Polarized parton distributions from charged–current deep-inelastic scattering and future neutrino factories

Neutrino Factory Workshop 2002
Department of Physics, Blackett Laboratory
Imperial College, London
1^{st} to 6^{th} July 2002

Giovanni Ridolfi - INFN Sezione di Genova

(in collaboration with S. Forte and M. Mangano)

Inclusive neutral-current polarized DIS experiments only allow a measurement of C-even polarized parton distributions

$$\Delta q^{+} = \Delta q + \Delta \bar{q}$$

- Flavor separation: difficult (weak sensitivity to Δs)
- Quark-antiquark separation: impossible

No polarized charged-current experiment performed so far:

- with neutrino beams: too large polarized target needed
- with electron or muon beams: too high energy required (a possibility for polarized HERA)

An interesting possibility:

highly focused neutrino beams arising from the decays of muons along straight sections of the accumulator of a muon storage ring.

This would allow an accurate decomposition of the partonic content of the nucleon in terms of individual (spin-averaged and spin-dependent) flavor densities.

More on neutrino factories:

I. Bigi et al., *The potential for neutrino physics at muon colliders and dedicated high current muon storage rings*, BNL-67404.

M. L. Mangano et al., *Physics at the front-end of a neutrino factory: a quantitative appraisal* QCD/DIS Working Group, to appear in the Report of the CERN/ECFA Neutrino Factory Study Group, `hep-ph/0105155`

Hadronic tensor decomposition:

$$\begin{aligned} W_{\mu\nu} &= \frac{1}{4\pi}\int d^4z\, e^{iqz}\,\langle p,s|\left[J_\mu(z),J_\nu^\dagger(0)\right]|p,s\rangle \\ &= \left(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}\right)F_1(x,Q^2)+\frac{\hat{p}_\mu\hat{p}_\nu}{pq}F_2(x,Q^2)+\frac{i\epsilon_{\mu\nu\alpha\beta}q^\alpha p^\beta}{2pq}F_3(x,Q^2) \\ &\quad -\frac{i\epsilon_{\mu\nu\alpha\beta}q^\alpha}{pq}\left[s^\beta g_1(x,Q^2)+\frac{pq\,s^\beta - sq\,p^\beta}{pq}g_2(x,Q^2)\right] \\ &\quad +\frac{1}{pq}\left[\frac{1}{2}\left(\hat{p}_\mu\hat{s}_\nu+\hat{p}_\nu\hat{s}_\mu\right)-\frac{sq}{pq}\hat{p}_\mu\hat{p}_\nu\right]g_3(x,Q^2) \\ &\quad +\frac{sq}{pq}\left[\frac{\hat{p}_\mu\hat{p}_\nu}{pq}g_4(x,Q^2)+\left(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}\right)g_5(x,Q^2)\right] \end{aligned}$$

$$\hat{p}_\mu = p_\mu - \frac{pq}{q^2}q_\mu; \qquad \hat{s}_\mu = s_\mu - \frac{sq}{q^2}q_\mu$$

The proton spin vector is normalized as $s^2 = -m^2$

$$\frac{d^2\sigma^{\lambda_\ell}(x,y,Q^2)}{dxdy} = \frac{G_F^2}{2\pi(1+Q^2/m_W^2)^2}\frac{Q^2}{xy}\left[-\lambda_\ell\, y\left(1-\frac{y}{2}\right)xF_3 + (1-y-x^2y^2\frac{m^2}{Q^2})F_2 + y^2xF_1\right]$$

$$\Delta\sigma = \sigma(\lambda_p = -1) - \sigma(\lambda_p = +1)$$

$$\begin{aligned}\frac{d^2\Delta\sigma^{\lambda_\ell}(x,y,Q^2)}{dxdy} \;=\; & \frac{G_F^2}{\pi(1+Q^2/m_W^2)^2}\frac{Q^2}{xy}\Bigg\{\left[-\lambda_\ell\, y(2-y)xg_1 - (1-y)g_4 - y^2xg_5\right] \\ & +2xy\frac{m^2}{Q^2}\Bigg[\lambda_\ell x^2y^2g_1 + \lambda_\ell 2x^2yg_2 + \left(1-y-x^2y^2\frac{m^2}{Q^2}\right)xg_3 \\ & -x\left(1-\frac{3}{2}y-x^2y^2\frac{m^2}{Q^2}\right)g_4 - x^2y^2g_5\Bigg]\Bigg\}\end{aligned}$$

Only g_1, g_4, g_5 survive at leading twist.

A Callan-Gross-like relation holds:

$$g_4(x,Q^2) = 2xg_5(x,Q^2)$$

Only two independent polarized structure functions at leading twist: g_1 and g_5 (true also beyond leading order).

Leading order analysis

In terms of parton densities

$$g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta\bar{c} + \Delta s$$
$$g_1^{W^-} = \Delta u + \Delta\bar{d} + \Delta c + \Delta\bar{s}$$
$$g_5^{W^+} = \Delta\bar{u} - \Delta d + \Delta\bar{c} - \Delta s$$
$$g_5^{W^-} = -\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}$$

Below charm threshold

$$g_1^{W^+} = \Delta\bar{u} + \cos^2\theta_c \Delta d + \Delta\bar{c}_{intr} + \sin^2\theta_c \Delta s$$
$$g_1^{W^-} = \Delta u + \cos^2\theta_c \Delta\bar{d} + \Delta c_{intr} + \sin^2\theta_c \Delta\bar{s}$$
$$g_5^{W^+} = \Delta\bar{u} - \cos^2\theta_c \Delta d + \Delta\bar{c}_{intr} - \sin^2\theta_c \Delta s$$
$$g_5^{W^-} = -\Delta u + \cos^2\theta_c \Delta\bar{d} - \Delta c_{intr} + \sin^2\theta_c \Delta\bar{s}$$

Light flavors and antiflavors below charm threshold completely determined by suitable combinations of structure functions:

$$\frac{1}{2}\left(g_1^{W^-} - g_5^{W^-}\right) = \Delta u + \Delta c \quad (1)$$

$$\frac{1}{2}\left(g_1^{W^+} + g_5^{W^+}\right) = \Delta \bar{u} + \Delta \bar{c} \quad (2)$$

$$\frac{1}{2}\left(g_1^{W^+} - g_5^{W^+}\right) = \Delta d + \Delta s \quad (3)$$

$$\frac{1}{2}\left(g_1^{W^-} + g_5^{W^-}\right) = \Delta \bar{d} + \Delta \bar{s} \quad (4)$$

Above c threshold (or even below, with intrinsic charm) we need more independent combinations. Use also neutron target: $\Delta u, \Delta \bar{u} \leftrightarrow \Delta d, \Delta \bar{d}$: only six independent combinations (and no help from neutral-current DIS):

$$\left.\begin{array}{lcl} (1)\text{ for proton} & \Rightarrow & \Delta u + \Delta c \\ (1)\text{ for neutron} & \Rightarrow & \Delta d + \Delta c \end{array}\right\} \Rightarrow \Delta u - \Delta d$$

$$\left.\begin{array}{lcl} (3)\text{ for proton} & \Rightarrow & \Delta d + \Delta s \\ (3)\text{ for neutron} & \Rightarrow & \Delta u + \Delta s \end{array}\right\} \Rightarrow \Delta u - \Delta d$$

and similarly for antiquarks.

$$\frac{1}{2}\left(g_1^{W^+} - g_5^{W^+}\right)[n-p] = \Delta u - \Delta d \tag{5}$$

$$\frac{1}{2}\left(g_1^{W^-} + g_5^{W^-}\right)[n-p] = \Delta \bar{u} - \Delta \bar{d} \tag{6}$$

$$\frac{1}{2}\left(g_1^{W^-} - g_5^{W^-}\right)[p] - \frac{1}{2}\left(g_1^{W^+} - g_5^{W^+}\right)[n] = \Delta s - \Delta c \tag{7}$$

$$\frac{1}{2}\left(g_1^{W^-} + g_5^{W^-}\right)[p] - \frac{1}{2}\left(g_1^{W^+} + g_5^{W^+}\right)[n] = \Delta \bar{s} - \Delta \bar{c} \tag{8}$$

$$\frac{1}{2}\left(g_1^{W^+} - g_5^{W^+}\right)[p+n] = \Delta u + \Delta d + 2\Delta s \tag{9}$$

$$\frac{1}{2}\left(g_1^{W^-} + g_5^{W^-}\right)[p+n] = \Delta \bar{u} + \Delta \bar{d} + 2\Delta \bar{s} \tag{10}$$

Complete separation of all 4 flavors and antiflavors not possible at a fixed scale.

It becomes feasible by combining measurements below and above the charm threshold: e.g. Δd and $\Delta \bar{d}$ from (3,4) below c, Δc and $\Delta \bar{c}$ (intrinsic) from (7,8) (a simple test of intrinsic charm), Δu and $\Delta \bar{u}$ from (1,2); Δd and $\Delta \bar{d}$ comparing (3,4) above and below threshold.

No new information from neutral-current structure functions, but consistency checks are possible. In particular, a direct measurement of

$$\left(g_1^{W^+} + g_1^{W^-}\right)[p] = \left(g_1^{W^+} + g_1^{W^-}\right)[n] = \Delta\Sigma^+$$

is an interesting and independent check of present indirect information.

In neutral-current DIS:

- First moment of $\Delta\Sigma^+$ directly measured, but based on knowledge of non-singlet first moments from other experiments
- All moments: only from scaling violations

Next-to-leading order analysis

Coefficient functions to order α_s and splitting function to order α_s^2 known since long time.

$$g_1^{W^\pm,\,\mathrm{NLO}} = \Delta C_q \otimes g_1^{W^\pm,\,\mathrm{LO}} + 2[n_f/2]\Delta C_g \otimes \Delta g$$
$$g_i^{W^\pm,\,\mathrm{NLO}} = \Delta C_i \otimes g_i^{W^\pm,\,\mathrm{LO}}, \quad i = 4,5$$

$$\Delta C_4^{(1)}(x) = \Delta C_q^{(1)}(x) + C_F x(1+x)$$
$$\Delta C_5^{(1)}(x) = \Delta C_q^{(1)}(x) + C_F x(1-x)$$

A full NLO evolution code for data analysis has been built [S. Forte, M. Mangano and GR, *Nucl.Phys.* **B 602** (2001) 585, `hep-ph/0101192`], based on previous work for neutral-current structure functions (Altarelli, Ball, Forte, R).

Experimental constraints

From semi-inclusive experiments $|\Delta\bar{u}| \ll |\Delta u^+|$, $|\Delta\bar{d}| \ll |\Delta d^+|$ (first moments).

Theoretical constraints

Positivity of cross sections requires

$$|\Delta q| \leq q \qquad |\Delta\bar{q}| \leq \bar{q}$$

at leading order, for each individual flavor.

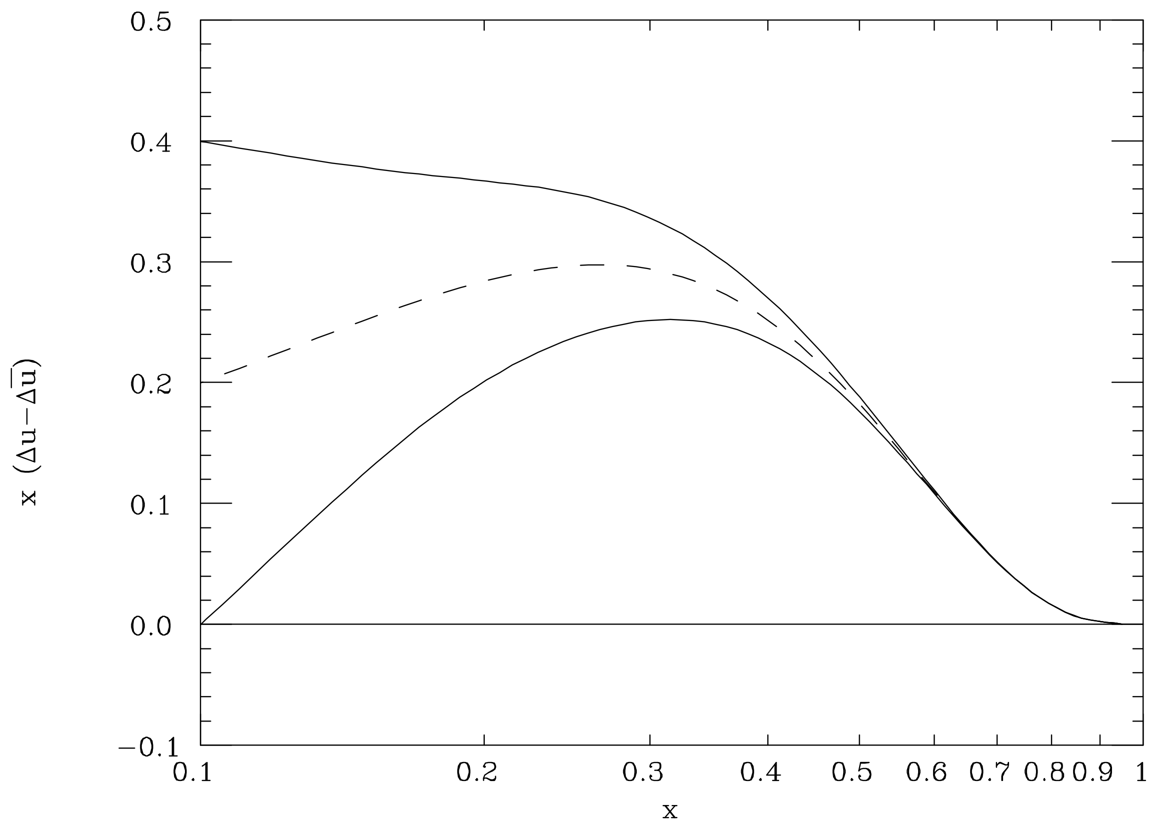
Next-to-leading corrections to these relations can be shown to be small (a few percent).

From these bounds, together with measured unpolarized densities, we can infer bounds on the C-odd combinations

$$\Delta q^- = \Delta q - \Delta\bar{q}.$$

Solid curves: bounds on $x(\Delta u - \Delta\bar{u})$ at $Q^2 = 5$ GeV^2, using CTEQ5 unpolarized u and $\bar{u}$ distributions.

Dashed curve: $x(\Delta u - \Delta\bar{u})$ obtained using $\Delta u + \Delta\bar{u}$ from fits to NC data (ABFR) and assuming $\Delta\bar{u} = 0$.



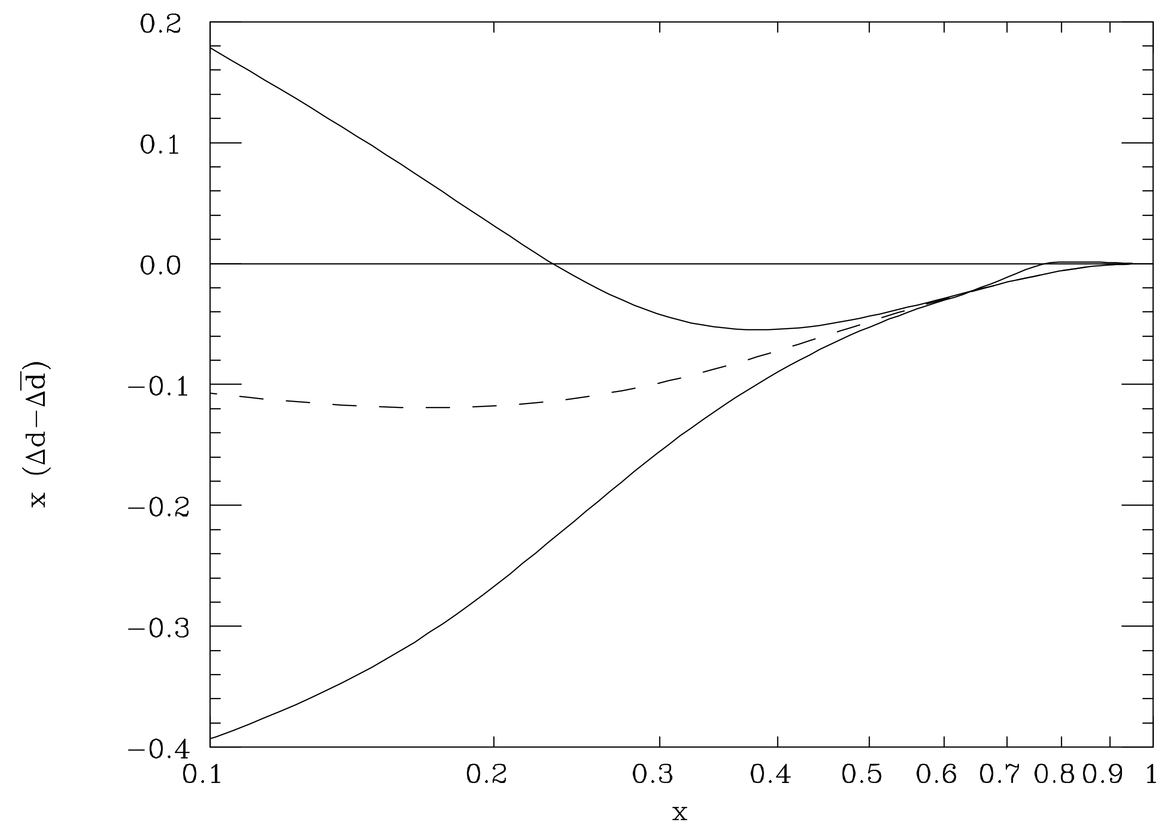
Forte, Mangano, R

$\Delta\bar{u} = \Delta u$ incompatible with the positivity bound in the large-x region.

Solid curves: bounds on $x(\Delta d - \Delta\bar{d})$ at $Q^2 = 5$ GeV^2, using CTEQ5 unpolarized d and $\bar{d}$ distributions.

Dashed curve: $x(\Delta d - \Delta\bar{d})$ obtained using $\Delta d + \Delta\bar{d}$ from fits to NC data (ABFR) and assuming $\Delta\bar{d} = 0$.

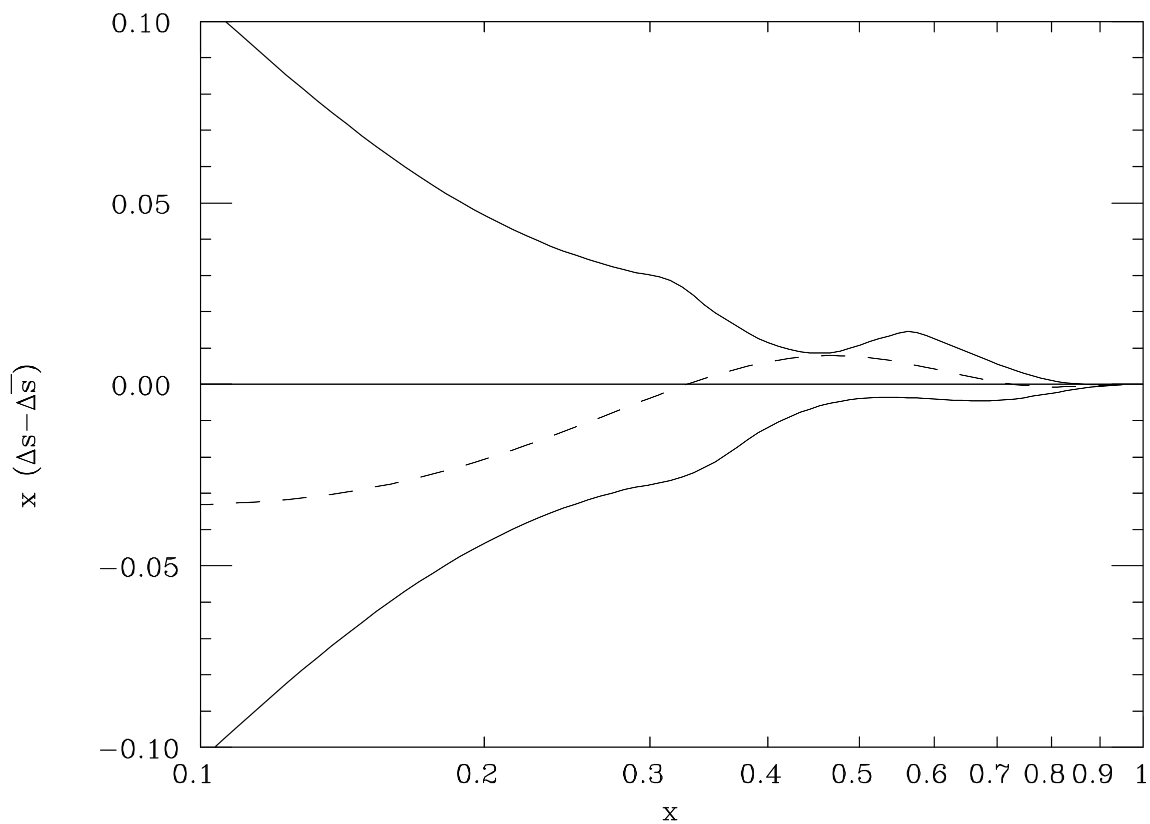
Forte, Mangano, R



$\Delta\bar{d} = \Delta d$ incompatible with the positivity bound in the large-x region.

For the unpolarized $s, \bar{s}$ distributions we use the parametrization of Barone, Pascaud an Zomer (more accurate in the strange sector).

Forte, Mangano, R



In this case, both $\Delta\bar{s} = 0$ and $\Delta\bar{s} = \Delta s$ are allowed by the positivity bound.

A central issue in physics of polarized nucleon since 1988: explain the unexpected smallness of the axial charge a_0.

Present data: a_0 compatible with zero, but values as large as $a_0(10\ \mathrm{GeV}^2) = 0.3$ not excluded.

Different theoretical scenarios proposed:

- Cancellation between a large (scale–independent, or AB–scheme) $\Delta\Sigma$ and a large Δg. In this case, $|\Delta u^+|, |\Delta d^+| \gg |\Delta s^+|$ (in the AB–scheme), as expected in the quark model.

  We call this the 'anomaly' scenario.

- Δg small, Δs^+ large and negative. Might be explained by invoking non–perturbative, instanton–like vacuum configuration. In this case, $\Delta s = \Delta\bar{s}$.

  We call this the 'instanton' scenario.

- Δs^+ large, but Δs significantly different from $\Delta\bar{s}$. Compatible with Skyrme models of the nucleon.

  We call this the 'skyrmion' scenario.

Main qualitative issues relevant for the nucleon spin structure:

1. how small is the axial charge?
2. how large is the polarized gluon distribution?
3. is Δs large?
4. is Δs different from $\Delta \bar{s}$?

Once individual quark and antiquark distributions have been measured, more detailed questions can be asked.

A challenge for future experiments.

The potential of a neutrino factory

Parameters still under study. Our reference choice:

- $E_\mu = 50$ GeV
- muon decays/year $N_\mu = 10^{20}$
- $L = 100$ m, $d = 30$ m, $\sigma_x = \sigma_y = 1.2$ mm, $\theta = 0.1 m_\mu / E_\mu$
- Target: $R = 50$ cm, thickness 10 g/cm^2

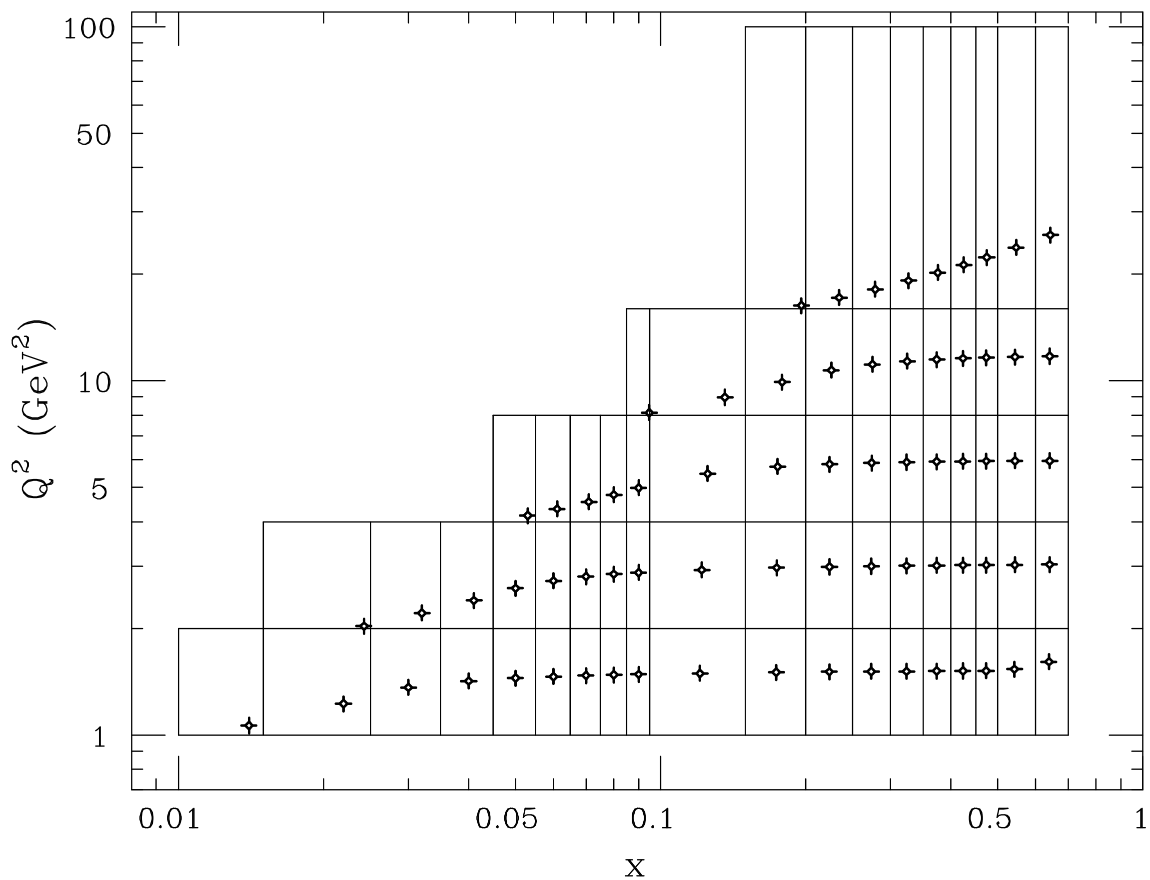
How accurately will charged-current structure functions be measured?

Exploit the different y dependence of each component and the wide-band nature of the ν beam:

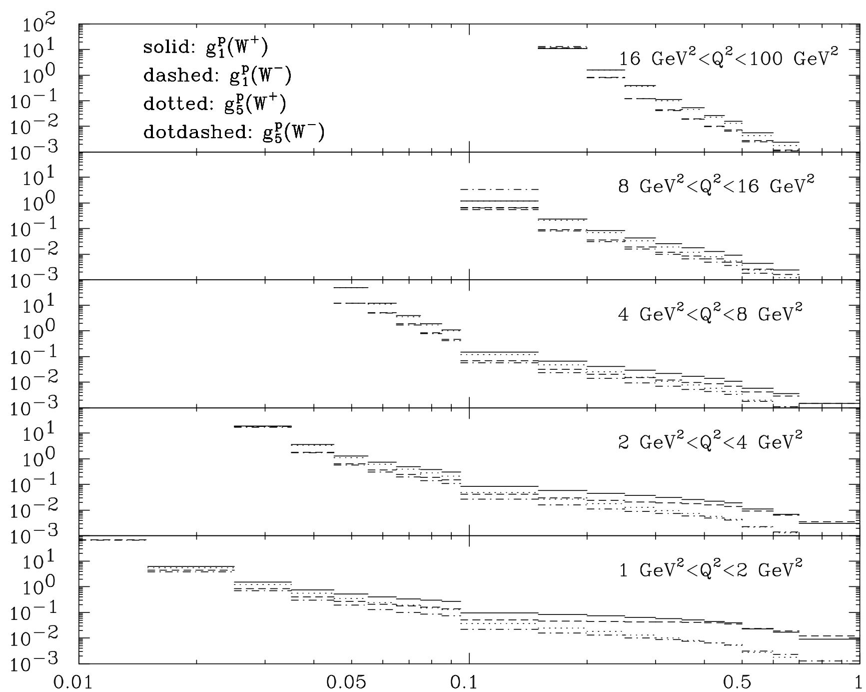
$$y = \frac{Q^2}{2xmE_\nu}$$

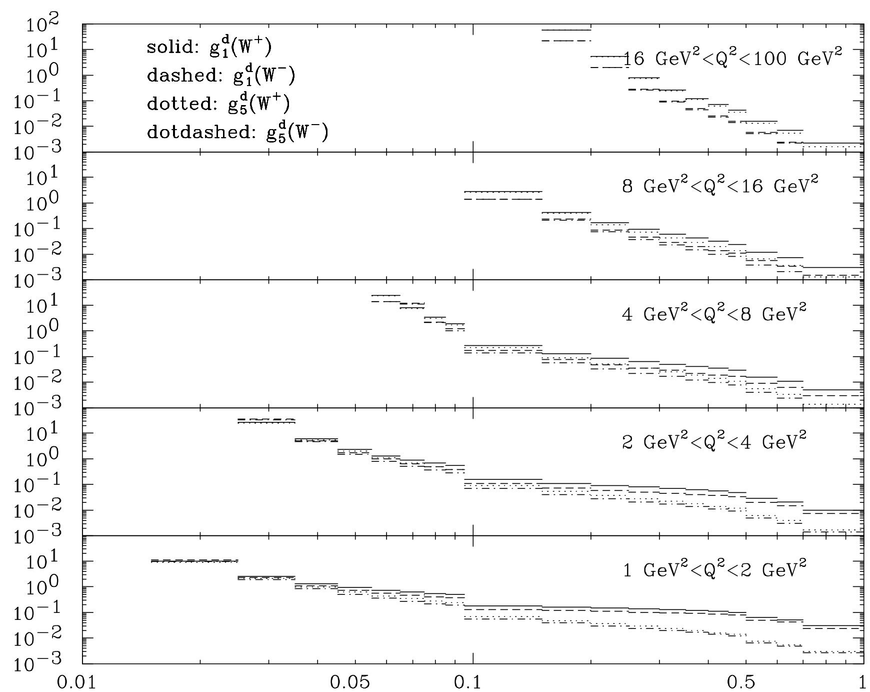
Different y in the same x, Q^2 bin varying E_ν. Measurement of μ and hadronic recoil energies allows event-by-event reconstruction of x, y and Q^2.

Step #1: Compute the expected errors on the measurements of g_1 and g_5 in a region of the x, Q^2 plane compatible with the features of the device (energy, number of ν per year, geometrical acceptances):



Forte, Mangano, R





Step #2: New fits of existing data, including recent E155 (no qualitative change).

	generic fit	$\Delta g = 0$ fit
η_Σ	0.38 ± 0.03	0.31 ± 0.01
η_g	0.79 ± 0.19	0
η_3	1.110 ± 0.043	1.039 ± 0.029
η_8	0.579	0.579
η_u	0.777	0.719
η_d	-0.333	-0.321
η_s	-0.067	-0.090
a_0	0.183 ± 0.030	0.284 ± 0.012

The fit with $\eta_g = 0$ has a higher χ^2, but once theoretical uncertainties are taken into account a vanishing gluon distribution can only be excluded at about two standard deviations.

η_u, η_d, η_s first moments of $\Delta q + \Delta \bar{q}$ at $Q^2 = 1$ GeV^2.

Step #3: Produce sets of "fake" data for charged-current structure functions according to three different assumptions:

1. generic fit of the previous table and $\Delta\bar{s} = 0$ (anomaly)
2. $\Delta g = 0$ fit of the previous table and $\Delta\bar{s} = \Delta s$ (instanton)
3. $\Delta g = 0$ fit of the previous table and $\Delta\bar{s} = 0$ (skyrmion)

In all three cases, $\Delta\bar{u} = \Delta\bar{d} = 0$.

Errors given by step #1, data gaussianly distributed about the central values. Data with $x > 0.7$ and /or error larger than 50 discarded. No estimate of systematics.

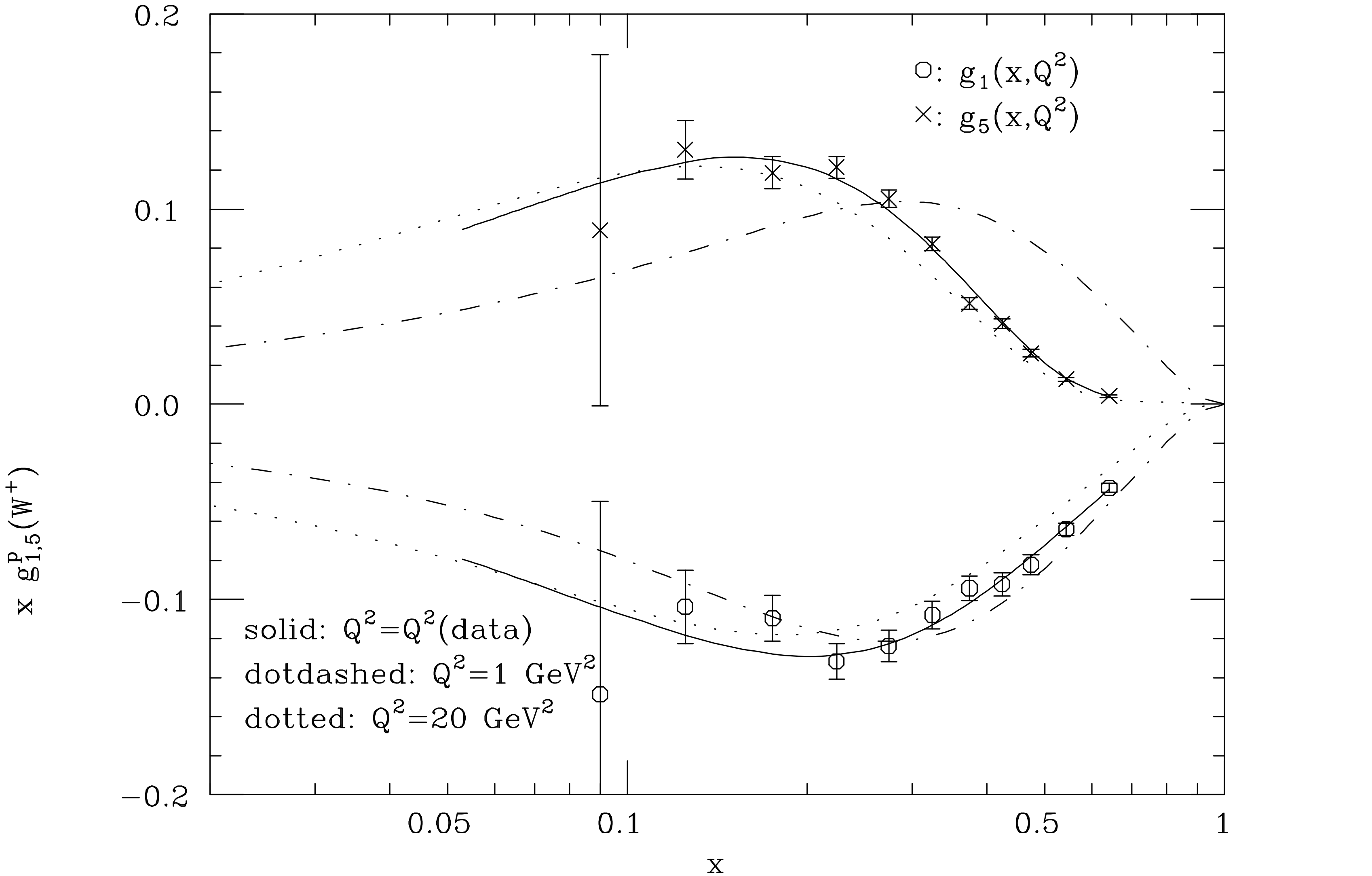
Total of 8 sets of fake data (2 structure functions $\times$ 2 beam types $\times$ 2 targets), with ~ 70 data points in each set (neutral-current real data: 176 points).

Step #4: Fit real data + fake data:

	'anomaly' refit	'instanton' refit	'skyrmion' refit
η_Σ	0.39 ± 0.01	0.321 ± 0.006	0.324 ± 0.008
η_g	0.86 ± 0.10	0.20 ± 0.06	0.24 ± 0.08
η_3	1.097 ± 0.006	1.052 ± 0.013	1.066 ± 0.014
η_8	0.557 ± 0.011	0.572 ± 0.013	0.580 ± 0.012
η_u	0.764 ± 0.006	0.722 ± 0.010	0.728 ± 0.009
η_d	-0.320 ± 0.008	-0.320 ± 0.009	-0.325 ± 0.009
η_s	-0.075 ± 0.008	-0.007 ± 0.007	-0.106 ± 0.008
a_0	0.183 ± 0.013	0.255 ± 0.006	0.250 ± 0.007

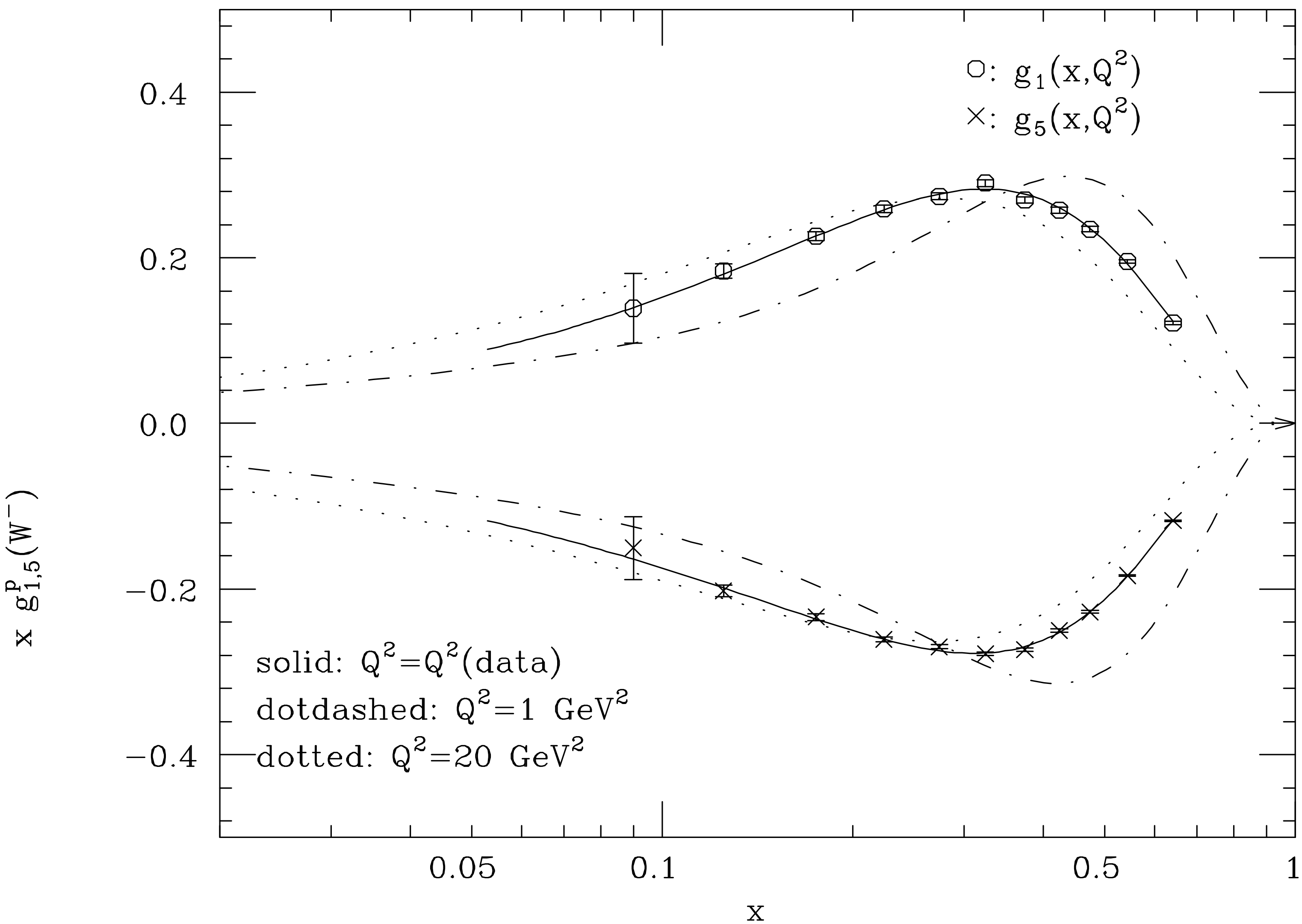
- marginal improvement on the error on η_g; η_g significantly non-zero even in the instanton and skyrmion cases.
- quark singlet and non-singlet first moments much better determined. Test of Bjorken sum rule and SU(3) violation.
- first moments of Δu^- and Δd^- determined at the few percent level, Δs^- at the 10% level.

Forte, Mangano, R



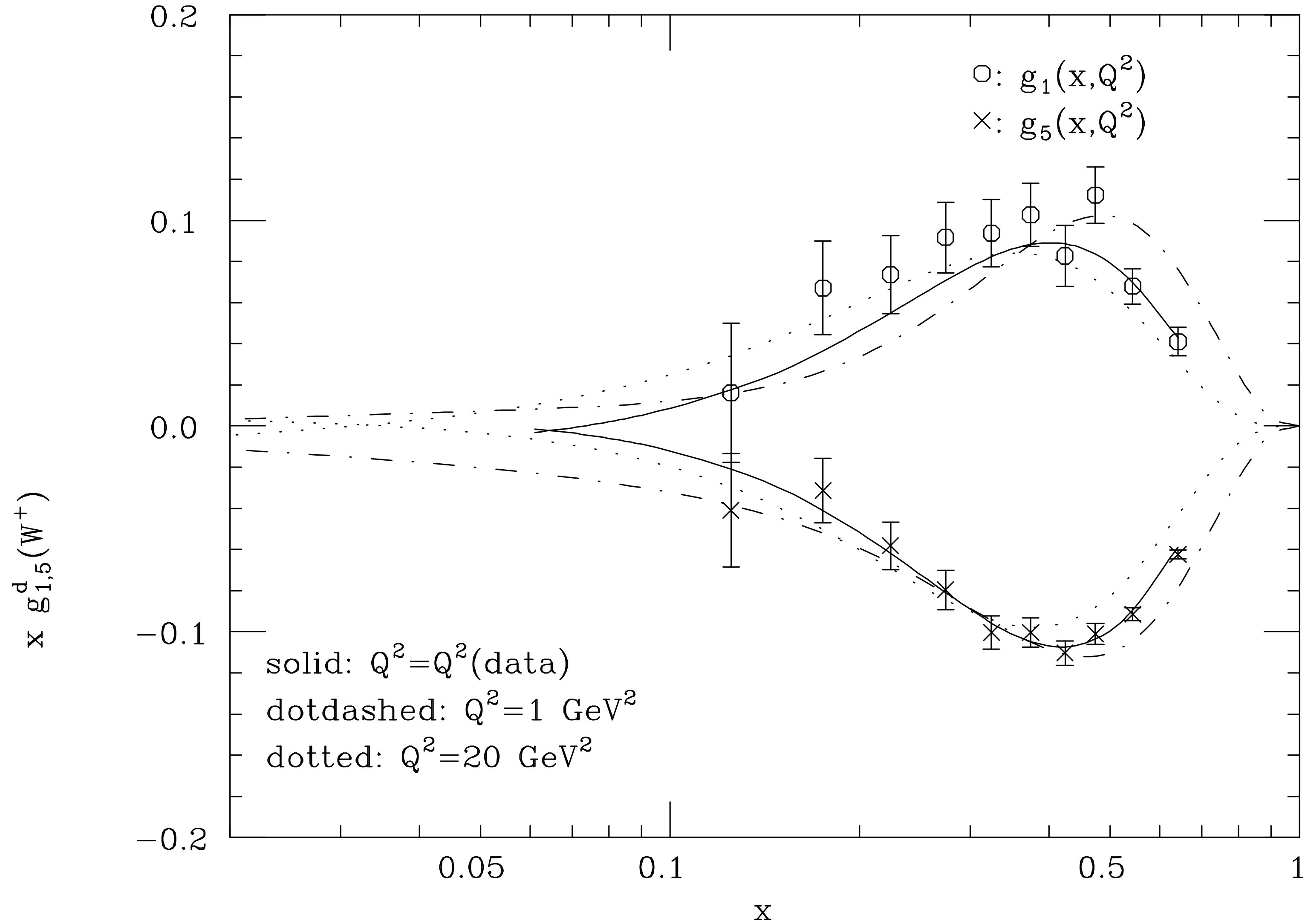
$4\ \mathrm{GeV}^2 \leq Q^2 \leq 8\ \mathrm{GeV}^2$

Forte, Mangano, R



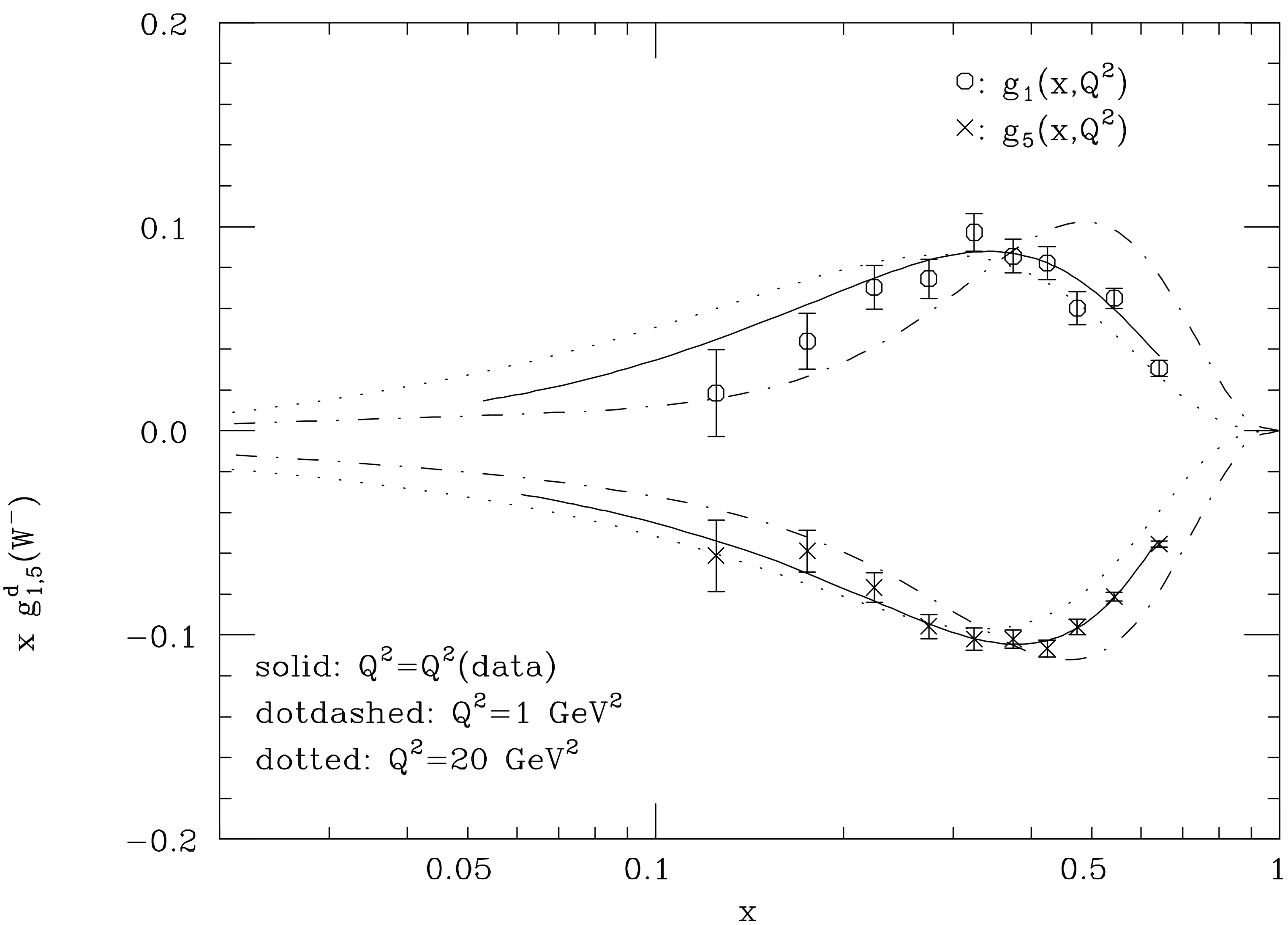
$4\ \mathrm{GeV}^2 \leq Q^2 \leq 8\ \mathrm{GeV}^2$

Forte, Mangano, R



$4\ \mathrm{GeV}^2 \leq Q^2 \leq 8\ \mathrm{GeV}^2$

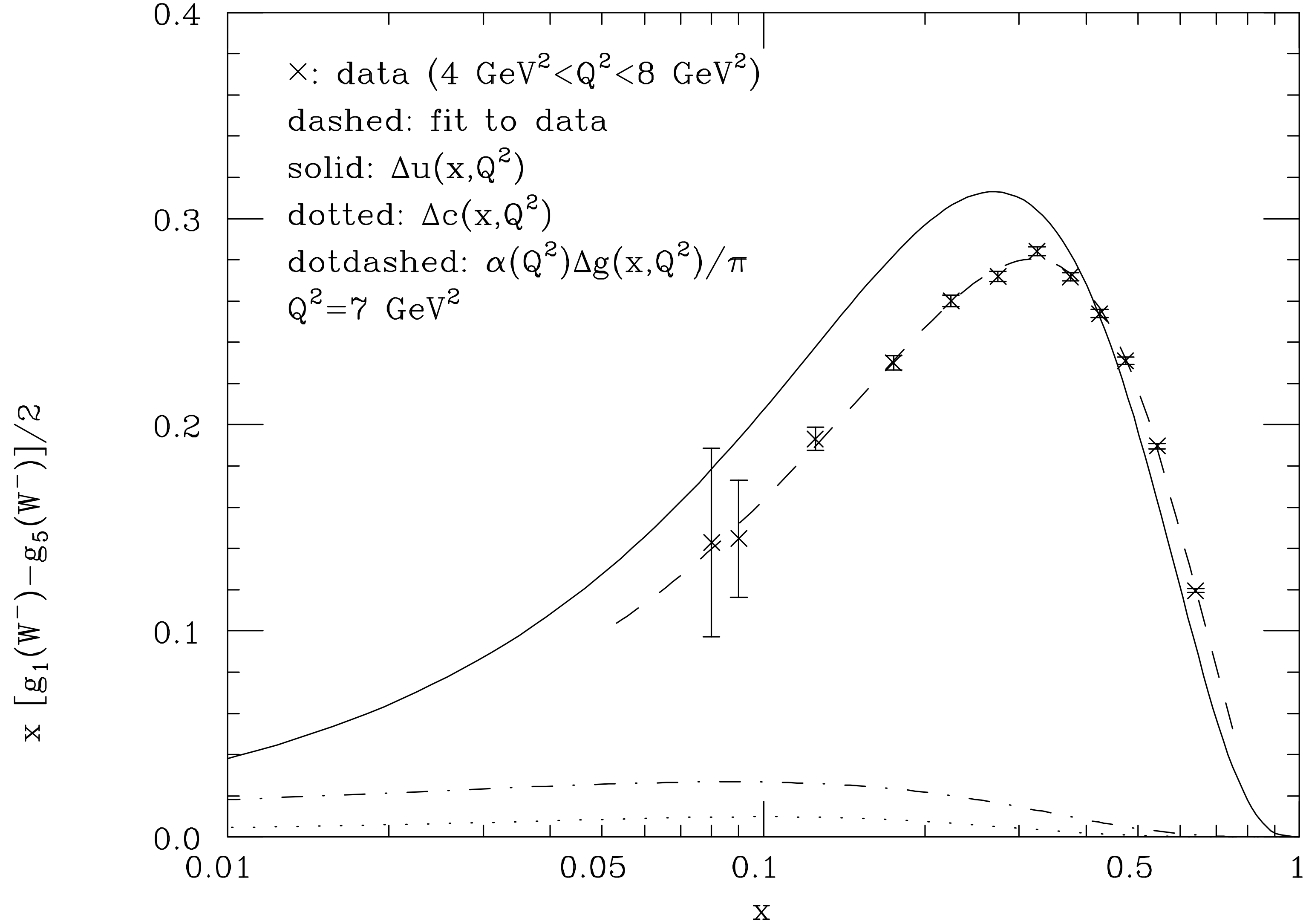
Forte, Mangano, R



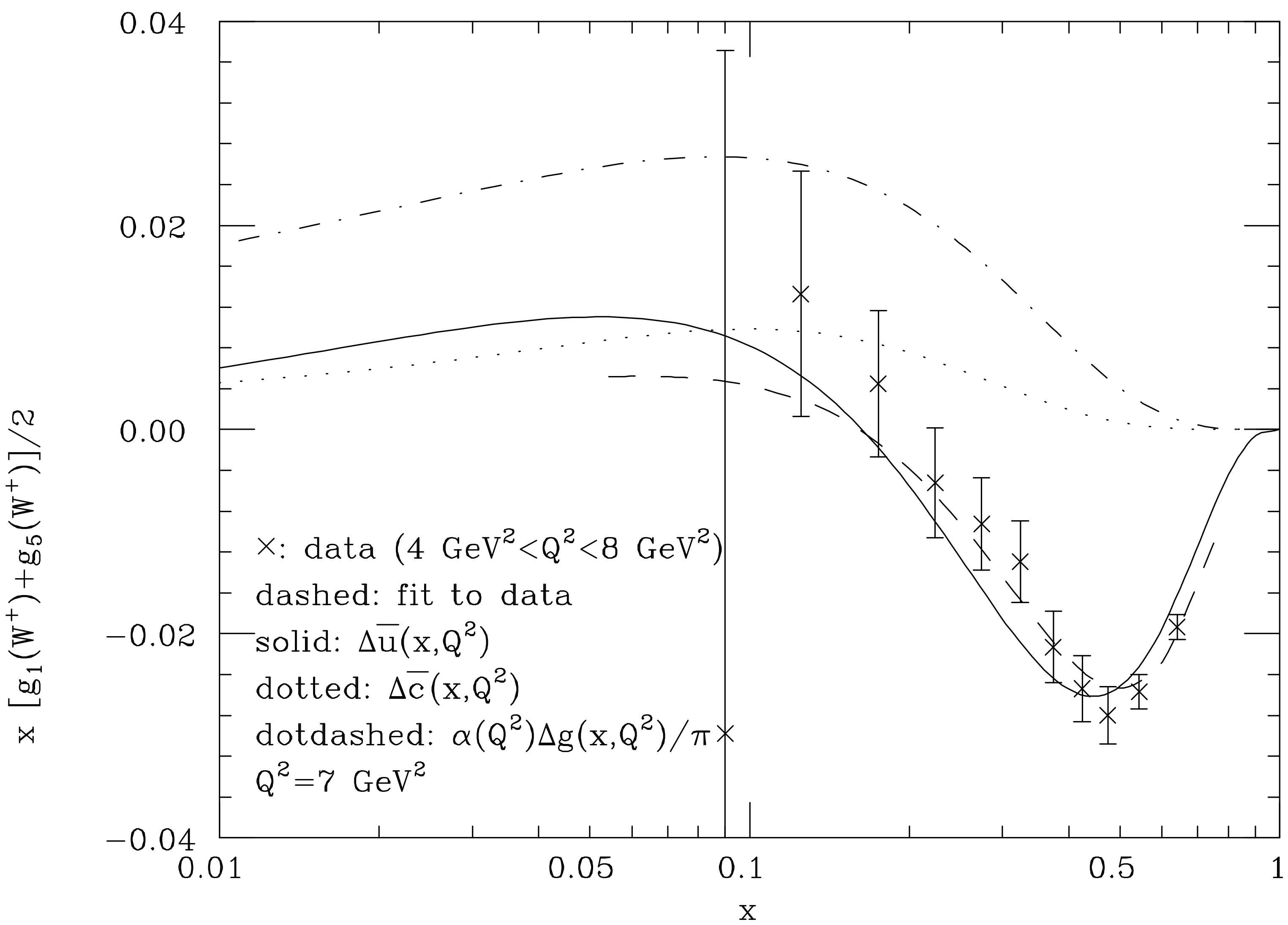
$4\ \mathrm{GeV}^2 \le Q^2 \le 8\ \mathrm{GeV}^2$

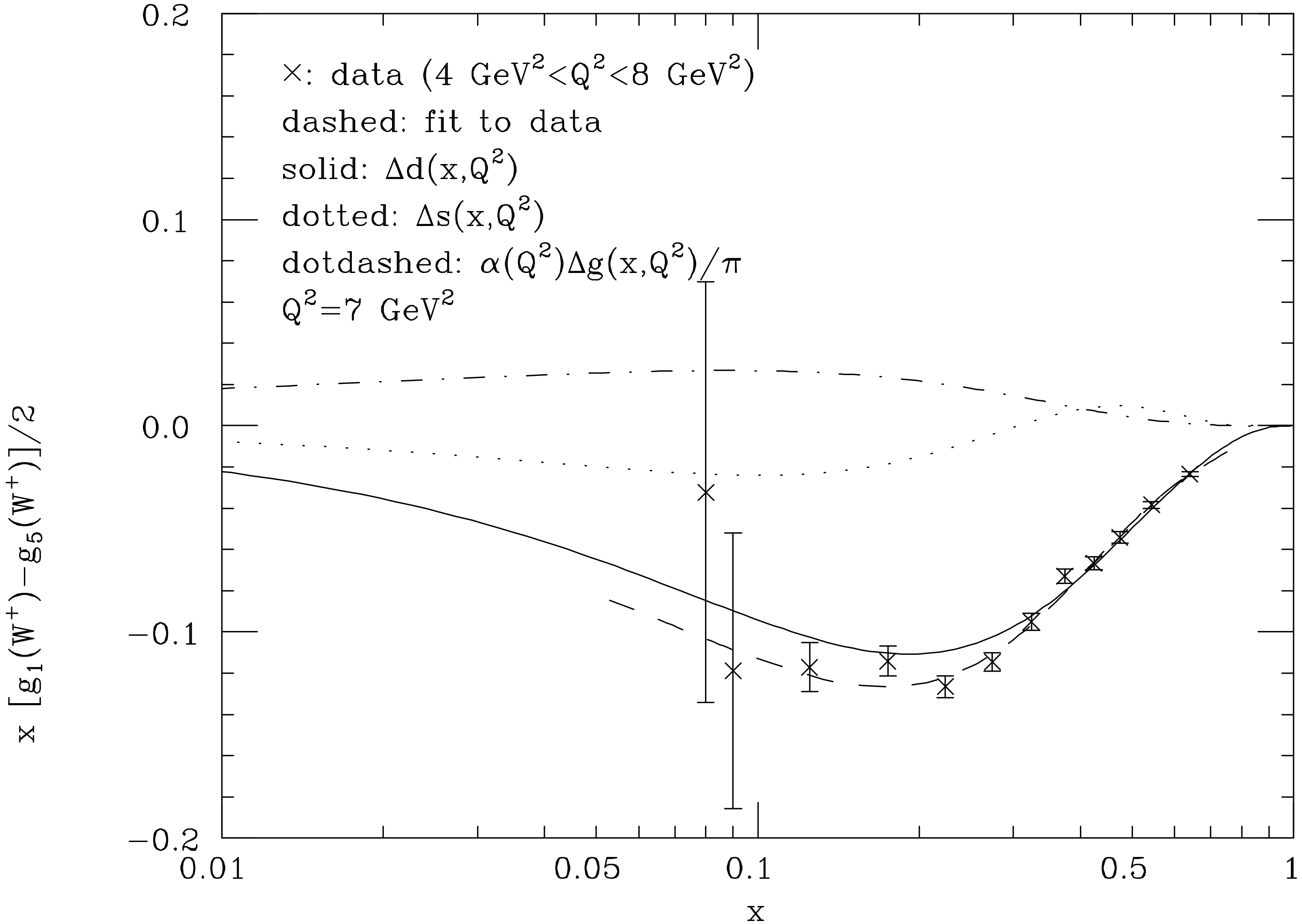
Shape of polarized parton distributions

A rough estimate: compare each parton distribution with the corresponding combination of structure function.

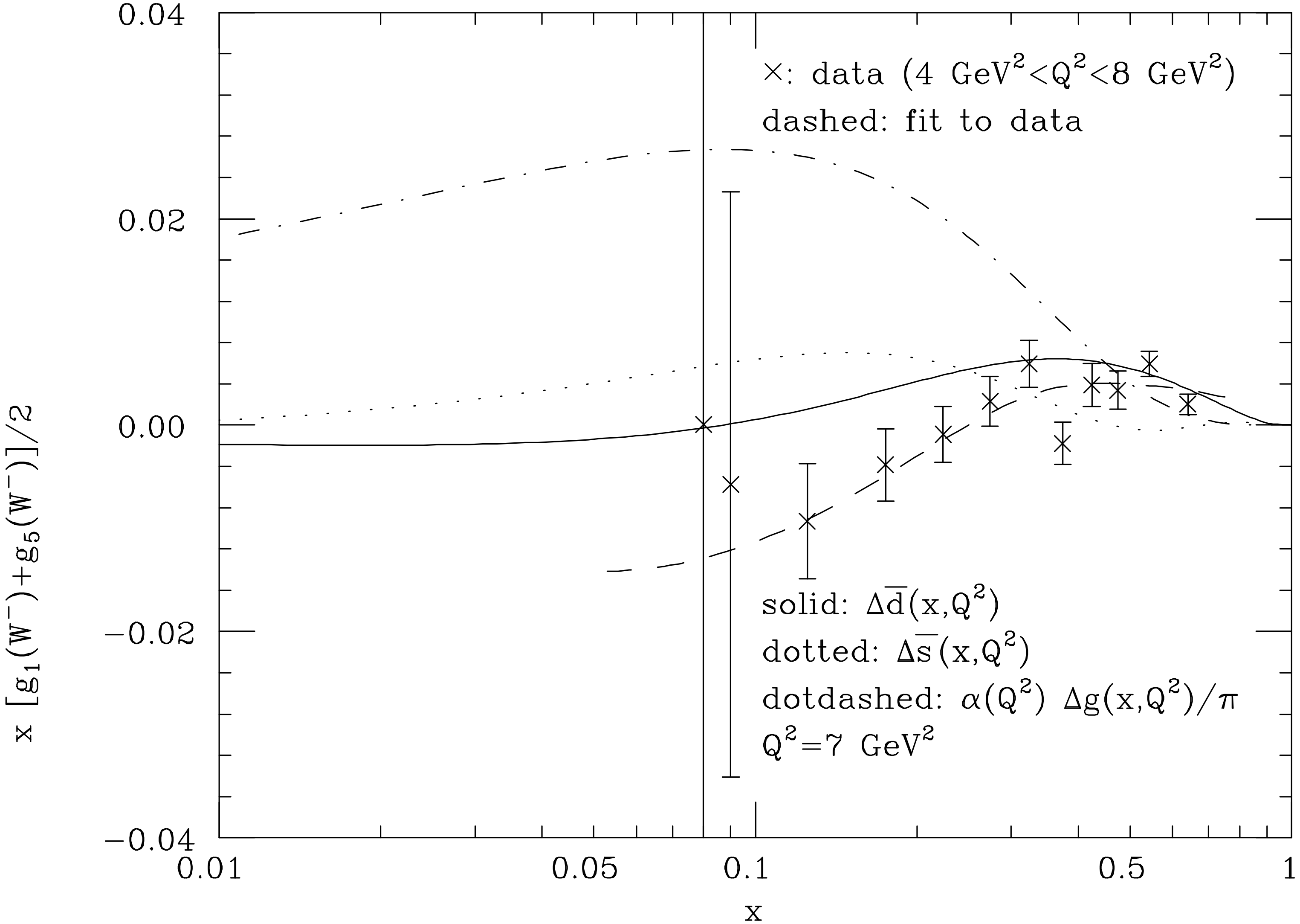

×: data (4 GeV^2<Q^2<8 GeV^2)
dashed: fit to data
solid: Δu(x,Q^2)
dotted: Δc(x,Q^2)
dotdashed: α(Q^2)Δg(x,Q^2)/π
Q^2=7 GeV^2
x [g$_1$(W$^-$)−g$_5$(W$^-$)]/2
x
0.0
0.1
0.2
0.3
0.4
0.01
0.05
0.1
0.5
1

Forte, Mangano, R





×: data (4 GeV²<Q²<8 GeV²)
dashed: fit to data
solid: Δd(x,Q²)
dotted: Δs(x,Q²)
dotdashed: α(Q²)Δg(x,Q²)/π
Q²=7 GeV²
x [g₁(W⁺)−g₅(W⁺)]/2
0.2
0.1
0.0
−0.1
−0.2
0.01
0.05
0.1
0.5
1
x


×: data (4 GeV^2<Q^2<8 GeV^2)
dashed: fit to data
solid: $\Delta\bar{d}(x,Q^2)$
dotted: $\Delta\bar{s}(x,Q^2)$
dotdashed: $\alpha(Q^2)\ \Delta g(x,Q^2)/\pi$
Q^2=7 GeV^2
x [$g_1(W^-)+g_5(W^-)$]/2
0.04
0.02
0.00
−0.02
−0.04
0.01
0.05
0.1
0.5
1
x

Conclusions

- NLO formalism for charged–current polarized DIS reviewed and numerically implemented.
- Experimental constraints: $|\Delta\bar{u}| \ll |\Delta u|$, $|\Delta\bar{d}| \ll |\Delta d|$; $\Delta\bar{s}$ and Δs allowed to have similar size.

  Theoretical constraints: $|\Delta q| < q$, $|\Delta\bar{q}| < \bar{q}$ from positivity;
- neutrino DIS at a ν factory: first moments of C–even distributions measured with accuracies which are up to one order of magnitude better than the current uncertainties

  $\Rightarrow$ definitive confirmation or refutation of the 'anomaly' scenario compared to the 'instanton' or 'skyrmion' scenarios

  $\Rightarrow$ determination of Δs^+ better than 10%; test of models of SU(3) violation when compared to the direct determination from hyperon decays.

- C–odd distributions: first moments of $\Delta u^-, \Delta d^-$ determined at the level of few percent, Δs^- at the level of 10%; sufficient to test for instrinsic strangeness, and distinguish between 'skyrmion' and 'instanton' scenarios.
- shape of the distributions: $\Delta u(x)$ and $\Delta d(x)$ at the level of 15-20%, mainly because of gluon contamination from radiative corrections. No significant shape information obtained for $\Delta s(x)$.