Review of COMPASS results

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– On behalf of COMPASS –

Low x meeting

Ischia Island, September 9 – 13, 2009

Outline

Outline

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

NA58, at the CERN SPS
$\sim$ 250 physicists
$\sim$ 30 institutes

Muon programme	Hadron programme
Spin dependent structure function g_1 Gluon polarisation in the nucleon Quark polarisation distributions Transversity Vector meson production Λ polarisation	Primakoff effect, π and K polarisabilities Exotic states, glueballs (Double) charmed mesons Multiquark states
Future: DVCS	Future: Drell–Yan on a polarised target

Outline

History: 2002 – 2009 and beyond

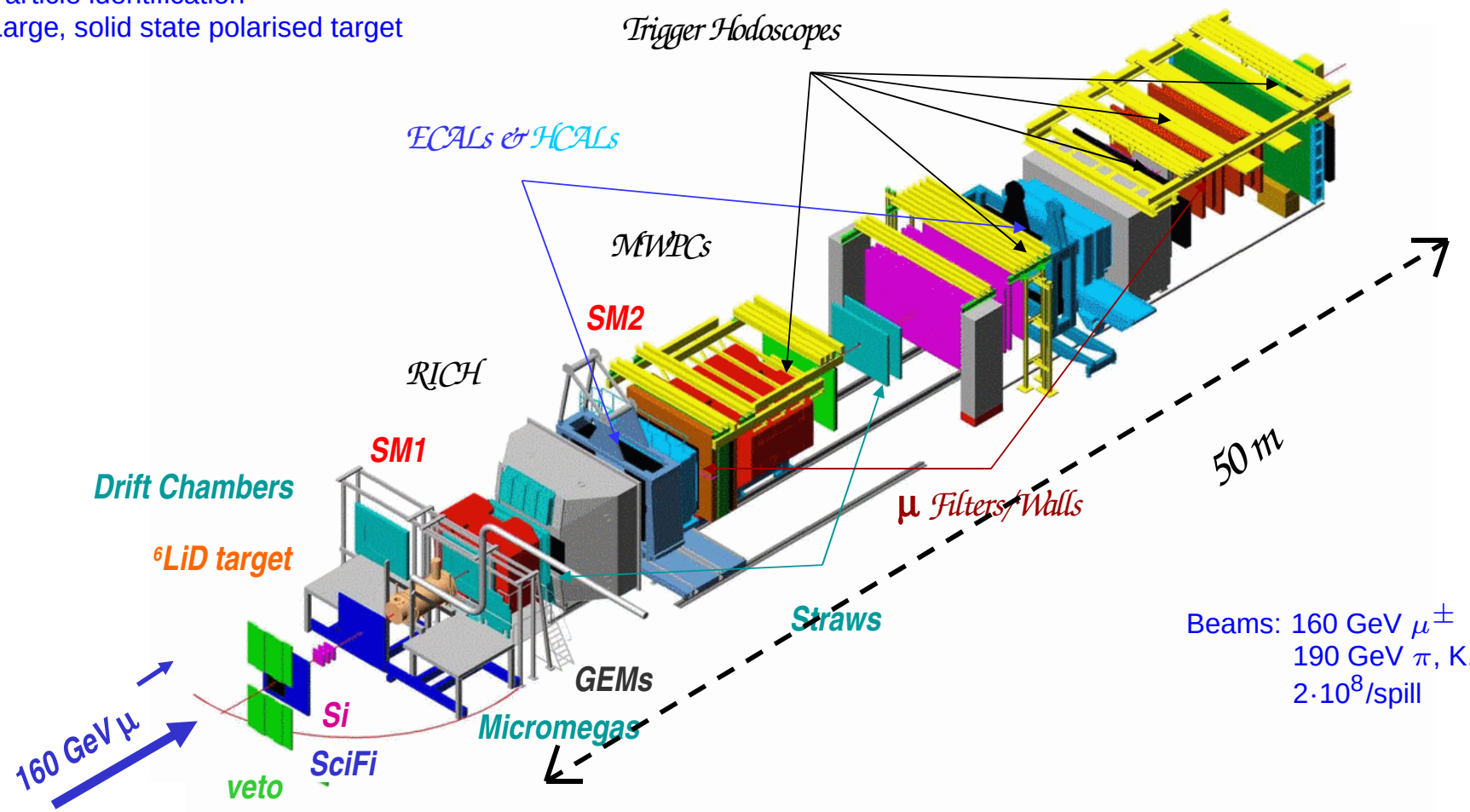
- 2002 160 GeV polarised μ beam & ^{6}LiD long./transv. polaris.
- 2003 *idem*
- 2004 *idem*
- 2004 pilot hadron run
- 2005 no SPS beam (several upgrades: target, RICH)
- 2006 160 GeV polarised μ beam & ^{6}LiD long. polarisation
- 2007 160 GeV polarised μ beam & NH_3 transv./long. polaris.
- 2008 190 GeV pion beam; diffractive and central production
- 2009 190 GeV pion, proton beams
- $\gtrsim$ 2010 Proposal Addendum: 2 1+1 year muon run with transv. and longit. polarised proton target
- $\gtrsim$ 2012 Letter-of-Intent: DVCS and Drell–Yan

Outline

COMPASS Spectrometer (muon run)

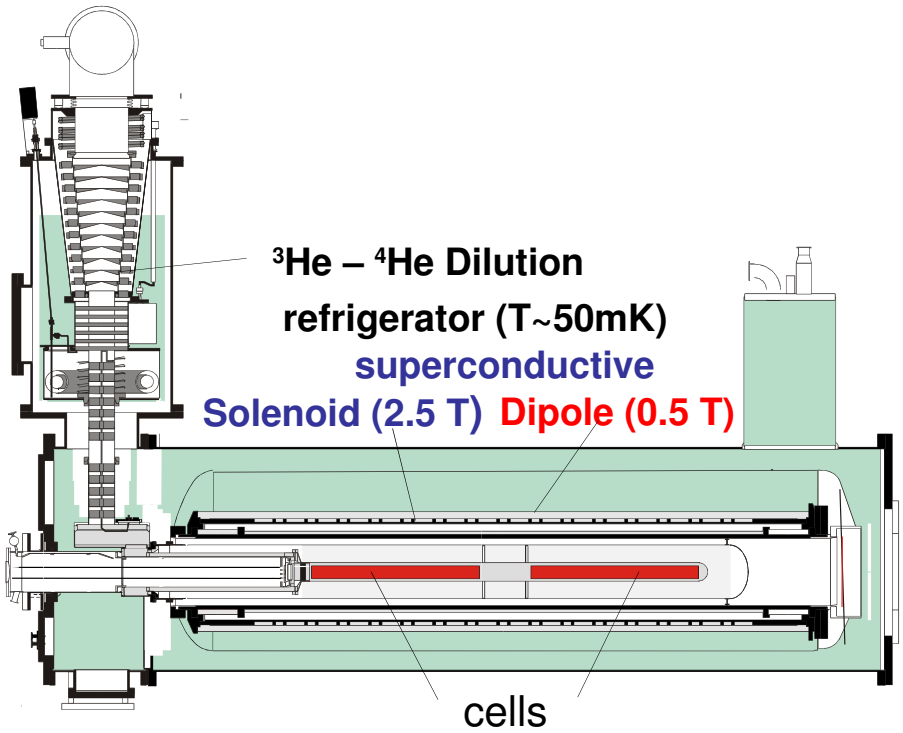
Nucl. Instr. Meth. A577 (2007) 455

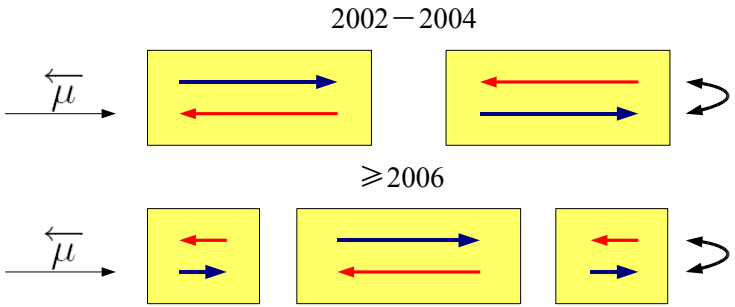
Two stages, $\sim$ 350 planes
Calorimetry
Particle identification
Large, solid state polarised target



Beams: 160 GeV $\mu^{\pm}$
190 GeV π, K, p
$2 \cdot 10^8$/spill

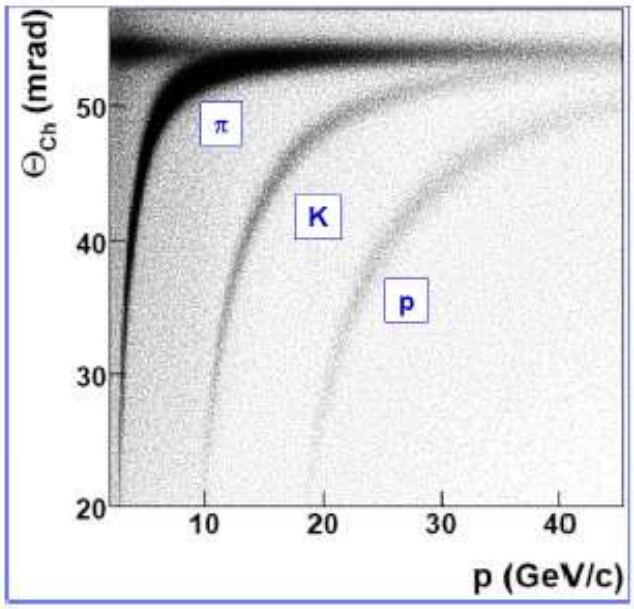
COMPASS polarised targets



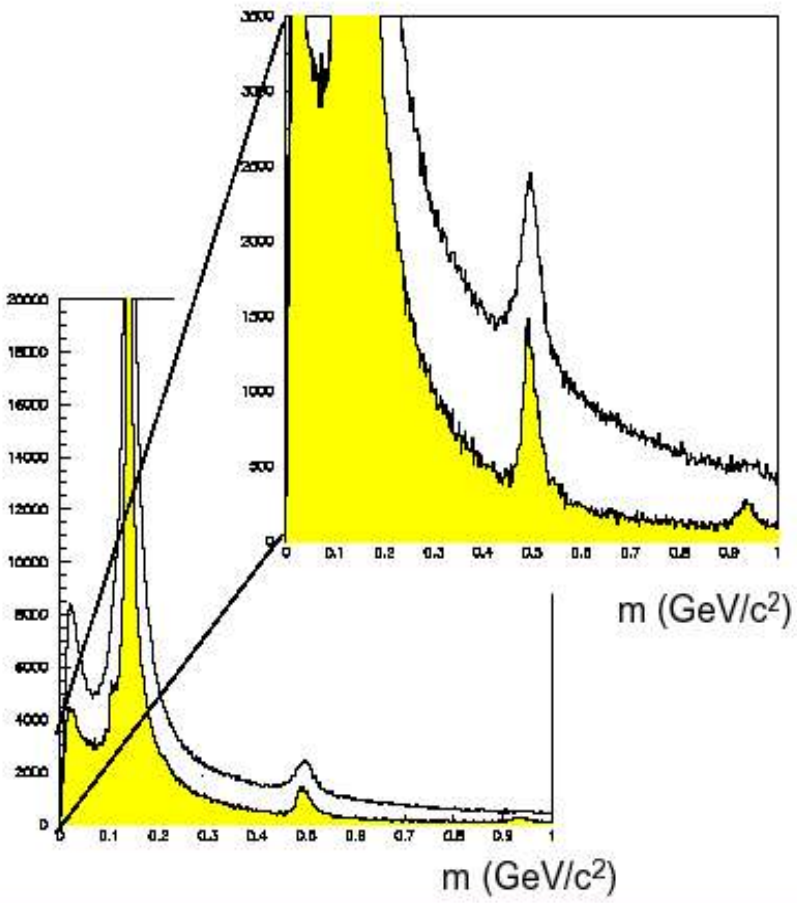


* Two (three in 2006, 2007) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent in 2006, 2007)
* Material: solid ^{6}LiD (NH_3 in 2007)
* Polarisation: ~ 50% (~90% in 2007), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15 in 2007)
* Polar acceptance: ~70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

COMPASS RICH



Before upgrade: white distribution
After upgrade: yellow distribution



RICH2007 Federica Sozzi 19

Outline

Acceptance of electroproduction experiments

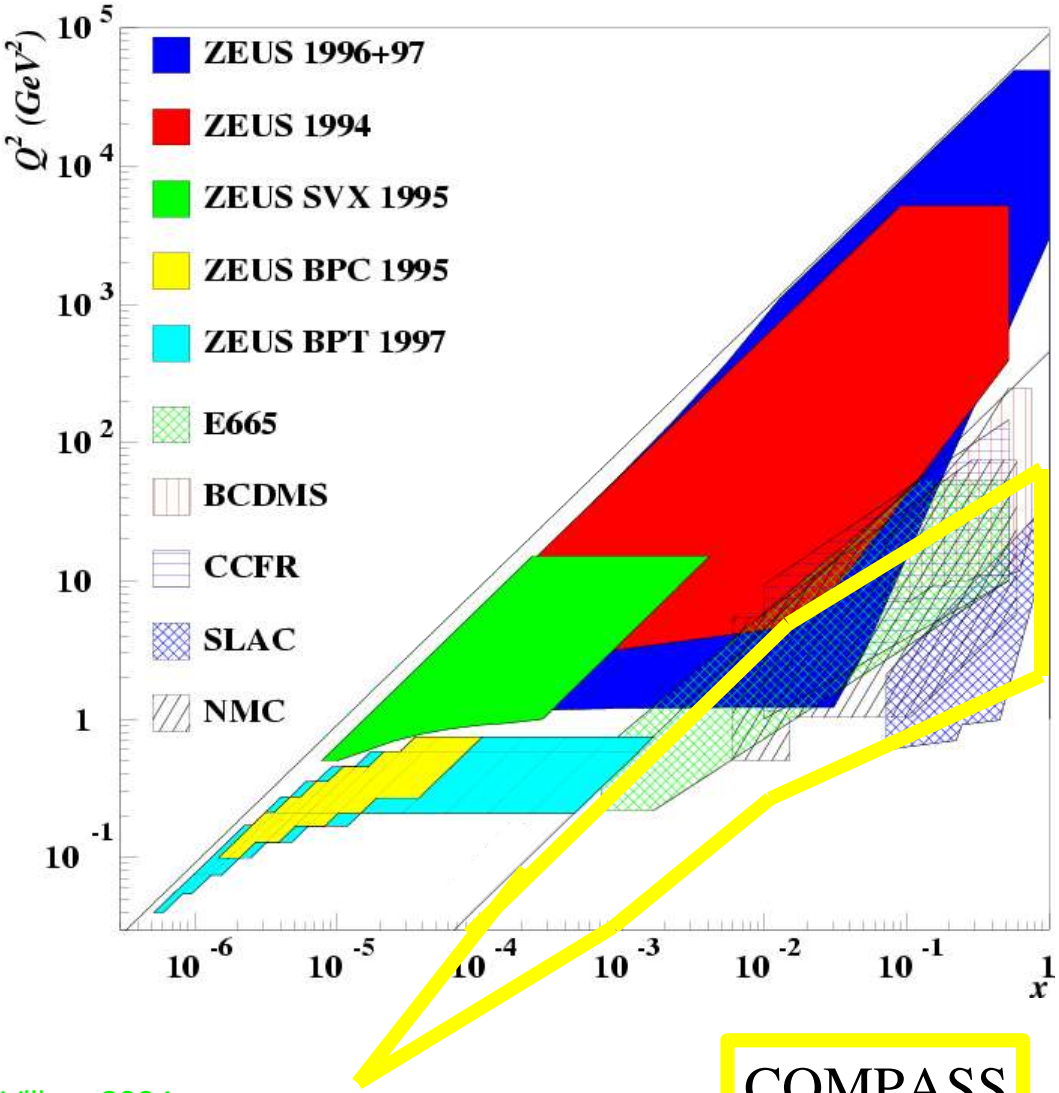
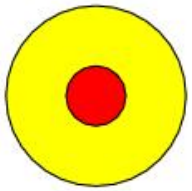


Figure from: N. D'Hose, Villars 2004

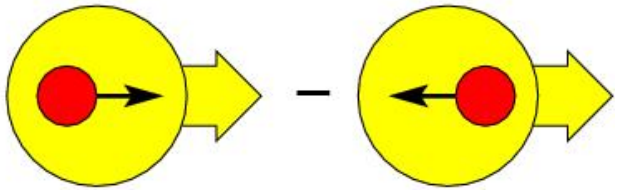
Outline

Partonic structure of the nucleon; distribution functions

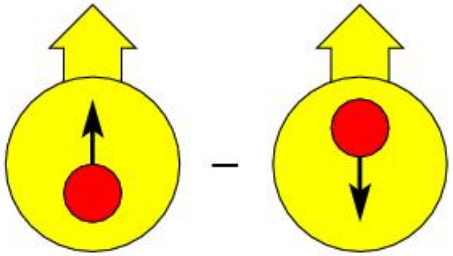
Three species of twist-two quark distributions in QCD (after integrating over the quark intrinsic k_t):

$q(x) =$ 

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 $\longrightarrow h_1(x)$).

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 distr.; one, $f_{1T}^{\perp}$ accessible through "Sivers asymmetry".

Observables in the polarised μ–p(d) scattering

- A direct observable, μ-p(d) cross section asymmetry $A_{meas}(x, Q^2)$, inclusive asymmetry $A_1(x, Q^2)$ and longitudinal spin–dependent structure function, $g_1(x, Q^2)$, are related as:

$$A_{meas} = \frac{1}{f P_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\rightleftarrows}}{N^{\leftrightarrows} + N^{\rightleftarrows}}\right) = D(A_1 + \eta A_2) \approx D \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)} = D \frac{g_1^d(x, Q^2)}{F_1^d(x, Q^2)}$$

(in the COMPASS kinematics η is small, $\mid \eta A_2 \mid \ll \mid A_1 \mid$)

$$f \sim 0.4, \quad P_T \sim 0.5, \quad P_B \sim -0.8, \quad \Delta q = q^+ - q^-, \quad q = q^+ + q^-$$

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

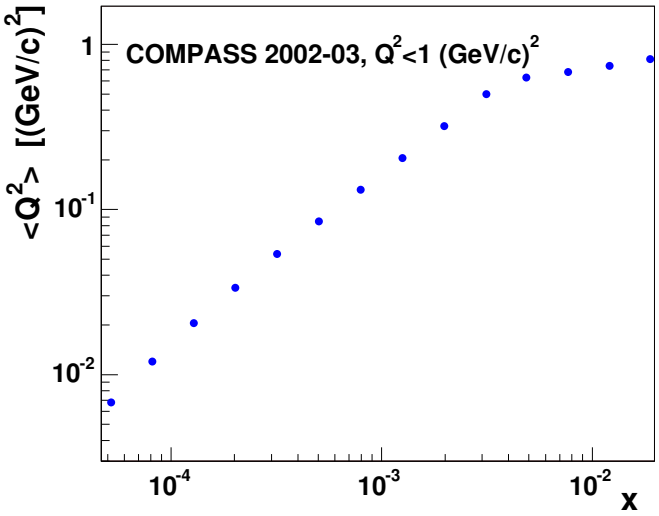
- Similarily, the semi–inclusive asymmetry A_1^h:

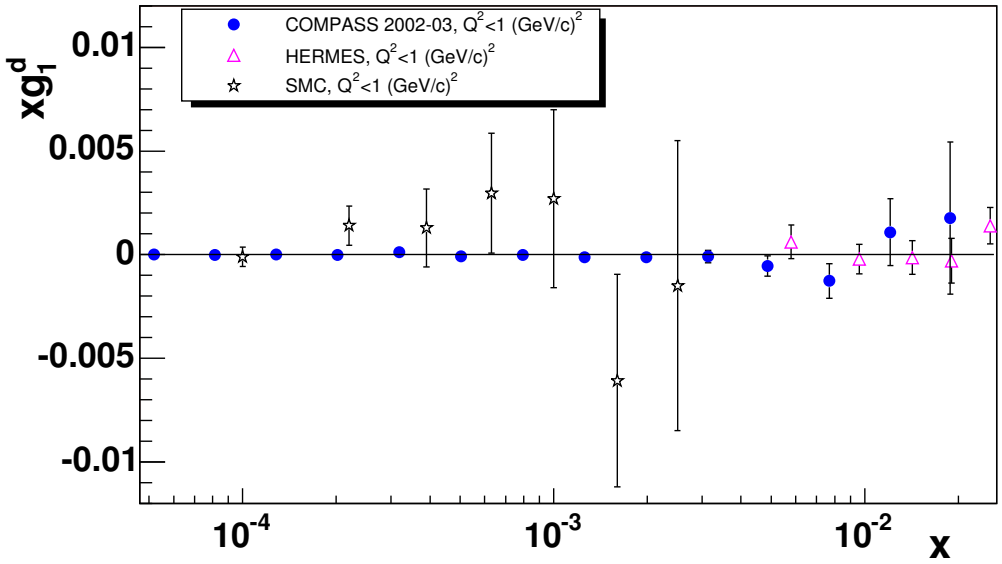
$$A_1^h(x, z, Q^2) \approx D \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)}$$

Outline

$g_1^d(x)$ in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)

V.Yu. Alexakhin (COMPASS) *et al.* Phys. Lett. B **647** (2007) 330

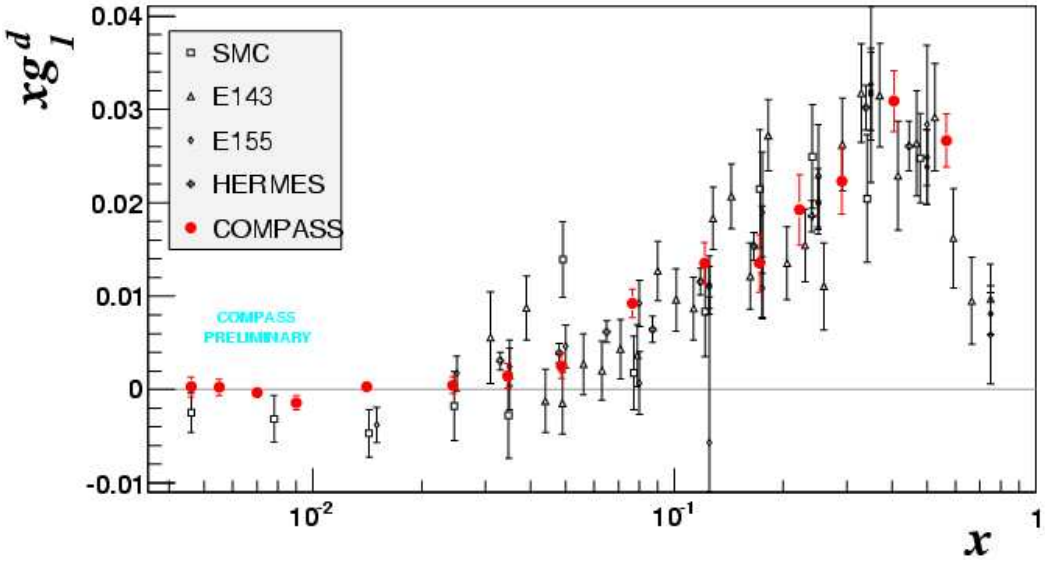


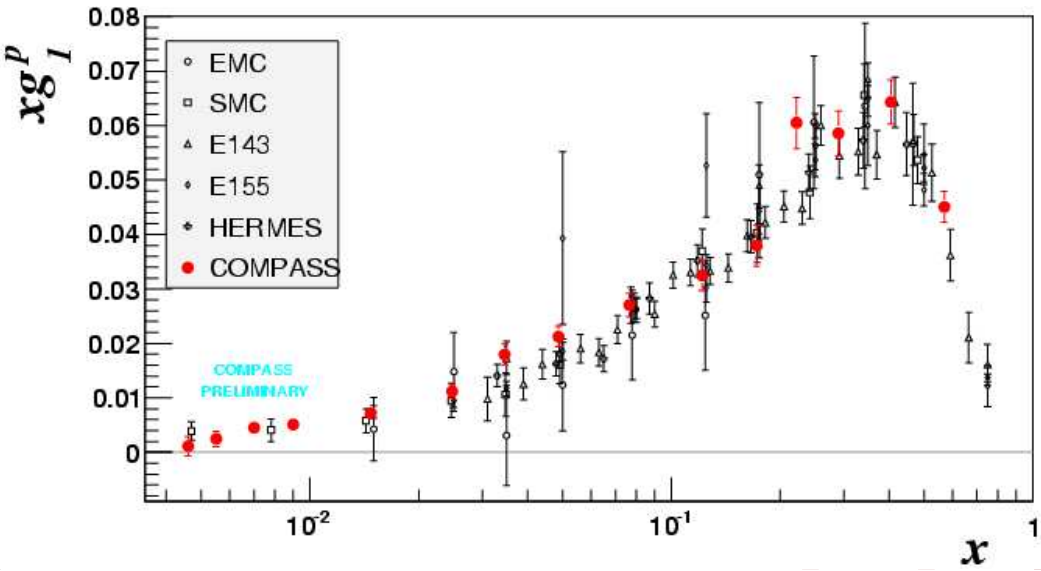


- Order of magnitude improvement over the statistical precision of the SMC.
- Interplay between perturbative and nonperturbative mechanisms.
- Spin effects in g_1^d at low x and Q^2 absent ?

$g_1(x)$ for proton and deuteron, $Q^2 > 1$ (GeV/c)^2

NEW: proton data 2007 (preliminary); full deuteron statistics

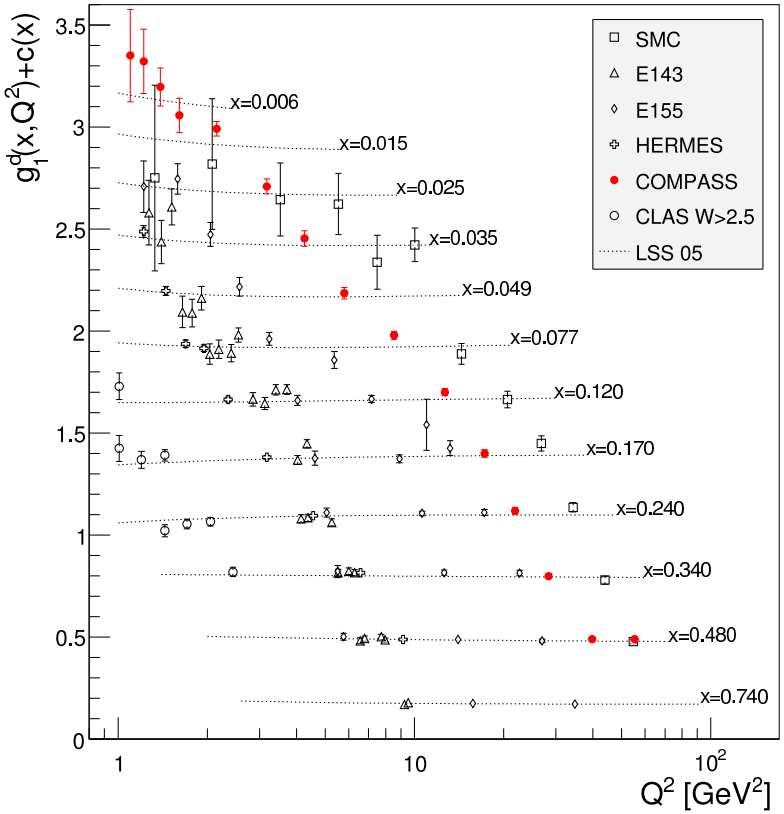


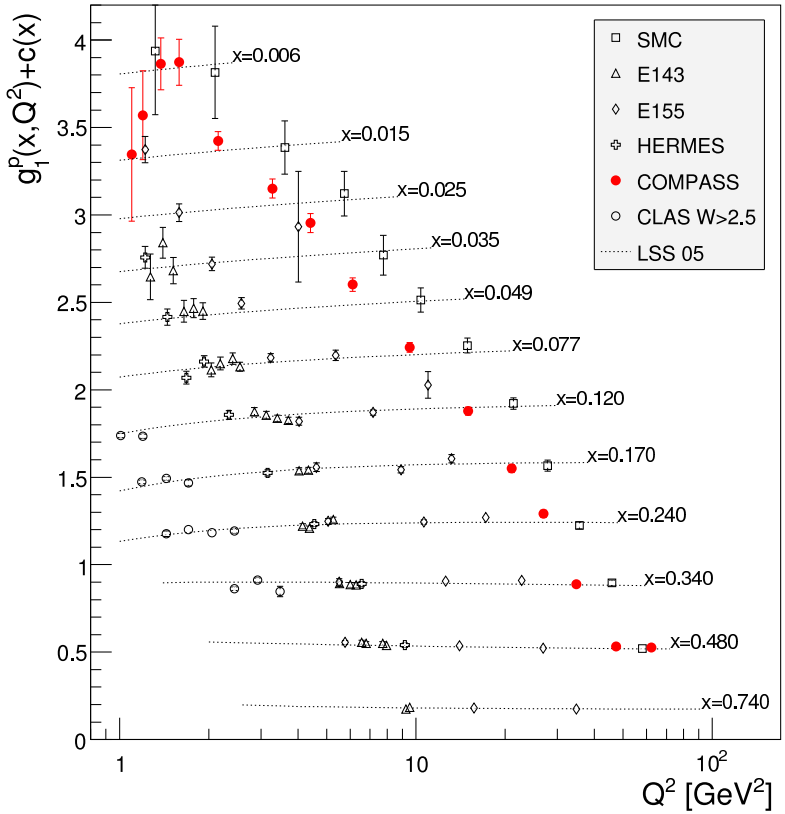


Good agreement
between the experiments

$g_1(x)$ for proton and deuteron, $Q^2 > 1$ (GeV/c)^2...cont'd

NEW: proton data 2007 (preliminary); full deuteron statistics

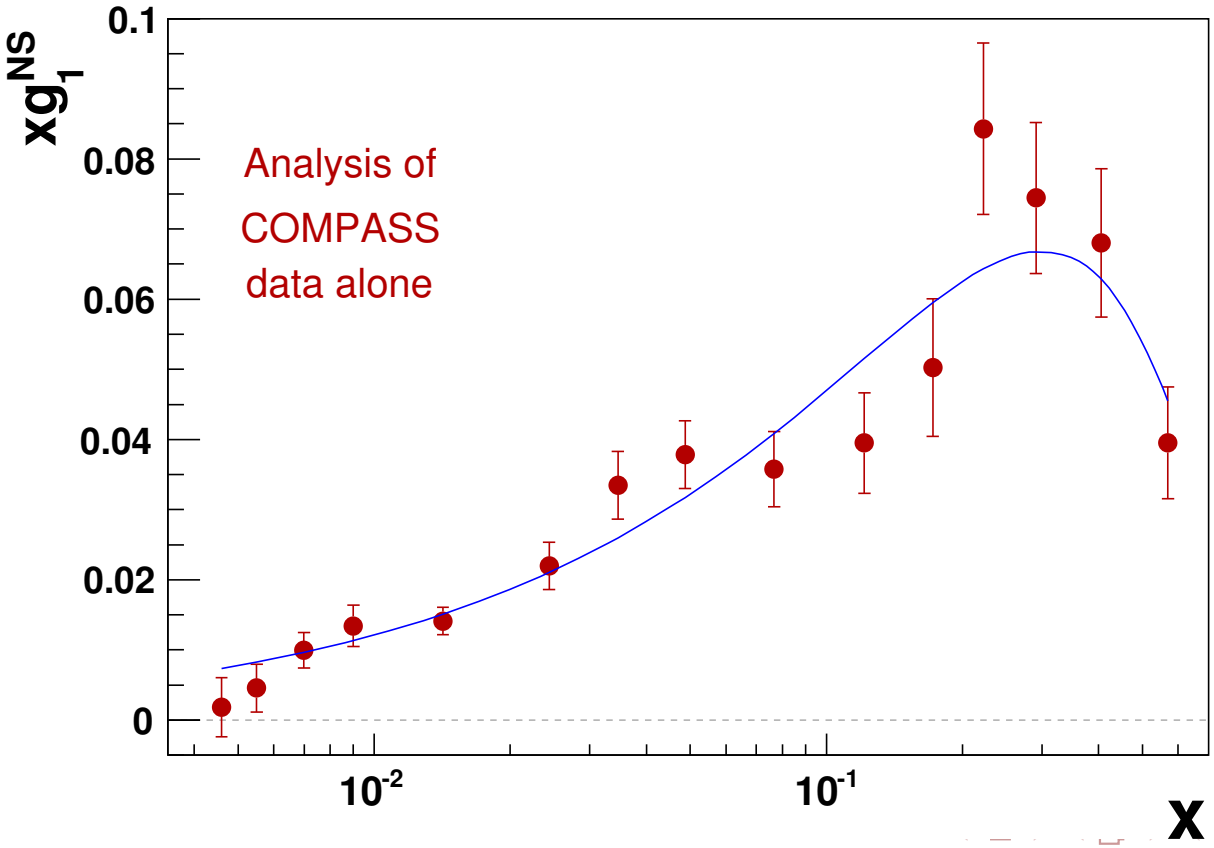




COMPASS measurements at high Q^2 important for the QCD analysis!

$g_1(x)$ for proton and deuteron, $Q^2 > 1$ (GeV/c)^2...cont'd

- From the new proton data: $g_1^{NS} = g_1^p - g_1^n$; its first moment, $\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C^{NS}(Q^2)$ (fundamental Bjorken sum rule)
- From QCD NLO fit to g_1^{NS} (COMPASS data only): $\frac{g_A}{g_V} = 1.30 \pm 0.07 \pm 0.10$ ($g_A/g_V = \Delta u - \Delta d = 1.260 \pm 0.003$ from the β decay of the neutron). Test and confirmation of the Bjorken sum rule.



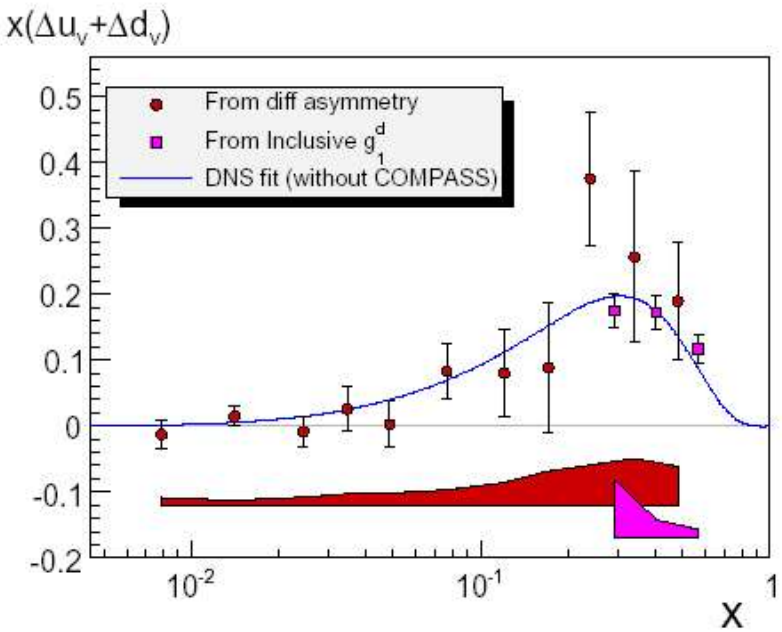
Outline

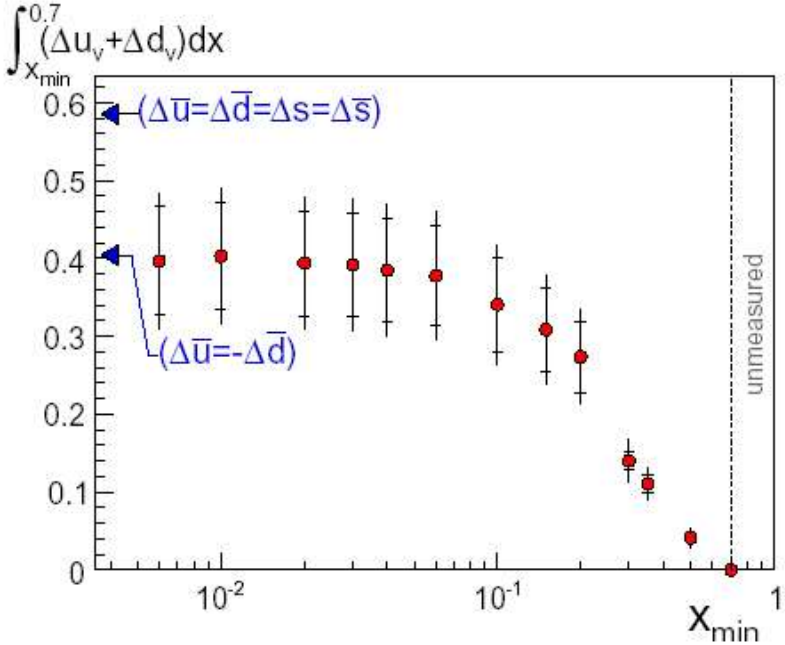
Flavour separation of helicity distributions (@ LO)

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

- Difference asymmetry: $A^{h^+-h^-}$: $A_d^{\pi^+-\pi^-}(x) = A_d^{K^+-K^-}(x) = \frac{\Delta u_v(x)+\Delta d_v(x)}{u_v(x)+d_v(x)}$
- At LO, the fragmentation functions drop out

$Q^2 = 10\ (\mathrm{GeV}/c)^2$ (SIDIS + DIS)

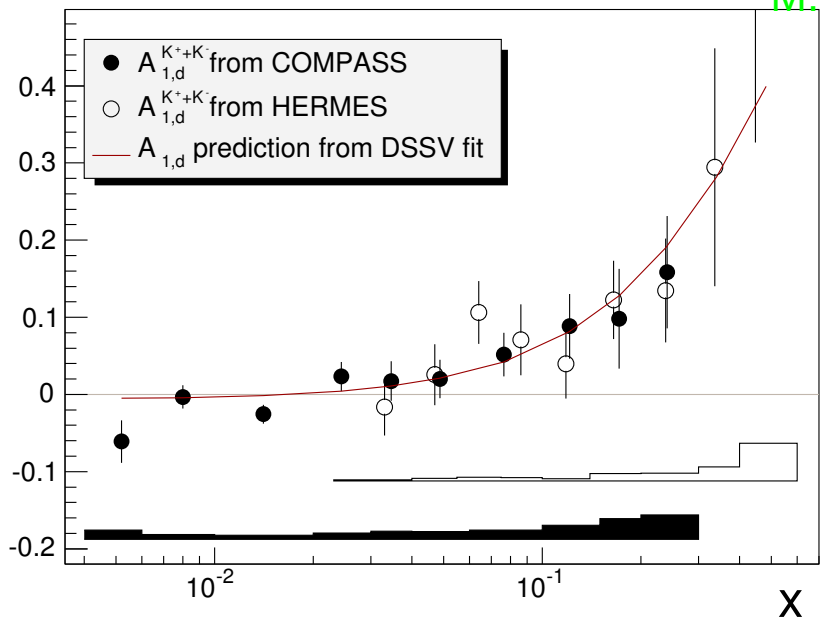


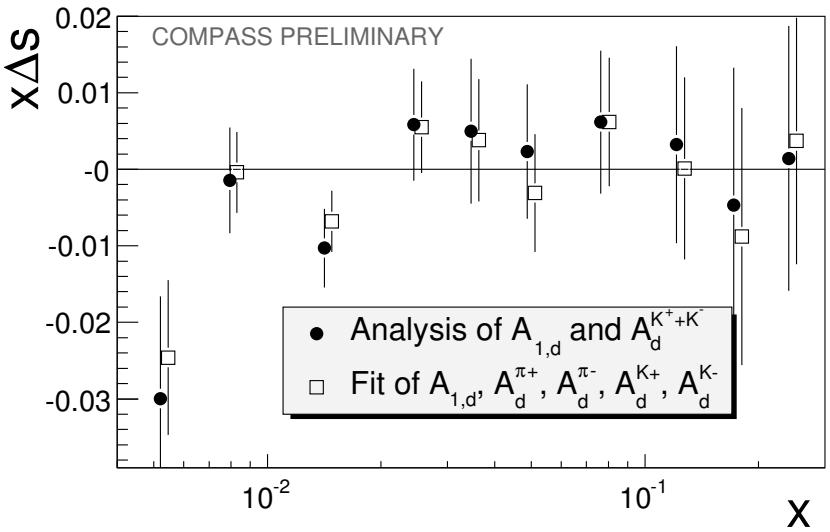


$$\int_{0.006}^{0.7} (\Delta u_v + \Delta d_v)\mathrm{d}x = 0.40 \pm 0.07 \pm 0.05$$

- Unmeasured regions contribute neligibly.
- Non-symmetric sea preferred ?

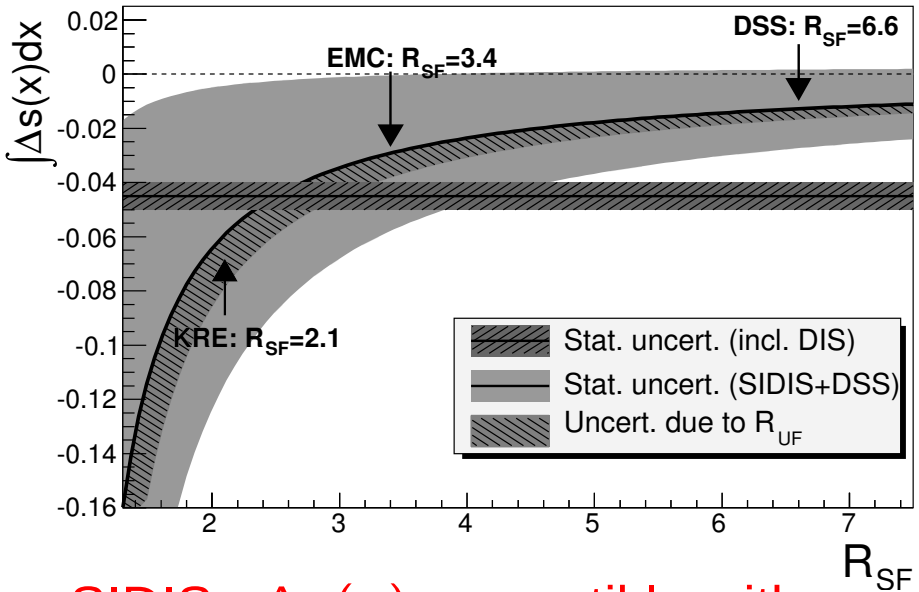
Flavour separation of helicity distributions (@ LO),....





M. Alekseev *et al.* (COMPASS), CERN-PH-EP/2009-008, hep-ex 0905.2828, to appear in Phys. Lett.

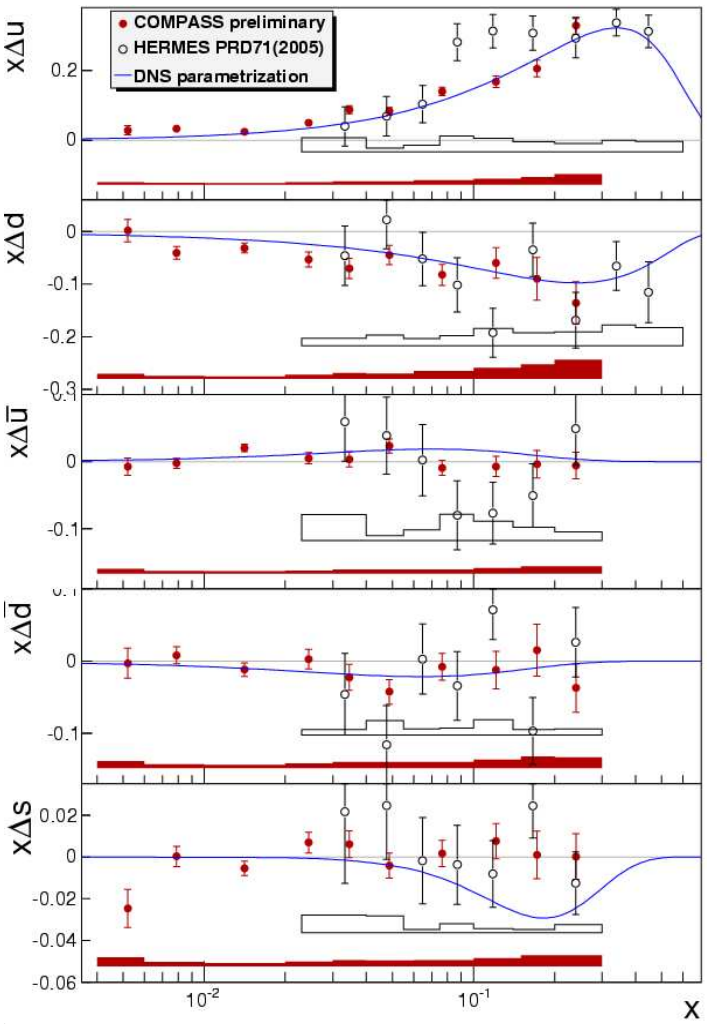
- $\frac{\Delta s}{s} = A_1^d + \left(A_1^{K^+ + K^-}\right) \frac{Q/s + \alpha}{\alpha - 0.8}$
- $\alpha = \frac{2R_{UF} + 2R_{SF}}{3R_{UF} + 2}, \quad Q = u + \bar{u} + d + \bar{d}$
- $R_{UF} = \frac{\int D_d^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z}, \quad R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z}$



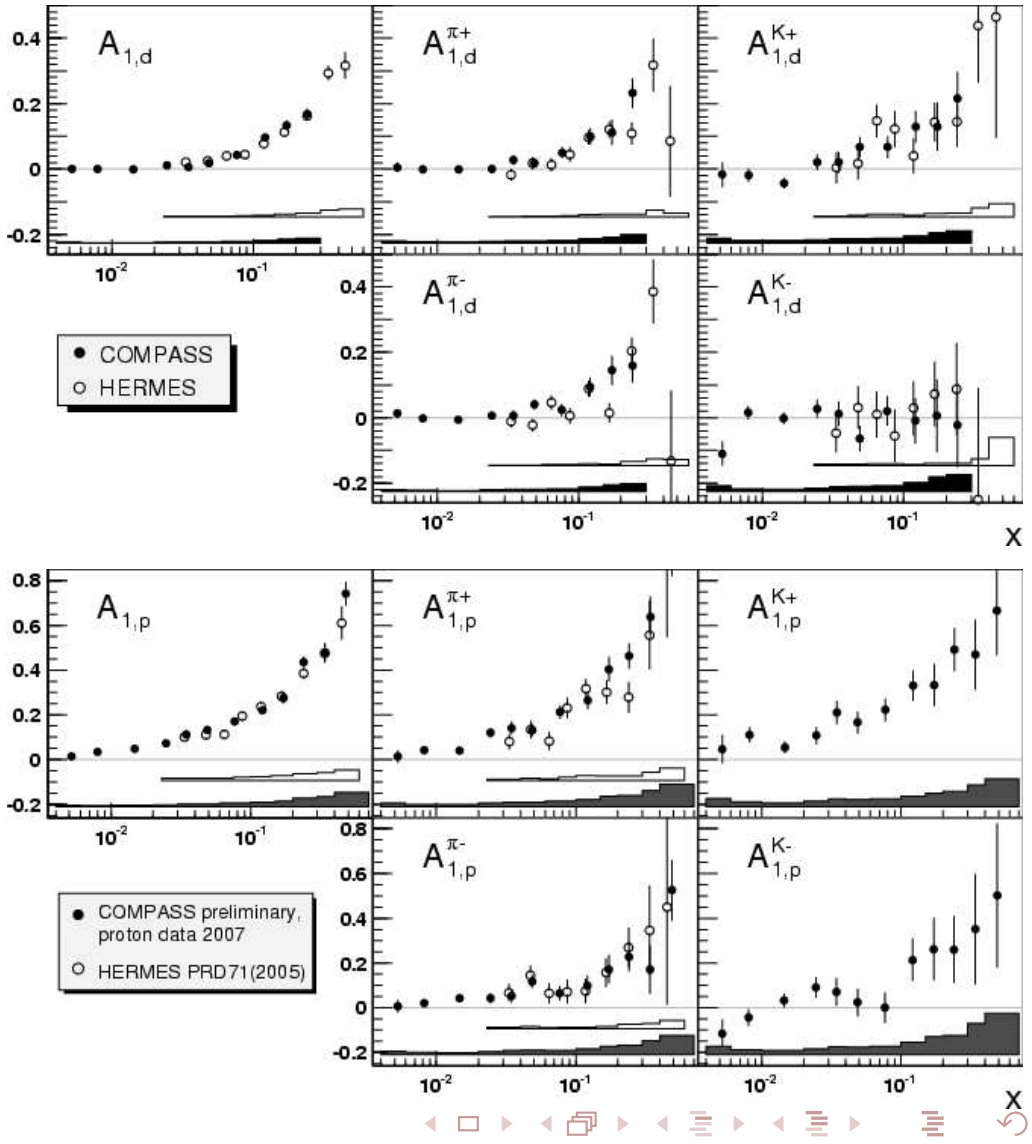
SIDIS: $\Delta s(x)$ compatible with zero ! contrary to most (LO, NLO) QCD fits.

Flavour separation of helicity distributions (@ LO),....

NEW: proton data 2007 (preliminary) full deuteron statistics

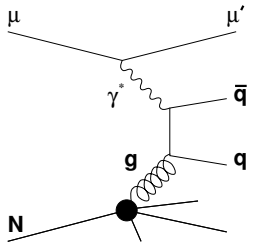


$Q^2 = 3\ (\mathrm{GeV/c})^2$



Gluon polarisation distribution, $\Delta g(x)$

- Scaling violation of g_1 (QCD fits, world data).
- Direct measurements – *via* the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into:

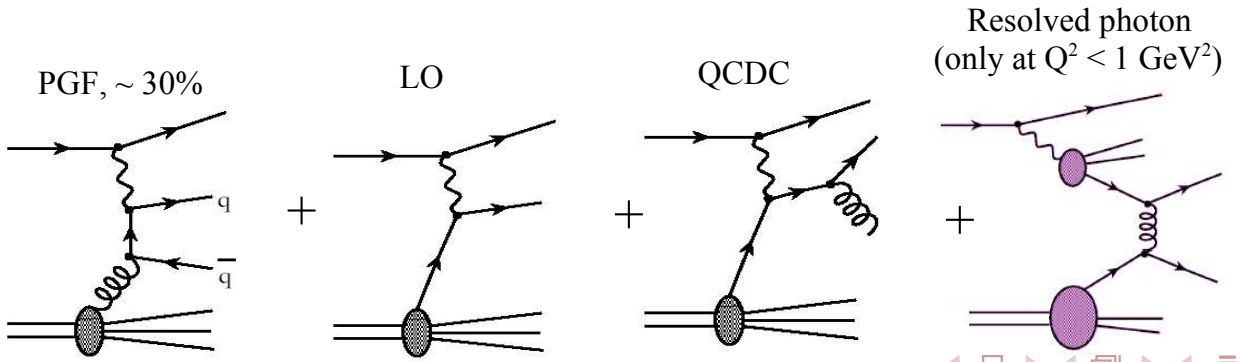


  - charm mesons, q≡c, (max. @ low Q^2, perturbative scale: e.g. m_c): low statistics, few theoretical assumptions;

$$A_{meas} = p_B\, p_T\, f\, a_{LL}\, \frac{\sigma_{PGF}}{\sigma_{PGF}+\sigma_{BGD}}\, \frac{\Delta g}{g} + A_{BGD}$$

  - a pair of hadrons of large p_T, q≡u, d, s, separately for low- and high Q^2 (perturbative scale: e.g. p_T): high statistics, several quantities from MC.

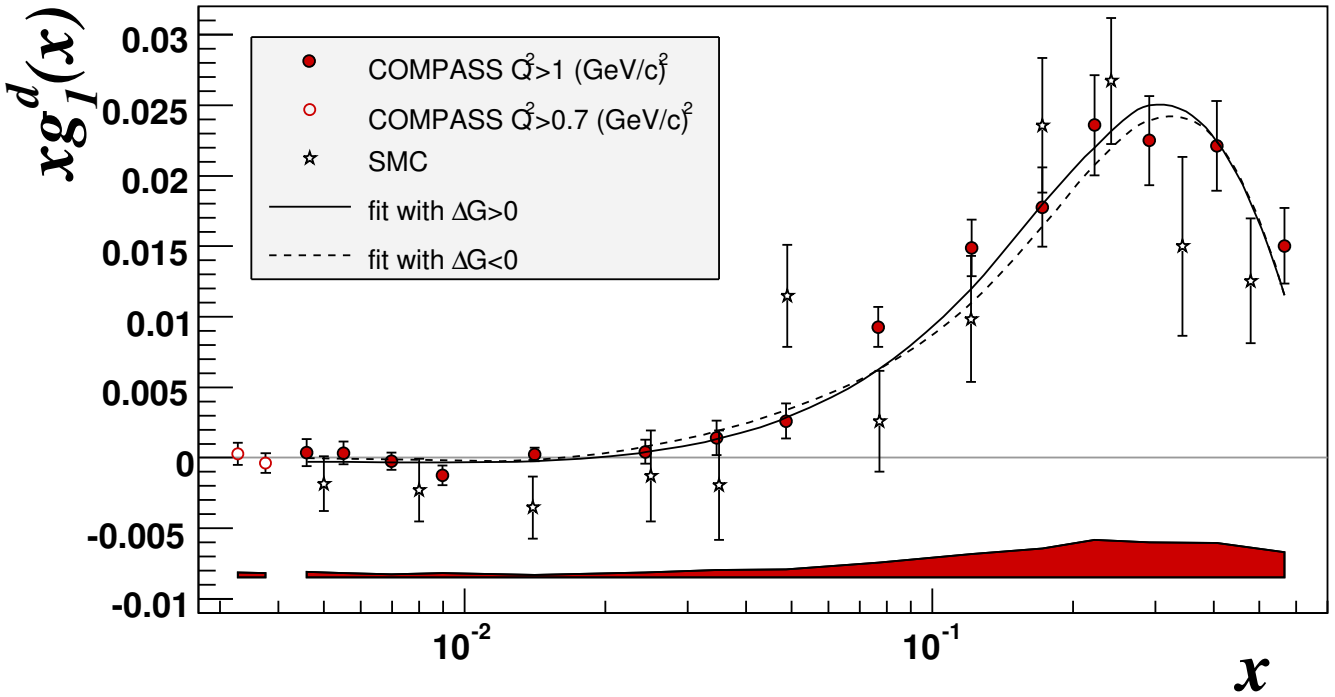
$$A_{meas} = p_B\, p_T\, f \left[R_{PGF} \cdot a_{LL}^{PGF} \cdot \frac{\Delta g}{g} + R_{LO} \cdot D \cdot A_1^{LO} + R_{QCDC} \cdot a_{LL}^{QCDC} \cdot A_1^{LO} \right]$$



COMPASS QCD analysis of inclusive g_1^d

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

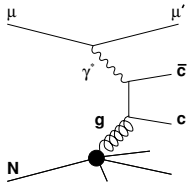
- Two programs: DGLAP evolution of structure functions and evolutions of moments
- NLO $\overline{MS}$ scheme
- World data: 9 experiments, 230 data points (43 from COMPASS)
- Two solutions, $\Delta G > 0$ and $\Delta G < 0$ describe data equally well.



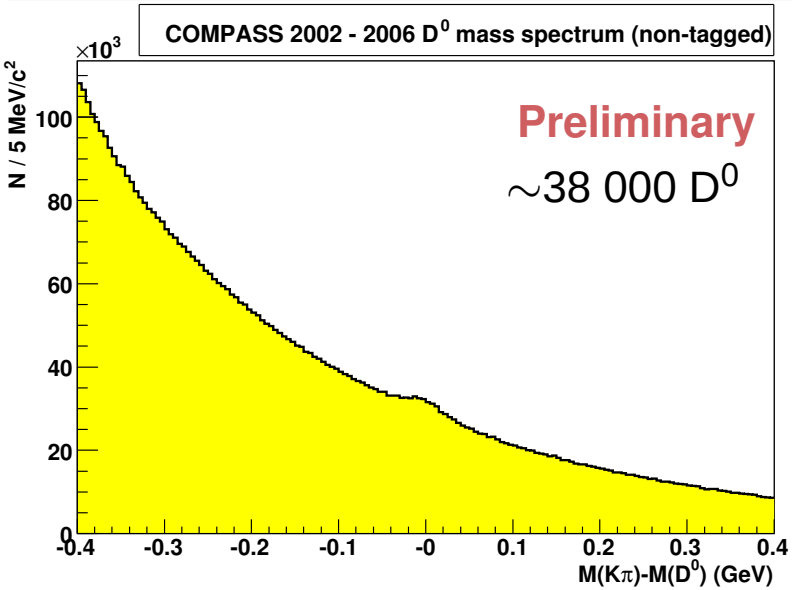
Quark polarisation from COMPASS data only (@ Q^2 = 3 (GeV/c)^2):

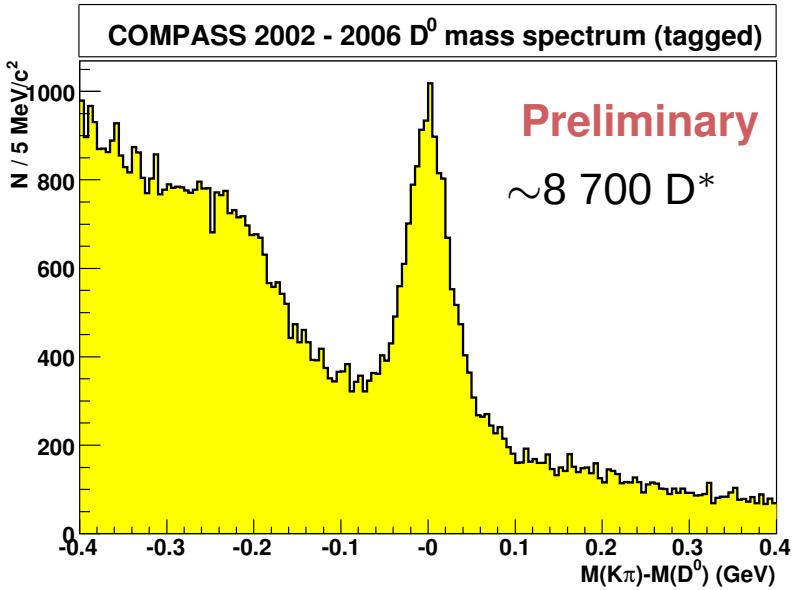
$a_0 = 0.35 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.})$ and gluon polarisation: $|\Delta G| \approx 0.2 - 0.3$

Direct Δg measurements; open charm production



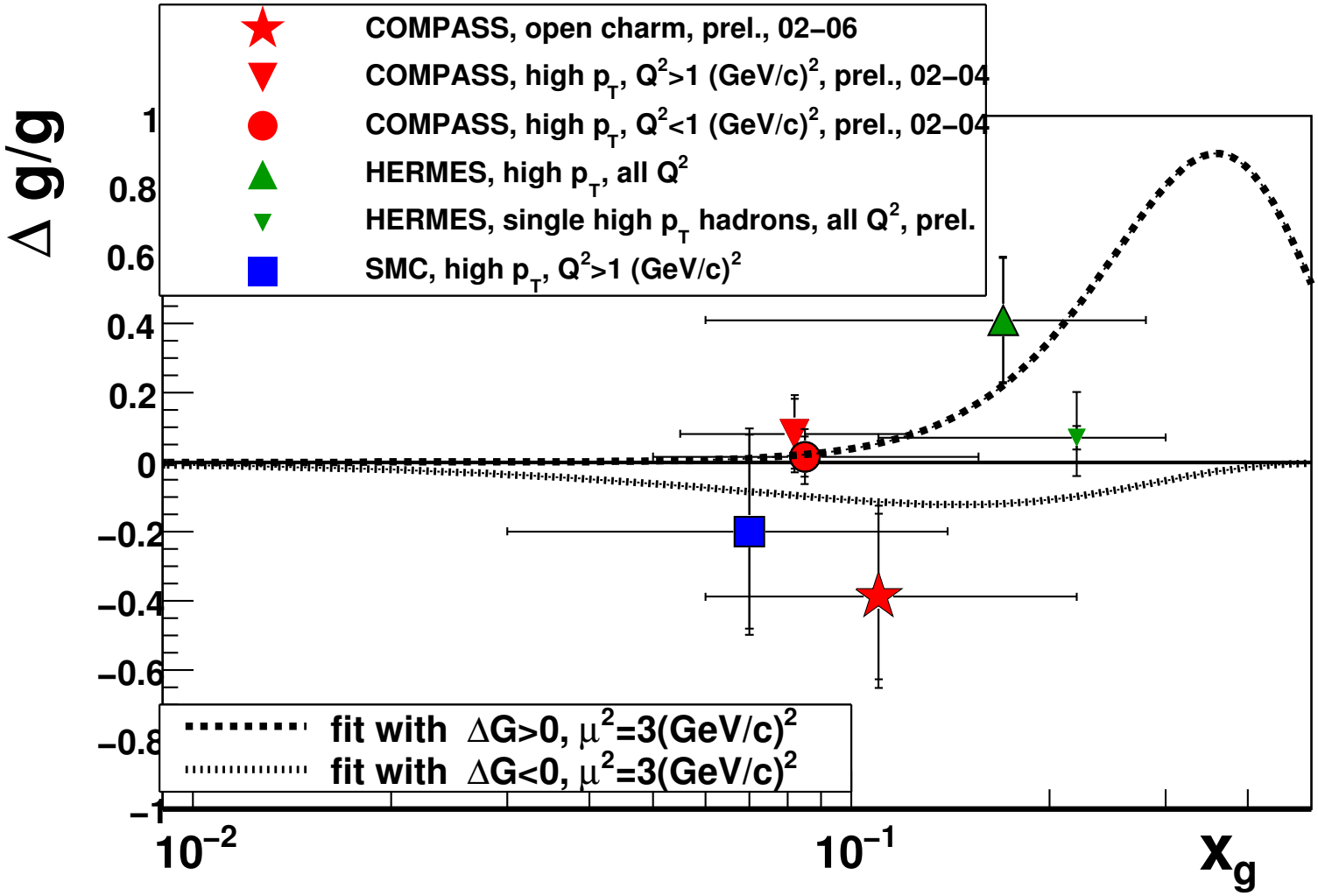
$$D^0 \to K + \pi, \qquad D^* \to D^0 + \pi_s \to K + \pi + \pi_s$$





- Choose $D^0 \to K\pi$ (BR$\sim$4%); pions and kaons identified by RICH.
- Combinatorial background significantly reduced for the $D^* \to D^0 + \pi_s \to K + \pi + \pi_s$.
- Charm in the nucleon neglected.
- A weighting method used to optimise the $\Delta g(x)$ extraction
- Recently added: $D^0 \to K\pi(\pi^0)$, D^* decays with K below RICH threshold of 9 GeV

Summary of the gluon polarisation measurements



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

Outline

Nucleon spin decomposition

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

Are we approaching the solution of the “proton spin puzzle”?

- Restoration of $\Delta\Sigma$=0.6 via the axial anomaly improbable.

COMPASS @ 3 GeV^2: $a_0 = 0.35 \pm 0.03 \pm 0.05$
As a consequence of the “axial anomaly” 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.

- Global, consistent NLO analysis of ΔG needed.
- Independent measurement of L necessary ($\Longrightarrow$ DVCS, lattice QCD?).
- All candidates are contributing about equally to the nucleon spin?

Outline

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)

Transversity measured *e.g. via* the Collins 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:

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

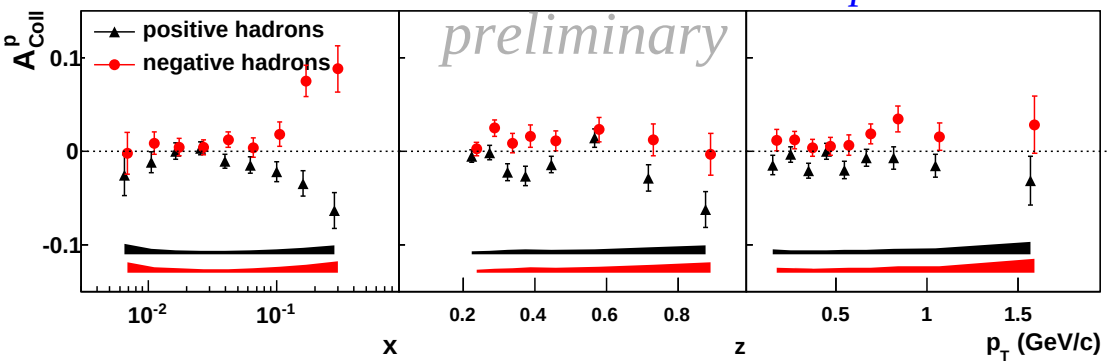
But transverse fragmentation functions $\Delta_T^0 D_q^h$ needed to extract $\Delta_T q(x)$ from the Collins assymmetry! Recently those FF measured by BELLE.

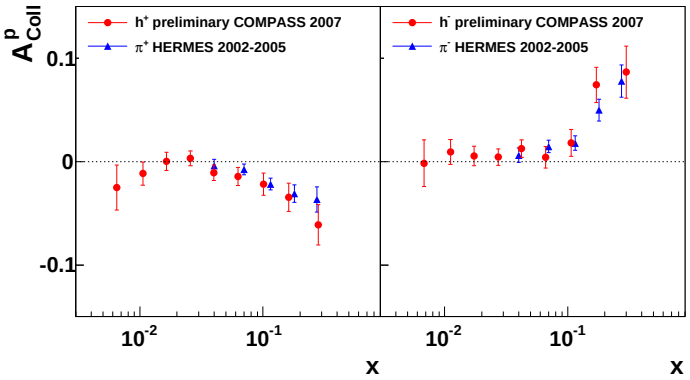
Properties of the Sivers process: it is related to L_q in the proton. Fundamental !

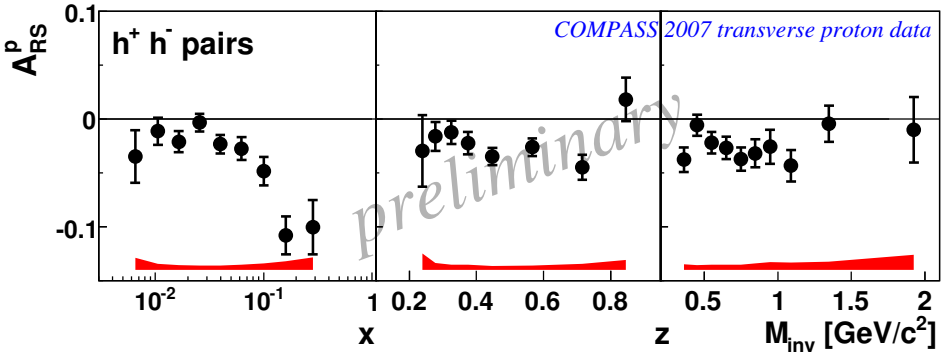
Results for the transverse asymmetries

NEW data for the proton target; full 2007 statistics

COMPASS 2007 proton data







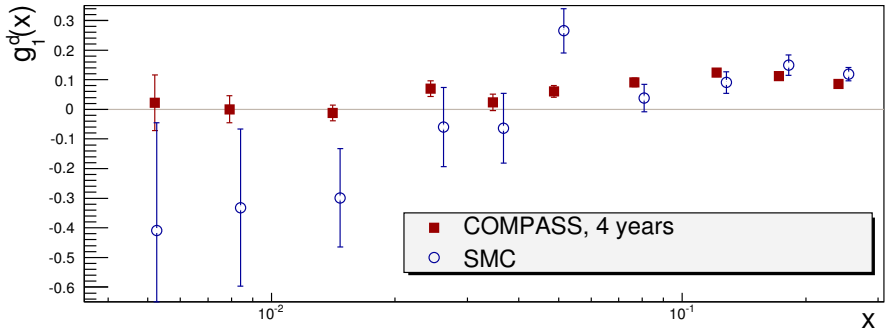
- Collins 1–h asymmetries for proton large at $x \gtrsim 0.1$, consistent with HERMES
- Sivers 1–h asymmetries for proton compatible with 0, contrary to HERMES
- 2–h asymmetry for proton large in the valence region; HERMES sees less.

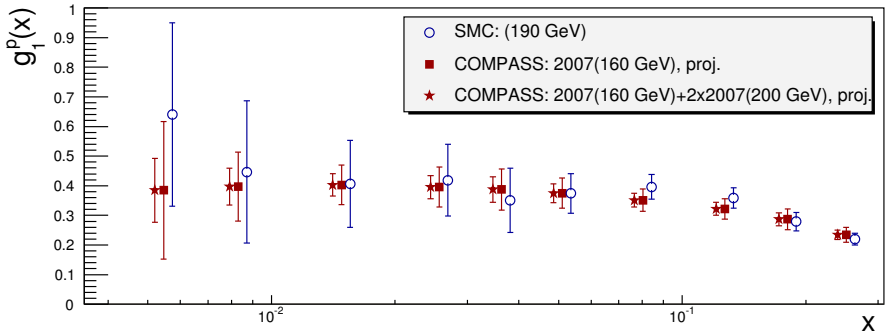
- COMPASS deuteron data: both Collins and Sivers asymmetries very small.
  These data + Hermes + Belle: $\Longrightarrow \Delta_T u + \Delta_T d \sim 0$
- First $\Delta_T q$ global analyses performed.

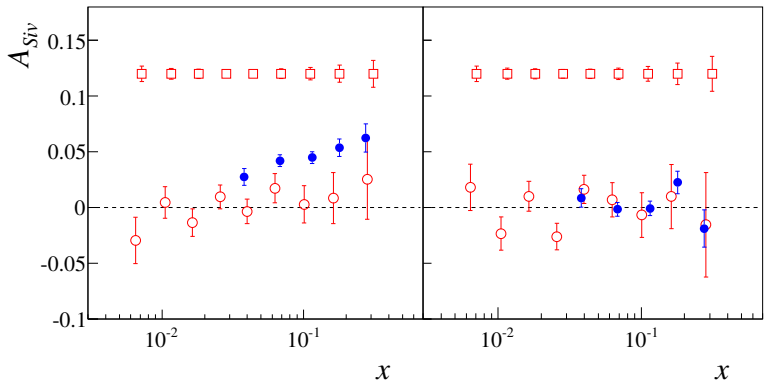
Outline

Plans for the 2010–2011

Addendum 2 to the COMPASS proposal, (CERN-SPSC-2009-025), not accepted yet, for 1+1 year μ run on protons, $\perp$ and $||$ polarised.







COMPASS data
(+ and – hadrons)
on protons

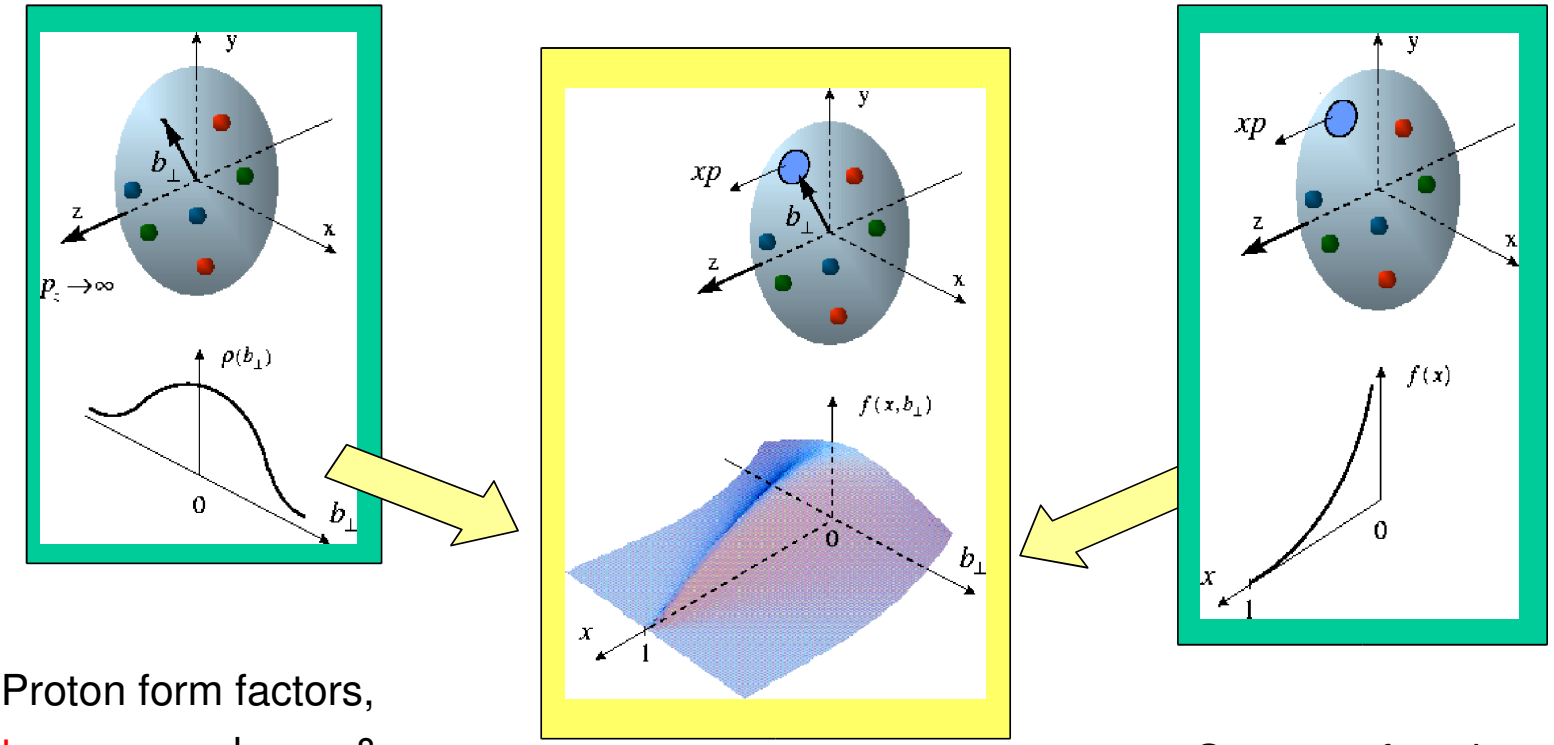
$\Longleftarrow$ projected precision

(blue points - HERMES)

Outline

3D picturing of the proton *via* GPD

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Slide from V.D. Volker, LANL 2007

Access GPD through the DVCS (DVMP) mechanism

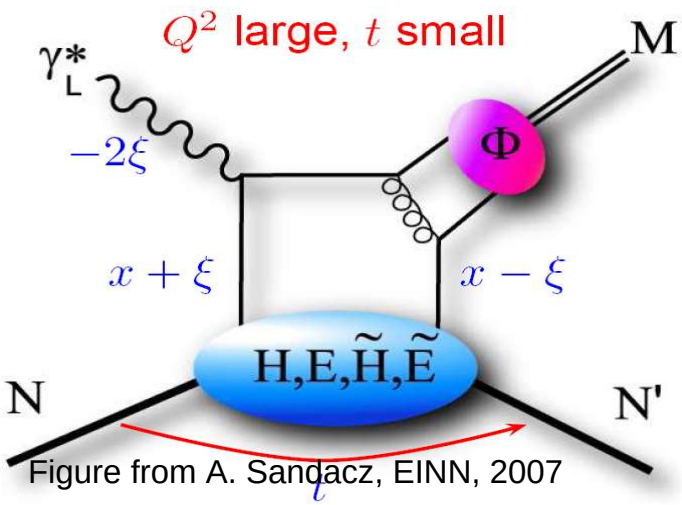
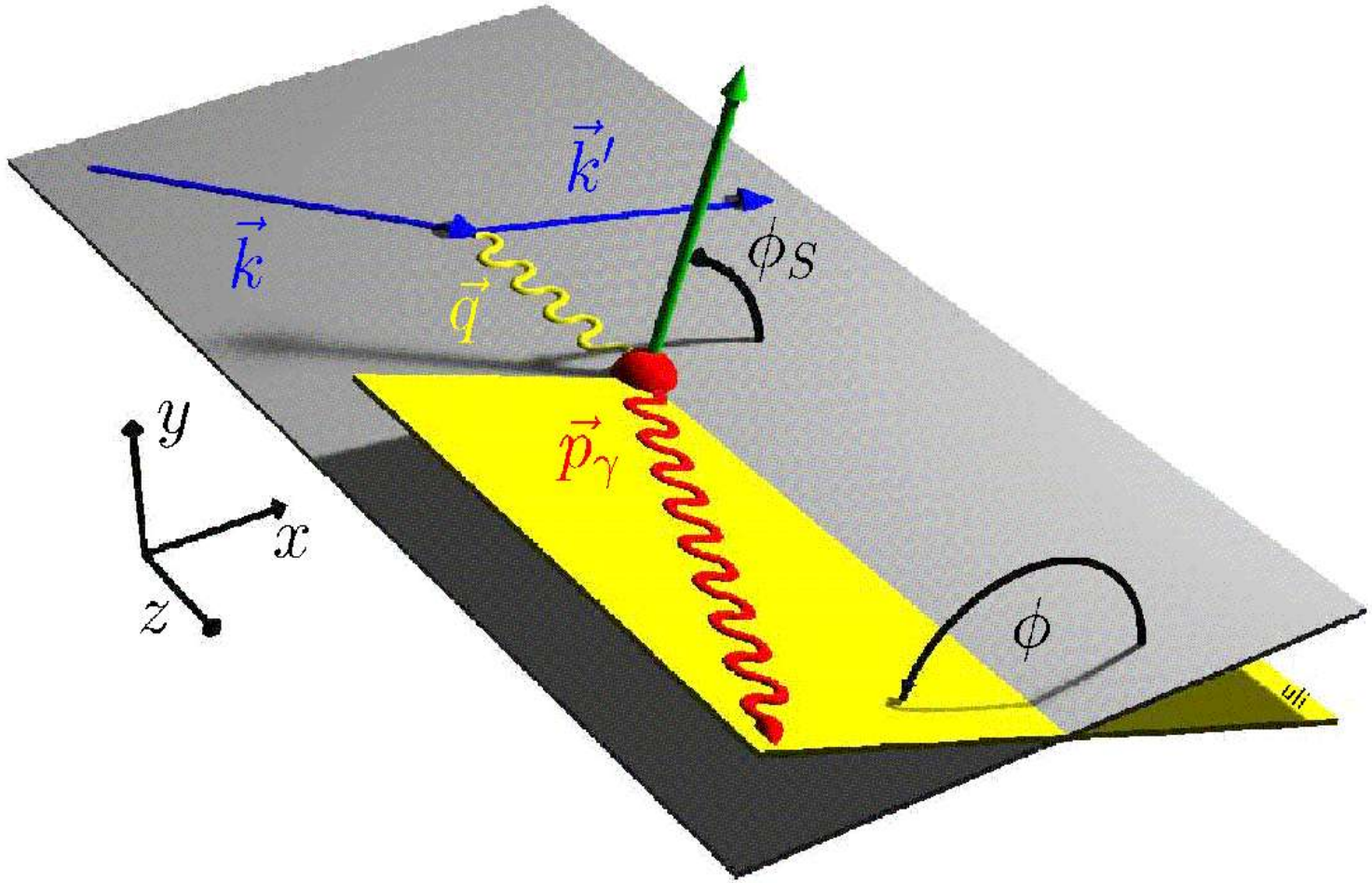


Figure from A. Sandacz, EINN, 2007

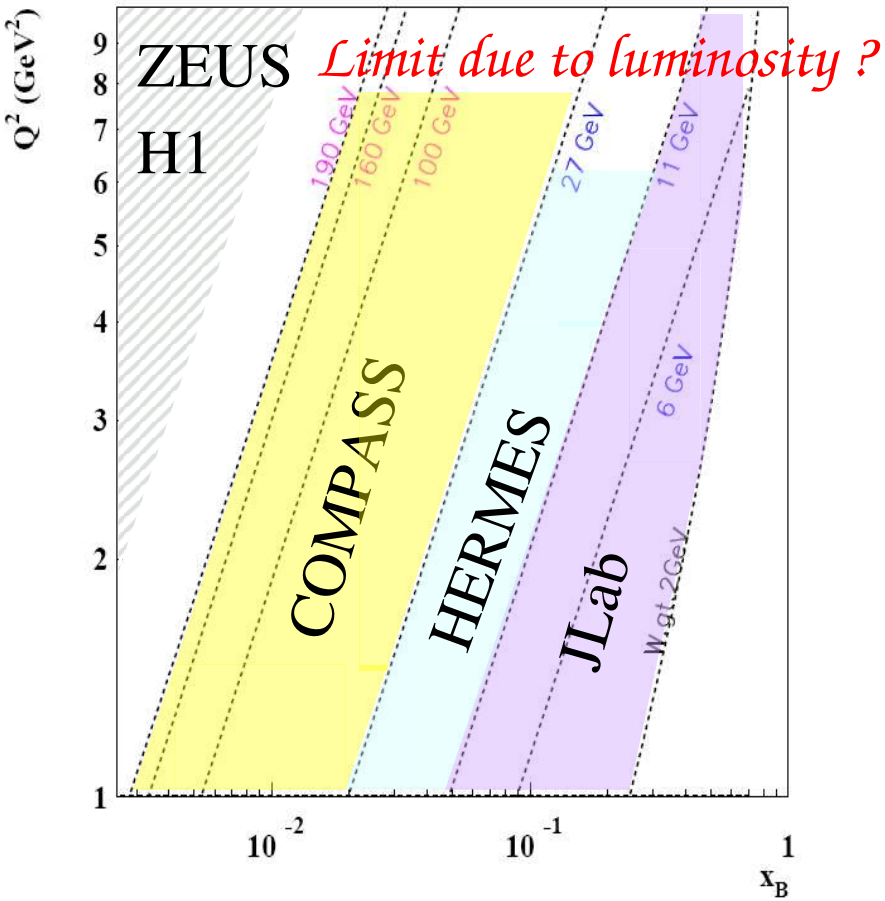
- Four GDPs ($H, E, \widetilde{H}, \widetilde{E}$) for each flavour and for gluons
- Factorisation proven for σ_L only
- All depend on 3 variables: x, ξ, t; DIS @ $\xi = t = 0$
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions

- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors resp.
- Important: $J^q_z = \frac{1}{2}\int dx\, x\left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right] = \frac{1}{2}\Delta\Sigma + L^q_z$ (X. Ji)

DVCS (μ p $\rightarrow$ μ' p γ) kinematics

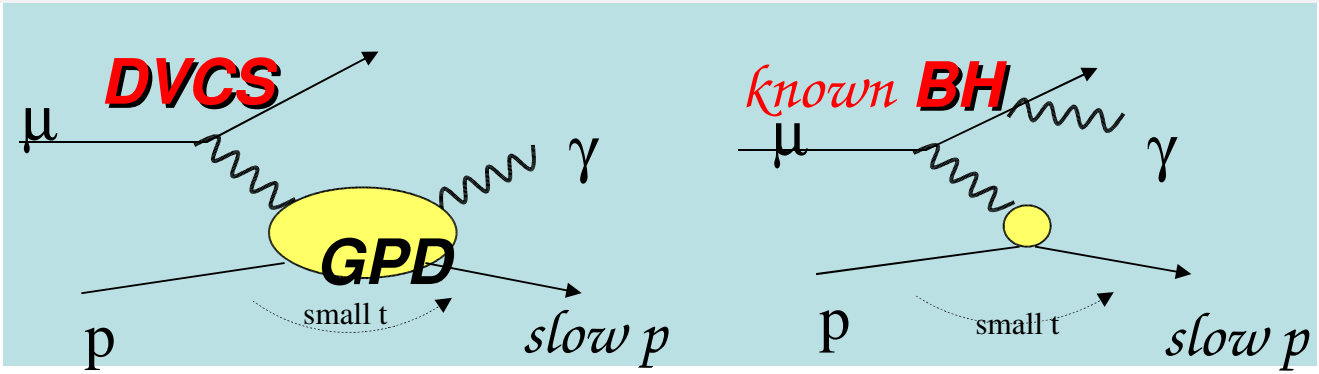


COMPASS DVCS programme



- $\mu^{\pm}$ beams available with opposite polarisations
- Energies: 100/190 GeV
- LH2 target, 2.5 m long $L = 10^{32}$ cm^{-2} s^{-1}
- Lumi limits Q^2 to ~ 8 (GeV/c)^2
- ENC@FAIR, E_e=3 GeV, E_p=15 GeV is equivalent to E_μ=100 GeV

DVCS and background



$$\mathrm{d}\sigma(\mu \mathrm{p} \to \mu \mathrm{p} \gamma) \sim |T_{DVCS}|^2 + |T_{BH}|^2 + \text{interference}$$

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{BH} + \mathrm{d}\sigma^{DVCS}_{unpol} + P_\mu \mathrm{d}\sigma^{DVCS}_{pol} + e_\mu a^{BH} Re T^{DVCS} + e_\mu P_\mu a^{BH} Im T^{DVCS}$$

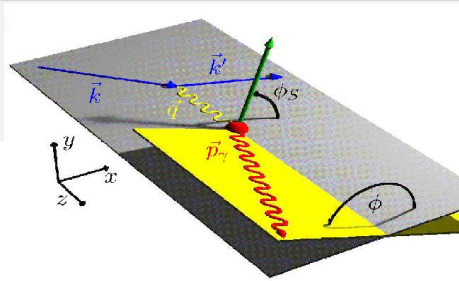
Observables:

$$D_{U,CS} \equiv \mathrm{d}\sigma(\mu^{+\downarrow}) - \mathrm{d}\sigma(\mu^{-\uparrow}) \quad \Longrightarrow \quad Re(F_1 H)$$

$$S_{U,CS} \equiv \mathrm{d}\sigma(\mu^{+\downarrow}) + \mathrm{d}\sigma(\mu^{-\uparrow}) \quad \Longrightarrow \quad Im(F_1 H)$$

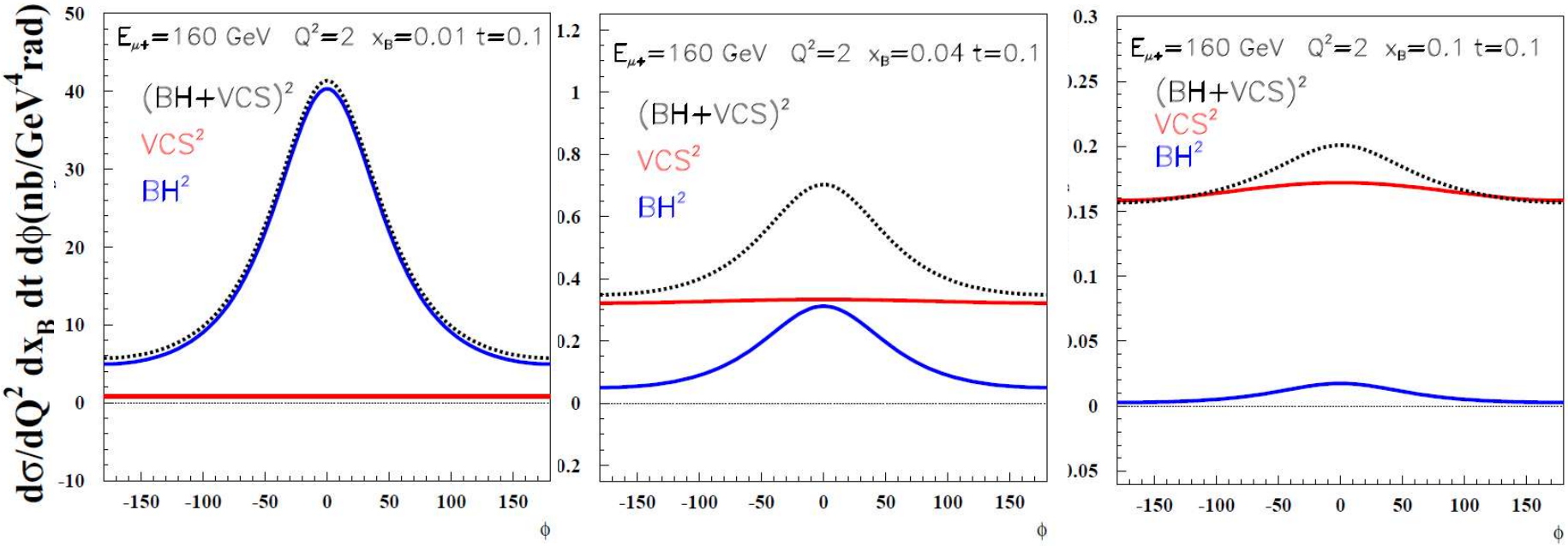
$$\mathrm{d}\sigma(\phi, \phi_s) - \mathrm{d}\sigma(\phi, \phi_s + \pi) \quad \Longrightarrow \quad Im(F_2 H - F_1 E)$$

DVCS and background, ...c.d.



At E=160 GeV, Q^2=2 GeV^2 $|t|$=0.1 GeV^2

x=0.01 x=0.04 x=0.1



BH dominates

(reference)

BH and DVCS at the same level

DVCS boosted by interference

Re T^{DVCS} or Im T^{DVCS}

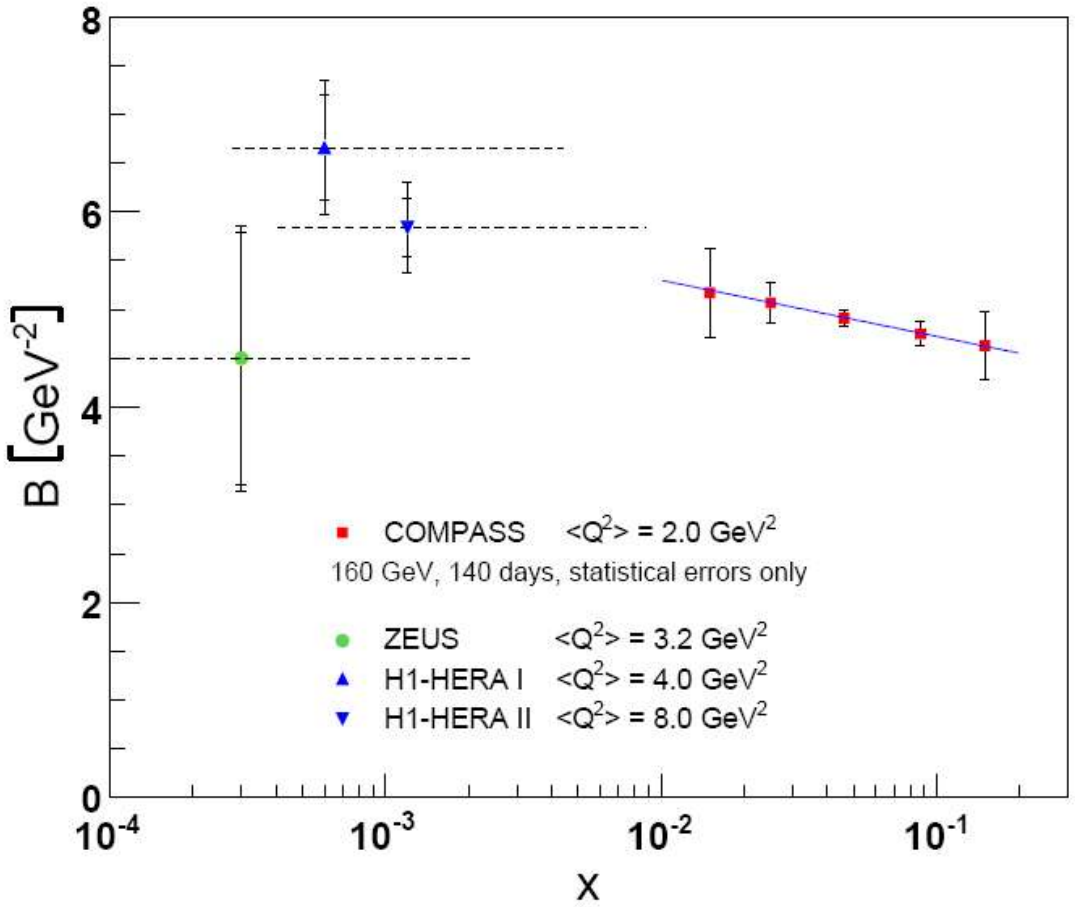
DVCS dominates

study of $d\sigma^{DVCS}/dt$

(not possible at JLab)

Transverse imaging of the nucleon

LOI CERN – SPSC – 2009-003



- $S_{U,CS}$ integrated over ϕ, BH subtr.
  $\Longrightarrow d\sigma^{DVCS}/dt \sim \exp(-B|t|)$
- $B(x) = b_0 + 2\alpha' \ln(x_0/x)$
- α' depends on component (models)
- For flavour f:
  $B^f(x) \sim 1/2\langle(b^f_\perp)^2\rangle(x)$

GPD at COMPASS (proposal); two phases

PHASE 1

- In $\sim$ 2012.
- To constrain H and to get $\mathrm{d}\sigma/\mathrm{d}t \longrightarrow$ transverse imaging of the nucleon.
- Measured: $D_{U,CS}$ and $S_{U,CS}$; $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beams + unpolarised, long LH_2 ($\equiv$ proton) target.
- To be designed and built: $\sim$ 2.5 m LH target and $\sim$ 4 m Recoil Proton Detector.

PHASE 2

- In $\sim$ 2014.
- To constrain E.
- Measured: $\mathrm{d}\sigma(\phi,\phi_s) - \mathrm{d}\sigma(\phi,\phi_s+\pi)$; μ^+ beam and transversely polarised NH_3 ($\equiv$ proton) target.
- To be designed and built: polarised transverse target, special RPD.

Outline

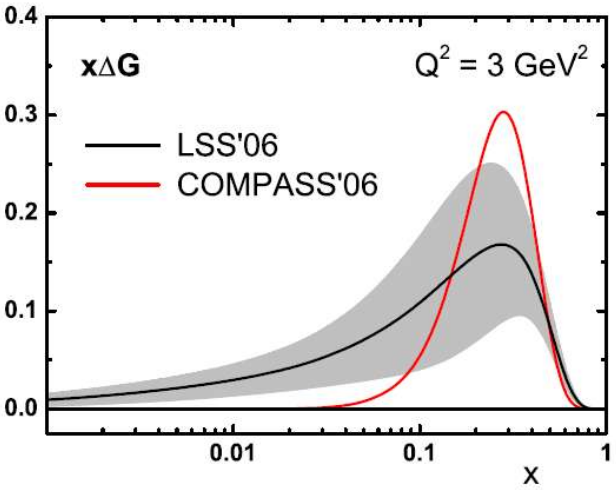
Outlook

COMPASS takes data since 2002 and is the only large fixed-target experiment @ CERN now. Energy larger than HERMES and physics processes different than that of RHICspin.

- Muon programme on proton and deuteron:
  - results of spin dependent structure function $g_1(x, Q^2)$;
  - polarisation distributions of quarks (valence, sea),Δq, and gluons, Δg;
  - measurements of transversity, $\Delta_T q$, and of the Sivers process;
  - several other measurements: exclusive ρ production, Λ polarisation, azimuthal asymmetries;
- Hadron programme:
  - data taking in 2008 with 190 GeV π and in 2009 with 190 GeV π, K and p on liquid H_2 target;
  - Search for exotic mesons and glueballs, diffractive dissociation and central production.
- Future:
  - Proposal addendum 2 for the μ run on the $\perp$ and $||$ polarised protons (2010–2011);
  - Letter-of-Intent for the DVCS and Drell-Yan running $\gtrsim$ 2012.

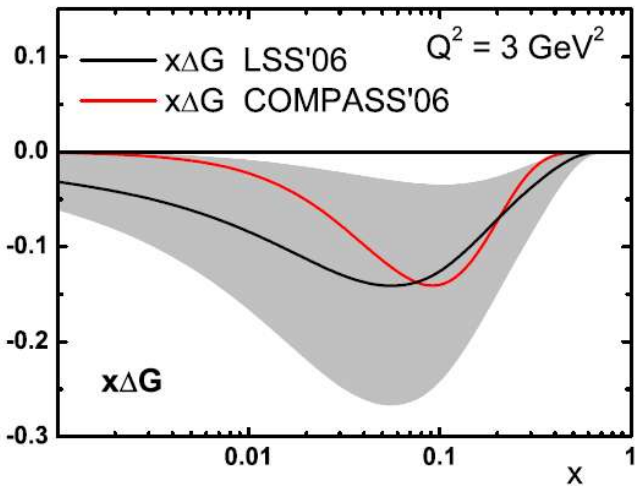
SPARE

LSS06 QCD analysis including COMPASS g_1^d



$\Delta G > 0$

$\Delta G < 0$



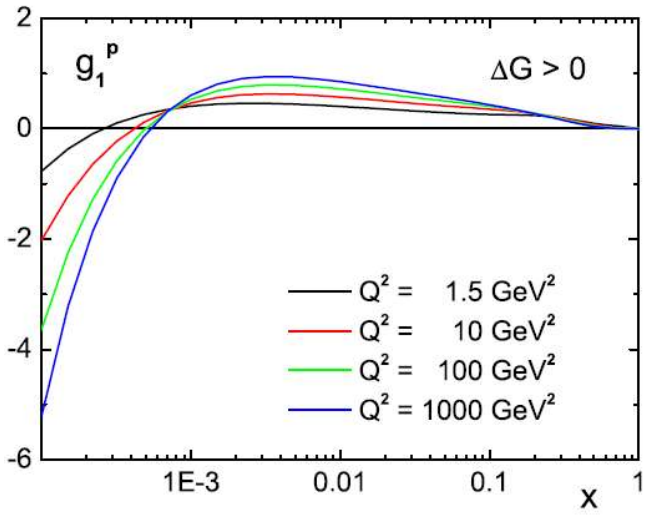
Can we ever tell the sign of ΔG ? ...

Figures from E. Leader, DIS2008

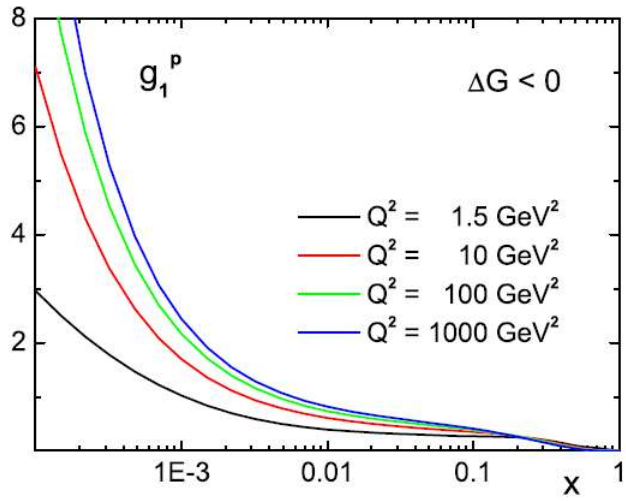
LSS06 QCD analysis including COMPASS g_1^d...cont'd

... except at an ep collider ?

LSS06, $\Delta G > 0$



LSS06, $\Delta G < 0$

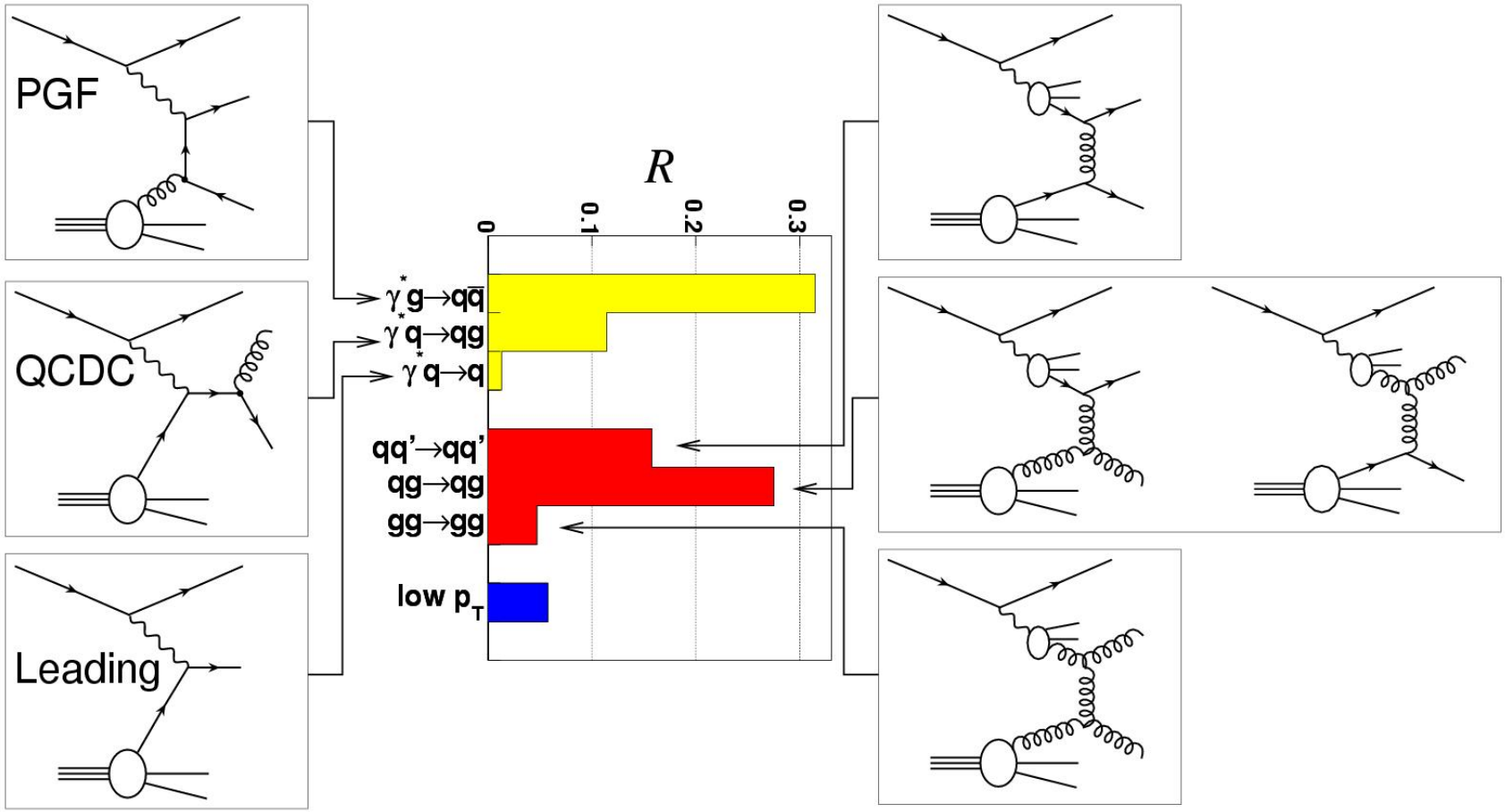


Figures from E. Leader, DIS2008

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

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

Resolved photons



Link to DIS and elastic form factors

DIS at $\xi = t = 0$

$H^q(x,0,0) = q(x)$

$\tilde{H}^q(x,0,0) = \Delta q(x)$

Form factors (sum rules)

$\int_{-1}^{1} dx \sum_q [H^q(x,\xi,t)] = F_1(t)$ Dirac f.f.

$\int_{-1}^{1} dx \sum_q [E^q(x,\xi,t)] = F_2(t)$ Pauli f.f.

$\int_{-1}^{1} dx \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$

$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$

Angular Momentum Sum Rule

$$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Slide from V.D. Volker, LANL 2007