New Results on the Spin-dependent Structure Function of the deuteron, $g_1^d(x,Q^2)$

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On Behalf of the COMPASS Collaboration

Advanced Studies Institute “Symmetries and Spin”
SPIN – PRAHA – 2006

Outline

- **The nucleon spin**
- **The COMPASS experiment**
- **Inclusive asymmetries**
- **The g_1 structure function**

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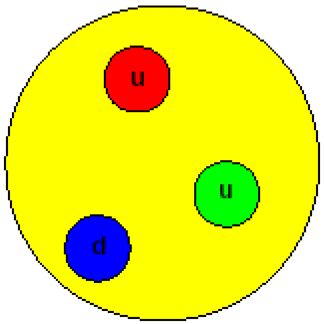
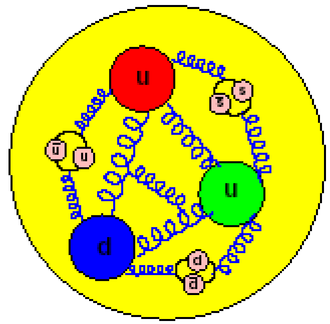
The Nucleon Spin



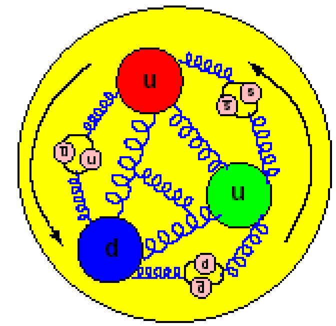
naïve parton model:

ΔΣ = Δu + Δd = 1

EMC (1988): ΔΣ = 0.12 ± 0.09 ± 0.14



Gluons, sea and *c* quarks are important



complete description: orbital angular momenta

$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

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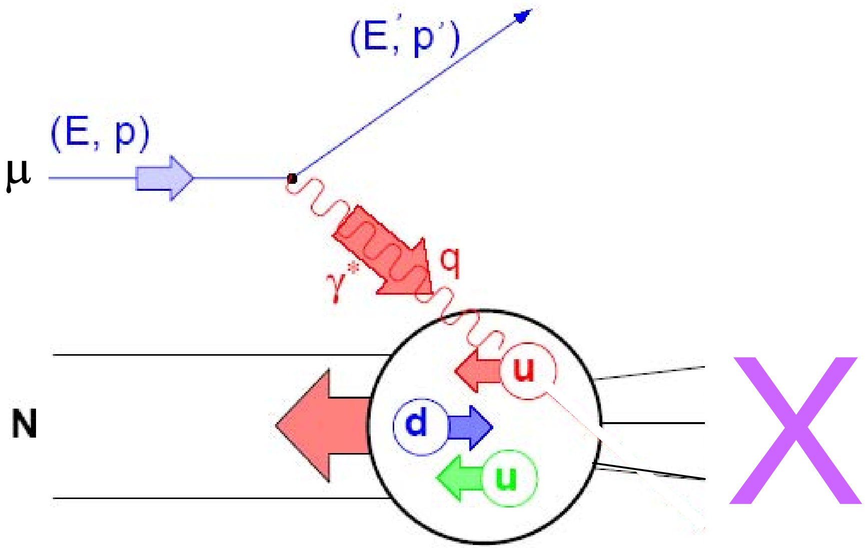
Deep Inelastic Scattering



$Q^2 = -q^2$

$\nu = E - E'$

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

$y = \nu/E$

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

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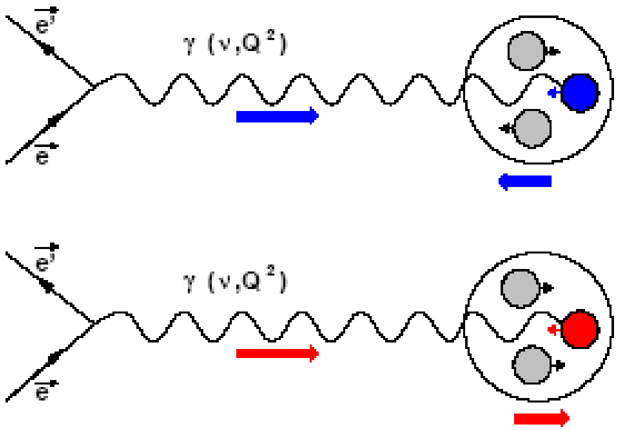
Polarised Deep Inelastic Scattering



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

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

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

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

+: quark ↑↑ nucleon

–: quark ↑↓ nucleon

photon-nucleon asymmetry

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

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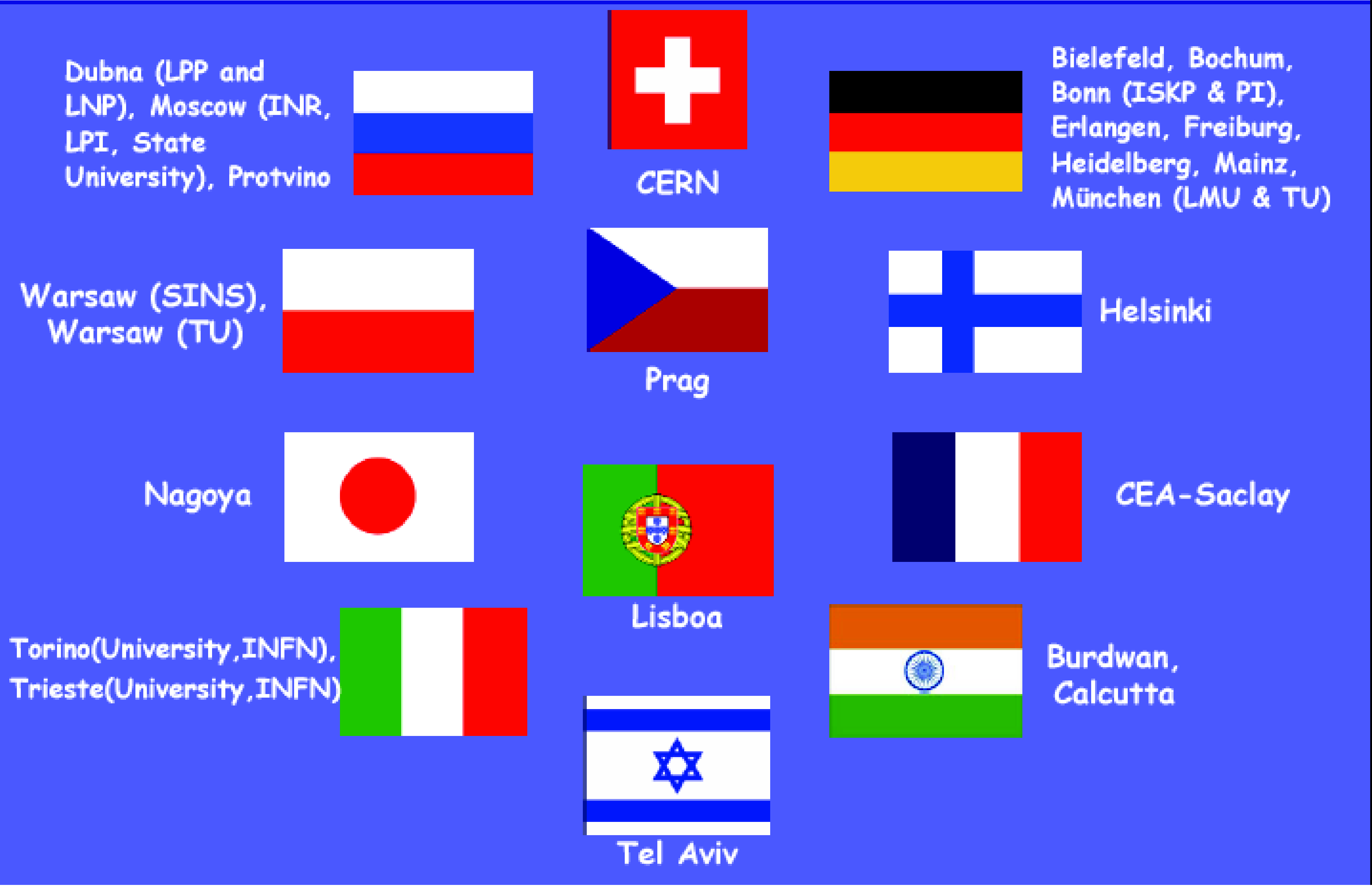
The COMPASS Collaboration

(230 Physicists from 12 Countries)




Luminosity: ~5 · 10^32 cm^-2 s^-1
Beam intensity: 2.10^8 μ+/spill (4.8s/16.2s)
Beam momentum: 160 GeV/c
COMPASS
LHC
SPS
N

The COMPASS Experimental Program

muon beam

nucleon spin structure

- $\Delta G/G$ (G.Brona)
- Transversity (A.Martin)
- Inclusive μ channel (this talk)
- Semi-inclusive channels
- exclusive vector-meson production
- Spin transfer in Λ production

hadron beam

nucleon spectroscopy

- Primakoff reactions:
  - Polarizability of π and K
- Exotics:
  - glue balls and hybrids
- Double charmed mesons and baryons

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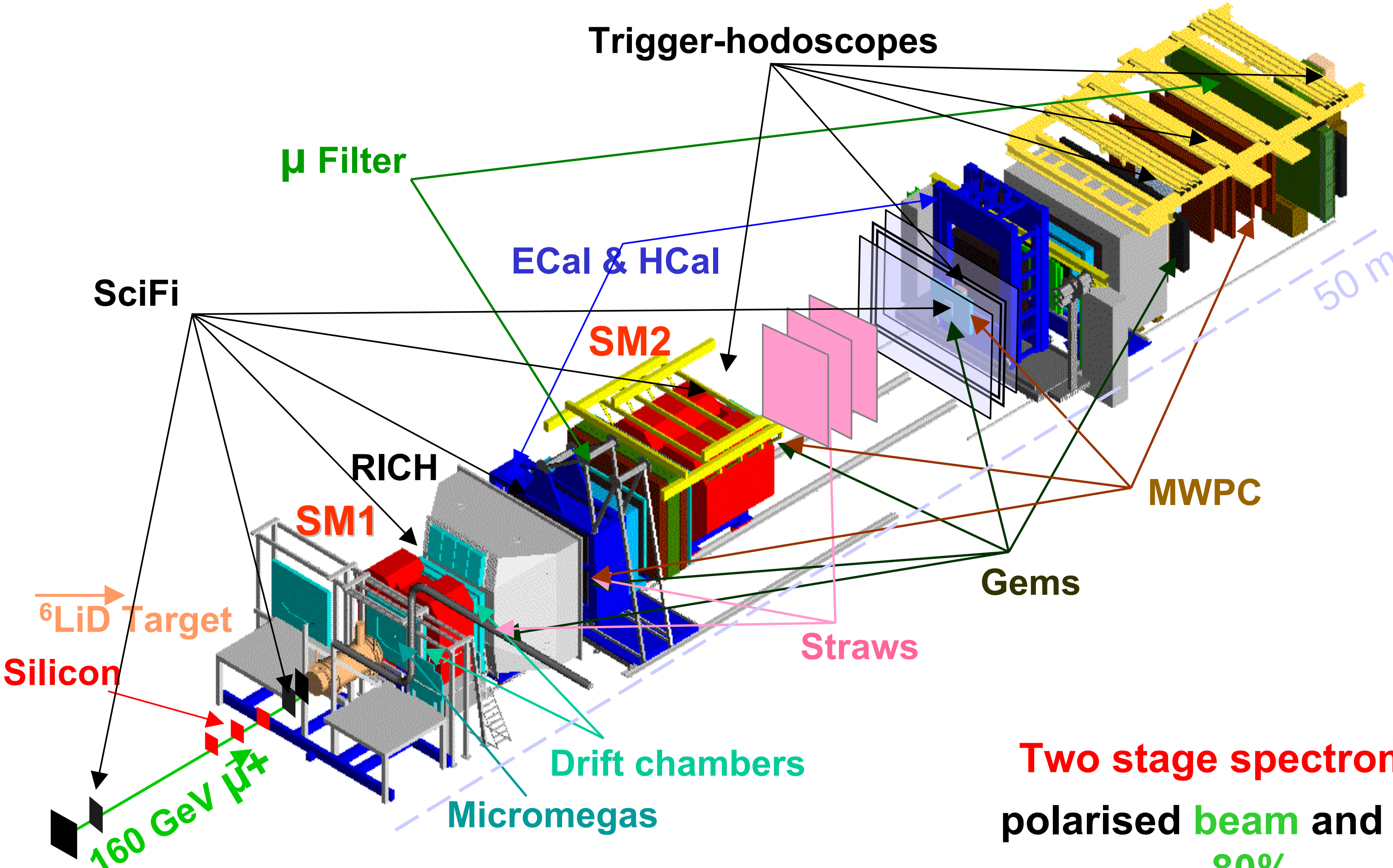
The COMPASS Spectrometer

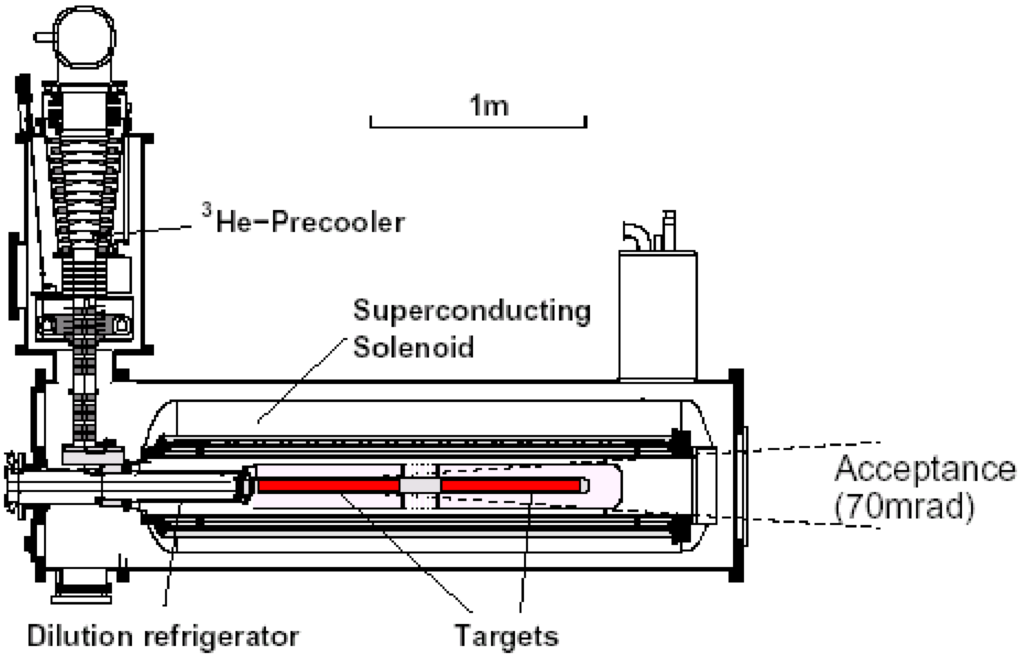


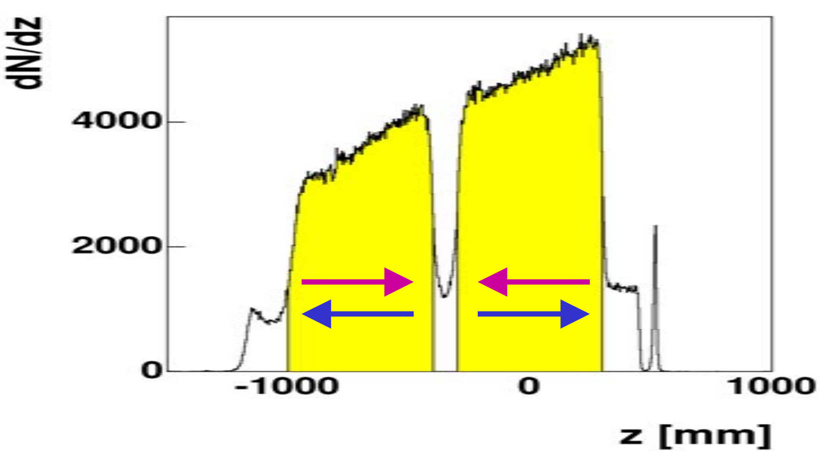
Two stage spectrometer

polarised beam and target

-80% ≥50%

The Target System





Two 60 cm long target cells with <u>opposite polarisation</u>

Target material: ^{6}LiD

Polarisation ~ 50%

Solenoid field: 2.5 T

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

Field reversal every 8h

New solenoid with 180 mrad acceptance in 2006

The COMPASS Trigger System

- 3 types of triggers
  - Inclusive triggers: reconstructed μ’ in hodoscpoes
  - Semi-inclusive triggers: μ energy loss + hadron signal in HCAL
  - Calorimetric triggers: hadron signal in calorimeter

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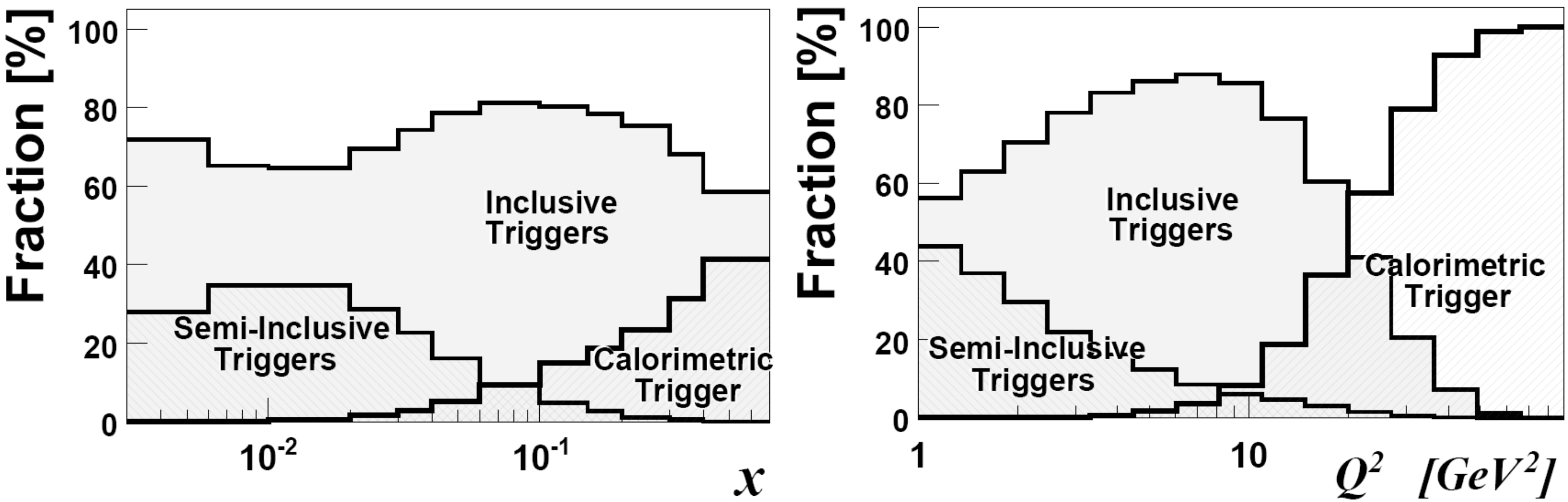
Fraction of the Different Triggers



60—75% of inclusive triggers over the full COMPASS x range

Semi-inclusive triggers dominant at low x and low Q^2

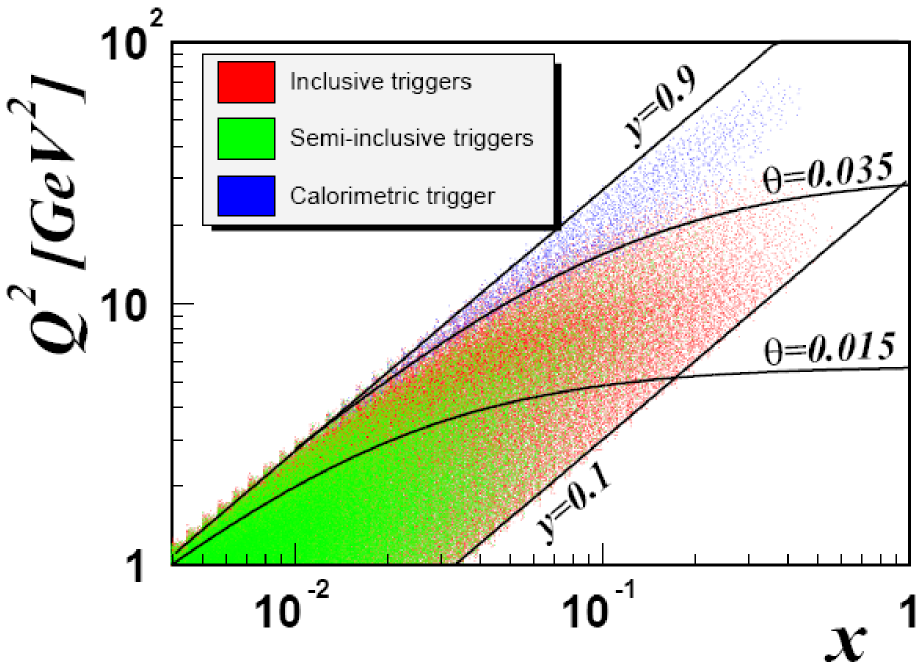
Calorimetric triggers dominant for $Q^2 > 30\ GeV^2$

Kinematic Domain

- $E_\mu \in [140, 180]$ GeV
- (Invariant mass)^2 of the virtual photon: $Q^2 > 1$ GeV^2
- Fraction of the energy carried by the virtual photon: $0.1 < y < 0.9$

  $\Rightarrow E_{lab}$ of the virtual photon: $\nu \in [14, 162]$ GeV

  $\Rightarrow$ Bjorken scaling variable: $x = Q^2/2M\nu \in [0.004, 0.7]$



Statistics of DIS data (2002+2003+2004):

89 x 10^6 events

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The Longitudinal Photon-deuteron Asymmetry

$$A^d = D(A_1^d + \eta A_2^d), \qquad A_2^d = \sigma_{TL}/\sigma_T$$ **(d ≡ deuteron)**

$$\eta = \frac{2(1-y)}{y(2-y)}\sqrt{Q^2}/E_\mu, \qquad y = \frac{\nu}{E_\mu}$$

η is small in the COMPASS kinematic range, as well as A_2

$$\Rightarrow \quad A_1^d \cong A^d/D$$

$$A_1^d = \frac{1}{D}\frac{1}{P_B P_T f}\frac{1}{2}\left(\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} + \frac{N'^{\uparrow\downarrow} - N'^{\uparrow\uparrow}}{N'^{\uparrow\downarrow} + N'^{\uparrow\uparrow}}\right)$$

- **N ≡ Number of detected events**
- **P_B ≡ Beam polarisation**
- **P_T ≡ Target polarisation**
- **f ≡ Dilution factor**
- **D ≡ Depolarisation factor**

$\uparrow\downarrow$ ≡ 1st cell (polarised anti-paralell to beam), $\uparrow\uparrow$ ≡ 2nd cell (polarised parallel to beam)

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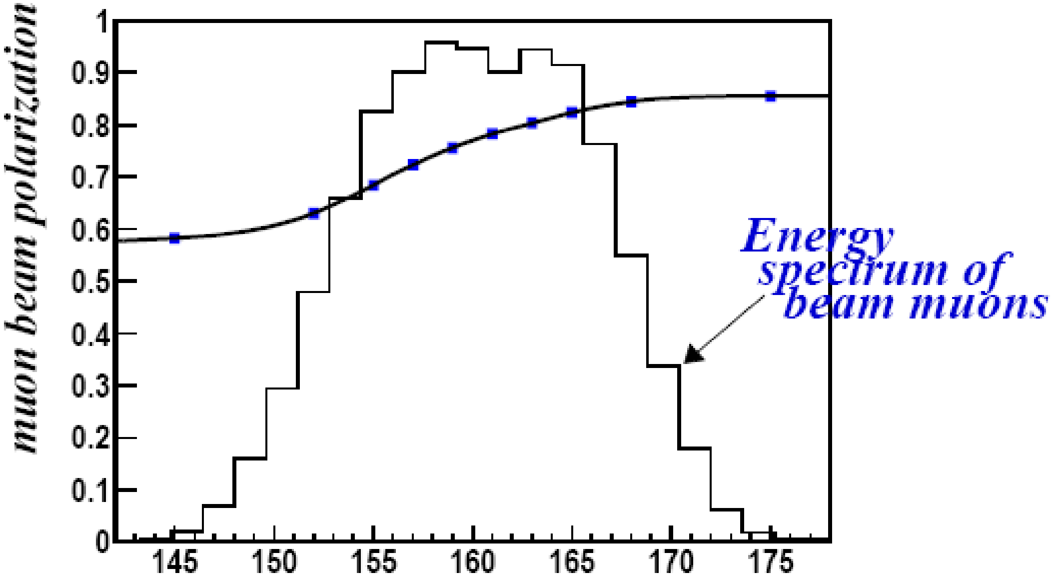
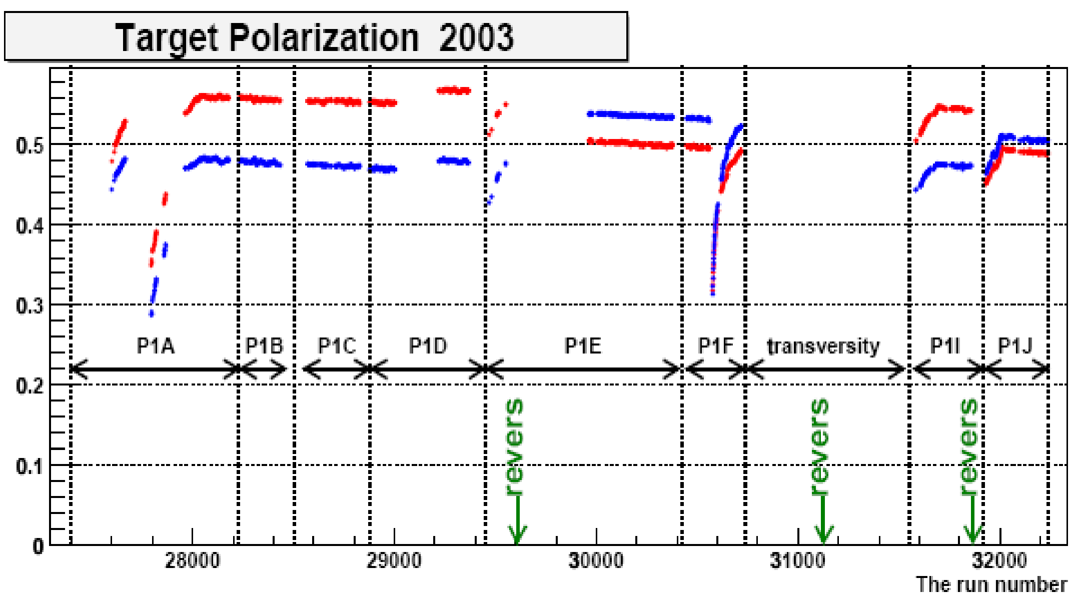
The Beam and Target Polarisations





- Polarisation is determined from Monte Carlo simulations
- The average beam polarisation is –80% (–76% in 2002 and 2003)
- $\Delta P_b \sim$ 4–5%

- After 5 days of build-up time: +53% and -50%
- Average polarisation over 2 years is 50%
- $\Delta P_T \sim$ 5%

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The Dilution Factor of the COMPASS ^{6}LiD Target

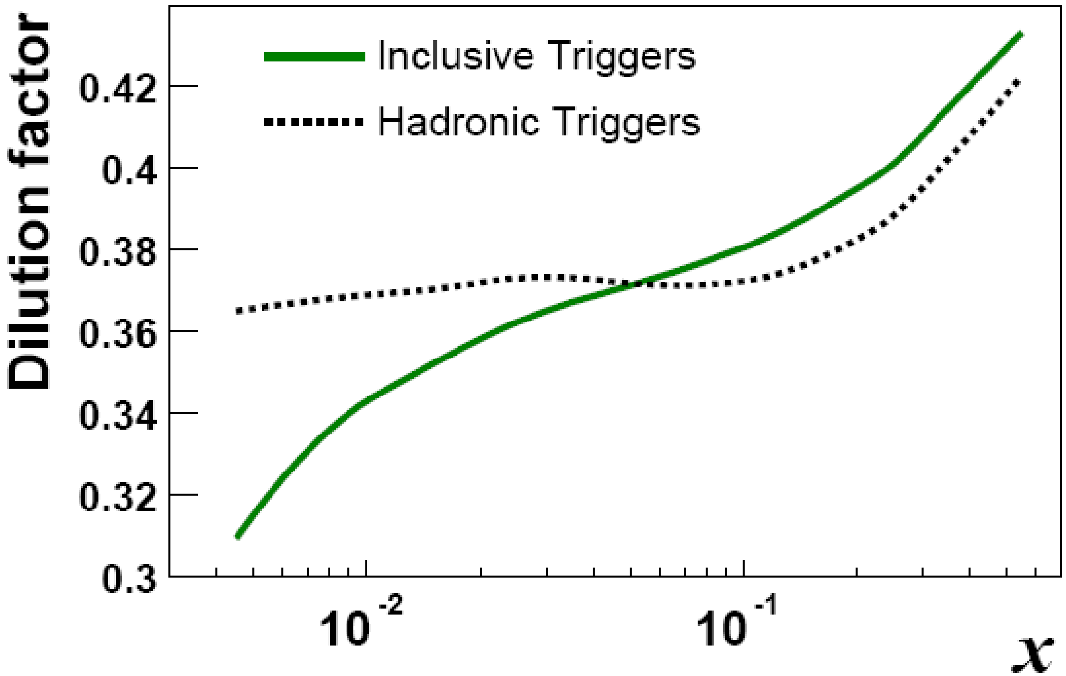
^{6}LiD $\approx$ ^{4}He+D $\rightarrow$ naïve expectation f(^{6}LiD) $\approx$ 0.5

$$f = \frac{n_d \bar{\sigma}_d^{Tot}}{n_d \bar{\sigma}_d^{Tot} - \sum_A n_A \bar{\sigma}_A^{Tot}} = \frac{n_d}{n_d - \sum_A n_A \frac{\bar{\sigma}_A^{Tot}}{\bar{\sigma}_d^{Tot}}}$$

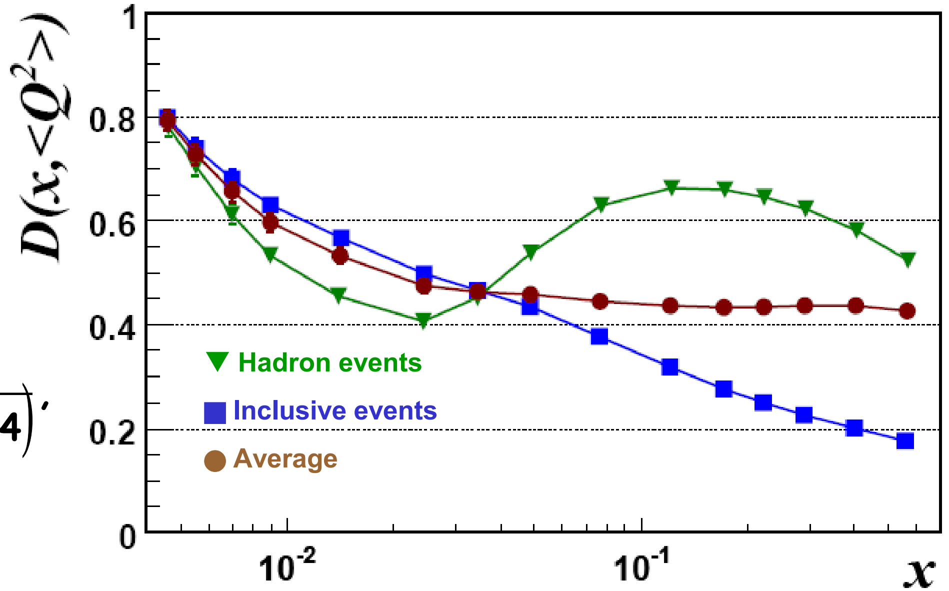
A = ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, C, F, Ni and Cu

$$\bar{\sigma}^T = \bar{\sigma}^{1\gamma} + \bar{\sigma}^{tail}$$

$$\bar{\sigma}^{tail} = \bar{\sigma}_{el}^{tail} + \bar{\sigma}_{qel}^{tail} + \bar{\sigma}_{inel}^{tail}$$



The Depolarisation Factor

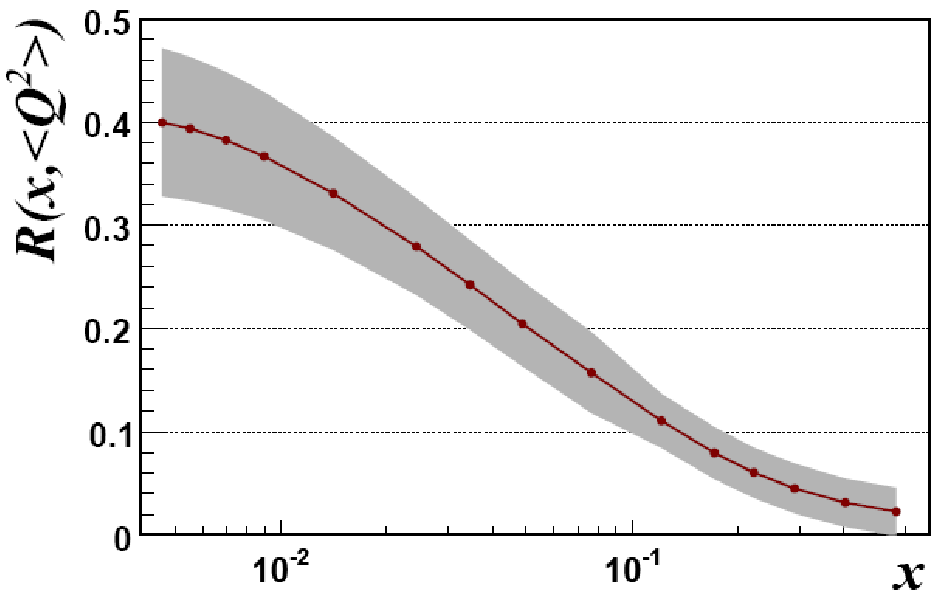


It accounts for polarisation transfer from μ to virtual γ

$$D = \frac{y\left(\left(1+\gamma^2 y/2\right)(2-y) - 2y^2 m_\mu^2 / Q^2\right)}{y^2\left(1-2m_\mu^2/Q^2\right)\left(1+\gamma^2\right) + 2(1+R)\left(1-y-\gamma^2 y^2/4\right)},$$

$$y = \nu / E_\mu, \qquad \gamma = \frac{2 m_p x_{Bj}}{\sqrt{Q^2}},$$

$$R \equiv R(x_{Bj}, Q^2) = \sigma_L / \sigma_T$$



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A_1 Calculation

$$A_1^d = \frac{1}{P_B P_T f\, D}\frac{1}{2}\left(\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} + \frac{N'^{\uparrow\downarrow} - N'^{\uparrow\uparrow}}{N'^{\uparrow\downarrow} + N'^{\uparrow\uparrow}}\right)$$

Starting point: numbers of detected events, in upstream and downstream cells ($N^{\uparrow\downarrow}$, $N^{\uparrow\uparrow}$)

$N_u = \phi a_u n_u \sigma_0 (1 \pm \omega P_u A_1{}^d)$ $\qquad$ $N_d = \phi a_d n_d \sigma_0 (1 \mp \omega P_d A_1{}^d)$

ϕ ≡ **incident μ-flux**

a_u ≡ **acceptance of the upstream cell,**

n_u ≡ **number of nucleons in upstream cell**

P_u ≡ **polarisation of the upstream cell**

σ_0 ≡ **unpolarised cross section**

ω ≡ $P_B fD$

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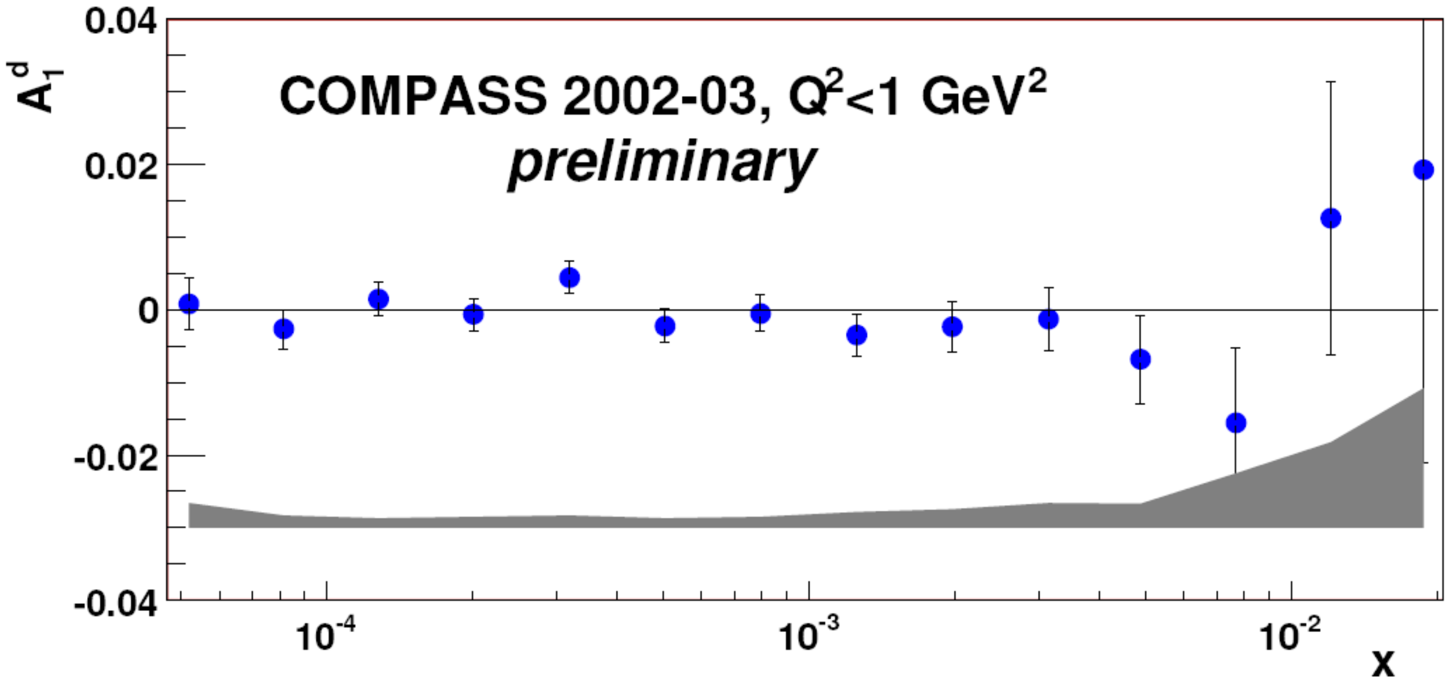
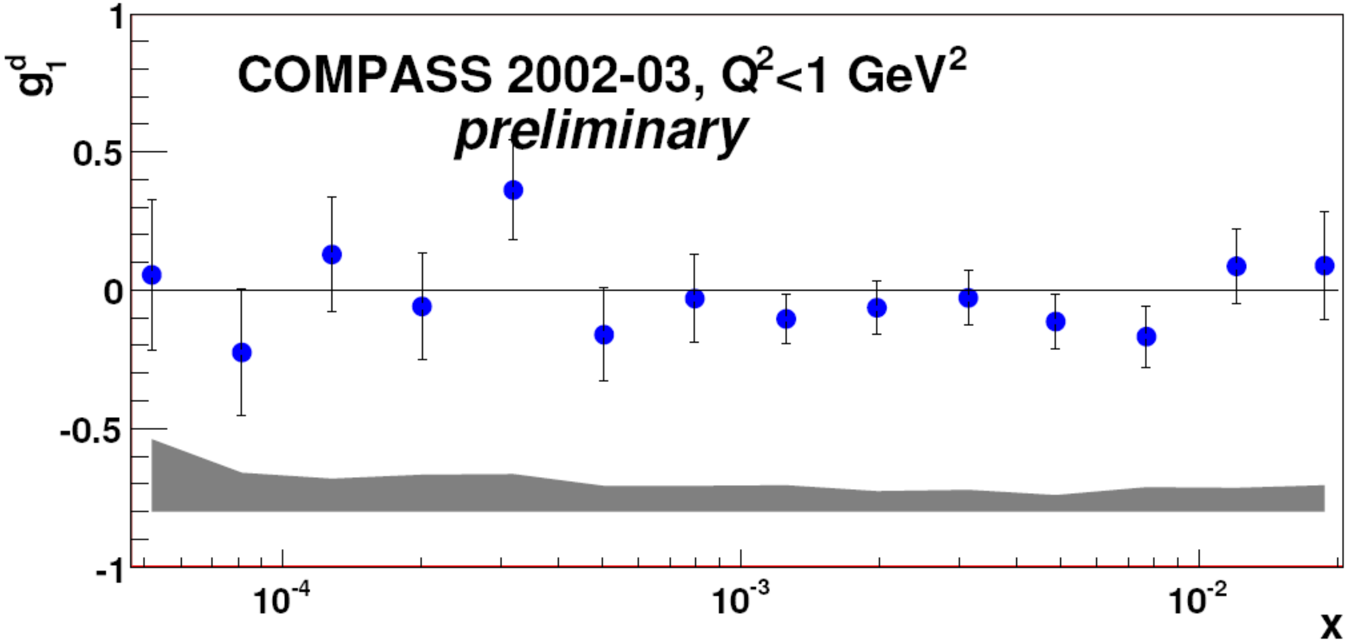
Inclusive Asymmetries, $Q^2 < 1\ GeV^2$



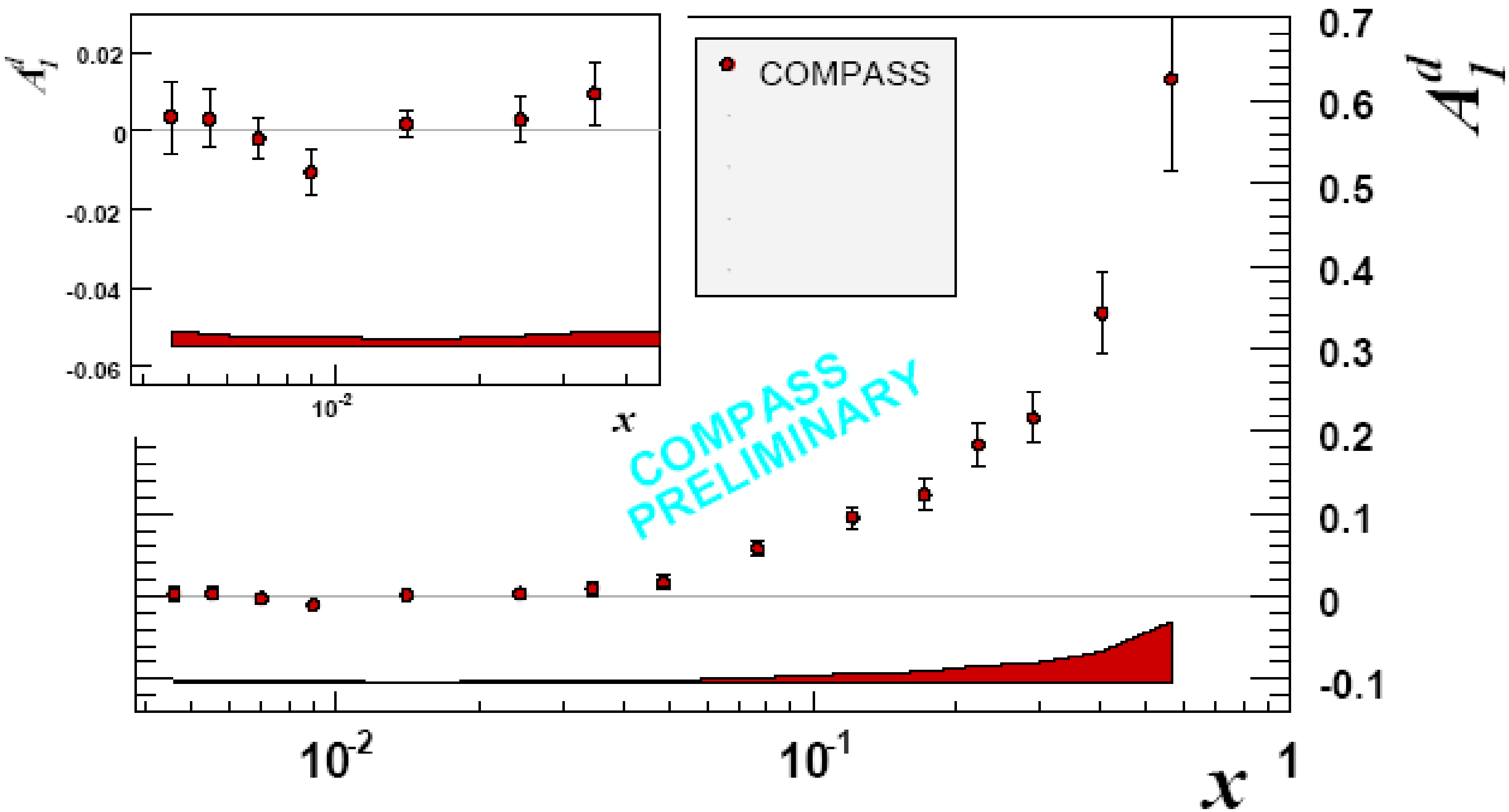
- A_1^d asymmetry compatible with 0 at low x range **(0.0005<x<0.02)**
- At low x A_1^d has been measured only by COMPASS and SMC
- Systematic errors are mainly due to false asymmetries

g_1^d at $Q^2 < 1$ GeV^2



- **Knowledge of g_1 at low Q^2 is needed to test non-perturbative models:**
  - **Regge models**
  - **(G)VDM**
- **F_2 is taken from the SMC parameterisation** (SMC + JKBB: B. Adeva *et al.* PRD60 (1999) 072004; Erratum-ibid.D62:079902,2000)

Inclusive DIS Asymmetry, $Q^2 > 1\ GeV^2$
COMPASS Results



- A_1^d compatible with 0 for x < 0.05
- Large asymmetry at large x

Main Sources of the Systematic Error

- Beam polarisation ~4–5%
- Target polarisation ~5%
- Dilution factor ~6%
- Depolarisation factor (R) ~4–5%

- A_2, radiative corrections to A_1 ⟶ small effect

- False asymmetries < 0.5 σ(stat)

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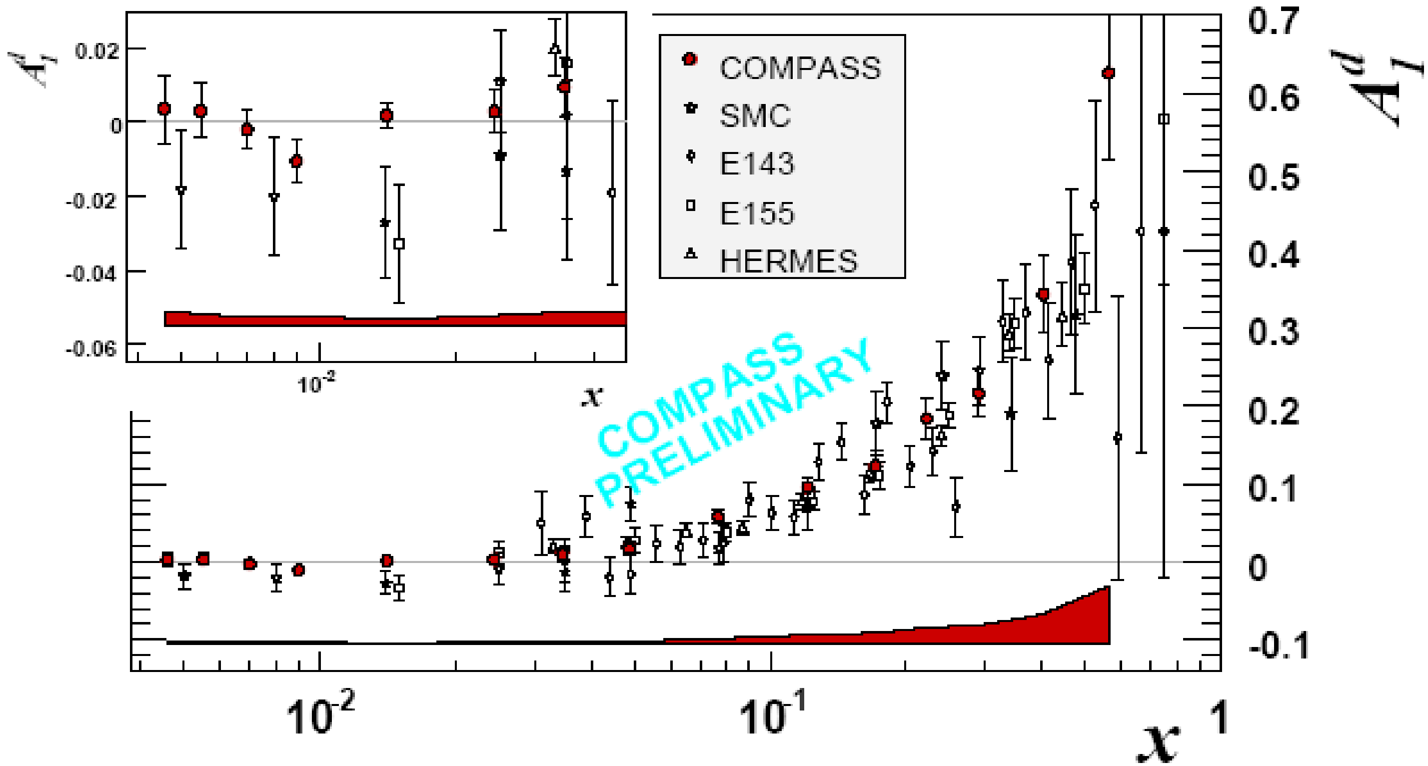
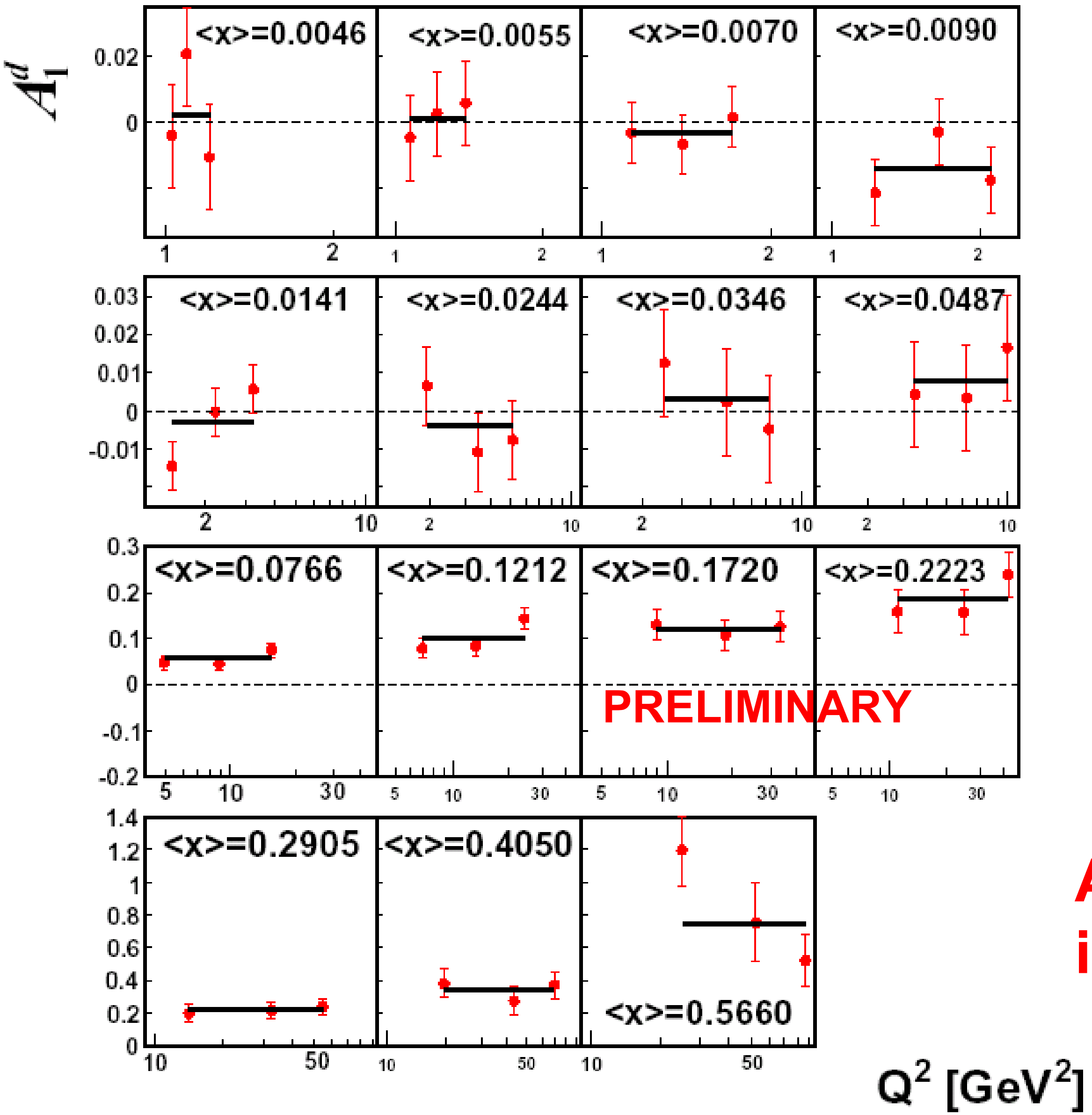
Inclusive DIS Asymmetry, $Q^2 > 1$ GeV^2
World Results



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

Inclusive DIS Asymmetry - QCD Analysis



$A_1(x,Q^2)$ almost independent of Q^2

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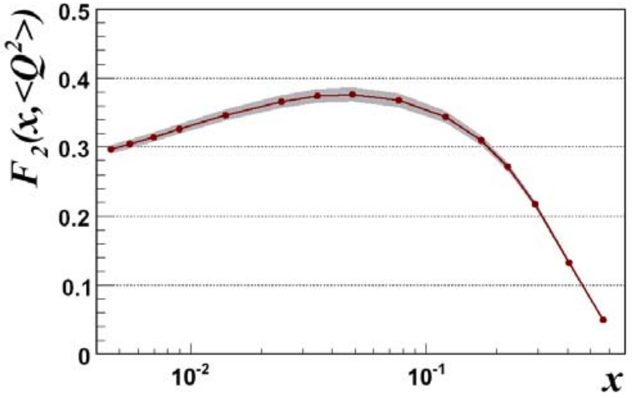
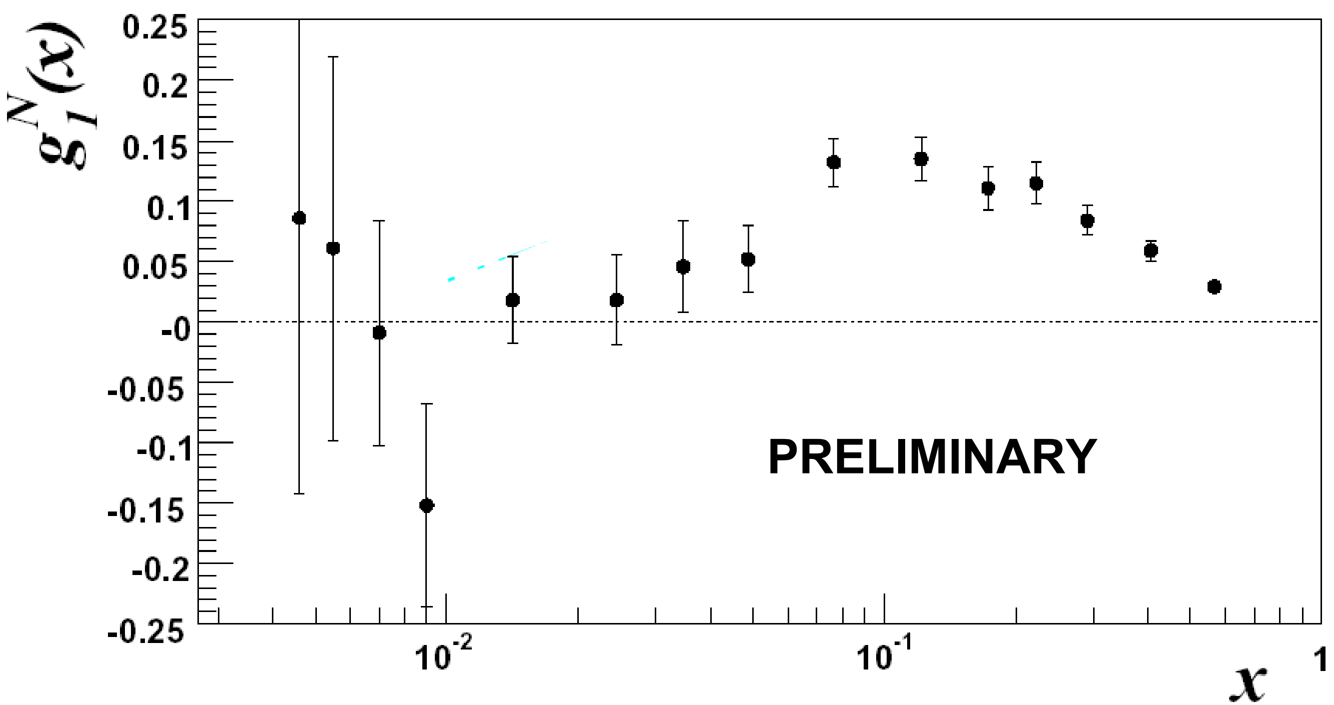
The $g_1^N(x)$ Structure Function

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

$$g_1^N = g_1^d \cdot \left(1 - \frac{3}{2}\omega_D\right)^{-1}, \quad \omega_D = 0.05 \pm 0.01$$





QCD analyses

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

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

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:

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

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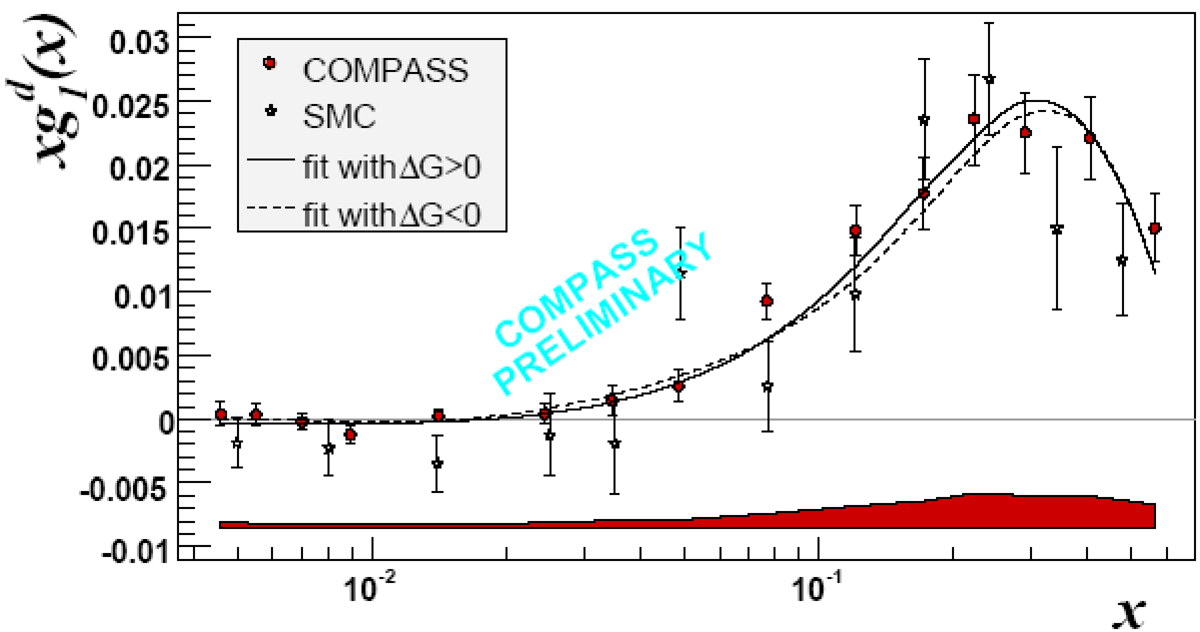
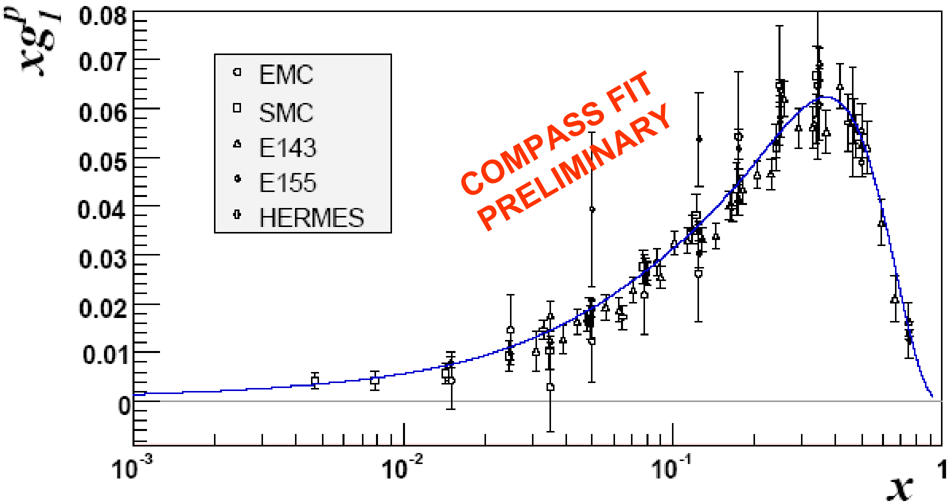
QCD analyses

- **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 ($\overline{\text{MS}}$ scheme)**



Data well described by two solutions: ΔG < 0 and ΔG > 0

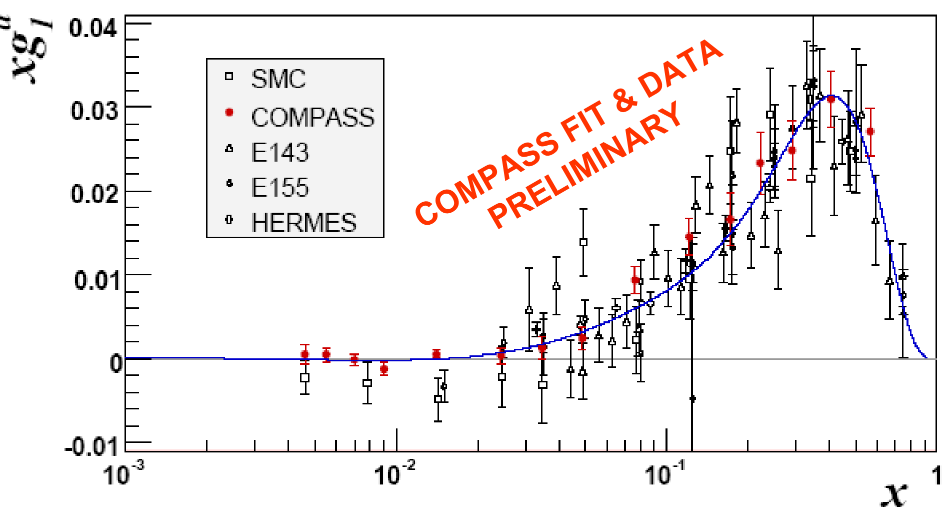
Towards Structure Functions

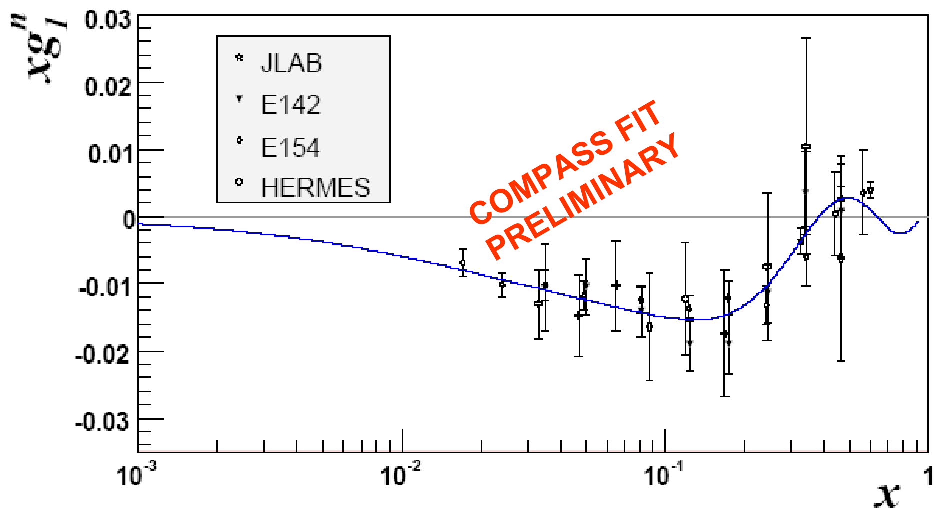


World data and QCD fits at Q_0^2 = 3 GeV^2

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

Solutions with $\Delta G < 0$





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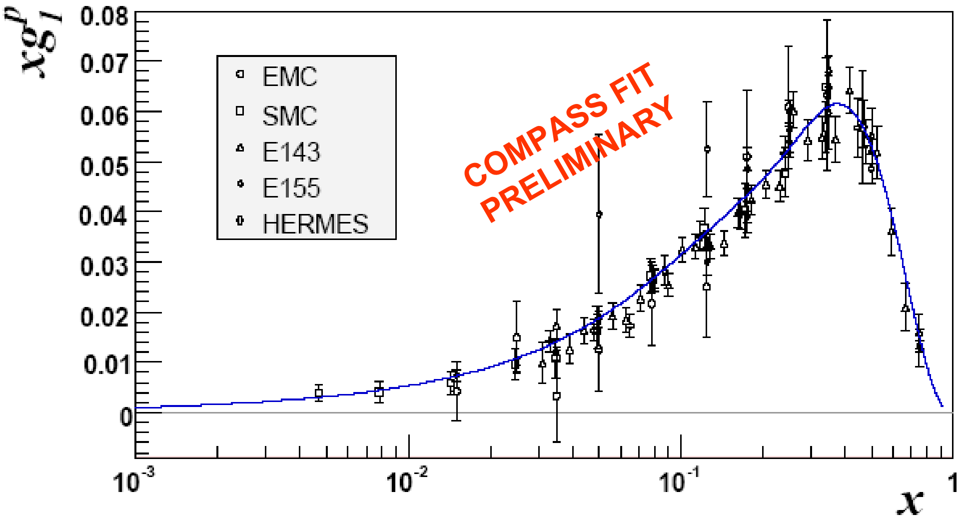
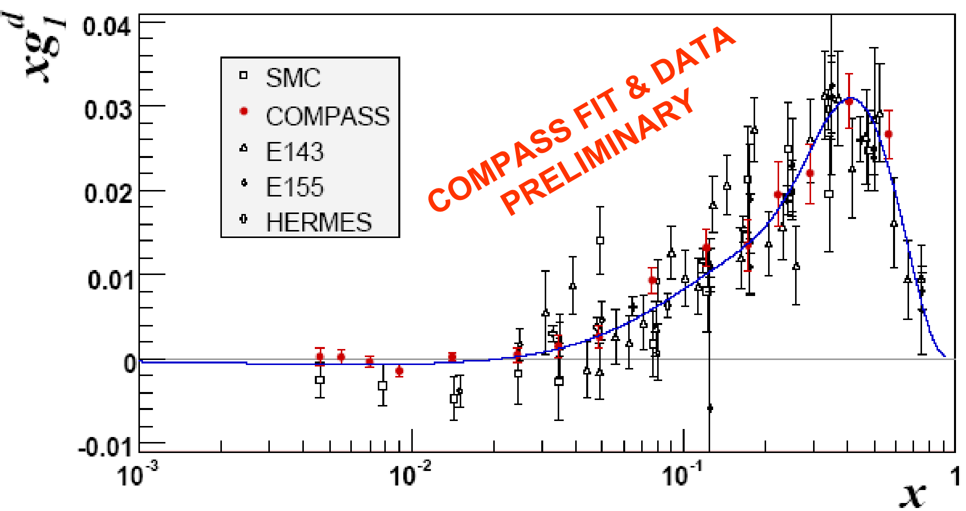
Towards Structure Functions

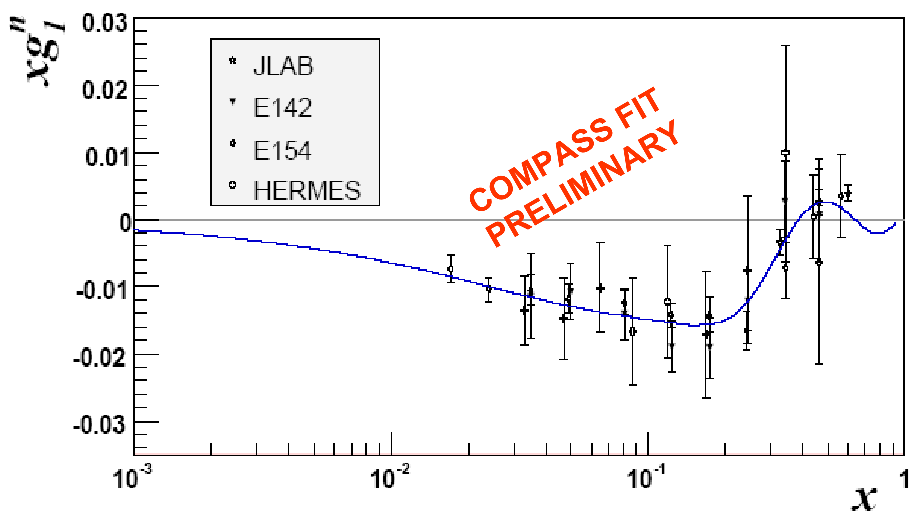
World data and QCD fits at $Q_0^2 = 3\ GeV^2$

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

Solutions with $\Delta G > 0$







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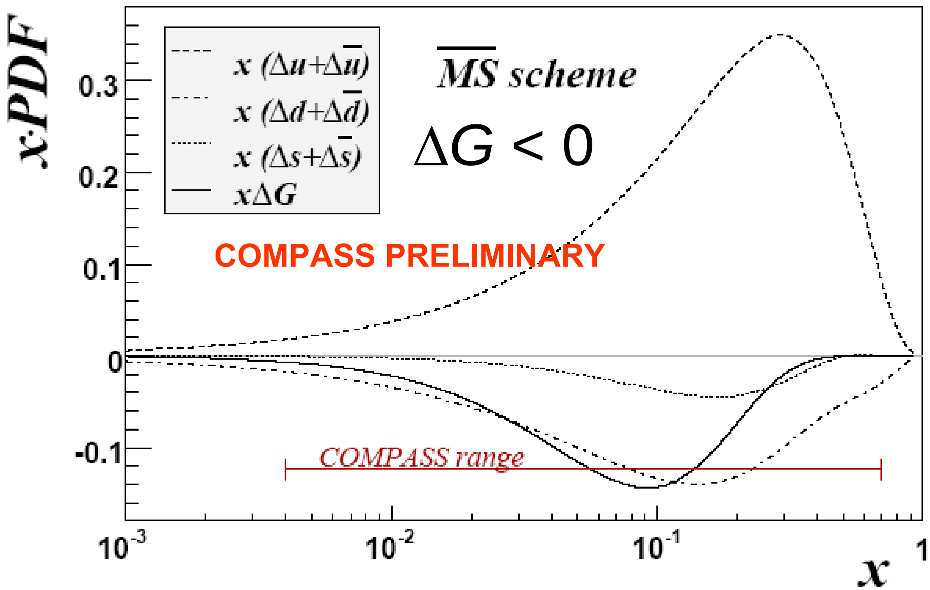
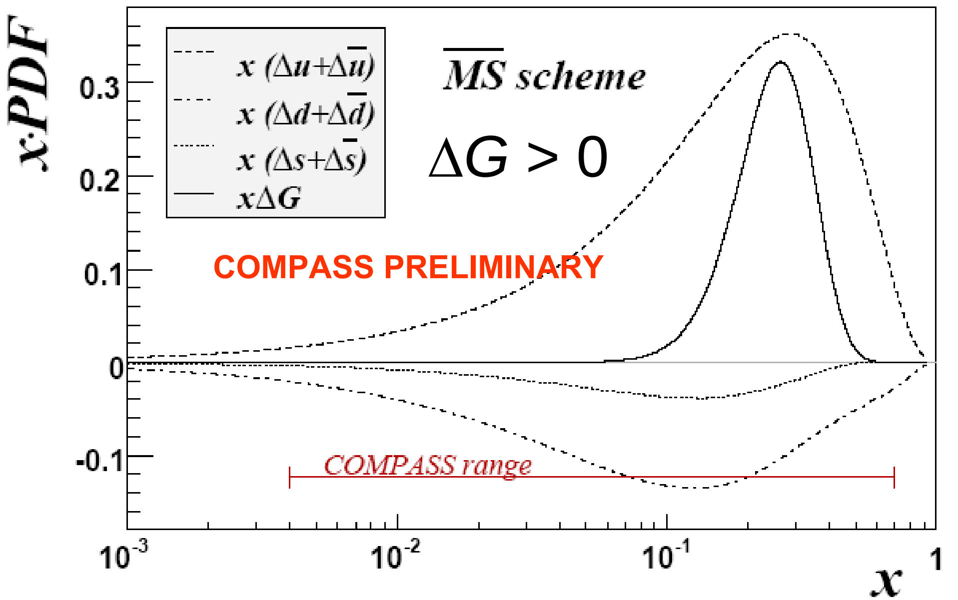
Parton Distributions

at $Q_0^2 = 3$ GeV^2





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

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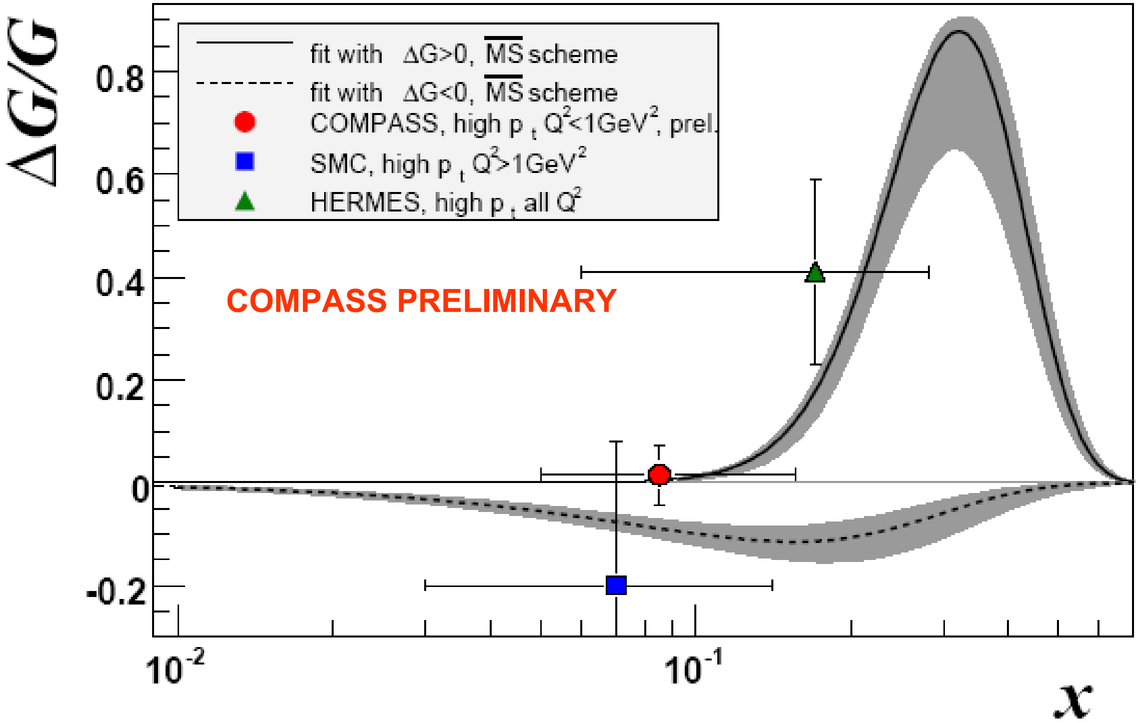
ΔG/G



- ✓ Gluon polarisation $\Delta G/G$
  - Unpolarised $G(x)$ from MRST
  - Bands correspond to statistical errors of ΔG

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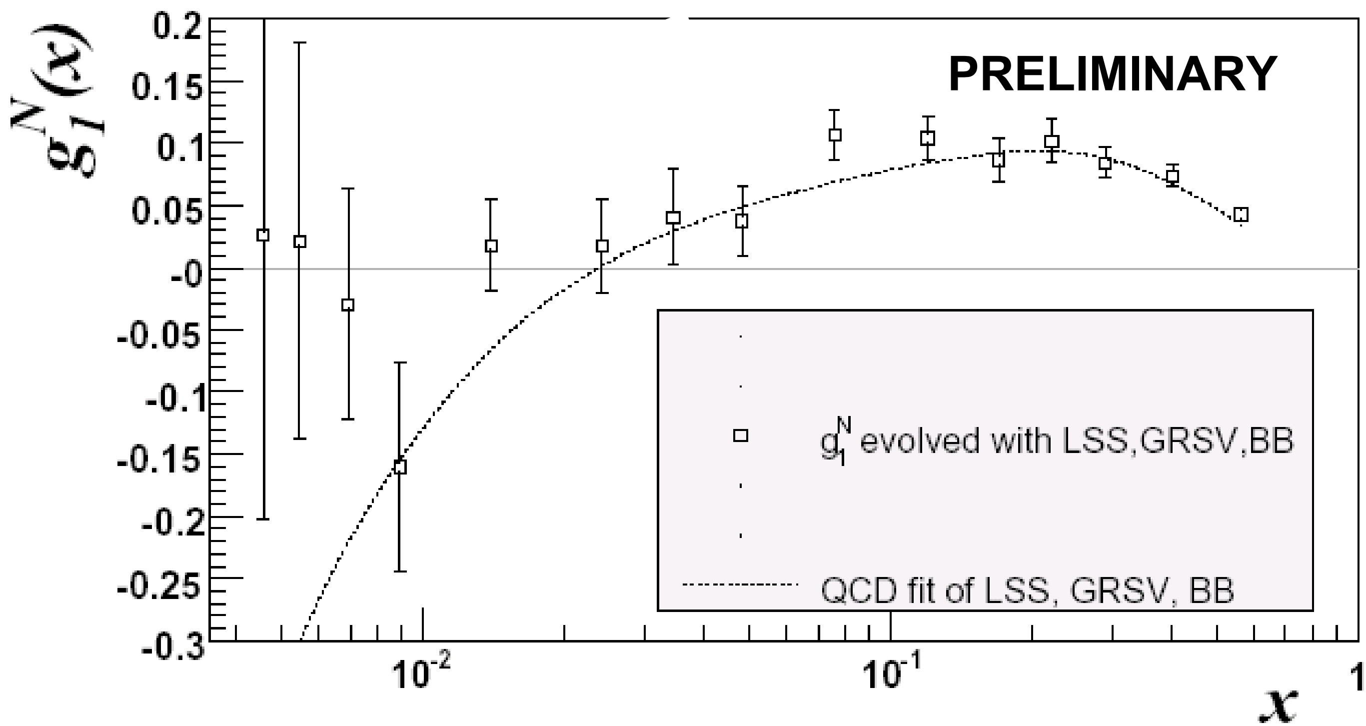
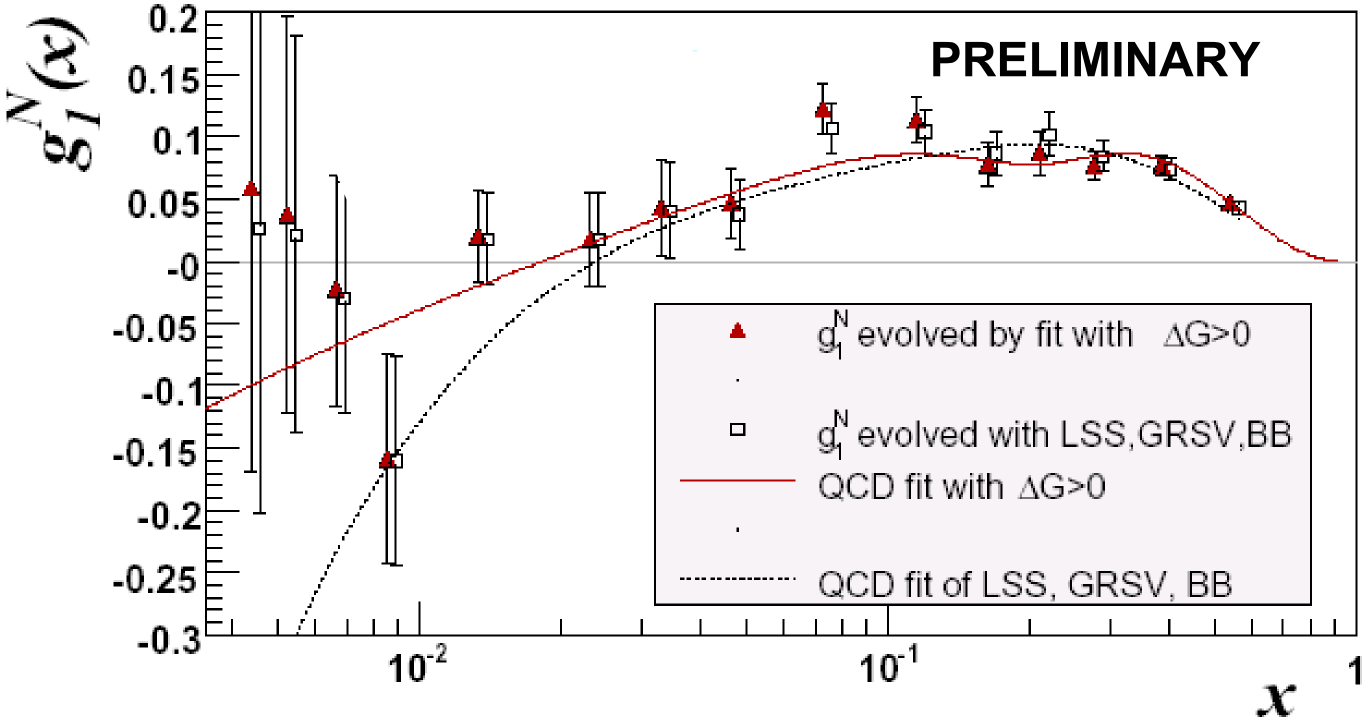
Comparison with previous QCD fits



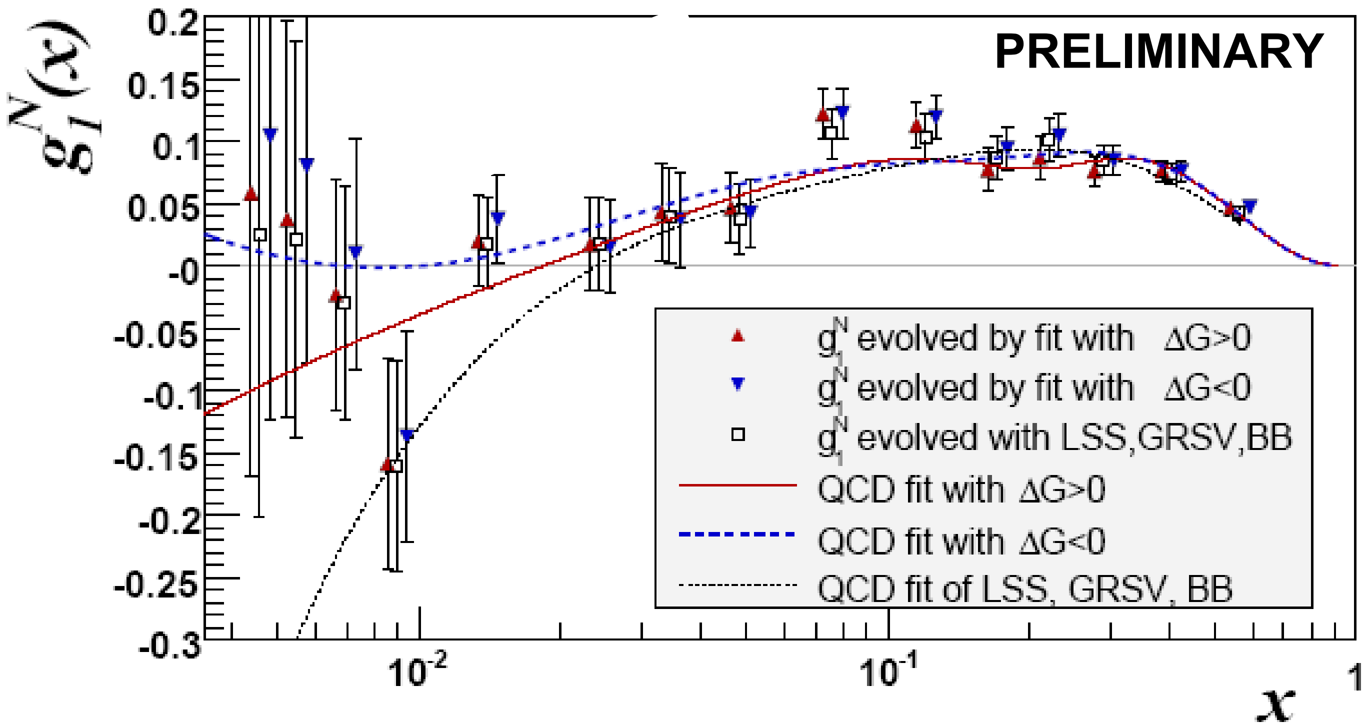
- Different results evolve within QCD to a common Q_0^2 (3 GeV^2)
- Previous QCD fits (LSS05, GRSV, Blumlein and Bottcher averaged) disagree with data at low x

Comparison with previous QCD fits



- Different results evolve within QCD to a common Q_0^2 (3 GeV^2)
- Previous QCD fits (LSS05, GRSV, Blumlein and Bottcher) disagree with data at low x
- QCD fit with $\Delta G > 0$ describes data well

Comparison with previous QCD fits



- Different results evolve within QCD to a common Q_0^2 (3 GeV^2)
- Previous QCD fits (LSS05, GRSV, Blumlein and Bottcher) disagree with data at low x
- Both QCD fits with $\Delta G > 0$ & $\Delta G < 0$ describe data well

QCD Fits Results

(world data)

PRELIMINARY

Quark polarisation:

	$\eta G > 0$	$\eta G < 0$
$\eta\Sigma$	0.28 ± 0.01	0.32 ± 0.01

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

$$\eta_\Sigma = 0.30 \pm 0.01(stat) \pm 0.02(evol)$$

Gluon polarisation (indirect determination via DGLAP):

- **Solutions with $\eta_G > 0$:** $\eta_G^{prog1} = 0.26^{+0.04}_{-0.06}$, $\eta_G^{prog2} = 0.19^{+0.01}_{-0.10}$
- **Solutions with $\eta_G < 0$:** $\eta_G^{prog1} = -0.31^{+0.1}_{-0.1}$, $\eta_G^{prog2} = -0.18^{+0.04}_{-0.03}$

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

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First Moment of g_1
(COMPASS data only)

➢ **First moment of g_1, obtained in the $\overline{\text{MS}}$ renormalisation scheme**

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

(extrapolations to the unmeasured x range give only ≈4% correction)

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

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

With $C_1^S(Q^2)$ and $C_1^{NS}(Q^2)$ evaluated in pQCD at NNLO in α_s and assuming SU(3) and results from hyperon beta decay (Y. Goto *et al*., PRD62 (2000) 034017):
$a_8 = 0.585 \pm 0.025$, $\alpha_s/\pi(Q^2{=}3\text{GeV}^2){=}0.084$

$$\hat{a}_0\left(Q^2\to\infty\right) = 0.33 \pm 0.03(stat) \pm 0.05(syst)$$

PRELIMINARY

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

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Conclusions & Outlook

✓ Longitudinal A_1 inclusive asymmetries measured using 2002, 2003 & 2004 COMPASS data

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

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

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

$$\eta_\Sigma = 0.30 \pm 0.01(stat) \pm 0.02(evol)$$

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

Semi-inclusive analysis, $A_1^{\pi^\pm}$, $A_1^{K^\pm}$ and $A_1^{K_s^0}$, is *in progress*

Data taking continues in 2006

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