COMPASS measurement of g_1 and QCD fits

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On behalf of the COMPASS Collaboration

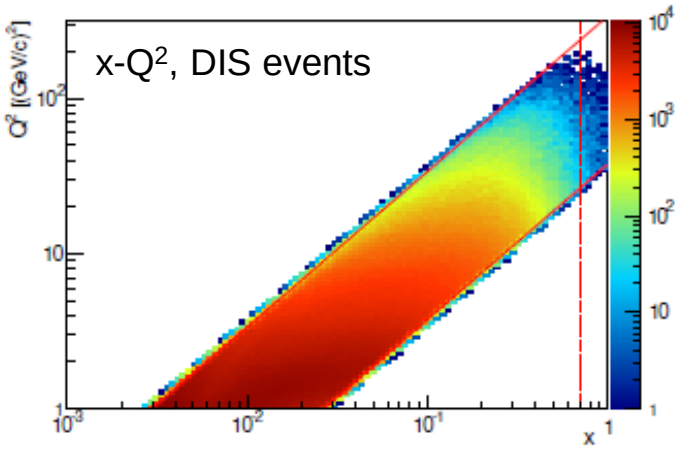
- **Measurement of g_1^p at 200 GeV**
- **NLO QCD fit of g_1 world data**
- **Test of Bjorken sum rule**

Longitudinal spin asymmetry measurements at COMPASS

Year	Pol.Target	Pol. μ beam	Status
2002-2006	d (^{6}LiD)	160 GeV	PLB 612 (2005) 154 PLB 647 (2007) 8 PLB 647 (2007) 330 (low x) PLB 660 (2008) 458 (SIDIS) PLB 680 (2009) 171 (SIDIS)
2007	p (NH_3)	160 GeV	PLB 690 (2010) 240 PLB 693 (2010) 227 (SIDIS)
2011	p (NH_3)	200 GeV	prelim. DIS-2013

Goal of 200 GeV proton data:
improve precision at low x, access slightly higher Q^2:

- Enlarge x-Q^2 coverage for QCD fits (ΔG, $\Delta\Sigma$)
- Improve precision of the integral of g_1^p ($\Delta\Sigma$)
- Improve precision on semi-inclusive data at low x ($\Delta\bar{u}$, $\Delta\bar{d}$)
- Balance proton and deuteron statistics



COMPASS at CERN

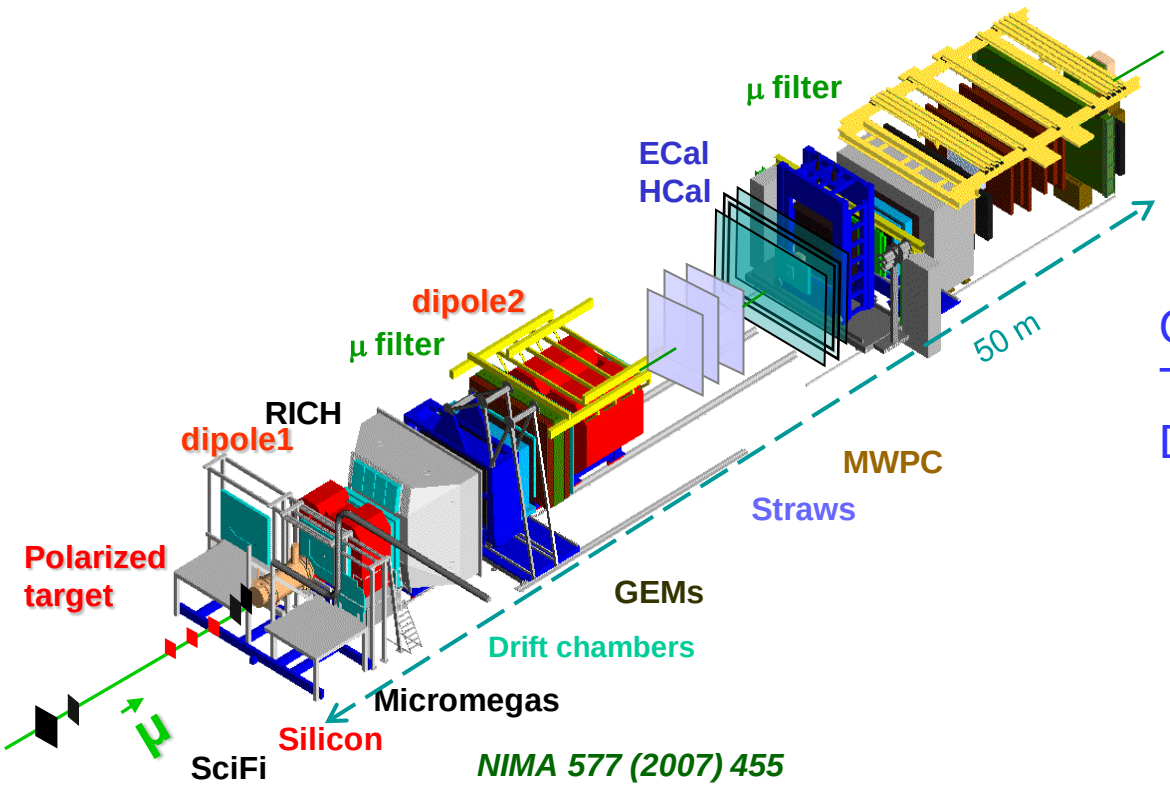
Fixed target
160-200 GeV muon and 190 GeV hadron beams from CERN SPS
→ Multipurpose setup

Polarized muon beam
& polarized target: d, p

Nucleon spin structure

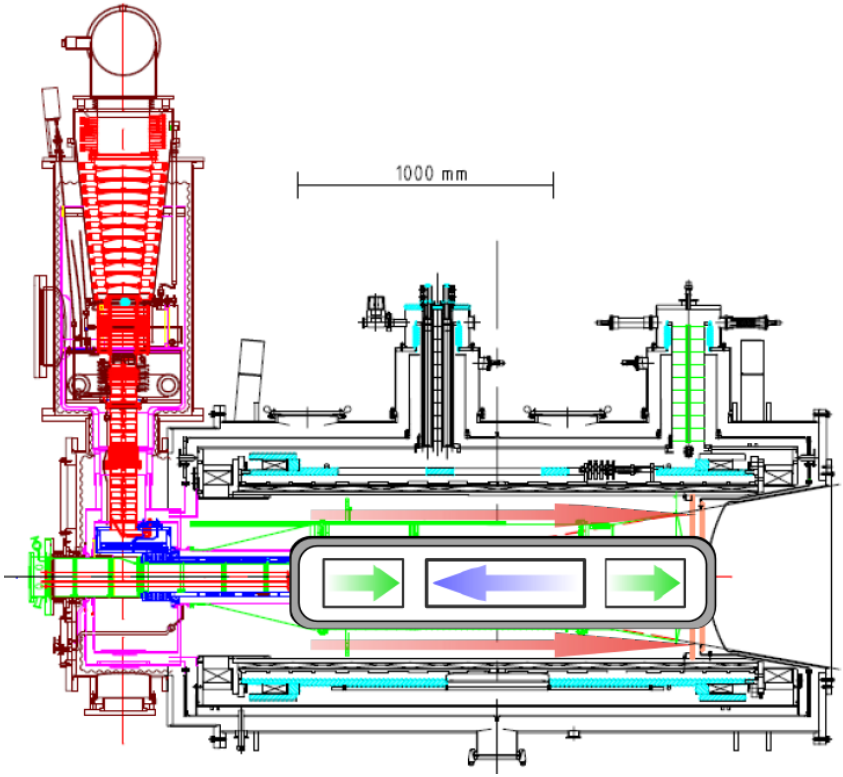
Hadron beam π / K / p
& LH_2 or nuclei

Meson spectroscopy
π, K polarisabilities



Future:
GPDs from DVCS
TMDs from Polarized Drell-Yan

Polarized target



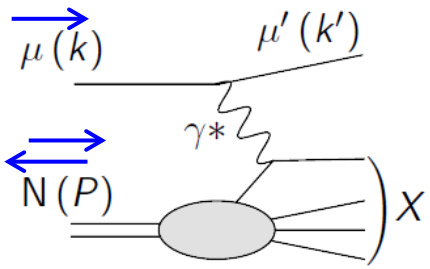
- NH_3 material
- Dilution (15 ± 0.3) %
- Polarisation (80 ± 3)%

- Dynamic Nuclear Polarization
- Superconducting solenoid 2.5T

- 3 cells with opposite polarizations
  Nice balance of acceptance from the 2 spin states
- Reversal of polarization by:
  - Adiabatic rotation of solenoid field
  - Different microwave settings
  → 4 measurements

→ Minimize systematics

Results for A_1^p

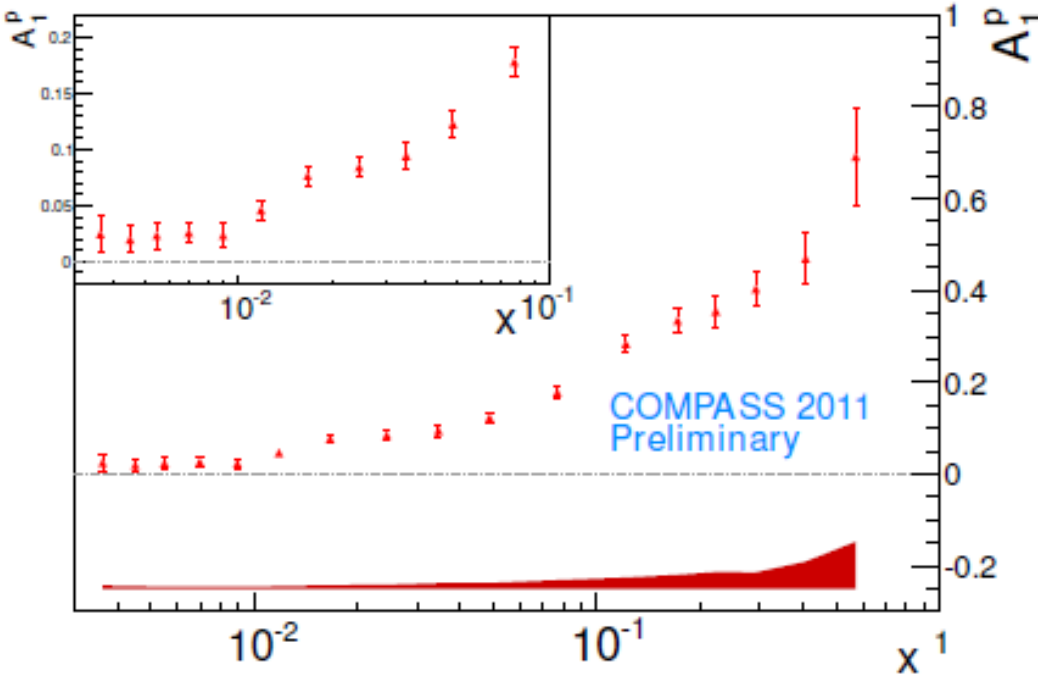


DIS events, $Q^2>1$

$$A_{\parallel} = \frac{d\sigma^{\rightleftarrows} - d\sigma^{\rightrightarrows}}{d\sigma^{\rightleftarrows} + d\sigma^{\rightrightarrows}} = D(A_1 + \eta A_2)$$

$$\frac{A_{\parallel}}{D} = \left\langle \frac{1}{2} \frac{1}{|P_B P_T| f D} \left(\frac{N^{\rightleftarrows} - N^{\rightrightarrows}}{N^{\rightleftarrows} + N^{\rightrightarrows}} + \frac{N^{\rightleftarrows} - N^{\rightrightarrows}}{N^{\rightleftarrows} + N^{\rightrightarrows}} \right) \right\rangle$$

f: target dilution D: depolarization factor



$$A_{\parallel} \approx D \cdot \frac{g_1}{F_1}$$

Systematic errors on A_1

- Multiplicative
- Additive

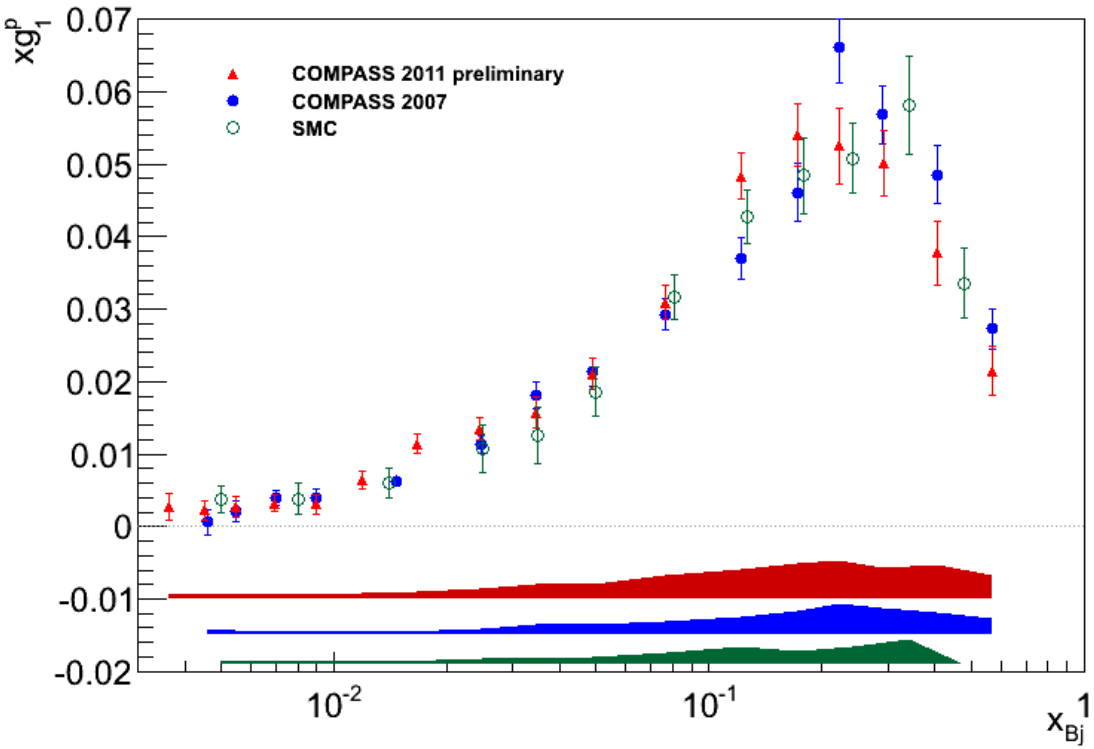
$$A_1^{1\gamma} = \frac{1}{fDP_BP_T}A^{raw} - \left(A_1^{RC} + \mathcal{O}(\frac{x}{Q}A_2) + \mathcal{O}(A_{False})\right)$$

Total of systematics always smaller than statistical error.
Dominant contributions:

- conservative limit put on possible false asymmetries (not seen)
- beam polarization at medium x

Multiplicative variables error, ΔA_1^{mult}	Beam polarisation	σ_{P_B}/P_B	5 %
	Target polarisation	σ_{P_T}/P_T	3.5 %
	Depolarisation factor	σ_D/D	2 – 3 %
	Dilution factor	σ_f/f	2 %
Additive variables error, ΔA_1^{add}	Transverse asymmetry	$\mathcal{O}(x/Q)\cdot\sigma_{A_2}$	$10^{-3} - 10^{-2}$
	Rad. corrections	$\sigma_{A_1^{RC}}$	$10^{-5} - 10^{-3}$
	False asymmetry	$\sigma_{A_{false}}$	$< 0.34 - 0.84 \cdot \sigma_{A_1^{stat}}$

Results for g_1^p at 200 GeV



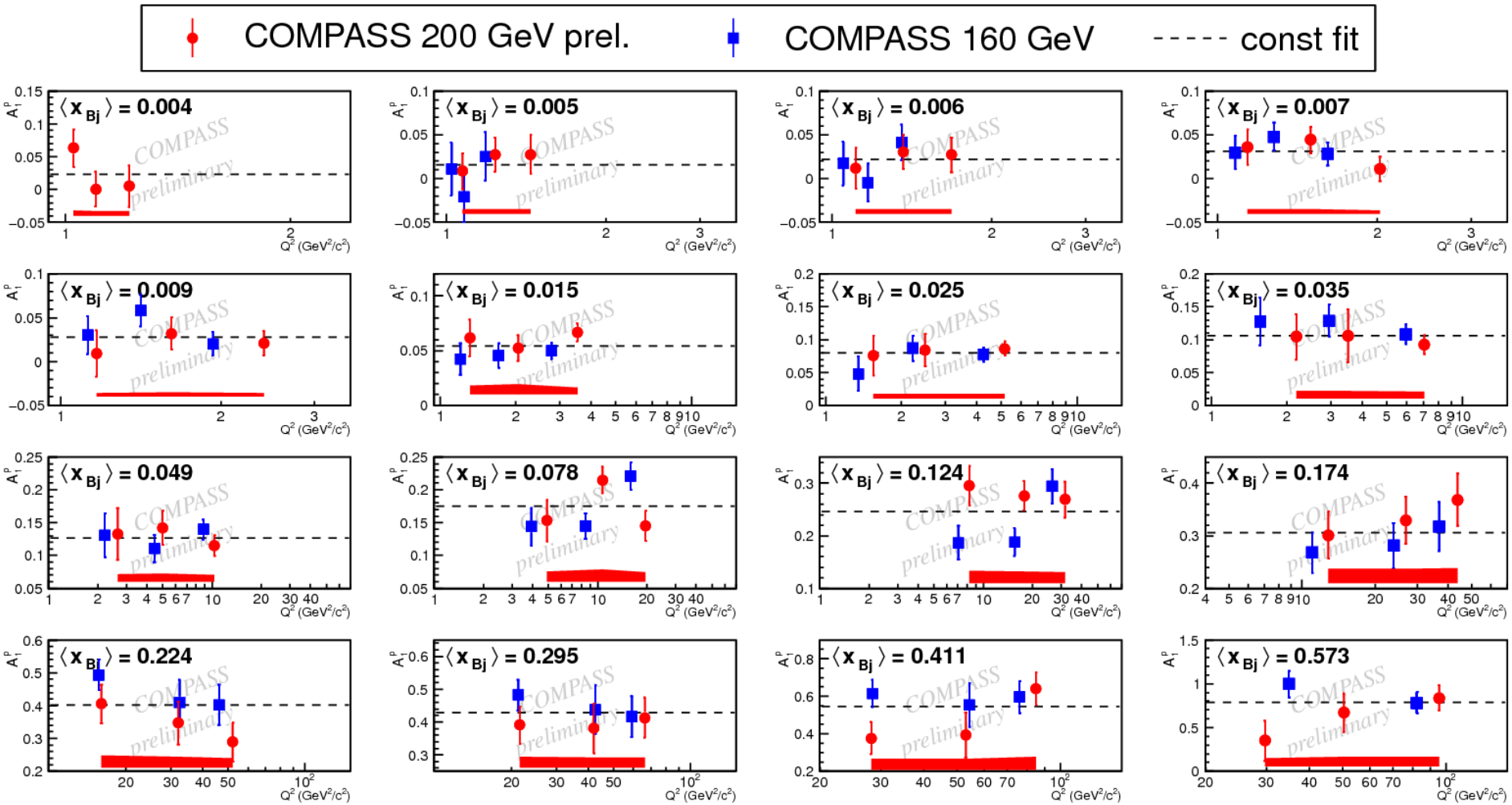
- COMPASS 200 GeV
- COMPASS 160 GeV
- SMC 190 GeV

shown at measured Q^2

V. Andrieux, DIS 2013

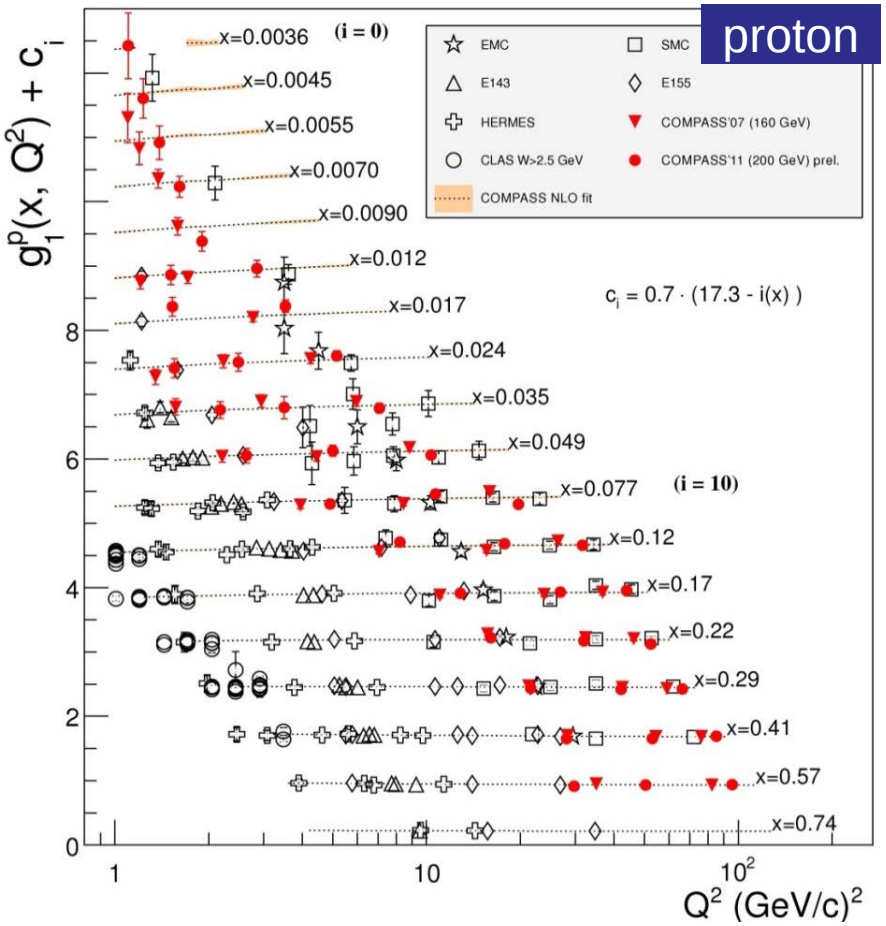
- All 3 sets of data compatible
- Lowest x value reached x=0.0036
- Statistical uncertainties (160 and 200 GeV) 3 times smaller than SMC in similar beam time

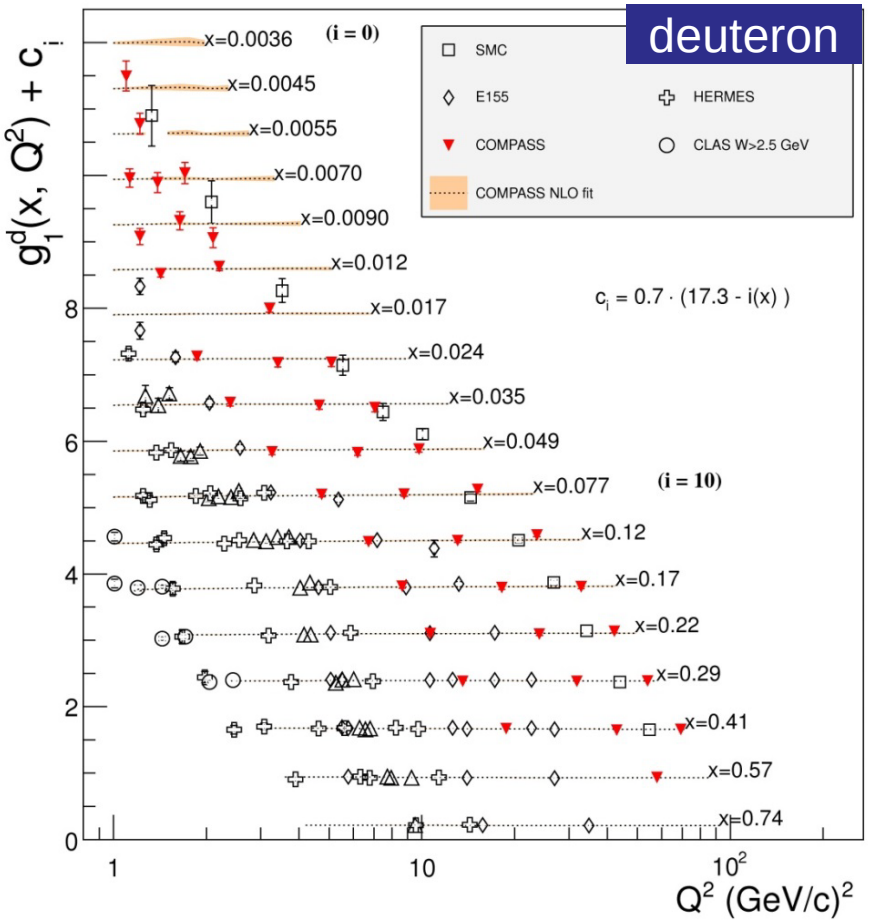
A1 (Q^2) at various x



160 and 200 Gev data: all Q^2 dependences well fitted by a constant

World data on g_1^p and g_1^d





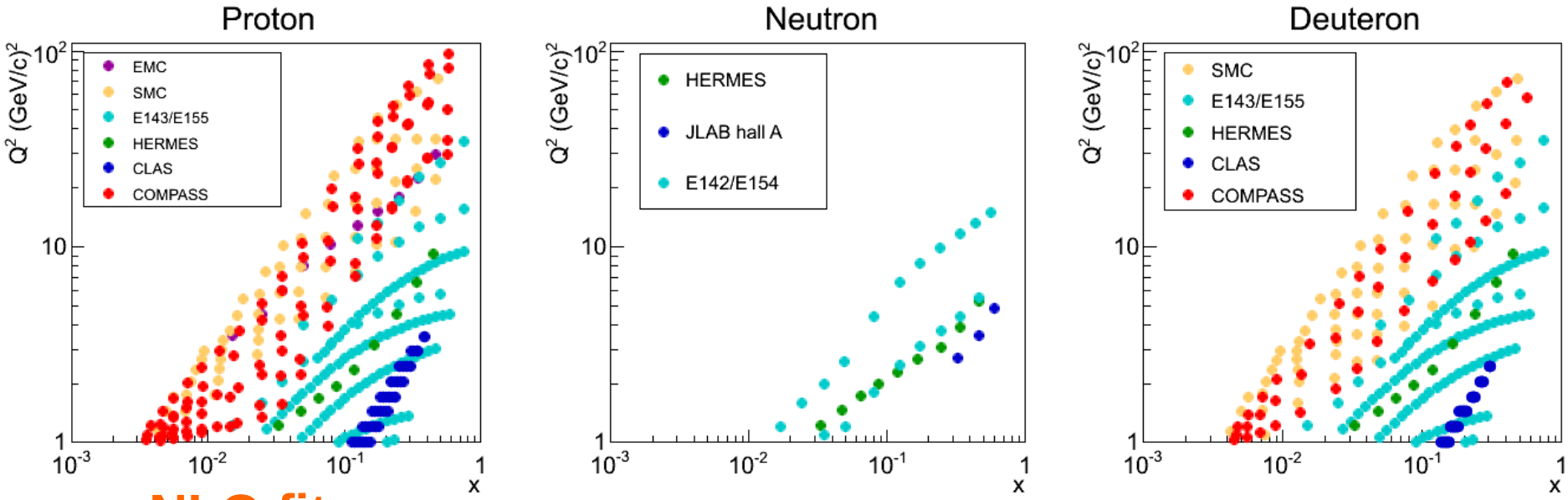
- New **proton** data from COMPASS 200 GeV : low x and high Q^2

g_1 as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$

$$\frac{d\, g_1}{d\, Log(Q^2)} \propto -\Delta g(x, Q^2)$$

Fit to proton, neutron and deuteron world data

x-Q^2 coverage of world data



NLO fit:

- Assume functional forms for $\Delta\Sigma$, ΔG and Δq^{NS} at a reference $Q_0^2 = 1(GeV/c)^2$

  e.g.: $\Delta q_{Si}(x|Q_0^2) = \eta_s x^{\alpha_s}(1-x)^{\beta_s}(1+\gamma_s x)/N_s$

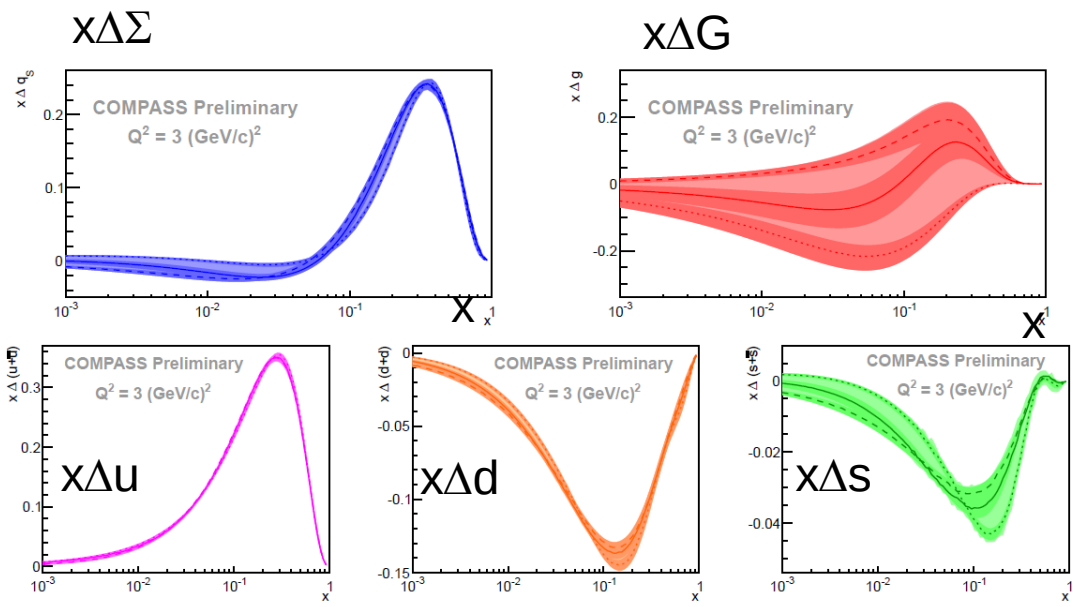
- Assume SU_3
- Use DGLAP equations
- Fit world data

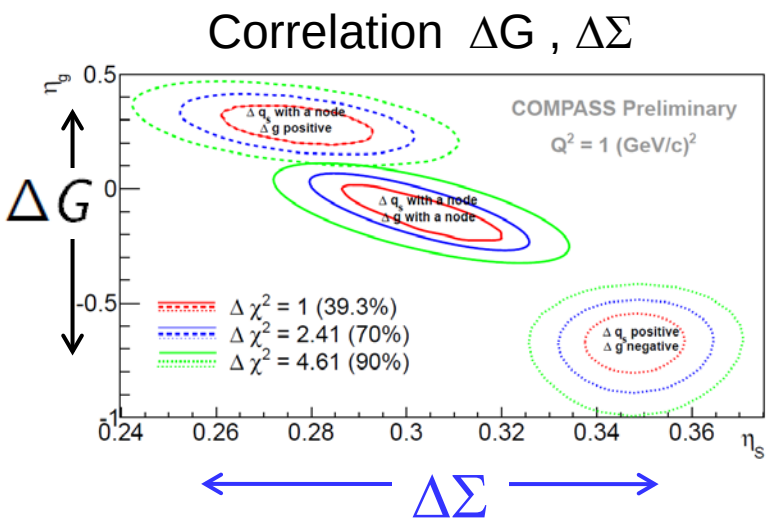
  679 points, 28 free parameters.

COMPASS NLO pQCD fit of g_1 world data

→ 3 classes of solutions, $\Delta G>0$, ΔG with a node, and $\Delta G<0$

V.Andrieux, QCD@Work -2014



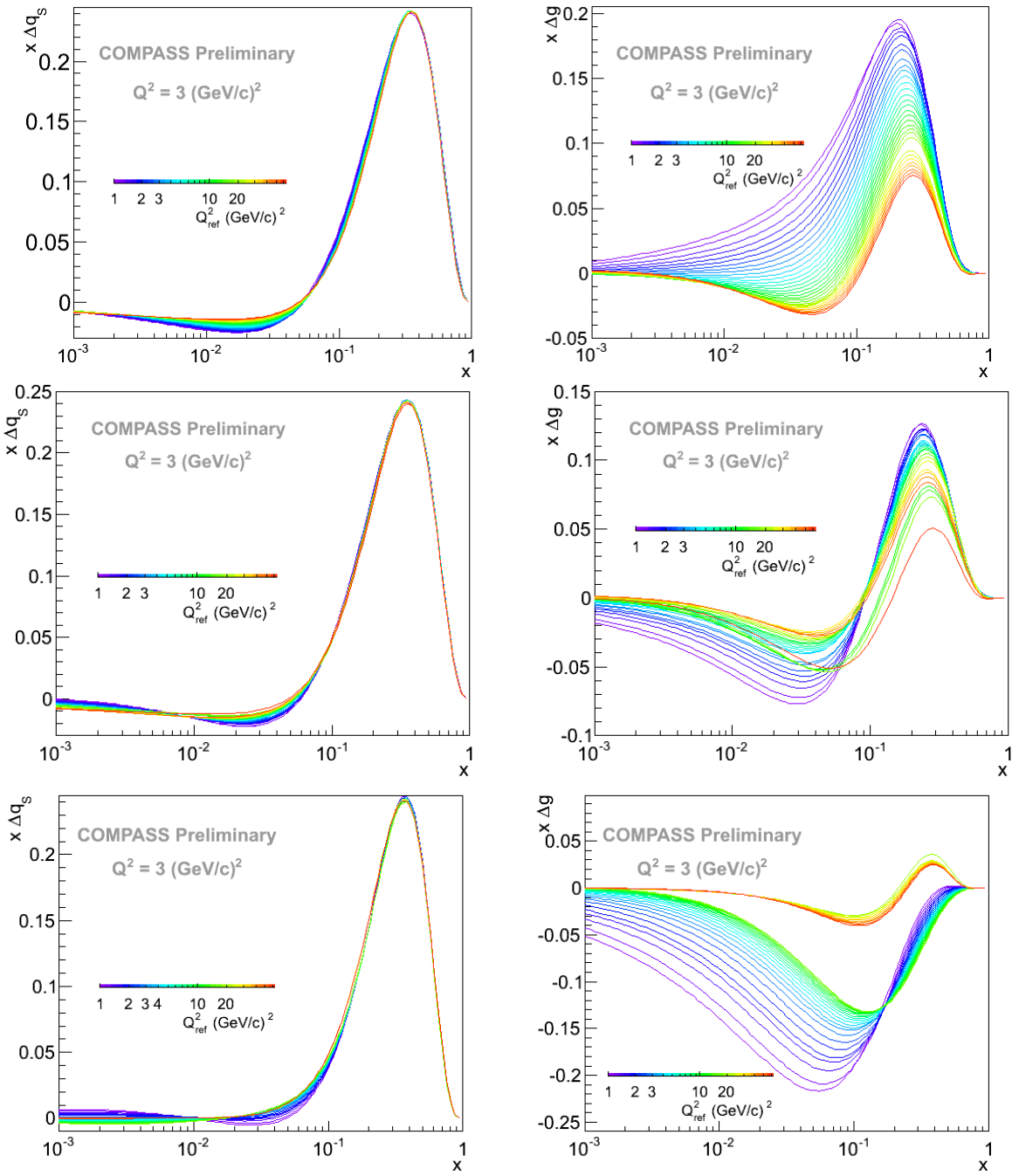


- Quark spin contribution : $0.26 < \Delta\Sigma < 0.34$ at $Q^2=3$ (GeV/c)^2

Largest uncertainty comes from the bad knowledge of functional forms.

Result in fair agreement with other global fits, and with Lattice QCD.

- Gluon spin contribution: ΔG not well constrained, even the sign, using DIS only
  Solution with node agrees with result from DSSV++ using RHIC pp data



Varying Q_0ref

from 1 to 60 GeV^2

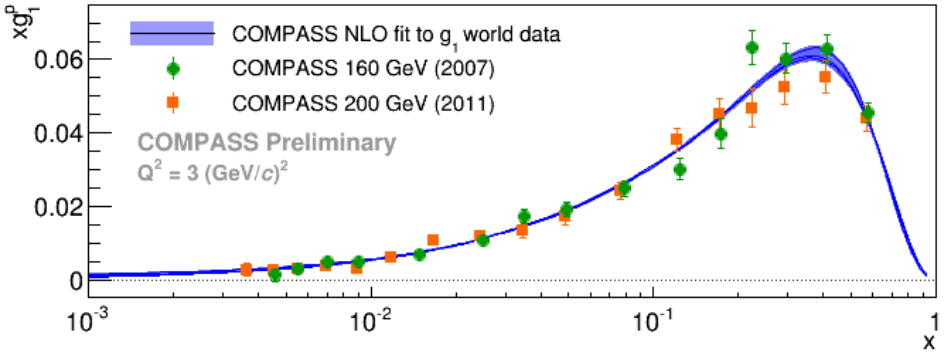
→ equivalent to changing the functional form

→ well visible on ΔG

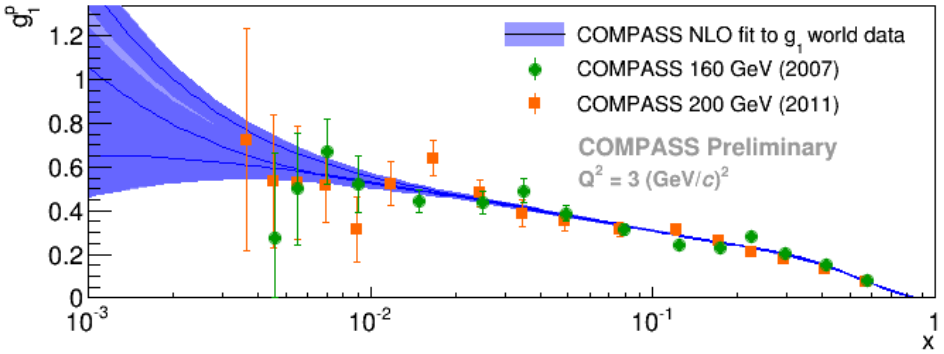
g_1^p and g_1^d

COMPASS data and NLO QCD fit

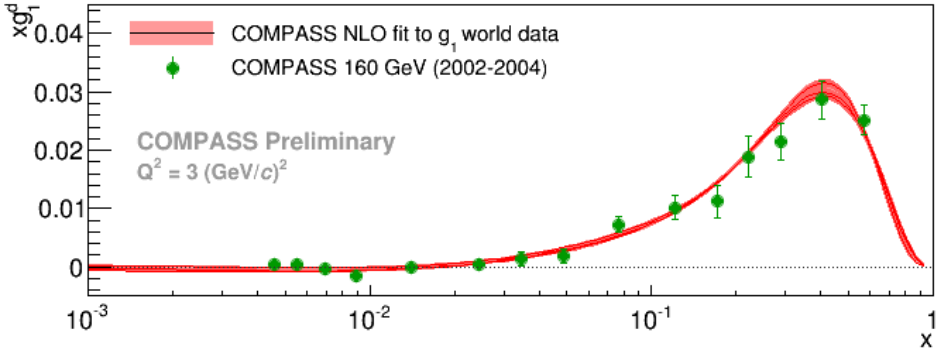
xg_1^p



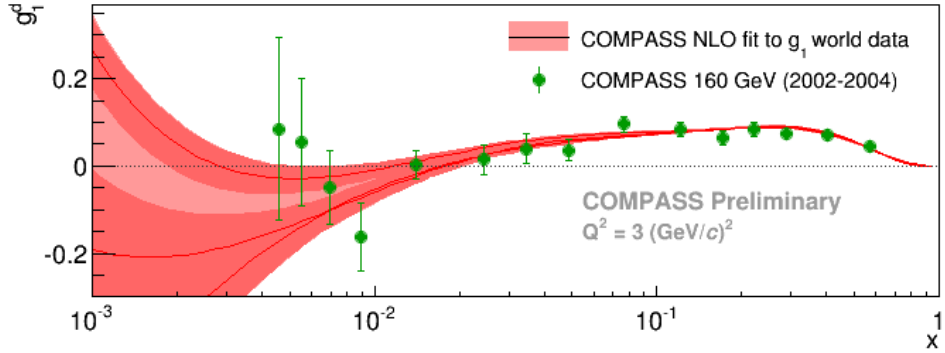
g_1^p



xg_1^d



g_1^d



- **g_1^p positive at low x**
- **Lower x data needed for sensitivity to ΔG**

Results for Bjorken sum rule from g_1 COMPASS data

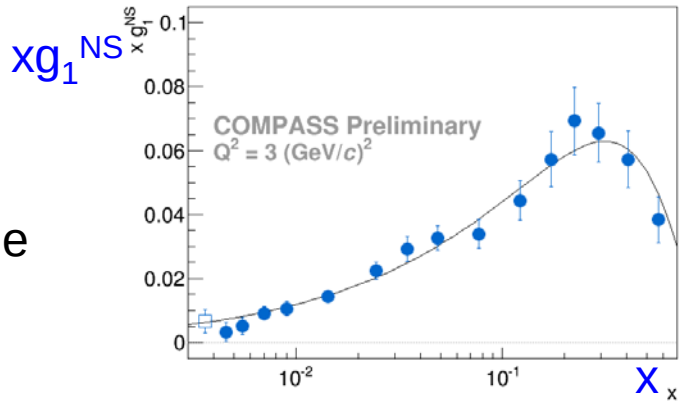
Fundamental QCD sum rule, which relates proton and neutron spin structure functions g_1.

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

Using COMPASS data alone:

- Non-singlet fit: independent from ΔG
- Reduce systematics

94% of the sum is from the measured range



M. Wilfert, DIS-2014

COMPASS $(g_A/g_V)_{\mathrm{NLO}} = 1.219 \pm 0.052(\mathrm{stat.}) \pm 0.095(\mathrm{syst.})$

to be compared to: $\left| \frac{g_A}{g_V} \right| = 1.269 \pm 0.002$ obtained from neutron β-decay.

→ **Bjorken sum rule verified to 8%**

Better statistics and extended systematics studies compared to past

Note that experimental value increases from 1.22 to 1.25 when C_1^{NS} at NNLO

Summary

g_1^p : Measurement down to x= 0.0036

Statistical precision improved by factor of ~3 compared to SMC

NLO QCD fit of g_1 world data:

Gluon and quark contributions to nucleon spin

Quarks : Sum $0.26 < \Delta\Sigma < 0.34$

Uncertainty dominated by initial functional forms

Gluon : Shape not constrained enough by DIS data alone

Bjorken sum rule from COMPASS p and d data: Verified to 8%

In progress

Semi-inclusive data $A_1^{\pi,\,k}$ for flavour separation $\Delta q_f(x,Q^2)$

COMPASS future

2015 : TMDs via polarized Drell-Yan $\pi\ p^{\uparrow} \rightarrow \gamma\ \gamma$

2016-2017 : GPDs via Deep Virtual Compton Scattering $\mu\ p \rightarrow \mu\ p\ \gamma$

In parallel, SIDIS $\mu\ p \rightarrow \mu\ h\ X$: Fragmentation functions and PDFs

Spares

NLO QCD fit – Q^2 evolution equations

- Decomposition of spin structure functions at NLO ($\overline{\text{MS}}$):

$$g_1 = \frac{1}{2} < e^2 > \left(C^s(\alpha_s) \otimes \underbrace{\Delta q_S}_{\text{singlet}} + C^{NS}(\alpha_s) \otimes \underbrace{\Delta q_{NS}}_{\text{non-singlet}} + C^g(\alpha_s) \otimes \Delta g \right)$$

with $\Delta q_S = \Delta u + \Delta d + \Delta s$ and

Δq_{NS}: a combinaison of $\Delta q_3 = \Delta u - \Delta d$ and $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$

- DGLAP equations:

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

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

with ΔP_{ij}: splitting functions

Probability for a parton j to radiate a parton i

NLO QCD fit – functional forms

Functional forms postulated at a given "reference" scale Q^2_{ref}:

$$\Delta q_S(x|Q^2_{ref}) = \eta_S\, x^{\alpha_S}\,(1-x)^{\beta_S}\,(1+\gamma_S x+\rho_S\sqrt{x})\,/\,N_S$$
$$\Delta g\,(x|Q^2_{ref}) = \eta_g\, x^{\alpha_g}\,(1-x)^{\beta_g}\,(1+\gamma_g x+\rho_g\sqrt{x})\,/\,N_g$$
$$\Delta q_3(x|Q^2_{ref}) = \eta_3\, x^{\alpha_3}\,(1-x)^{\beta_3}\,/\,N_3$$
$$\Delta q_8(x|Q^2_{ref}) = \eta_8\, x^{\alpha_8}\,(1-x)^{\beta_8}\,/\,N_8$$

N_q defined such as η_q represent the first moment of the distributions at Q^2_{ref}

$\Downarrow$

DGLAP equations to evolve to any Q^2

$\Downarrow$

give

$\Delta q_S(x,Q^2)$, $\Delta g\,(x,Q^2)$, $\Delta q_3(x,Q^2)$, $\Delta q_8(x,Q^2)$

for all Q^2 values

NLO QCD fit – Constrains

- Additional inputs:
  - $\eta_3 = F + D = g_A/g_V$ with $\mathrm{SU}(2)_{\mathrm{flavour}}$
  - $\eta_8 = 3F - D$ with $\mathrm{SU}(3)_{\mathrm{flavour}}$ (PRD 87 (2013) 016002)
  - Positivity : $|\Delta g| < g(x)$ and $|\Delta(s+\bar{s})| < s(x) + \bar{s}(x)$ (MSTW2008)
  - β_g fixed to 7.5 (preferential value)

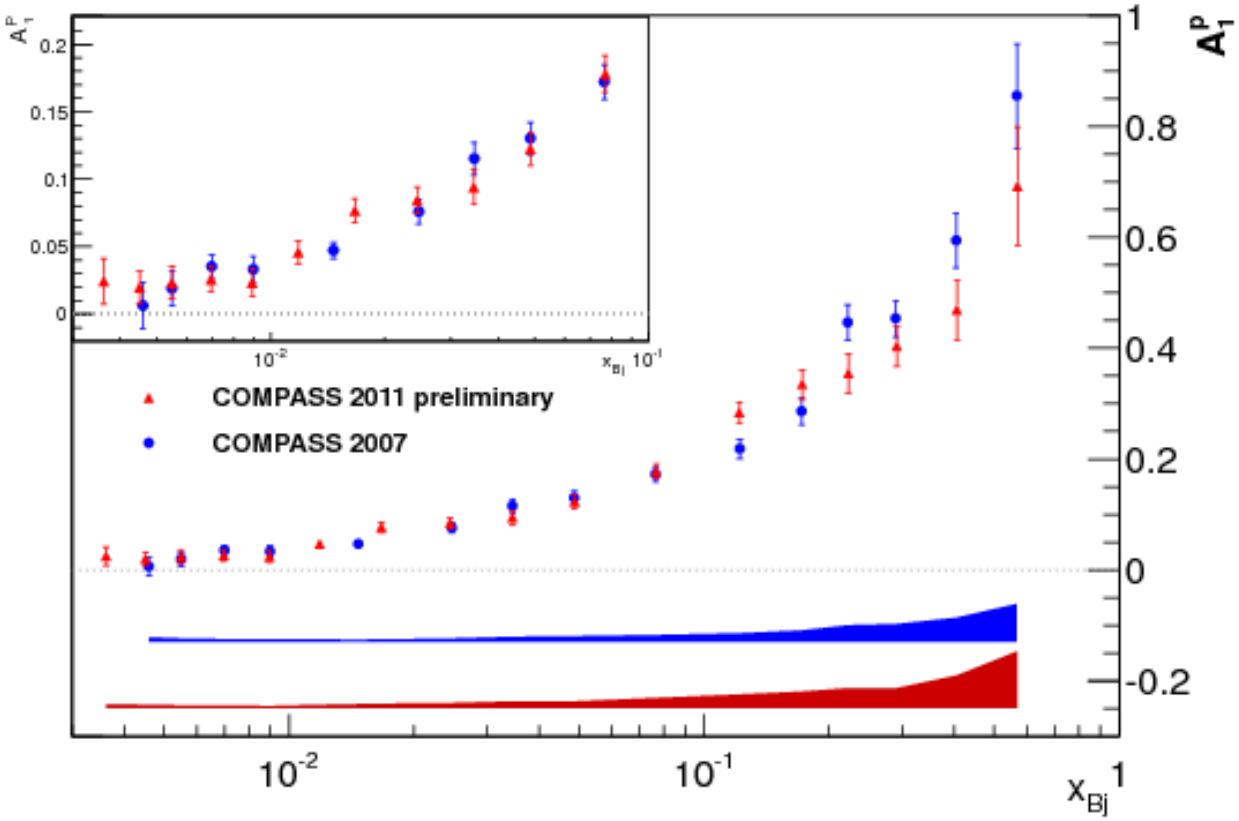
- Minimisation of $\chi^2 =$

$$\sum_{data} \left(\frac{g_1^{fit}(x_{data}, Q^2_{data}) - \mathcal{N}_{exp} \cdot g_1^{data}}{\mathcal{N}_{exp} \cdot \sigma^{stat}_{data}} \right)^2 + \sum_{exp} \left(\frac{1 - \mathcal{N}_{exp}}{\delta \mathcal{N}_{exp}} \right)^2$$

N_{exp} parameters accounting for experimental normalisation uncertainties

Overall: $\sim$ 28 free parameters for 679 data points

Results for A_1^p at 200 GeV



- 200 GeV
- 160 GeV

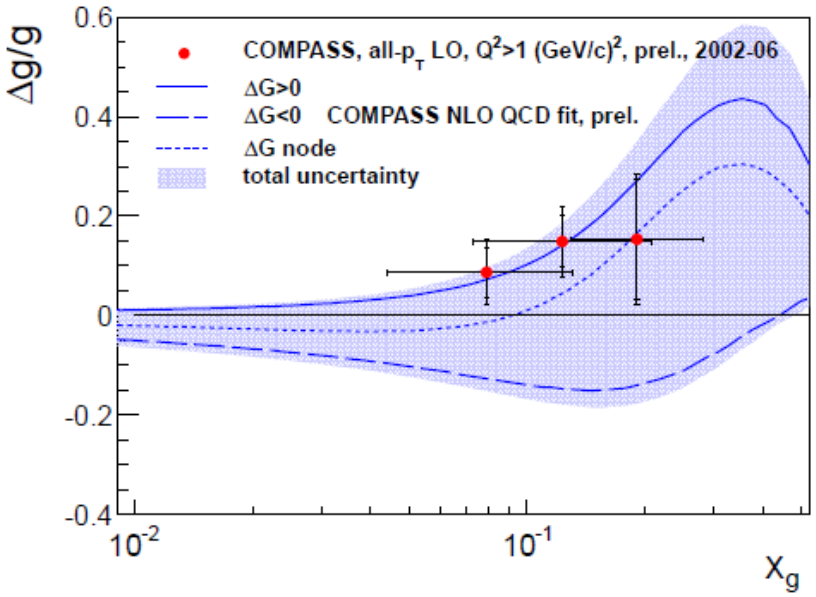
- Compatible results for the different beam energies at their measured Q^2
- Statistical uncertainties (160 GeV and 200 GeV) 3 times smaller than SMC for a similar beam time.
- Lowest x value reached: $x = 0.0036$

$$\Delta\Sigma \in [0.264,\ 0.356] \text{ at } Q^2 = \ \ 1\ (GeV/c)^2$$
$$\Delta\Sigma \in [0.256,\ 0.335] \text{ at } Q^2 = \ \ 3\ (GeV/c)^2$$
$$\Delta\Sigma \in [0.258,\ 0.299] \text{ at } Q^2 = 10\ (GeV/c)^2$$

ΔG/G from hadron prod. in DIS (all-p_T)

New COMPASS results (better precision)

ΔG/G extracted at LO, in 3 x-bins



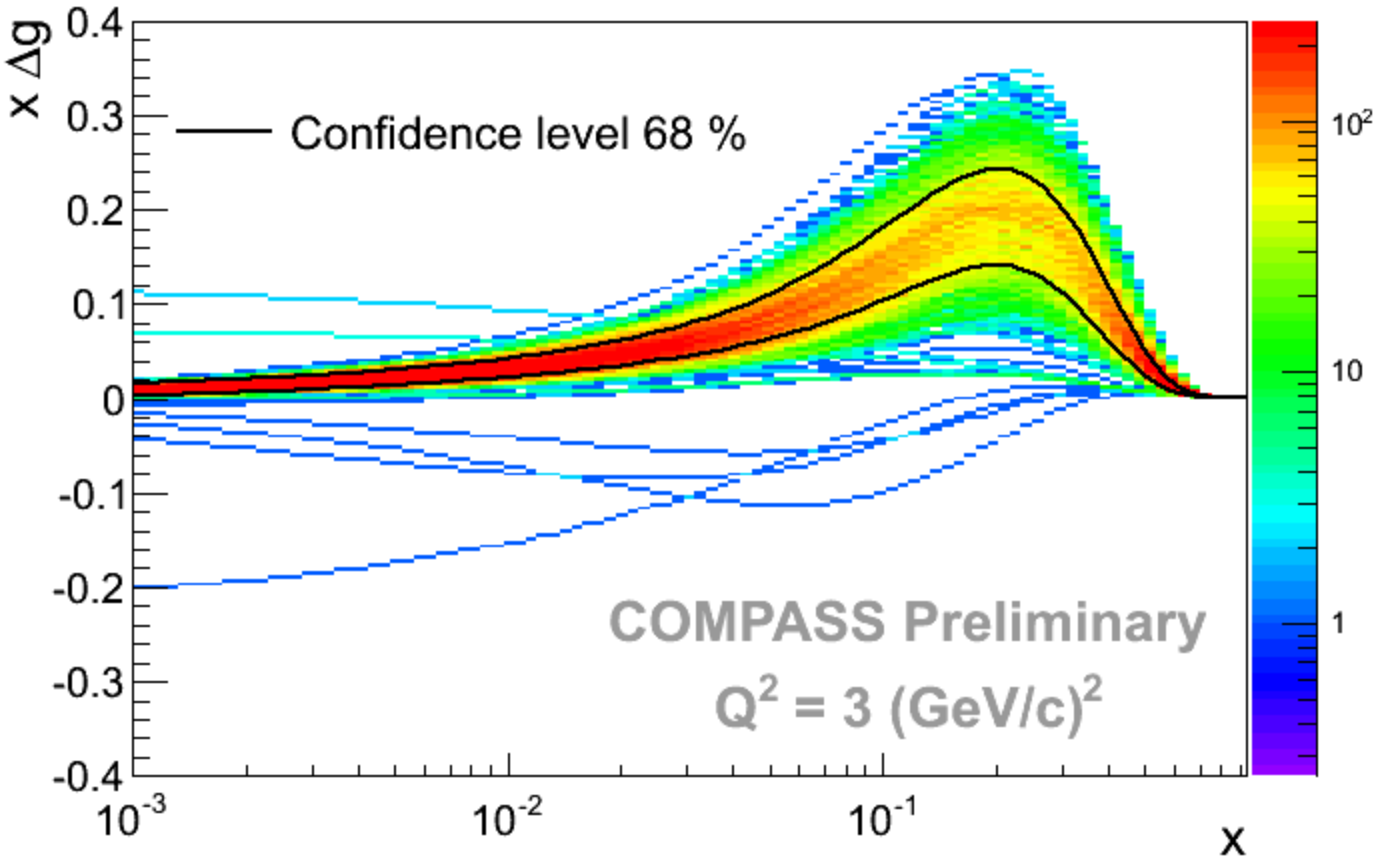
3 solutions from COMPASS NLO QCD fit of g_1 world data

M. Stolarski, DIS 2014

Uncertainty on ΔG/G could be reduced if these results could be included in NLO fits

Statistical error on fit

Estimated from multiple fits on replicas of pseudo data generated within the error on g_1. Example for the 'positive' solution.



Truncated integral vs x_min