Parton Distribution Functions

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A review of **global fit** analyses of deep inelastic scattering and other data to determine the (unpolarised) parton distribution functions of the nucleon.

- anatomy of a global fit
- recent results
- some theoretical issues
- errors on parton distributions
- neutrino factory?
- conclusions

Parton distributions from global fits

- DIS structure functions (e.g. F_2^{ep})

$$\mathcal{F}_i(x,Q^2) = \int_x^1 \frac{dy}{y} \Big\{ \sum_j C_{ij}(y,\alpha_S)\; q_j(\frac{x}{y},Q^2) + C_{ig}(y,\alpha_S)\; g(\frac{x}{y},Q^2) \Big\}$$

- hadronic cross sections (e.g. $\sigma(p\bar{p} \to W X)$)

$$d\sigma_X = \sum_{\text{partons } a,b} \int dx_a dx_b\; f_a(x_a,Q^2)\; f_b(x_b,Q^2)\; d\hat{\sigma}_{ab\to X}$$

- DGLAP evolution

$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{dy}{y} \Big\{ P_{q_i q_j}(y,\alpha_S)\; q_j(\frac{x}{y},Q^2) + P_{q_i g}(y,\alpha_S)\; g(\frac{x}{y},Q^2) \Big\}$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{dy}{y} \Big\{ P_{g q_j}(y,\alpha_S)\; q_j(\frac{x}{y},Q^2) + P_{gg}(y,\alpha_S)\; g(\frac{x}{y},Q^2) \Big\}$$

- NLO: coefficient functions C, $\hat{\sigma}$ and splitting functions P evaluated to next-to-leading order in α_S at present

Recent work

H1, ZEUS: ongoing fits for pdfs + uncertainties from HERA and other DIS data (see previous talk)

Martin, Roberts, WJS, Thorne (MRST): updated 'MRST2001' global fit (hep-ph/0110215) and LO/NLO/'NNLO' comparison (hep-ph/0201127)

Pumplin et al. (CTEQ): updated 'CTEQ6' global fit (hep-ph/0201195), including uncertainties on pdfs

Giele, Keller, Kosower (GKK): restricted global fit, focusing on data-driven pdf uncertainties (hep-ph/0104052)

Alekhin: restricted global fit (DIS data only), focusing on effect of both theoretical and experimental uncertainties on pdfs, including 'NNLO' fit (hep-ph/0011002)

Ingredients: data used in current global fits

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

ZEUS $F_2^{e^+p}(x,Q^2)$ 1996-97

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

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

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

E665 $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$

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

ZEUS $F_{2,c}^{e^+p}(x,Q^2)$ 1996-97

E605, E772, E866 Drell-Yan $pN \to \mu\bar{\mu} + X$

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

CDF W-asymmetry u/d ratio at high x

CDF, D0 Inclusive jet data

CCFR Dimuon data constrains strange sea

Note: no prompt photon data

Method and assumptions*

Choose theoretical framework (e.g. $\overline{\mathrm{MS}}, \mathrm{NLO}$) and data set

Perform fit by minimizing χ^2 to all data, including both statistical and (correlated, where available) systematic errors $\longrightarrow$ 'best fit' set of pdfs

Start evolution at $Q_0^2 = 1\ \mathrm{GeV}^2$, where pdfs parametrised with functional form $xf(x, Q_0^2) = (1-x)^\eta(1+\epsilon x^{0.5}+\gamma x)x^\delta$

Cut data at $Q^2_{\mathrm{min}} = 2\ \mathrm{GeV}^2$ (HERA at $Q^2_{\mathrm{min}} = 1.5\ \mathrm{GeV}^2$) and at $W^2_{\mathrm{min}} = 12.5\ \mathrm{GeV}^2$ to avoid higher twist.

$\bar{u} \neq \bar{d}$ and is constrained by E866 Drell-Yan asymmetry.

$s(=\bar{s})$ is constrained by CCFR (NuTev) Dimuon data $\Rightarrow$ $s = 0.5(\bar{u}+\bar{d})/2$ at Q_0^2

Use Thorne-Roberts VFNS (improves global fit compared to ZM-VFNS and FFNS, important for charged current data)

Our best fit has

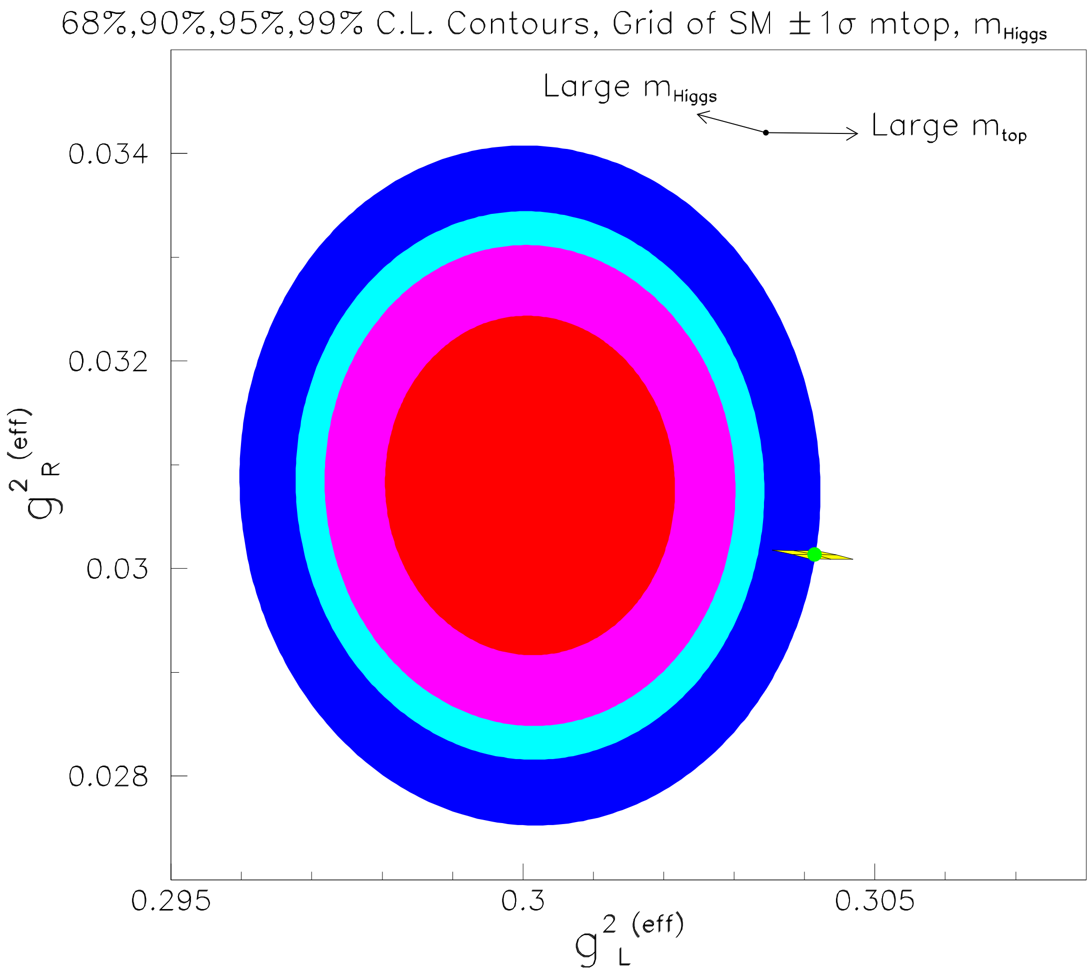
$$\boxed{\alpha_S^{\overline{MS},NLO}(M_Z^2) = 0.119}$$

* MRST2001 parameters as example, CTEQ6 similar – important difference is $Q^2_{\mathrm{min}} = 4\ \mathrm{GeV}^2$

A comment on the strange distribution

NuTeV (2001): $\sigma^{\nu N,\bar{\nu} N} \Rightarrow \sin^2\theta_W = 0.2277 \pm 0.0016$

cf. world average: $\sin^2\theta_W = 0.2227 \pm 0.0004$



New physics?

The NuTeV measurement of $\sin^2\theta_W$ assumes

— isospin symmetry: $u_p(x) = d_n(x)$ etc.
— strange–antistrange symmetry: $s(x) = \bar{s}(x)$

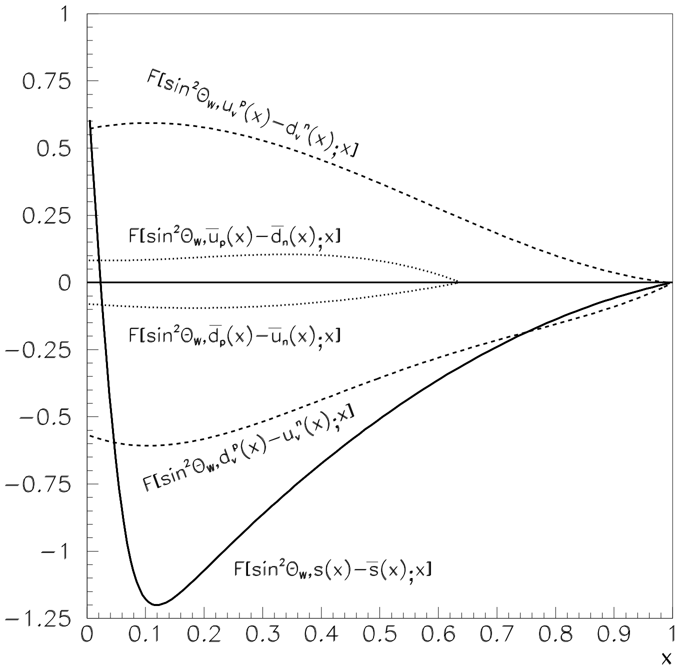
otherwise

$$\begin{aligned}\Delta\sin^2\theta_W &= \int_0^1 dx F_s(x)[s(x) - \bar{s}(x)] \\ &+ \int_0^1 dx F_I(x)[u_p(x) - d_n(x)] + \ldots\end{aligned}$$

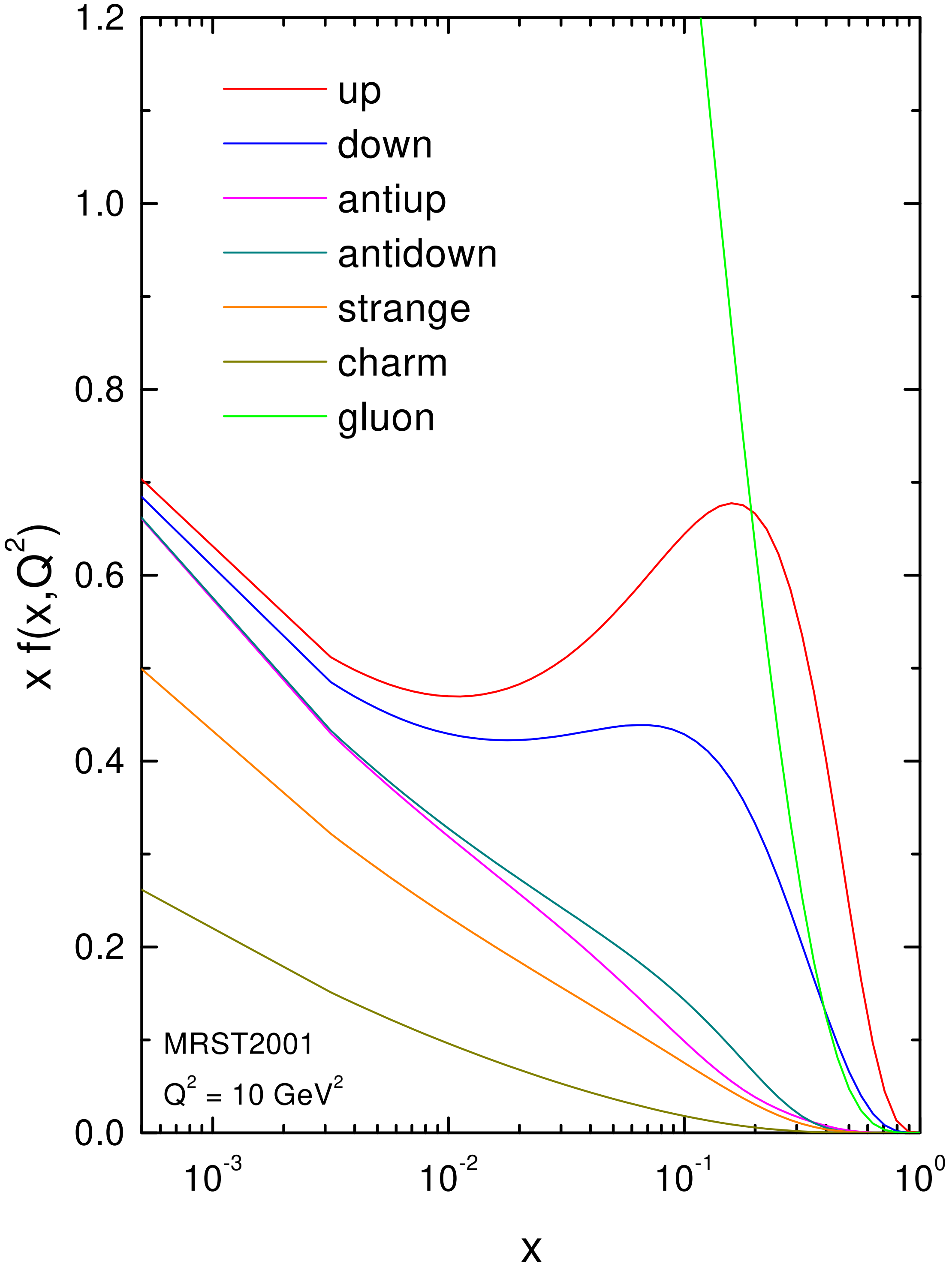
and in particular $s > \bar{s} \;\Rightarrow\; \sin^2\theta_W \downarrow$.

Further constraints on $s(x)$, $\bar{s}(x)$ from dimuon data, $\nu N, \bar{\nu}N \to \mu^+\mu^- + X$

The issue of $s(x) \neq \bar{s}(x)$ still not settled. Note that global pdf analyses usually assume $s = \bar{s}$ and isospin symmetry



The MRST 2001 parton distributions



Quality of fit

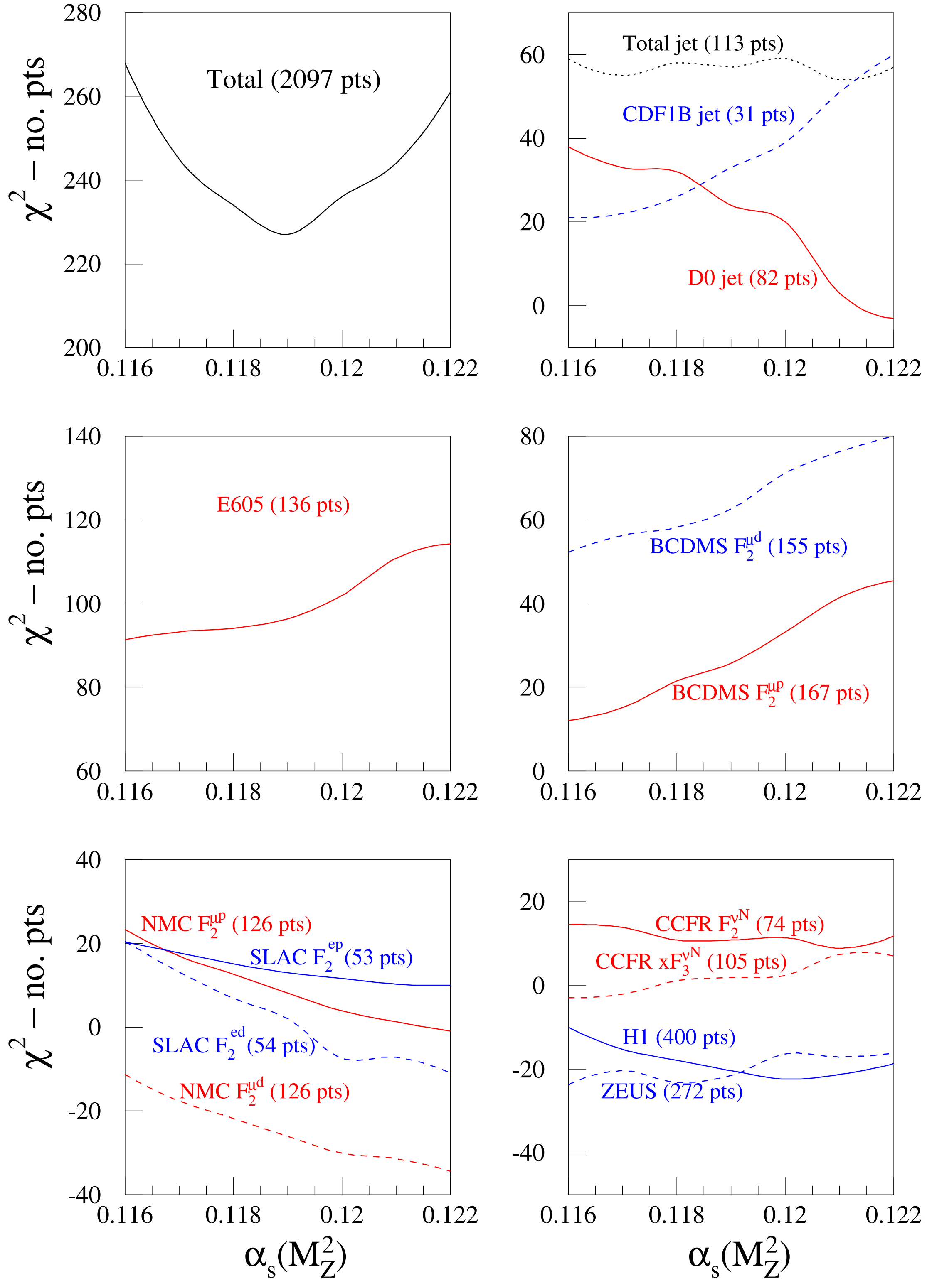
Total fit reasonably good, e.g CTEQ6

Data set	No. of data pts	χ^2
H1 ep	230	228
ZEUS ep	229	263
BCDMS μp	339	378
BCDMS μd	251	280
NMC μp	201	305
E605 (Drell-Yan)	119	95
D0 Jets	90	65
CDF Jets	33	49

... and about 1 per point for smaller sets; $\alpha_S(M_Z^2)$ fixed at 0.118. Total $\chi^2 = 1954/1811$.

For MRST $\alpha_S(M_Z^2) = 0.119$. Compromise between different data sets. Total $\chi^2 = 2328/2097$ – but errors treated differently, and different data sets and cuts

α_S and individual data sets



Fit to structure function data

New HERA data with larger coverage and much smaller errors have far more significant weight in fit

Data require MRST gluon to be negative (at $Q_0^2 = 1\ \mathrm{GeV}^2$), but CTEQ6 has positive gluon at $Q_0^2 = 4\ \mathrm{GeV}^2$

Thus, for MRST2001:

$$xg(x, Q_0^2) = A(1-x)^\eta(1+\epsilon x^{0.5}+\gamma x)x^\delta - A_-(1-x)^{\eta_-}x^{-\delta_-}$$

$\eta_- \sim 10,\ \delta_- \sim 0.3$

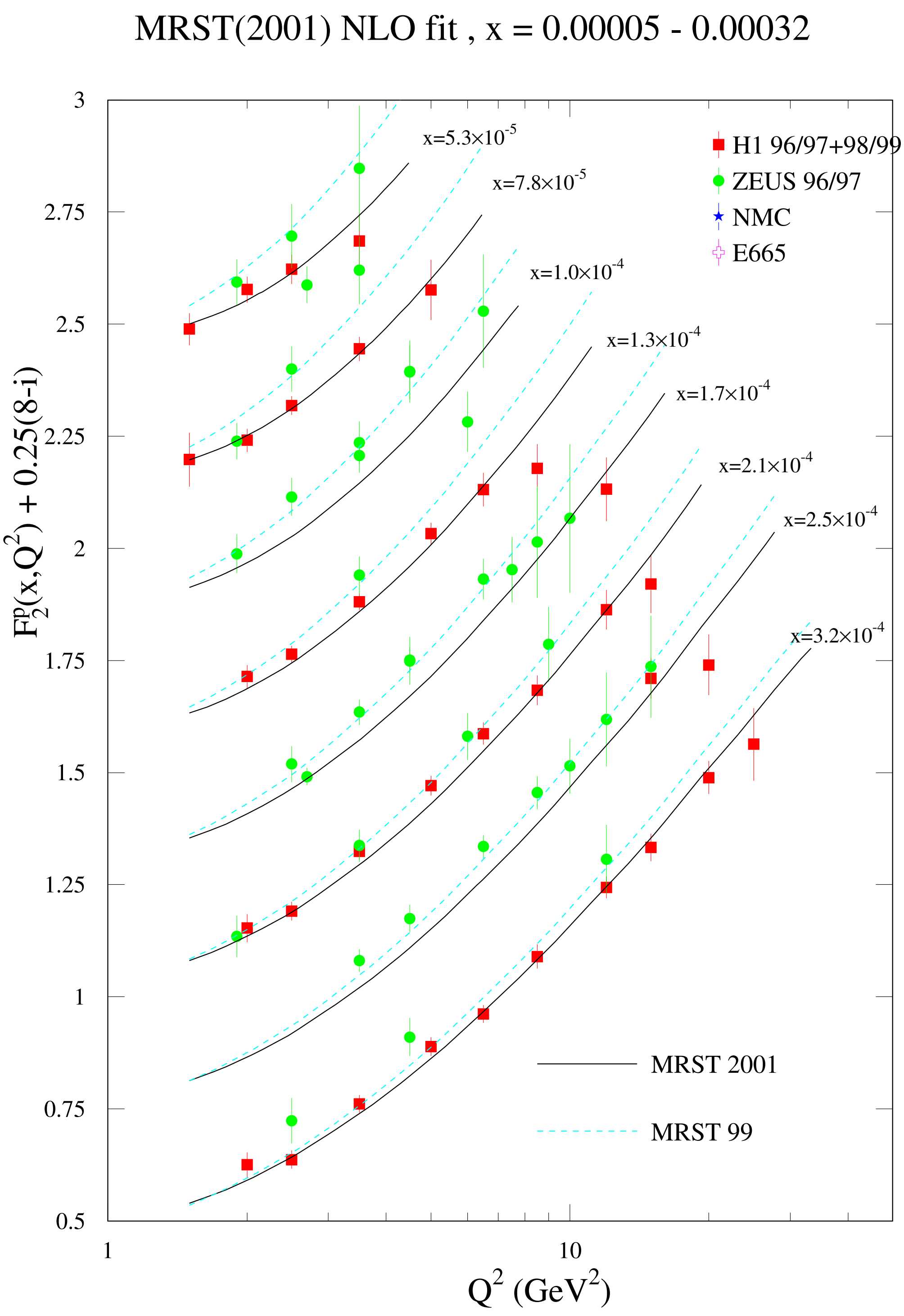
Not using this extended parameterization $\rightarrow \Delta\chi^2 \approx 100$

Good fit to HERA data, but some problem at highest Q^2 at moderate x, i.e. in $dF_2/d\ln Q^2$.

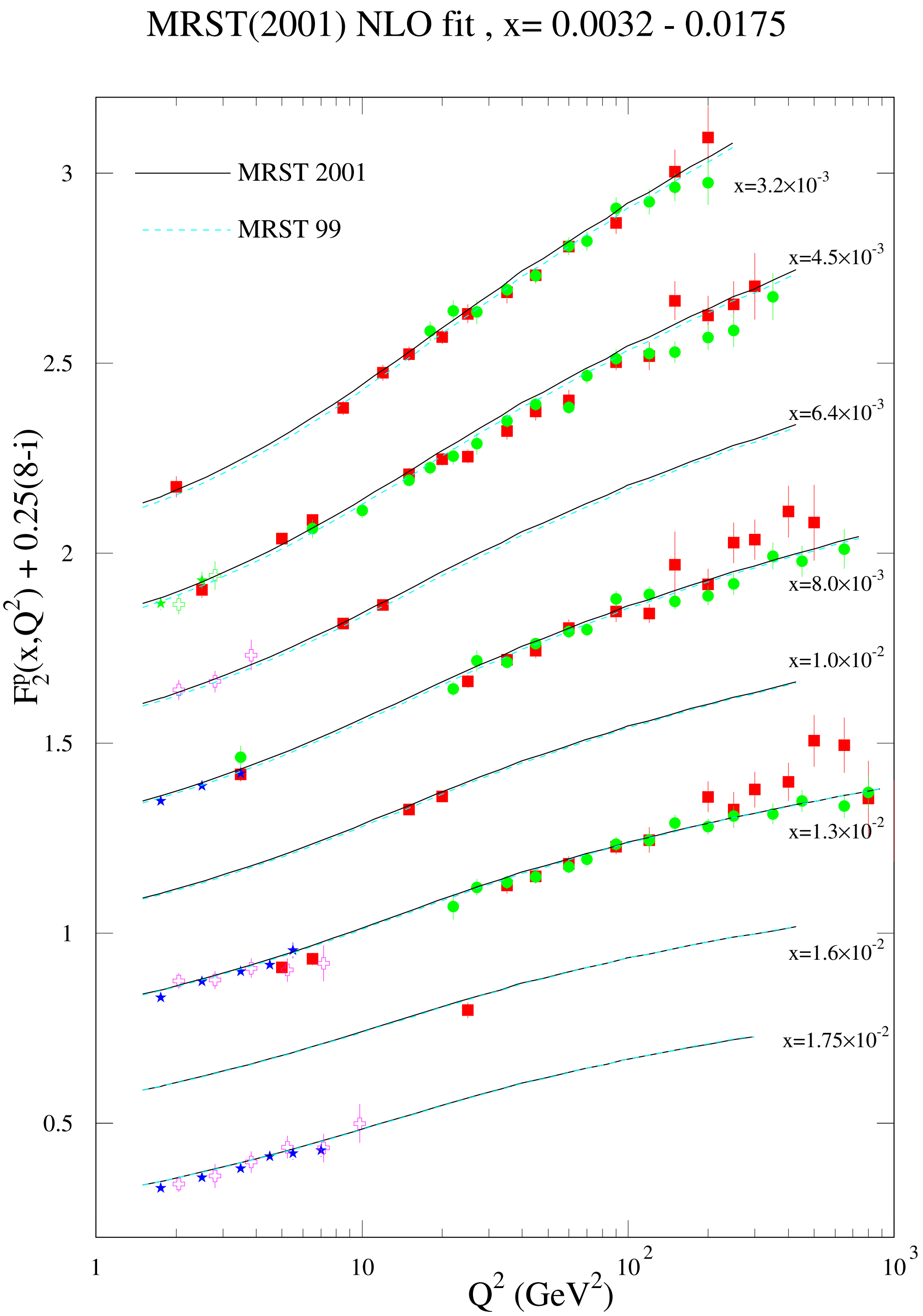
Not just low x low Q^2 data that require negative gluon. Moderate x data need lots of gluon to get reasonable $dF_2/d\ln Q^2$, and jet data favour large high-x gluon, which must be compensated for elsewhere

$\Rightarrow F_L(x, Q^2)$ dangerously small at smallest x, Q^2 (see later)

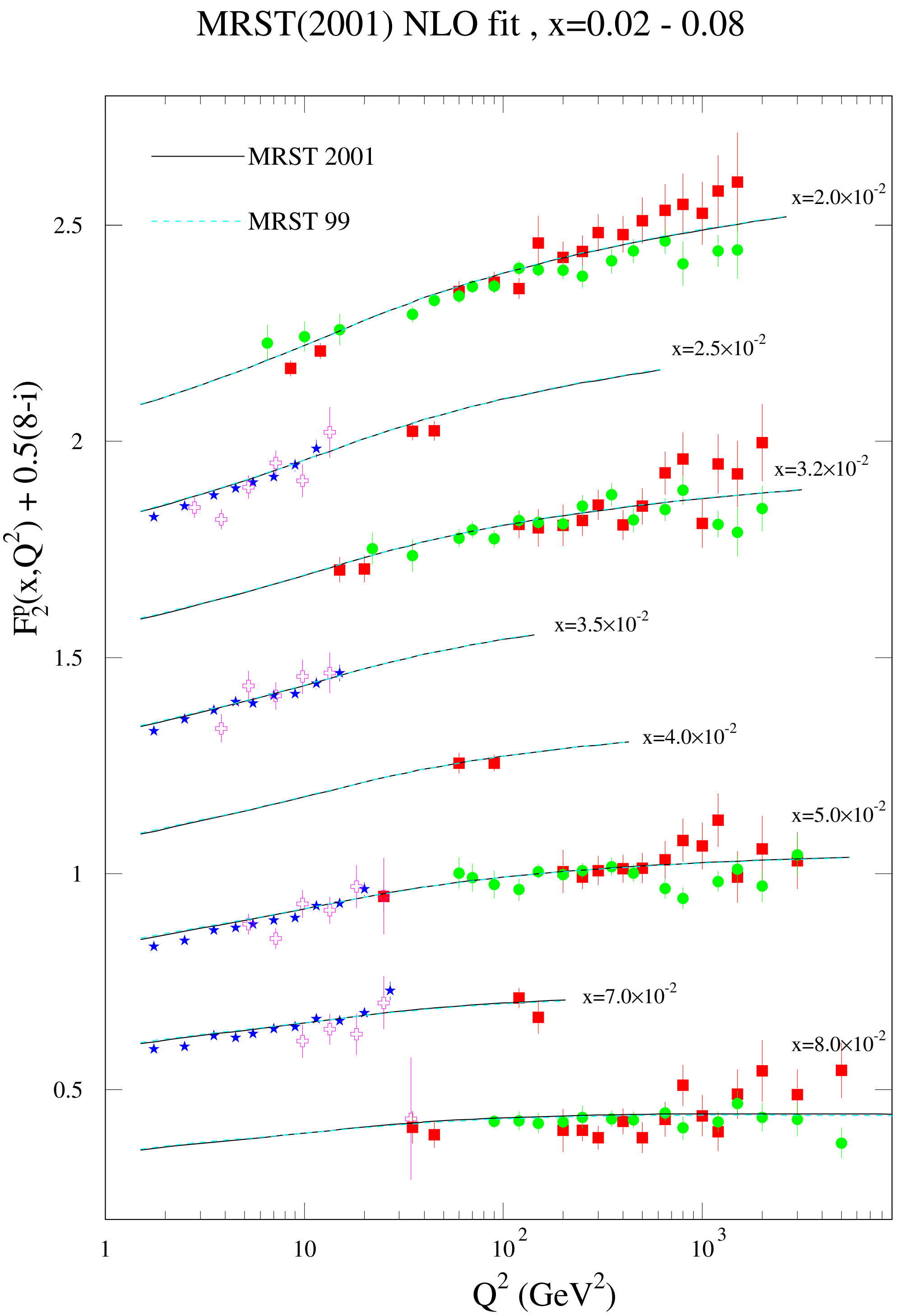
Comparison of MRST(2001) and MRST(1999)



Comparison of MRST(2001) and MRST(1999)



Comparison of MRST(2001) and MRST(1999)

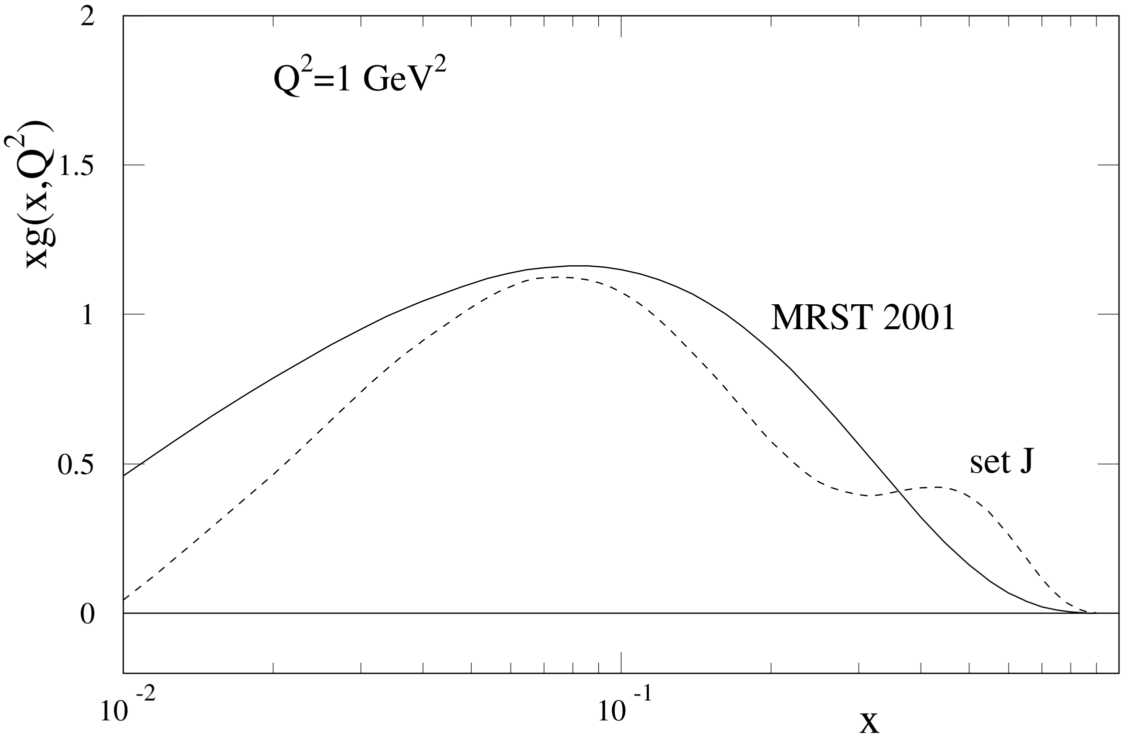


High–x gluon

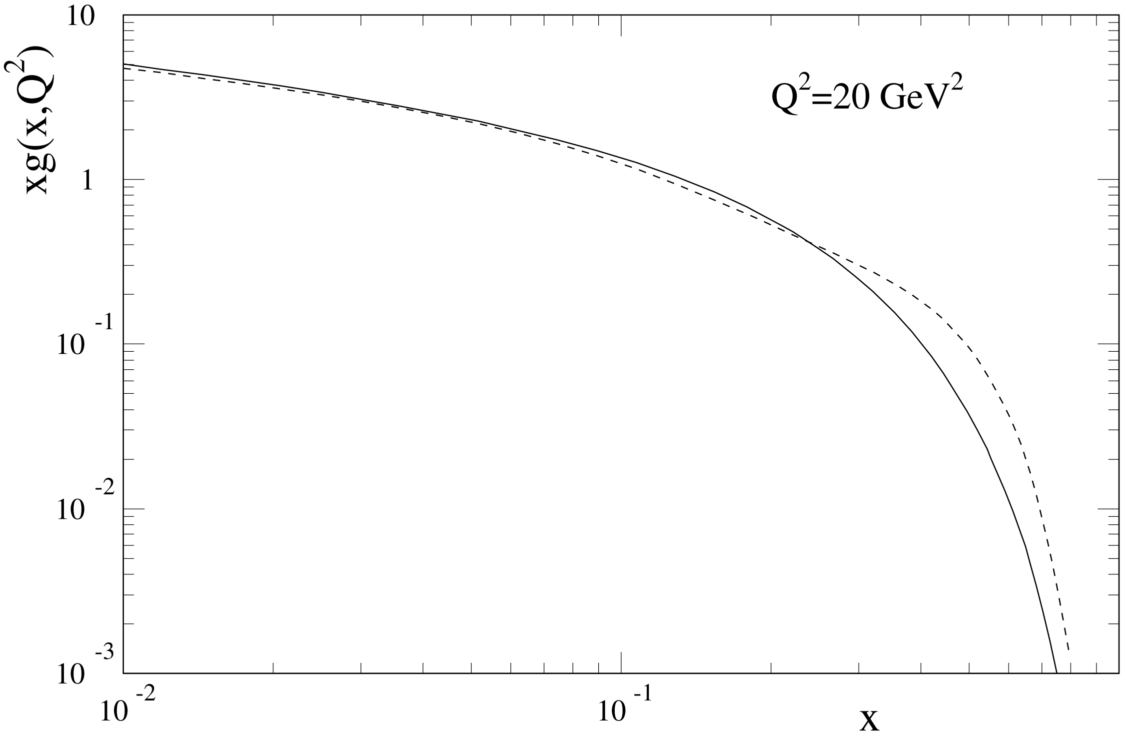
- Previously used prompt photon data to determine high-x gluon; but uncertainty in consistency of experiments and stability of theory $\Rightarrow$ replaced in fits by high-E_T Tevatron jet data

- But difficult to reconcile fit to jets and rest of data (DIS, DY), since jet data requires large high-x gluon, must be compensated for elsewhere. Standard MRST fit to jet data is reasonable ($\chi^2/\mathrm{dof} = 170/113$), but the **best** fit ('MRSTJ', $\chi^2/\mathrm{dof} = 110/113$) requires $\alpha_S(M_Z^2) = 0.121$ and an unusual shape

- standard CTEQ jet fit is better than MRST (see below)



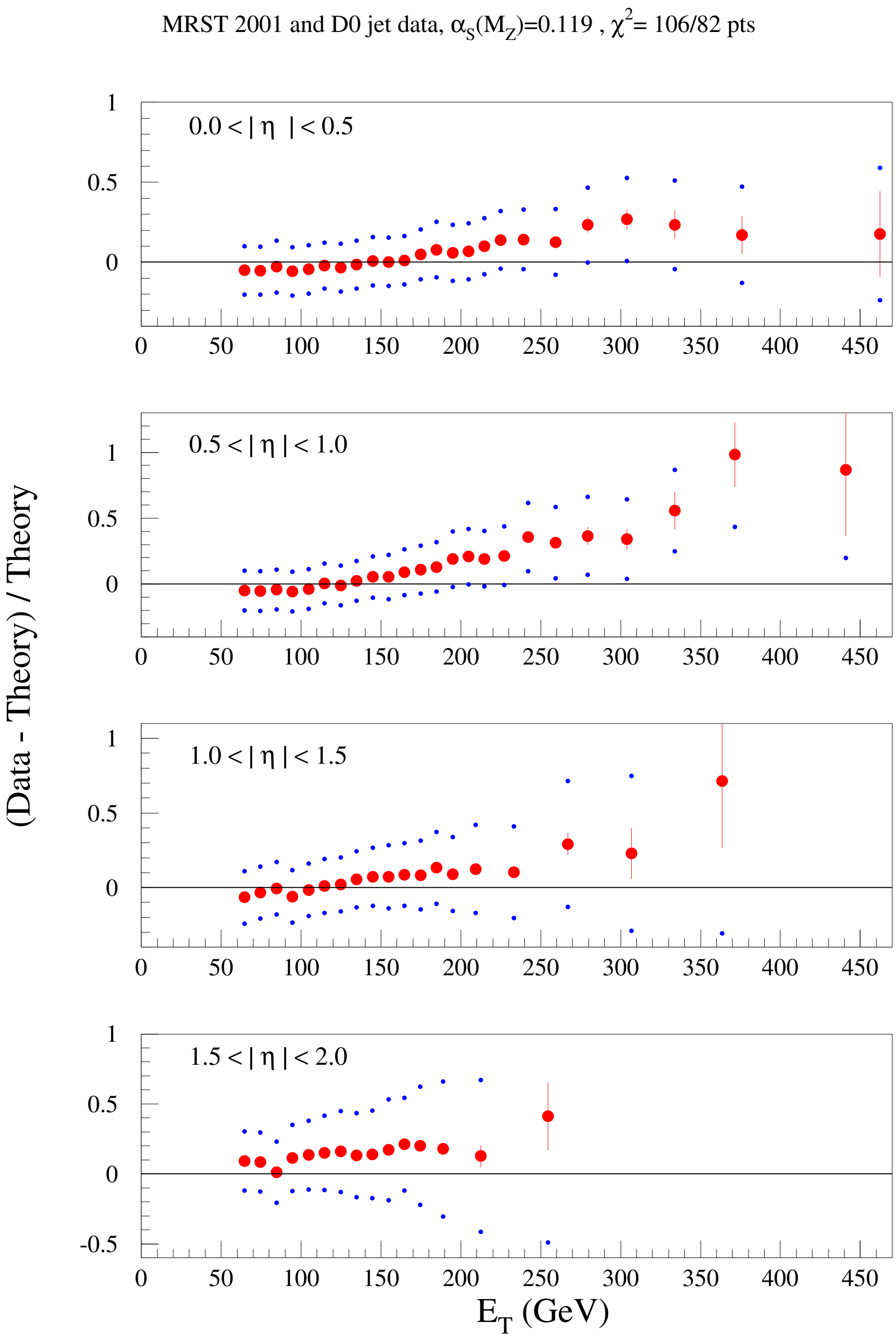
Q^2=1 GeV^2
xg(x,Q^2)
MRST 2001
set J
2
1.5
1
0.5
0
10^{-2}
10^{-1}
x



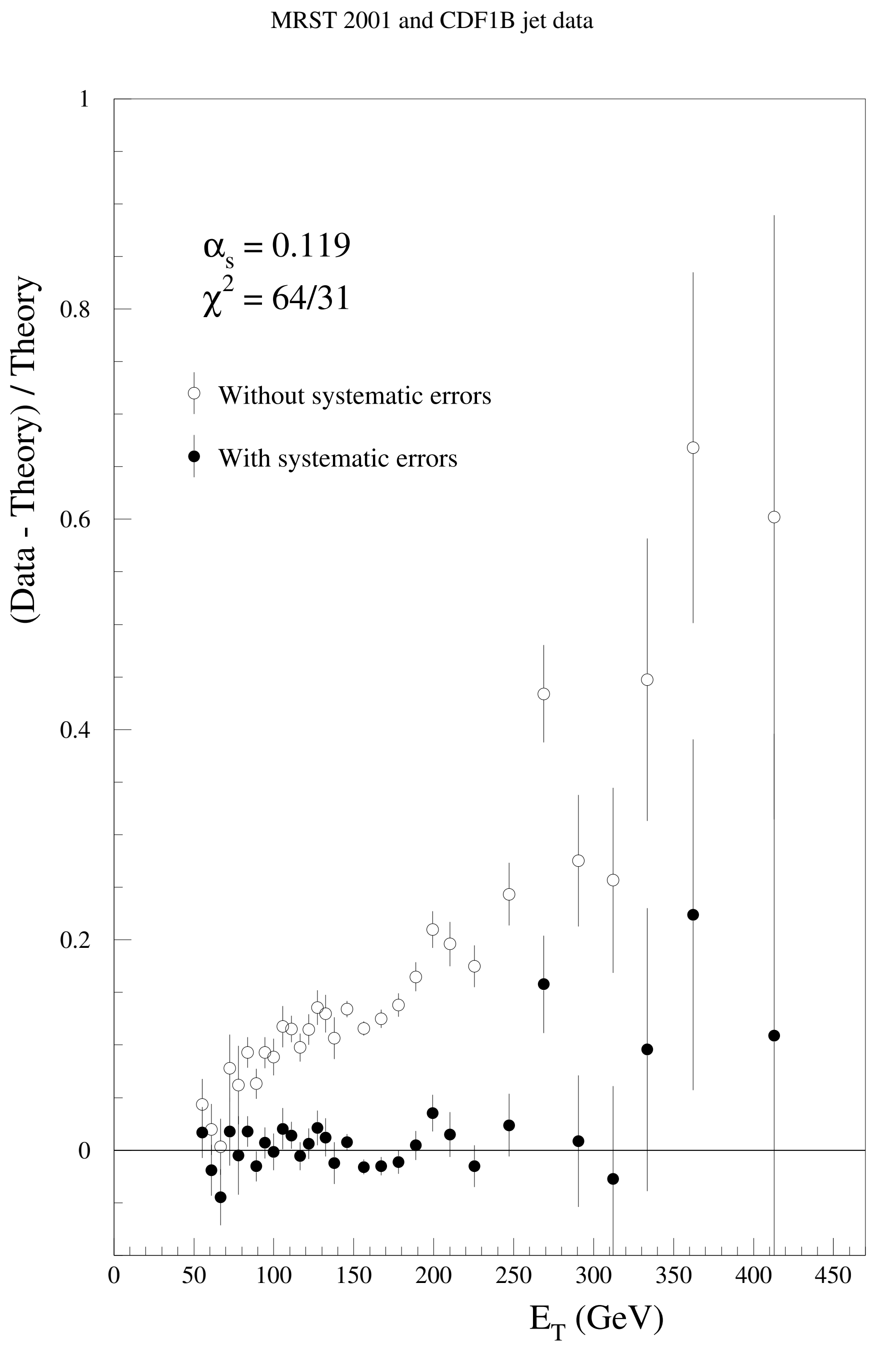
Q^2=20 GeV^2
xg(x,Q^2)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
x

Fit to recent D0/CDF jet data

Good fit to D0 data; normalization about correct and shape cured by correlated errors

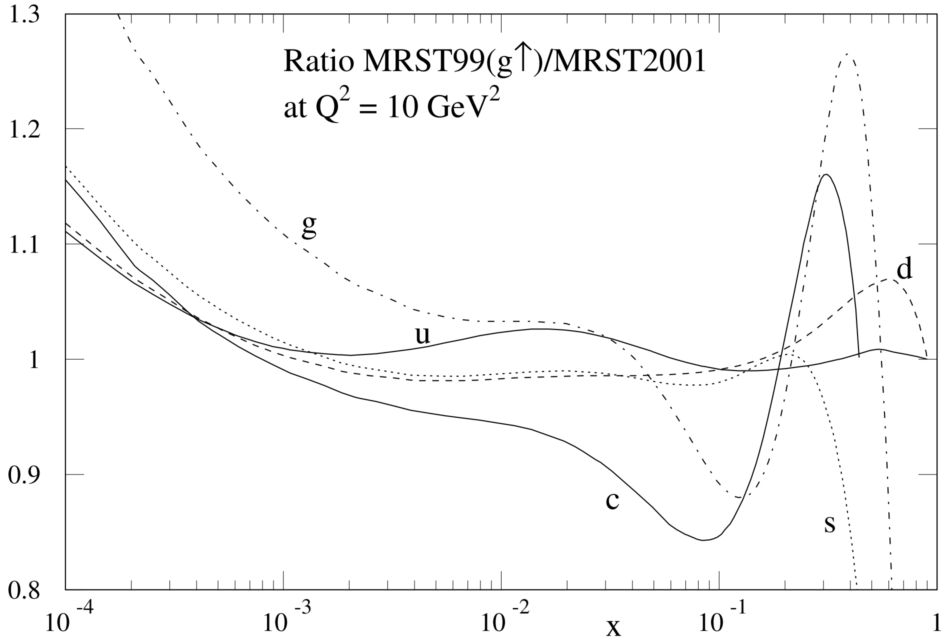


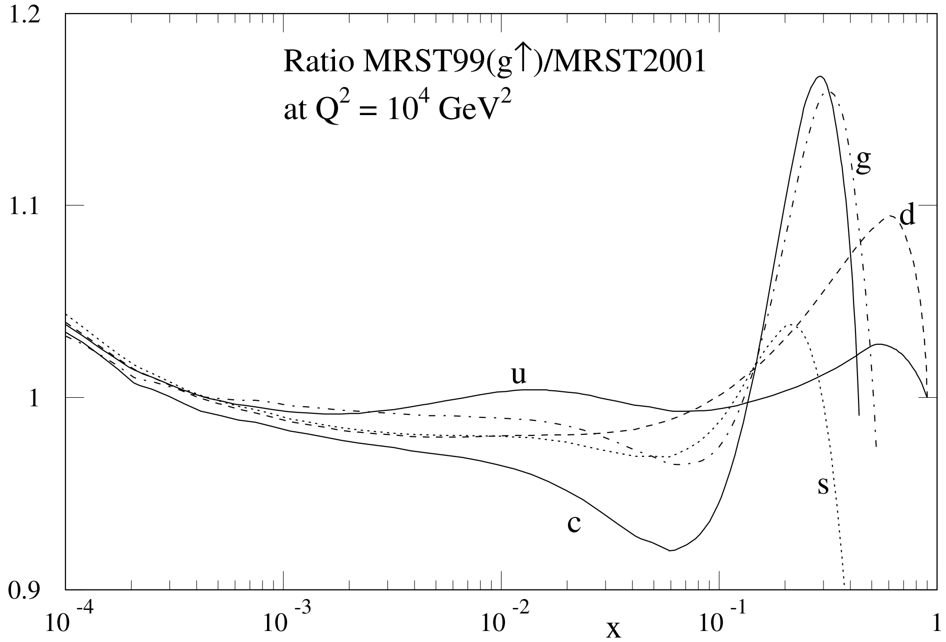
Good fit to CDF data; normalization slightly low and shape cured by correlated errors



Ratio of MRST(2001) and MRST(1999) partons

Comparison of updated MRST2001 partons with MRST99 partons





Comparison of MRST2001 with CTEQ6

The recent CTEQ6 set gives a better fit ($\Delta\chi^2 \approx 50$) to the jet data than MRST(2001). Why?

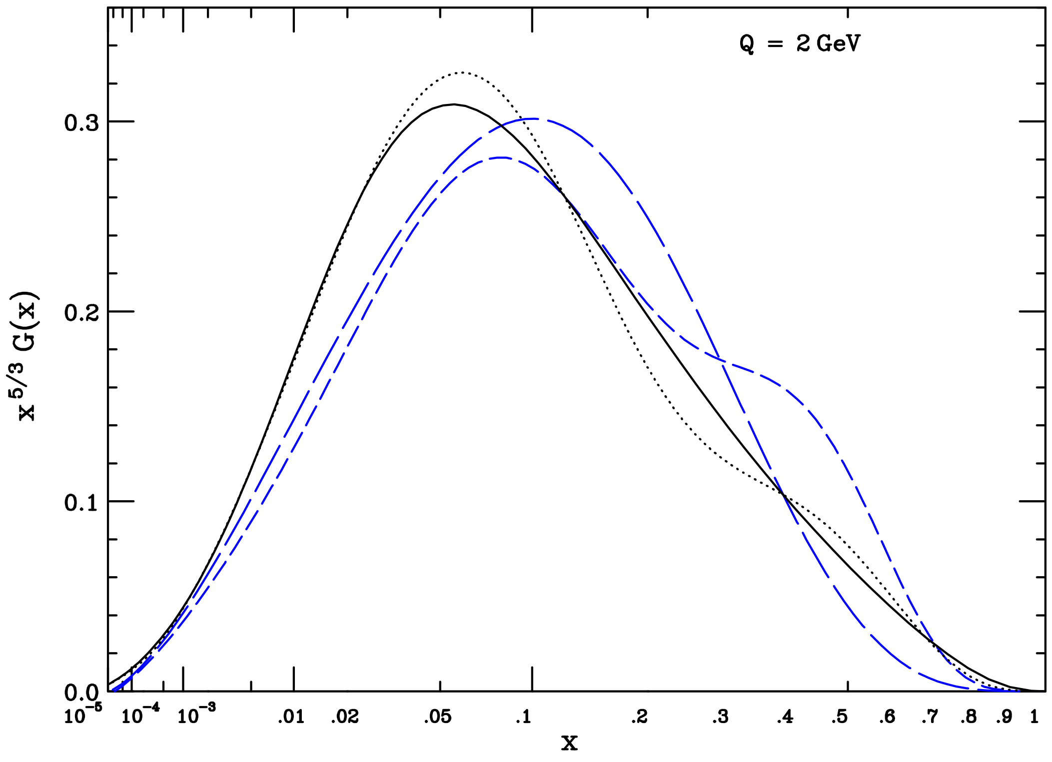
1. Data cut at $Q^2 = 4\ \mathrm{GeV}^2$ compared to $2\ \mathrm{GeV}^2$ for MRST

2. Some data sets missing (parts of SLAC, H1)

3. Use 10% systematic error for Drell-Yan data – MRST use only statistical errors

4. Positive definite gluon at small x at starting scale Q_0^2

5. Massless charm, different parametrisation, ...



Theory issues to address for improvements/error estimates

- massive quarks (VFNS for charm and bottom) – solved
- higher orders (NNLO) – nearly solved (2003?)
- small x ($\alpha_s^n \ln^{n-1}(1/x)$)
- large x ($\alpha_s^n \ln^{2n-1}(1-x)$)
- low Q^2 (higher twist)

Also need to consider effect of assumptions made during fit, e.g. constraint on large x gluon, form of strange sea, heavy flavour prescription, assumption of no isospin violation, cuts made on data ...

NNLO

DGLAP: $P(x,\alpha_s) = P^{(0)} + \alpha_s P^{(1)}(x) + \alpha_s^2 P^{(2)}(x) + \ldots$

Coeff. Function: $\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_s \hat{\sigma}^{(1)} + \alpha_s^2 \hat{\sigma}^{(2)} + \ldots$

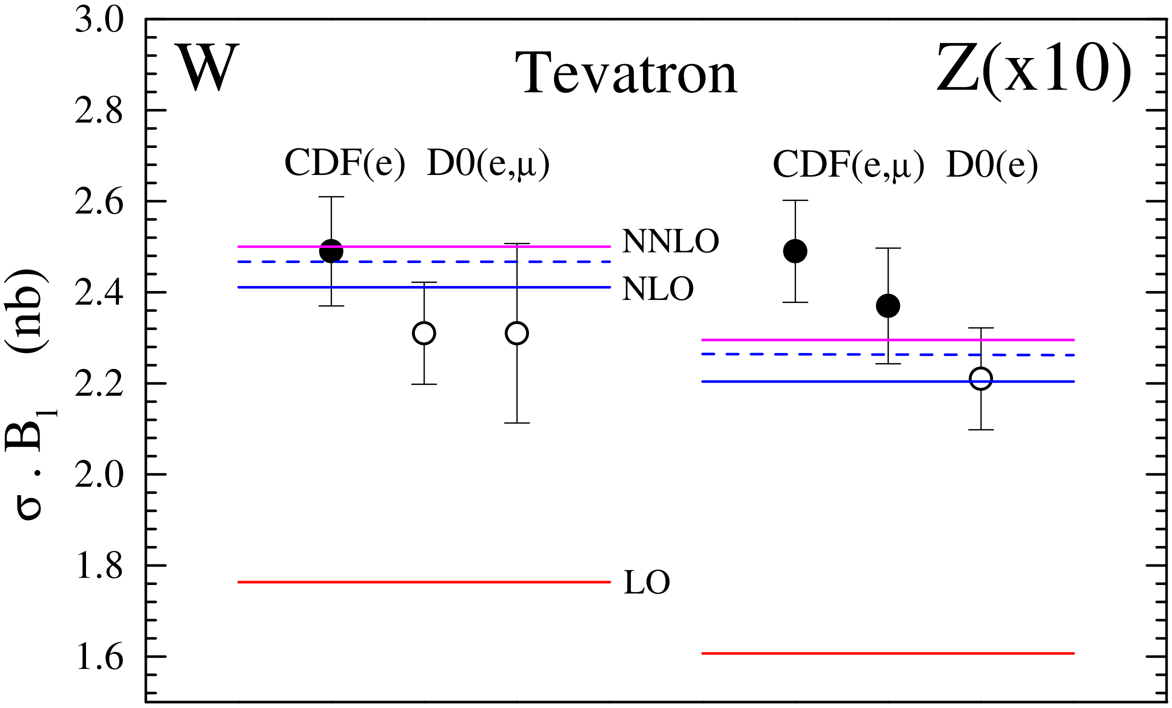
- approximations for $P^{(2)}(x)$ by van Neerven, Vogt using exact moment calculations by Larin, Nogueira, van Ritbergen, Retey, Vermaseren (combined with sum rule and symmetry constraints and known leading behaviour for $x \to 0,1)$; certainly sufficient for $x > 10^{-2}$ phenomenology, probably OK for $x > 10^{-4}$

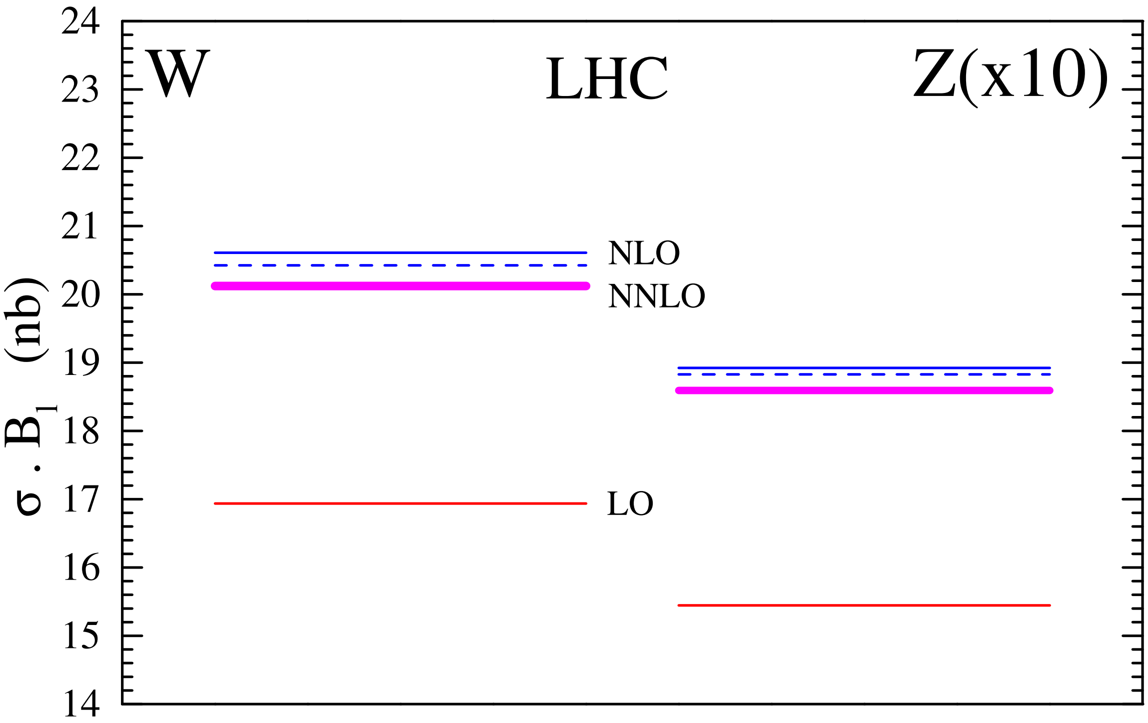
- full NNLO splitting functions expected soon (Note: Moch, Vermaseren, Vogt (hep-ph/0209100) exact n_f part of three-loop non-singlet splitting function)

- but note: $\hat{\sigma}^{(2)}$ still not calculated for many of the cross sections used in global fits, e.g. $d\sigma/dE_T^{jet}$, $d\sigma/dy_W$, $d^2\sigma^{DY}/dMdy$, ...

The (MRST2001) ‘NNLO’ fit

- quality of fit improved, but only slightly
- $\alpha_S^{NNLO}(M_Z^2) = 0.1155$ (determined mainly by high-x data)
- comparison of NLO and NNLO pdfs: differences in quarks reflects NNLO *vs.* NLO coefficient functions; NNLO gluon is smaller at small x due to positive NNLO $g \to q\bar{q}$ splitting function
- reasonable perturbative stability (LO $\to$ NLO $\to$ NNLO) for quark-dominated quantities, e.g. $\sigma_{W,Z}$, less so in gluon-dominated quantities, e.g. in F_L



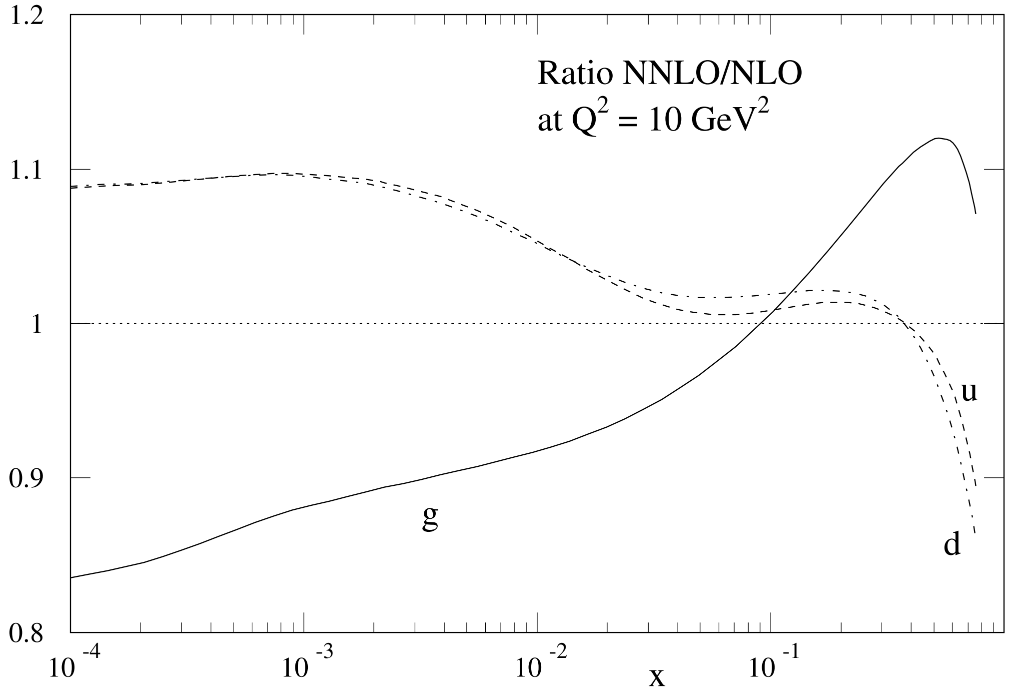


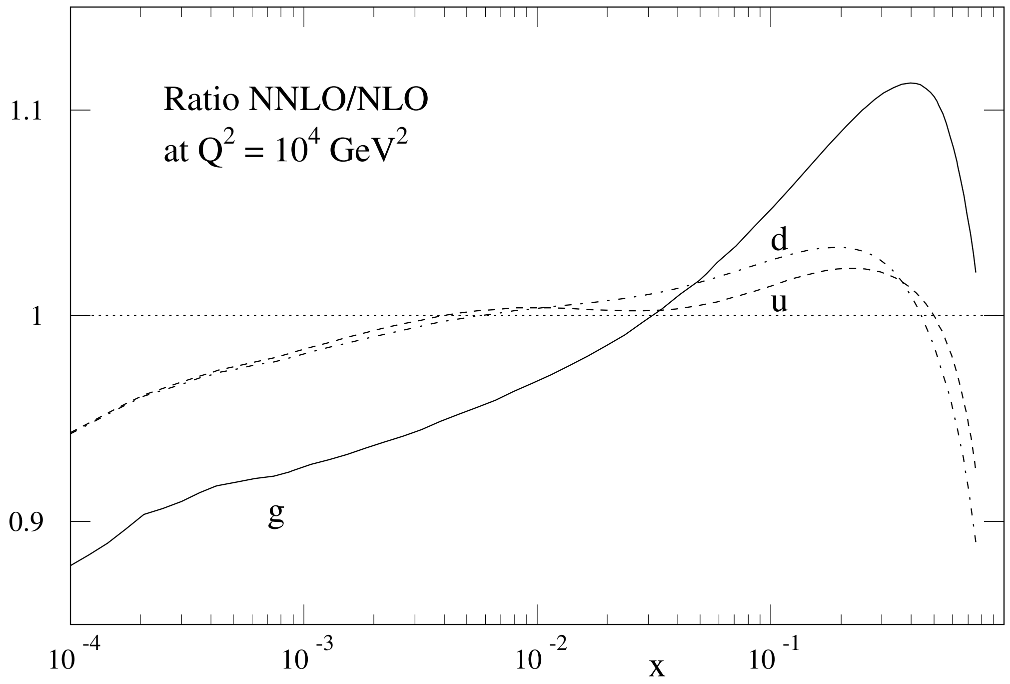
partons: MRST2001

NNLO evolution: van Neerven, Vogt approximation to Vermaseren et al. moments

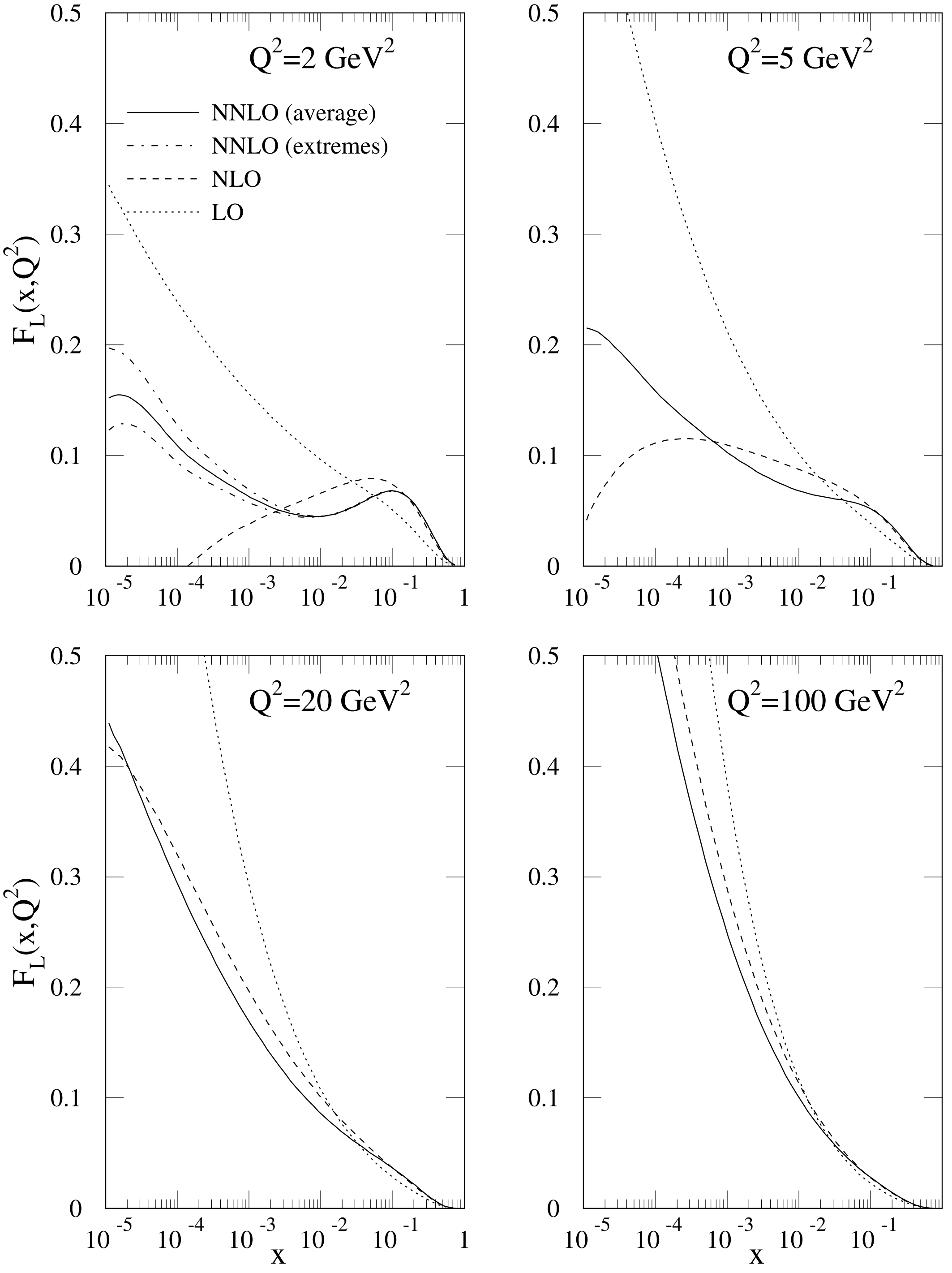
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

Comparison of MRST2001 NNLO and NLO Partons





Longitudinal structure function F_L



Influence of choice of cuts on fits

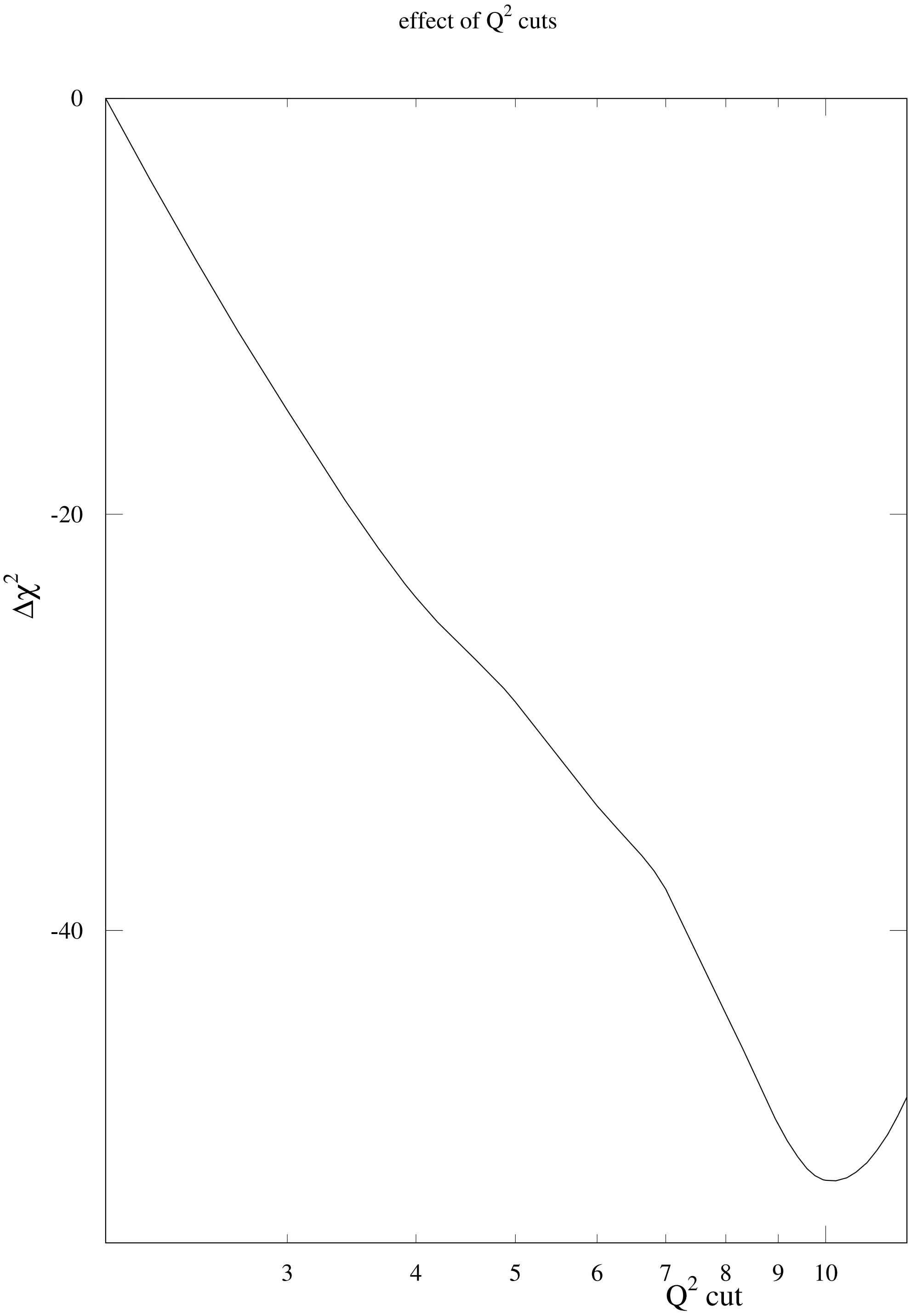
In order to investigate the real quality of fit and regions with problems we try varying kinematic cuts on data. Procedure is to change $W^2_{\rm cut}$, $Q^2_{\rm cut}$ and $x_{\rm cut}$, re-fit and see if quality of fit to remaining data improves and/or input parameters change dramatically.

For $W^2_{\rm cut}$ raising from $12.5\ {\rm GeV}^2$ has no effect.

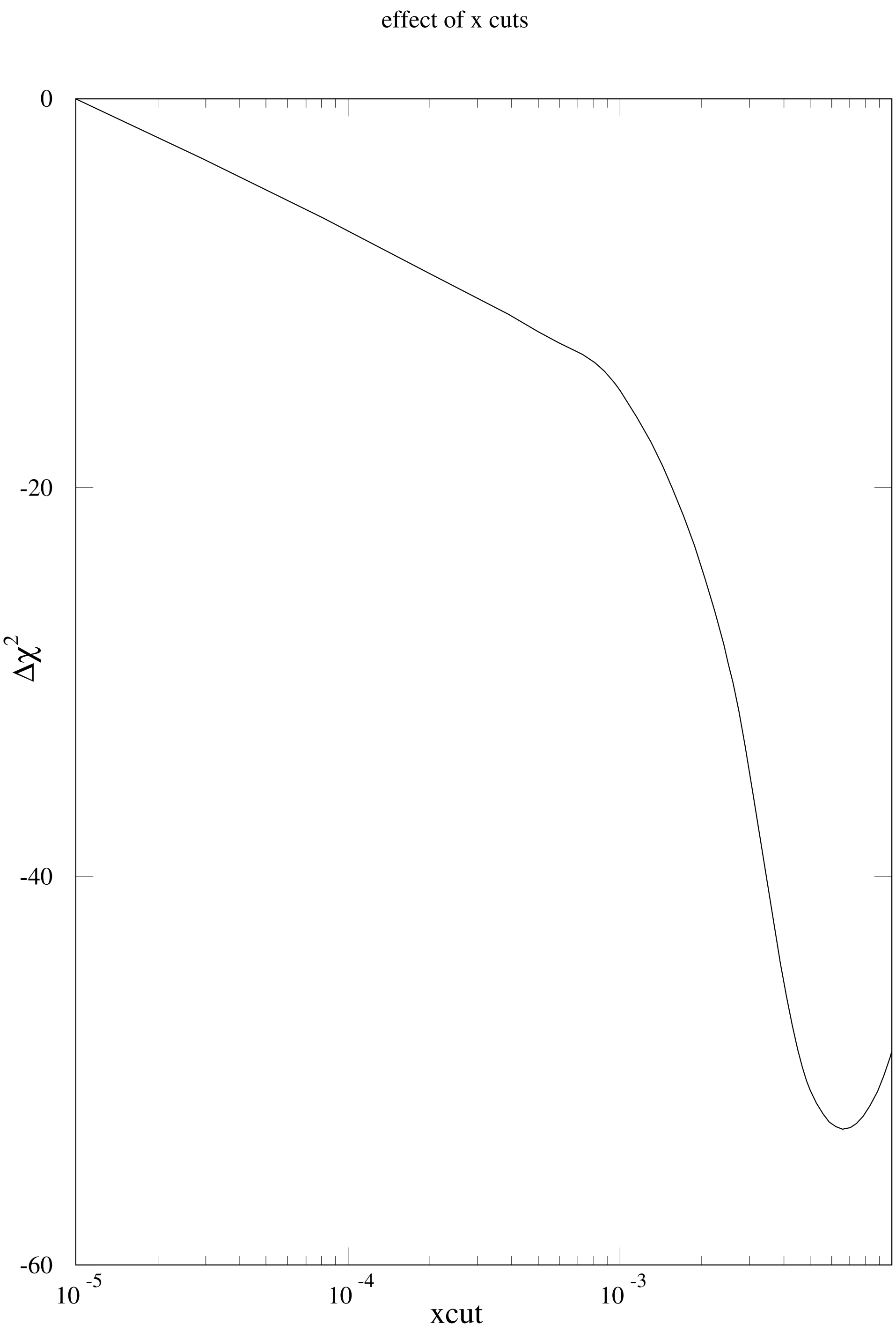
Raising $Q^2_{\rm cut}$ from $2\ {\rm GeV}^2$ gives slow continuous improvement up to about $Q^2_{\rm cut} = 12\ {\rm GeV}^2$ – $\Delta\chi^2 \approx -50$ and gluon becomes slightly smaller at small x and larger at high x ... no further improvement above this. Suggests any corrections are leading twist higher-order, not higher twist.

Raising $x_{\rm cut}$ from 0 to 0.0002 to 0.001 to 0.005 gives continuous improvement – $\Delta\chi^2 \approx -50$, $\delta_- \rightarrow 0.5$ and $\alpha_S(M_Z^2) \rightarrow 0.118$. Stability reached at $x \approx 0.005$. Input gluon now very negative at small x and fit to F_2 outside range is bad; tension reduced for data sets remaining in fit. Suggestive of higher-order $\log(1/x)$ corrections at small x?

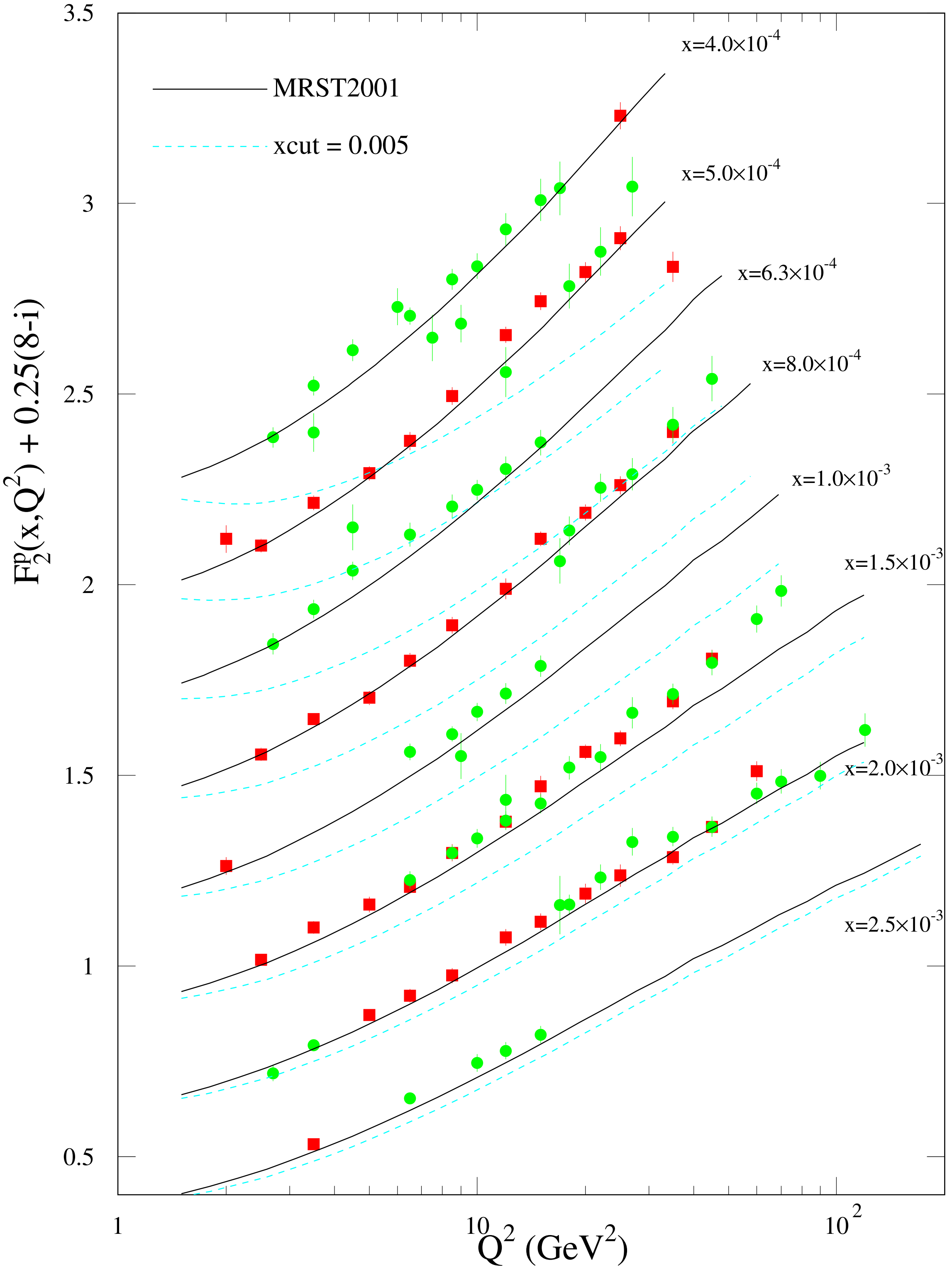
Improvement in fit when Q^2 cut on data is increased

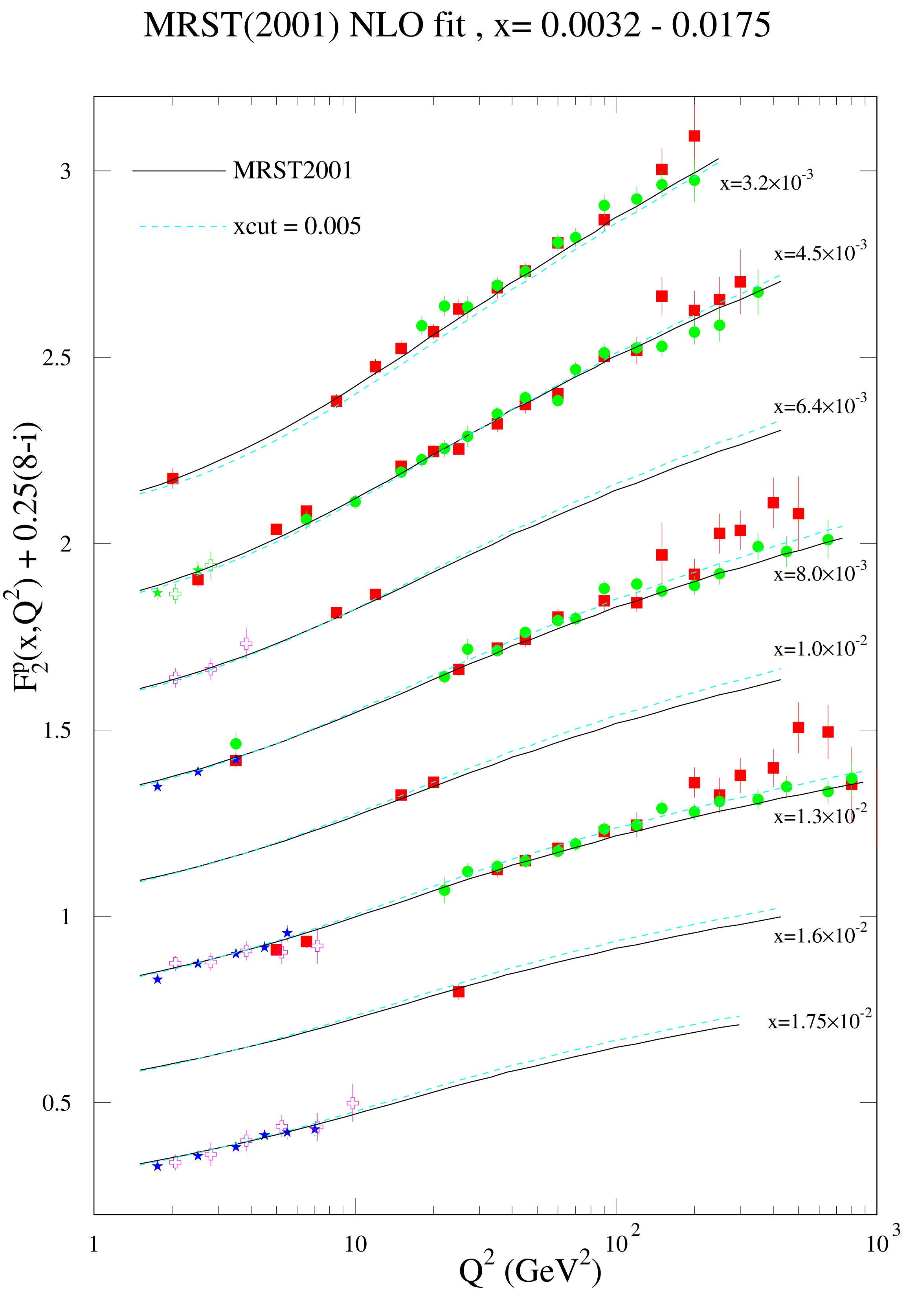


Improvement in fit when x cut on data is increased



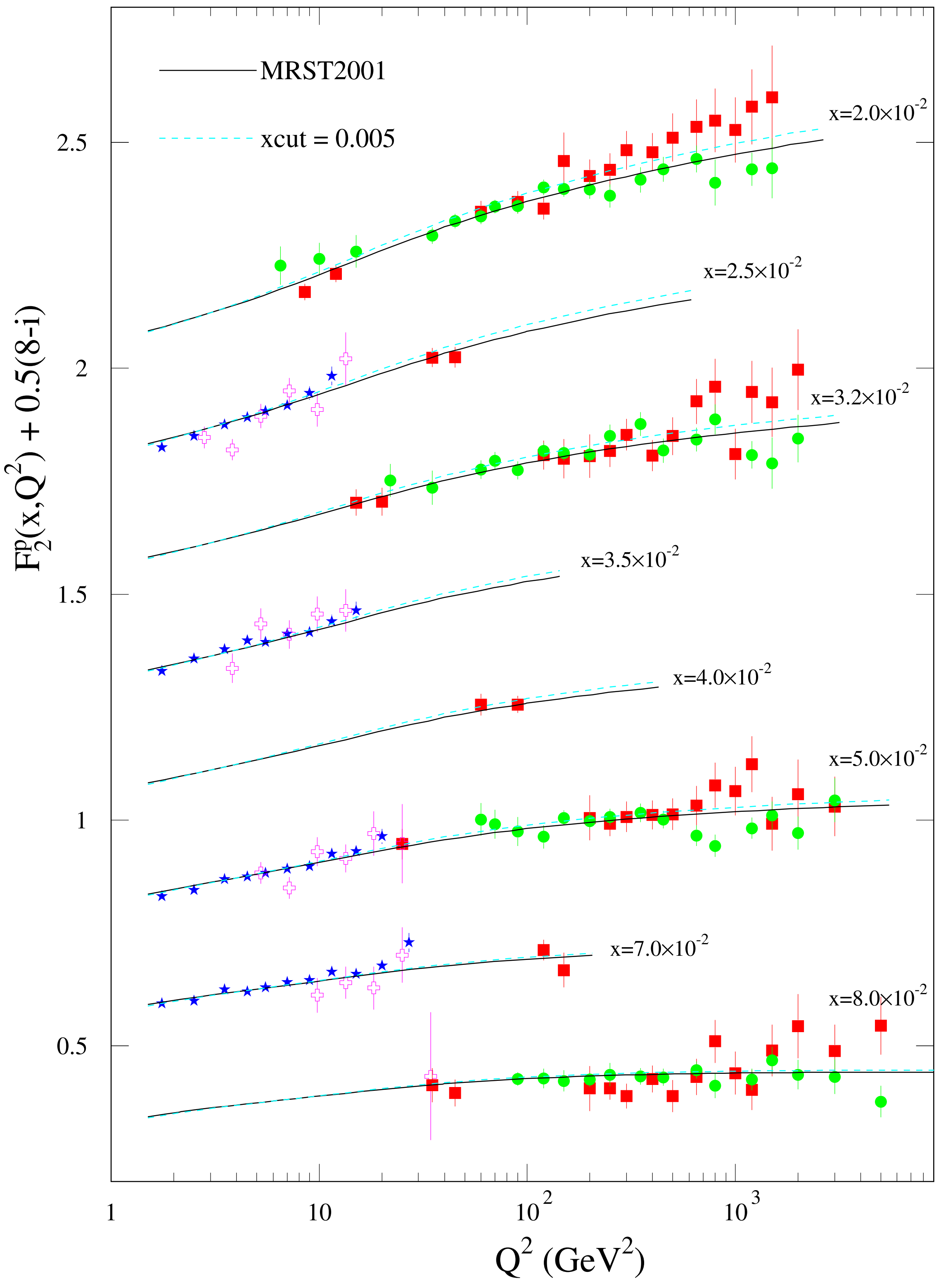
MRST(2001) NLO fit , x=0.0004 - 0.0025





MRST(2001) NLO fit , x= 0.0032 - 0.0175
MRST2001
xcut = 0.005
x=3.2×10^-3
x=4.5×10^-3
x=6.4×10^-3
x=8.0×10^-3
x=1.0×10^-2
x=1.3×10^-2
x=1.6×10^-2
x=1.75×10^-2
F2p(x,Q2) + 0.25(8-i)
Q2 (GeV2)

MRST(2001) NLO fit , x=0.02 - 0.08



Errors on partons and parton-related quantities

Currently receiving a lot of attention; various approaches being used. For review see Thorne et al. hep-ph/0205233 (Working Group at IPPP Statistics Workshop, March 2002)

1. Hessian (error matrix) approach (H1, ZEUS, CTEQ, Alekhin,...)

2. Offset method (H1, ZEUS, Zomer, Pascaud, Botje,...)

3. Statistical method (Giele, Keller, Kosower)

4. Lagrange Multiplier method (CTEQ, MRST, ...)

Contrast 1. ($\rightarrow$ generic pdfs sets which form uncertainty 'envelope') with 2. ($\rightarrow$ predicted error on particular observable due to pdfs)

In both cases, the main problem is **normalising** the overall uncertainty, i.e. $\Delta\chi^2 = ??$

Hessian Matrix approach

$$\chi^2 - \chi^2_{min} \equiv \Delta\chi^2 = \sum_{i,j} H_{ij}(a_i - a_i^{(0)})(a_j - a_j^{(0)})$$

The Hessian matrix H is related to the covariance matrix of the parameters by

$$C_{ij}(a) = \Delta\chi^2 (H^{-1})_{ij}$$

Then using the standard formula for linear error propagation:

$$(\Delta F)^2 = \Delta\chi^2 \sum_{i,j} \frac{\partial F}{\partial a_i}(H)^{-1}_{ij}\frac{\partial F}{\partial a_j}$$

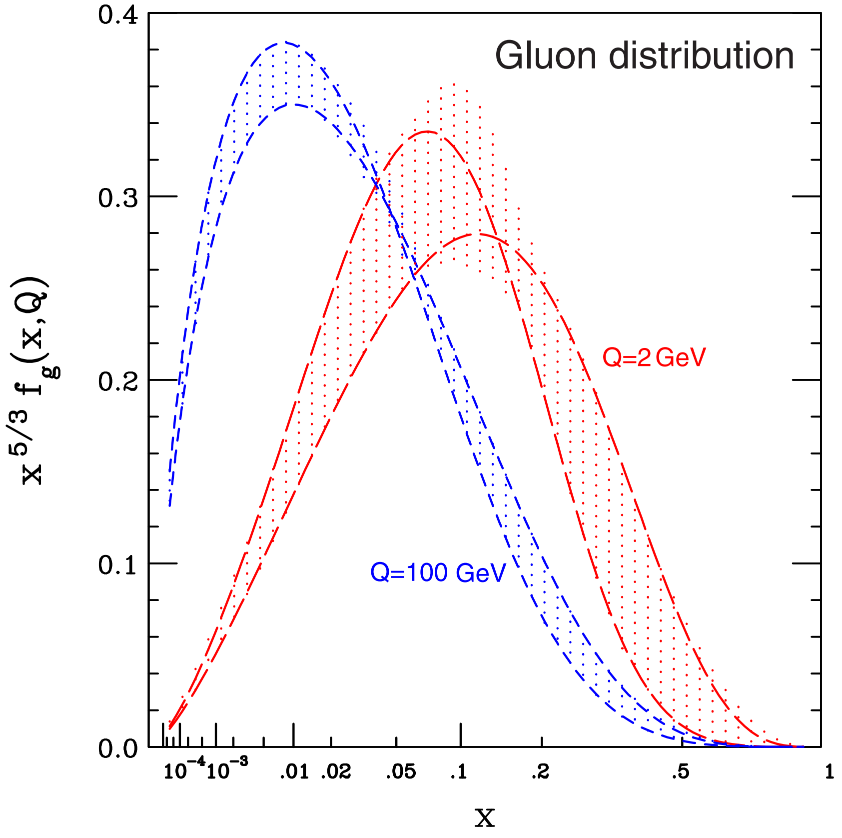
Problem due to extreme variations in $\Delta\chi^2$ in different directions in parameter space solved by finding and rescaling eigenvectors of H leading to diagonal form $\Delta\chi^2 = \sum_i z_i^2$

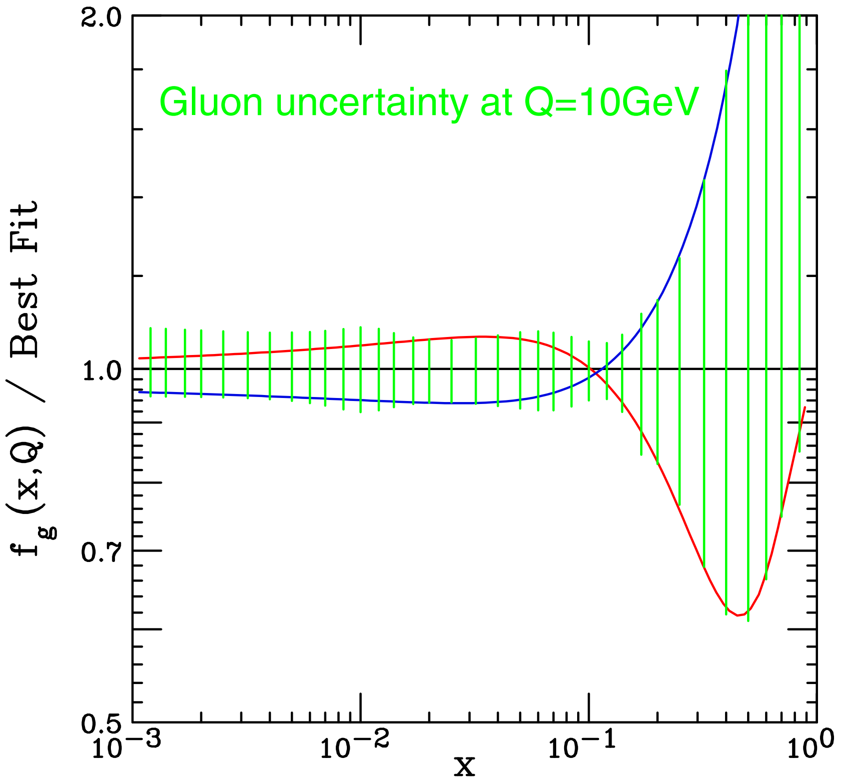
Uncertainty on physical quantity then given by

$$(\Delta F)^2 = \sum_i \left(F(S_i^{(+)}) - F(S_i^{(-)})\right)^2$$

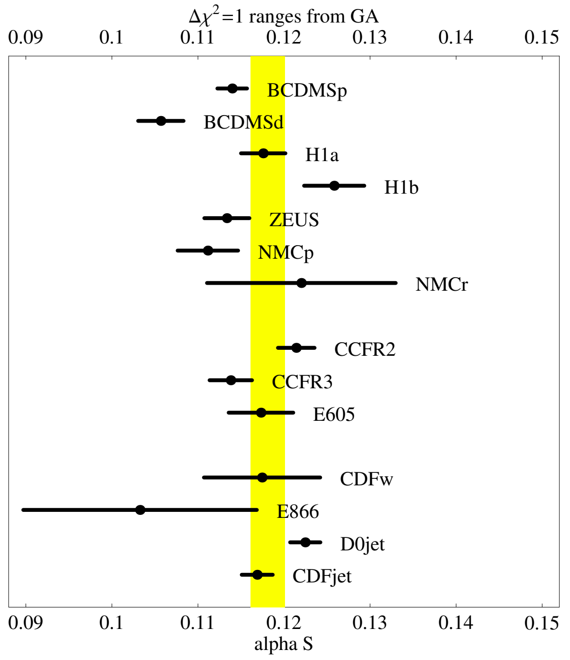
where $S_i^{(+)}$ and $S_i^{(-)}$ are pdf sets displaced along eigenvector direction by given $\Delta\chi^2$. Art in choosing 'correct' $\Delta\chi^2$ given complication of errors in full fit: CTEQ choose $\Delta\chi^2 \sim 100$

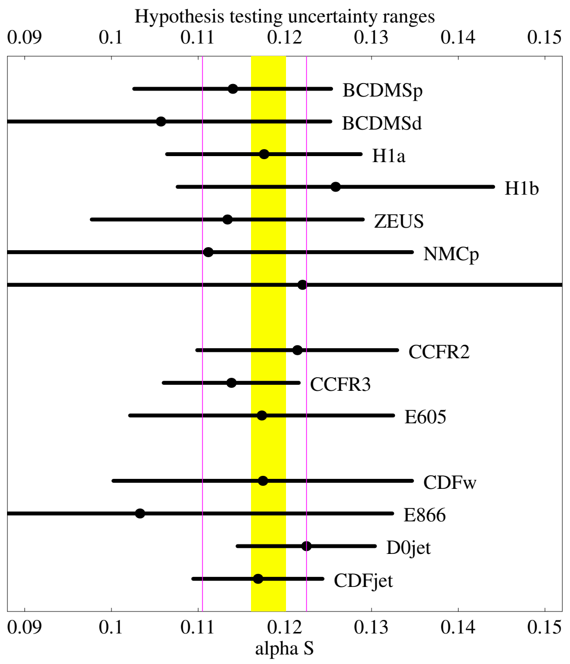
Results of CTEQ Hessian approach for gluon uncertainty





CTEQ α_S values, with $\Delta\chi^2 = 1,\ 100$





Statistical approach (GKK)

Construct an ensemble of distributions labeled by $\mathcal{F}$ each with probability $P(\{\mathcal{F}\})$. Mean μ_O and deviation σ_O of observable O then given by

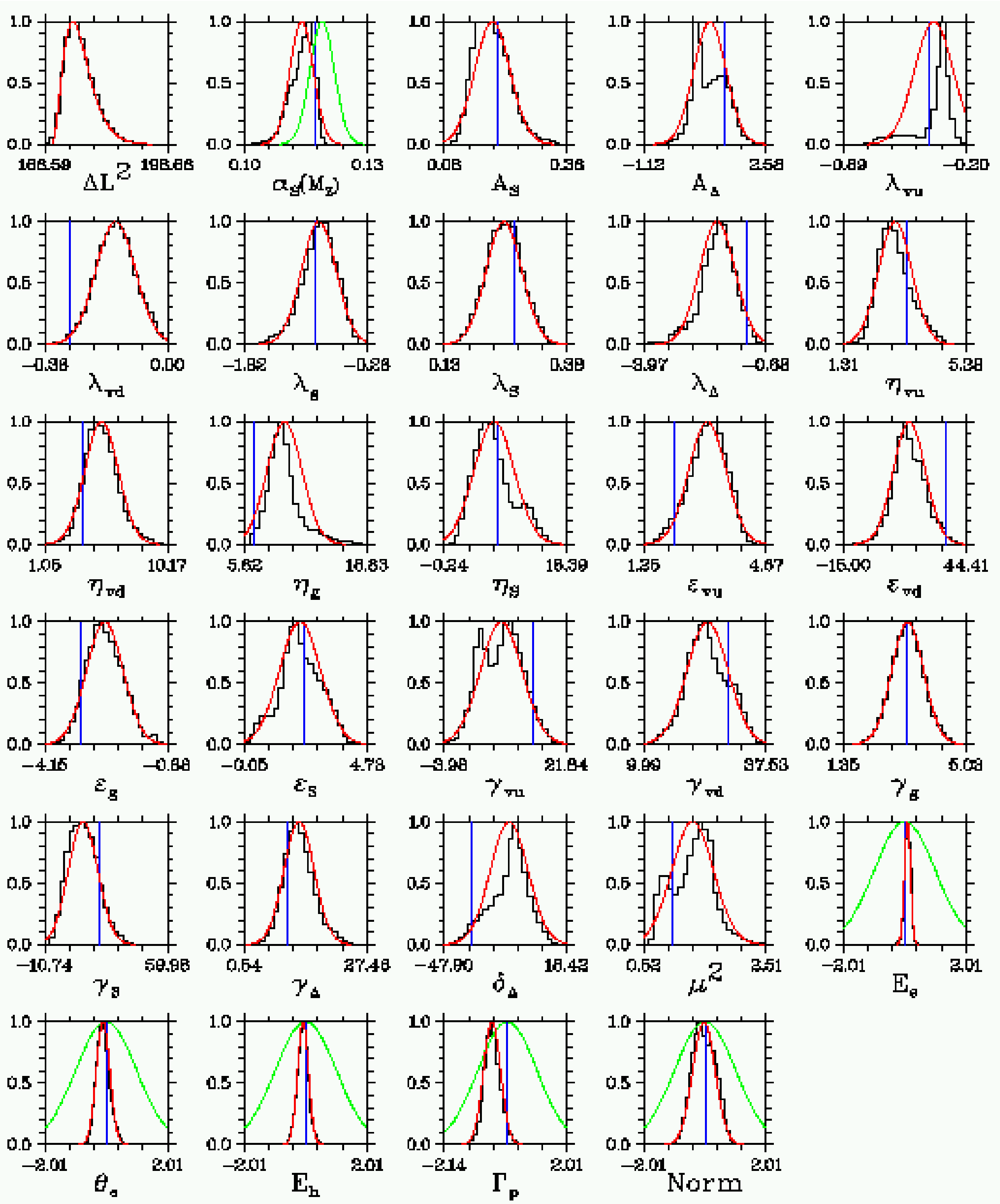
$$\mu_O = \sum_{\{\mathcal{F}\}} O(\{\mathcal{F}\})P(\{\mathcal{F}\}), \quad \sigma_O^2 = \sum_{\{\mathcal{F}\}} (O(\{\mathcal{F}\}) - \mu_O)^2 P(\{\mathcal{F}\}).$$

Note that this is statistically correct, and does not rely on the approximation of linear propagation errors in calculating observables. However it is somewhat inefficient – in practice generate $N_{pdf} \sim 100$ different sets of pdfs with unit weight but distributed according to $P(\{\mathcal{F}\})$

$$\mu_O = \frac{1}{N_{pdf}} \sum_{1}^{N_{pdf}} O(\{\mathcal{F}\}), \quad \sigma_O^2 = \frac{1}{N_{pdf}} \sum_{1}^{N_{pdf}} (O(\{\mathcal{F}\}) - \mu_O)^2.$$

Can incorporate full information about measurements and their error correlations in the calculation of $P(\{\mathcal{F}\})$

Currently uses only proton DIS data sets in order to avoid complicated uncertainty issues such as shadowing effects for nuclear targets etc



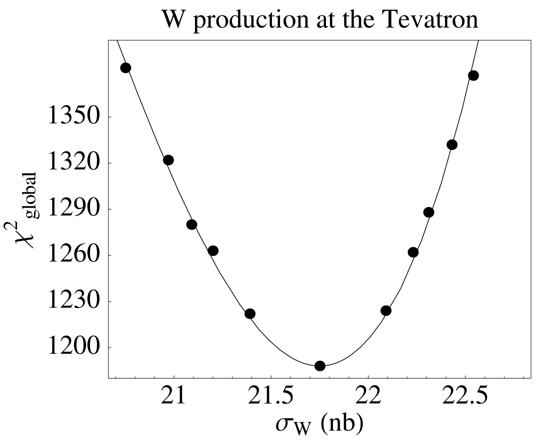
'H1' set of parton parameters from GKK. Red curve Gaussian approx. and blue line MRST value. Green curve for α_S is LEP result.

Lagrange Multiplier method

First suggested by CTEQ. Perform fit while constraining value of some physical quantitity F. Minimize

$$\Psi(\lambda, a) = \chi^2_{\mathrm{global}}(a) + \lambda F(a)$$

for various values of λ and parton parameters $\{a\}$. Gives set of best fits for particular values of parameter $F(a)$ without relying on Gaussian approximation for χ^2, e.g. W cross section at Tevatron:



Uncertainty then determined by deciding allowed range of $\Delta\chi^2$. Can also see which data sets in global fit most directly influenced by variation in $F(a)$. Typically deterioration in χ^2 comes from 2 or 3 data sets. MRST impose (rough) criterion that for all data well fit by central best fit no data set has worse than 1% confidence level $\Rightarrow \Delta\chi^2 \approx 50$

As a specific example, we consider W and Higgs cross sections at Tevatron and LHC

Find for $\alpha_S = 0.119$

$$\Delta\sigma_W(\mathrm{Tev}) \approx \pm 1.2\% \quad \Delta\sigma_{\mathrm{W}}(\mathrm{LHC}) \approx \pm 2\%$$

$$\Delta\sigma_H(\mathrm{Tev}) \approx \pm 4\% \quad \Delta\sigma_{\mathrm{H}}(\mathrm{LHC}) \approx \pm 2\%.$$

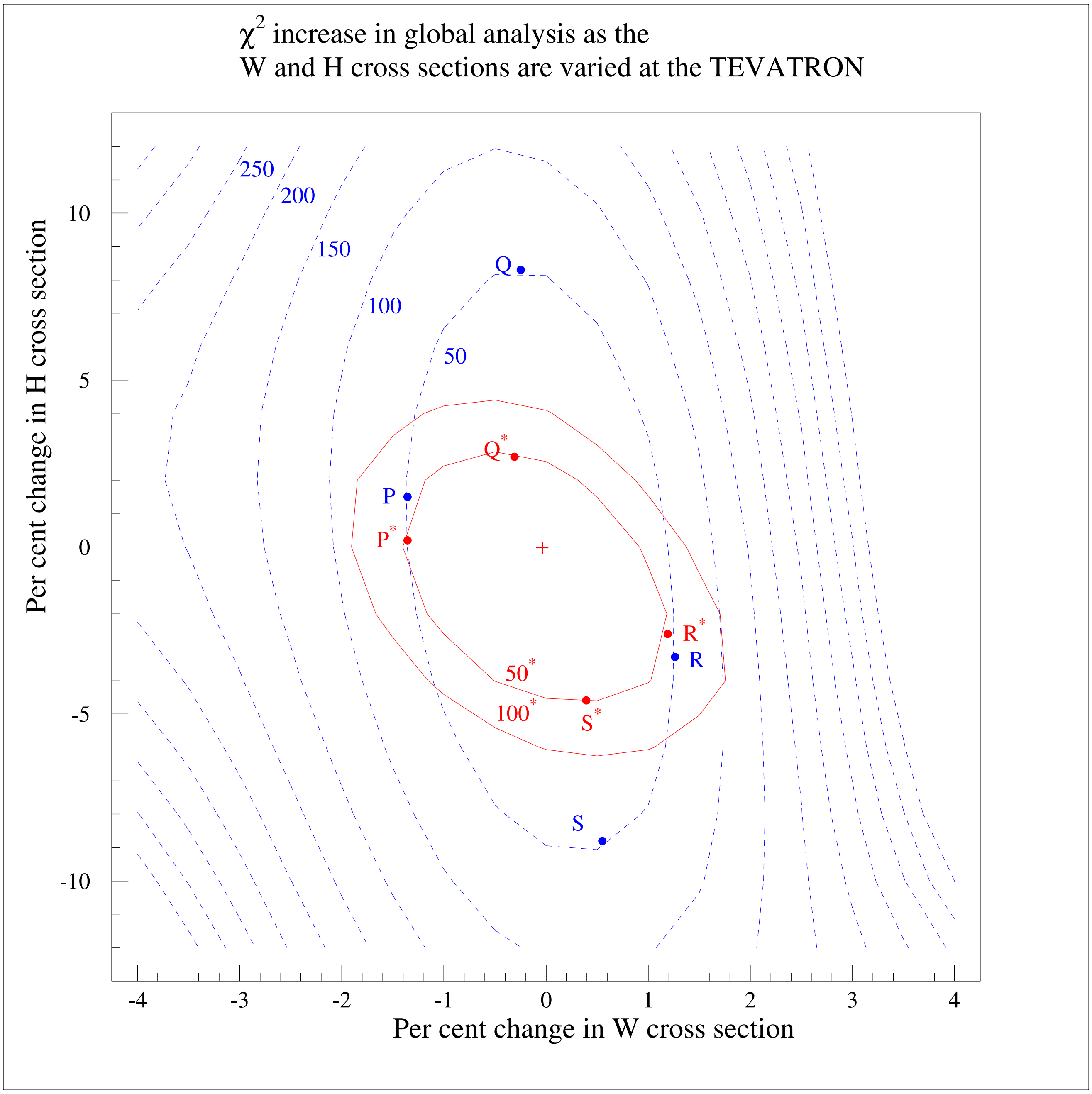
(Note: if α_S also varies $\Delta\sigma_W$ fairly stable but $\Delta\sigma_H$ almost doubles)

Can repeat for other processes, for example

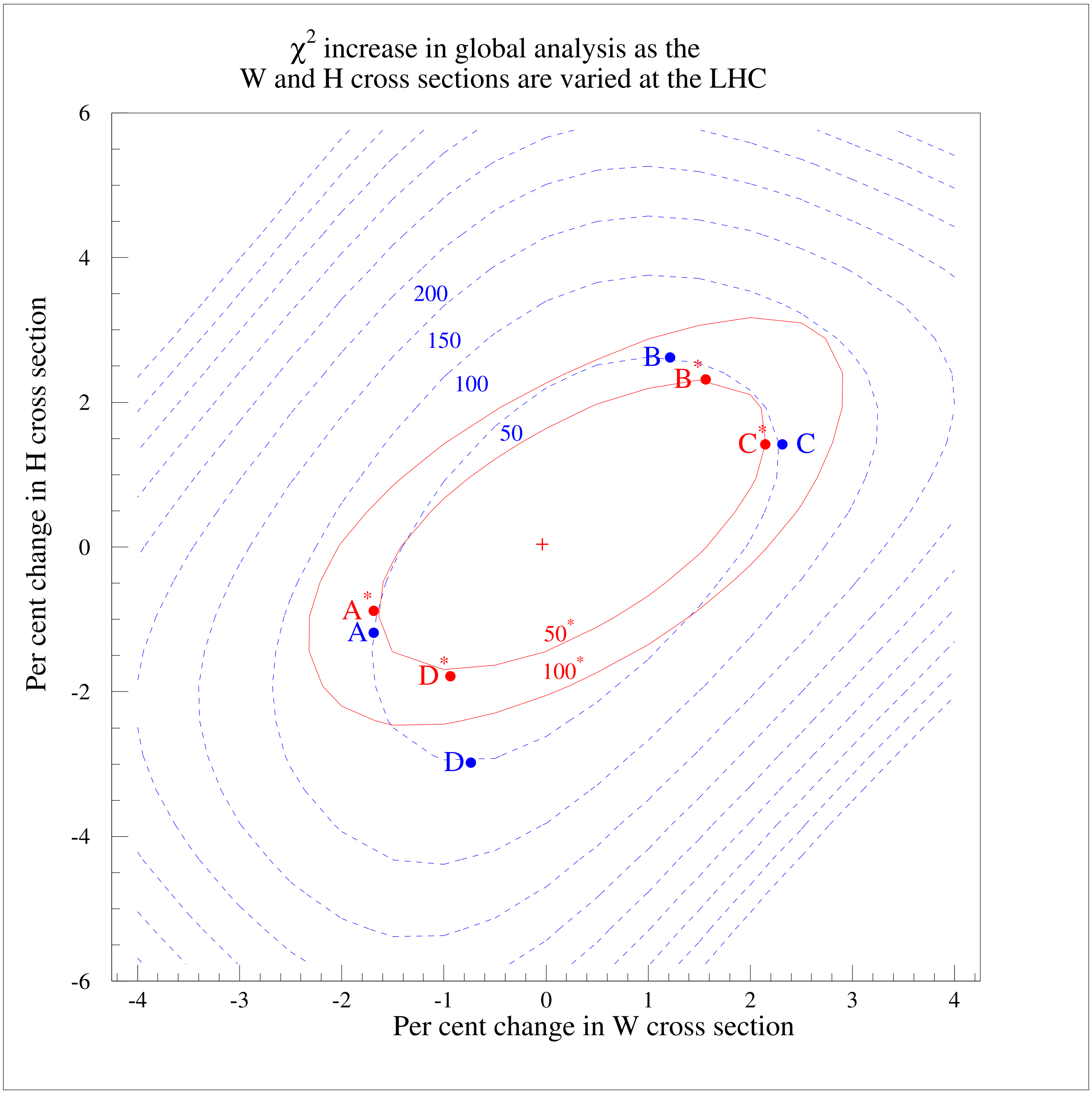
- HERA charged current data sensitive to very high x quarks
- Tevatron jet data sensitive to high x gluon.
- moments of pdfs (e.g. for comparison with lattice calculations)

Hence conclude that uncertainty due to experimental errors rather small; only more than few $\%$ for quantities determined by high x gluon and very high x down quark.

χ^2-plot for W and Higgs production at the Tevatron α_S free and fixed at $\alpha_S = 0.119$.



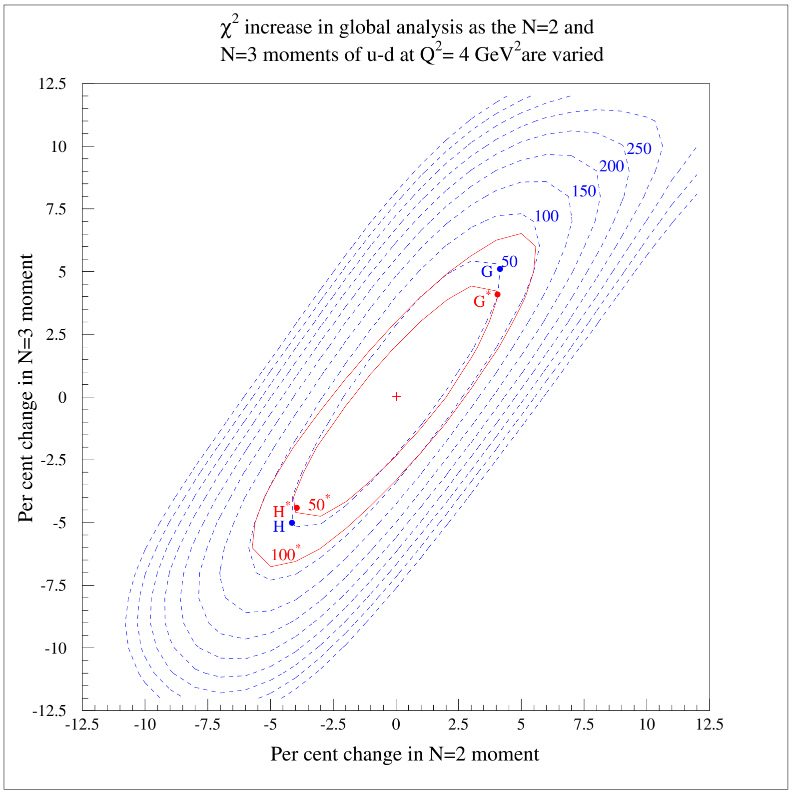
χ^2-plot for W and Higgs production at the LHC α_S free and fixed at $\alpha_S = 0.119$.



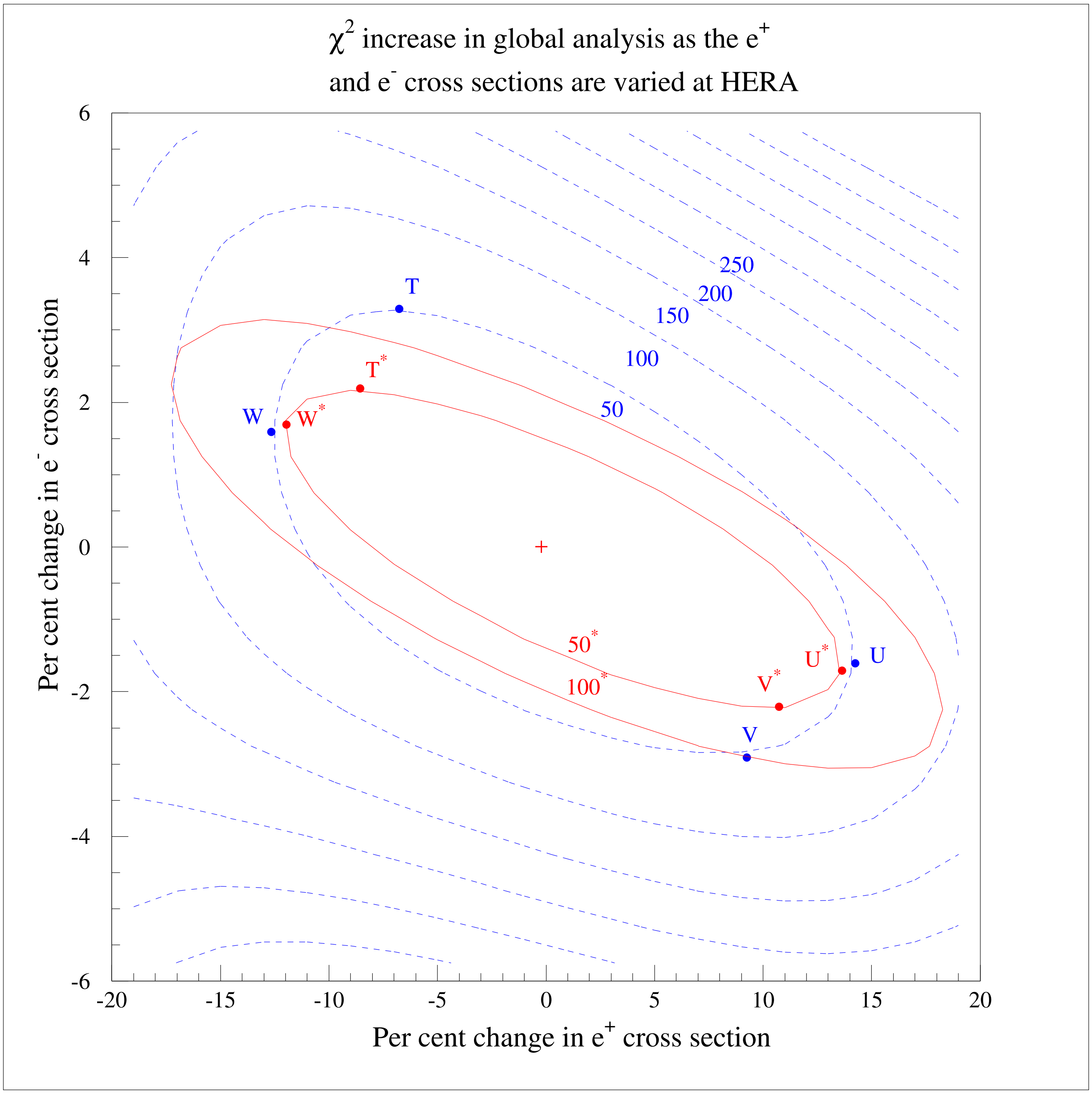
Predictions for moments

$$M_N(Q^2) = \int_0^1 dx\; x^{N-1}\; [u(x,Q^2) - d(x,Q^2)]$$

N	M_N	% error
2	0.1655(66)	4
3	0.0544(27)	5
4	0.0232(14)	6



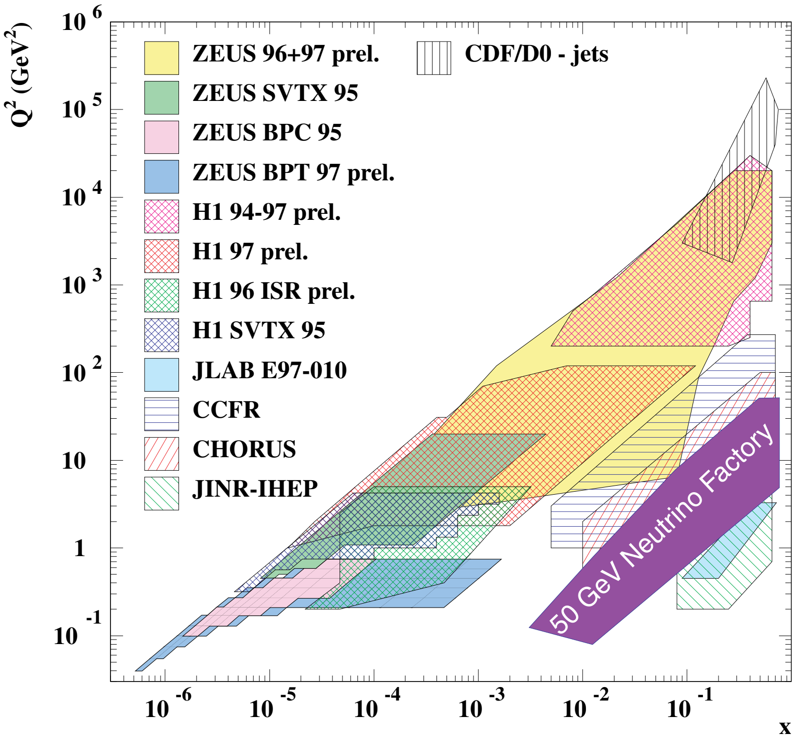
χ^2-plot for $F_2^{CC}(e^{\pm}p)$ at HERA at $x = 0.5$ for α_S free and fixed at $\alpha_S = 0.119$.



DIS at a Neutrino Factory?

- υN plays a central role in current DIS unpolarised phenomenology, but precision is limited because
  - dense nuclear targets required ($\Rightarrow$ heavy target effects)
  - E_ν not well determined
  - $N_\nu \neq N_{\bar{\nu}}$
  - no *polarised* υN, therefore fewer constraints on spin-dependent pdfs

- a $\boxed{\text{neutrino factory}}$ would allow
  - high-intensity, collimated, polarised ν and $\bar{\nu}$ beams
  - high statistics for H_2, D_2 (polarisable) targets
  - well-defined (variable) beam energies
  - medium-high x in the deep $Q^2 > \mathcal{O}(1\ \mathrm{GeV}^2)$ region



Physics summary

(see e.g. Mangano et al. 2001, hep-ph/0105155)

- flavour decomposition (unpolarised)

$$\frac{d^2\sigma^{\nu,\bar\nu}}{dxdy} = \frac{sG_F^2}{4\pi(1+Q^2/M_W^2)^2}\left[Y_+F_2^{\nu,\bar\nu} \mp Y_- xF_3^{\nu,\bar\nu} - \ y^2F_L^{\nu,\bar\nu}\right]$$

with $Y_\pm = 1 \pm (1-y)^2$. $F_L^{\nu,\bar\nu} = 0$ in parton model and

$$\begin{aligned}
F_2^{\nu} &= 2x\,[\,d+s+\bar u+\bar c\,] \\
F_2^{\bar\nu} &= 2x\,[\,u+c+\bar d+\bar s\,] \\
xF_3^{\bar\nu} &= 2x\,[\,u+c-\bar d-\bar s\,] \\
xF_3^{\nu} &= 2x\,[\,d+s-\bar u-\bar c\,] \qquad \text{(no CKM)}
\end{aligned}$$

with 6 linearly independent SFs from $\nu,\bar\nu$ on p,n measuring 6 combinations of $u,d,c,s,\bar u,\bar d,\bar s,\bar c$ — charm tagging gives further separation and CKM angles V_{dc}, V_{sc}

- sum rules, e.g. Gross–Llewellyn Smith ($a = \alpha_S/\pi$)

$$\begin{aligned}
\int_0^1 dx[F_3^{\nu p} + F_3^{\bar\nu p}] &= 6\Big[1 - a - 3.58a^2 - 18.98a^3 + \ldots \\
&\qquad -C_2/Q^2 + \mathcal{O}(1/Q^4)\Big]
\end{aligned}$$

and DGLAP evolution $\partial F_3/\partial\ln Q^2 = (a/2)P_{qq}\otimes F_3 + \ldots$

- heavy target dependence of individual pdfs

Conclusions

- More and more precision data being added to global fit analyses; but overall the (NLO-QCD) fit is still good, although perhaps evidence of a slight problem in F_2 at medium x, high Q^2, and in reconciling jet and DIS data

- NNLO is the next frontier. No significant improvement likely in full NNLO fit to DIS data. Still a number of important input cross sections not yet known to NNLO.

- Much effort being devoted to parton distribution uncertainties, either as errors on the pdfs themselves or effect on particular observables, e.g. σ_H. Important to distinguish quantifiable errors from input data, from hard-to-estimate uncertainties due to theoretical input assumptions (treatment of heavy quarks, heavy target corrections, parametrisation form, data cuts, etc). In many cases these are likely to dominate.