Update on MRST Parton Distributions

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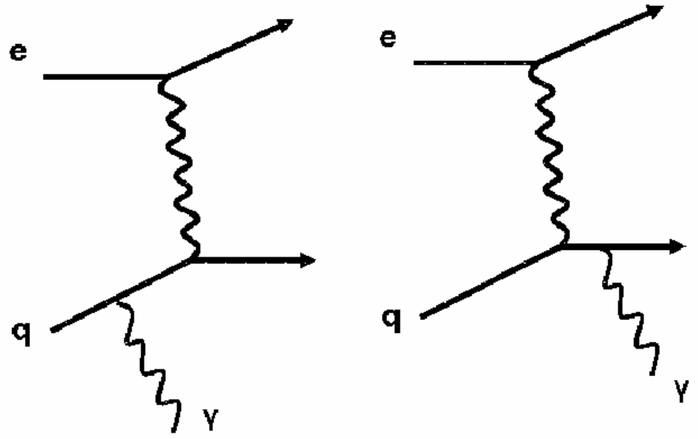
- QED-improved parton distributions
- a new approach to the high-x gluon distribution

(with Alan Martin, Dick Roberts and Robert Thorne)

QED effects in pdfs

De Rujula, Petronzio, Savoy-Navarro 1979
Krifganz, Perlt 1988
Bluemlein 1990
Spiesberger 1994
Roth, Weinzierl 2004

QED corrections to DIS include:

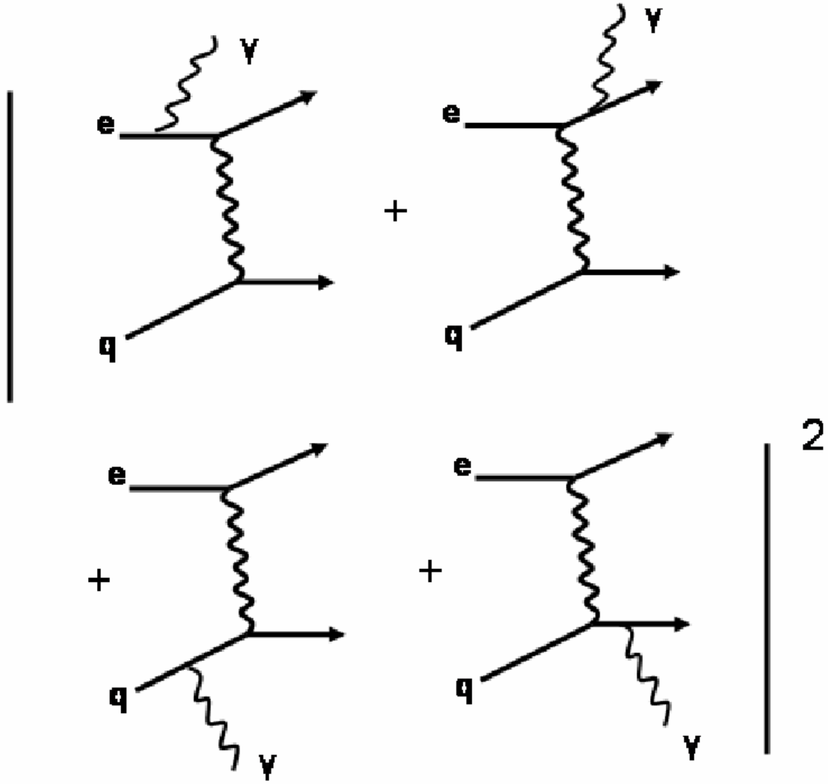


$\Rightarrow$ mass singularity when $\gamma \parallel q$

$$\frac{\alpha}{2\pi} \langle e_q^2 \rangle \ln \left(\frac{Q^2}{m_q^2} \right) \simeq 0.01$$

for $Q = 100$ GeV, $m_q = 10$ MeV, $\langle e_q^2 \rangle = 5/18$.

included in standard radiative correction packages (HECTOR, HERACLES)

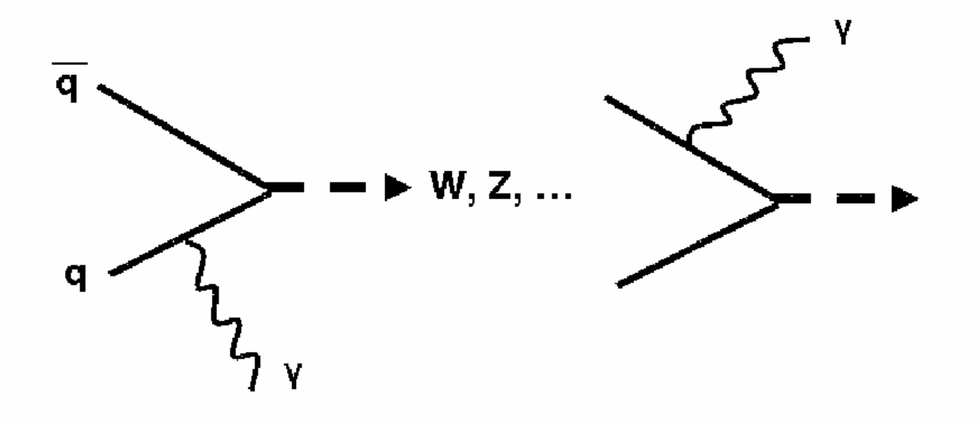


$+$ loop corrections

$$\Rightarrow \quad \frac{\alpha}{\pi} \left[\mathcal{C}_{\text{lept}} + e_q^2\, \mathcal{C}_{\text{quark}} + e_q\, \mathcal{C}_{\text{int}} \right]$$

Note: C_{int} finite as $m_q \to 0$

- above QED corrections are *universal* and can be absorbed into pdfs, exactly as for QCD singularities, leaving finite (as $m_q \to 0$) O(α) QED corrections in coefficient functions



- relevant for electroweak correction calculations for processes at Tevatron & LHC, e.g. W, Z, WH, …

  (see e.g. U. Baur et al, PRD 59 (2003) 013002)

QED-improved DGLAP equations

- at leading order in α and α_S

$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{qq}(y)\ q_i(\frac{x}{y},\mu^2) + P_{qg}(y,\alpha_S)\ g(\frac{x}{y},\mu^2)\right\}$$
$$+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{\tilde{P}_{qq}(y)\ e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\ e_i^2\gamma(\frac{x}{y},\mu^2)\right\}$$

$$\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{gq}(y)\ \sum_j q_j(\frac{x}{y},\mu^2) + P_{gg}(y)\ g(\frac{x}{y},\mu^2)\right\}$$

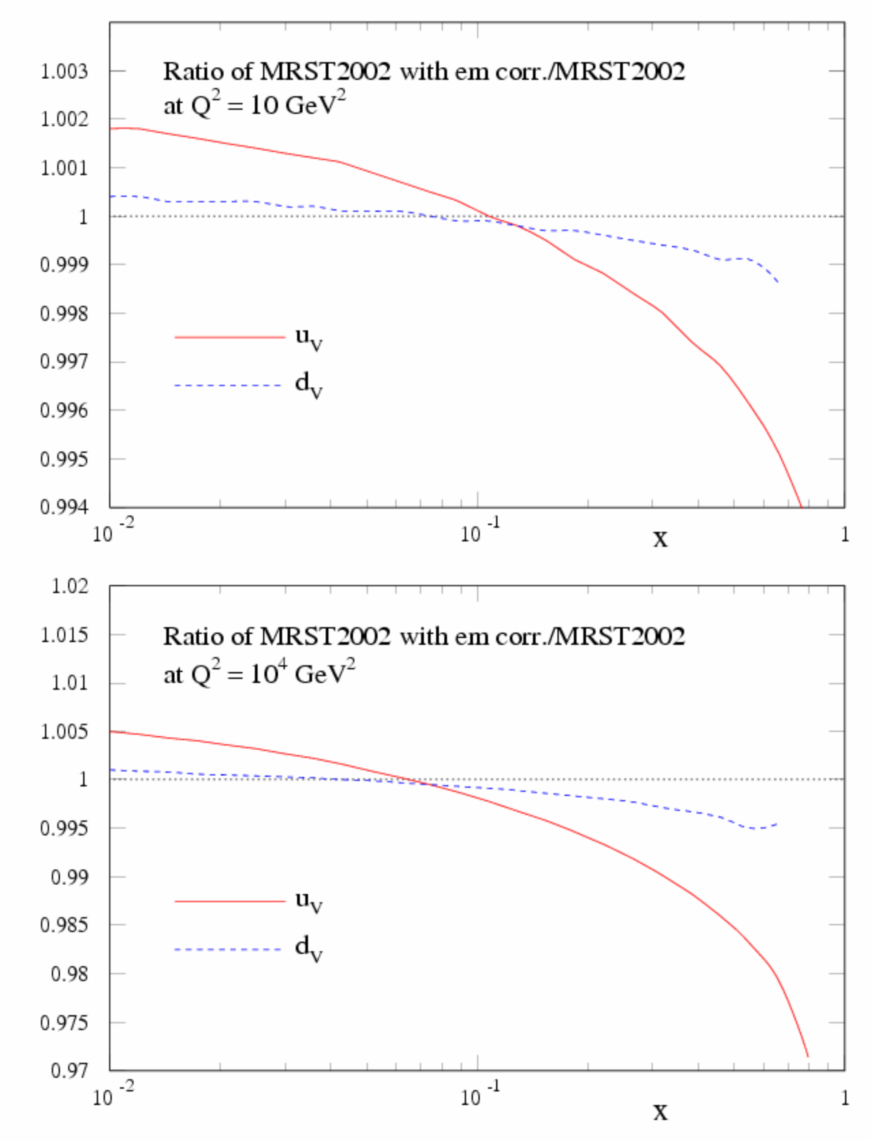
$$\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{\gamma q}(y)\ \sum_j e_j^2\ q_j(\frac{x}{y},\mu^2) + P_{\gamma\gamma}(y)\ \gamma(\frac{x}{y},\mu^2)\right\}$$

where

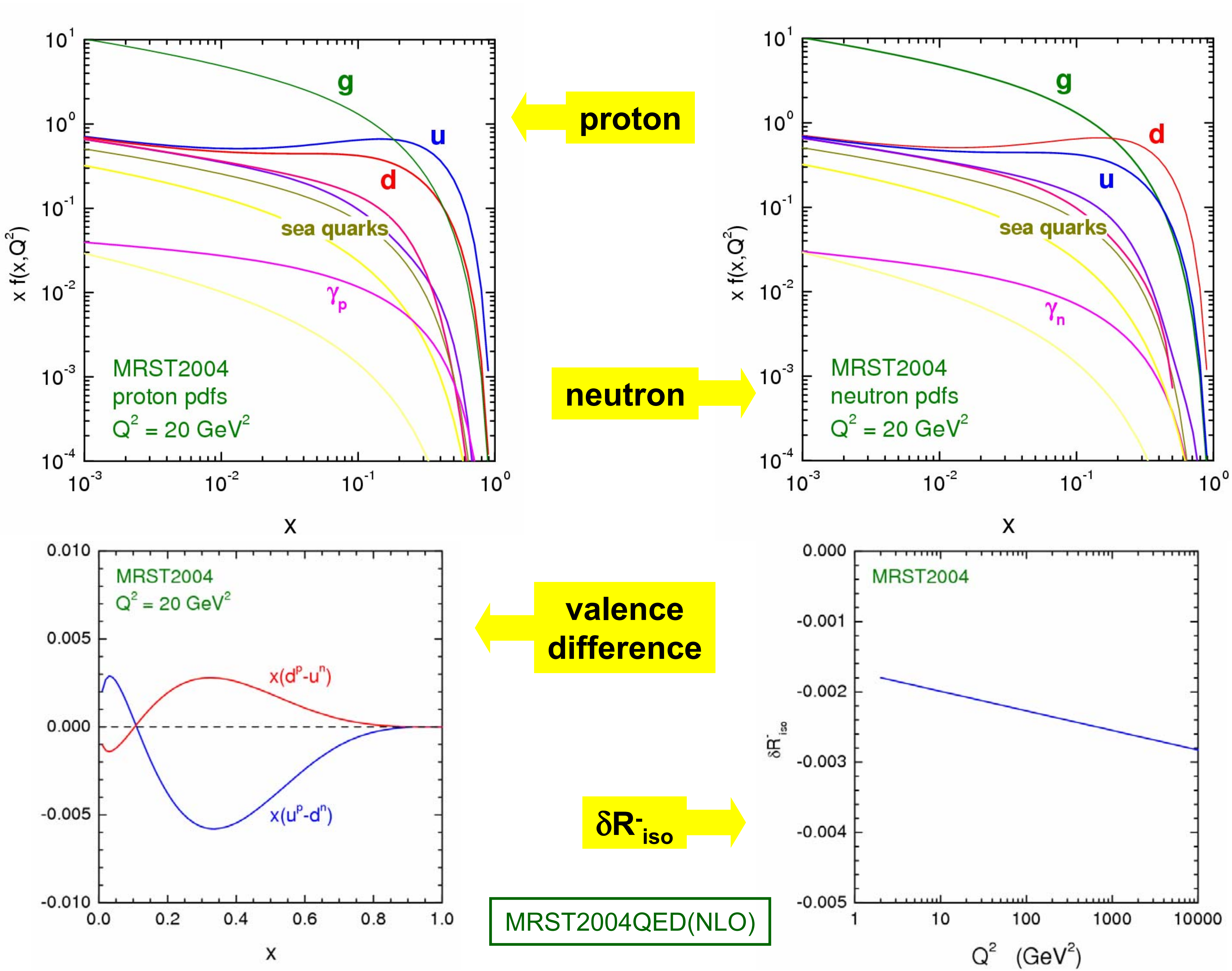
$$\tilde{P}_{qq} = C_F^{-1} P_{qq}, \qquad P_{\gamma q} = C_F^{-1} P_{gq},$$
$$P_{q\gamma} = T_R^{-1} P_{qg}, \qquad P_{\gamma\gamma} = -\frac{2}{3}\sum_i e_i^2\ \delta(1-x)$$

- momentum conservation: $\int_0^1 dx\ x\left\{\sum_i q_i(x,\mu^2) + g(x,\mu^2) + \gamma(x,\mu^2)\right\} = 1$

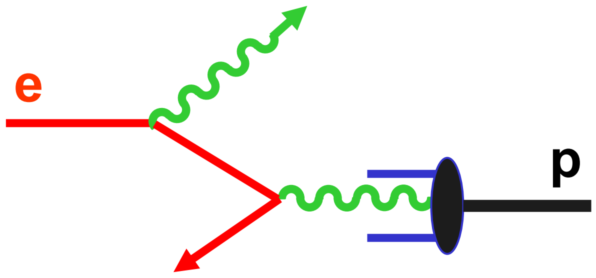
effect on valence quark evolution:

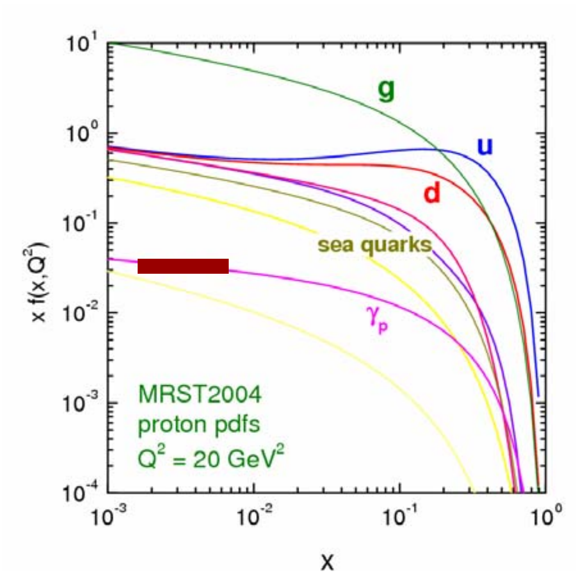


- effect on quark distributions negligible at small x where gluon contribution dominates DGLAP evolution
- at large x, effect only becomes noticeable (order percent) at very large Q^2, where it is equivalent to a shift in α_S of $\Delta\alpha_S \approx 0.0003$
- dynamic generation of photon parton distribution
- isospin violation: $u^p(x) \neq d^n(x)$
- first consistent global pdf fit with QED corrections included (MRST2004QED @ NLO and NNLO QCD)
- QED fit is of very similar quality to standard global fit: improved fit to deuterium data balanced by overall deterioration due to smaller gluon


proton
neutron
valence difference
δR⁻iso
MRST2004QED(NLO)
MRST2004
proton pdfs
Q² = 20 GeV²
MRST2004
neutron pdfs
Q² = 20 GeV²
g
u
d
sea quarks
γp
γn
x f(x,Q²)
x
MRST2004
Q² = 20 GeV²
x(dᵖ-uⁿ)
x(uᵖ-dⁿ)
MRST2004
δR⁻iso
Q² (GeV²)

first measurement of $\gamma_p(x,Q^2)$?





ZEUS: "Observation of high E_T photons in deep inelastic scattering", hep-ex/0402019

$\sqrt{s}$ = 318 GeV, $Q^2 > 35\ GeV^2$, $E_e > 10$ GeV
$139.8^o < \theta_e < 171.8^o$
$5 < E_T^\gamma < 10$ GeV, $-0.7 < \eta^\gamma < 0.9$

$\sigma(ep \to e\gamma X) = 5.64 \pm 0.58\ (stat.) \pm {}^{0.47}_{0.72}\ (syst.)$ pb

prediction using MRST2004 QEDpdfs:

$\sigma(ep \to e\gamma X) = 6.2 \pm 1.2$ pb

scale dependence

$\sin^2\theta_W$ from νN

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

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

3 σ difference

Paschos-Wolfenstein ratio

$$R^- \equiv \frac{\sigma^{\nu}_{\rm NC} - \sigma^{\bar{\nu}}_{\rm NC}}{\sigma^{\nu}_{\rm CC} - \sigma^{\bar{\nu}}_{\rm CC}} \simeq \frac{1}{2} - \sin^2\theta_W + \delta R^-_{\rm A} + \delta R^-_{\rm EW} + \delta R^-_{\rm NLO} + \delta R^-_s + \delta R^-_{\rm iso}$$

Global fit: $\delta R^-_{\rm iso} = -0.002$

Lagrange Multiplier method: $-0.007 < \delta R^-_{\rm iso} < +0.007$ at 90%cl

(MRST, hep-ph/0308087)

a new look at the high-x gluon distribution

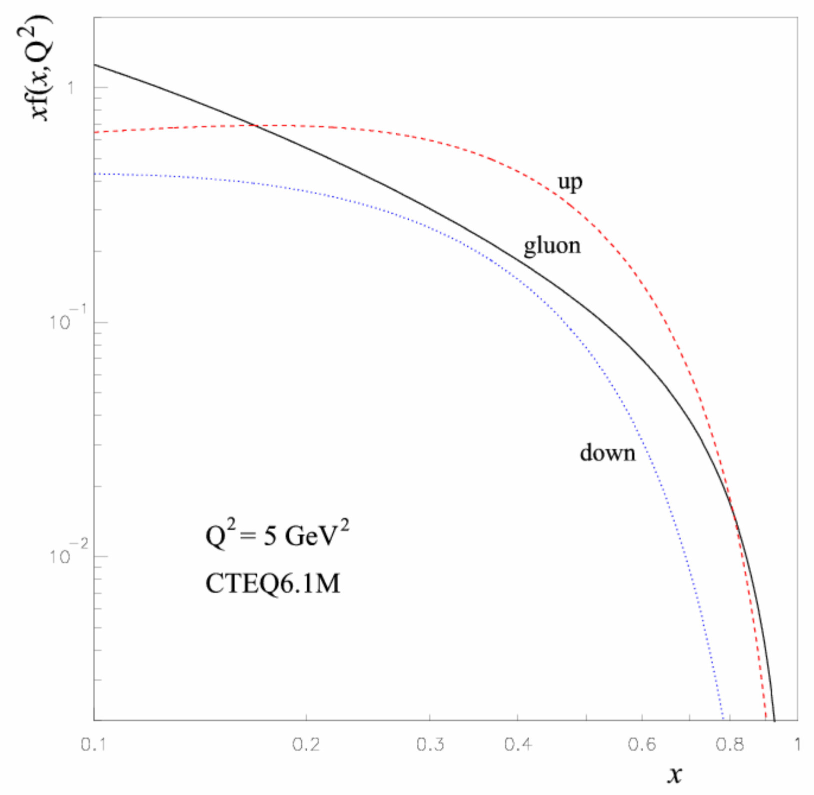
- good fit to Tevatron high E_T jet data requires 'hard' gluon distribution

- MRST use traditional parametrisation $Ax^a(1-x)^n[1+b\sqrt{x}+cx]$, not quite as good a fit as CTEQ; note that $n_g = 2.98$ for the MSbar NLO global fit

- but recall dimensional counting arguments for $x \to 1$ behaviour of parton distributions

$$q_{\rm val} \sim (1-x)^3, \quad g(x) \sim (1-x)^5$$

(but in what factorisation scheme, and at what Q^2 scale?)



the DIS-scheme gluon distribution

- Kramer and Klasen (1996) noticed that it was easier to get a good fit to the Tevatron high E_T jet data in the DIS scheme, schematically:

$$q^{\text{DIS}} = q^{\overline{\text{MS}}} + C_{2,q}^{\overline{\text{MS}}} \otimes q^{\overline{\text{MS}}} + C_{2,g}^{\overline{\text{MS}}} \otimes g^{\overline{\text{MS}}},$$

$$g^{\text{DIS}} = g^{\overline{\text{MS}}} - C_{2,q}^{\overline{\text{MS}}} \otimes q^{\overline{\text{MS}}} - C_{2,g}^{\overline{\text{MS}}} \otimes g^{\overline{\text{MS}}}.$$

this term negligible

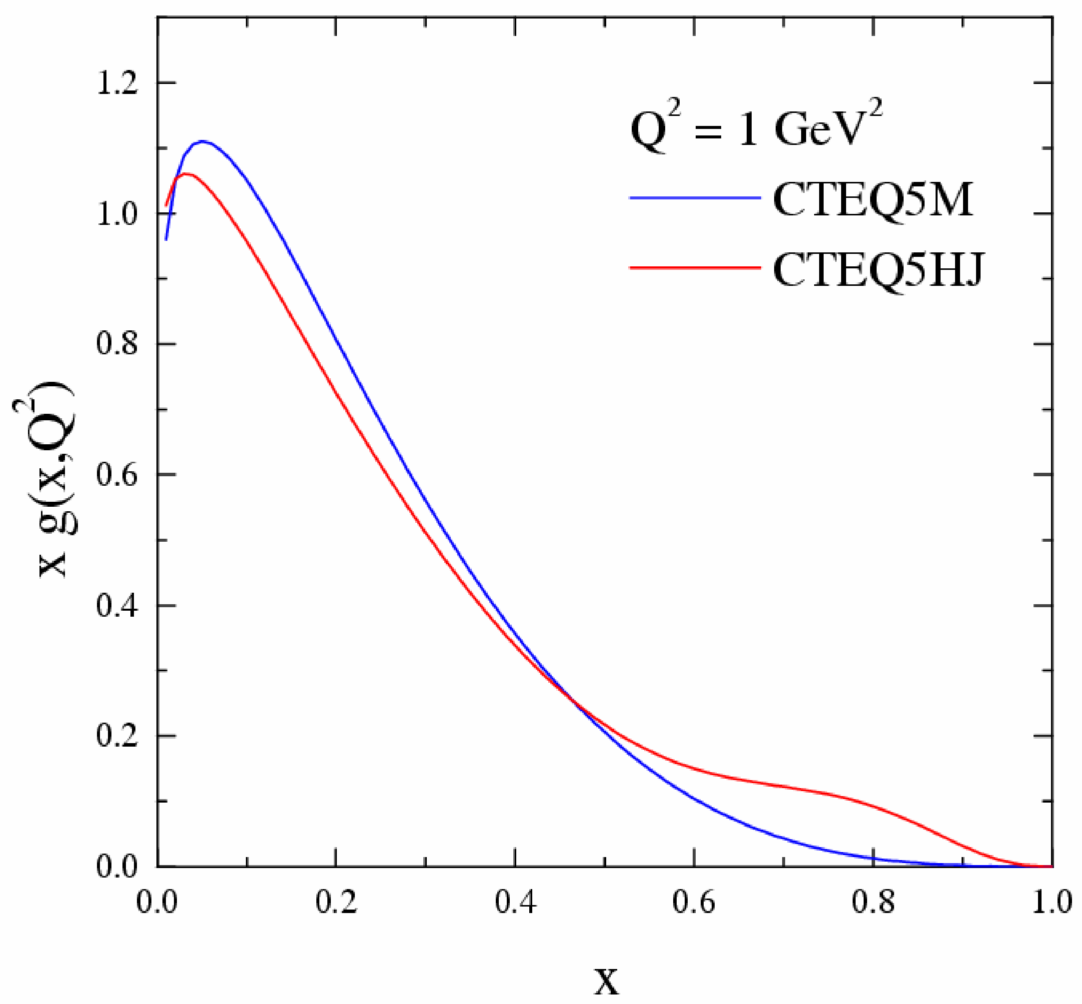
so that the DIS quarks (gluons) are harder (softer) at large x. (In fact the MRST g^{DIS} obtained from the above is negative at large x)

- Therefore, suppose we write

$$g^{\overline{\text{MS}}}(x, Q_0^2) = g^{\text{DIS}}(x, Q_0^2) + C_{2,\text{NS}}^{\overline{\text{MS}}} \otimes \sum_{q=u,d} q_{\text{val}}^{\overline{\text{MS}}}(x, Q_0^2),$$

and use the canonical parametrisation for g^{DIS} (Note: no new parameters!)

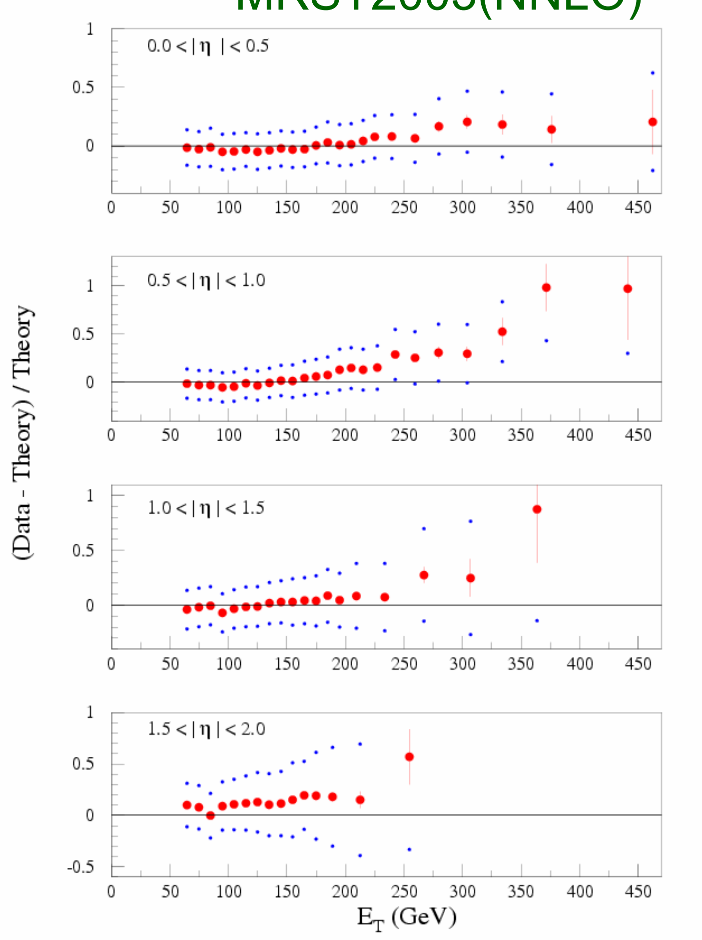
- If g^{DIS} satisfies usual dimensional counting, then g^{MS} dominated by the second term, and will have non-trivial high-x structure as a result.



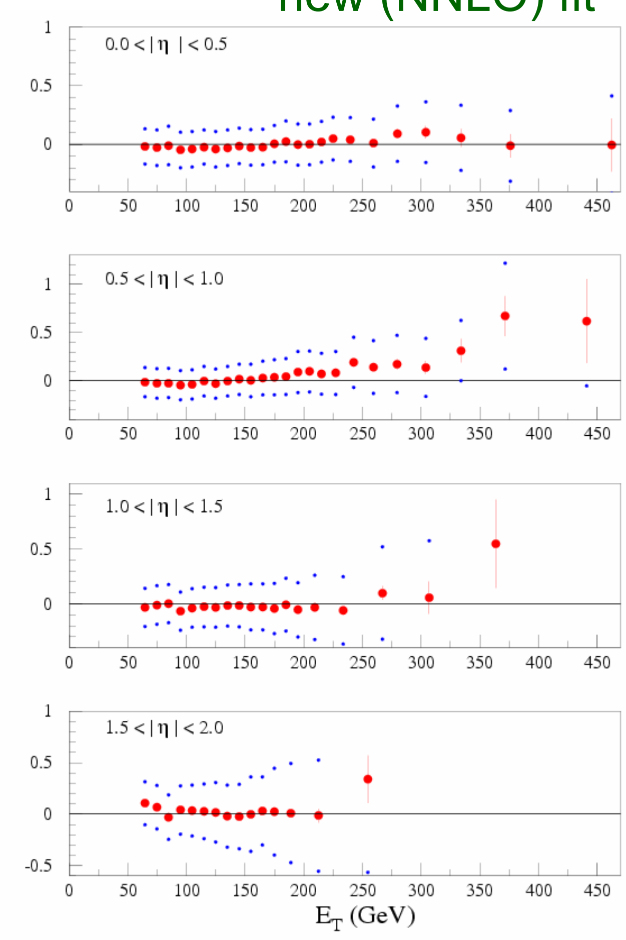
$Q^2 = 1\ GeV^2$
CTEQ5M
CTEQ5HJ
$x\ g(x,Q^2)$
x
0.0
0.2
0.4
0.6
0.8
1.0
1.2

DZero
Run 1b
jet data

MRST2003(NNLO)



new (NNLO) fit



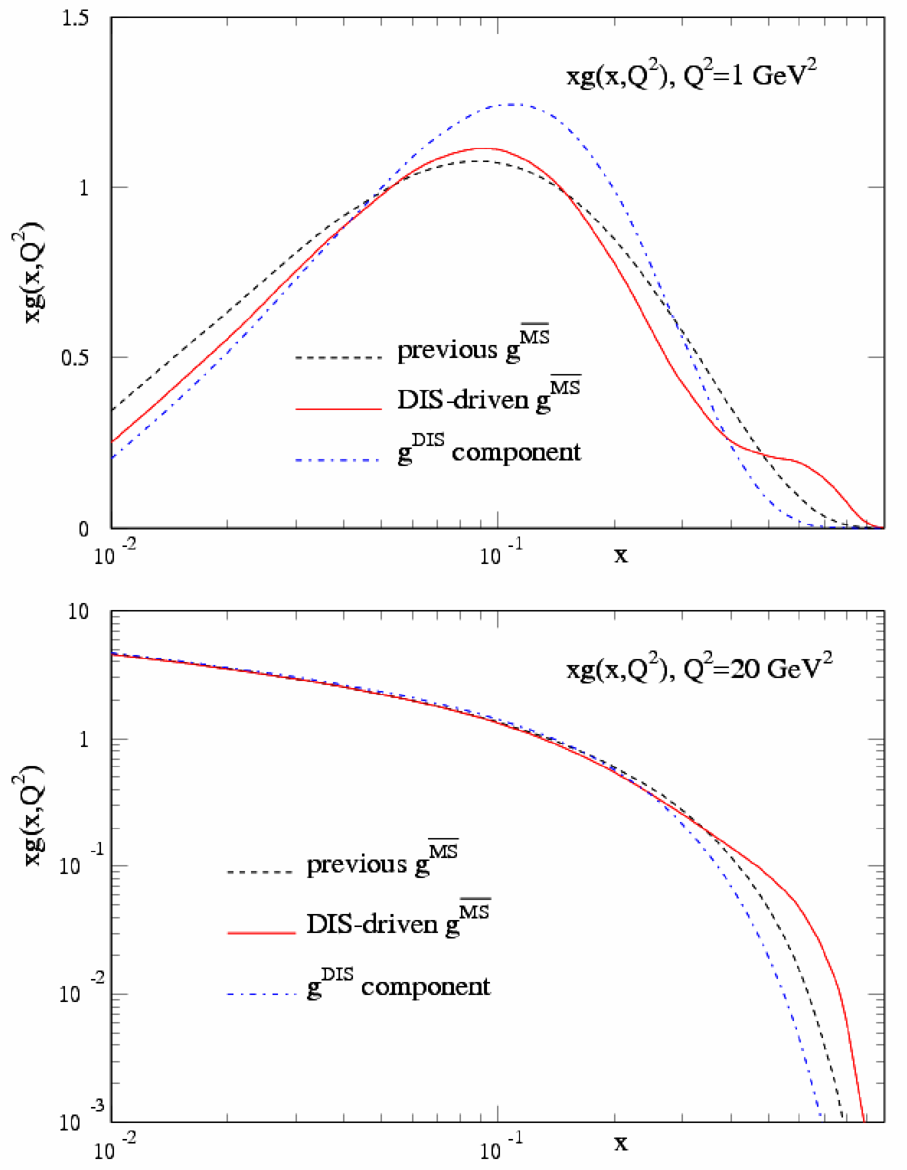
jet data only: $\chi^2 = 164 \rightarrow 117$

global fit: $\Delta\chi^2 = -79$

same number of parameters as before

… and now $n_g = 4.5$

sensitivity to x, Q^2 cuts reduced but not eliminated – see next talk



MRST2004(NNLO)

summary

- pdf sets with $\mathcal{O}(\alpha)$ QED effects are now available and allow pEW corrections at hadron colliders to be consistently included
- isospin violation arises naturally and reduces the NuTeV $\sin^2\theta_W$ 'anomaly'

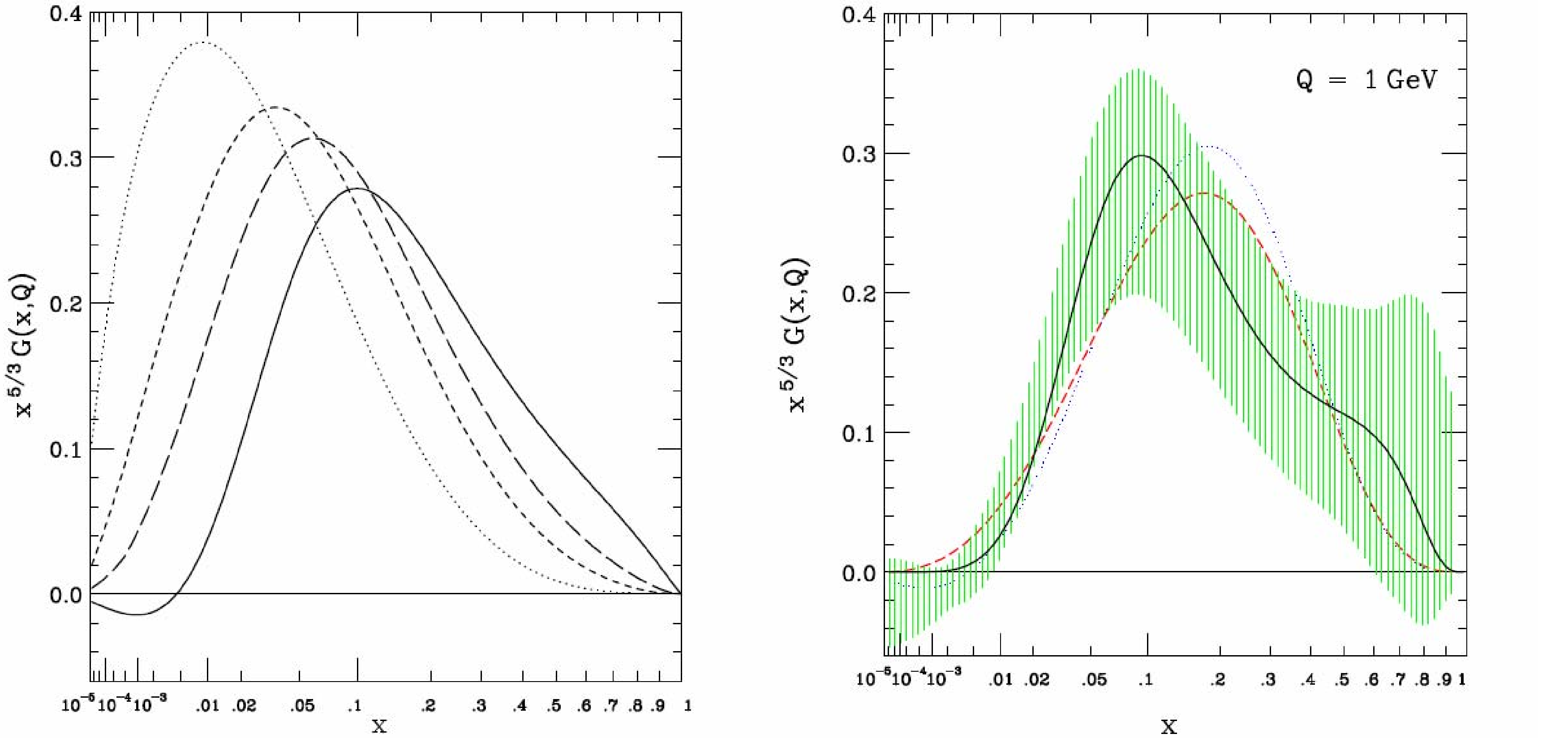
- the structure in the *high-x* $\overline{\text{MS}}$ gluon distribution is explained as an artefact of the unphysical factorisation scheme
- dimensional counting behaviour is obtained in the DIS scheme at $Q^2 \sim 1$ GeV^2
- at the very least, an efficient and well-motivated way of parametrising the starting gluon distribution

extra slides

the President tells me he doesn't allow negative gluons over there
University of Durham
THE HIGGS BOSON
The Higgs boson is the only missing ingredient of the Standard Model
Ogden Centre for Fundamental Physics

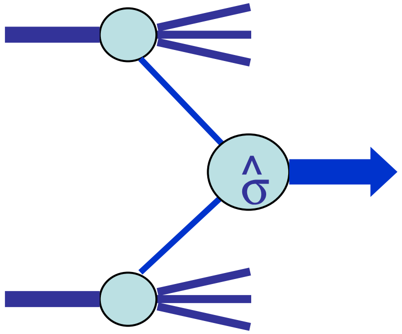
CTEQ, hep-ph/0201195

Fig. 24 : (a) The gluon distribution at $Q = 1, 2, 5, 100$ GeV obtained from a global fit in our parametrization, but allowing for negative gluon at small-x; and (b) Gluon uncertainty band at $Q = 1$ GeV, covering both + and − regions. Dashed:CTEQ5, dotted:MRST2001.



precision QCD at hadron colliders

the QCD **factorization theorem** for hard-scattering (short-distance) inclusive processes:



$$\sigma_X = \sum_{a,b}\int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

where X=W, Z, H, high-E_T jets, SUSY sparticles, … and Q is the 'hard scale' (e.g. = M_X), usually $\mu_F = \mu_R = Q$, and $\hat{\sigma}$ is known to some fixed order in pQCD and pEW (or to all orders in some LL approximation)

what limits the precision?

- the order of the perturbative expansion
- the uncertainty in the input parton distribution functions

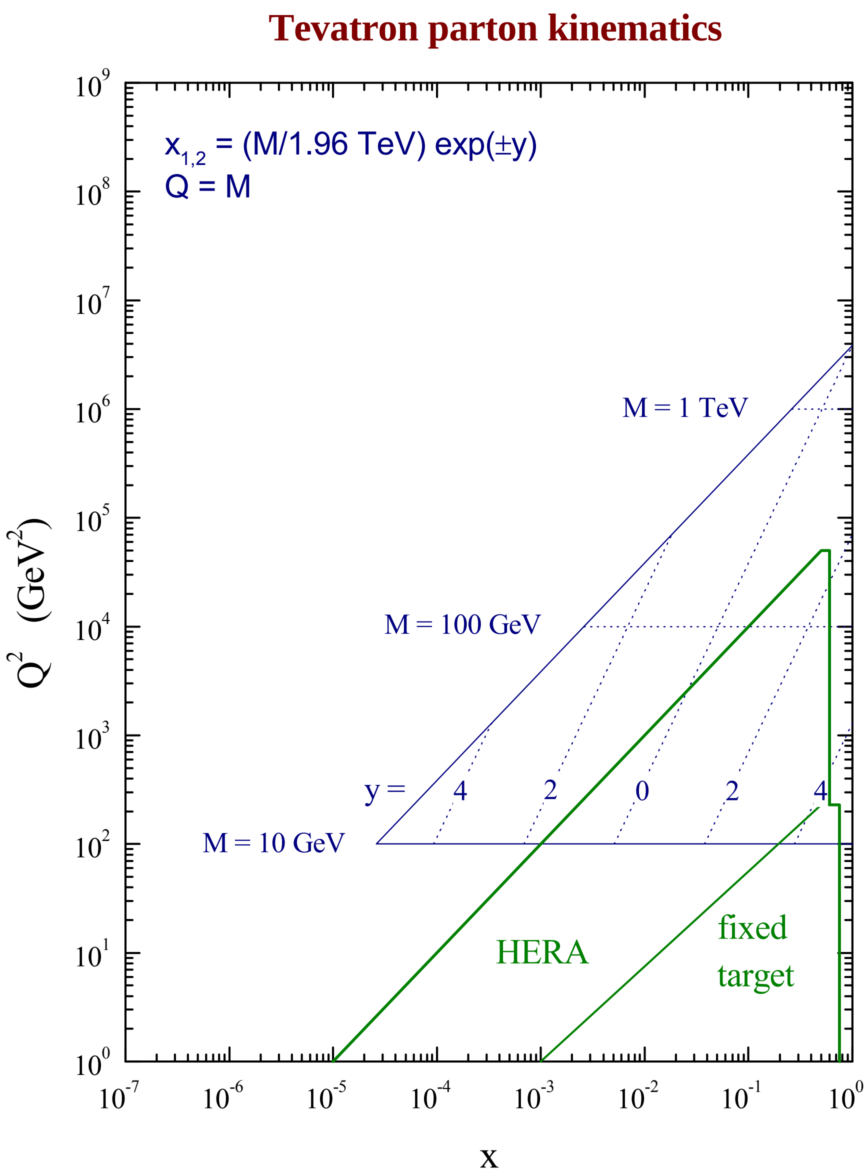
example σ(Z) @ LHC

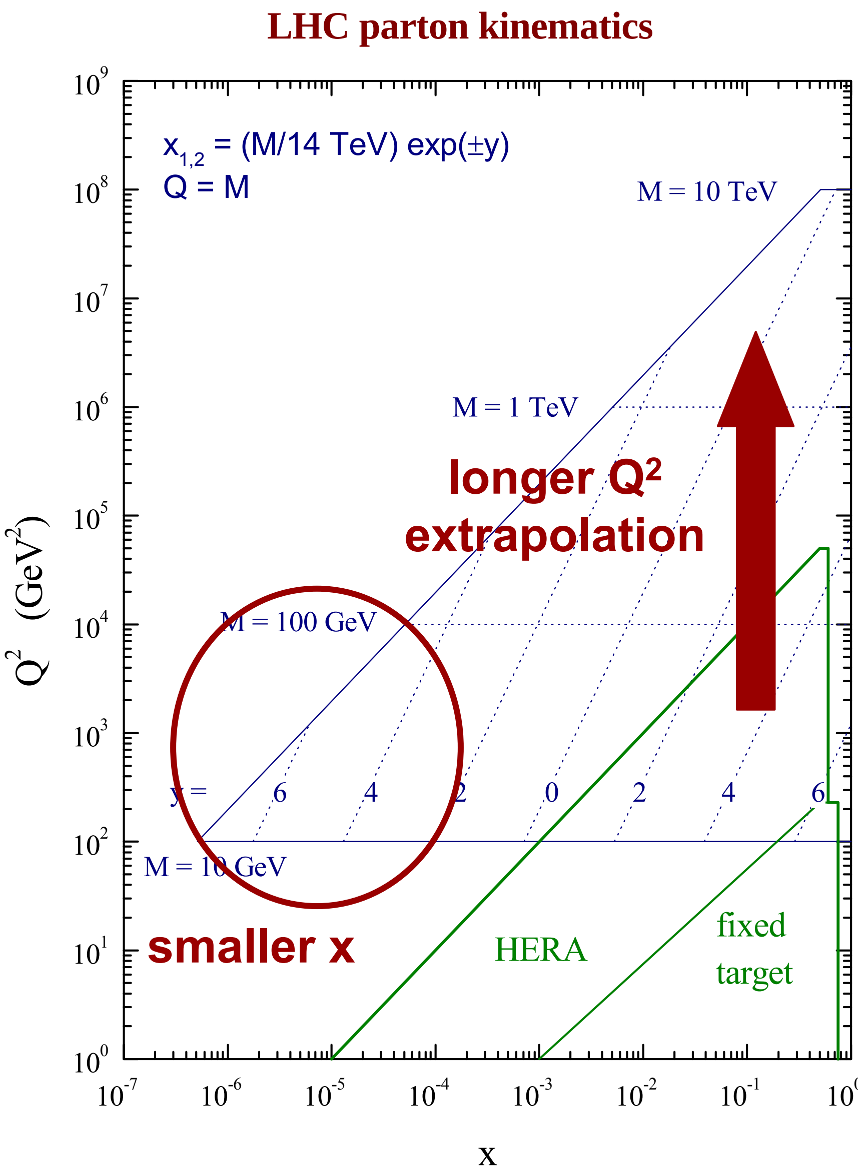
$\delta\sigma_{pdf} \approx \pm 3\%$, $\delta\sigma_{pt} \approx \pm 2\%$

$\rightarrow$ $\delta\sigma_{theory} \approx \pm 4\%$

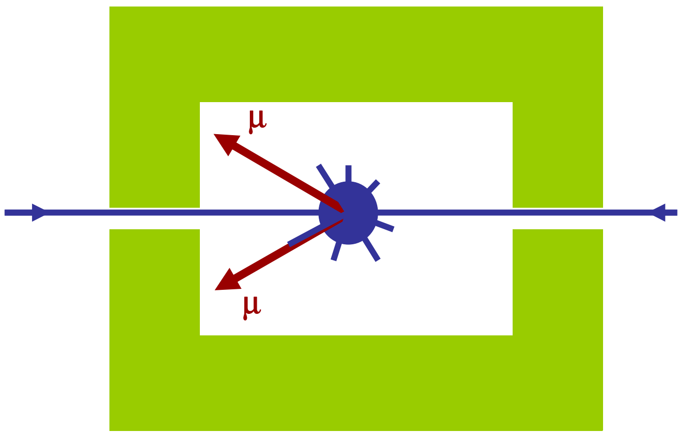
whereas for gg→H :

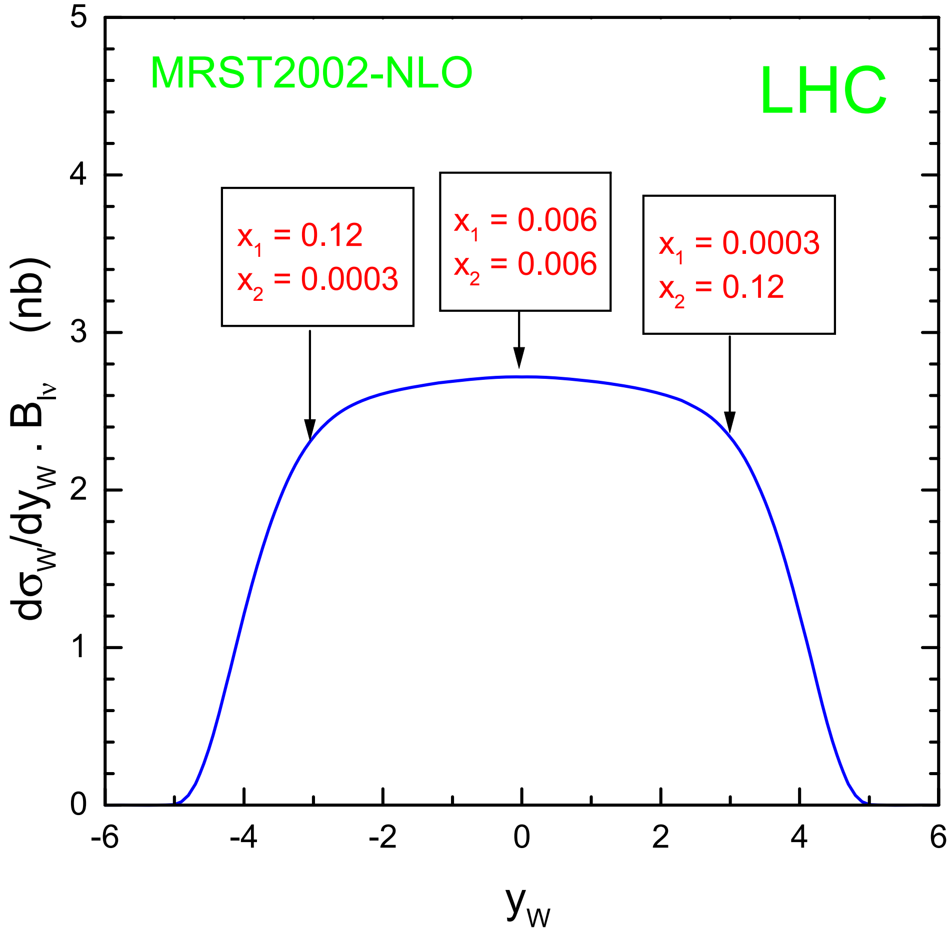
$\delta\sigma_{pdf} << \delta\sigma_{pt}$


Tevatron parton kinematics
x1,2 = (M/1.96 TeV) exp(±y)
Q = M
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 4 2 0 2 4
HERA
fixed target
Q2 (GeV2)
x


LHC parton kinematics
x1,2 = (M/14 TeV) exp(±y)
Q = M
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 2 4 6
longer Q²
extrapolation
smaller x
HERA
fixed target
Q2 (GeV2)
x

forward W, Z, dijet… production at LHC samples small and high x

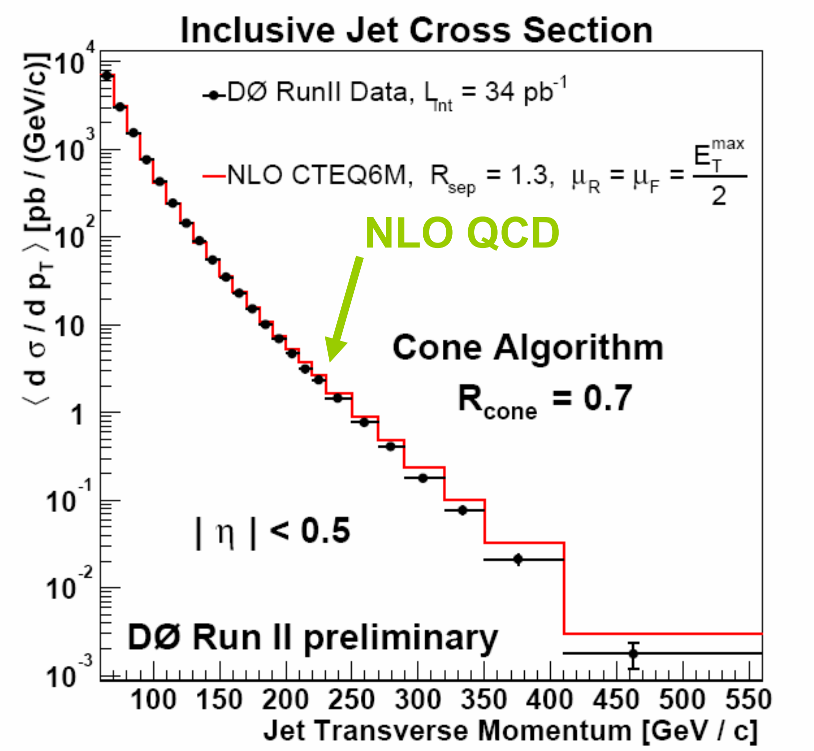




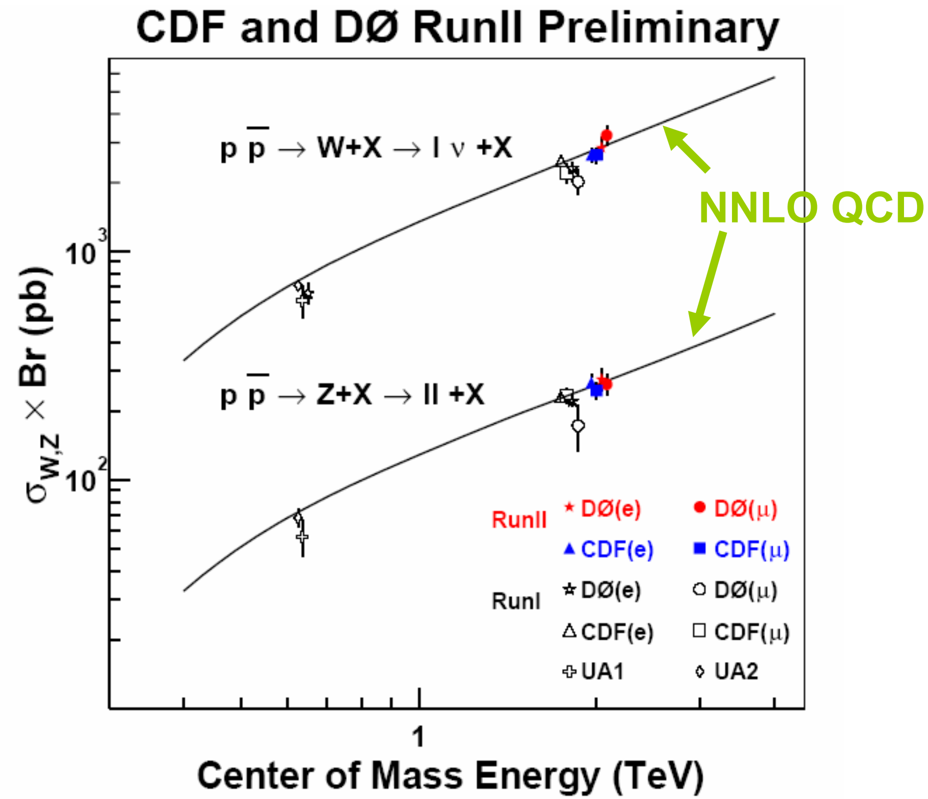
but no acceptance, no triggers?!

examples of 'precision' phenomenology

jet production

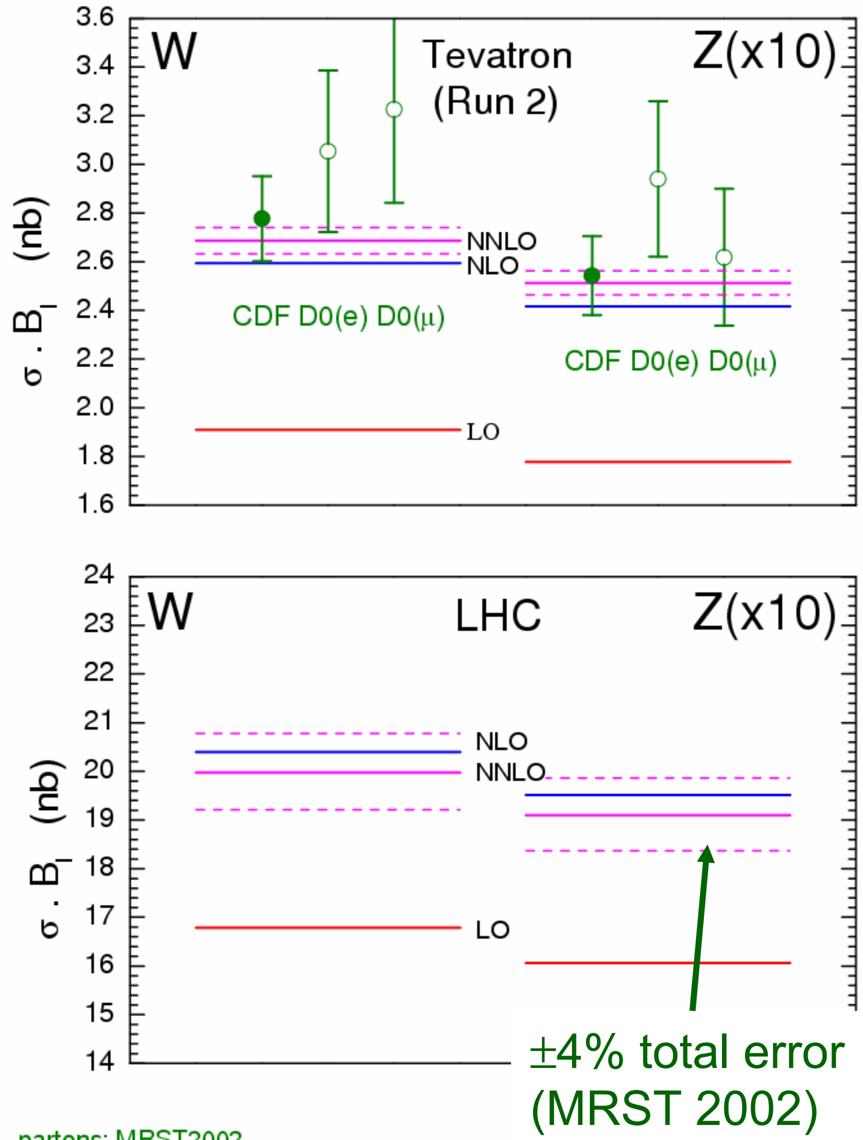


W, Z production



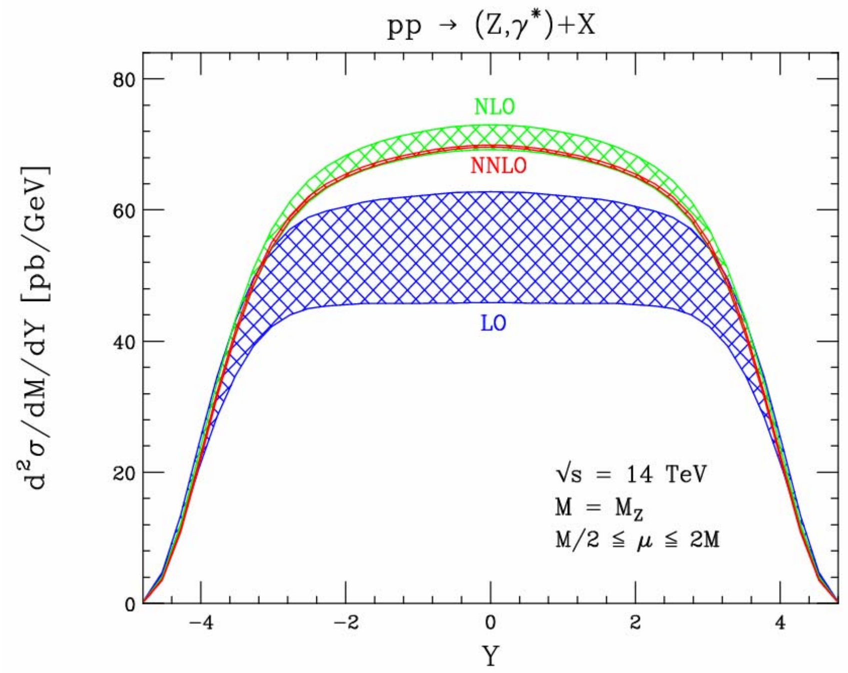
σ(W) and σ(Z) : precision predictions and measurements at the Tevatron and LHC

- the pQCD series appears to be under control
- the EW corrections are known and can in principle be included (see below)
- with sufficient theoretical precision, these ‘standard candle’ processes can be used to measure ***machine luminosity***



partons: MRST2002
NNLO evolution: Moch, Vermaseren, Vogt
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

the rapidity distributions dσ/dy are also known to NNLO ⇒ matching to experimental acceptance



Anastasiou et al.
hep-ph/0306192
hep-ph/0312266

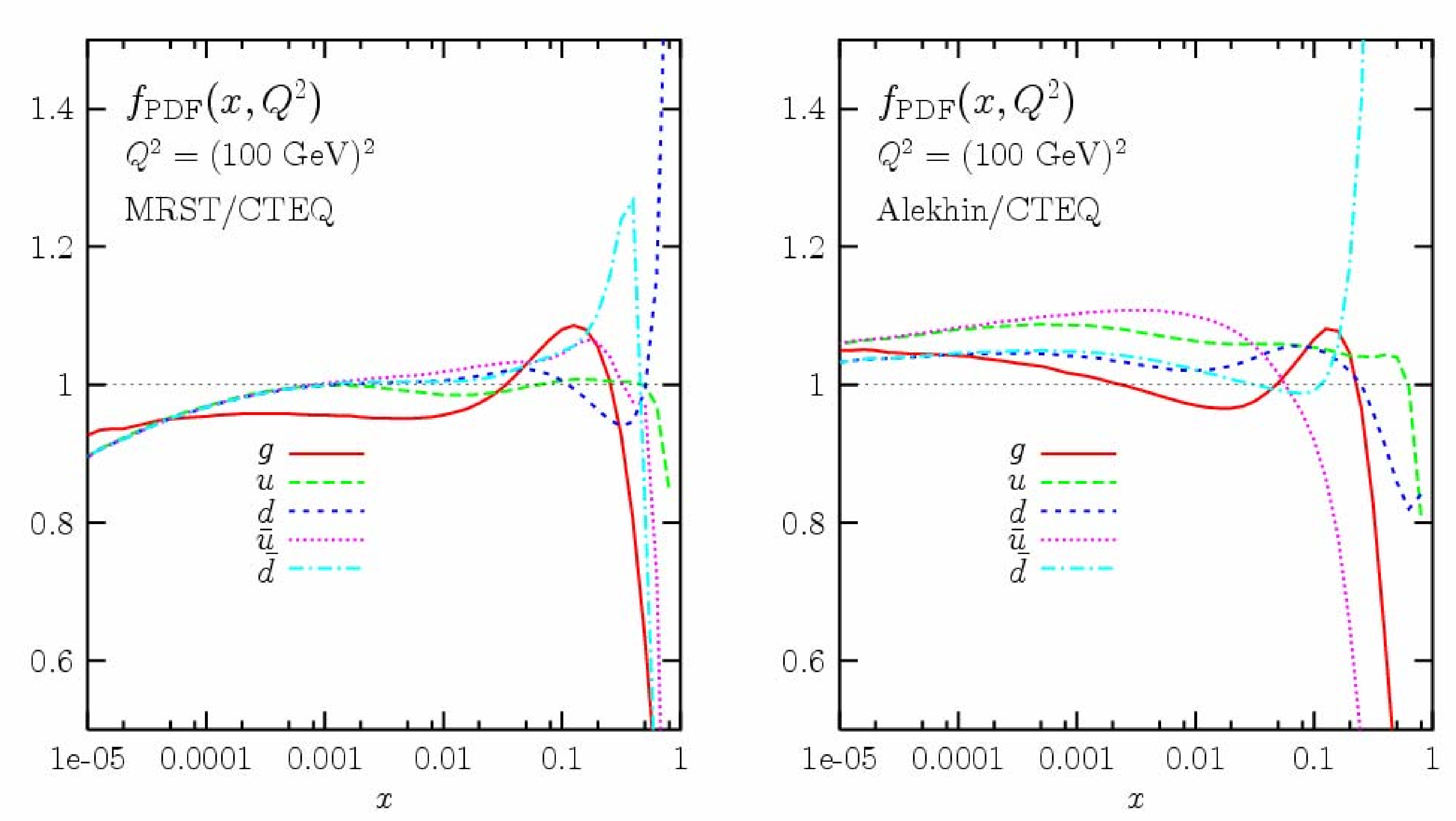
however…

LHC	$\sigma_{NLO}(W)$ (nb)
MRST2002	204 ± 6 (expt)
CTEQ6	205 ± 8 (expt)
Alekhin02	215 ± 6 (tot)

similar partons

different $\Delta\chi^2$

different partons



the differences between pdf sets needs to be better understood!

Djouadi & Ferrag, hep-ph/0310209

why do ‘best fit’ pdfs and errors differ?

- different data sets in fit
  - different subselection of data
  - different treatment of exp. sys. errors
- different choice of
  - tolerance to define $\pm \delta f_i$ (CTEQ: $\Delta\chi^2$=100, Alekhin: $\Delta\chi^2$=1)
  - factorisation/renormalisation scheme/scale
  - Q_0^2
  - parametric form $Ax^a(1-x)^b[..]$ etc
  - α_S
  - treatment of heavy flavours
  - theoretical assumptions about $x \to 0,1$ behaviour
  - theoretical assumptions about sea flavour symmetry
  - evolution and cross section codes (removable differences!)

→ see ongoing HERA-LHC Workshop PDF Working Group

- small MRST and CTEQ differences largely understood, see hep-ph/0211080

  mainly: CTEQ gluon at Q_0^2 required to be positive at small x means $g_{CTEQ} > g_{MRST}$ there, also $\Delta\chi^2 = 50$ (MRST), 100 (CTEQ)

- ALEKHIN gluon smaller at high x (no Tevatron jet data in fit) and different content of sea at small x from different assumptions about *ubar-dbar* as $x \to 0$ and (ii) ratio of strange to non-strange pdfs. Also $\Delta\chi^2 = 1$ allowed by use of smaller overall data set.

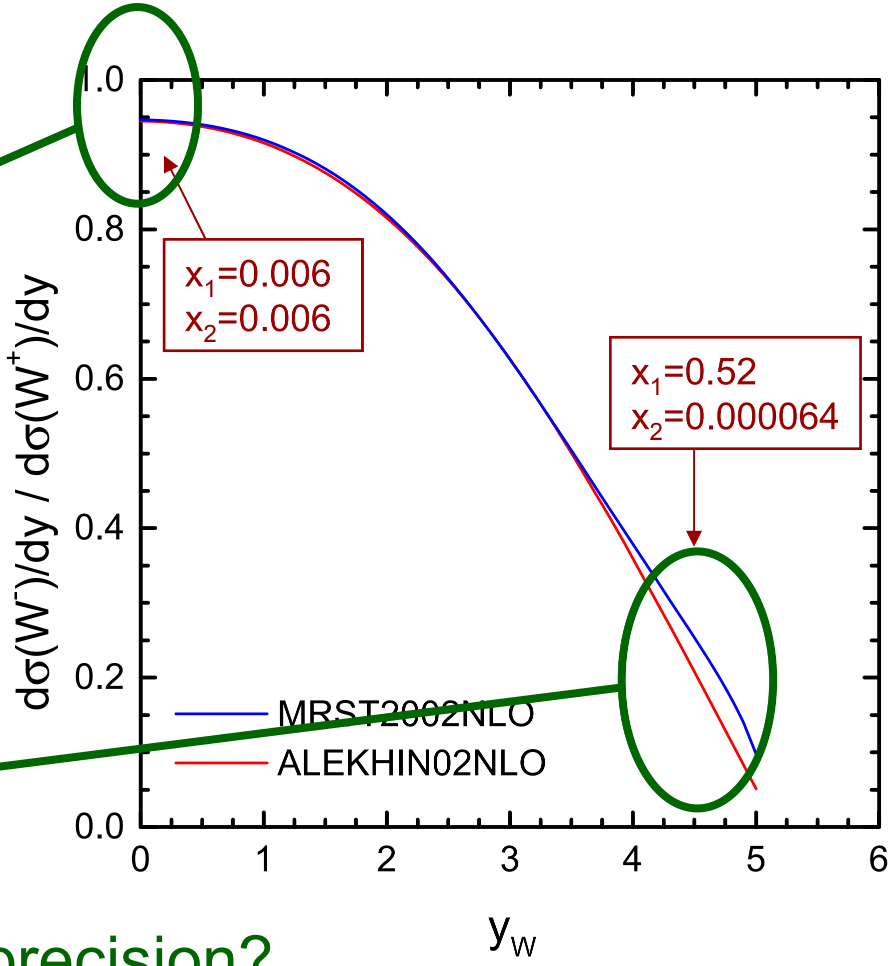
ratio of W^- and W^+ rapidity distributions

$$\frac{d\sigma(W^-)}{d\sigma(W^+)} = \frac{d(x_1)\,\bar{u}(x_2) + \bar{u}(x_1)\,d(x_2) + \ldots}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2) + \ldots}$$

ratio close to 1 because $u \approx \bar{u}$ etc.
(note: MRST error = ±1½%)

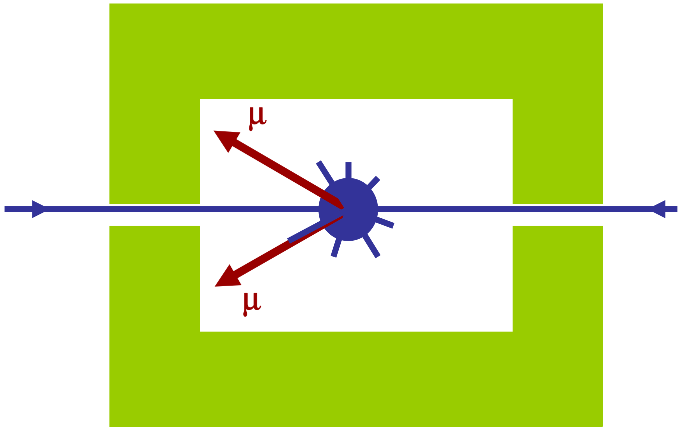
LHC	W^-/W^+
MRST2002	0.75
CTEQ6	0.75
Alekhin02	0.74

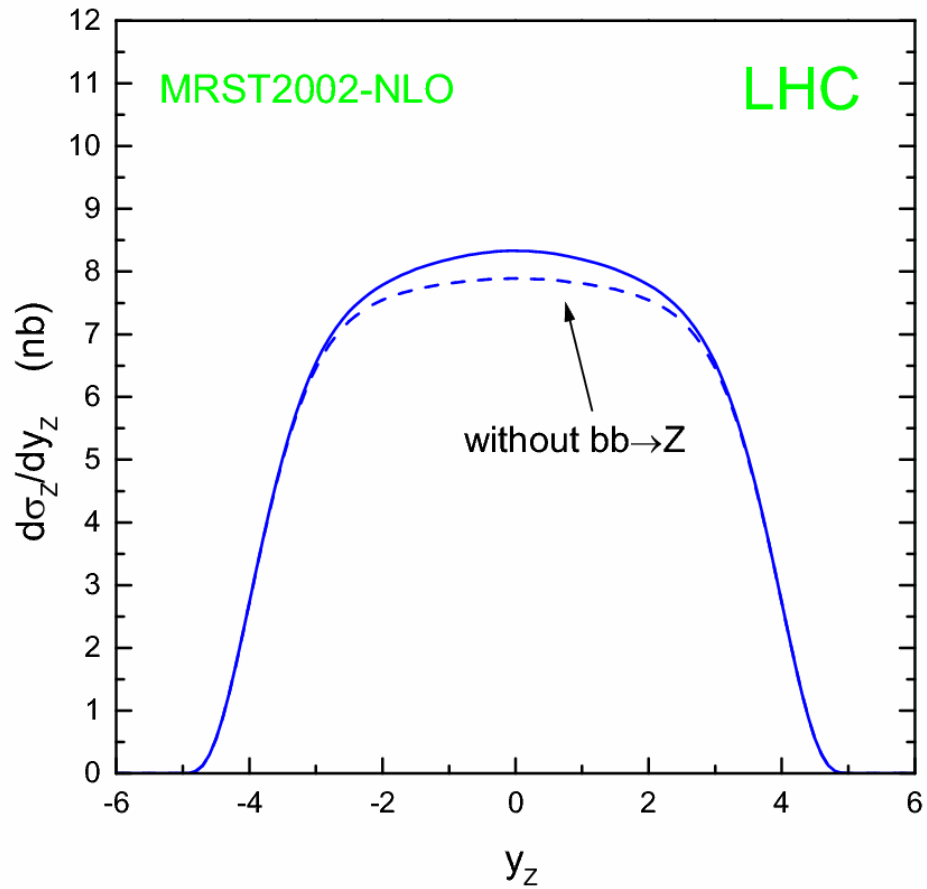
sensitive to large-x d/u and small x $\bar{u}/\bar{d}$ ratios



Q. What is the experimental precision?

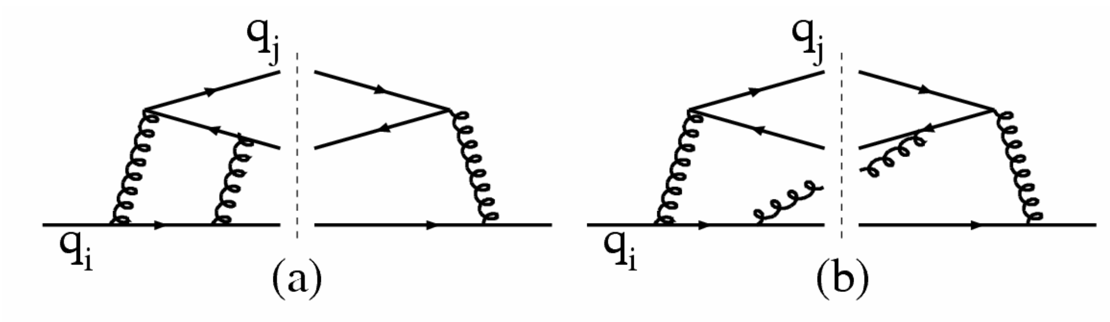
bb→Z contribution to Z production @ LHC





Note: much smaller effect at Tevatron

perturbative generation of $s(x) \neq s(x)$



$P^{us}(x) \neq P^{us}(x)$

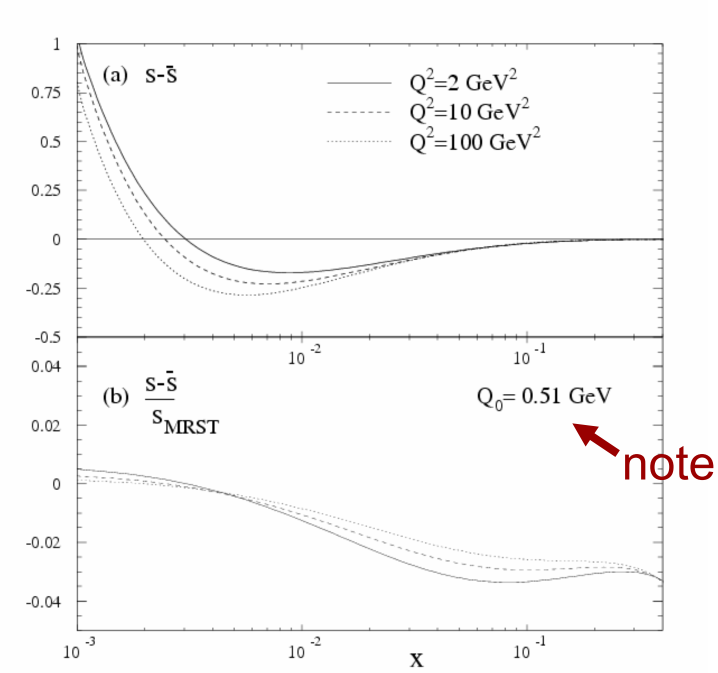
at $O(\alpha_S^3)$

Quantitative study by de Florian et al hep-ph/0404240

$\Rightarrow \quad \langle x(s-s)\rangle_{pQCD} <\approx -0.0005$

cf. from global pdf fit (Olness et al, hep-ph/0312322,3)

$\Rightarrow \quad -0.001 < \langle x(s-s)\rangle_{fit} < +0.004$



partial explanation of NuTeV $\sin^2\theta_W$ "anomaly"?

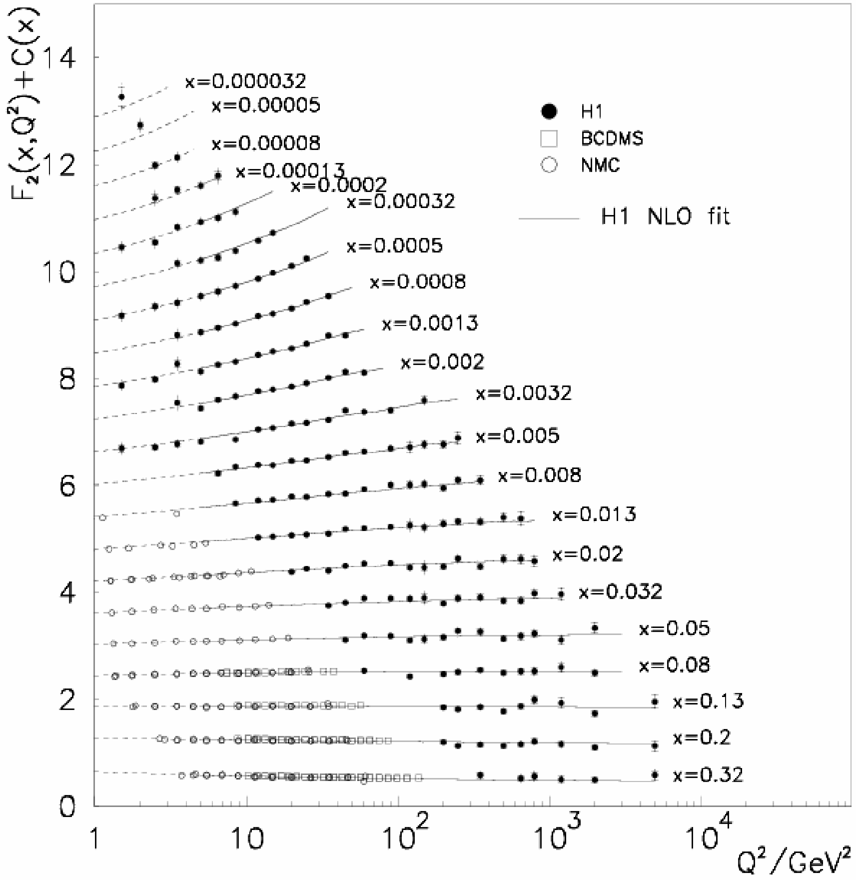
$$\frac{\partial \mathbf{q_i}(\mathbf{x}, \mathbf{Q}^2)}{\partial \log \mathbf{Q}^2} = \frac{\alpha_\mathbf{S}}{2\pi} \int_\mathbf{x}^1 \frac{\mathbf{dy}}{\mathbf{y}} \Big\{ \mathbf{P}_{\mathbf{q_i q_j}}(\mathbf{y}, \alpha_\mathbf{S})\ \mathbf{q_j}(\frac{\mathbf{x}}{\mathbf{y}}, \mathbf{Q}^2) + \mathbf{P}_{\mathbf{q_i g}}(\mathbf{y}, \alpha_\mathbf{S})\ \mathbf{g}(\frac{\mathbf{x}}{\mathbf{y}}, \mathbf{Q}^2) \Big\}$$

$$\frac{\partial \mathbf{g}(\mathbf{x}, \mathbf{Q}^2)}{\partial \log \mathbf{Q}^2} = \frac{\alpha_\mathbf{S}}{2\pi} \int_\mathbf{x}^1 \frac{\mathbf{dy}}{\mathbf{y}} \Big\{ \mathbf{P}_{\mathbf{g q_j}}(\mathbf{y}, \alpha_\mathbf{S})\ \mathbf{q_j}(\frac{\mathbf{x}}{\mathbf{y}}, \mathbf{Q}^2) + \mathbf{P}_{\mathbf{gg}}(\mathbf{y}, \alpha_\mathbf{S})\ \mathbf{g}(\frac{\mathbf{x}}{\mathbf{y}}, \mathbf{Q}^2) \Big\}$$

DGLAP equations

$F_2(x,Q^2) = \Sigma_q e_q^{\,2}\, x\, q(x,Q^2)$ etc

x dependence of $f_i(x,Q^2)$ determined by 'global fit' to deep inelastic scattering (H1, ZEUS, NMC, …) and hadron collider data



pdfs from global fits

Formalism
NLO DGLAP
MSbar factorisation
Q_0^2
functional form @ Q_0^2
sea quark (a)symmetry
etc.

$f_i(x,Q^2) \pm \delta f_i(x,Q^2)$

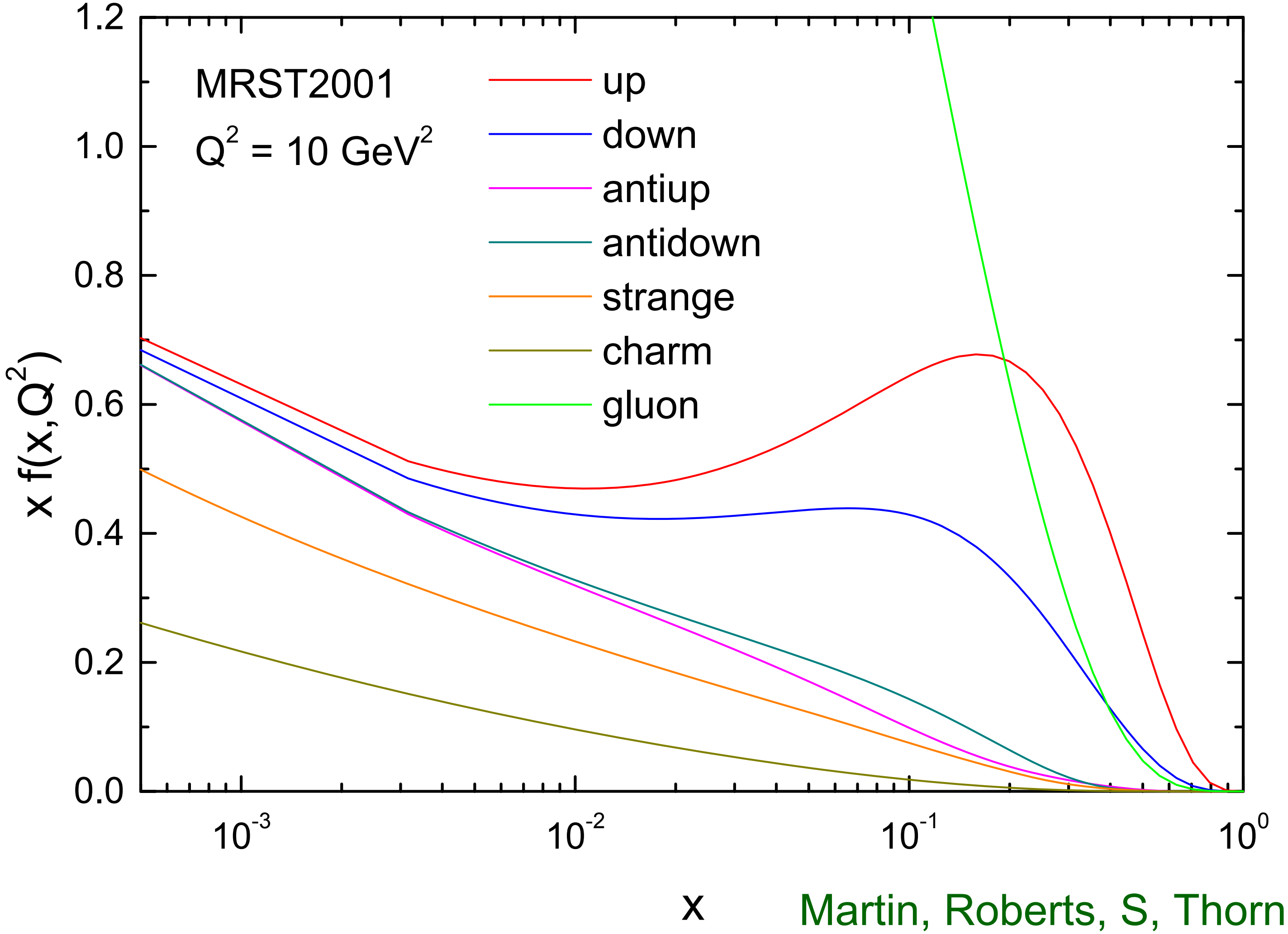
$\alpha_S(M_Z)$

Data
DIS (SLAC, BCDMS, NMC, E665, CCFR, H1, ZEUS, …)
Drell-Yan (E605, E772, E866, …)
High E_T jets (CDF, D0)
W rapidity asymmetry (CDF)
νN dimuon (CCFR, NuTeV)
etc.

Who?
Alekhin, CTEQ, MRST, GKK, Botje, H1, ZEUS, GRV, BFP, …

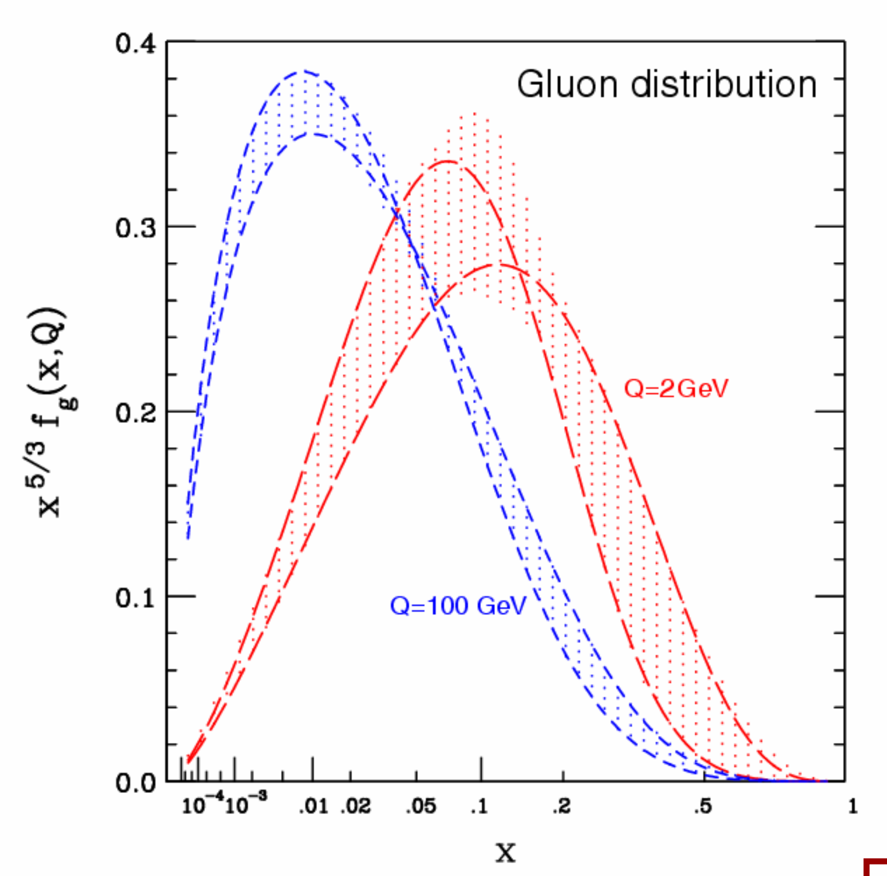
http://durpdg.dur.ac.uk/hepdata/pdf.html

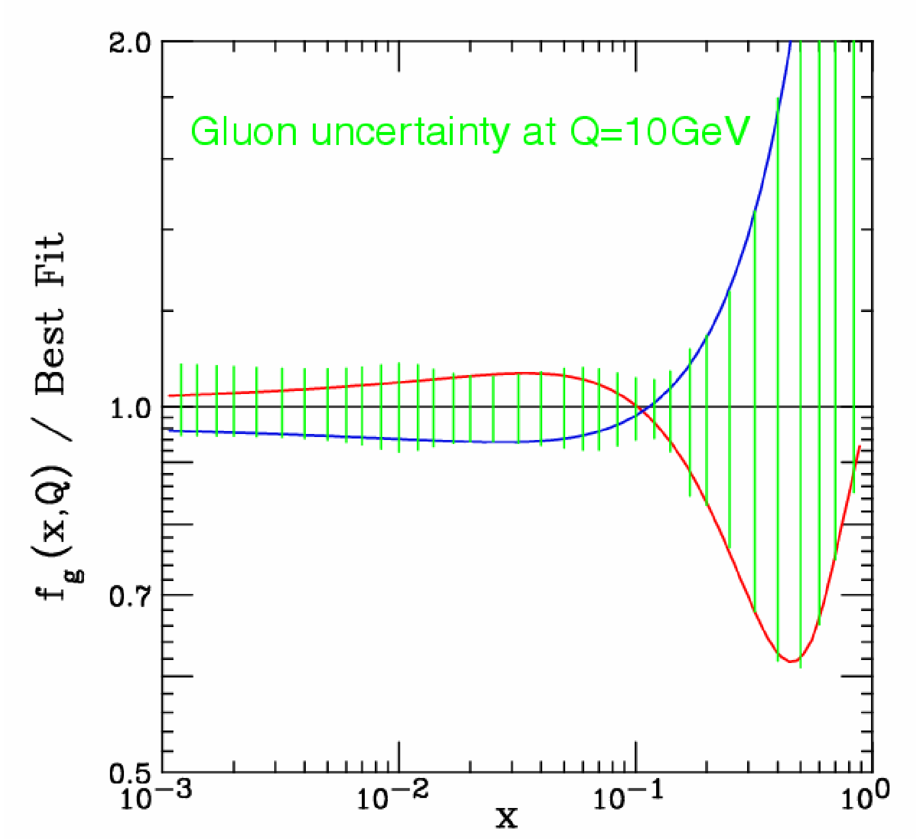
(MRST) parton distributions in the proton



Martin, Roberts, S, Thorne

uncertainty in gluon distribution (CTEQ)





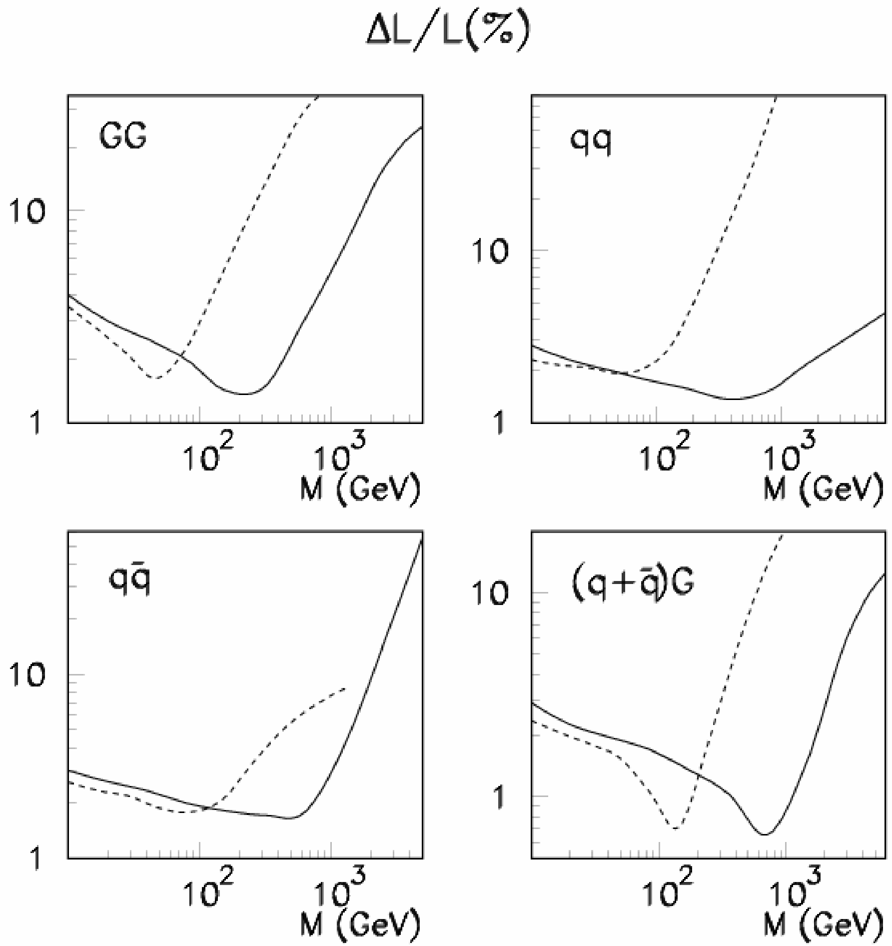
then $\delta f_g \rightarrow \delta\sigma_{gg\rightarrow X}$ etc.

pdf uncertainties encoded in parton-parton *luminosity functions*:

$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_\tau^1 \frac{dx}{x} \, f_a(x, Q^2) f_b(\tau/x, Q^2)$$

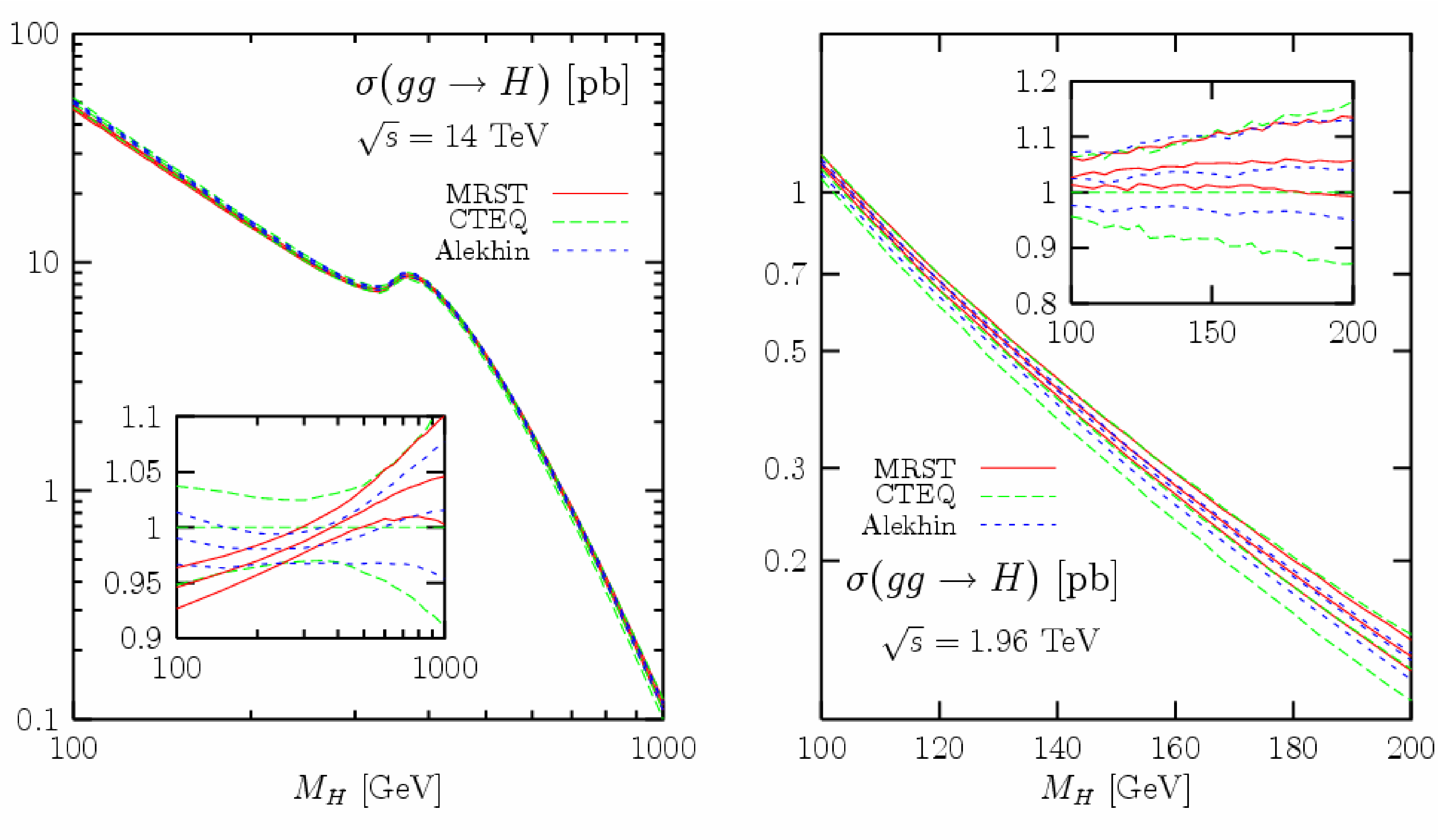
with $\tau = M^2/s$, so that for $ab \to X$

$$\sigma_X \propto \frac{1}{s} \frac{\partial \mathcal{L}_{ab}}{\partial \tau}$$

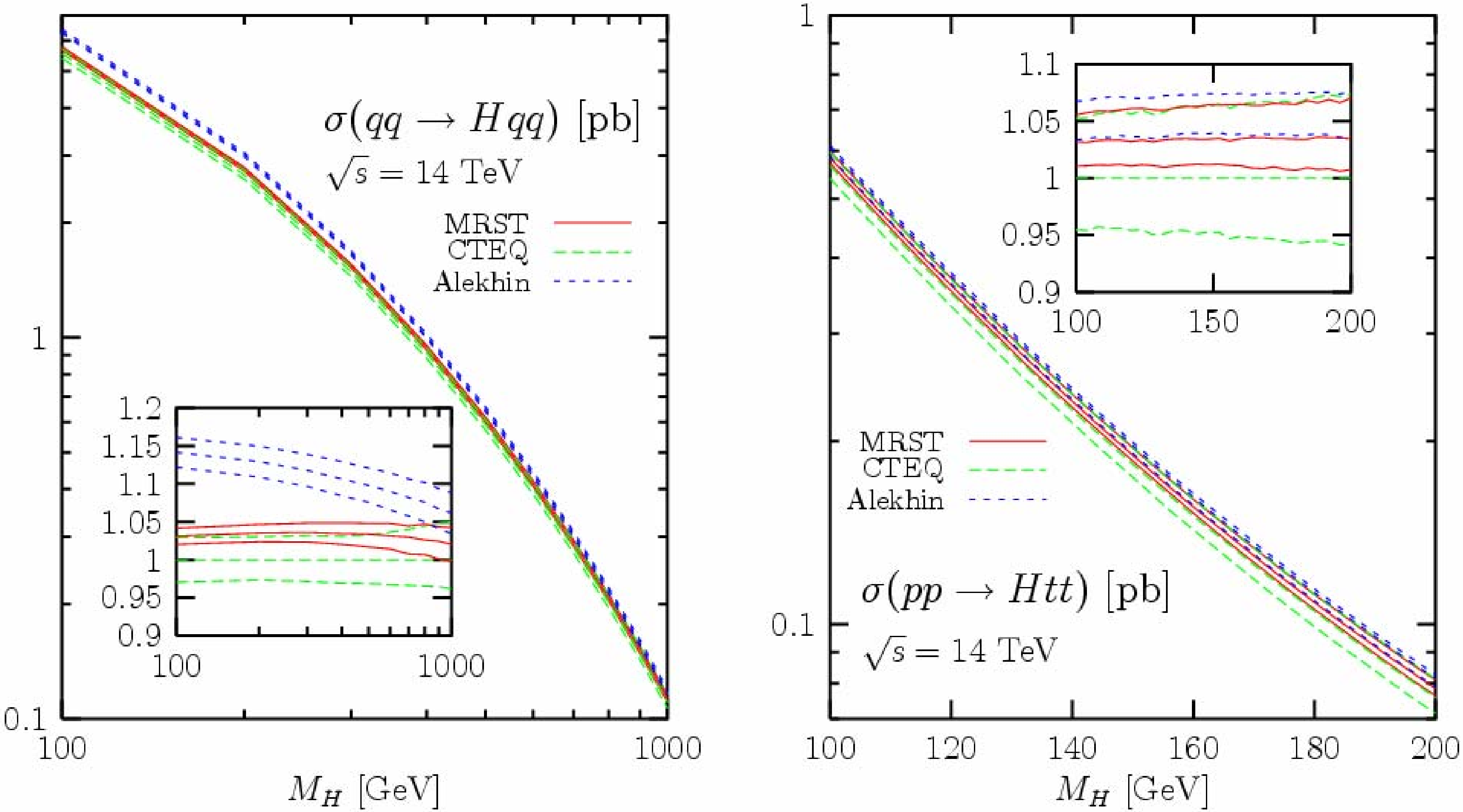


solid = LHC
dashed = Tevatron
Alekhin 2002

Higgs cross section: dependence on pdfs



Djouadi & Ferrag, hep-ph/0310209



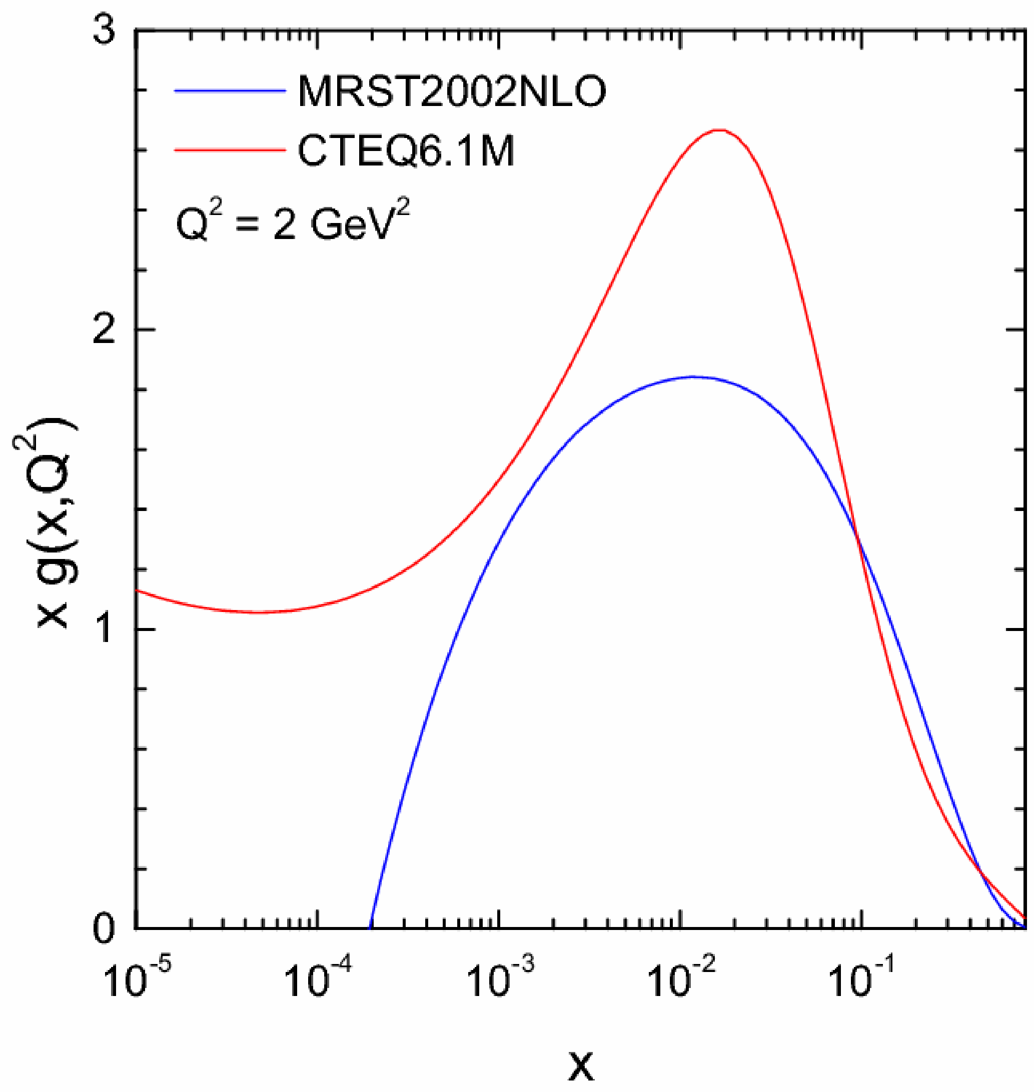
Djouadi & Ferrag, hep-ph/0310209

- MRST: Q_0^2 = 1 GeV^2, Q_{cut}^2 = 2 GeV^2

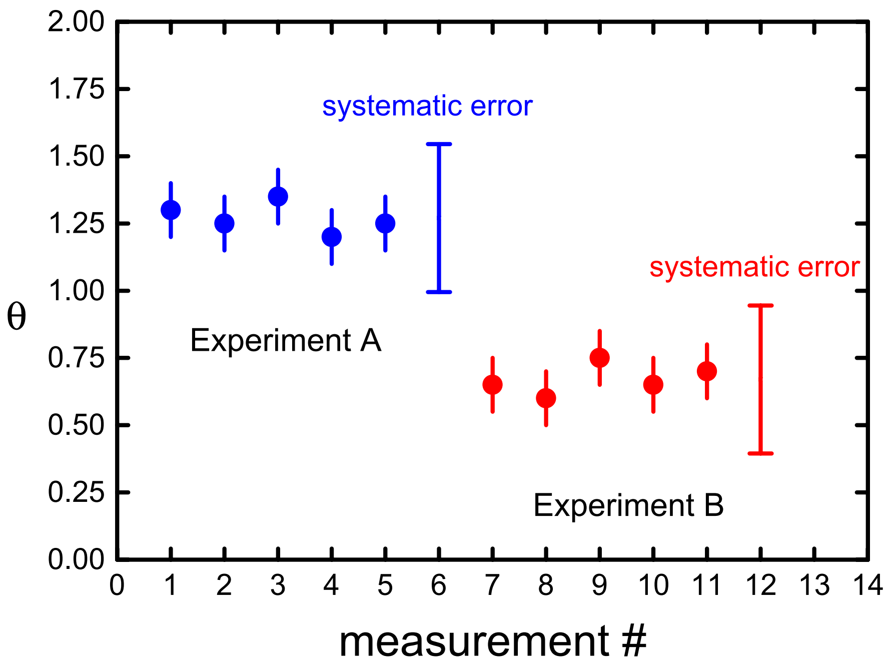
$$xg = Ax^a(1-x)^b(1+Cx^{0.5}+Dx) - Ex^c(1-x)^d$$

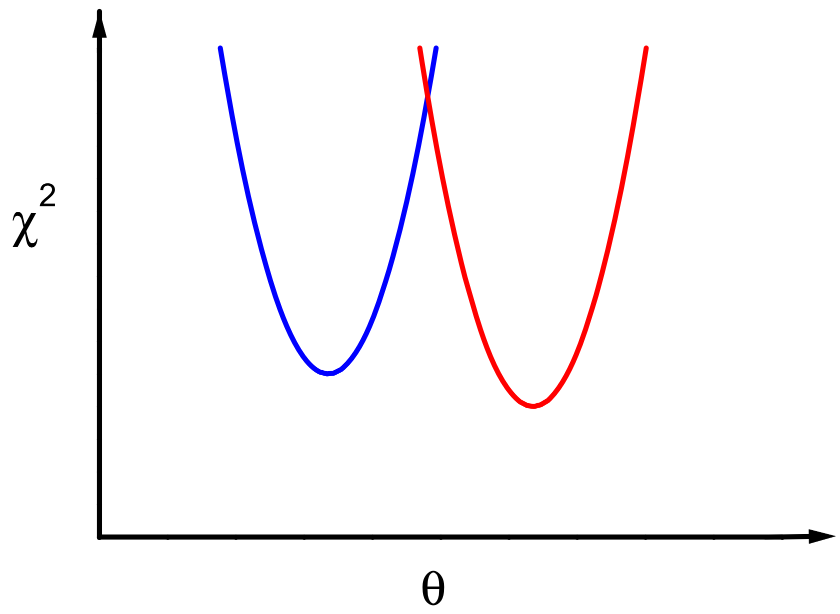
- CTEQ6: Q_0^2 = 1.69 GeV^2, Q_{cut}^2 = 4 GeV^2

$$xg = Ax^a(1-x)^b e^{cx}(1+Cx)^d$$



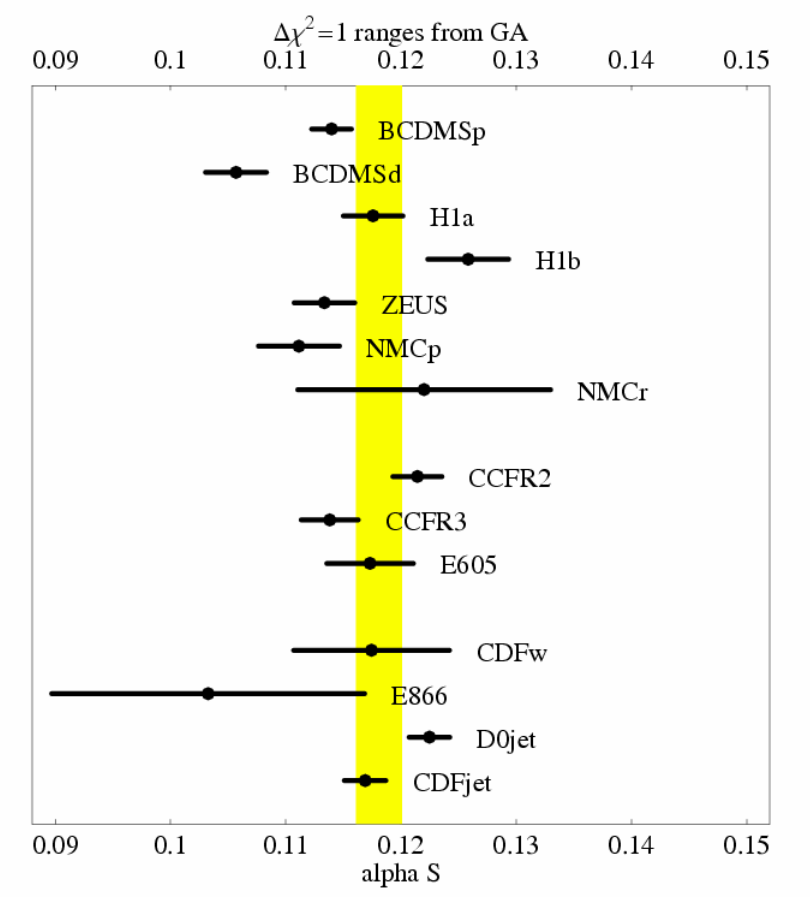
tensions within the global fit?

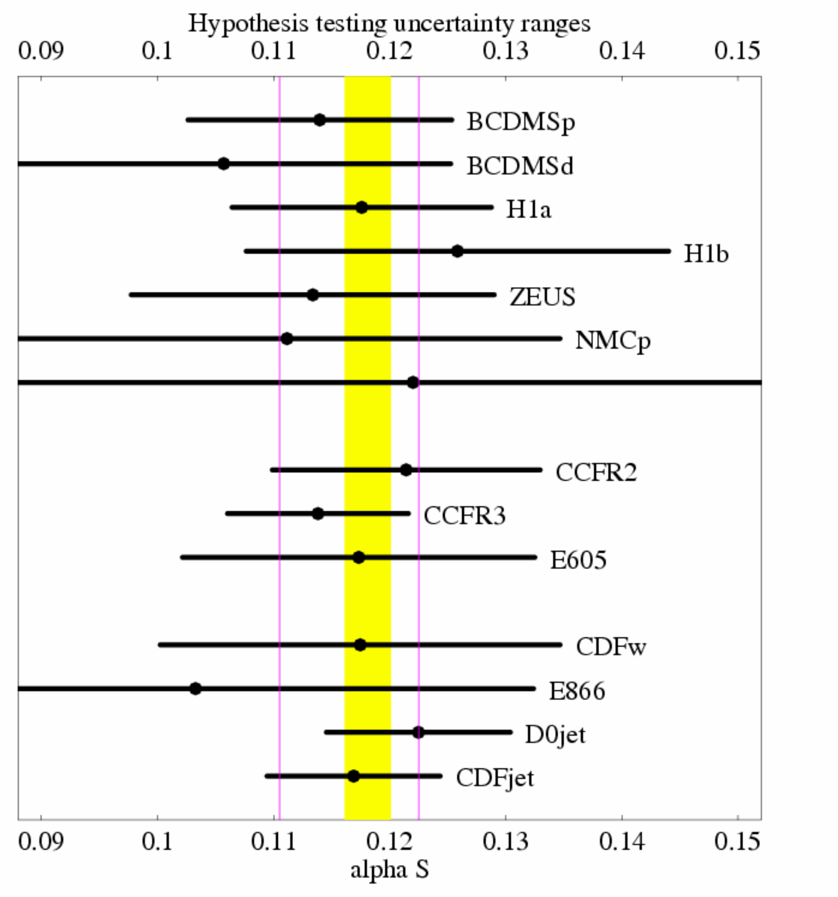




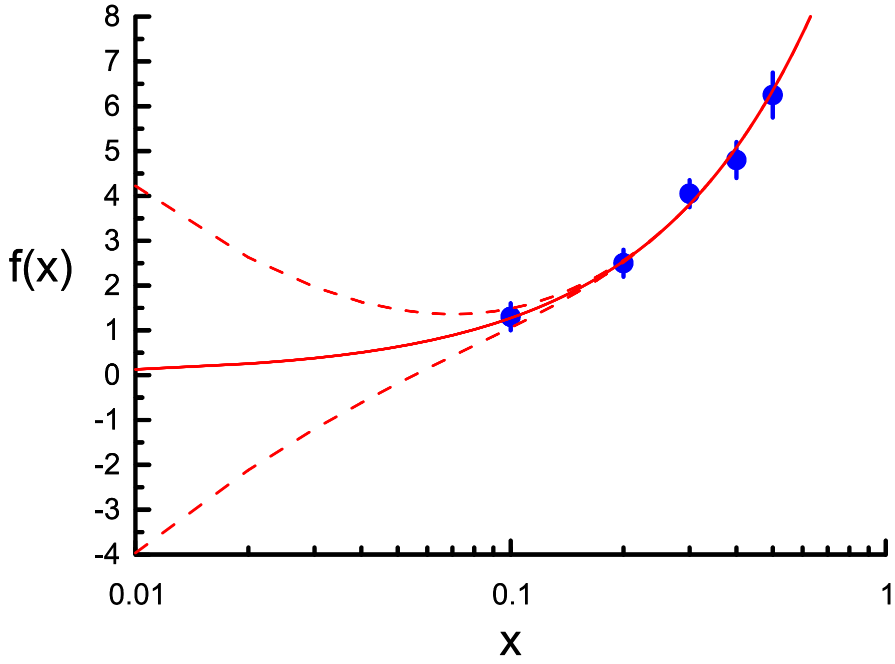
- with dataset A in fit, $\Delta\chi^2=1$; with A and B in fit, $\Delta\chi^2=?$
- 'tensions' between data sets arise, for example,
  - between DIS data sets (e.g. **μH** and **νN** data)
  - when jet and Drell-Yan data are combined with DIS data

CTEQ $\alpha_S(M_Z)$ values from global analysis with $\Delta\chi^2$ = 1, 100





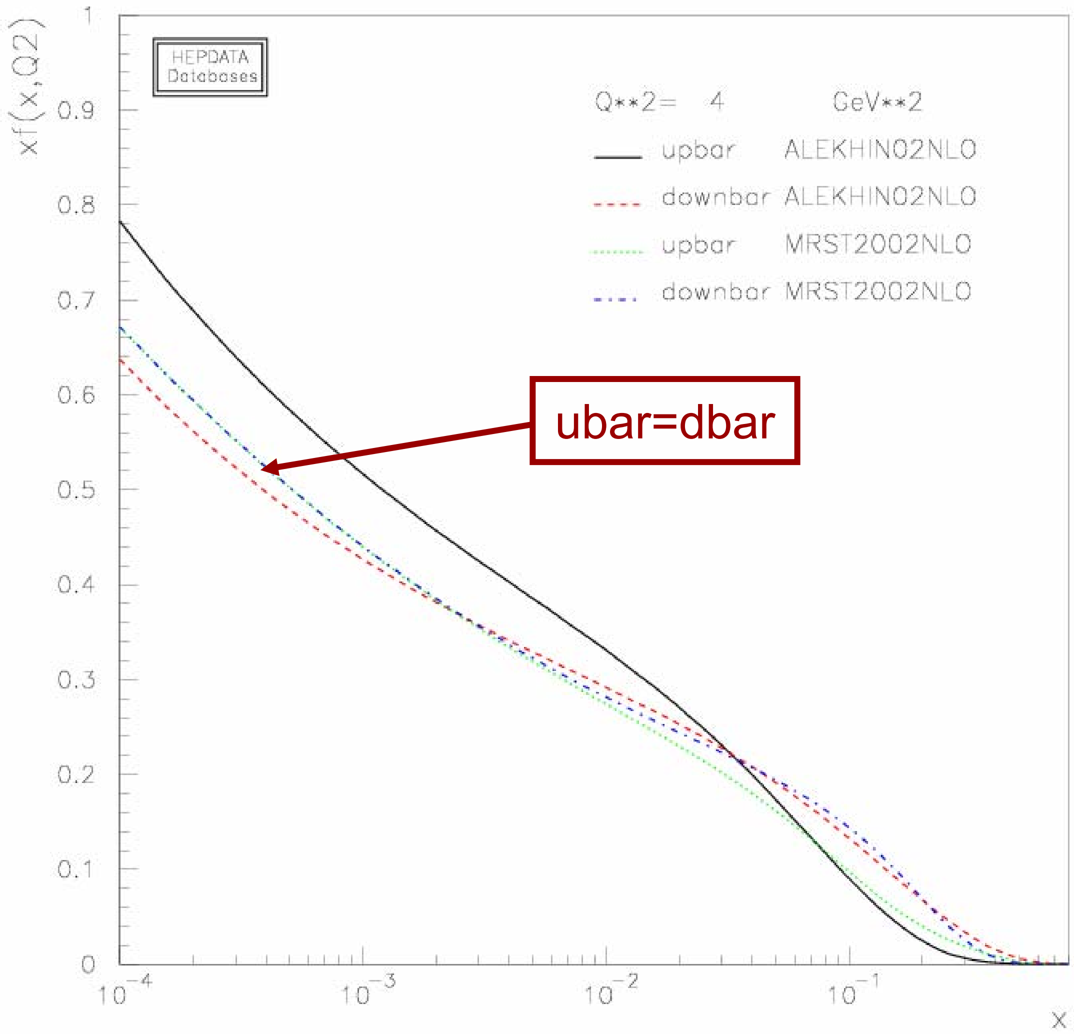
extrapolation errors

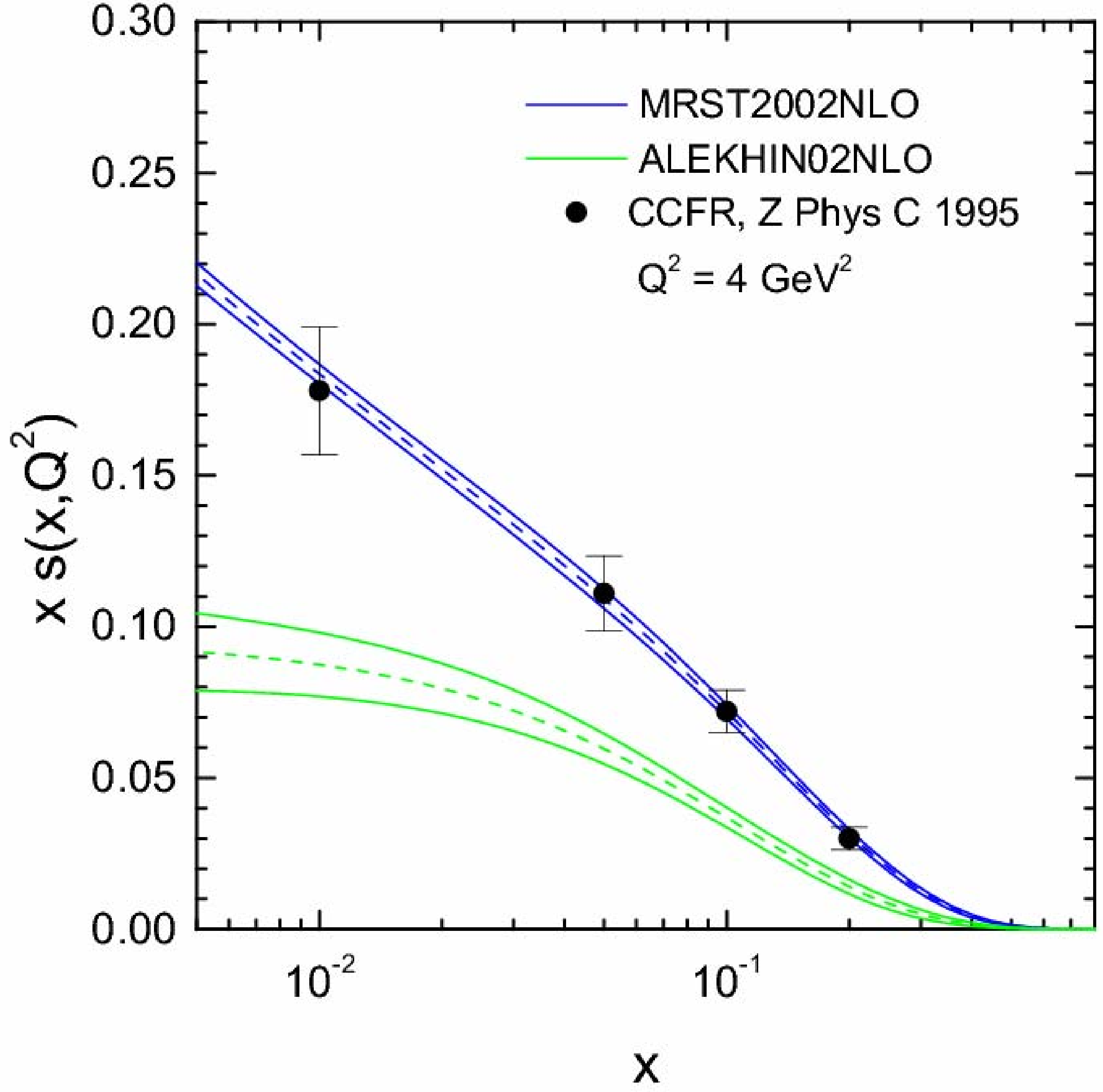


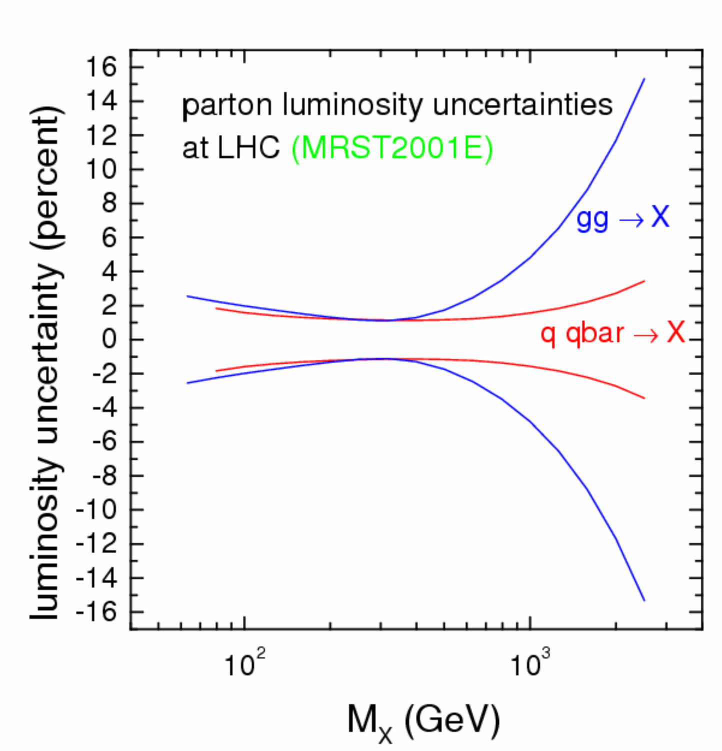
theoretical insight/guess: $f \sim A\,x$ as $x \to 0$

theoretical insight/guess: $f \sim \pm A\,x^{-0.5}$ as $x \to 0$

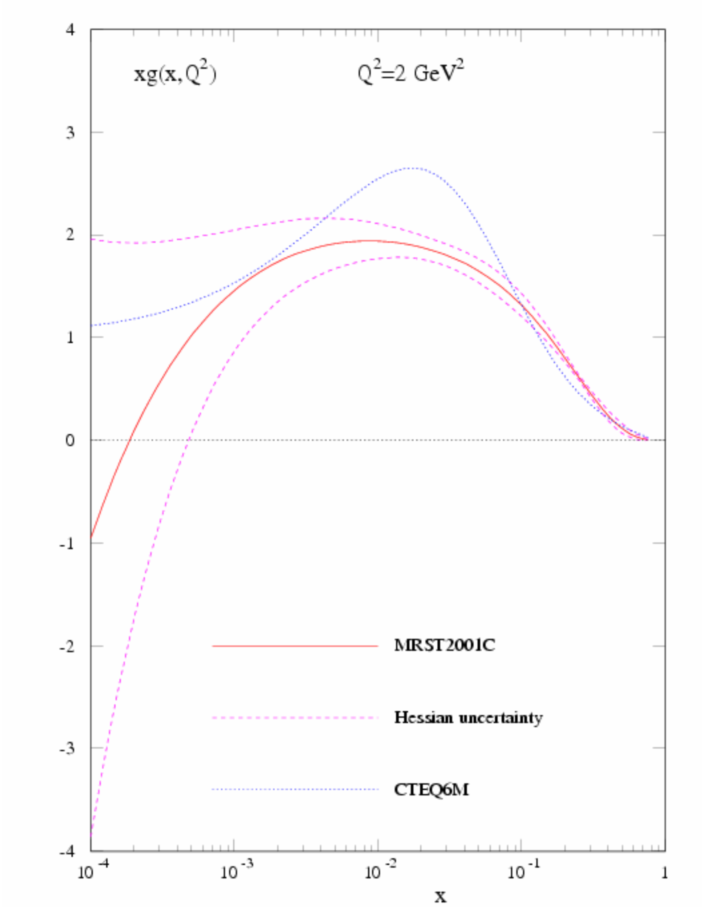
differences between the MRST and Alekhin *u* and *d* sea quarks near the starting scale




MRST2002NLO
ALEKHIN02NLO
CCFR, Z Phys C 1995
Q² = 4 GeV²
x s(x,Q²)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10⁻²
10⁻¹
x



Note: CTEQ gluon 'more or less' consistent with MRST gluon



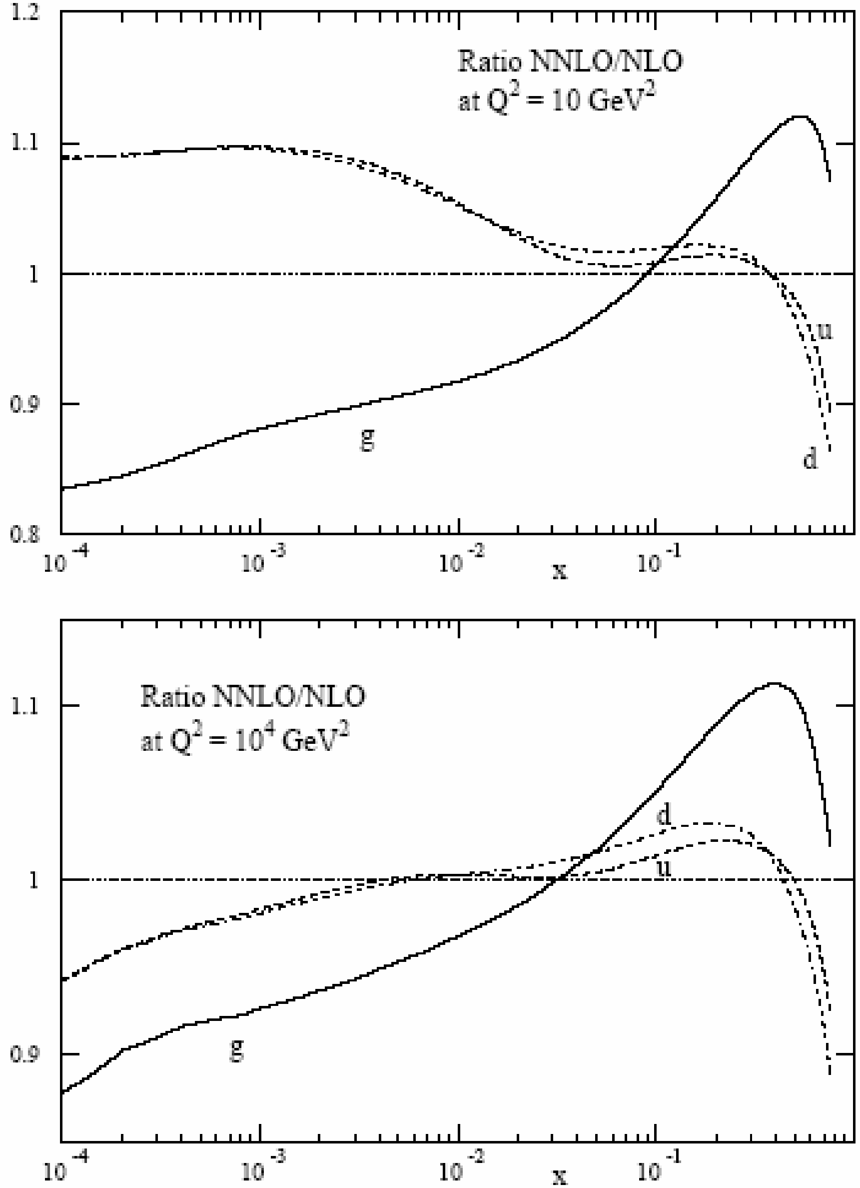
Note: high-x gluon should become better determined from Run 2 Tevatron data

Q. by how much?

comparison with existing approximate NNLO fits? (MRST, Alekhin)

- exact NNLO splitting functions are very close to approximate splitting functions (van Neerven, Vogt) based on moments & known small- and large-x behaviours…
- … and therefore the corresponding pdfs are almost identical
- Note:
  - the full NNLO pdf fit awaits calculation of the inclusive high E_T jet cross section at NNLO
  - including NNLO (splitting & coefficient functions) gives a slight improvement in overall fit quality, and reduction in $\alpha_S(M_Z)$ from 0.119 to 0.116

ratio of MRST2001 NLO and 'NNLO' parton distributions



summary of NNLO collider calculations

- $p + p \to jet + X$ *; in progress
- $p + p \to \gamma + X$; in principle, subset of the jet calculation but issues regarding photon fragmentation, isolation etc
- $p + p \to QQbar + X$; requires extension of above to non-zero fermion masses
- $p + p \to (\gamma^*, W, Z) + X$ *; van Neerven et al, Harlander and Kilgore corrected (2002)
- $p + p \to (\gamma^*, W, Z) + X$ differential rapidity distribution *; Anastasiou, Dixon, Melnikov (2003)
- $p + p \to H + X$; Harlander and Kilgore, Anastasiou and Melnikov (2002-3)

Note: knowledge of processes * needed for a full NNLO global parton distribution fit

pdfs from global fits

Formalism

LO, NLO, NNLO DGLAP
MSbar factorisation
Q_0^2
functional form @ Q_0^2
sea quark (a)symmetry
etc.

Data

DIS (SLAC, BCDMS, NMC, E665, CCFR, H1, ZEUS, …)
Drell-Yan (E605, E772, E866, …)
High E_T jets (CDF, D0)
W rapidity asymmetry (CDF)
νN dimuon (CCFR, NuTeV)
etc.

$$f_i(x,Q^2) \pm \delta f_i(x,Q^2)$$

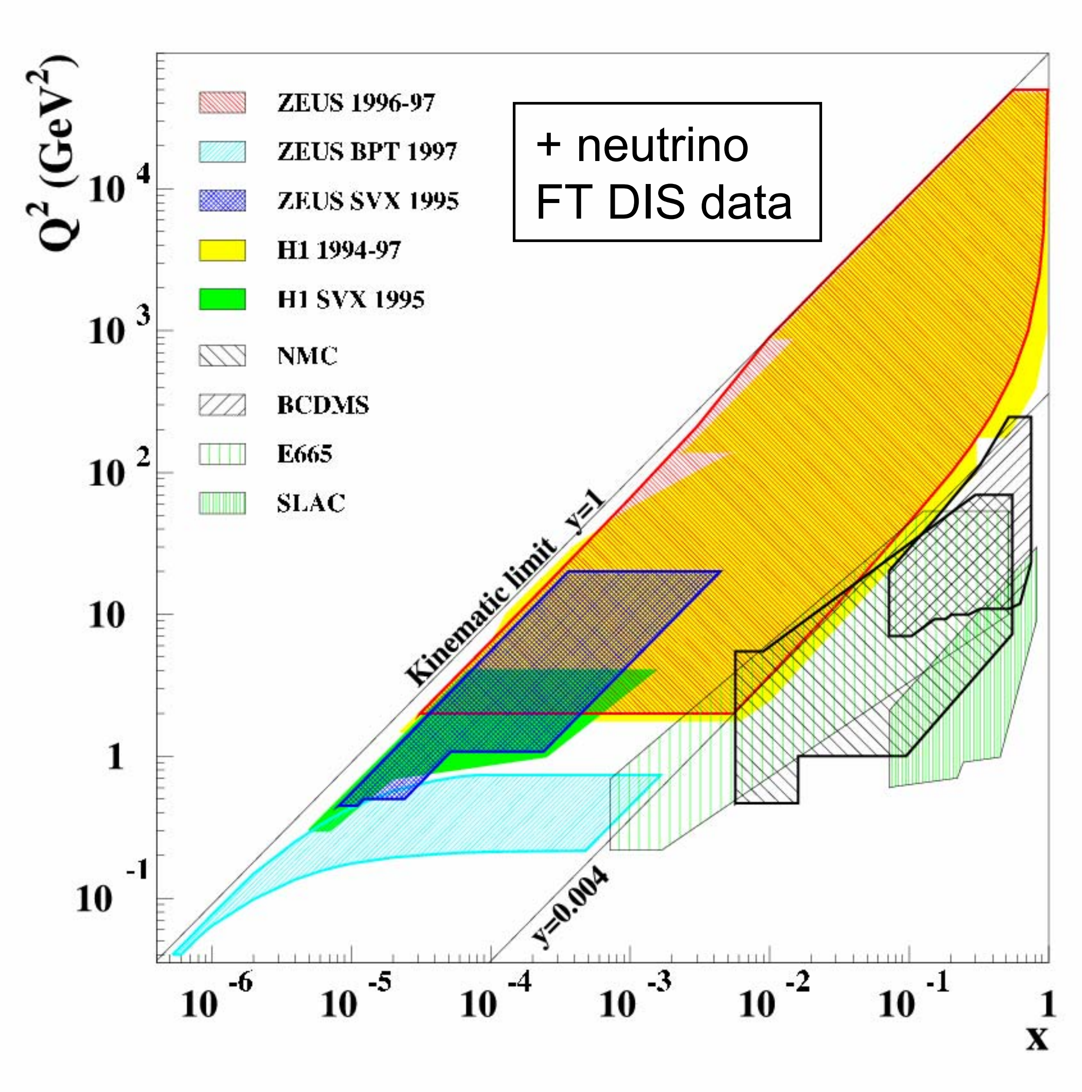
$$\alpha_S(M_Z)$$

Who?

Alekhin, CTEQ, MRST, GGK, Botje, H1, ZEUS, GRV, BFP, …

http://durpdg.dur.ac.uk/hepdata/pdf.html

summary of DIS data



Note: must impose cuts on DIS data to ensure validity of leading-twist DGLAP formalism in the global analysis, typically:

$Q^2 > 2 - 4$ GeV^2

$W^2 = (1-x)/x\, Q^2 > 10 - 15$ GeV^2

typical data ingredients of a global pdf fit

H1, ZEUS $F_2^{e^+p}(x,Q^2)$, $F_2^{e^-p}(x,Q^2)$

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

$\rightarrow q$, $\bar{q}$ at all x and g at medium, small x

H1, ZEUS $F_{2,c}^{e^+p}(x,Q^2) \rightarrow c$

E605, E772, E866 Drell-Yan $pN \rightarrow \mu\bar{\mu} + X \rightarrow \bar{q}\ (g)$

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

CDF W rapidity asymmetry $\rightarrow u/d$ ratio at high x

CDF, D0 Inclusive jet data $\rightarrow g$ at high x

CCFR, NuTeV Dimuon data constrains strange sea s, $\bar{s}$

Note: nowadays, no prompt photon data included in fits

recent global fit work

- H1, ZEUS: ongoing fits for pdfs + uncertainties from HERA and other DIS data

- Martin, Roberts, WJS, Thorne (MRST): updated `MRST2001' global fit (hep-ph/0110215); LO/NLO/'NNLO' comparison (hep-ph/0201127); pdf uncertainties: from experiment (hep-ph/0211080) and theory (hep-ph/0308087)

- Pumplin et al. (CTEQ): updated 'CTEQ6' global fit (hep-ph/0201195), including uncertainties on pdfs; dedicated study of high E_T jet cross sections for the Tevatron (hep-ph/0303013); strangeness asymmetry from neutrino dimuon production (hep-ph/0312323)

- 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 and higher-twist contributions (hep-ph/0011002); updated and including 'NNLO' fit (hep-ph/0211096)

HEPDATA pdf server

Comprehensive repository of past and present polarised and unpolarised pdf codes (with online plotting facility) can be found at the HEPDATA pdf server web site:

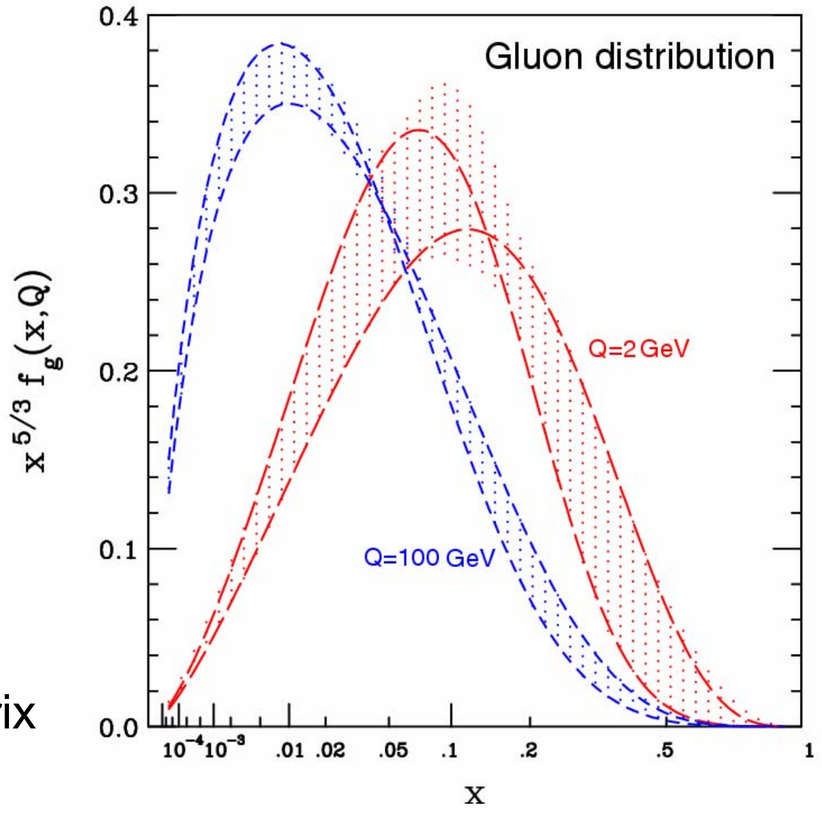
http://durpdg.dur.ac.uk/hepdata/pdf.html

… this is also the home of the LHAPDF project

pdfs with errors….

CTEQ gluon distribution uncertainty using Hessian Method

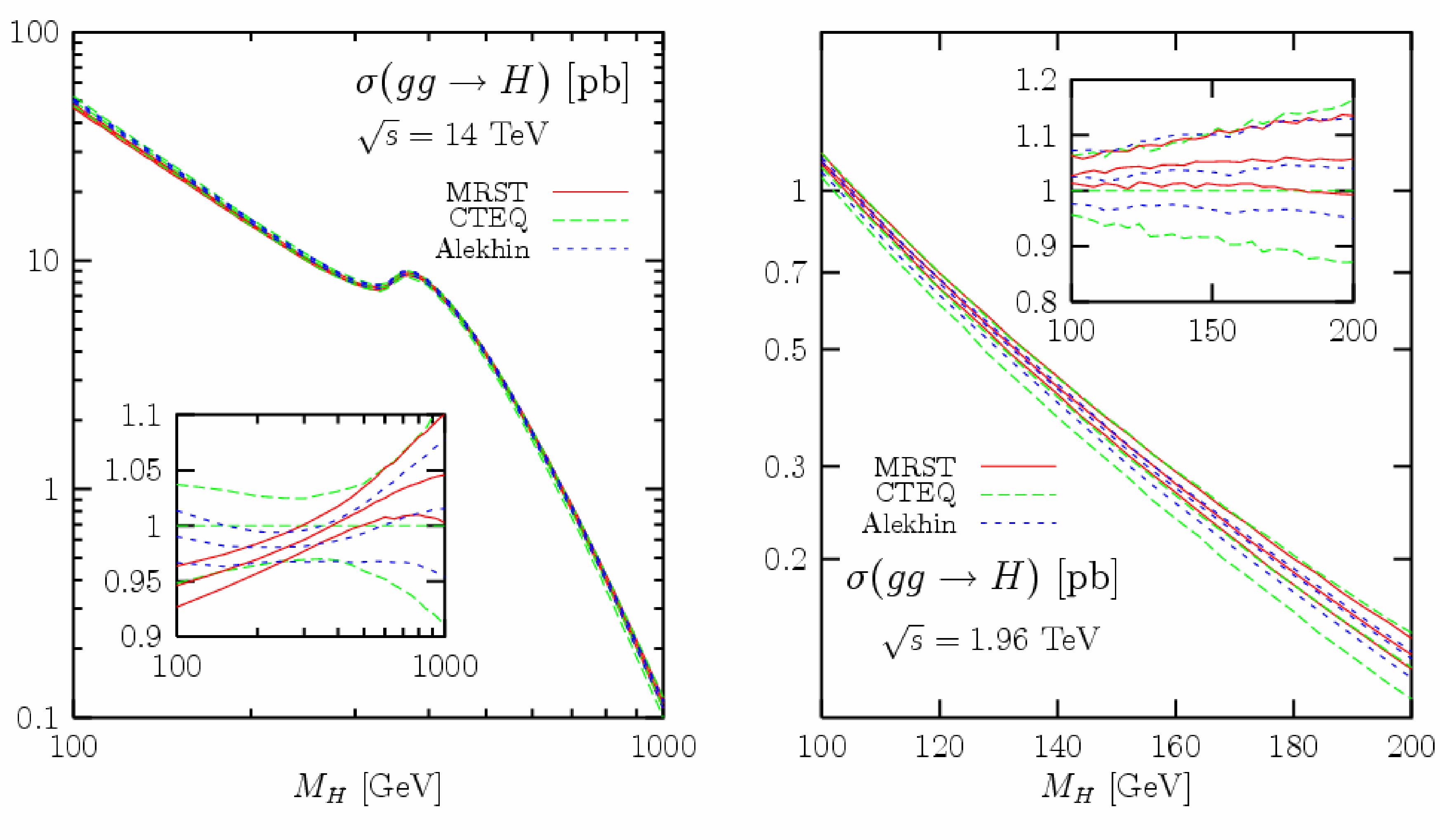
output = best fit set + $2N_p$ error sets



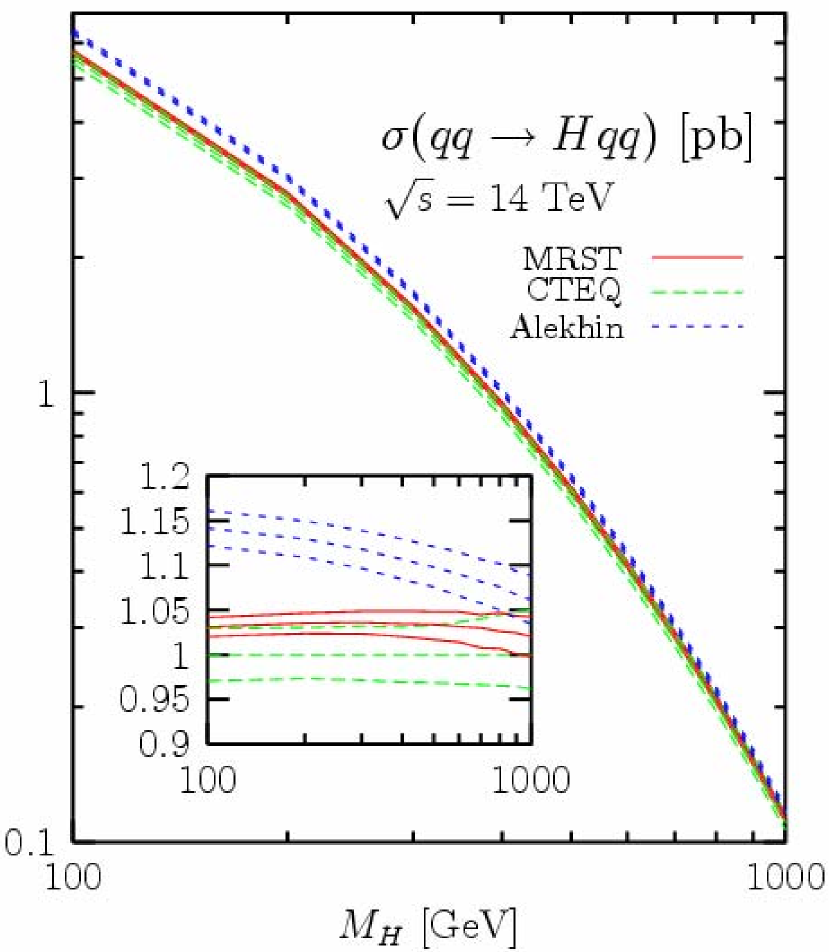
Hessian Matrix

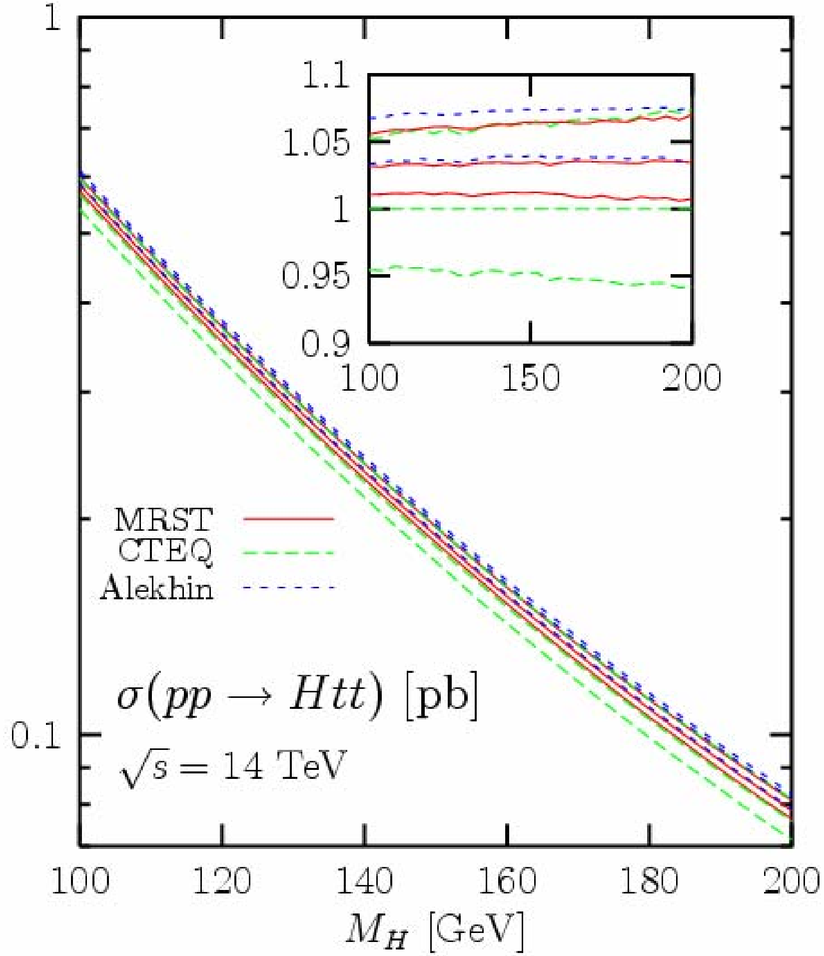
$$\chi^2 - \chi^2_{min} \equiv \Delta\chi^2 = \sum_{i,j} H_{ij}(a_i - a_i^{(0)})(a_j - a_j^{(0)})$$

"best fit" parameters



Djouadi & Ferrag, hep-ph/0310209





Djouadi & Ferrag, hep-ph/0310209

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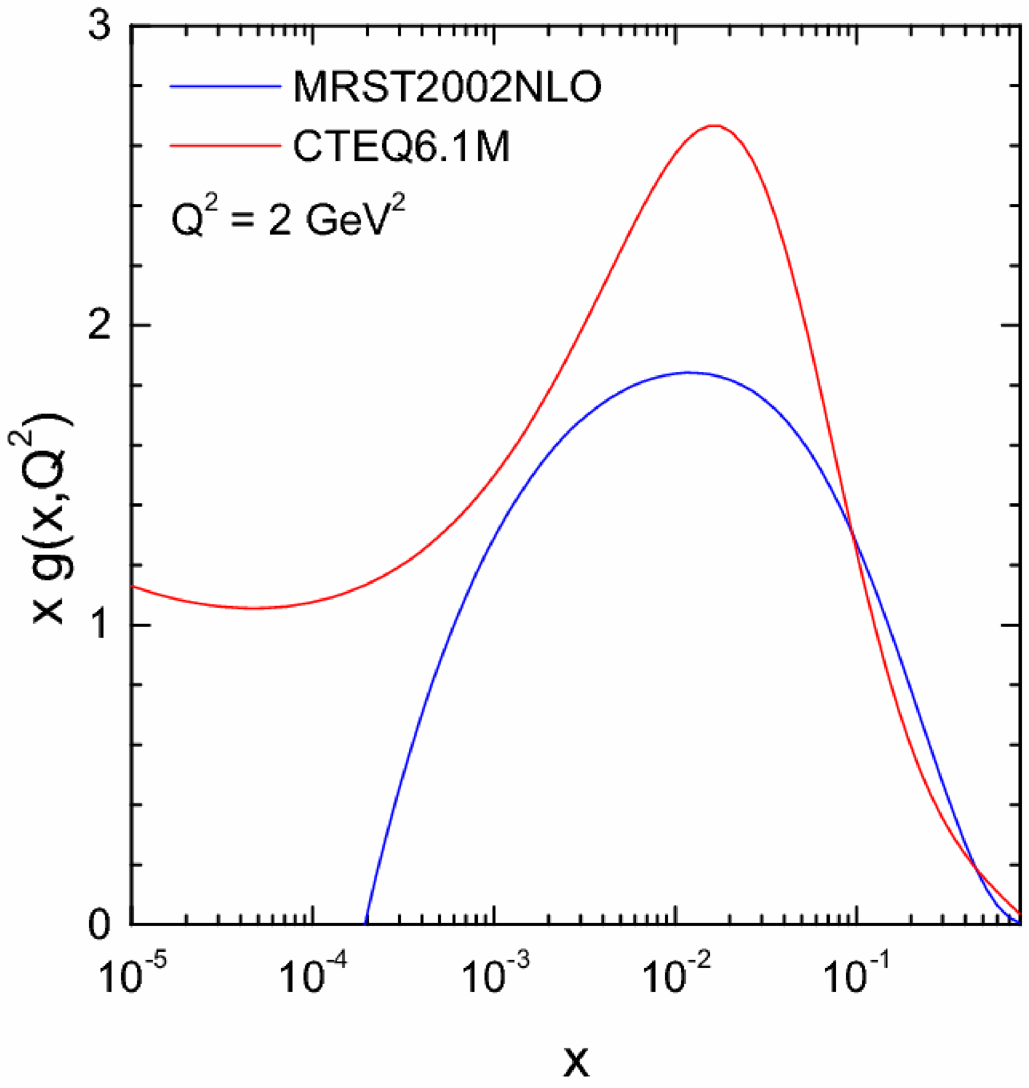
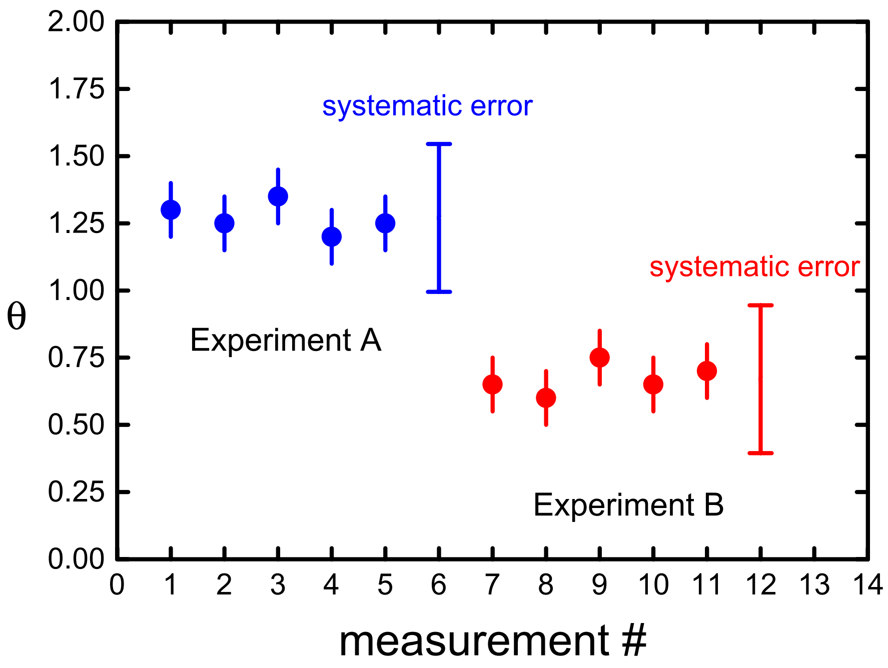
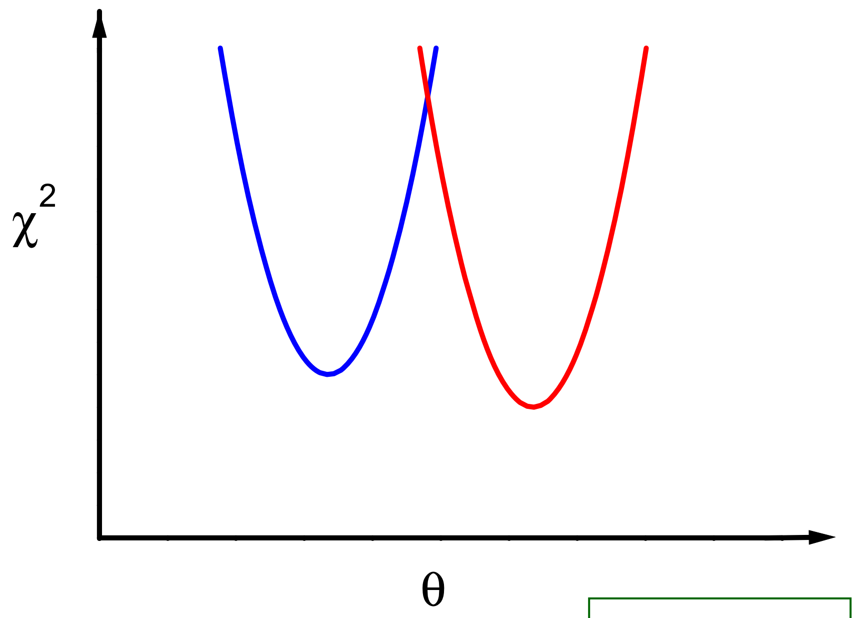


tensions within the global fit?





pictures from
W-K Tung

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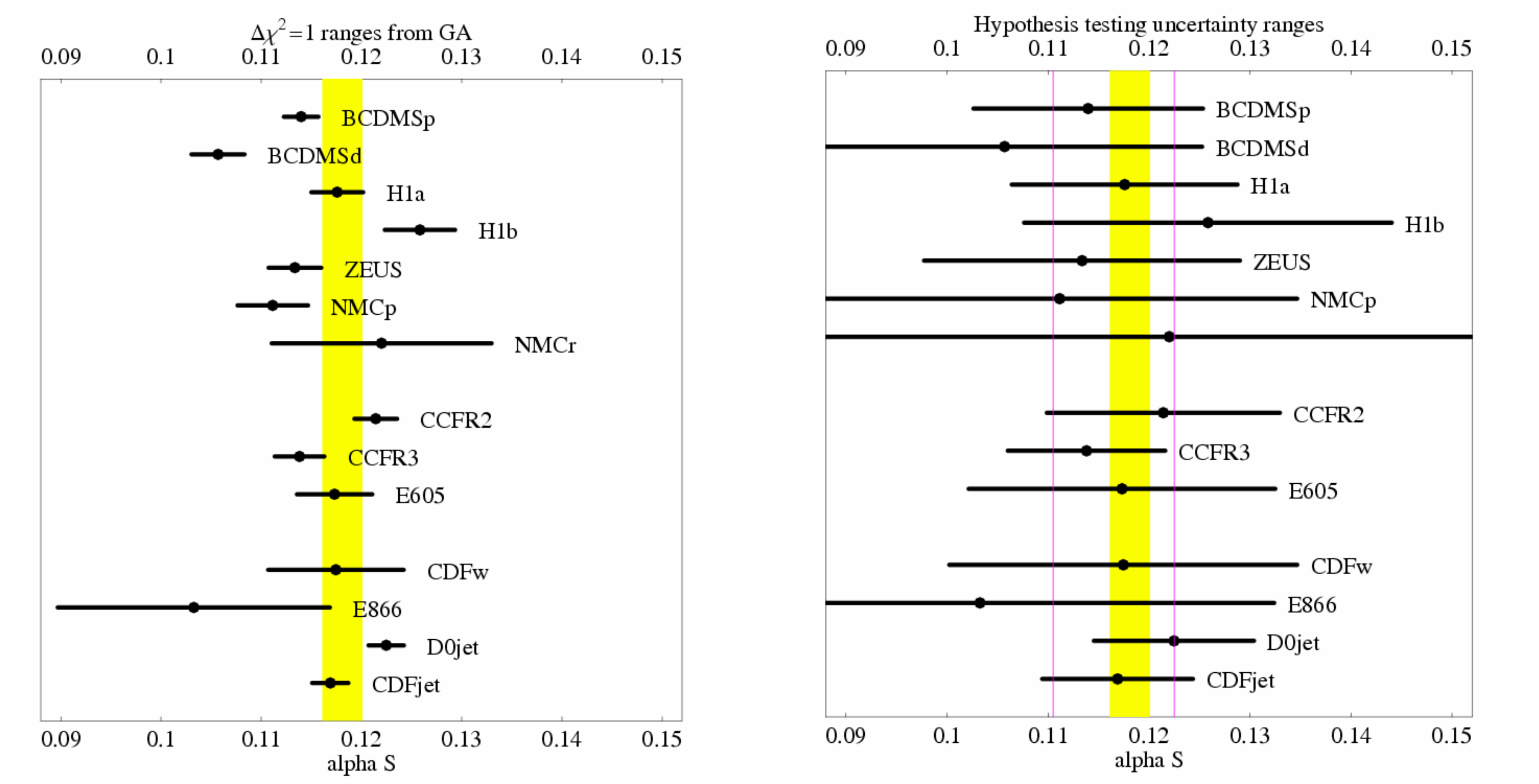
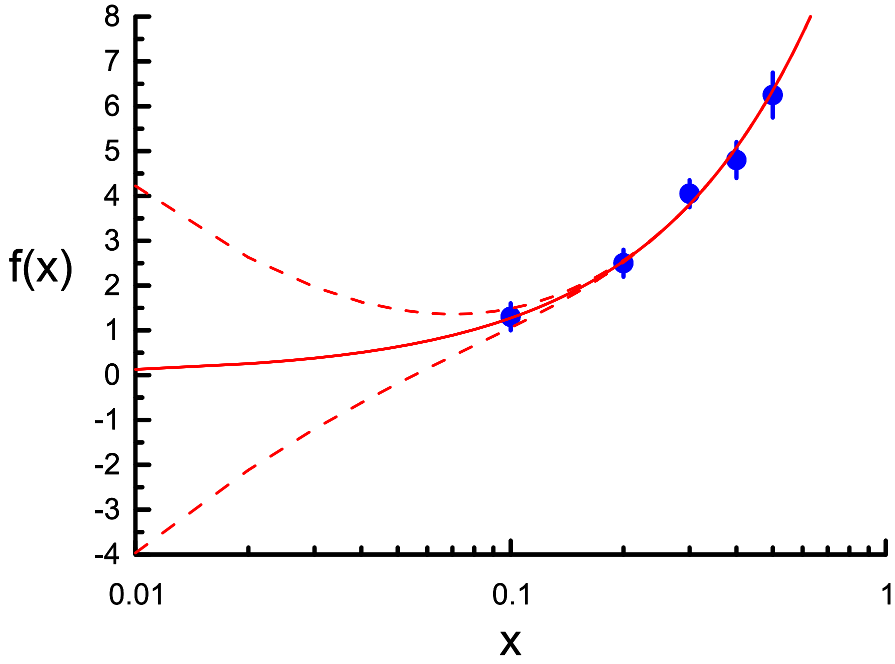


extrapolation errors



theoretical insight/guess: $f \sim A\, x$ as $x \to 0$

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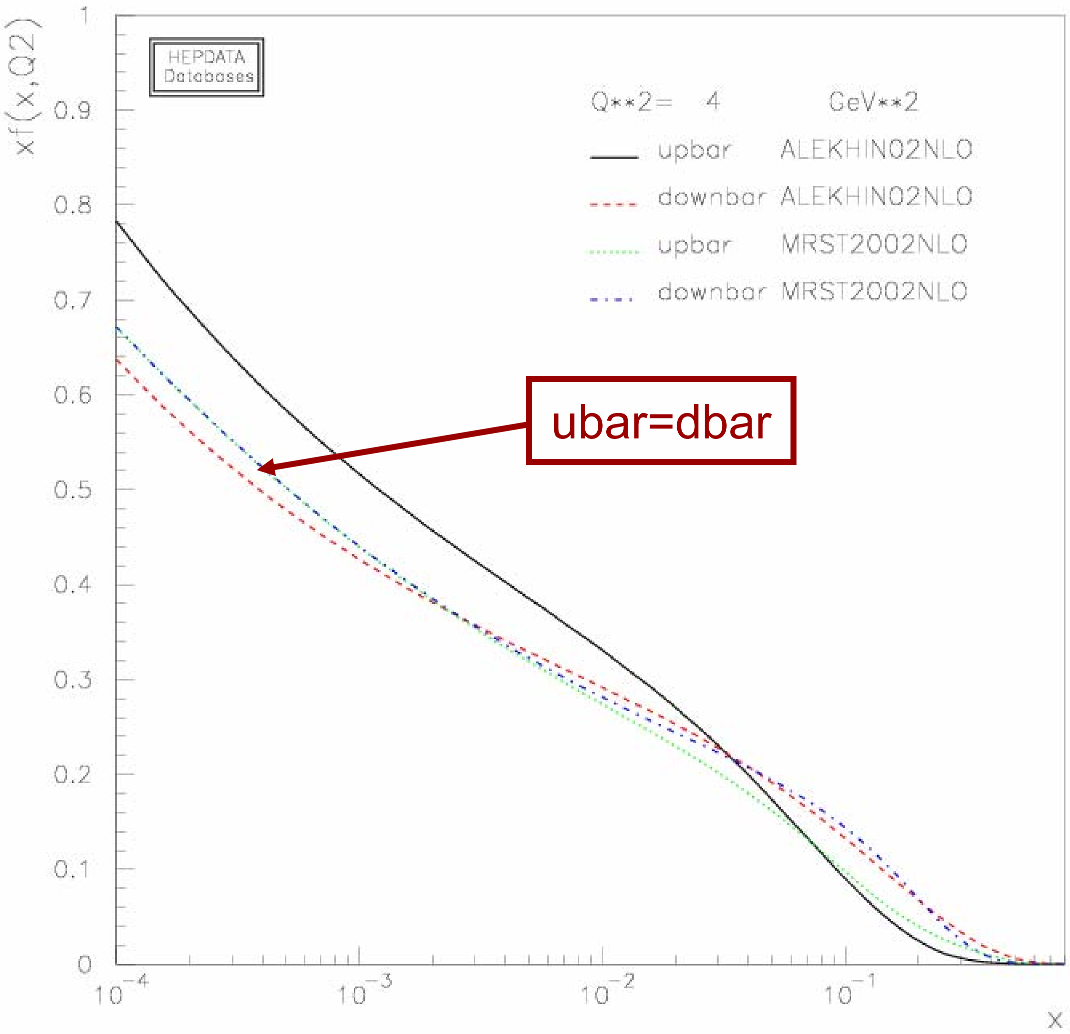
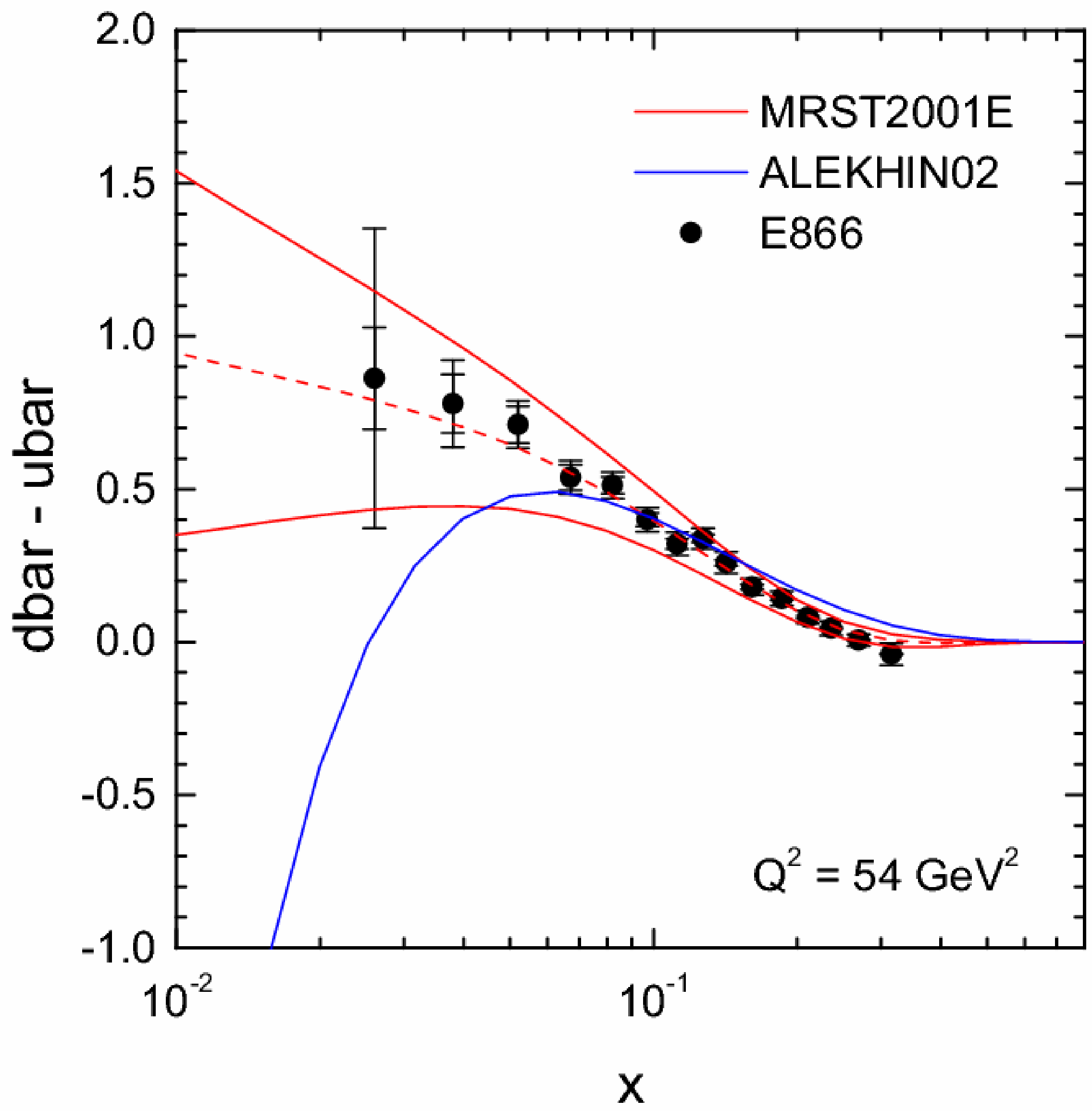
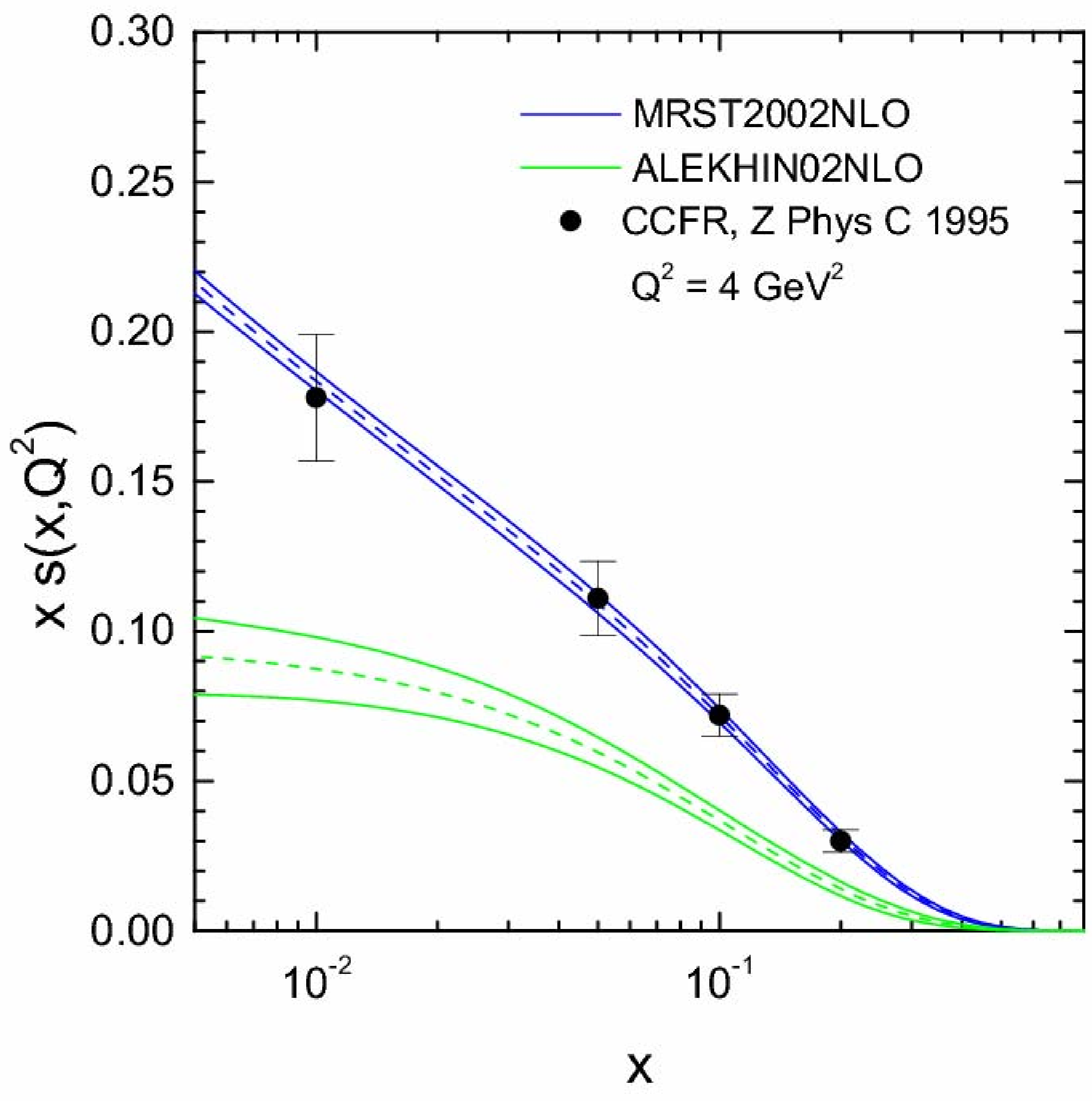
differences between the MRST and Alekhin *u* and *d* sea quarks near the starting scale

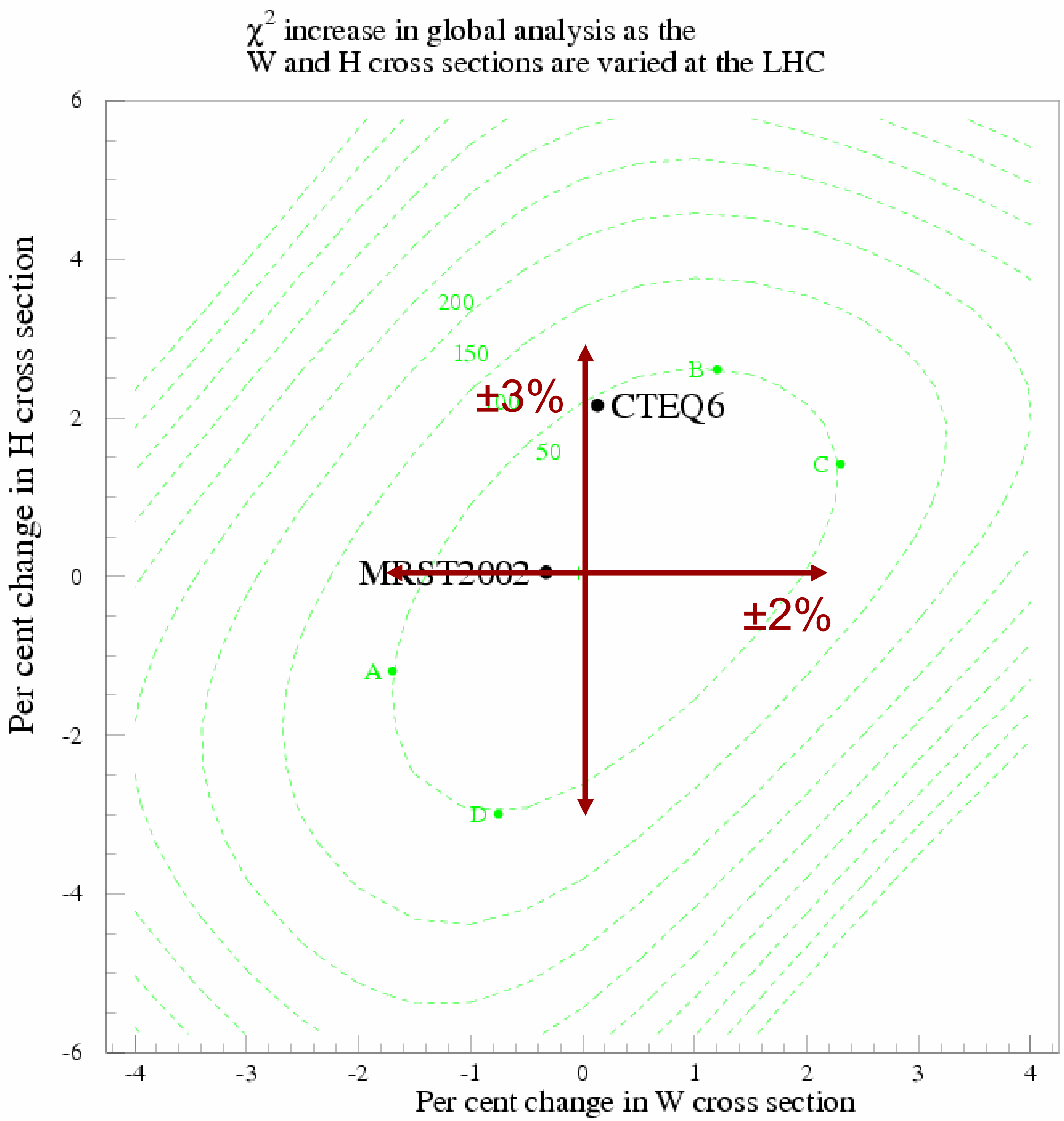




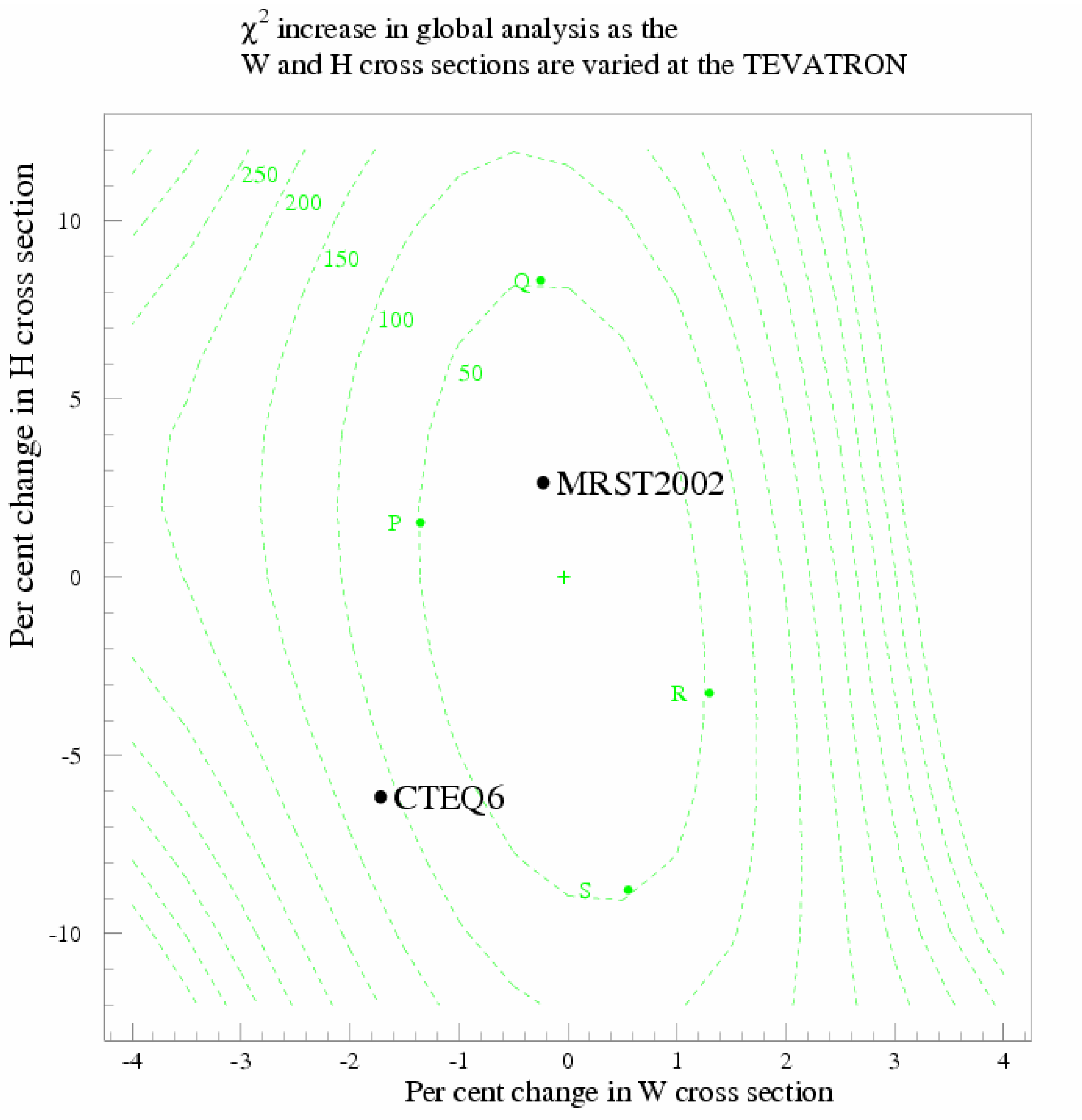
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
dbar - ubar
MRST2001E
ALEKHIN02
E866
Q^2 = 54 GeV^2
10^{-2}
10^{-1}
x



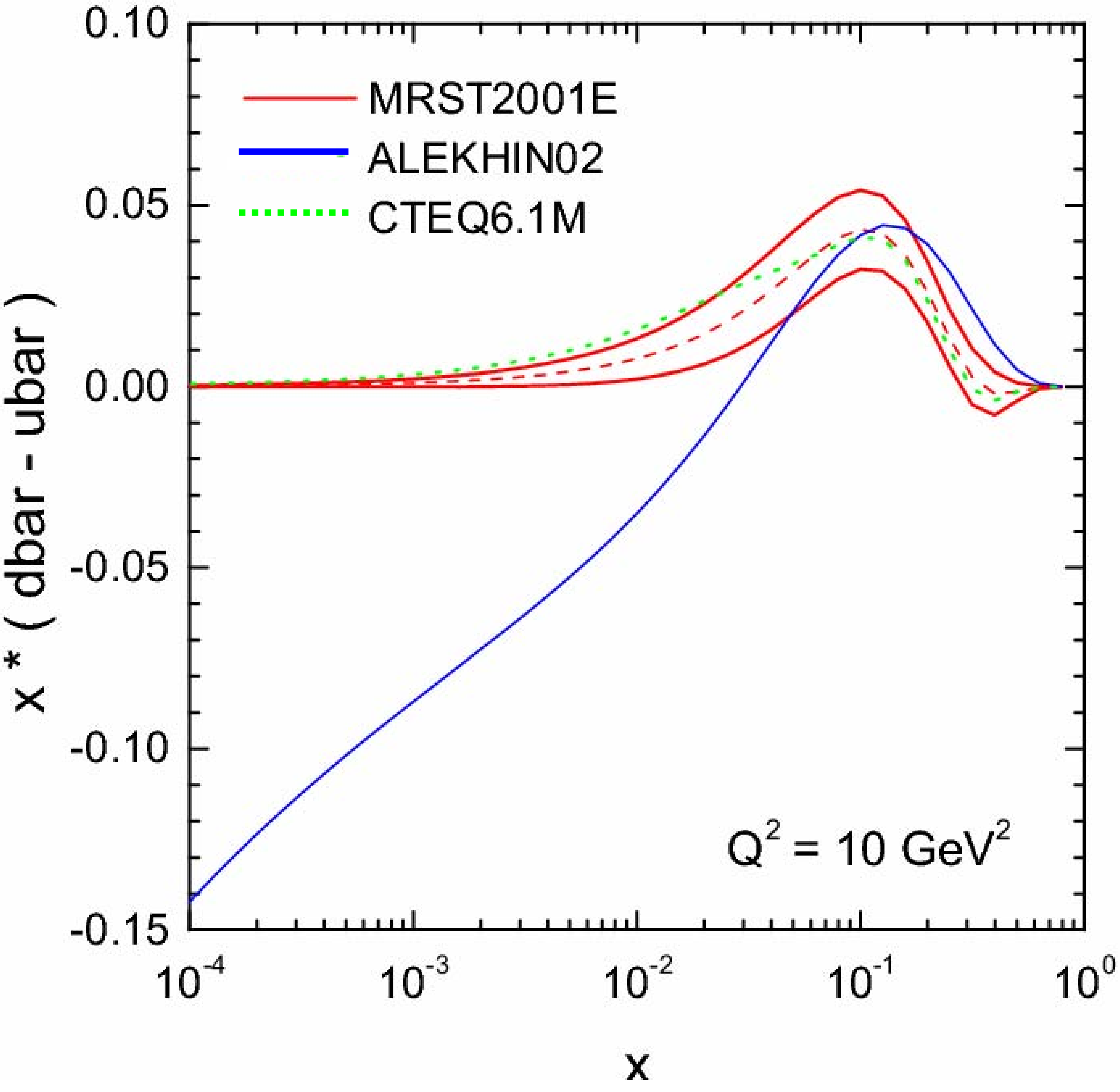
MRST2002NLO
ALEKHIN02NLO
CCFR, Z Phys C 1995
Q^2 = 4 GeV^2
0.30
0.25
0.20
0.15
0.10
0.05
0.00
$x\, s(x,Q^2)$
10^{-2}
10^{-1}
x



contours correspond to ‘ experimental’ pdf errors only; shift of prediction using CTEQ6 pdfs shows effect of ‘theoretical’ pdf errors



χ^2 increase in global analysis as the
W and H cross sections are varied at the TEVATRON
250
200
150
100
50
Q
P
R
S
MRST2002
CTEQ6
Per cent change in H cross section
10
5
0
-5
-10
-4
-3
-2
-1
0
1
2
3
4
Per cent change in W cross section



MRST2001E
ALEKHIN02
CTEQ6.1M
$Q^2 = 10\ GeV^2$
x * (dbar - ubar)
x
0.10
0.05
0.00
-0.05
-0.10
-0.15
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

as small *x* data are systematically removed from the MRST global fit, the quality of the fit improves until stability is reached at around *x* ~ 0.005 (MRST hep-ph/0308087)

Q. Is fixed–order DGLAP insufficient for small-x DIS data?!

Δ = improvement in χ^2 to remaining data / # of data points removed

$x_{\rm cut}$:	0	0.0002	0.001	0.0025	0.005	0.01
# data points	2097	2050	1961	1898	1826	1762
$\alpha_S(M_Z^2)$	0.1197	0.1200	0.1196	0.1185	0.1178	0.1180
$\chi^2(x > 0)$	2267					
$\chi^2(x > 0.0002)$	2212	2203				
$\chi^2(x > 0.001)$	2134	2128	2119			
$\chi^2(x > 0.0025)$	2069	2064	2055	2040		
$\chi^2(x > 0.005)$	2024	2019	2012	1993	1973	
$\chi^2(x > 0.01)$	1965	1961	1953	1934	1917	1916
Δ_i^{i+1}		0.19	0.10	0.24	0.28	0.02

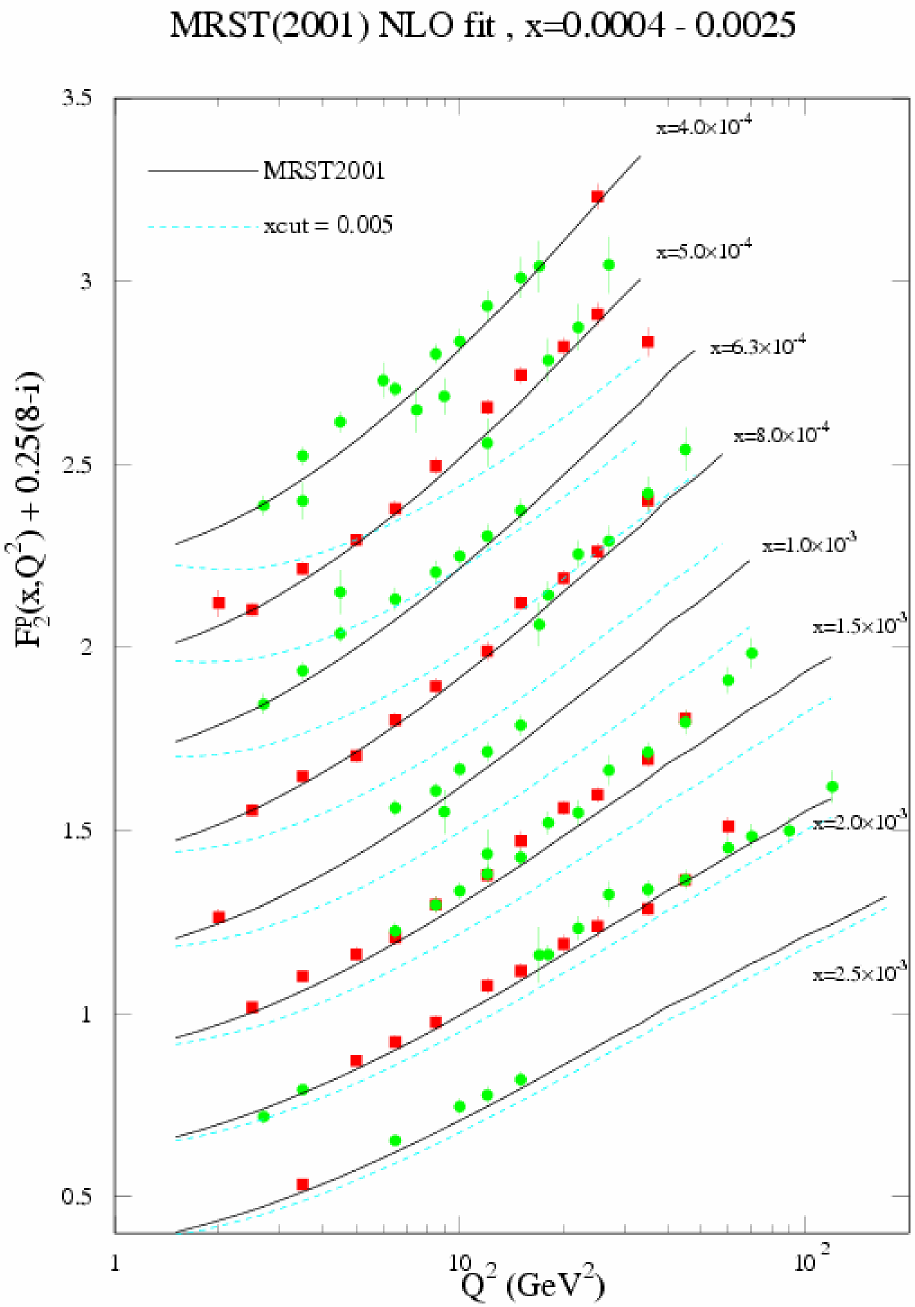
the stability of the small-*x* fit can be recovered by adding to the fit empirical contributions of the form

$$P_{gg} \to P_{gg}^{\rm NLO} + A\overline{\alpha}_S^4 \left(\frac{\ln^3 1/x}{3!} - \frac{\ln^2 1/x}{2!} \right)$$

$$P_{qg} \to P_{qg}^{\rm NLO} + B\alpha_S \frac{n_f}{3\pi} \overline{\alpha}_S^4 \left(\frac{\ln^3 1/x}{3!} - \frac{\ln^2 1/x}{2!} \right)$$

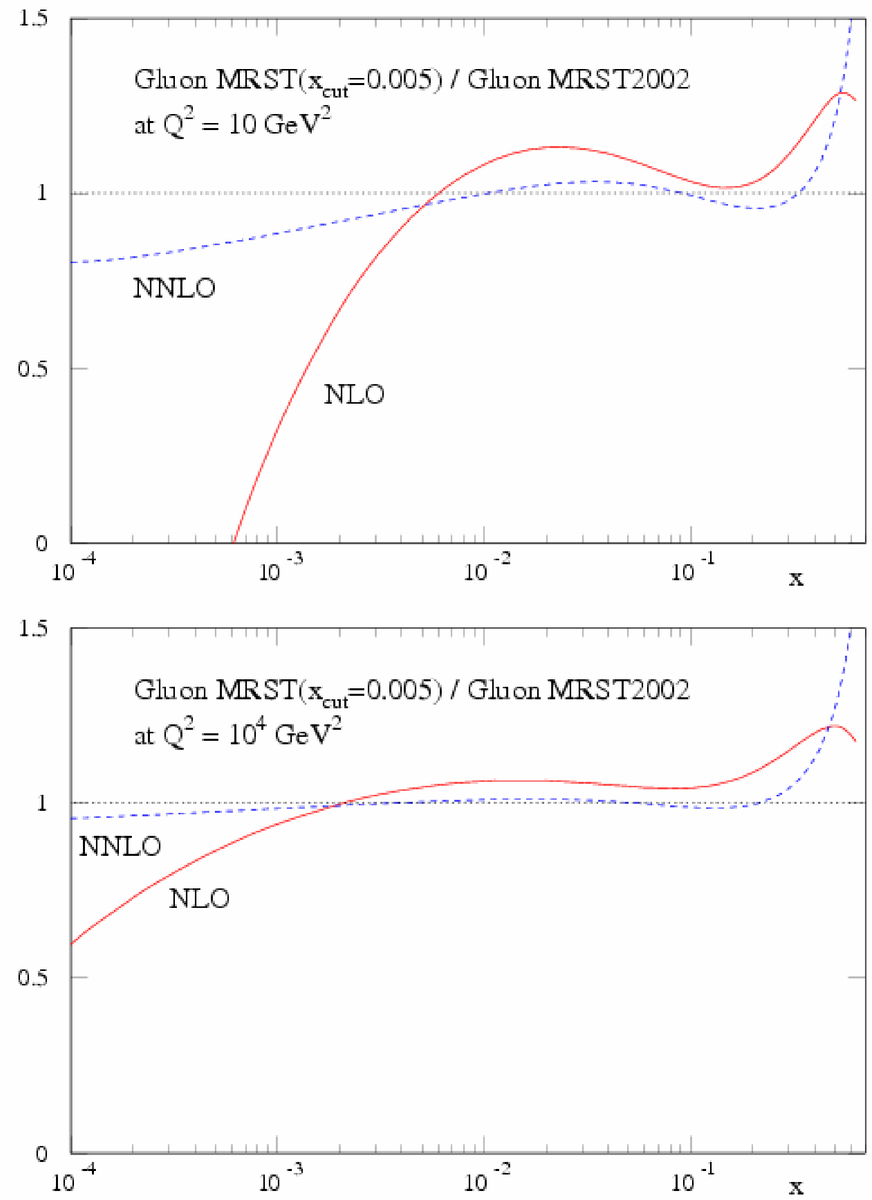
... with coefficients *A*, *B* found to be O(1) (and different for the NLO, NNLO fits); the starting gluon is still very negative at small *x* however the ‘conservative’ pdfs (blue lines) do not describe the very low x DIS data not included in the fit

MRST, hep-ph/0308087



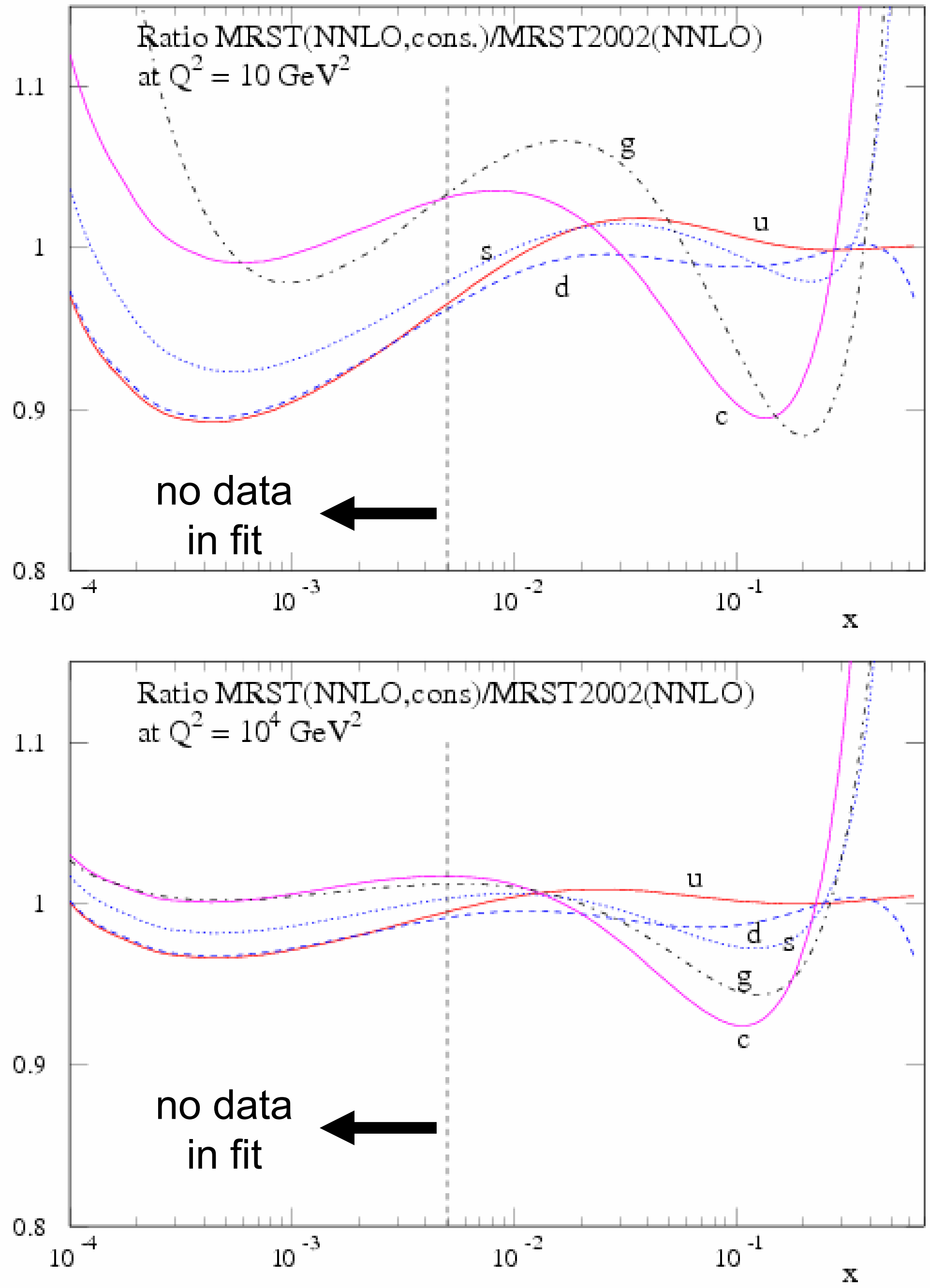
the change in the NLO and NNLO gluons when DIS data with x < 0.005 are removed from the global fit

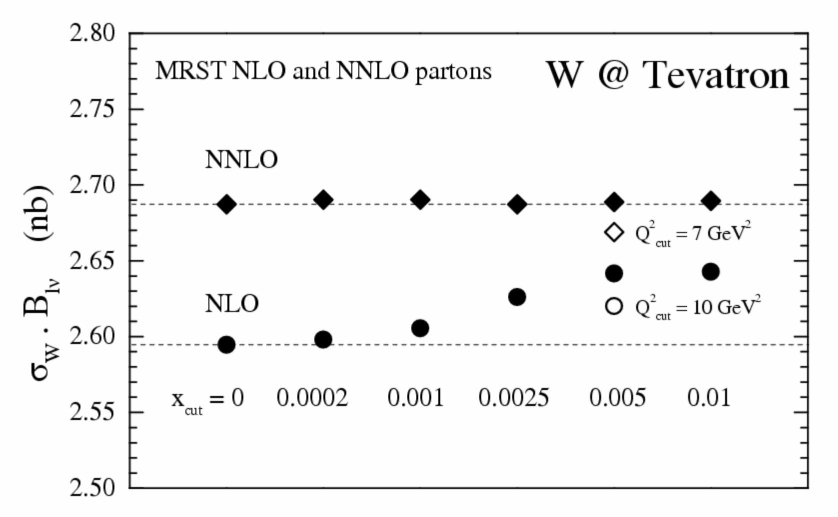
MRST, hep-ph/0308087

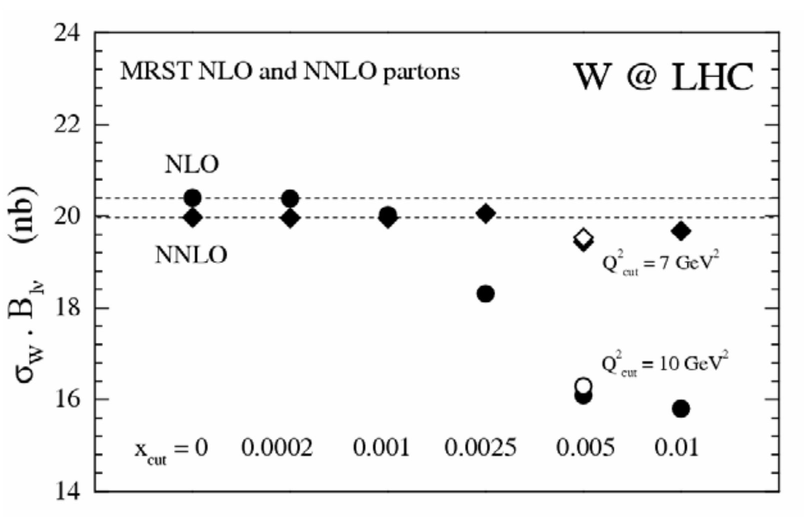


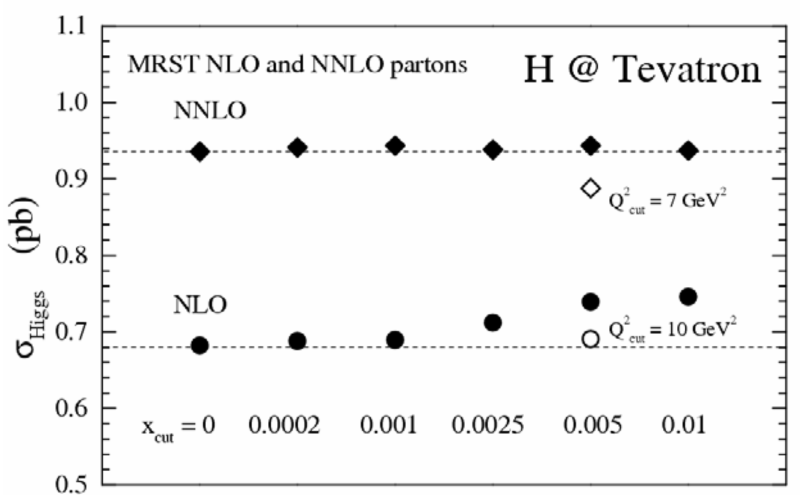
comparison of the standard MRST and 'conservative' NNLO pdfs

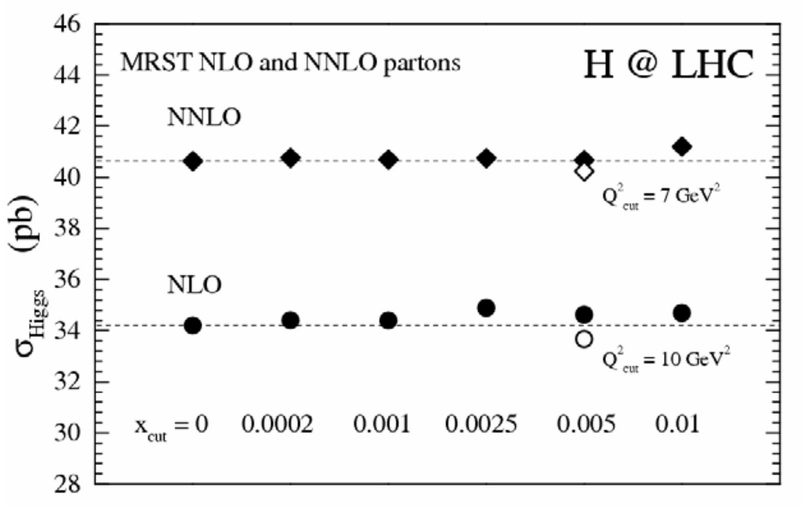
MRST, hep-ph/0308087




MRST NLO and NNLO partons
W @ Tevatron
NNLO
NLO
Q^2_{cut} = 7 GeV^2
Q^2_{cut} = 10 GeV^2
x_{cut} = 0
0.0002
0.001
0.0025
0.005
0.01
$\sigma_W \cdot B_{l\nu}$ (nb)


MRST NLO and NNLO partons
W @ LHC
NLO
NNLO
Q^2_{cut} = 7 GeV^2
Q^2_{cut} = 10 GeV^2
x_{cut} = 0
0.0002
0.001
0.0025
0.005
0.01
$\sigma_W \cdot B_{l\nu}$ (nb)


MRST NLO and NNLO partons
H @ Tevatron
NNLO
NLO
Q^2_{cut} = 7 GeV^2
Q^2_{cut} = 10 GeV^2
x_{cut} = 0
0.0002
0.001
0.0025
0.005
0.01
σ_{Higgs} (pb)

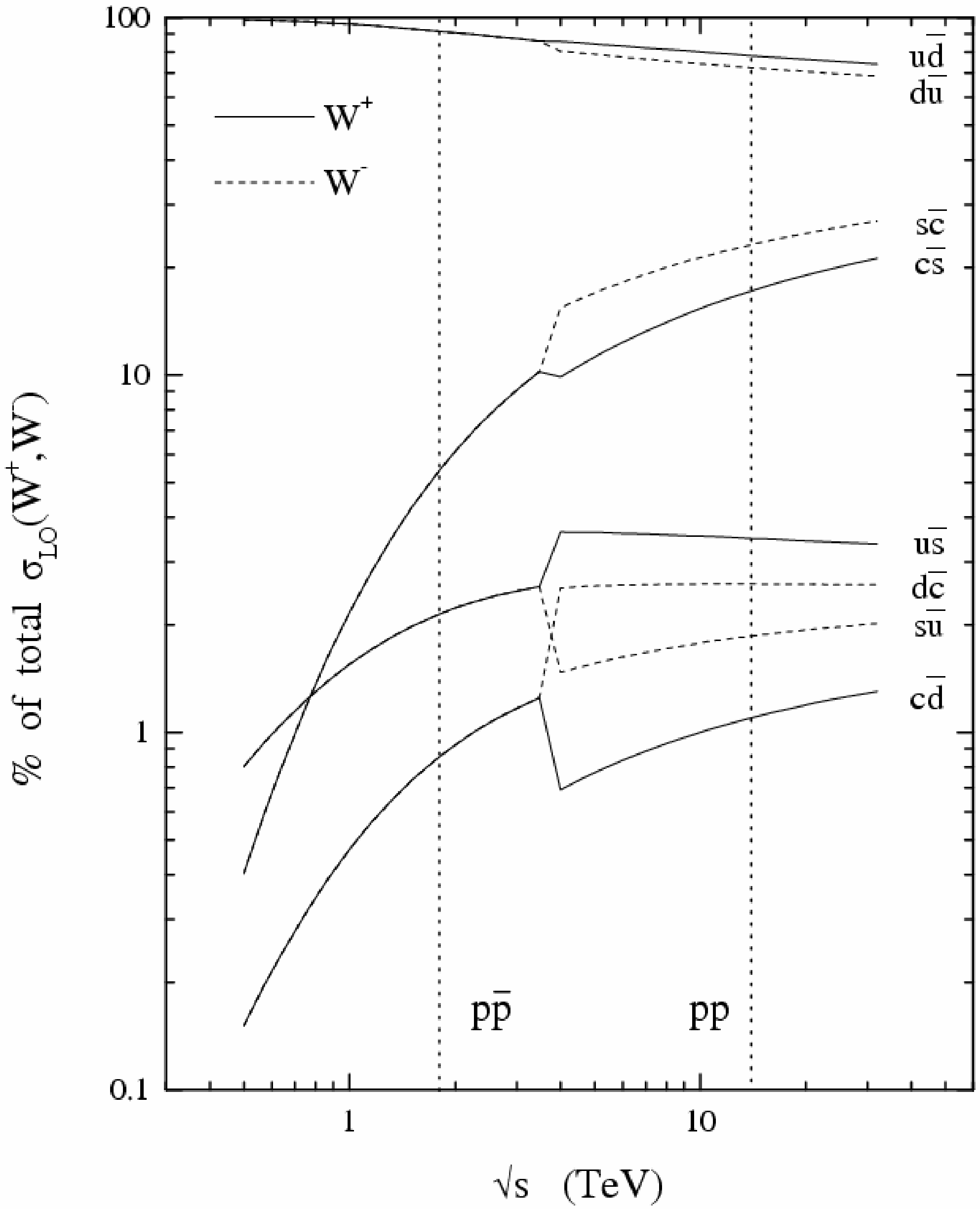

MRST NLO and NNLO partons
H @ LHC
NNLO
NLO
Q^2_{cut} = 7 GeV^2
Q^2_{cut} = 10 GeV^2
x_{cut} = 0
0.0002
0.001
0.0025
0.005
0.01
σ_{Higgs} (pb)

(LO) W cross sections at the Tevatron and LHC using (NLO) partons from MRST, CTEQ and Alekhin

Tevatron	B.σ(W) (nb)
MRST2002	2.14
CTEQ6	2.10
Alekhin02	2.22

LHC	B.σ(W^+) (nb)	B.σ(W) (nb)	W^+/W^-
MRST2002	10.1	7.6	1.33
CTEQ6	10.2	7.6	1.34
Alekhin02	10.7	7.9	1.35

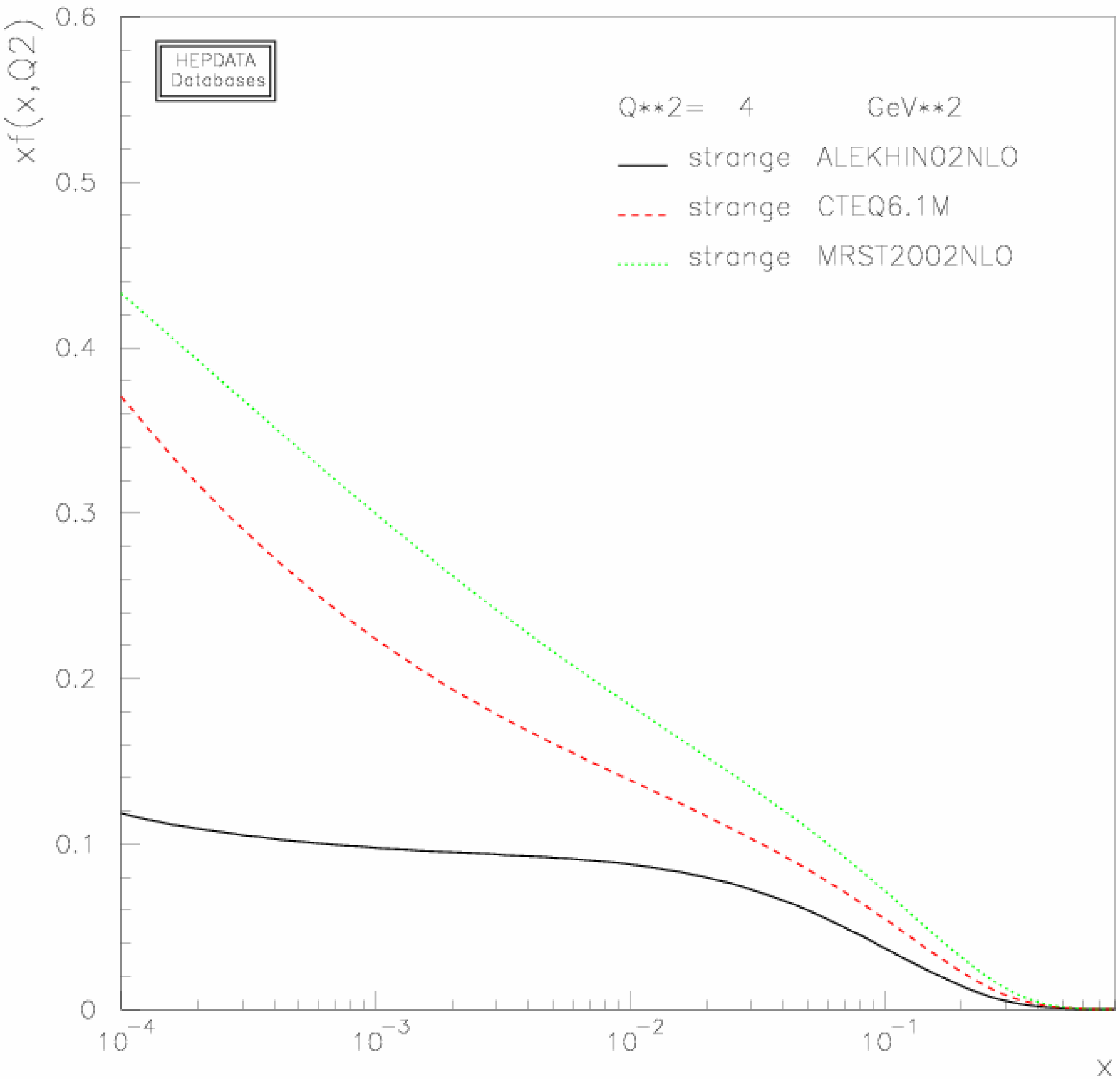
flavour decomposition of W cross sections at hadron colliders



recall that the only constraint on very small x quarks from inclusive DIS (F_2^{ep}) data is on the combination

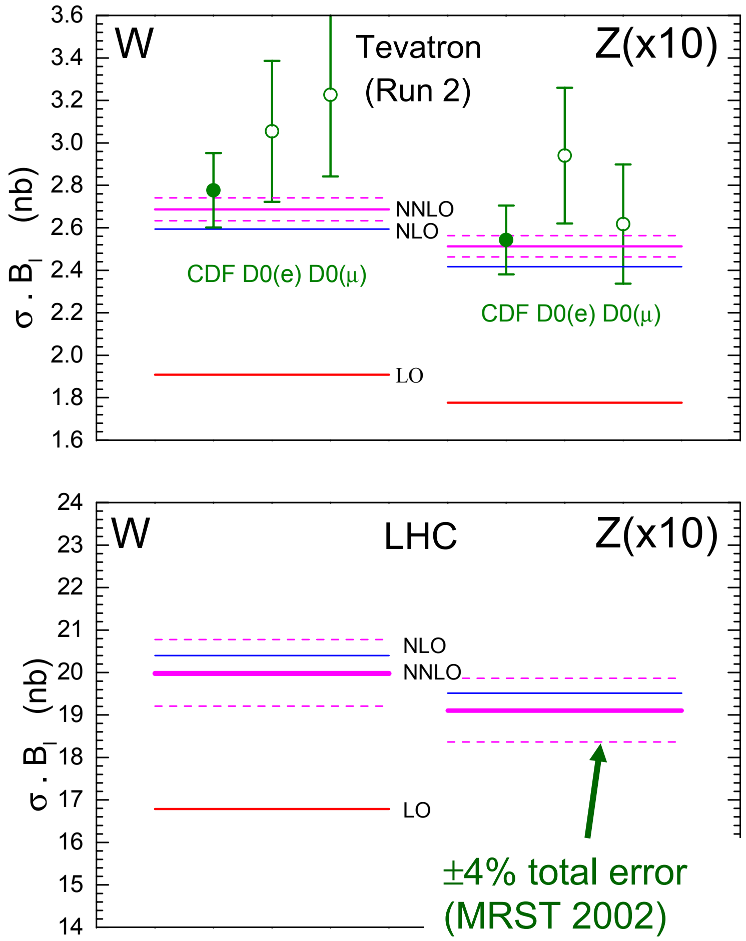
4/9 [u+c+ubar+cbar]
+ 1/9 [d+s+dbar+sbar]

differences between the MRST, CTEQ and Alekhin strange quarks near the starting scale



NNLO precision phenomenology

- predictions calculated (MRST 2002) using 'old' approximate two-loop splitting functions
- width of ▬ shows uncertainty from $P^{(2)}$ (biggest at small x)
- this uncertainty now removed, NNLO prediction unchanged



partons: MRST2002
NNLO evolution: van Neerven, Vogt approximation to Vermaseren et al. moments
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections