An Update of the MRST (MSTW) Parton Distributions

Robert Thorne

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University College London

Royal Society Research Fellow

Major update in people involved.

Dick Roberts completely retired from project.

Graeme Watt started as responsive RA on parton distributions from April 1st 2006. Now making major contribution to project – responsible for many of these new results.

Major changes in theory.

Implementation of updated heavy flavour VFNS, particularly at NNLO.

Already used a general VFNS since 1998 but change in details.

Inclusion of NNLO corrections to Drell-Yan data.

Some important changes as NLO $\rightarrow$ NNLO.

Most important change compared to previous NNLO – new VFNS. $\rightarrow$ significant change in partons.

Implementation of fastNLO – fast perturbative QCD calculations Kluge, Rabbertz, Wobisch. Allows easy inclusion of new data.

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 – $25\text{GeV} < E_T < 35\text{GeV}$ and $35\text{GeV} < E_T < 45\text{GeV}$.

HERA inclusive jet data (in DIS).

New CDFII high-E_T jet data.

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

Update to include all recent charm structure function data.

Look at dependence of fit on m_c – defined as pole mass.

Obtain NNLO partons with uncertainties due to experimental errors for the first time.

Reported last year.

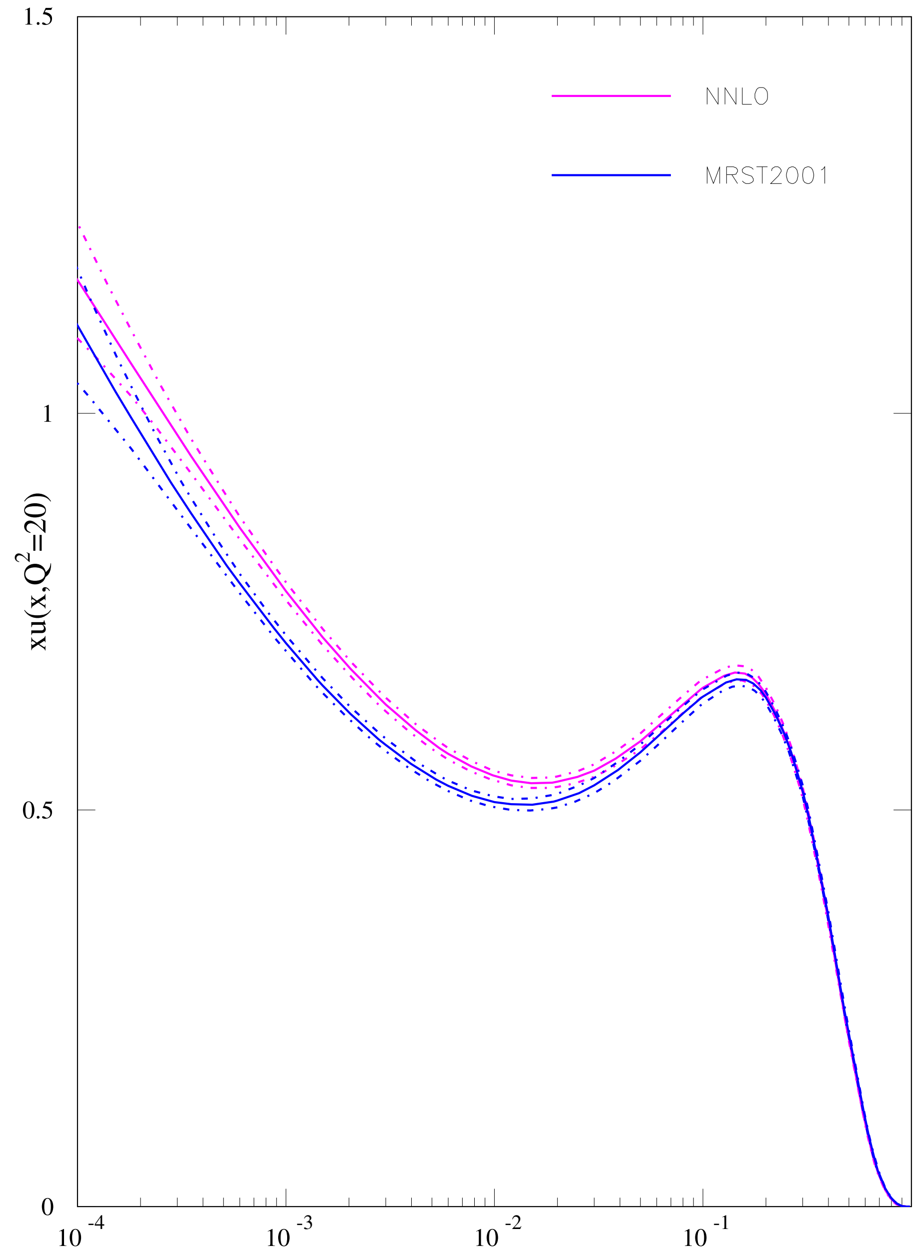
Same procedure as before – 15 eigenvector sets of partons and $\Delta\chi^2 = 50$ for 90% confidence limit.

First time we have full NNLO with no major approximations. (Heavy flavours a major issue.)

In general size of uncertainties similar (perhaps a little smaller) to at NLO.

Change from NLO to NNLO greater than uncertainty in each.

NNLO fit consistently better than NLO.



Comparison to other (Alekhin) NNLO gluon.

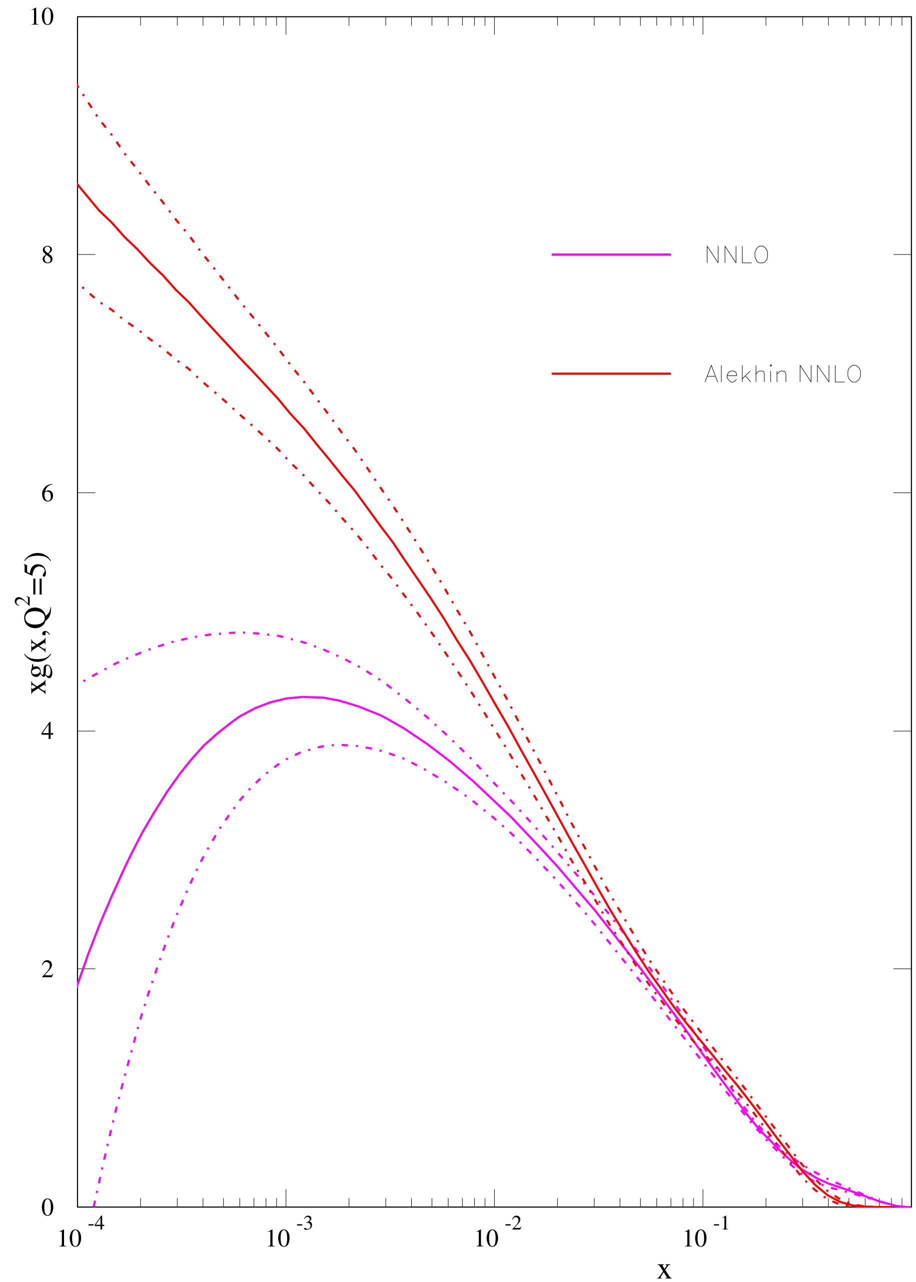
Hugely different at small x.

Differences much bigger than uncertainties.

Differences in heavy flavour treatments - disagreement on what constitutes definition of NNLO.

Differences in data fit and also in $\alpha_S(M_Z^2)$.

Note difference in uncertainty at low x not just in shape.

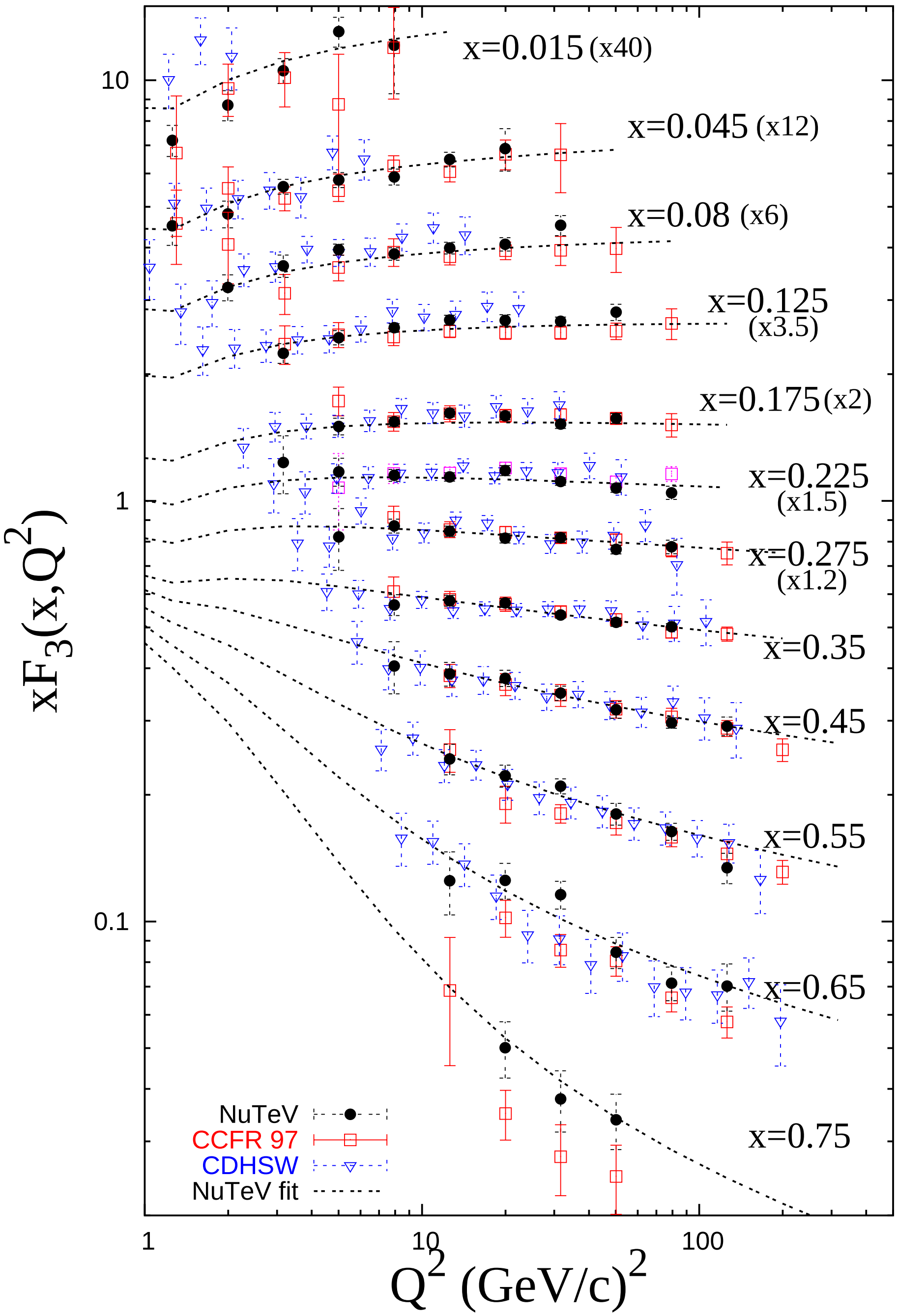


New Data

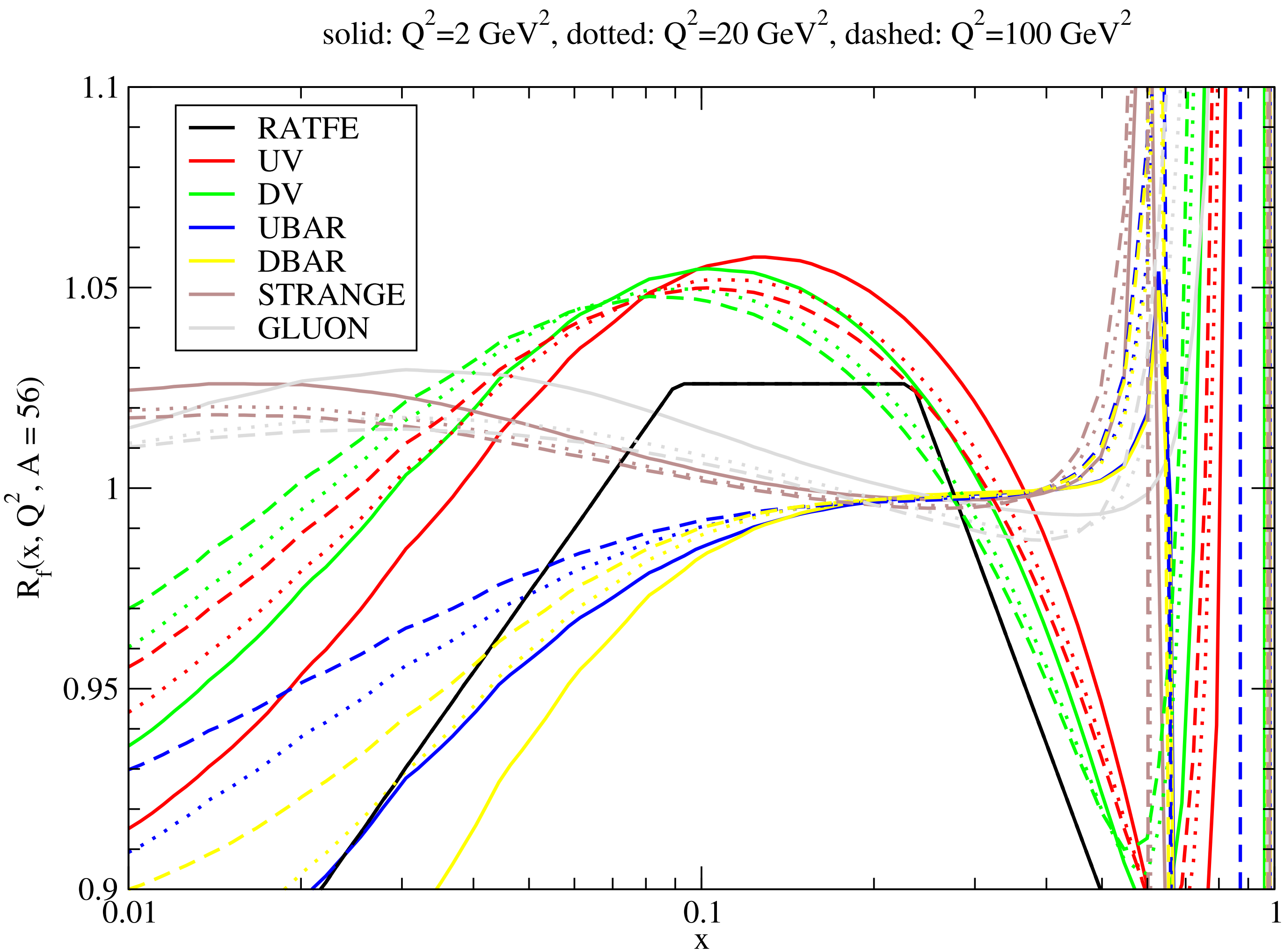
New NuTeV data not completely compatible with the older CCFR data.

Main source of discrepancy's calibration of magnetic field map of muon spectrometer $\longrightarrow$ muon energy scale.

However, previous parton distribution fits were perfectly compatible with CCFR data using EMC inspired Q^2 independent nuclear correction



Now implement far more sophisticated nuclear correction De Florian, Sassot. Extracted using NLO partons.



Same general shape as before. Allow $\sim 3\%$ uncertainty on corrections. Cannot match high NuTeV data.

Chorus data also consistent with CCFR (lead not iron).

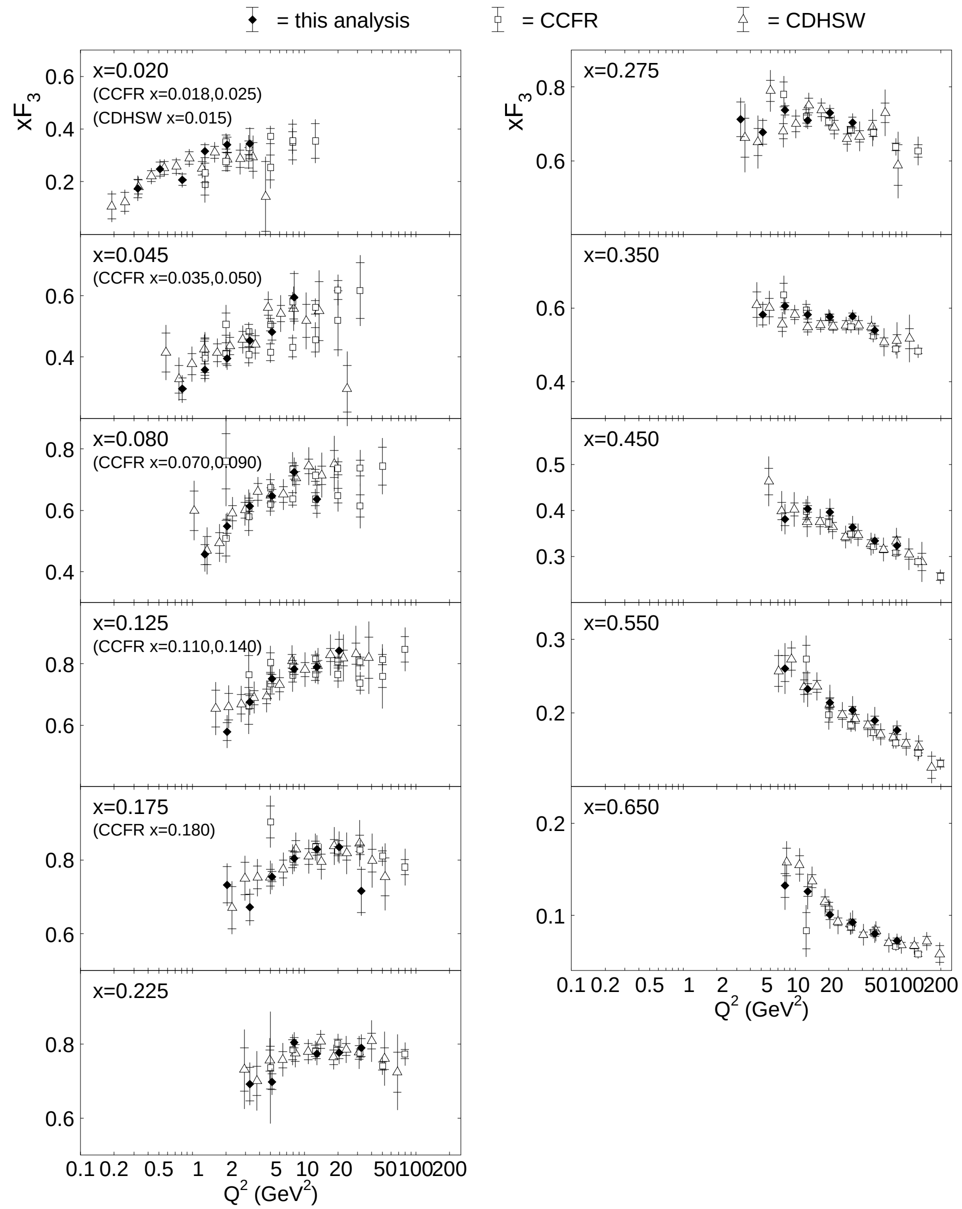
Inconsistencies at high x.

Partons in region of high x already well-determined from charged lepton structure functions.

Important information in the region $x < 0.3$, e.g. low x valence quarks - general consistency here.

Choose to cut neutrino structure function data for $x \geq 0.5$.

Also Chorus data at lower W^2. $F_3(x, Q^2)$ expected to have larger higher twist corrections than $F_2(x, Q^2)$. Cut for $W^2 \leq 20\mathrm{GeV}^2$.



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.

ν_μ 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

$$s(x, Q_0^2) = \bar{s}(x, Q_0^2) = \frac{\kappa}{2}[\bar{u}(x, Q_0^2) + \bar{d}(x, Q_0^2)] \qquad \kappa \approx 0.5$$

Now fit strange directly rather than assuming same shape as average of $\bar{u} + \bar{d}$ at input and some **fixed** fraction.

Also allow possibility of $s(x, Q_0^2) \neq \bar{s}(x, Q_0^2)$.

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, i.e.

$$\int_0^1 dx\, s^-(x,Q_0^2) = 0.$$

Extra freedom in both s^+ and s^- confirmed by fit.

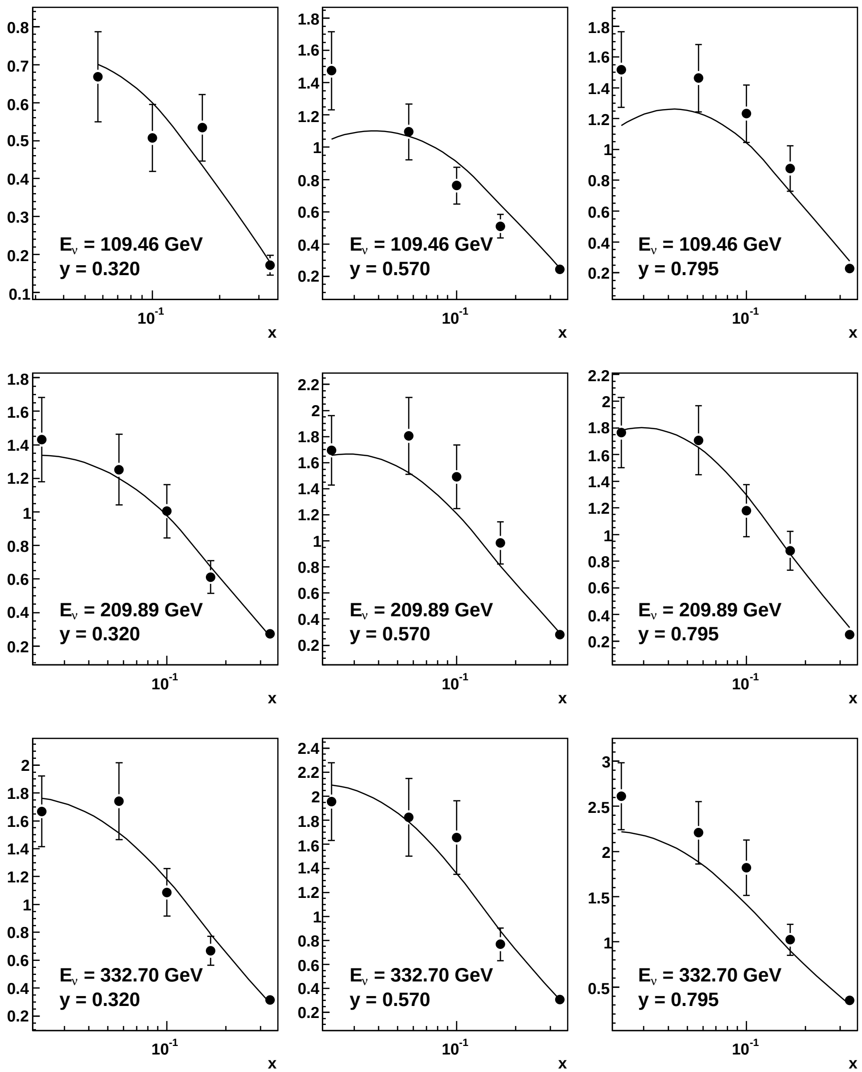
	χ^2_{CCFR} 86 pts	χ^2_{NuTeV} 84 pts	χ^2_{global} 2659 pts
$s = \bar{s} = (\bar{u}+\bar{d})/4$	71	63	2501
s^+ free, $s^- = 0$	65	52	2486
s^+ free, s^- free	65	38	2472

No improvement with further parameters.

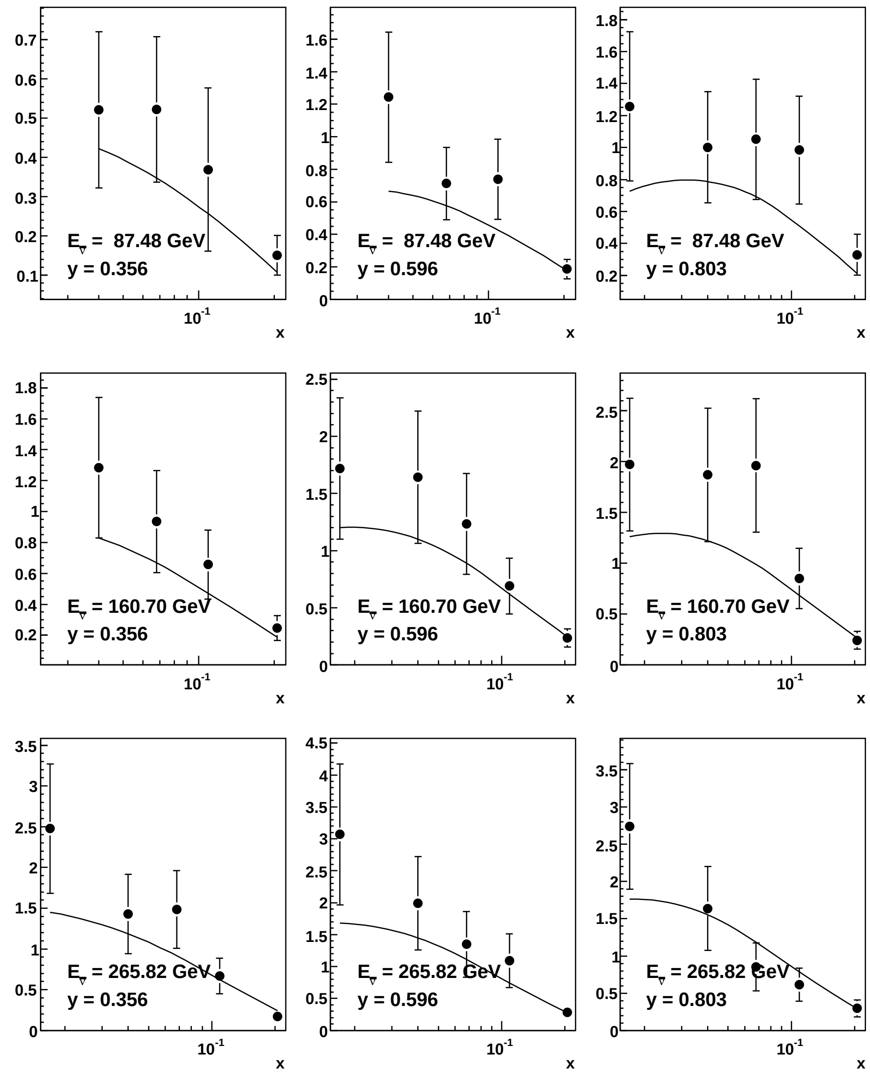
Data generally prefer s^+ free. Dimuon data only affected by s^-. Decoupled from other parameters to good approximation. $\delta_- = 0.2$ fixed, i.e. valence-like value.

Fit to data clearly very good.

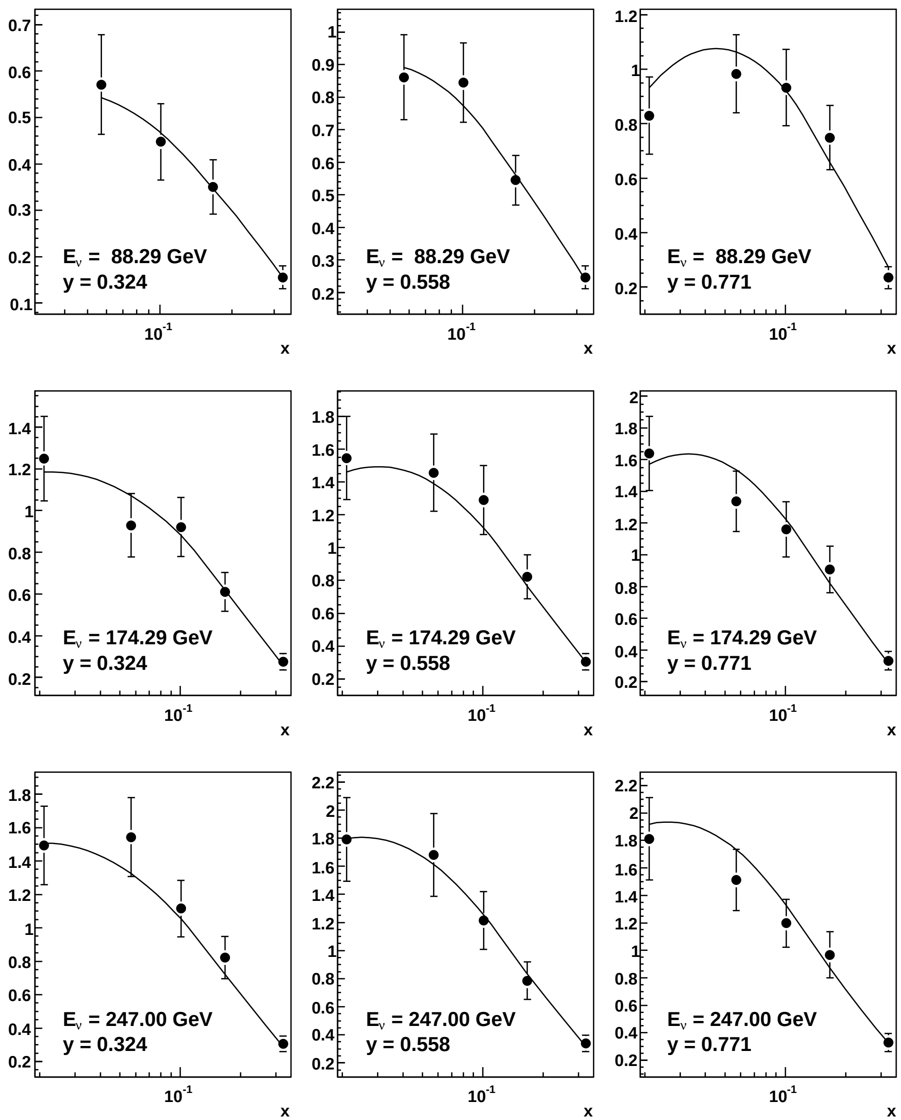
CCFR $\frac{100\pi}{G_F^2 M_N E_\nu} \frac{d\sigma}{dxdy}(\nu_\mu N \rightarrow \mu^+\mu^- X)$ in GeV^{-2}, χ^2 = 33/44 pts.



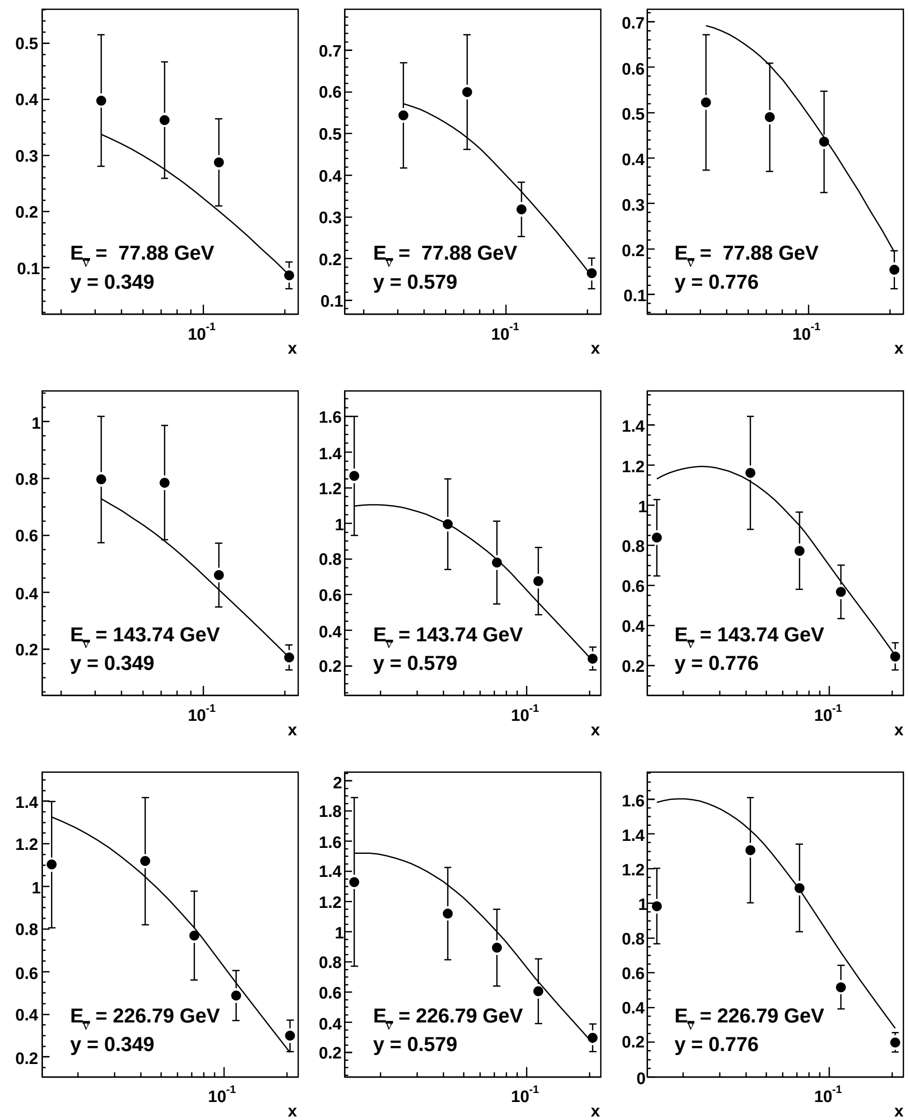
CCFR $\frac{100\pi}{G_F^2 M_N E_{\bar\nu}} \frac{d\sigma}{dxdy}(\bar\nu_\mu N \rightarrow \mu^+\mu^- X)$ in GeV^{-2}, χ^2 = 32/42 pts.



NuTeV $\frac{100\pi}{G_F^2 M_N E_\nu} \frac{d\sigma}{dxdy}(\nu_\mu N \rightarrow \mu^+\mu^- X)$ in GeV^{-2}, χ^2 = 11/21 DOF

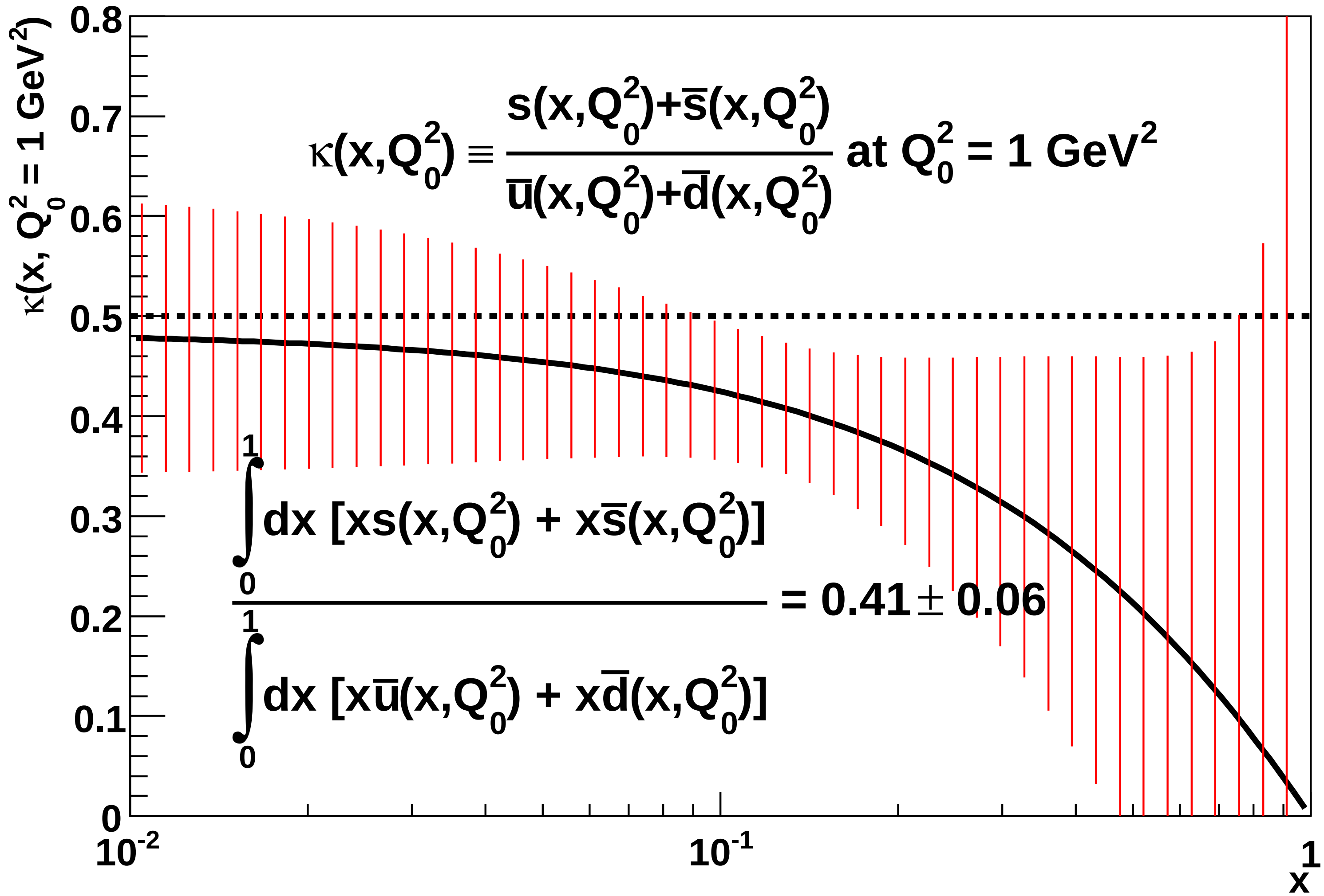


NuTeV $\frac{100\pi}{G_F^2 M_N E_{\bar{\nu}}} \frac{d\sigma}{dxdy}(\bar{\nu}_\mu N \rightarrow \mu^+\mu^- X)$ in GeV^{-2}, χ^2 = 27/19 DOF



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

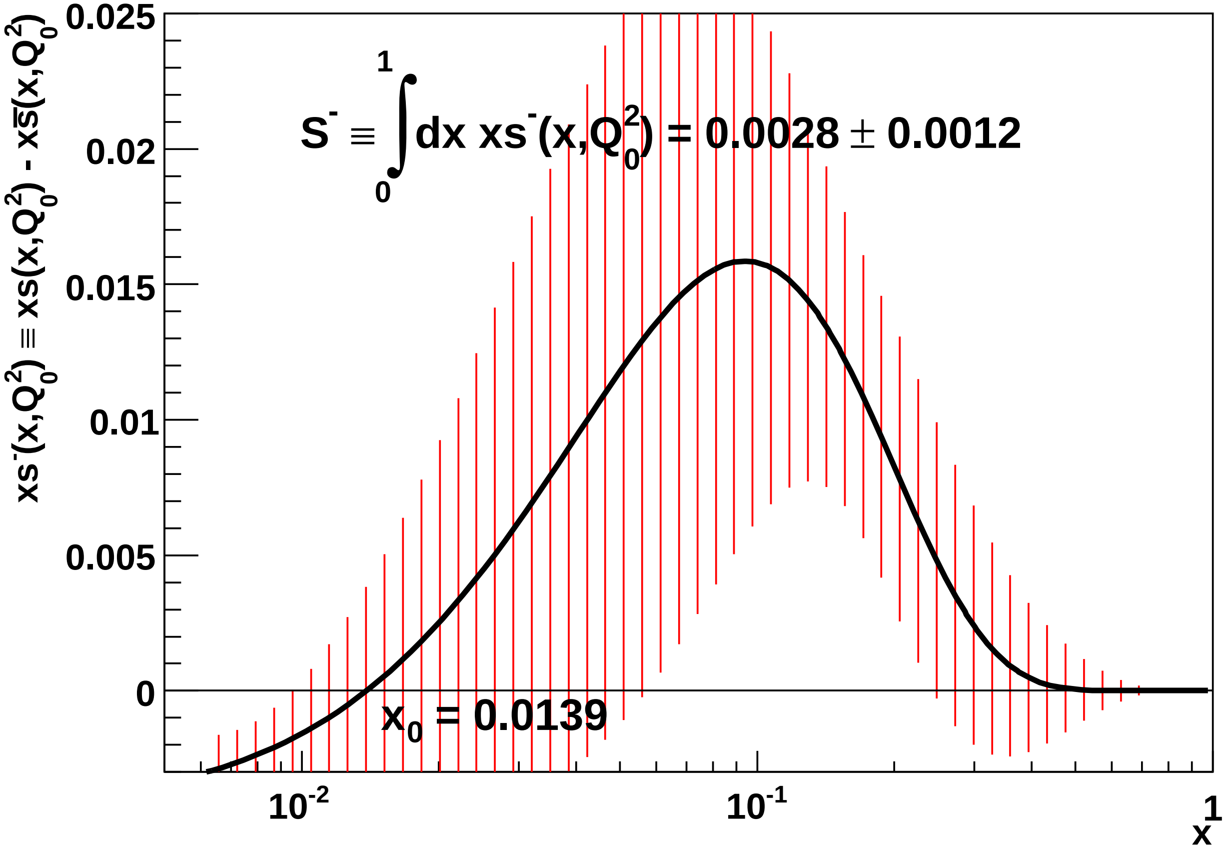
Suppression at high x, i.e. low W^2. Effect of m_s?



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 0.0028 ± 0.0012 (1σ). Nonzero value significantly greater than 1σ significance. At $Q^2 = 10\mathrm{GeV}^2$ asymmetry of 0.0021 ± 0.0009.

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



Fitting to strange from NUTEV dimuon data affects uncertainties on partons other than strange.

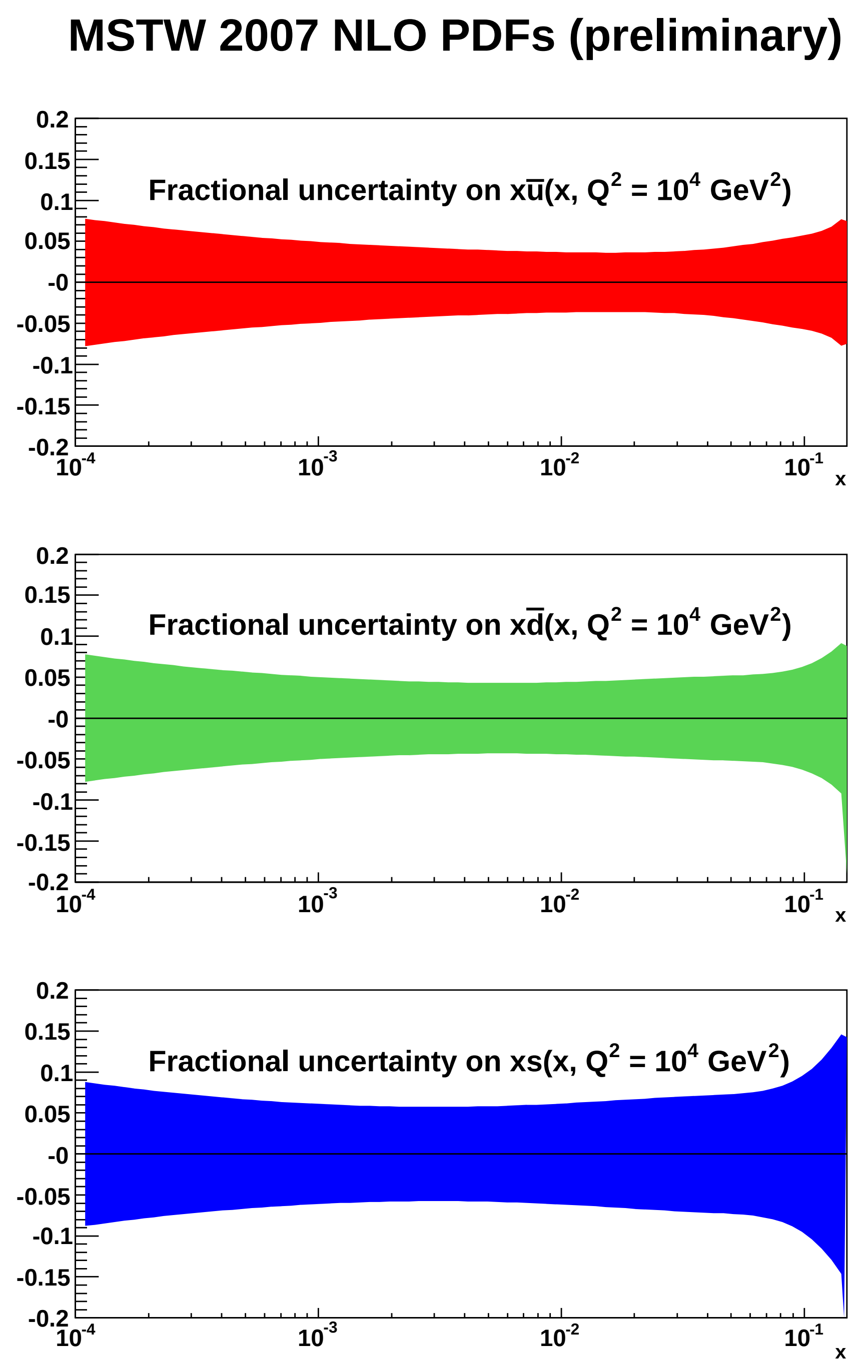
Previously for us (and everyone else) strange a fixed proportion of total sea in global fit.

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 roughly doubles – $\sim 1.5\% \rightarrow\sim 3\%$. (Remember uncertainties quoted as 90% confidence limits.)



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}

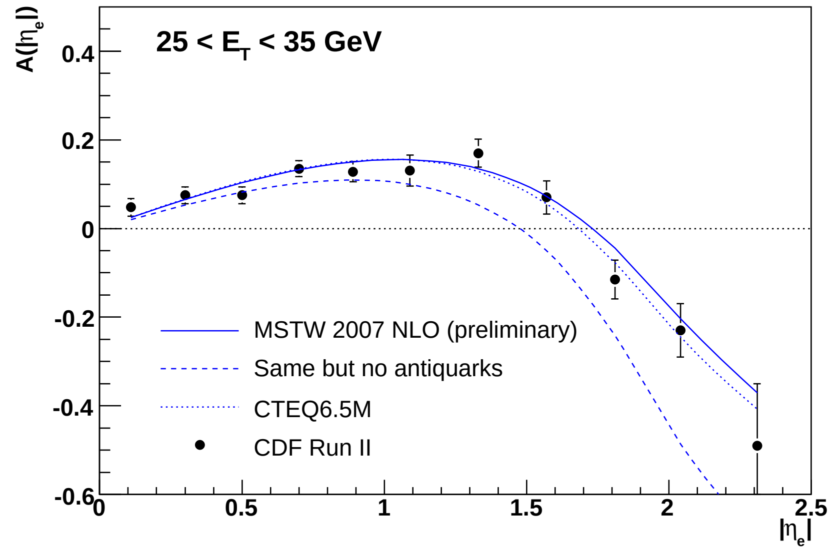
$$\sigma(l^+) - \sigma(l^-) \propto u(x_1)d(x_2)(1-\cos\theta^*)^2 + \bar{u}(x_1)\bar{d}(x_2)(1+\cos\theta^*)^2 - u(x_2)d(x_1)(1+\cos\theta^*)^2$$

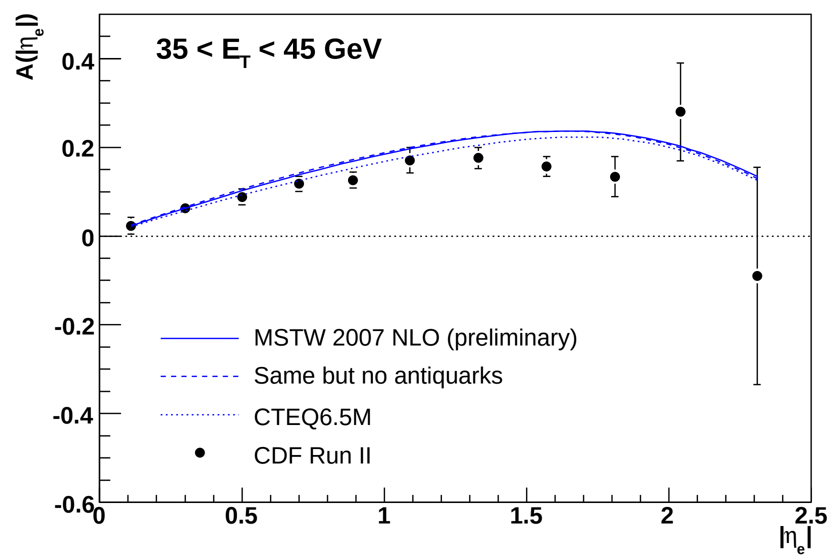
so fairly sensitive to anti-quarks at lower E_T.

Comparison of fits with various partons. Some tension with neutrino structure function data.

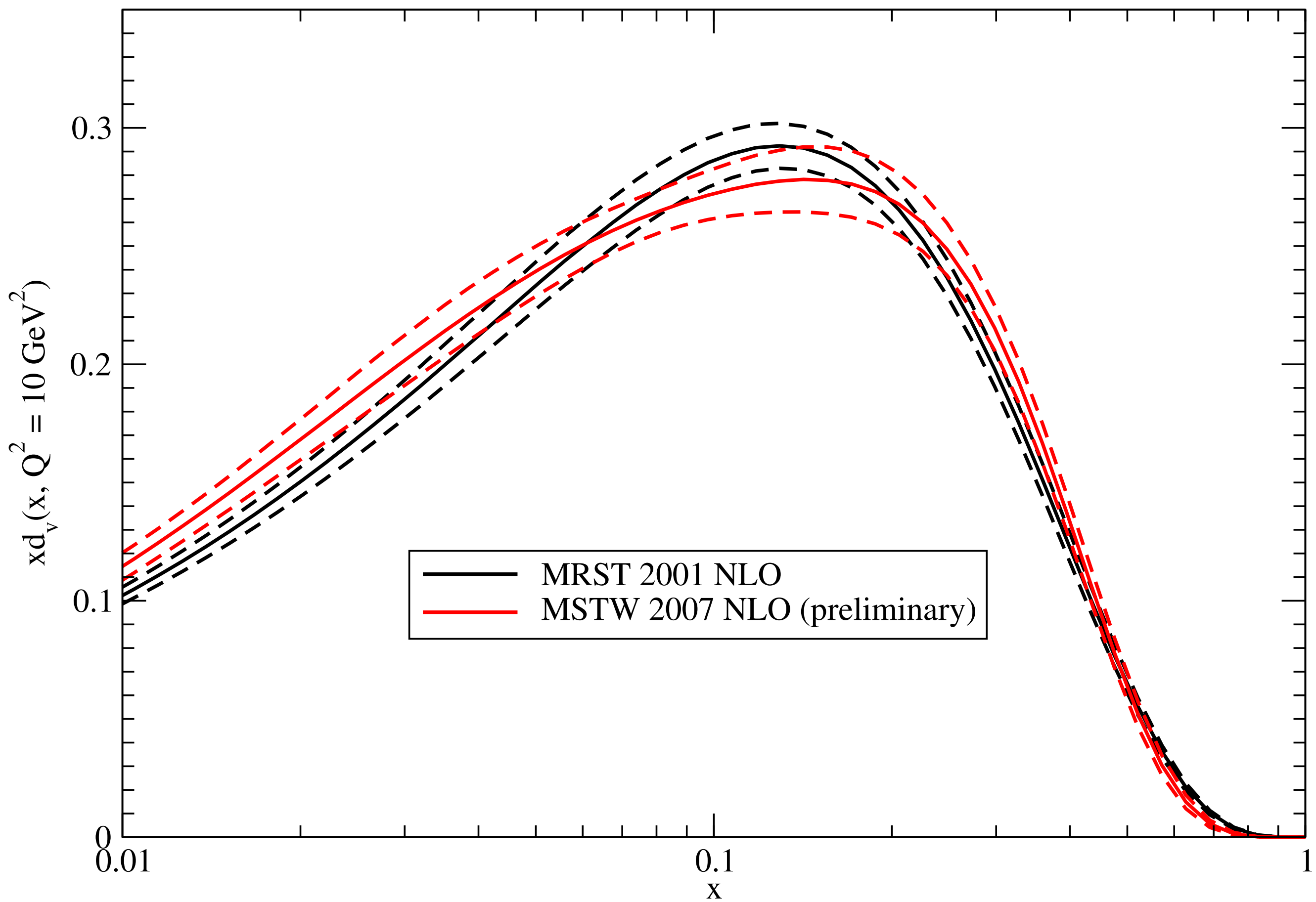
CTEQ seems to be better shape for some reason.

New CDF data does influence $d(x,Q^2)$ in MSTW fit.





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

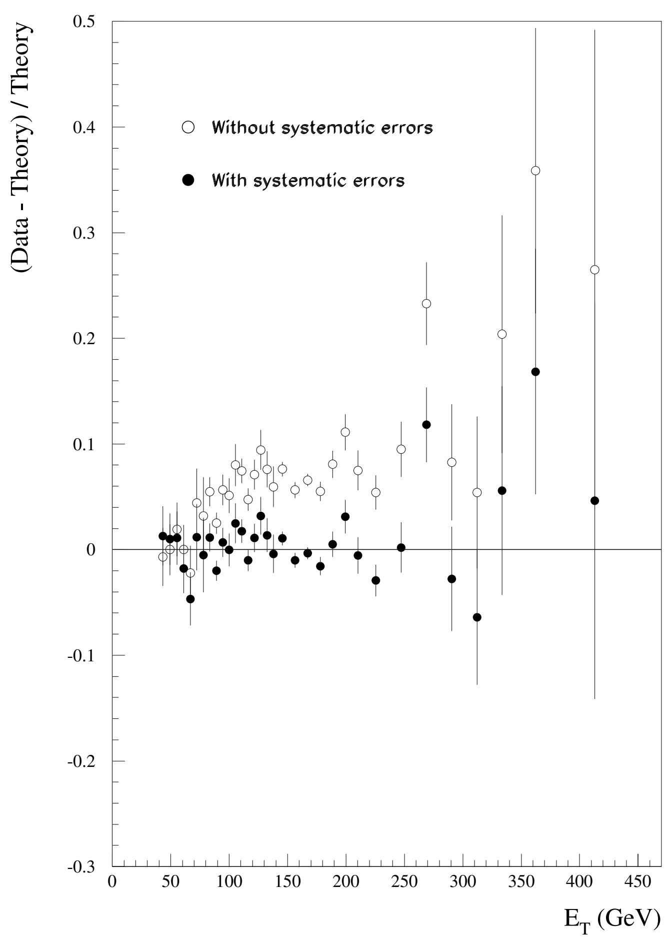


Uncertainty growing more quickly as $x \to 0$ than before due to better parameterization in determining uncertainty eigenvectors.

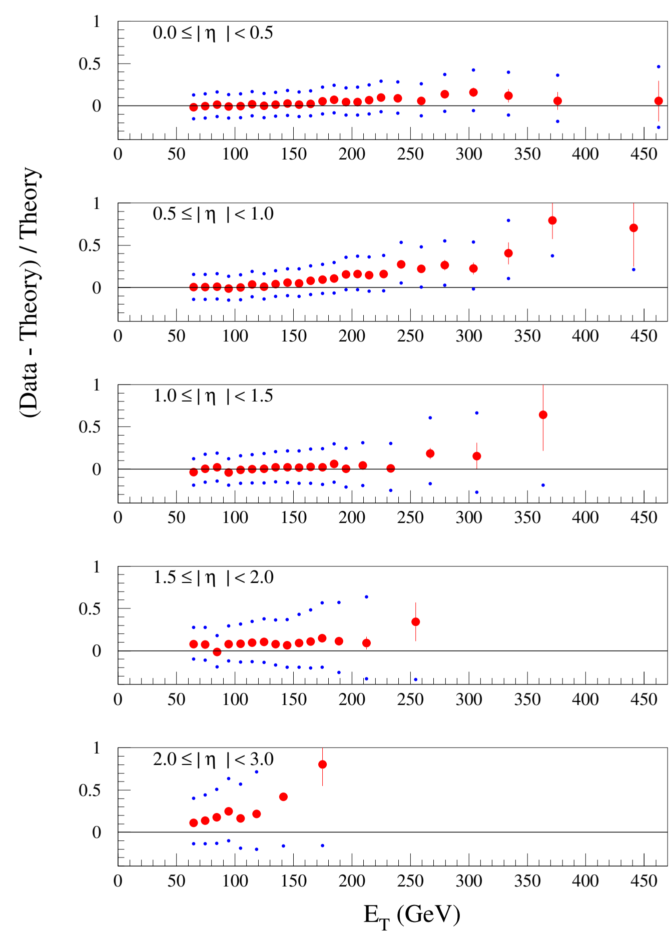
Now use fast NLO to implement NLO hard cross-section corrections to both Tevatron and HERA jets. Replaces previous "K-factors" and "pseudo-gluon data".

No major effect on speed of fitting program. Slight influence on shape of gluon even using just Tevatron Run I data. (Hadronization corrections now included).

CDF Run I inclusive jet data, χ^2= 50/33 pts.



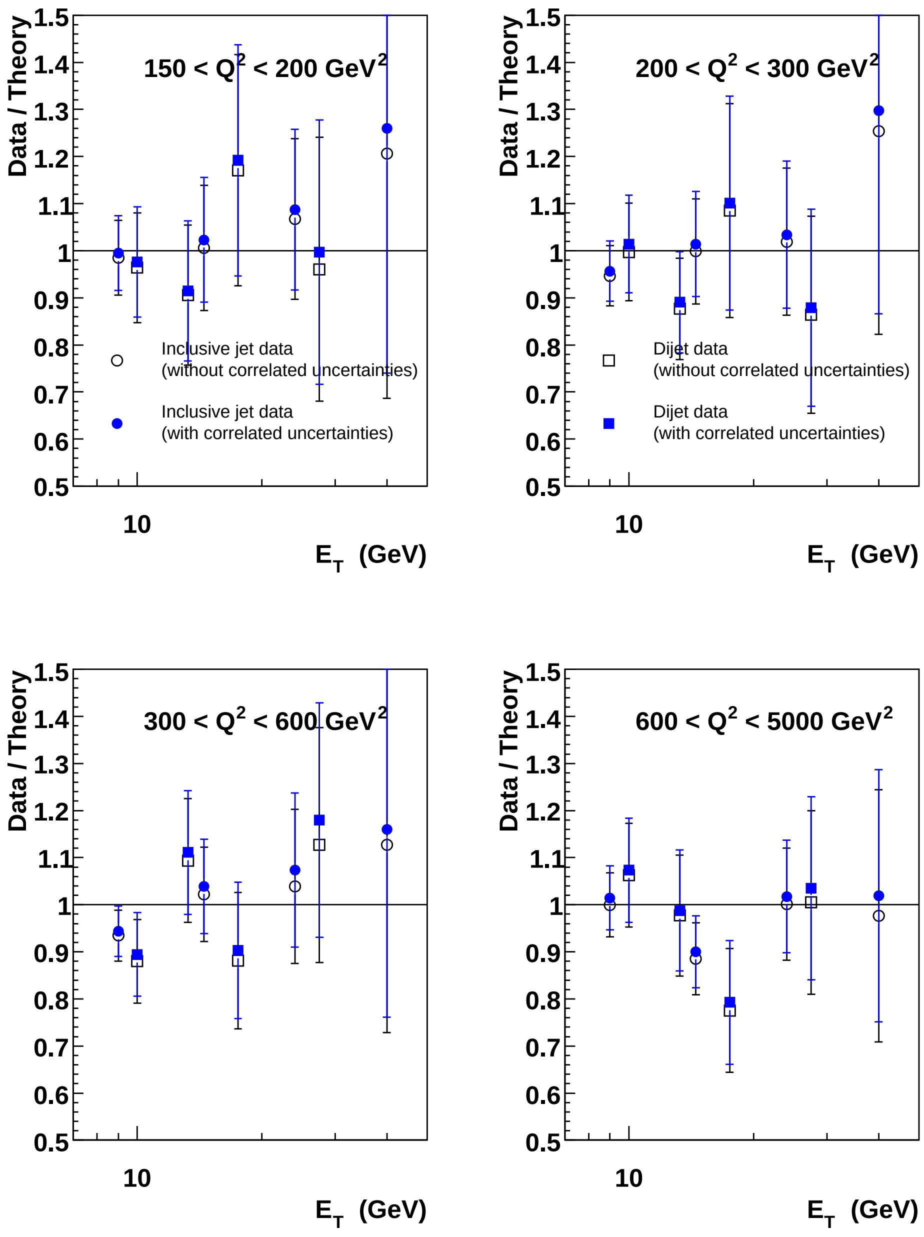
DØ Run I inclusive jet data, χ^2= 58/90 pts.



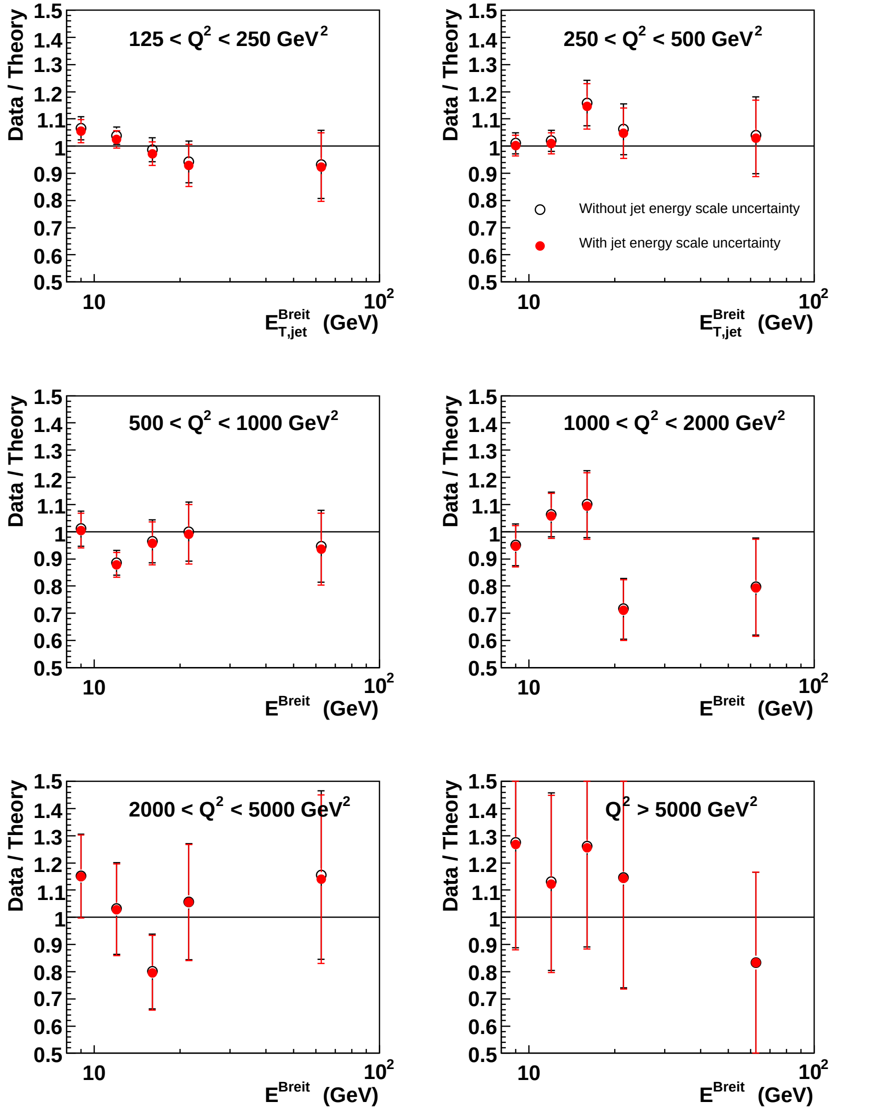
Also now include HERA inclusive and dijet DIS data using fastNLO.

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

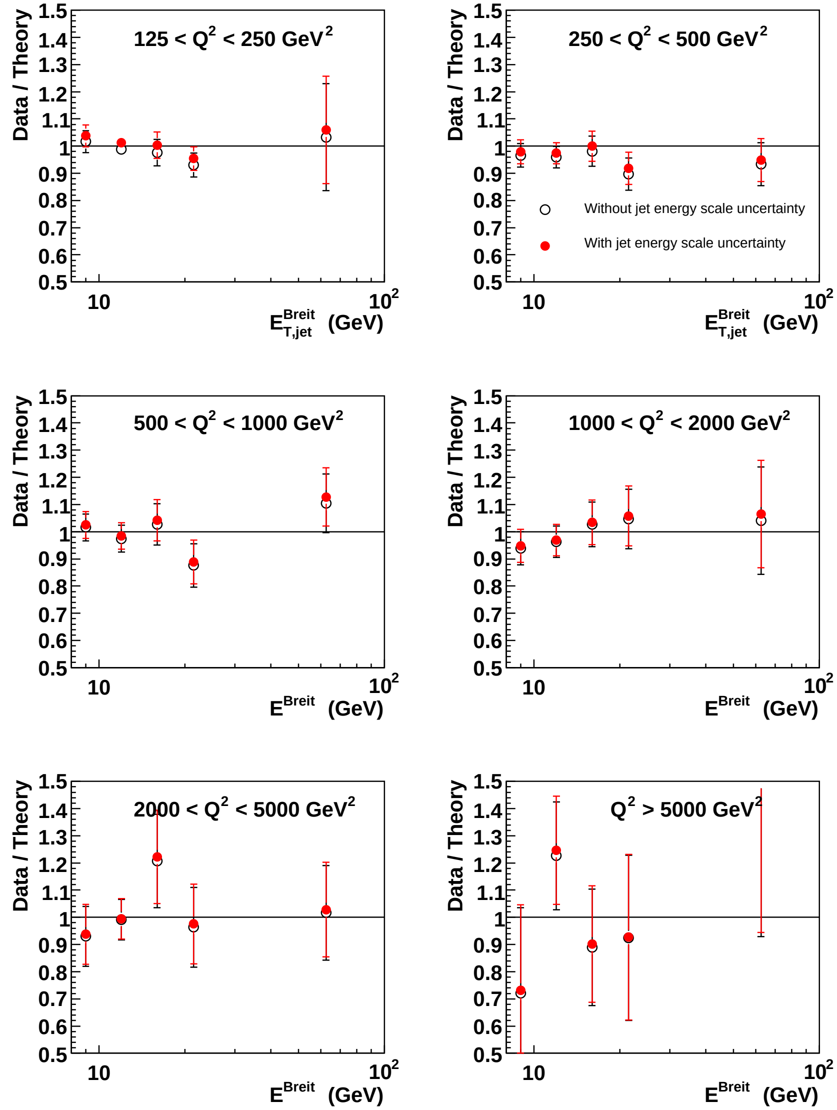
H1 95-97 incl. jet and dijet data, χ^2 = 14/32 pts.



ZEUS 96-97 inclusive jet data, χ^2 = 30/30 pts.

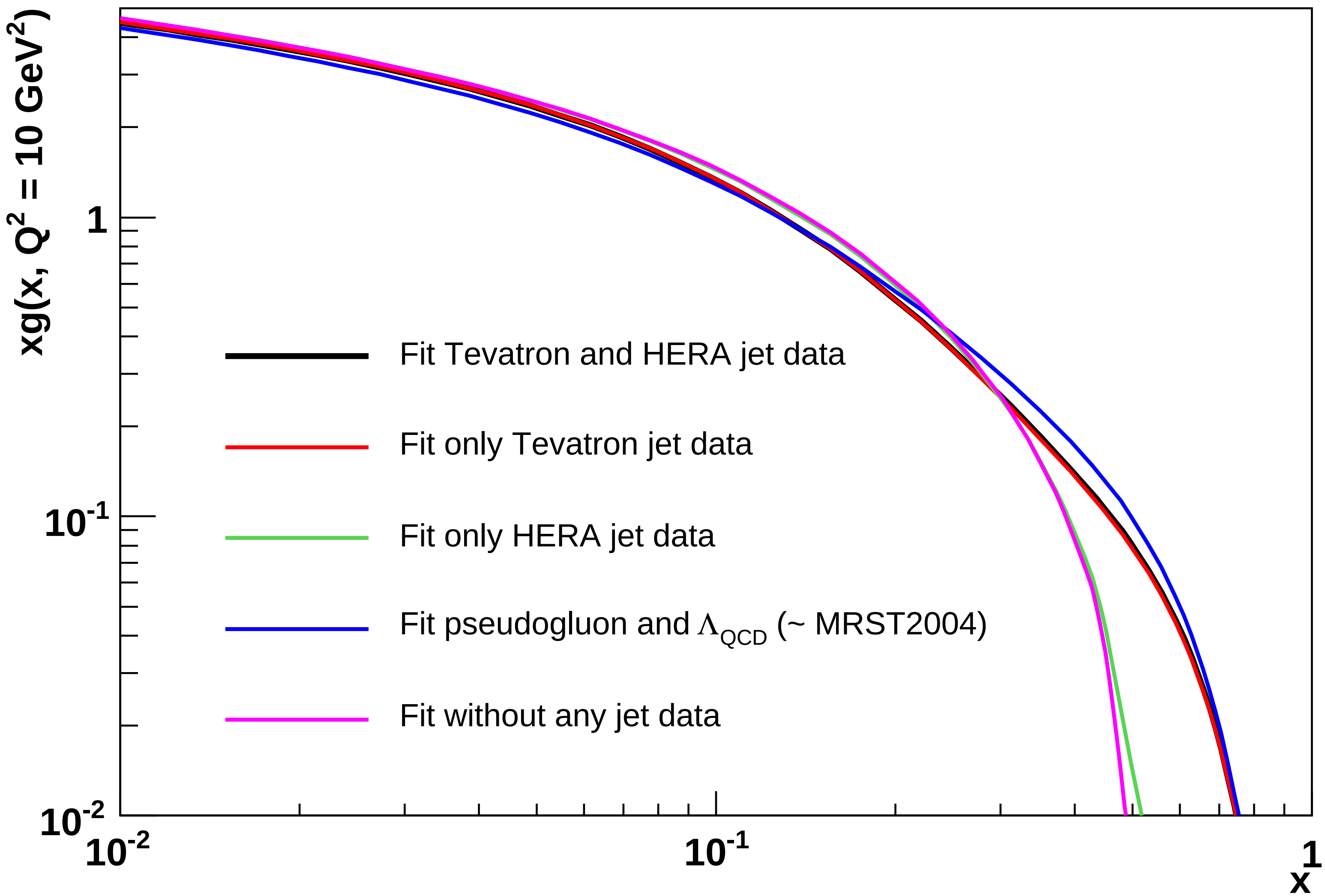


ZEUS 98-00 inclusive jet data, χ^2 = 16/30 pts.



Perhaps more constraint from photoproduction data, but requires (rather uncertain) photon distributions.

Tevatron jet data are essential for constraining high x gluon – HERA jet data not sensitive to these x values and have much less pull.

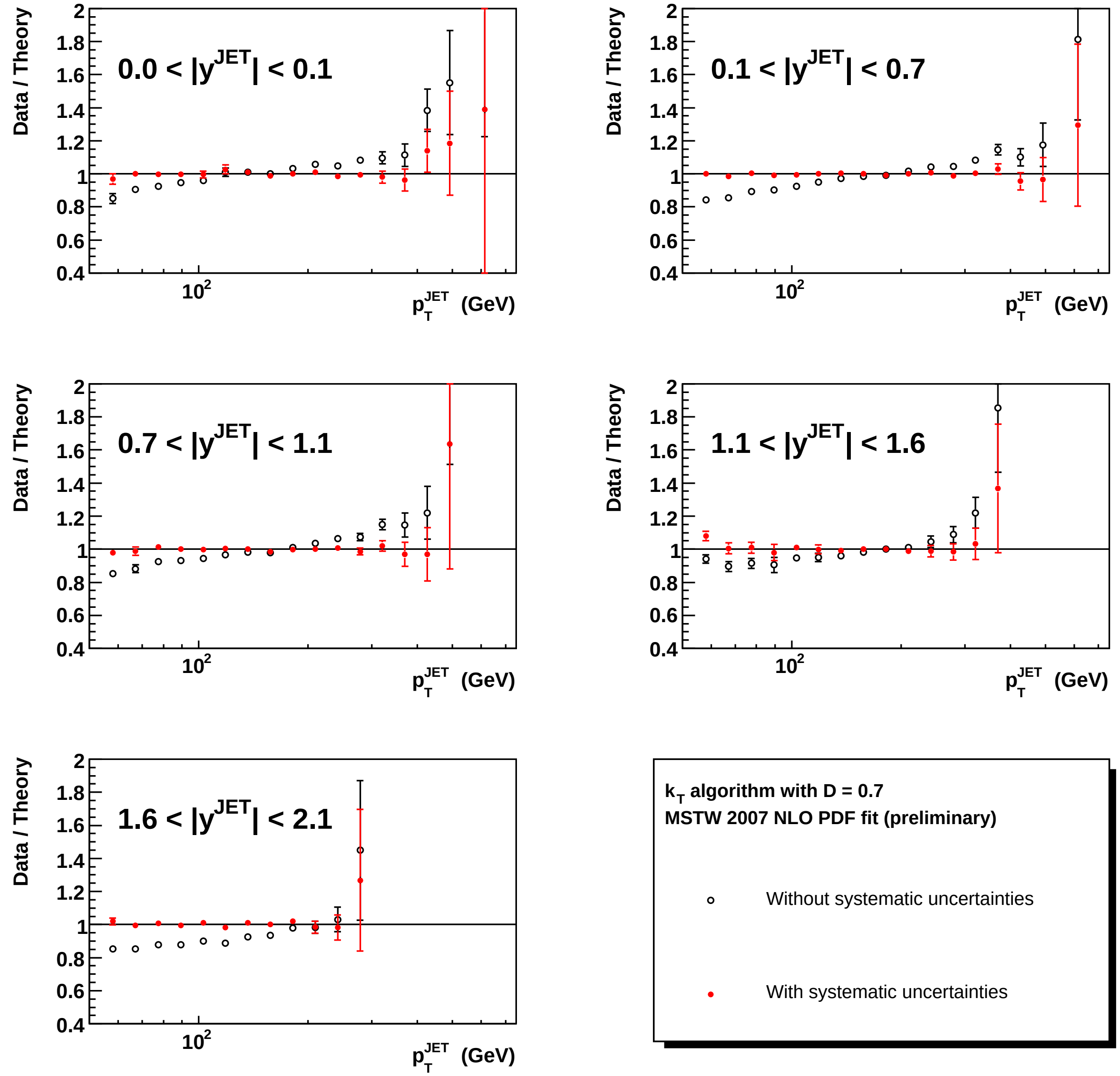


Now also include CDF Run II inclusive jet data in different rapidity bins using k_T jet algorithm (mid-point cone algorithm data seems very similar, but numbers not yet available).

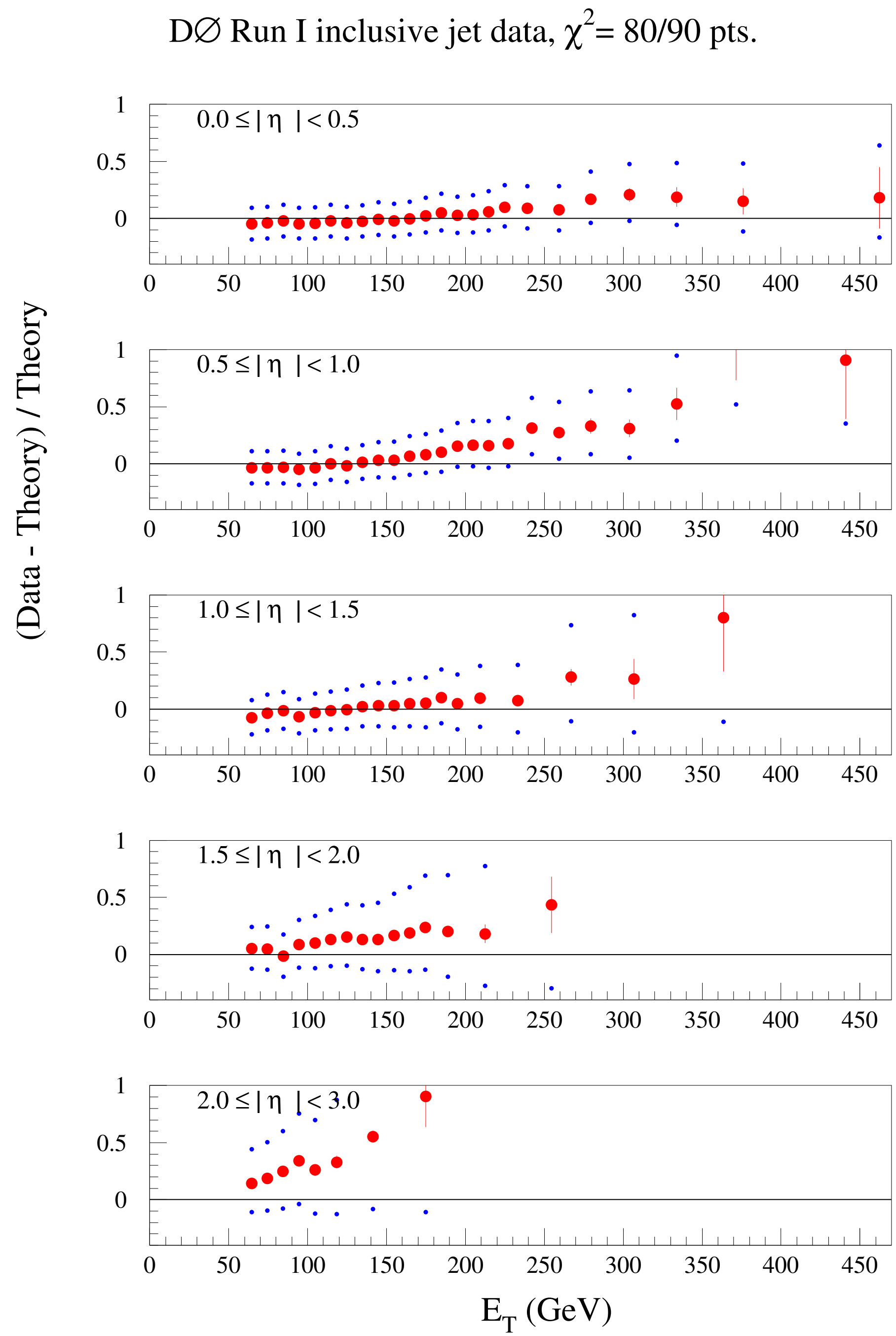
Very good fit – $\chi^2 = 56/76$.

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

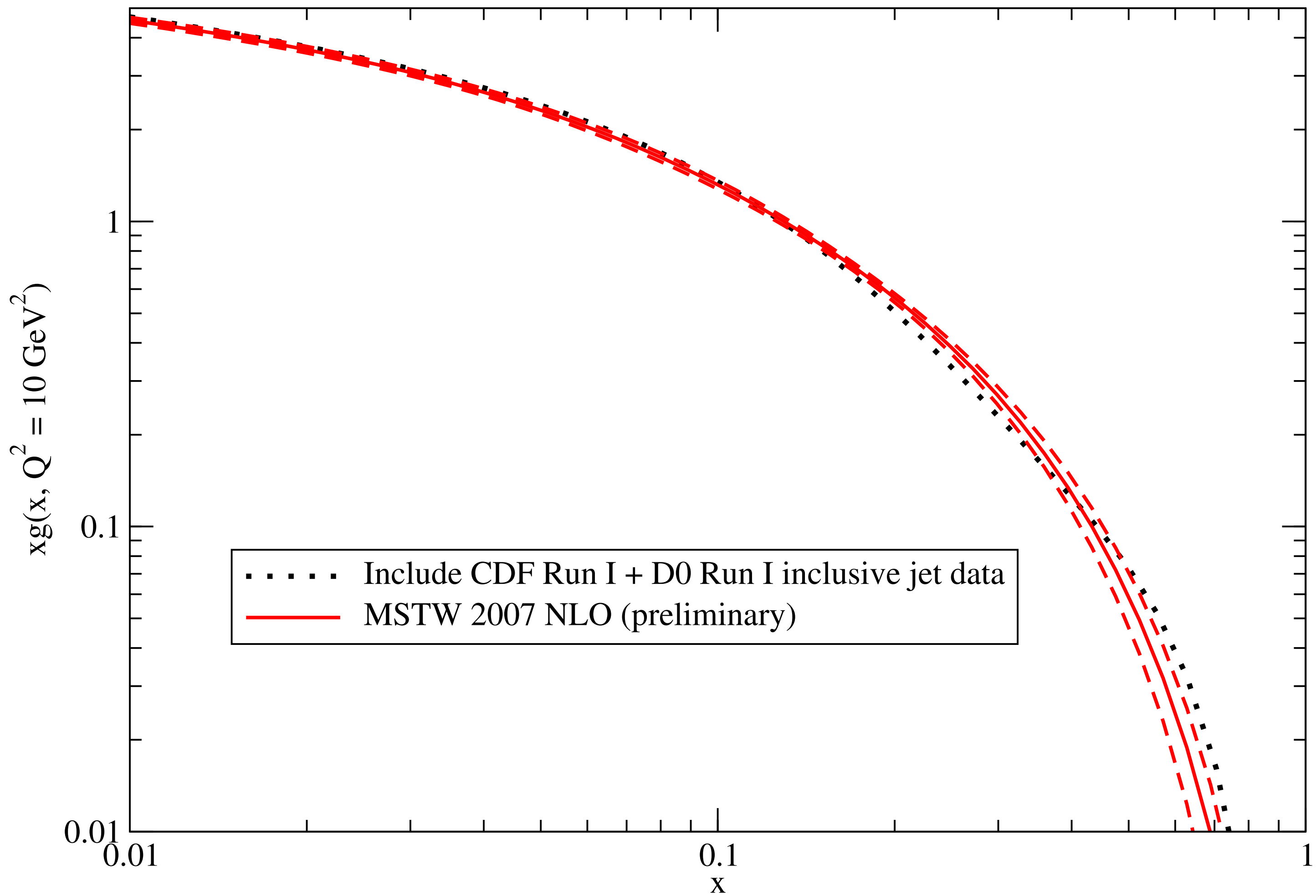
CDF Run II inclusive jet data, χ^2 = 56/76 pts.



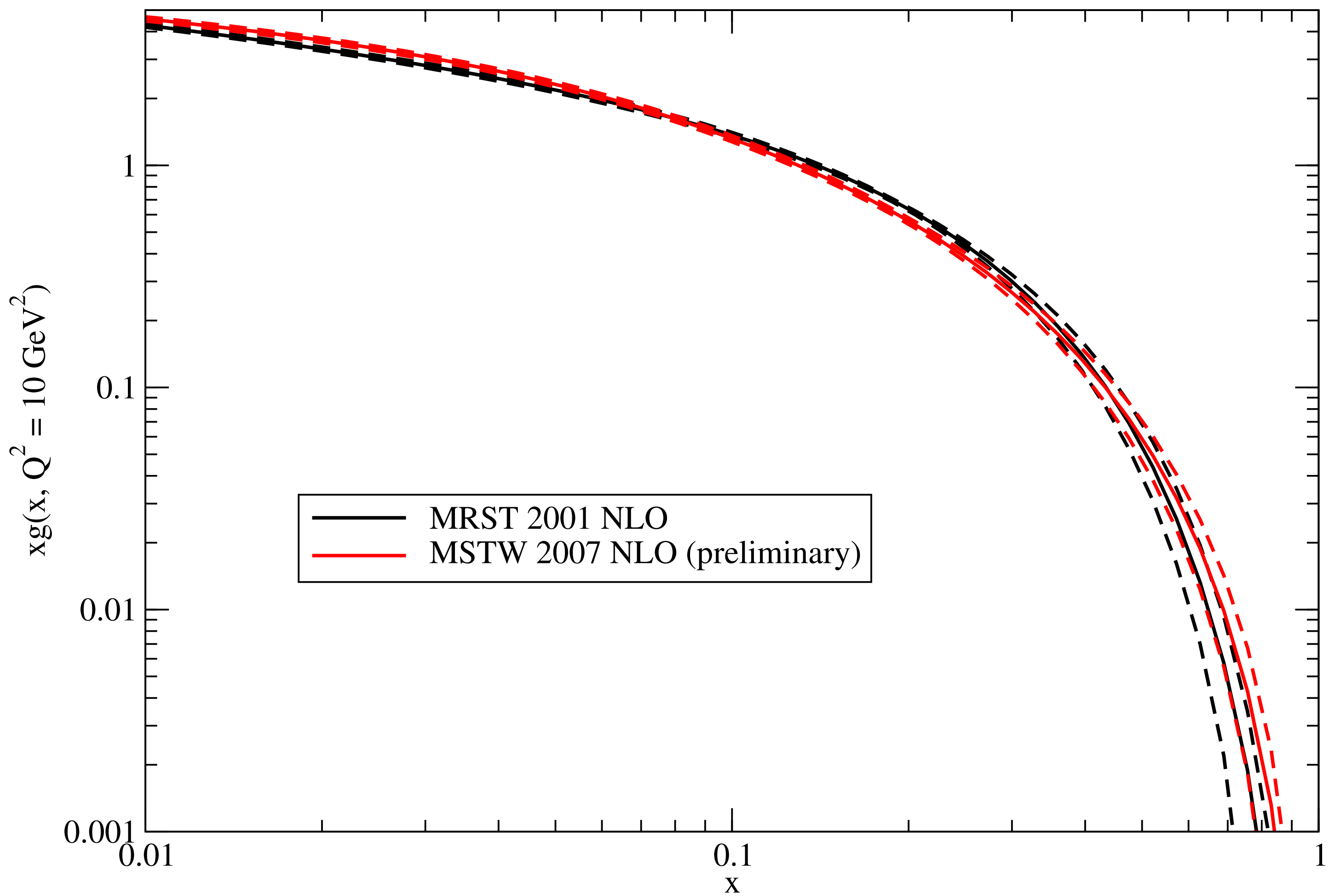
Slight deterioration in fit to D0 run I data in different rapidity bins.



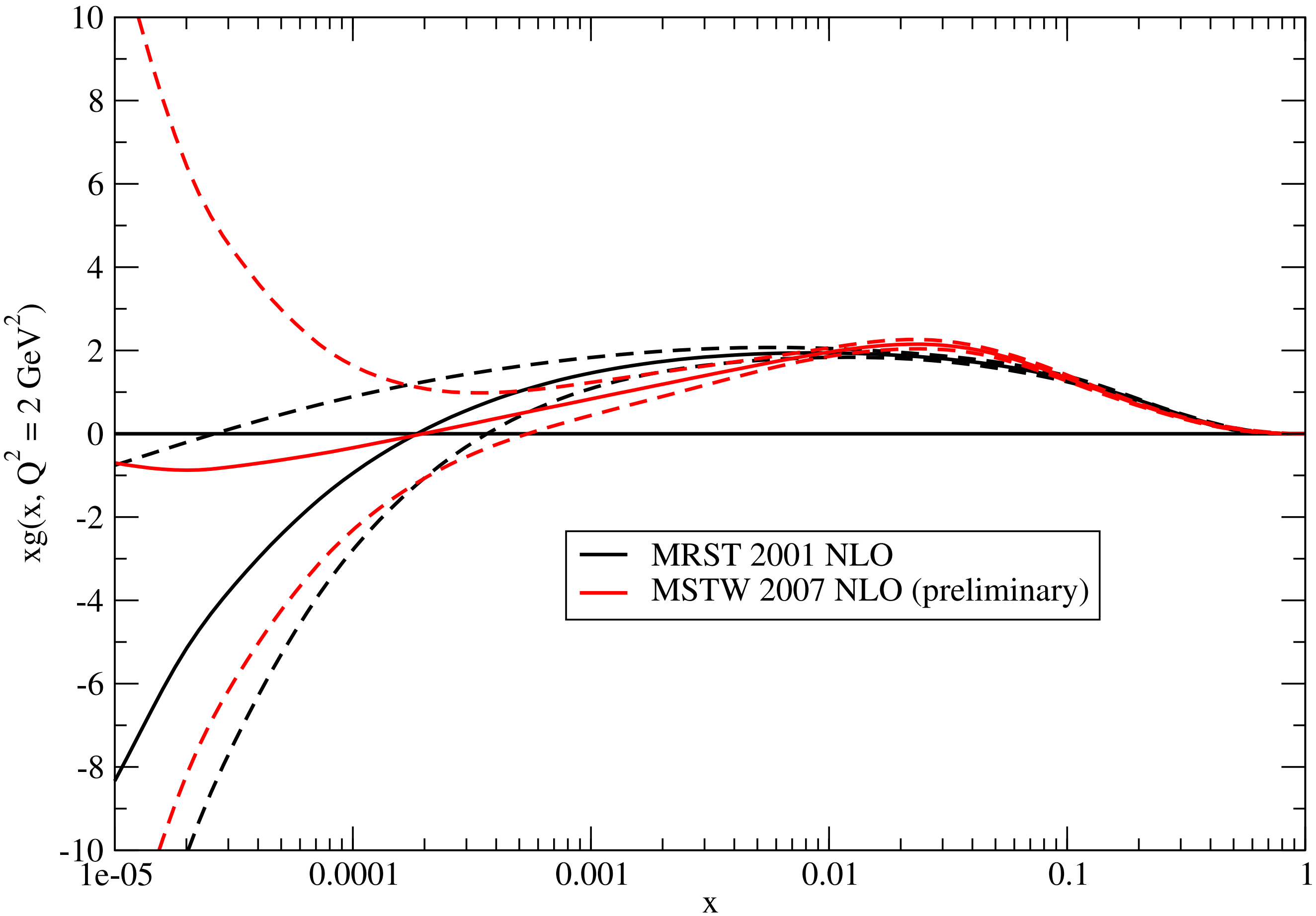
CDF run II data prefers a smaller very high x gluon distribution compared to run I data. Just outside uncertainties at our 1σ level.



Uncertainties, shown at 1σ level, similar at high x to those for MRST2001.



Overall input gluon of same general shape to previously. Still dips negative at low x, not quite so much. (Again 1σ uncertainties).

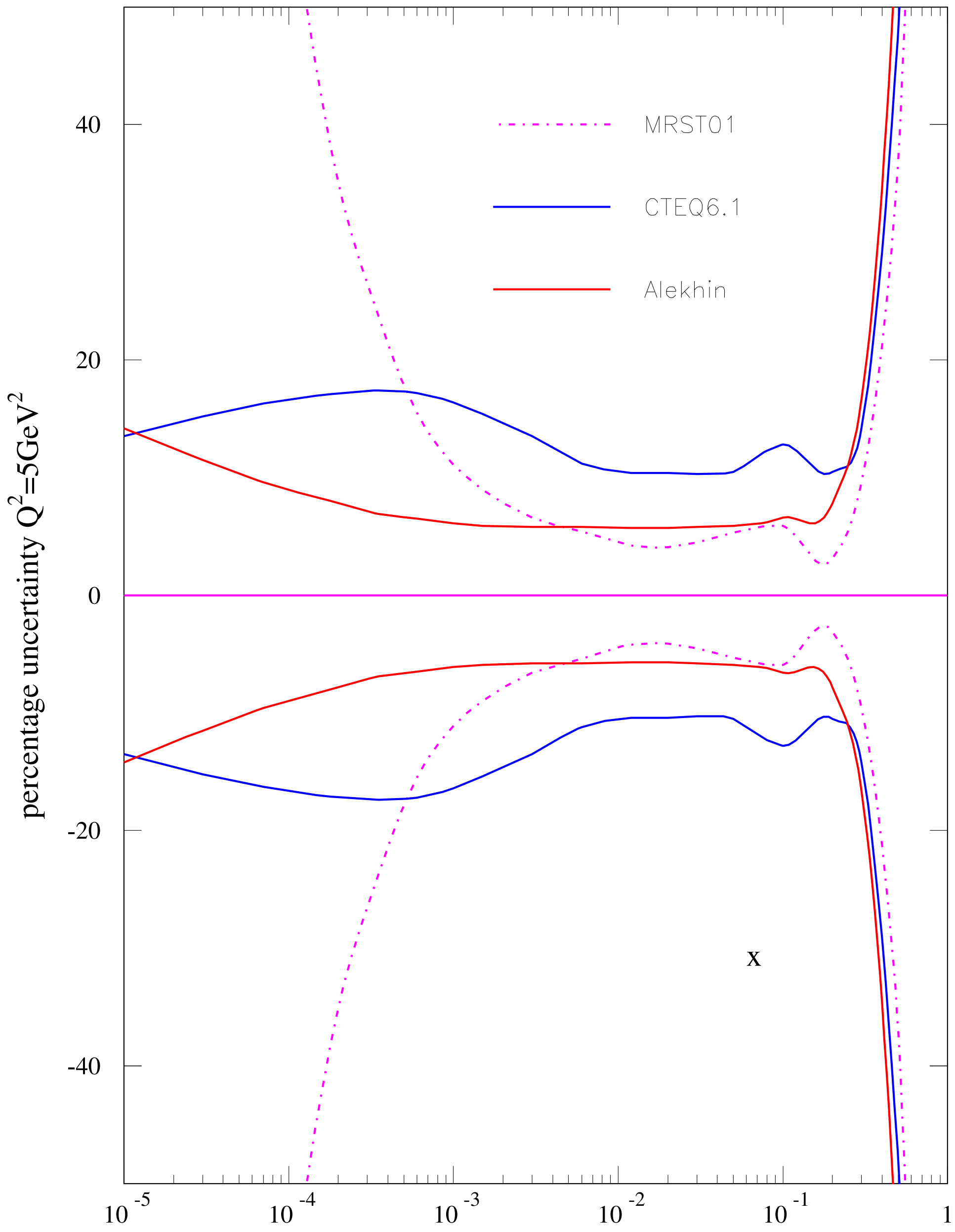


Uncertainty on gluon (without theoretical predjudice) extremely large at $x = 10^{-5}$.

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^{λ} at small x where λ 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 $x = 0.01 - 0.001$.

Dependence on m_c

Vary m_c in steps of $0.1\mathrm{GeV}$.

m_c (GeV)	χ^2_{global} 2659 pts	$\chi^2_{F_2^c}$ 78 pts	$\alpha_s(M_Z^2)$
1.2	2541	179	0.1183
1.3	2485	129	0.1191
1.4	2472	100	0.1206
1.5	2479	95	0.1213
1.6	2518	101	0.1223
1.7	2576	123	0.1221

Clear correlation between m_c and $\alpha_S(M_Z^2)$.

For low m_c overshoot low Q^2 medium x data badly.

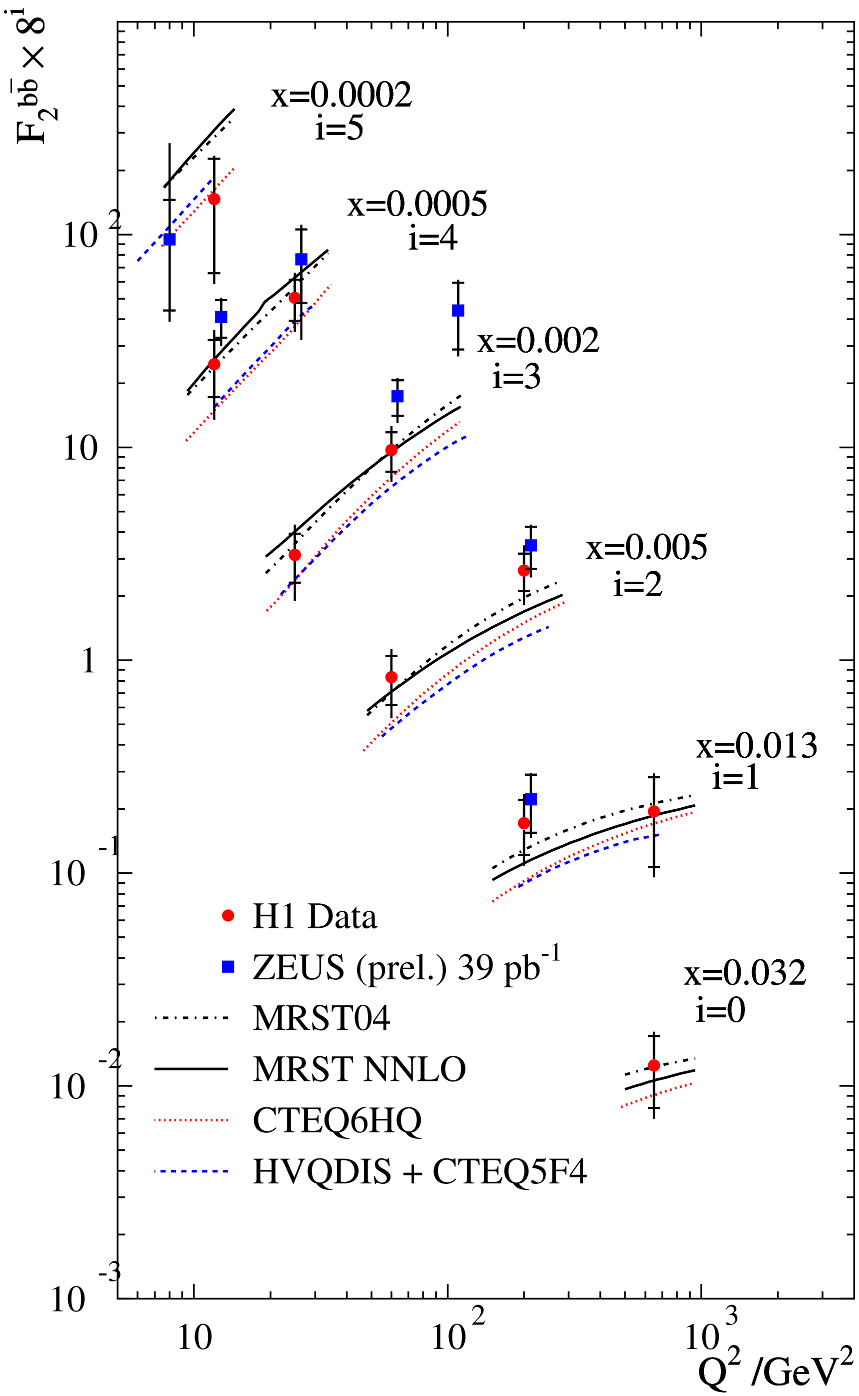
Preference for $m_c = 1.4\mathrm{GeV}$. Towards lower end of pole mass determinations. Uncertainty from fit $\sim 0.1 - 0.15\mathrm{GeV}$.

Also now choose $m_b = 4.75\mathrm{GeV}$, i.e. reasonable pole mass value. Not determined well by fit.

Good comparison to both H1 and ZEUS data on $F_2^b(x, Q^2)$

The difference in the NLO predictions from MRST and CTEQ is due to details of definition of VFNS near threshold.

Both VFNS curves for $m_b = 4.3\text{GeV}$. Should be corrected to $m_b = 4.75\text{GeV}$. Lowers both prediction slightly, particularly at low Q^2.



Conclusions

NNLO partons in principle exist now. Fit data well but NLO better. Provisional update of partons, need to input full data sets. Main difference due to better NNLO heavy flavour prescription. This is important.

Inclusion of new data. Neutrino structure function data inconsistent at high x. Cut at $x = 0.5$. Important constraint at lower x. 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.

New CDF W-asymmetry data more constraining for d_V and to some extent $\bar{d}$. Slightly different shape for $d_v(x, Q^2)$.

HERA jets, and Tevatron high-E_T jets, now fit using fastNLO. Works well and fit good. New run II CDF jet data included in fit. Small, but significant change. Smaller high-x gluon.

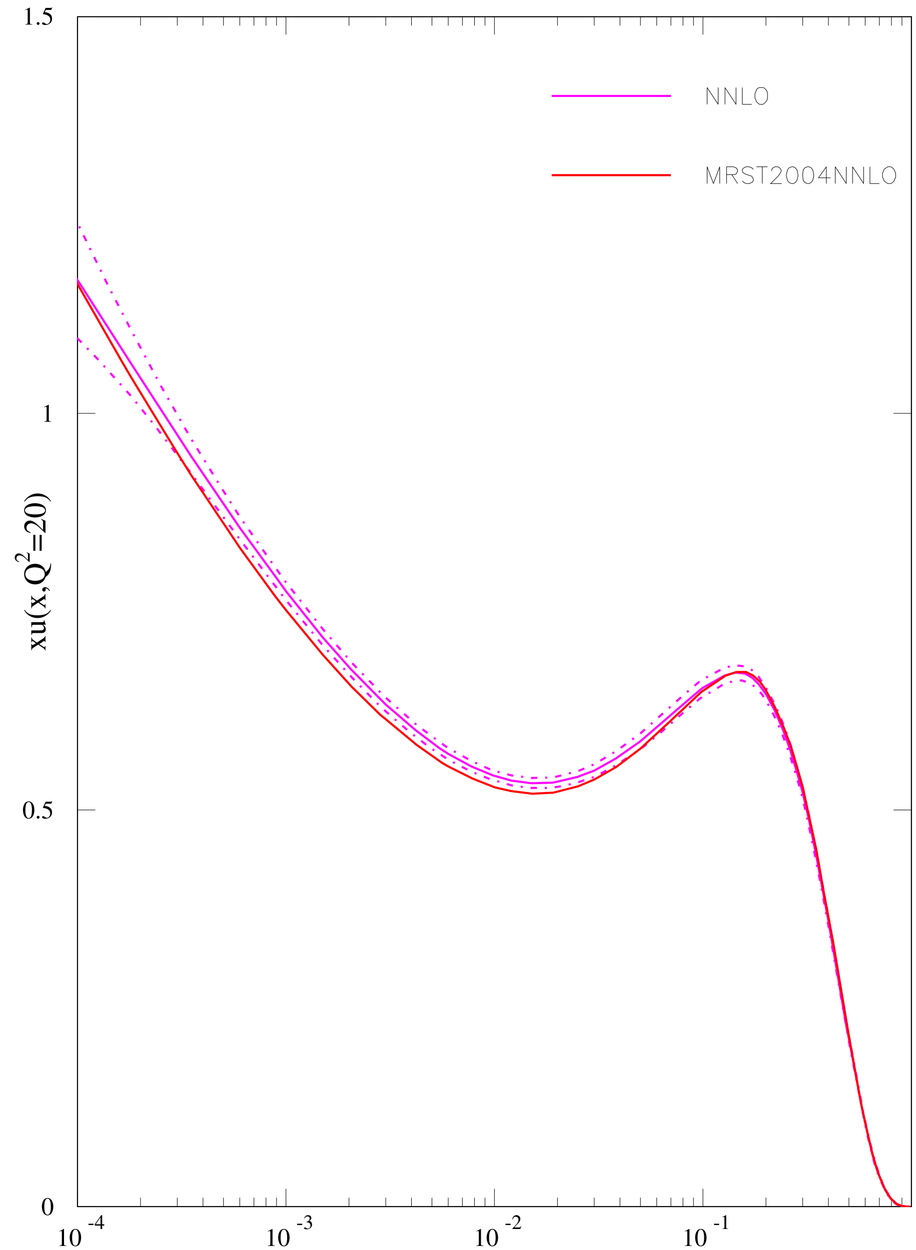
Will have full updated NLO and NNLO partons for LHC complete with uncertainties – experimental and theoretical.

Not much change in light quarks due these to theoretical updates.

Minor change – bit bigger than MRST2004 at small x.

Slightly lower $s(x,Q^2)$ $\rightarrow$ more $u(x,Q^2)$.

Also slightly higher $\alpha_S(M_Z^2)$. Negative NNLO correction bigger $\rightarrow$ more $u(x,Q^2)$.



Previously used correction applied to theoretical prediction.

$x < 0.0903 \quad R = 1.238 + 0.203 log_{10} x$

$x > 0.2340 \quad R = 0.783 - 0.385 log_{10} x$

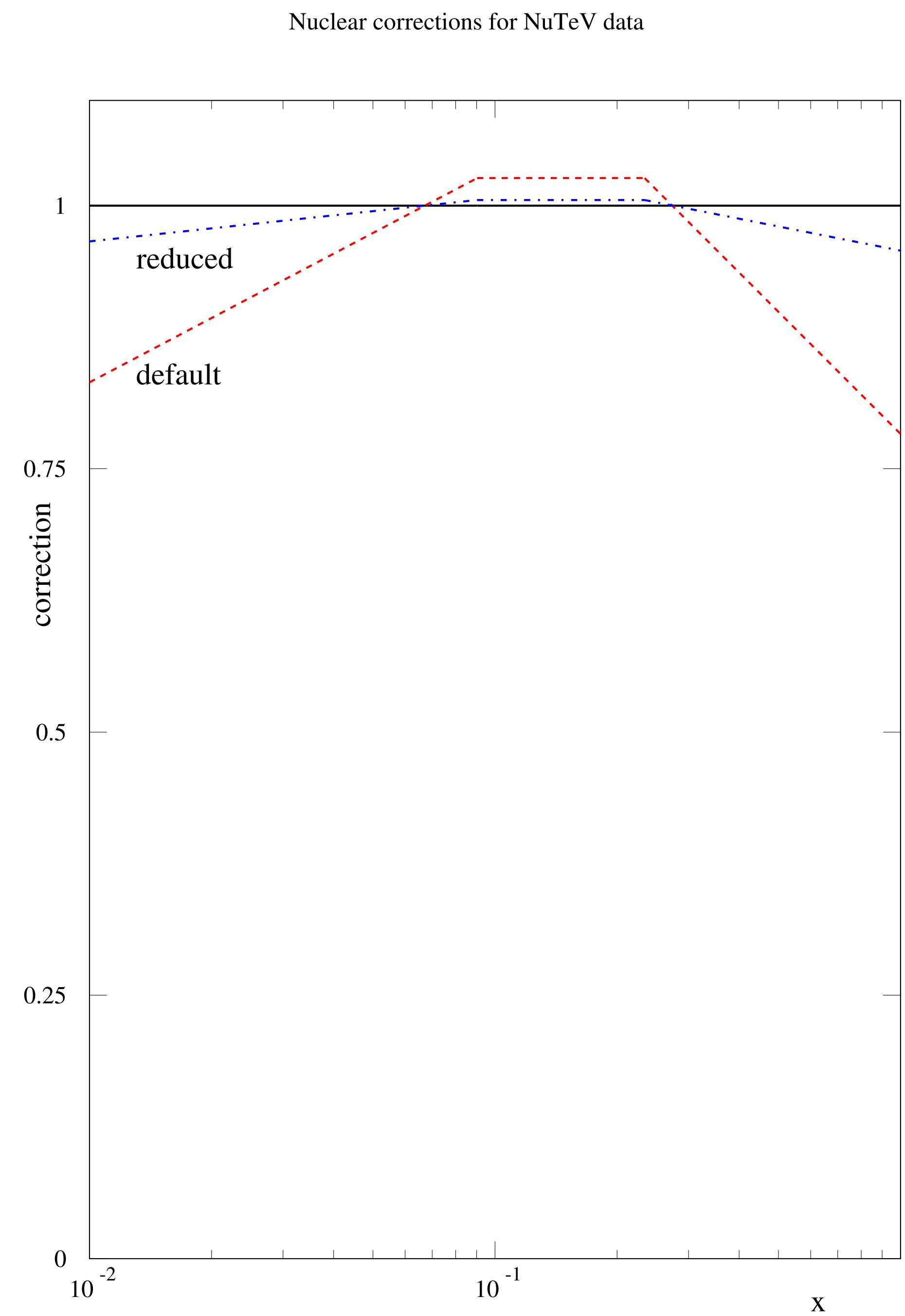
$0.234 > x > 0.0903 \quad R = 1.026$

Far too large for new NuTeV data. High-x completely determined by valence quarks for both $F_2^{\nu,\bar{\nu}}(x,Q^2)$ and $F_3^{\nu,\bar{\nu}}(x,Q^2)$.

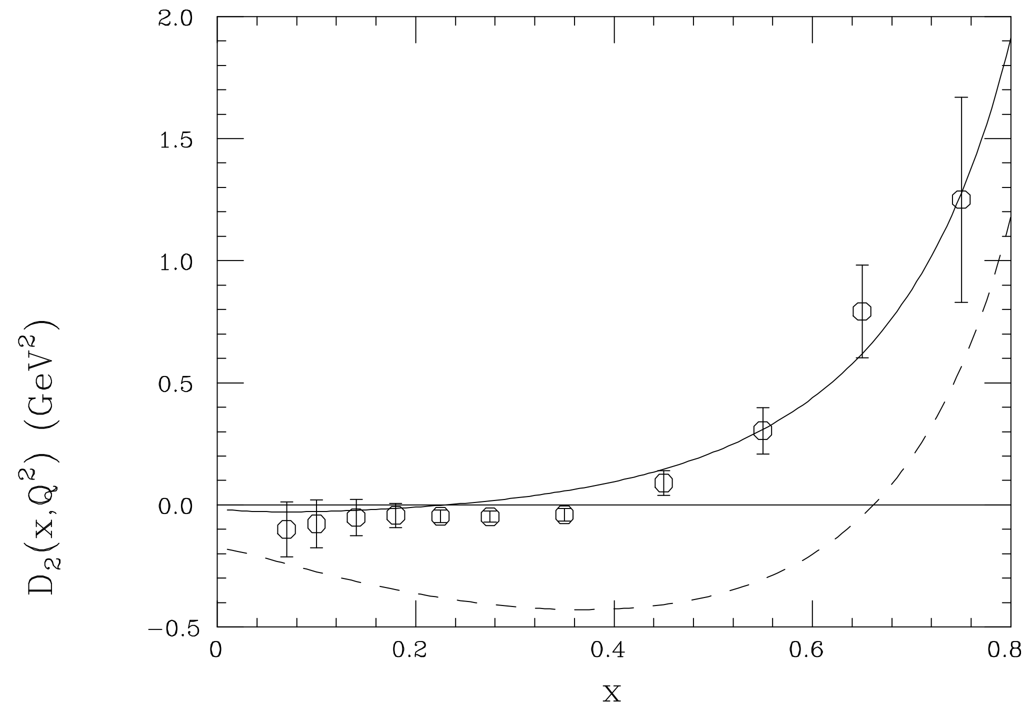
These well known from fixed target $F_2^p(x,Q^2)$ and $F^d(x,Q^2)$.

Try form $R^{eff} = 1 + A*(R-1)$.

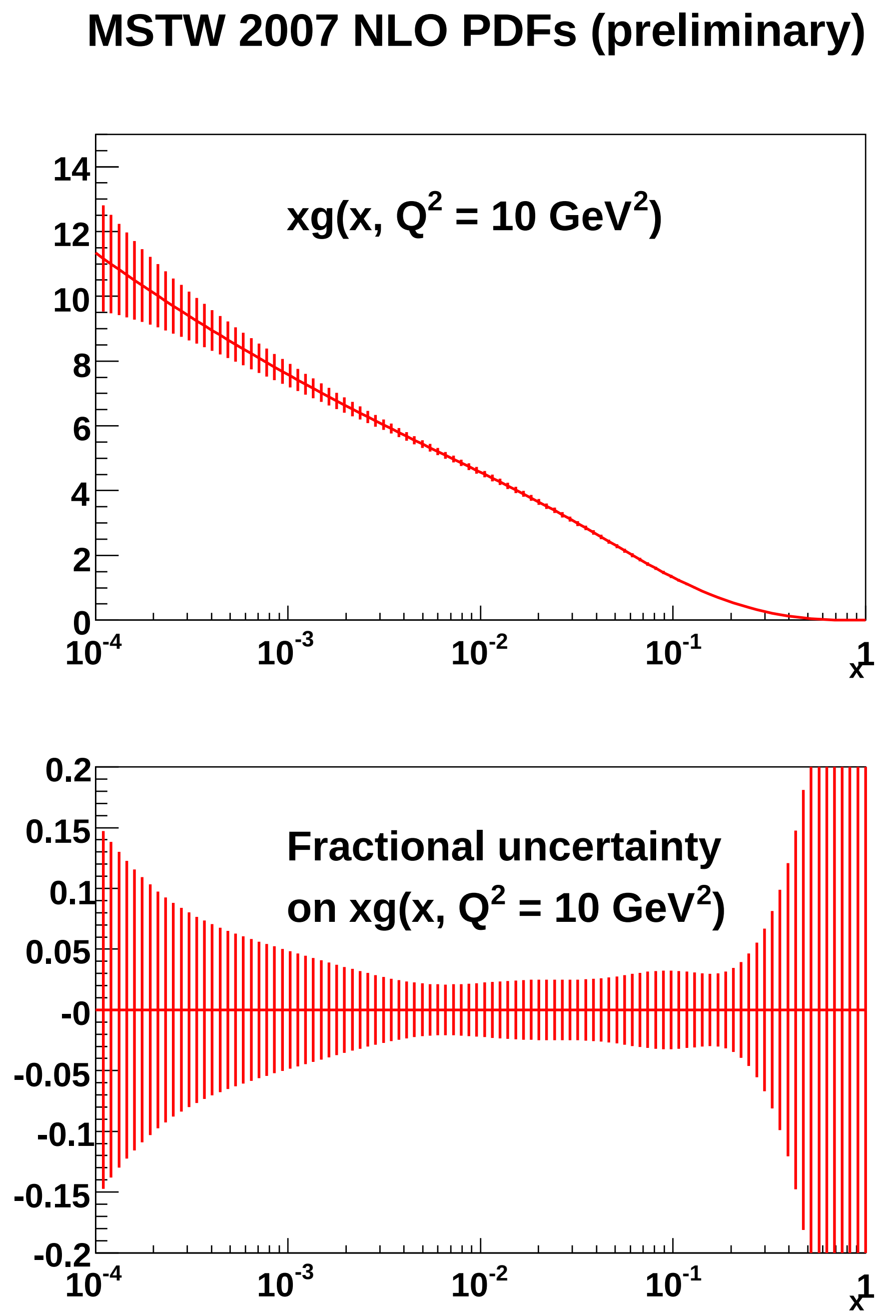
Best fit $A = 0.2$.



Renormalon prediction for $1/Q^2$ corrections for $F_2(x,Q^2)$ (solid line) and $xF_3(x,Q^2)$ (dashed line) Dasgupta and Webber.



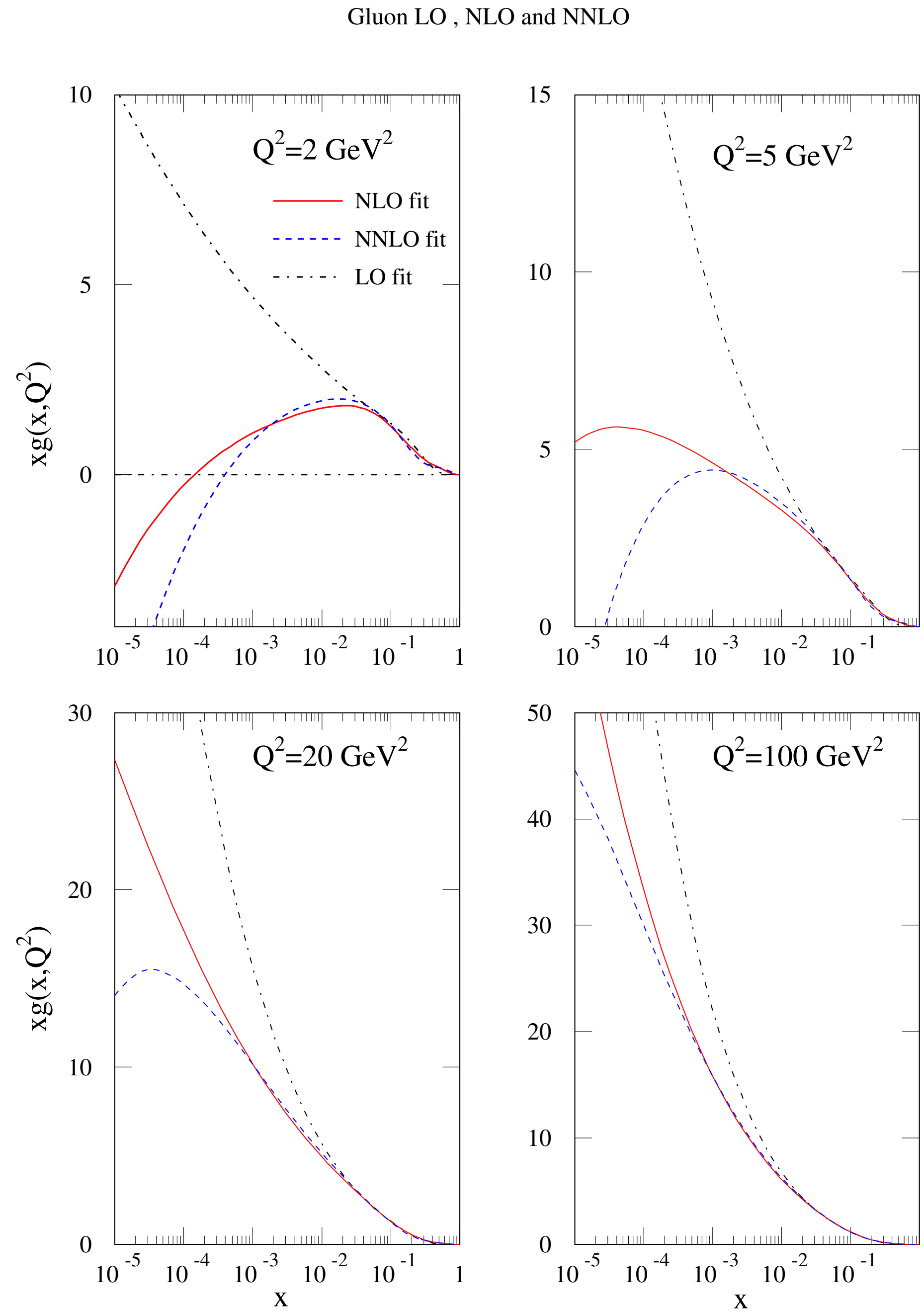
Fractional uncertainty (at one-σ level) for MSTW gluon.



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

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

Note - this conclusion relied on correct application of flavour thresholds in a General Variable Flavour Number Scheme at NLO not present in earlier approximate NNLO MRST fits. Correct treatment of flavour particularly important at NNLO because discontinuities in unphysical quantities appear at this order.

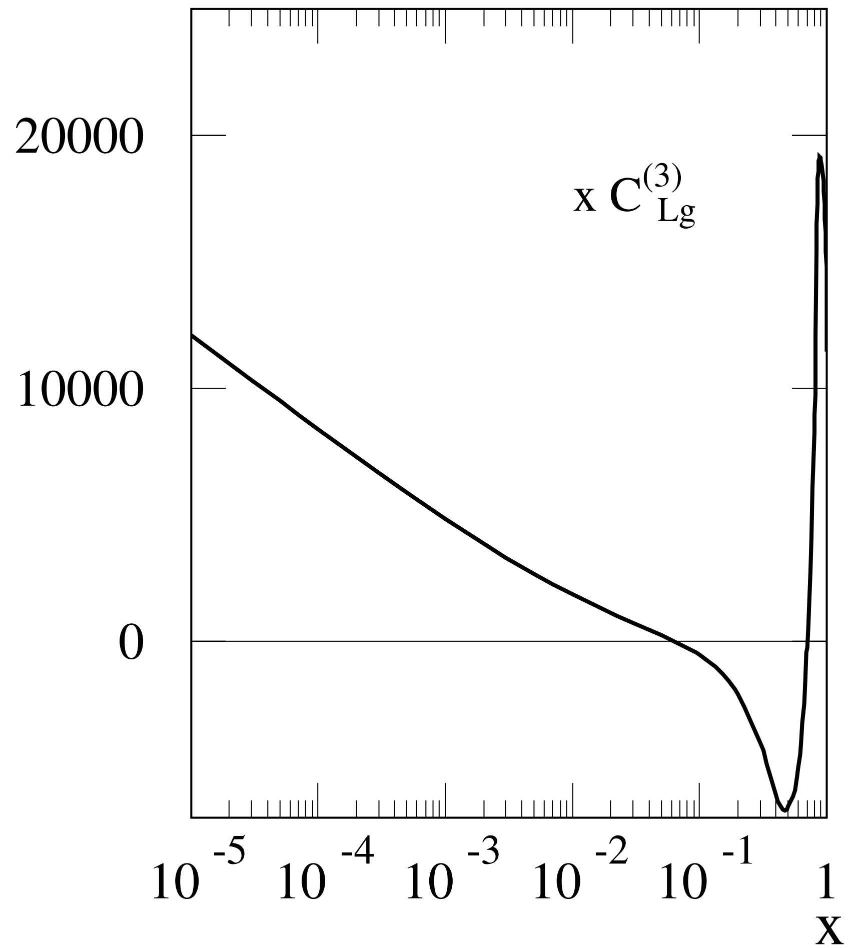


The NNLO $\mathcal{O}(\alpha_s^3)$ longitudinal coefficient function $C_{Lg}^3(x)$ given by

$$C_{Lg}^3(x) = n_f \left(\frac{\alpha_S}{4\pi}\right)^3 \left(\frac{409.5\ln(1/x)}{x} - \frac{2044.7}{x} - \cdots\right.$$

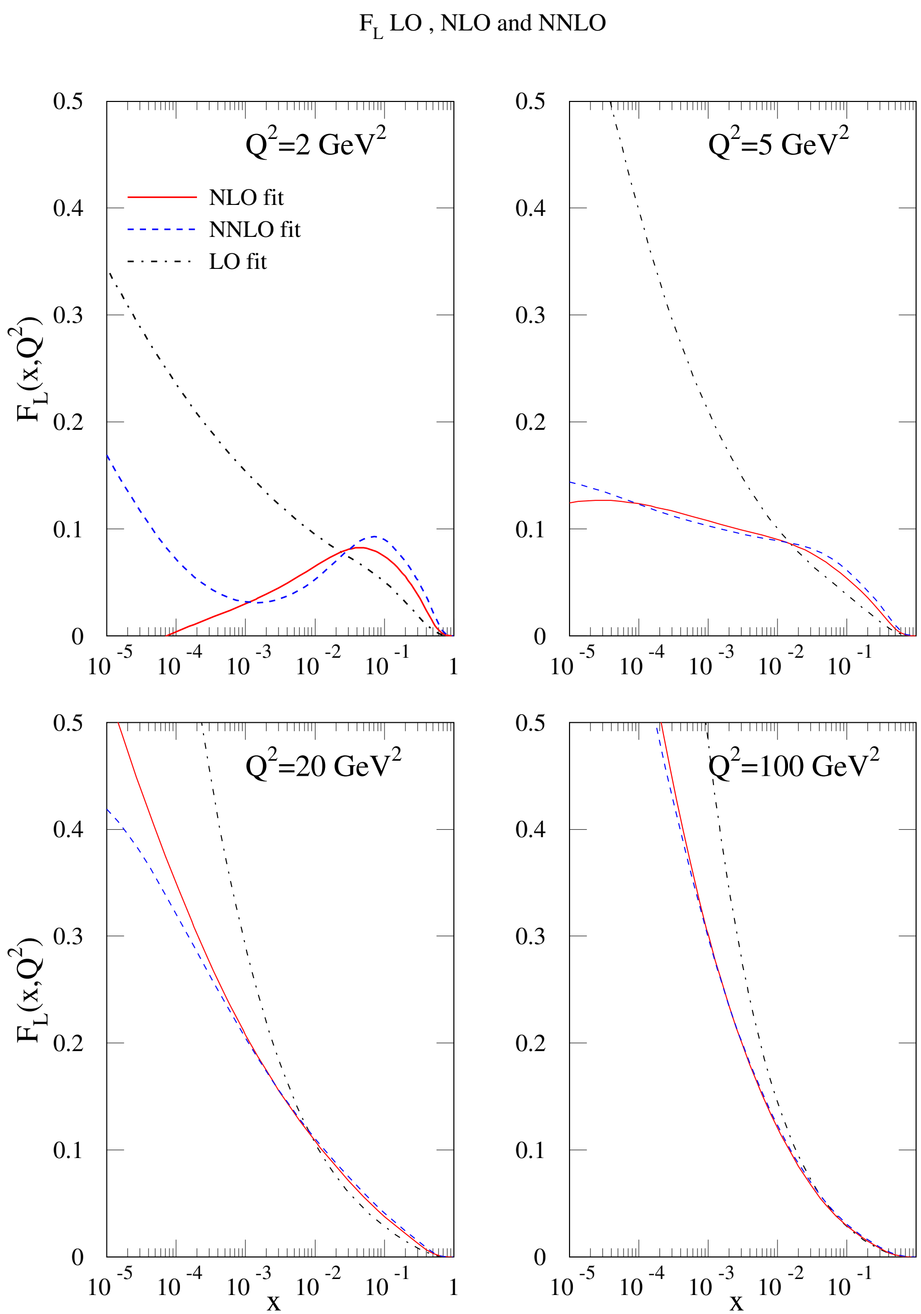
Clearly a significant positive contribution at small x.

Counters decrease in small-x gluon.



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

NNLO coefficient function more than compensates decrease in NNLO gluon.



Comparisons

Compare with only other NNLO partons on market – Alekhin2002.

Nothing from CTEQ?

Much larger $\alpha_S(M_Z^2)$ in this fit than that of Alekhin ($\alpha_S(M_Z^2) = 0.119$ compared to 0.114).

Not much difference in high-x valence quarks, except than explained by difference in $\alpha_S(M_Z^2)$. Very well-constrained.

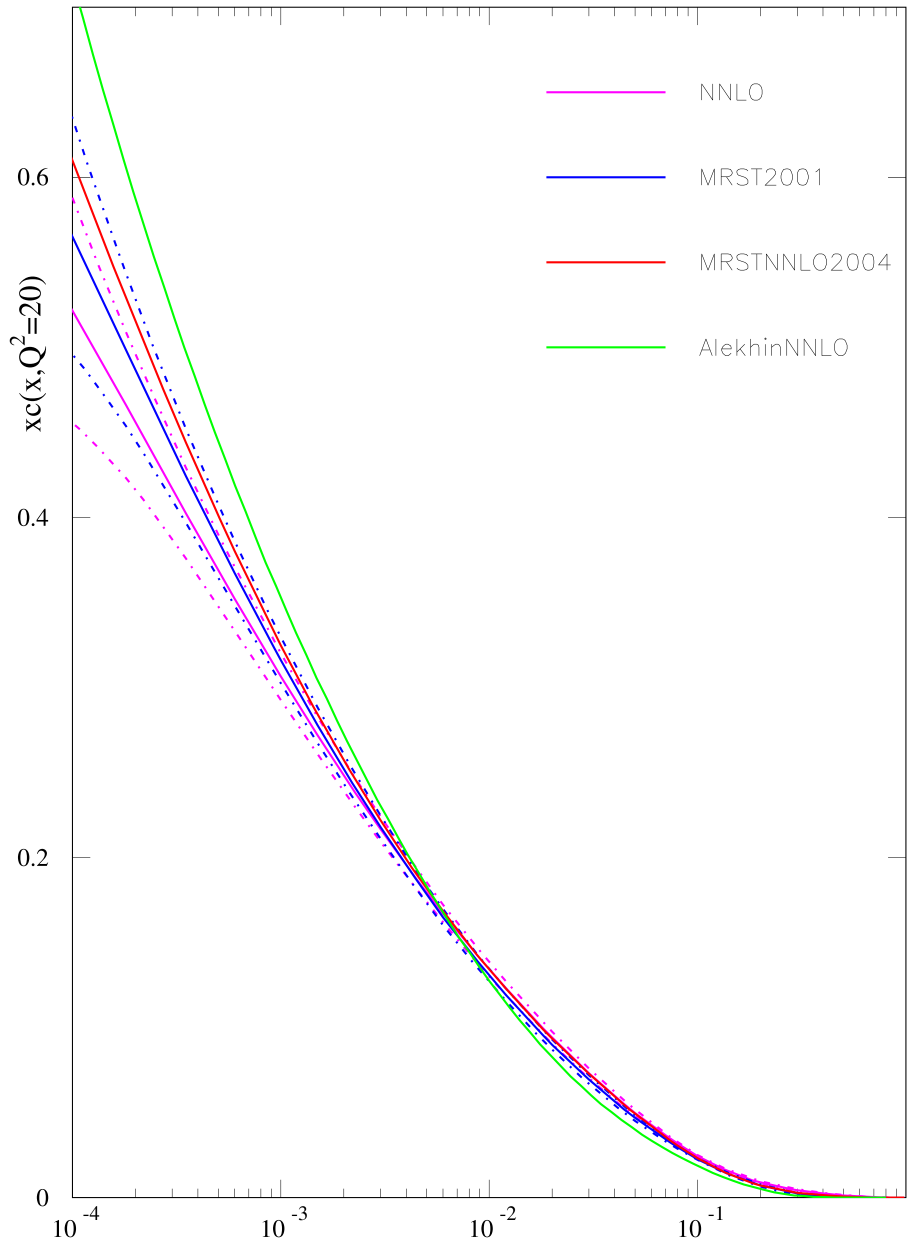
Differences in low-x sea quarks. Swamped by differences in flavour treatments – $\bar{u} - \bar{d}$ and $s(x, Q^2)$.

Main difference in gluon distribution.

Difference in gluon feeds through to charm.

Alekhin2002 much bigger at small x.

Starts from zero as with MRST2004NNLO.



Big difference at high x and Q^2.

Determined by Tevatron jet data for MRST. Fit now excellent.

Divergences at $x = 0.25$ corresponds to $E_T \sim 225\mathrm{GeV}$.

In $\overline{MS}$ scheme gluon more important for jets at high x at NNLO because high-x quarks smaller.