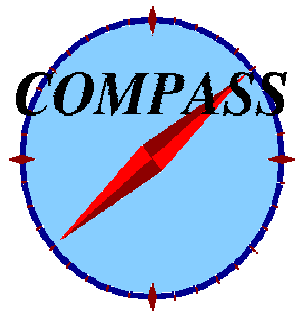
Inclusive and semi-inclusive DIS results from COMPASS



Helena Santos

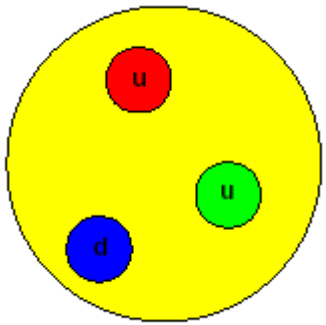
LIP - Lisboa

On Behalf of the COMPASS Collaboration

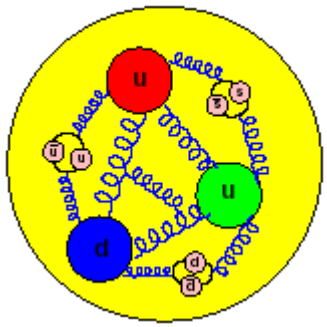
- The nucleon spin
- The COMPASS experiment
- Longitudinal spin structure functions
- Valence quark polarisations

Parity-Violating Spin Asymmetries at RHIC

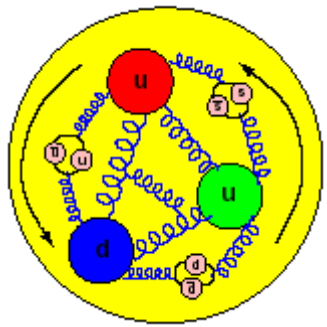
The Nucleon Spin



naïve parton model:
$\Delta\Sigma = \Delta u + \Delta d = 1$



gluons, sea and *c* quarks are important



complete description: orbital angular momenta

EMC (1988):
$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$
$\Delta s + \Delta\bar{s} = -0.14 \pm 0.03$

$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g \qquad (\hbar=1)$$

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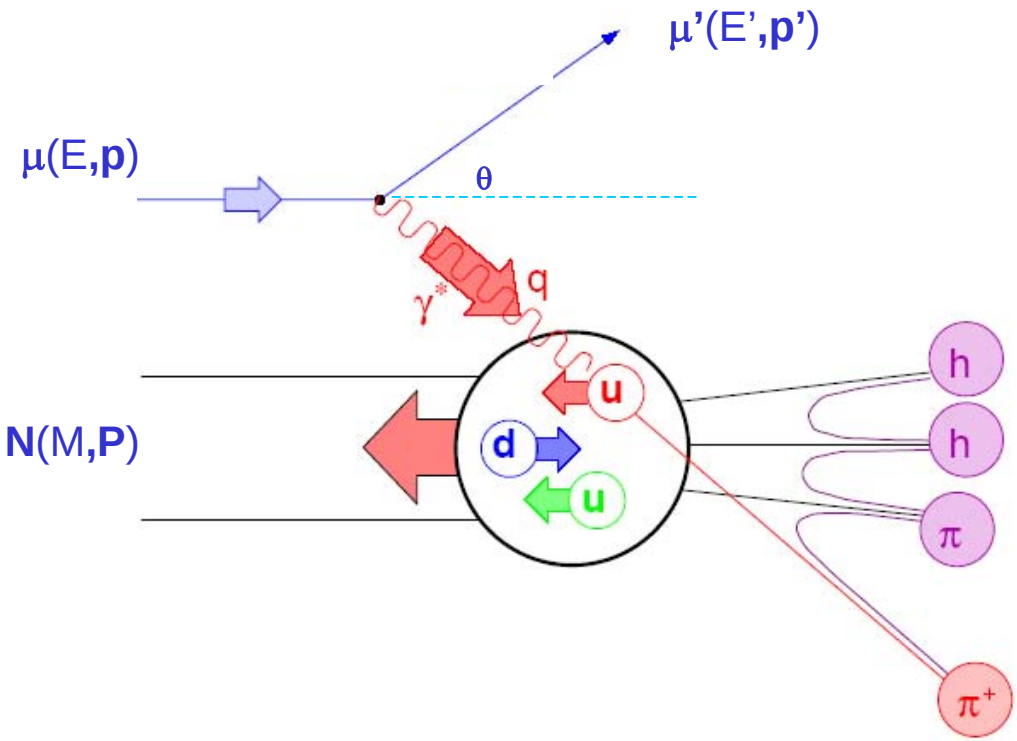
Deep Inelastic Scattering



$Q^2 = -q^2 = (p - p')^2$

$\nu = E - E'$

$x = Q^2/2M\nu$

$y = \nu/E$

$z = E_h/\nu$

$$\frac{d^2\sigma}{d\Omega dE'} = \underbrace{c_1F_1(x,Q^2) + c_2F_2(x,Q^2)}_{\text{spin independent}} + \underbrace{c_3g_1(x,Q^2) + c_4g_2(x,Q^2)}_{\text{spin dependent}}$$

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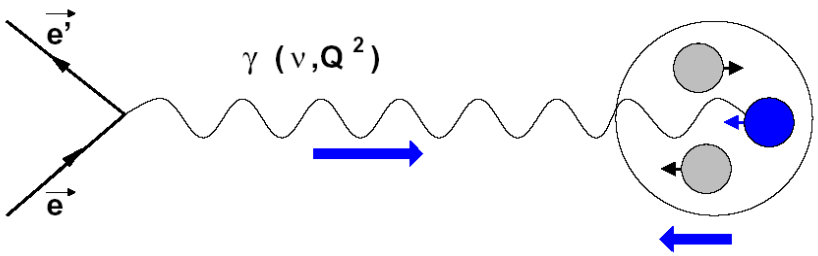
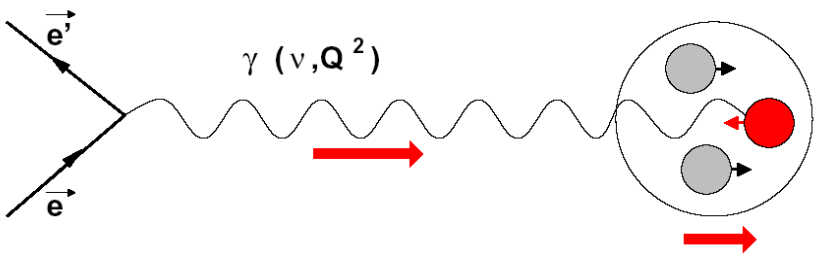
Polarised Deep Inelastic Scattering

photon-nucleon asymmetry

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\sum_q e_q^2 \, \Delta q(x)}{\sum_q e_q^2 \, q(x)} = \frac{g_1(x)}{F_1(x)}$$



$\sigma_{\frac{1}{2}} \sim q^+$



$\sigma_{\frac{3}{2}} \sim q^-$

$$\Delta q(x) = q(x)^+ - q(x)^-$$

$$q(x) = q(x)^+ + q(x)^-$$

+: quark ↑↑ nucleon

–: quark ↑↓ nucleon

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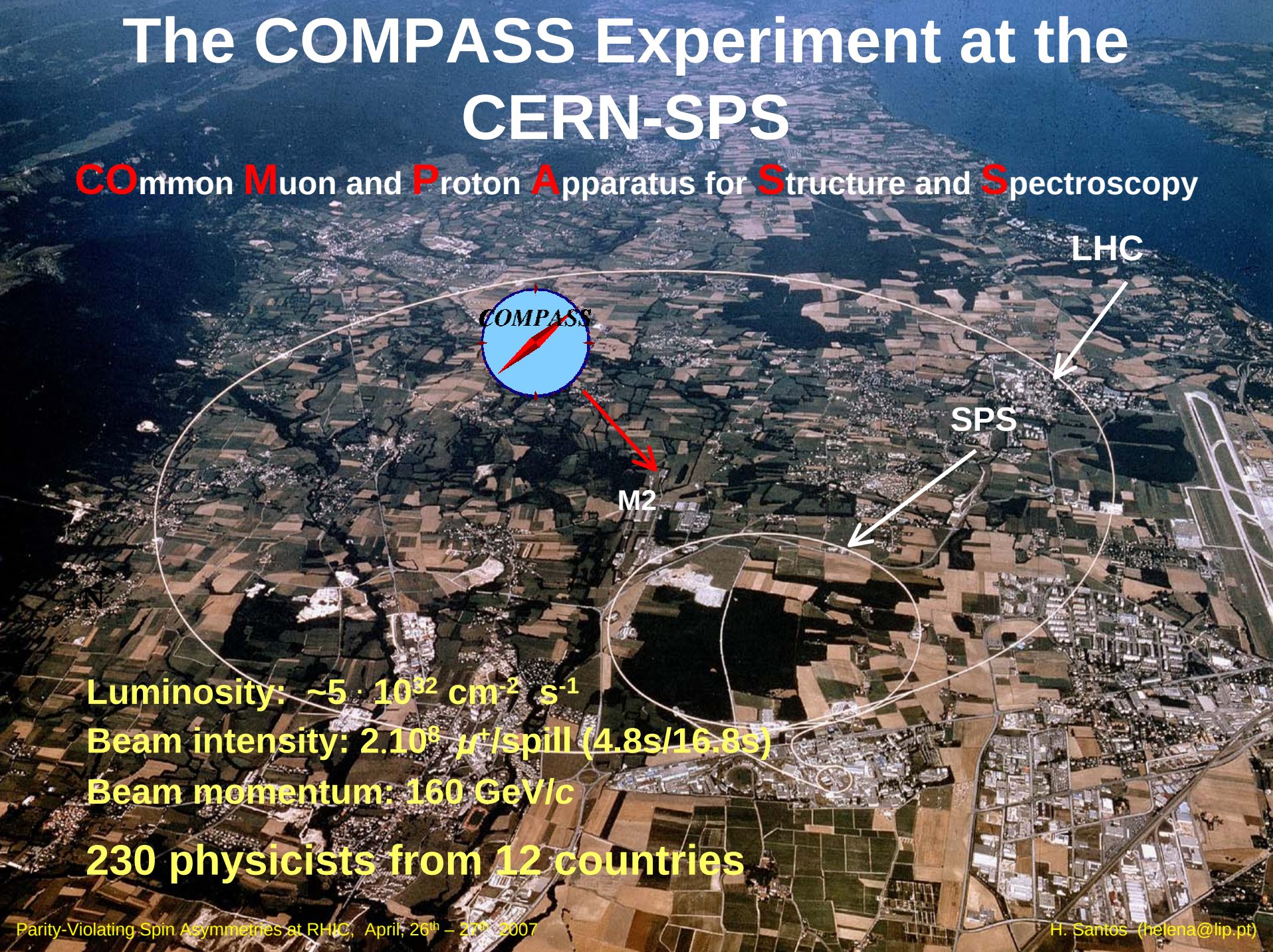
The COMPASS Experiment at the CERN-SPS

COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



Luminosity: ~5 · 10^{32} cm^{-2} s^{-1}

Beam intensity: 2.10^{8} μ^{+}/spill (4.8s/16.8s)

Beam momentum: 160 GeV/*c*

230 physicists from 12 countries

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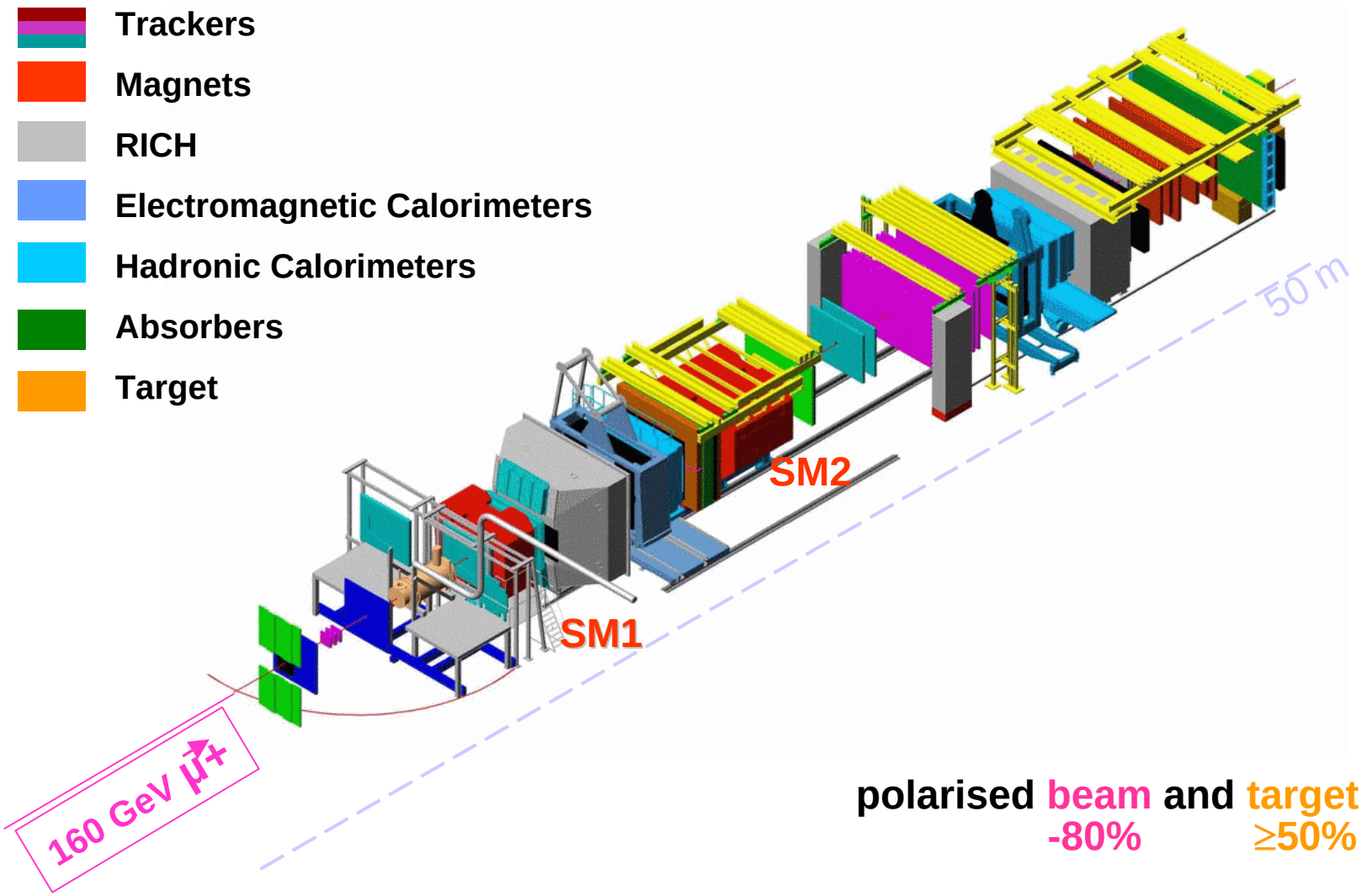
The COMPASS Spectrometer



polarised beam and target
-80% ≥50%

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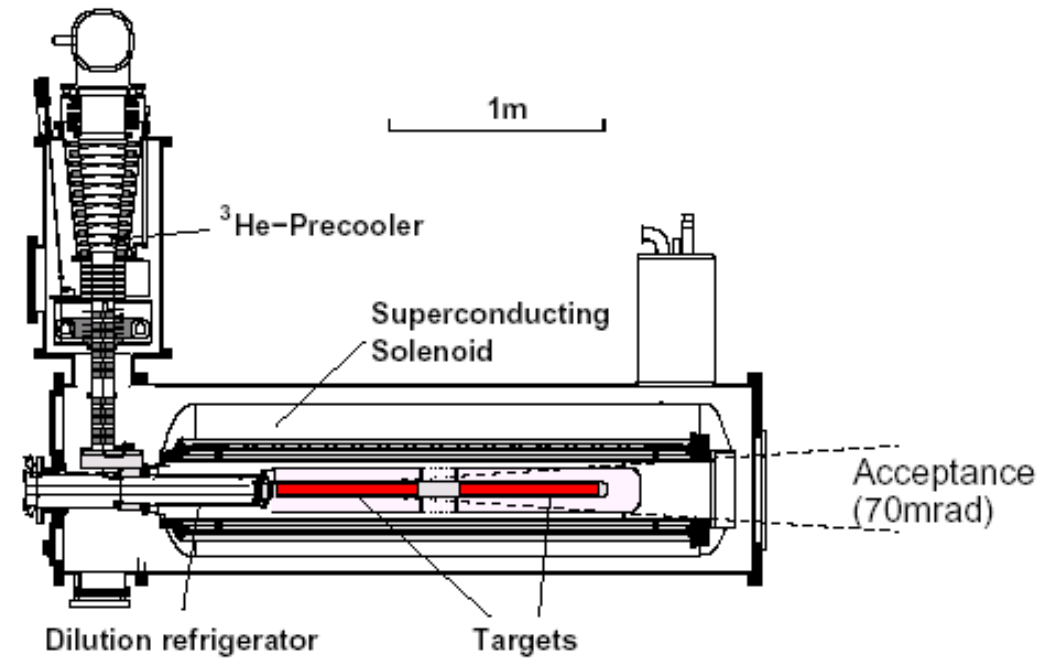
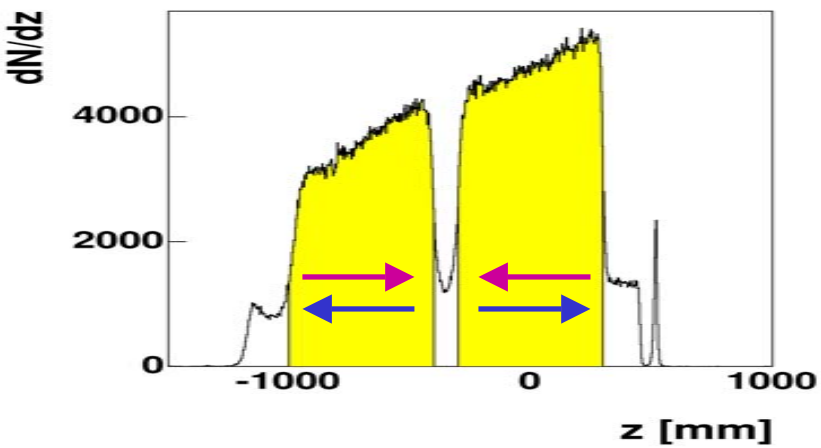
The Target System





Two 60 cm long target cells with opposite polarisation

Target material: ^{6}LiD

Polarisation ~ 50%

Solenoid field: 2.5 T

^{3}He/^{4}He: T_{min} ~ 50mK

Field reversal every 8h

In 2006:

New solenoid with 180 mrad acceptance

Three target cells (better to face systematics)

Inclusive Asymmetry, $Q^2 < 1$ (GeV/c)^2

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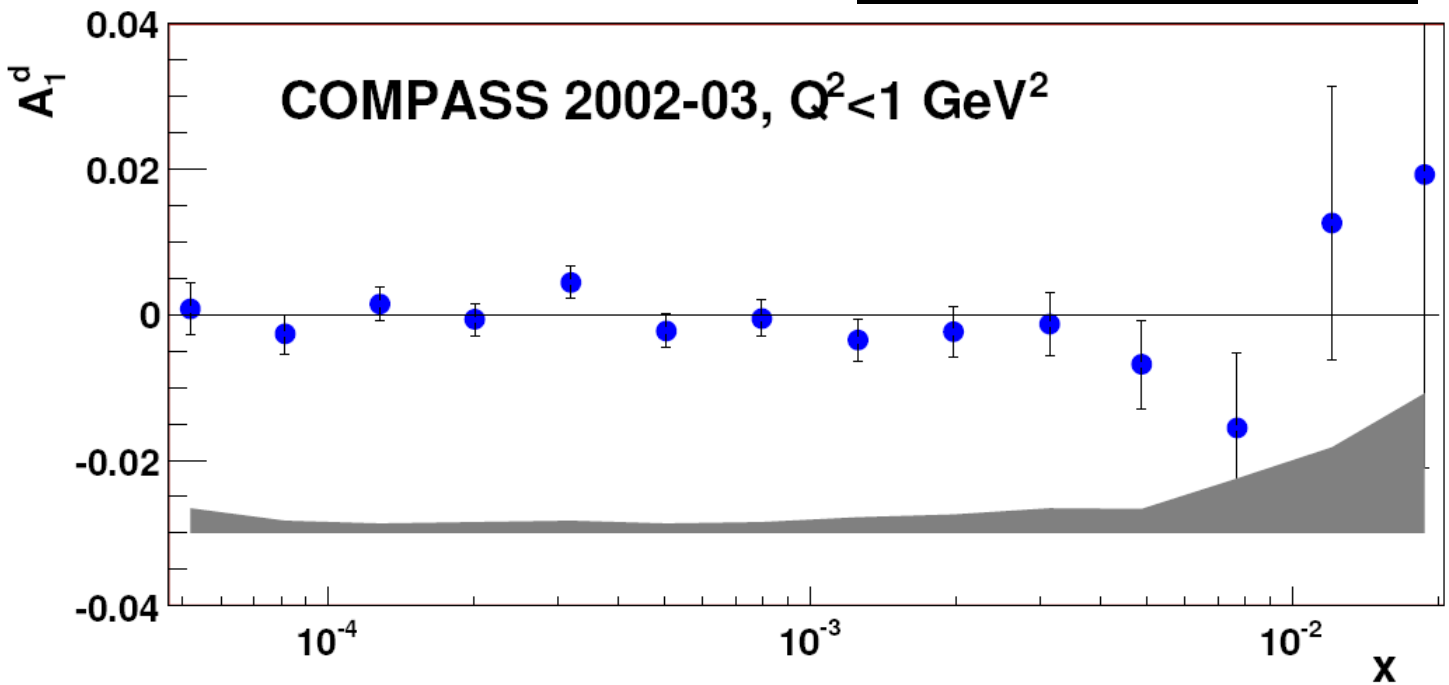


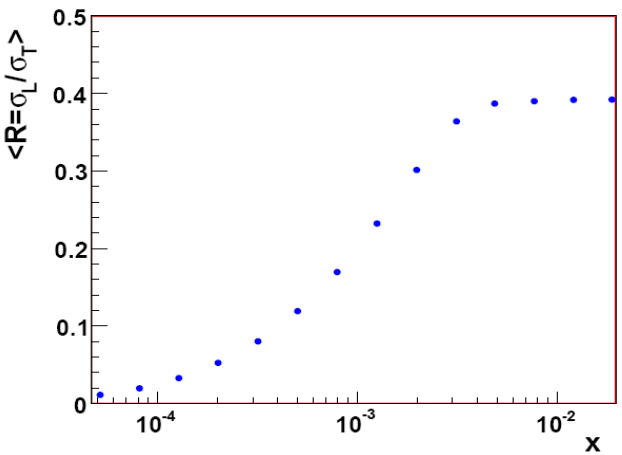
- A_1^d asymmetry compatible with 0 at low x range (0.0005<x<0.02)
- At low x A_1^d has been measured only by COMPASS and SMC
- Systematic errors are mainly due to false asymmetries

The $g_1(x)$ Structure Function

Knowledge of g_1 at low Q^2 is needed to test non-perturbative models: Regge and (G)VDM

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

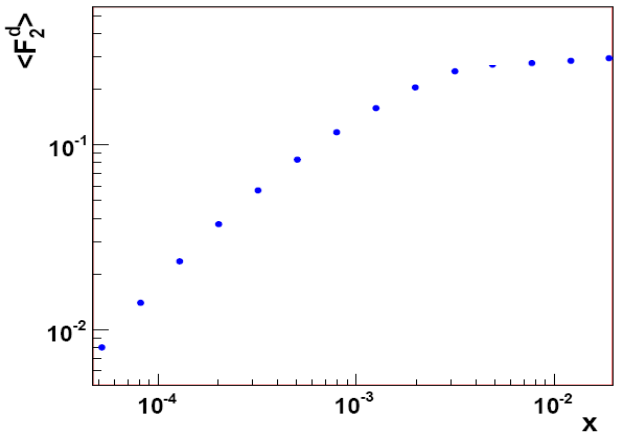
$$R(x,Q^2) = \sigma_L / \sigma_T$$



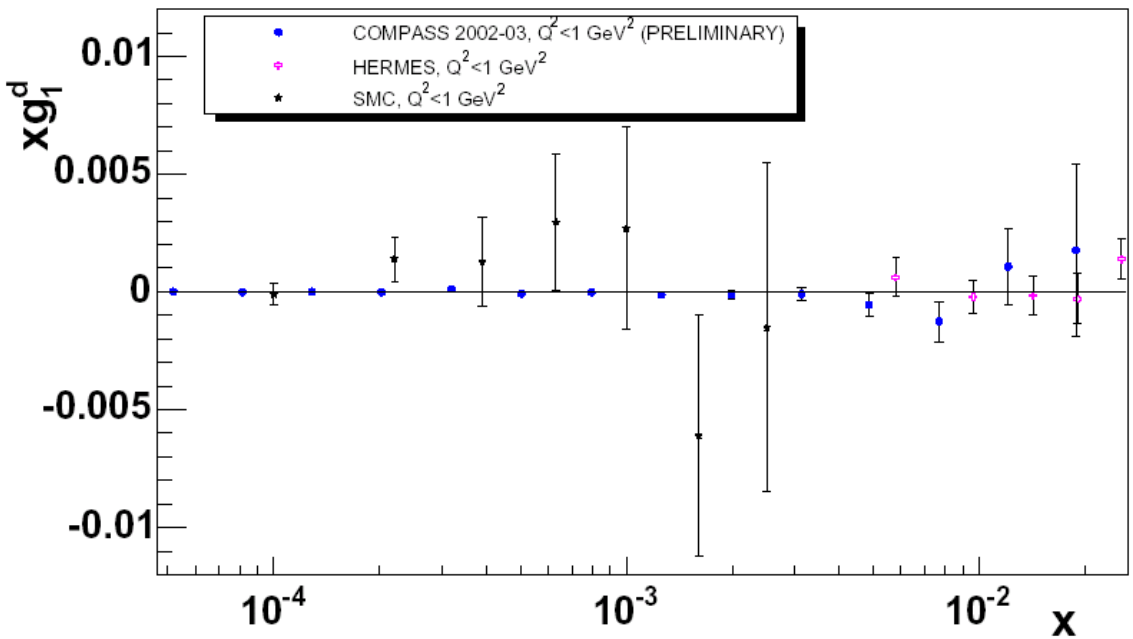
x > 0.12 SLAC
(PLB250 (1990) 193; B52(1999)1994)

0.003 < x < 0.12 NMC
(R param. unpublished)

x < 0.003 ZEUS (EPJ7 (1999) 609)



$F_2(x)$ taken from SMC param. (SMC + JKBB: B. Adeva *et al* PRD60 (1999) 072004; Erratum-ibid.D62:079902,2000)



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Inclusive DIS Asymmetry

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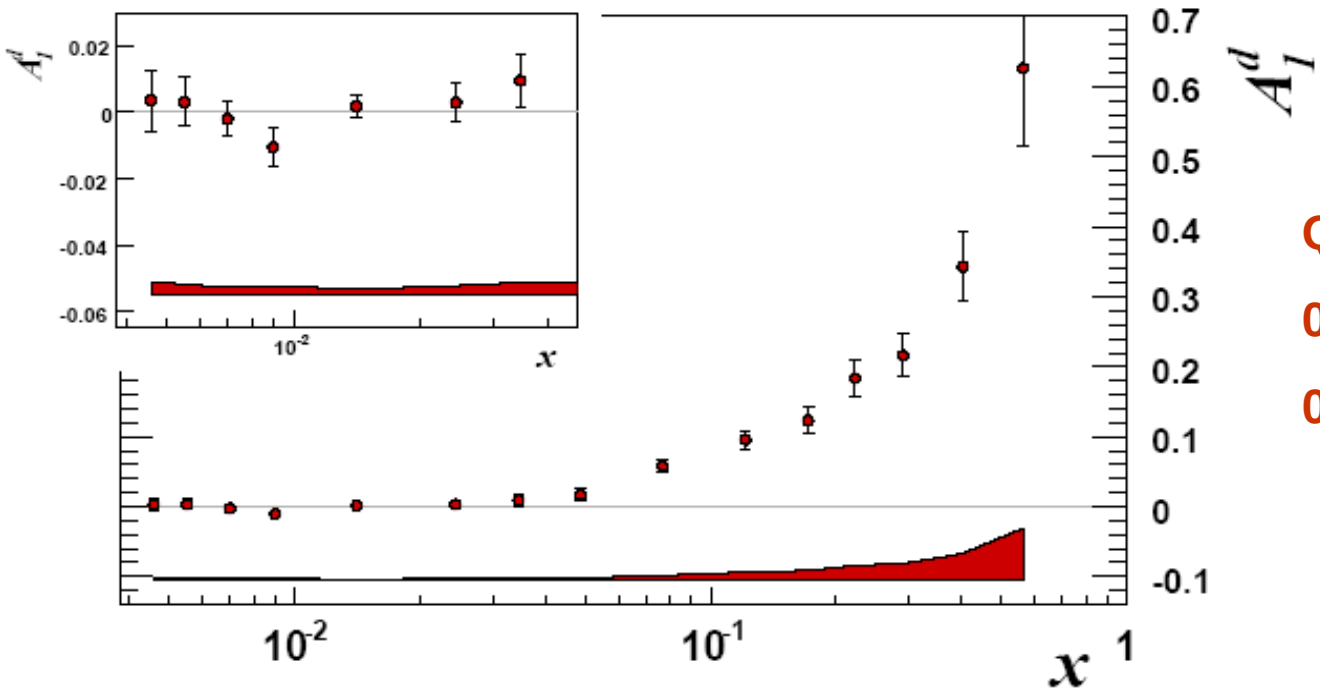

$Q^2 > 1\ (GeV/c)^2$

$0.004 < x < 0.7$

$0.1 < y < 0.9$

- A_1 compatible with 0 for $x < 0.05$
- Large asymmetry at large x
- Systematic errors: Multiplicative $\rightarrow \delta \cong 0.10A$ (δP_B, δP_T, δf and δD)

  Additive $\rightarrow$ rad. corrections $\approx 10^{-4}$ — 10^{-3}; $A_{false} < 0.4\delta A_{stat}$

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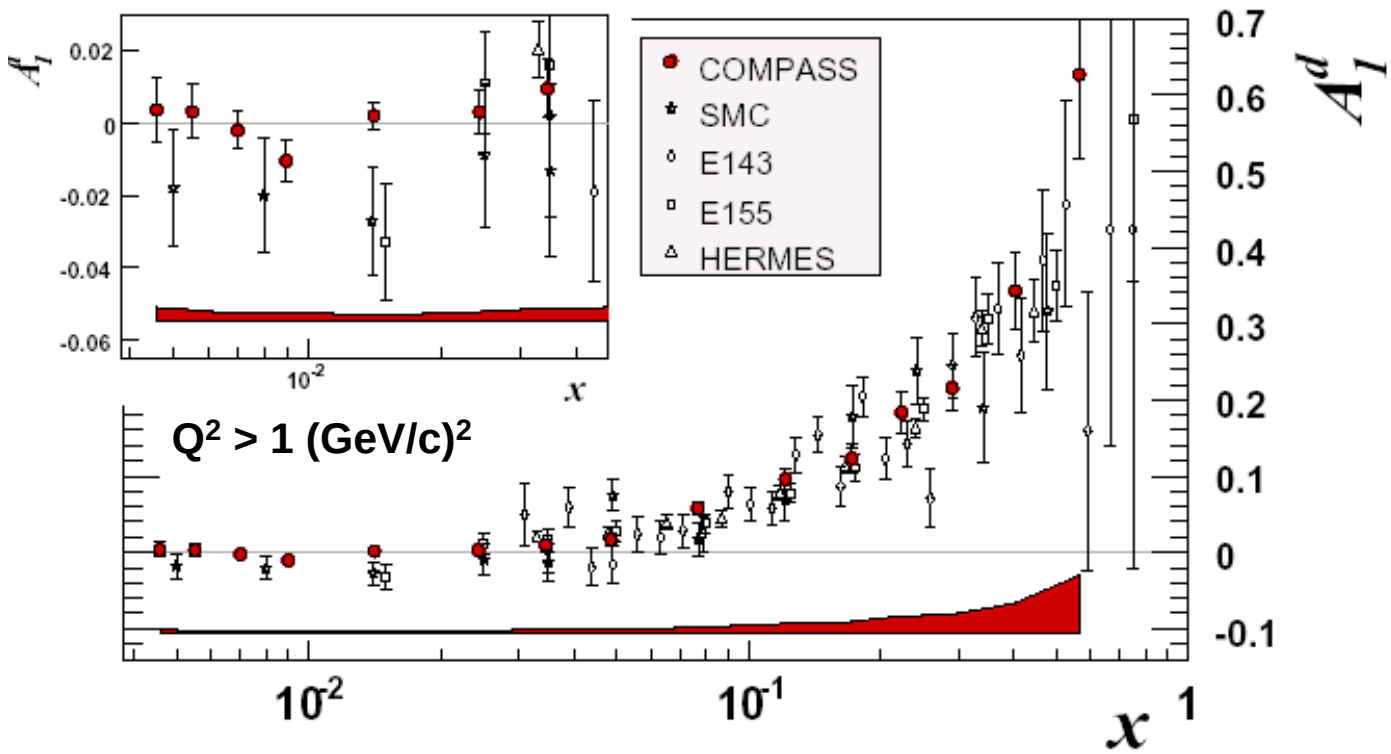
Inclusive DIS Asymmetry



- **Good agreement with previous experiments**
- **Improved significantly statistics at low x**
- **No tendency towards negative values at x < 0.03**

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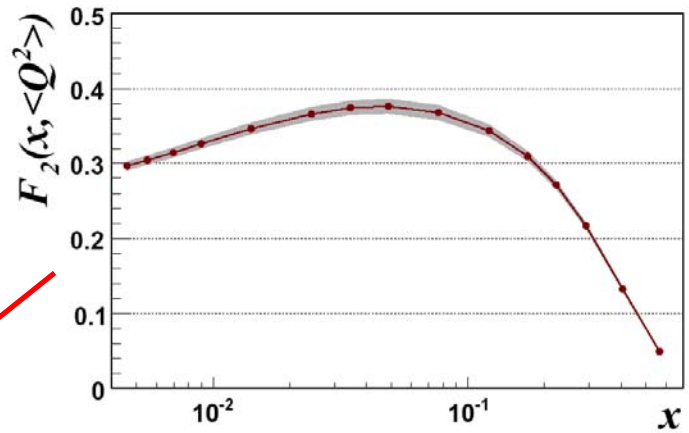
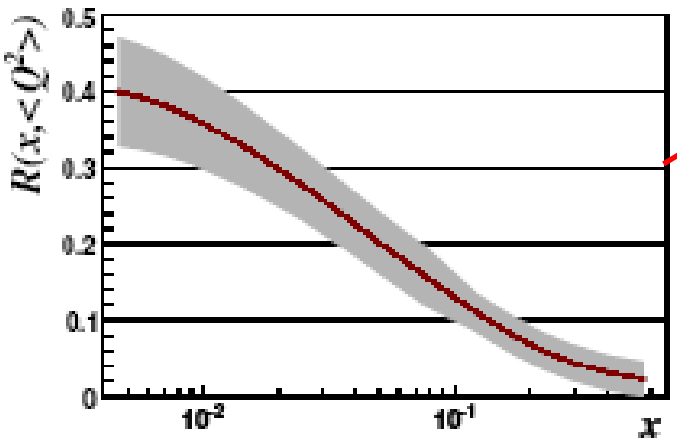
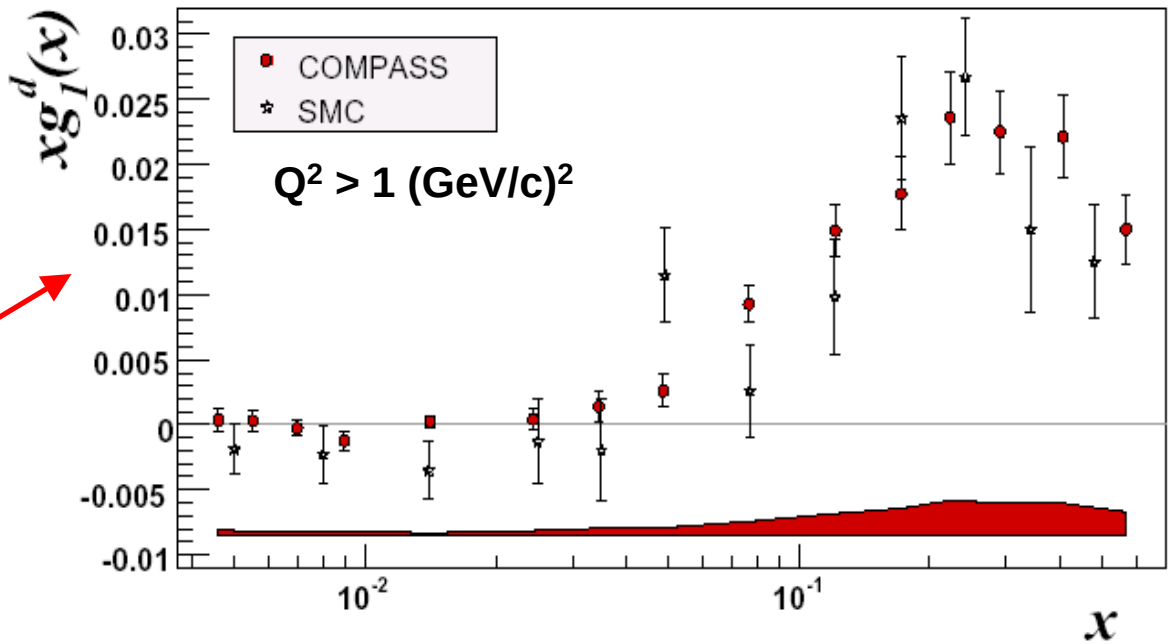
The $g_1^d(x)$ Structure Function

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



$$R(x,Q^2) = \sigma_L / \sigma_T$$





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QCD Analyses

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

$\Delta\Sigma = \Delta u + \Delta d + \Delta s$, $\quad \Delta q_3 = \Delta u - \Delta d$, $\quad \Delta q_8 = \Delta u + \Delta d - 2\Delta s$

DGLAP equations:

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

$$\frac{d}{dt}\begin{pmatrix} \Delta\Sigma \\ \Delta G \end{pmatrix} = \frac{\alpha_s(t)}{2\pi} \begin{pmatrix} P_{qq}^S & 2n_f P_{qG}^S \\ P_{Gq}^S & P_{GG}^S \end{pmatrix} \otimes \begin{pmatrix} \Delta\Sigma \\ \Delta G \end{pmatrix}, \quad t = \log\left(\frac{Q^2}{\Lambda^2}\right)$$

Input parameterisations (x–dependence at a fixed Q_0^2):

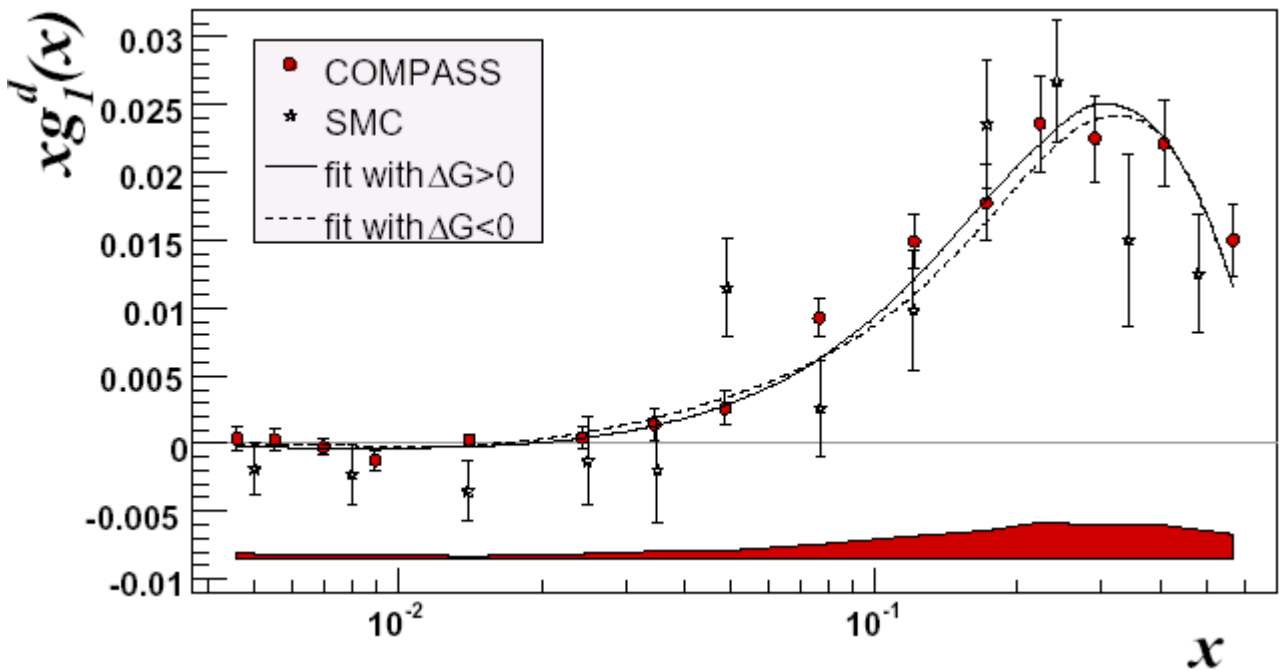
$$(\Delta\Sigma, \Delta q_3, \Delta q_8, \Delta G) = \eta \frac{x^\alpha (1-x)^\beta (1+\gamma x)}{\int_0^1 x^\alpha (1-x)^\beta (1+\gamma x) dx}$$

Minimization routine:

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

QCD Fits

- **Two different approaches have been used:**
  - **1 - Numerical integration in (x,Q^2) space (PRD58(1998) 112002)**
  - **2 - Solution of DGLAP in space of moments (PRD70(2004) 074032)**
- **Fits to world data → 230 world data points, 43 from COMPASS**
- **NLO analysis ($\overline{MS}$ scheme)**



Data well described by two solutions: $\Delta G > 0$ and $\Delta G < 0$

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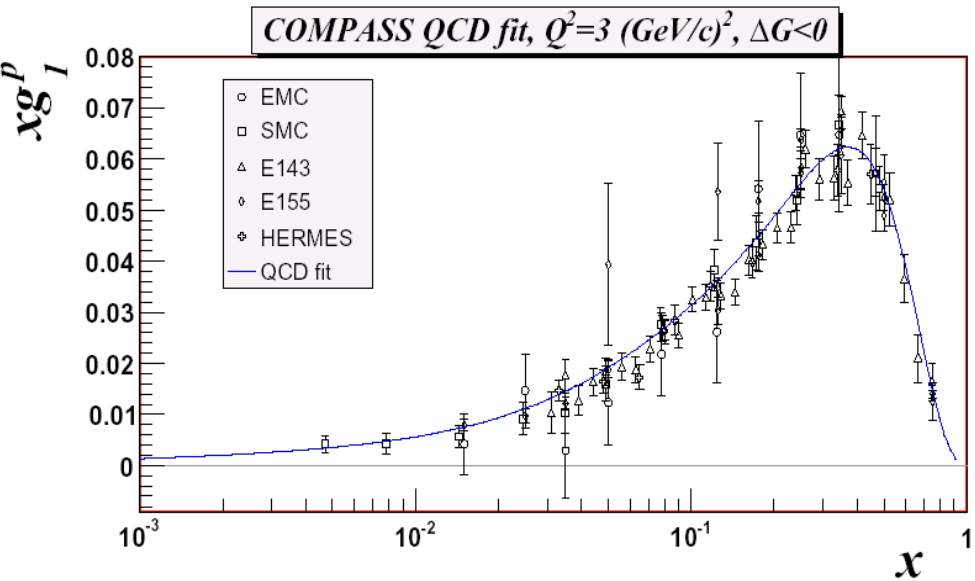
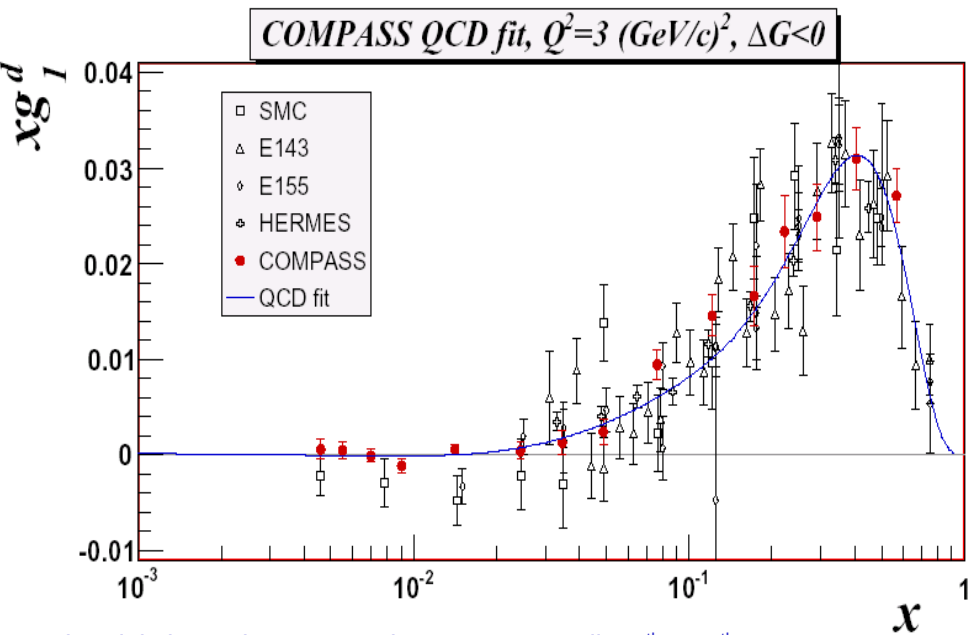
Towards Structure Functions

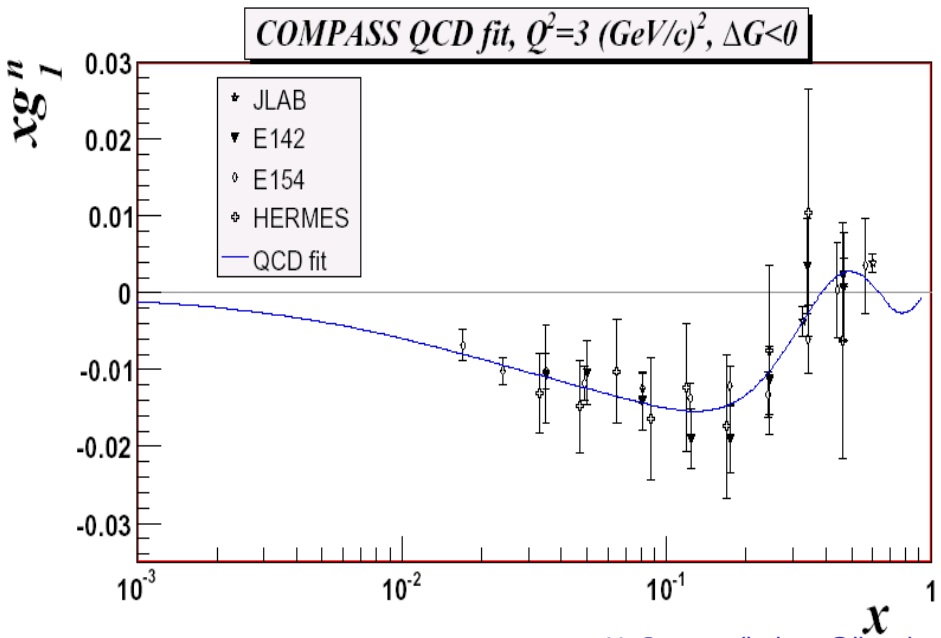


World data and QCD fits at $Q_0^2 = 3$ (GeV/c)^2

$$g_1(x,Q_0^2) = g_1(x,Q_i^2) + \left[g_1^{fit}(x,Q_0^2) - g_1^{fit}(x,Q_i^2) \right]$$

Solutions with ΔG < 0





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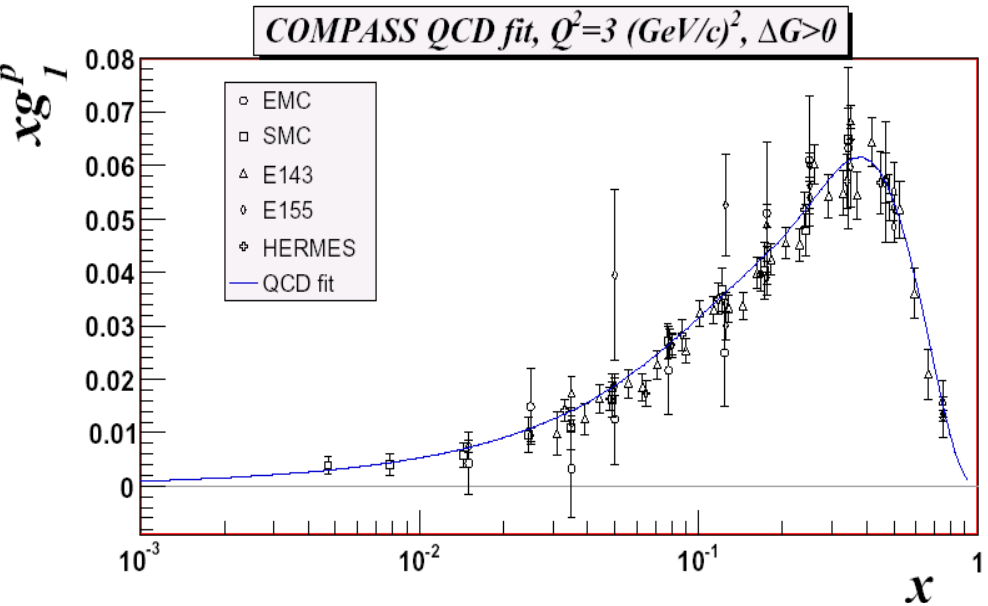
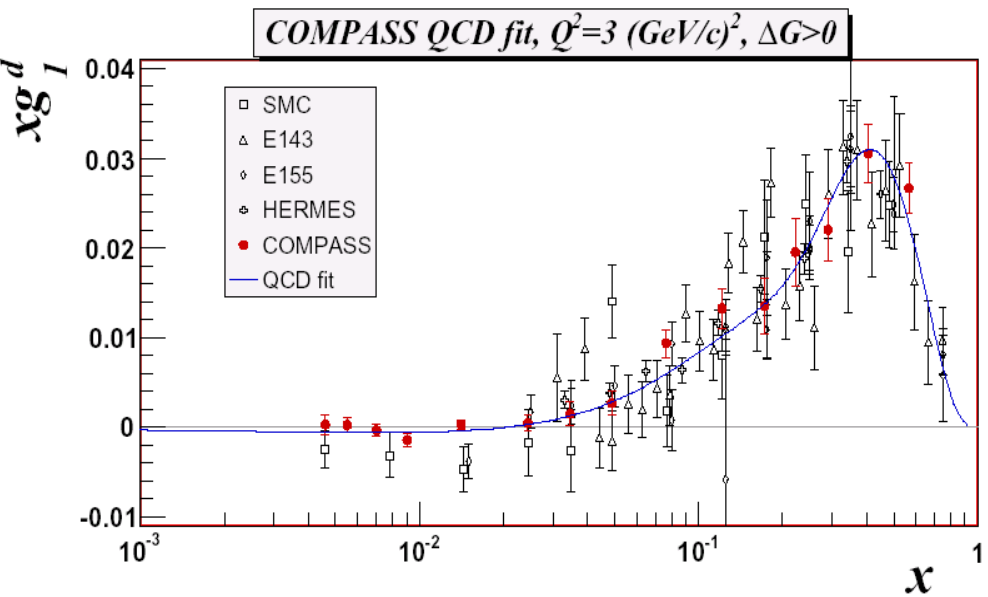
Towards Structure Functions

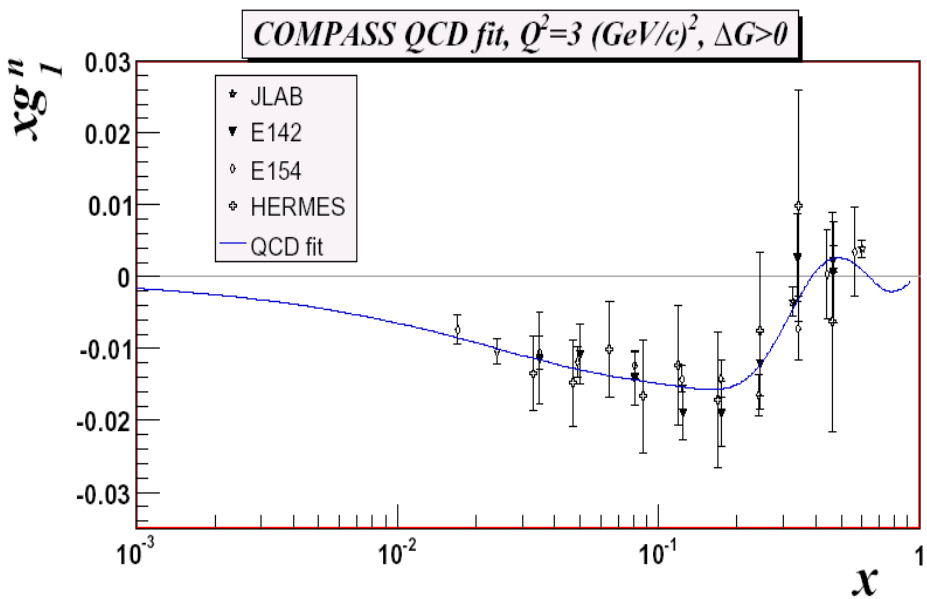


World data and QCD fits at $Q_0^2 = 3$ (GeV/c)^2

$$g_1(x,Q_0^2) = g_1(x,Q_i^2) + \left[g_1^{fit}(x,Q_0^2) - g_1^{fit}(x,Q_i^2) \right]$$

Solutions with ΔG > 0





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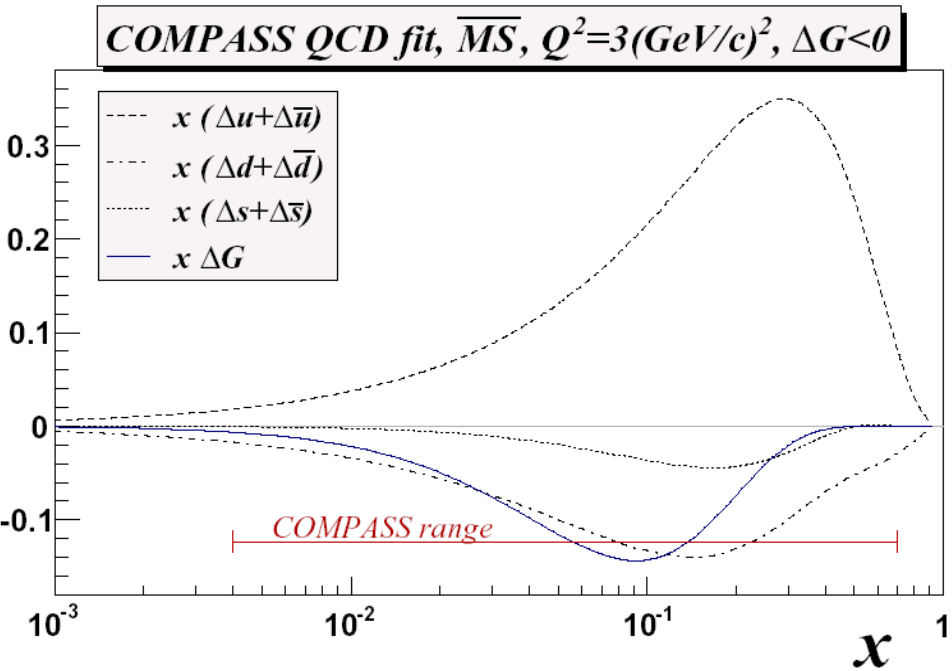
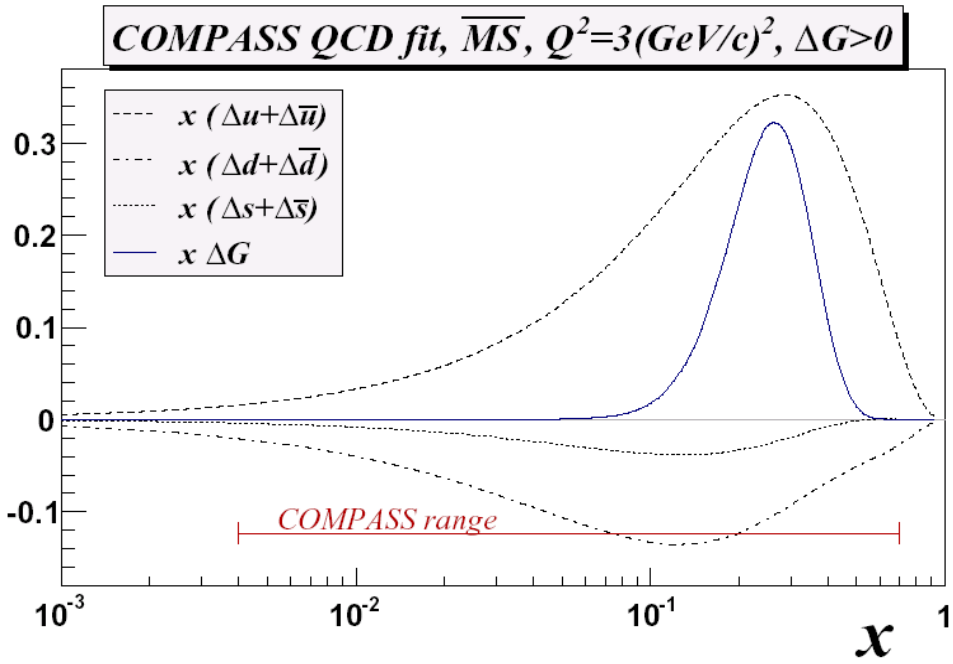
Polarised Parton Distributions





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

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QCD Fits Results

(world data)

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Quark polarisation:

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

$$\left(\eta_K = \int_0^1 \Delta k \, dx\right) \longrightarrow \eta_\Sigma = 0.30 \pm 0.01(\text{stat}) \pm 0.02(\text{evol})$$

(error ≈ factor 2 larger without COMPASS)

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 $\eta_G < 0$:** $\eta_G^{prog1} = -0.31^{+0.10}_{-0.14}$, $\eta_G^{prog2} = -0.19^{+0.06}_{-0.11}$

$$|\eta_G| \approx 0.2 - 0.3$$

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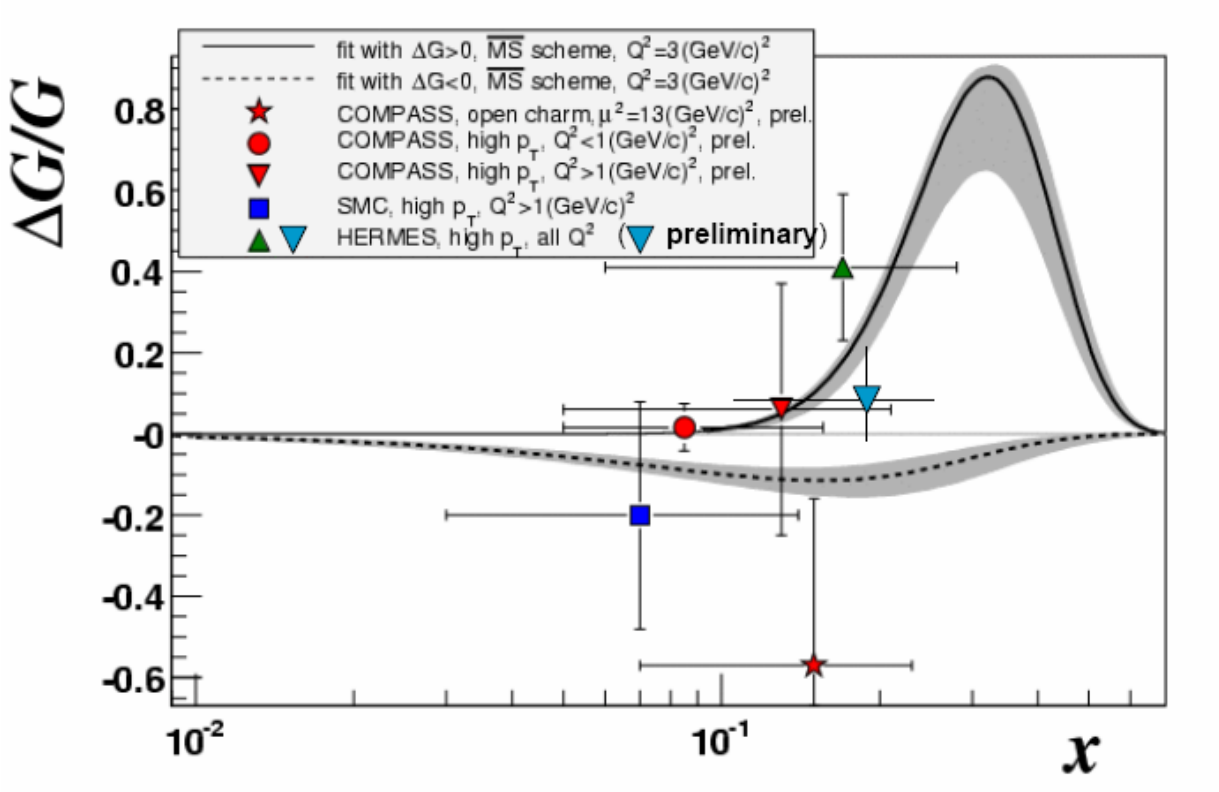
Gluon Polarisation $\Delta G/G$



Comparison between direct measurement of gluon polarisation and COMPASS NLO QCD fits to g_1

- **Unpolarised G(x) from MRST**
- **Bands correspond to statistical errors of ΔG**

First Moment of g_1

(COMPASS data only)

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$$\Gamma_1^N\left(Q_0^2 = 3(\mathrm{GeV}/c)^2\right) = \int_0^1 g_1^N(x)\,dx = 0.0502 \pm 0.0028(\mathrm{stat}) \pm 0.0020(\mathrm{evol}) \pm 0.0051(\mathrm{syst})$$

- **in literature (S.A. Larin *et al.*, PLB404 (1997) 153):**

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

(from Y. Goto *et al.*, PRD62 (2000) 034017: $a_8 = 0.585 \pm 0.025$)

$$a_0(Q_0^2 = 3(\mathrm{GeV}/c)^2) = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

extrapolating to $Q^2 \to \infty$

$$\hat{a}_{0\left(Q^2 \to \infty\right)} = 0.33 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

$\hat{a}_0$ is interpreted as the fraction of the nucleon spin carried by the quarks,
$\Delta\Sigma = \Delta u + \Delta d + \Delta s$

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

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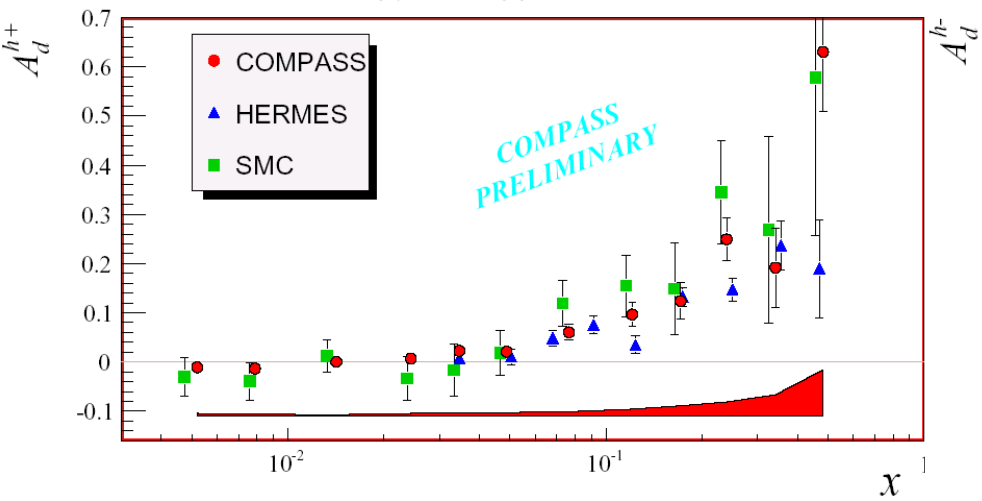
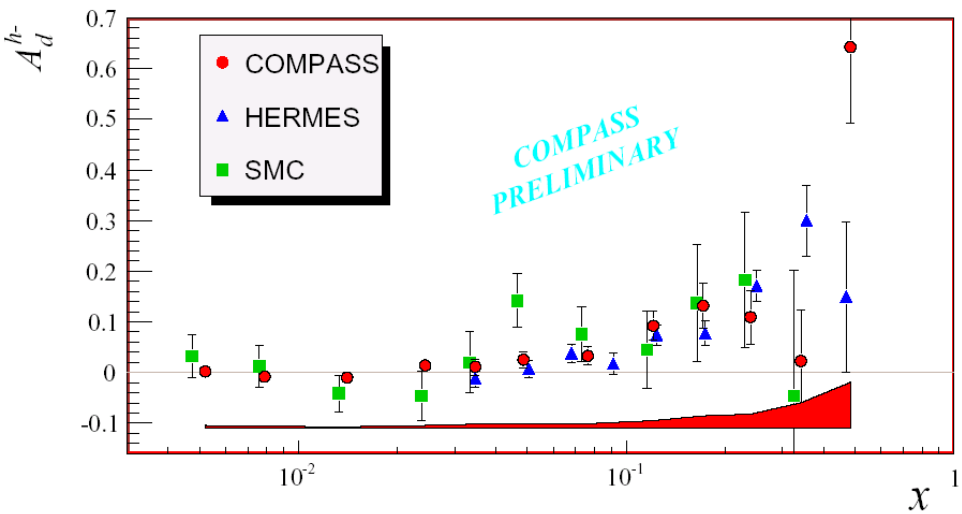
Semi-inclusive asymmetries

$$A_1^h(x) = \frac{\sum_q e_q^2(\Delta q(x) D_q^h + \Delta\bar{q}(x) D_{\bar{q}}^h)}{\sum_q e_q^2(q(x) D_q^h + \bar{q}(x) D_{\bar{q}}^h)}$$

$$A^+ = \frac{\sigma_{\uparrow\downarrow}^{h+} - \sigma_{\uparrow\uparrow}^{h+}}{\sigma_{\uparrow\downarrow}^{h+} + \sigma_{\uparrow\uparrow}^{h+}}$$

$$A^- = \frac{\sigma_{\uparrow\downarrow}^{h-} - \sigma_{\uparrow\uparrow}^{h-}}{\sigma_{\uparrow\downarrow}^{h-} + \sigma_{\uparrow\uparrow}^{h-}}$$





- **COMPASS kinematic domain: inclusive DIS + $0.2 < z < 0.85$**
- **Statistics: $N^+ = 30\times10^6$, $N^- = 25\times10^6$, corr(N^+,N^-) ≈ 20%**
- **Systematic errors: Multiplicative → $\delta \cong 0.08A$ (δP_B, δP_T, δf and δD)**

  Additive: rad. corrections ≈ 10^{-5} — 10^{-4}; $A_{false} < 0.52\delta A_{stat}$

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Difference asymmetry

$$A^{+-} = \frac{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) - (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) + (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}$$

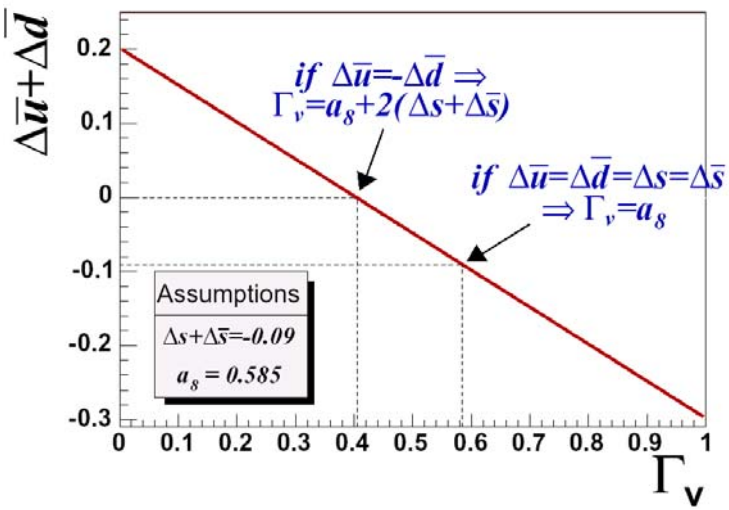
- **In LO QCD FF do cancel out in A^{+-}. For a deuteron target:**

$$A_d^{h^+-h^-} = A_d^{\pi^+-\pi^-} = A_d^{K^+-K^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}$$

- **The contribution of sea quarks to the nucleon spin can be obtained by combining the matrix elements a_0 and a_8 and the integral**

$$\Gamma_v \equiv \int_0^1 (\Delta u_v(x) + \Delta d_v(x))dx$$

$$\begin{aligned} \Delta\bar{u} + \Delta\bar{d} &= (\Delta s + \Delta\bar{s}) + \frac{1}{2}(a_8 - \Gamma_v) \\ &= 3\,\Gamma_1^N - \frac{1}{2}\Gamma_v + \frac{1}{12}a_8 \end{aligned}$$



- **To disentangle between symmetric and asymmetric sea scenarios**

  $\delta\Gamma_v < 2|\Delta s+\Delta\bar{s}|$ is needed

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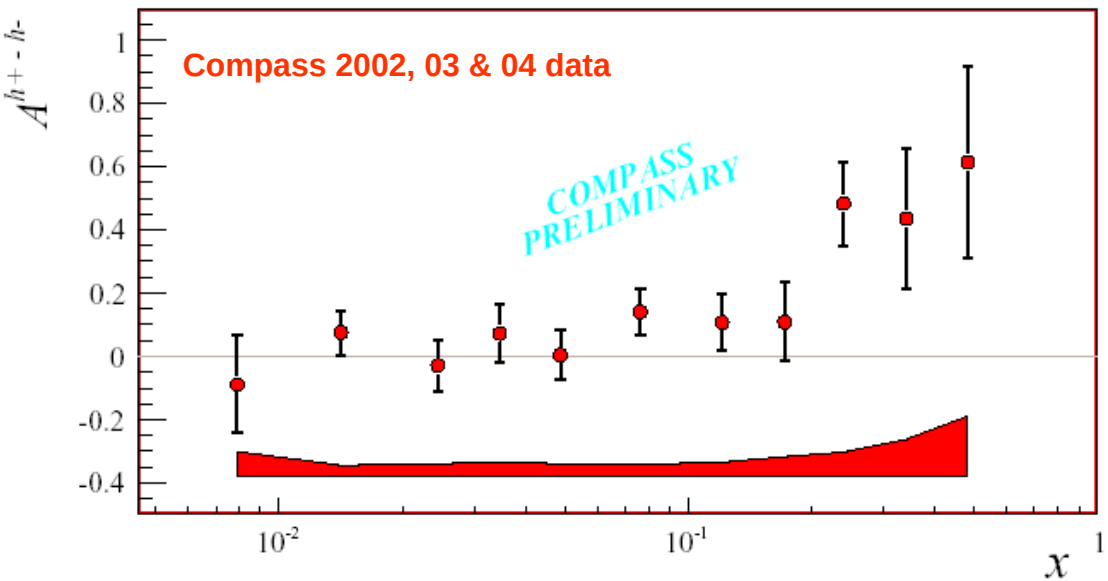
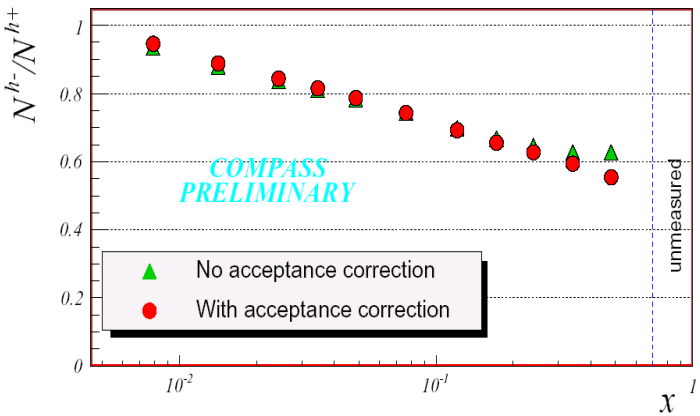
Difference asymmetry

$$A^{+-} = \frac{1}{1-r}(A^{+} - rA^{-}), \quad \text{with} \quad r = \frac{\sigma^{h-}_{\uparrow\downarrow} + \sigma^{h-}_{\uparrow\uparrow}}{\sigma^{h+}_{\uparrow\downarrow} + \sigma^{h+}_{\uparrow\uparrow}} = \frac{\sigma^{h-}}{\sigma^{h+}}$$

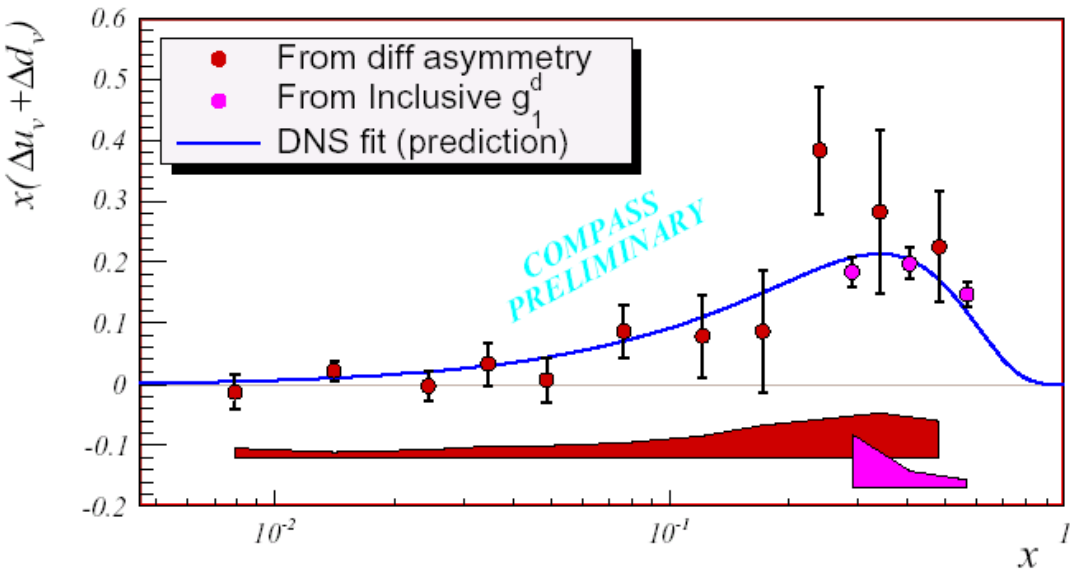




- **The measured x range is 0.006 < x < 0.7, as the precision at smaller x is too low. (The statistical error is inversily proportional to $N^{h+} - N^{h-}$)**
- **For the acceptance studies full chain of MC simulation (spectrometer + same cuts as for data) with default LEPTO settings was performed**

Valence quark polarisations

$$x(\Delta u_v + \Delta d_v) = \frac{x(u_v + d_v)}{(1 + R(x,Q^2))(1 - 1.5\omega_D)} A^{+-} \qquad (\omega_D = 0.05 \pm 0.01)$$



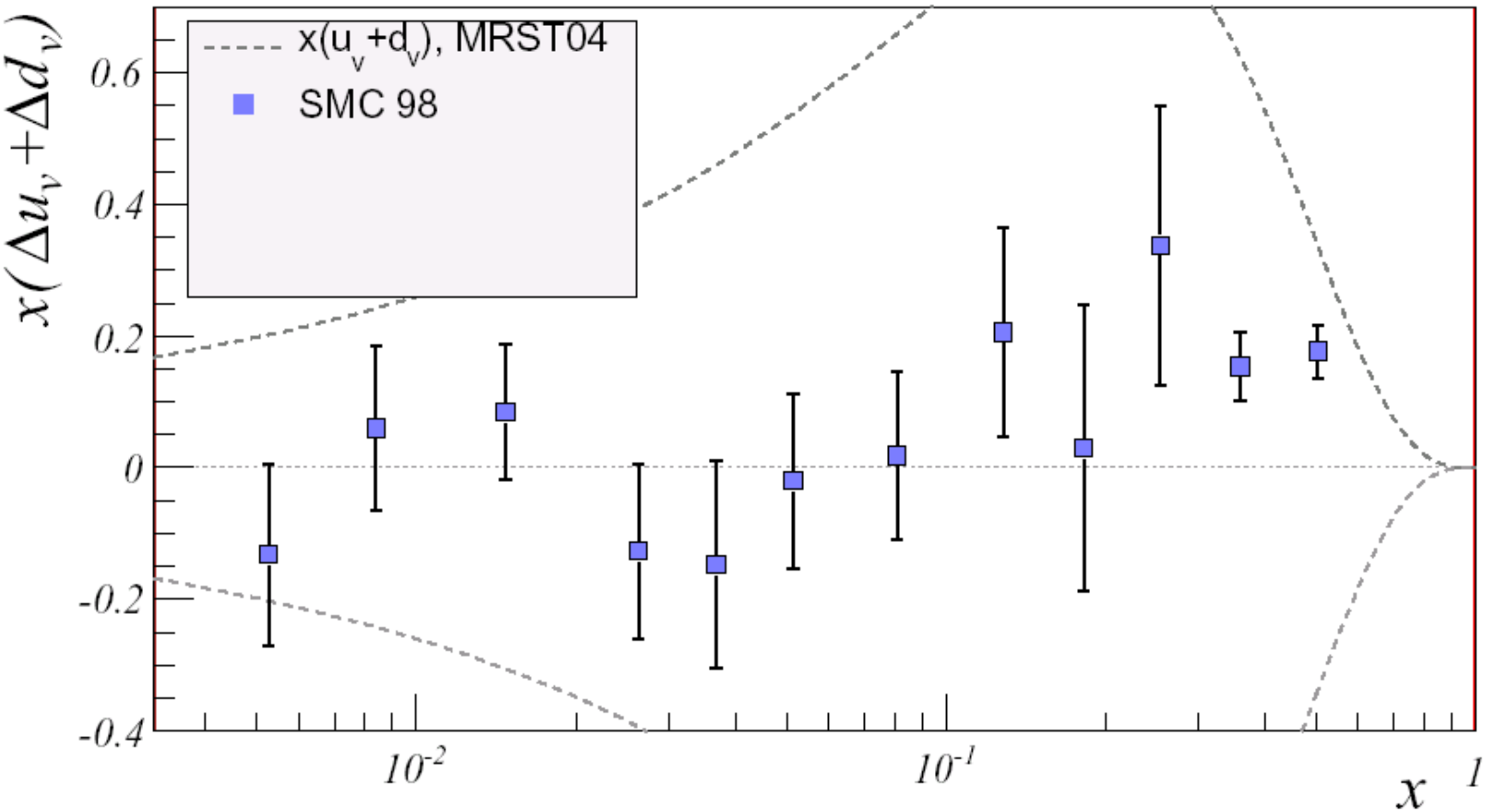
- **Unpol. sea contribution to F_2 vanishes for x > 0.3**
- **$|\Delta\bar{u}+\Delta\bar{d}| < \bar{u}+\bar{d}$**

$$\Delta u_v + \Delta d_v = \frac{36}{5}\frac{g_1^d(x,Q^2)}{(1-1.5\omega_D)} - \left[2(\Delta\bar{u}+\Delta\bar{d}) + \frac{2}{5}(\Delta\bar{s}+\Delta\bar{s})\right]$$

- **Much better precision**

- **All points evolve to $Q_0^2 = 10$ (GeV/c)^2 accordingly to DNS parameterisation**
  (D. De Florian, G.A. Navarro and R. Sassot, Phys. Rev. D71 (2005) 094018)
- **LO DNS analysis, based on KKP param. of FF, includes:**
  All DIS g_1 prior to COMPASS 2004 data;
  All SIDIS data from SMC and HERMES ($\Delta\bar{u} = \Delta\bar{d} = \Delta s = 0$ for x > 0.3)
- **Unpolarised MRST 2004 LO PDFs have been used**

Comparison with other experiments



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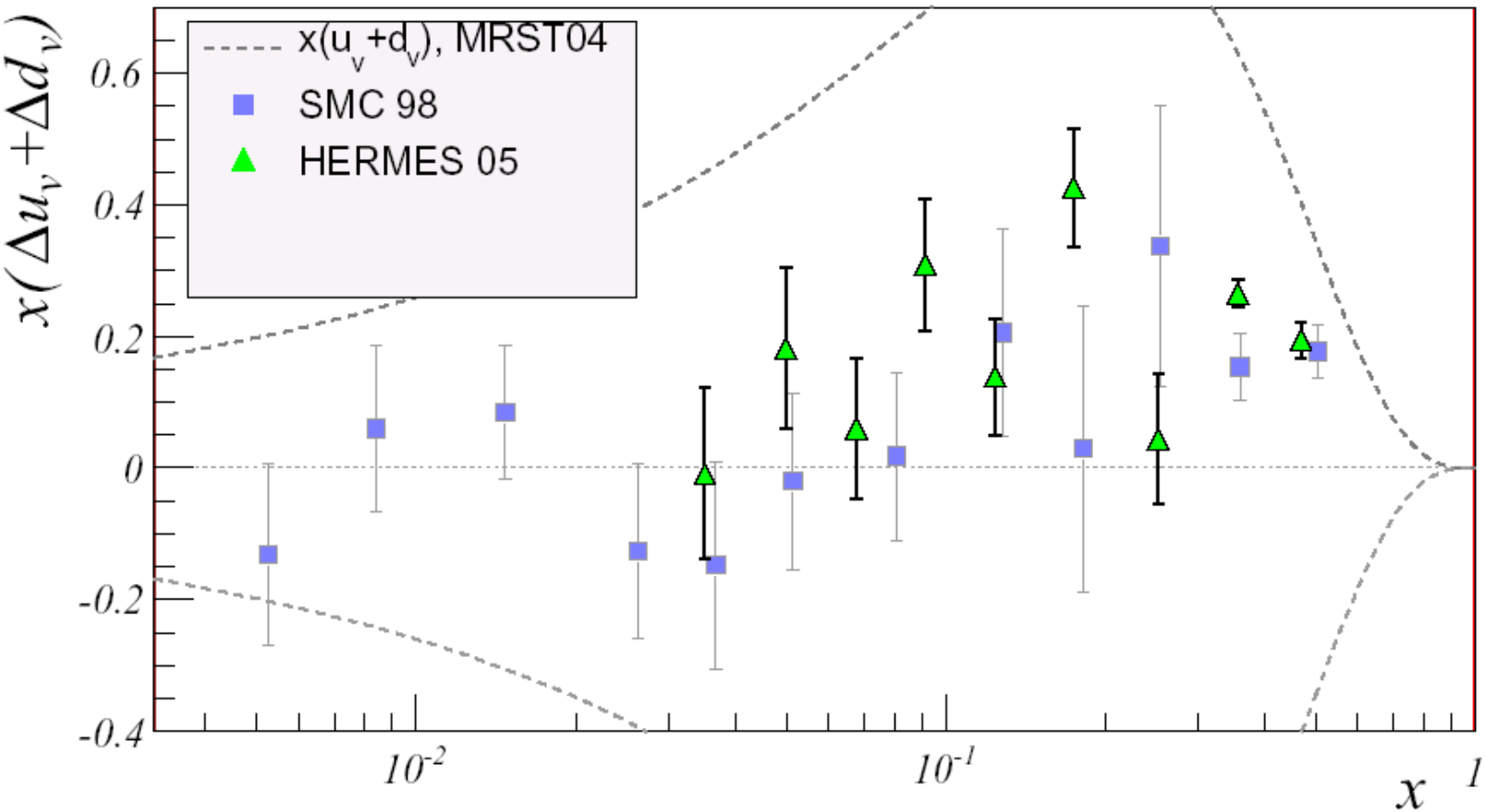
Comparison with other experiments



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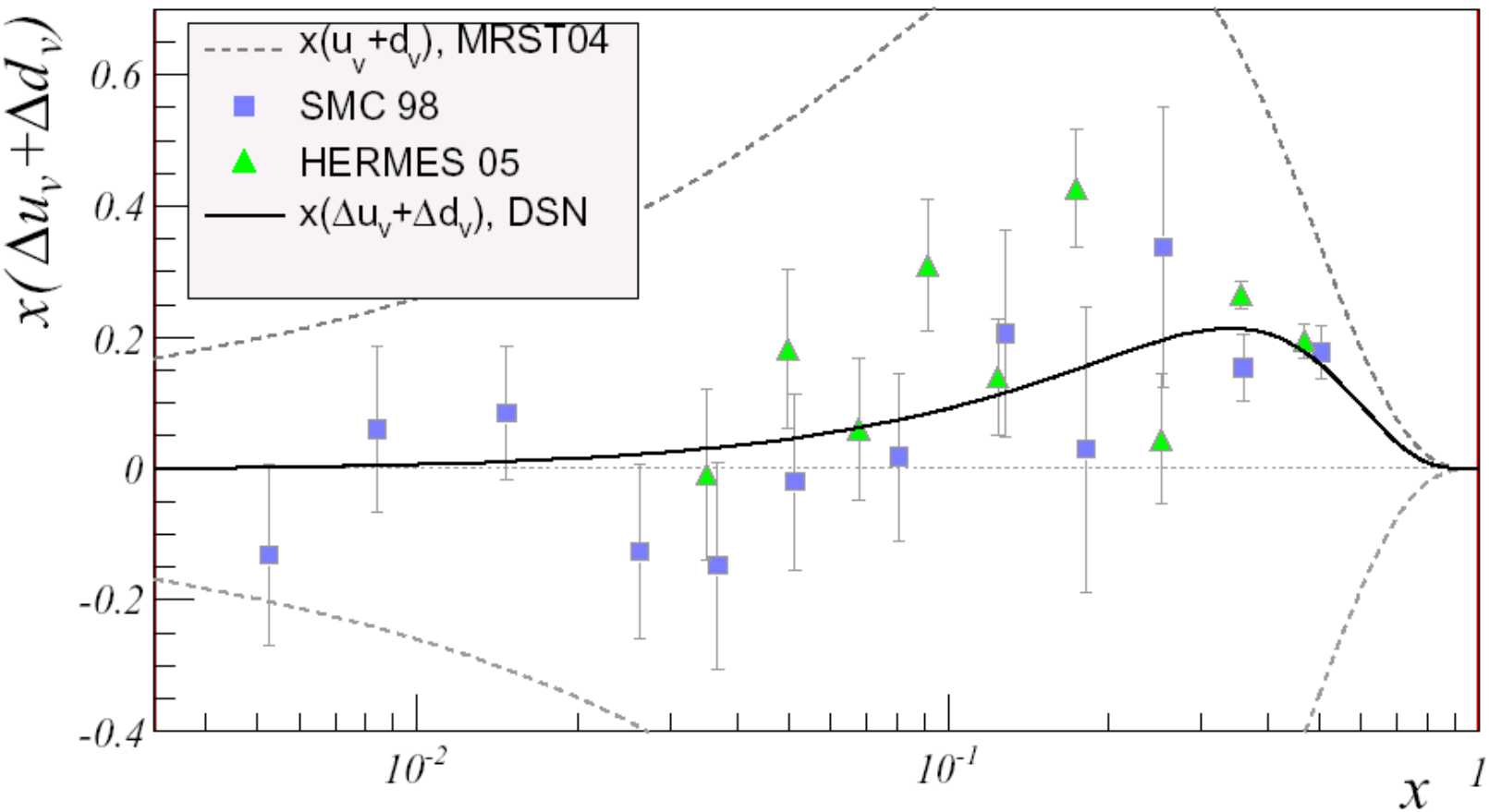
Comparison with other experiments



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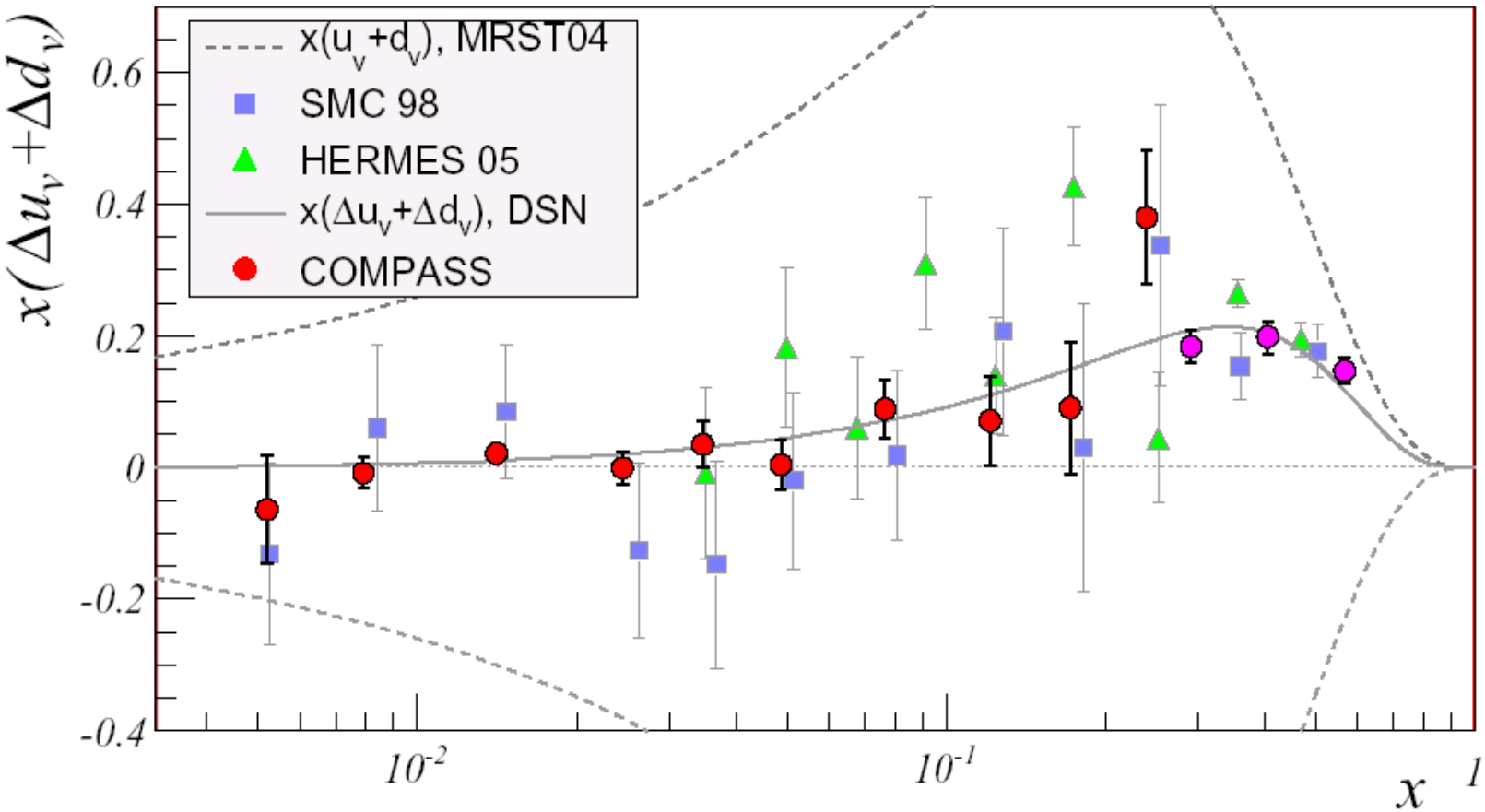
Comparison with other experiments



DNS parameterisation predicts successfully COMPASS SIDIS data

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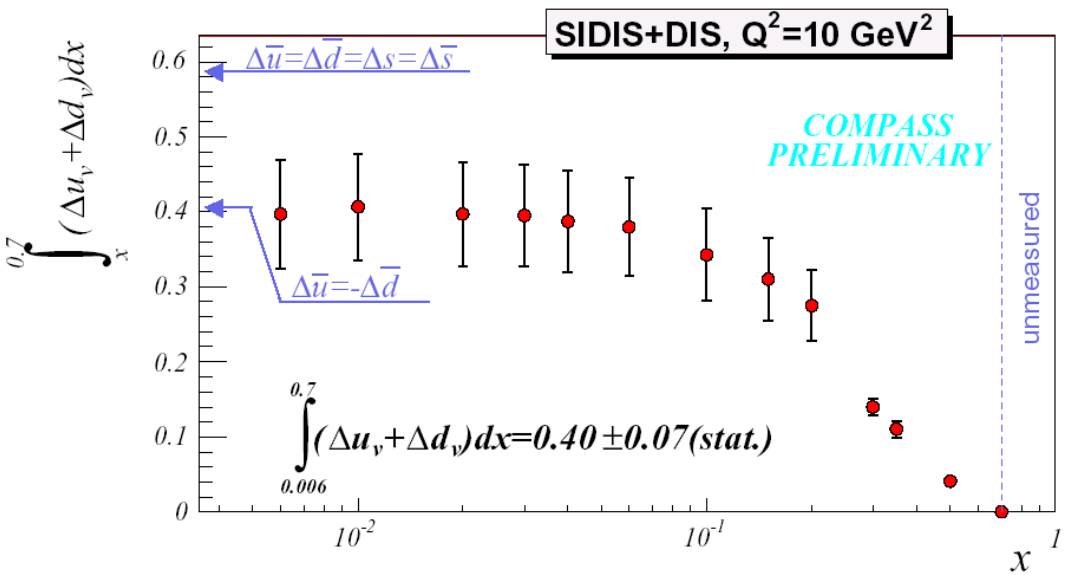
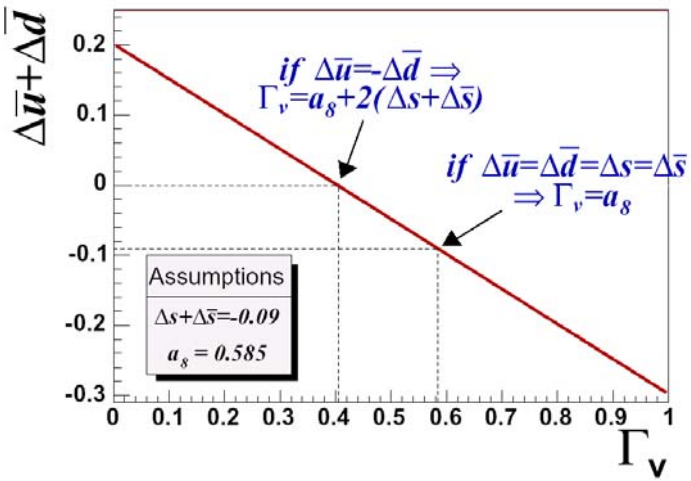
Estimate for the first moments (LO)





	x-range	Q^2 GeV^2	$\Delta u_v+\Delta d_v$ measurem.	$\Delta u_v+\Delta d_v$ DNS	$\Delta\bar{u}+\Delta\bar{d}$ measurem.	$\Delta\bar{u}+\Delta\bar{d}$ DNS
SMC 98	0.003–0.7	10	$0.26\pm0.21\pm0.11$	0.386	$0.02\pm0.08\pm0.06$	−0.009
HERMES 05	0.023–0.6	2.5	$0.43\pm0.07\pm0.06$	0.363	$-0.06\pm0.04\pm0.03$	−0.005
COMPASS	0.006–0.7	10	$0.40\pm0.07\pm0.05$	0.385	$0.0\pm0.04\pm0.03$	−0.007

- **Contribution from the unmeasured 0.7 < x < 1 region is 0.004 (DNS fit)**
- **SU(3) symmetric sea was assumed in SMC**
- **The estimated Γ_v (SIDIS + DIS) is 2.5σ_{stat} away from the symmetric sea scenario**

Conclusions

✓ From the first moment of g_1^d, we extract the quark contribution to the nucleon spin (COMPASS data only):

$$\hat{a}_0 \equiv \Delta\Sigma = 0.33 \pm 0.03(\text{stat}) \pm 0.05(\text{syst})$$

$$(\Delta s + \Delta\bar{s}) = -0.08 \pm 0.01(\text{stat}) \pm 0.02(\text{syst})$$

✓ QCD fits to world data give for quark and gluon contributions:

$$\eta_\Sigma(Q_0^2 = 3(\text{GeV}/c)^2) = 0.30 \pm 0.01(\text{stat}) \pm 0.02(\text{evol})$$

$$|\Delta G| \approx 0.2 \text{ — } 0.3$$

✓ $\Delta u_v + \Delta d_v$ have been extracted from difference asymmetry approach

✓ Increase of the precision at small x by a factor of ~6 as compared to SMC

✓ DNS parameterisation predicts successfully COMPASS SIDIS data

✓ SU(3) symmetric sea scenario is disfavoured

2006 data analysis is in *progress*