MRST/MSTW Parton Distributions for the LHC

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The general procedure of the MRST/MSTW group is to revolve partons upwards using NLO (or NNLO) DGLAP equations, and fit all relevant data for scales above $\sim 2\mathrm{GeV}^2$. Need many different types of experiment for full determination.

H1 $F_2^{e^+p}(x,Q^2)$ 1996-97 moderate Q^2 and 1996-97 high Q^2, and $F_2^{e^-p}(x,Q^2)$ 1998-99 high Q^2 small x. ZEUS $F_2^{e^+p}(x,Q^2)$ 1996-97 small x wide range of Q^2. 1999-2000 high Q^2. H1 and ZEUS $F_2^{c,b}(x,Q^2)$.

NMC $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2), (F_2^{\mu n}(x,Q^2)/F_2^{\mu p}(x,Q^2))$, E665 $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$ medium x.

BCDMS $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$, SLAC $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$ large x.

CCFR $F_2^{\nu(\bar{\nu})p}(x,Q^2), F_3^{\nu(\bar{\nu})p}(x,Q^2)$ large x , singlet, valence.

E605, E866 $pN \rightarrow \mu\bar{\mu} + X$ large x sea.

E866 Drell-Yan asymmetry $\bar{u}, \bar{d}$ $\bar{d} - \bar{u}$.

CDF W-asymmetry u/d ratio at high x.

CDF D0 Inclusive jet data high x gluon.

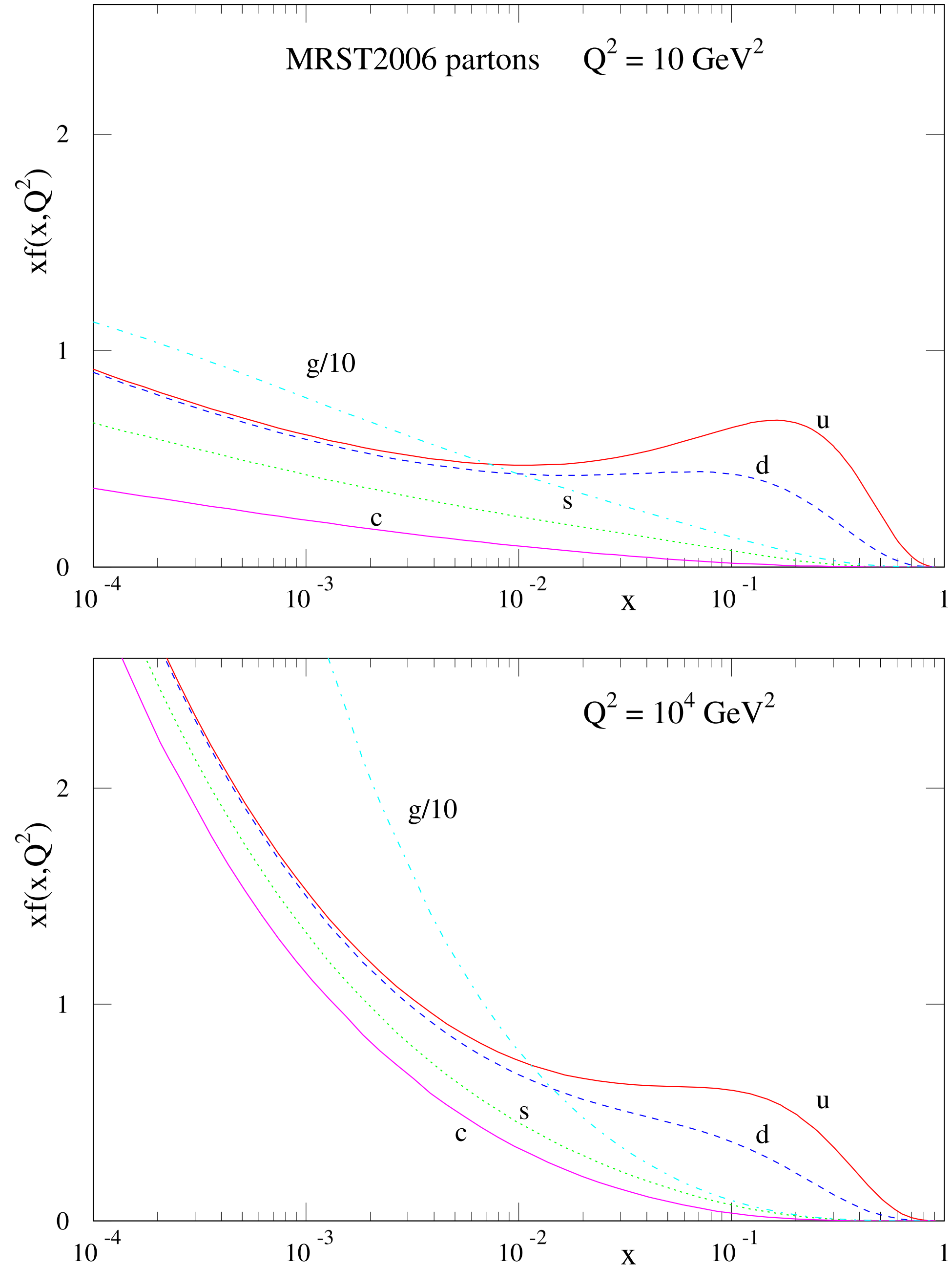
This procedure is generally successful and is part of a large-scale, ongoing project.

Results in partons of the form shown.

All hadron collider (HERA, Tevatron, LHC) cross-sections rely on our understanding of these partons.

Dick Roberts retired from project and in 2006 Graeme Watt joined.

Hence, MRST $\rightarrow$ MSTW.



Intermediate Update at NNLO

Recently updated partons at NNLO - officially MRST06. Fit to same data as MRST04.

Previously only central values. No NNLO partons with uncertainties due to experimental errors.

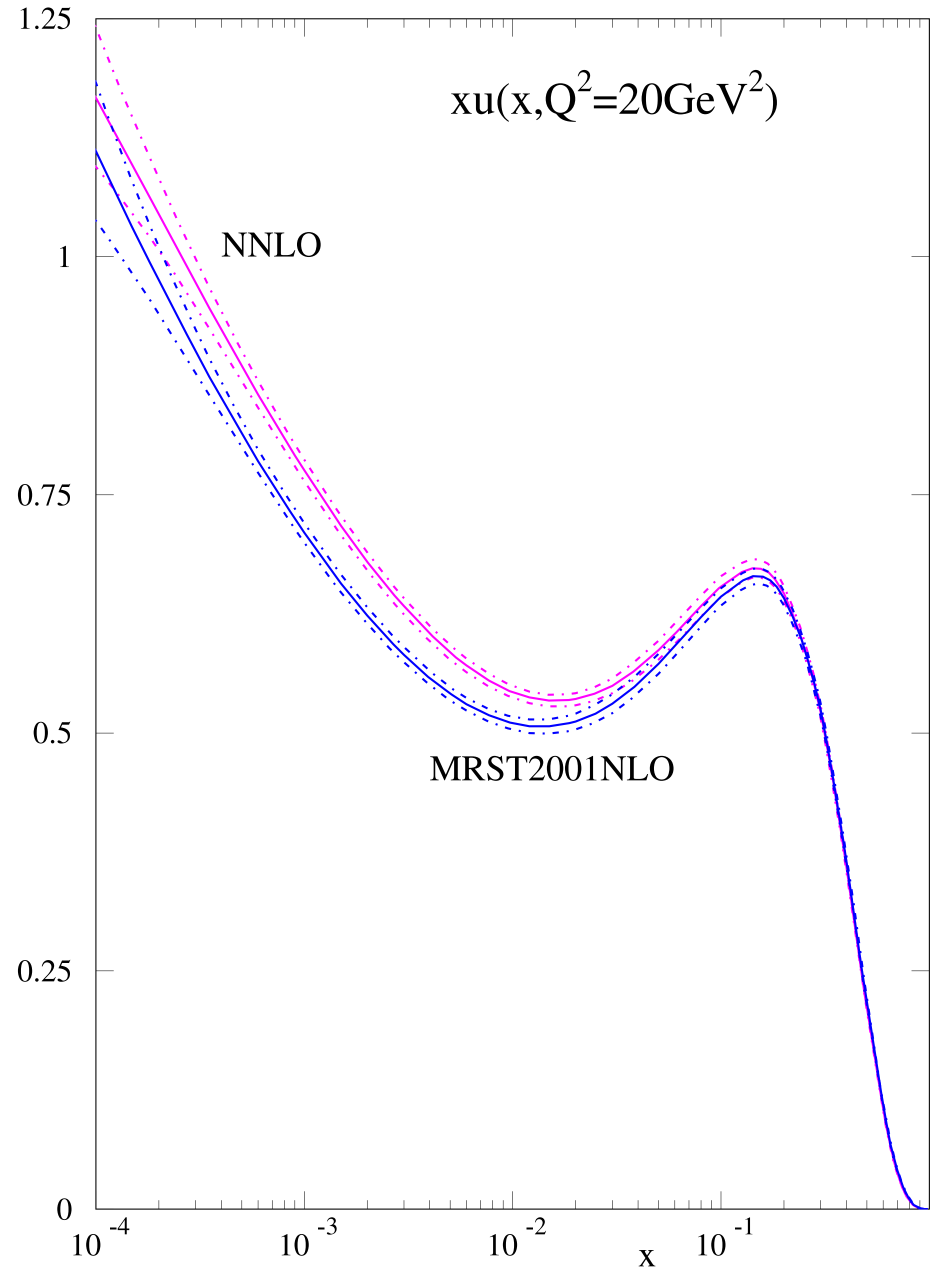
Same procedure as before – 15 eigenvector sets of partons and $\Delta\chi^2 = 50$ for 90% confidence limit.

Example, $u(x, Q^2)$ at NNLO compared to NLO.

Size of uncertainties similar to at NLO.

At small x effect of coefficient functions, particularly $C_{2,g}(x, Q^2)$, important.

Change from NLO to NNLO greater than uncertainty in each. Similar for other partons.



Second reason for intermediate update of NNLO partons due to improvement to previous approximate treatment of heavy flavour, i.e. a much improved **General Mass Variable Flavour Number Scheme** at NNLO.

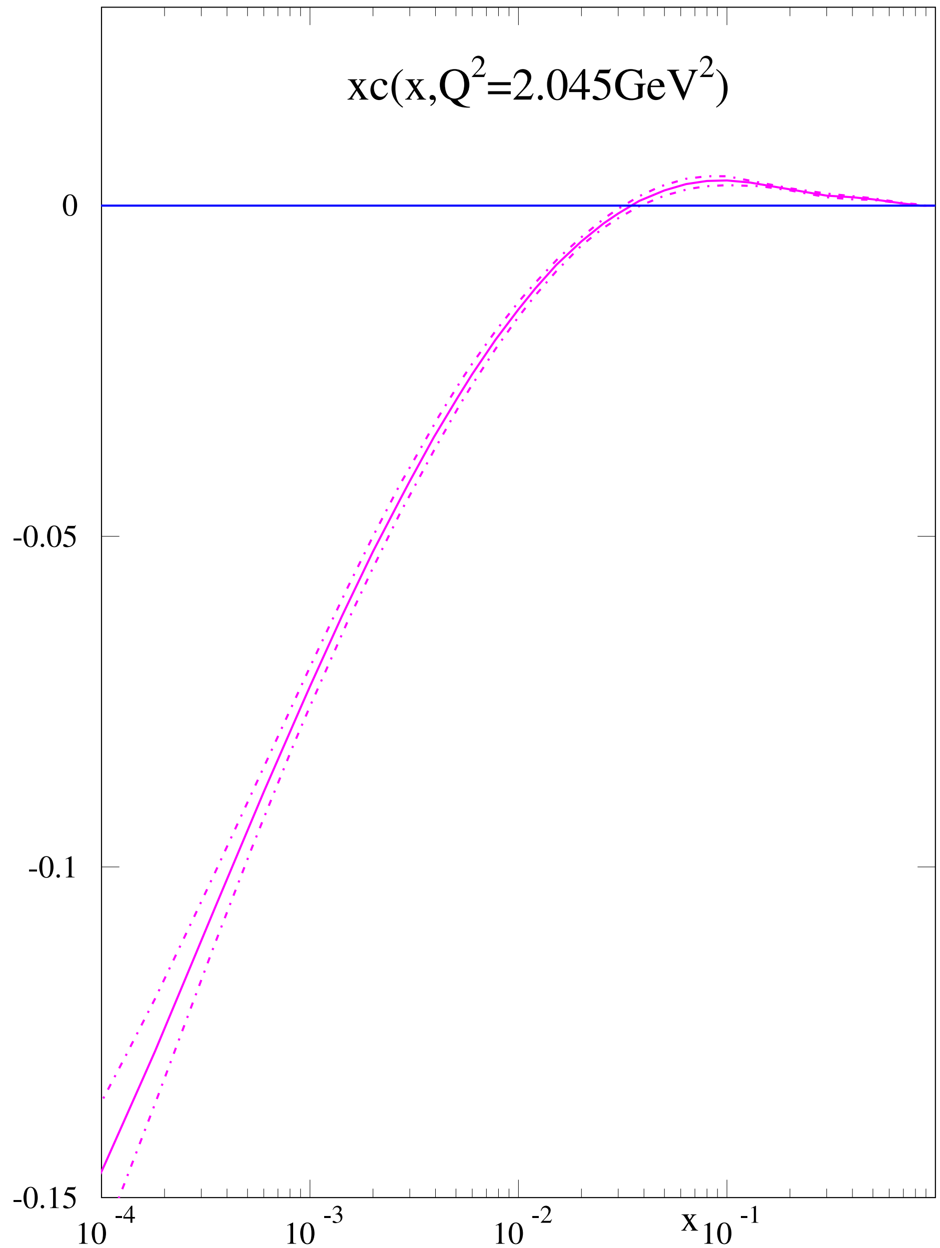
In reality at NNLO heavy flavour no longer turns on from zero at $\mu^2 = m_c^2$

$$(c+\bar{c})(x, m_c^2) = A_{Hg}^{(2)}(m_c^2) \otimes g(m_c^2)$$

In practice turns on from negative value (for general gluon).

Also, previous approximation had no $\mathcal{O}(\alpha_S^3)$ heavy quark coefficient functions.

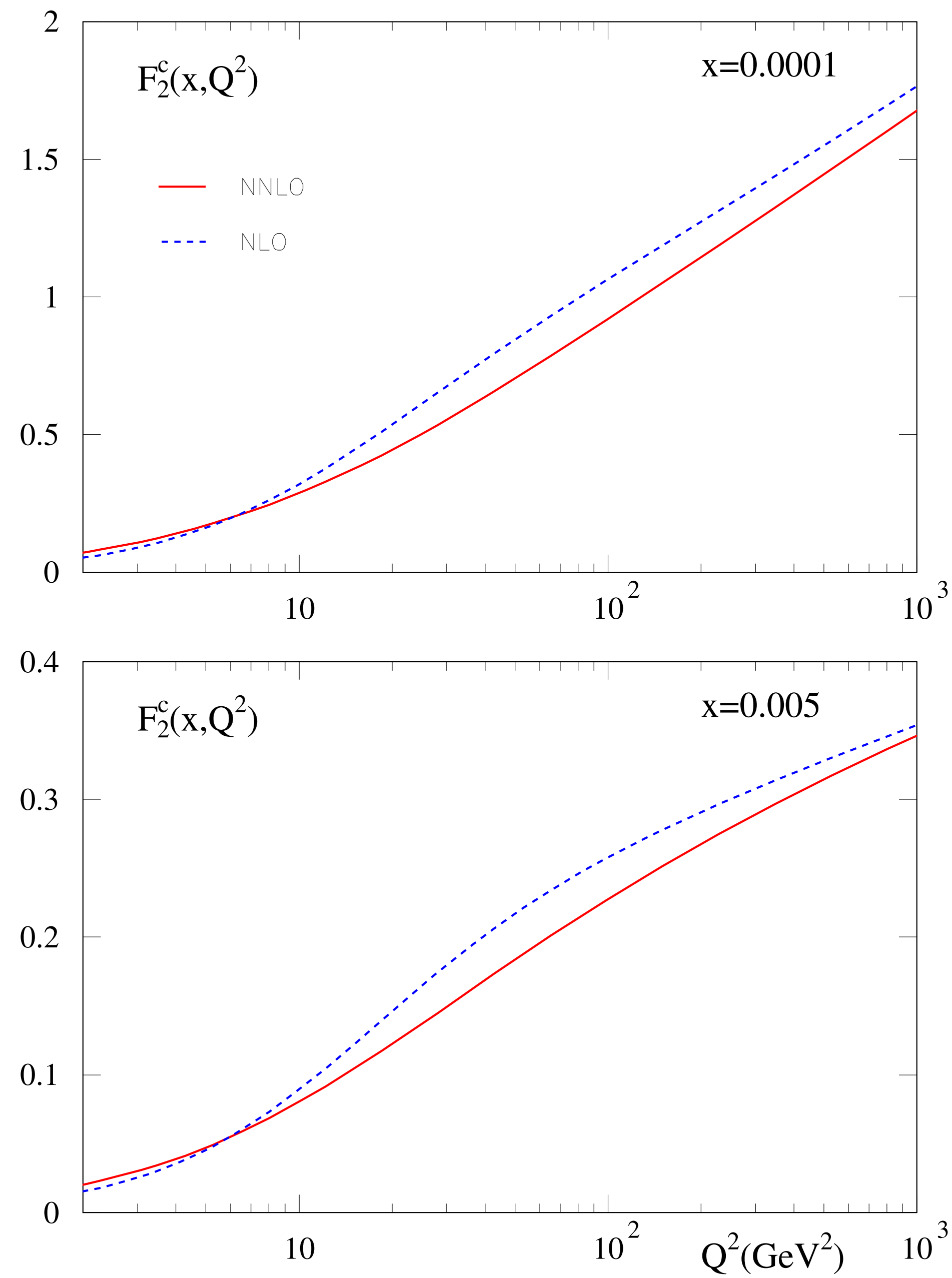
Now modelled using high and small-x limits. Additional positive contribution at low Q^2.



NNLO $F_2^c(x,Q^2)$ starts from higher value at low Q^2.

At high Q^2 dominated by $(c+\bar{c})(x,Q^2)$. This has started evolving from negative value at $Q^2 = m_c^2$. Remains lower than at NLO for similar evolution.

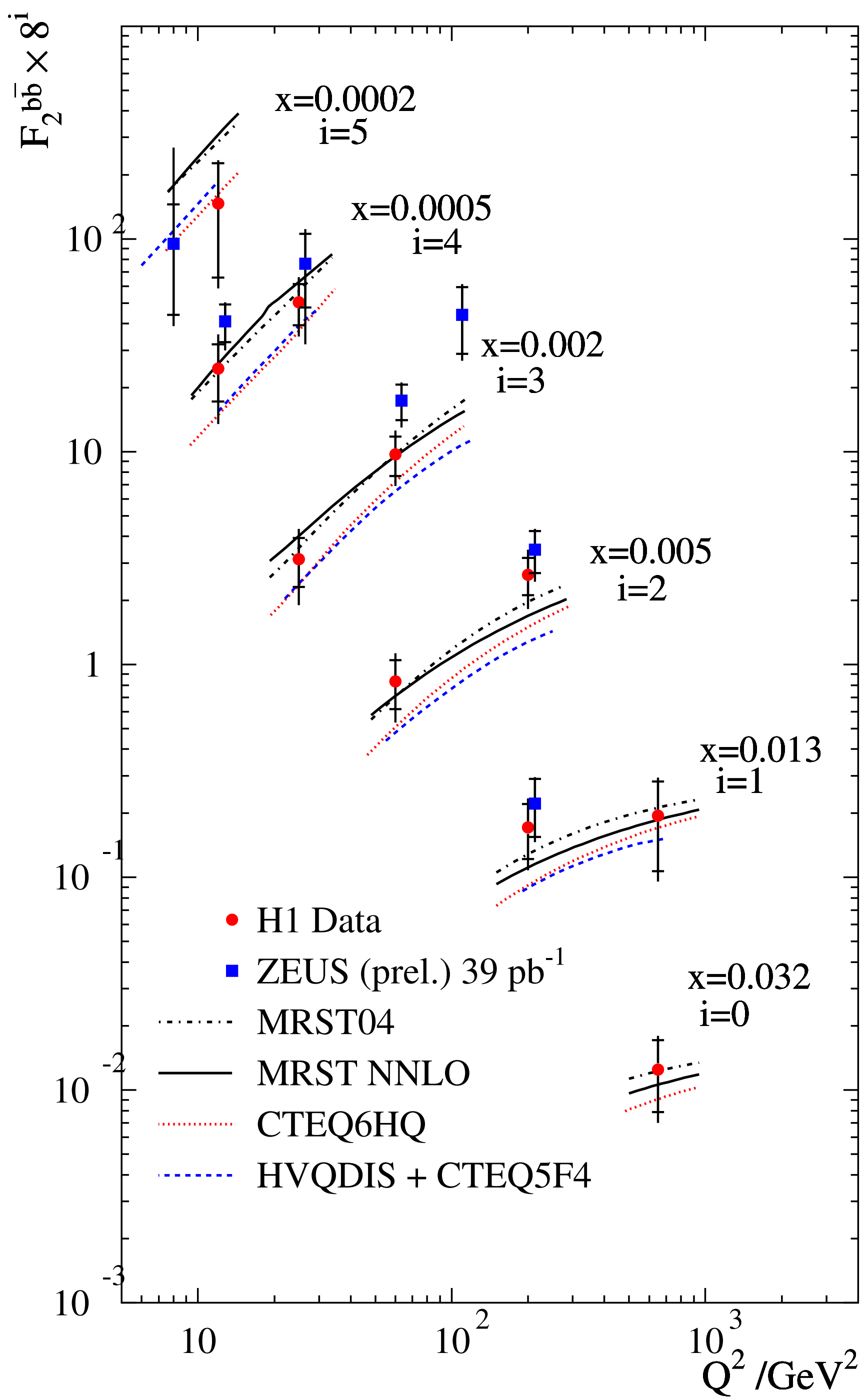
General trend – $F_2^c(x,Q^2)$ flatter in Q^2 at NNLO than at NLO. Important effect on gluon distribution going from one to other.



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



Change in partons greater than uncertainty in many places. Correct heavy flavour treatment vital.

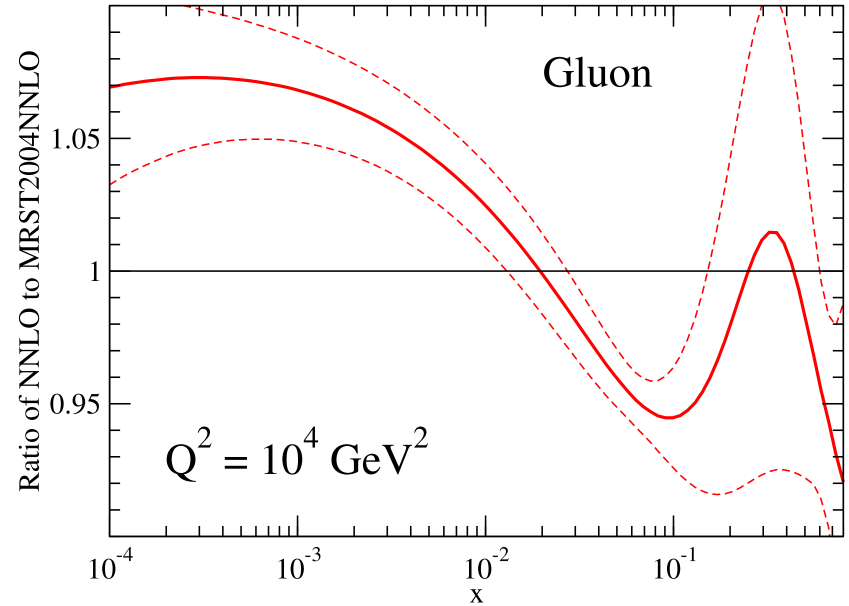
Requires larger coupling for increased evolution – $\alpha_S(M_Z^2) = 0.119$.

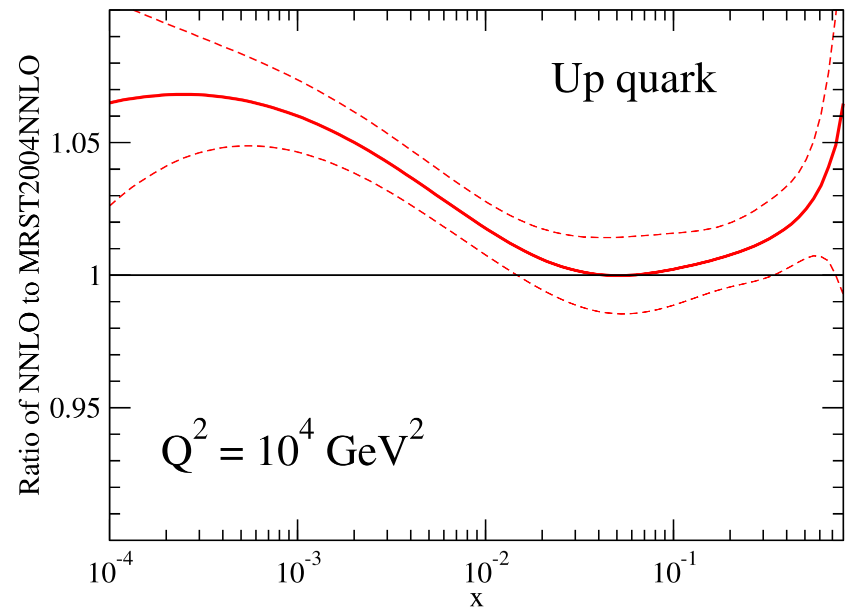
$\rightarrow$ bigger gluon and more evolution of light sea.

$\rightarrow$ 6% increase in σ_W and σ_Z at the LHC.

With hindsight this and CTEQ result are corrections not uncertainty.

Very important changes nonetheless.





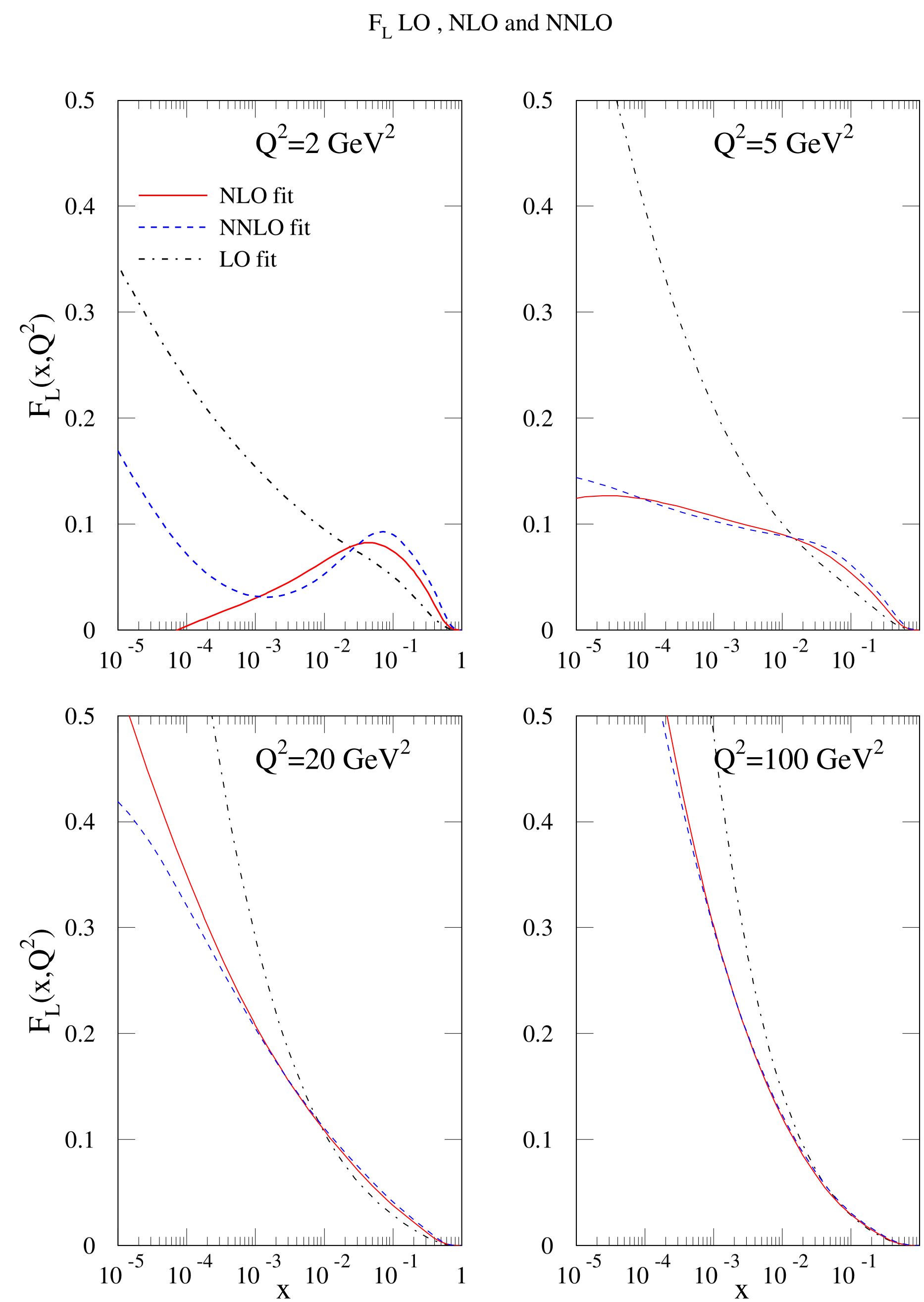
Instability in physical, gluon dominated, quantity $F_L(x,Q^2)$ going from LO $\rightarrow$ NLO $\rightarrow$ NNLO.

Gluon at NLO $\rightarrow$ $F_L(x,Q^2)$ dangerously small at smallest x, Q^2.

Note very large effect of exact NNLO coefficient function.

Possible sign of required $\ln(1/x)$ corrections.

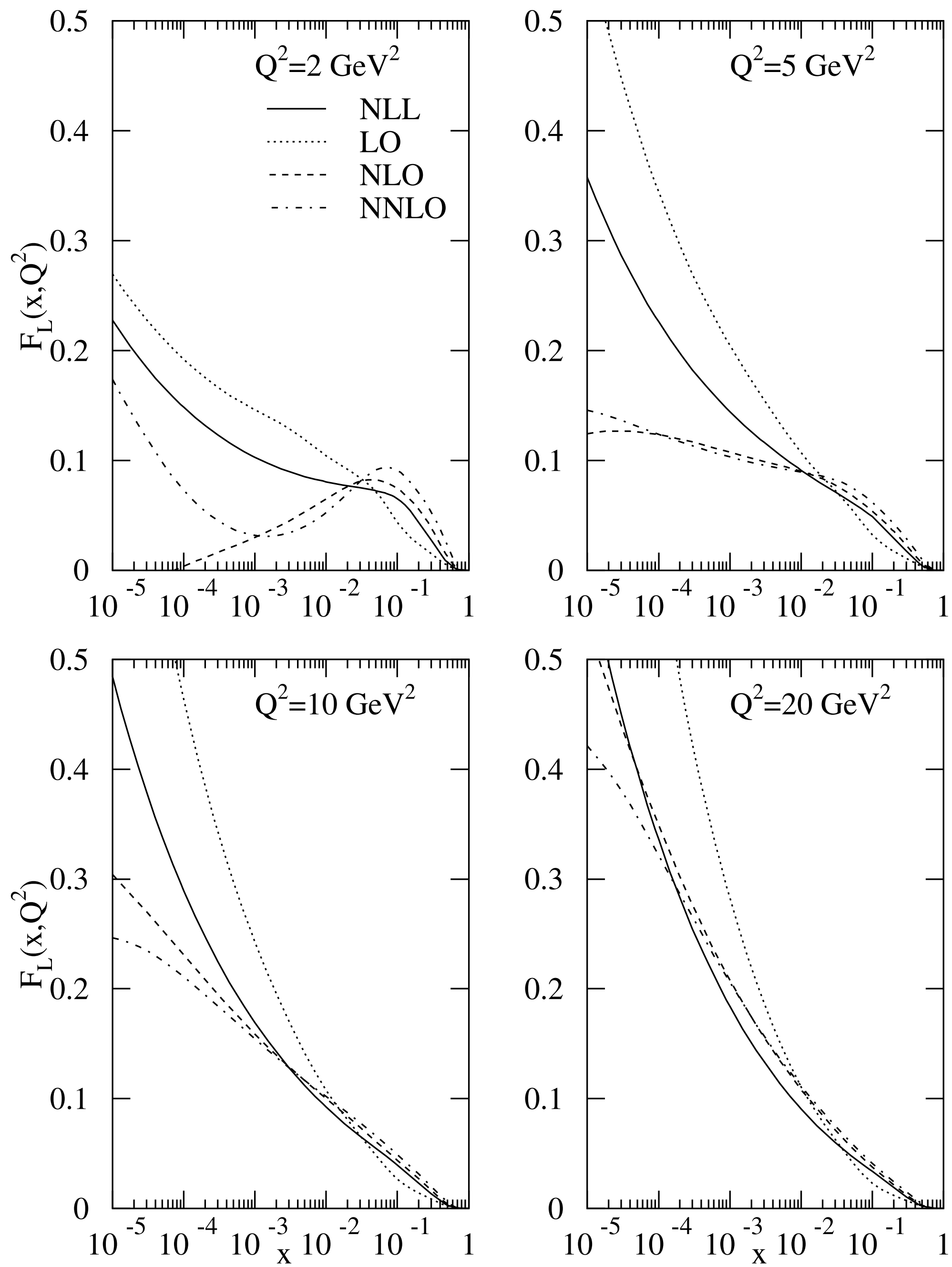
Similar problems possible for charm and/or bottom production, and low-mass Drell-Yan (γ) production at the LHC.



Noted an instability in physical, gluon dominated, quantity $F_L(x, Q^2)$ going from LO $\rightarrow$ NLO $\rightarrow$ NNLO.

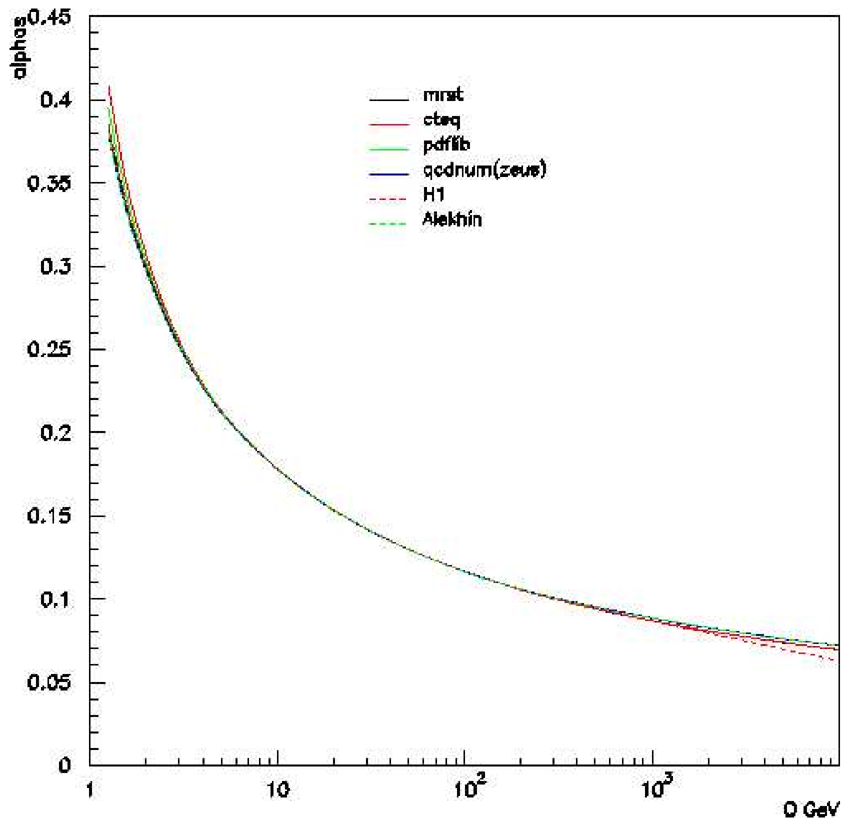
Improved by next-to-leading $\ln(1/x)$ resummation in the global fit and prediction (White, RT).

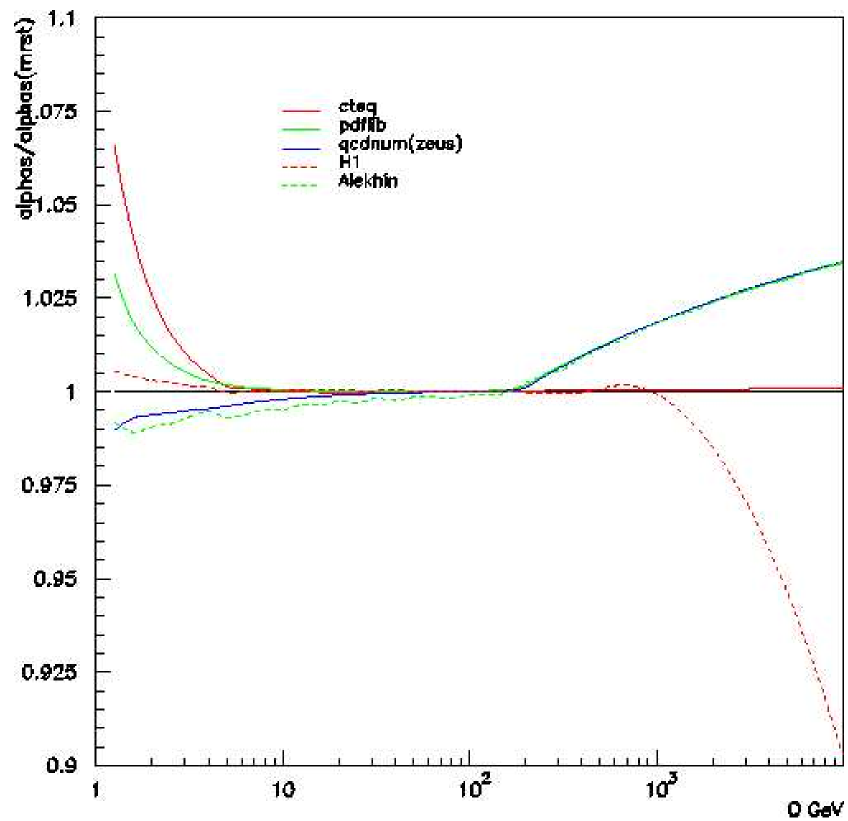
HERA analysis of $F_L(x, Q^2)$ will hopefully help us to determine best theoretical approach.



Most recent Updates - change in definition of α_S.

Variations in α_S definitions shown at HERA-LHC 2005 Workshop by Whalley. None wrong (except at very high Q^2 maybe) just different choices.





Old MRST prescription unwieldy in terms of flavour thresholds, particularly at NNLO.

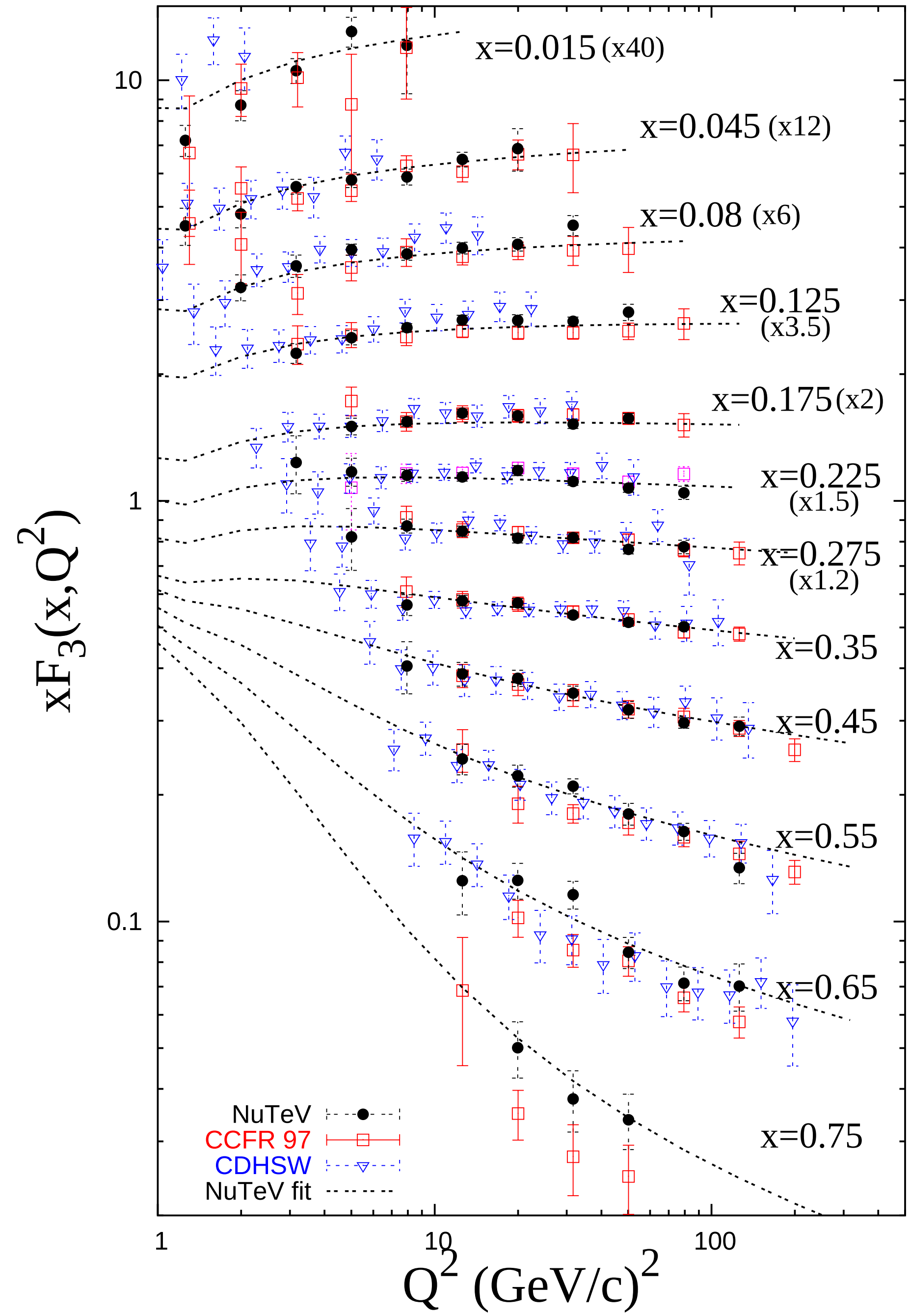
MSTW now use same definition as QCDNUM. Effectively input $\alpha_S(Q_0^2)$ rather than Λ_{QCD}.

New Data

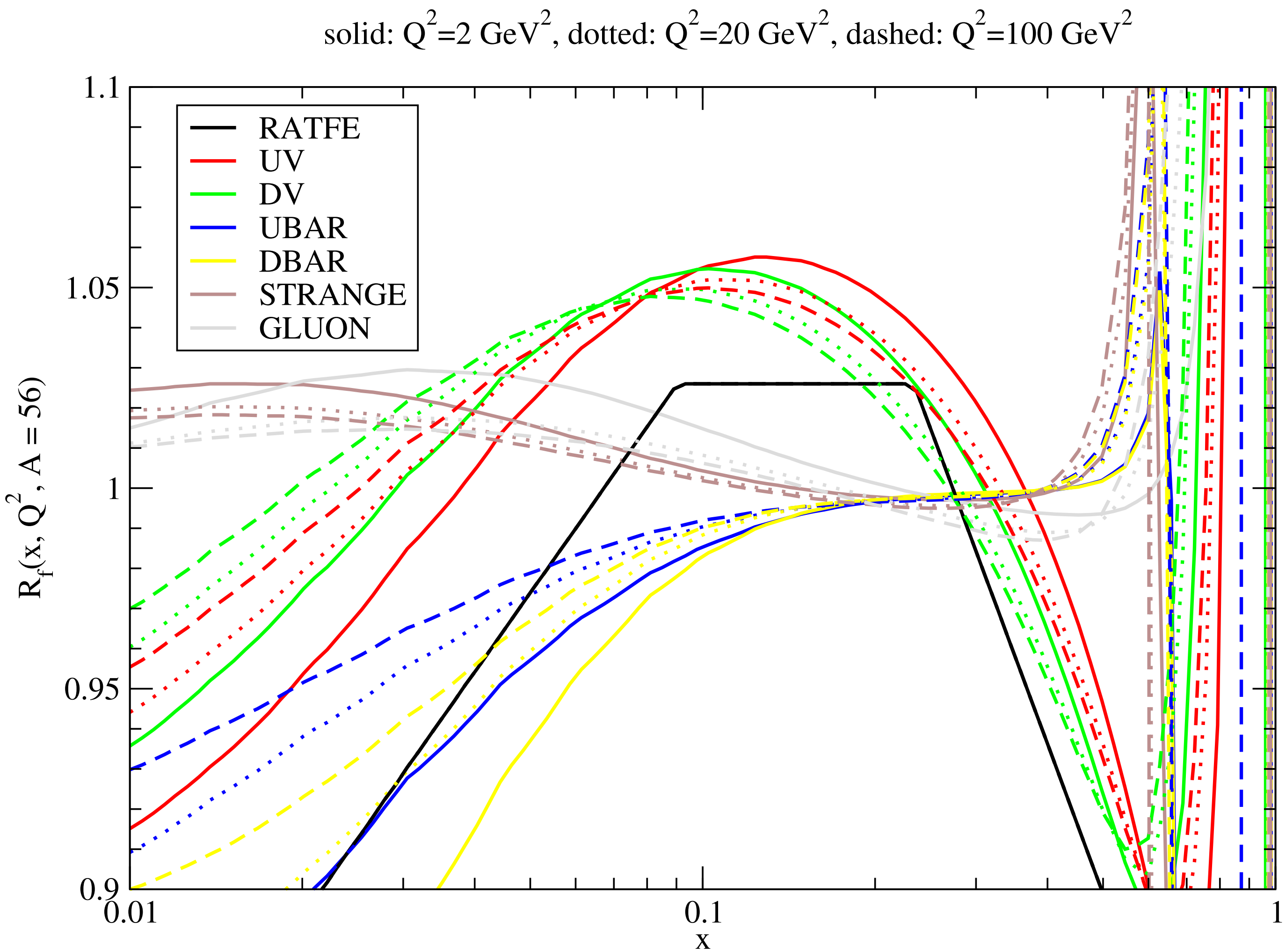
New NuTeV data not completely compatible with the older CCFR data.

Main source of discrepancy is 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 x NuTeV data.

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

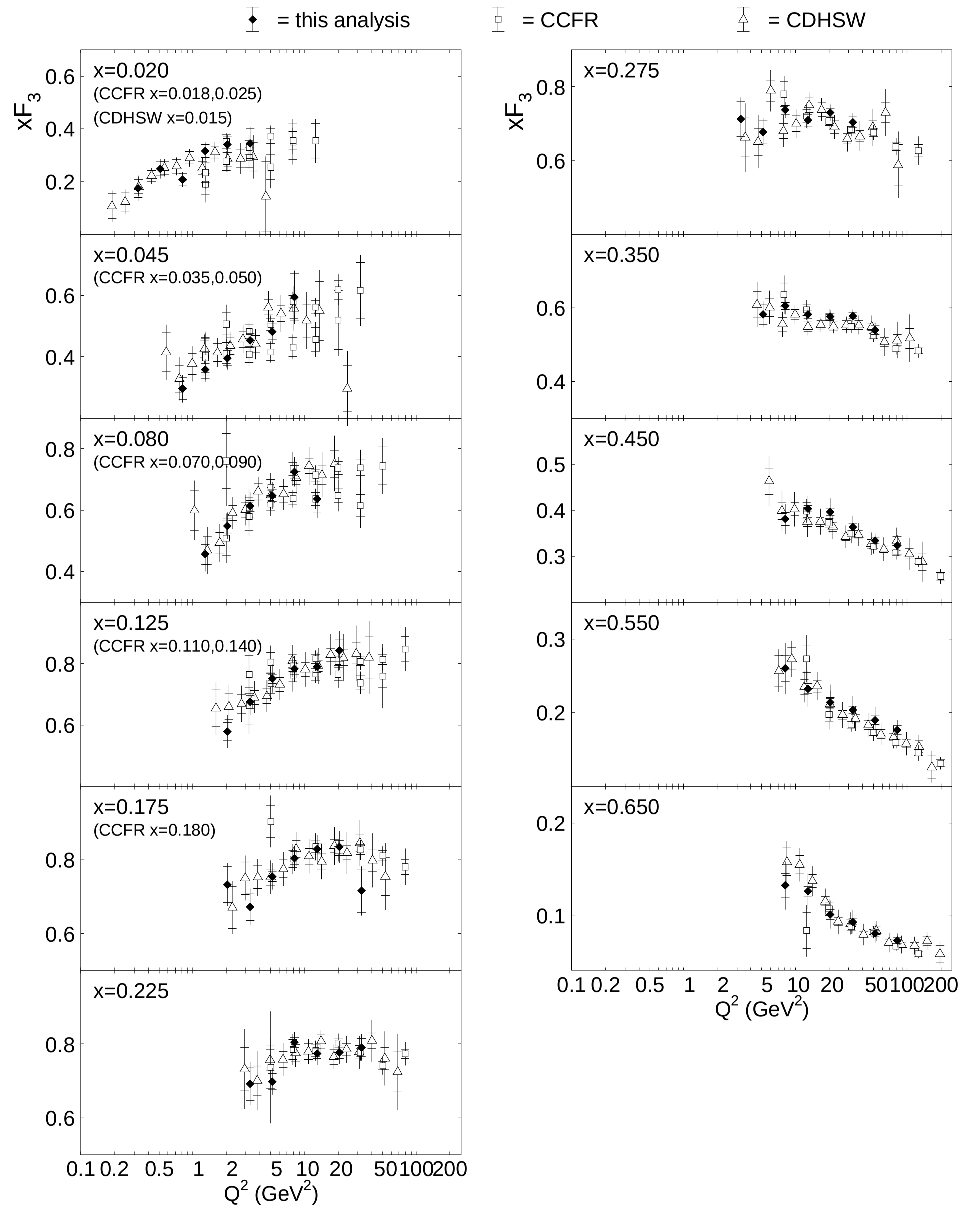
Inconsistencies at high x.

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 $F_2(x, Q^2)$, which we observe. 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. Expect low-x shape the same but normalisation suppressed by mass effects (cf charm and bottom).

x_0 is determined by zero strangeness of proton, i.e.

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

Compared to $s = \bar{s} = (\bar{u}+\bar{d})/4$ letting s^+ free, $s^- = 0 \rightarrow \Delta\chi^2 \sim -15$ with improvement mainly in dimuon data.

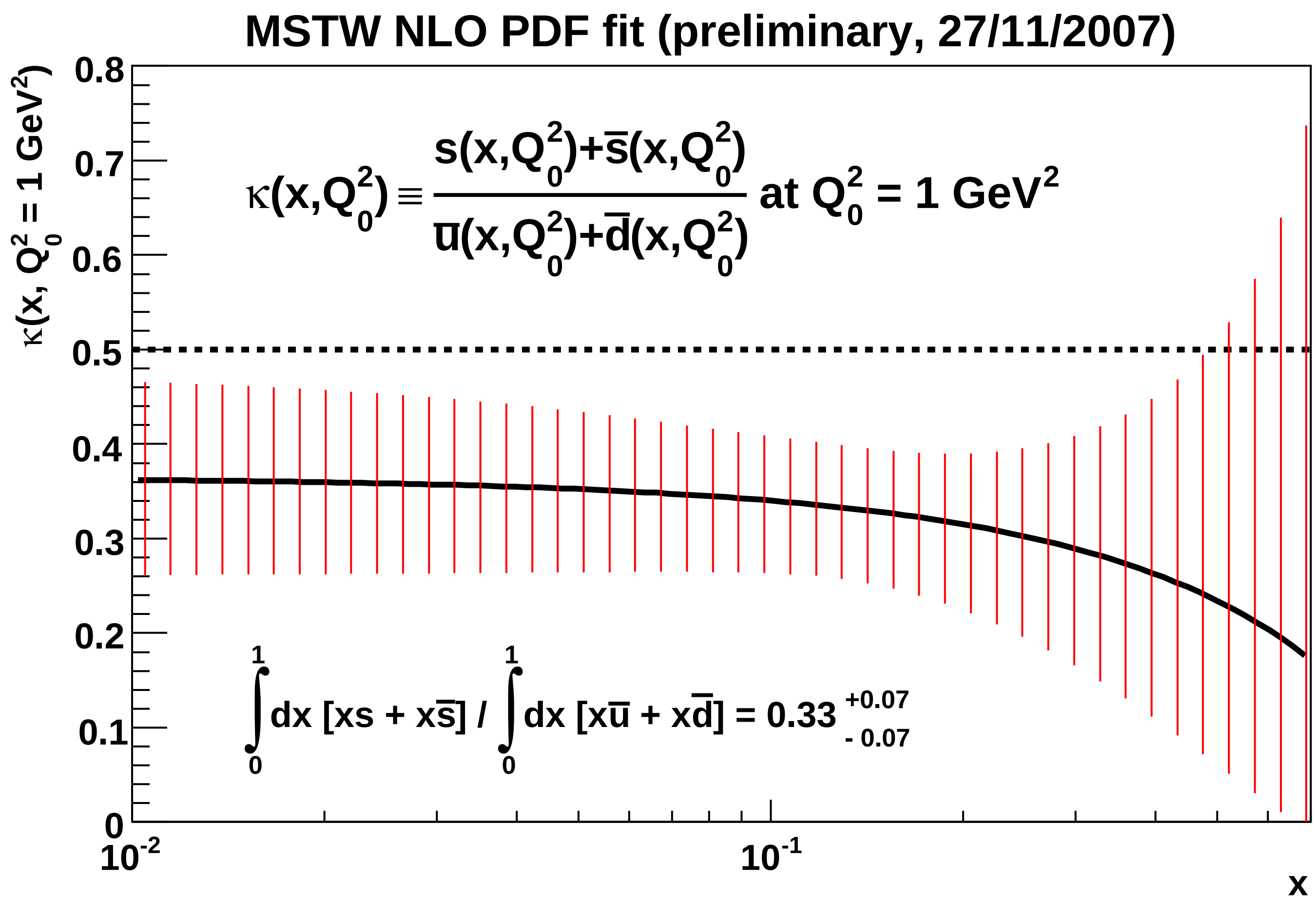
Letting both s^+ free and s^- free $\rightarrow \Delta\chi^2 \sim -30$ with improvement even more restricted to dimuon data.

No real improvement with further parameters.

All 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.

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?

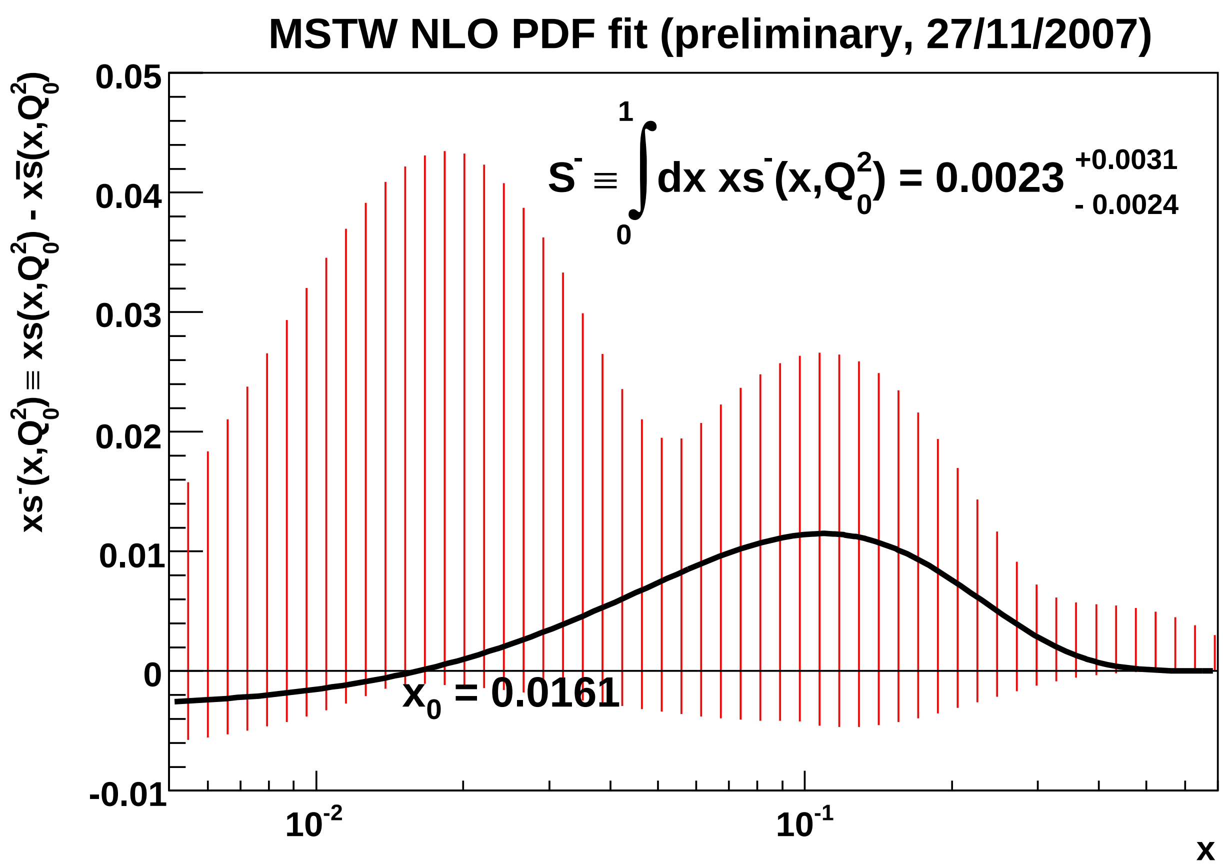


Suppression at *nonperturbative* $Q_0^2 = 1\mathrm{GeV}^2$ now ~ 0.3, i.e. value in hadronization models (probability to generate $\bar{s}s$ compared to $\bar{u}u, \bar{d}d$).

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

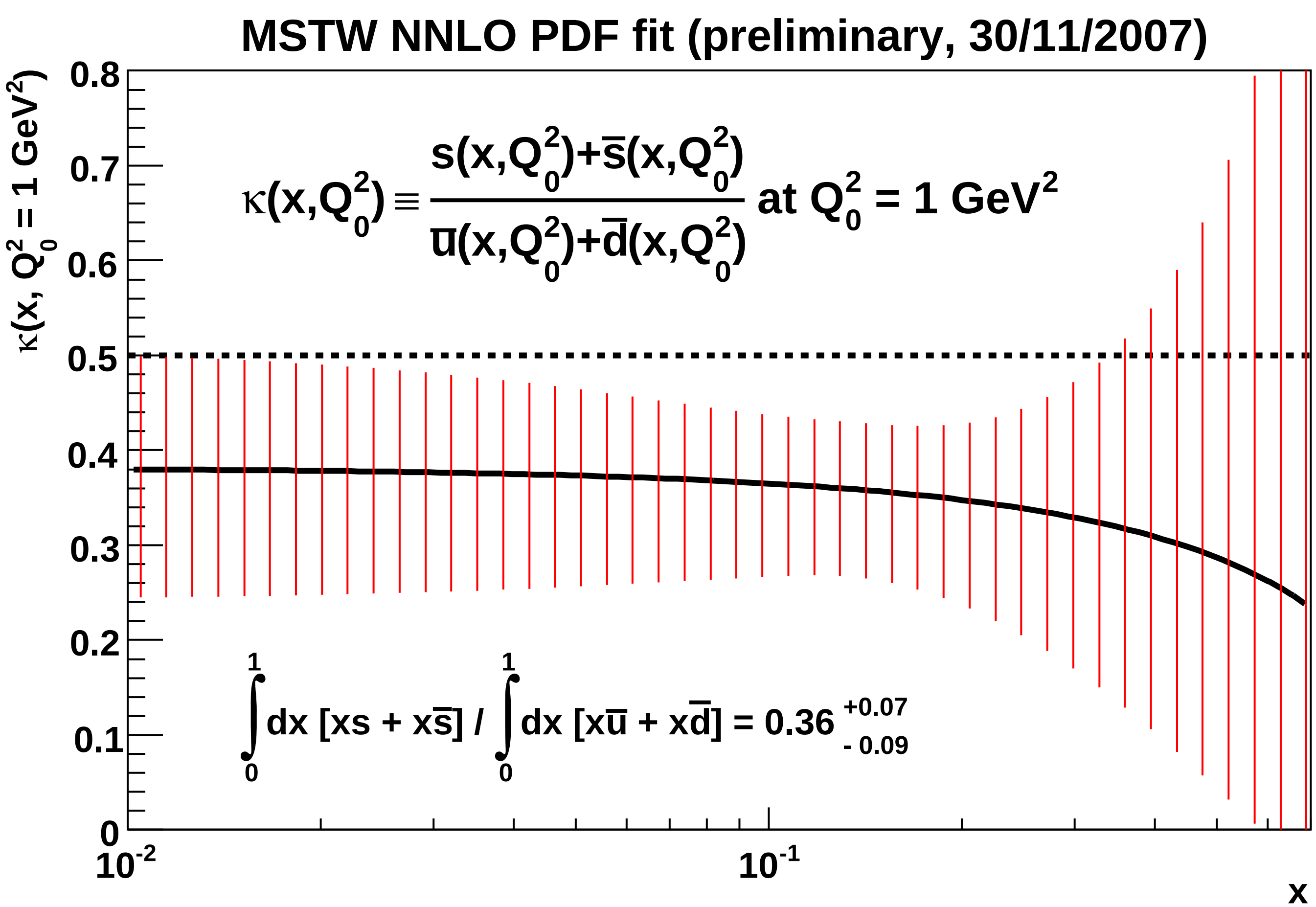
Positive, with central value 0.0023 ± 0.0025 (roughly 90% confident limit). Nonzero value not huge significance. At $Q^2 = 10\text{GeV}^2$ asymmetry of 0.0017 ± 0.002.

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

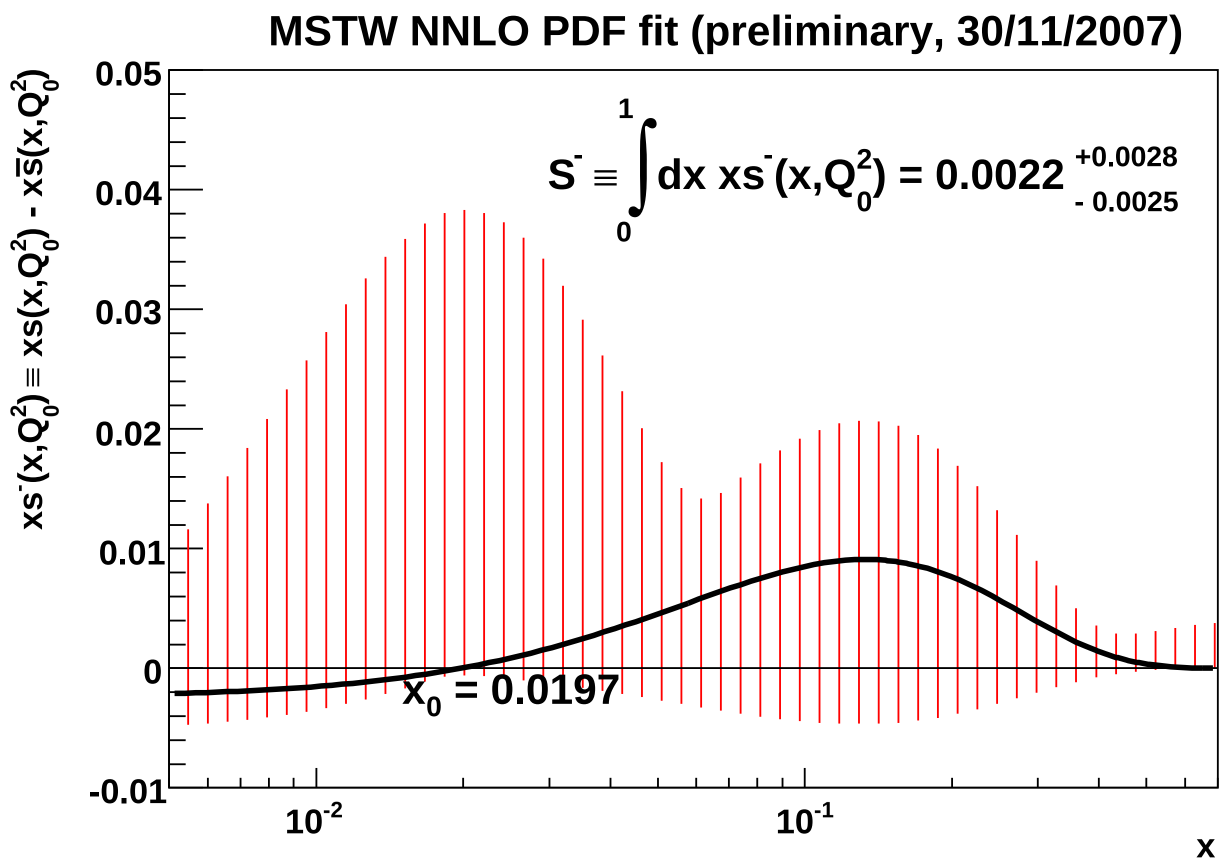


Now also completed at NNLO. Requires careful treatement of charged current heavy flavour scheme - depends on $F_2(x,Q^2)$, $F_L(x,Q^2)$ and $F_3(x,Q^2)$ with significant cancellations between them.

Results rather similar overall to NLO. Not completely obvious *a priori* that this would be so.



Asymmetry results also rather similar overall to NLO.



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

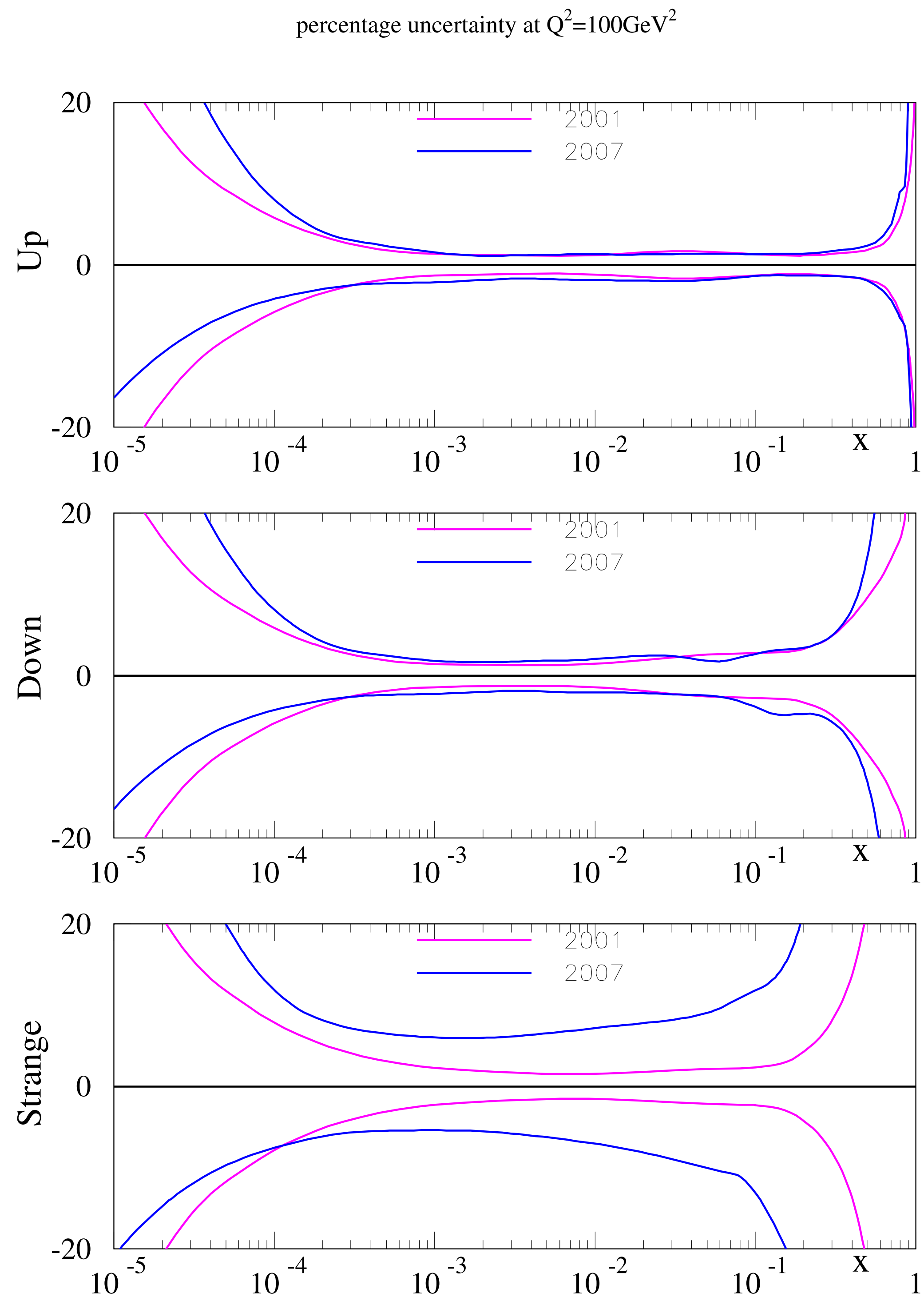
Previously for us (and everyone else) strange a fixed proportion of total sea in global fit.

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 increases – $\sim 1.5\% \rightarrow \sim 2-2.5\%$, despite additional constraints on quarks in new fit.



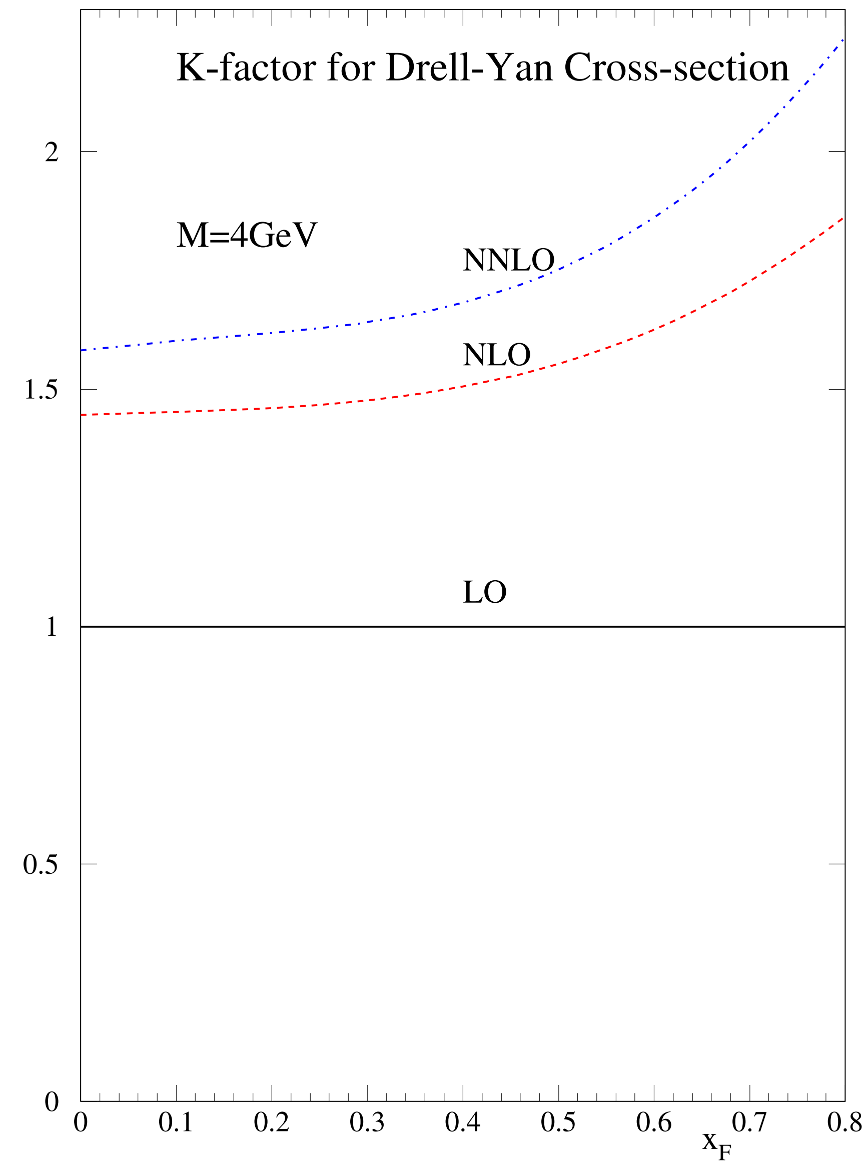
Drell-Yan corrections

Now include NNLO corrections (Anastasiou, Dixon, Melnikov, Petriello) for W, Z and γ^* data using Vrap and FEWZ.

The K-factors for Drell-Yan production at E866 – $\sqrt{s} = 38.8\mathrm{GeV}$.

Enhancement at higher $x_F = x_1 - x_2$ due to logarithms. Similar to $\ln(1-x)$ enhancement in structure functions.

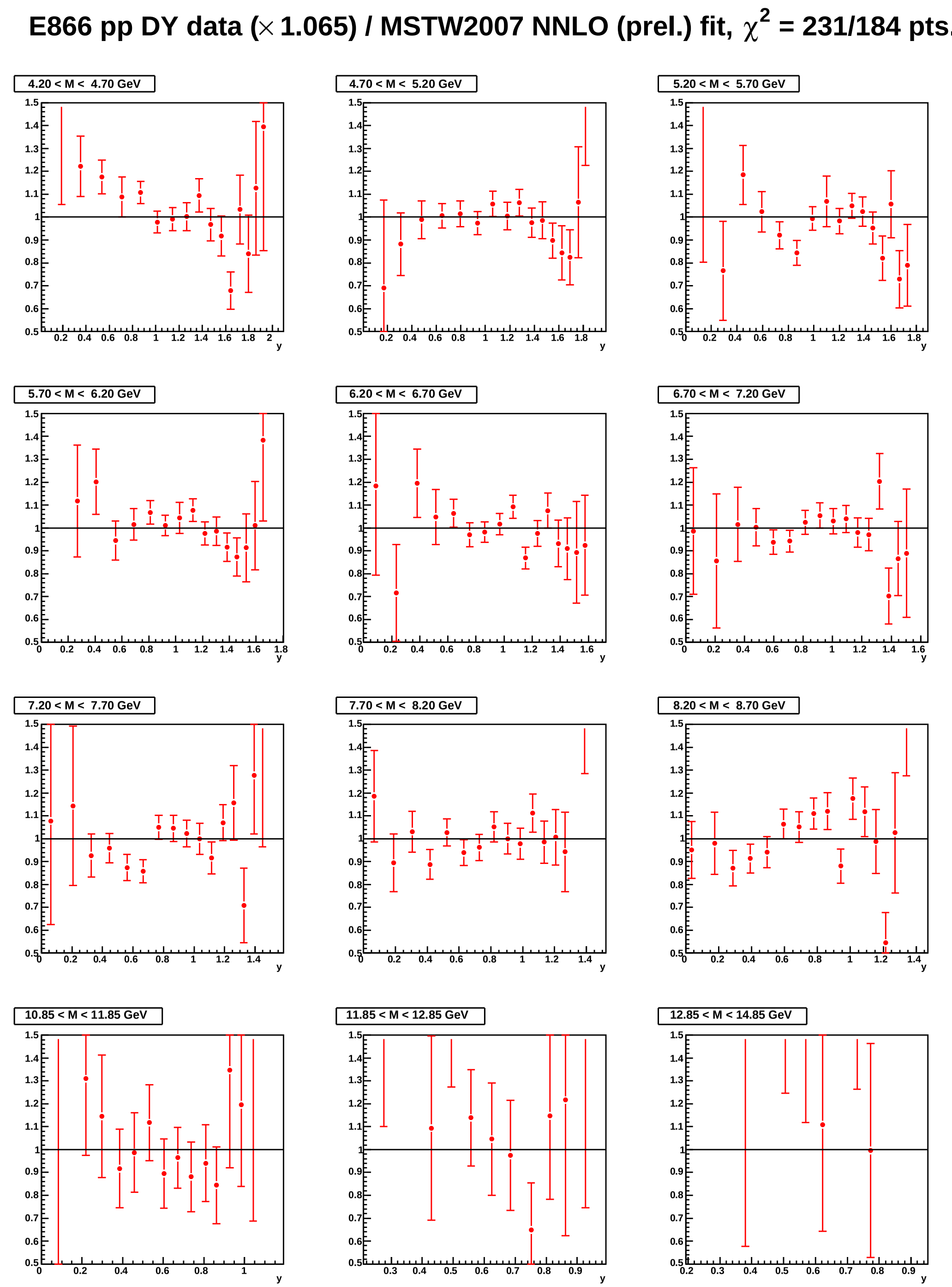
NLO corrections large, NNLO corrections significant – 10% or more.



Quality of fit to E866 Drell-Yan production at E866 in proton-proton collisions – now with radiative corrections.

At NNLO requires normalization set to upper error band, i.e. 1.065.

Apart from some suggestion in lowest M bin no systematic problem with fit (contrary to other claims).



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}

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

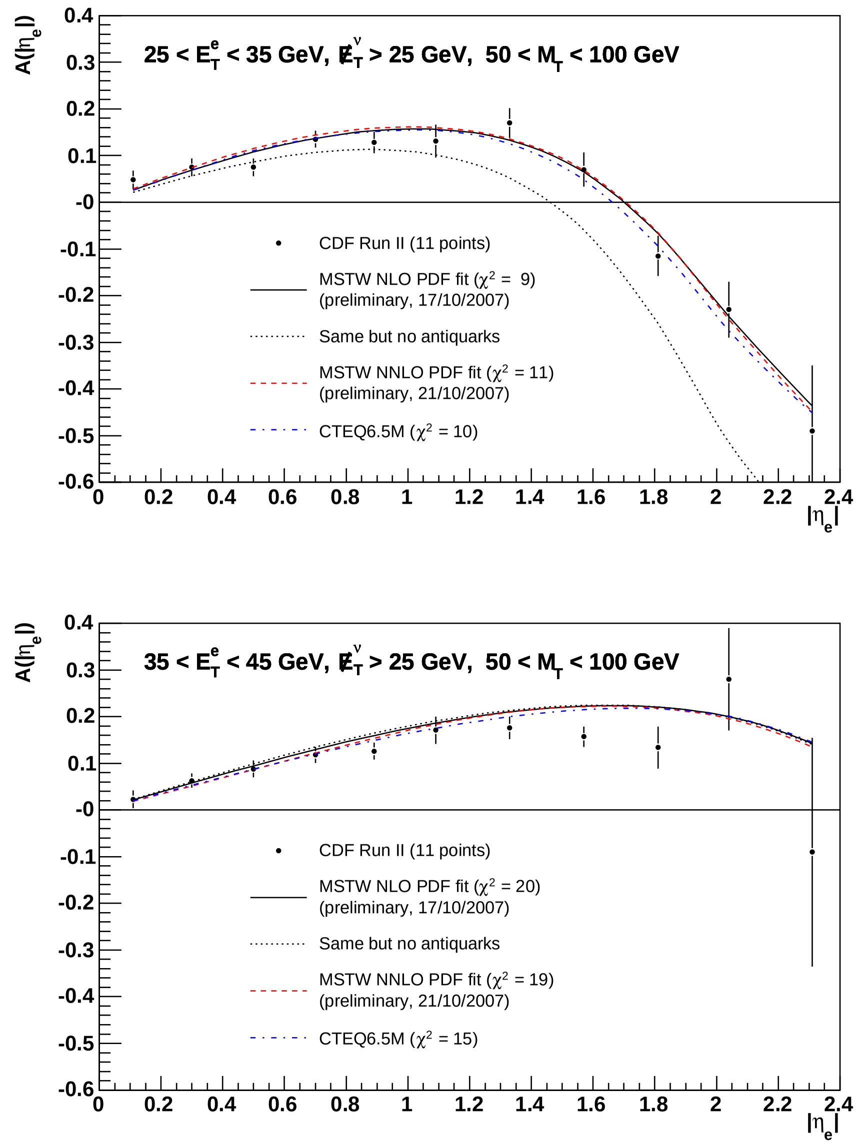
so fairly sensitive to anti-quarks at lower E_T.

Comparison of fits to CDF data with various partons. 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.

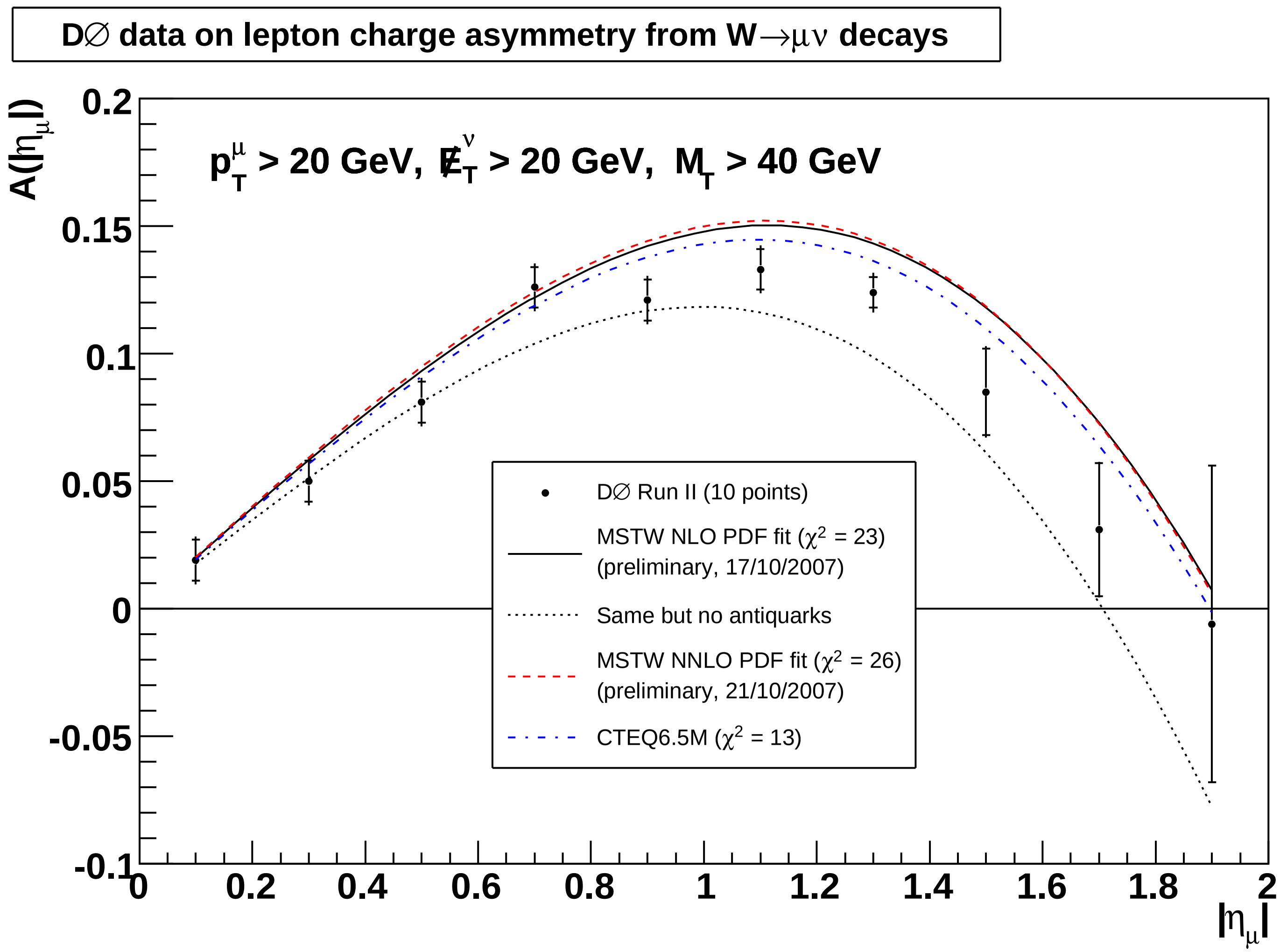
New CDF data does influence $d(x, Q^2)$ in MSTW fit.

CDF data on lepton charge asymmetry from W→eν decays



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.

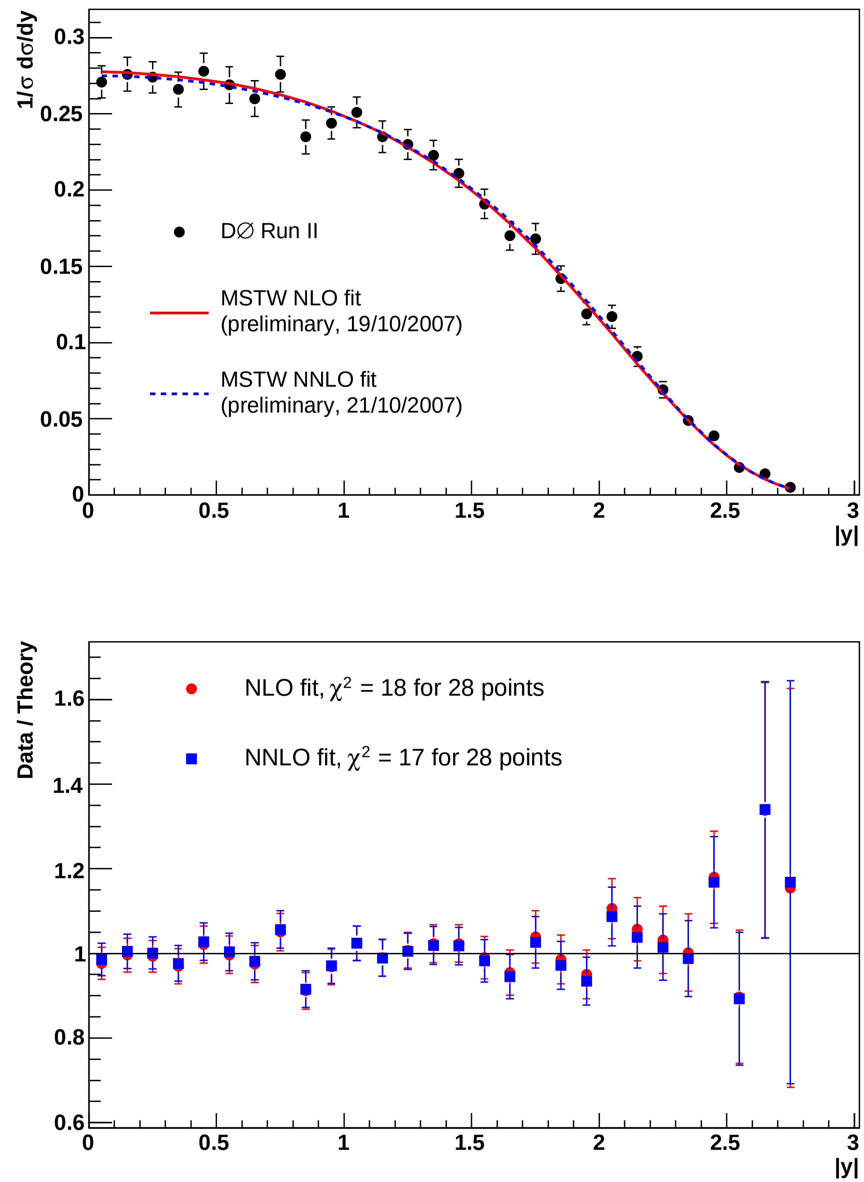


$$\frac{d\sigma(Z)}{dy} \propto 0.37u(x_1)\bar{u}(x_2)+0.54d(x_1)\bar{d}(x_2)$$

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

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

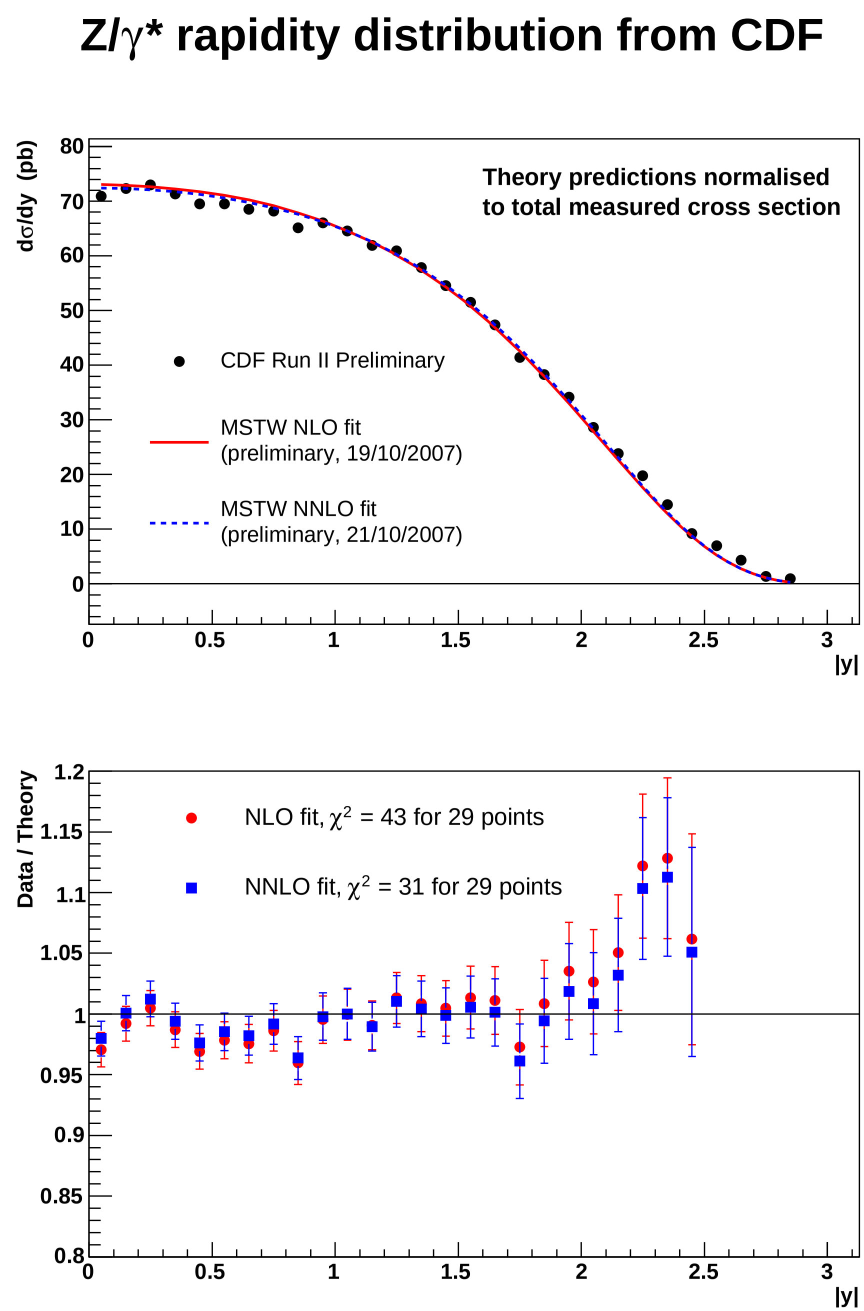
Z/γ* rapidity shape distribution from D∅



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

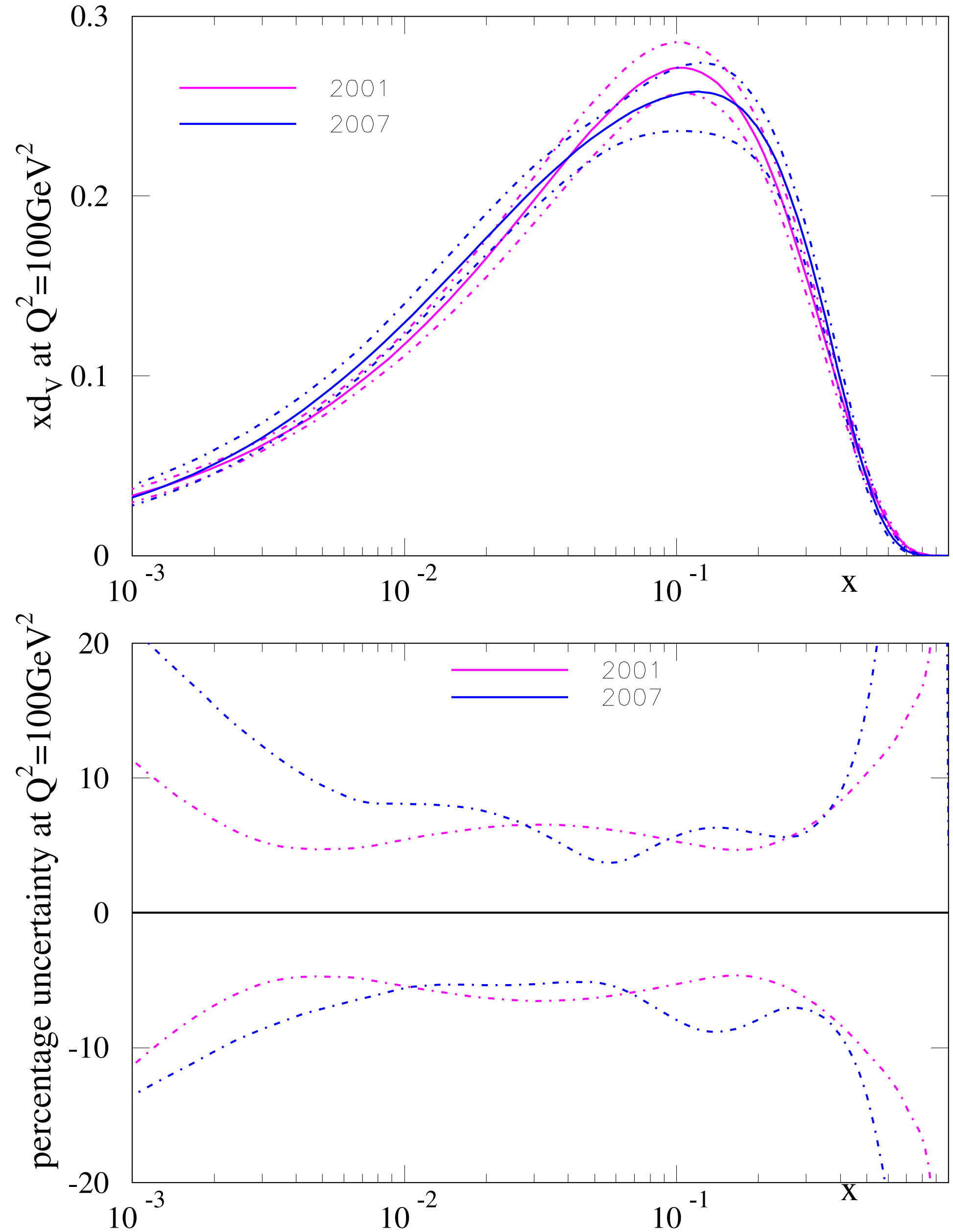
Improves in refit and constrains $d(x, Q^2)$. Pulls in opposite direction to W-asymmetry.

Automatically fit better at NNLO. Both cross-section and partons produce better shape.



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

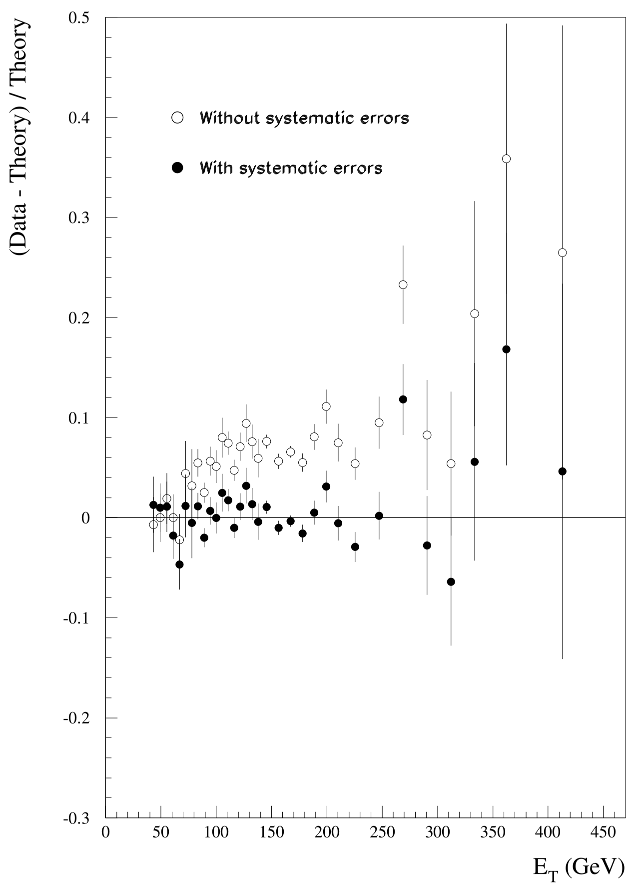
Uncertainty growing more quickly as $x \rightarrow 0$ and $x \rightarrow 1$ than before due to better parameterisation in determining uncertainty eigenvectors.



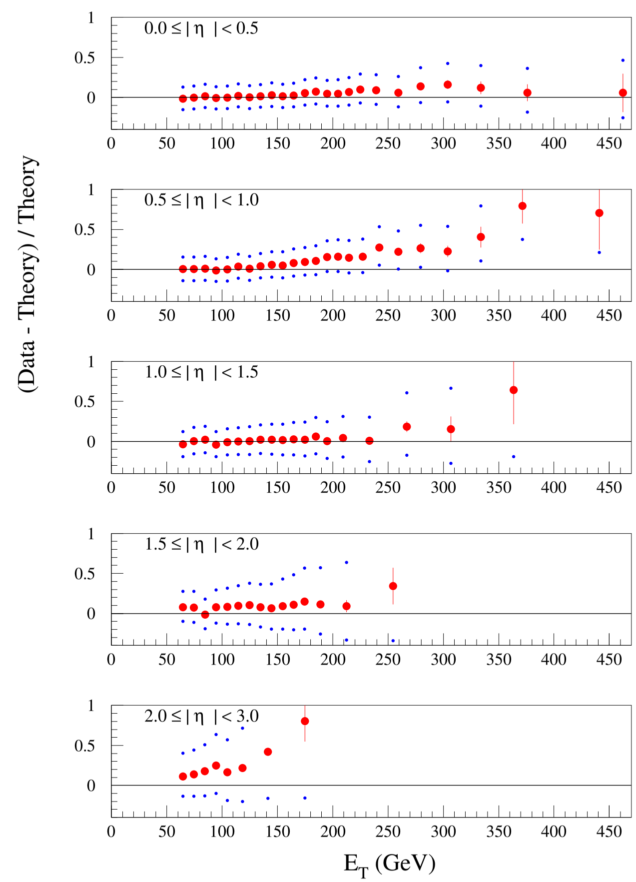
Now use fastNLO – fast perturbative QCD calculations Kluge, Rabbertz, Wobisch. Allows easy implemenation of NLO hard cross-section corrections to both Tevatron and HERA jets. Replaces previous "K-factors" and "pseudo-gluon data".

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, $\chi^2 = 50/33$ pts.



DØ Run I inclusive jet data, $\chi^2 = 58/90$ pts.



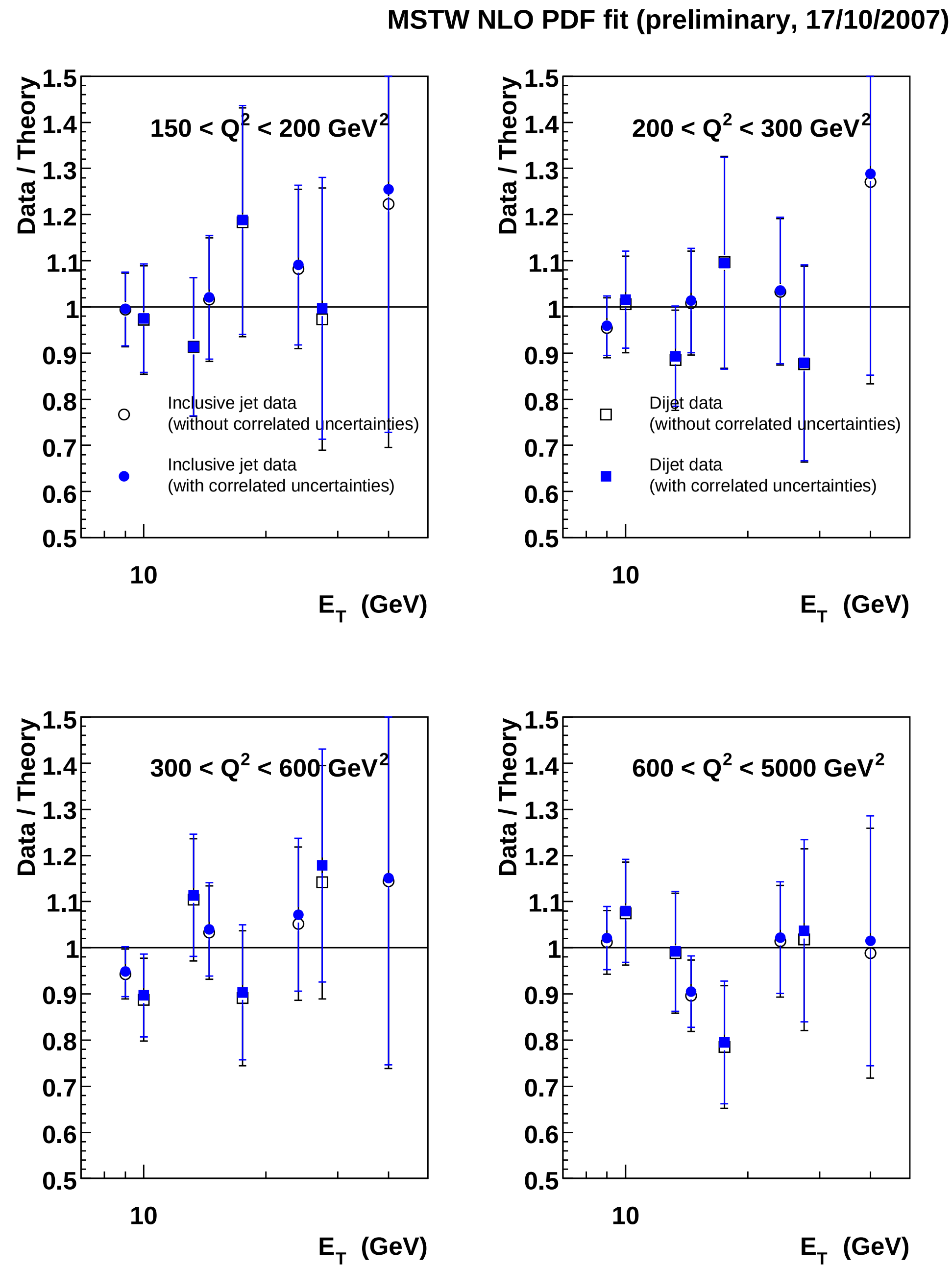
Also now include HERA inclusive and dijet DIS data using fastNLO.

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

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

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

H1 95-97 incl. jet and dijet data, χ^2 = 13/32 pts.

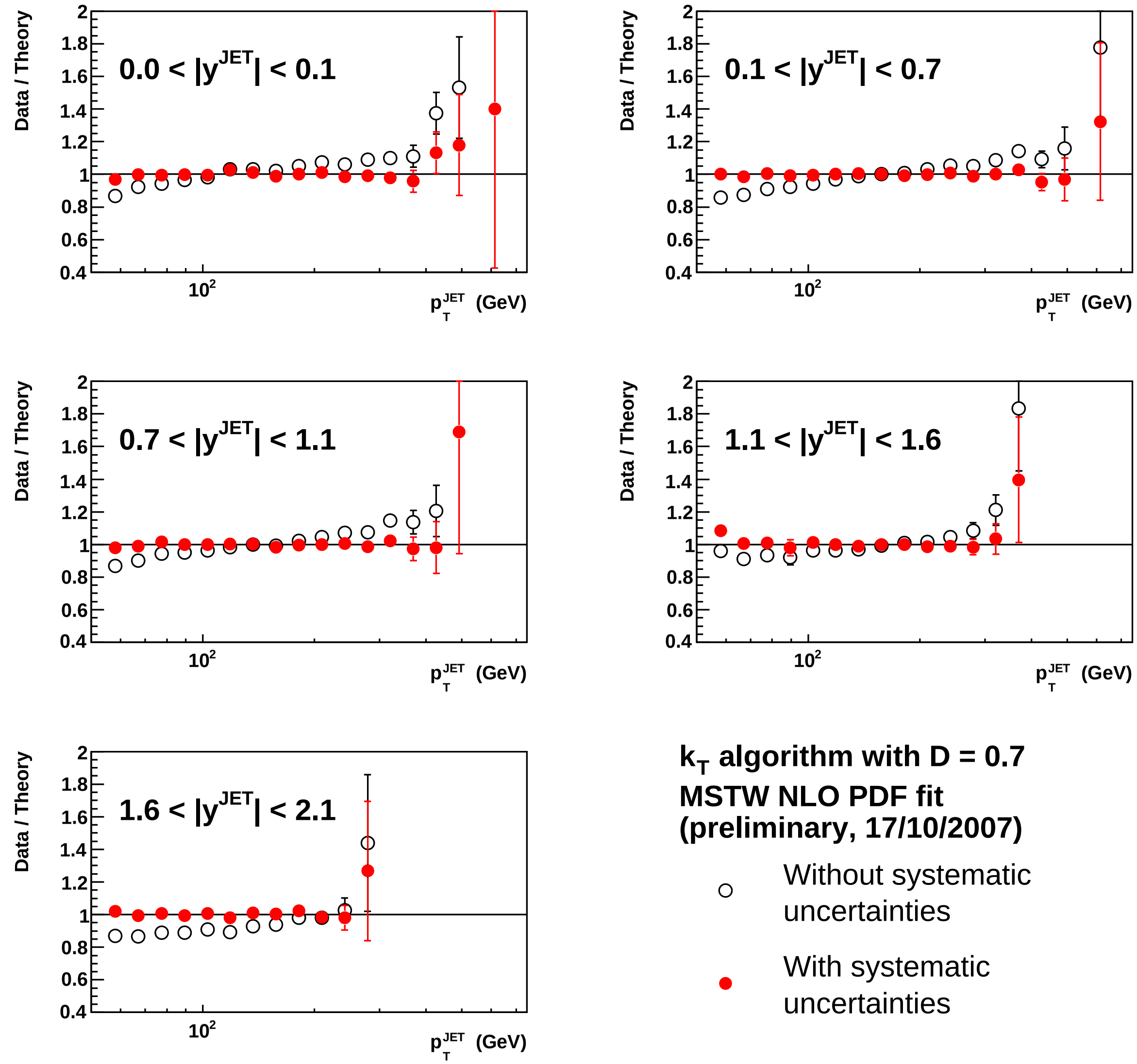


Now also include CDF Run II inclusive jet data in different rapidity bins using k_T jet algorithm (mid-point cone algorithm data seems very similar, but numbers not yet available).

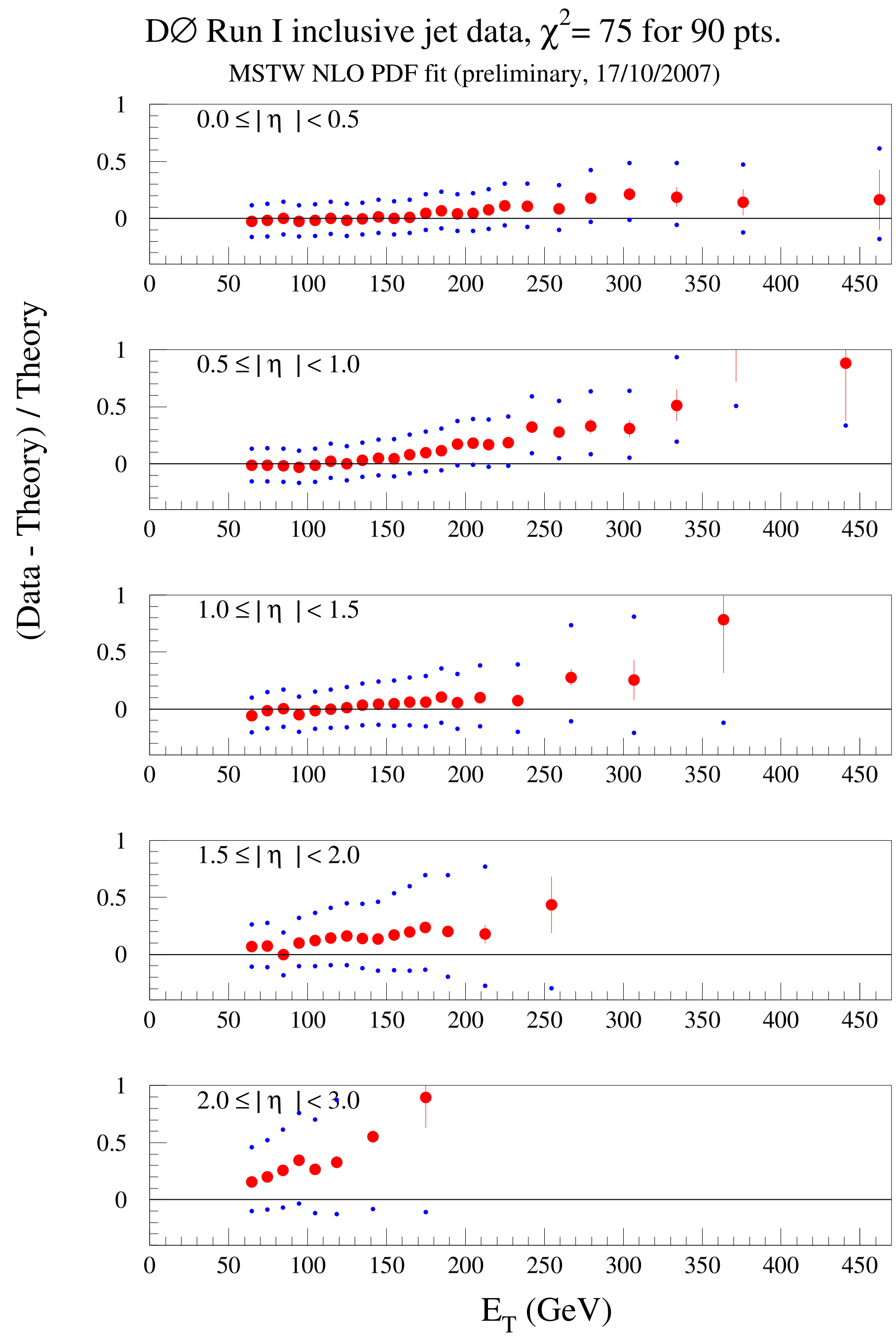
Very good fit – $\chi^2 = 58/76$.

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

CDF Run II inclusive jet data, χ^2 = 58 for 76 pts.

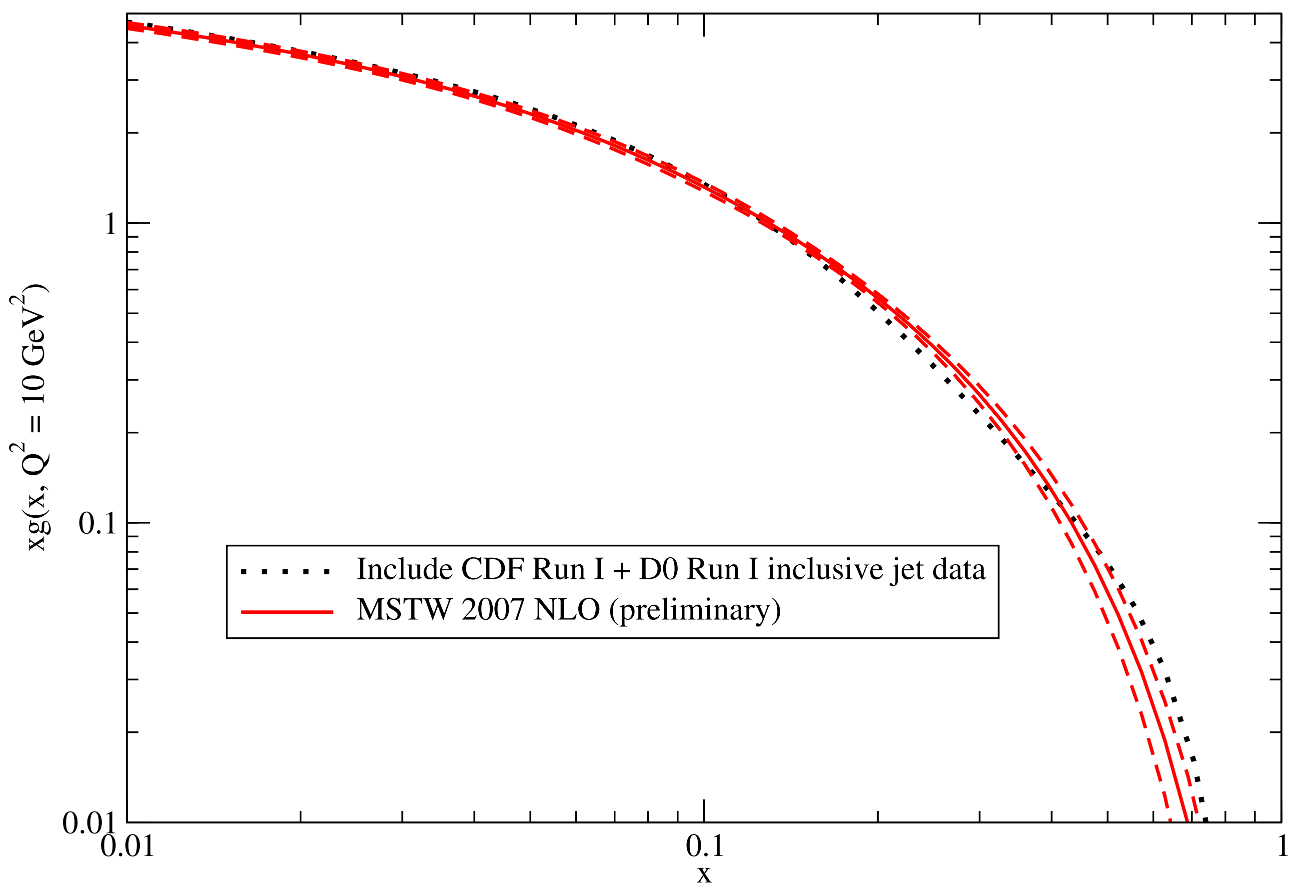


Slight deterioration in fit to D0 run I data in different rapidity bins compared to using CDF run I data.

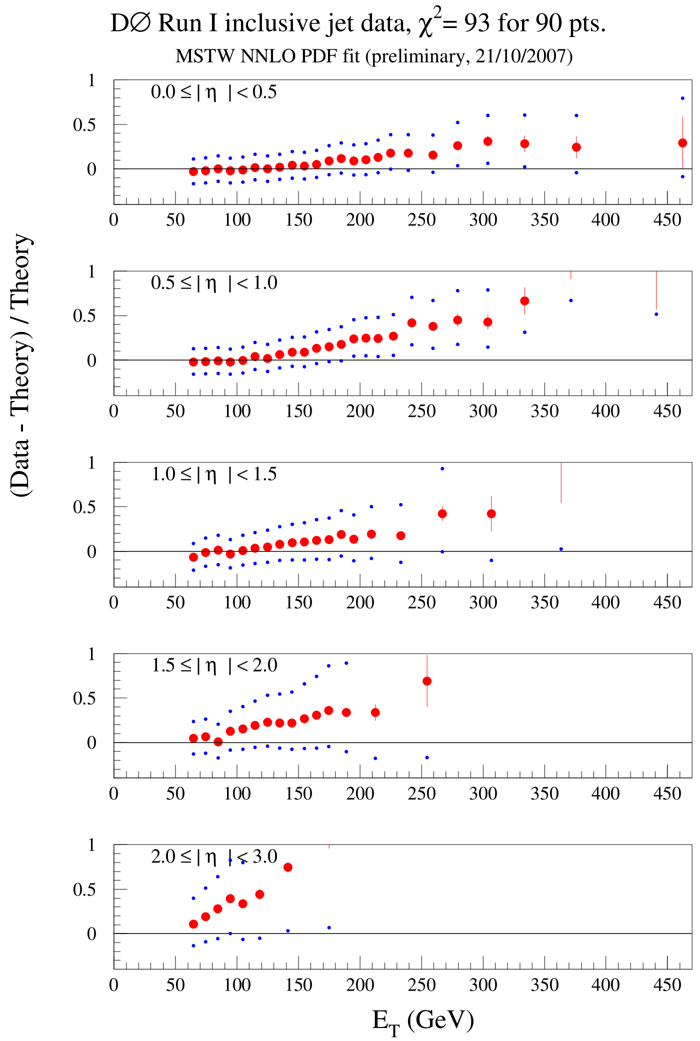


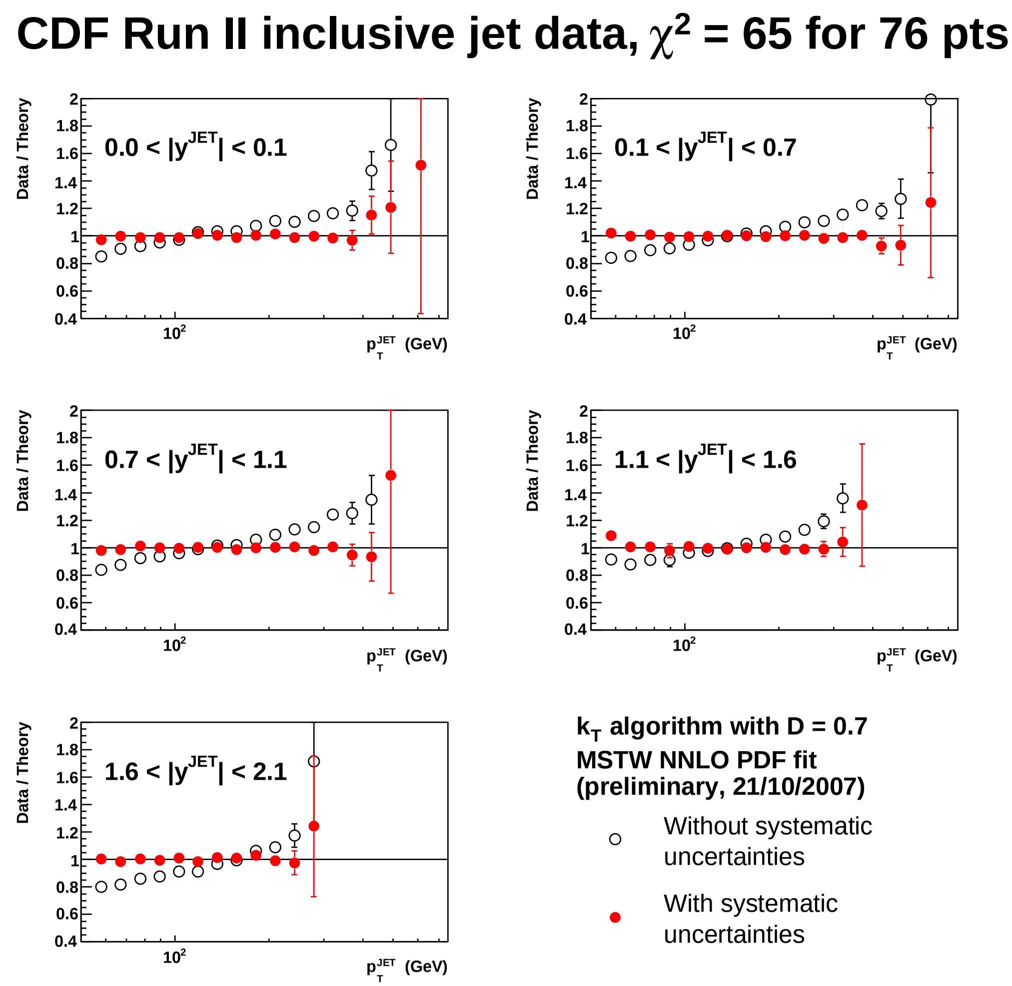
CDF run II data prefers a smaller very high x gluon distribution compared to run I data. Just outside uncertainties at our 1σ level.

Uncertainties at high x are a little smaller than for MRST2001.



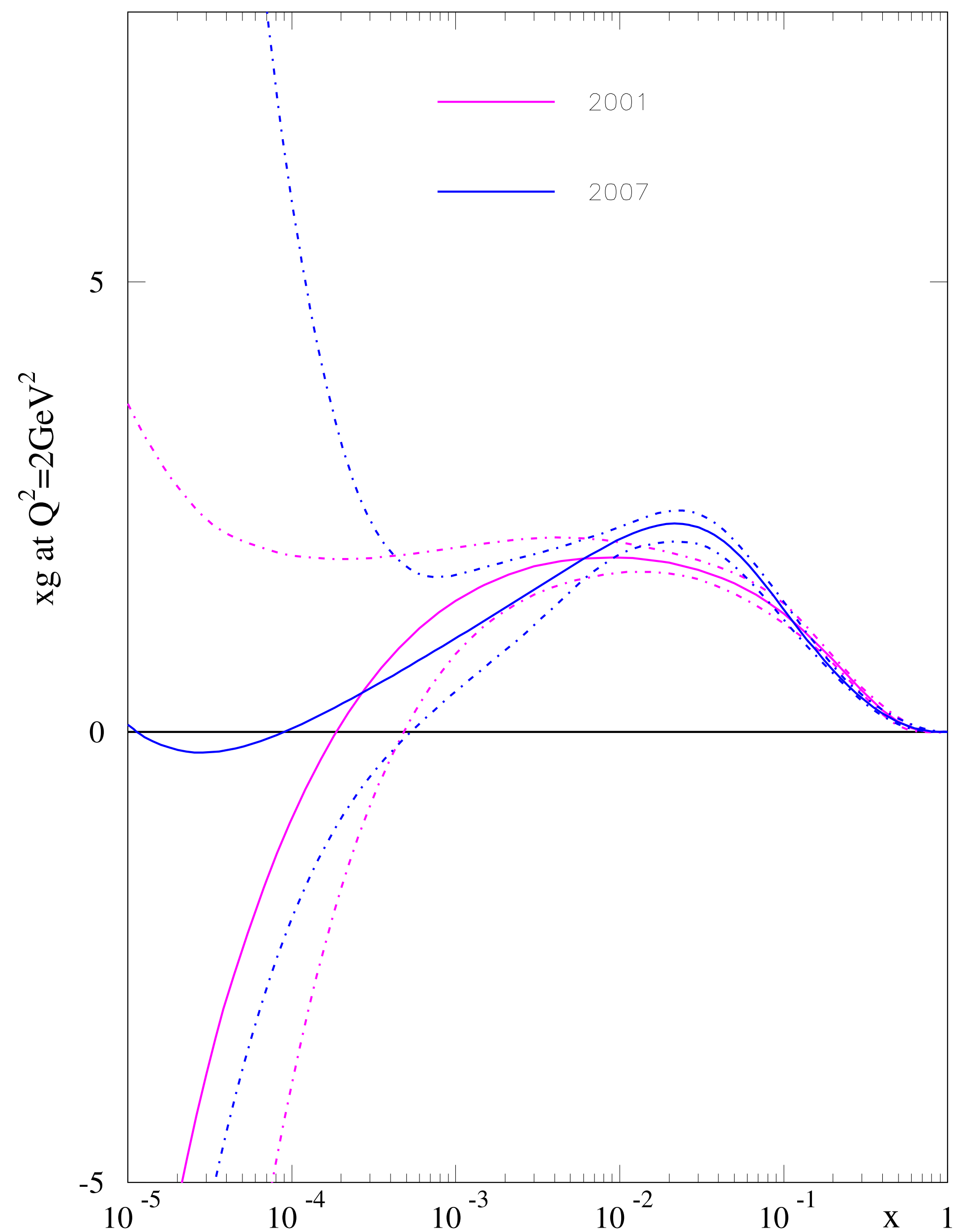
Fit to Tevatron jet data little worse at NNLO since high-x quarks automatically smaller.





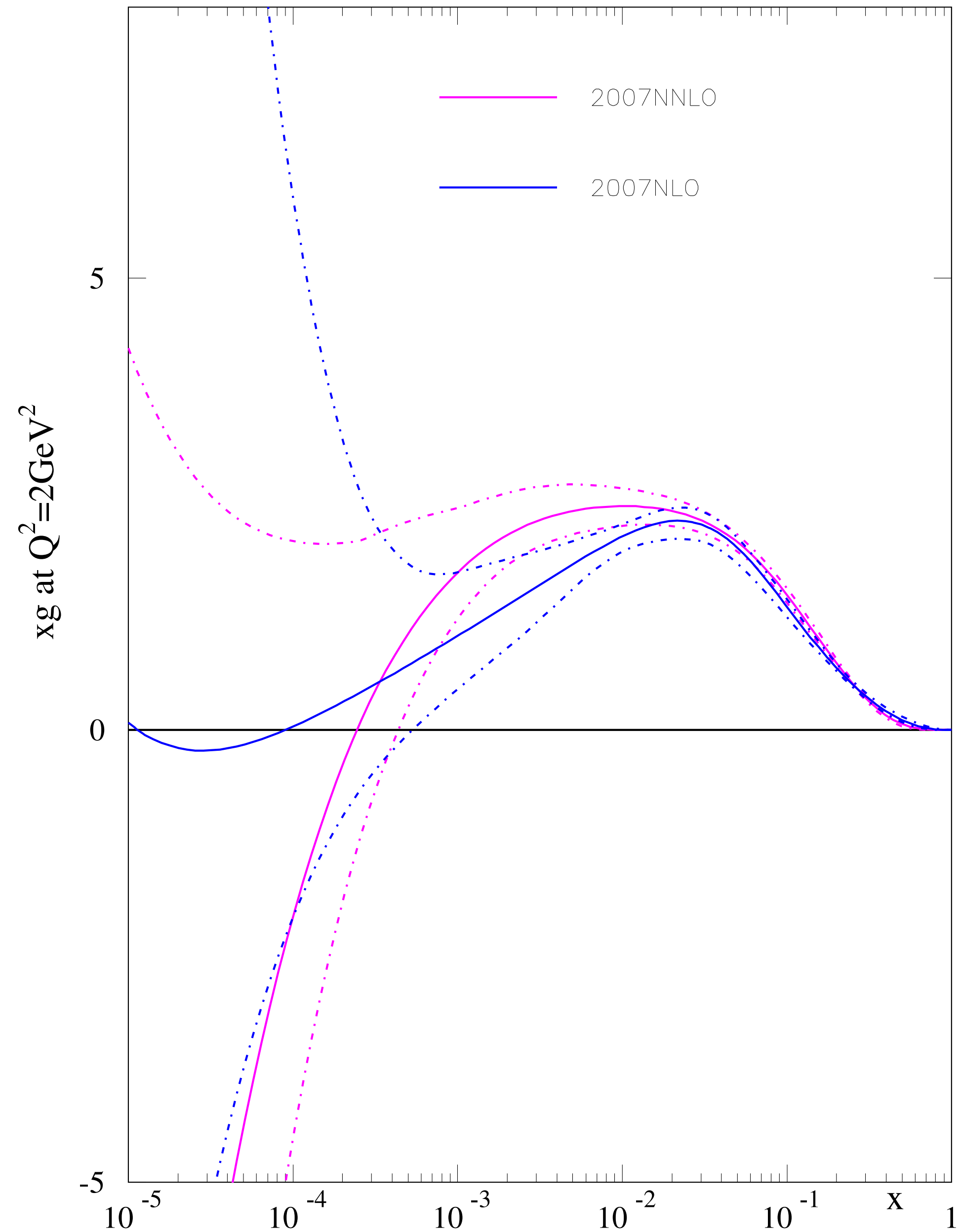
At NNLO only know threshold corrections to cross-section. Few % and flat in E_T. Total NLO corrections only $\sim 10\%$ and smooth with $E_T \rightarrow$ unlikely NNLO corrections larger than systematic uncertainties.

Overall input gluon at NLO of same general shape to previously. Still dips negative at low x, not quite so much.



Comparison of most up-to-date gluon distributions at NLO and NNLO. General result that NNLO becomes more negative at very low x, still true.

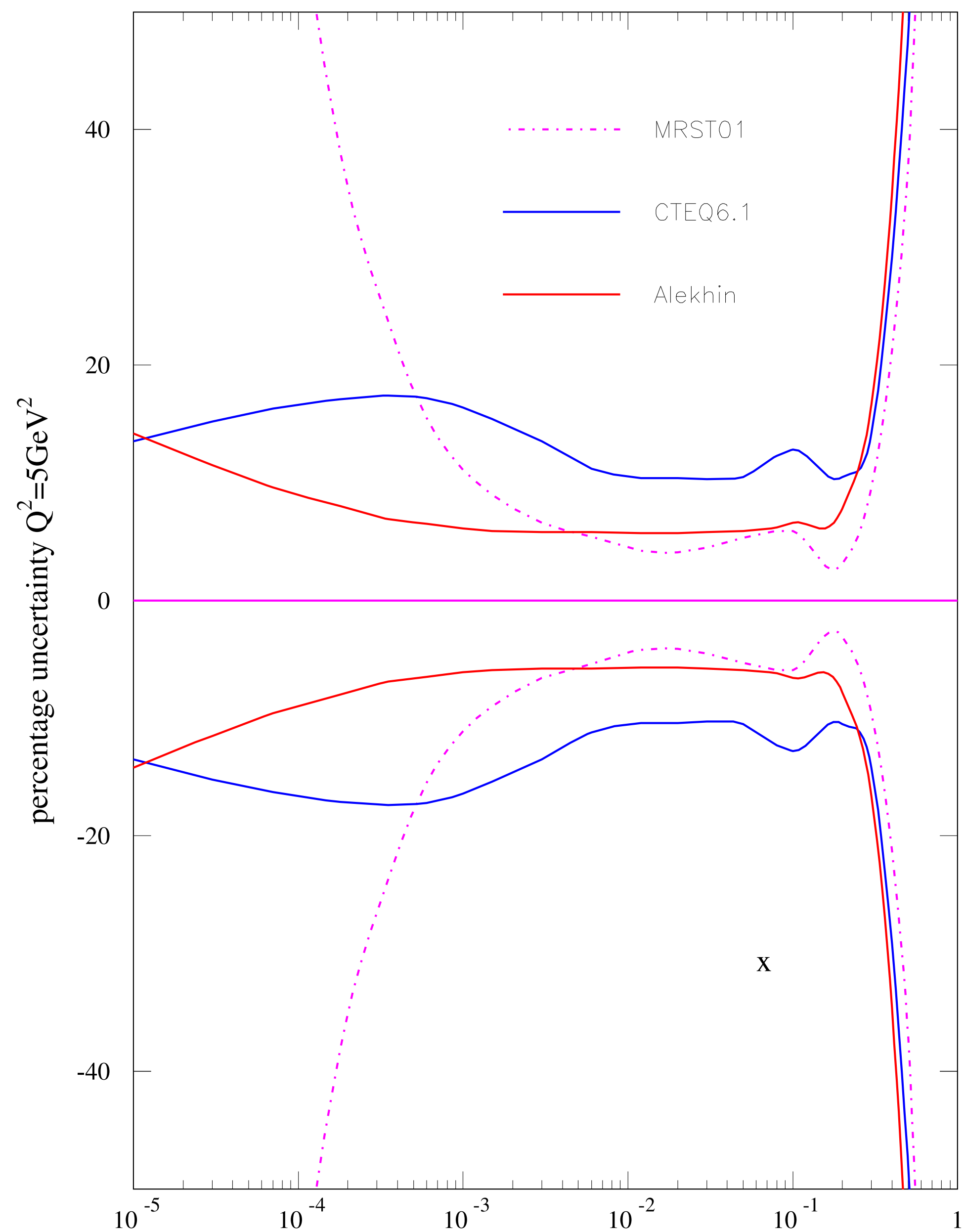
Uncertainty on gluon also extremely large at $x \sim 10^{-5}$ at NNLO.



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 $x = 0.01 - 0.001$.

Summary of Updates.

Implemented all new data at both NLO and NNLO. Fit very good in both cases though NLO better for some data sets.

Obtain $\alpha_S(M_Z^2) = 0.1197$ at NLO and $\alpha_S(M_Z^2) = 0.116$ at NNLO – new data and change in definition lead to slightly lower value. Fit $m_c = 1.4\mathrm{GeV}$ (pole mass).

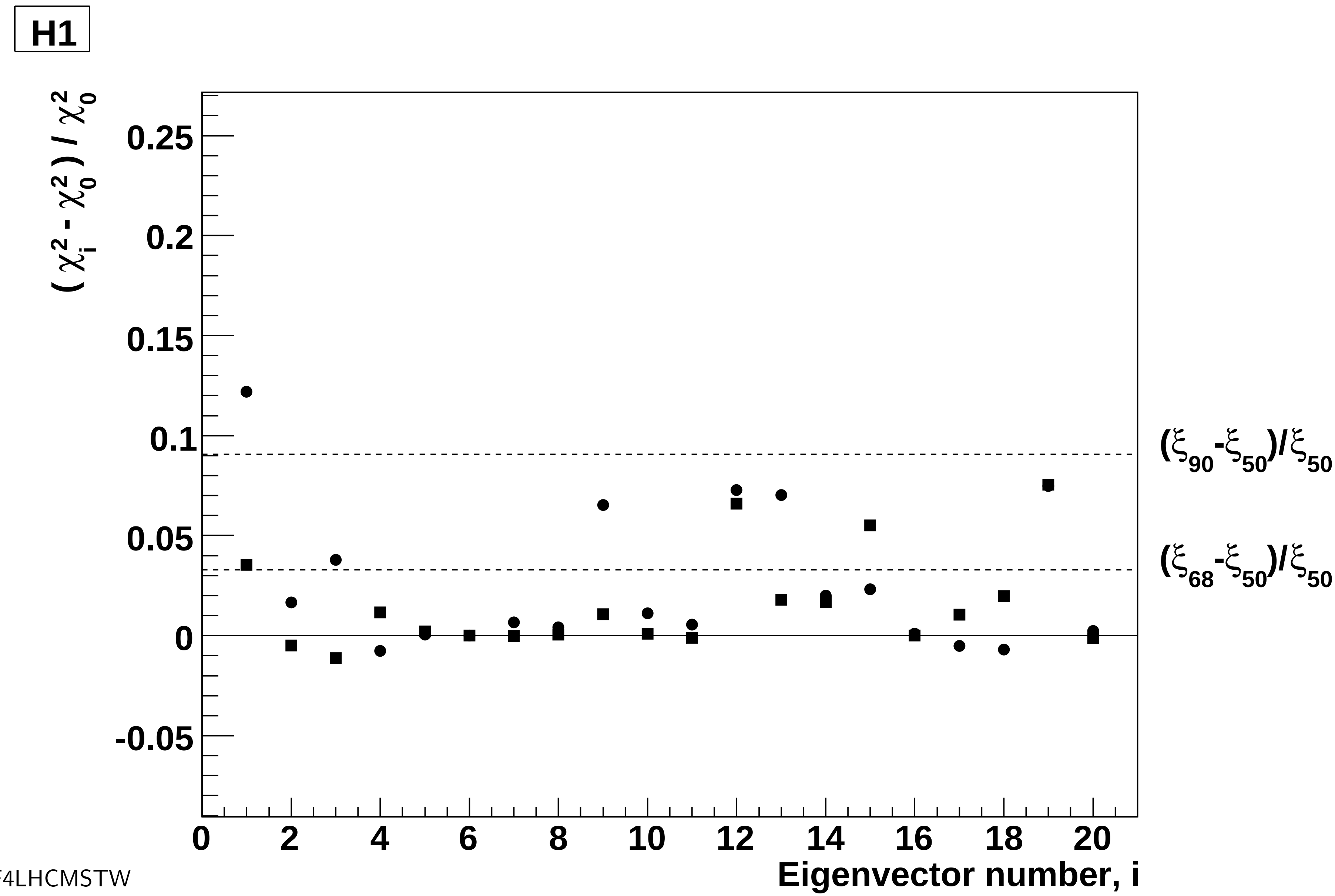
Two new parameters for $s^+(x, Q^2)$ and two for $s^-(x, Q^2)$. Additional one for gluon compared to previous sets whilst maintaining stability for eigenvectors, and better choice of parameters for quarks $\rightarrow$ more realistic uncertainties, particularly at small x.

$\rightarrow$ now 20 eigenvector sets. $\Delta\chi^2 = 50$ still a rough general rule for uncertainty.

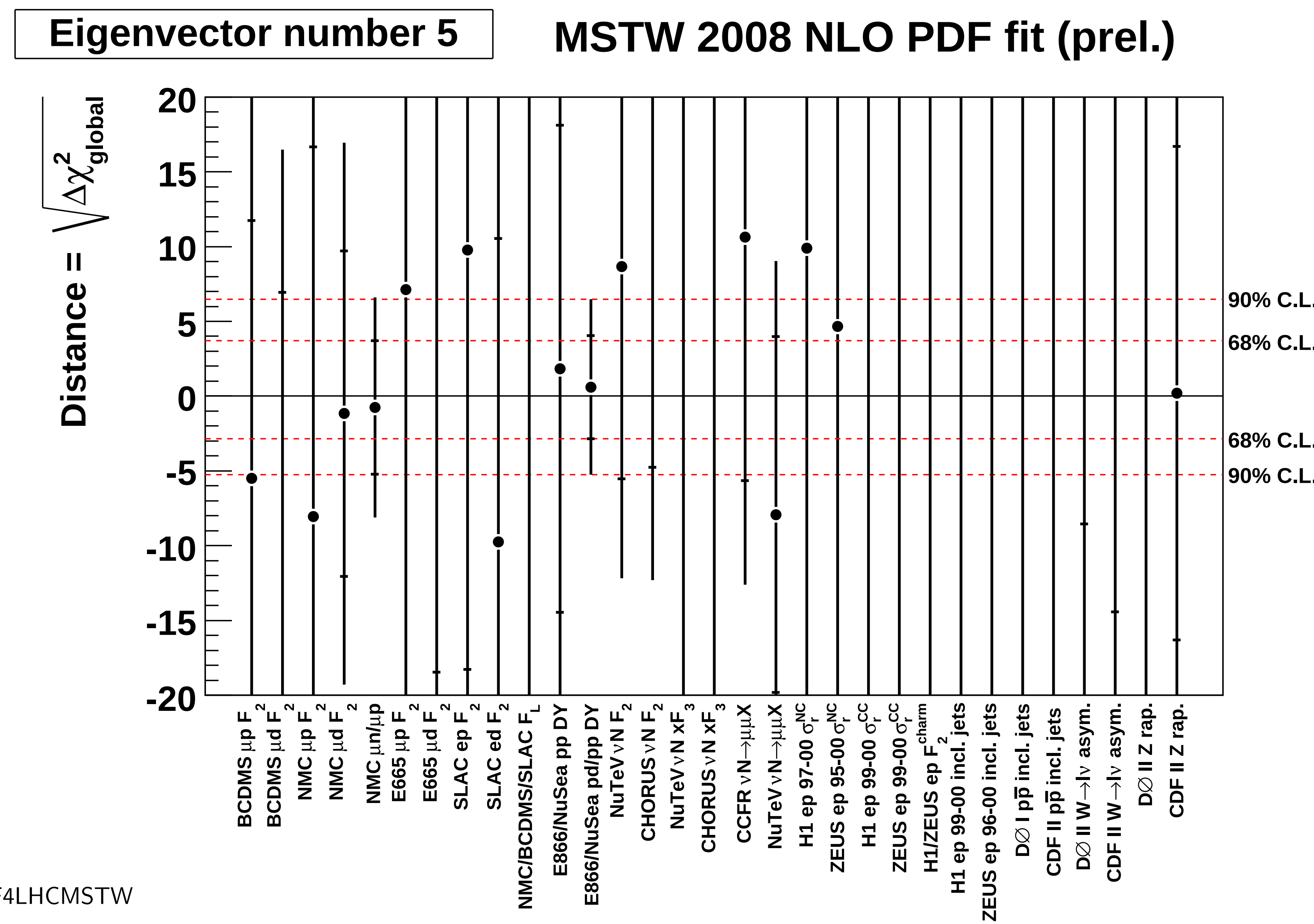
However, all parameters, or parameter eigenvectors sensitive to only some data sets, particularly those for $s^-(x, Q^2)$. Detailed examination of this sensitivity performed to improve definition of uncertainties (see later talk by Watt).

Can quickly see main features of which data sets are constraining which parameters, and how much.

H1 data on $F_2(x, Q^2)$ constrains many parameters. Mainly small-x gluon (vector 1) and high-x gluon (19). $\Delta\chi^2 = 50$ increase in some eigenvector directions takes fit to about 90% confidence limit (or beyond).



Can also look at variation in χ^2 for each data set for an eigenvector. Number 5, related to $\bar{d} - \bar{u}$ normalization constrained most by E866 Drell-Yan asymmetry but also, and consistently by NMC data on $F_2^n(x, Q^2)/F_2^p(x, Q^2)$.



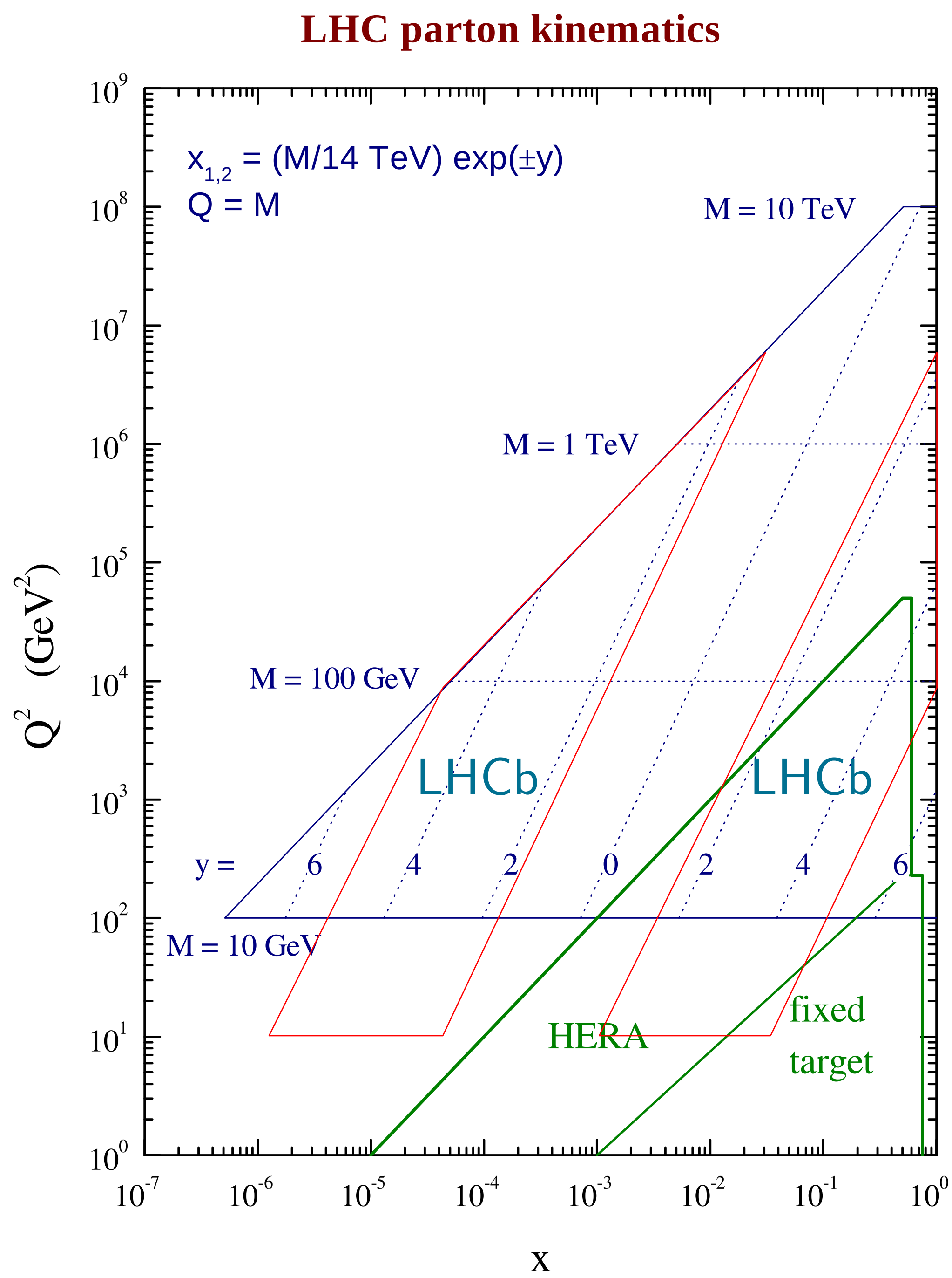
Predictions/tests at the LHC

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

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.

Already seen different predictions from different groups or prescriptions, e.g $\sigma_{tot}(W)$.



Uncertainty on all cross-sections grows at high rapidity.

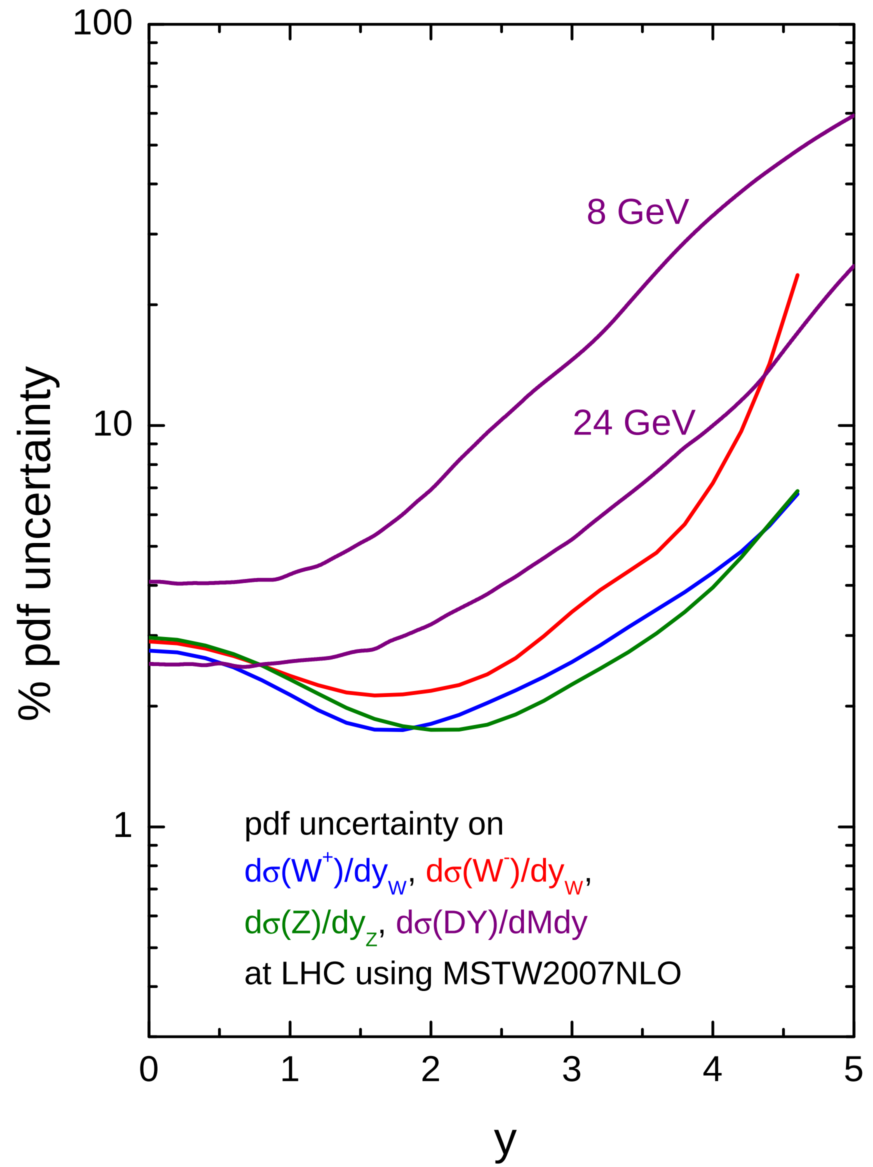
Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ converges – both dominated by $u(x_1)\bar{u}(x_2)$ at very high y.

Uncertainty on $\sigma(W^-)$ grows more quickly at very high y.

Uncertainty on $\sigma(\gamma^\star)$ is greatest as y increases.

All but low mass $\gamma^\star$ very precise at $y \leq 2$. Consistency tests for ATLAS and CMS, or added constraints with very precise data.

At $y = 0$ MRST give 0.026 ± 0.005 while CTEQ give 0.036 ± 0.004.



Potential Results from LHCb

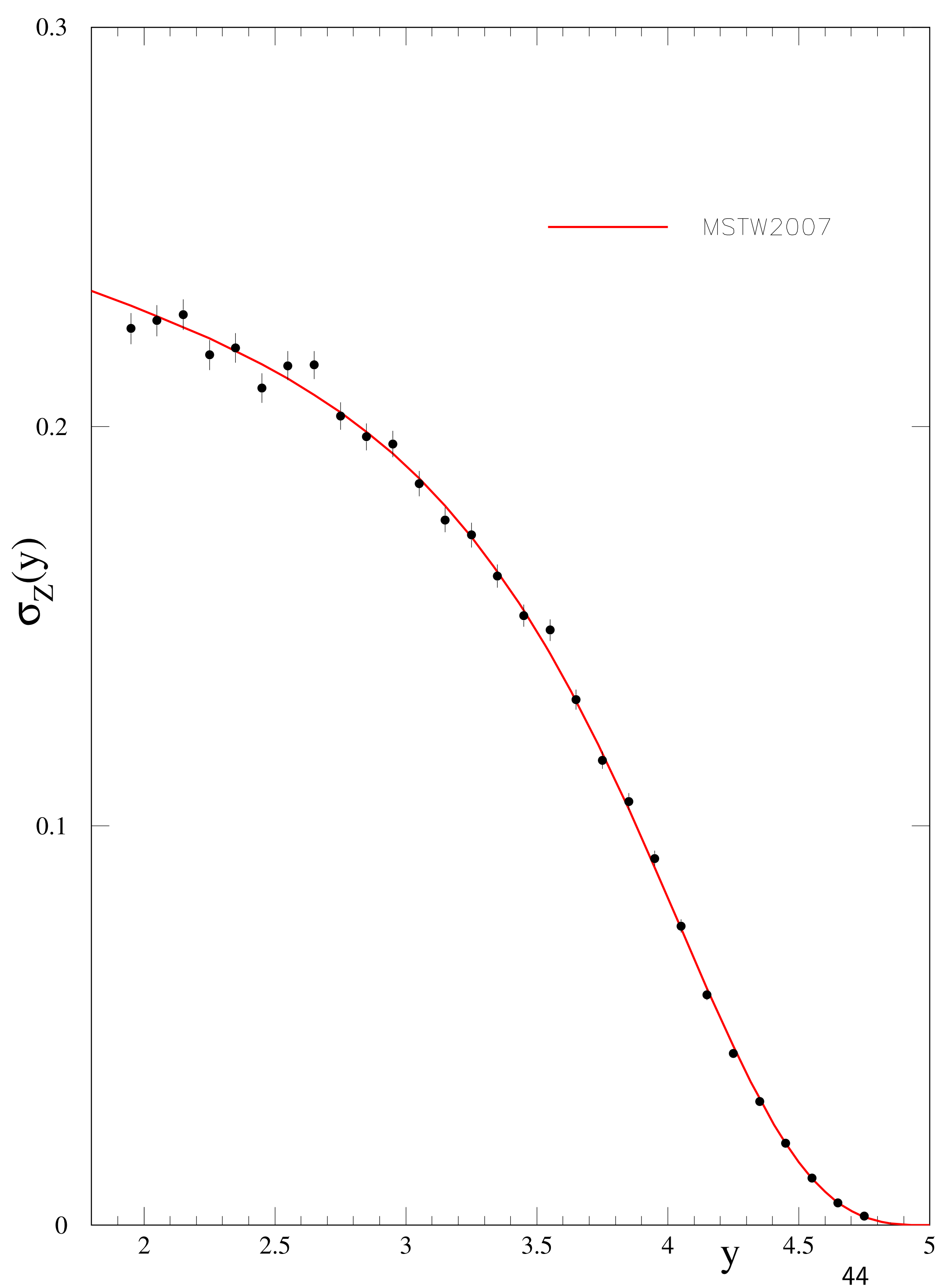
With $1 fb^{-1}$ of data LHCb expects to obtain 212100 events for $Z \to \mu^+\mu^-$ for $1.9 < y < 4.9$.

Can correspond to 30 equal rapidity bins with $\sim 1\%$ statistical error at lowest rapidity becoming higher as data falls of at high y.

Systematic uncertainties also $\sim 1\%$ with fairly high correlation.

Luminosity uncertainty similarly projected at $\sim 1\%$. Since this is a common factor less important in parton determination/QCD test since no impact on shape.

Possible data if completely consistent with current prediction shown opposite.



Main discriminating power in this type of data if result is not exactly what is expected.

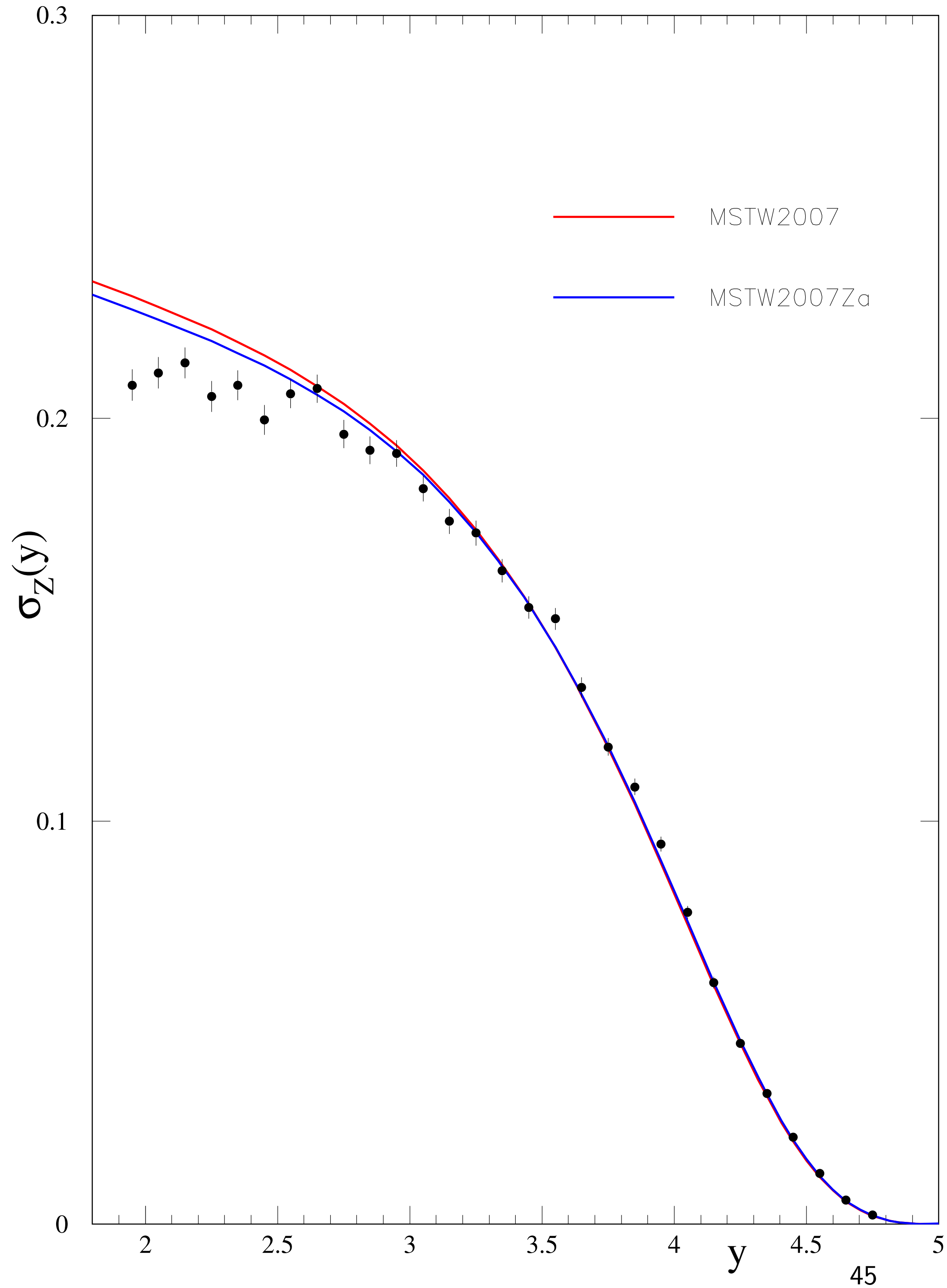
Illustrated opposite is data shifted compared to current prediction where data shifted by factor $0.05(y-3.4)$. Relatively small shift.

Comparing to prediction $\chi^2 = 153/30$.

Blue line shows result of new fit. Not possible to obtain good agreement $\chi^2 = 103/30$.

HERA data and Tevatron high-E_T jet data do not allow enough movement for good fit.

Discrepancy with theory discovered.



Also look at influence of data from LHCb on $\sigma(W^-)/\sigma(W^+)$.

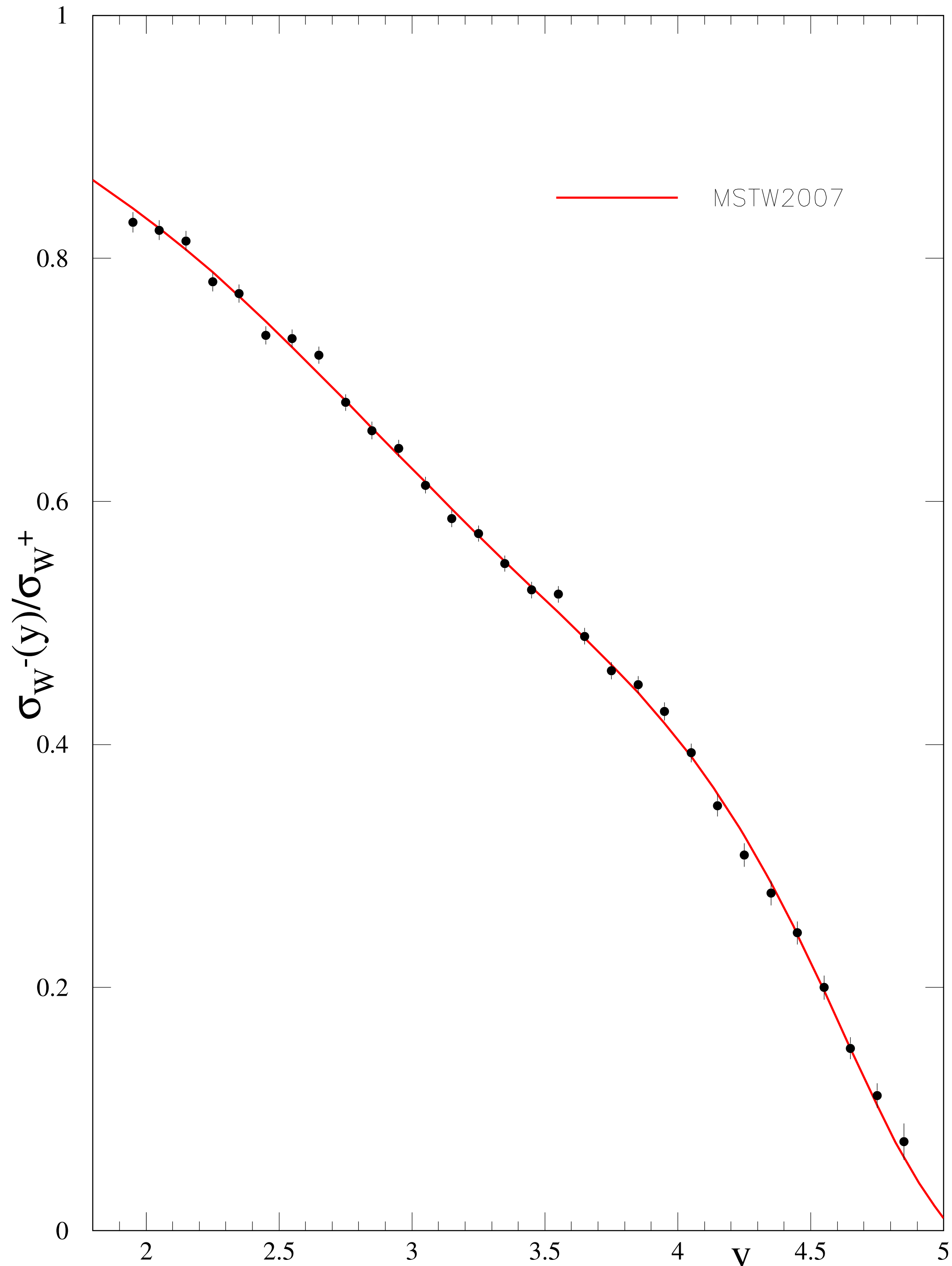
Cross-section for $W \to \mu\nu_\mu$ ten times $Z \to \mu^+\mu^-$, but more difficult and more systematics.

In particular measure lepton rapidity not W. Ignore this here. (CDF now work back to W).

Systematics also cancel in ratio.

Assume that for $1fb^{-1}$ error $\sim 1\%$ at lowest y with similar decrease to before at high y.

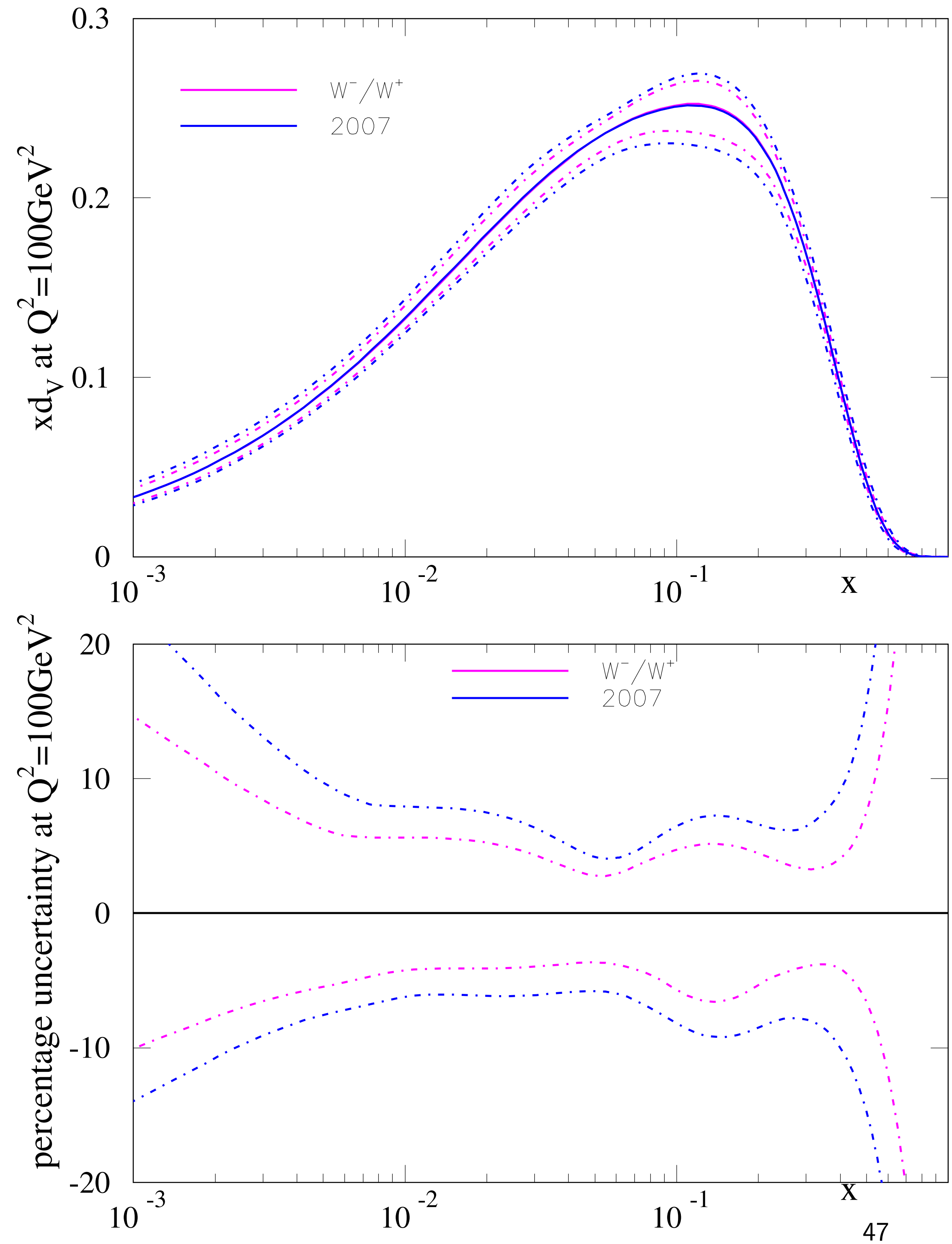
Data compared with prediction shown.



This time data most sensitive to high-x down distribution, i.e. $d_V(x, Q^2)$.

Significant reduction in this at all x (helped by sum rule).

Immediately just about main constraint on this parton.

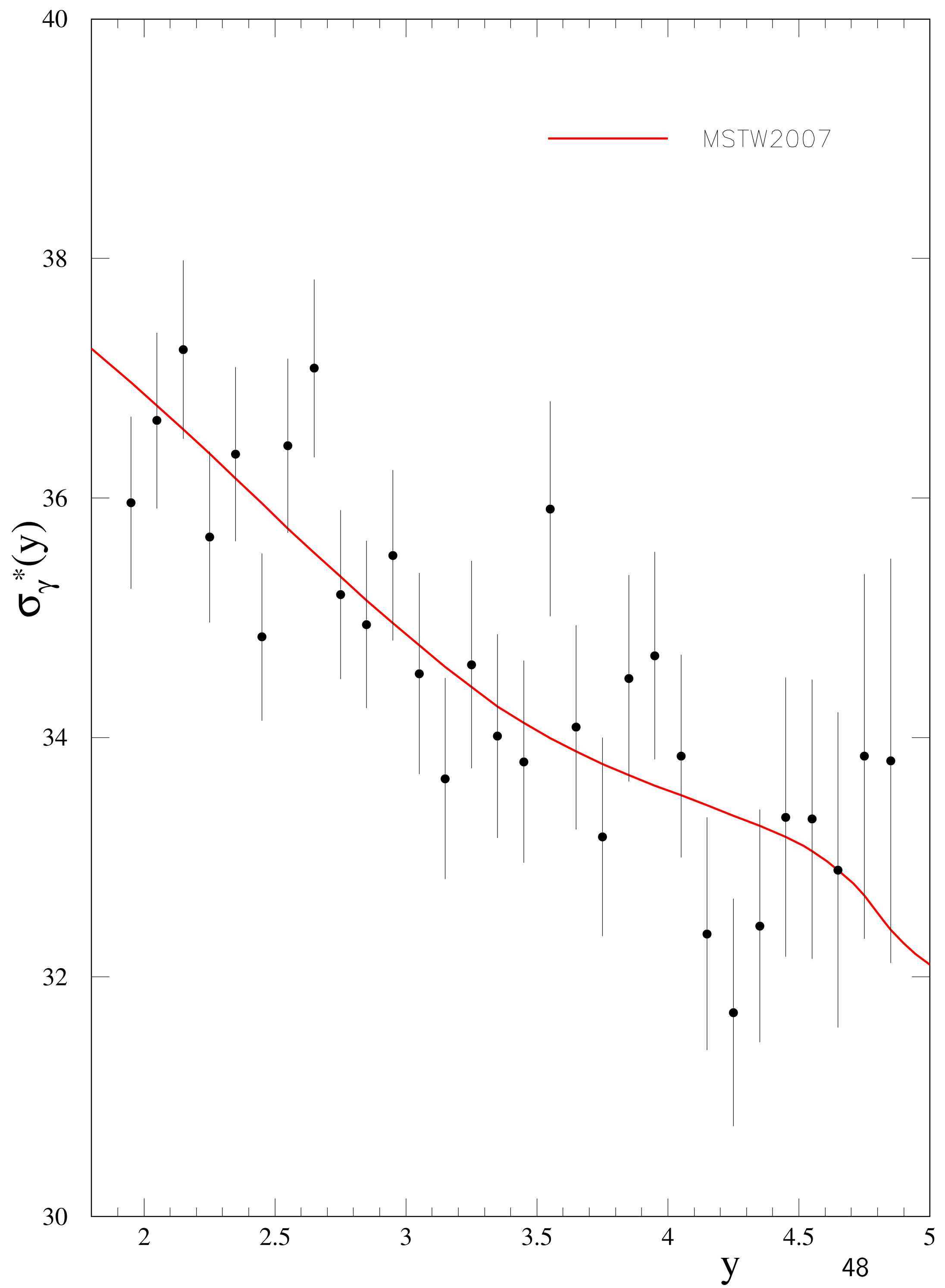


Finally look at influence of data from LHCb on $\sigma(\gamma^\star)$ for $M_{\gamma^\star} = 14\mathrm{GeV}$.

$d\sigma/dMdy$ for $\gamma^\star$ for this virtuality similar to that for $Z \rightarrow \mu^+\mu^-$, at the Z peak.

Assume that for $1fb^{-1}$ error a bit bigger than for $Z \rightarrow \mu^+\mu^-$ at lowest y but much less decrease at high y since cross-section is not falling off – not reaching valence quark fall off.

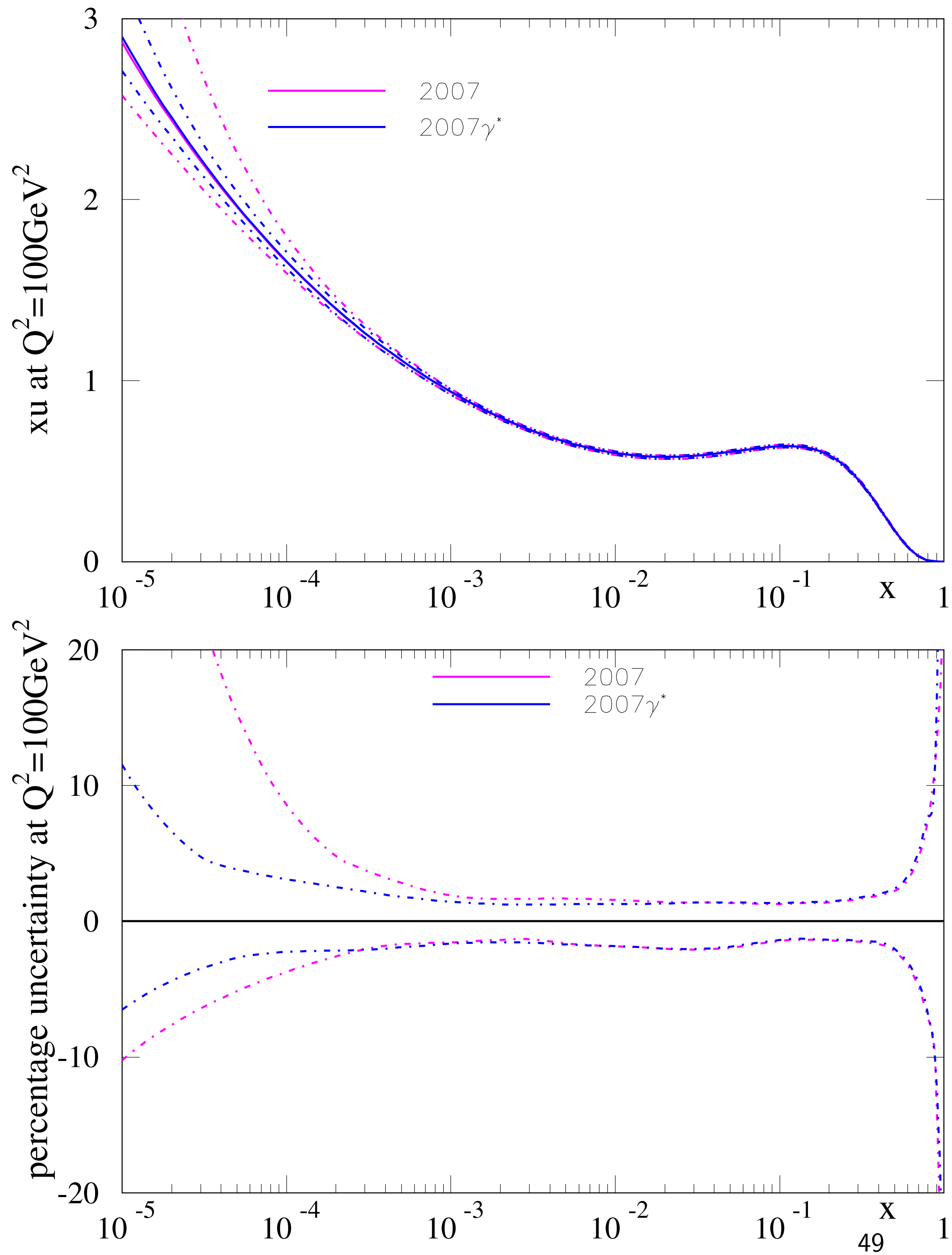
Data compared with prediction shown.



This time data most sensitive to very low-x quark distributions.

Very significant reduction in uncertainty.

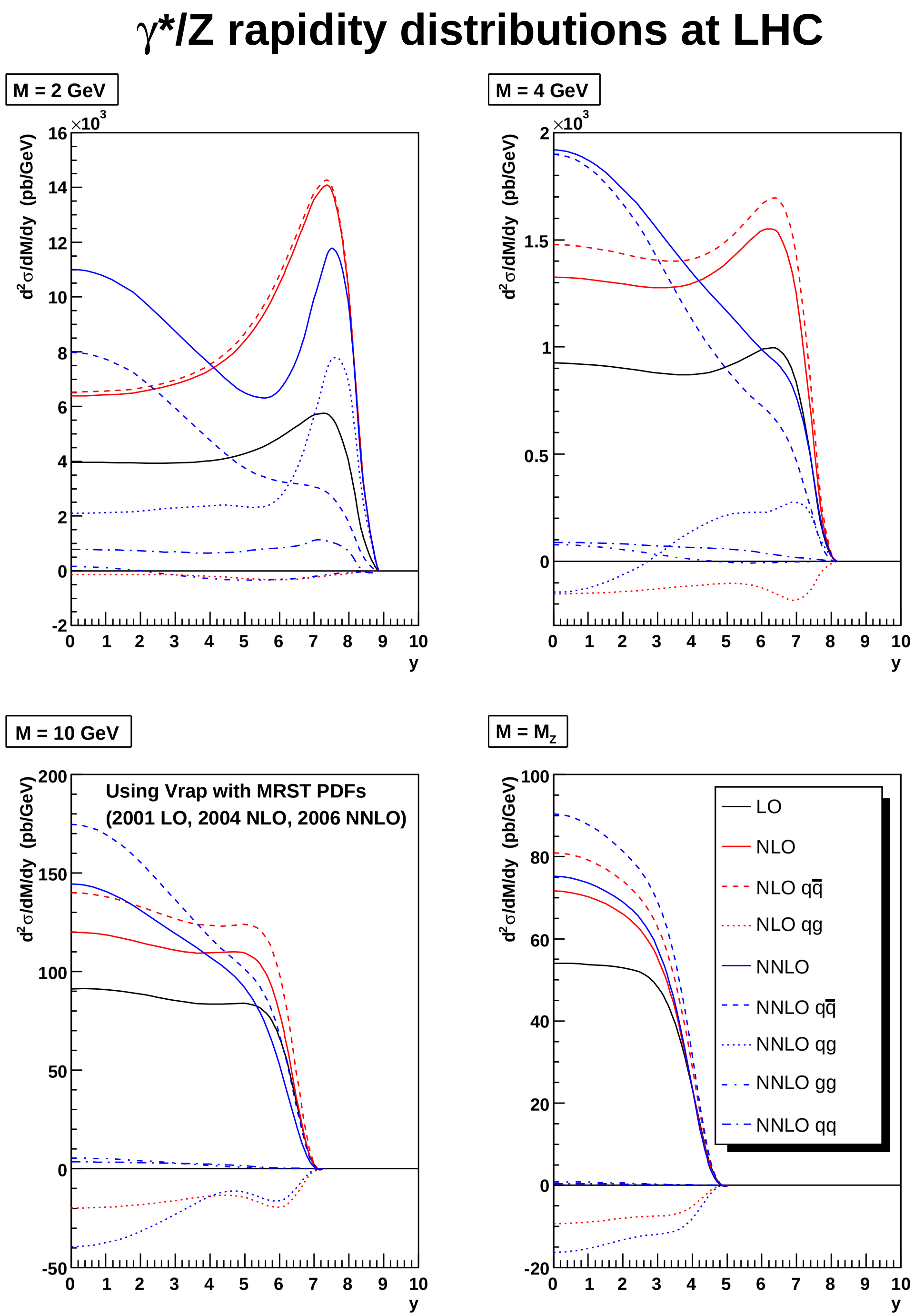
Immediately just about main constraint on quarks for $x \leq 0.0003$.



However, this assumes perturbative prediction of Drell-Yan production is reliable.

As seen very large change in prediction from order to order, particularly for low M and high y.

Problem with perturbative stability. Is this due to partons or cross-sections?



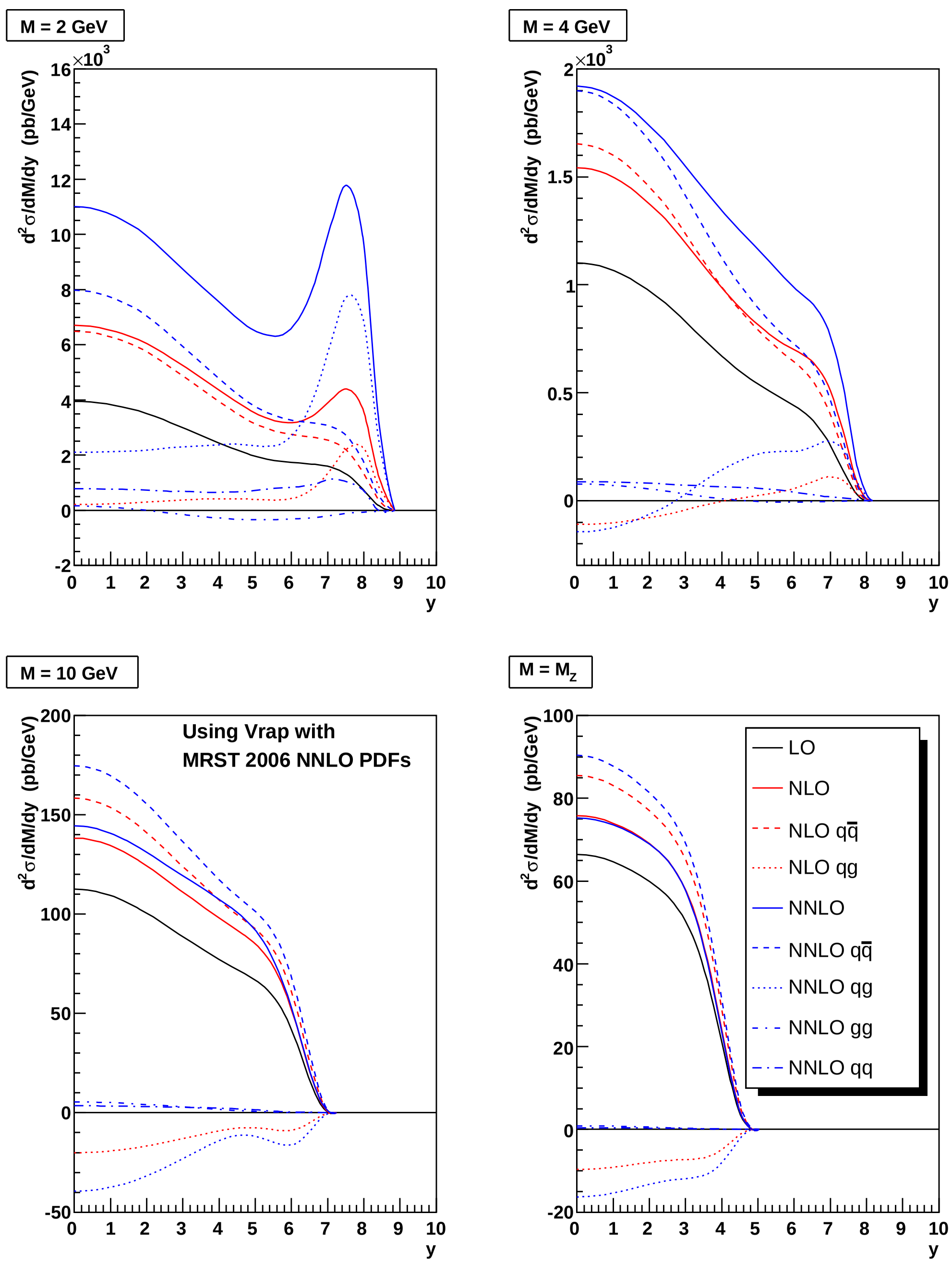
Keeping partons fixed while changing cross-sections (using MRST2006 NNLO partons) shows part of instability due to partons. Unusual behaviour in very small x partons at NNLO.

However, large change in quark-gluon (and quark-quark) contributions at NNLO due to $1/z$ divergences in cross-sections appearing at this order.

Reminiscent of behaviour of $F_L(x, Q^2)$. As in this case further $\ln(1/z)$ divergences at higher orders.

may be sensitive to resummations (amongst other things) at lowest M and highest y. In region where measurements can be made?

γ*/Z rapidity distributions at LHC



Conclusions

NNLO partons exist now. Provisional update of partons MRST06, need to input full data sets. Main difference due to better NNLO heavy flavour prescription. This is important. Change in W, Z cross-section predictions.

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.

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

HERA and Tevatron jets now fit using fastNLO. Works well and fit good. New run II CDF jet data included in fit. Slightly smaller high-x gluon $\rightarrow$ lower α_S.

Will have full updated NLO and NNLO partons for LHC complete with experimental uncertainties with weeks. Theoretical uncertainties require more work.

Looking forward to having HERA data on $F_L(x, Q^2)$ to help determine small-x dynamics and "averaged" HERA structure function data to help determine uncertainties on quarks and gluon.

Vector boson production at the LHC good constraint on parton distributions. In some cases HERA has helped pin down partons so that uncertainties of $\sim 2\%$ are possible (in principle).

Fairly central rapidity measurements at ATLAS and CMS will help verify our current partons. Asymmetries will provide info on valence quarks at smallish x.

High rapidity measurements at LHCb will constrain high-x down quarks, and test small-x extrapolations. Lower mass γ^* measurements will potentially probe quarks and gluons at lower x than even HERA – particularly in perturbative range.

However, perturbation series not that convergent for predictions at lowish scales and small x, similar to $F_L(x, Q^2)$.

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. See talk tomorrow.

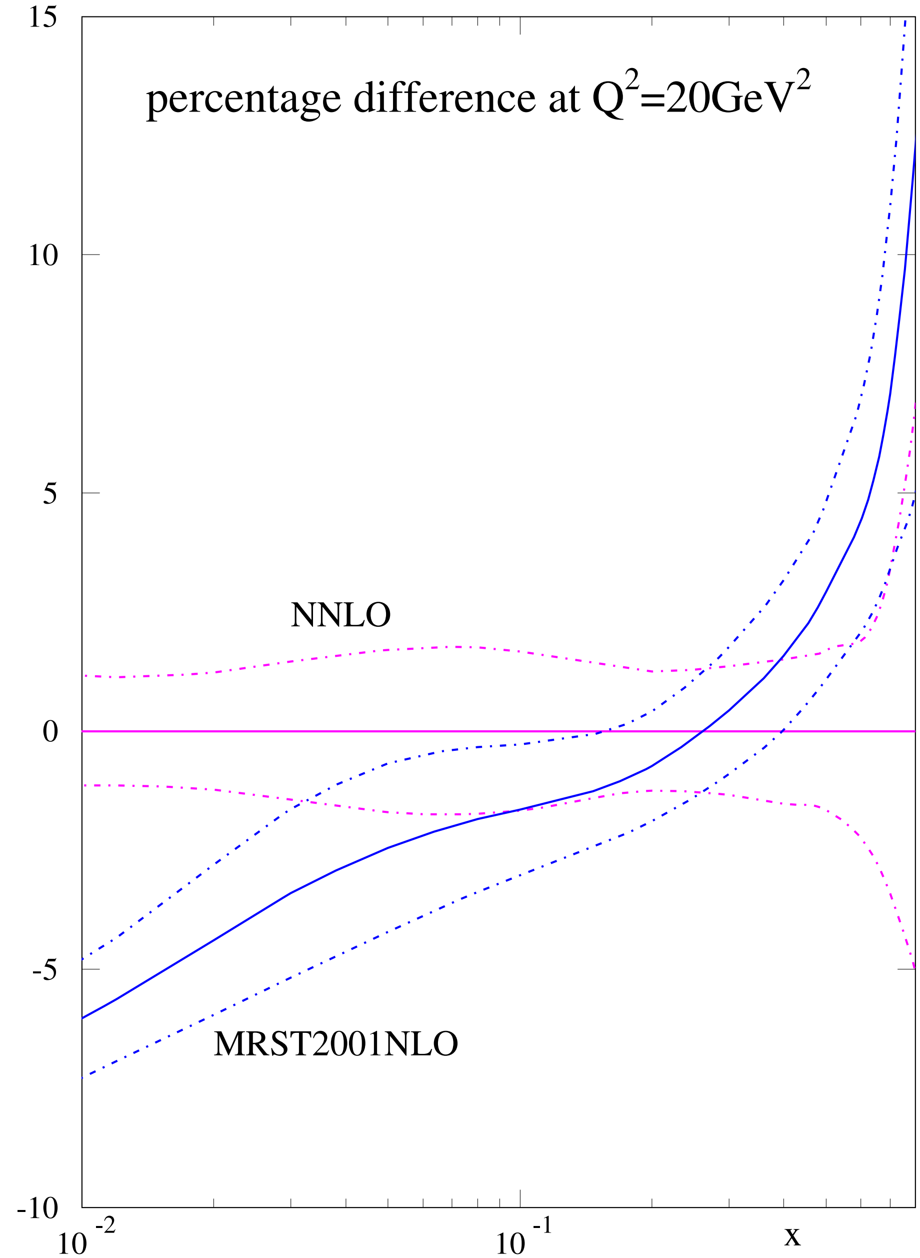
Structure of the proton incredibly well-constrained by lots of different data sets. Still lots to test/check at LHC and quite a few uncertain realms for predictions. Plenty of scope for surprises.

At large x coefficient functions important again,

$$C_{2,q}^{(2)}(x) \sim \left(\frac{\ln^3(1-x)}{1-x}\right)_+$$

Change from NLO to NNLO again larger than uncertainty in each.

No real change from MRST2004NNLO partons.

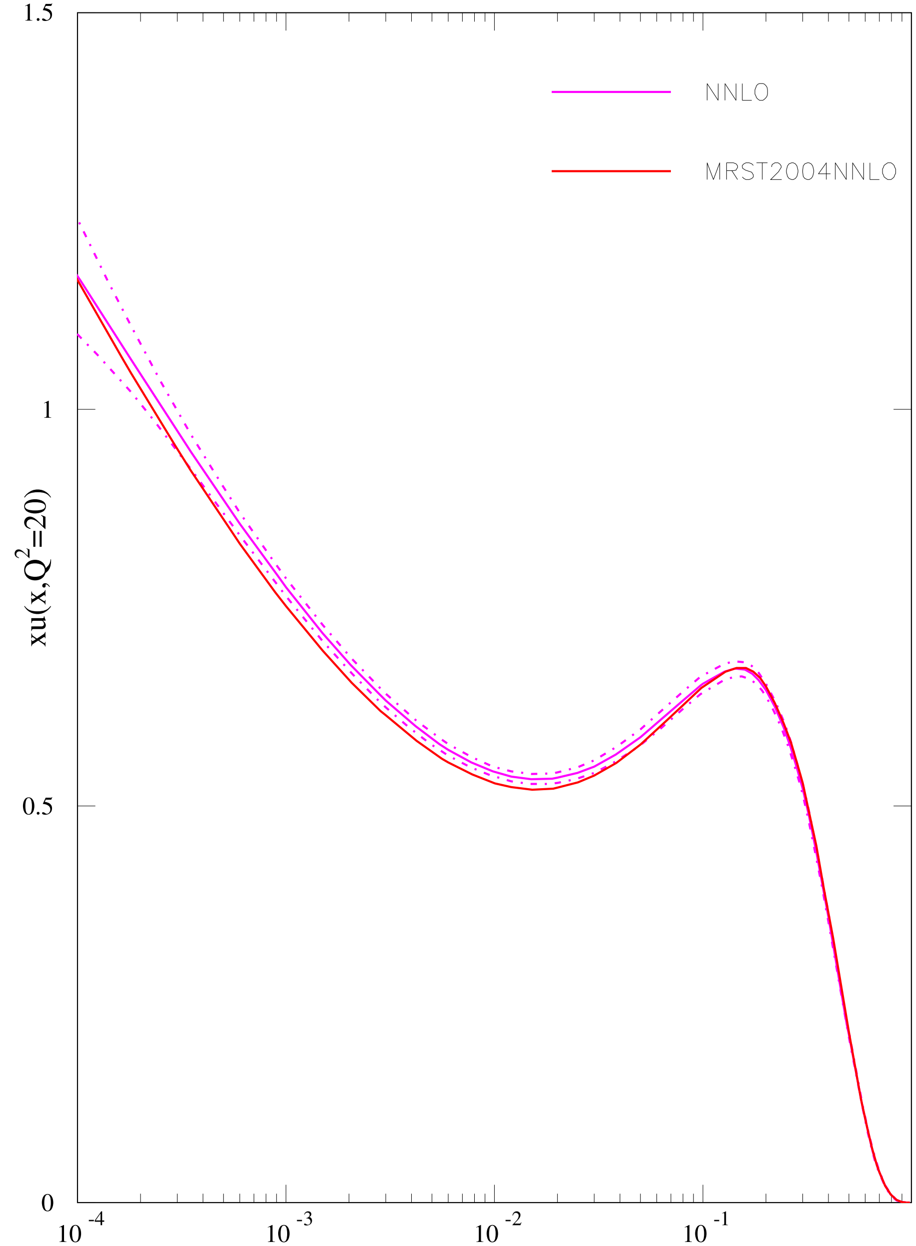


Not much change in light quarks due to these to theoretical updates.

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 $u(x, Q^2)$.

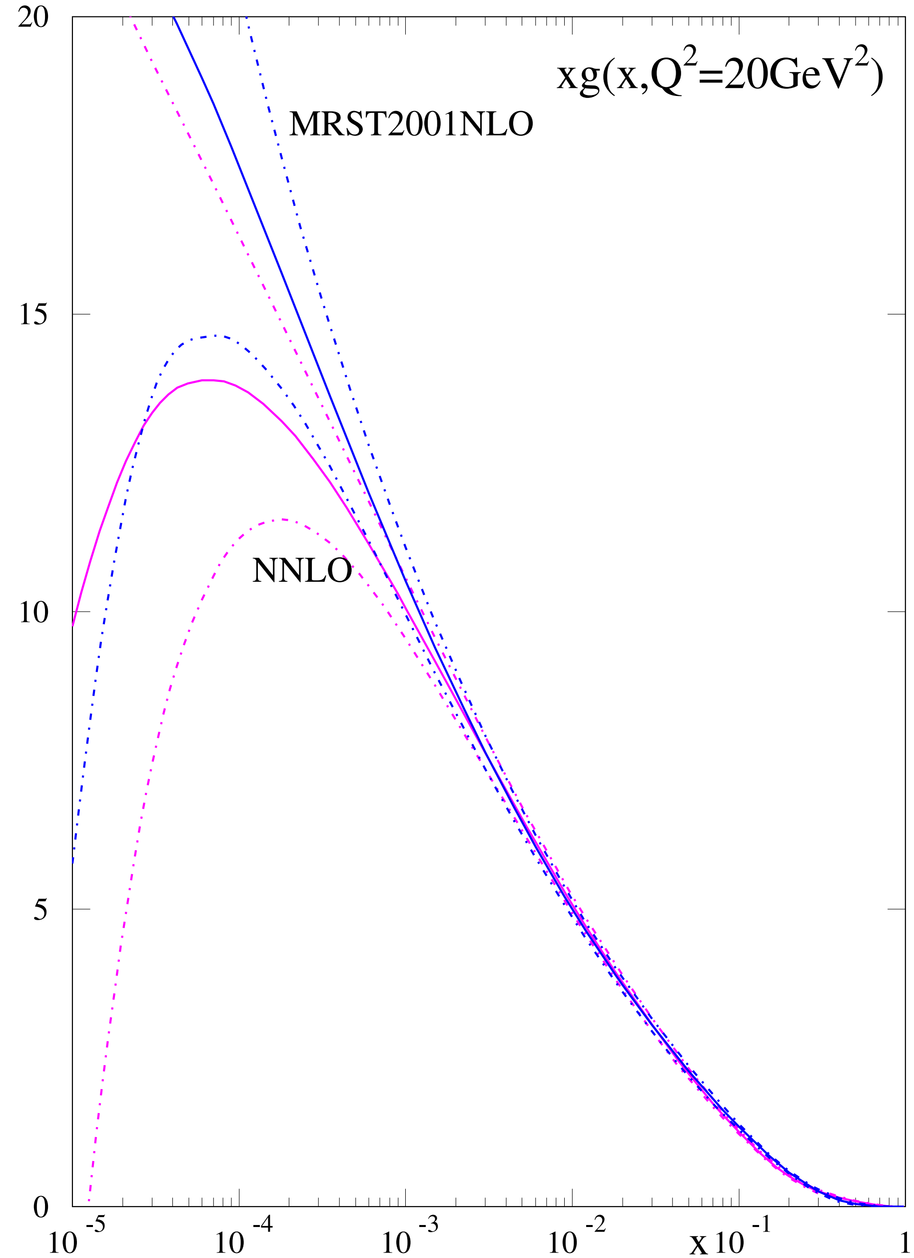


At small x effect of splitting functions particularly $P_{qg}^{(2)}(x,Q^2)$ important.

Positive $\ln(1/x)/x$ contribution at low x.

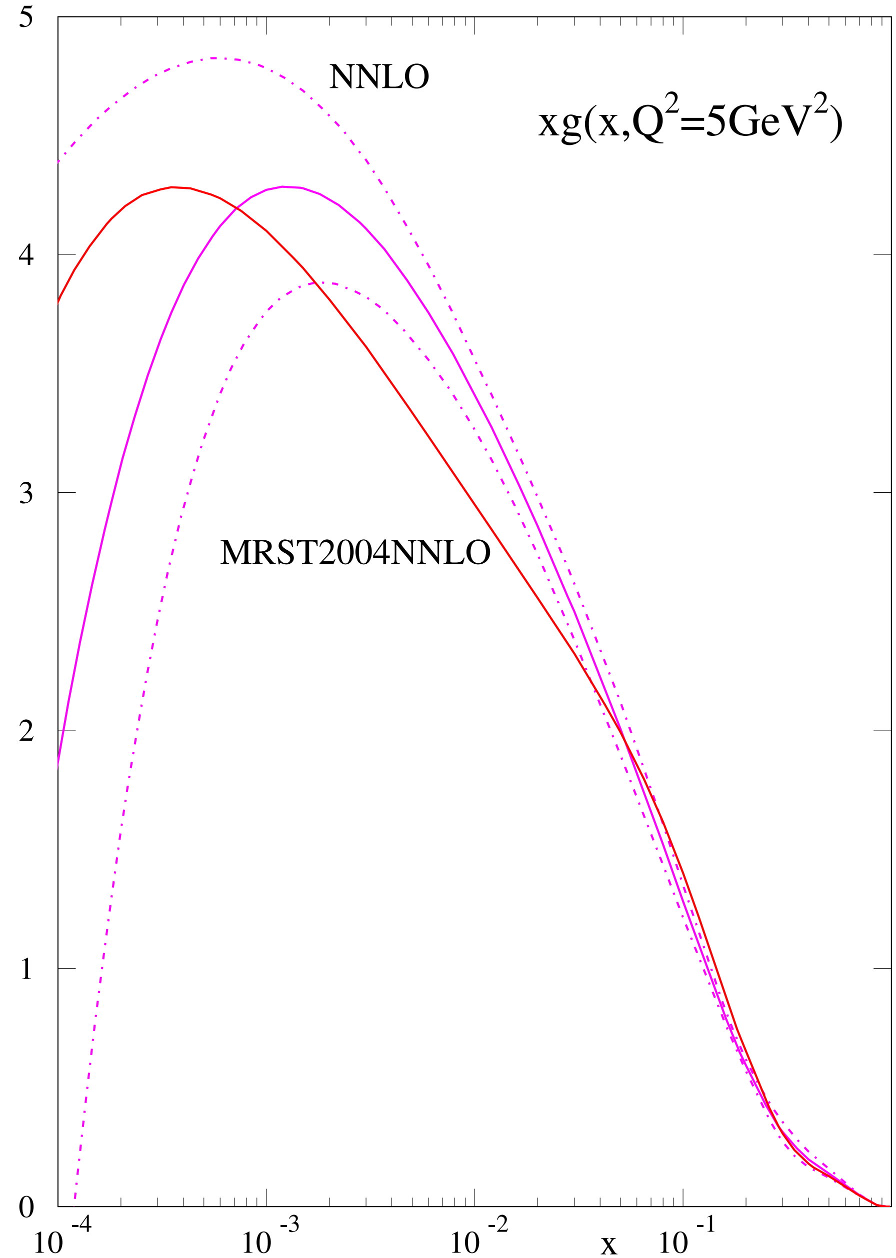
Affects gluon by fitting $dF_2(x,Q^2)/d\ln Q^2$.

Smaller at very low x.



Difference in charm procedure affects gluon compared to approx MRST2004 NNLO fit.

Far more of a turnover at small x.



Comparison to other (Alekhin) NNLO gluon.

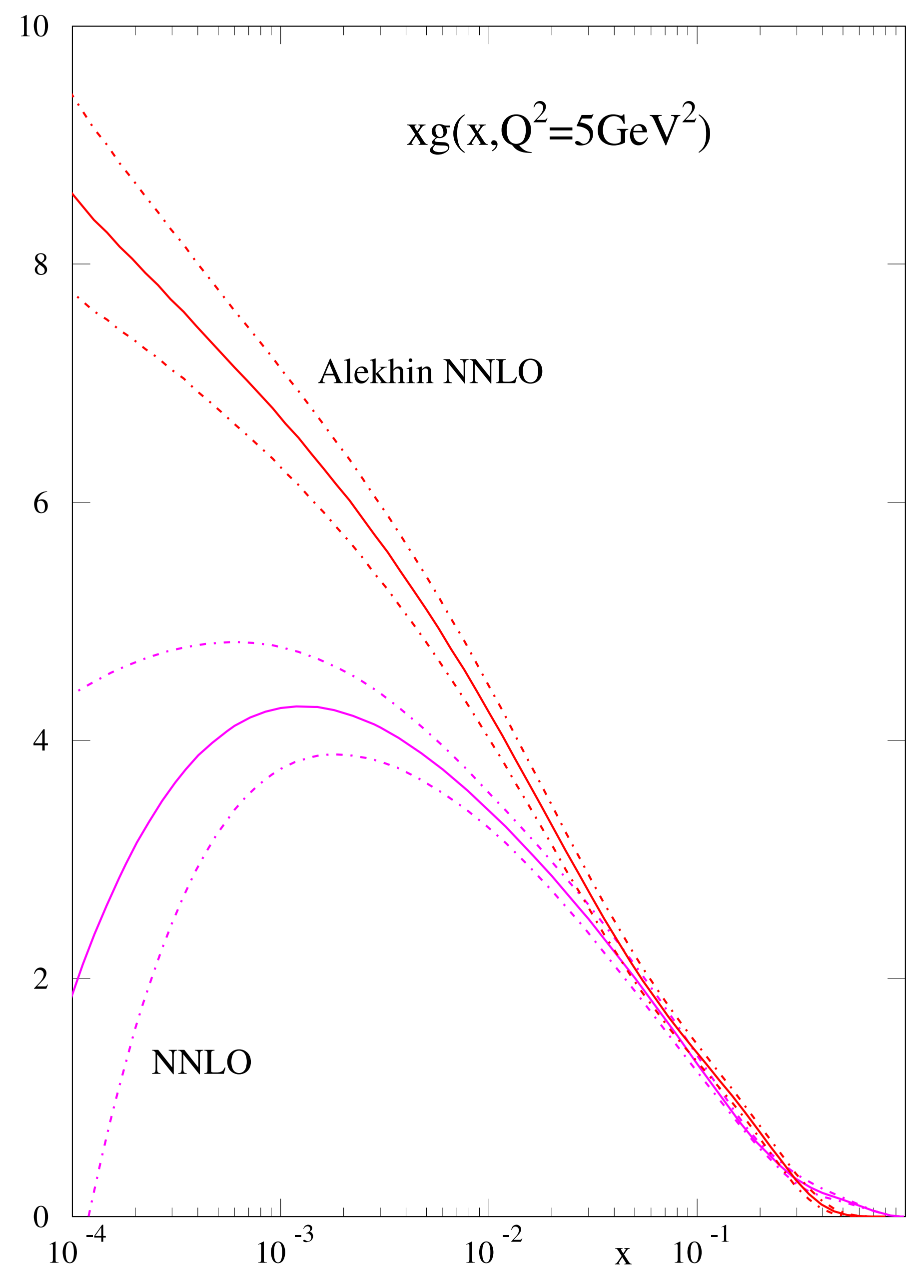
Hugely different at small x.

Differences much bigger than uncertainties.

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

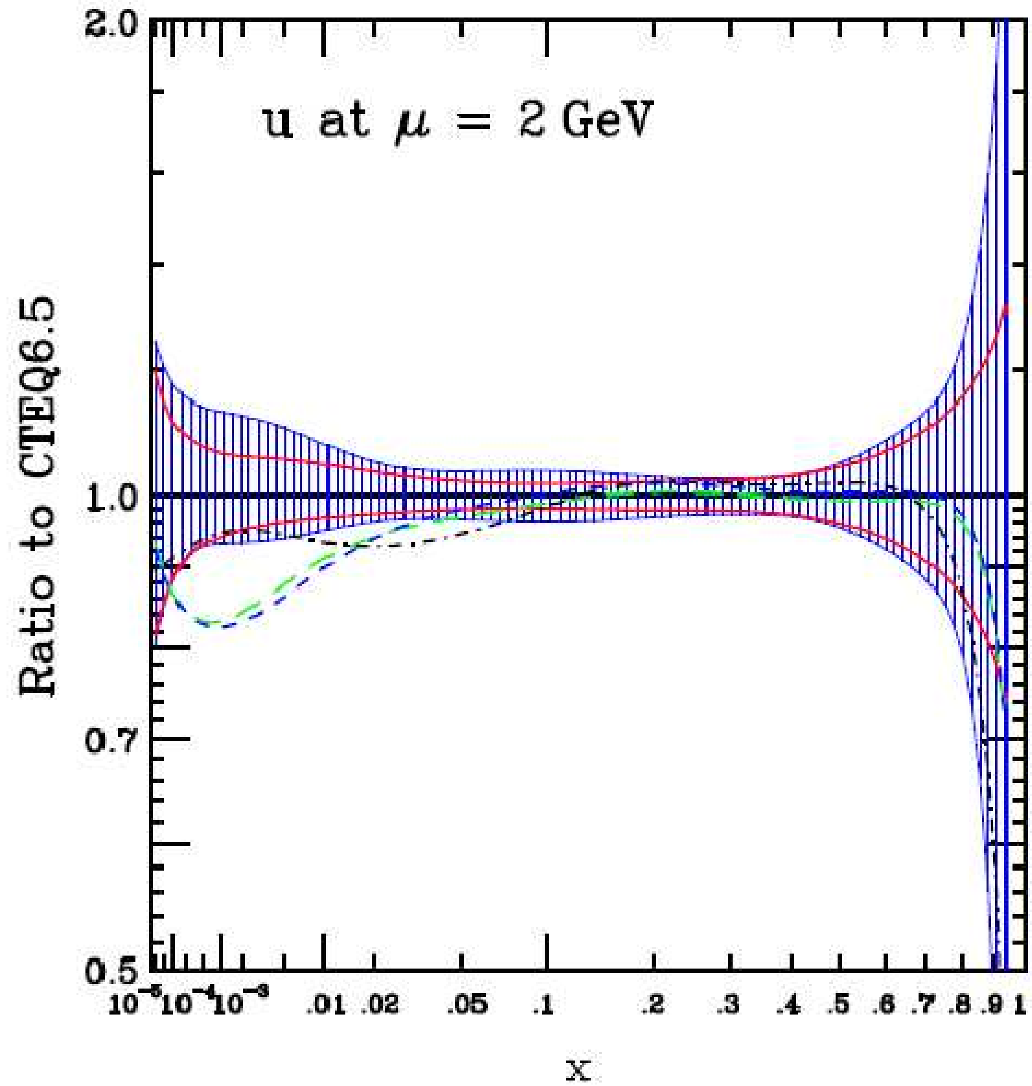
Differences in data fit and also in $\alpha_S(M_Z^2)$ ($\alpha_S(M_Z^2) = 0.114$).

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

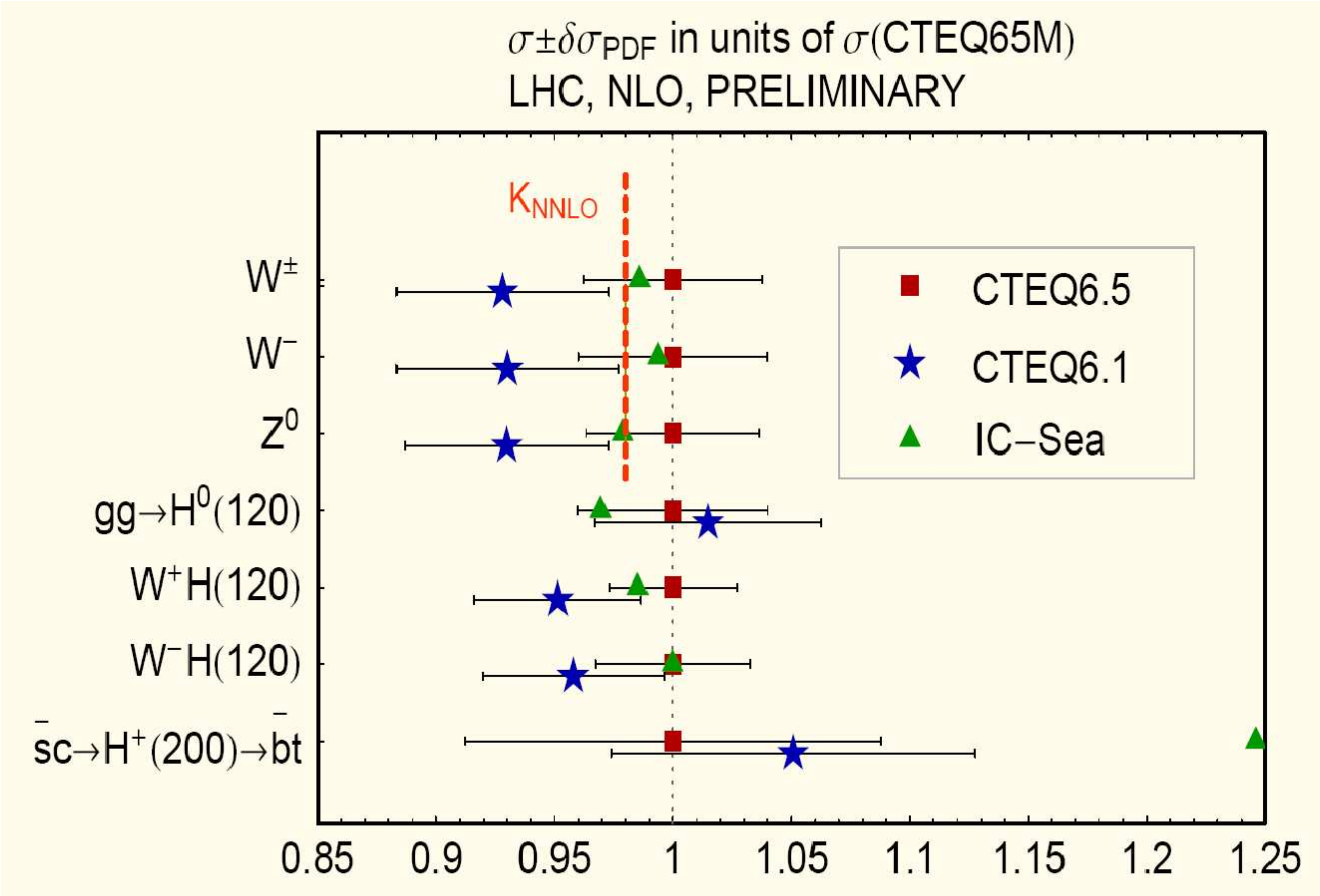


Importance of treating heavy flavour correctly illustrated by CTEQ6.5 up quark with uncertainties compared with previous versions, e.g. CTEQ6 in green.

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



Leads to large change in predictions using CTEQ partons at LHC



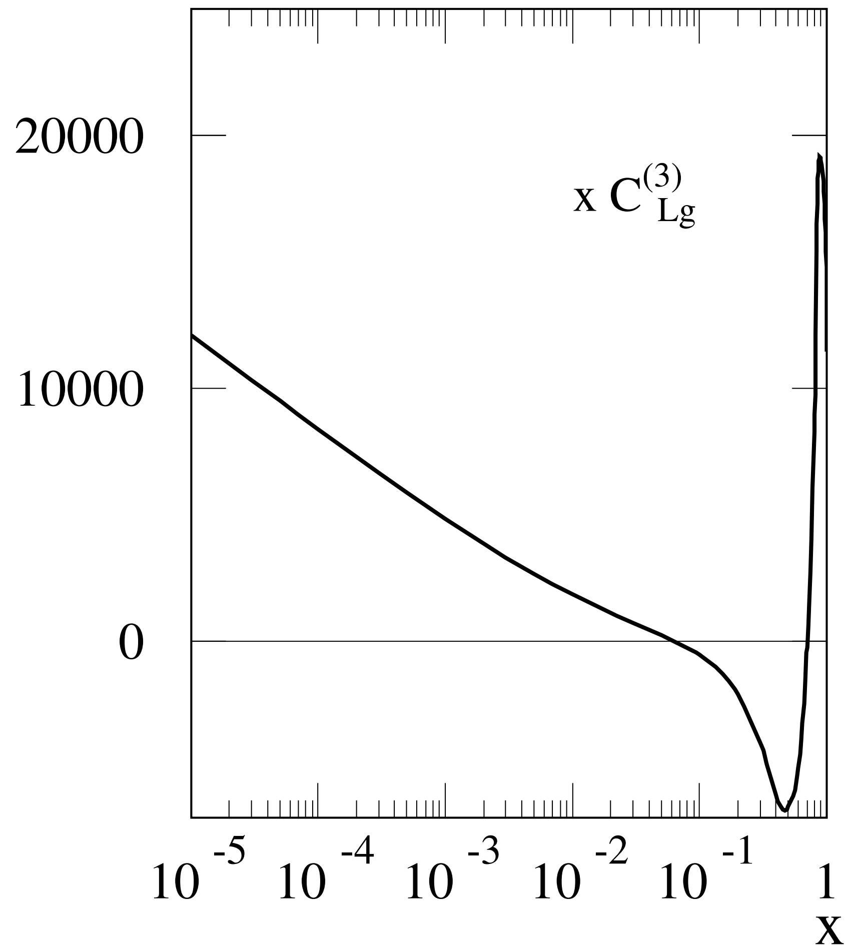
Some disagreements with MRST partons due to different gluon distributions.

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

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

Clearly a significant positive contribution at small x.

Counters decrease in small-x 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.

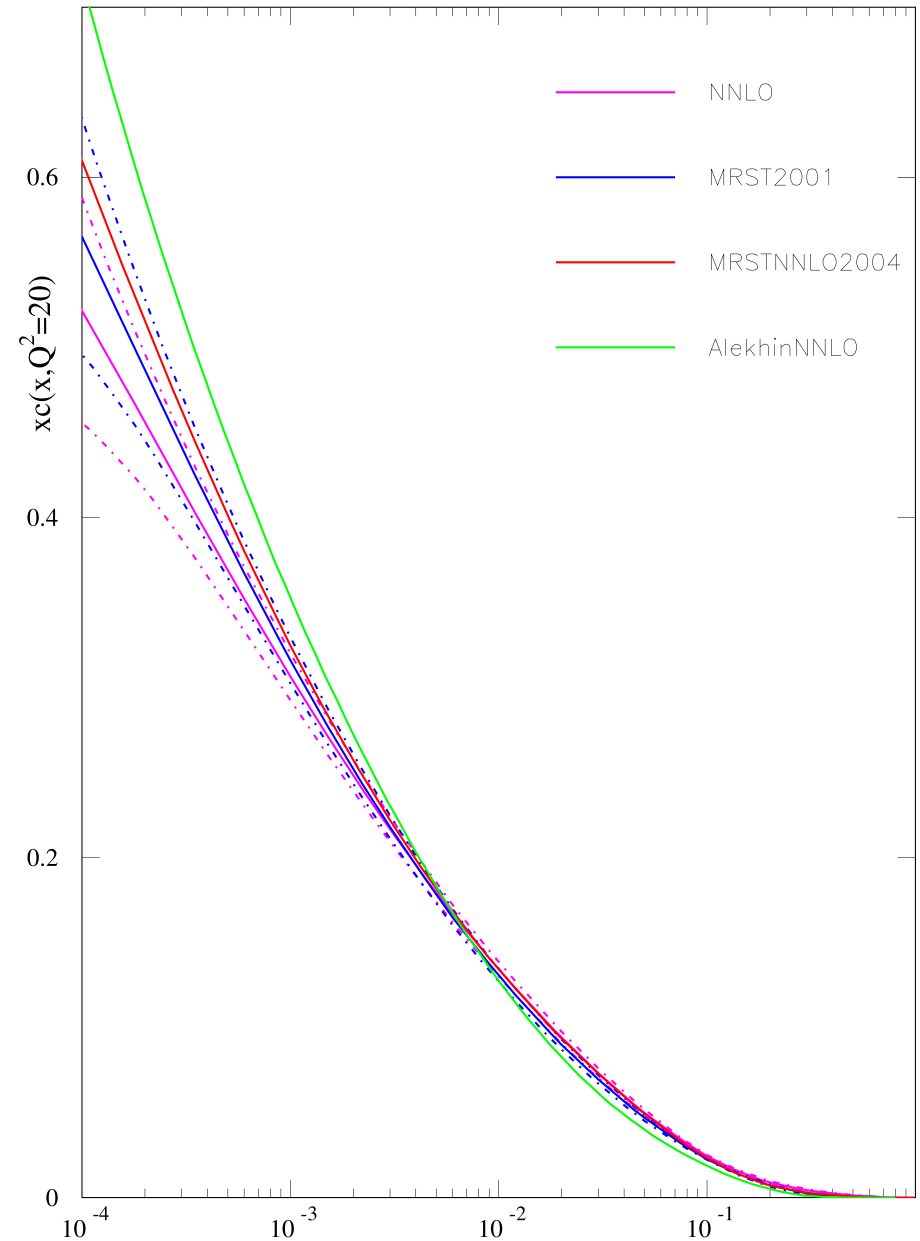
Differences in low-x sea quarks. Swamped by differences in flavour treatments – $\bar{u} - \bar{d}$ and $s(x, Q^2)$.

Main difference in gluon distribution.

Difference in gluon feeds through to charm.

Alekhin2002 much bigger at small x.

Starts from zero as with MRST2004NNLO.

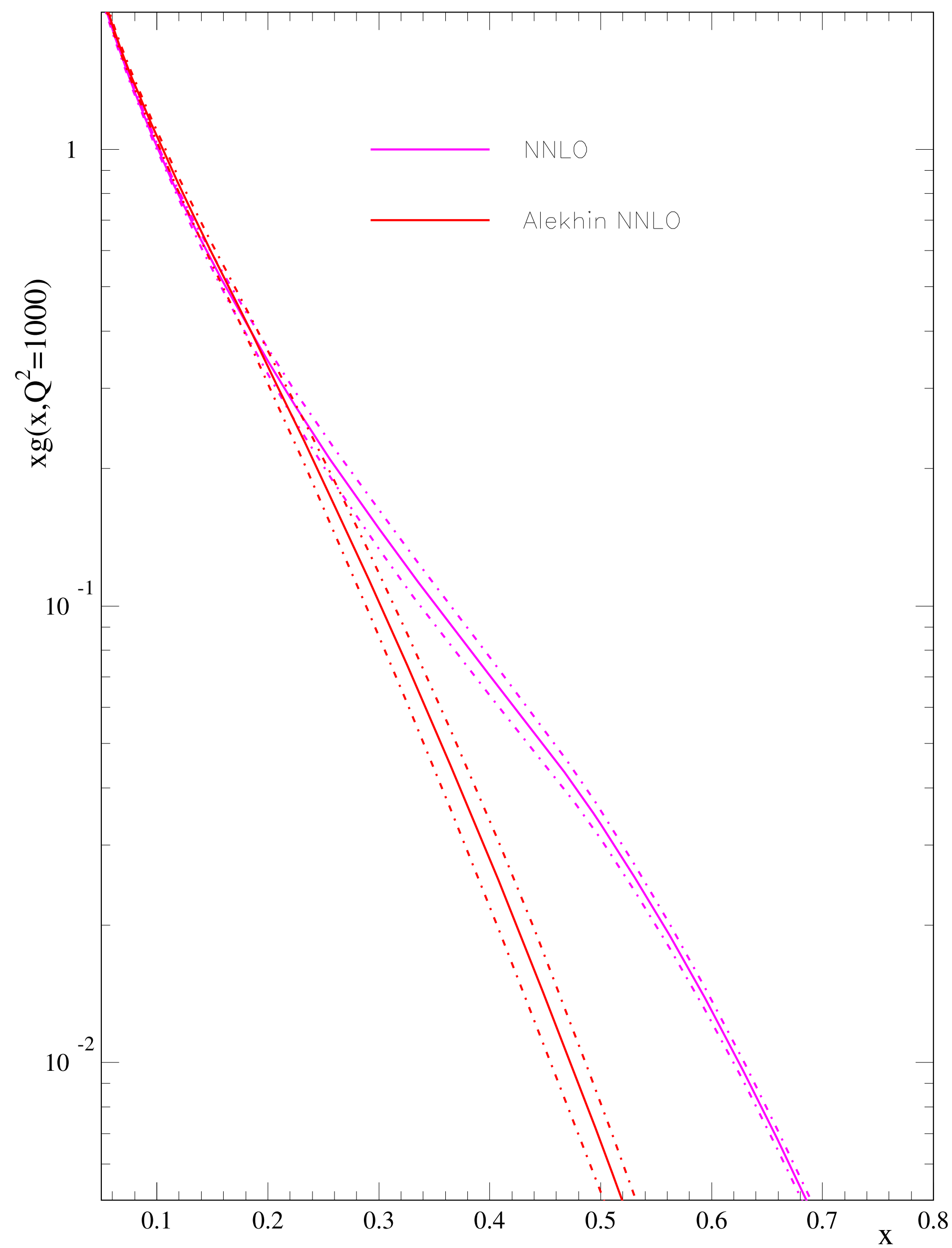


Big difference at high x and Q^2.

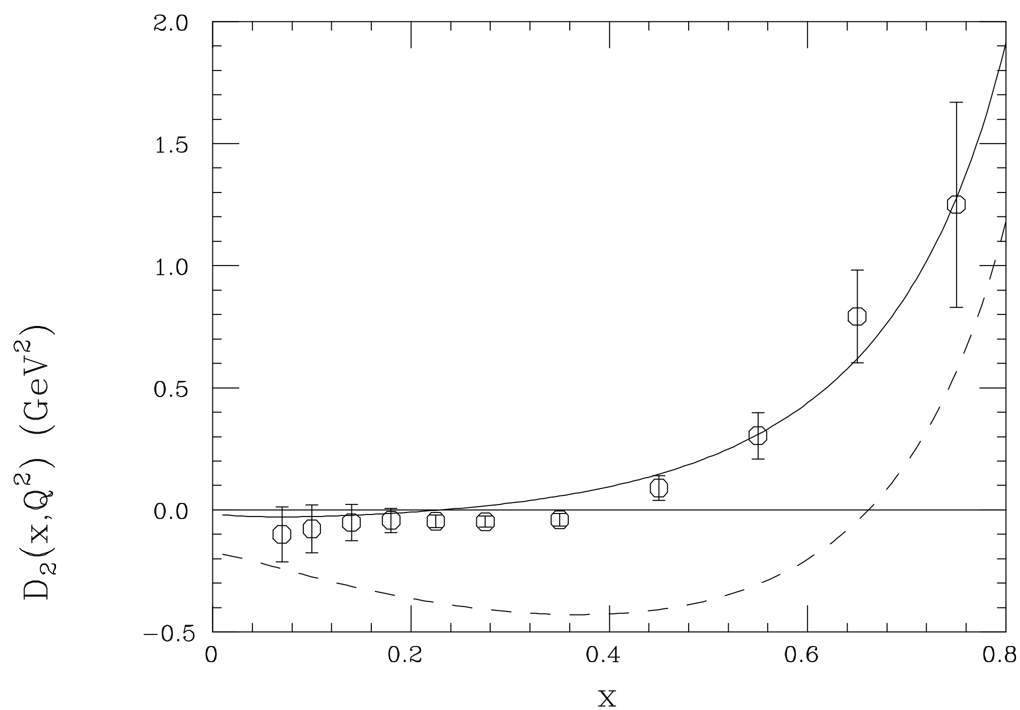
Determined by Tevatron jet data for MRST. Fit now excellent.

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.



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.



Most recent Updates

Change in definition of α_S. At NLO satisfies equation

$$\frac{\partial \alpha_S}{\partial \ln Q^2} = -\frac{\beta_0}{4\pi}\alpha_S^2 - \frac{\beta_1}{(4\pi)^2}\alpha_S^3,$$

where $\beta_0 = 11 - 2/3N_f$ and $\beta_1 = 102 - 38/3N_f$.

Solve equation exactly. However, heavy flavour thresholds still allow for ambiguity. Previously MRST solved defining Λ_{QCD} via

$$\ln(Q^2/\Lambda_{QCD}^2) = \frac{4\pi}{\beta_0\alpha_S} - \frac{\beta_1}{\beta_0^2}\ln\left[\frac{4\pi}{\beta_0\alpha_S} + \frac{\beta_1}{\beta_0^2}\right].$$

where Λ_{QCD} defined by case where $N_f = 4$. Extrapolate outside this range using

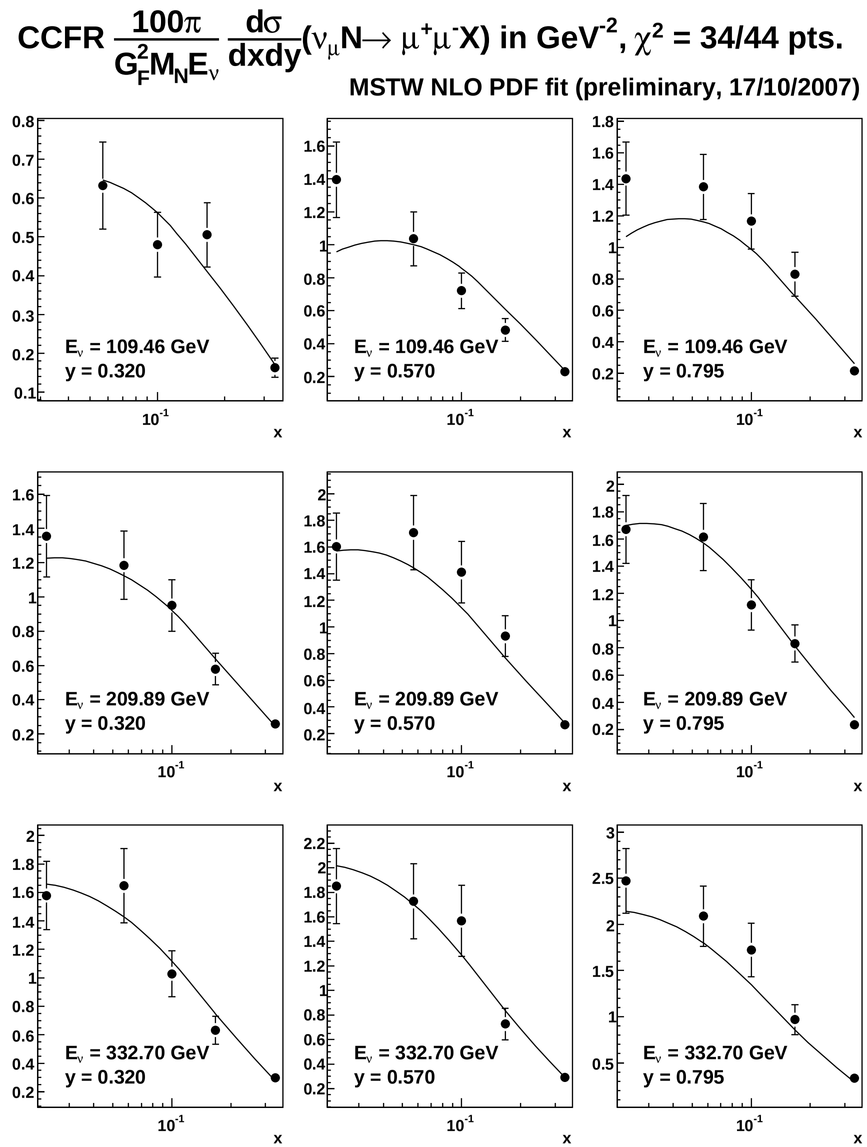
$$\frac{1}{\alpha_{S,5}(Q^2)} = \frac{1}{\alpha_{S,4}(Q^2,5)} + \frac{1}{\alpha_{S,4}(m_b^2,4)} - \frac{1}{\alpha_{S,4}(m_b^2,5)}.$$

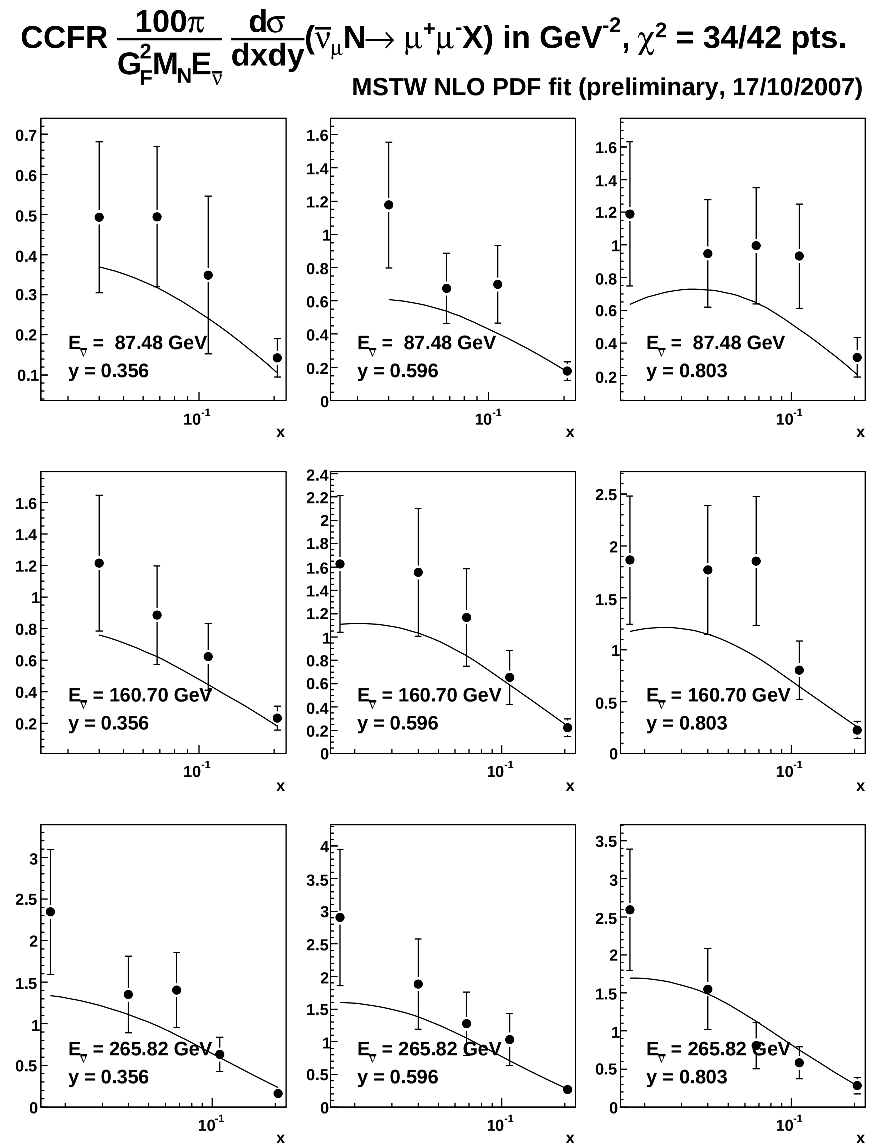
QCDNUM definition solves evolution equation using $\alpha_S(M_Z^2)$ as boundary condition and changes N_f in equations at thresholds. Now adopt this definition.

Equivalent to higher orders but can differ by $\sim 1\%$.

Old MRST prescription not very wieldy for NNLO. Small errors (could be corrected) similar to size of ambiguity.

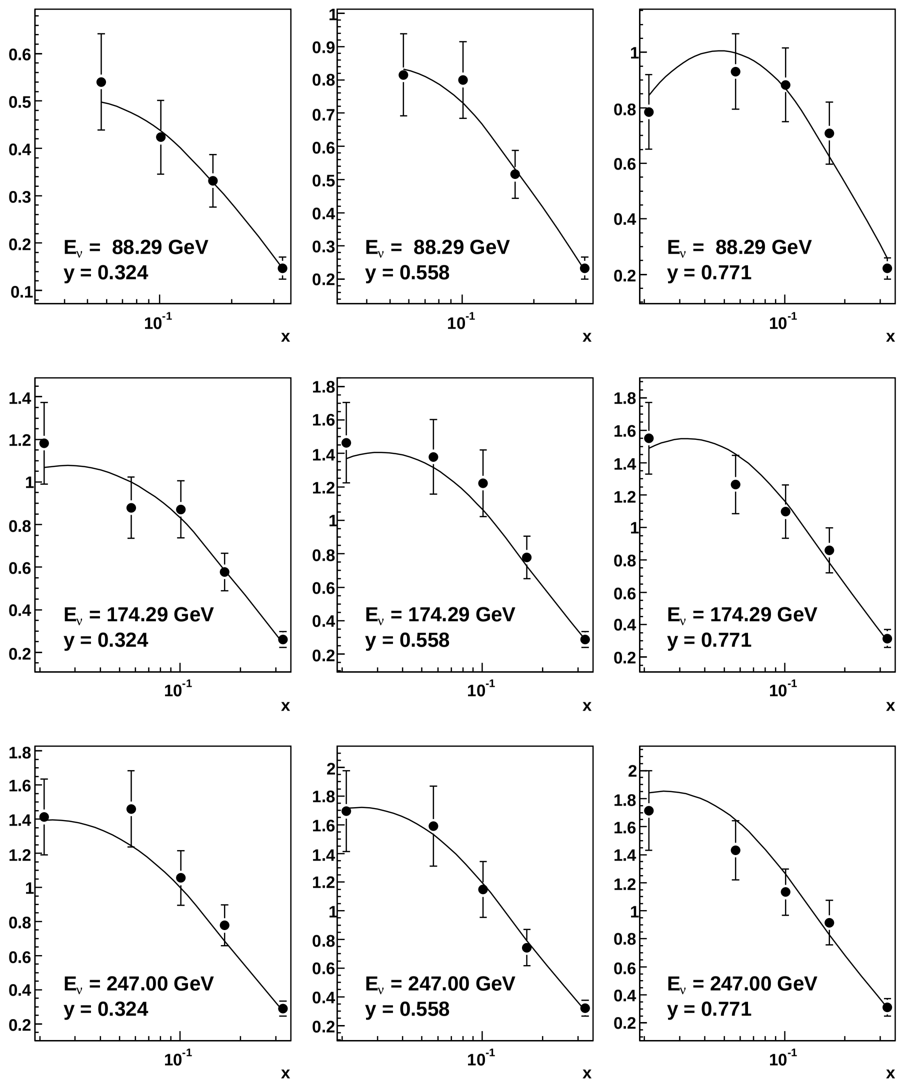
Fit to data clearly very good.





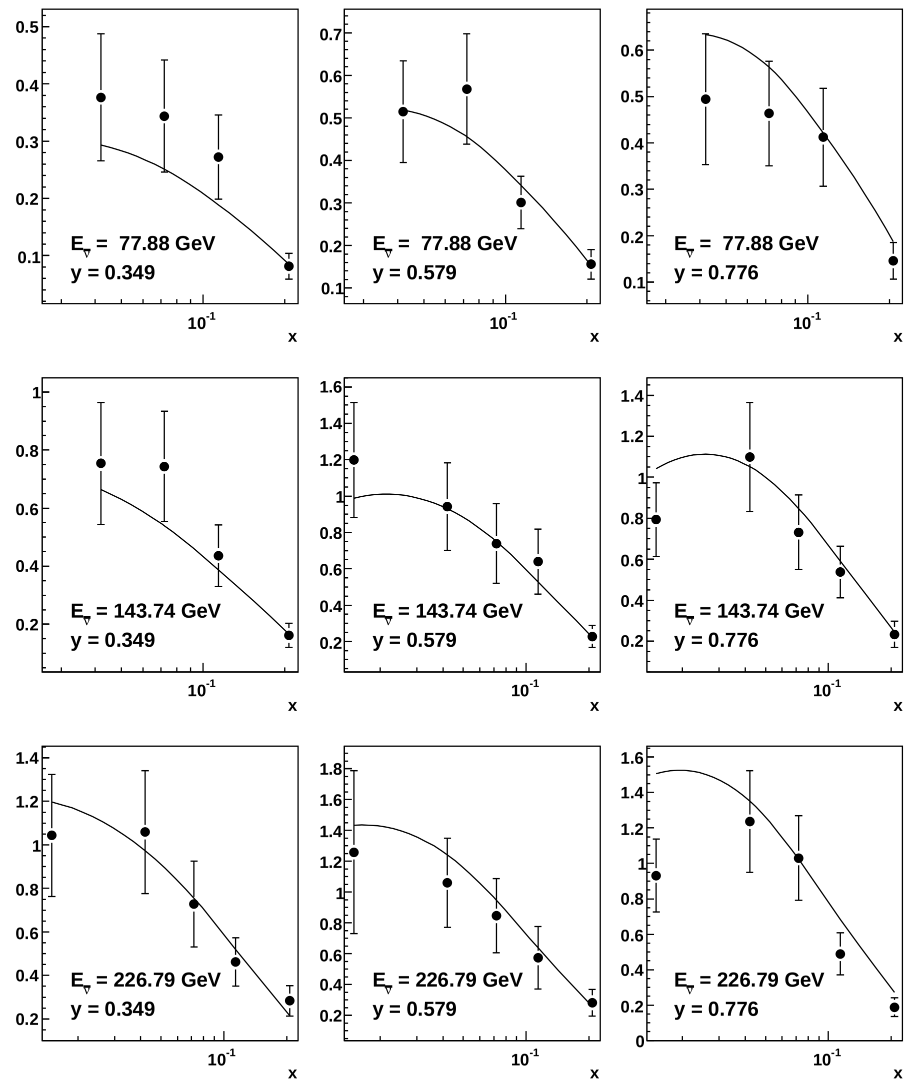
NuTeV $\frac{100\pi}{G_F^2 M_N E_\nu} \frac{d\sigma}{dxdy}(\nu_\mu N \rightarrow \mu^+\mu^- X)$ in GeV^{-2}, χ^2 = 11/21 DOF

MSTW NLO PDF fit (preliminary, 17/10/2007)



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 = 28/19 DOF

MSTW NLO PDF fit (preliminary, 17/10/2007)

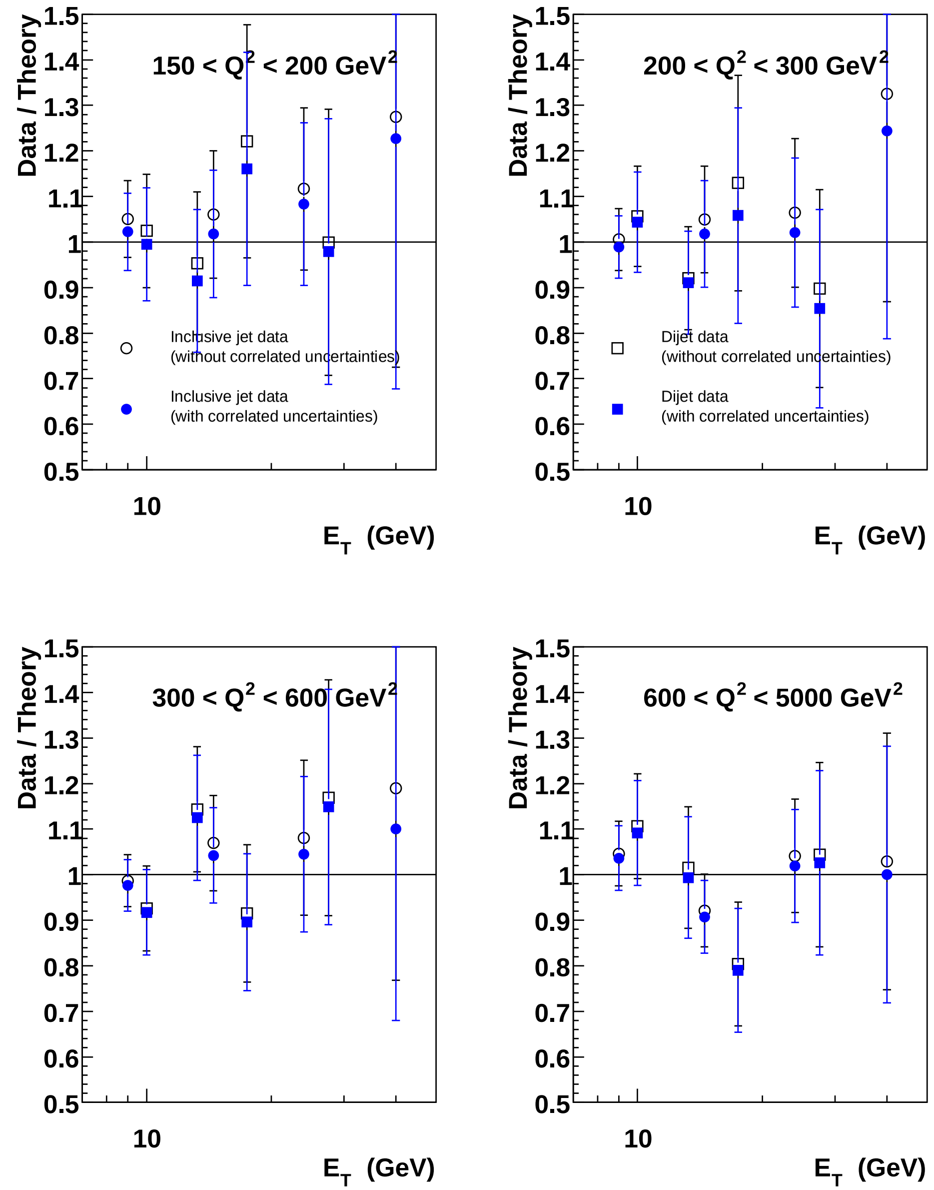


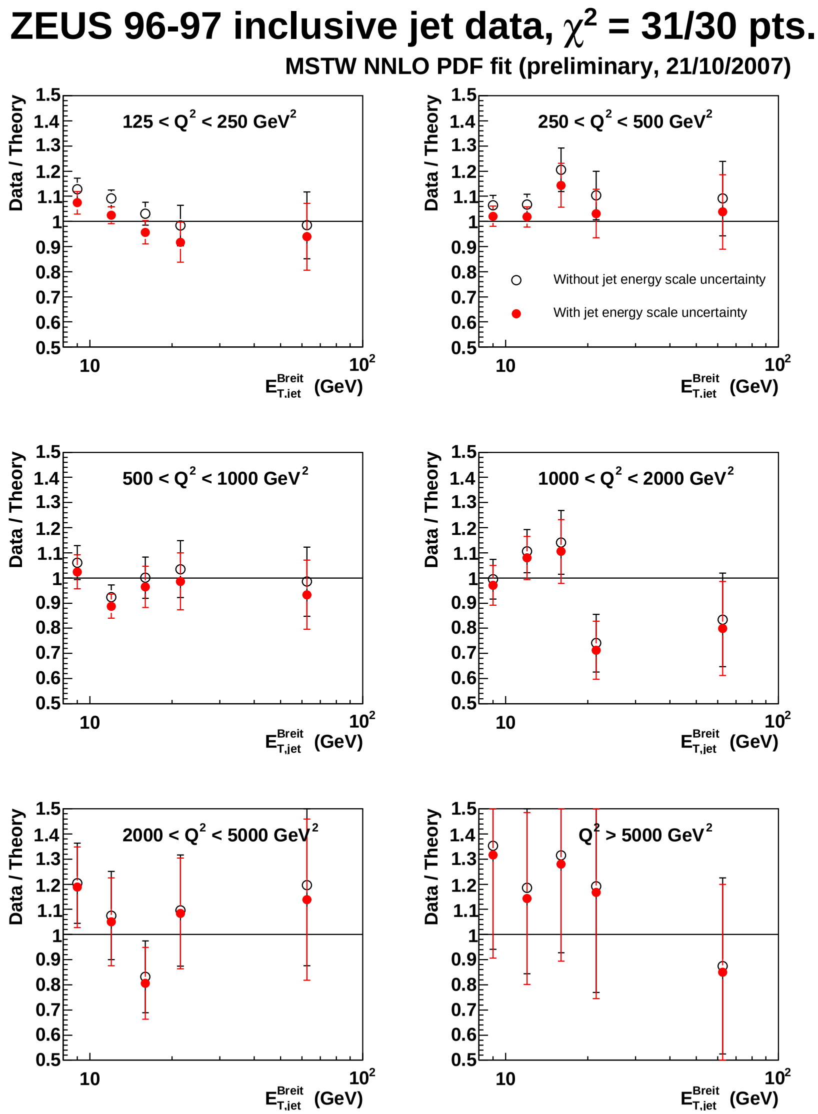
Fit to HERA inclusive and dijet DIS data using fastNLO at NNLO using NLO cross-section.

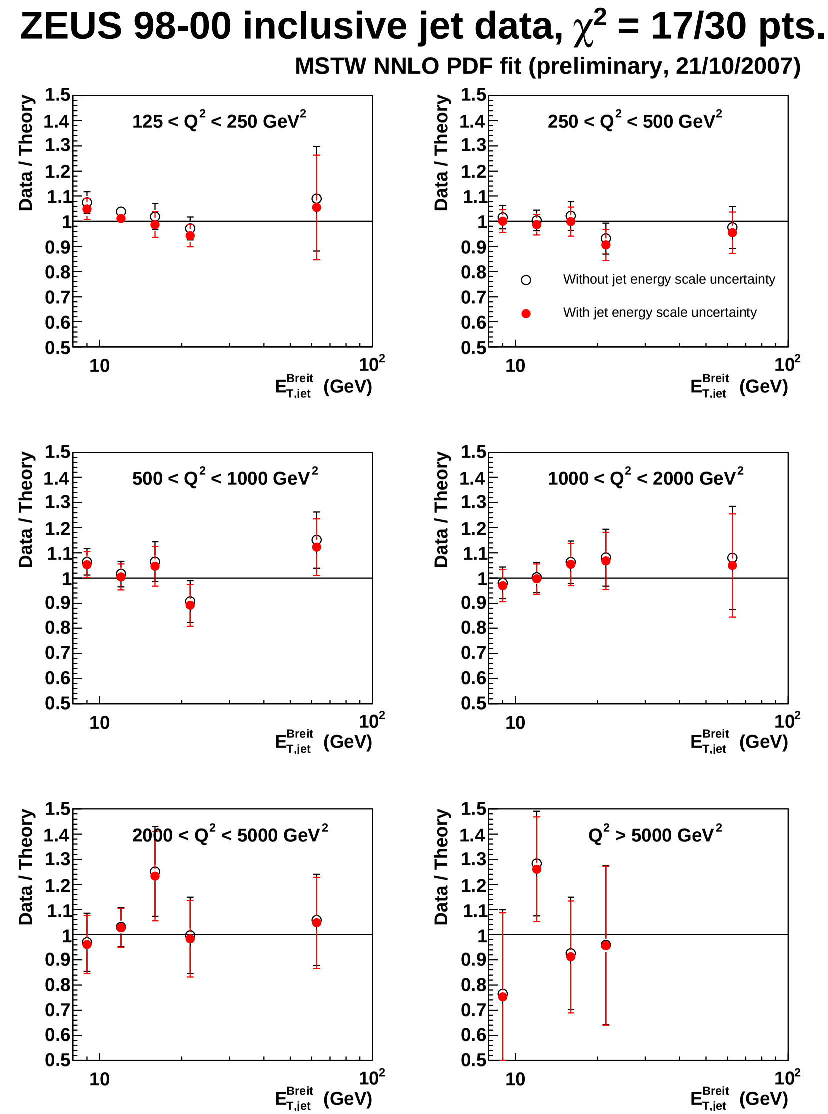
Fit generally excellent.

H1 95-97 incl. jet and dijet data, $\chi^2 = 11/32$ pts.

MSTW NNLO PDF fit (preliminary, 21/10/2007)

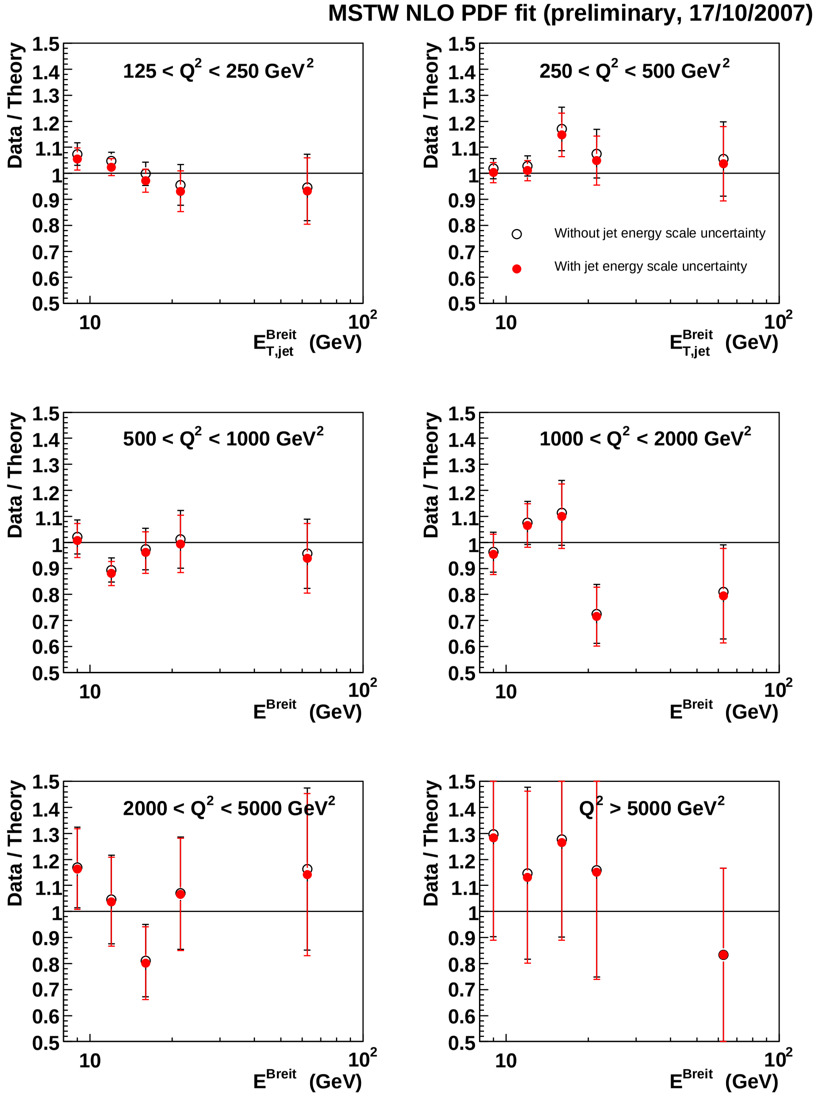




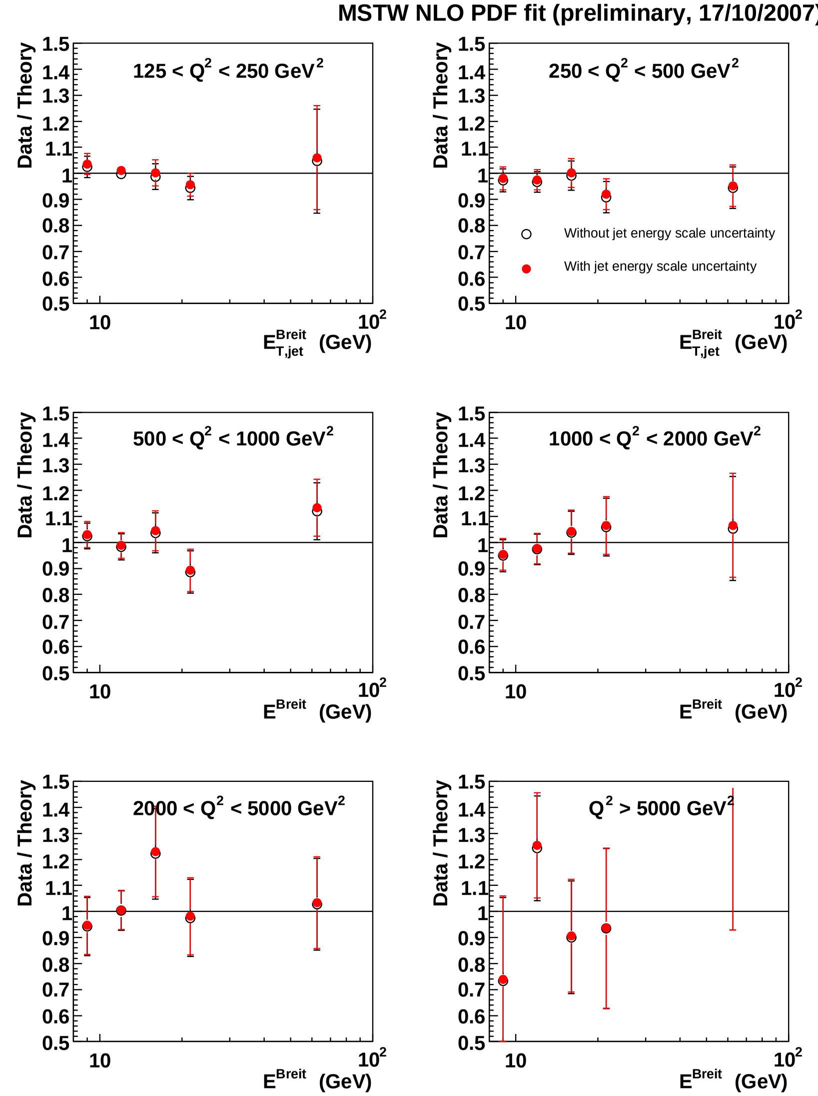


Same for ZEUS data.

ZEUS 96-97 inclusive jet data, $\chi^2 = 29/30$ pts.

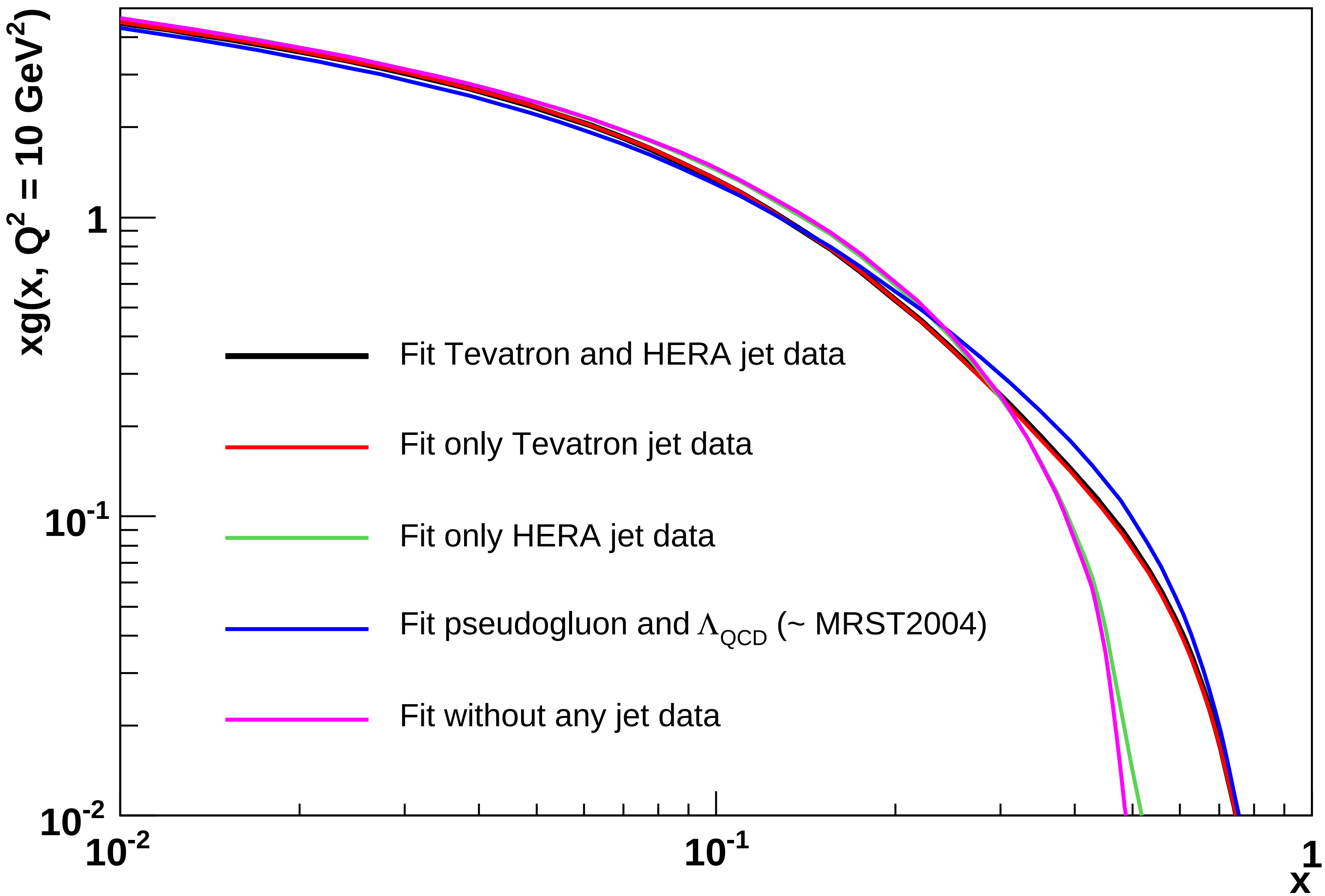


ZEUS 98-00 inclusive jet data, $\chi^2 = 16/30$ pts.



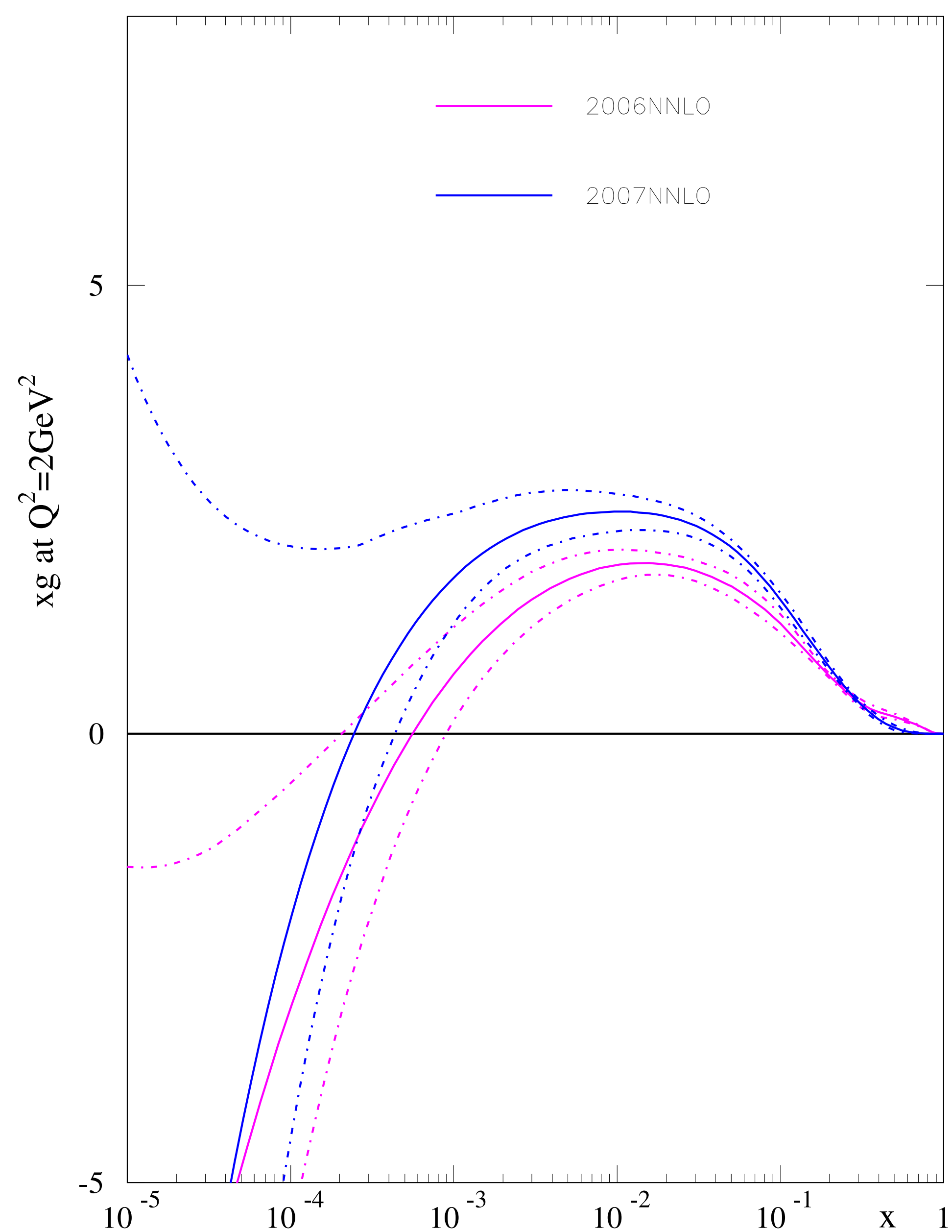
Perhaps more constraint from photo-production data, but requires (rather uncertain) photon distributions.

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



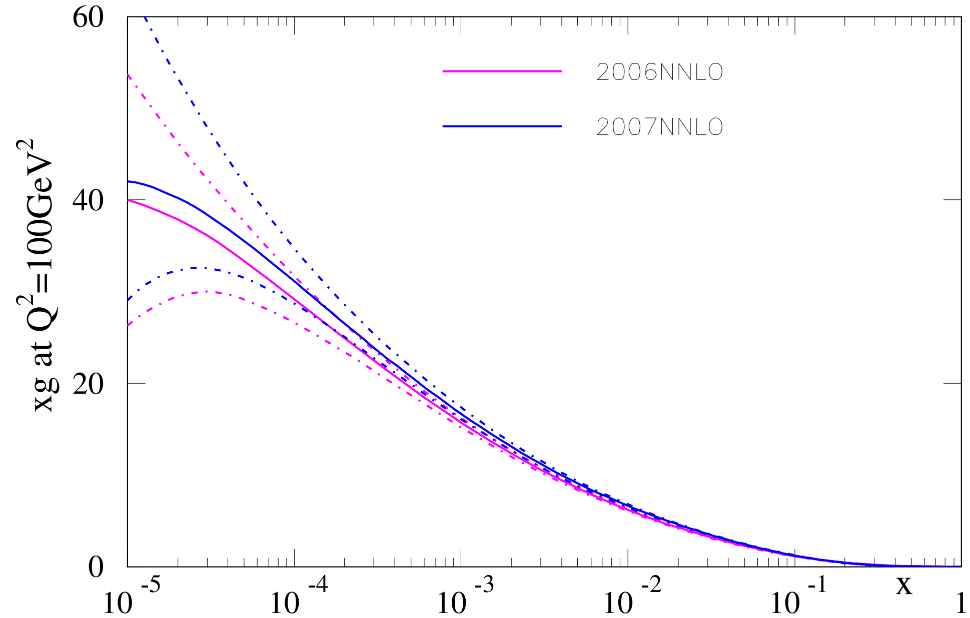
Comparison of most up-to-date gluon distributions at NNLO and MRST06.

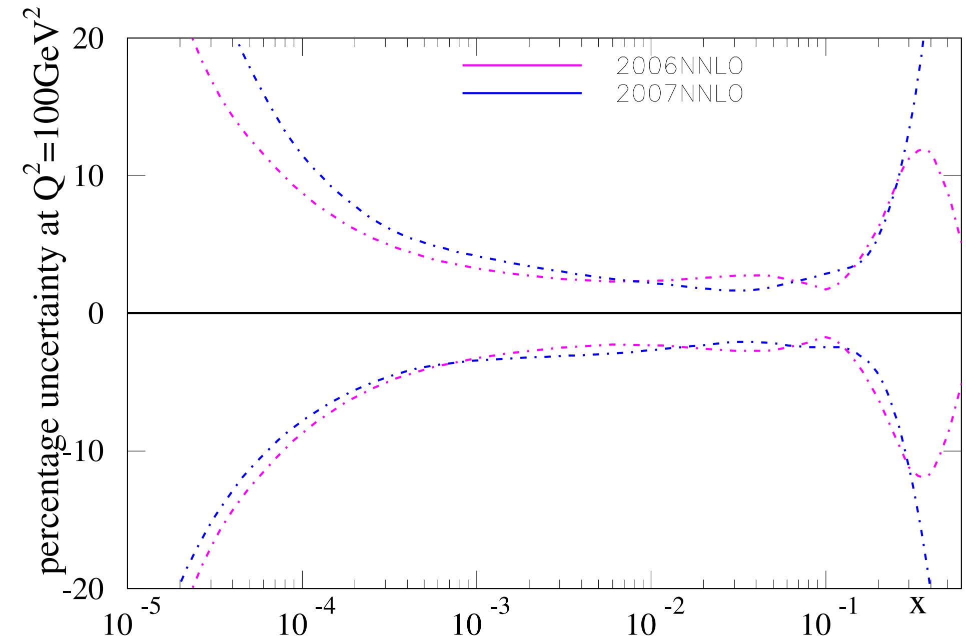
New CDFII jet data $\longrightarrow$ smaller very high-x distribution at low Q^2. Due to different couplings washes out at higher Q^2.



Comparison of most up-to-date gluon distributions at NNLO and MRST06 at $Q^2 = 100\mathrm{GeV}^2$.

MSTW2007 has smaller high-x distribution with better uncertainty determination. Slightly bigger at low x.





Dependence on m_c

Vary m_c in steps of $0.1\mathrm{GeV}$ (DIS07 - expect each $\alpha_S(M_Z^2)$ about 0.001 lower).

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 $\alpha_S(M_Z^2)$.

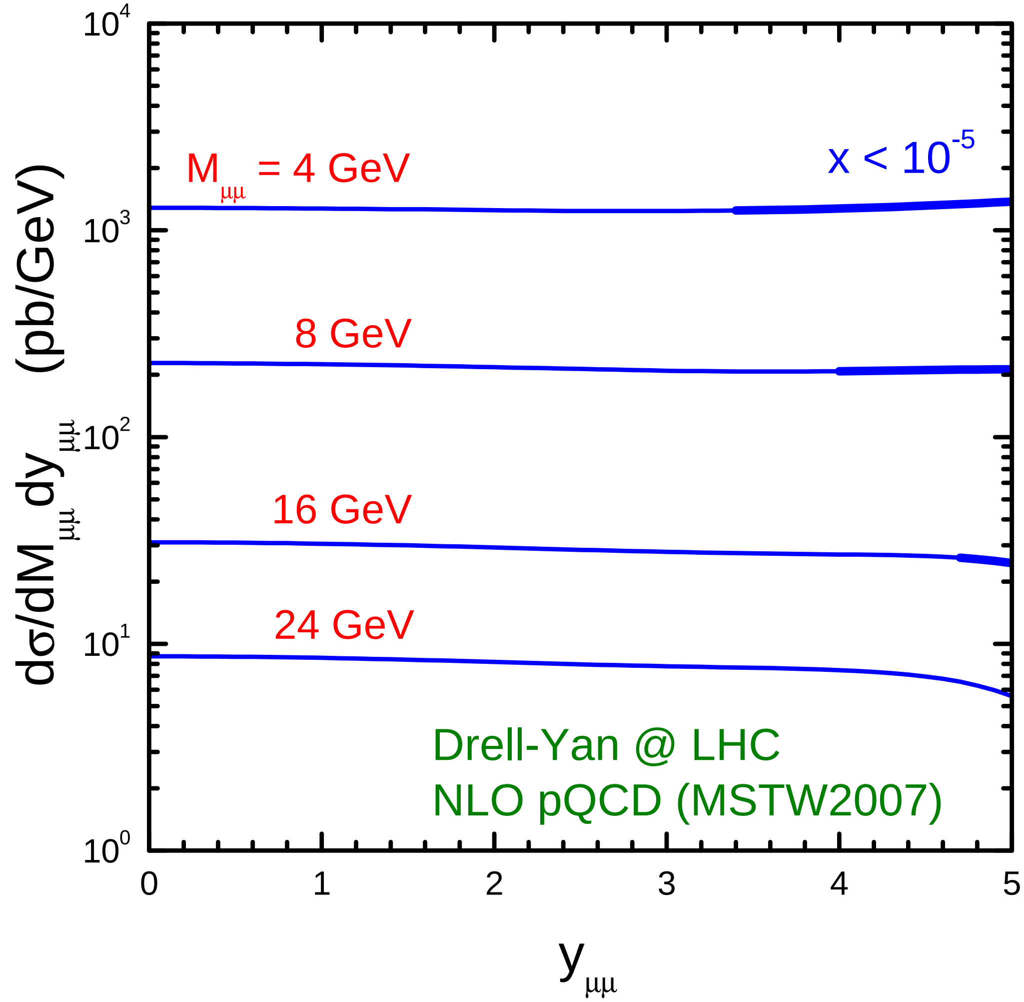
For low m_c overshoot low Q^2 medium x data badly.

Preference for $m_c = 1.4\mathrm{GeV}$. Towards lower end of pole mass determinations. Uncertainty from fit $\sim 0.1 - 0.15\mathrm{GeV}$. At NNLO best fit gives $m_c = 1.3GeV$.

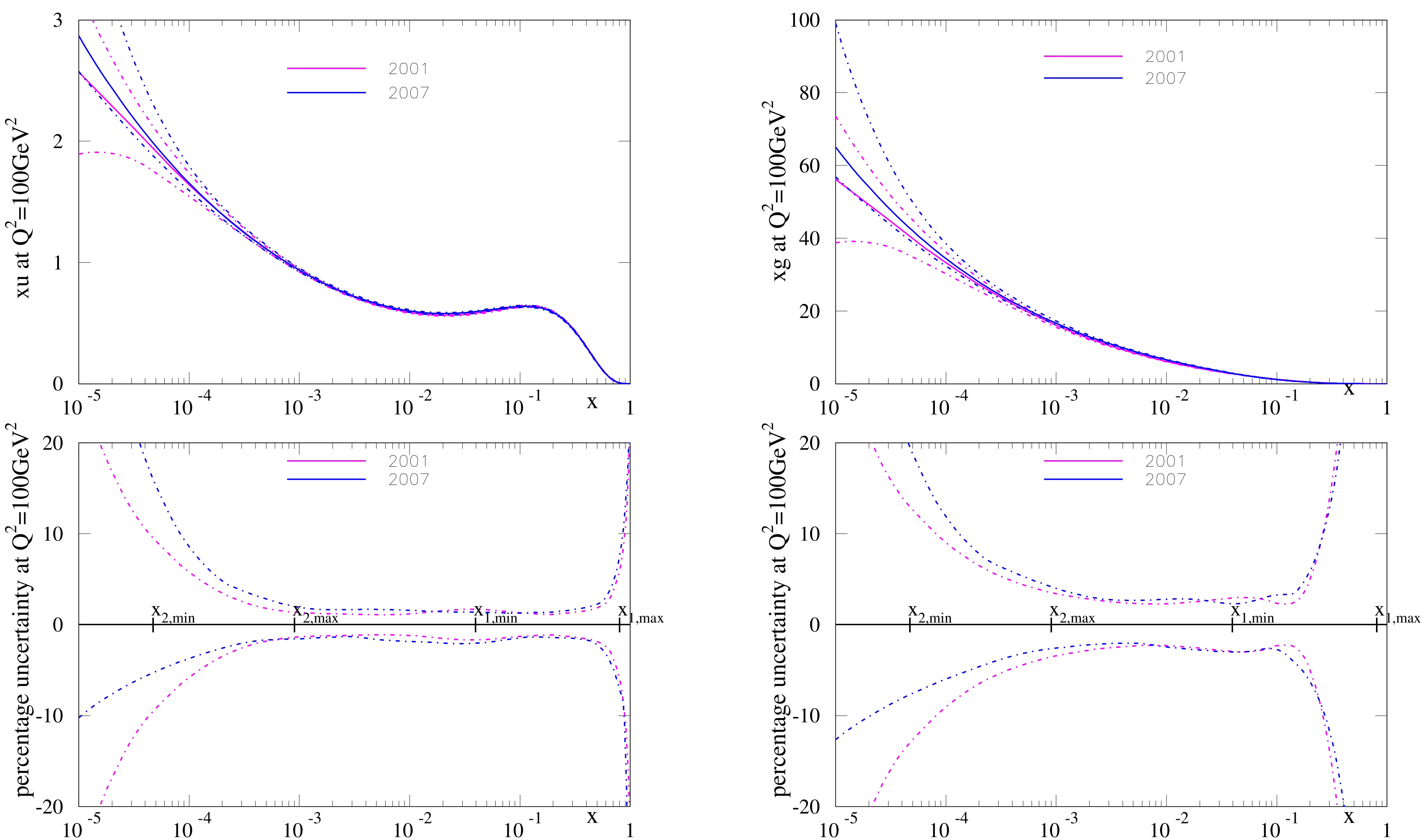
Also now choose $m_b = 4.75\mathrm{GeV}$, i.e. reasonable pole mass value. Not determined well by fit.

Possible to get to very low values of x at the LHC, particularly LHCb.

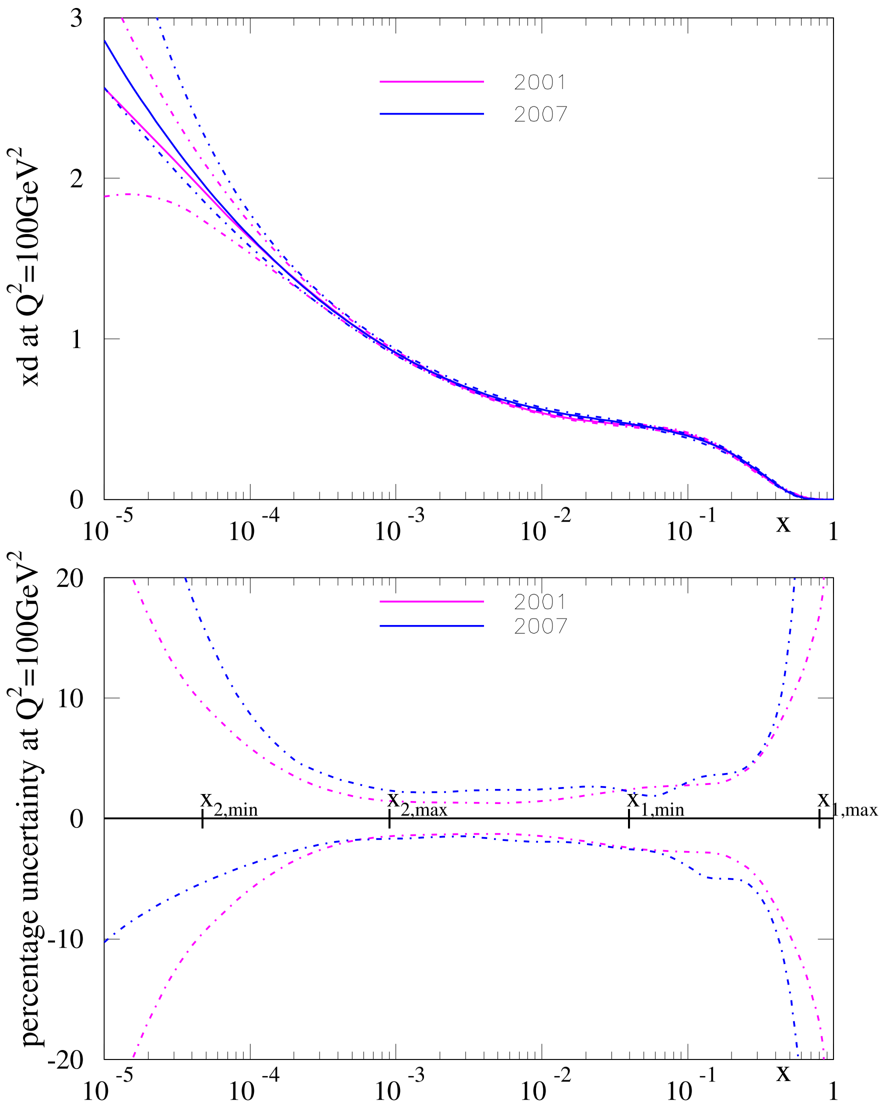
Can probe below $x = 10^{-5}$ - beyond range tested at HERA.

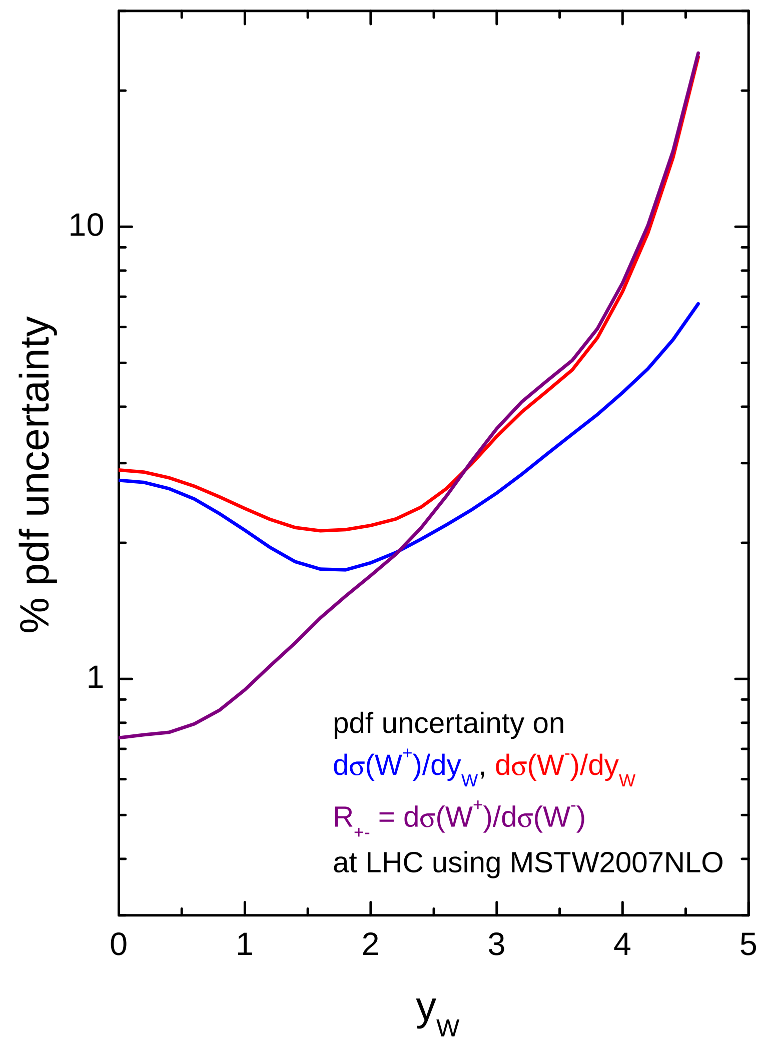


Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ dominated at high y by sea quark small-x uncertainty rather than high-x $u_V(x)$. Related to evolution and gluon distribution.

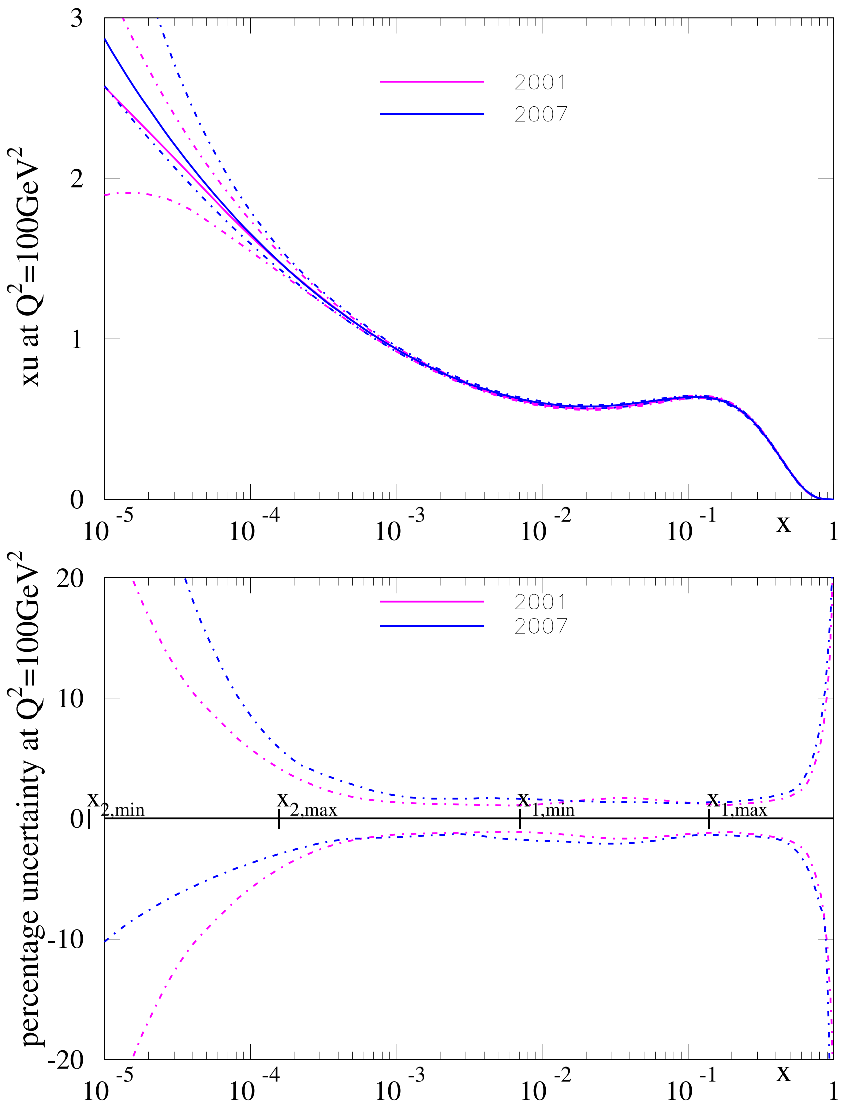


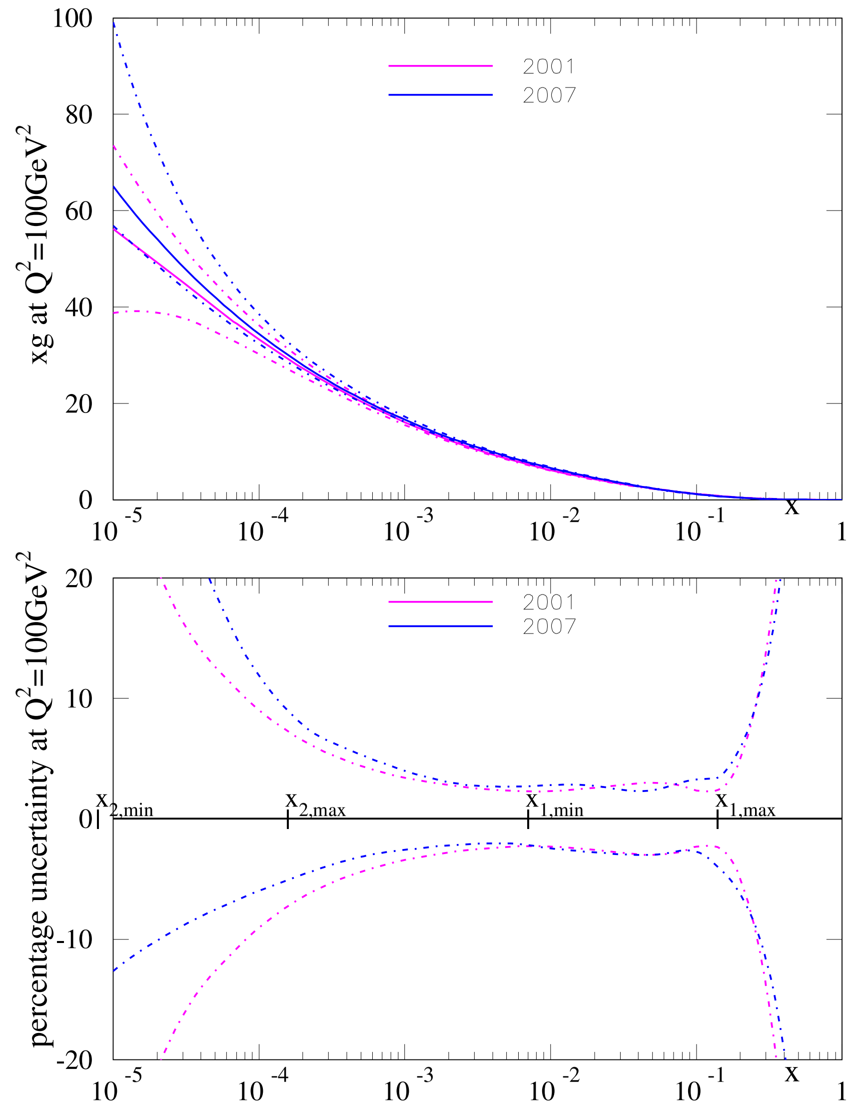
Uncertainty on $\sigma(W^-)$ dominated at very high y by high-x $d_V(x)$. Cleaner probe in ratio.





Uncertainty on $\sigma(\gamma^\star)$ driven by very small-x parton distributions not very well determined by HERA. Dominated by evolution, gluon distribution and small-x physics. Consider $M_{\gamma^\star} = 14\mathrm{GeV}$ as example.



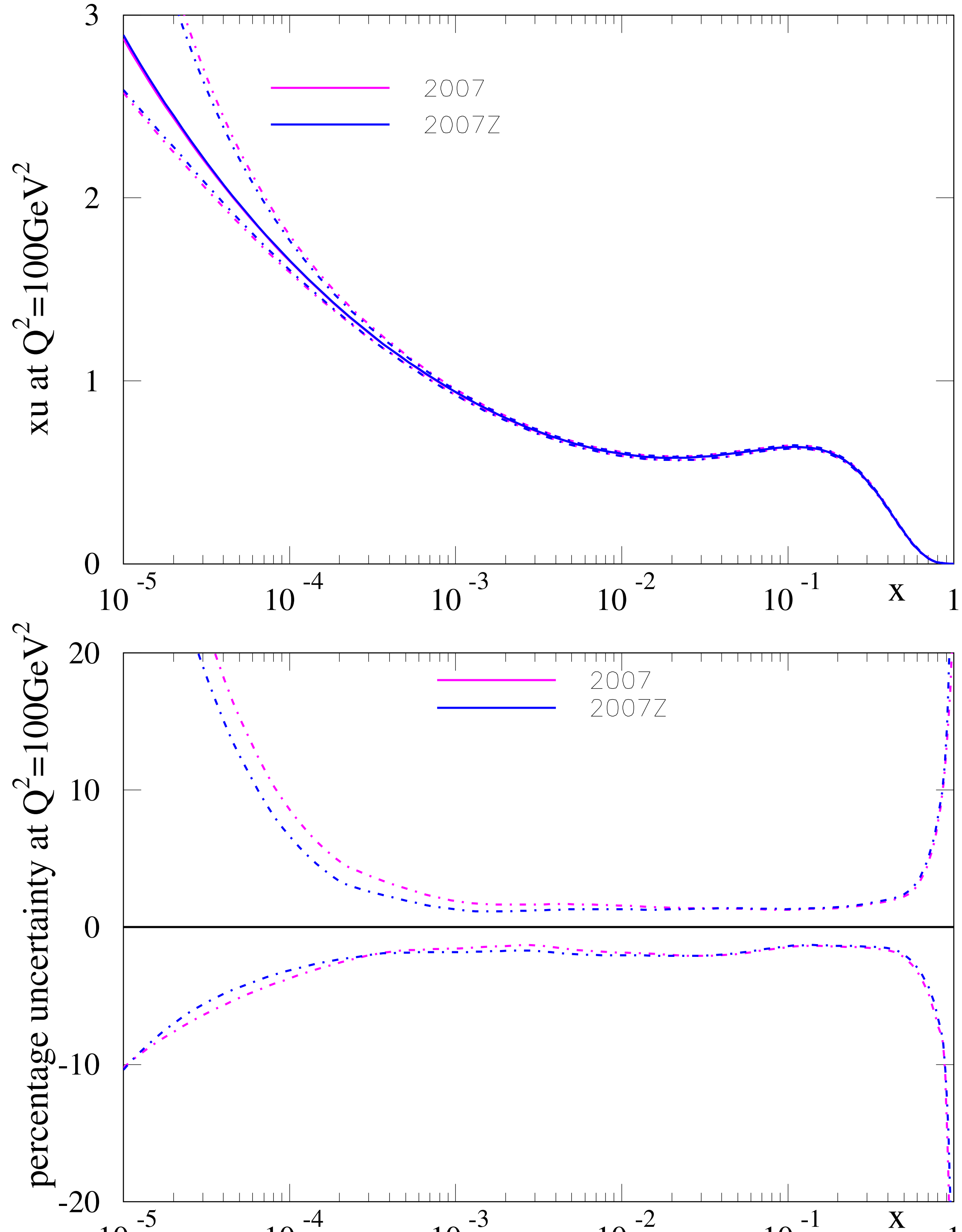


Constrains parton distributions almost entirely at small x.

With previous data improvement on uncertainty on $u(x, Q^2)$ shown. Essentially identical for $d(x, Q^2)$.

Definite narrowing of uncertainty band for $x < 0.01$.

Maximum reduction in uncertainty of $\sim 20\%$. However, can improve to perhaps $\sim 50\%$ with $10 fb^{-1}$ data.



Again we obtain even more information if the measurement is not as predicted.

As before shift predicted data by by factor $0.05(y - 3.4)$.

Comparing to prediction $\chi^2 = 338/30$.

Blue line shows result of new fit. Not possible to obtain good agreement $\chi^2 = 109/30$.