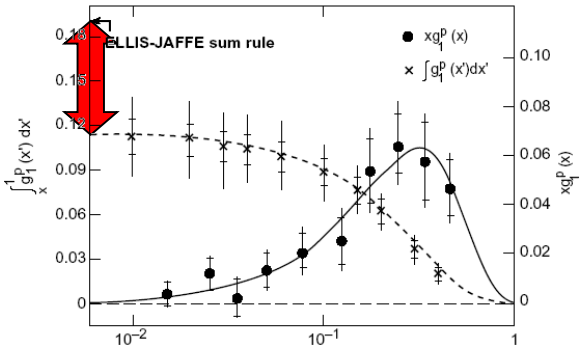
COMPASS Legacy

Longitudinal spin structure and gluon polarisation

G.K. Mallot

Historical excursion

- 1987: EMC nucleon spin puzzle



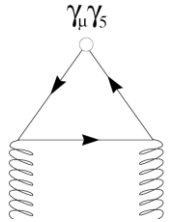
35th anniversary

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.12 \pm 0.17$$
$$\Delta s = -0.19 \pm 0.06$$

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x$$

- 1988/9: axial anomaly may mask quark polarisation
  - Altarelli,Ross; Efremov, Teryaev

$$a_0 = \Delta\Sigma - n_f \frac{\alpha_s}{2\pi}\Delta G$$



Lepton-Photon Stanford 1989

To summarise, let us return to the fit of Fig. 7 and 8. At $Q^2=10GeV^2$ this corresponds to $\Delta g=6.3$ and so the proton helicity is given by

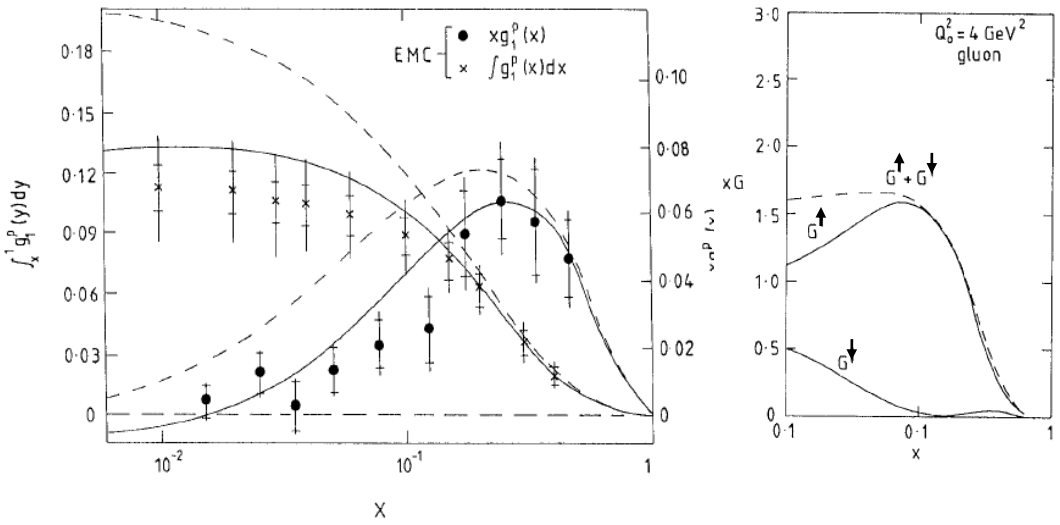
$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta g + L_z$$

$$= 0.35 + 6.3 - 6.15$$

G.G. Ross 1989

Need huge $\Delta G \approx 6$ for $\Delta\Sigma = 0.7$

$\rightarrow$ measure ΔG



Historical excursion

- 1993: SMC measures deuteron g_1

  in agreement with Bjorken sum rule

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_a$$

- 1995: with new SMC and SLAC g_1 data about $\Delta G \simeq 2.5$

  needed to restore parton model value $\Delta\Sigma \simeq 0.7$

  via axial anomaly

- 1995: HMC and Cheops LoI's

  – Gluon and quark polarisations, transversity

  – Spectroscopy, pion polarisability

HMC & CHEOPS LoI's

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSLC 95-27
SPSC/I 204
March 28, 1995

Letter of Intent

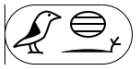
SEMI-INCLUSIVE MUON SCATTERING FROM A POLARISED TARGET

'Hadron Muon Collaboration'

28 March 1995

- Independent LoI's
- Both require new spectrometer
- Both propose to use same experimental hall

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



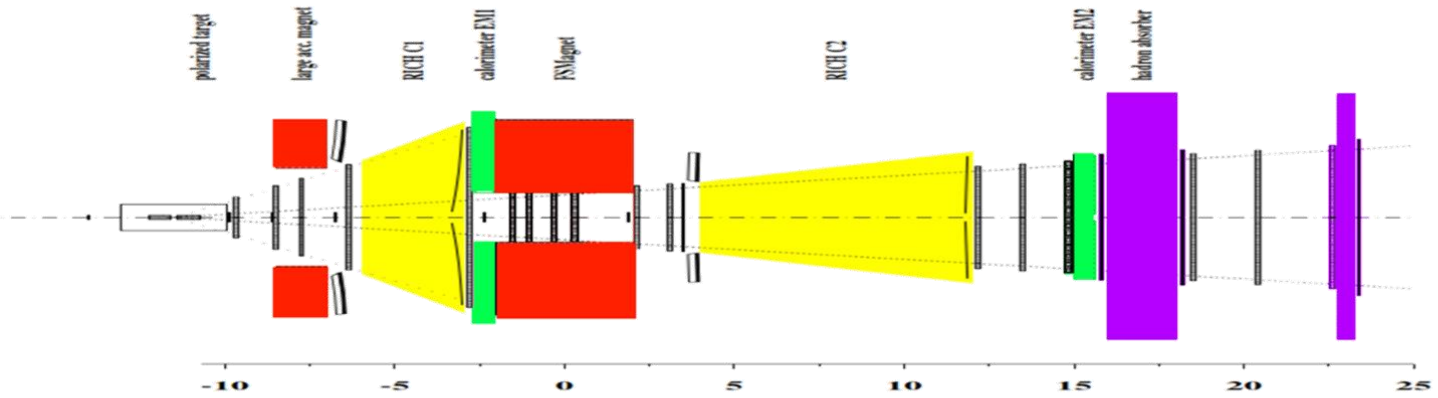
CERN/SPSLC 95-22
SPSLC/I202
March 28, 1995

LoI

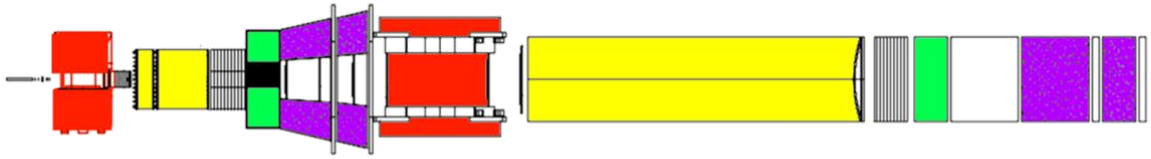
CHEOPS

CHarm Experiment with Omni-Purpose Setup

Spectrometers



HMC

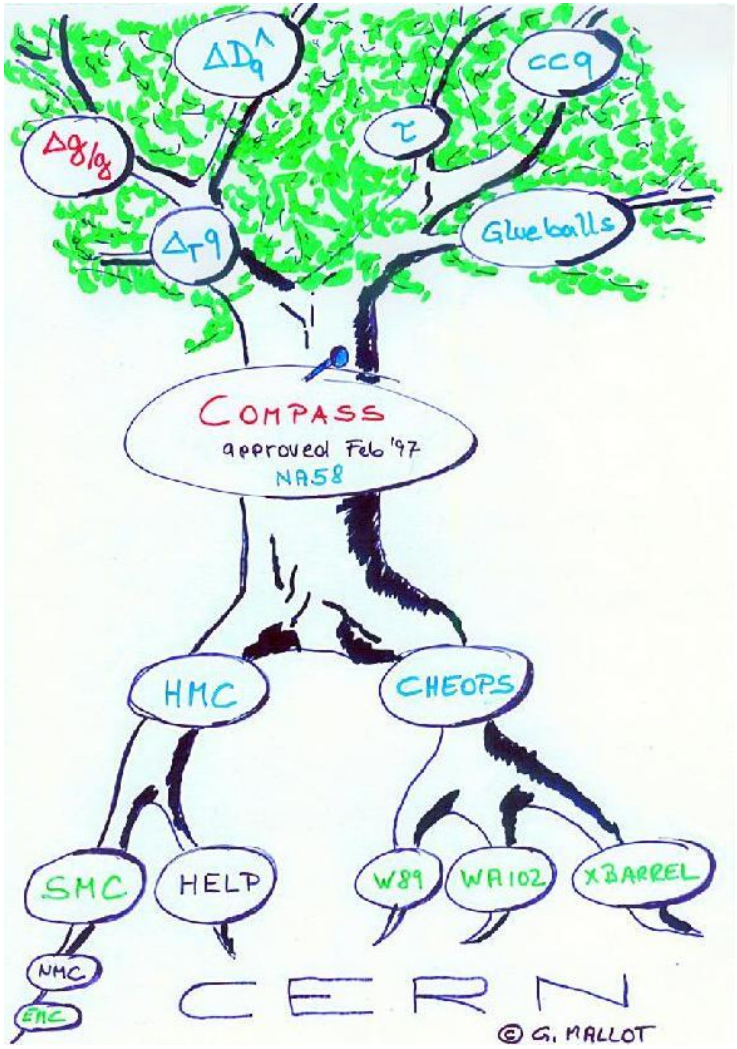


CHEOPS

magnet
calorimeter
RICH/Cherenkov
muon wall

SPSLC, June 1995: join forces!

COMPASS Proposal



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSLC 96-14
SPSC/P 297
March 1, 1996

PROPOSAL

Common Muon and Proton Apparatus for Structure and Spectroscopy

The COMPASS Collaboration

Abstract

We propose to study hadron structure and hadron spectroscopy with high-rate hadron and muon beams and a new spectrometer to be built at the CERN SPS. The experiment can start up in 1999 and a program of physics measurements for an initial period of 5 more years is planned.

Approval Feb 1997

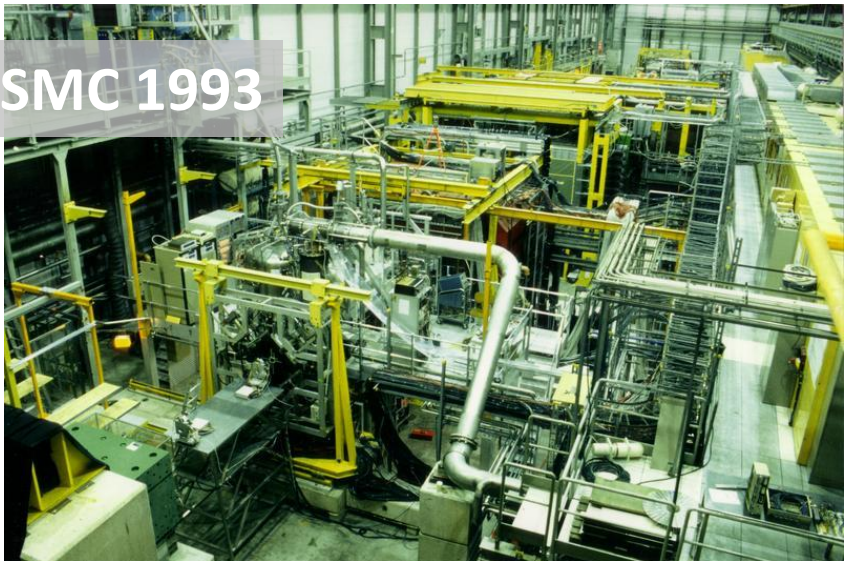
CERN/DG/Research Board 97-252
Minutes 130
14 February, 1997

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

The Research Board then discussed the COMPASS proposal. The physics programme was recognised to be of topical interest. The re-design of the spectrometer in order to cope with the available funds was appreciated. In conclusion the Research Board **approved** the experiment under the conditions spelled out by the SPSC and subject to the availability of funds. Its code number will be **NA58**.

EHN2

SMC 1993



1999

2001

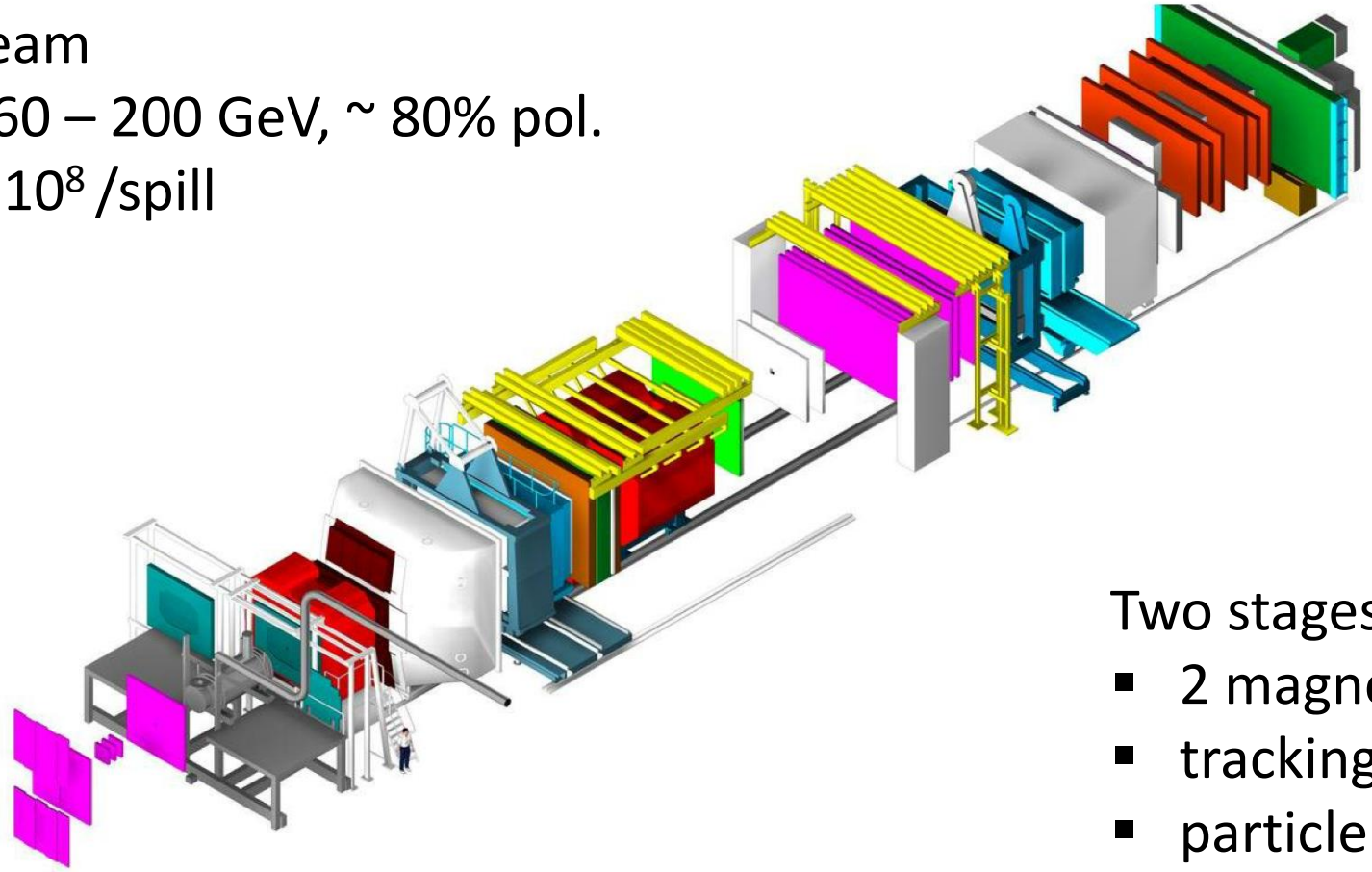
2004

COMPASS Spectrometer

NIM A577 (2007) 455

μ beam

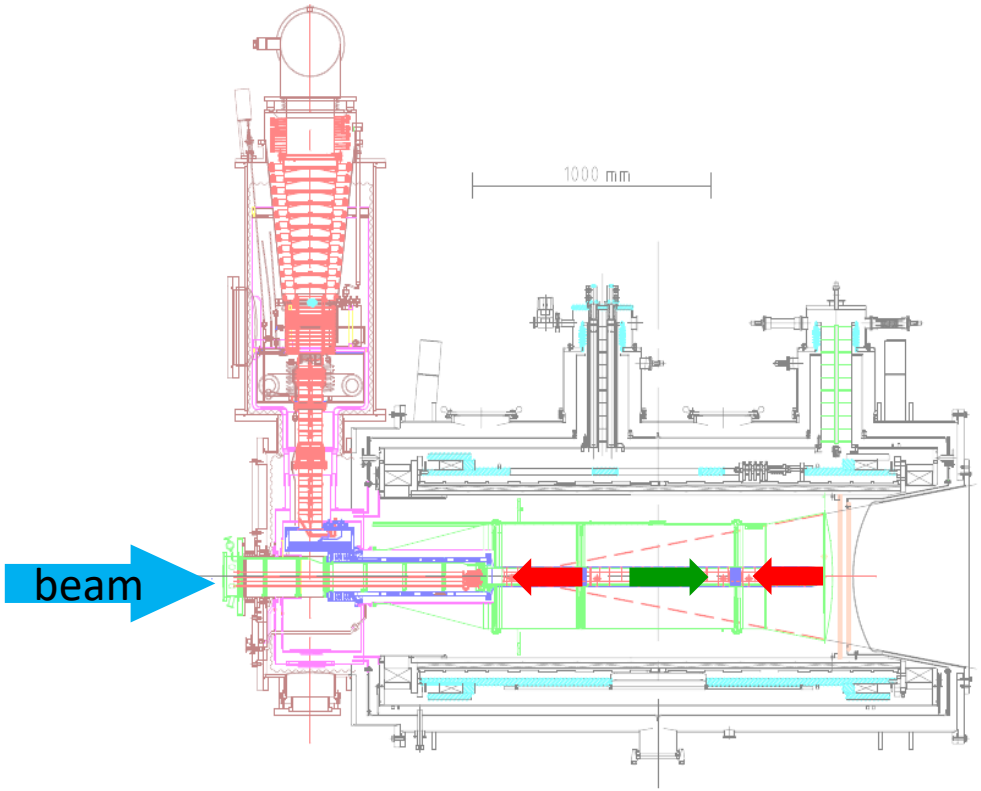
- 160 – 200 GeV, ~ 80% pol.
- 2 10^8 /spill



Two stages

- 2 magnets
- tracking
- particle ID

Polarised target



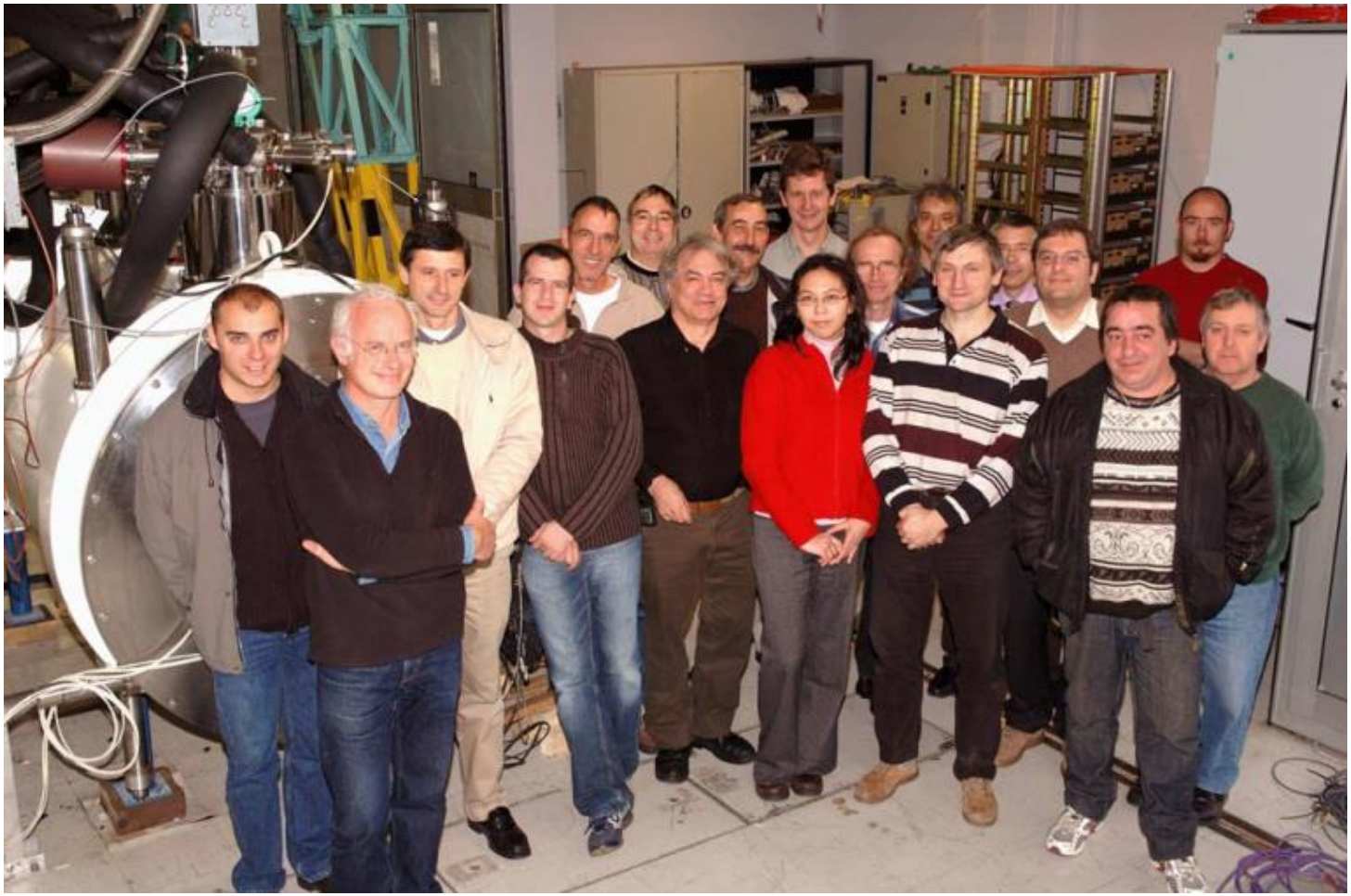
- 2.5 T solenoid, 0.6 T dipole
- ~ 50 mK
- 2 or 3 oppositely pol. cells
- pol. reversal by rotation of magnet field

- ^{6}LiD ~ 50%
- NH_3 ~ 85%

New large acceptance COMPASS magnet in 2005

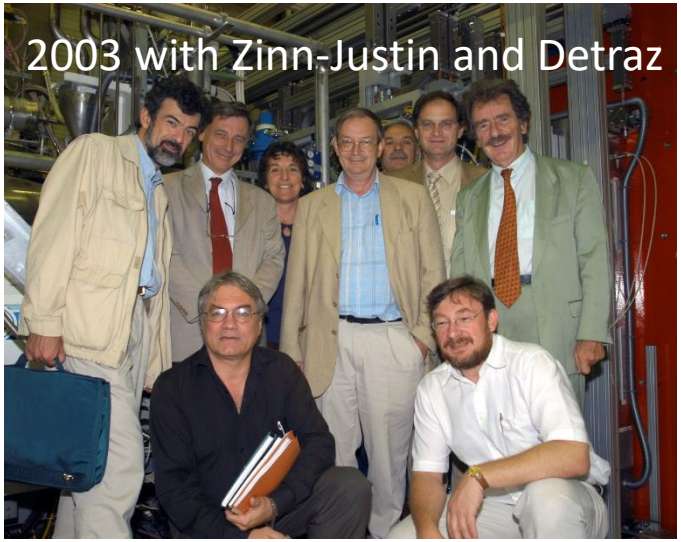
Repaired and instrumented at Saclay

COMPASS magnet at Saclay



Alain Magnon, J. Ball, C. Marchand, JY Rousse, …

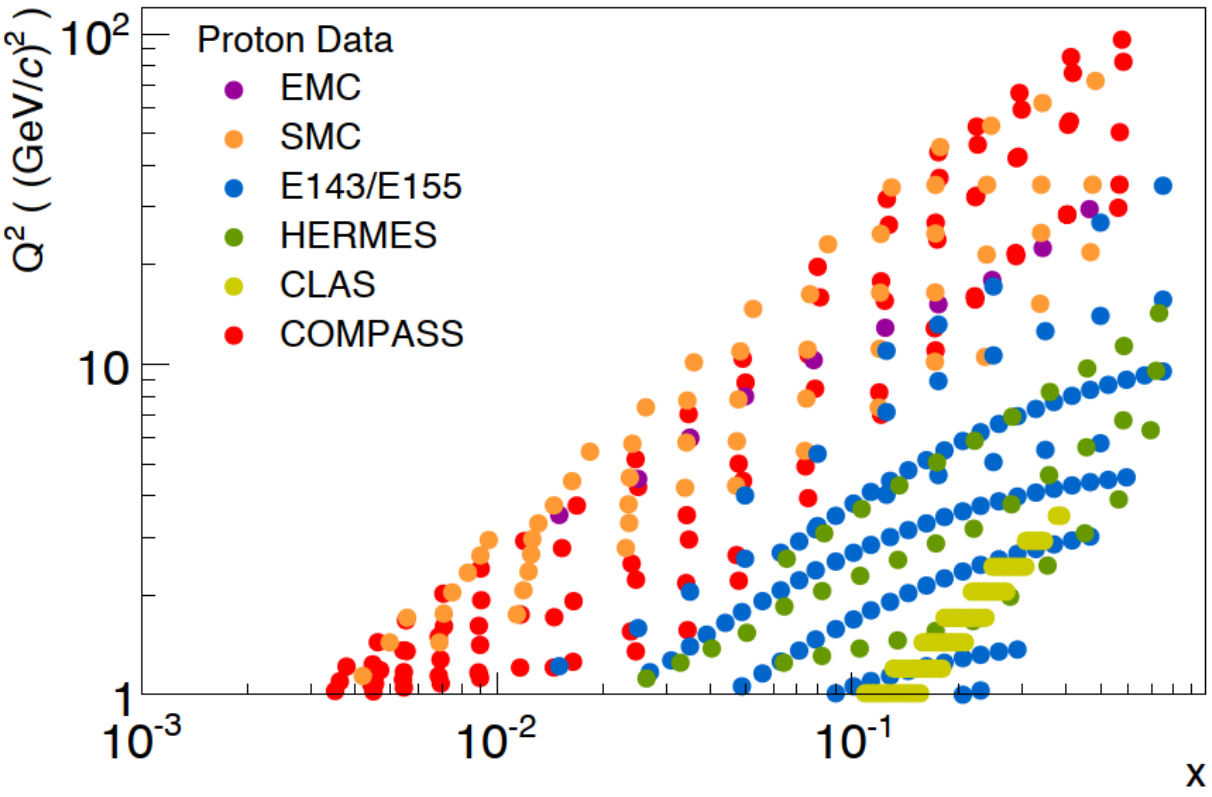
Alain Magnon (1944 – 2022)



Alain Magnon (1944 – 2022)

Merci Alain

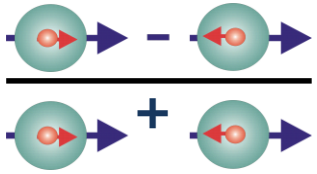
Kinematic coverage



- Lowest *x* data from COMPASS and SMC

Reminder

Measured asymmetry A_{exp}
yields the virtual photon asymmetry



$$A_1 \simeq \frac{A_{exp}}{f\, P_\mu\, P_T\, D}$$

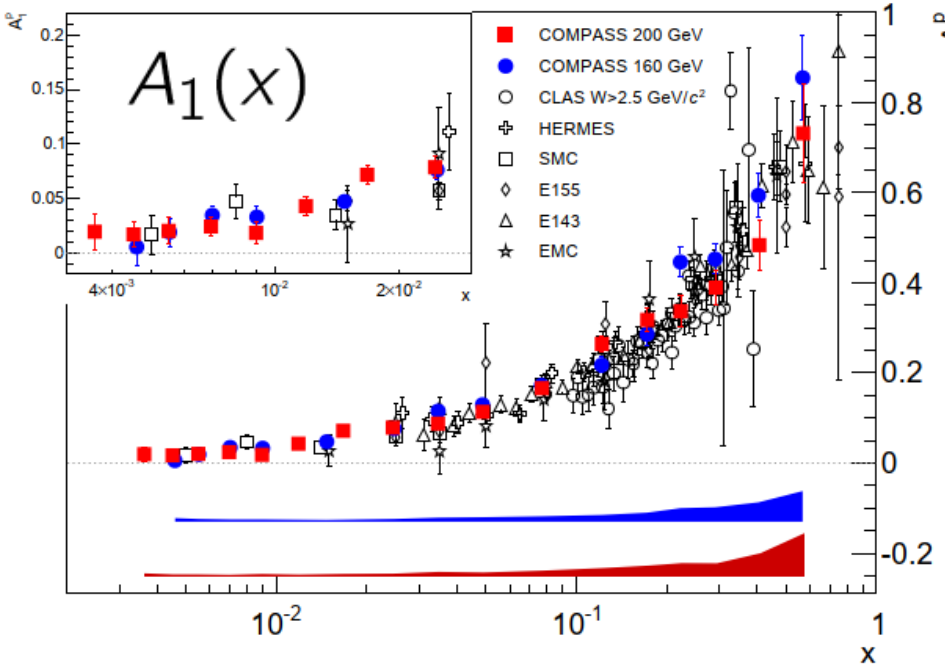
f: dilution factor
P: polarisations
D: depolarisation factor

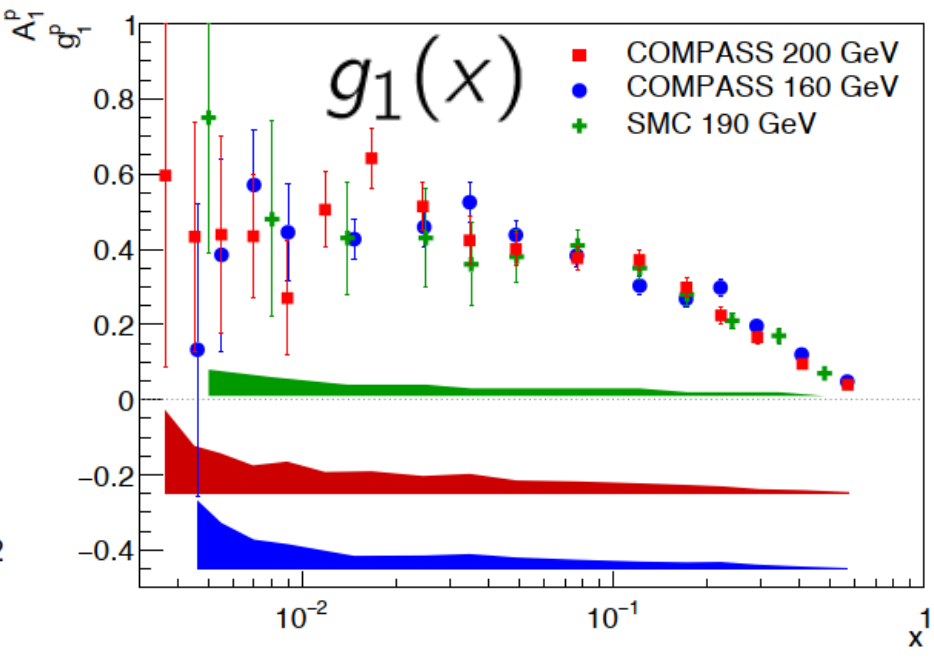
and the structure function g_1 via

$$A_1(x,Q^2) = \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

Proton A_1 and g_1

PLB 753 (2016) 18

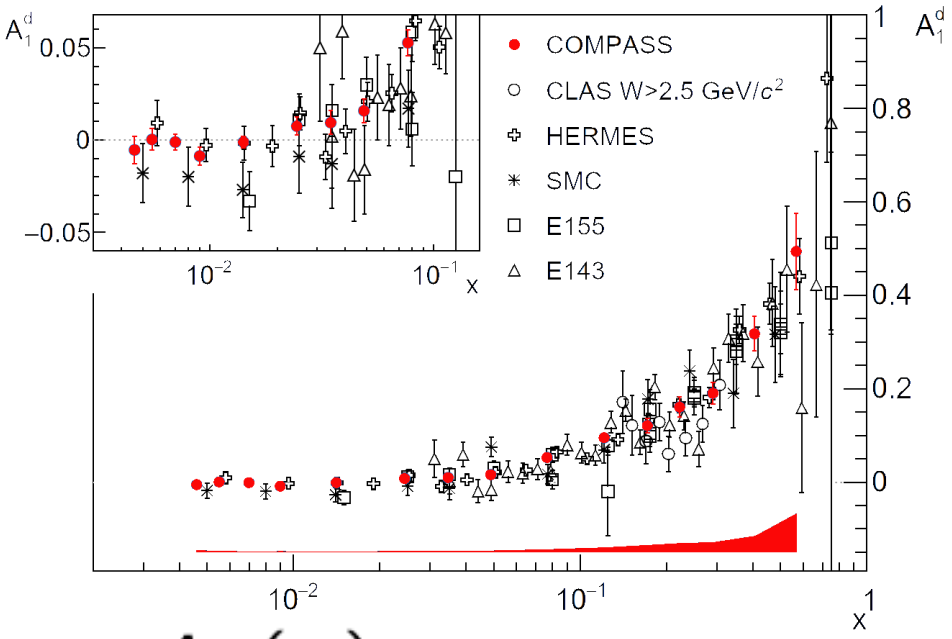




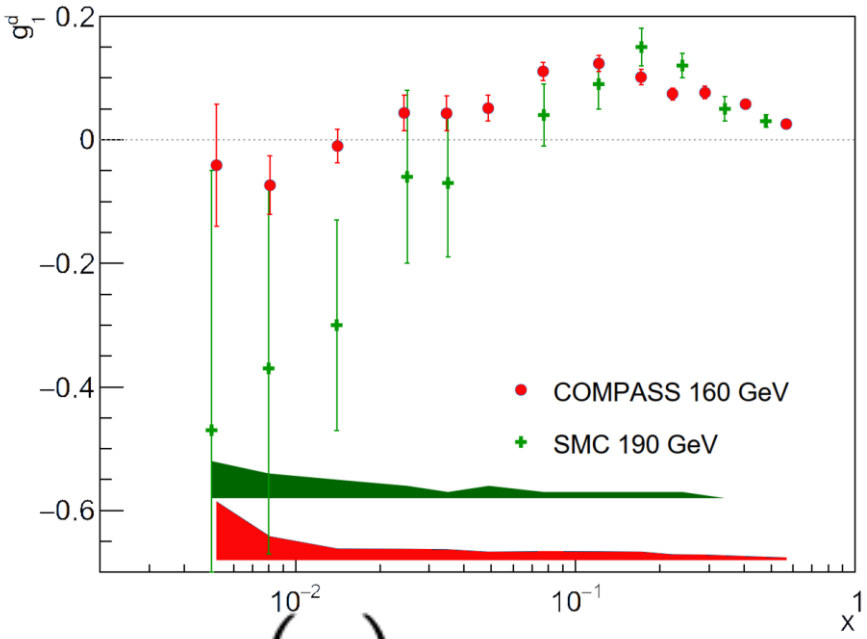
- COMPASS contributes the lowest *x* and highest Q^2 data
- A_1 is still positive at lowest *x* ($Q^2 > 1$ GeV^2)

Deuteron for A_1 and g_1

PLB 769 (2017) 34



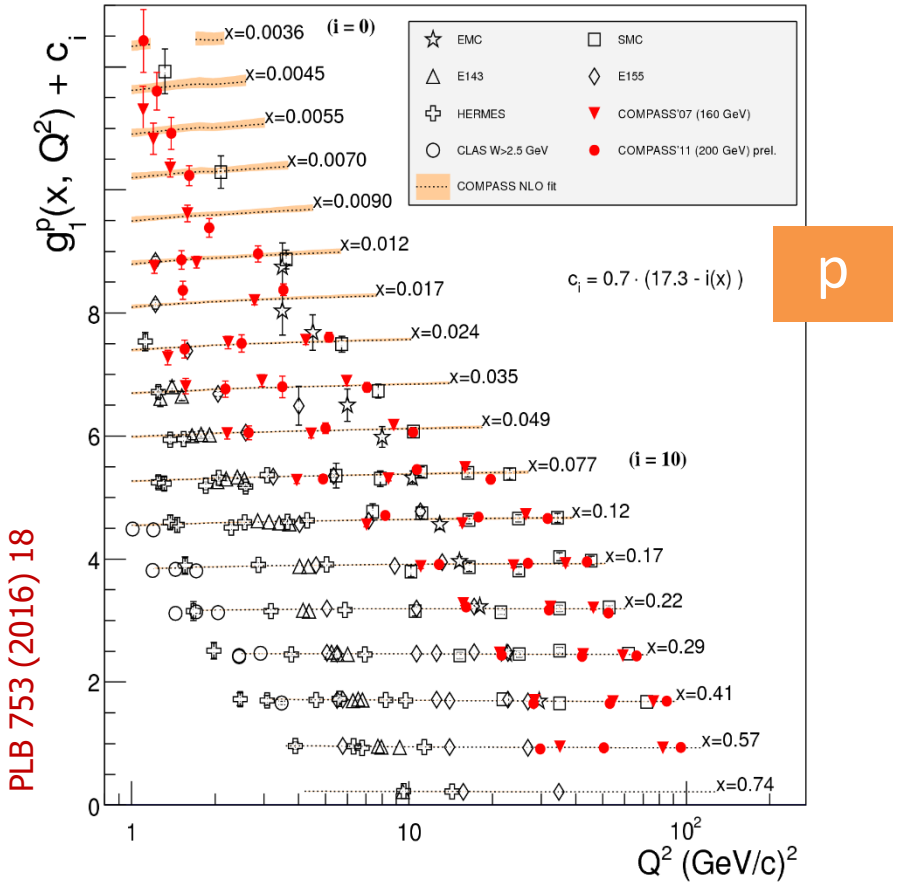
$A_1(x)$



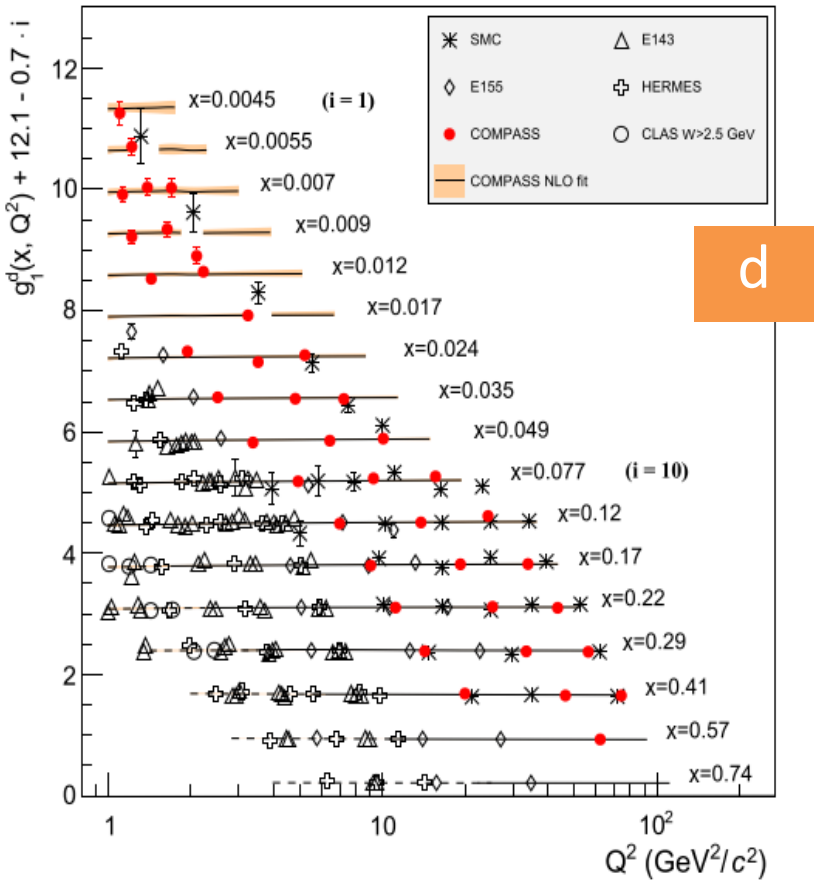
$g_1(x)$

- COMPASS contributes the lowest *x* and highest Q^2 data
- A_1 , g_1 are compatible with zero at lowest *x* (*c.f.* SMC)

Proton and deuteron $g_1(x,Q^2)$



p



d

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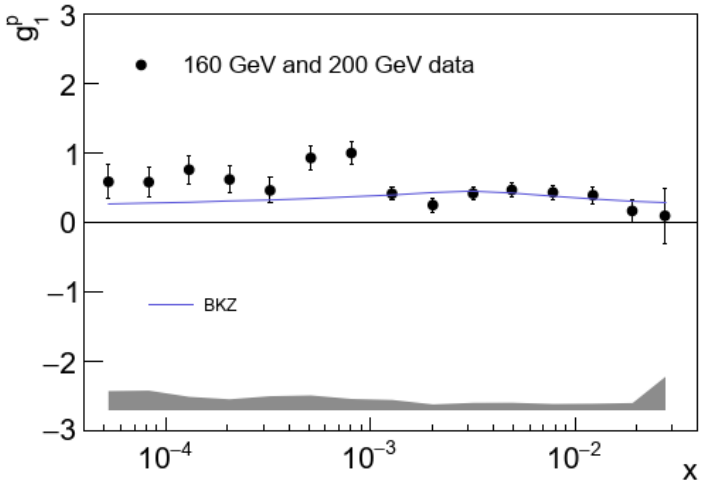
PLB 769 (2017) 034

Curve: Compass QCD fit to world data

$W^2 > 10\ \mathrm{GeV}^2$

g_1 for small x ($Q^2 < 1$ GeV^2)

proton

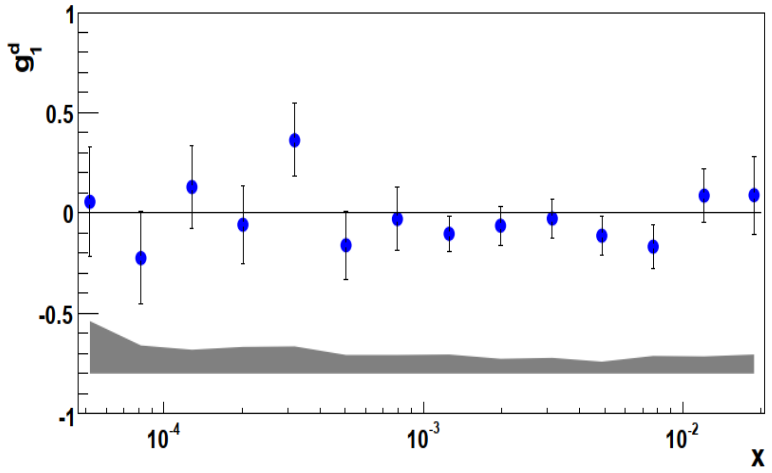


PLB 781 (2018) 464

- $0.006 < Q^2 < 1$ (GeV/c)^2
  $4 \cdot 10^{-5} < x < 4 \cdot 10^{-2}$
- Spin effects are present even below $x < 10^{-3}$

Curve: phenom. Model by
B.Badełek, J. Kwiecinski, B. Ziaja
Eur. Phys. J. C 26 (2002) 45

deuteron



PLB 647 (2007) 330

- $0.006 < Q^2 < 1$ (GeV/c)^2
  $4 \cdot 10^{-5} < x < 2 \cdot 10^{-2}$
- Compatible with zero

Bjorken sum rule

- First moment of g_1

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x$$

- Non-singlet structure function

$$g_1^{\mathrm{NS}} = g_1^{\mathrm{p}} - g_1^{\mathrm{n}}$$

- Bjorken sum rule

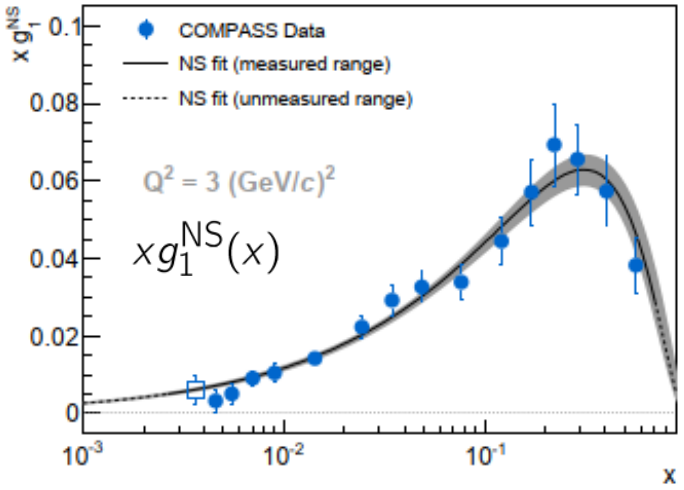
$$\Gamma_1^{\mathrm{NS}} = \frac{1}{6}(\Delta u - \Delta d) = \frac{1}{6}\left|\frac{g_A}{g_V}\right|$$

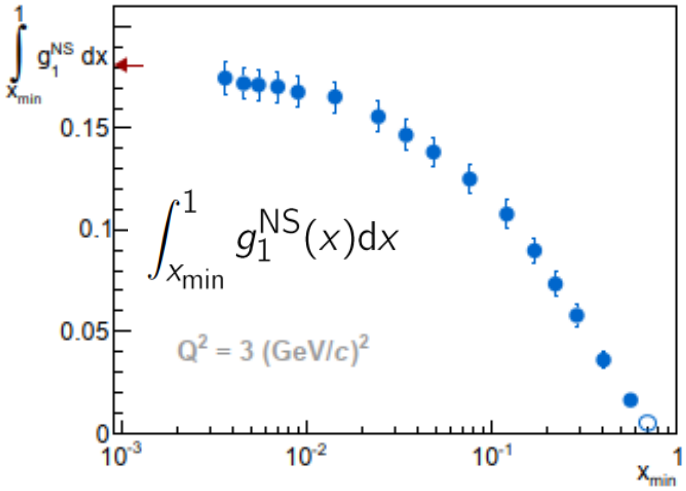
- COMPASS Γ_1^{NS} corresponds to

$$\left|\frac{g_A}{g_V}\right| = 1.29 \pm 0.05_{\mathrm{stat.}} \pm 0.10_{\mathrm{syst.}}$$

- *c.f.* PDG 2022: 1.2754 ± 0.0013

BJ sum rule tested at 9% level





PLB 769 (2017) 034

Flavour singlet axial charge

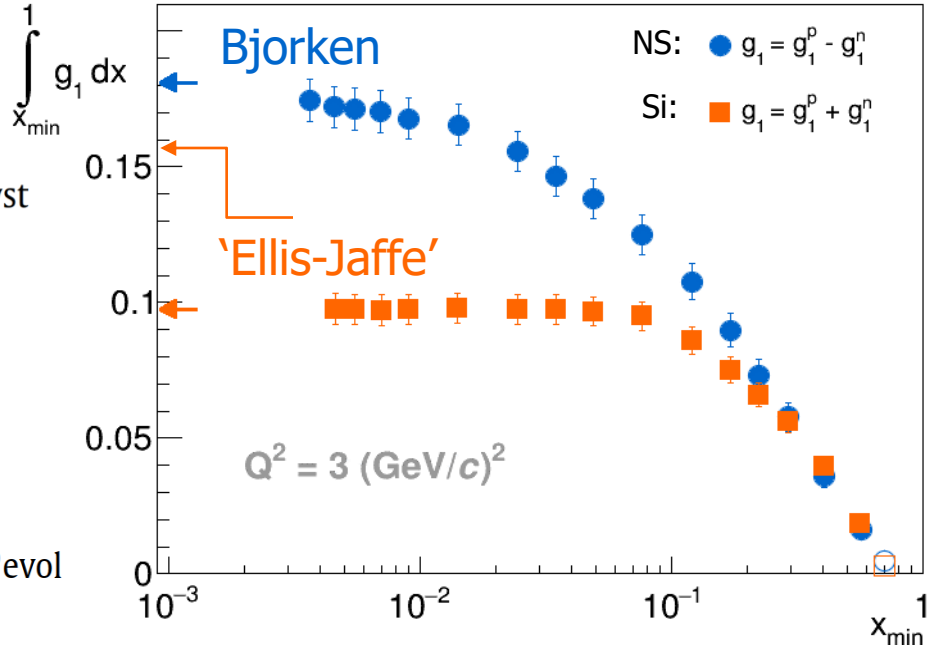
- BJ SR major contribution from small x

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

- EJ SR no contribution from small x

$$\Gamma_1^{N}(Q^2 = 3\,(\mathrm{GeV}/c)^2) = 0.046 \pm 0.002_{stat} \pm 0.004_{syst} \pm 0.005_{evol}$$

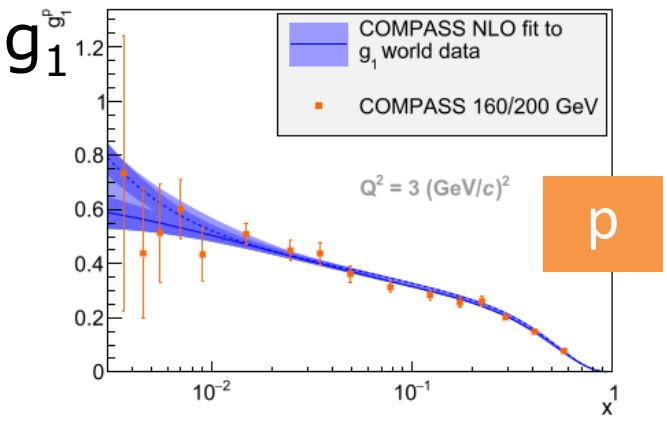
- From deuteron (Γ_1^N) and SU_3:

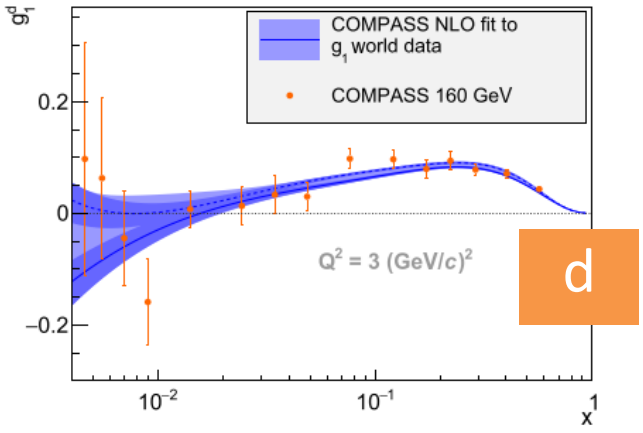


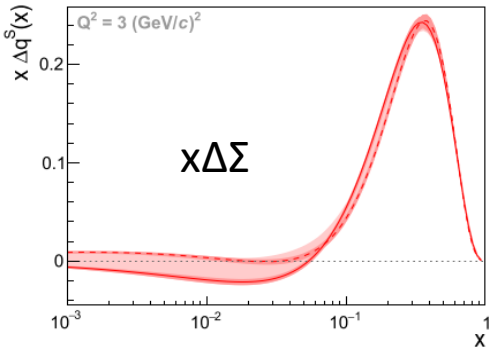
PLB 753 (2016) 18; 769 (2017) 034

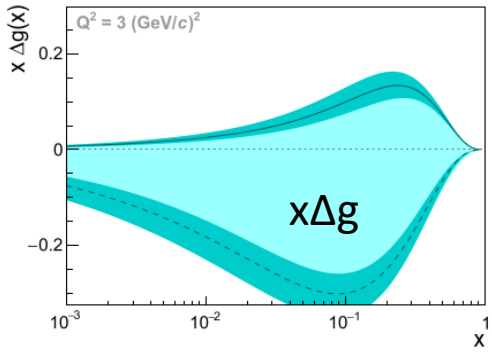
$$a_o \overset{\overline{MS}}{=} \Delta\Sigma = 0.32 \pm 0.02_{stat} \pm 0.04_{syst} \pm 0.05_{evol}$$ at 3 GeV^2

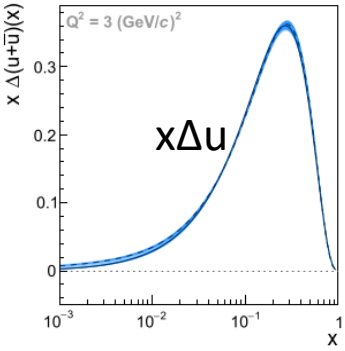
QCD fit to world data

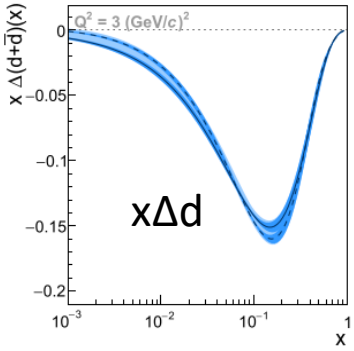


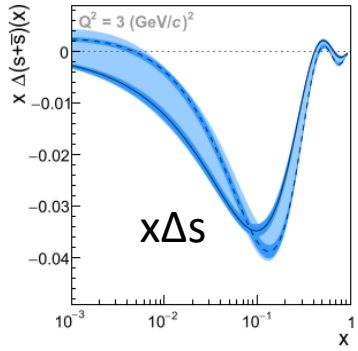












PLB 753 (2016) 18

- NLO to world DIS data (2016/18)
- Gluon polarisation hardly constrained, a positive and a negative solution

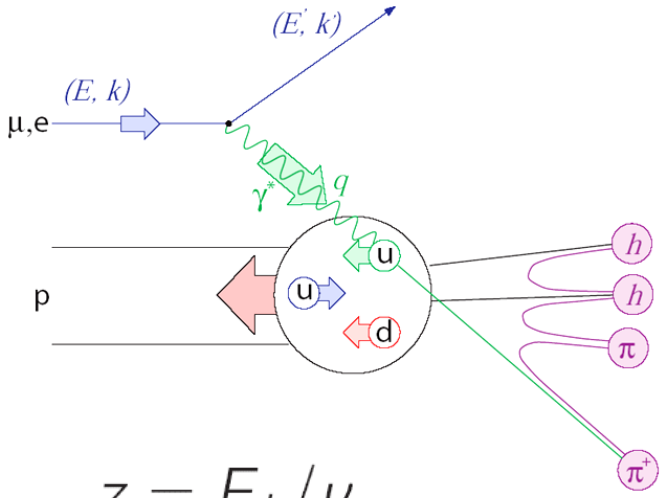
$$\Delta G \in [-1.6, 0.5] \text{ at } 3 \text{ GeV}^2$$

Semi-inclusive DIS results

Additional hadron observed in FS

$$A_1^h = \frac{\sum_q e_q^2 g_1^q(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1q}^h(z,Q^2)}$$

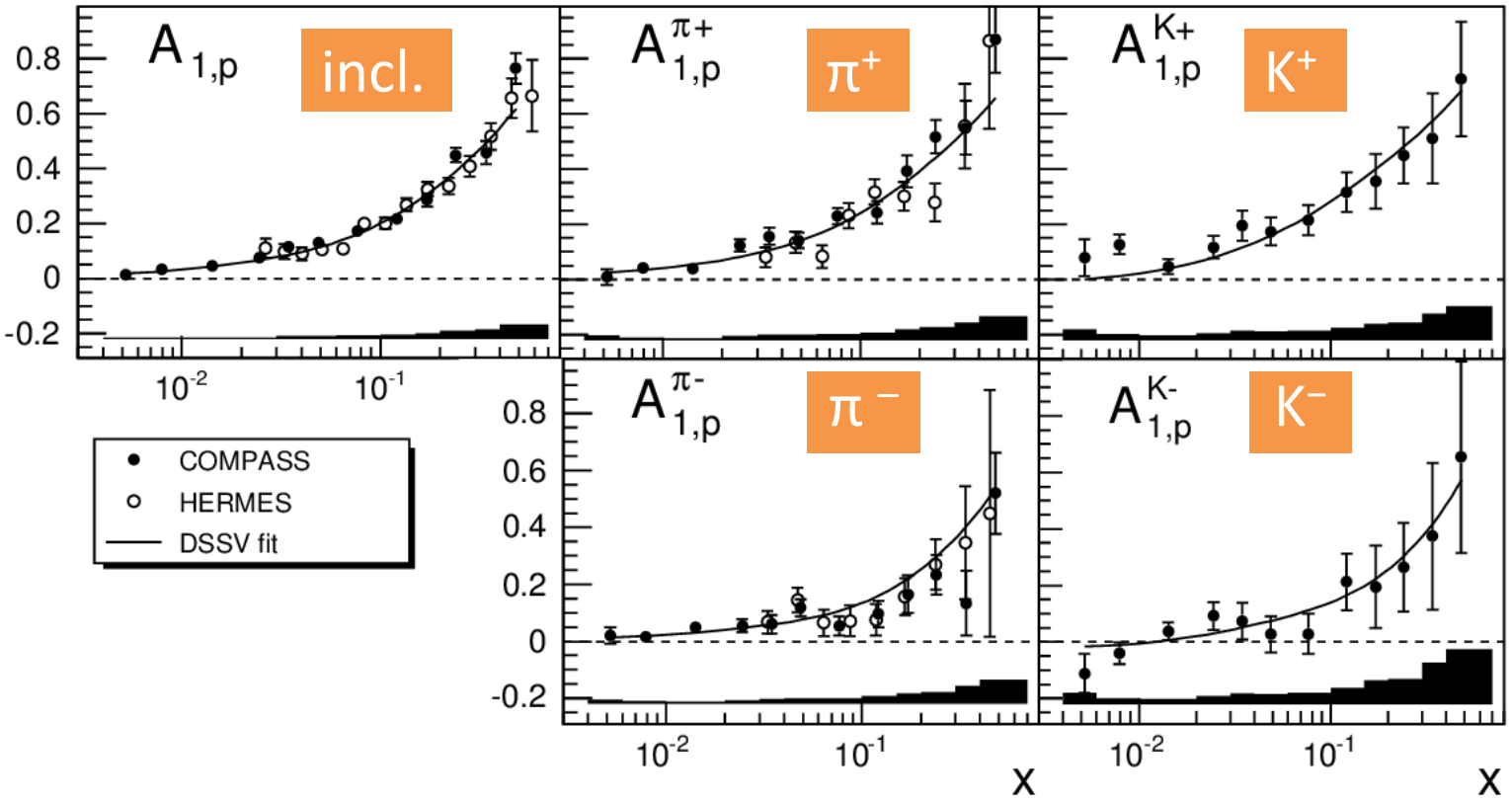
gives access to flavour information via the fragmentation functions D_{1q}



$$z = E_h/\nu$$

Proton: Incl. & semi-incl. A_1

- Compass and Hermes data for proton

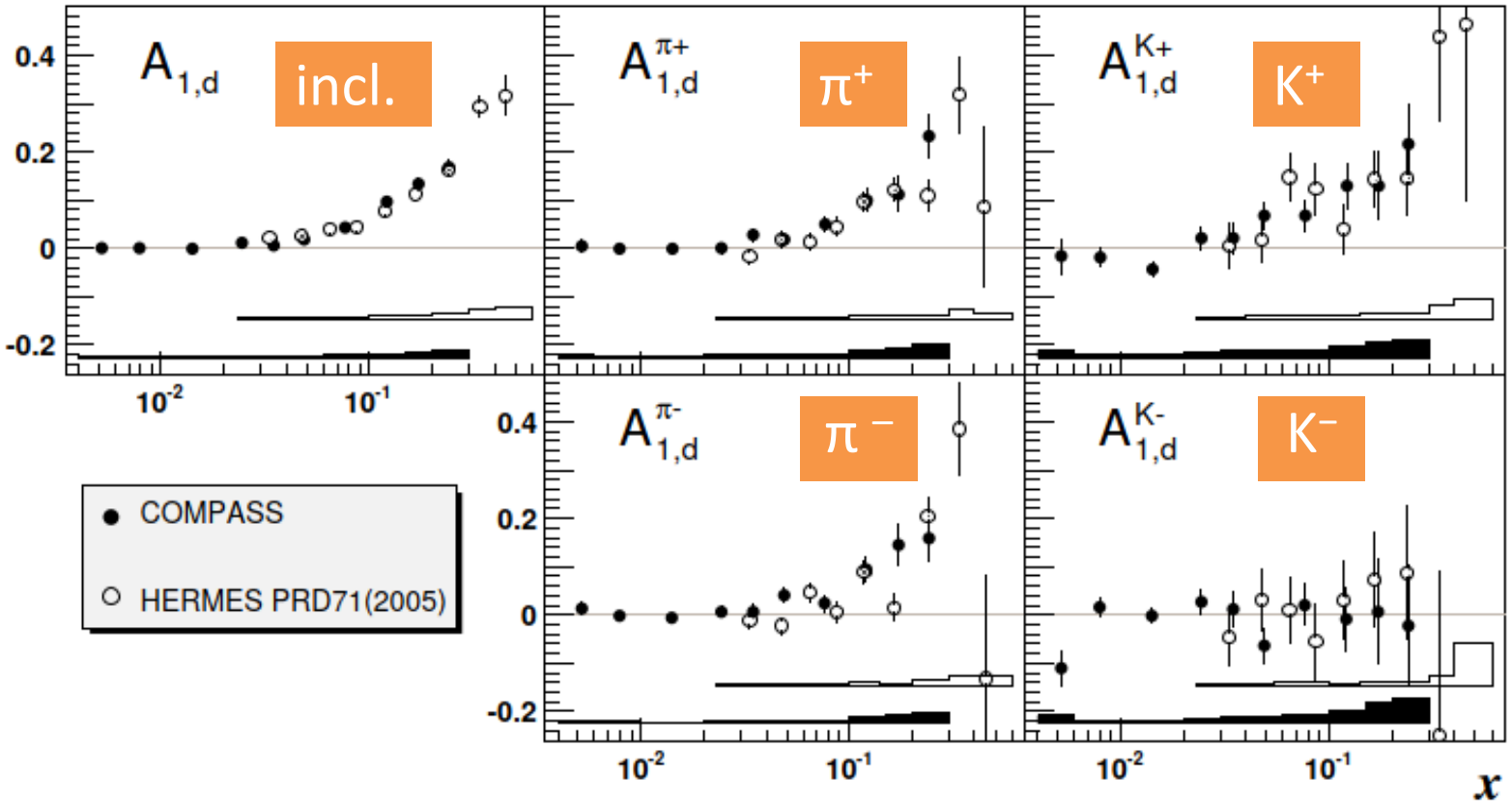


First kaon data

PLB 693 (2010) 227

Deuteron: Incl. & semi-incl. A_1

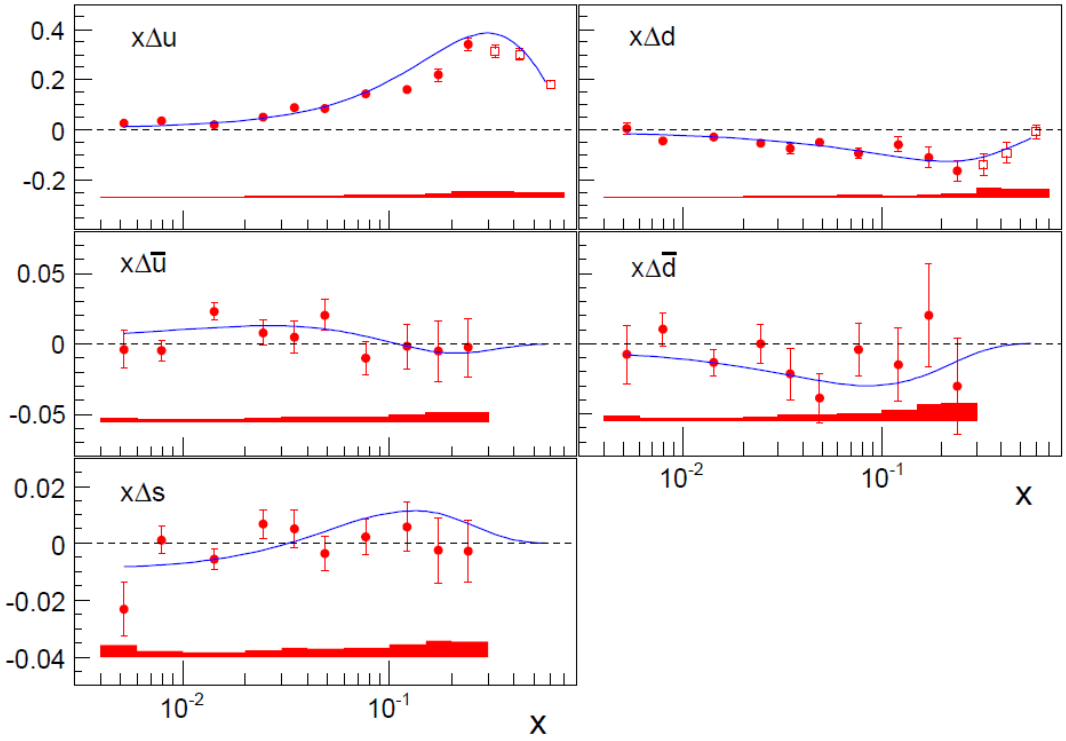
- Compass and Hermes data for deuteron



First kaon data

PLB 680 (2009) 217

Polarisation by flavour



PLB693 (2010) 227

LO analysis of 5p+5d asymmetries, DSS FF

Line: NLO DSSV not including these data

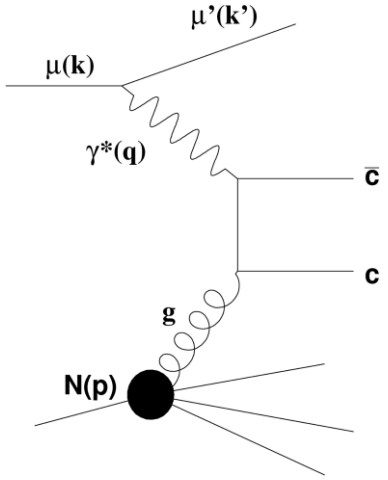
5-flavour fit, assuming $\Delta s = \Delta\bar{s}$

Δu	$0.71 \pm 0.02 \pm 0.03$
Δd	$-0.34 \pm 0.04 \pm 0.03$
$\Delta \bar{u}$	$0.02 \pm 0.02 \pm 0.01$
$\Delta \bar{d}$	$-0.05 \pm 0.03 \pm 0.02$
$\Delta s(\Delta \bar{s})$	$-0.01 \pm 0.01 \pm 0.01$
Δu_v	$0.68 \pm 0.03 \pm 0.03$
Δd_v	$-0.29 \pm 0.06 \pm 0.03$
$\Delta \Sigma$	$0.32 \pm 0.03 \pm 0.03$

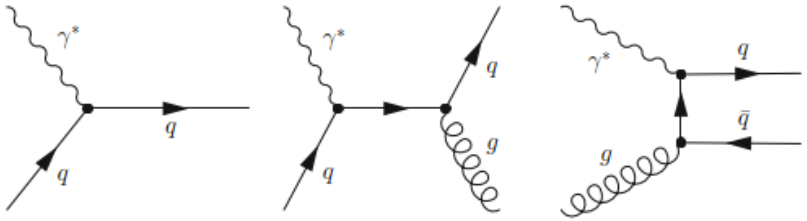
‘direct’ Δg measurements

Δg assessable via photon-gluon fusion (PGF)

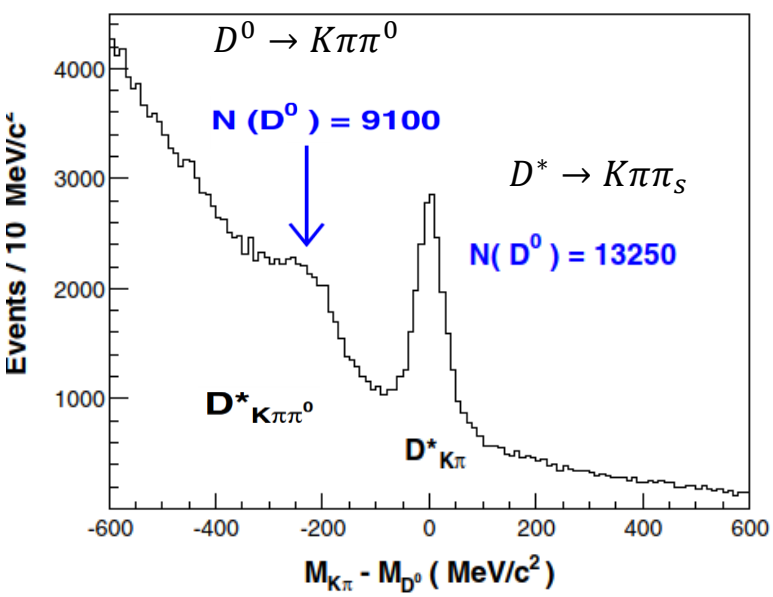
- Measure double-spin asymmetry
  - Open charm production (D mesons),
    PGF is only process in LO
    scale set by charm quark mass

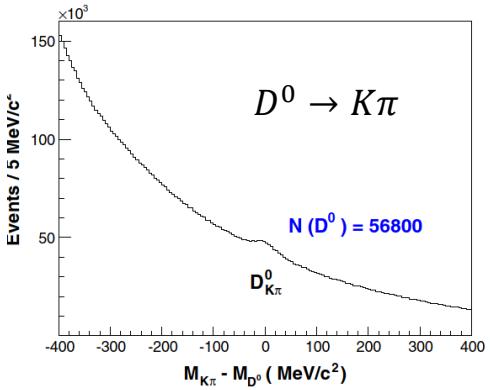


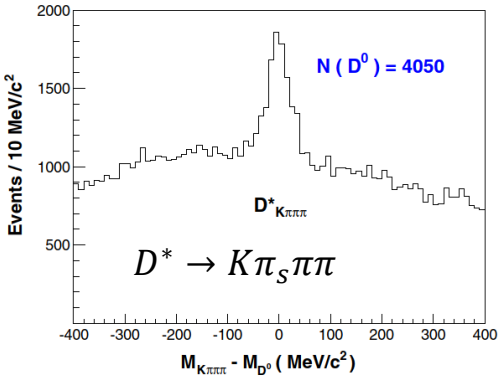
  - Single hadrons or hadron pairs
    contributions from LP, QCD-C, PGF

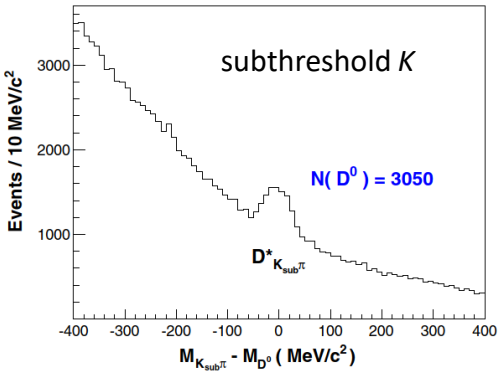


Open charm: *D* meson samples









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- Statistics limited, $D^0 \to \pi K$ (BR ~ 4%)
- Large combinatorial background
- drastically reduced in
  $D^* \to D^0 \pi_s \to K \pi \pi_s$ with detected slow π_s
- Background checked using wrong sign charge combinations

Open charm: $\langle \Delta g/g \rangle$

$$A^{\mu N} = DA^{\gamma N} = a_{LL}\frac{\Delta g}{g}$$

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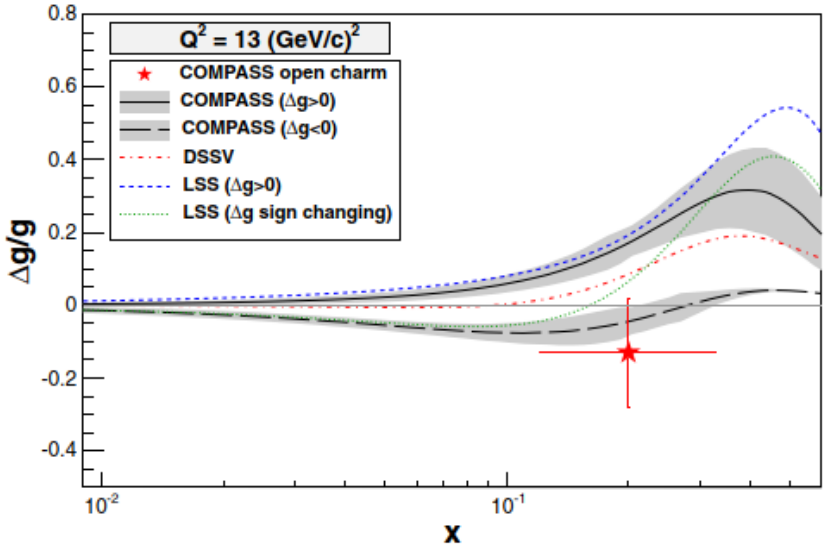
- Leading order: $\left\langle \frac{\Delta g}{g} \right\rangle = -0.06 \pm 0.21(\text{stat.}) \pm 0.08(\text{syst.})$ $\quad 0.06 < x < 0.22;\ \langle x \rangle \approx 0.11$
- NLO: a_{LL} in NLO using Aroma generator and parton shower

$$\left\langle \frac{\Delta g}{g} \right\rangle^{NLO} = -0.13 \pm 0.15(\text{stat.}) \pm 0.15(\text{syst.})$$

$0.12 < x < 0.33;\ \langle x \rangle \approx 0.20$

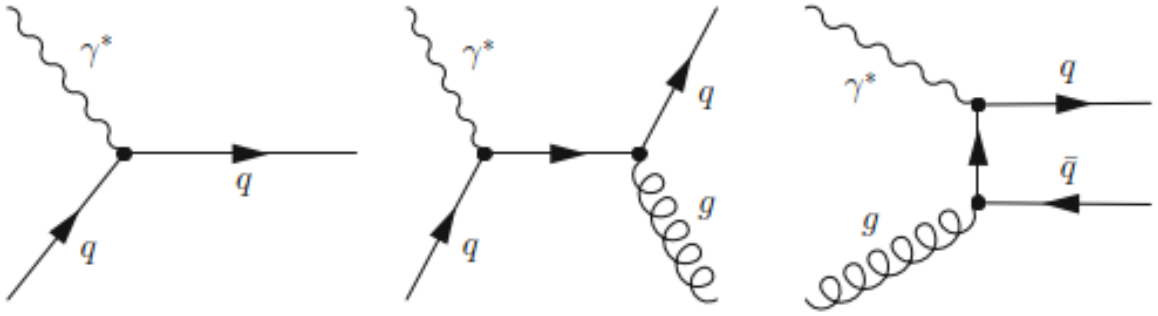


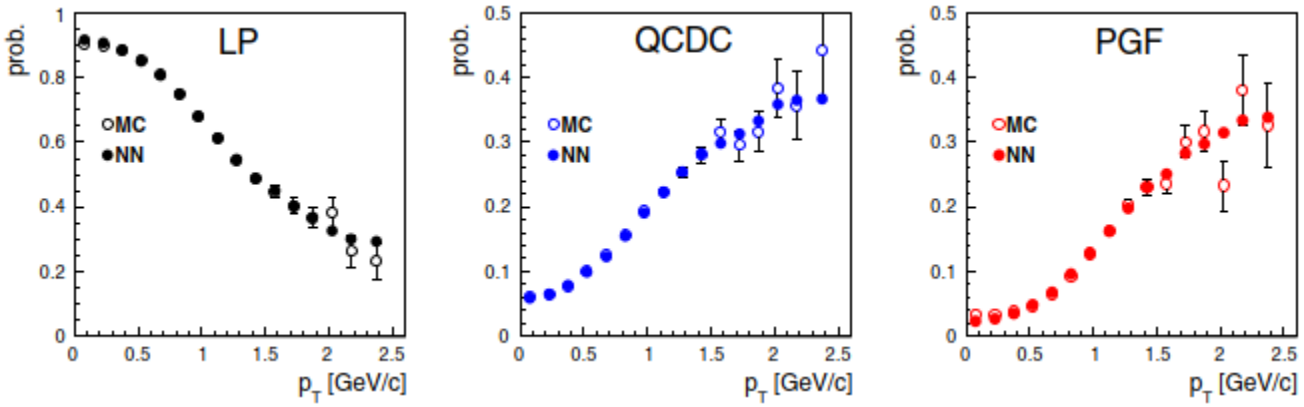
Agrees with NLO fit with negative ΔG

Large positive ΔG less likely

All-p_T hadrons method $\langle \Delta g/g \rangle$

- Contributions in leading order (gluon)





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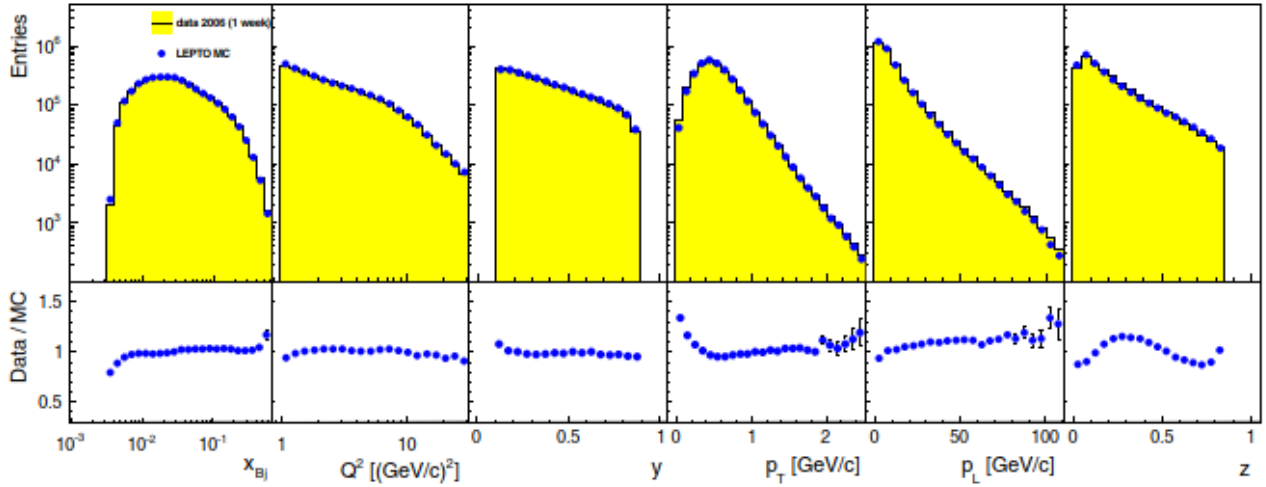
All-p_T hadrons method

- $0.05 < p_T < 2.5\ \mathrm{GeV};\ Q^2 > 1\ \mathrm{GeV}^2$
- Determine contribution and analysing power for the three processes by a NN trained on MC data.
- MC agrees well with measured kinematic distributions



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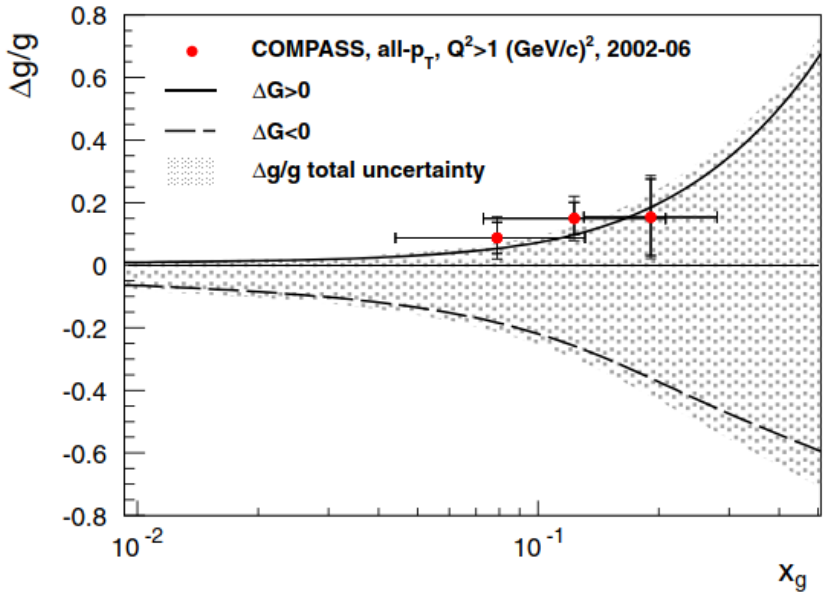
All-p_T hadrons method

- Result:

$$\langle \Delta g/g \rangle = 0.113 \pm 0.038_{(\text{stat.})} \pm 0.036_{(\text{syst.})}$$

$$\langle x \rangle \approx 0.10, \quad \langle Q^2 \rangle = 3\ \text{GeV}^2$$

- Statistics allows splitting in three x_g bins



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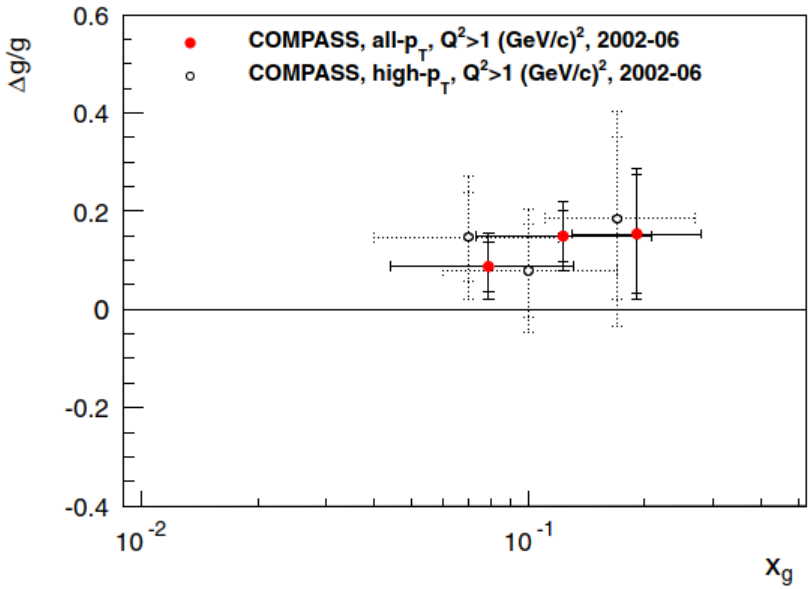
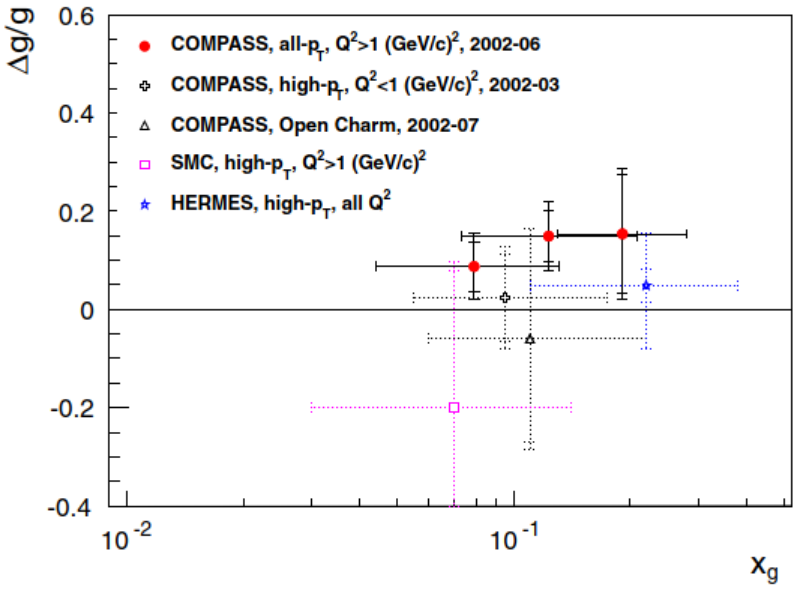
Summary of Δg





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- All-p_T agrees well with previous less precise result from high-p_T data
- Compatible with result from open charm
- Large ΔG ruled out

Conclusion

- Compass united several physics communities since decades, a real success story and highly on-trivial.
- Rewarded by great physics outputs, incl. longitudinal spin structure data 2002-2011.
- Proposal precision for $\langle \Delta g/g \rangle$ of 0.11 in open charm almost reached despite many difficulties.
- Precision from all-p_T even much better, about 0.04.
- COMPASS was the first to rule out a large gluon polarisation in the nucleon! Certainly not 6 (after EMC) nor 2.5 (after SMC, Slac).
- Today we have new, more complicated view on nucleon spin being shared between orbital angular momentum and quark and gluon spins.
- Precise test of Bjorken sum rule
- Quark polarisations Δq

Thanks for your attention