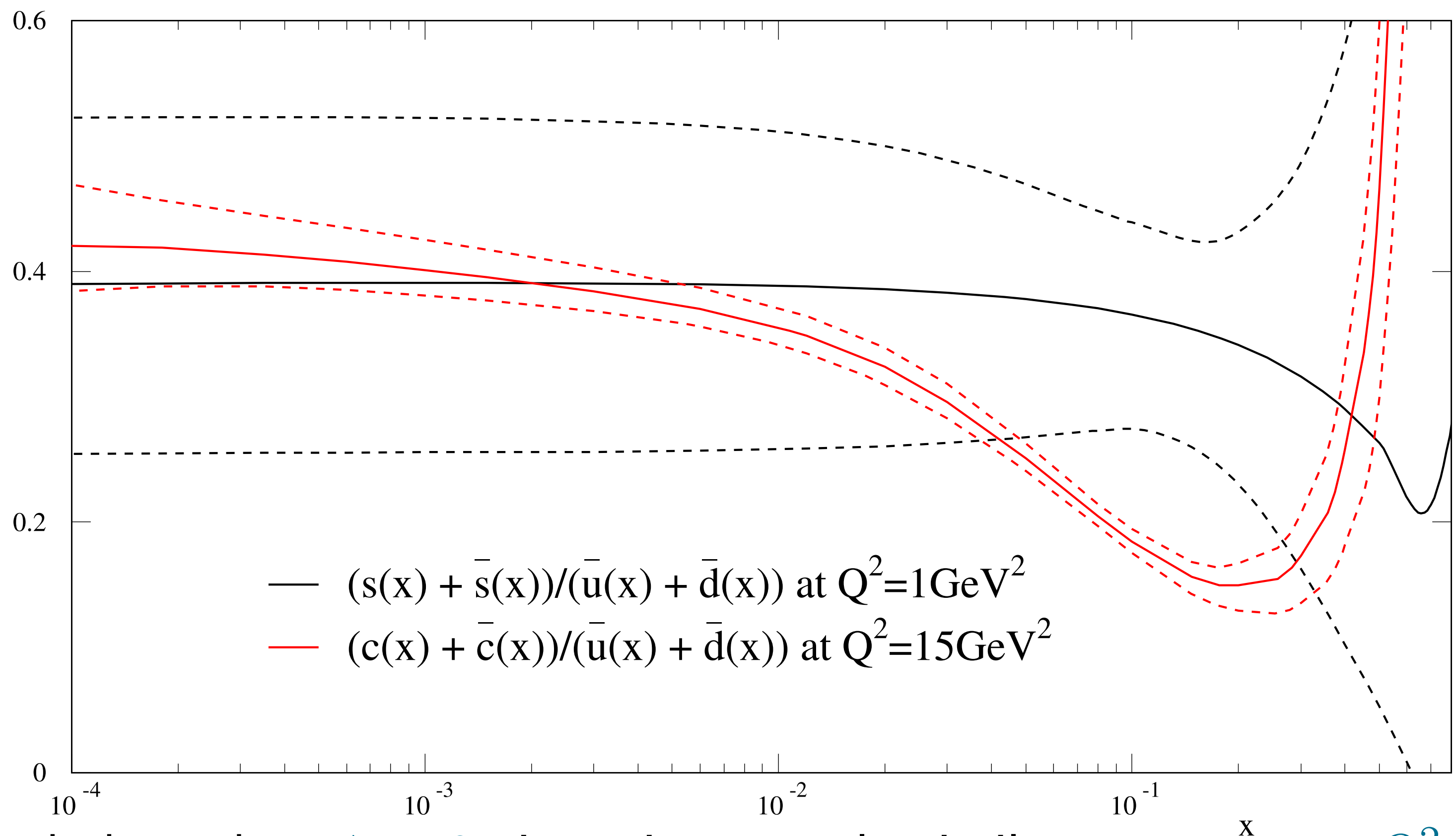


Change in shape in $d(x, Q^2)$ between MRST2006 and MRST2008 at NNLO at $x > 0.05$ also mainly due to smaller $\alpha_S$ giving smaller coefficient function corrections to structure functions.



Strange itself has some non-insignificant mass, and this should qualitatively lead to suppression compared to light sea quarks up and down.

When $c$ and $b$ turn on they evolve like massless quarks, but always lag behind. $\rightarrow$ some suppression at all $x$ for finite $Q^2$.




$c + \bar{c}$ evolved through $\sim 7 - 8$ times input scale similar to $s + \bar{s}$ at $Q^2 = 1\mathrm{GeV}^2$. Do not expect exact correspondence, but very good except $c + \bar{c}$ more suppressed at $x \sim 0.1$. (Implication for $s + \bar{s}$ from recent HERMES $K^{\pm}$ data).

# W-**asymmetry**

The $W$-asymmetry at the Tevatron is defined by

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)},$$

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

In practice it is the final state leptons that are detected, so it is really the lepton asymmetry

$$A(y_l) = \frac{\sigma(l^+) - \sigma(l^-)}{\sigma(l^+) + \sigma(l^-)}$$

which is measured. Defining angle of lepton in $W$ rest frame

$$\cos^2\theta^* = 1 - 4E_T^2/M_W^2 \quad \rightarrow \quad y_{lep} = y_W \pm 1/2 \log((1+\cos\theta^*)/(1-\cos\theta^*))$$

In practice at highish $y_{lep}$

$$\sigma(l^+) - \sigma(l^-) \propto u(x_1)d(x_2)(1-\cos\theta^*)^2 + \bar{d}(x_1)\bar{u}(x_2)(1+\cos\theta^*)^2 - u(x_2)d(x_1)(1+\cos\theta^*)^2$$

so fairly sensitive to anti-quarks at lower $E_T$.

Same with D0 data. Similar results. Would like larger $d(x, Q^2)$ for $x \sim 0.2$.

More sensitivity to sea quarks due to lower $p_T$ values.