Spin structure of the nucleon in COMPASS

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Outline

- The nucleon spin puzzle
- Longitudinally polarized DIS
  - A_1, g_1^d and the Bjorken sum rule
  - Flavour separation
  - Gluon polarization
- Transversely polarized SIDIS
- TMD PDFs from polarized Drell-Yan
- GPDs from DVCS
- Conclusions

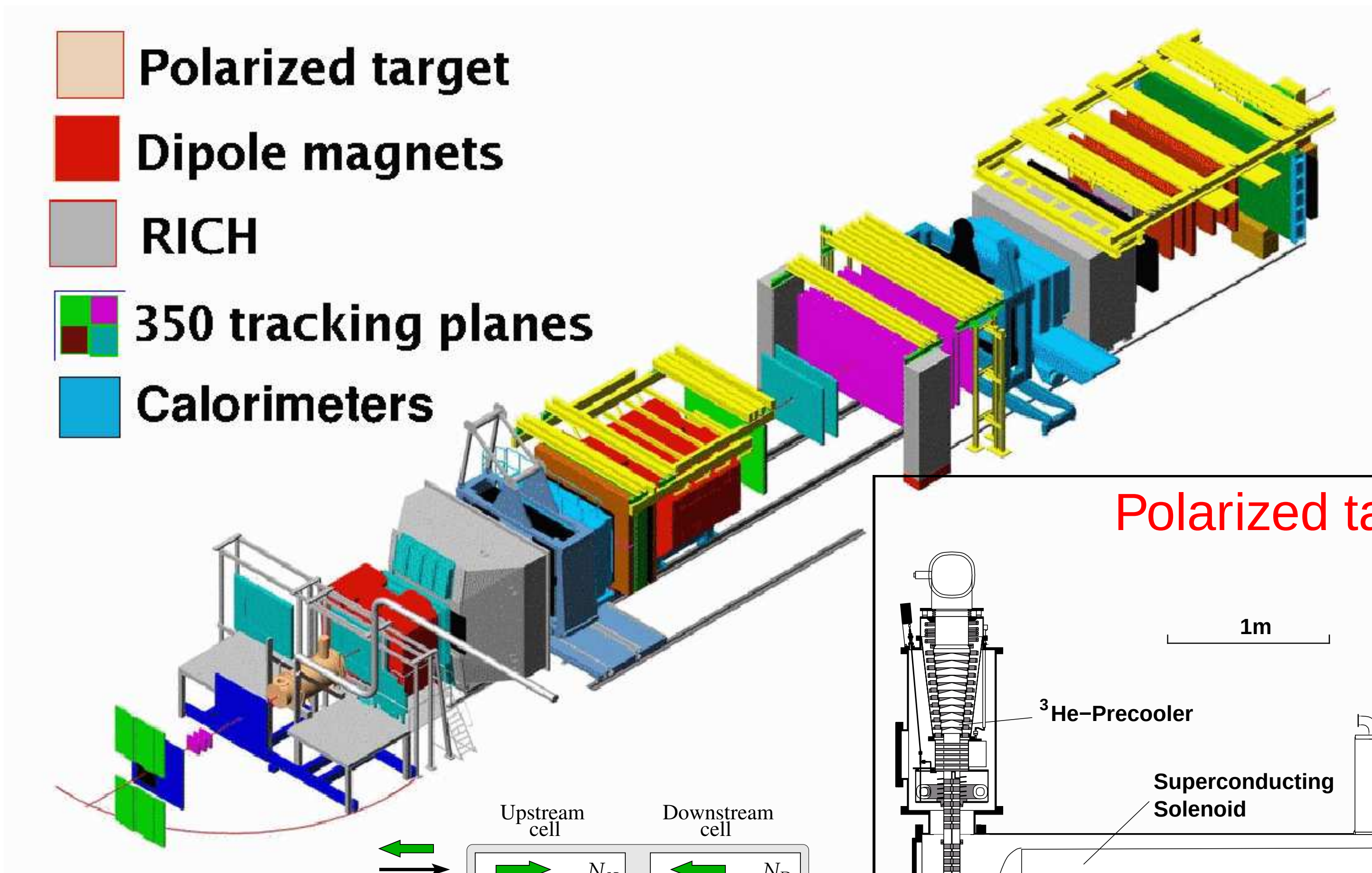
The COMPASS Experiment at CERN

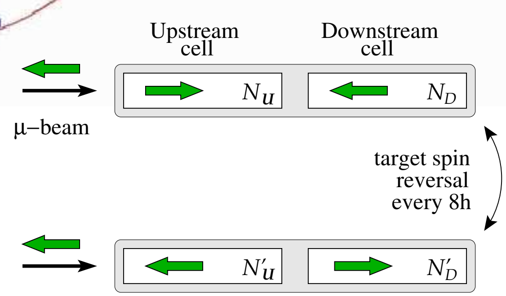
- Studies of the nucleon spin structure (2002 – 2007, 2010 – 2011)
  - with polarized muon beam (μ^+ at 160 GeV/c, ≈80% polarized) and polarized targets (^{6}LiD and NH_3)

- Studies of hadron spectroscopy (2008 – 2009)
  - with h^- beam at 190 GeV/c (95% π^-, 4% K^-, 1% $\bar{p}$) and unpolarized targets (liquid H_2, Ni, Cu, Pb, W)
  - with h^+ beam at 190 GeV/c (75% p, 24% π^+, 1% K^+) and unpolarized liquid H_2 target

- Future studies on the nucleon structure (2013 – 2015)
  - GPDs from DVCS: with polarized muon beam ($\mu^\pm$ at 100-190 GeV/c and long unpolarized liquid H_2 (1st phase) or transversely polarized NH_3 target (2nd phase)
  - TMD PDFs from polarized Drell-Yan: with hadron beam (95% π^-) and a polarized NH_3 target

COMPASS spectrometer and target

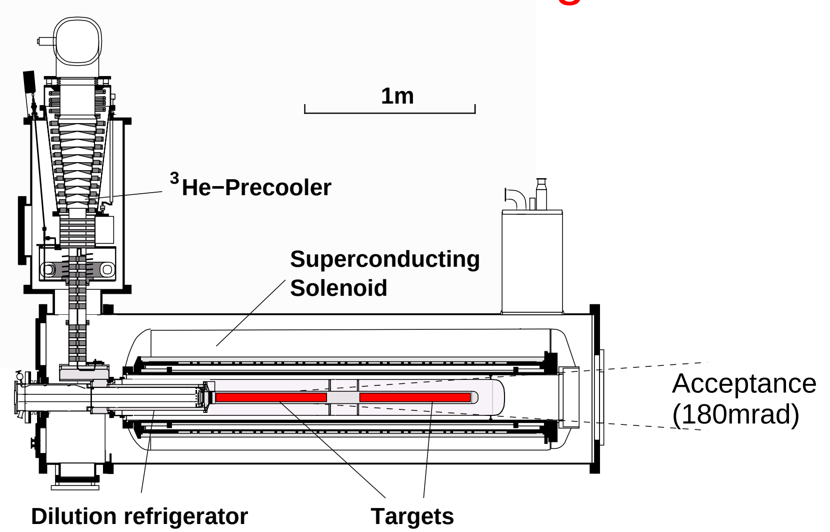




μ^+ beam @160 GeV

-80% polarization

Polarized target

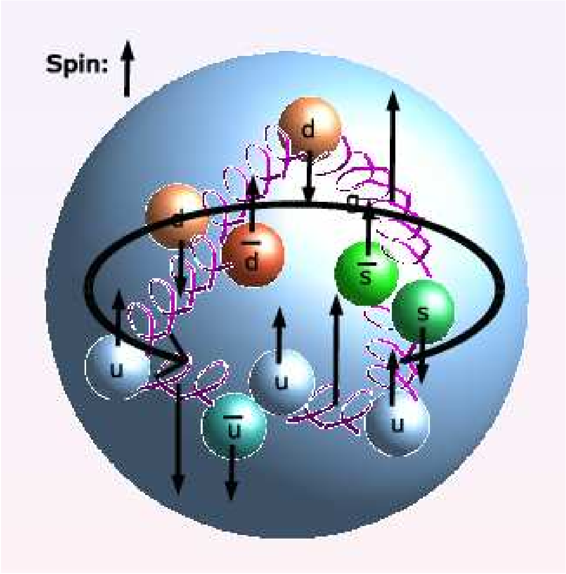


^6LiD or NH_3 targets

The nucleon spin puzzle

Nucleon spin: $\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_Z$

quarks spin — gluons spin — orbital ang. mom.



- In the quark-parton model, including relativistic corrections, expect $\Delta\Sigma \approx 0.6$
- 1988: EMC measured the quarks contribution to the spin of the nucleon to be very small !
- Present world data:

$$\Delta\Sigma = 0.30 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{evol})$$

$\mapsto$ COMPASS, PLB 647 (2007) 8-17

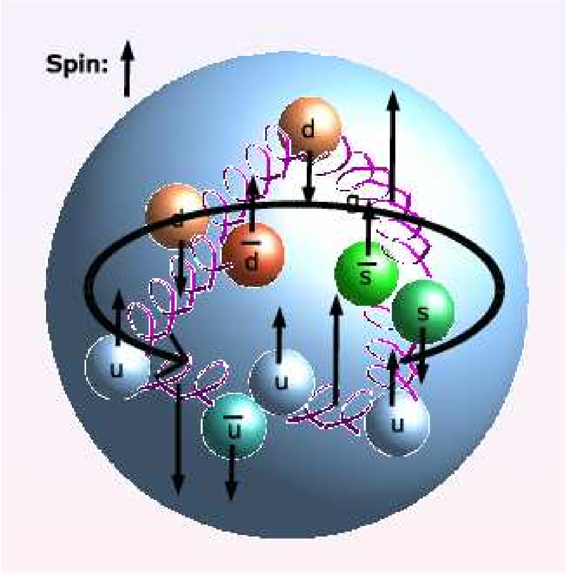
The nucleon spin puzzle

Nucleon spin: $\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_Z$

quarks spin — small

gluons spin — poorly known

orbital ang. mom. — unknown



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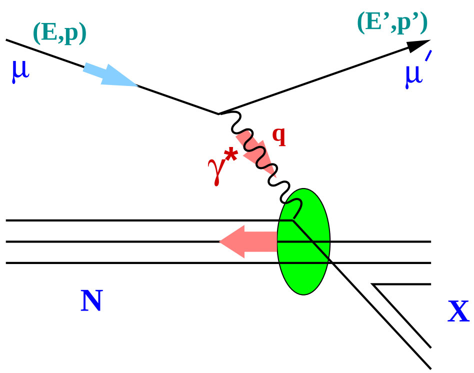
$\mapsto$ COMPASS, PLB 647 (2007) 8-17

Spin asymmetries in DIS

For its deep inelastic scattering (DIS) programme, COMPASS uses beam and target polarized to measures double spin asymmetries.



- $Q^2 = -q^2$
- $\nu = E - E'$
- $x = \frac{Q^2}{2M\nu}$
- $z = \frac{E_h}{\nu}$

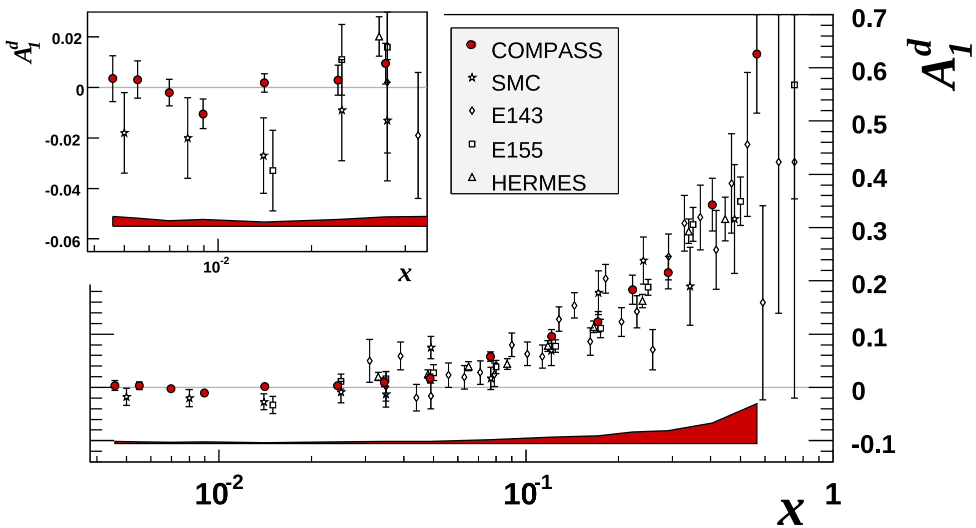
The μ-deuteron/proton asymmetry is measured from the difference between cross-sections from 2 oppositely polarized target cells:

$$A^{\mu N} = \frac{1}{f P_T P_B} \left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}} \right)$$

This measured asymmetry relates to the longitudinal and transverse γ^*-deuteron/proton asymmetries: $\frac{A^{\mu N}}{D} \approx A_1$

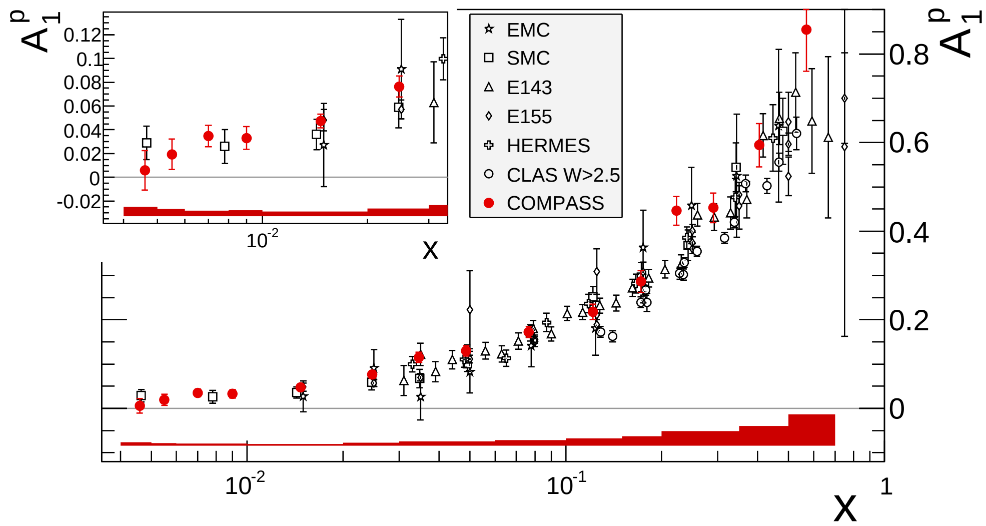
Longitudinal polarization: inclusive asymmetries

deuteron (2002-2006 data)



COMPASS, PLB 647 (2007) 330-340.

proton (2007 data)



COMPASS, PLB 690 (2010) 466-472.

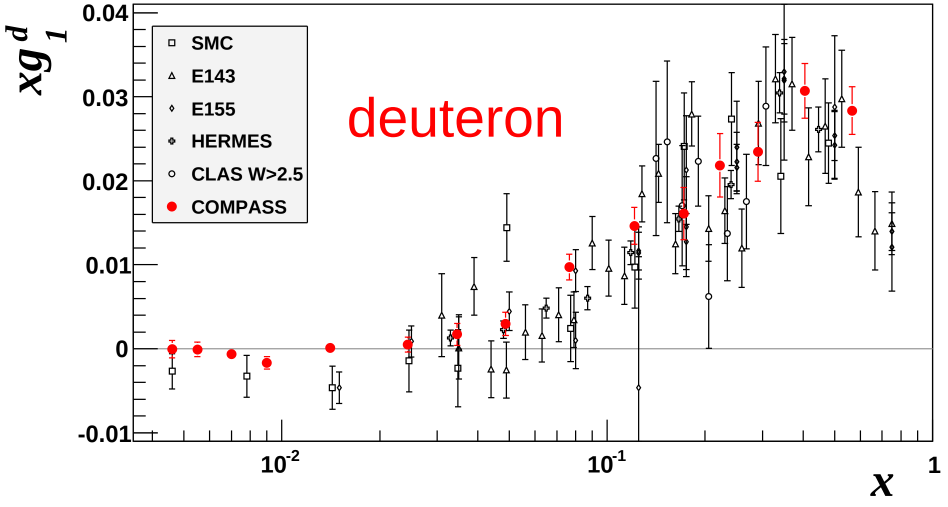
- Significant improvement of precision in the low x region.
- Large asymmetry observed at high x, in agreement with other experiments.

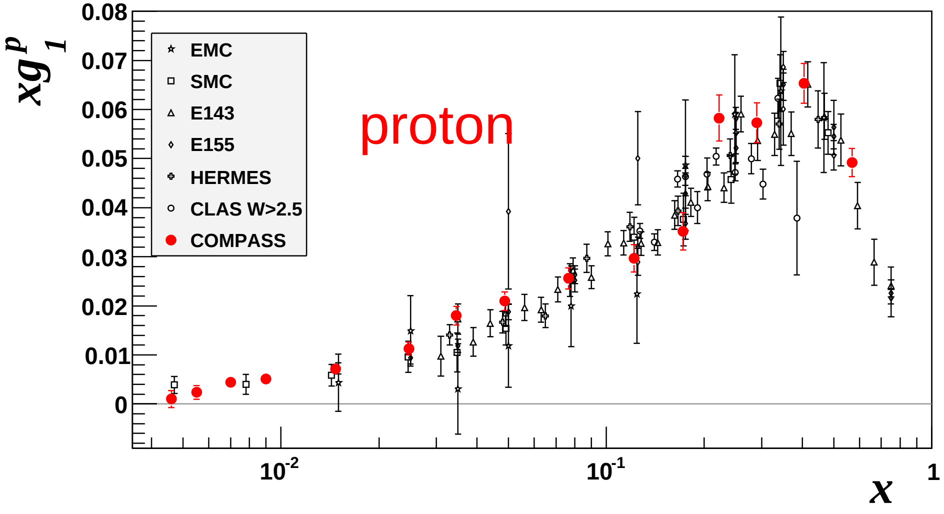
Longitudinal spin-dependent g_1 PDF

g_1 is obtained from the asymmetry A_1, for proton or deuteron:

$$g_1 = A_1 \frac{F_2}{2x(1+R)}$$

$F_2 \rightarrow$ SMC parameterization; $R = \sigma^L/\sigma^T \rightarrow$ SLAC parameterization





From the 1st moment of $g_1^d(x)$:

$\Delta\Sigma = a_0 = 0.33 \pm 0.03(stat) \pm 0.05(syst)$ at $Q^2 = 3$ (GeV/c)^2

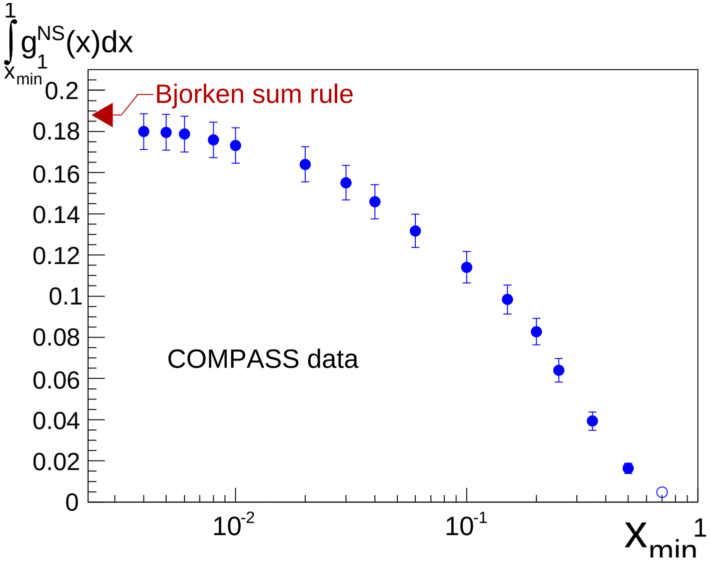
$\Delta s + \Delta\bar{s} = \frac{1}{3}(a_0 - a_8) = -0.08 \pm 0.01 \pm 0.02$ at $Q^2 \rightarrow \infty$

Bjorken sum rule

Combining deuteron and proton data, one can access the non-singlet spin structure function $g_1^{NS} = g_1^p - g_1^n$.

According to the Bjorken sum rule the first moment of g_1^{NS} is proportional to the ratio of axial and vector coupling constants g_A/g_V:

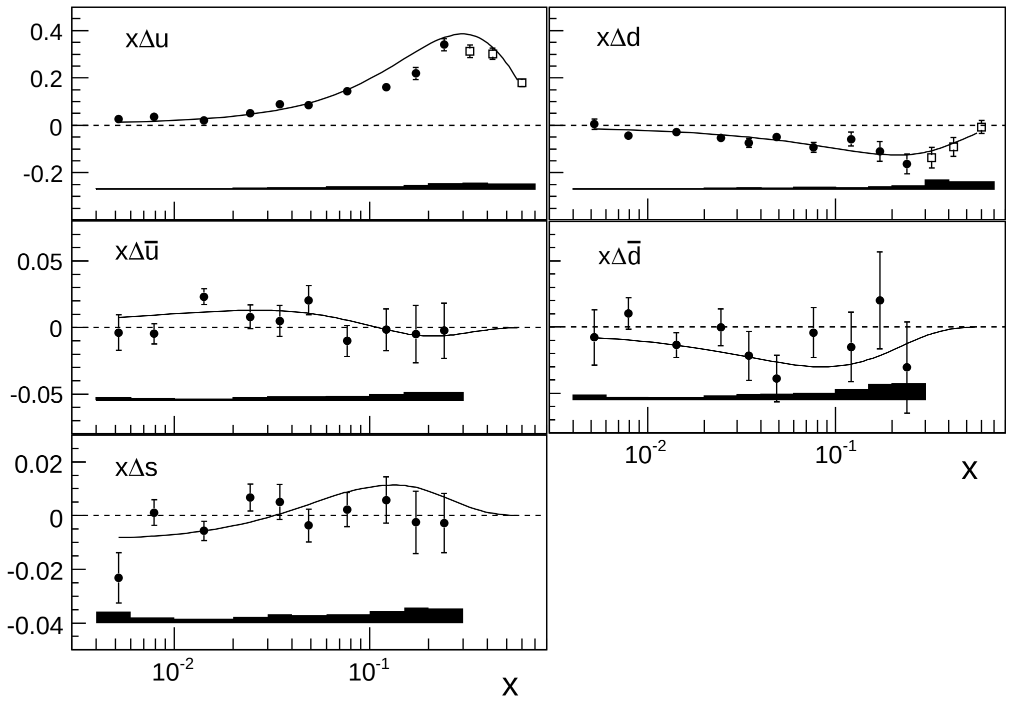
$$\int_{x_{min}}^{1} dx\, g_1^{NS}(x, Q^2) = \frac{1}{6} \left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$



- 92% of the first moment of g_1^{NS} comes from the measured region
- At the lowest accessible x in COMPASS, $\int_{0.004}^{1} dx\, g_1^{NS} = 0.180 \pm 0.009$
- The value expected from the Bjorken sum rule is 0.188, taking $|\frac{g_A}{g_V}|$ from neutron β decay
- Validity of the Bjorken sum rule confirmed with 5% statistical precision.

Flavour separation

From a semi-inclusive DIS analysis, using charged kaons and pions identified in the RICH detector, with both deuteron and proton polarized targets, full quarks flavour decomposition (in LO) can be done:



PLB 693 (2010) 227-235

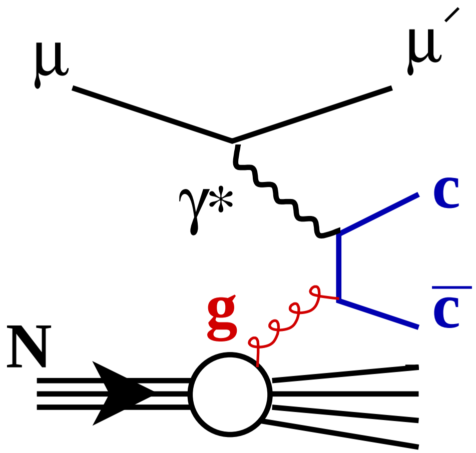
- Using the DSS fragmentation functions (D.Florian, Sassot, Stratmann, Phys.Rev. D75 (2007) 114010)
- The curves are predictions from the DSSV fi t calculated at NLO (D.Florian, Sassot, Stratmann, Vogelsang, Phys.Rev.D 80 (2009) 034030)
- The flavour asymmetry of the sea helicity distributions $\Delta\bar{u} - \Delta\bar{d}$ is slightly positive, compatible with zero.

Gluon polarization

The direct measurement of ΔG is of crucial importance for the understanding of the spin puzzle.

$\hookrightarrow$ Access it via the photon-gluon fusion (PGF) process.

PGF events are selected by analysing:



- Open Charm production
  - ⋆ Very clean: almost no physics background
  - ⋆ Low statistics

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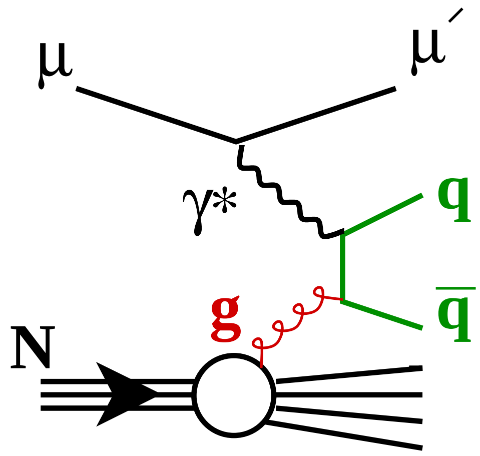


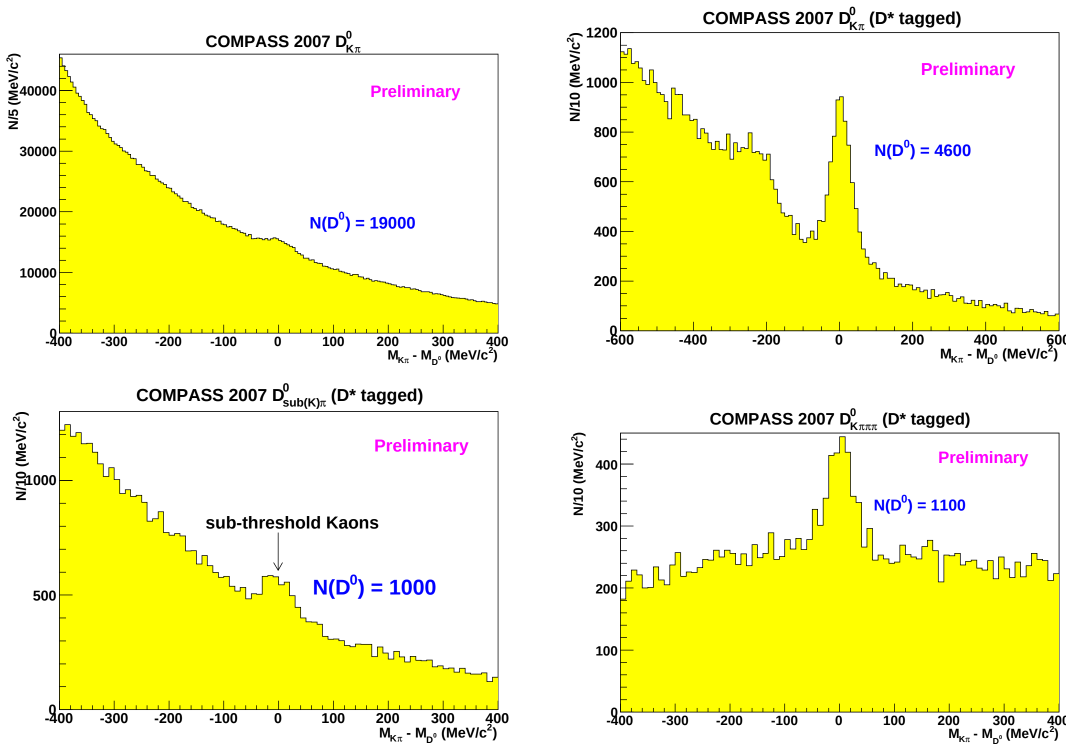
PGF events are selected by analysing:

- Open Charm production
  - ⋆ Very clean: almost no physics background
  - ⋆ Low statistics
- High p_T hadron pairs
  - ⋆ Large statistics available
  - ⋆ Very dependent on Monte-Carlo

ΔG from open-charm

5 channels with D^o production are studied (data 2002-2007):

- $D^o \rightarrow K\pi$ (untagged)
- D^* tagged : $D^o \rightarrow K\pi$, $K\pi\pi^o$, $K\pi\pi\pi$, sub(K)π



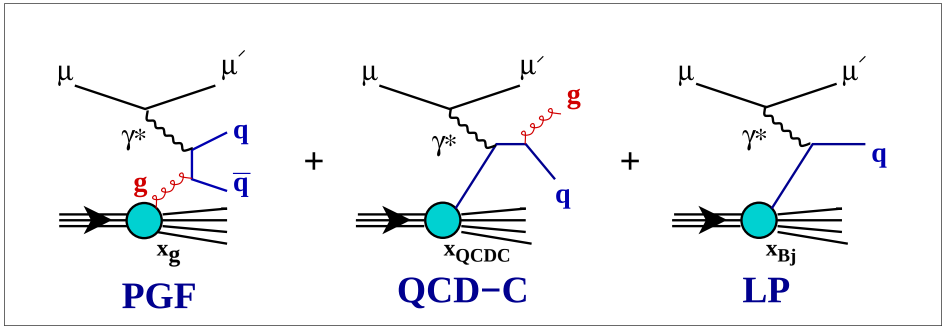
$$A_{raw} = P_t P_b f a_{LL} \frac{S}{S+B} \frac{\Delta G}{G}$$

Weighted events: all factors between A_{raw} and $\Delta G/G$ enter in the weight. The method implies simultaneous extraction of the background asymmetry:

$$A_{bkg} = \frac{1}{P_t P_b f D \frac{B}{S+B}} A_{raw}$$

ΔG *from high* p_T *hadron pairs*

In LO and $Q^2 > 1$ (GeV/c)^2, besides PGF 2 background processes must be considered: leading processes (LP) and QCD-Compton (QCDC). Generically, the higher the hadrons p_T, the larger is the PGF fraction expected.



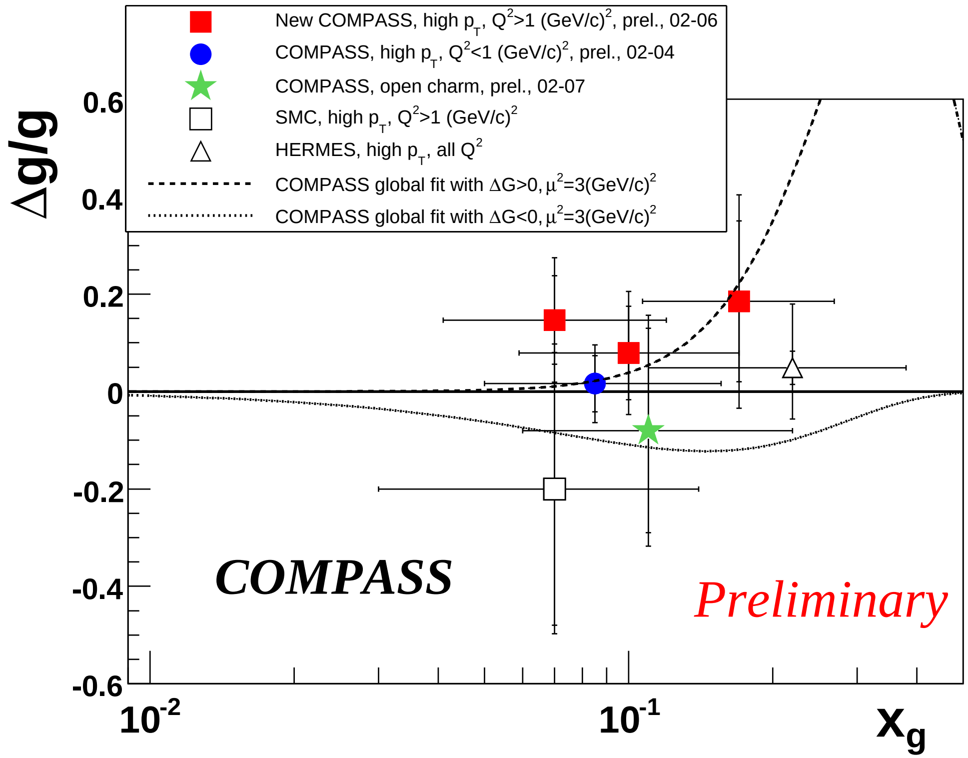
The fractions **R** and the analysing powers **a**$_{LL}$ of each process are calculated from Monte-Carlo. They are parameterized on an event basis by a Neural Network trained on MC.

- Data 2002-2006 were analysed
- Analysis in 3 bins of x_g
- The present analysis requires leading hadron with $p_T > 0.7$ and sub-leading with $p_T > 0.4$ GeV/c, and uses fractions R and a_{LL} to weight the events.

Results on $\Delta G/G$

Open-charm analysis: $\Delta G/G = -0.08 \pm 0.21(stat) \pm 0.03(syst)$ at $\langle x_g \rangle = 0.11$ and $\langle \mu^2 \rangle = 13$ GeV^2.

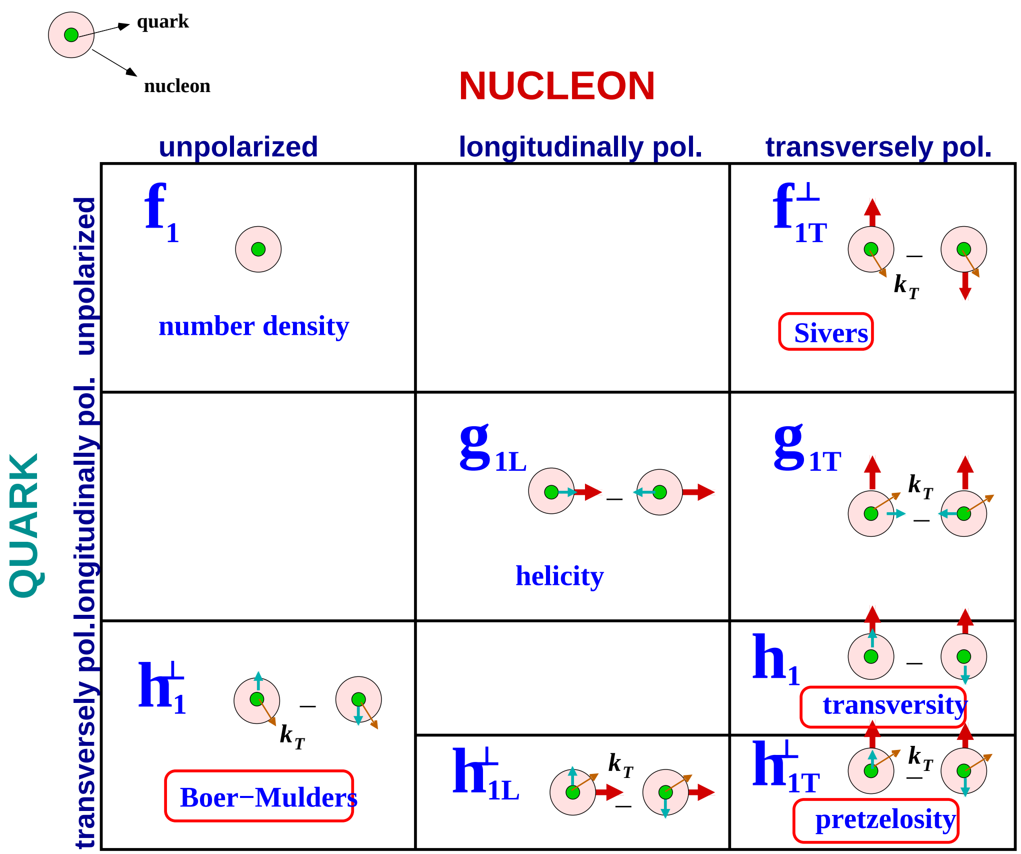
High p_T analysis: $\Delta G/G = 0.125 \pm 0.060(stat) \pm 0.063(syst)$ at $\langle x_g \rangle = 0.094$ and $\langle \mu^2 \rangle = (\langle Q^2 \rangle) = 3.4$ GeV^2.



Transverse momentum dependent PDFs

At leading order, 3 PDFs are needed to describe the structure of the nucleon in the collinear approximation.

But if one takes into account also the quarks intrinsic transverse momentum k_T, 8 PDFs are needed:



Interpreting the PDFs

- Sivers: the $f_{1T}^{\perp}(x, k_T^2)$ function describes the distortion of the probability distribution of a non-polarized quark when inside a transversely polarized nucleon.

- Boer-Mulders: the $h_1^{\perp}(x, k_T^2)$ function describes the correlation between the transverse spin and the transverse momentum of a quark in an unpolarized hadron.

- Transversity: results from the integration over k_T^2 of $h_1(x, k_T^2)$.

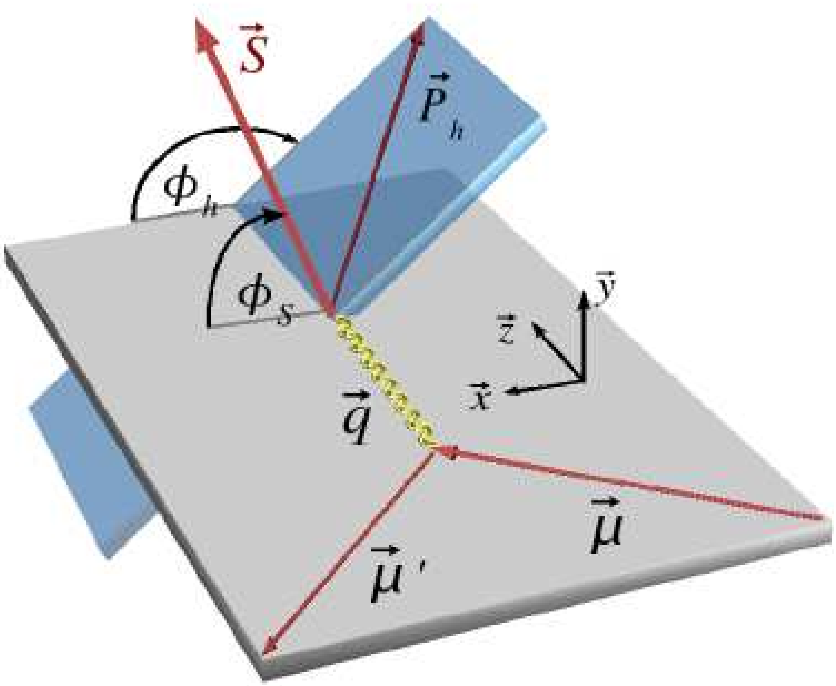
The last 2 are **chiral-odd** – as a consequence, they can only be observed convoluted with another chiral-odd object.

$\hookrightarrow$ in SIDIS, the PDF is convoluted with a fragmentation function.

Transverse Polarization

The transverse momentum dependent (TMD) PDFs of the nucleon carry important information about the nucleon spin dynamics, that can be revealed from SIDIS in a transversely polarized target.

$\Longrightarrow$ 8 azimuthal asymmetries that can be measured at once.



ϕ_h: azimuthal angle of the outgoing hadron momentum

ϕ_S: azimuthal angle of the initial quark spin

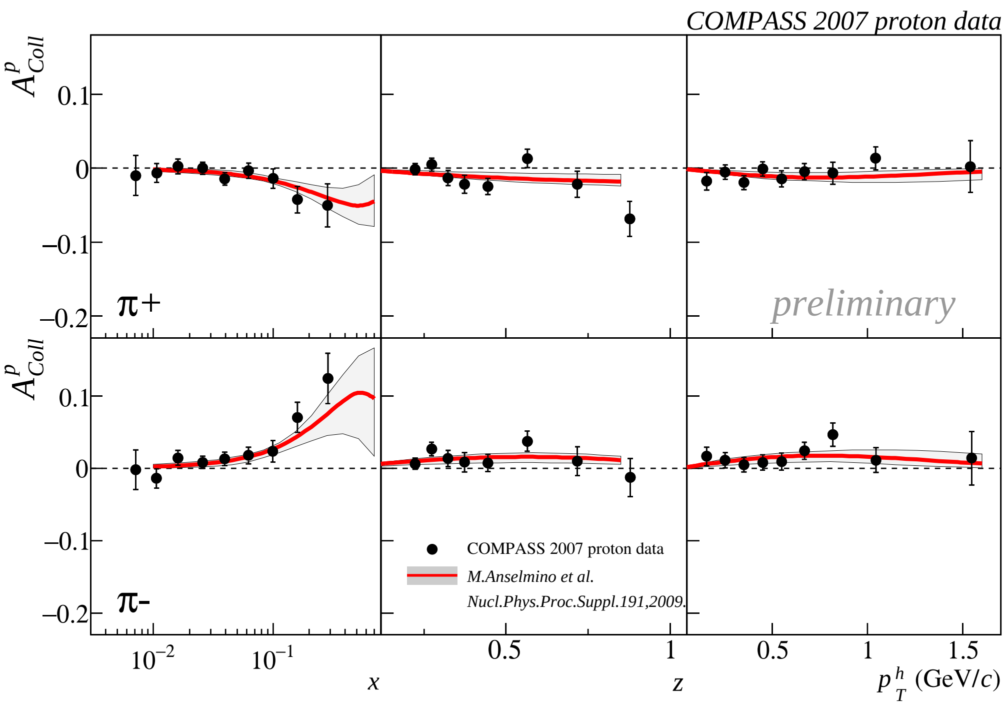
Transversity PDF

$$lN^{\uparrow} \rightarrow l'hX$$

Collins effect: a quark moving "horizontally" and polarized "upwards" emits the leading meson preferentially on the "left" side of the jet (Collins FF).

The Collins asymmetry is proportional to the convolution of the transversity PDF $h_1(x)$ with the Collins FF.

Collins angle: $\phi_C = \phi_h + \phi_S - \pi$

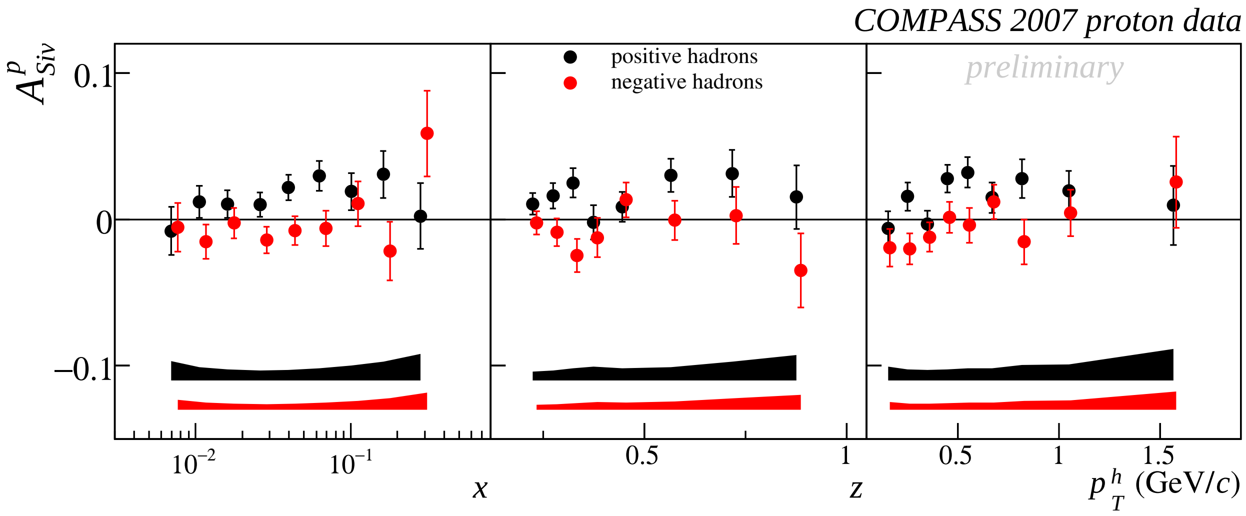


- Identifi ed hadron Collins asymmetries in agreement with theory predictions.
- Agreement with previous measurements from HERMES and BELLE – both transversity and Collins FF are non-zero!
- Same asymmetries measured in COMPASS with deuteron target are zero – in deuteron there is cancellation between u and d quark contributions.

Sivers PDF

Another azimuthal modulation that can be extracted from SIDIS is the Sivers effect, measured to be non-zero by HERMES

Sivers angle: $\phi_{Siv} = \phi_h - \phi_S$

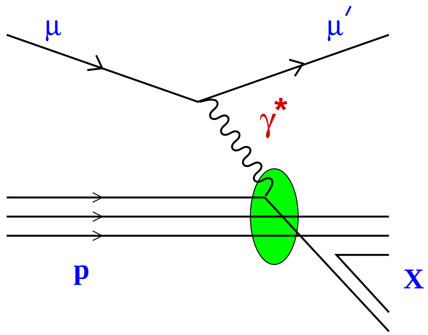


- Non-zero Sivers asymmetry for h^+, measured on proton target.
- Sivers asymmetry measured on deuteron is compatible with zero.
- HERMES measures larger asymmetries – COMPASS result still to be understood.
- 2010 data on proton target to be analysed soon.

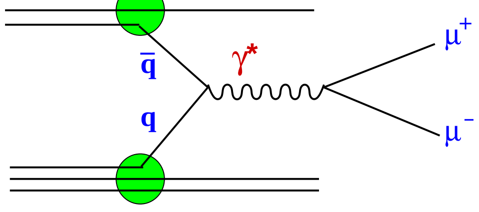
Accessing PDFs

TMD PDFs, like Sivers, can be accessed not only from SIDIS but also from the Drell-Yan process (DY).

SIDIS



DY



The spin asymmetry is given by the convolution of structure function with fragmentation function.

The spin asymmetry is proportional to a product of structure functions, one for beam and one for target.

Because Sivers is T-odd, it is expected that:

$$\boxed{f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)}$$

The experimental check of this relation is a crucial test of QCD. The same is true for Boer-Mulders.

The future: COMPASS-II

The COMPASS programme is expected to be completed in 2011, a year for data-taking with muon beam on longitudinally polarized proton target.

A new proposal for further spin studies in COMPASS was delivered to the SPS committee in May 2010 (CERN-SPSC-2010-014).

The proposal was recommended for approval in September 2010.

Drell-Yan @ COMPASS

COMPASS has the unique opportunity to study, with the same spectrometer, TMD PDFs both from SIDIS and from polarized DY processes, thanks to a multipurpose spectrometer:

- Availability of both muon and pion beams
- Unique polarized NH_3 target, well suited for transversity studies
- Wide angular acceptance and a muon detection system
- Measurement requires large hadron absorber downstream of the target, and a dimuon trigger.

$$\pi^- p^\uparrow \to \mu^+ \mu^- X$$

The COMPASS phase-space covers the proton quarks valence region ($x_p > 0.1$), for high mass Drell-Yan events ($4. < M_{\mu\mu} < 9.$ GeV/c^2).

COMPASS has sensitivity to measure Sivers, Boer-Mulders, transversity and pretzelosity PDFs from Drell-Yan.

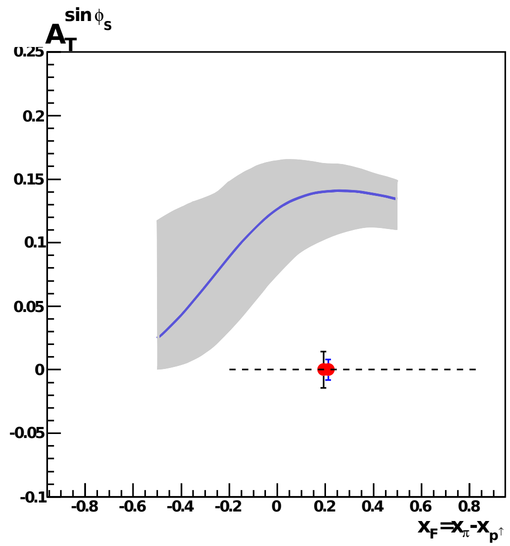
TMD PDFs from DY@COMPASS

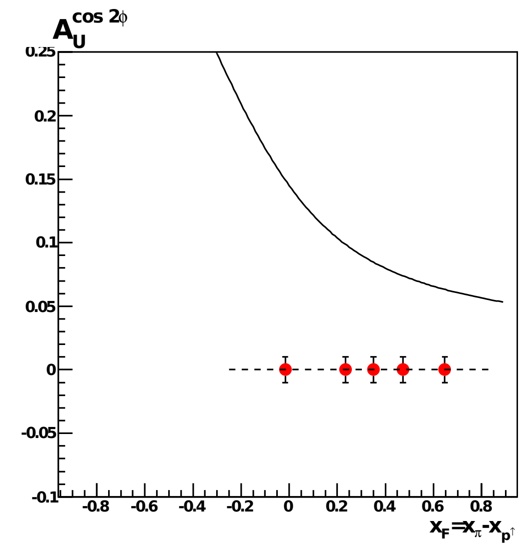
DY $4.-9.$ GeV/c^2

Sivers

M. Anselmino et al,

PRD79 (2009) 054010





Boer-Mulders

B. Zhang et al,

Phys.Rev.D77

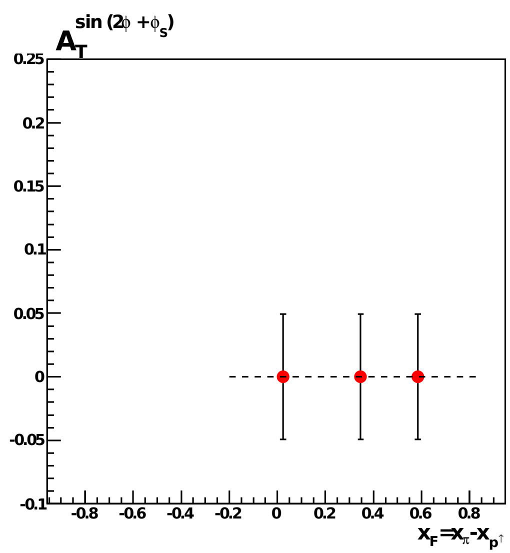
(2008)054011

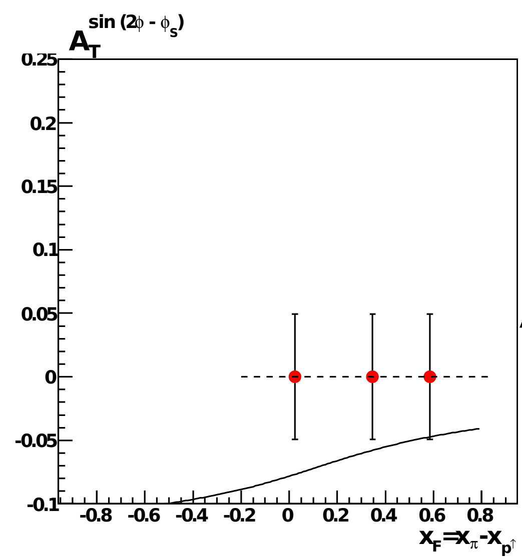
BM $\otimes$ pretzelosity

A.N.Sissakian et al,

Phys.Par t.Nucl.41:

64-100,2010





BM $\otimes$ transversity

A.Efremov et al,

in preparation

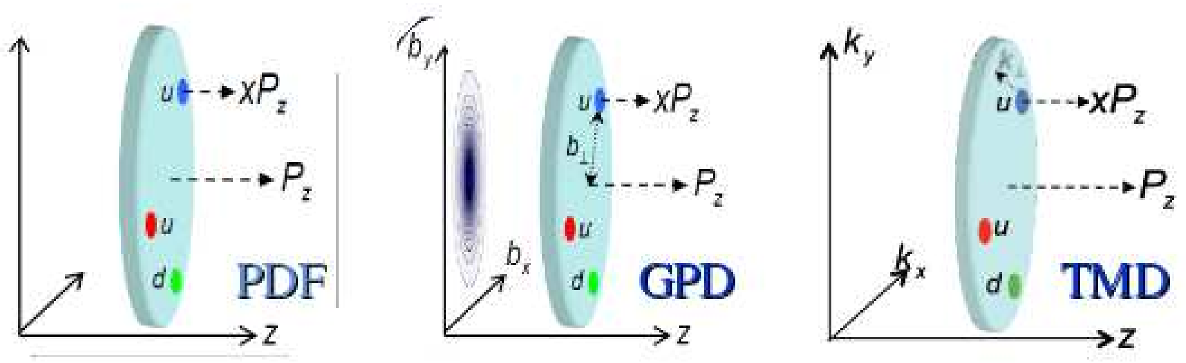
TMDs and GPDs

TMD PDFs: adding information about intrinsic transverse momentum dependence or

GPDs: adding information about the transverse distance of the constituent quark

are 2 "complementary" ways to improve our knowledge about the nucleon structure.

They are related via Fourier transform. They both allow to access information about the quarks orbital angular momentum – although their interpretation is diffi cult.

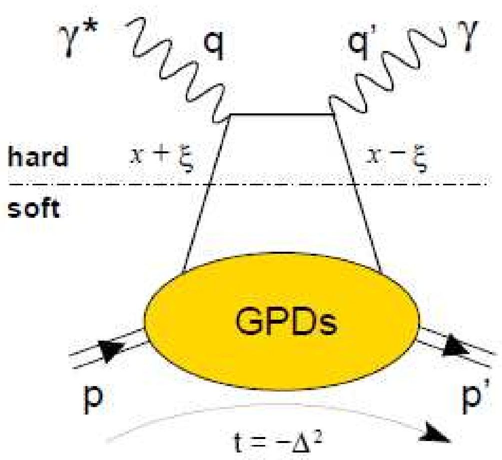


- 4 GPDs: H, E, $\tilde{H}$ and $\tilde{E}$ for each quark flavour and gluons.
- They depend on 3 variables: x, $\xi = \frac{x_B}{2-x_B}$ and t.
- GPDs have no direct probabilistic interpretation.

DVCS with unpolarized target

Using $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams on a long (2.5m) unpolarized liquid H_2 target, one can do transverse imaging (tomography) of the nucleon.
$\hookrightarrow$Access the GPD **H** from Deeply Virtual Compton Scattering (DVCS).

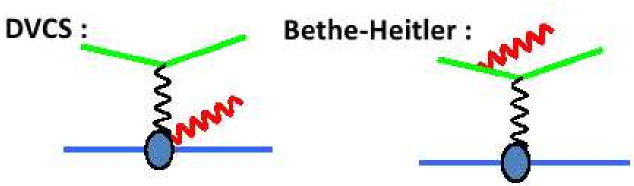
$$\mu p \rightarrow \mu' p \gamma \ (\mu' p \rho)$$



$$d\sigma^{DVCS}/dt \approx exp(-Bt)$$

$$B \approx \langle r^2 \rangle / 2$$

- Measurement requires a large recoil proton detector, and large coverage electromagnetic calorimetry.
- Main priority is DVCS. Meson production will be studied in parallel.
- 2 competing processes: DVCS and Bethe-Heitler. Low x_B: BH; High x_B: DVCS; intermediate x_B: interference DVCS-BH.
- BH is well-known: used as reference process.

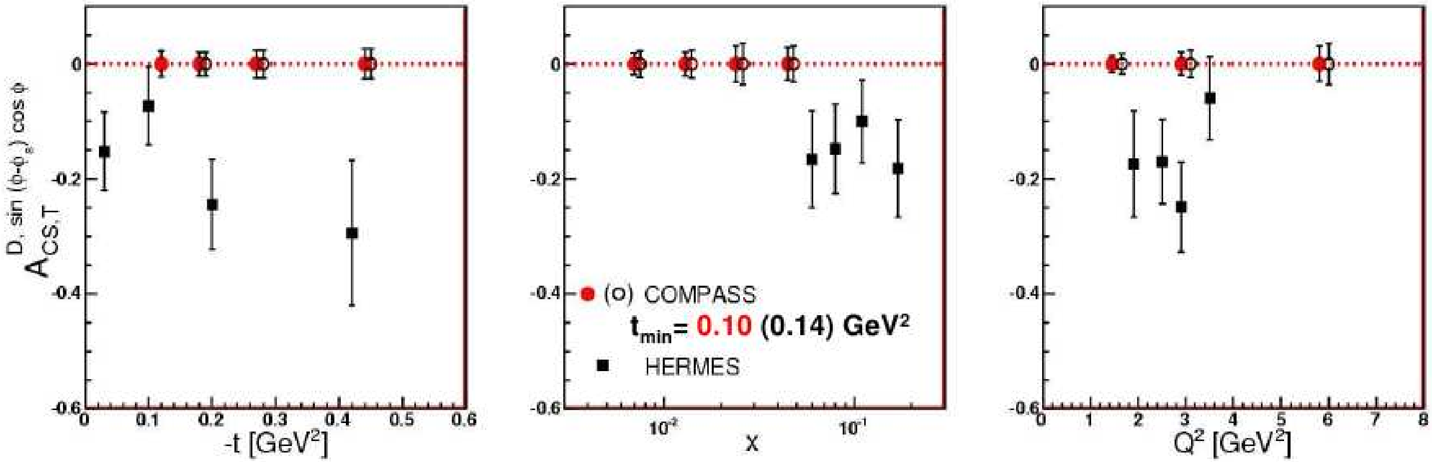


DVCS in COMPASS

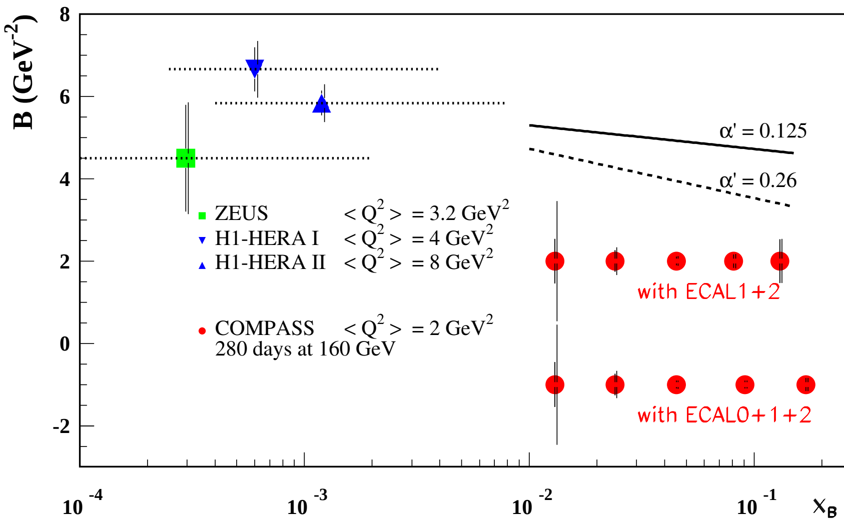
In a 2^{nd} phase of the measurement: use a transversely polarized target (NH_3), inside a large Recoil Proton Detector.

$\hookrightarrow$ Access GPD E: from measured azimuthal asymmetries

Phase 2



Phase 1



Present conclusions

COMPASS takes data since 2002, for studies both on the nucleon spin structure and on hadron spectroscopy.

COMPASS results on spin physics give an important contribution to our understanding:

- The most precise data on A_1 at the low x_{Bj} region, with impact in the determination of g_1^d and g_1^p.
- A direct measurement of the gluon polarization, with a result compatible with zero, within errors, in the measured x_g range.
- Collins and Sivers asymmetries on deuteron target compatible with zero – understood now to be due to cancellation between u and d quark contributions.
- Sizable Collins asymmetry on proton target – access to the transversity PDF.
- Positive Sivers asymmetry for h^+ on proton target, but diffi cult systematics – still to be understood.

$\Longrightarrow$ Data from 2010 (transverse pol.) and 2011 (longitudinal pol.) still to be analysed!

COMPASS future

A proposal for new spin studies in COMPASS was recommended for approval by the CERN Scientifi c Committee in September 2010:

- Study of TMD PDFs from polarized Drell-Yan – It can be the fi rst ever polarized Drell-Yan experiment.
- Drell-Yan COMPASS phase-space (in the proton's valence quarks region) seems to be very favorable to access TMDs, according to theory predictions.
- Study of GPDs from DVCS – the COMPASS measurement will be in an intermediate x range, not covered by any other experiment in the near future.
- DVCS process using unpolarized proton target in a 1^{st} phase, to constrain GPD H, and do transverse imaging of the nucleon. Use of a transversely polarized proton target in a 2^{nd} phase, to constrain GPD E.

Thank you!