New COMPASS results on A_1^p and g_1^p and QCD fit

Ana S. Nunes (LIP-Lisbon)
on behalf of the COMPASS Collaboration

QCD 14, Montpellier, France
June 30 - July 3, 2014

Outline

1. Introduction
2. New results on A_1^p and g_1^p for $Q^2 > 1~\mathrm{GeV}^2/c^2$
   - QCD fit
   - Test of the Bjorken sum rule
3. New results on A_1^p and g_1^p for $Q^2 < 1~\mathrm{GeV}^2/c^2$
   - Comparison with previous experiments and with model
4. Summary and outlook

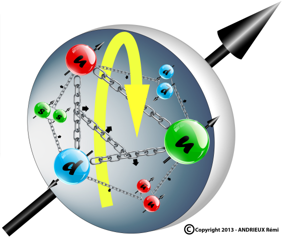
Introduction

Nucleon spin

Decomposition

$$S = \frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quarks}} + \underbrace{\Delta G}_{\text{gluons}} + \underbrace{L_q + L_q}_{\text{orbital angular momenta}}$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$



$\Delta q \equiv \Delta(q + \bar{q})$
$\Delta q = \overrightarrow{q} - \overleftarrow{q}$ (parallel minus antiparallel to the nucleon spin)
$\mathbf{g_1(x, Q^2)} \simeq \sum_q e_q^2 \Delta q(x, Q^2)$

"Spin crisis"

- Relativistic quark model prediction: $\Delta\Sigma \simeq 0.6$
- SMC measurement (1988): $\Delta\Sigma = 0.12 \pm 0.17$

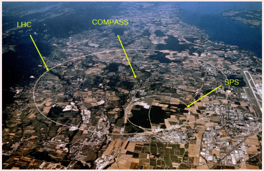
Recent status

- Quark spin contributes only about 30% to the nucleon spin
- Gluon contribution constrained only for a limited x range
- Very few experimental results on orbital angular momentum

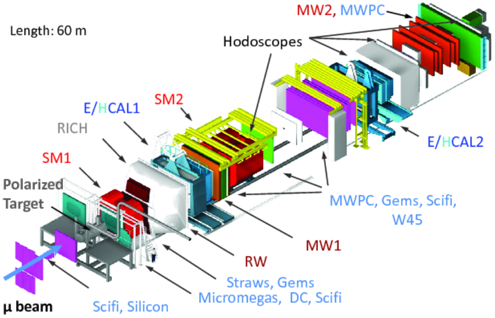
COMPASS experiment

COMPASS @ CERN

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



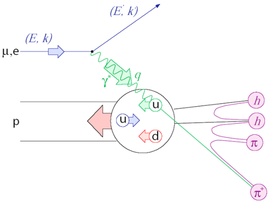
- **Fixed target experiment** at the SPS using a tertiary **muon beam**
- Collaboration of about 200 members from 11 countries and 23 institutions



- 160/200 GeV μ^+ **polarised beam**, $P_b \sim -80\%$
- **^{6}LiD** or **NH_3**, 1.2 m long, **polarised target** @ 2.5 T and 60 mK, $P_{target} \sim 50/85\%$

- large acceptance, two staged spectrometer
- tracking, calorimetry, RICH

DIS and spin observables



$$k_\mu = (E_\mu, \mathbf{k}_\mu)$$
$$k'_\mu = (E'_\mu, \mathbf{k}'_\mu)$$
$$P = (M, 0)$$
$$q = \mathbf{k}_\mu - \mathbf{k}'_\mu = (\nu, \mathbf{q})$$
$$Q^2 = -q^2$$
$$\nu = P \cdot q / M = E_\mu - E'_\mu$$
$$W^2 = M^2 + 2M\nu - Q^2$$
$$x = Q^2/(2M\nu)$$
$$y = \nu / E_\mu$$

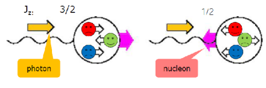
Experimental asymmetry

$$\mathbf{A_{exp}} = \frac{N^{\stackrel{\rightarrow}{\Leftarrow}} - N^{\stackrel{\rightarrow}{\Rightarrow}}}{N^{\stackrel{\rightarrow}{\Leftarrow}} + N^{\stackrel{\rightarrow}{\Rightarrow}}} = P_{\text{beam}} P_{\text{target}} f \, A_{\parallel}$$

Lepton-nucleon asymmetry

$$A_{\parallel} = \frac{d\sigma^{\stackrel{\rightarrow}{\Leftarrow}} - d\sigma^{\stackrel{\rightarrow}{\Rightarrow}}}{d\sigma^{\stackrel{\rightarrow}{\Leftarrow}} + d\sigma^{\stackrel{\rightarrow}{\Rightarrow}}} \simeq D A_1 \qquad \mathbf{A_1} \simeq A_{\parallel}/D$$

Virtual photon-nucleon asymmetry



$$A_1 = A_1^{\gamma^* N} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1}$$

Spin dependent structure function g_1

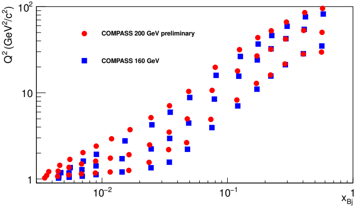
$$\mathbf{g_1(x, Q^2)} \simeq \frac{F_2(x, Q^2)}{2x(1 + R(x, Q^2))} A_1(x, Q^2), \quad \text{with } R \equiv \frac{\sigma_L}{\sigma_T}$$

New results on A_1^p and g_1^p for $Q^2 > 1$ GeV$^2/c^2$

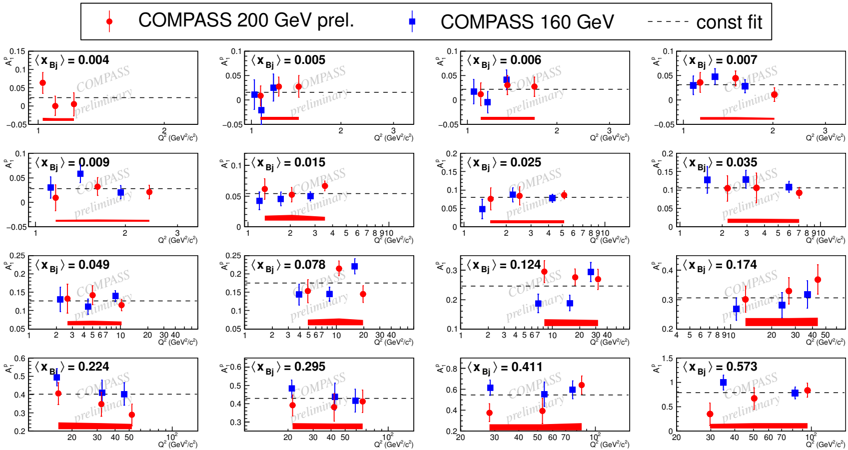
Inputs for A_1^p and g_1^p @ $Q^2 > 1$ GeV$^2/c^2$

- Data taken by COMPASS in 2007 @ 160 GeV/c and in 2011 @ 200 GeV/c
- Obtained giving each event a weight $\omega = \mathbf{f\,D}|\mathbf{P_b}|$ to optimize the statistical errors of the results
- Unpolarised radiative corrections (RC), included in the dilution factor, from TERAD[1]
- Polarised radiative corrections from POLRAD[2]
- Corrected for polarisable ^{14}N in the ammonia target

Acceptance

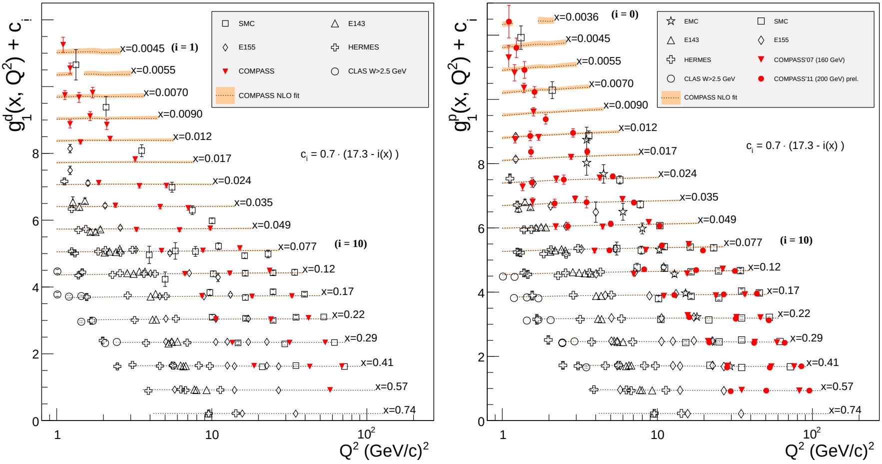


Results on A_1^p in DIS ($Q^2 > 1$ GeV$^2/c^2$)



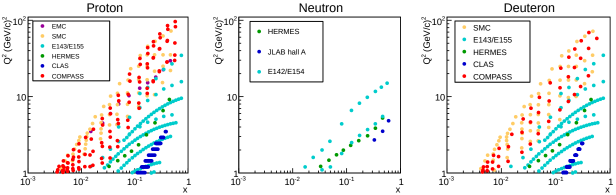
- New asymmetries at **low x**
- Results from two beam energies compatible
- Well fit by constant

Results on g_1^d and g_1^p in DIS ($Q^2 > 1\ \mathrm{GeV}^2/c^2$)



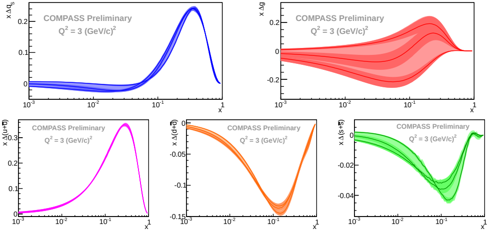
- New COMPASS point for the proton at **low x**
- **New COMPASS NLO QCD fit** describes the data well

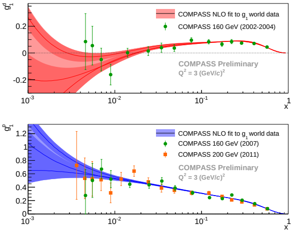
Inputs and constraints for NLO QCD fit



- 139 out of 674 points are from COMPASS
- $g_1^{p(n)} = \frac{1}{9}\left[C_S \otimes \mathbf{\Delta q_S} + C_{NS} \otimes \left(\pm\frac{3}{4}\mathbf{\Delta q_3} + \frac{1}{4}\mathbf{\Delta q_8}\right) + C_g \otimes \mathbf{\Delta g}\right]$
  - $\Delta q_S = \Delta u + \Delta d + \Delta s$ (spin singlet parton distribution)
  - $\Delta q_3 = \Delta u - \Delta d$ (triplet non-singlet spin distribution)
  - $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$ (octet non-singlet spin distribution)
  - C_S, C_{NS}, C_g: Wilson coefficients associated to each distribution
- Functional forms are assumed at a given reference scale Q_0^2
- $SU(3)_f$ to fix the non-singlet distributions first moments: $\int_0^1 (\Delta u - \Delta d)\, dx = F + D = g_A/g_V$ and $\int_0^1 (\Delta u + \Delta d - 2\Delta s)\, dx = 3F - D$
- Positivity: $|\Delta g(x)| < |g(x)|$ and $|\Delta(s(x) + \bar{s}(x))| < |s(x) + \bar{s}(x)|$

NLO QCD fit results





- Depending upon assumed fonctional forms, **3 categories of solutions**: $\Delta G > 0$, $\Delta G \sim 0$ and $\Delta G < 0$
- Gluon polarisation: ΔG **not well constrained by the fit**
  $\hookrightarrow$ direct measurements needed
- Quark polarisation: **0.26** $<$ $\mathbf{\Delta\Sigma}$ $<$ **0.34** @ $Q_0^2 = 3\ (\mathrm{GeV}/c)^2$ ($\overline{\mathrm{MS}}$)
  $\hookrightarrow$ largest uncertainty from functional forms
- Large uncertainty at very low x for g_1^p and g_1^d

Test of the Bjorken sum rule

Bjorken sum rule

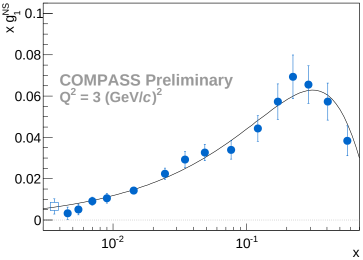
$$\int_0^1 \mathbf{g_1^{NS}(x, Q^2)}\, dx = \int_0^1 \left[g_1^p(x, Q^2) - g_1^n(x, Q^2)\right]\, dx = \frac{1}{6}\left|\frac{\mathbf{g_A}}{\mathbf{g_V}}\right| C_1^{NS}(Q^2)$$

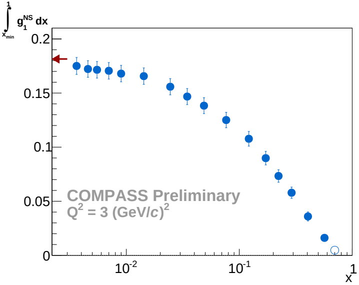
- Fundamental QCD prediction connecting p and n
- Test of $SU(2)_{\text{flavour}}$
- Decorrelated from ΔG
- g_1^{NS} from COMPASS data alone (w/ proton and deuteron targets):

$$g_1^{NS} = g_1^p - g_1^n = 2\left[g_1^p - \frac{g_1^d}{1 - 3/2 \cdot \omega_D}\right], \text{ with } \omega_D = 0.05 \pm 0.01$$

- $C_1^{NS} = \underbrace{1}_{LO} - \underbrace{\left(\frac{\alpha_S}{\pi}\right)}_{NLO} - \underbrace{p_1\left(\frac{\alpha_S}{\pi}\right)^2}_{NNLO} - \underbrace{p_2\left(\frac{\alpha_S}{\pi}\right)^3}_{NNNLO} - \ldots$
- $\left|\frac{g_A}{g_V}\right| = 1.2701 \pm 0.0020$ (from neutron β decay)

Results on the Bjorken sum rule





- $\Gamma_1^{NS}(Q_0^2 = 3\text{GeV}^2/c^2) = 0.181 \pm 0.008(\text{stat}) \pm 0.014(\text{syst})$
- $\left|\frac{g_A}{g_V}\right| = 1.2701 \pm 0.0020$ (from neutron β decay)
- $\left|\frac{g_A}{g_V}\right| = 1.220 \pm 0.053(\text{stat}) \pm 0.095(\text{syst})$ using C_1^{NS} @ NLO
- $\left|\frac{g_A}{g_V}\right| = 1.256 \pm 0.054(\text{stat}) \pm 0.098(\text{syst})$ using C_1^{NS} @ NNLO
- **Bjorken sum rule validated within 4%**

New results on A_1^p and g_1^p for $Q^2 < 1$ GeV$^2/c^2$

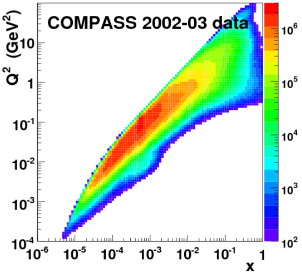
Motivation for the low x, low Q^2 studies

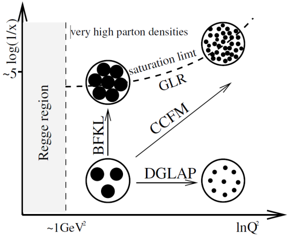
- Low x $\Leftrightarrow$ **high parton densities**

- Fixed target experiments $\Leftrightarrow$ **strong correlation** between x and Q^2: low $x \Rightarrow$ low Q^2, where pQCD isn't expected to work

- Some **models, to be confronted with data**, allow a **smooth extrapolation to the low-Q^2 and high-Q^2 regions** (resummation, VMD):
  B. Badełek et al, B.I. Ermolaev et al.

- A_1^p and g_1^p at low x and low Q^2:
  - can be measured with **improved precision**
  - complement our measurement of A_1^d and g_1^d at low x and low Q^2
  - $g_1^{\mathbf{NS}} = g_1^p - g_1^n$ can be extracted
  - also as functions of ν, as suggested by theoreticians



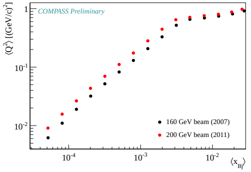


- Data taken in 2007 & 2011 with a NH_3 target
- 676×10^6 events ($150\times$ more than SMC)

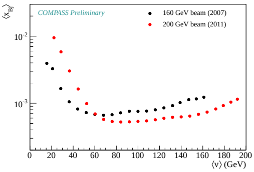
Main event selection criteria:

- at least one additional track (besides the scattered muon) in the interaction vertex
- not a μe elastic scattering event
- $Q^2 < 1$ $(\text{GeV}/c)^2$
- $x \geq 4 \times 10^{-5}$
- $0.1 < y < 0.9$

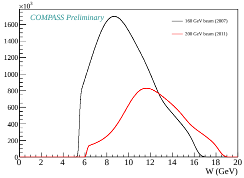
$\langle Q^2 \rangle$ (GeV$^2/c^2$) vs $\langle x \rangle$



$\langle x \rangle$ vs $\langle \nu \rangle$ (GeV)

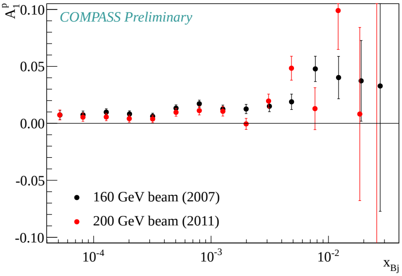


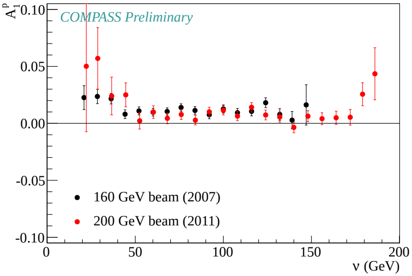
W (GeV)



First COMPASS results for A_1^p at low x and low Q^2

- Procedure similar to the one for $Q^2 > 1$ $(\mathrm{GeV}/c)^2$ (weighting, radiative corrections, ^{14}N correction)





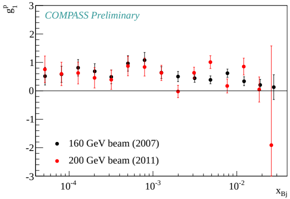
- The results for the two beam energies are compatible within errors.
- The systematic errors are smaller than the statistical errors (not shown here).
- A **significantly positive asymmetry** is observed.
- No significant dependence with ν is seen.

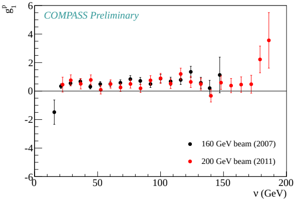
First COMPASS results for g_1^p at low x and low Q^2

- The structure function is obtained in bins of x or ν according to:

$$\mathbf{g_1^p}\left(\langle\mathbf{x}\rangle,\langle\mathbf{Q^2}\rangle\right)=\frac{\mathbf{F_2^p}\left(\langle\mathbf{x}\rangle,\langle\mathbf{Q^2}\rangle\right)}{\mathbf{2x}\left[\mathbf{1}+\mathbf{R}\left(\langle\mathbf{x}\rangle,\langle\mathbf{Q^2}\rangle\right)\right]}\mathbf{A_1^p}\left(\langle\mathbf{x}\rangle,\langle\mathbf{Q^2}\rangle\right)$$

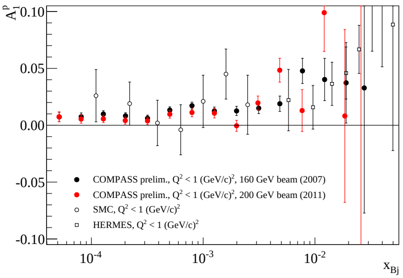
- $\mathbf{F_2^p}(\langle\mathbf{x}\rangle,\langle\mathbf{Q^2}\rangle)$ from the SMC fit on data or from a model (for low x and Q^2) [3]
- $\mathbf{R}(\langle\mathbf{x}\rangle,\langle\mathbf{Q^2}\rangle)$ based on SLAC parameterization, extended to low Q^2 [4]

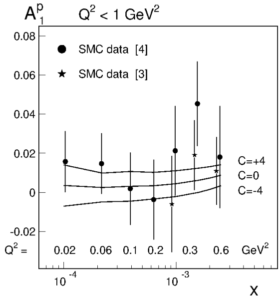




- The results for the two beam energies are compatible within errors.
- The systematic errors are smaller than the statistical errors (not shown here).
- g_1^p is **significantly positive**.
- No significant dependence with ν is seen.

Comparison with previous experiments and with model





- The COMPASS results significantly **improve the precision** of the measurement.
- Comparing with B. Badełek *et al.* [Phys. Rev. D 61 (1999) 014009], the COMPASS data favour $\mathbf{C} \in [\mathbf{0}, +\mathbf{4}]$, *i.e.* a VMD contribution to g_1 of the same sign of the partonic contribution.

Summary and outlook

Summary and outlook

- **$Q^2 > 1$ (GeV/c)^2:**
  - New measurements of A_1^p and g_1^p at 200 GeV/c
  - New value at low x, overall improved precision
  - Updated NLO QCD fit
  - Bjorken sum rule verified more accurately
- **$Q^2 < 1$ (GeV/c)^2:**
  - First COMPASS results on A_1^p and g_1^p for $Q^2 \in]0.001, 1[$ (GeV/c)^2, $x \in]4 \cdot 10^{-5}, 4 \cdot 10^{-2}[$, and $\nu \in]14, 194[$ GeV, in bins of x or in bins of ν
  - Results of A_1^p and g_1^p are significantly positive
  - $A_1^p(x)$ results are compatible with the model of Badełek et al. (1999) for $C \in [0, +4]$, *i.e.* they favour a VMD contribution to g_1 of the same sign as the partonic one

Next:

- **$Q^2 > 1$ (GeV/c)^2:**
  - $A_{1,p}^{\pi^\pm}$ and $A_{1,p}^{K^\pm}$, polarised PDFs for each flavour
- **$Q^2 < 1$ (GeV/c)^2:**
  - A_1^p and g_1^p in 2D bins, g_1^{NS} from g_1^p and g_1^d

References

[1] A.A. Akhundov *et al.*, Sov.J.Nucl.Phys. 26 (1977) 660.

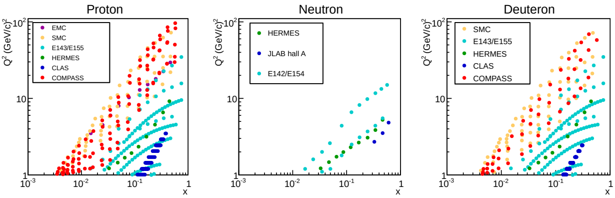
[2] I. Akushevich *et al.*, Comput.Phys.Commun. 104 (1997) 201.

[3] SMC, Phys.Rev. D58 (1998), 112001; J. Kwieciński & B. Badełek, Z.Phys. C43 (1989), 251; B. Badełek & J. Kwieciński, Phys.Lett. B295 (1992) 263.

[4] COMPASS, PLB 647 (2007) 330.

Backup

Inputs and constraints for NLO CQD fit



- 139 out of 674 points are from COMPASS
- $g_1^{p(n)} = \frac{1}{9}\left[C_S \otimes \mathbf{\Delta q_S} + C_{NS} \otimes \left(\pm\frac{3}{4}\mathbf{\Delta q_3} + \frac{1}{4}\mathbf{\Delta q_8}\right) + C_g \otimes \mathbf{\Delta g}\right]$
  - $\Delta q_S = \Delta u + \Delta d + \Delta s$ (spin singlet parton distribution)
  - $\Delta q_3 = \Delta u - \Delta d$ (triplet non-singlet spin distribution)
  - $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$ (octet non-singlet spin distribution)
  - $C_S,\ C_{NS},\ C_g$: Wilson coefficients associated to each distribution
- Functional forms at a given reference scale Q_0^2:
  - $\Delta q_S(x, Q_0^2) = \eta_S x^{\alpha_S}(1-x)^{\beta_S}(1+\gamma_S+\rho_S\sqrt{x})/N_S$
  - $\Delta q_g(x, Q_0^2) = \eta_g x^{\alpha_g}(1-x)^{\beta_g}(1+\gamma_g+\rho_g\sqrt{x})/N_g$
  - $\Delta q_3(x, Q_0^2) = \eta_3 x^{\alpha_3}(1-x)^{\beta_3}/N_3$
  - $\Delta q_8(x, Q_0^2) = \eta_8 x^{\alpha_8}(1-x)^{\beta_8}/N_8$

Inputs and constraints to the NLO QCD fit

- $SU(3)_f$ to fix the non-singlet distributions first moments:
  - $\int_0^1 (\Delta u - \Delta d)\, dx = F + D = g_A/g_V$
  - $\int_0^1 (\Delta u + \Delta d - 2\Delta s)\, dx = 3F - D$

    F, D: parameters describing the weak axial-vector/vector coupling contants
  - β_g is fixed

- Evolution using DGLAP equations

- Minimize: $$\chi^2 = \sum_{n=1}^{N_{exp}} \left[\underbrace{\sum_{i=1}^{N_n^{data}} \left(\frac{g_1^{fit} - \mathcal{N}_n g_{1,i}^{data}}{\mathcal{N}_n \sigma_i} \right)^2}_{Statistics} + \underbrace{\left(\frac{1 - \mathcal{N}_n}{\delta \mathcal{N}_n} \right)^2}_{Normalizations} \right] + \chi^2_{positivity}$$

- Positivity: $|\Delta g(x)| < |g(x)|$ and $|\Delta(s(x) + \bar{s}(x))| < |s(x) + \bar{s}(x)|$

- Unpolarised PDFs for the positivity constraint: MSTW2008

- In total: 28 free parameters and 679 data points

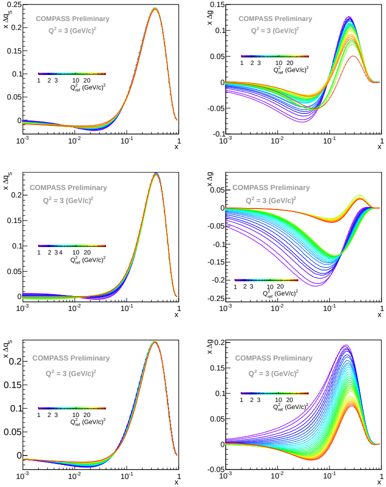
Influence of the input scale Q_0^2

$x\Delta q_S$ | $x\Delta g$

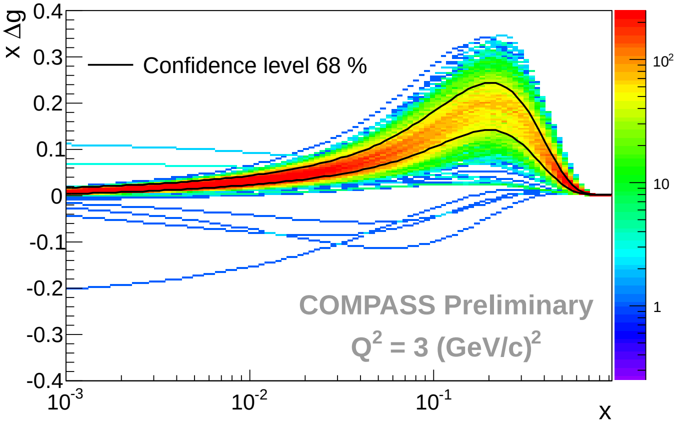
ΔG with a node

$\Delta G < 0$

$\Delta G > 0$

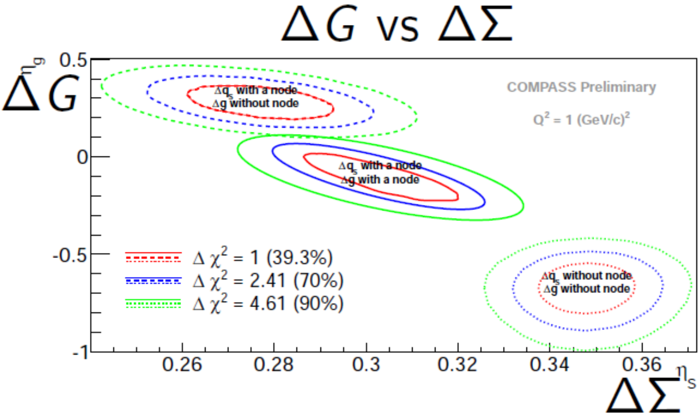


Error band associated to statistical uncertainties



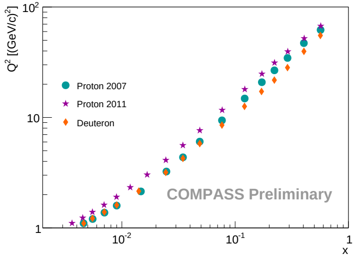
- Results of 2,000 fits to the replicas
- Color: density of replicas at a given x
- Black curves: the border of the interval at 68% CL

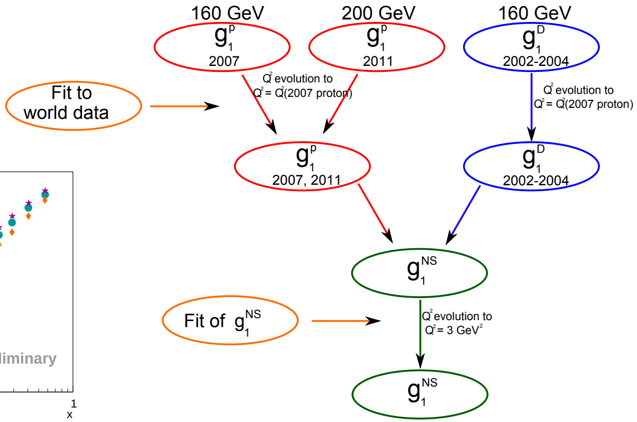
Fit results



ΔG vs ΔΣ
ΔG^{η_g}
0.5
0
-0.5
-1
COMPASS Preliminary
$Q^2 = 1\ (GeV/c)^2$
Δq_s with a node
Δg without node
Δq_s with a node
Δg with a node
Δq_s without node
Δg without node
$\Delta\chi^2 = 1$ (39.3%)
$\Delta\chi^2 = 2.41$ (70%)
$\Delta\chi^2 = 4.61$ (90%)
0.26
0.28
0.3
0.32
0.34
0.36
$\Delta\Sigma^{\eta_s}$

Calculation of $\int_0^1 g_1^{NS}\, dx$



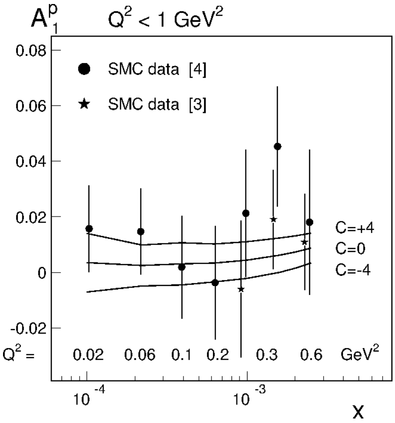


- Calculate g_1^{NS}
- Perform a NLO QCD fit, fitting only Δq_3 (3 parameters needed) @$Q_0 = 1$ (GeV$/c)^2$
- Evolve g_1^{NS} to $Q_0 = 3$ (GeV$/c)^2$
- Use extrapolation to $x \to 0$ and to $x \to 1$ (94% of $\int_0^1 g_1^{NS}\, dx$ is in the measured range)

Model details

B. Badełek *et al.* [Phys. Rev. D 61 (1999) 014009]

(VMD contribution and QCD improved parton model extended to low Q^2)



$$g_1(x,Q^2)=g_1^{VMD}(x,Q^2)+g_1^{part}(x,Q^2). \qquad (4)$$

$$g_1^{VMD}(x,Q^2)=\frac{pq}{4\pi}\sum_{V=\rho,\omega,\phi}\frac{m_V^4\Delta\sigma_V(W^2)}{\gamma_V^2(Q^2+m_V^2)^2}. \qquad (5)$$

$$\Delta\sigma_V=\frac{\sigma_{1/2}-\sigma_{3/2}}{2}, \qquad (6)$$

$$\frac{pq}{4\pi}\sum_{V=\rho,\omega}\frac{m_V^4\Delta\sigma_V}{\gamma_V^2(Q^2+m_V^2)^2} = C\left[\frac{4}{9}(\Delta u_V^0(x)+2\Delta\bar{u}^0(x))+\frac{1}{9}(\Delta d_V^0(x)+2\Delta\bar{u}^0(x))\right] \times\frac{m_\rho^4}{(Q^2+m_\rho^2)^2}, \qquad (7)$$

$$\frac{pq}{4\pi}\frac{m_\phi^4\Delta\sigma_\phi}{\gamma_\phi^2(Q^2+m_\phi^2)^2}=C\frac{2}{9}\Delta\bar{s}^0(x)\frac{m_\phi^4}{(Q^2+m_\phi^2)^2}, \qquad (8)$$

$$\Delta p_j^0(x)=C_j(1-x)^{\eta_j}. \qquad (3)$$