Final COMPASS results on the spin dependent structure functions g_1^d and g_1^p

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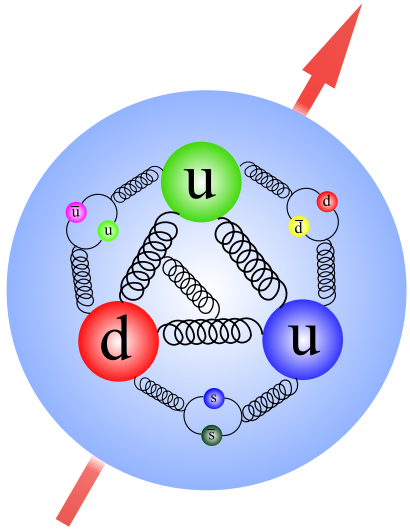
Motivation

Longitudinal spin composition of the nucleon:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

$$\Delta\Sigma = \Delta U + \Delta D + \Delta S$$

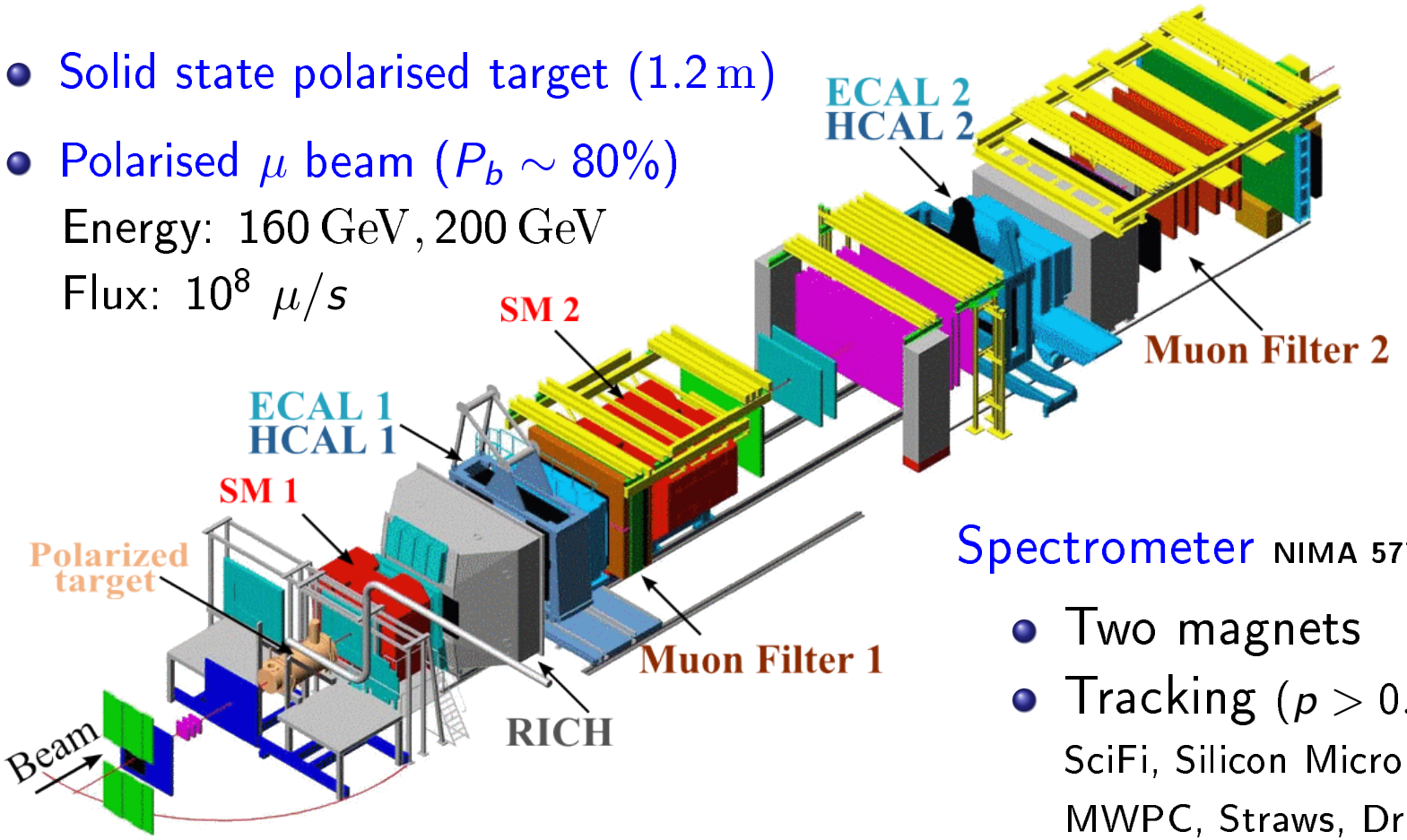


- Quark spin $\Delta\Sigma$ contributes only about 30% to the nucleon spin investigation started with EMC PLB 206 (1988) 364
- Gluon contribution ΔG some experimental constrains available
- Hardly any experimental information on orbital angular momentum L

COMPASS @ CERN

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

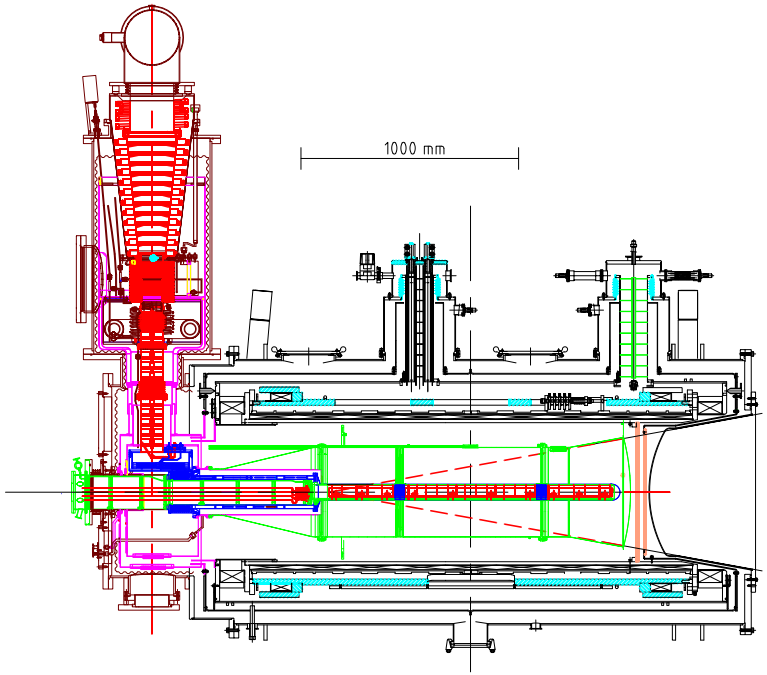
- M2 beamline
- Solid state polarised target (1.2 m)
- Polarised μ beam ($P_b \sim 80\%$)
  Energy: 160 GeV, 200 GeV
  Flux: 10^8 μ/s

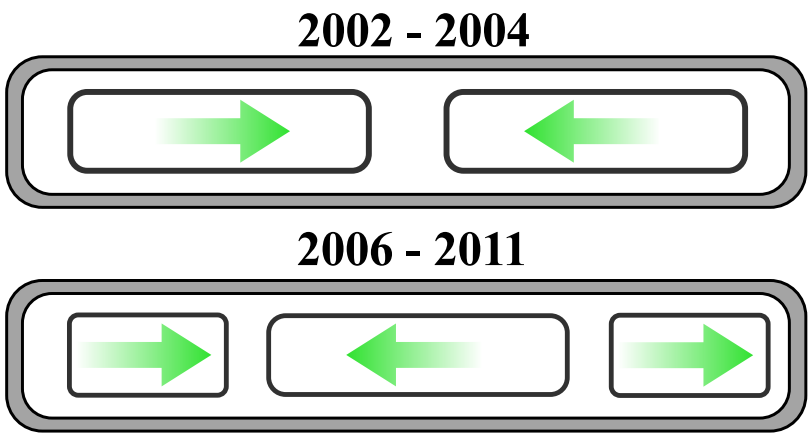


Spectrometer NIMA 577 (2007) 455

- Two magnets
- Tracking ($p > 0.5\,\mathrm{GeV}/c$)
  SciFi, Silicon MicroMega, GEM, MWPC, Straws, Drift tubes
- PID: RICH(π, K, p)
  ECAL, HCAL, muon filters

Polarised target



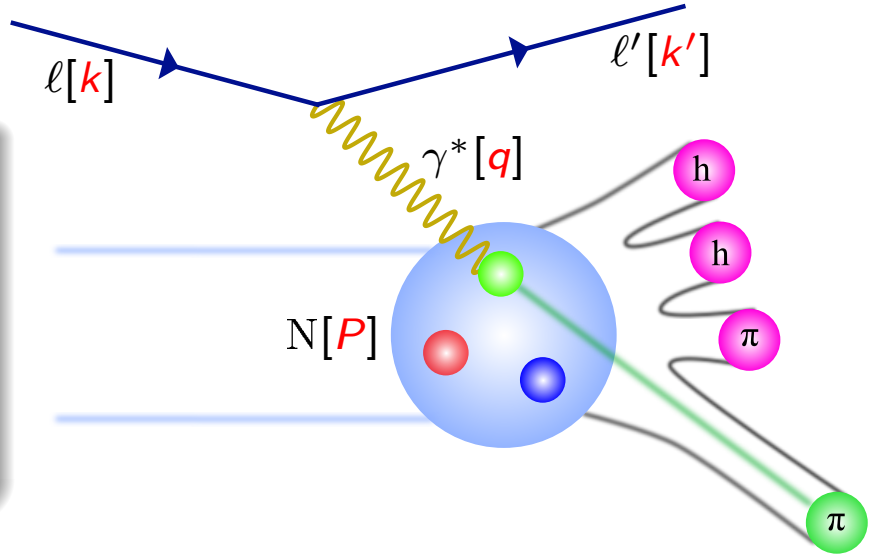


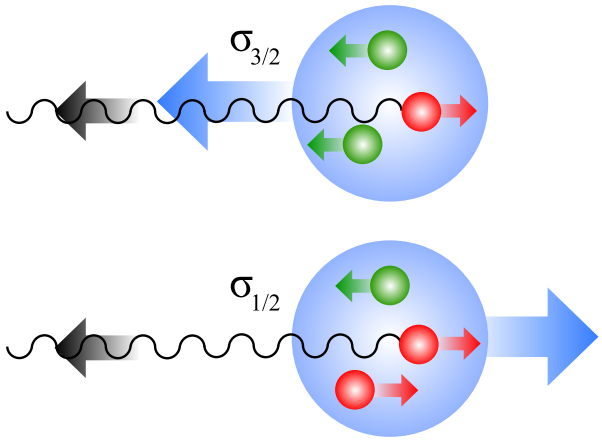
- Two/three target cells, oppositely polarised
- 180 mrad geometrical acceptance
- 2.5 T solenoid field
- Low temperature 50 mK
- Regular polarisation reversals by field rotation
- ^{6}LiD (Longitudinal deuteron polarisation: $\sim 50\%$)
- NH_3 (Longitudinal proton polarisation: $\sim 90\%$)

Deep Inelastic Scattering

DIS variables

- Photon virtuality: $Q^2 = -q^2$
- Bjorken scaling variable: $x = \frac{Q^2}{2 \cdot P \cdot q}$
- Relative photon energy: $y = \frac{E - E'}{E}$





- Absorption of polarised photons

$$\sigma_{1/2} \sim q^+ \qquad \sigma_{3/2} \sim q^-$$

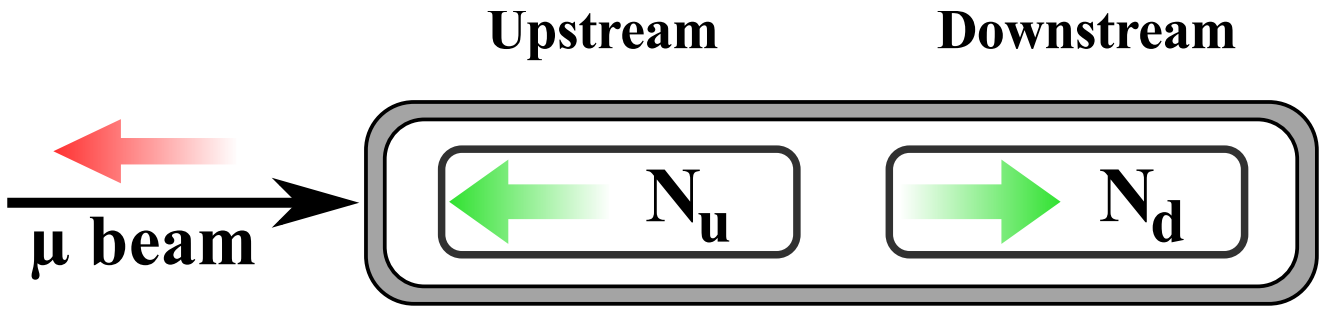
$$q(x) = q^+(x) + q^-(x)$$

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

- Photon nucleon asymmetry

$$A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \overset{\text{LO}}{=} \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$

Method (idea)



- Aim: $A = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$
- Measured: $A_{exp} = \frac{N_u - N_d}{N_u + N_d}$
- $A_{exp} = A \cdot P_B \cdot P_T \cdot f$

  $A \approx A_1 \cdot D$

  f: Dilution factor

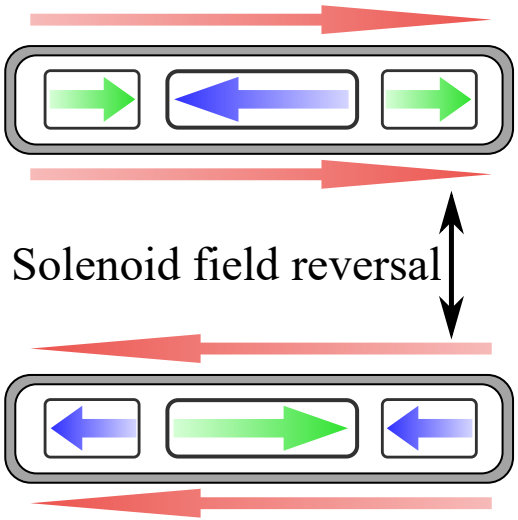
  D: Depolarisation factor

- Needed:
  - Flux cancellation
  - Acceptance cancellation

    $\rightarrow$ 2/3 target cells

    $\rightarrow$ polarisation rotation

Method (idea)



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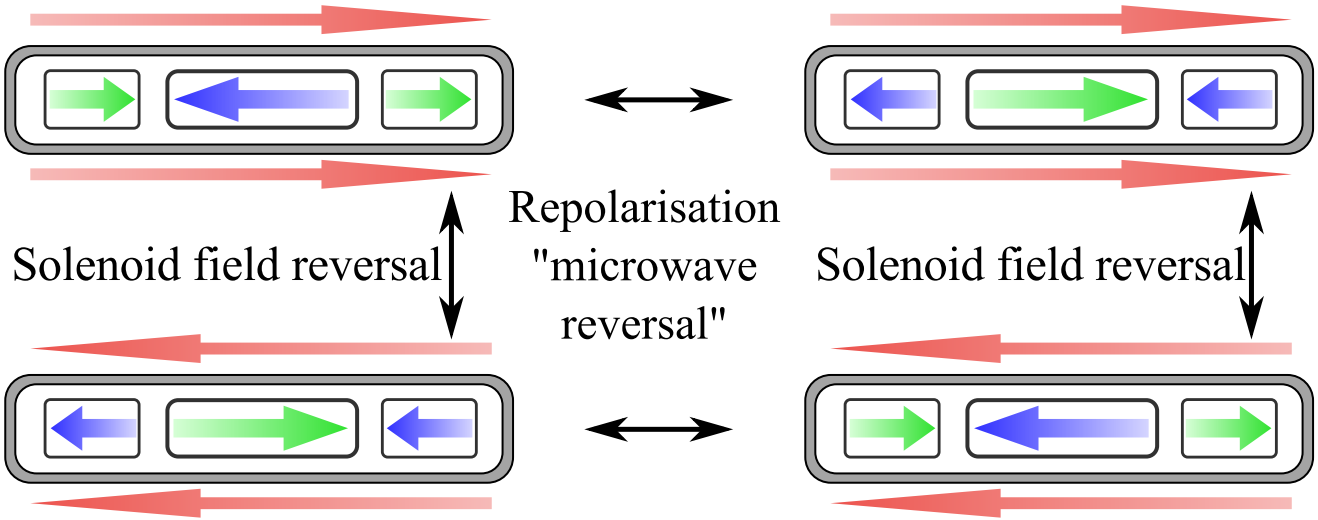

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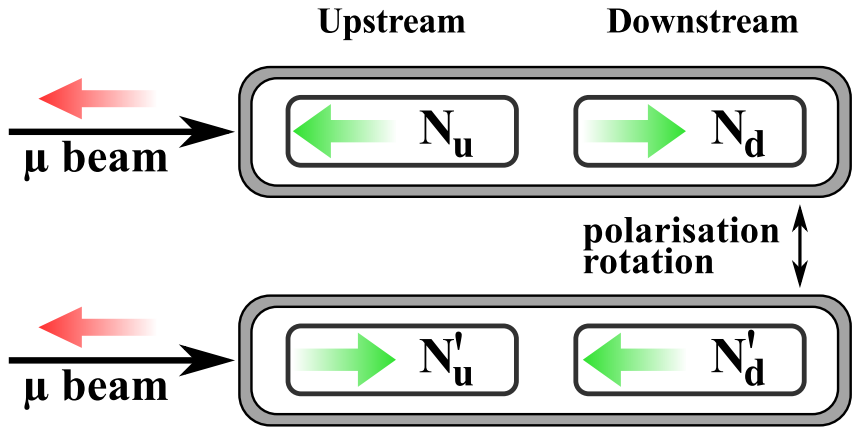
Asymmetry calculation

- Number of interactions in each cell: $N_i = a_i \phi_i n_i \overline{\sigma}(1 + f D P_B P_T A_1)$
  - Acceptance: a_i
  - Incoming flux: ϕ_i
  - Number of target nuclei: n_i
  - Spin independent cross section: $\overline{\sigma}$

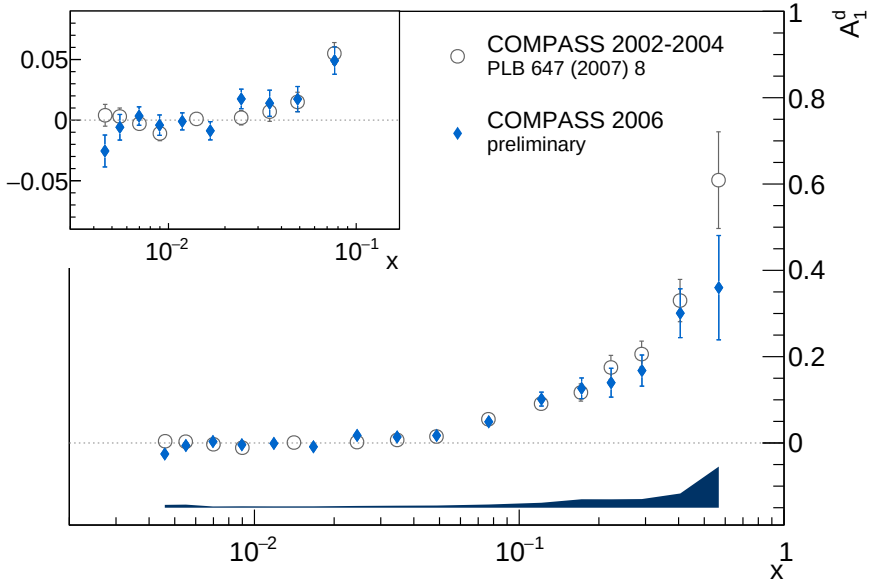
- Choose event weight: $w = f D P_B$
  No P_T due to possible false asymmetries
- Calculate $P_i = \sum_{\text{data}} w_i$
- Calculate A_1 from $\delta = \frac{P_{u+d} P'_c}{P'_{u+d} P_c}$

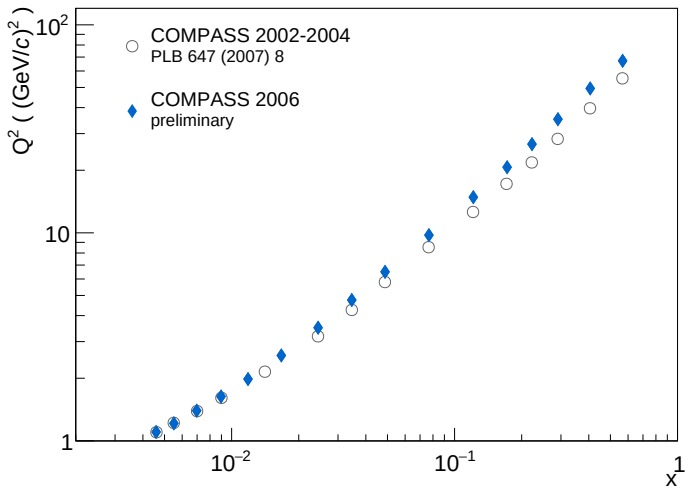
  $\rightarrow a A_1^2 + b A_1 + c = 0$



Results from the 2006 deuteron data

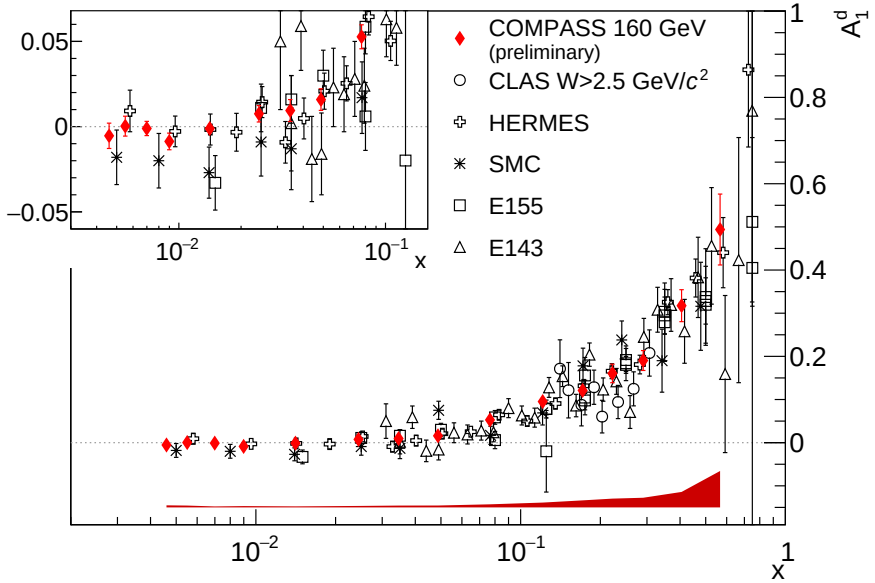
- 2002-2004 results already published **PLB 647 (2007) 8**
- Unpublished 2006 data give 2× increase in statistics
- 160 GeV muon beam
- Unpol. rad. correction TERAD included in dilution factor
- Pol. rad. correction from POLRAD
- ^{7}Li correction applied
- Good agreement

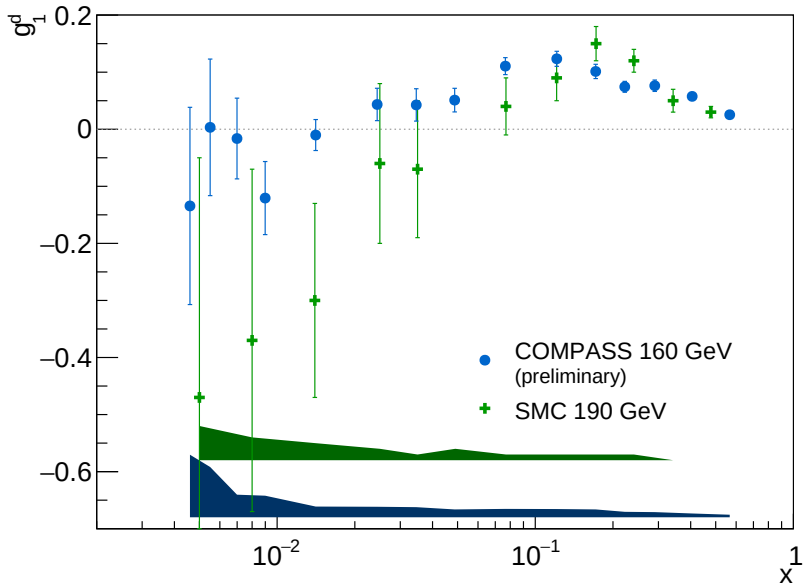




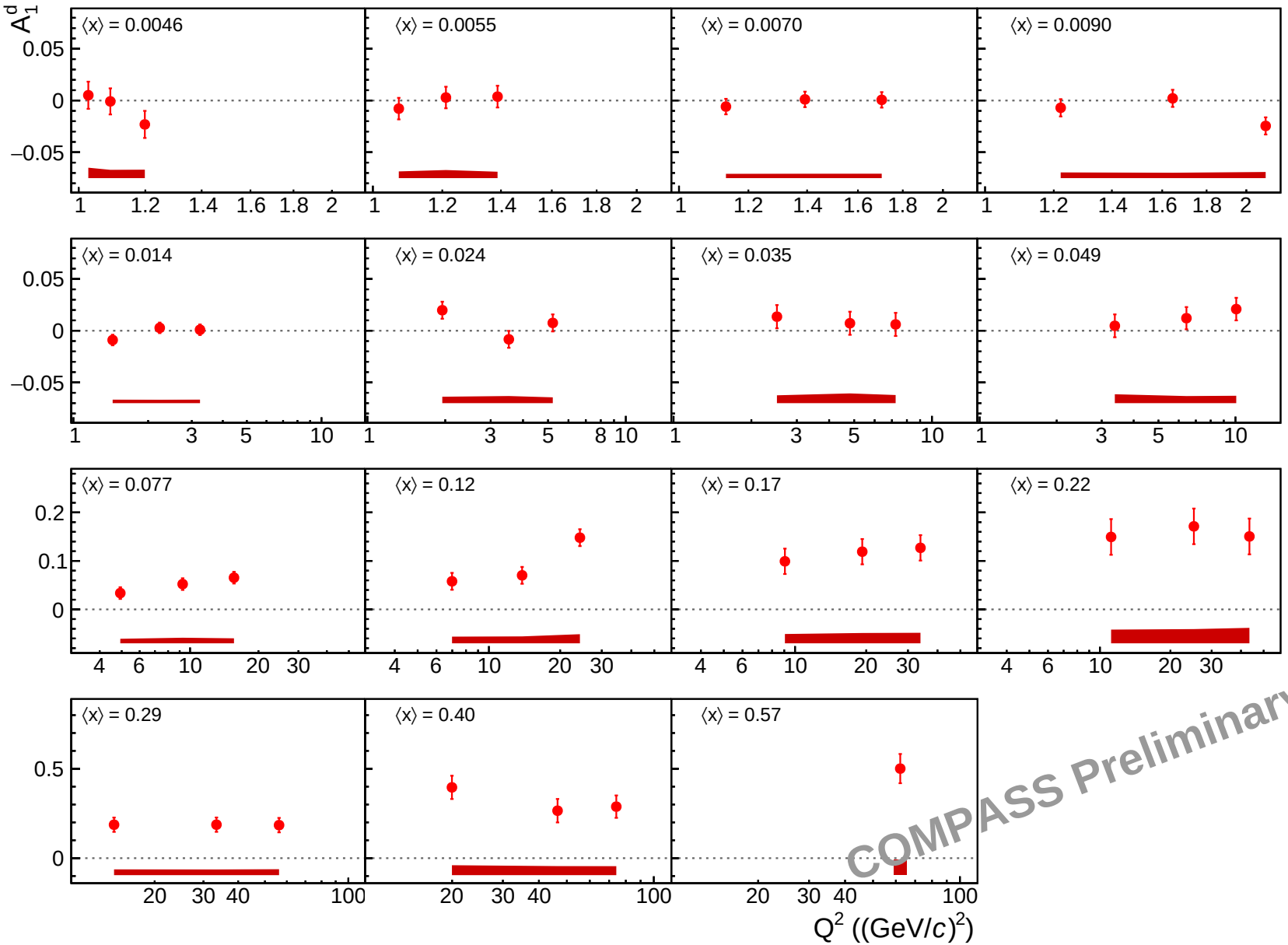
Results in bins of x

- Combined COMPASS results
- Good agreement with world data
- Small statistical uncertainty at low x
- Compatible with zero at low x
- $g_1^{\mathrm{d}}(x, Q^2) = \frac{F_2^{\mathrm{d}}(x,Q^2)}{2x(1+R(x,Q^2))} A_1^{\mathrm{d}}(x, Q^2)$
- F_2 from SMC **PRD 58 (1998) 11201**
- R1998 **PLB 452 (1999) 194**
  used with improvements





A_1^d in bins of x and Q^2

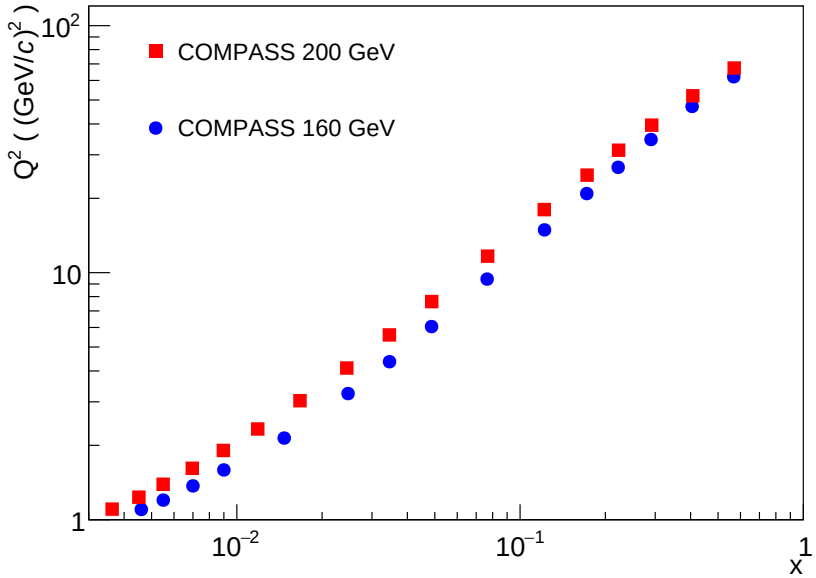


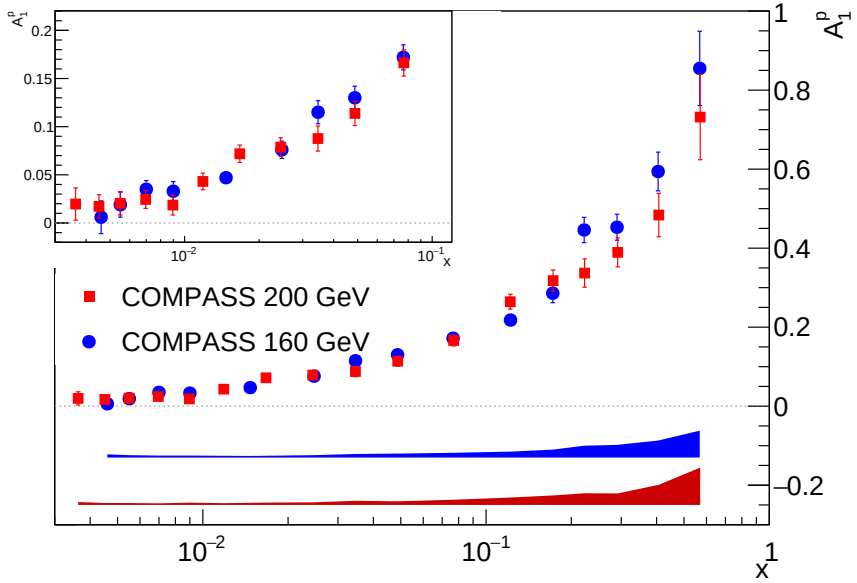
Results from the 2011 proton data

- 2007 results already published

  PLB 690 (2010) 466

- Increased beam energy in 2011
  $160\,\mathrm{GeV} \rightarrow 200\,\mathrm{GeV}$
- Higher Q^2 and lower x reached
- ^{14}N correction applied
- Good agreement
- $g_1^{\mathrm{p}}(x, Q^2) = \frac{F_2^{\mathrm{p}}(x,Q^2)}{2x(1+R(x,Q^2))} A_1^{\mathrm{p}}(x, Q^2)$





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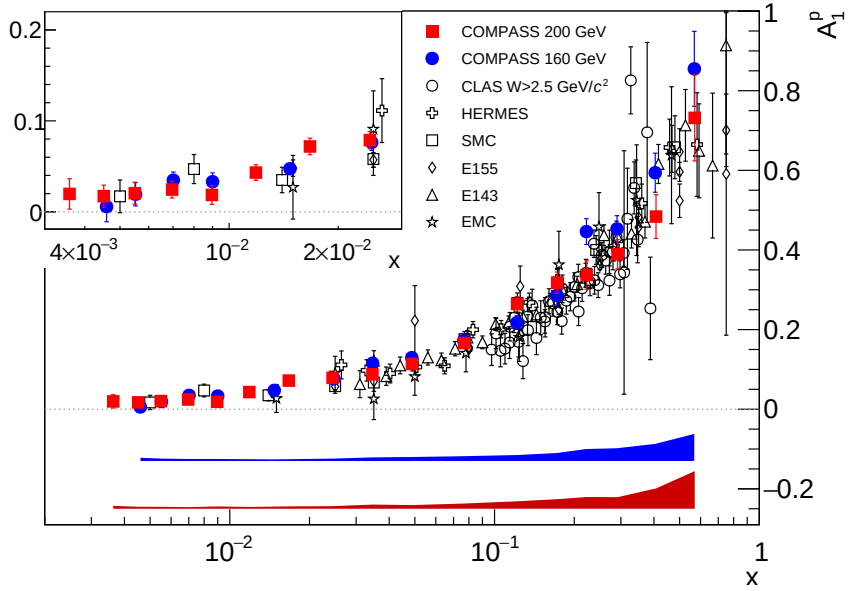
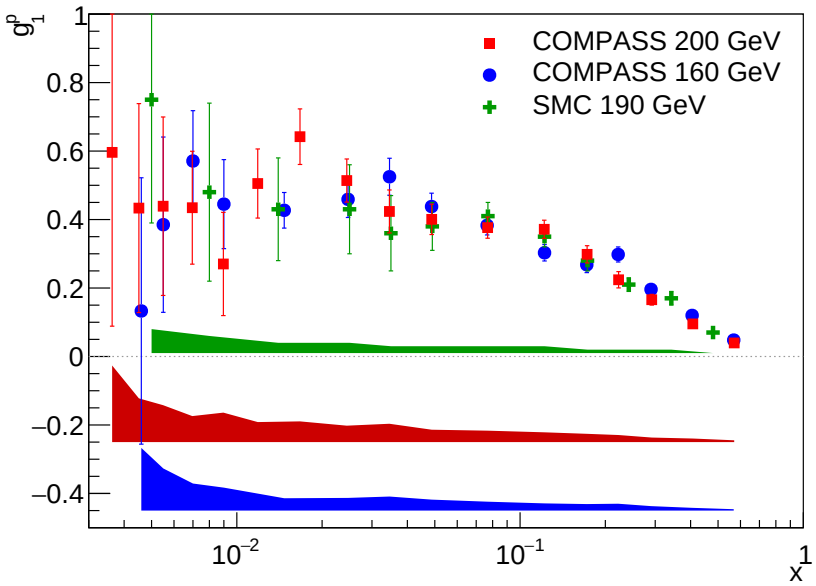
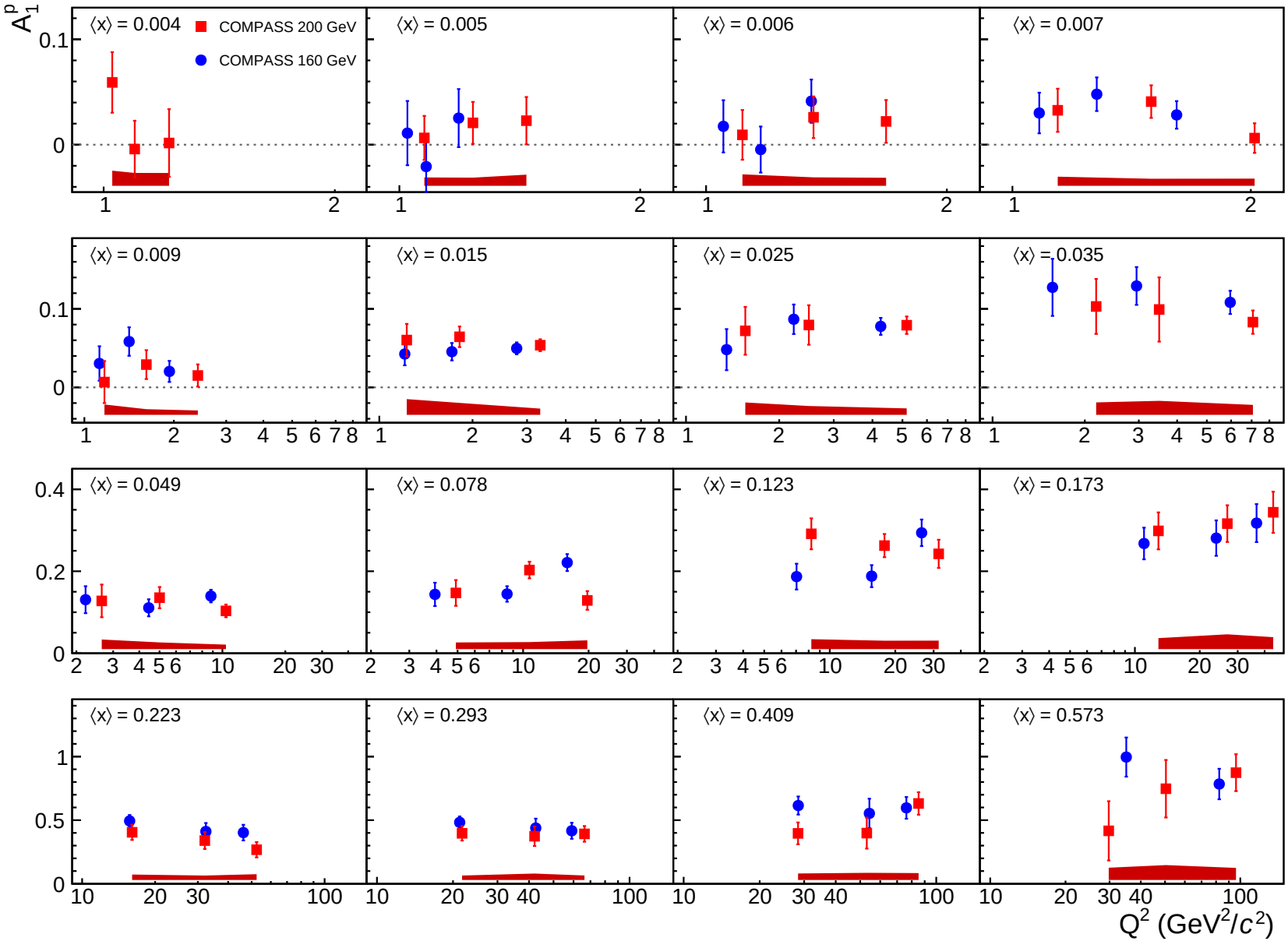




A_1^p in bins of x and Q^2



NLO QCD analyses

- DGLAP equations

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\ \Delta q^{\mathrm{NS}} = \frac{\alpha_s(Q^2)}{2\pi}\ \Delta P_{qq}^{\mathrm{NS}} \otimes \Delta q^{\mathrm{NS}}$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\begin{pmatrix}\Delta q^{\mathrm{S}}\\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq}^{\mathrm{S}} & 2n_f\Delta P_{qg}\\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Delta q^{\mathrm{S}}\\ \Delta g\end{pmatrix}$$

- Structure function:

$$g_1 = \tfrac{1}{2}\langle q^2\rangle\left(C^{\mathrm{S}}(\alpha_s)\otimes\Delta q^{\mathrm{S}} + C^{\mathrm{NS}}(\alpha_s)\otimes\Delta q^{\mathrm{NS}} + C^{g}(\alpha_s)\otimes\Delta g\right)$$

- Input parametrisation f of $\Delta q^{\mathrm{S}}, \Delta q_3, \Delta q_8, \Delta g$ at $Q_0^2 = 1\,(\mathrm{GeV}/c)^2$ needed

$$f = \eta\frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)\mathrm{d}x}$$

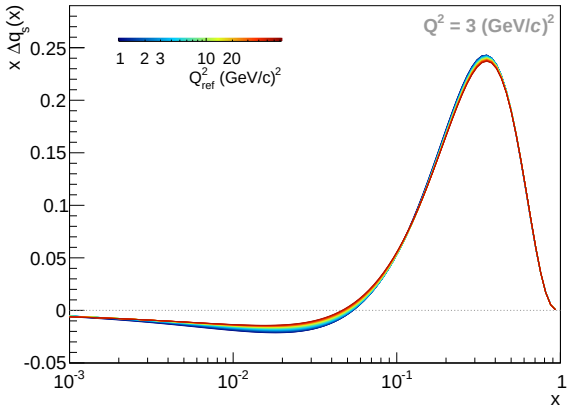
- Using only inclusive asymmetries quarks and anti-quarks cannot be disentangled *e.g.* determination of $\Delta(u+\bar{u})$, $\Delta(d+\bar{d})$, $\Delta(s+\bar{s})$ and Δg

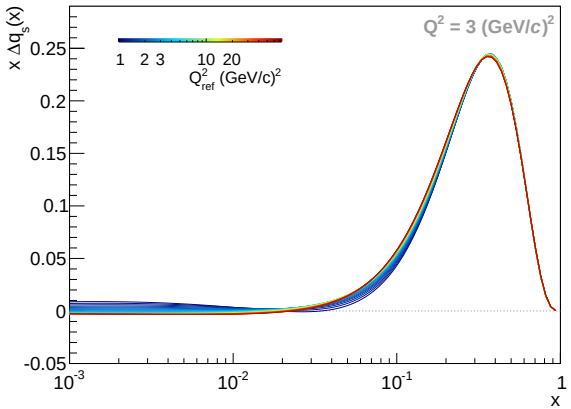
$$\Delta q^{\mathrm{S}} = \Delta U + \Delta D + \Delta S, \Delta q_3 = \Delta U - \Delta D, \Delta q_8 = \Delta U + 2\Delta D - \Delta S$$

Systematic studies

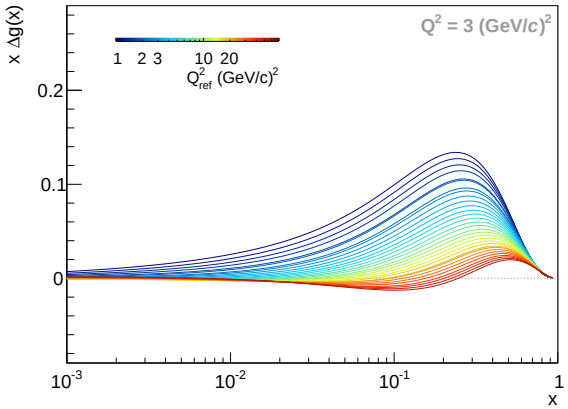
- Remarks on the previously published fit:
  - No systematic uncertainties
- Study impact of:
  - Different parametrisations
  - Reference scale Q_0^2
- χ^2 very stable

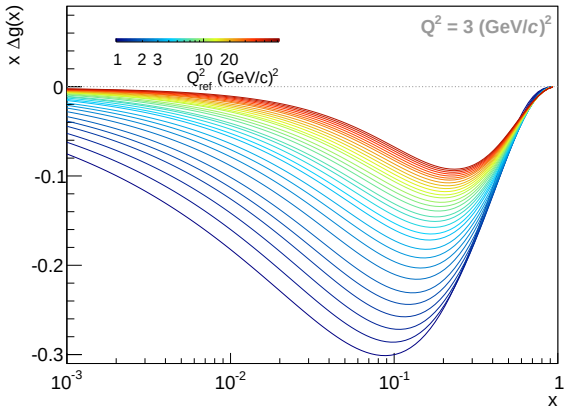
Singlet





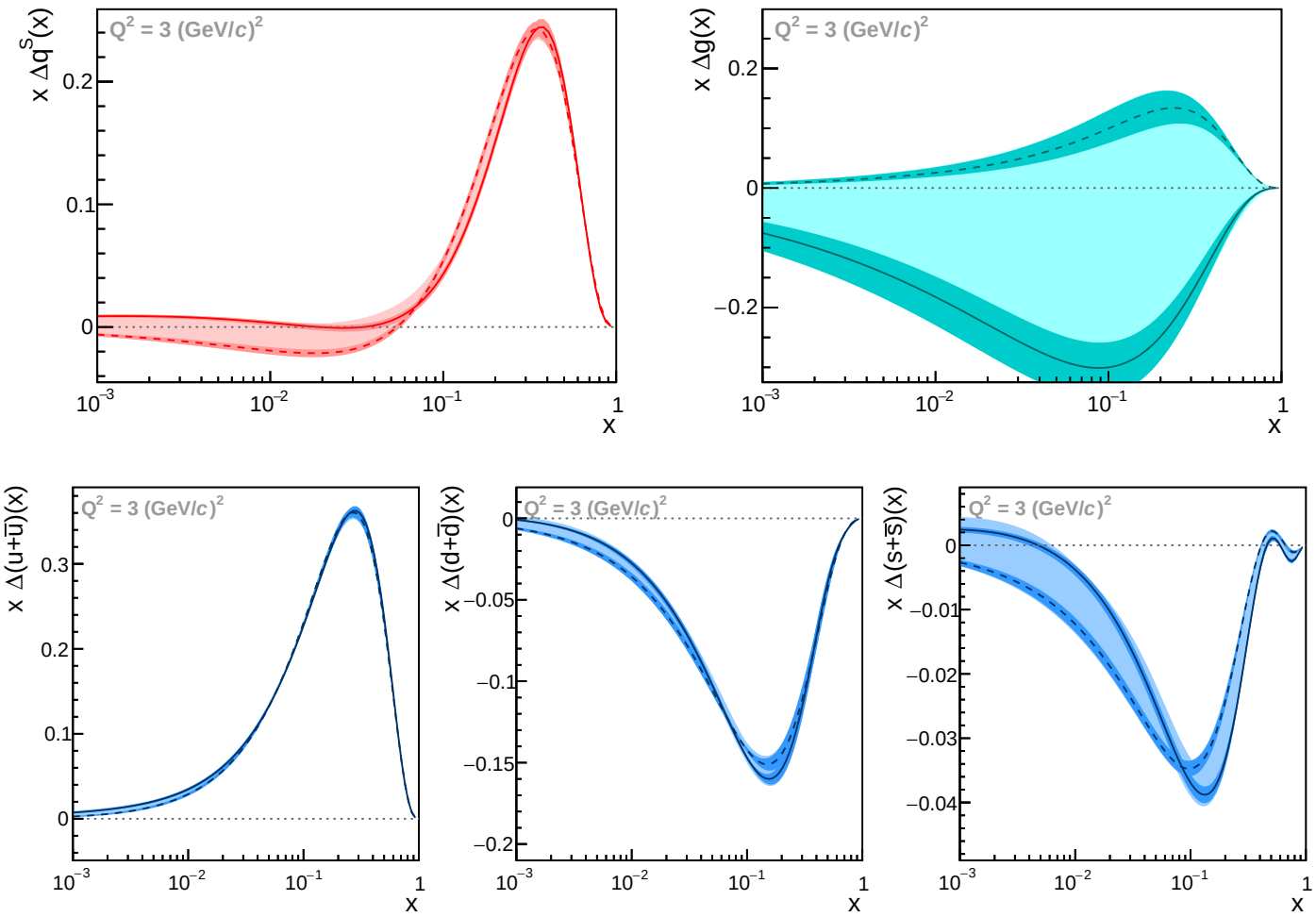
Gluon





→ Systematic uncertainty larger than statistical

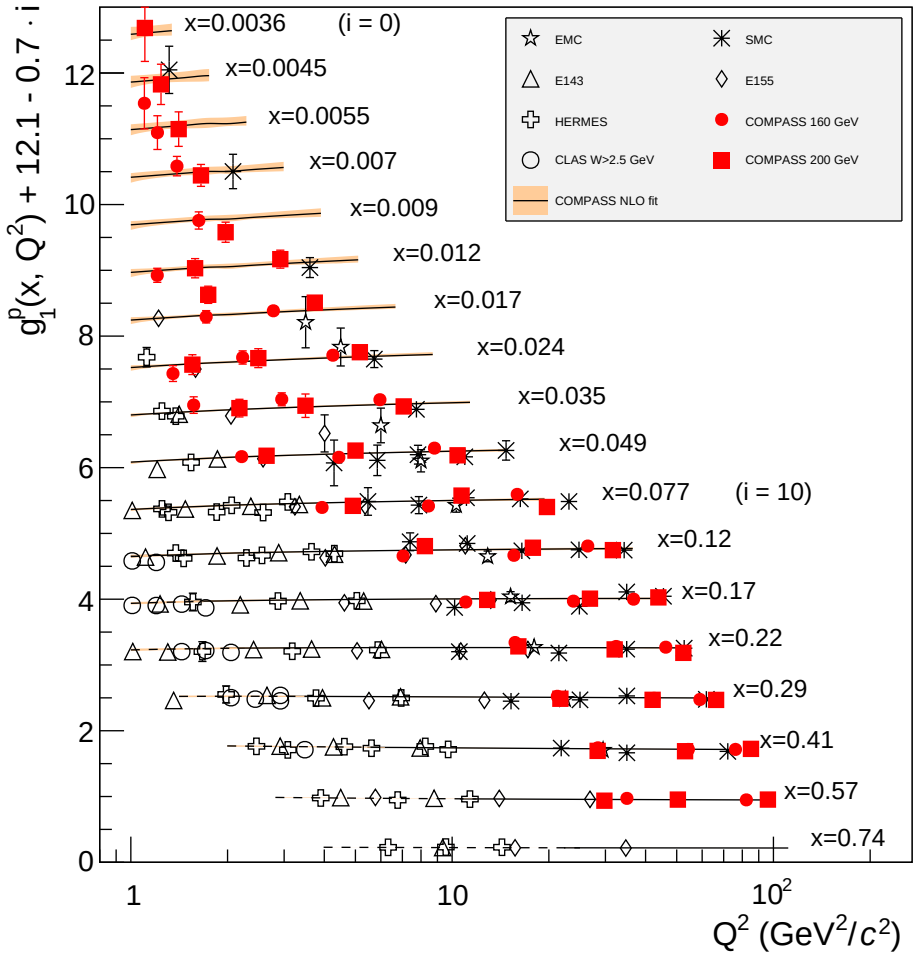
Polarised parton distributions

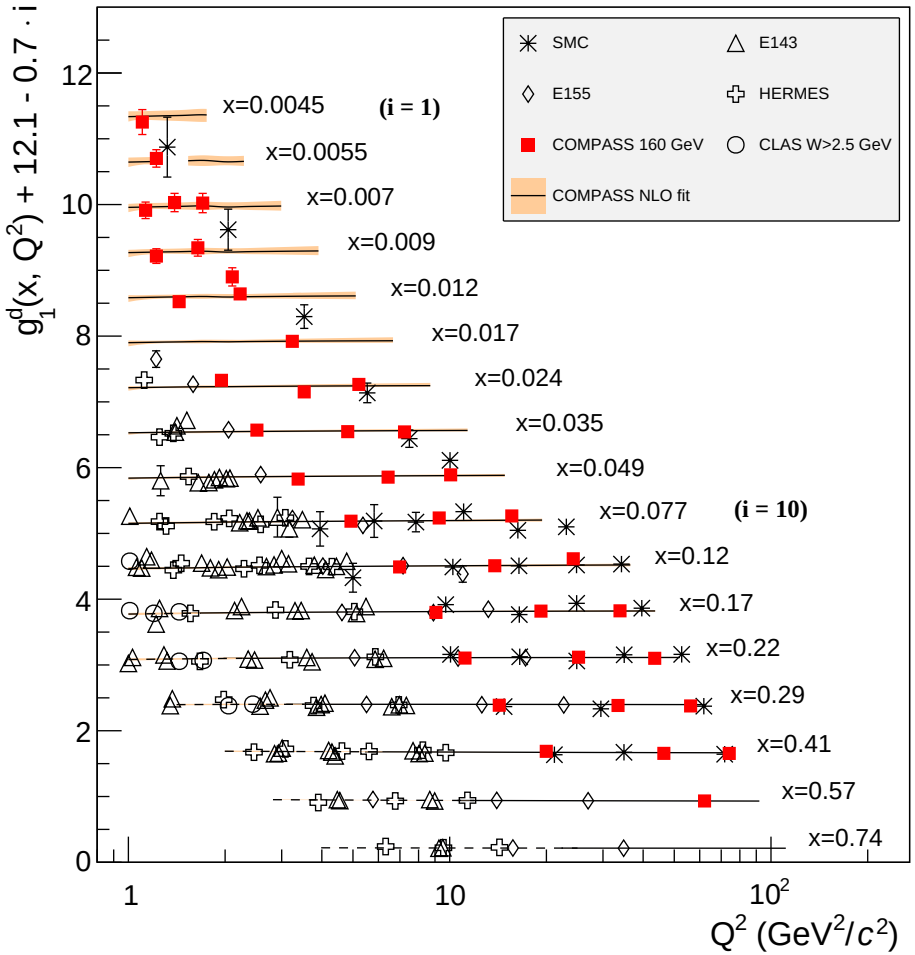


- Quark polarisation $0.26 < \Delta\Sigma < 0.36$
- Gluon polarisation $\Delta G = \int \Delta g(x) \mathrm{d}x$ Not well constrained
  $\rightarrow$ Direct measurement

$g_1^p(x, Q^2)$, $g_1^d(x, Q^2)$ world data

- COMPASS NLO QCD fit for $W^2 > 10\,(\mathrm{GeV}/c^2)^2$
- Extrapolation for $W^2 < 10\,(\mathrm{GeV}/c^2)^2$ (dashed)





First moment from COMPASS data

$$\Gamma_1^{\mathrm{N}}(Q^2) = \int_0^1 \frac{1}{1-1.5\omega_D} g_1^{\mathrm{d}}(x, Q^2)dx = \frac{1}{36}\left[a_8 C^{\mathrm{NS}}(Q^2) + 4a_0 C^{\mathrm{S}}(Q^2)\right]$$

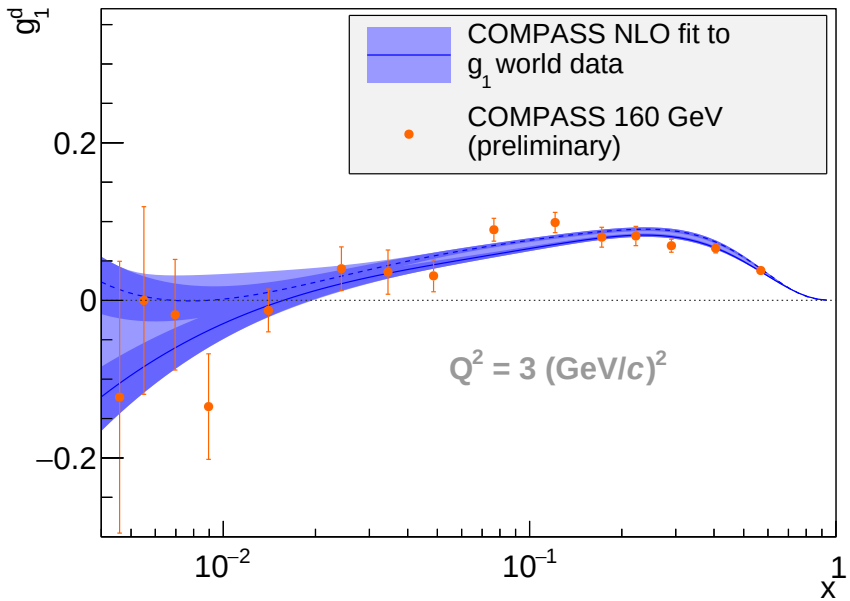
- Evolve g_1 to $Q^2 = 3\,(\mathrm{GeV}/c)^2$
- Use results from QCD fit

  PLB 753 (2016) 18
- Calculate contributions from unmeasured region ($x \to 0, 1$)
- 97% in measured range

$$\Gamma_1^{\mathrm{N}} = 0.047 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}} \pm 0.004_{\mathrm{evol}}$$

- Previous result **(PLB 647 (2007) 8)**:

  $\Gamma_1^{\mathrm{N}} = 0.050 \pm 0.003_{\mathrm{stat}} \pm 0.005_{\mathrm{syst}} \pm 0.003_{\mathrm{evol}}$



Flavour-singlet axial charge

$$a_0 = \frac{1}{C^{\mathrm{S}}(Q^2)} \left(9\Gamma_1^{\mathrm{N}}(Q^2) - \frac{1}{4} a_8 C^{\mathrm{NS}}(Q^2) \right)$$

- Using our first moment and the axial charge a_8 **PRD 82 (2010) 114018**
- a_0 connected to the quark contribution to the nucleon spin
- $\overline{\mathrm{MS}}$: $a_0 = \Delta\Sigma = \Delta U + \Delta D + \Delta S$
- Preliminary result:

$$a_0(Q^2 = 3\,(\mathrm{GeV}/c)^2) = 0.32 \pm 0.02_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}} \pm 0.04_{\mathrm{evol}}$$

- QCD fit: $0.26 \leq \Delta\Sigma(Q^2 = 3\,(\mathrm{GeV}/c)^2) \leq 0.36$
- Previous result **(PLB 647 (2007) 8)**:

$$a_0(Q^2 = 3\,(\mathrm{GeV}/c)^2) = 0.33 \pm 0.03_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}$$

Bjorken sum rule from COMPASS measurement

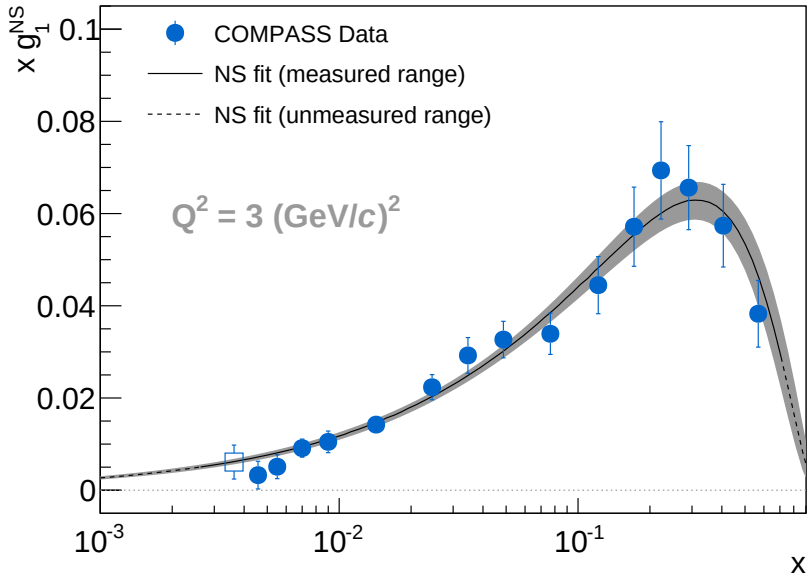
$$\int_0^1 g_1^{\mathrm{NS}}(x,Q^2)dx = \int_0^1 \left(g_1^{\mathrm{p}}(x,Q^2) - g_1^{\mathrm{n}}(x,Q^2)\right) dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{\mathrm{NS}}(Q^2)$$

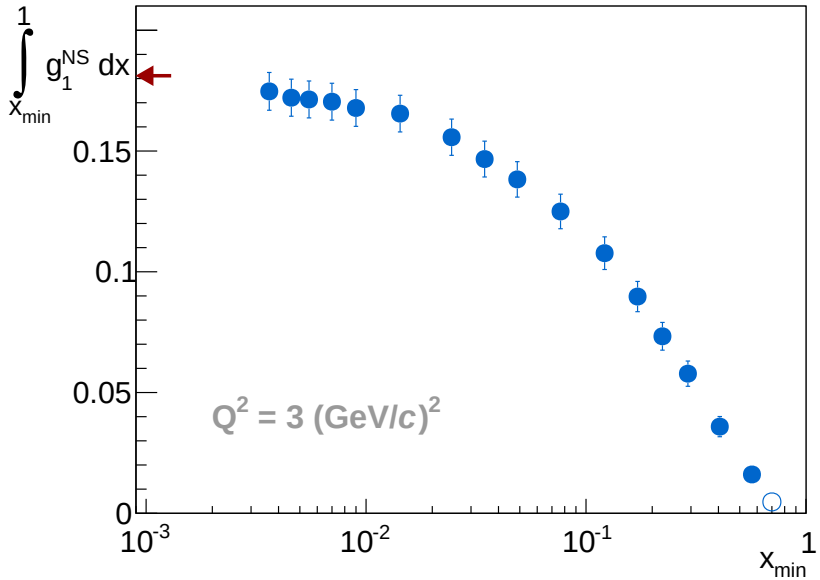
- Non-singlet spin structure function
  $g_1^{\mathrm{NS}} = g_1^{\mathrm{p}} - g_1^{\mathrm{n}} = 2\left[g_1^{\mathrm{p}} - \frac{g_1^{\mathrm{d}}}{1-3/2\omega_D}\right]$, $\omega_D = 0.05$
- g_1^{NS} determined from COMPASS data only
- $\left|\frac{g_A}{g_V}\right| = 1.2701 \pm 0.0020$ obtained from neutron β-decay
  PRD 86 (2012) 010001
- Aim: Verification of the Bjorken sum rule

Non-singlet structure function

- Calculate g_1^{NS}
- Perform NLO QCD fit
  - Fit only Δq_3
  - 3 parameters needed
- Evolve g_1^{NS} to $Q^2 = 3\,(\mathrm{GeV}/c)^2$
- Extrapolation used for unmeasured region ($x \to 0, 1$)
- 94% in measured range
- Verification of the Bjorken sum rule on the level of 9%:

$$\left|\frac{g_A}{g_V}\right|_{\mathrm{NLO}} = 1.22 \pm 0.05_{(\mathrm{stat.})} \pm 0.10_{(\mathrm{syst.})}$$





Summary

- Final results on $A_1^{\mathrm{d}}, A_1^{\mathrm{p}}, g_1^{\mathrm{d}}$ and g_1^{p}
  - Including the 2006 deuteron data ($\sim 2\times$ more data)
  - Smaller values of x using the $200\,\mathrm{GeV}$ proton data
  - Higher values of Q^2 using the $200\,\mathrm{GeV}$ proton data
  - COMPASS legacy on the measurements of g_1
- Results from a NLO QCD fit to the world data
- First moments of g_1 from COMPASS data
  - Contribution from quarks to the nucleon spin: Axial charge a_0
  - Verification of the Bjorken sum rule (level of 9%)