Final COMPASS results on the spin-dependent structure functions g_1^p and g_1^d in the deep-inelastic and nonperturbative region

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On behalf of COMPASS Collaboration

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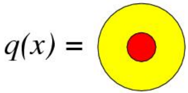
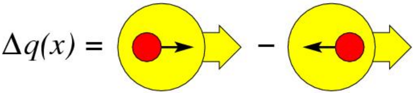
Partonic structure of the nucleon; distribution functions

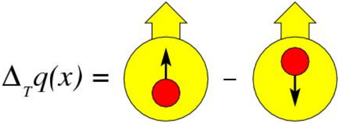
Three twist-two quark distributions in QCD and after integrating over the quark intrinsic k_t



Quark momentum DF;
well known (unpolarised DIS $\rightarrow$ $\mathbf{F_{1,2}(x, Q^2)}$).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a longitudinaly polarised nucleon;
less well known (polarised DIS $\rightarrow$ $\mathbf{g_1(x, Q^2)}$).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow$ $\mathbf{h_1(x, Q^2)}$).

Nonrelativistically: $\Delta_T q(x, Q^2) \equiv \Delta q(x, Q^2)$. OBS.! $\Delta_T q(x, Q^2)$ are C-odd and chiral-odd

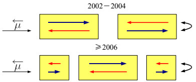
Our goal: measurement of $\mathbf{g_1(x, Q^2)}$ and determination of $\mathbf{\Delta q(x, Q^2)}$

Method of extraction of g_1

- Inclusive asymmetry, $A_{meas}(x,Q^2)$, γ^*-N asymmetry, $A_1(x,Q^2)$, and $g_1(x,Q^2)$:

$$A_{meas} = \frac{1}{f P_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}}\right) \approx D A_1 = D\,\frac{g_1(x,Q^2)}{F_1(x,Q^2)} \stackrel{\mathrm{LO}}{=} D\,\frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

f, D: dilution and depolarisation factors; P_T, P_B: target and beam polarisations;
$N^{\leftrightarrows,\leftleftarrows}$: number of $\vec{\mu}$ interactions in each target cell:
(upstream, downstream) or (outer, central)



- Then $g_1(x,Q^2)$:

$$g_1(x,Q^2) = A_1(x,Q^2)\cdot F_1(x,Q^2) = A_1(x,Q^2)\cdot \frac{F_2(x,Q^2)}{2x(1+R(x,Q^2))}$$

- For the deuteron target:

$$(\text{per nucleon})\, g_1^d = g_1^N\left(1-\frac{3}{2}\omega_D\right) = \frac{g_1^p + g_1^n}{2}\left(1-\frac{3}{2}\omega_D\right); \qquad \omega_D = 0.05 \pm 0.01$$

Method of extraction of g_1,... cont'd

- Polarisation of all two/three target cells measured simultaneously...
- ... and reversed regularly by field reversal or microwave repolarisation
- Number of events in each target cell: $N_i = a_i \phi_i n_i \bar{\sigma}(1 + P_B P_T f D A_1)$
  (a_i - acceptance, ϕ_i - incident flux, n_i - number of target nuclei,
  $\bar{\sigma}$ - spin independent cross section)
- Each event weighted by $w = f D P_B$
  (no P_T as it changes in time $\Longrightarrow$ false asymmetries)
- Calculate A_1 from combinations of Σw; fluxes and acceptances cancel,
  if ratio of acceptances for two sets of cells does not change during field rotation
- f corrected for spin-independent radiative processes: TERAD
- A_1 corrected for spin-dependent radiative processes: POLRAD
- A_1 corrected for polarisable ^{14}N and ^{7}Li in respective targets

Method of extraction of g_1,... cont'd

- Final $g_1^{\mathrm{p,d}}(x,Q^2)$ is extracted as:

$$g_1^{\mathrm{p,d}}(x,Q^2) = A_1^{\mathrm{p,d}}(x,Q^2) \cdot \frac{F_2^{\mathrm{p,d}}(x,Q^2)}{2x(1+R(x,Q^2))}$$

- Input $F_2^{\mathrm{p,d}}(x,Q^2)$: from NMC measurements at $Q^2 > 0.2$ (GeV/c)^2 PRD 58, 112001; at $Q^2 < 0.2$ (GeV/c)^2 – from the model based on the GVMD concept PLB 295 (1992) 263

- Input $R(x,Q^2)$: R1998, PLB 452 (1999) 194, suitably extended to low Q^2, PLB 647 (2007) 330

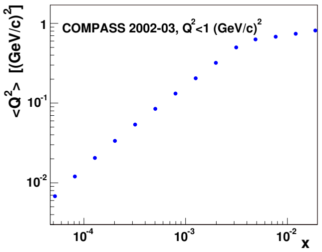
- Maximal systematic uncertainties on A_1:

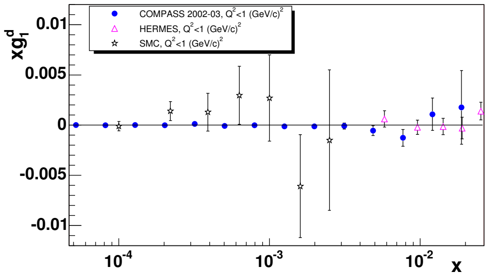
  at low Q^2: from $D(R)$, $\sim (0.01 - 0.39)D$ (mult.)
  and false asymm., $\sim 1.5\,\sigma_{\mathrm{stat.}}$ (additive)
  at high Q^2: from P_B, P_T, $\sim 0.05 P_B, P_T$ (mult.)
  and false asymm., $< 0.8\,\sigma_{\mathrm{stat.}}$ (additive)

g_1^{d} at low Q^2

g_1^{d} in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)

V.Yu. Alexakhin (COMPASS) *et al.* Phys. Lett. B **647** (2007) 330

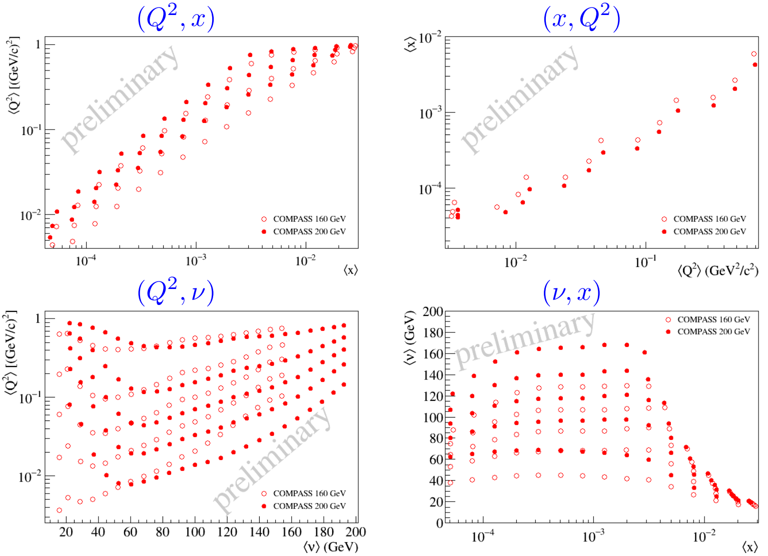




- More than ten-fold improvement over the statistical precision of SMC.
- Spin effects in g_1^{d} at low x and Q^2 absent ?

g_1^{p} at low Q^2

Phase space coverage of the low Q^2, low x measurement of $g_1^{\rm p}$



g_1^{p} at low Q^2: data sample

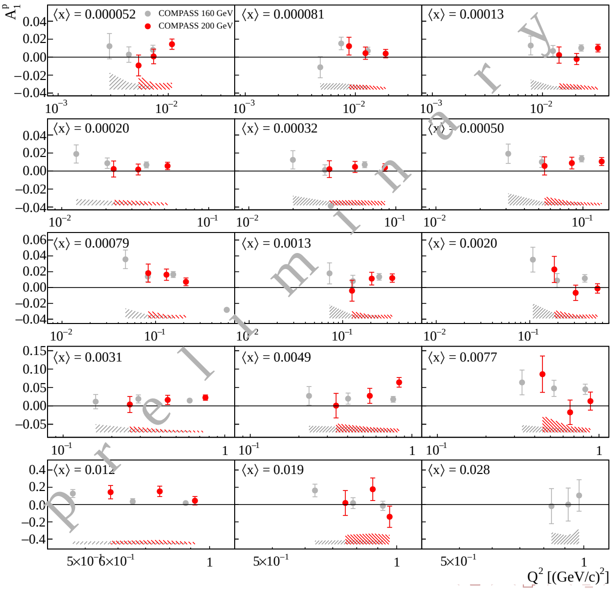
- Reconstructed event: (incident μ) $\wedge$ (outgoing μ) $\wedge$ (at least 1 outtrack)
  This “hadron method” does not bias inclusive asymmetry @ low x (SMC)
  but improves resolution of interaction point and decreases radiative bckg.

- Kinematic cuts
  - $Q^2 < 1$ (GeV/c)^2
  - $x > 4 \times 10^{-5}$ (at smaller x uncertainties on x large)
  - 0.1 $< y <$0.9 (bad reconstruction @ low y, large rad. corr. @ large y)
  - Above cuts result in: $W \gtrsim$ 5 GeV/c^2

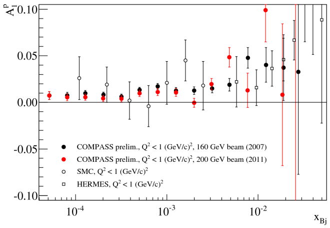
- Removed $\mu e \to \mu e$ events, around $x_{\mu e} = m_{\mathrm{e}}/M_{\mathrm{p}} = 5.45 \times 10^{-4}$

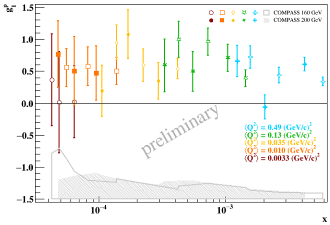
- Final sample: 447 million events @ 160 GeV + 229 million events @ 200 GeV
  $\Longrightarrow \sim 150\times$ SMC statistics

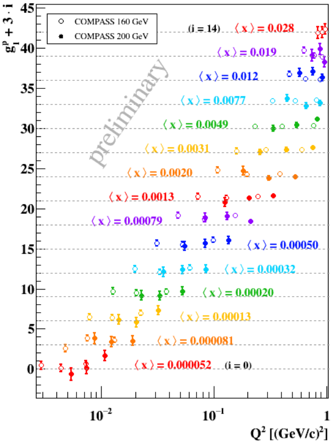
Low Q^2: results on $A_1^p(x, Q^2)$



Low Q^2: results on $A_1^{\rm p}(x)$ and $g_1^{\rm p}(x, Q^2)$







- More than ten-fold improvement over the statistical precision of SMC.
- Very clear spin effects in $g_1^{\rm p}$ at low x and Q^2

Importance of $g_1(x, Q^2)$ at low x, Q^2

- At low x: strong increase of parton density with decreasing x
  $\Longrightarrow$ parton recombination effects

- Low x effects particularly visible in $g_1^{\rm NS} \Longrightarrow \ln^2(1/x)$ terms

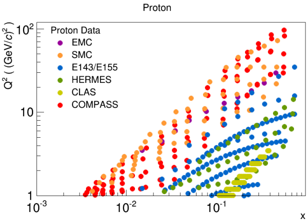
- BUT: in fixed-target experiments low x correlated with low Q^2 region
  $\Longrightarrow$ nonperturbative effects must be considered
  and parton mechanisms have to be suitably extended to low Q^2.

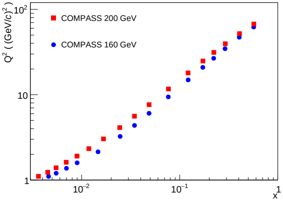
- Attempts to describe that region phenomenologically:
  - B. Badelek, J. Kwiecinski, J. Kiryluk, Phys. Rev. D61 (2000) 014009.
  - B. Badelek, J. Kwiecinski, B. Ziaja, Eur. Phys. J. C26 (2002) 45.
  - B.I. Ermolaev, M. Greco, S.I. Troyan, Eur. Phys. J. C50 (2007) 823; *ibid.* C51 (2007) 859.
  - W. Zhu, J. Ruan, Int. J. Mod. Phys. E24 (2015) 1550077.

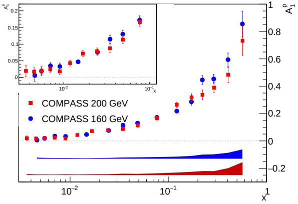
g_1^{p} at $Q^2 > 1$ (GeV/c)^2

g_1^{p}: data samples

- Measurements at incident E = 160 GeV (from 2007): PLB 690 (2010) 466
- Measurements at incident E = 200 GeV (from 2011): PLB 753 (2016) 18
  energy increased to reach lower x and higher Q^2
  (and to balance the amount of data from the deuteron target)
- Final sample: 85 million events @ 160 GeV + 77 million events @ 200 GeV
- Results on A_1^{p} at both energies agree very well

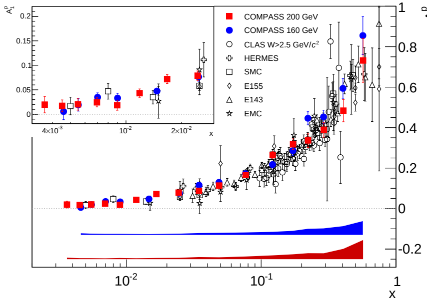


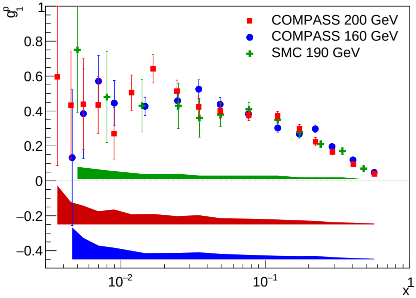




Results on $A_1^{\rm p}(x)$ and $g_1^{\rm p}(x)$

- $A_1^{\rm p}(x)$ and $g_1^{\rm p}(x)$ shown at the measured values of Q^2
- Bands of systematic uncertainties for each energy separately

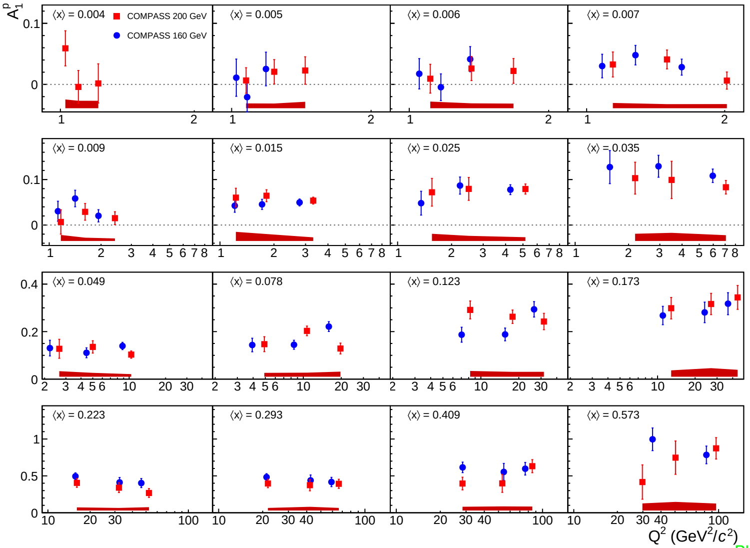




PLB 753 (2016) 18

- Good agreement of $A_1^{\rm p}(x)$ and $g_1^{\rm p}(x)$ with world data
- $g_1^{\rm p}(x)$ clearly positive at lowest measured values of x

Results on $A_1^p(x, Q^2)$ at 160 and 200 GeV

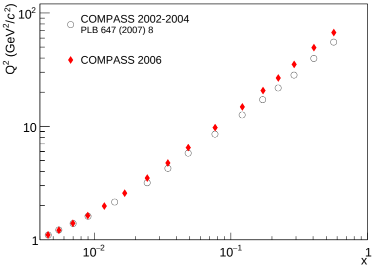


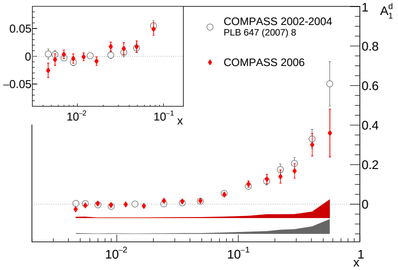
PLB 753 (2016) 18

g_1^{d} at $Q^2 > 1$ (GeV/c)^2

g_1^{d}: data samples

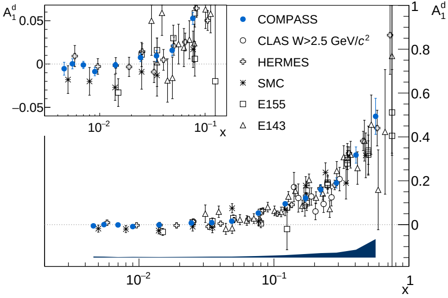
- Data at E = 160 GeV (from 2002–2004) published PLB 647 (2007) 8
- Data at E = 160 GeV (from 2006)
  combined results in hep-ex/1612.00620, accepted PLB
- Final sample: 135 million events
- Results on A_1^{d} in both samples agree very well

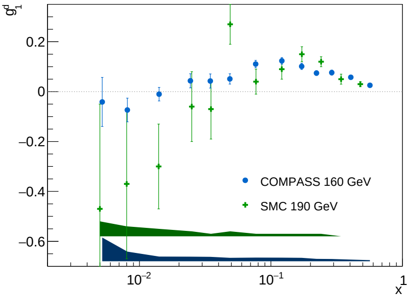




Results on $A_1^{\mathrm{d}}(x)$ and $g_1^{\mathrm{d}}(x)$

- Combined results from 2002–2004 and 2006
- $A_1^{\mathrm{d}}(x)$ and $g_1^{\mathrm{d}}(x)$ shown at the measured values of Q^2

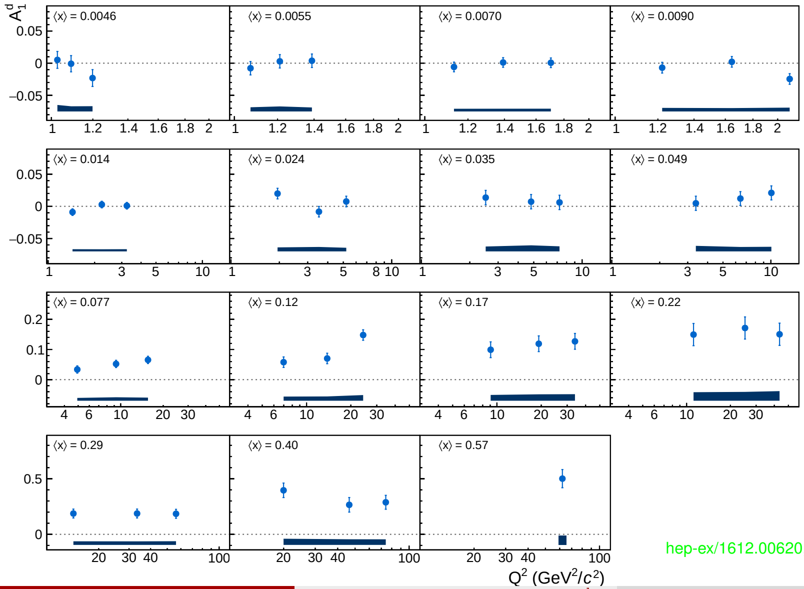




hep-ex/1612.00620, accepted PLB

- Good agreement of $A_1^{\mathrm{d}}(x)$ and $g_1^{\mathrm{d}}(x)$ with world data
- $g_1^{\mathrm{d}}(x)$ compatible with zero at lowest measured values of x, contrary to hints from SMC

Results on $A_1^{\mathrm{d}}(x, Q^2)$



hep-ex/1612.00620, accepted PLB

NLO QCD fit to p,d, ^{3}He world data

PLB 753 (2016) 18

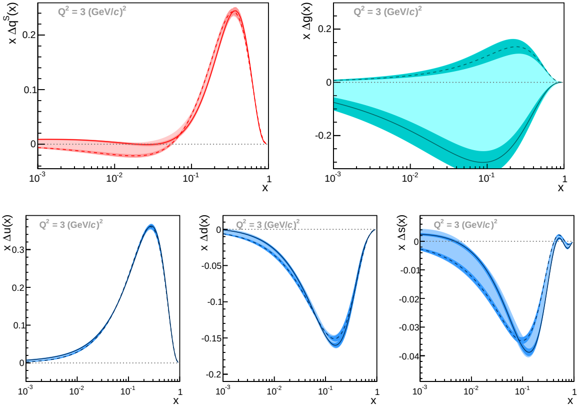
NLO QCD fit: conditions

- A fit of the g_1^{p}, g_1^{d}, $g_1^{^3\mathrm{He}}$ inclusive data
- $\overline{\mathrm{MS}}$ scheme
- $W^2 < 10$ (GeV/c^2)^2 excluded
- Number of data points total/COMPASS: 495/138
- Fitted: Δg, $\Delta q^{\mathrm{s}} = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) + \Delta(s+\bar{s})$, gluons, singlet
  $\Delta q_3 = \Delta(u+\bar{u}) - \Delta(d+\bar{d})$ nonsinglet
  $\Delta q_8 = \Delta(u+\bar{u}) + 2\Delta(d+\bar{d}) - \Delta(s+\bar{s})$ nonsinglet
- Parameterisation (at $Q_0^2 = 1$ (GeV/c)^2):

$$\Delta f_k(x) = \eta_k \frac{x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)}{\int_0^1 x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)\mathrm{d}x}, \quad (k = s, 3, 8, g)$$

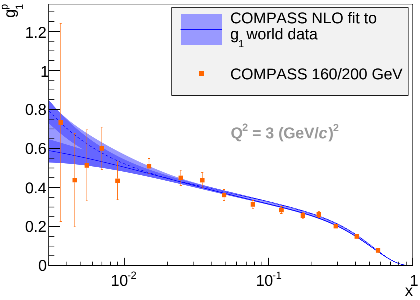
  η_k = first moment of $\Delta f_k(x)$ at Q_0^2
- Number of free parameters in the fitted pdfs: 11
- Only statistical errors taken, normalisations of each data set varied
- Required at every iteration:
  $|\Delta q(x) + \Delta\bar{q}(x)| \leq q(x) + \bar{q}(x)$, $|\Delta g(x)| \leq g(x)$ at $Q^2 = 1$ (GeV/c)^2
- Studied: parameterisation $\Delta f_k(x)$ dependence and Q_0^2 dependence of the fit.

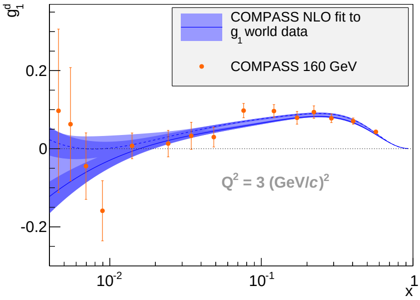
NLO QCD fit: results



- Statistical uncertainties (dark bands) $\ll$ systematic (light bands)
- Gluon polarisation poorly constraint $\Longrightarrow$ “direct” methods
- Quark spin contribution to the nucleon spin: 0.26 $< \Delta\Sigma <$0.36 (due to poor Δg)

NLO QCD fit: results...cont'd

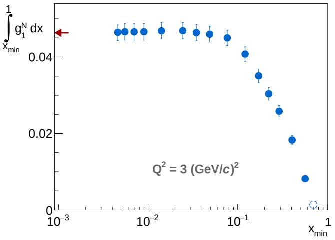




- g_1^{p} clearly positive at low x and raising with decreasing x
- g_1^{d} consistent with zero at low x ?

First moments of g_1 and singlet axial charge a_0

hep-ex/1612.00620, accepted PLB



- First moments $\Gamma_1^{\rm p}, \Gamma_1^{\rm d}, \Gamma_1^{\rm N}$
  where $\Gamma_1^{\rm i} = \int_0^1 g_1^{\rm i}(x, Q^2){\rm d}x$
- In particular:
  $$\Gamma_1^{\rm N}(Q^2) = \frac{1}{36}\left[4a_0 C_{\rm S}(Q^2) + a_8 C_{\rm NS}(Q^2)\right]$$
  $$= \int_0^1 \frac{g_1^{\rm d}(x, Q^2)}{1 - 1.5\omega_{\rm D}}{\rm d}x$$
- In the $\overline{\rm MS}$: $a_0 = \Delta\Sigma = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})$
- $\Gamma_1^{\rm N}$ approaches asymptotic value already at Q^2 = 3 (GeV/c)^2
- From COMPASS data alone:
  $\Gamma_1^{\rm N}(Q^2$ = 3 (GeV/c)^2) = 0.046 $\pm 0.002_{\rm stat.} \pm 0.004_{\rm syst.} \pm 0.005_{\rm evol.}$
- From COMPASS data alone (and a_8 from PRD 82 (2010) 114018):
  $a_0(Q^2$ = 3 (GeV/c)^2)= 0.32 $\pm 0.02_{\rm stat.} \pm 0.04_{\rm syst.} \pm 0.05_{\rm evol.}$
  (consistent with value from the COMPASS NLO QCD fit of world data).

Non-singlet structure function, $g_1^{\mathrm{NS}}(x, Q^2)$

- Non-singlet structure function:

$$g_1^{\mathrm{NS}} = g_1^{\mathrm{p}}(x, Q^2) - g_1^{\mathrm{n}}(x, Q^2) = 2\left[g_1^{\mathrm{p}}(x, Q^2) - g_1^{\mathrm{N}}(x, Q^2)\right]$$

- Its moment connected to the Bjorken sum rule:

$$\Gamma_1^{\mathrm{NS}}(Q^2) = \int_0^1 g_1^{\mathrm{NS}}(x, Q^2)\mathrm{d}x = \frac{1}{6}\left|\frac{g_\mathrm{A}}{g_\mathrm{V}}\right| C_1^{\mathrm{NS}}(Q^2)$$

- g_1^{NS} calculated, NLO QCD fitted (only Δq_3), evolved to Q^2= 3 (GeV/c)^2 and fit-extrapolated $x \to 0, 1$:

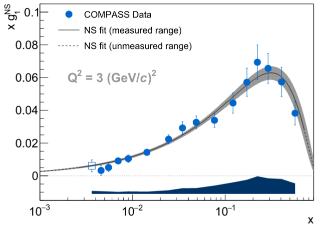
$$\Gamma_1^{\mathrm{NS}} = 0.192 \pm 0.007_{\mathrm{stat.}} \pm 0.015_{\mathrm{syst.}}$$

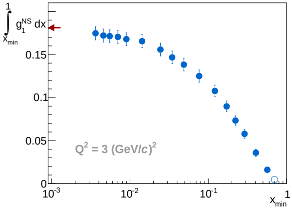
$$\left|\frac{g_\mathrm{A}}{g_\mathrm{V}}\right| = 1.29 \pm 0.05_{\mathrm{stat.}} \pm 0.10_{\mathrm{syst.}}$$

- Neutron β decay gives: $|g_\mathrm{A}/g_\mathrm{V}| = 1.2701 \pm 0.002$

PDG, PRD86 (2012) 010001

PLB 753 (2016) 18





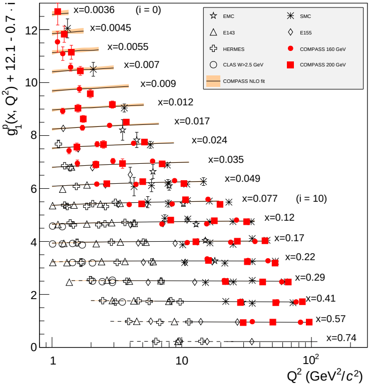
- This validates the Bjorken sum rule with an accuracy of 9%

g_1^p and g_1^d, Q^2 >1 (GeV/c)^2, COMPASS full statistics

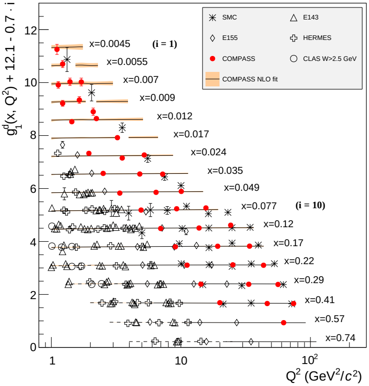
COMPASS NLO QCD fit to the world data at $W^2 > 10$ (GeV/c^2)^2

dashed line: extrapolation to $W^2 < 10$ (GeV/c^2)^2

proton



deuteron



Phys.Lett.B753(2016)18

hep-ex/1612.00620, accepted PLB

COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

To remember

- COMPASS legacy on $g_1^{\mathrm{p}}(x, Q^2)$ and $g_1^{\mathrm{d}}(x, Q^2)$ presented for DIS (Q^2 >1 (GeV/c)^2) and nonperturbative (Q^2 <1 (GeV/c)^2) regions

- The $g_1^{\mathrm{p}}(x)$ at low x and low Q^2 is clearly positive ($g_1^{\mathrm{d}}(x)$ is consistent with zero) $\Longrightarrow$ first observation of the spin effect at such low x

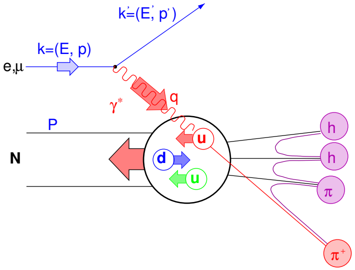
- The $g_1^{\mathrm{p}}(x)$ at low x is positive (and $g_1^{\mathrm{d}}(x) \approx 0$) also at Q^2 >1 (GeV/c)^2

- NLO QCD fit of g_1 world data gave well constrained quark distributions; gluons poorly determined. Quark helicity contribution to nucleon spin: $0.26 < \Delta\Sigma < 0.36$

- From the COMPASS data alone:
  - first moments determined and Bjorken sum rule verified to 9% accuracy
  - flavour-singlet axial charge a_0 extracted:
    $a_0(Q^2$ = 3 (GeV/c)^2)= 0.32 $\pm 0.02_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}} \pm 0.05_{\mathrm{evol.}}$
    (in $\overline{\mathrm{MS}}$ identified with total contribution of quark helicities to the nucleon spin)

SPARES

Nucleon spin structure in DIS: $\mu + \mathrm{N} \rightarrow \mu' + \mathrm{X}$

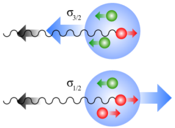


- $\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\mathrm{d}E'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}$, $q(x,Q^2) \longrightarrow g_{1,2}$, $\Delta q(x,Q^2)$ where $q = q^+ + q^-$, $\Delta q = q^+ - q^-$, but...
- ...anomalous gluon contribution to $g_1(x,Q^2)$
- ...$g_2(x,Q^2)$ has no interpretation in terms of partons.

Definitions of DIS variables...

$Q^2 = -q^2$	γ^* virtuality
$x = Q^2/(2Pq)$	Bjorken variable
$y = Pq/(Pk)$	relative γ^* energy
$W = P + q$	γ^*-N cms energy

...and of the γ^*-N asymmetry (e.g. for γ^*-p):



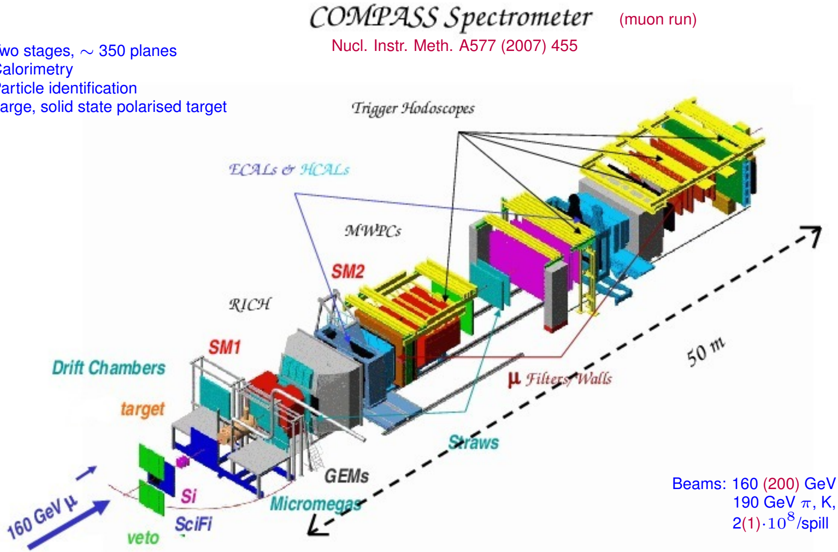
$$A_1(x,Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

NA58, at the CERN SPS
$\sim$ 250 physicists
$\sim$ 30 institutes

Muon programme	Hadron programme
Spin dependent structure functions g_1 Gluon polarisation in the nucleon Quark polarisation distributions Transversity Vector meson production Λ polarisation	Primakoff effect, π and K polarisabilities Exotic states, glueballs (Double) charmed barions Multiquark states
DVCS/GPD	Drell–Yan process on a polarised target

Two stages, $\sim$ 350 planes
Calorimetry
Particle identification
Large, solid state polarised target

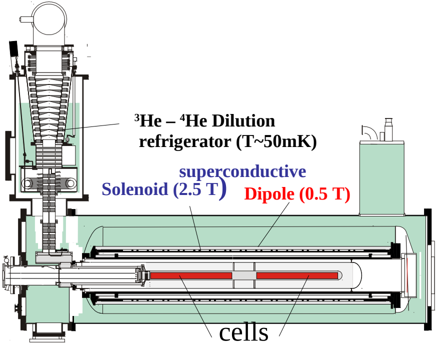


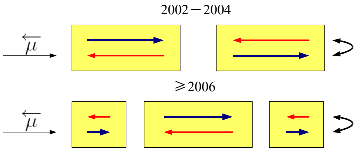
(muon run)

Nucl. Instr. Meth. A577 (2007) 455

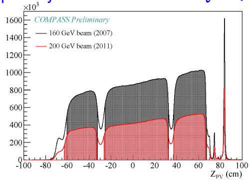
Beams: 160 (200) GeV $\mu^{\pm}$
190 GeV π, K, p
2(1)$\cdot 10^8$/spill

COMPASS polarised targets: NH_3 and ^{6}LiD





NH_3, primary vertex resolution at $Q^2 < 1$ (GeV/c)^2



* Two (three) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent after 2005) by field rotation
* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after 2005)