STATUS OF DEEP INELASTIC LEPTON-NUCLEON SCATTERING

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NuFact02, 1 July 2002

- overview of DIS
- electroweak
- hadron structure
- polarised DIS
- DIS at a neutrino factory
- conclusions

DIS kinematics

- variables
  - momentum transferred into target by photon:

$$Q^2 \;=\; -q^2 \;>\; 0$$

  - resolution:

$$\lambda \;=\; \frac{\hbar}{Q} \;=\; \frac{2\times 10^{-16}\ \mathrm{m\ GeV}}{Q}$$

  - inelasticity:

$$x \;=\; \frac{Q^2}{Q^2+M_X^2-M_p^2} \qquad (0 \le x \le 1)$$

hence “deep $(Q^2 \to \infty)$ inelastic $(x < 1)$ scattering”

(other variables: $s = (p+k)^2$, $y = Q^2/(xs)$)

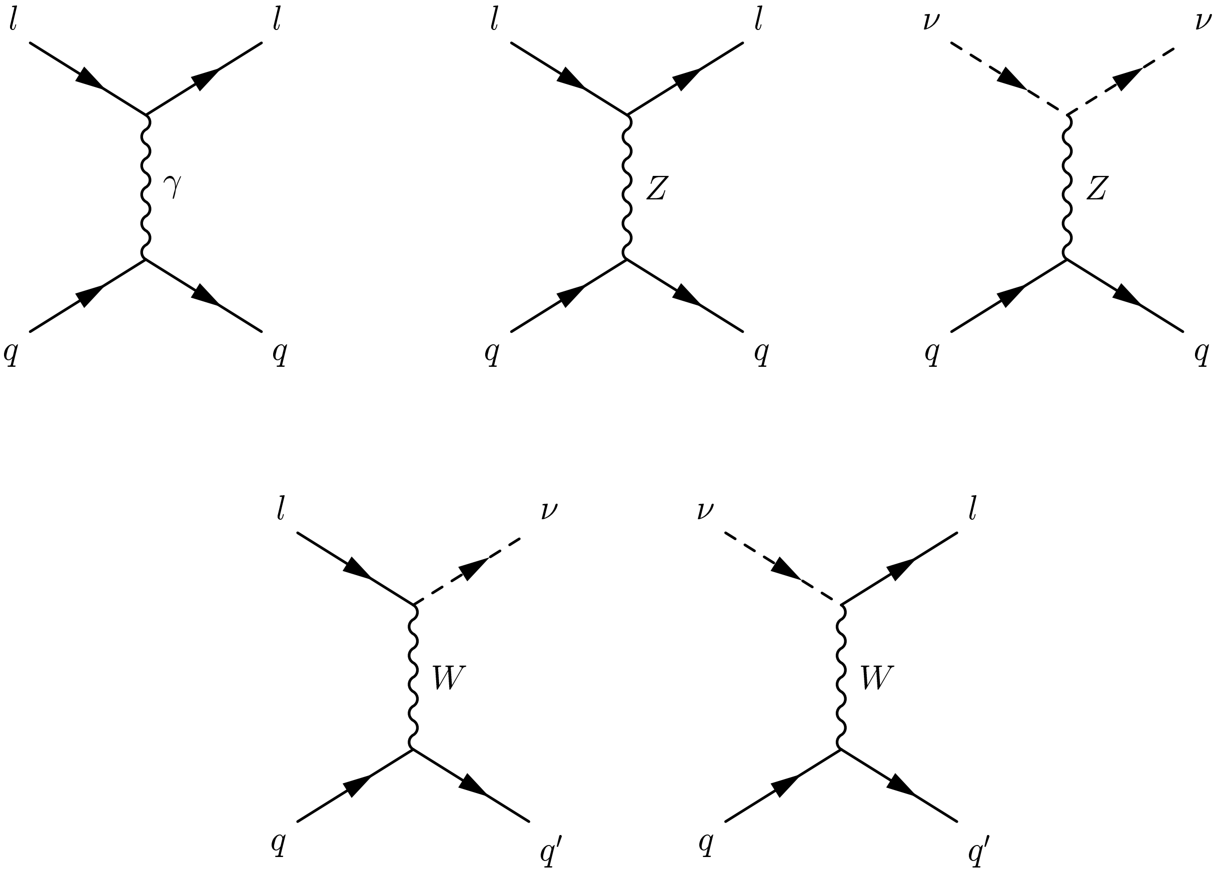
- experiments up to $\sqrt{s} \simeq 300\ \mathrm{GeV}$ (HERA)

$$\Rightarrow \quad Q^2 \;\lesssim\; 10^5\ \mathrm{GeV}^2$$

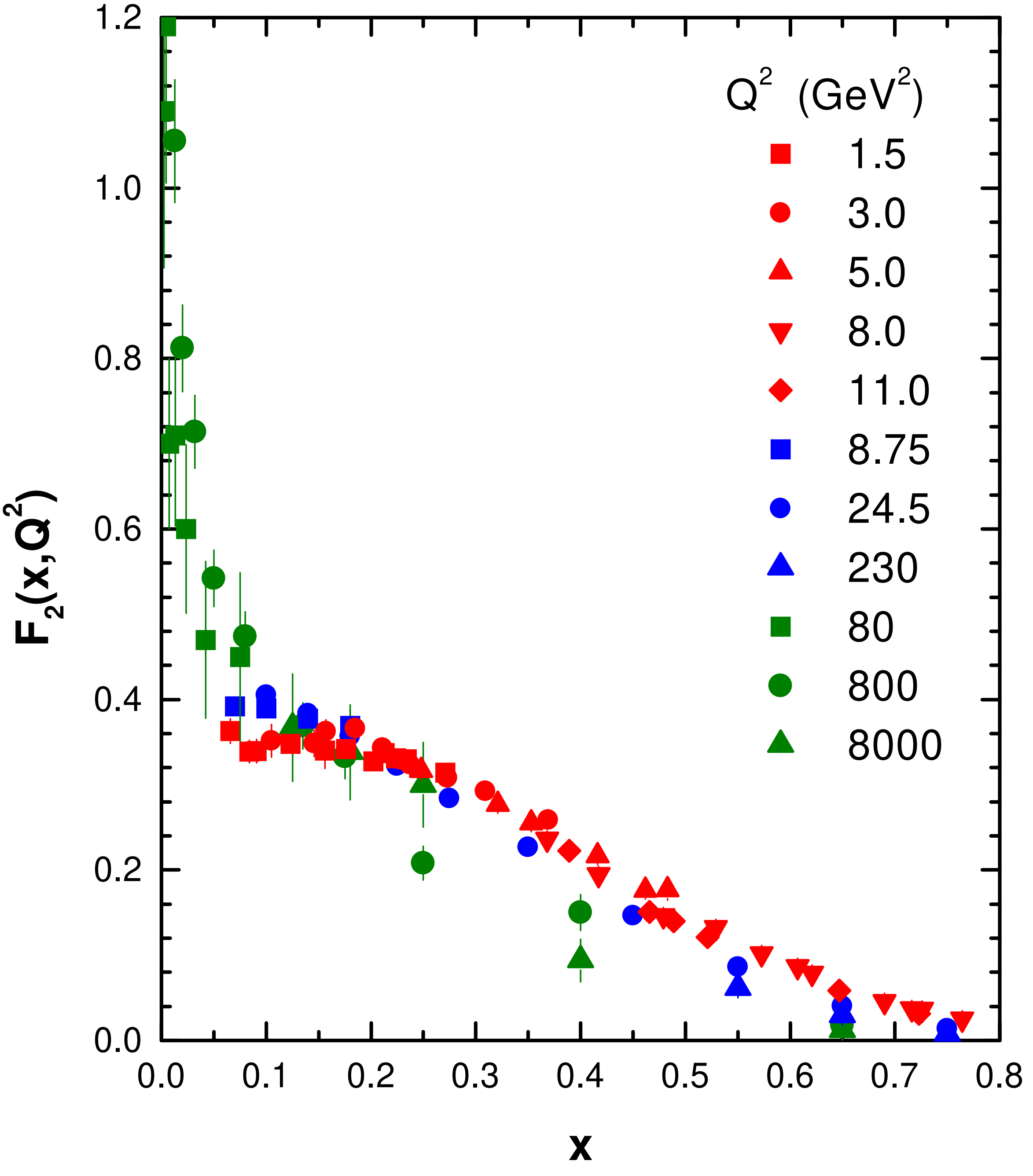
$$\leftrightarrow \quad \lambda \;\gtrsim\; 10^{-18}\ \mathrm{m} \;\simeq\; r_{\mathrm{proton}}/1000$$

- differential cross sections ⟶ structure functions

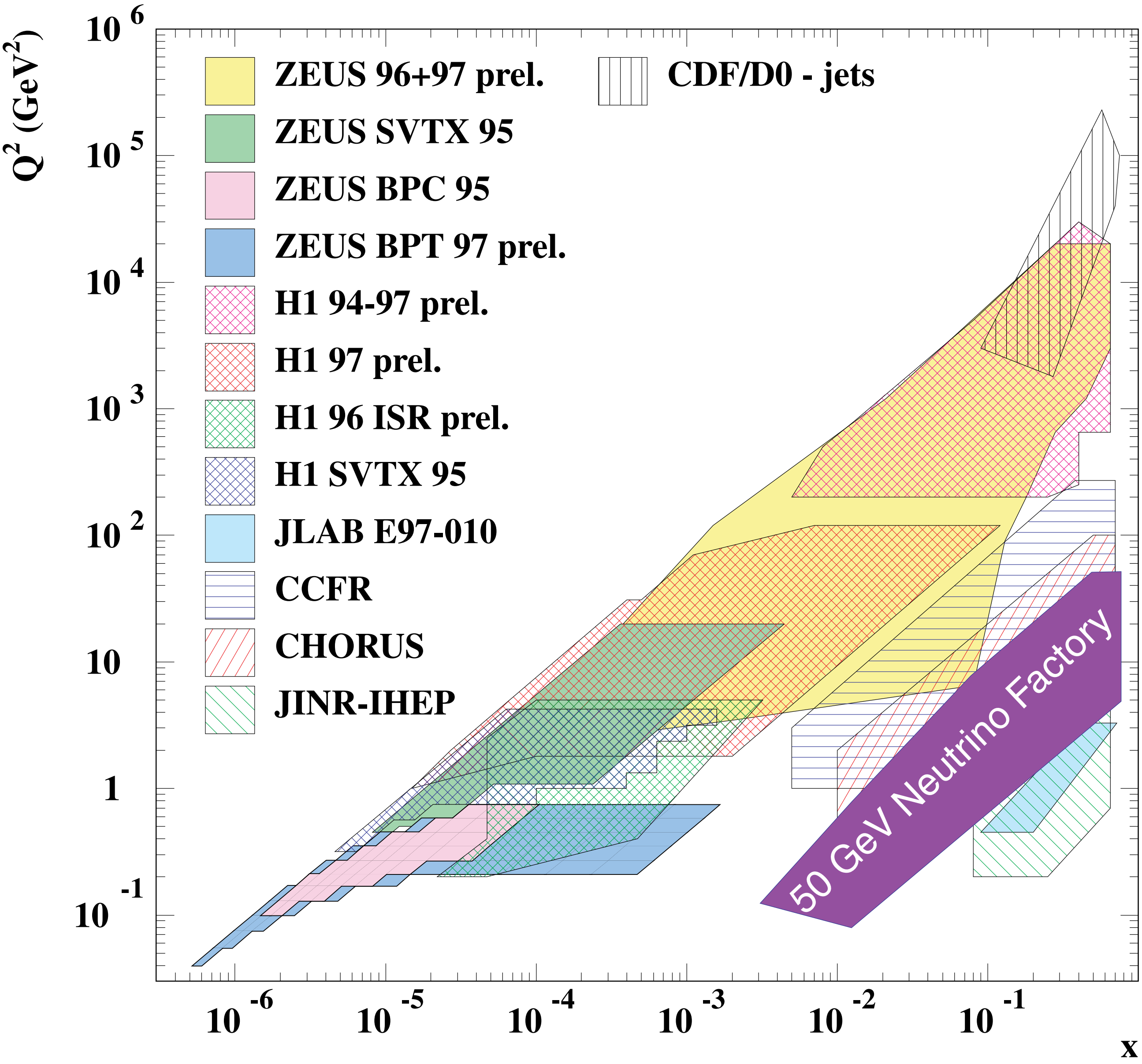
$$\frac{d^2\sigma}{dx\;dQ^2} = \sum_{\text{exchanges}} \text{couplings} \times \mathcal{F}_i(x, Q^2)$$



30 years of F_2^{lp} measurements

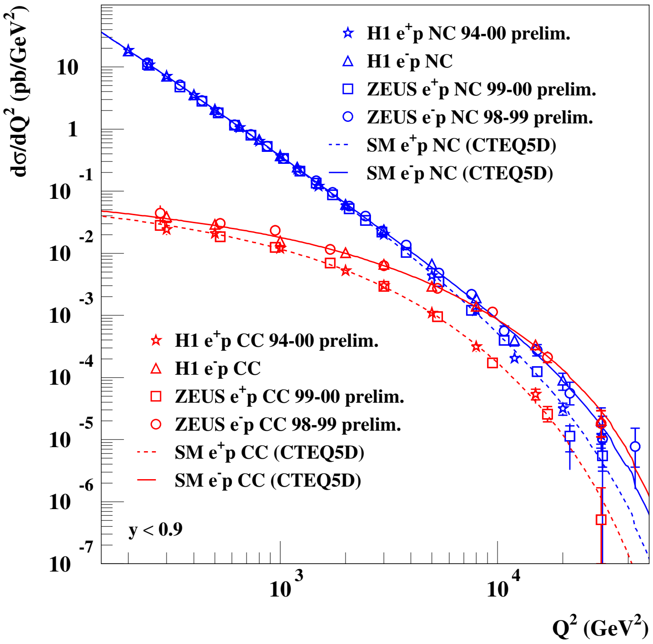


kinematic coverage in the $x - Q^2$ plane



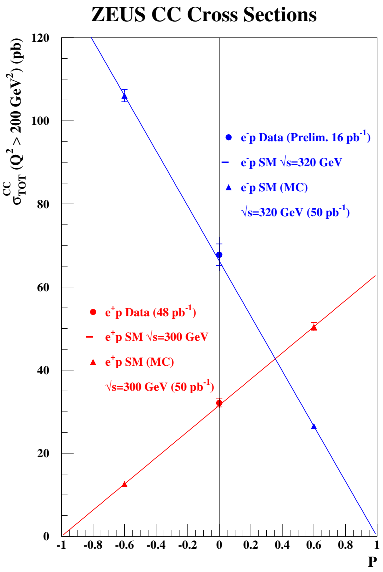
electroweak

- in lN, electroweak 'unification' at high Q^2 $\Rightarrow$ precision space-like electroweak tests



$\Rightarrow$ M_W etc, and of course tests of parton substructure, new heavy particle production etc.

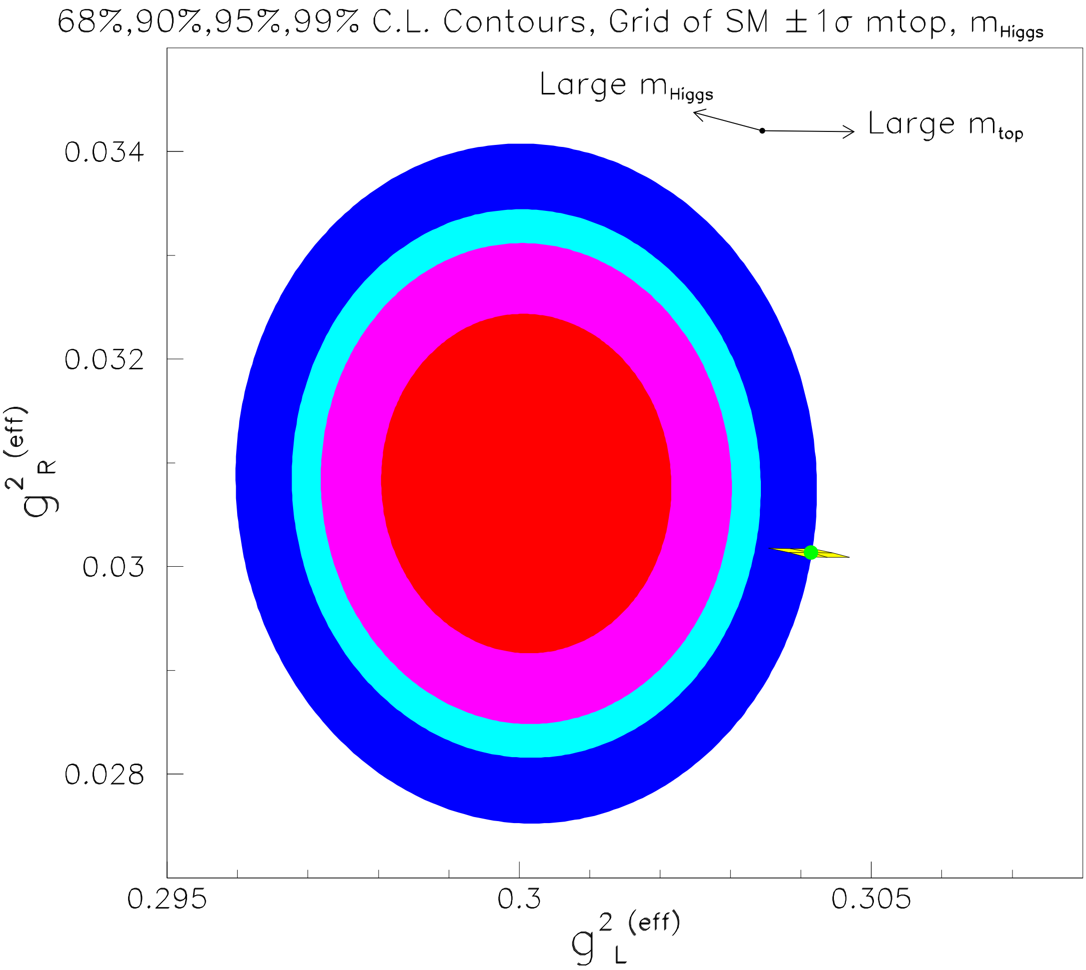
- HERA2: polarised $e_{L,R}$ CC DIS will directly probe $V - A$ structure of SM charged current interaction

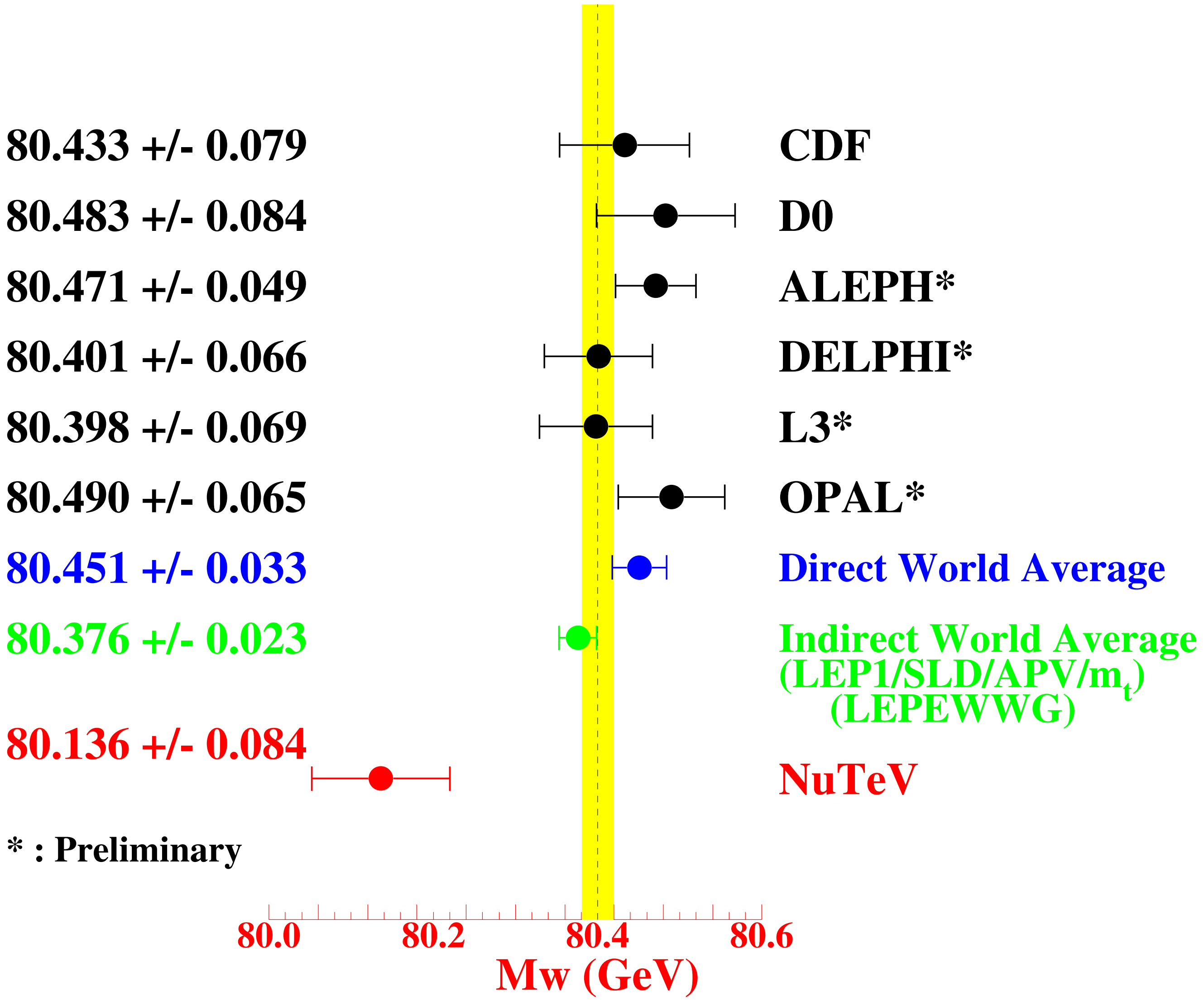


electroweak contd.

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

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




80.433 +/- 0.079
CDF
80.483 +/- 0.084
D0
80.471 +/- 0.049
ALEPH*
80.401 +/- 0.066
DELPHI*
80.398 +/- 0.069
L3*
80.490 +/- 0.065
OPAL*
80.451 +/- 0.033
Direct World Average
80.376 +/- 0.023
Indirect World Average
(LEP1/SLD/APV/m_t)
(LEPEWWG)
80.136 +/- 0.084
NuTeV
* : Preliminary
80.0
80.2
80.4
80.6
Mw (GeV)

new physics?

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

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

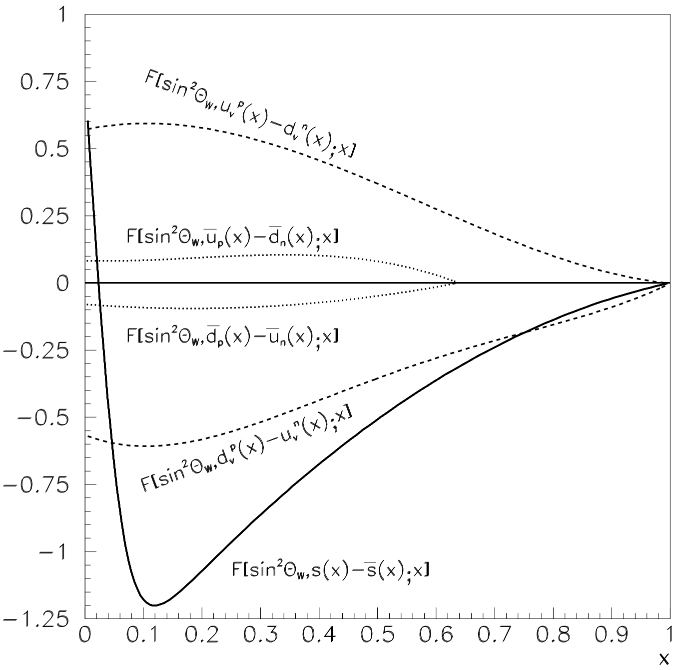
otherwise

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

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



hadron structure: DIS in the QCD-improved parton model

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

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

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

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

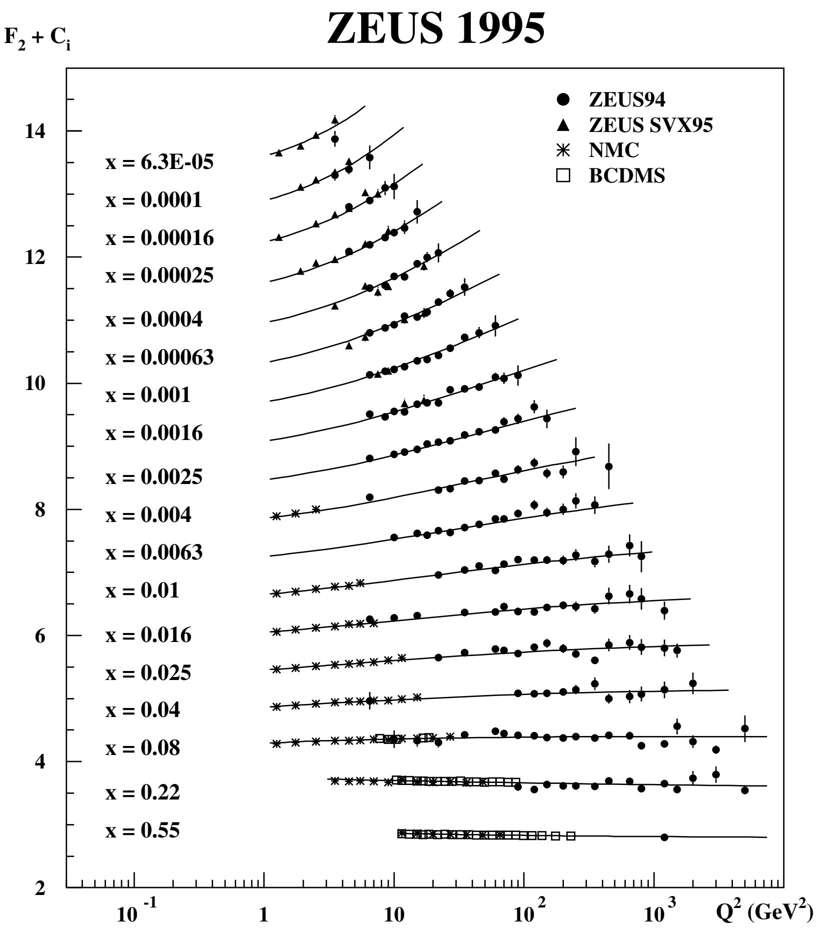
- DGLAP evolution

$$\begin{aligned}\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{q_iq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2) \\ &\quad + P_{q_ig}(y,\alpha_S)\, g(\frac{x}{y},Q^2)\Big\} \\ \frac{\partial g(x,Q^2)}{\partial \log Q^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{gq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2) \\ &\quad + P_{gg}(y,\alpha_S)\, g(\frac{x}{y},Q^2)\Big\}\end{aligned}$$

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

precision QCD

NLO DGLAP works 'well' for $Q^2 > \mathcal{O}(1\ \mathrm{GeV}^2)$



- α_S measurements
- precision extraction of parton distributions (and their uncertainties – see Thorne et al. hep-ph/0205233) through global fits
- tests of QCD dynamics (final state structure, heavy quark production, leading logarithm resummations for $x \to 0, 1$ etc.)

ingredients of a global fit

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 $pN \to \mu\bar{\mu} + X$

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

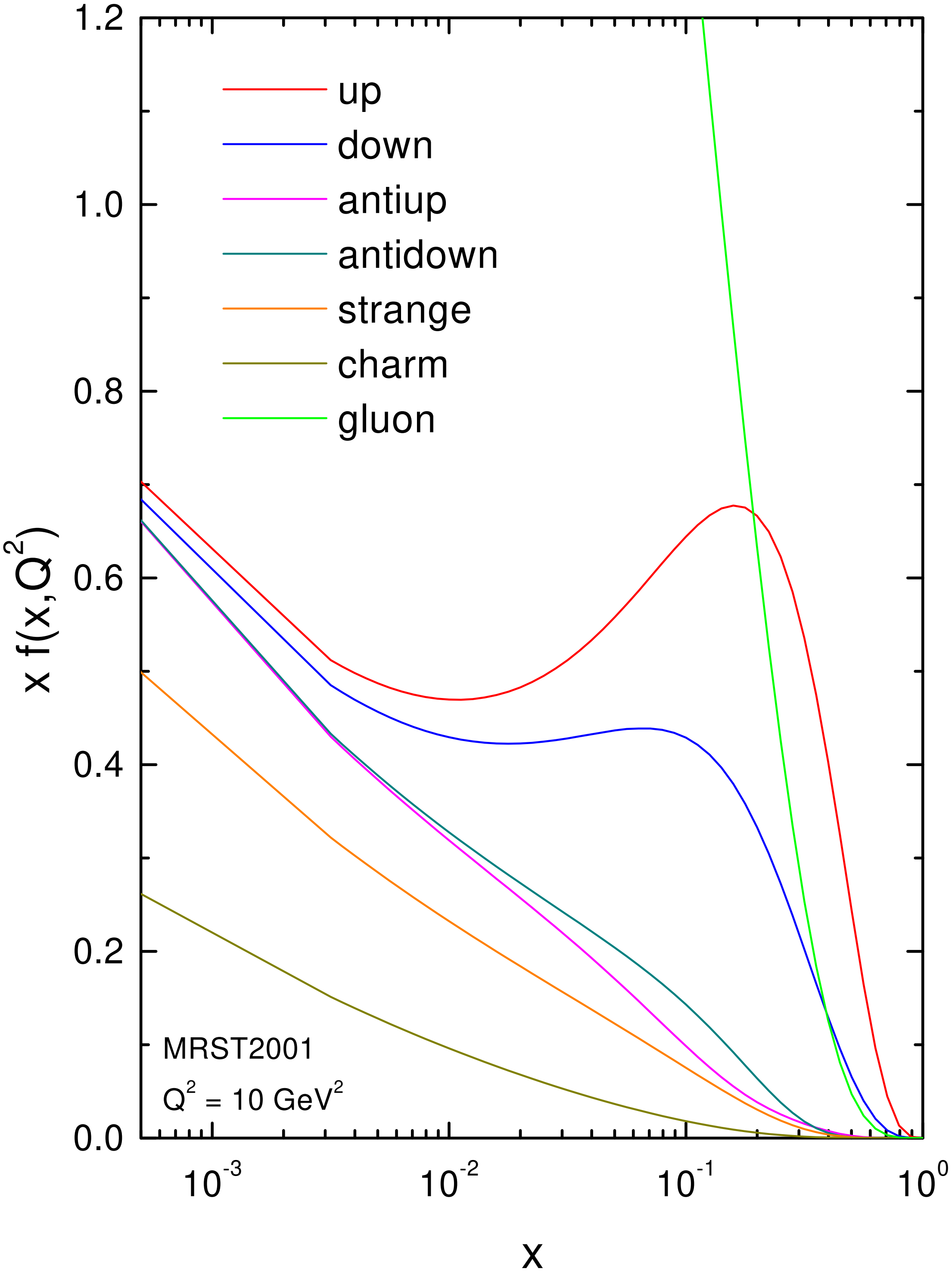
CDF W-asymmetry u/d ratio at high x

CDF, D0 Inclusive jet data

CCFR Dimuon data

(MRST 2001)

parton distributions from global fits



NNLO – the new theory frontier

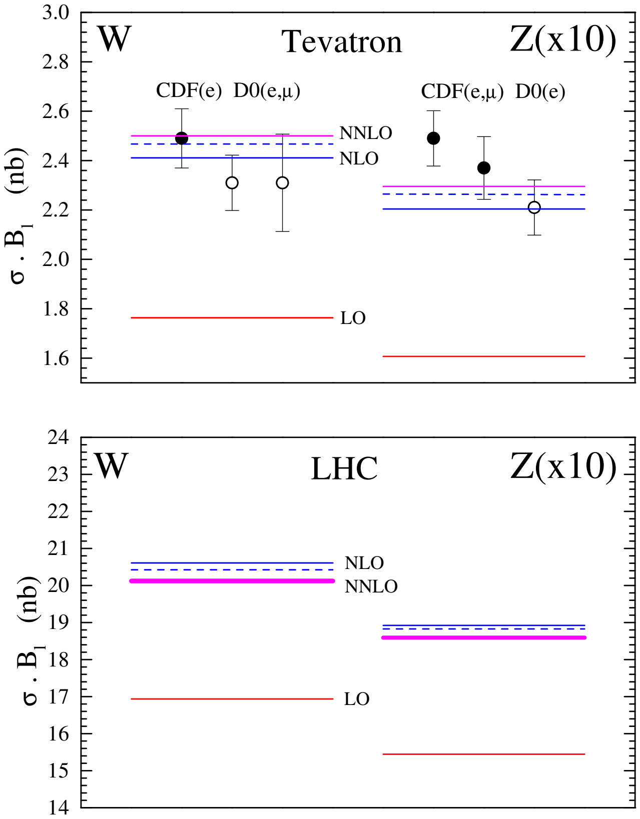
DGLAP: $P(x, \alpha_S) = P^{(0)} + \alpha_S P^{(1)}(x) + \alpha_S^2 P^{(2)}(x) + \ldots$

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

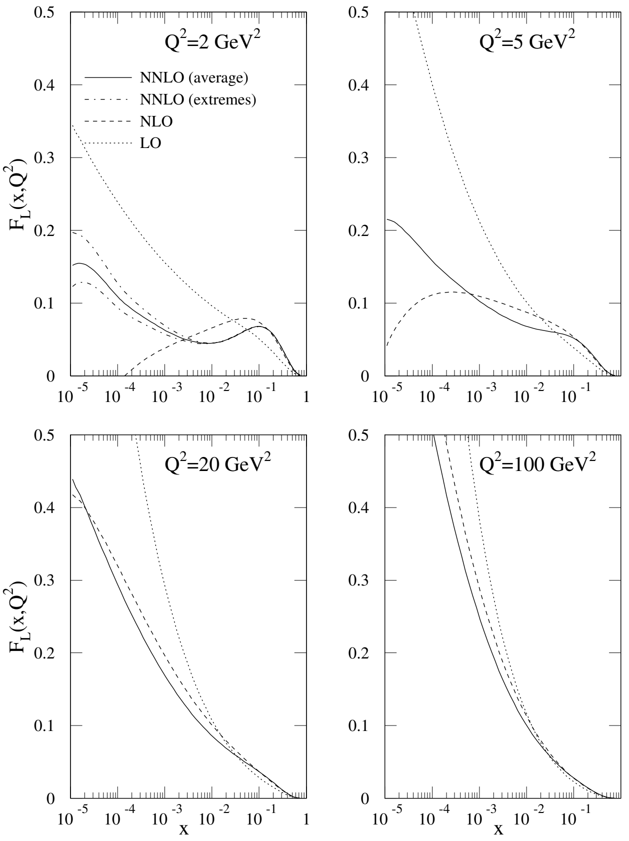
the NNLO fit

- quality of fit improved, but only slightly
- $\alpha_S^{NNLO}(M_Z^2) = 0.1155$ (determined mainly by high-x data)
- NLO & NNLO pdfs differ because of coefficient functions
- reasonable perturbative stability (LO → NLO → NNLO) for quark-dominated quantities, e.g. $\sigma_{W,Z}$, less so in gluon-dominated quantities, e.g. in F_L

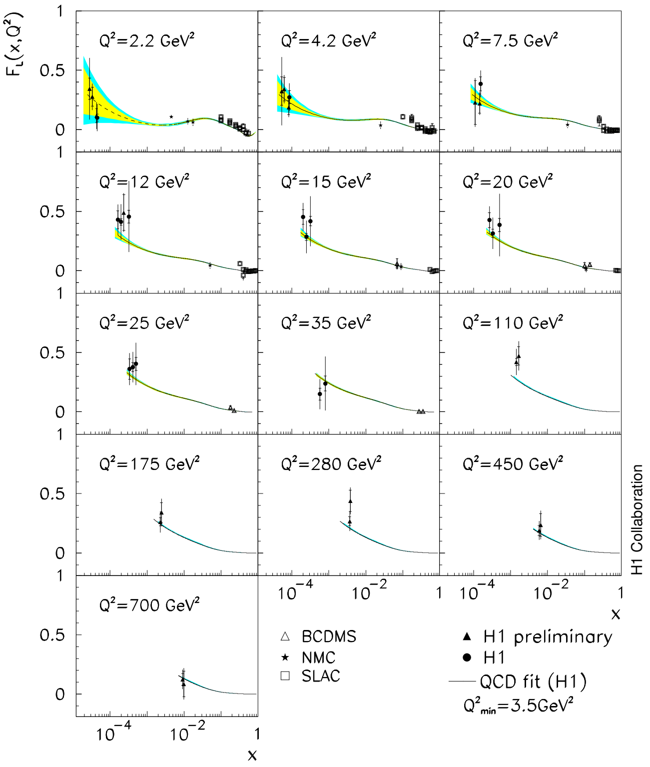


partons: MRST2001
NNLO evolution: van Neerven, Vogt approximation to Vermaseren et al. moments
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

F_L prediction at NNLO



and H1 'measurement':



heavy flavours

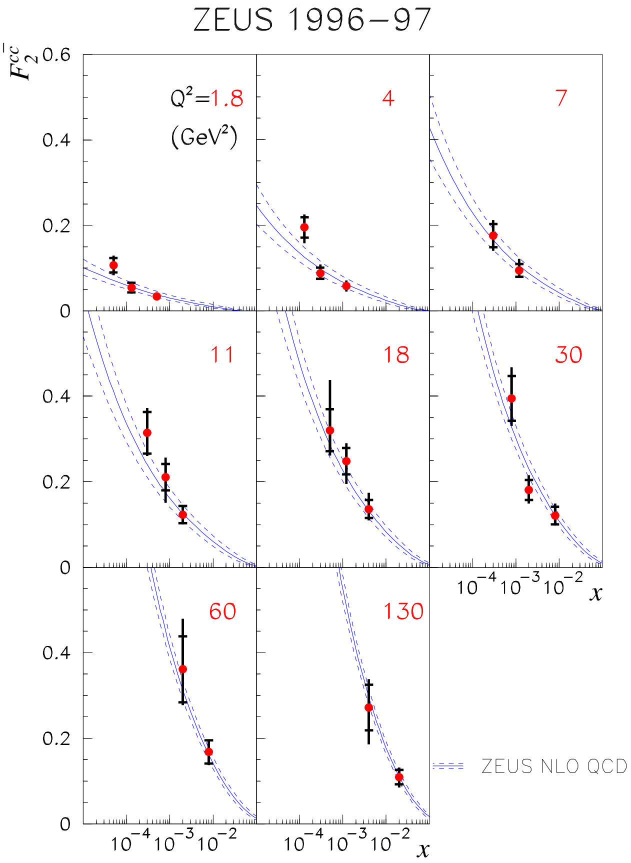
- inclusive heavy quark production $(c, b, \ldots)$ now understood as a *perturbative* process:

$$\sigma_Q \sim \hat{\sigma}_{\gamma^* g \to Q\bar{Q}} \otimes g(x, \mu^2)$$

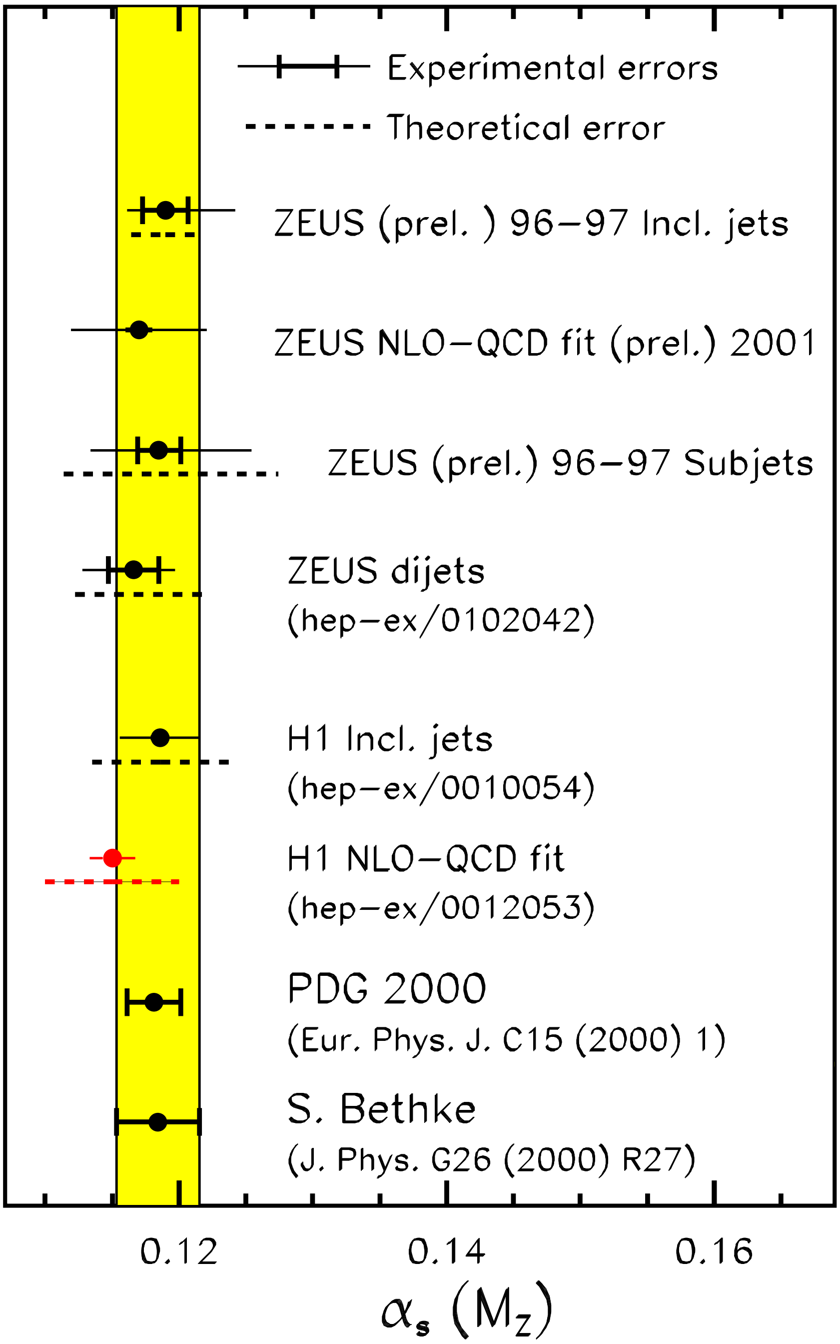
$\Rightarrow$ gluon measurements etc

- issues of *scheme dependence* (FFNS, VFNS + variants) also understood

- measured b cross section at HERA too high?



α_S from DIS



… and also

- ‘BFKL’ physics — the search for evidence of high-energy resummation (e.g. $\alpha_S^n \ln^{n-1}(1/x)$) in F_2, forward jets and photons, etc

- saturation; high density of partons in nucleon at small x, recombination, effect on F_2 evolution

- DIS final state structure: jets, event shapes, energy flow, multiplicities, ep *vs.* e^+e^-, …

- diffractive deep inelastic scattering (F_2^D, rapidity gaps, factorisation, …)

- Deeply Virtual Compton Scattering ($ep \to e\gamma p$), generalised parton distributions

- quarkonium production

- photon structure

- …

see DIS02, Krakow, April 2002, http://dis2002.ifj.edu.pl/

spin-dependent DIS

- polarised DIS experiments probe spin-dependent parton distributions, e.g. $\Delta q_i = q^{\Rightarrow} - q^{\Leftarrow}$, $\Delta g = g^{\Rightarrow} - g^{\Leftarrow}$, an important and subtle test of perturbative (DGLAP, sum rules) and non-perturbative QCD dynamics

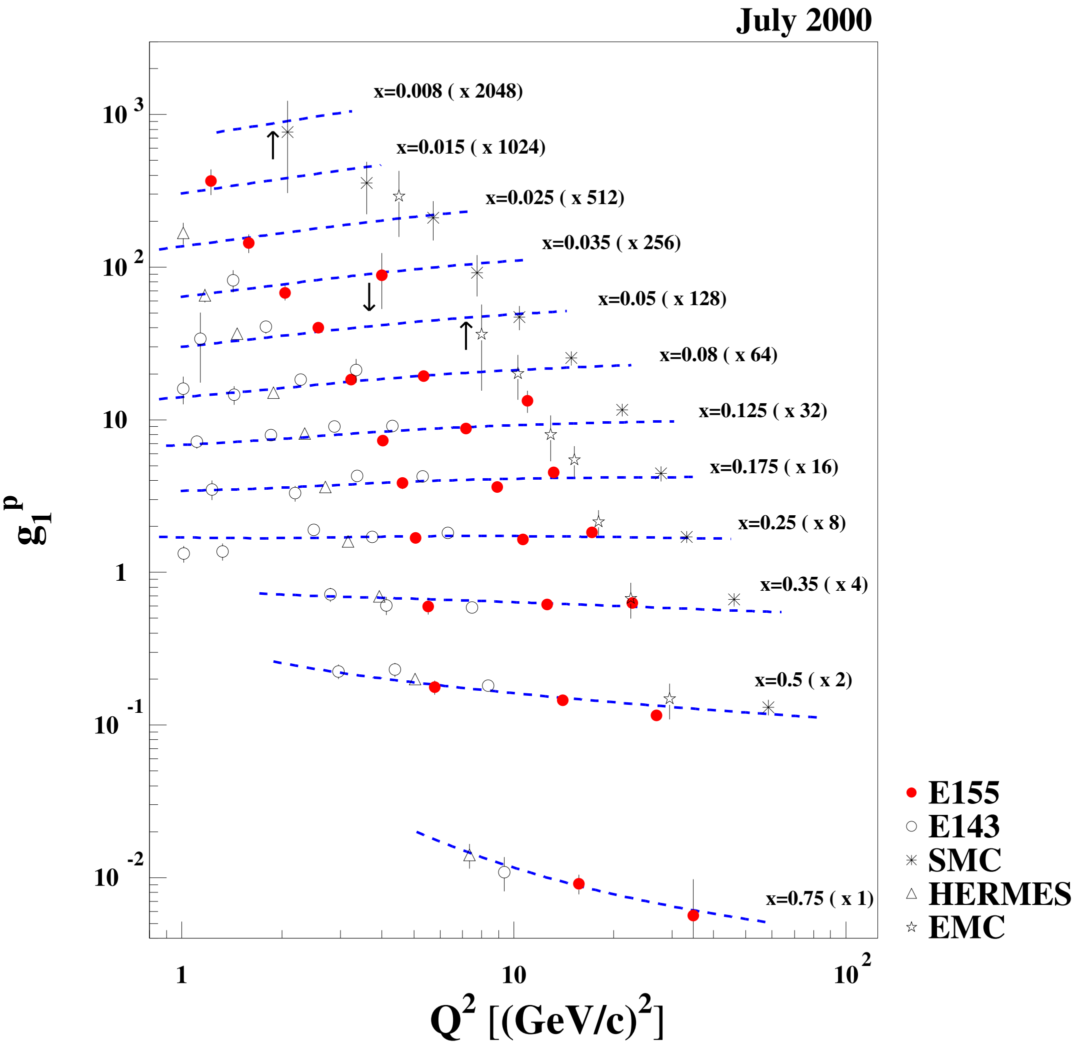
- precision $(e,\mu) + (p,n)$ data from EMC, SMC, E142, E143, E154, E155, HERMES, ... QCD-based polarised pdf fits from ..., Gehrmann et al., Altarelli et al., Goto et al., Glück et al., Leader et al., Blümlein et al. (→ fig.)

$$\int_0^1 dx\; g_1^p(x) = a_0 + a_3 + a_8$$

- a_3 from nucleon β-decay, a_8 from hyperon decay, and in the parton model $a_0 = \int_0^1 dx \Delta\Sigma(x) \approx_{\rm expt} 0 \Rightarrow$ "spin crisis" (late 1980s). But in QCD

$$a_0(x,Q^2) = \Delta\Sigma(x) - \frac{3\alpha_S(Q^2)}{2\pi}\Delta G(x,Q^2) \otimes \Delta\mathcal{C}_G$$

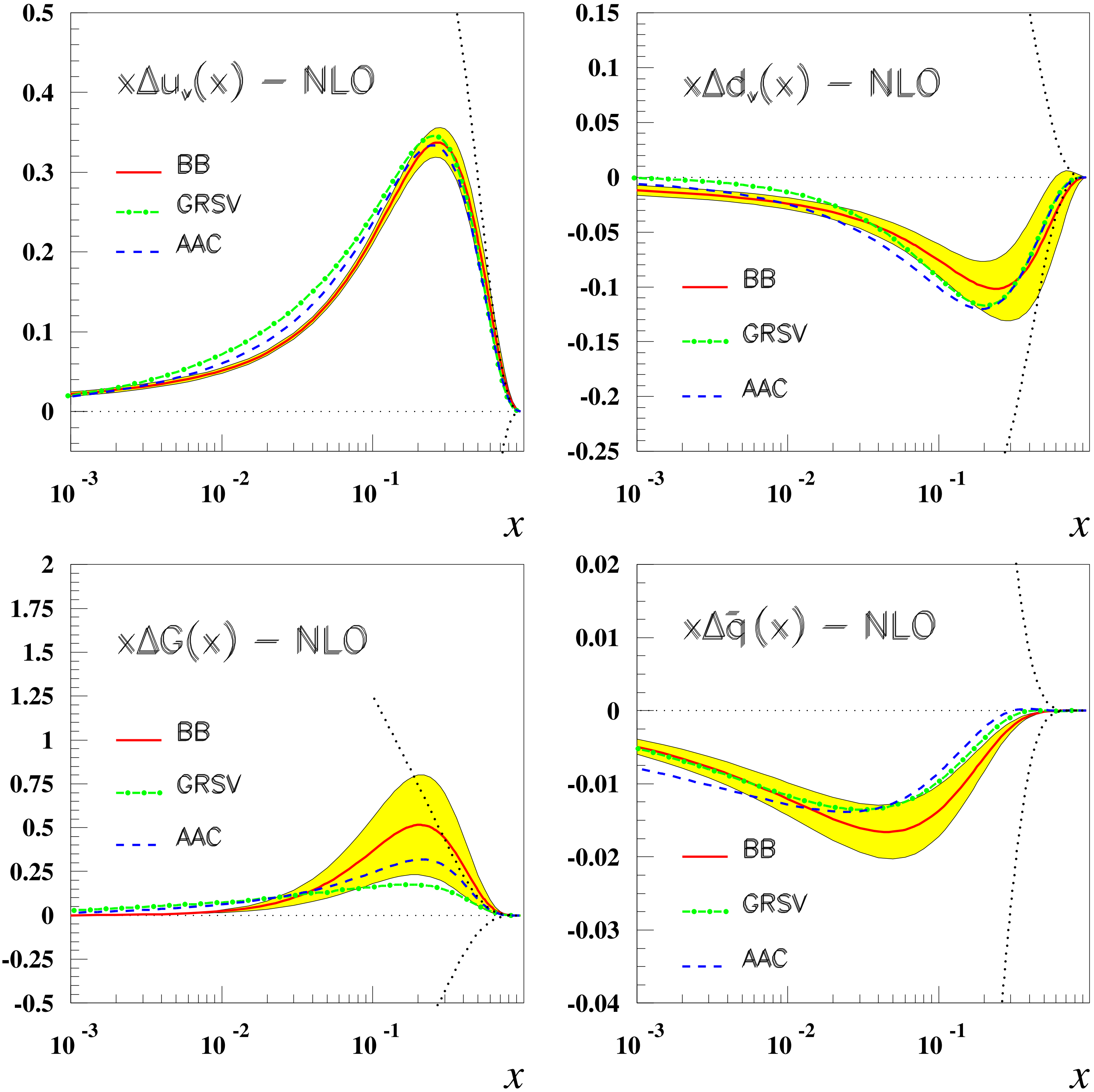
... which suggests ΔG is large, and important to test this directly (COMPASS, RHIC, ...)



- But all DIS data is NC (therefore always $\Delta q + \Delta\bar{q}$) and no pN Drell-Yan to probe $\Delta\bar{q}$ directly $\Rightarrow$ impossible to determine flavour content of polarised quark sea. Also limited Q^2 range makes $\Delta\Sigma, \Delta q_{NS}, \Delta G$ separation via DGLAP difficult.

- pdf fits therefore assume $\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s}$ and fix values of poorly determined parameters in the fits

an example of a NLO polarised pdf fit



(pdfs shown at $Q_0^2 = 4\ \mathrm{GeV}^2$; 7+1 parameter fit based on asymmetry data; yellow band is fully correlated $\pm 1\sigma$ Gaussian error propagation at Q_0^2; dotted line is positivity limit from GRV unpolarised pdfs)

Blümlein and Böttcher, hep-ph/0203155

parton distribution moments from the lattice

parton distribution functions $f(x,Q_0^2)$, $\Delta f(x,Q_0^2)$ are fundamental (non-perturbative) QCD quantities, and should be calculable *from first principles* — the lattice is currently the most promising method

$$\langle x^n \rangle_f(Q^2) = \int_0^1 dx\; x^n\; f(x,Q^2)$$

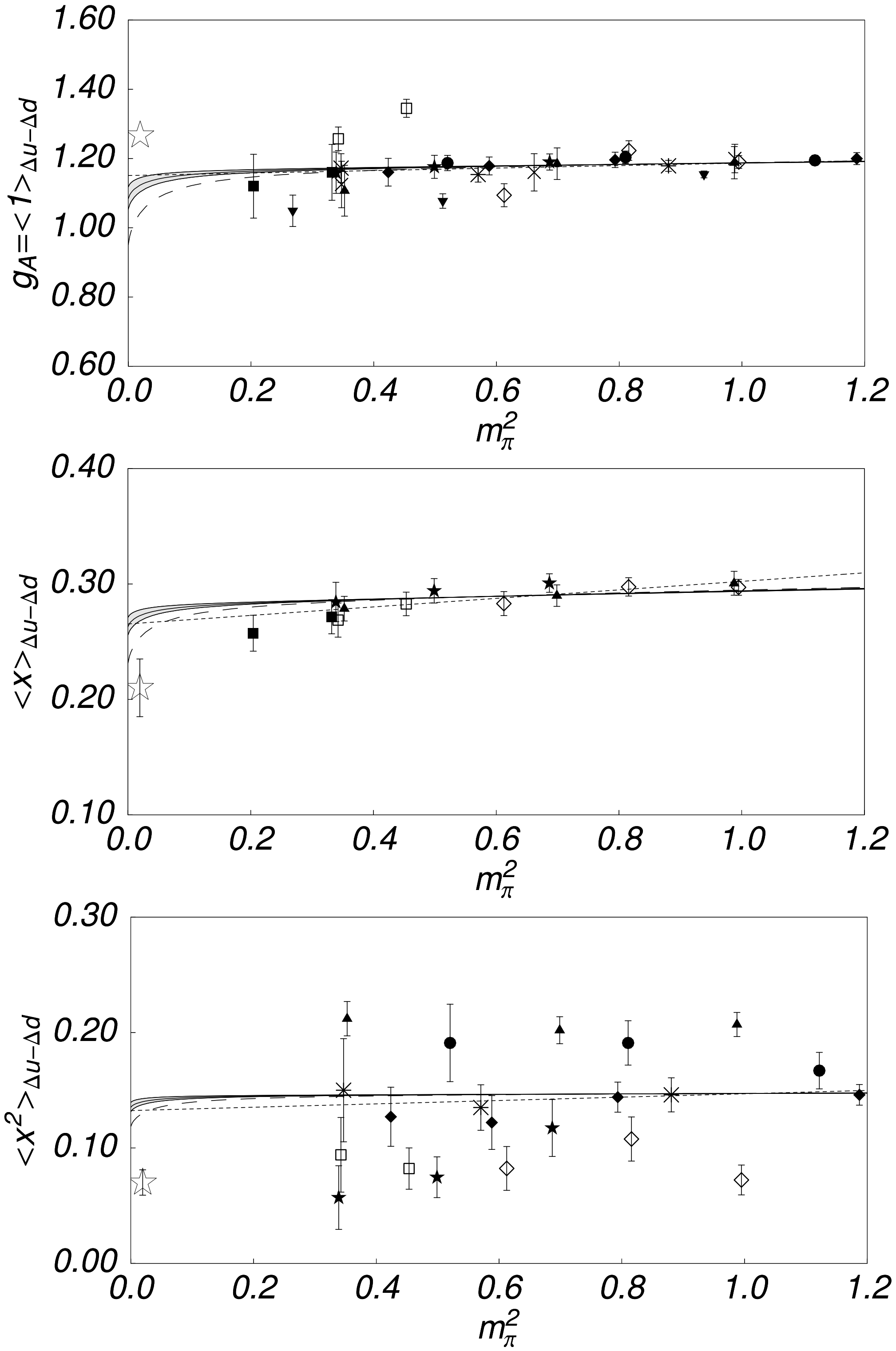
- lattice calculations from Göckeler et al. (QCDSF), Güsken et al. (SESAM), Dolgov et al. (LHPC); 'data' via pdf fits (MRST, CTEQ, ...) — note recent analysis by Blümlein and Böttcher, hep-ph/0203155 (polarised moments with errors from global fit), e.g.

Δu_v moment	lattice (QCDSF)	BB fit
$\langle x \rangle$	0.889 ± 0.029	0.926 ± 0.071
$\langle x^2 \rangle$	0.198 ± 0.008	0.163 ± 0.014
$\langle x^3 \rangle$	0.041 ± 0.009	0.055 ± 0.006

- approach to chiral limit more direct for *polarised* moments (linear extrapolation) than for *unpolarised* moments (Detmold et al., hep-lat/0206001)

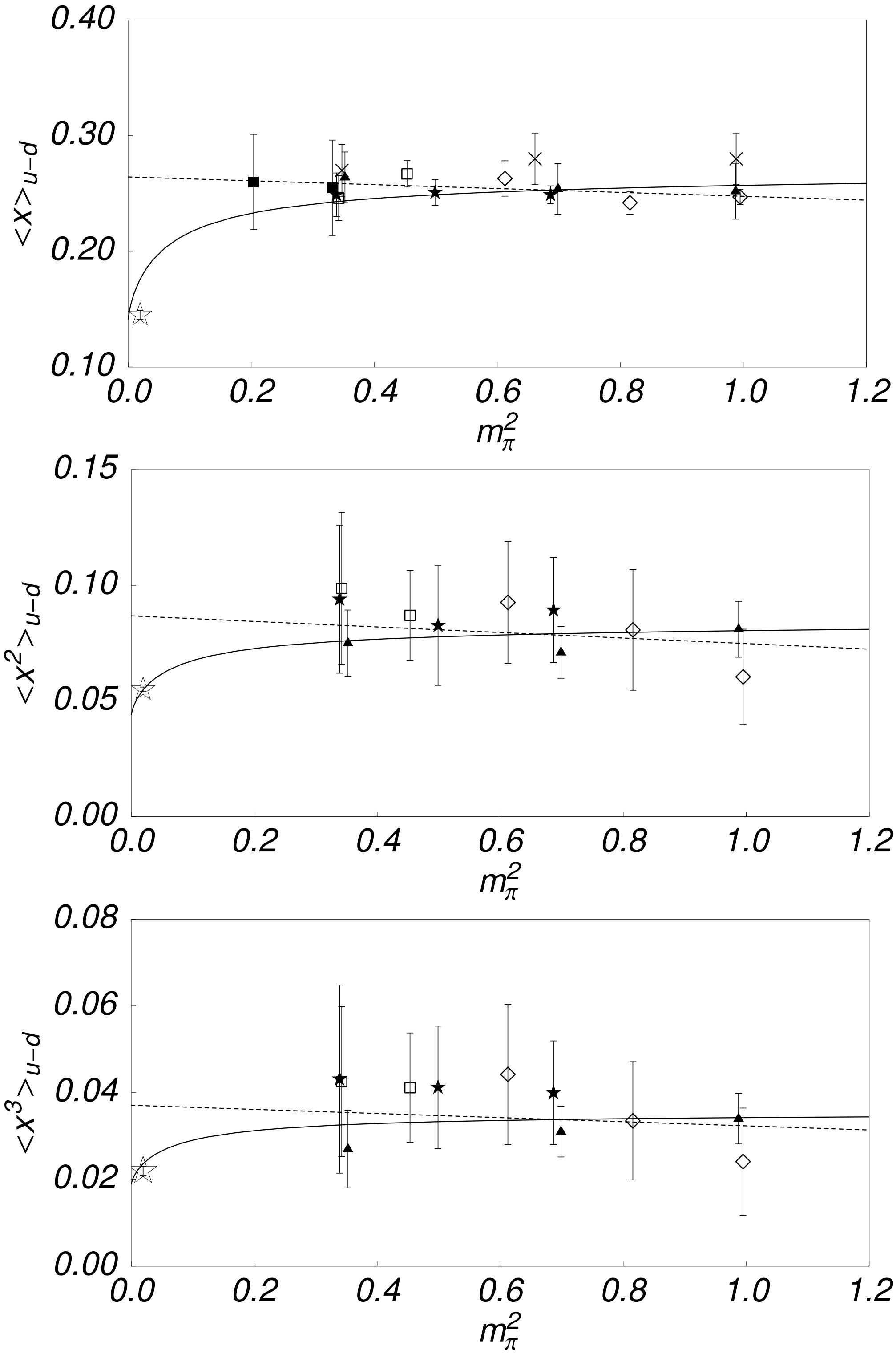
- the higher the moment, the more sensitivity to $x \to 1$

chiral limit – polarised moments



Detmold, Melnitchouk, Thomas, hep-lat/0206001

chiral limit – unpolarised moments



Detmold, Melnitchouk, Thomas, hep-lat/0206001

so what *are* the issues?

- the Q^2 of parton distributions is understood; ‘singlet’ quark and gluon distributions are well measured over a broad range of x, and their uncertainties (or the effect of these on predicted physical quantities) are being pinned down, and NNLO will soon be the standard

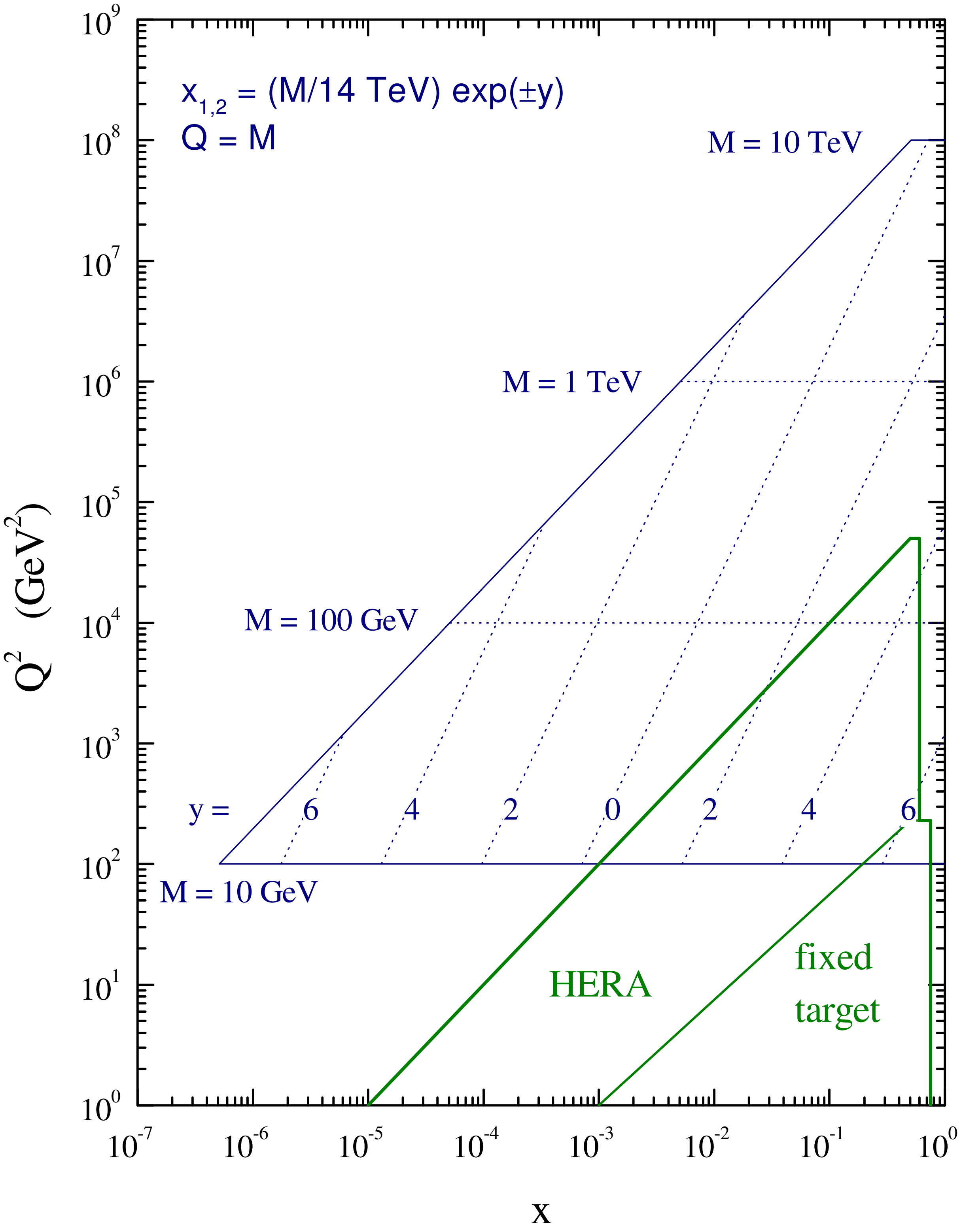
- there are still open questions about the role of $\alpha_S^n \ln^{n-1}(1/x)$ and $\alpha_S^n \ln^{2n-1}(1-x)$ contributions for $x \to 0, 1$, and not yet any solid theory for higher-twist $1/Q^n$ contributions

$\Rightarrow$ but for present and future hadron-hadron collider phenomenology, everything appears to be in good shape
…. however

- we do not understand in detail the quark flavour content of the nucleon

- there is still the issue of the NuTev $\sin^2\theta_W$

- polarised DIS is not yet studied on the same level of precision; the flavour decomposition of the polarised see is essentially unknown

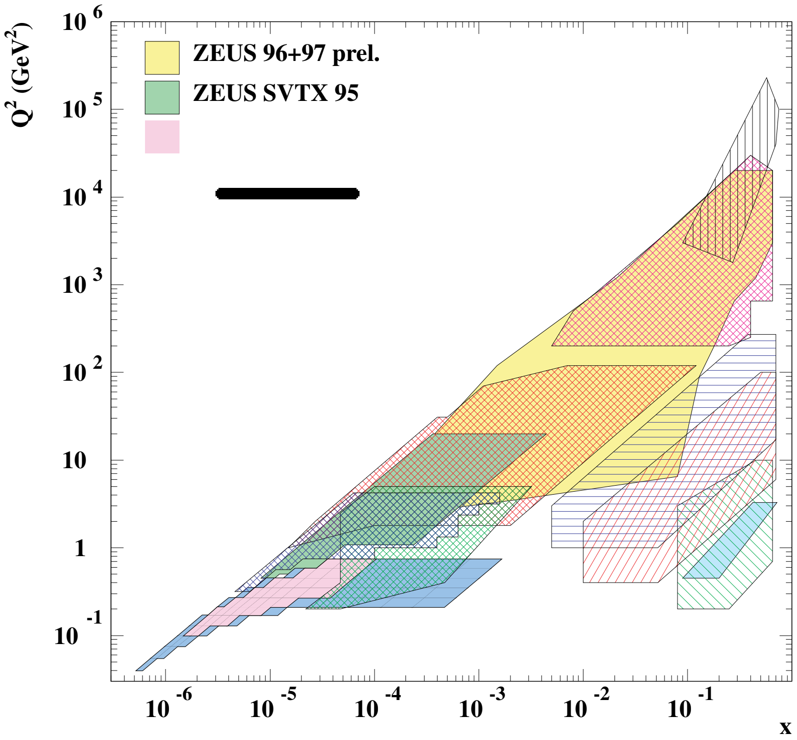


LHC parton kinematics

νN @ NuFact

- vN 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* vN, therefore fewer constraints on spin-dependent pdfs

- a 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



- flavour decomposition (polarised)

$$\frac{d^2\sigma^{\nu,\bar{\nu}}(\Leftarrow)}{dx\,dy} - \frac{d^2\sigma^{\nu,\bar{\nu}}(\Rightarrow)}{dx\,dy} =$$

$$\frac{sG_F^2}{\pi(1+Q^2/M_W^2)^2}\left[\pm(2-y)yxg_1^{\nu,\bar{\nu}} - (1-y)g_4^{\nu,\bar{\nu}} + y^2xg_5^{\nu,\bar{\nu}}\right]$$

— in the parton model $g_4 = 2xg_5$, and

$$\begin{aligned} g_1^{\nu} &= \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{c} \\ g_1^{\bar{\nu}} &= \Delta u + \Delta c + \Delta\bar{d} + \Delta\bar{s} \\ g_5^{\bar{\nu}} &= \Delta\bar{d} + \Delta\bar{s} - \Delta u - \Delta c \\ g_5^{\nu} &= \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c} \end{aligned}$$

with 6 linearly independent SFs from $\nu, \bar{\nu}$ on p, n measuring 6 combinations of $\Delta u, \Delta d, ..., \Delta\bar{s}, \Delta\bar{c}$ — further separation with charm tagging, $sW^{+*} \to c$ etc

- many sum rules (see e.g. Blümlein et al.)

$$\int_0^1 dx[g_5^{\nu p} - g_5^{\nu n}] = g_A\left[1 + \mathcal{O}(\alpha_S)\right]$$

and DGLAP evolution $\partial g_5/\partial \ln Q^2 = \frac{1}{2}a\Delta P_{qq} \otimes g_5 + \ldots$

- transverse polarisation

$$\frac{d^3\sigma^{\nu,\bar{\nu}}(\Uparrow)}{dx\,dy} - \frac{d^3\sigma^{\nu,\bar{\nu}}(\Downarrow)}{dx\,dy} = \frac{2M\sqrt{s}G_F^2\cos\phi}{(1+Q^2/M_W^2)^2}\sum_{i=1}^{5}\mathcal{C}_i(x,y)g_i^{\nu,\bar{\nu}}$$

conclusions

- 30 years of deep inelastic scattering experiments have taught us much about nucleon structure
- we have information on all unpolarised parton flavours over a broad range in x, and the Q^2 dependence is under control (still interest in very small and large x, F_L, and the transition to the non-perturbative $Q^2 \to 0$ region)
- information on polarised parton structure much less precise, because of (a) smaller experimental coverage in x and Q^2, (b) lack of CC data, (c) as yet no hadron-hadron data
- lattice calculations of moments of f_i and Δf_i set to improve significantly in coming years — will need matching precision from experiments

DIS at a neutrino factory would complement present and near-future information beautifully!