Review of COMPASS results

Barbara Badelek, University of Warsaw
– On behalf of COMPASS –

Diffraction 2008

La Londe-les-Maures, September 9 – 14, 2008

Outline

1. The experiment
   - The Collaboration
   - Programmes
   - History
   - Detector
2. Results
   - Acceptance
   - Results of inclusive measurements
   - Sea quark polarisation
   - Nucleon spin structure
   - Results from the transversely polarised target
3. Outlook

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COmmon Muon and Proton Apparatus for Structure and Spectroscopy

$\sim$ 250 physicists

$\sim$ 30 institutes

NA58, at the CERN SPS

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Physics programmes

- Muon beam programme
  - Gluon polarisation in the nucleon
  - Quark polarisation (spin-dependent structure function g_1, flavour separation Δq)
  - Transversity
  - Production of ρ, Φ, J/Ψ, Λ
  - Pentaquarks
- Hadron beam programme
  - Primakoff effect, π and K polarisabilities
  - Exotic states, glueballs
  - Double charmed hadrons
- After $\sim$2009: a proposal in preparation

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COMPASS history: 2002 – 2008. Where are we now?

- 2002 160 GeV polarised μ beam & ^{6}LiD long/transv polarisations (time sharing: $\sim$ 80/20)
- 2003 *idem*
- 2004 *idem*
- 2004 pilot hadron run
- 2005 no SPS beam (several upgrades: target, RICH)
- 2006 160 GeV polarised μ beam & ^{6}LiD long. polarisation
- 2007 160 GeV polarised μ beam & NH_3 transverse and longitudinal polarisation
- 2008 190 GeV pion beam; diffractive and central production

Published or (almost) ready results for:

gluon polarisation, g_1, valence quarks polarisation, transversity, exclusive ρ^0 production, pentaquarks, Λ polarisation.

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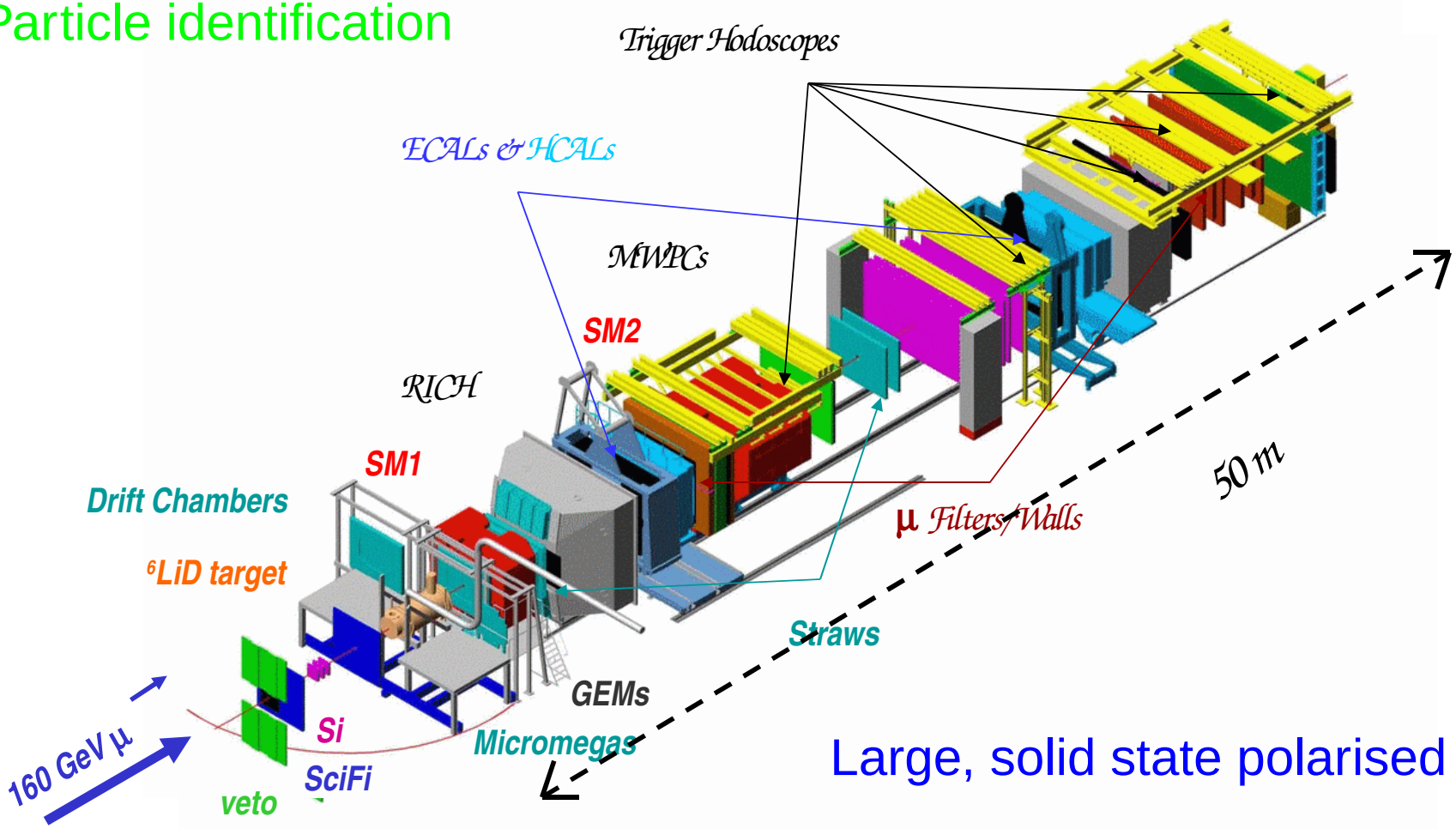
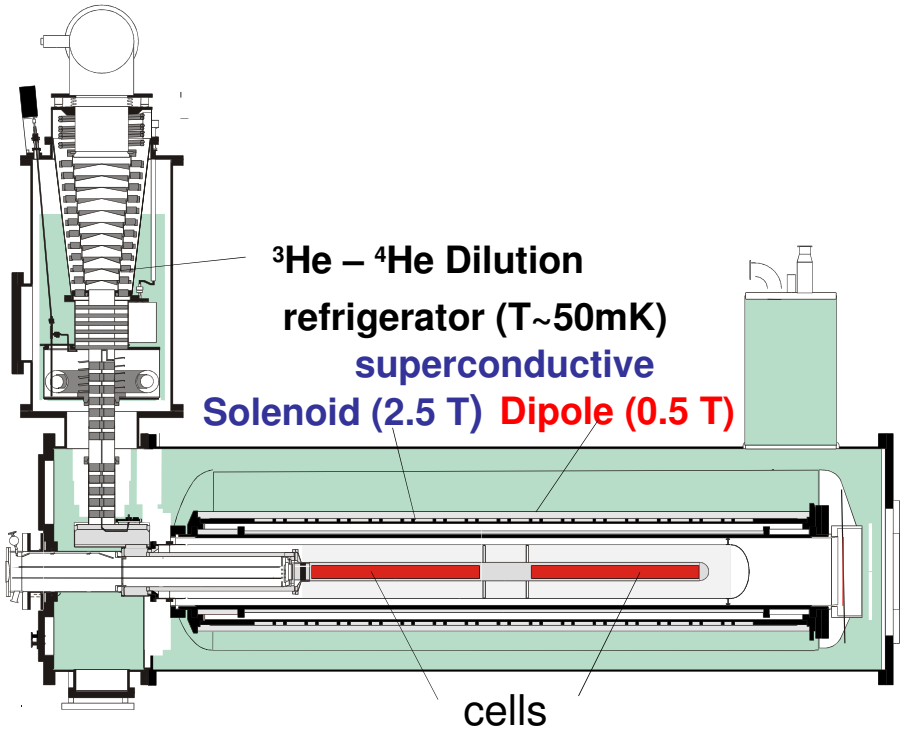
COMPASS Spectrometer

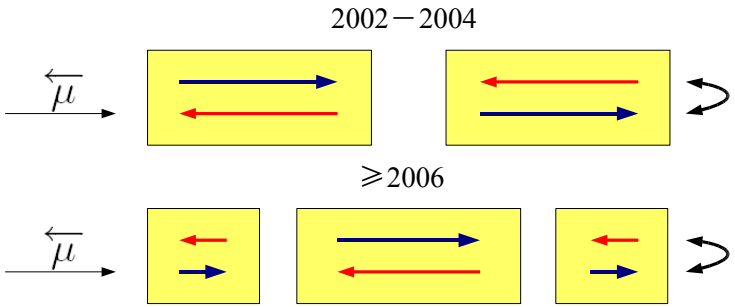
Two stages
Calorimetry
Particle identification



Large, solid state polarised target

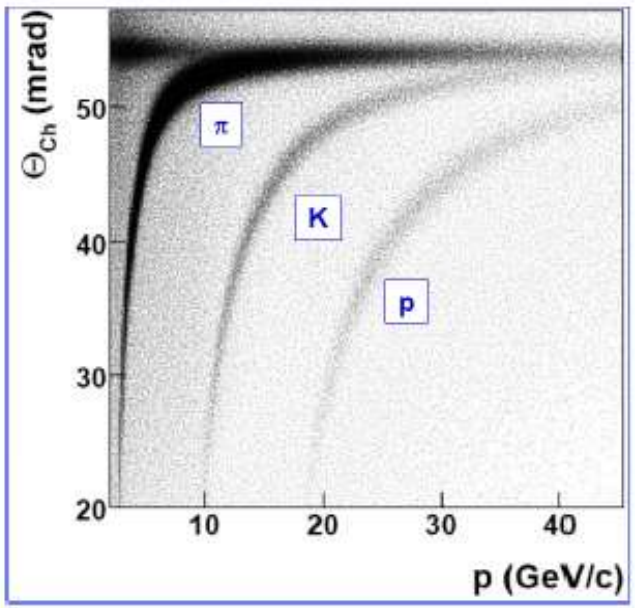
COMPASS polarised target



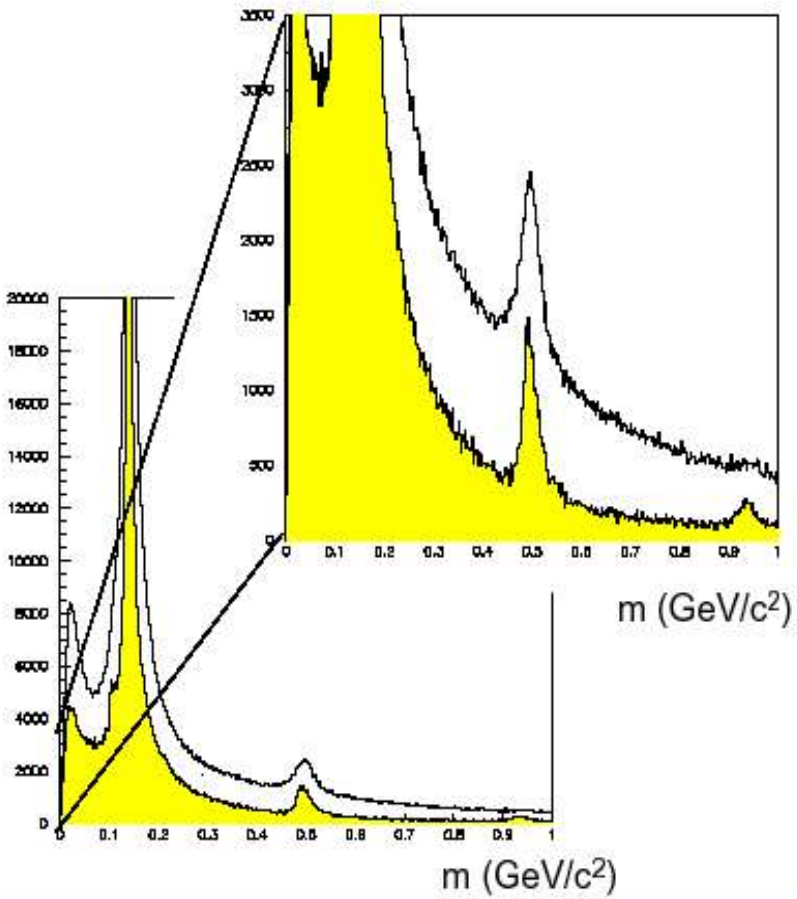


* Two (three in 2006, 2007) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent in 2006, 2007)
* Material: solid ^{6}LiD (NH_3 in 2007)
* Polarisation: ~ 50% (~90% in 2007)
* Dilution: f~0.4 (~0.15 in 2007)
* Polar acceptance: ~70 mrad (~180 mrad in 2006, 2007)

COMPASS RICH



Before upgrade: white distribution
After upgrade: yellow distribution



RICH2007 Federica Sozzi 19

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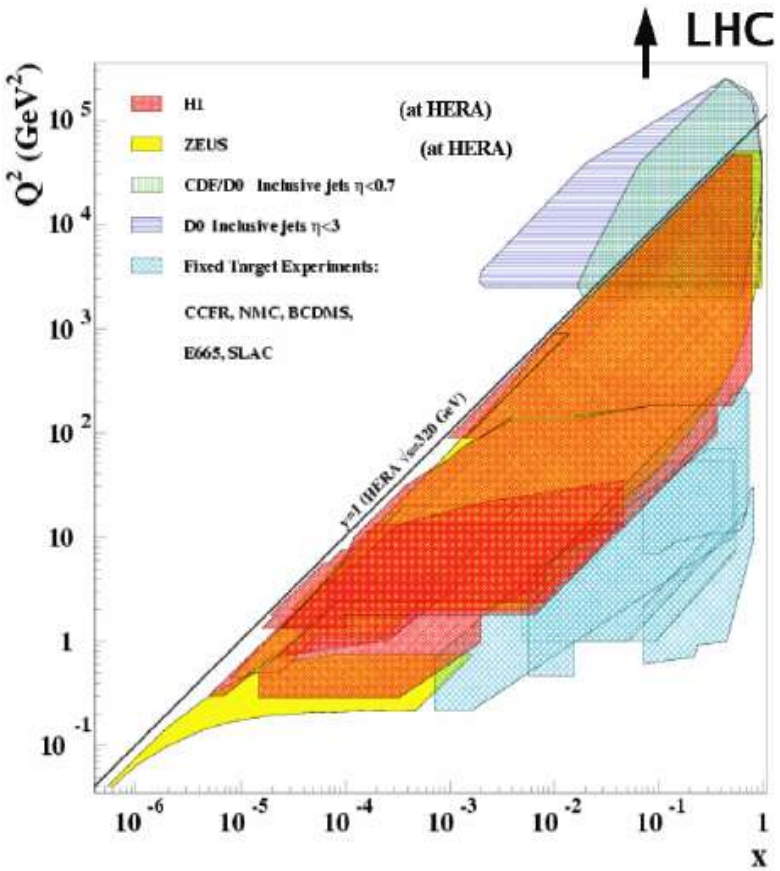
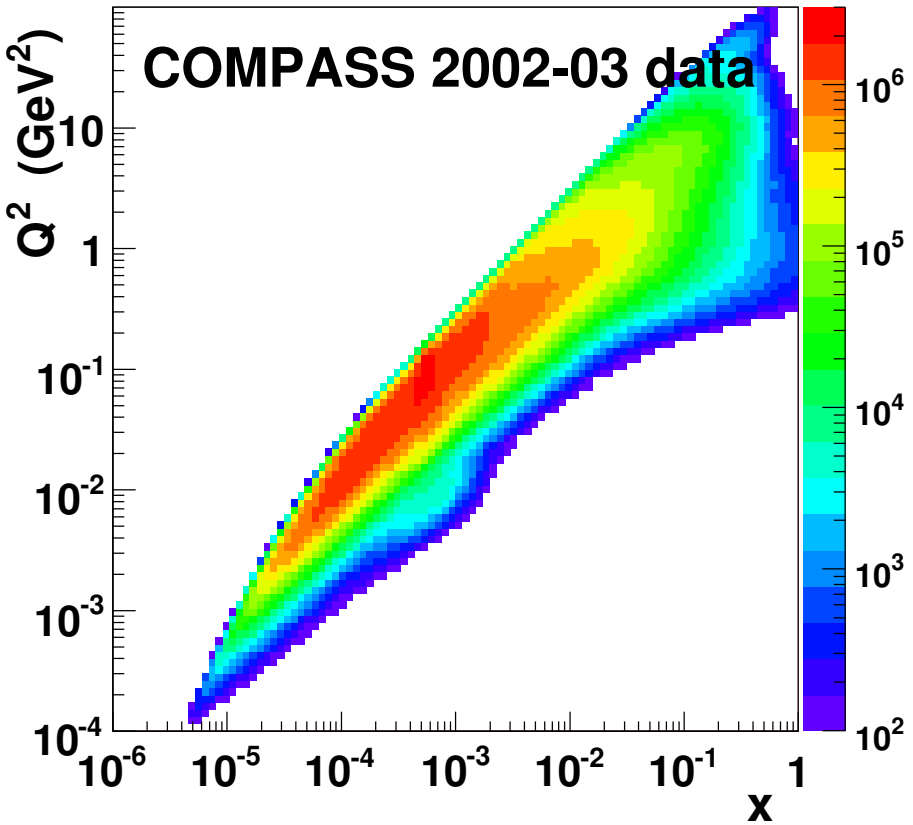
Acceptance of electroproduction experiments





H. Schellmann, DIS2008

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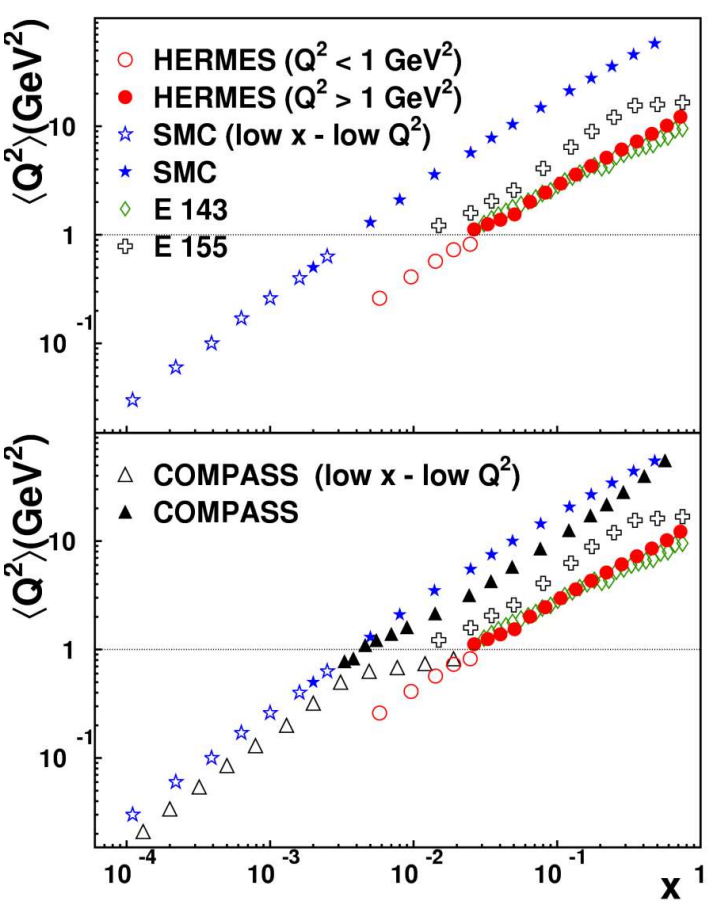
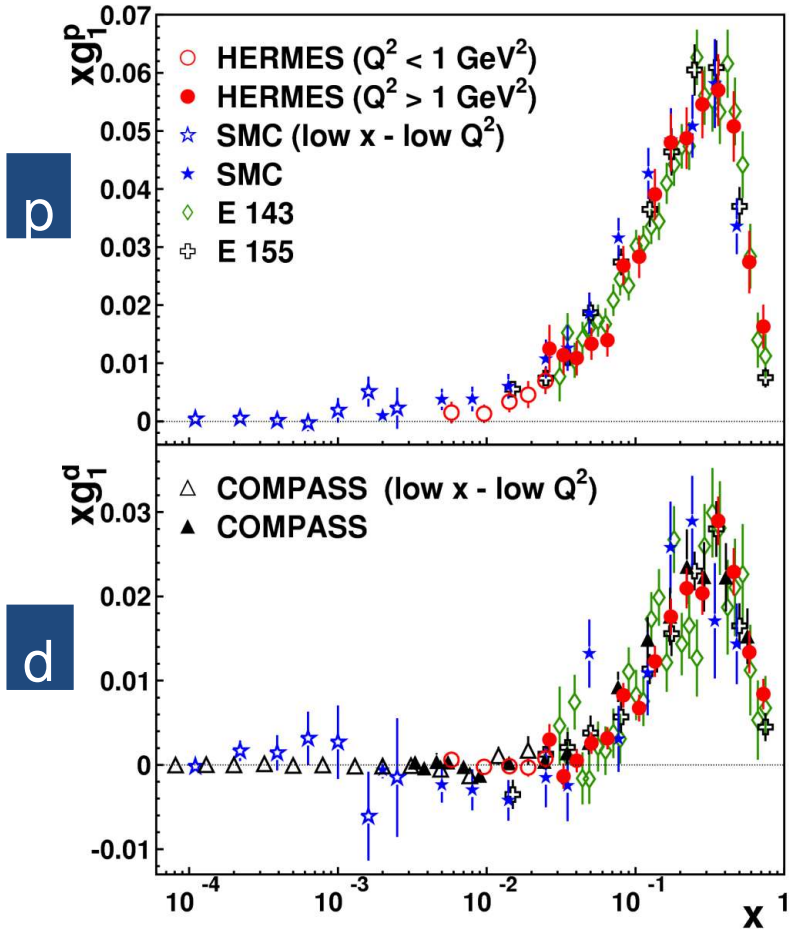
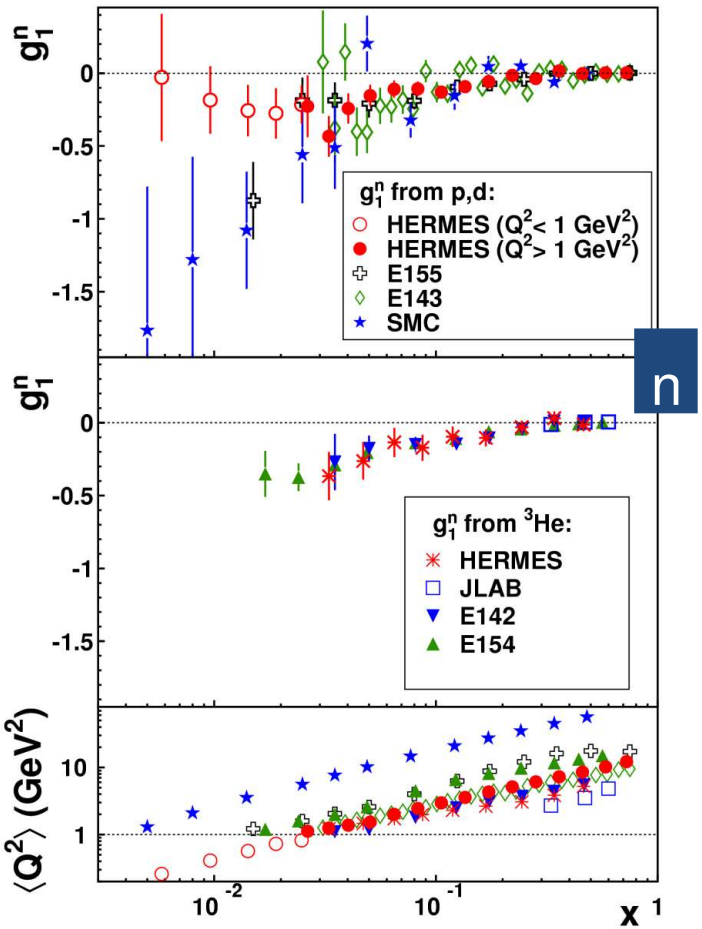
World data on the nucleon g_1





G. Mallot, APS, May 2008

World data on the nucleon g_1...cont'd



n

from p and d

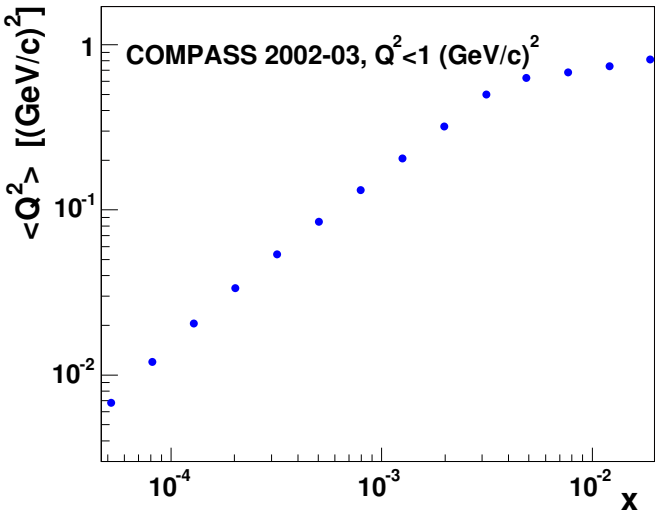
$$g_1^n = \frac{2}{1 - \frac{3}{2}\omega_D} g_1^d - g_1^p$$

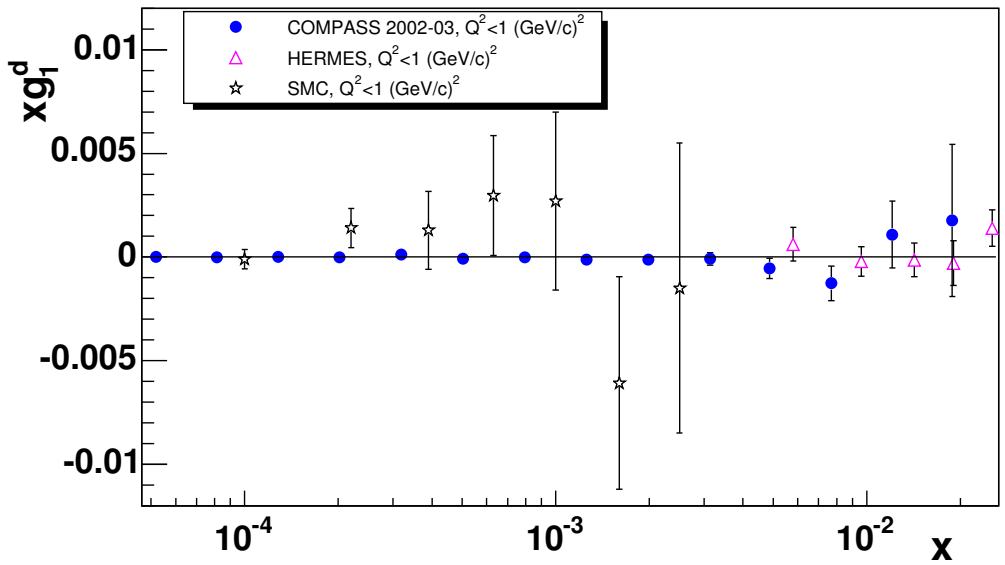
from ^{3}He

G. Mallot, APS, May 2008

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





- Order of magnitude improvement over the statistical precision of the SMC.
- Interplay between perturbative and nonperturbative mechanisms.
- Spin effects in g_1^d at low x and Q^2 absent ?

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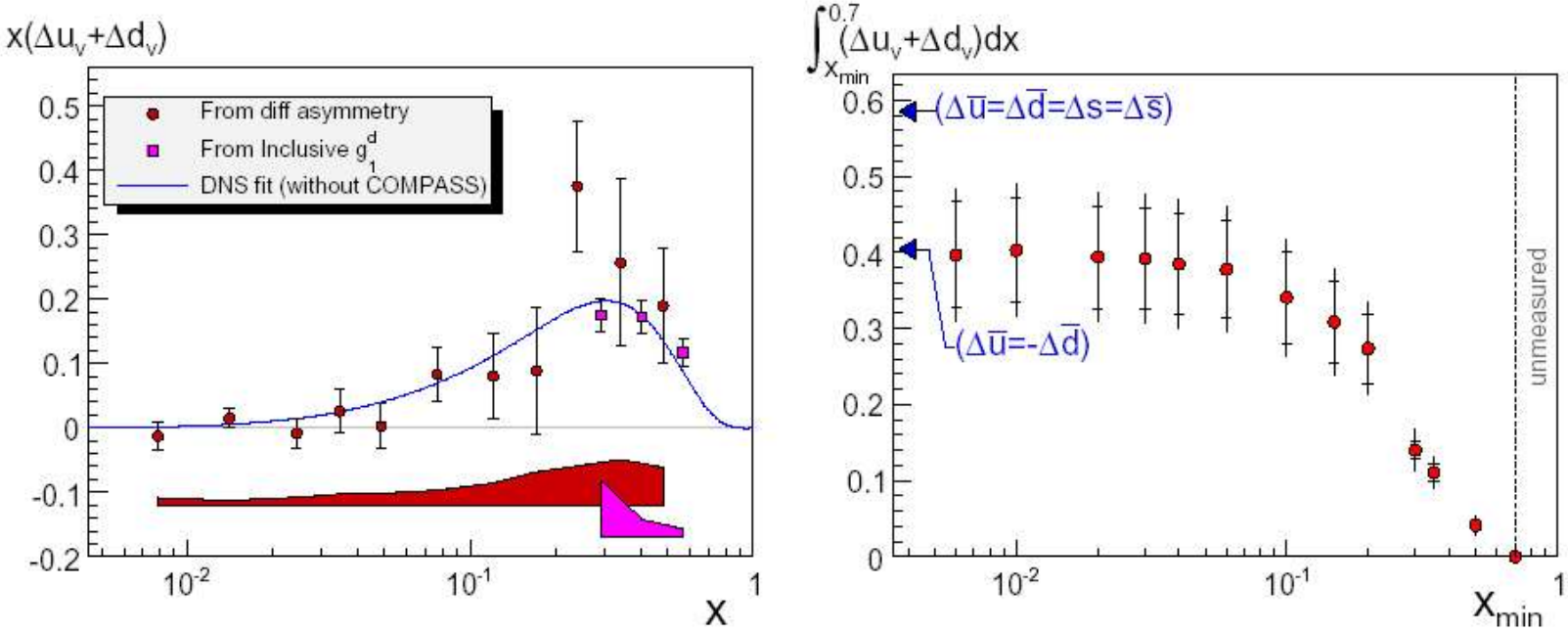
Sea quark polarisation

M. Alekseev *et al.* (COMPASS), Phys. Lett. **B660** (2008) 458.

- Difference asymmetry: $A^{h^+-h^-} : A_d^{\pi^+-\pi^-} = A_d^{K^+-K^-}$
- At LO, the fragmentation functions drop out



$$\int_{0.006}^{0.7} (\Delta u_V + \Delta d_V)\mathrm{d}x = 0.40 \pm 0.07 \pm 0.05$$

- Unmeasured regions contribute neligibly.
- Non-symmetric sea preferred ?
- Next step: determine Δs from $K^{\pm}$ asymmetries.

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Nucleon spin decomposition

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

- EMC (1988): $a_0 = \Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$ (expected: ~ 0.6 if $\Delta s = 0$).
  Here $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ and $\Delta q = \int \Delta q(x)dx$, $\Delta G = \int \Delta G(x)dx$

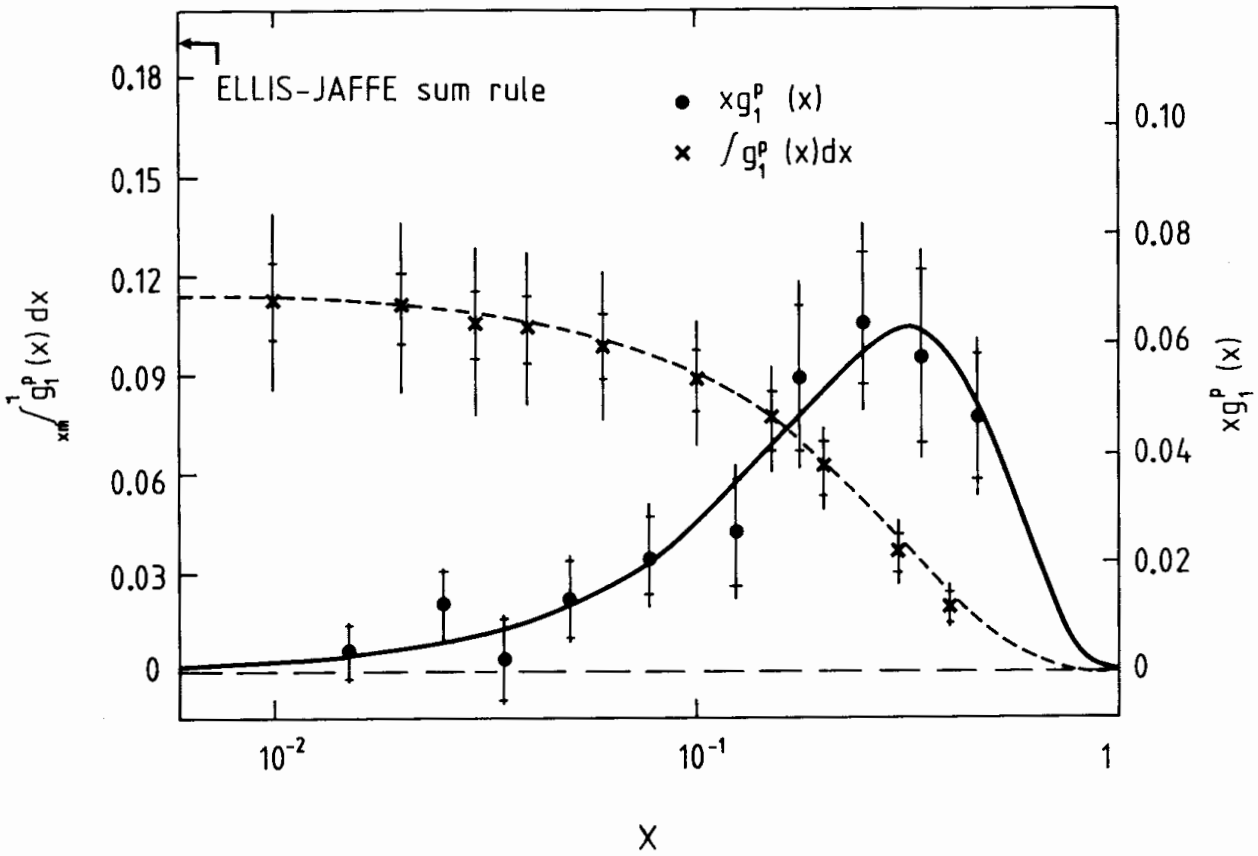
- COMPASS @ 3 GeV^2: $a_0 = 0.35 \pm 0.03 \pm 0.05$
- But as a consequence of the "axial anomaly" (axial vector current not conserved) the measured quantity is:

$$a_0(Q^2) = \Delta\Sigma^{AB} - (\tfrac{3\alpha_s}{2\pi})\Delta G(Q^2)$$

  and the "spin crisis" can be solved ($\Delta\Sigma \sim 0.6$) if $\Delta G \sim 2.2$ (and $L \sim -2$) at $Q^2 = 3$ GeV^2.

- Impressive spin-off since 1988: SLAC (E142, E143, E155, E156), SMC, HERMES, JLAB, COMPASS, RHIC Spin.
- Need to measure ΔG (and L)!

“Spin puzzle”: 20 years



European Muon Collaboration, J.Ashman *et al.* Phys. Lett. **B206** (1988) 364 Fig. 2

$$\Gamma_1^p = 0.123 \pm 0.013 \pm 0.019 \qquad \Delta\Sigma = 0.12 \pm 0.17$$

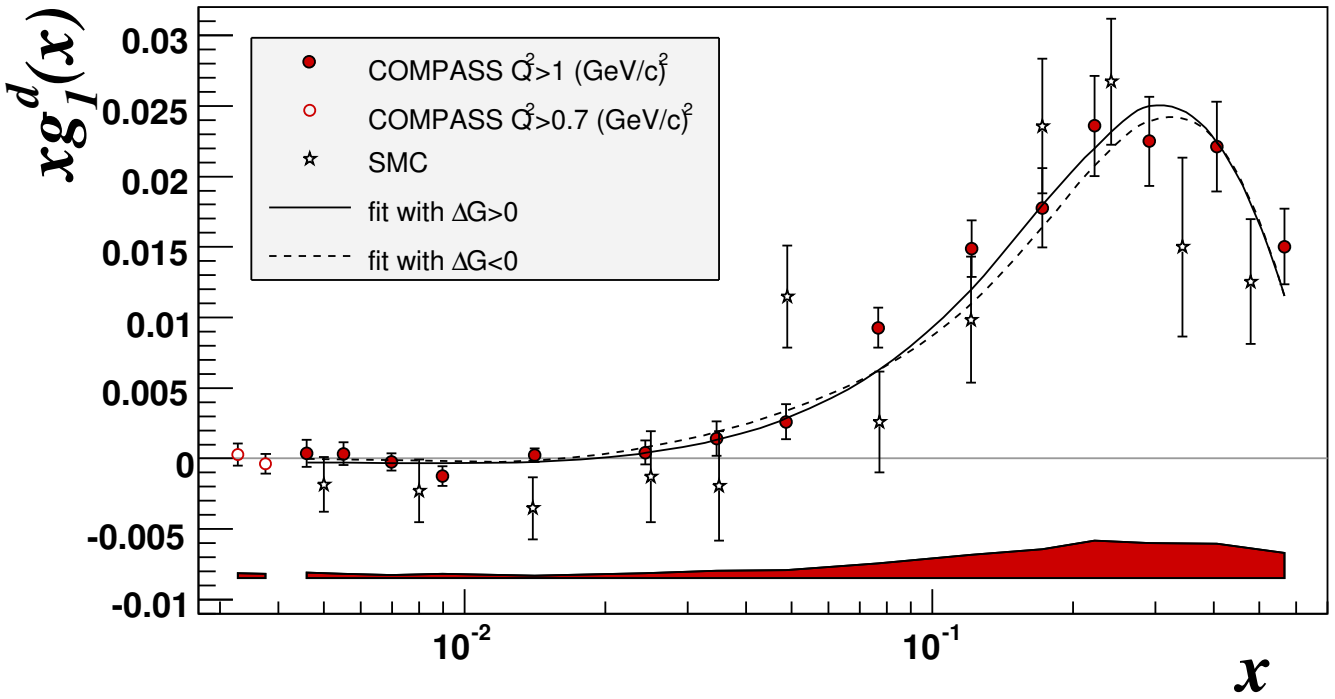
Ways of measuring the ΔG

- Scaling violation of g_1 (QCD fits, world data).
- Direct measurements
  - Cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into the charm mesons (max. @ low Q^2, perturbative scale: e.g. mass of the charm quark).
  - Cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into a pair of hadrons of large p_T, separately for low- and high Q^2 (perturbative scale: e.g. p_T).

COMPASS QCD analysis of inclusive g_1^d

V.Yu. Alexakhin (COMPASS) *et al.* Phys Lett B**647** (2007) 8

- Two programs: DGLAP evolution of structure functions and evolutions of moments
- NLO $\overline{MS}$ scheme
- World data: 9 experiments, 230 data points (43 from COMPASS)
- Two solutions, $\Delta G > 0$ and $\Delta G < 0$ describe data equally well.

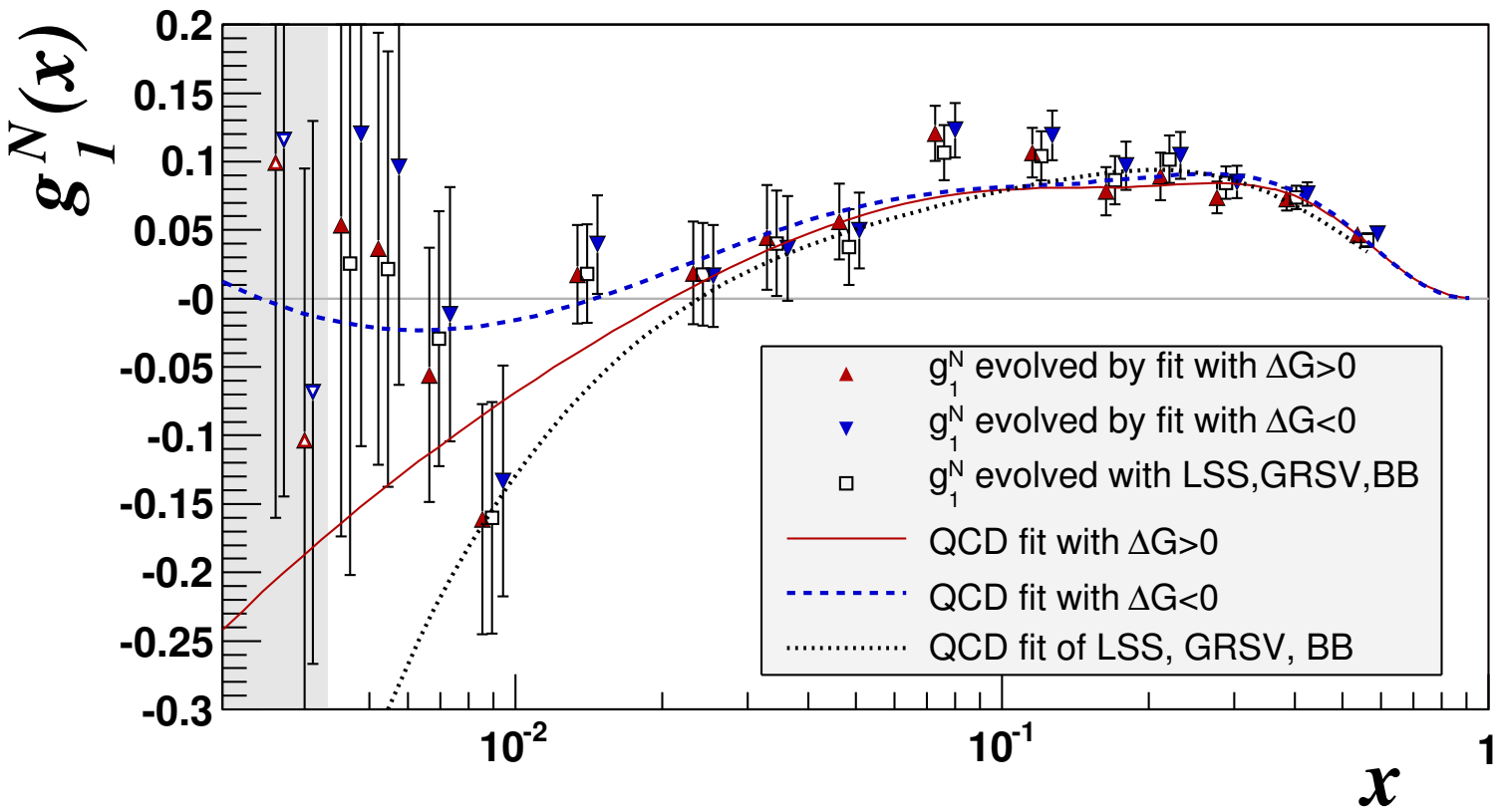


Quark polarisation from COMPASS data only (@ Q^2 = 3 GeV^2):

$a_0 = 0.35 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.})$ and gluon polarisation: $|\Delta G| \approx 0.2 - 0.3$

COMPASS QCD analysis of g_1^d...cont'd

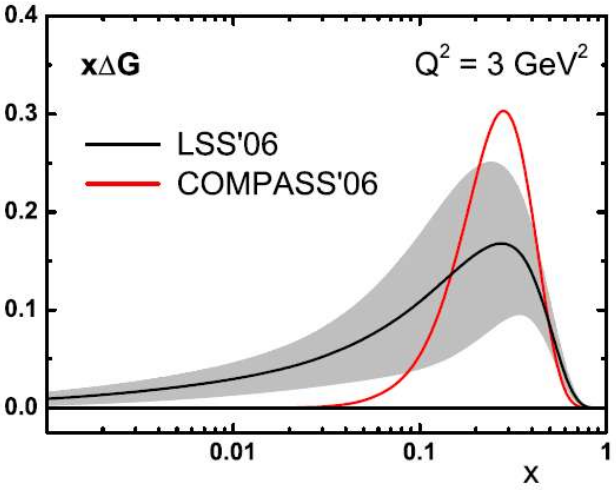
V.Yu. Alexakhin (COMPASS) *et al.* Phys Lett B**647** (2007) 8



COMPASS g_1^N evolved to Q^2 = 3 GeV^2; LSS, GRSV, BB are NLO fits to world (but no COMPASS) data.

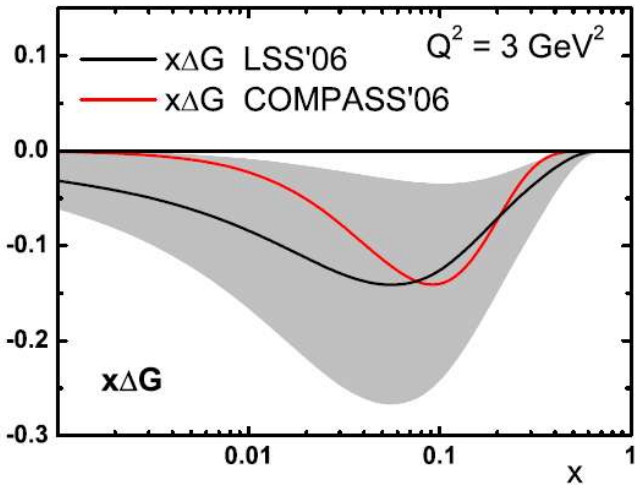
Low x data prefer $\Delta G < 0$??? Sign of ΔG not fixed by the g_1 measurements...

LSS06 QCD analysis including COMPASS g_1^d



$\Delta G > 0$

$\Delta G < 0$



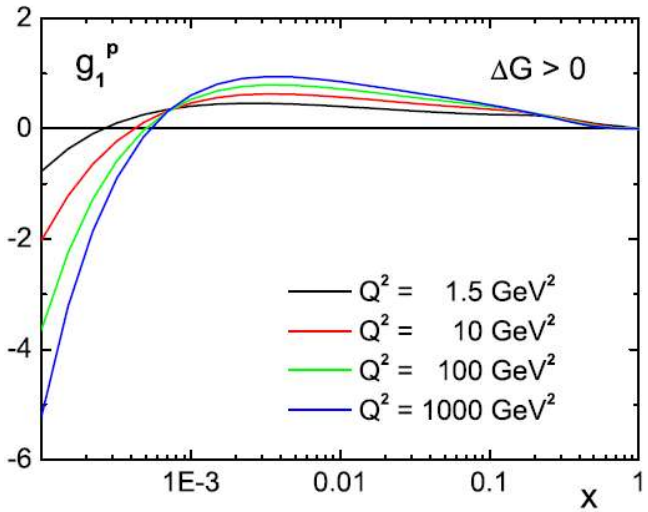
Can we ever tell the sign of ΔG ? ...

Figures from E. Leader, DIS2008

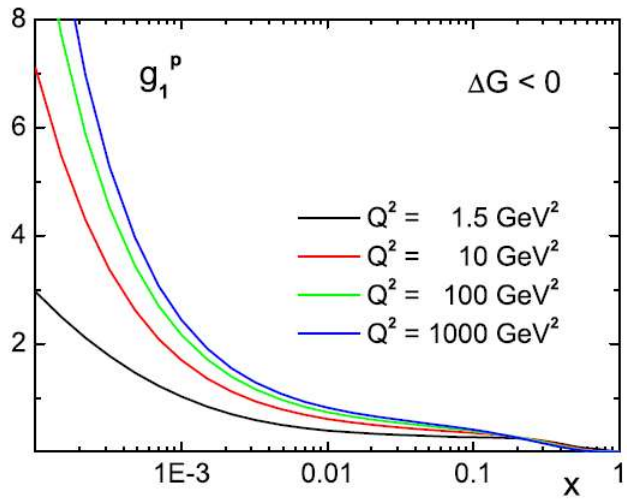
LSS06 QCD analysis including COMPASS g_1^d...cont'd

... except at an ep collider ?

LSS06, $\Delta G > 0$



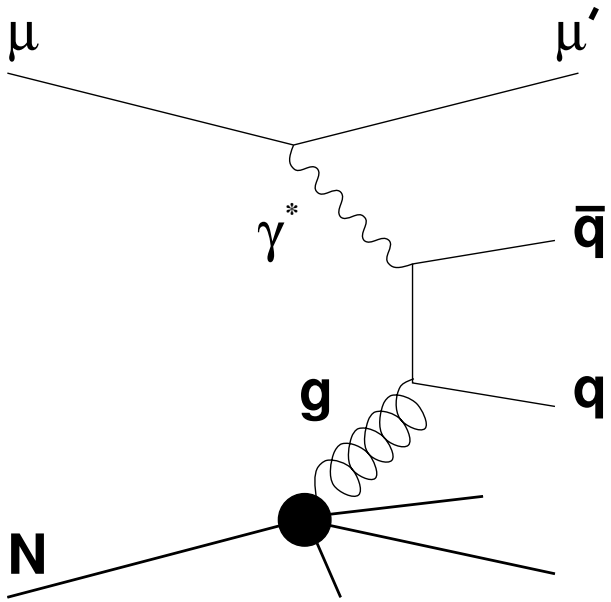
LSS06, $\Delta G < 0$



Figures from E. Leader, DIS2008

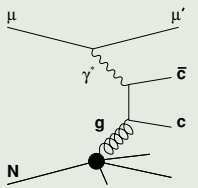
Direct $\Delta G/G$ measurements

Mechanism employed: photon–gluon fusion. Observable: asymmetry in the hadron production

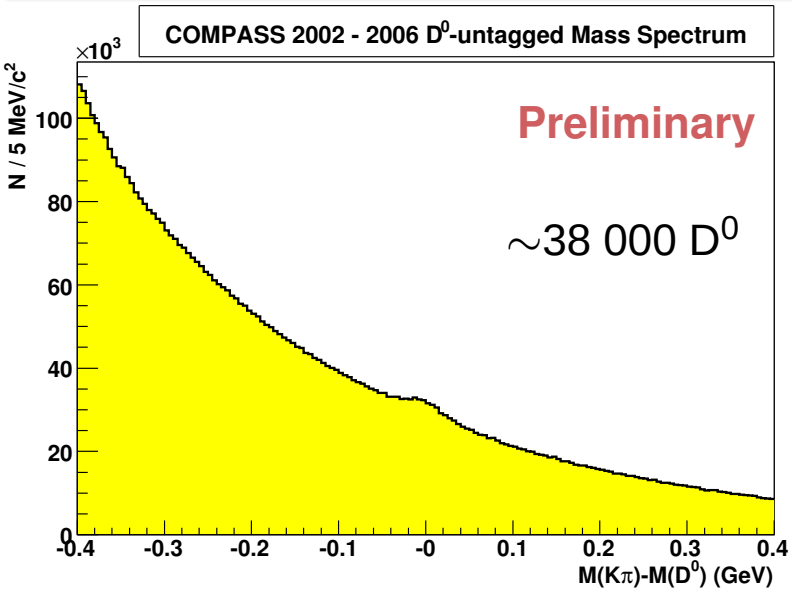


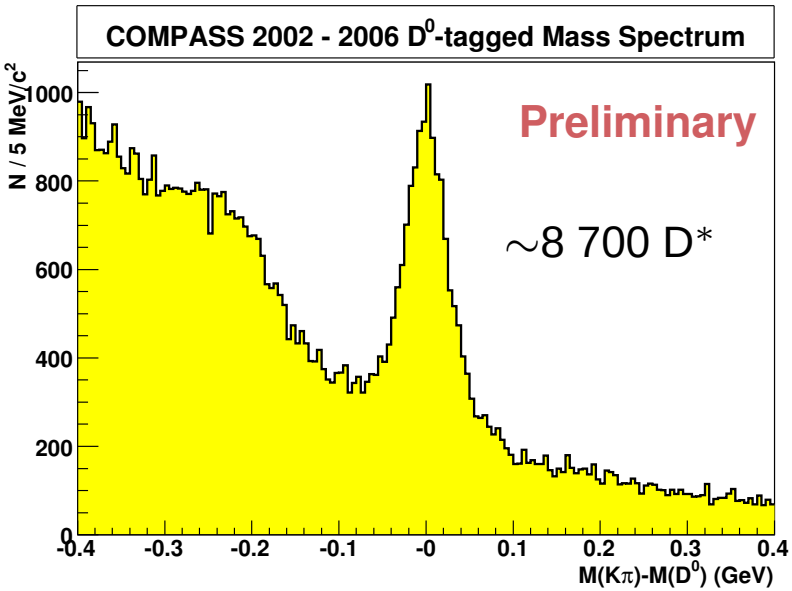
- If q≡ c $\Longrightarrow$ a pair of charmed mesons (we demand only one) in the final state;
  - measurement difficult (low statistics),
  - few theoretical assumptions.
- If q≡ u,d,s $\Longrightarrow$ a pair of jets or (in COMPASS) of high-p_T hadrons;
  - measurement simple (high statistics),
  - several theoretical assumptions.

Direct $\Delta G/G$ measurements; open charm production



$$D^0 \to K + \pi, \qquad D^* \to D^0 + \pi_s \to K + \pi + \pi_s$$

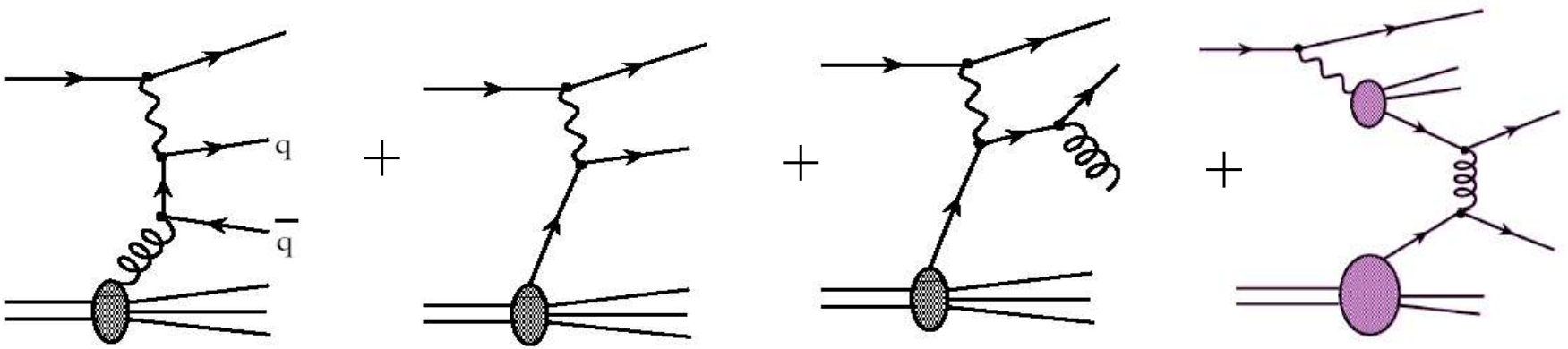




- Choose $D^0 \to K\pi$ (BR∼4%); pions and kaons identified by RICH.
- Clean sample of the PGF events (but low statistics); little physics background.
- Combinatorial background significantly reduced for the $D^* \to D^0 + \pi_s \to K + \pi + \pi_s$.
- Charm in the nucleon neglected.
- Weak dependence on the MC in the analysis.
- A weighting method used to optimise the $\Delta G/G$ extraction $\Longrightarrow$ C. Quintans' talk

Direct $\Delta G/G$ measurements; high p_T hadrons

PGF, ~ 30% | LO | QCDC | Resolved photon (only at $Q^2 < 1$ GeV^2)



$$A_{LL}^{2h}(x) = R_{pgf} \cdot a_{LL}^{pgf} \cdot \frac{\Delta G}{G}(x_g) + R_{LO} \cdot D \cdot A_1^{LO}(x) + R_{QCDQ} \cdot a_{LL}^{QCDQ} \cdot A_1^{LO}(x_c)$$

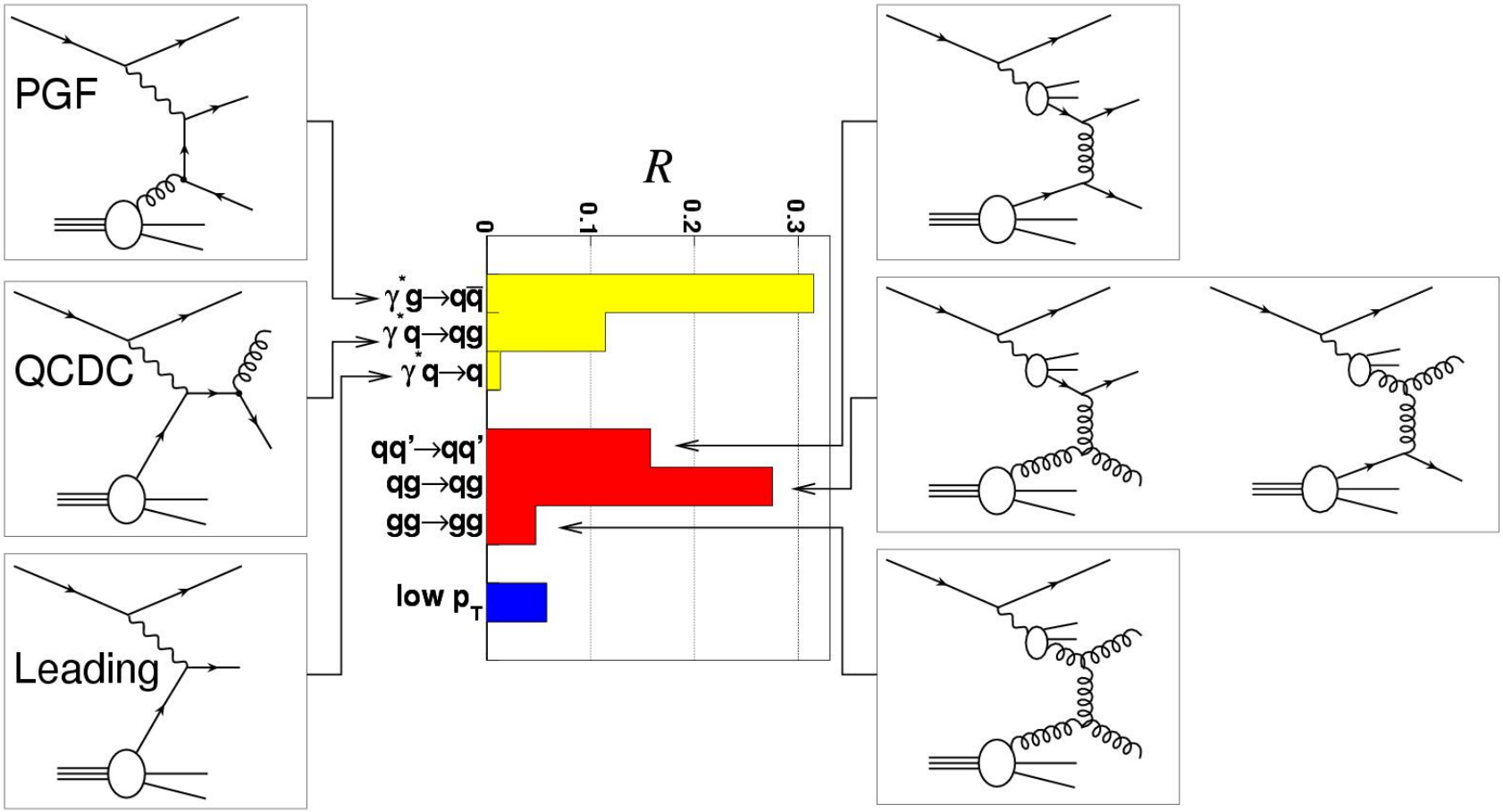
$\frac{\Delta G}{G}$ evaluated from $A_{LL}^{2h} = A_{meas}/(P_b P_T f)$ and from inclusive asymmetries, $A_1 = A_{meas}^{incl}/D$
if contributions of PGF and of background processes (LO, QCDQ) taken from MC

$\Longrightarrow$ C. Quintans' talk.

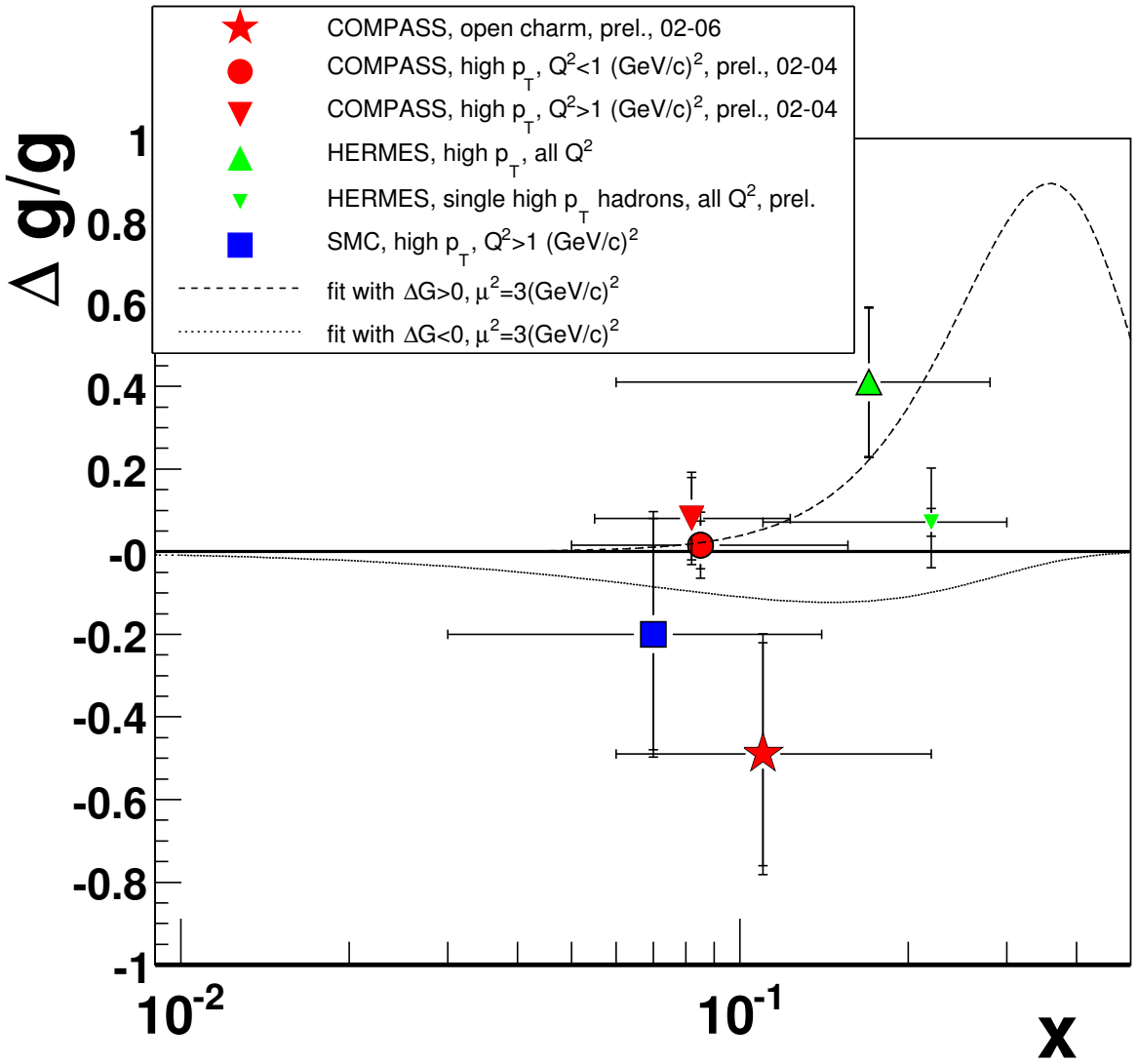
Direct $\Delta G/G$ measurements; high p_T hadrons @ $Q^2 < 1$ GeV^2

E.S. Ageev (COMPASS) *et al.* Phys. Lett. B **633** (2006) 25

Resolved photons



Summary of the gluon polarisation measurements



At $x_g \sim 0.1$, $\Delta G/G$ is compatible with zero! Qualitative agreement with RHIC results.

Summary of the gluon polarisation measurements

...cont'd

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

Are we approaching the solution of the "proton spin puzzle"?

- Restoration of $\Delta\Sigma$=0.6 via the axial anomaly improbable.
- Global, consistent NLO analysis of ΔG needed.
- Independent measurement of L necessary.
- All candidates are contributing about equally to the nucleon spin?

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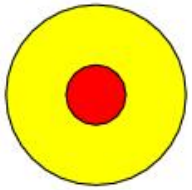
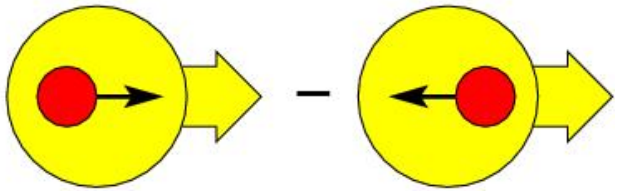
Partonic structure of the nucleon; distribution functions

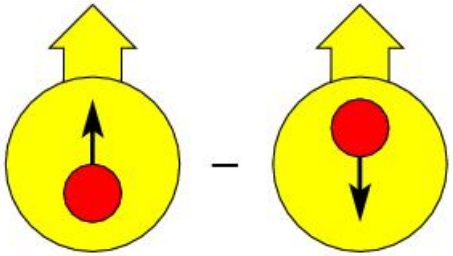
Three species of twist-two quark distributions in QCD (after integrating over the quark intrinsic k_t):

$q(x) =$ 

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

$\Delta q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;
known (polarised DIS $\longrightarrow g_1(x)$).

$\Delta_T q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in the transversely polarised nucleon;
unknown (polarised DIS $\longrightarrow$ Collins asymmetry).

In the nonrelativistic approach $\Delta_T q(x)$ identical with $\Delta q(x)$.
$\Delta_T q(x)$ are C-odd and chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.

If the k_t taken into account $\Longrightarrow$ 8 TMD appear; one, $f_{1T}^{\perp}$ accessible through "Sivers asymmetry".

Properties of transversity

Properties of $\Delta_T q(x)$:

- is chiral–odd $\Longrightarrow$ hadron(s) in final state needed to be observed
- simple QCD evolution since no gluons involved
- related to GPD
- sum rule for transverse spin
- first moment gives “tensor charge” (now being studied on the lattice)

Asymmetry measured *e.g. via* the Collin’s asymmetry (asymmetry in the distribution of hadrons):

$$N_h^{\pm}(\phi_c) = N_h^0 \left[1 \pm p_T D_{NN} A_{Coll} \sin \phi_c\right]$$

which in turn gives at LO:

$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

But transverse fragmentation functions $\Delta_T^0 D_q^h$ needed to extract $\Delta_T q(x)$ from the Collin’s assymmetry! Recently those FF measured by BELLE.

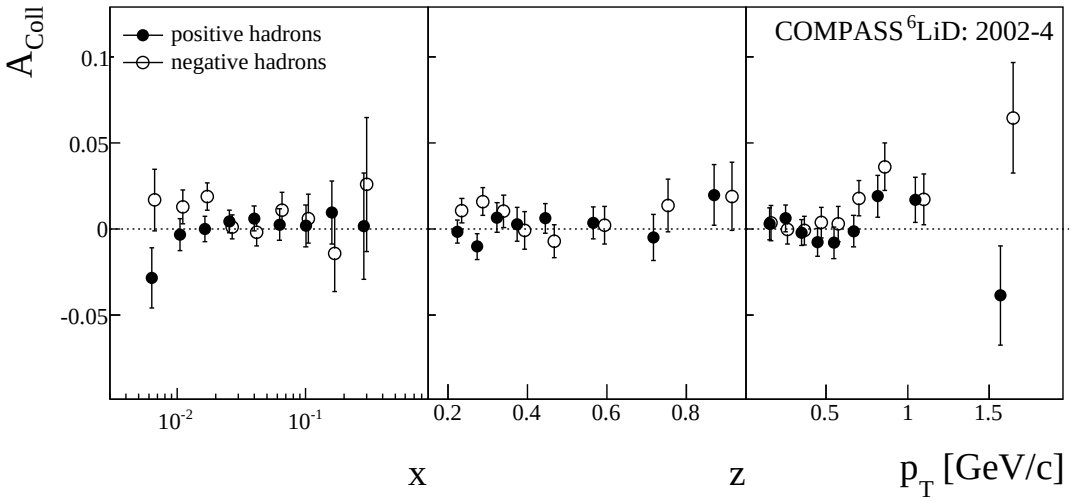
Properties of the Sivers process:

it is related to L_q in the proton. Fundamental !

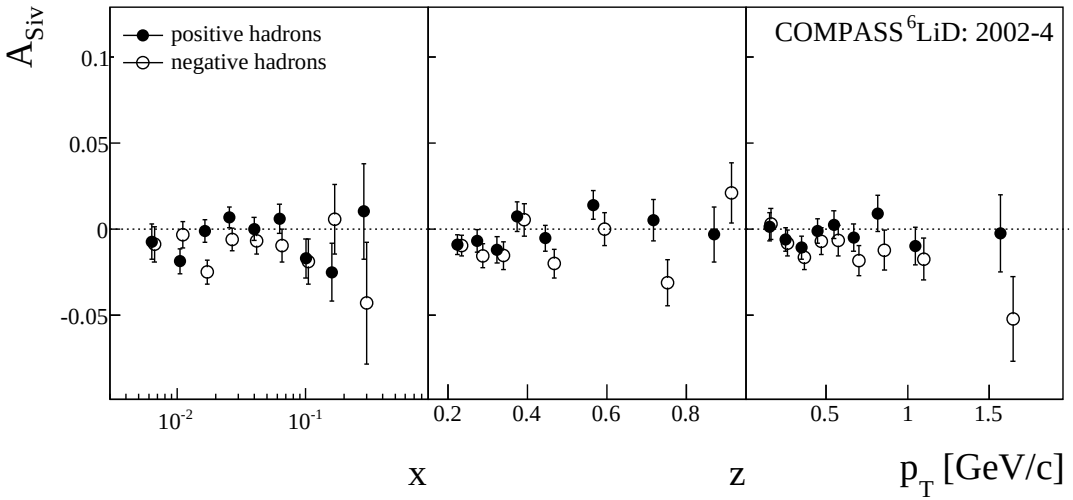
Results for the Collins and Sivers asymmetries

Deuteron target; all hadrons: positive and negative

E.S. Ageev *et al.* (COMPASS) Nucl.Phys.B **765**(2007) 31



Collins asymmetries very small.
These data + Hermes + Belle:
$\Longrightarrow \Delta_T u + \Delta_T d \sim 0$

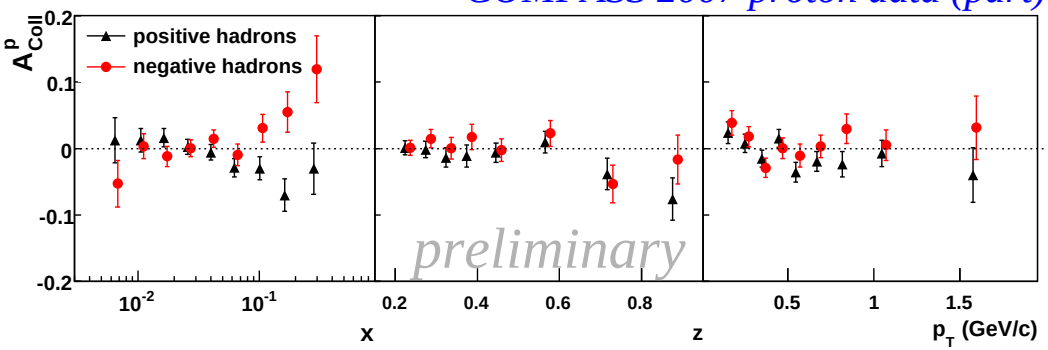


Sivers asymmetries very small.
S.Brodsky & S. Gardner (2006): no gluon orbital angular momentum in the nucleon?

Results for the Collins and Sivers asymmetries...cont'd

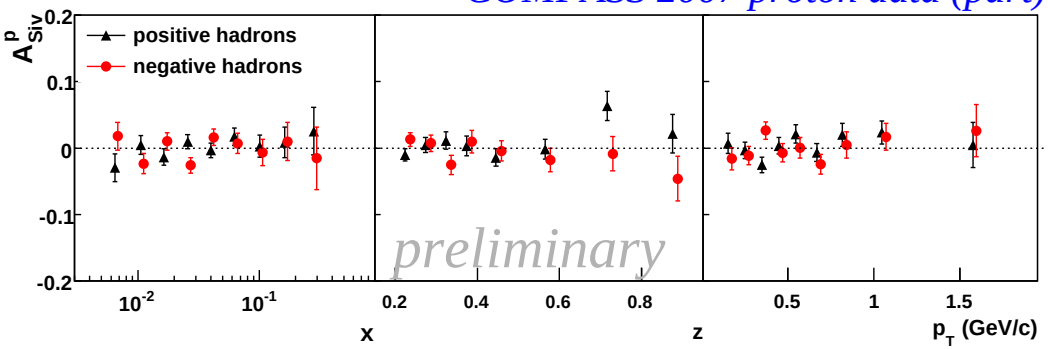
Proton target; all hadrons: positive and negative

COMPASS 2007 proton data (part)



Asymmetries nonzero at $x \gtrsim 0.1$.

COMPASS 2007 proton data (part)



Sivers asymmetries very small.

More $\Longrightarrow$ Giulia Pesaro's talk

Outline

1. The experiment
   - The Collaboration
   - Programmes
   - History
   - Detector
2. Results
   - Acceptance
   - Results of inclusive measurements
   - Sea quark polarisation
   - Nucleon spin structure
   - Results from the transversely polarised target
3. Outlook

Outlook

COMPASS takes data since 2002; the only large fixed-target experiment @ CERN now. Energy larger than Hermes and physics processes different than @ RHIC spin.

- Muon programme on proton and deuteron:
  - Polarisation of partons
  - Measurements of transversity and Sivers process
  - Many other measurements: exclusive ρ production, Λ polarisation, azimuthal asymmetries.
  - Lots of data await analysis!
- Hadron programme:
  - Data taking in 2008 with 190 GeV π on liquid H_2 target $\Longrightarrow$ search for exotic mesons and glue balls.
  - Results on diffractive 3π production on Pb from 2004 pilot run
- Future: a proposal for many interesting measurements is in preparation.

SPARE

Cross section asymmetries $\longrightarrow$ structure functions

- A direct observable, μ-d cross section asymmetry $A^{\mu d}$:

$$A^{\mu d} = \frac{1}{f P_T P_B} \left(\frac{N^{\leftrightarrows} - N^{\rightleftarrows}}{N^{\leftrightarrows} + N^{\rightleftarrows}} \right); \quad f \sim 0.4, \quad P_T \sim 0.5, \quad P_B \sim -0.8$$

- is related to the longitudinal and transverse $\gamma^* d$ asymmetries:

$$\frac{A^{\mu d}}{D} = A_1^d + \eta A_2^d$$

- In the COMPASS kinematics η is small; also the SLAC and SMC measurements show that:

$$| \eta A_2^d | \ll | A_1^d | \qquad \text{so that :} \qquad \frac{A^{\mu d}}{D} \approx A_1^d = \frac{\sigma_0^T - \sigma_2^T}{\sigma_0^T + \sigma_2^T}$$

- Longitudinal spin–dependent structure function:

$$g_1^d(x, Q^2) \approx A_1^d(x, Q^2) \frac{F_2^d(x, Q^2)}{2x(1 + R(x, Q^2))}$$

- $$\textit{Here :} \quad g_1^d = g_1^N (1 - \frac{3}{2}\omega_D) = \frac{g_1^p + g_1^n}{2}(1 - \frac{3}{2}\omega_D) \quad \text{and} \quad \omega_D = 0.05 \pm 0.01$$