The deuteron spin-dependent structure function g_1^d

Krzysztof Kurek
The Andrzej Sołtan Institute for Nuclear Studies, Warsaw,Poland

on behalf of the COMPASS Collaboration

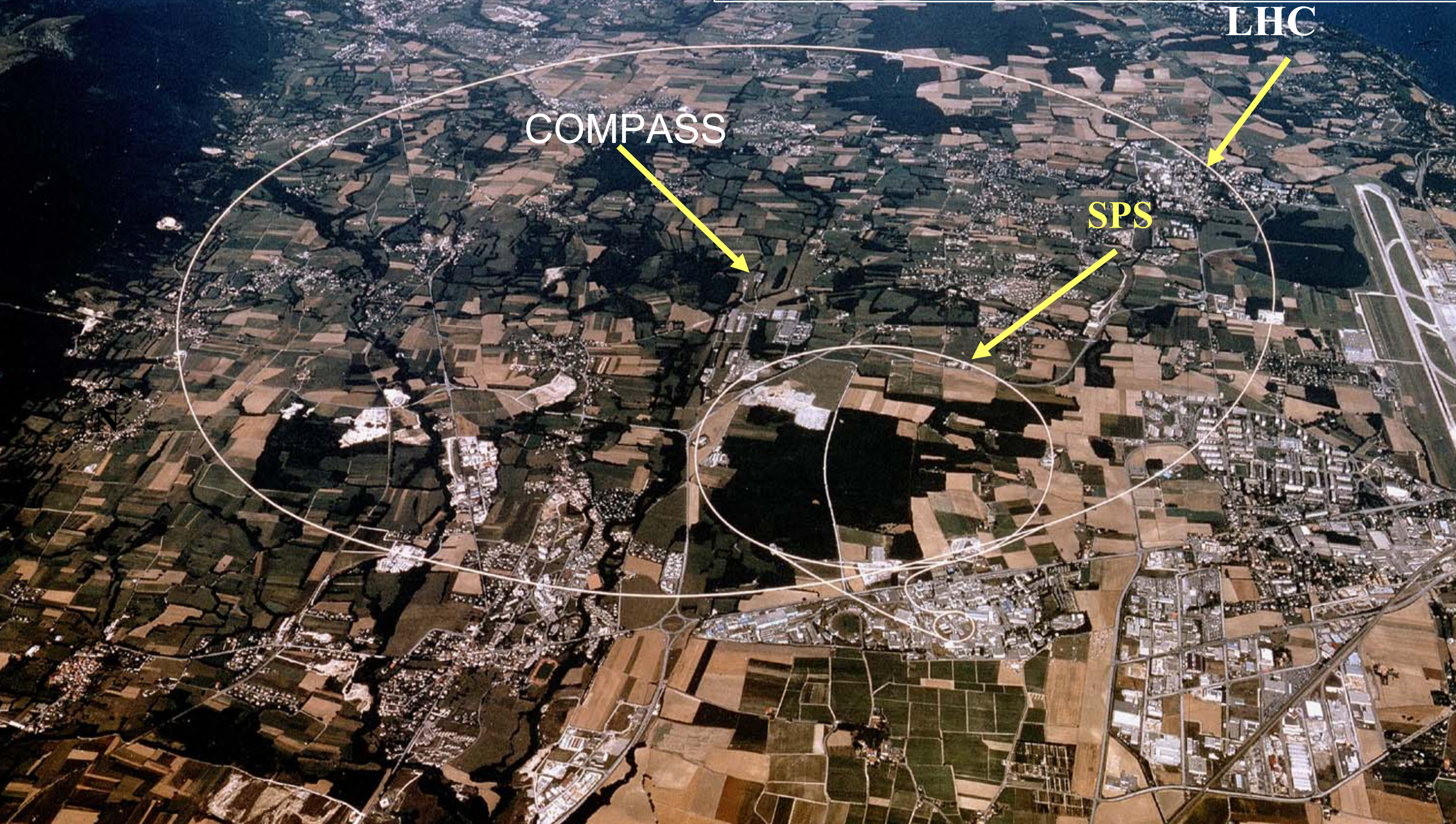
COmmon Muon Proton Apparatus for Structure and Spectroscopy COMPASS

Bielefeld,Bochum,Bonn,Burdwan/Calculta,CERN,Dubna,Erlangen, Freiburg,Lisbon,Mainz,Moscow,Munich,Nagoya,Prague,Protvino, Saclay,Tel Aviv,Turin,Trieste,Warsaw, ~240 physicists

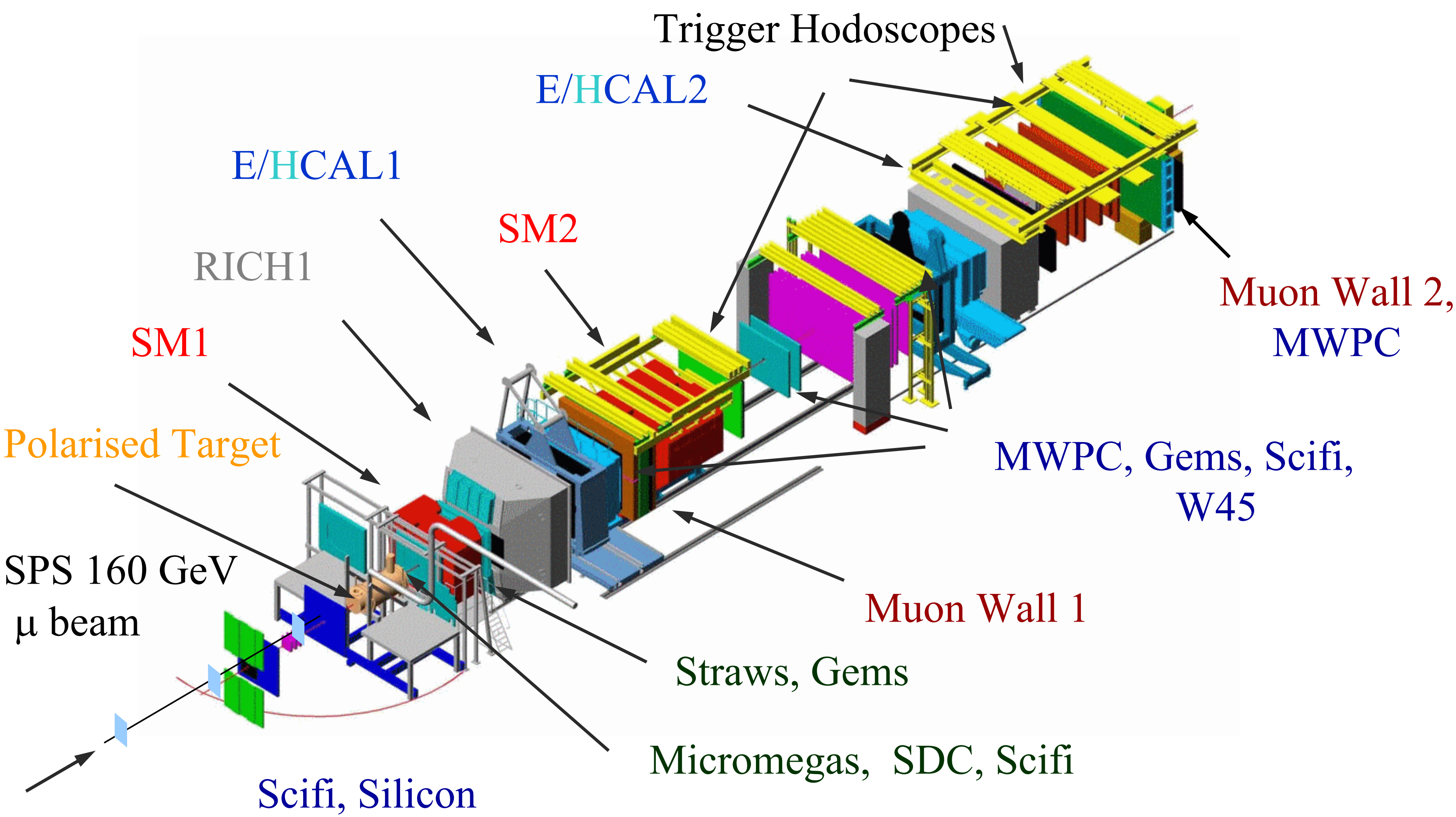
- Muon beam program:
  - gluon polarisation,
  - spin-dependent structure function
  - polarised quark distributions,
  - transversity,
  - Lambda polarisation,
  - vector meson production,
  - GPD (future)

- longitudinally polarised muon beam
- longitudinally or transversely polarised deuteron (^{6}LiD) target
- momentum and calorimetry measurement
- particle identification

luminosity: ~5 · 10^{32} cm^{-2} s^{-1}
beam intensity: 2·10^8 μ+/spill (4.8s/16.2s)
beam momentum: 160 GeV/*c*
beam polarization: ~76 %
target polarization: ~50 %

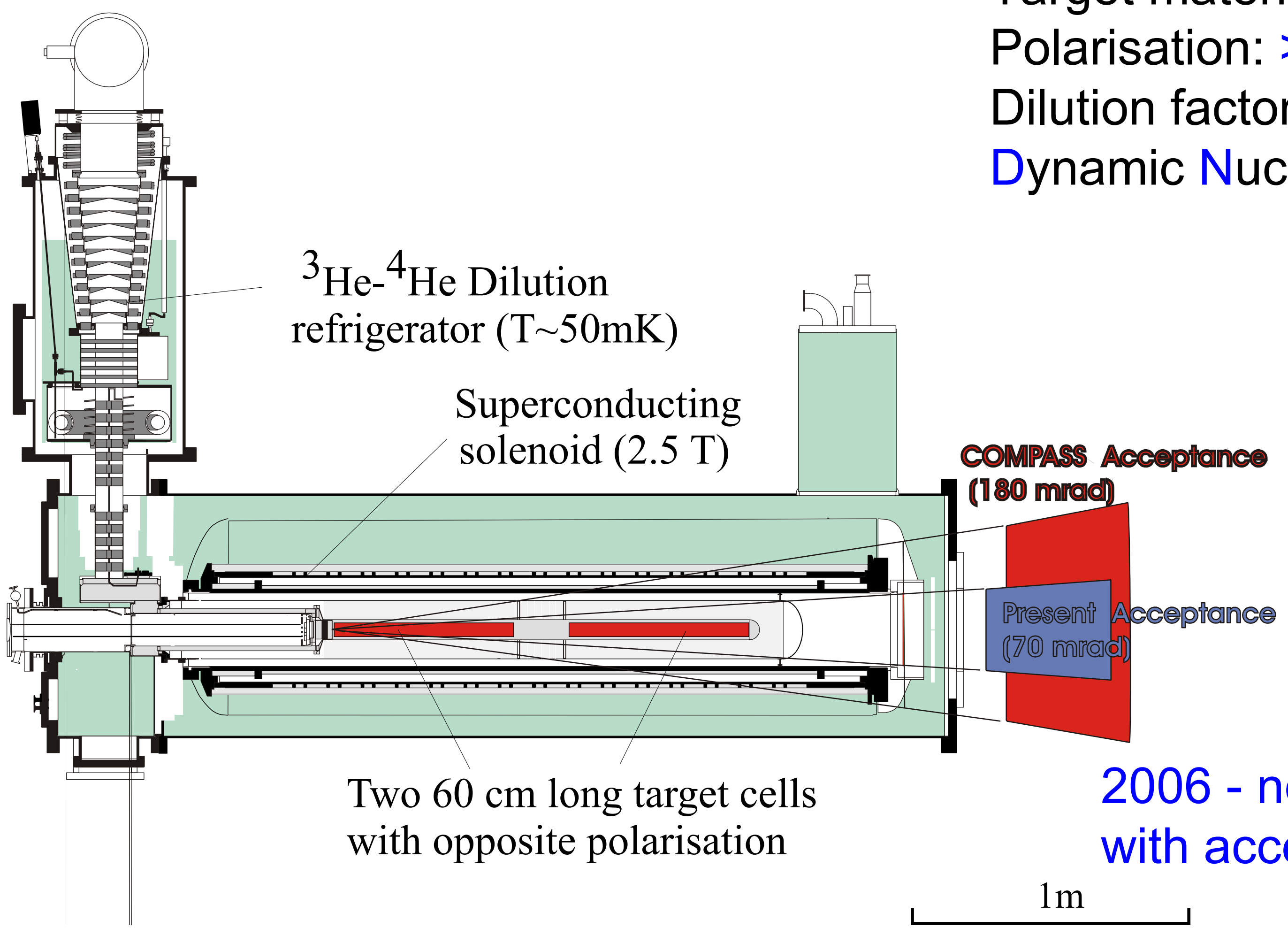


The COMPASS Spectrometer



The COMPASS polarised target

Target material: ^{6}LiD
Polarisation: >50%
Dilution factor: ~0.4
Dynamic Nuclear Polarisation



2006 - new solenoid with acceptance 180 mrad

Content

- Definitions.
- Inclusive asymmetry A_1^d and structure function g_1^d for $Q^2 < 1\ (GeV/c)^2$ (quasi-real photon).
- Inclusive asymmetry A_1^d, structure function g_1^d and QCD analysis for $Q^2 > 1\ (GeV/c)^2$ (fits).
- First moment of g_1^d.
- Conclusions.

Definitions

A_1^d and structure function g_1^d

$$A^{\mu d} = A_{\|} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = D\,(A_1^d + \eta\, A_2^d)$$

$$|\eta\, A_2^{d,p,n}| \ll |A_1^{d,p,n}|\,, \qquad \eta = \frac{2(1-y)}{y(2-y)}\sqrt{Q^2}\Big/E',$$

$$\Longrightarrow \quad A_1^d \approx \frac{A_{\|}}{D}$$

$$A_1^{p,n} = A^{\gamma N} = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}}$$ for nucleon

$$A_1^d = A^{\gamma d} = \frac{\sigma^0 - \sigma^2}{\sigma^0 + \sigma^2}$$ for deuteron

$A_{meas} \sim A^{\mu d} \sim A_1^d$;

Measurement of A_1 gives access to g_1 structure function

$$g_1^d = ½\,(g_1^p + g_1^n)\,(1 - \frac{3}{2}\omega_d) \simeq A_1^d\, F_1^d = A_1^d\, \frac{F_2^d}{2x(1+R)}$$

A_1^d and structure function g_1^d

- A_1^d and g_1^d for small Q^2 ($Q^2<1$ (GeV/c)^2):
  physics at small x, parton saturation,
  non-perturbative models (Regge,VDM)
  poorly known (only SMC data)

- A_1^d and g_1^d for high Q^2 ($Q^2>1$ (GeV/c)^2):
  QCD analysis possible: ΔG estimation

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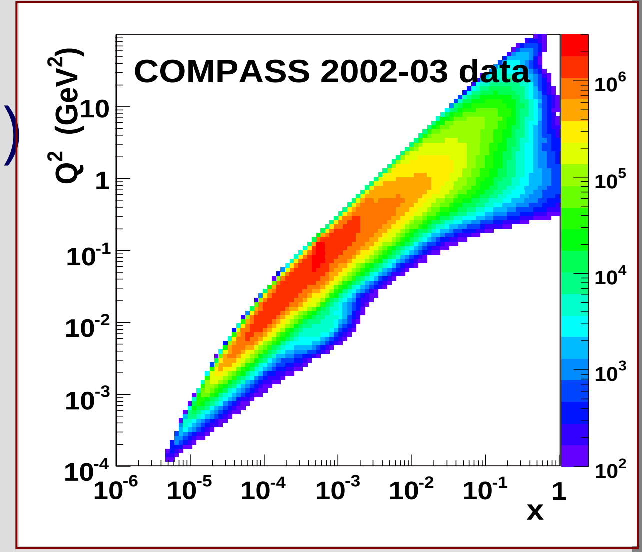


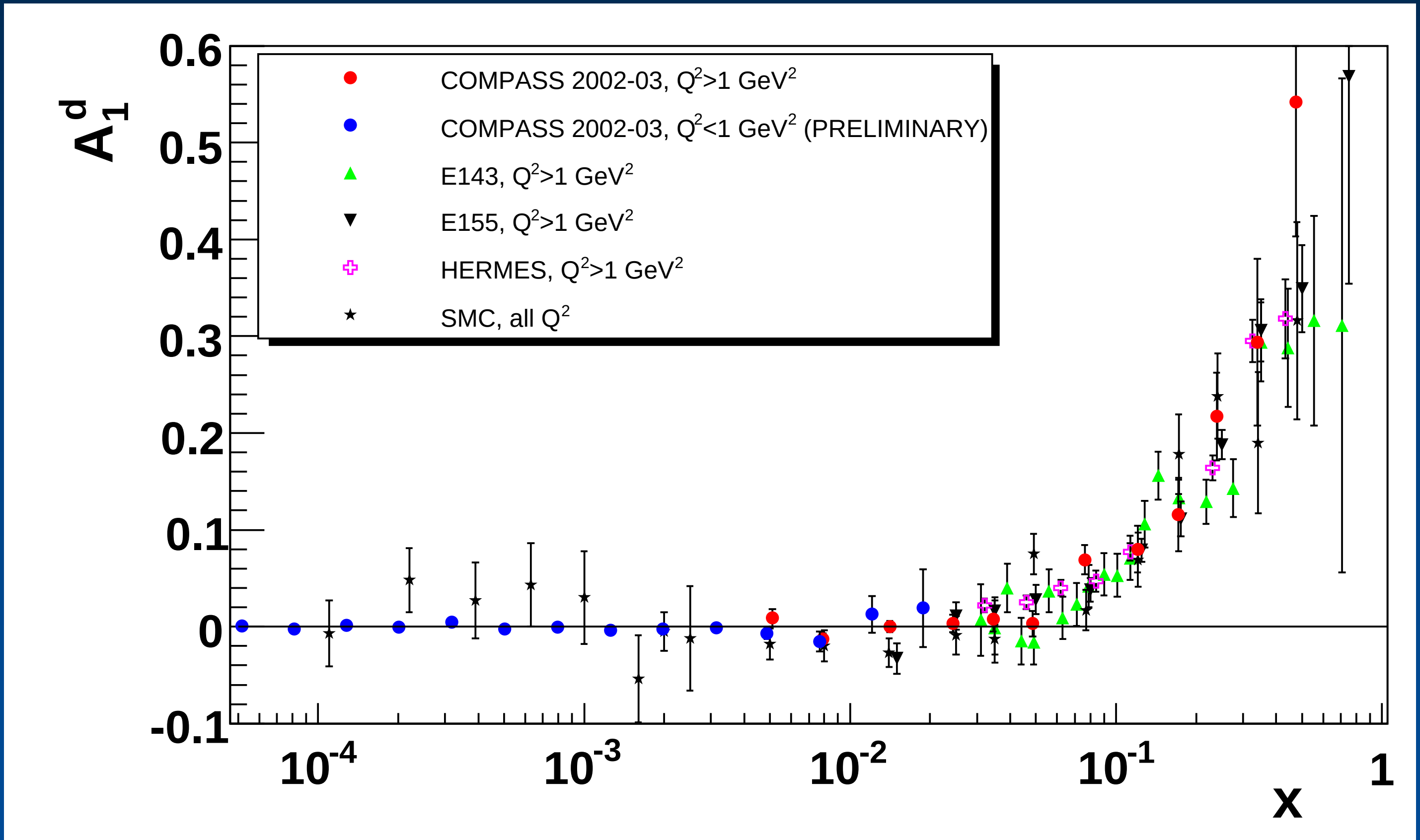
Q^2 and x are strongly correlated for small Q^2 in COMPASS (fixed target)

Inclusive asymmetry A_1^d and structure function g_1^d for $Q^2<1$ $(GeV/c)^2$

Inclusive asymmetry A_1^d and structure function g_1^d for $Q^2<1$ $(GeV/c)^2$

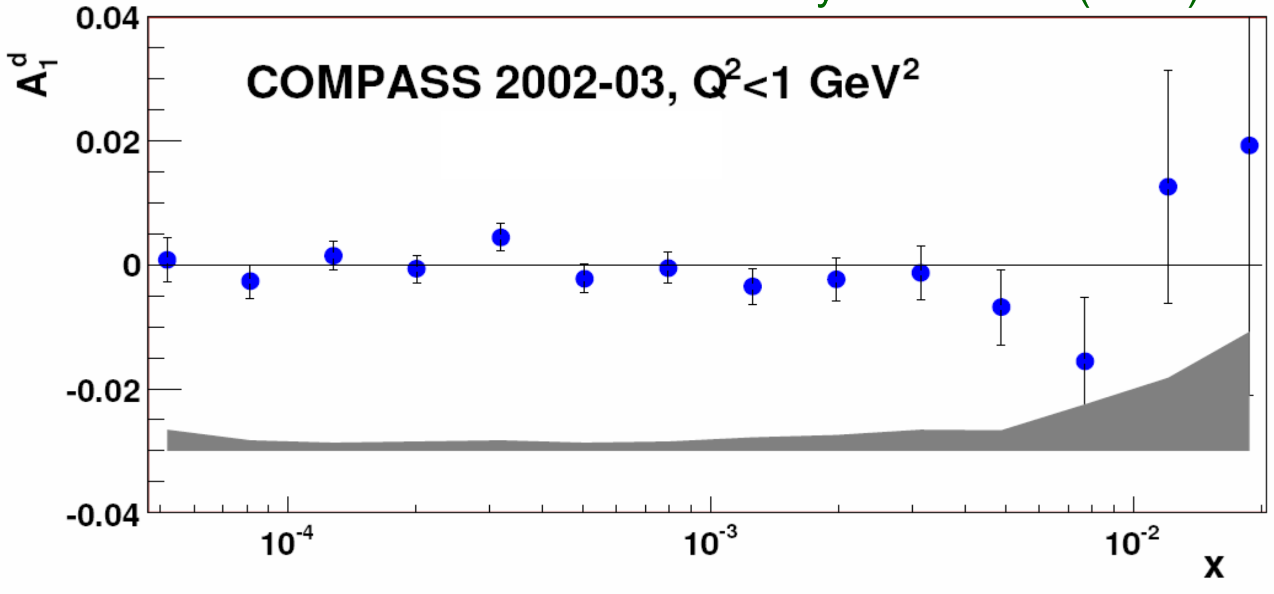
blue points – Compass 2002-2003 data ($Q^2<1(GeV/c)^2$)

10-20 times lower statistical errors compared to SMC



Inclusive asymmetry A_1^d and structure function g_1^d for Q^2<1 $(GeV/c)^2$

Phys.Lett.B 647 (2007)330



A_1^d asymmetry compatible with 0 at low x range (0.0005<x<0.02)

At low x A_1^d has been measured only by COMPASS and SMC

Systematic errors are mainly due to false asymmetries

Inclusive asymmetry A_1^d and structure function g_1^d for $Q^2<1\ (\mathrm{GeV}/c)^2$

$$g_1(x) = A_1(x)\frac{F_2(x)}{2x(1+R)}$$

F_2 taken from SMC param.,

R depends on x: x>0.12

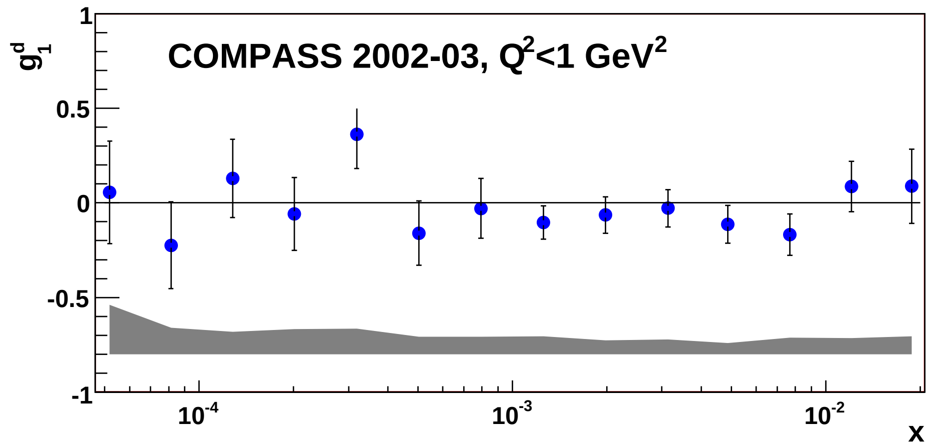
SLAC (Phys.Lett.B250(1990)193, B52(1999)194)

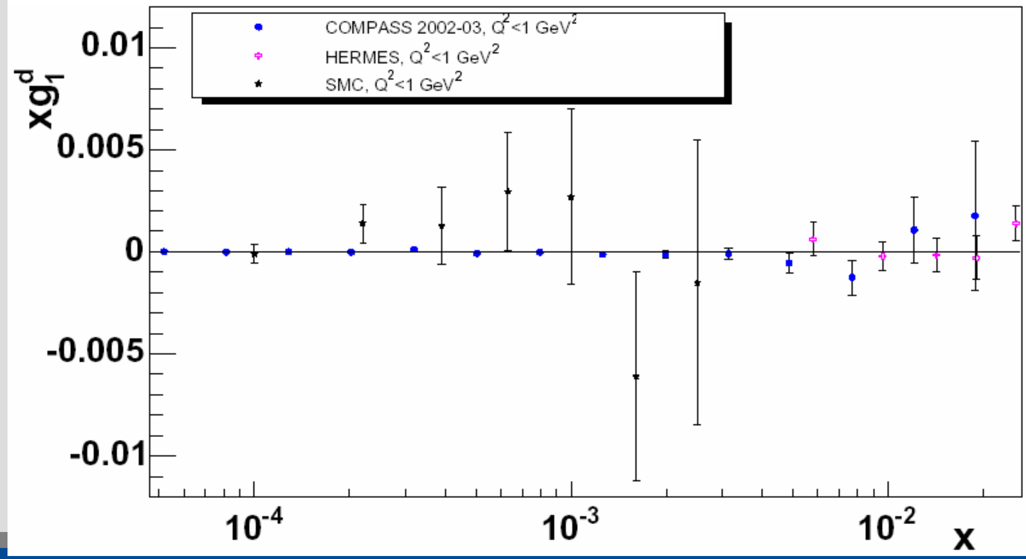
0.003<x<0.12 NMC

(R param. unpublished)

x<0.003 ZEUS

(Eur.Phys.JC7(1999)609,σ_L, σ_T cross sections param.)

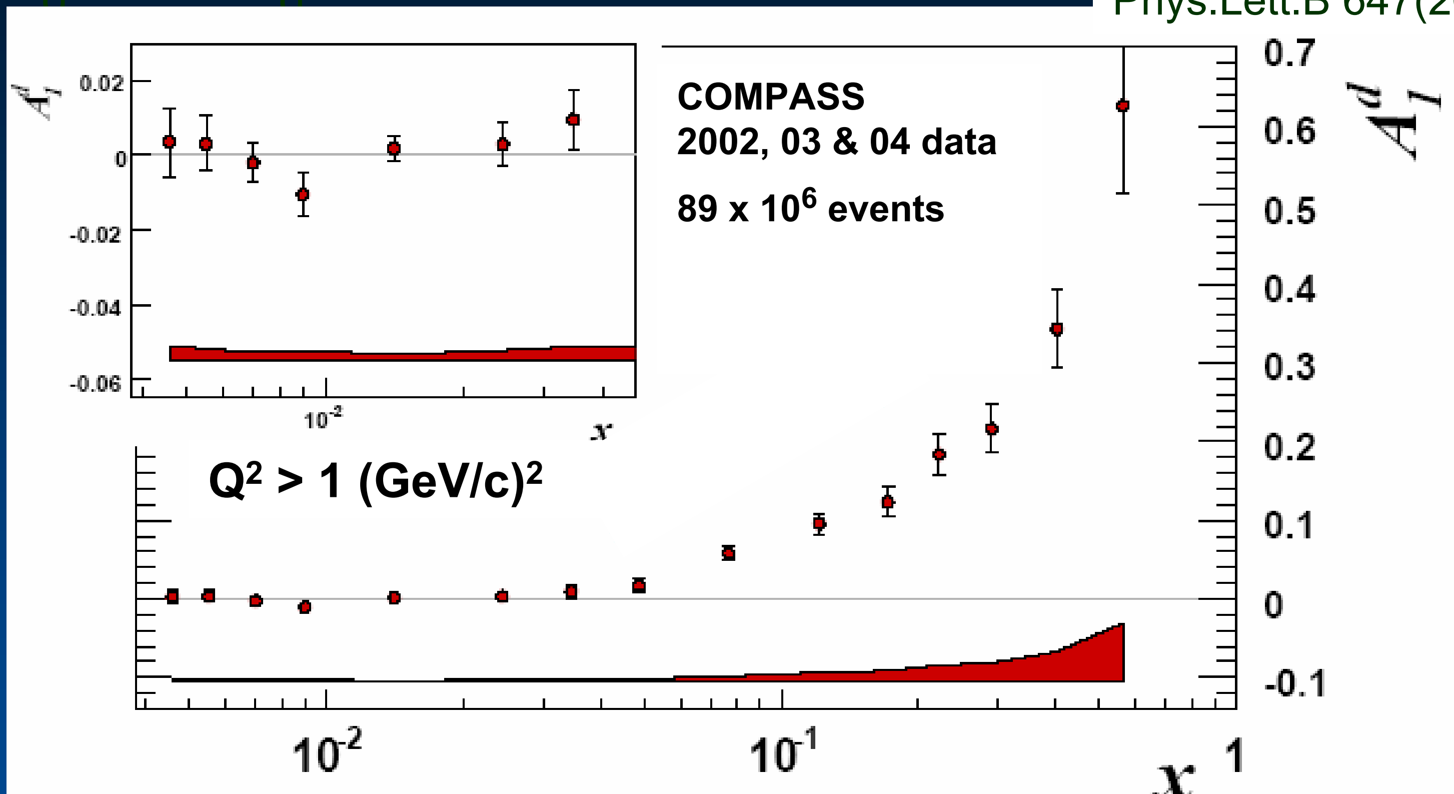




Inclusive asymmetry A_1^d and structure function g_1^d for Q^2>1 $(GeV/c)^2$

Inclusive asymmetry A_1^d and structure function g_1^d for $Q^2>1$ $(GeV/c)^2$

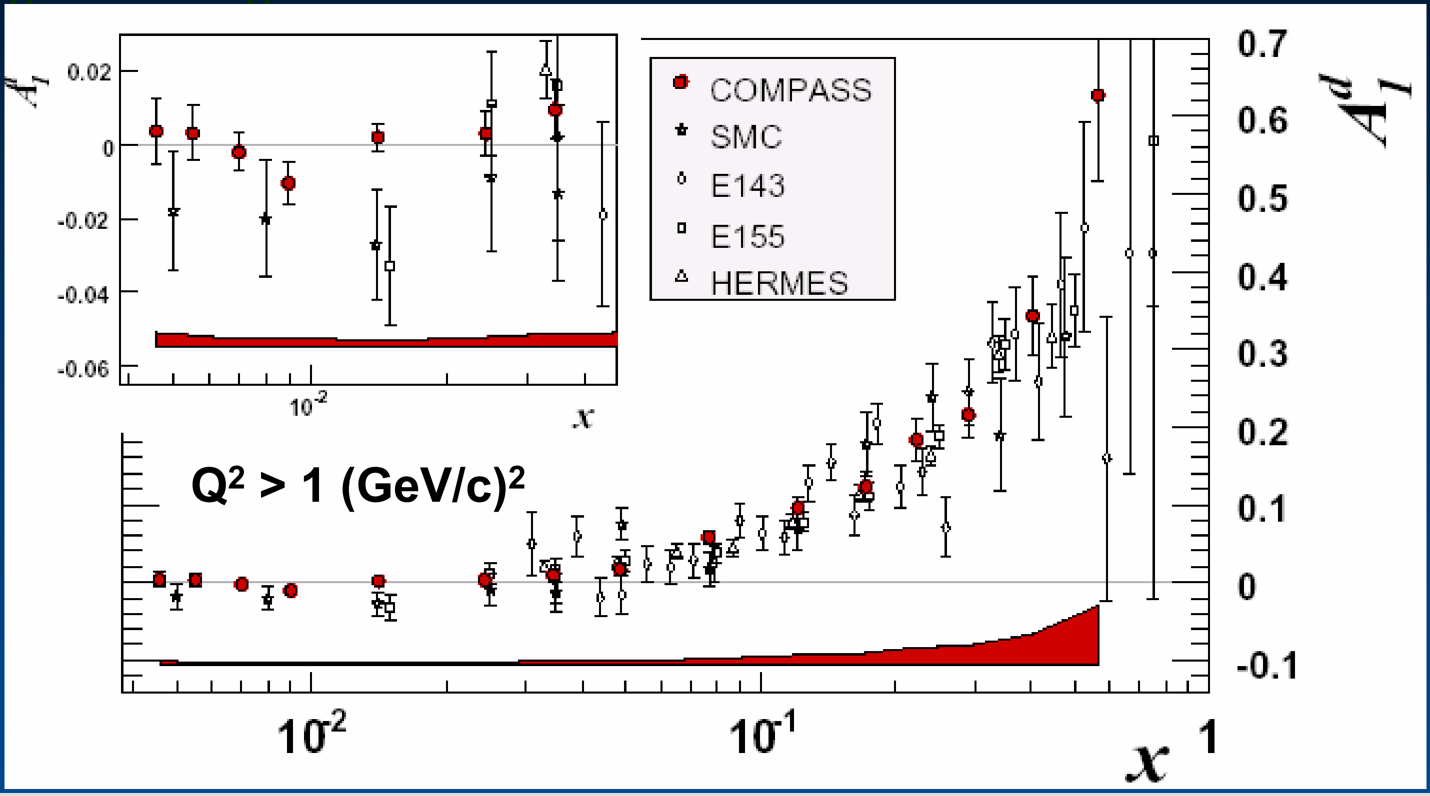
Phys.Lett.B 647(2007)8



A_1 compatible with 0 for $x < 0.05$

Large asymmetry at large x

Inclusive asymmetry A_1^d and structure function g_1^d for $Q^2>1$ $(GeV/c)^2$



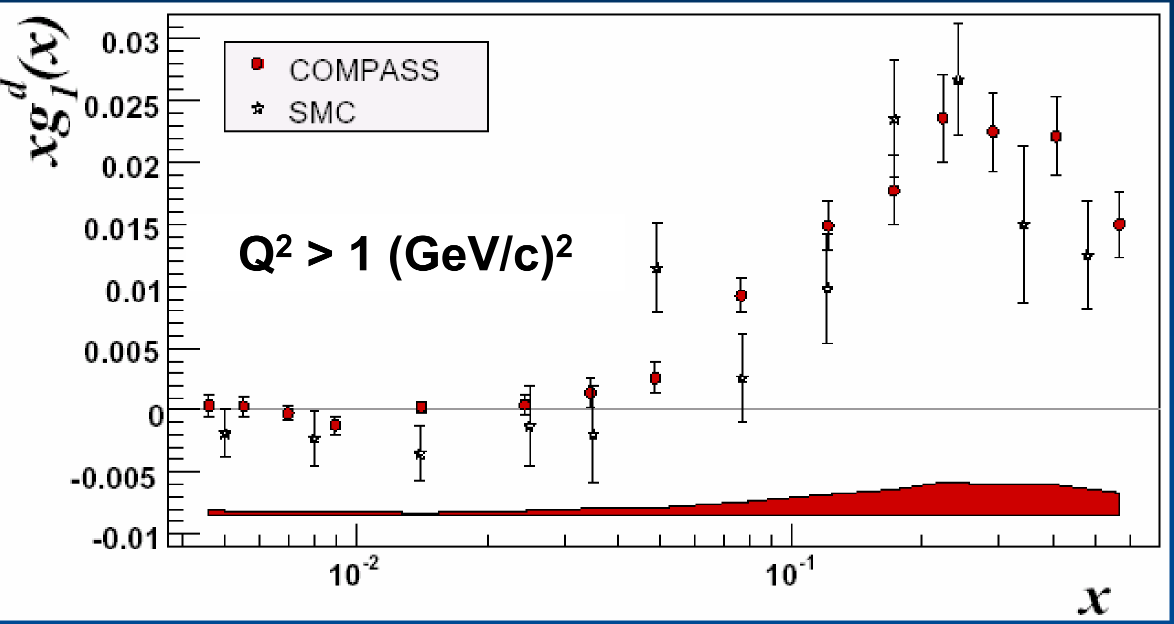
Good agreement with previous experiments

Improved significantly statistics at low x

No tendency towards negative values at x < 0.03

Inclusive asymmetry A_1 and structure function g_1 for $Q^2>1$ (GeV/c)^2

$$g_1^d = g_1^N\left(1-\tfrac{3}{2}\omega_d\right) = \frac{F_2^d}{2x(1+R)}A_1^d$$



Inclusive asymmetry A_1 and structure function g_1 for $Q^2>1\ (GeV/c)^2$

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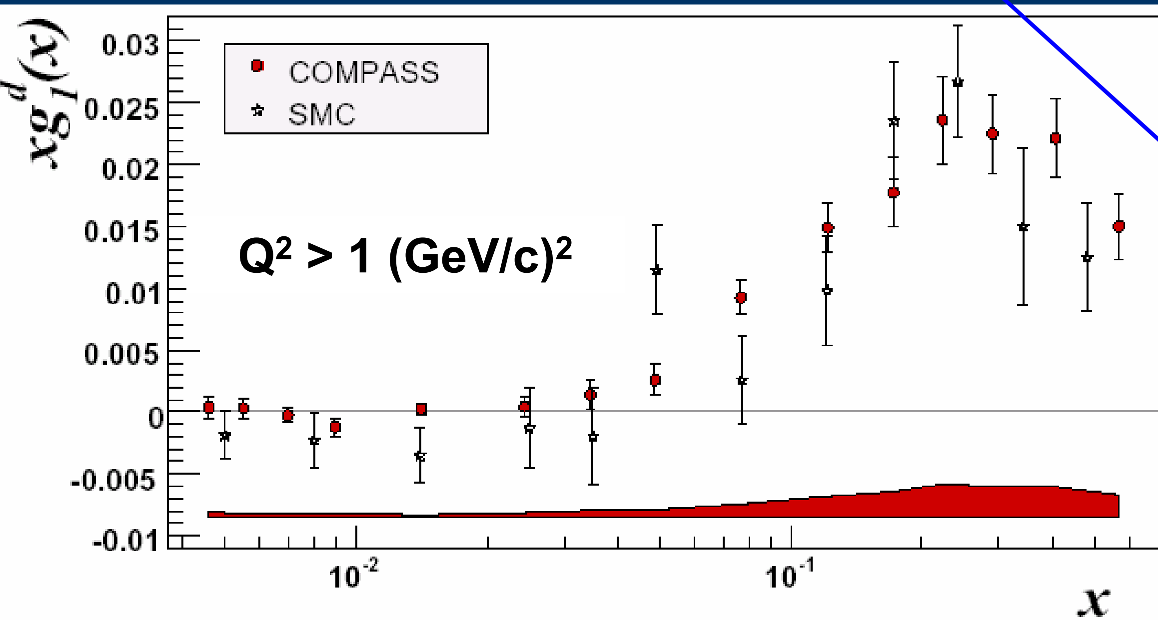

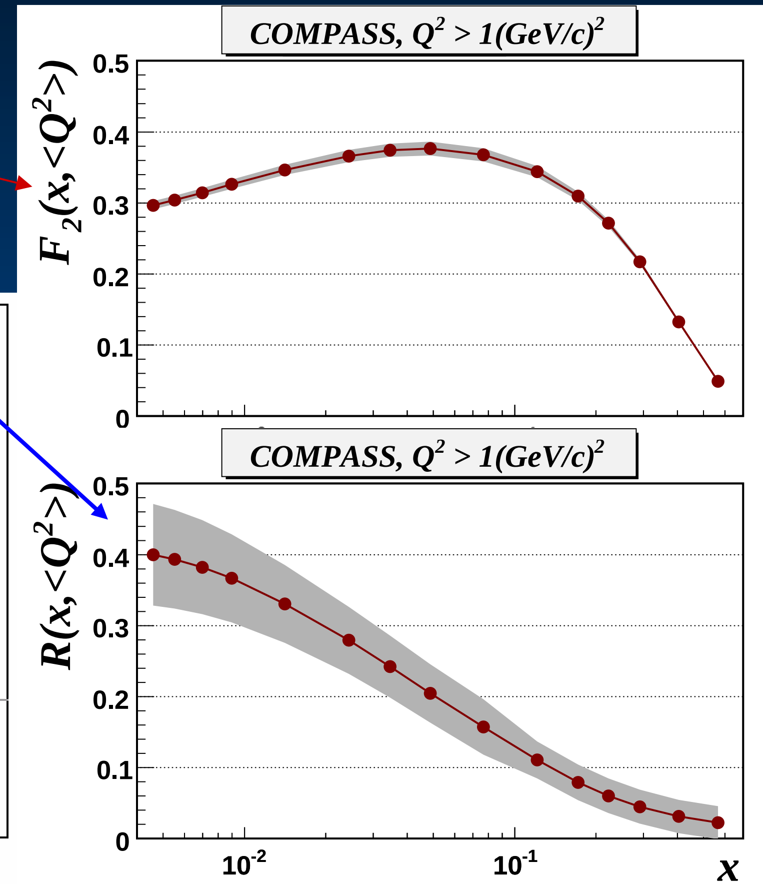

R(1998)

QCD analysis of the world data on structure function g_1

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$$g_1(x,Q^2) = \tfrac{1}{2}\langle e^2\rangle\left[C_q^s \otimes \Delta\Sigma + C_q^{NS} \otimes \Delta q^{NS} + 2n_f C_G \otimes \Delta G\right]$$

- DGLAP equations:

$$\frac{d}{dt}\Delta q^{NS} = \frac{\alpha_S(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q^{NS}$$

$$\frac{d}{dt}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} = \frac{\alpha_S(t)}{2\pi}\begin{pmatrix}P_{qq}^S & 2n_f P_{qG}^S \\ P_{Gq}^S & P_{GG}^S\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix}$$

$$t = \log\left(\frac{Q^2}{\Lambda^2}\right)$$

- Initial parametrization: x dependence at fixed Q^2

($\gamma \neq 0$ for singlet only for $\Delta G > 0$)

$$\left(\Delta\Sigma, \Delta q_s, \Delta q_8, \Delta G\right) = \eta \frac{x^\alpha (1-x)^\beta (1+\gamma x)}{\int_0^1 x^\alpha (1-x)^\beta (1+\gamma x)\,dx}$$

- Minimization routine

$$\chi^2 = \sum_{i=1}^{N} \frac{\left[g_1^{calc}(x,Q^2) - g_1^{\exp}(x,Q^2)\right]^2}{\left[\sigma_{stat}^{\exp}(x,Q^2)\right]^2}$$

QCD analysis of the world data on structure function g_1

Two different approaches in NLO $\overline{MS}$ scheme have been used:
- grid in (Q^2,x) space (Phys.Rev.D58(1998)112002)
- Mellin transform + moments space (Phys.Rev.D70(2004)074032)

World data fit: 9 experiments, total 230 points, 43 from COMPASS

Experiment	Target nucleon	Nb of points	Reference
EMC	p	10	Nucl. Phys. B 328 (1989) 1
SMC	p	12	Phys.Rev. D 58 (1998) 112001
SMC	d	12	Phys.Rev. D 58 (1998) 112001
COMPASS	d	43	Phys.Lett. B 647 (2007)8
E143	p	28	Phys.Rev. D 58 (1998) 112003
E143	d	28	Phys.Rev. D 58 (1998) 112003
E155	d	24	Phys. Lett. D 463 (1999) 339
E155	p	24	Phys.Lett. B 493 (2000) 19
JLAB	n	3	Phys. Rev. Lett. 92 (2004) 012004
E142	n	8	Phys.Rev. D 54 (1996) 6620
E154	n	11	Phys.Rev. Lett. 79 (1997) 26
HERMES	n	9	Phys.Lett. B 404 (1997) 383
HERMES	p	9	Phys.Rev. D75 (2005) 012003
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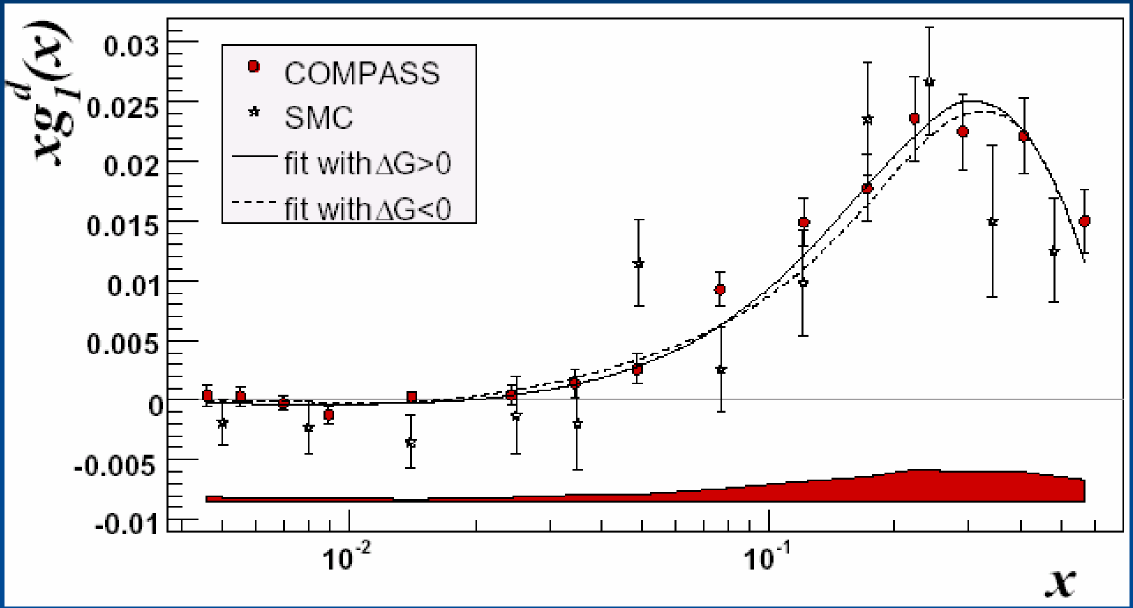
World data fit: 9 experiments, 230 points, 43 from COMPASS

Two solutions describe data equally well: ΔG>0 and ΔG<0.



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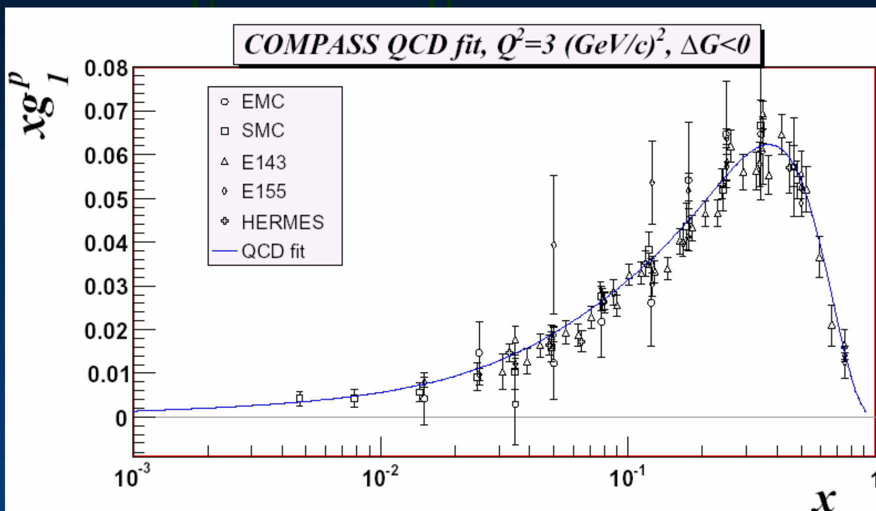
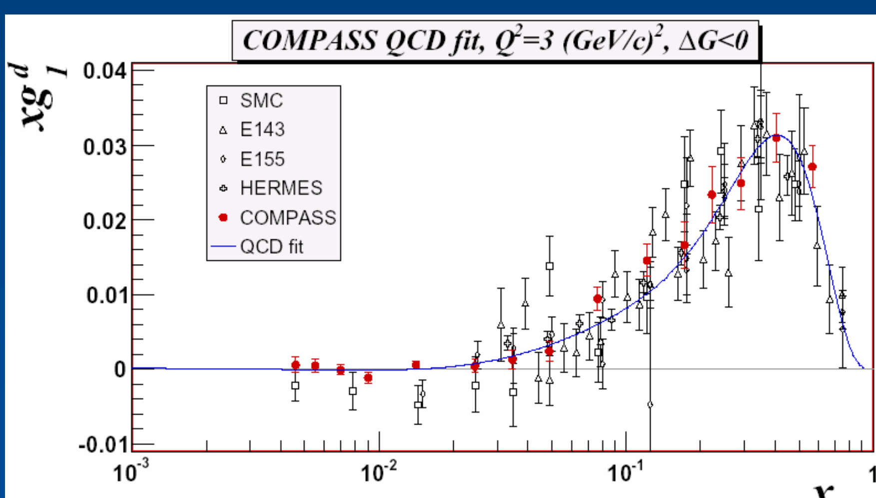
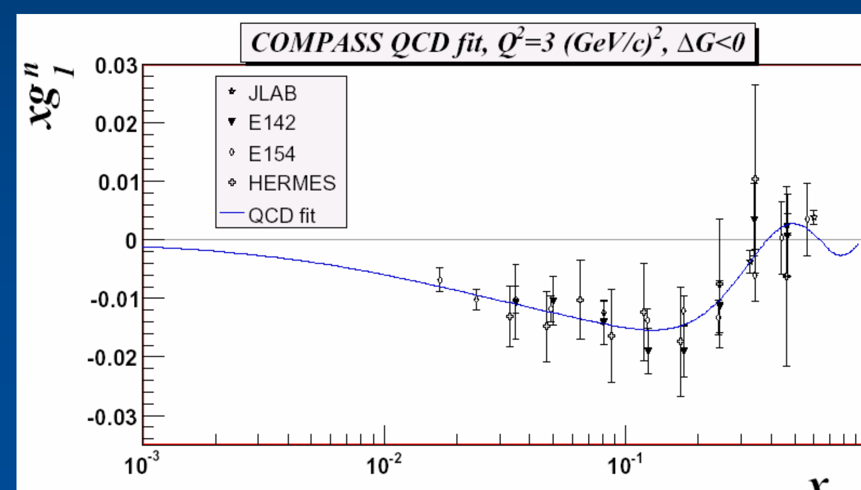


World data and QCD fits at $Q_0^2 = 3\ (GeV/c)^2$

Solutions with $\Delta G < 0$





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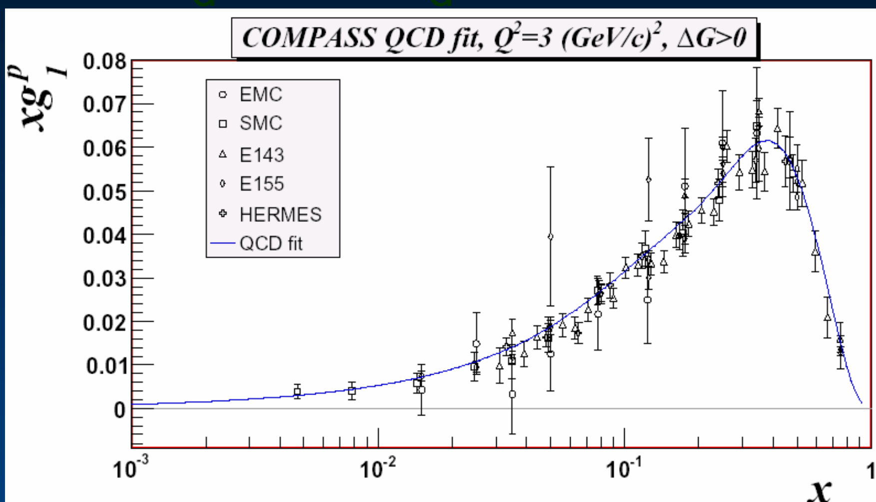
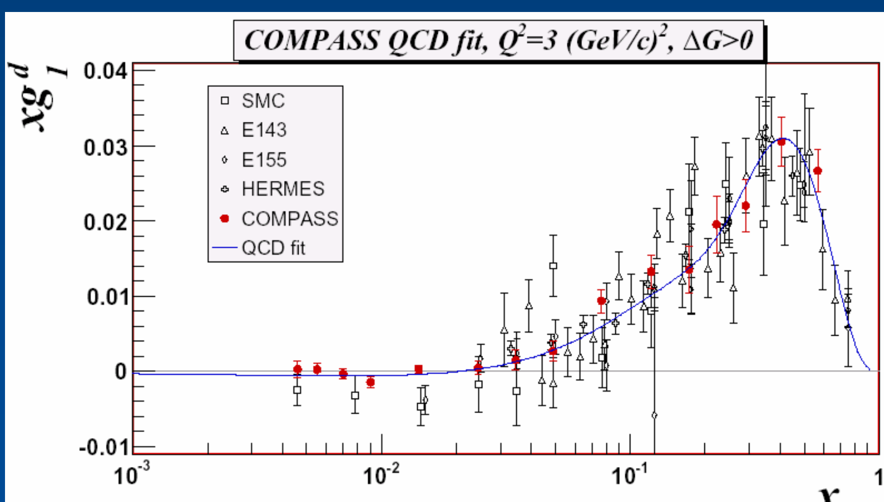
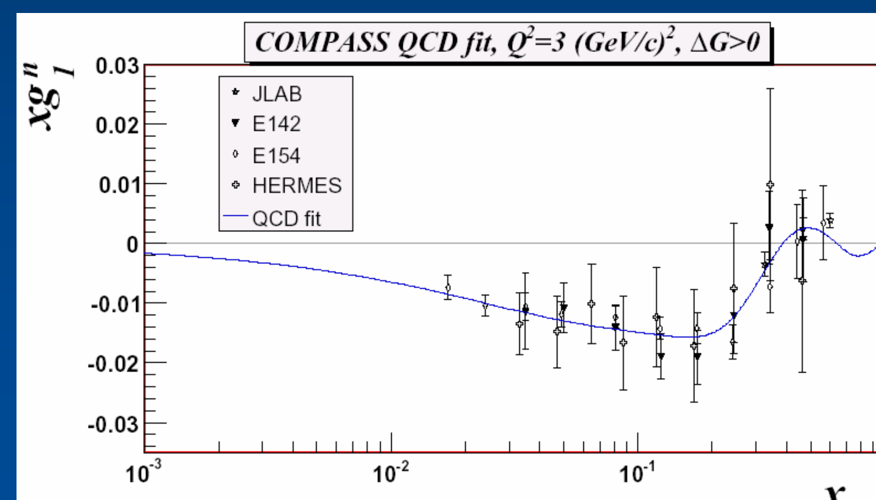


World data and QCD fits at $Q_0^2 = 3\ (GeV/c)^2$

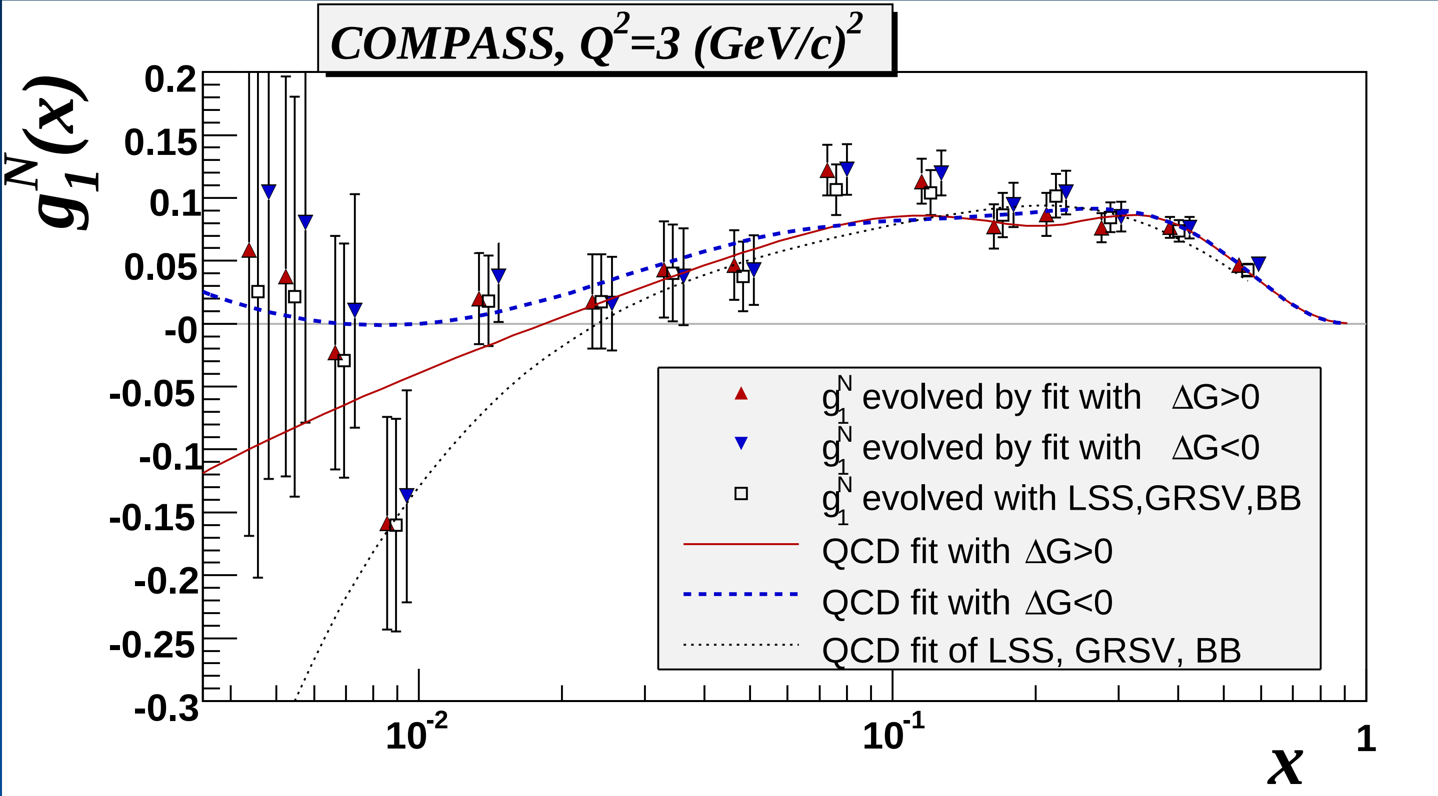
Solutions with $\Delta G > 0$





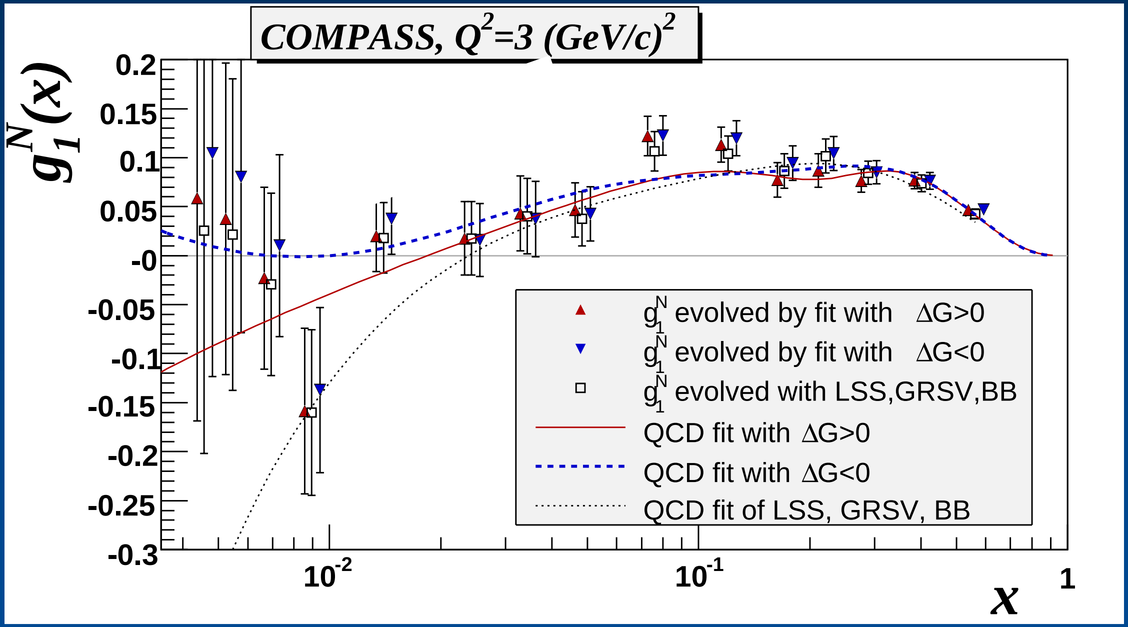
QCD analysis of the world data on structure function g_1

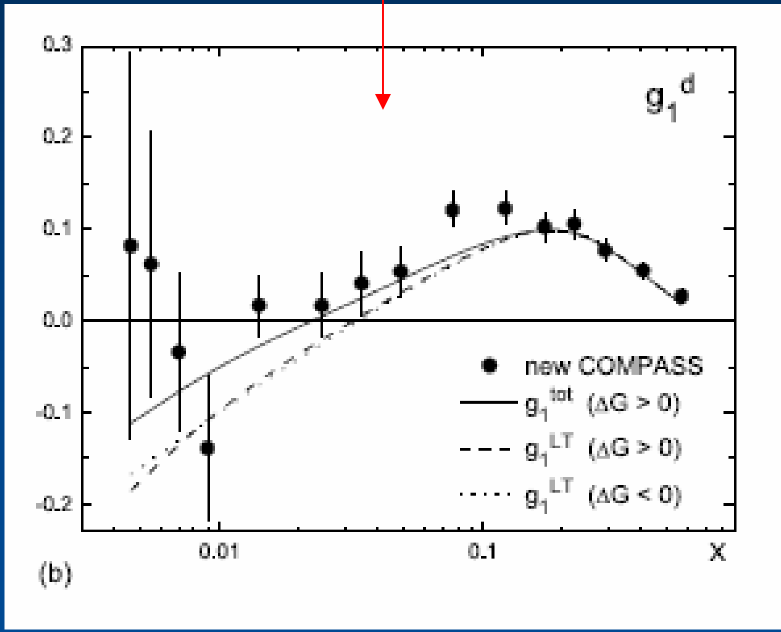
Comparison of fits - disagreement of data with previous QCD fits (LSS05,BB,GRSV)



QCD analysis of the world data on structure function g_1

Comparison of data and fits - LSS06 (hep-ph/0612360





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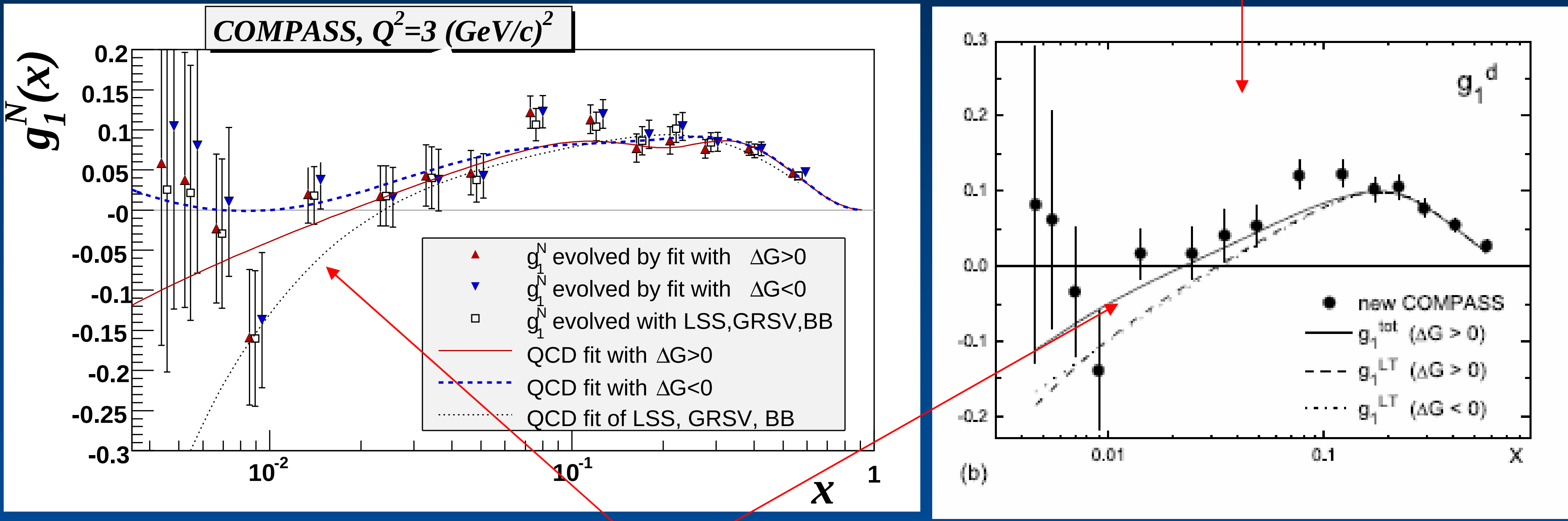
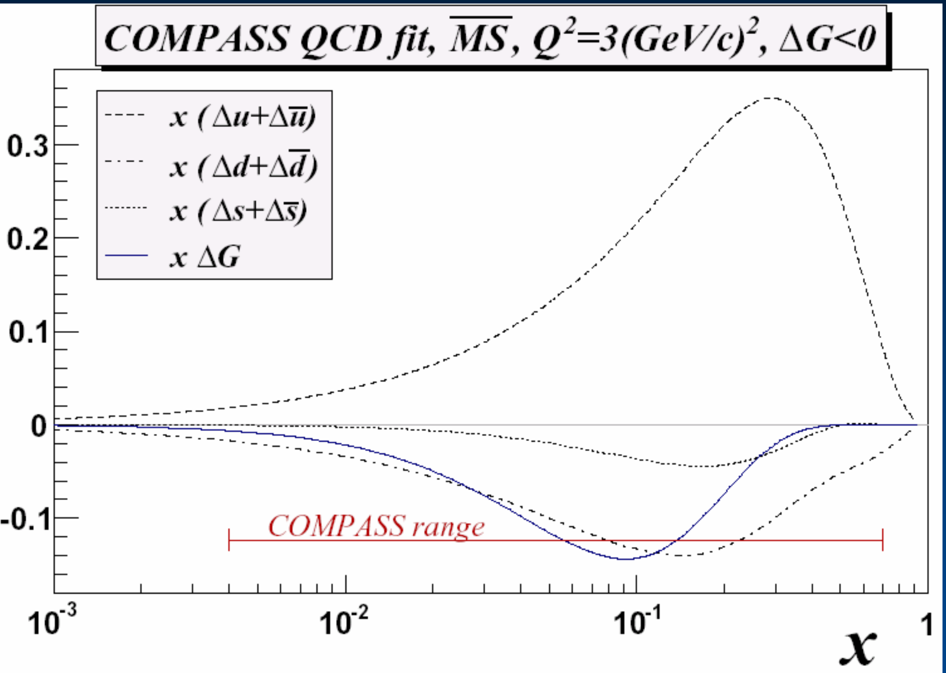
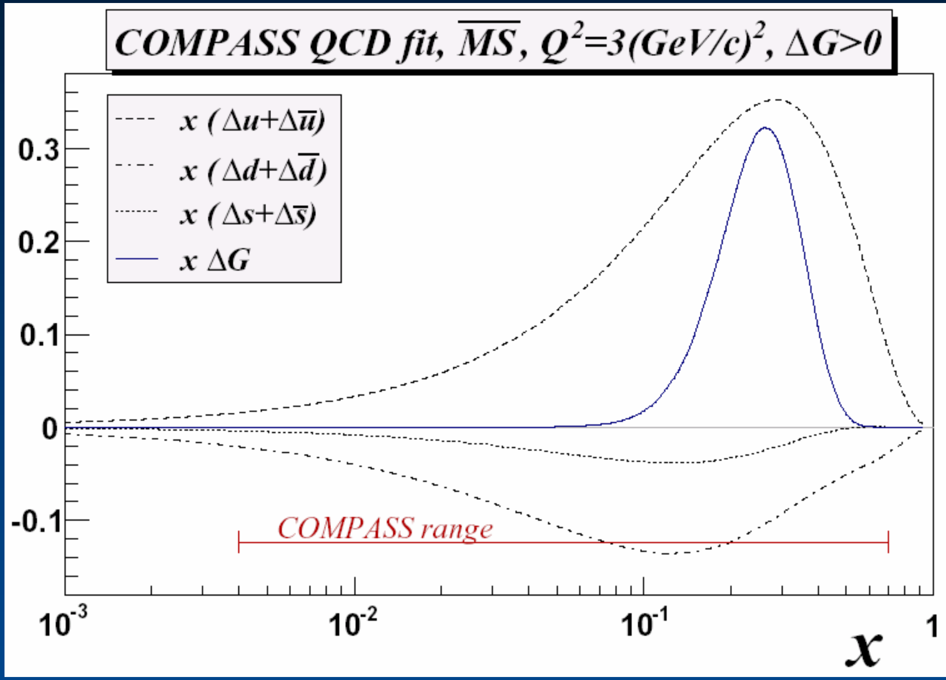


LSS05 vs LSS06

QCD analysis
Polarised parton distributions





Very small sensitivity of $x(\Delta q+\overline{\Delta q})$ to $x\Delta G$

QCD fits results

(world data)

Phys.Lett.B 647(2007)8

Quark polarisation:

	$\eta_G > 0$	$\eta_G < 0$
η_Σ	0.27 ± 0.01	0.32 ± 0.01

$\rightarrow$ $\eta_\Sigma = \mathbf{0.30 \pm 0.01(stat) \pm 0.02(evol)}$

$$\left(\eta_K = \int_0^1 \Delta k \, dx \right)$$

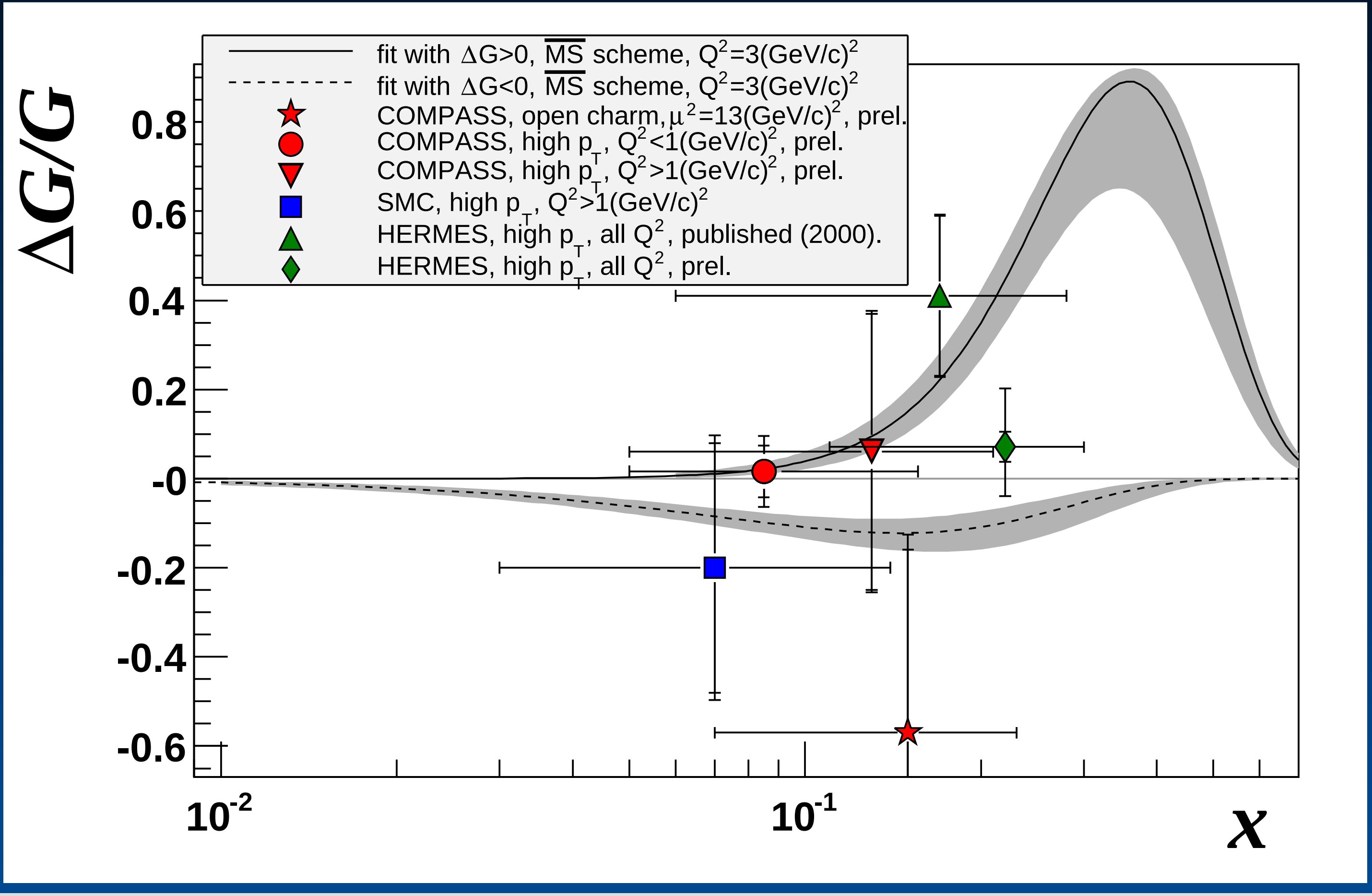
(error ≈ factor 2 larger without COMPASS data)

Gluon polarisation (indirect determination via DGLAP):

- Solutions with $\eta_G > 0$: $\eta_G^{prog1} = 0.34^{+0.05}_{-0.07}$, $\eta_G^{prog2} = 0.23^{+0.04}_{-0.05}$
- Solutions with $\eta_G < 0$: $\eta_G^{prog1} = -0.31^{+0.10}_{-0.14}$, $\eta_G^{prog2} = -0.19^{+0.06}_{-0.11}$

$$|\eta_G| \approx \mathbf{0.2 - 0.3}$$

QCD fits results: Gluon polarisation



Unpolarised G(x) from MRST (NLO 2004)

Bands correspond to errors from fit of $\Delta G(x)$

First moment of g_1^d

First moment of g_1^d

(Compass data only)

Phys.Lett.B 647(2007)8

$$\Gamma_1^N\left(Q_0^2 = 3GeV^2\right) = \int_0^1 g_1^N(x)dx = 0.050 \pm 0.003(stat) \pm 0.003(evol) \pm 0.005(syst)$$

$$\Gamma_1^N\left(Q^2\right) = \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2)\right)\left(a_0(Q^2) + \frac{1}{4}a_8\right)$$ (NLO QCD)

from Y. Goto *et al.*, PRD62 (2000) 034017: (SU(3)$_f$ assumed for weak decays)

$a_8 = 0.585 \pm 0.025$

$$a_{0|Q_0^2=3(GeV/c)^2} = 0.35 \pm 0.03(stat) \pm 0.05(syst)$$

Contribution from unmeasured x range ≈ 4%

First moment of g_1^d (COMPASS data only)

Another notation: in the limit $Q^2 \longrightarrow \infty$ (beyond NLO)

$$\widehat{a}_0 \equiv a_{0|Q^2 \to \infty}$$

$$\Gamma_1^N\left(Q^2\right) = \frac{1}{9} C_1^S(Q^2)\widehat{a}_0 + \frac{1}{36} C_1^{NS}(Q^2) a_8$$

C_1 calculated behind 3 loops app.
S.A.Larin *et al*.,Phys.Lett.B404(1997)153

$$a_{0|Q^2 \to \infty} = 0.33 \pm 0.03(stat) \pm 0.05(syst)$$

$$(\Delta s + \Delta \bar{s}) = \frac{1}{3}(\hat{a}_0 - a_8) = -0.08 \pm 0.01(stat) \pm 0.02(syst)$$

Summary

Summary

- New measurements of A_1^d, g_1^d have been presented.
- Good agreement with results from previous experiments in the region of middle and high x.
- Improvement in statistical precision factor 4 for $x<0.03$.
- No tendency toward negative values at $x<0.03$.

- New QCD fits have been performed.
- Fits have produced consistent results and yield two solutions for PDF with $\Delta G(x)>0$ and $\Delta G(x)<0$ which equally well describe the present g_1 data. The shapes of $\Delta G(x)$ are very different in two cases.
- The first moment of the polarised gluon distribution has been estimated from the QCD fits.
- Polarised strange quark distribution has been found.

Spares


DIS 2007
April 16-20, 2007, Munich, Germany
XV International Workshop on Deep-Inelastic Scattering and Related Subjects

Spare 0 - Nucleon spin decomposition

$$\Gamma_1 = \int g_1(x)dx$$

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6g_V} C_1^{NS}$$ (Bjorken sum rule)

$$\Gamma_1^{p,n} = \left(\pm a_3 + \frac{a_8}{\sqrt{3}}\right)\frac{C_1^{NS}}{12} + a_0 \frac{C_1^S}{9}$$ (Ellis-Jaffe sum rule)

$a_3, a_8, g_{A,V}$ - hyperon β decay + $SU_f(3)$;

$C_1^{S,NS}$ - calculable in QCD

But - due to △ anomaly - $a_0 = \Delta\Sigma - (3\alpha_S/2\pi)\,\Delta G$ and

If $\Delta G \approx 2.5 \rightarrow \Delta\Sigma \approx 0.6 \rightarrow$ can “solve the spin crisis”

$\Downarrow$

Need direct measurement of ΔG

Spare 1 – QCD fits

1. $\gamma \neq 0$ only for singlet in the case of $\Delta G > 0$ (and β_G fixed to 10);
   for keeping same number of prameters as for $\Delta G < 0$.
   From the fit for $\Delta G < 0$ β_G is 13 with large error
   so fixed number 10 is reasonable.
2. χ^2 – statistical errors because systematical is highly correlated.

3. p24: curve is made from points taken from fits for Q^2 corresponds to Q^2 of the experimental point and interpolated between by spline
4. p31: for $Q^2 = 11\ (\mathrm{GeV}/c)^2$ (close to charm scale)
   $\Delta G/G(x=0.13) = -0.072$ instead of 0.082 for $Q^2 = 3\ (\mathrm{GeV}/c)^2$
   $x\Delta G\ (x=0.13) = -0.077$ instead of -0.127
   $xG(x=0.13) = 1.0678$ instead of 1.1551

Spare 2 – QCD fits

$\alpha_S(M_Z)$	0.1137 (lower)	0.1187(standard)	0.1237(high)	α_S fitted
$\eta_G<0$	-0.342±0.117	-0.329±0.107	-0.326±0.1104	α_S= 0.1276+0.0015-0.0017 η_G= -0.34±0.1
$\eta_G>0$	0.253±0.08	0.231±0.049	0.216±0.054	α_S= 0.1269+0.0016-0.0018 η_G= 0.20±0.05

Effect of a_8 on evaluation of a_0:

$a_8 \pm 20\% \longrightarrow \pm 0.11 \longrightarrow$ changes a_0 by ±0.03

$a_0 = 9\ \Gamma_1^N - ¼\ a_8$

$(\Delta s+\Delta\bar{s}) = 1/3\ (a_0 - a_8) = 3\ \Gamma_1^N - 1/12\ a_8$

$a_8 \pm 0.11 \longrightarrow$ changes $(\Delta s+\Delta\bar{s})$ by ± 0.048

Spare 3 – R for Q^2<1 GeV^2

2.1 The R function

The R function which was previously used by the SMC, and it is commonly used by COMPASS [2] is composed of three different parameterizations in different regions of x (see [4] for references and explanations):

- SLAC, $x > 0.12$,
- NMC, $0.003 < x < 0.12$,
- ZEUS, $x < 0.003$.

Values of R have large discontinuities close to the validity limits of the parametrizations, Fig.4. To partially overcome the problem, a new SLAC parametrization was used for $Q^2 > 0.5$ GeV^2, [5]. Below the $Q^2 = 0.5$ GeV^2 the following formula was employed:

$$R(Q^2 < 0.5, x) = R_{SLAC}(0.5, x) \times \beta(1 - exp(-Q^2/\alpha)) \qquad (1)$$

where $\alpha = 0.2712$, $\beta = 1/(1 - exp(-0.5/\alpha)) = 1.1880$. At $Q^2 = 0.5$ GeV^2 the function and its first derivative are continuous. In the Q^2=0 limit: $R \sim Q^2$, which is expected from the current conservation. The new R parametrization is shown in the right plot of Fig.4. The error on R, δR, above $Q^2 = 0.5$ GeV^2 was taken from [5] and below $Q^2 = 0.5$ GeV^2 was set to $\delta R = 0.2$. For that value and for the simplest assumption about R for $Q^2 < 0.5$ GeV^2 and any x, e.g. $R = 0.2$, there is an approximate agreement (within 1σ) with the value at the photo-production limit where R=0 and with measurements at higher Q^2 from HERA, where $R \approx 0.4$.