Exploring QCD with COMPASS-II

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Outline

- Unpolarized Deep Inelastic Scattering and the strange quark PDF
- Deeply Virtual Compton Scattering and Generalized Parton Distributions
- Drell-Yan and Transverse Momentum Dependent PDFs
- Primakoff reaction as a test of Chiral Perturbation Theory
- Summary

A bit of history

COMPASS has been taking data at the SPS/CERN since 2002, with main goals:

- Helicity PDF g_1 from double polarized DIS, and flavor separation
- Gluon polarization $\Delta G/G$ from double polarized DIS
- Transversity PDF h_1 in transversely polarized SIDIS

➥ Naturally polarized μ^+ beam (@160 GeV/c), on ^6LiD and NH_3 transversely or longitudinally polarized targets.

- Hadron spectroscopy: searches of exotics, hybrids and glueballs
- Pion polarizabilites

➥ Unpolarized hadron beams (@190 GeV/c) on several unpolarized targets (Liquid H_2, Pb, Ni, Cu and W)

Studying QCD in COMPASS...

Thanks to a multi-purpose spectrometer, and a versatile beam line, COMPASS has been doing extensive QCD studies.

The nucleon spin puzzle, that has been intriguing us since EMC times, comes now with new clues:

- The quarks spin is responsible for only $\approx$ 30% of the nucleon spin
- The gluons spin does not contribute much, at least in the x-region scanned by COMPASS ($x_g \approx 0.1$)
- What about angular momentum contributions from quarks and gluons?

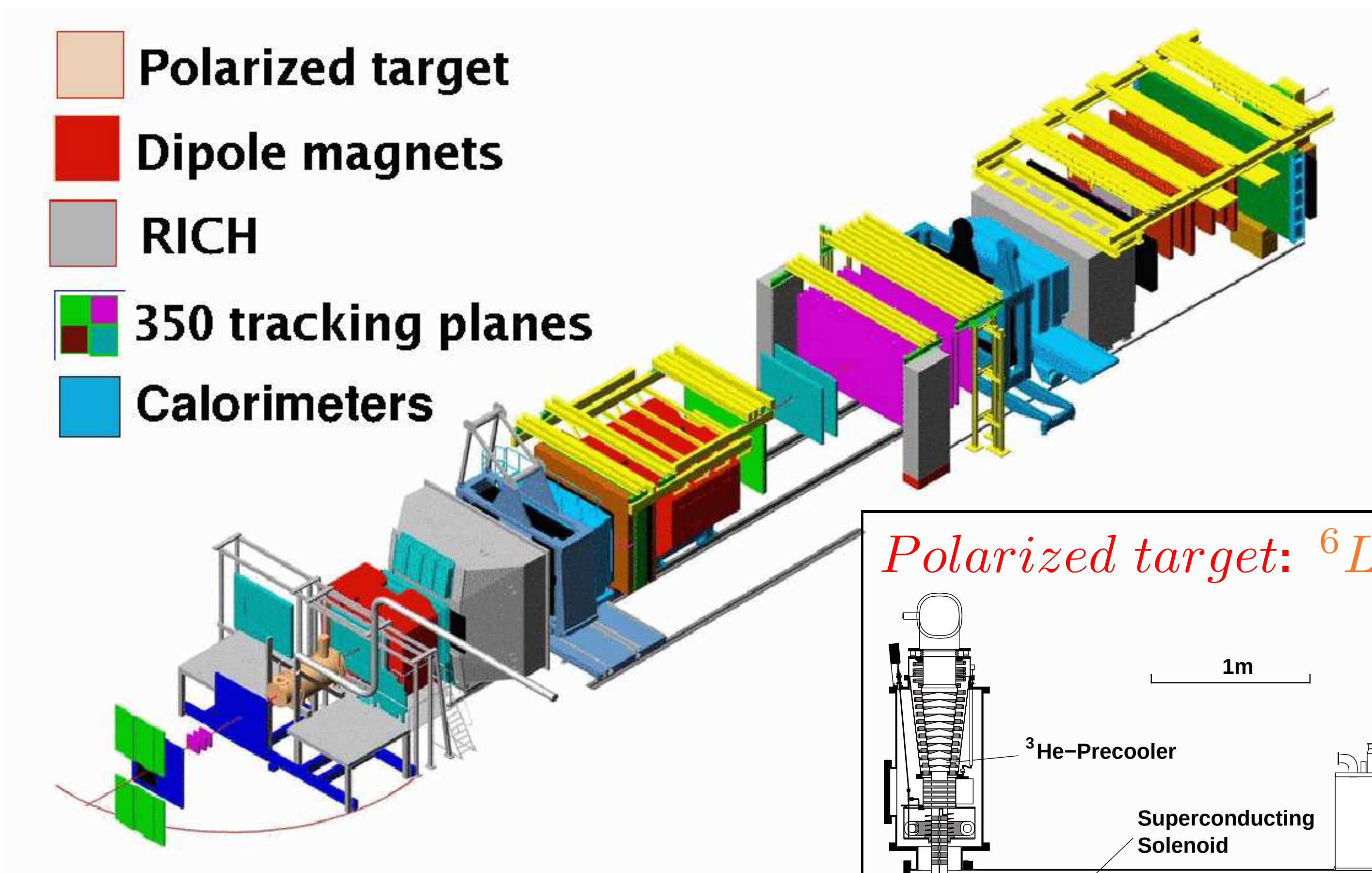
In LO 3 PDFs are needed for a full description of the nucleon: unpolarized, helicity and transversity – all investigated in COMPASS.

...and in COMPASS-II

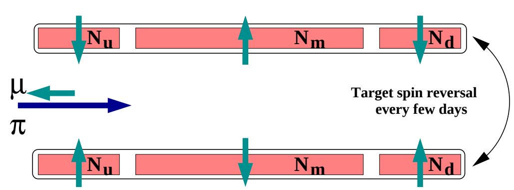
But the 1-dimensional picture of the nucleon is now to be improved:

- quarks flavor matters: improve namely the strange PDF;
- 3-dimensional description, via GPDs;
- account for intrinsic transverse momentum of partons, via TMD PDFs;
- ...and low energies QCD: a test of Chiral Perturbation Theory.

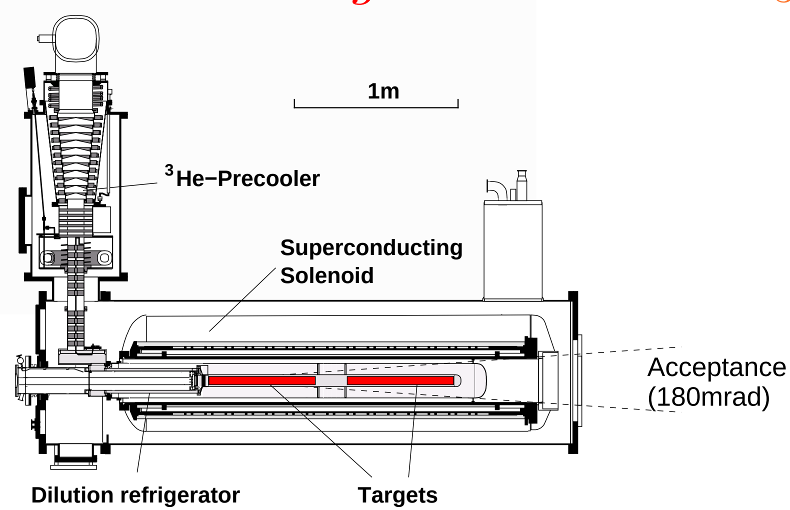
COMPASS Experiment



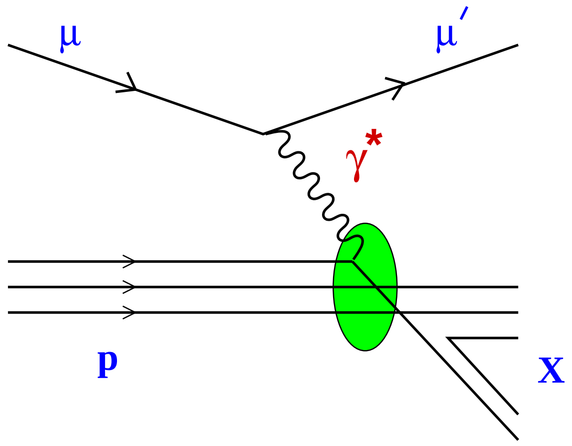
$\mu^{\pm}$, π^{-} or p beam



Polarized target: ^{6}LiD or NH_3



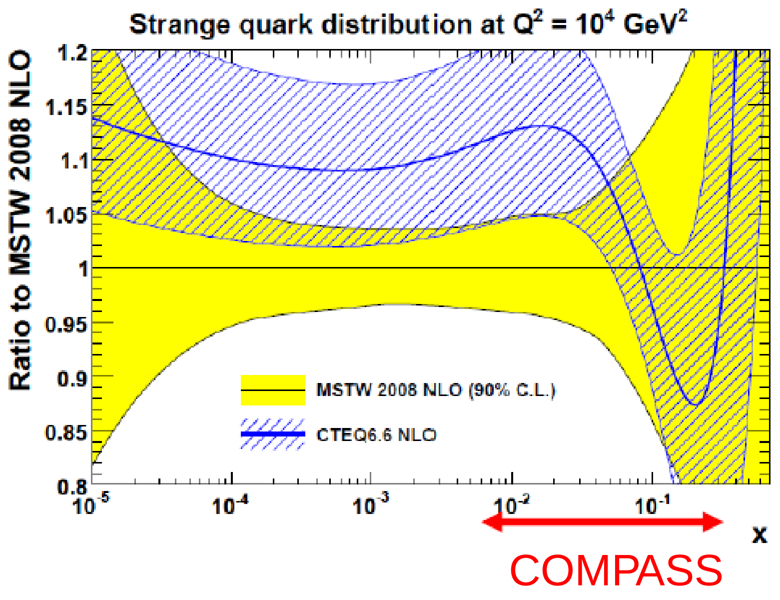
Deep Inelastic Scattering



DIS is used since long to access the parton distributions $q(x)$.

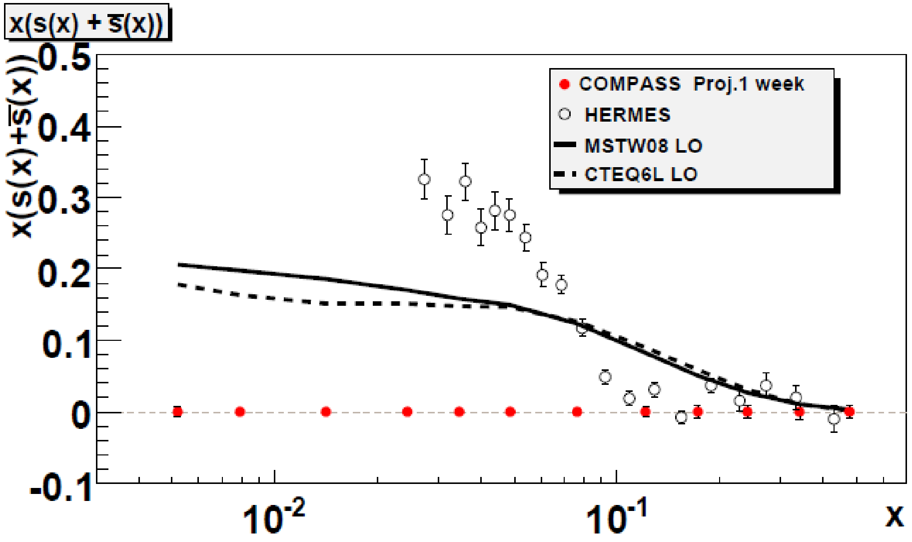
Flavor separation: identify one outgoing hadron, besides μ' – SIDIS.

While the unpolarized light quark PDFs are well constrained, the strange quark distribution has still a large uncertainty:



Unpolarized SIDIS

Unpolarized SIDIS measurement, with PID and charge separation from the COMPASS RICH and Calorimeters: $K^{\pm}$, K^0, $\pi^{\pm}$, π^0, Λ,...



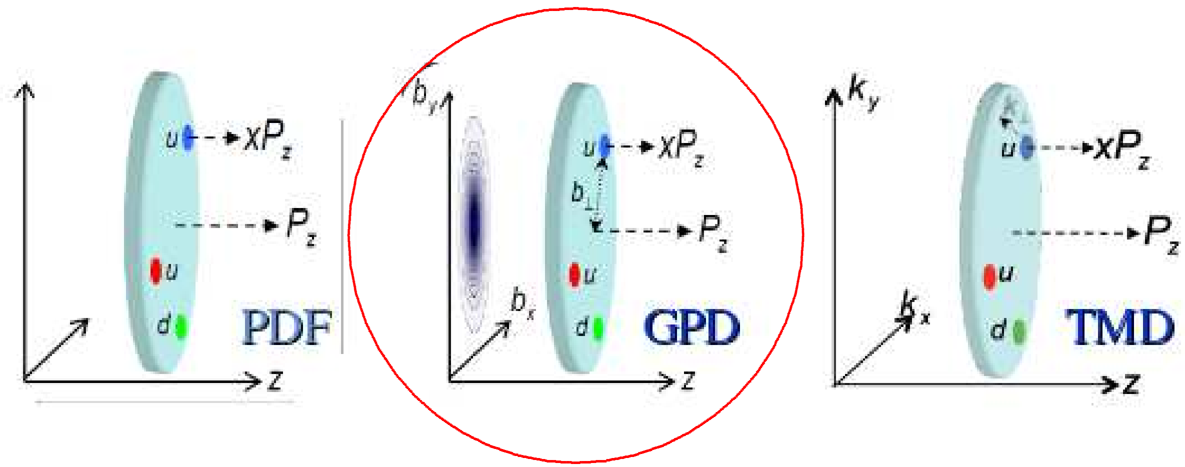
- Improve on unpolarized PDFs, namely $s(x)$
- Improve on fragmentation functions, namely kaon FF
- LO analysis of COMPASS data alone
- Scan PDFs and FFs on (x,z,...), towards a NLO global analysis

Measurement in parallel with the GPDs program, using a long liquid H_2 target.

Generalized Parton Distributions

GPDs: a 3D picture of the nucleon, by adding information about the transverse distance of the constituent quark.

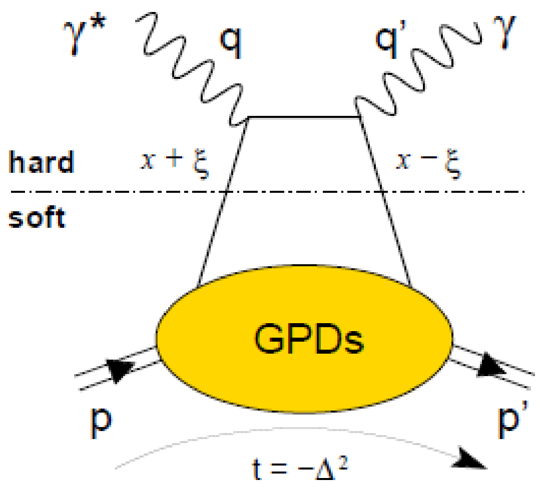
They allow to access information on the quarks orbital angular momentum.



- 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.

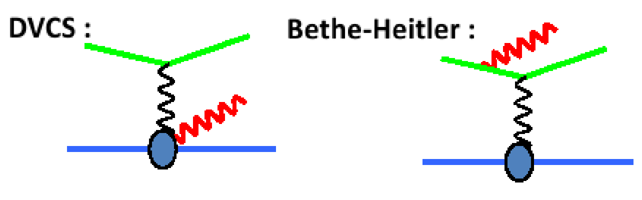
DVCS in COMPASS

Transverse imaging (tomography) of the nucleon from Deeply Virtual Compton Scattering (DVCS): $\mu p \rightarrow \mu' p \gamma$



$$\frac{d\sigma}{dt} \approx e^{-Bt} \qquad B \approx \langle r_\perp^2 \rangle / 2$$

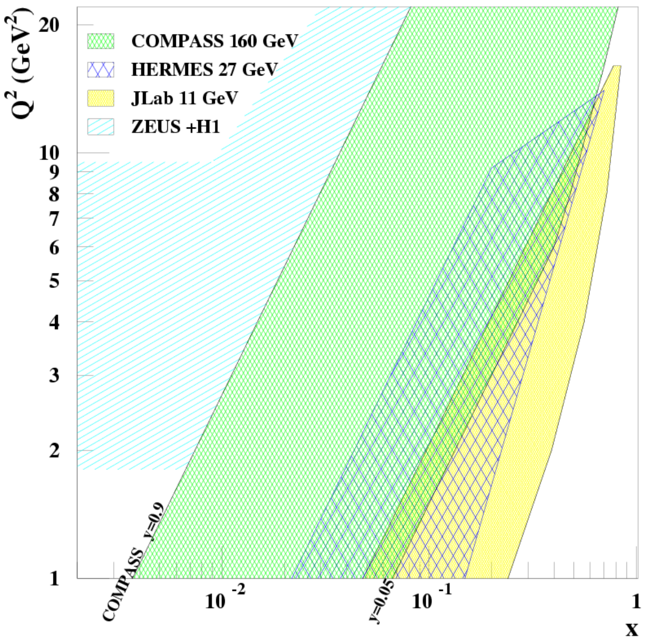
- Main priority is DVCS.
- Deeply Virtual Meson Production (DVMP): $\mu p \rightarrow \mu' p \rho$ will be studied in parallel.
- 2 competing processes: DVCS and Bethe-Heitler
  - ⋆ Low x_B: BH;
  - ⋆ High x_B: DVCS;
  - ⋆ intermediate x_B: interference DVCS-BH.
- BH is well-known: used as reference process.



Phase 1: $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams off a 2.5m unpolarized liquid H_2 target $\Rightarrow$ GPD H.

Phase 2: $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams off a transversely polarized NH_3 target $\Rightarrow$ GPD E.

DVCS: phase-space and goals



COMPASS will cover an unexplored region of the phase-space, the intermediate x_B.

Measure the modulations given by the sum and difference of "spin and charge" dependent DVCS cross-sections, whose amplitudes are proportional to $\mathcal{I}m(F_1 H)$ and $\mathcal{R}e(F_1 H)$

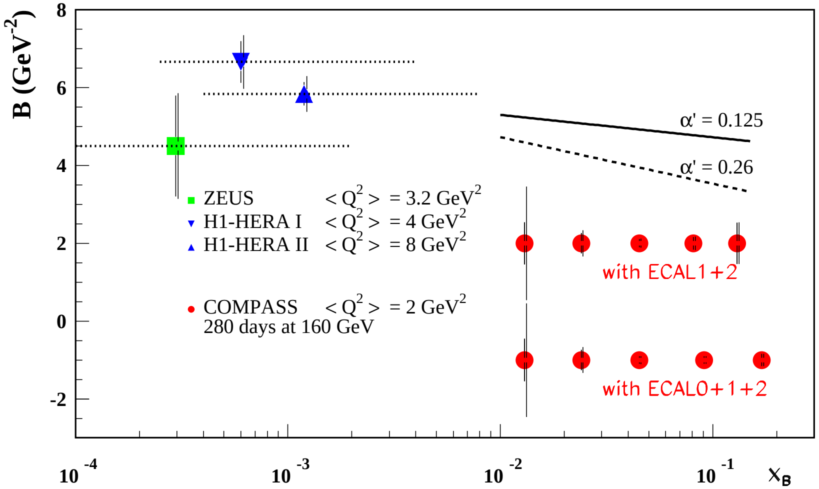
$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow})$$

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow})$$

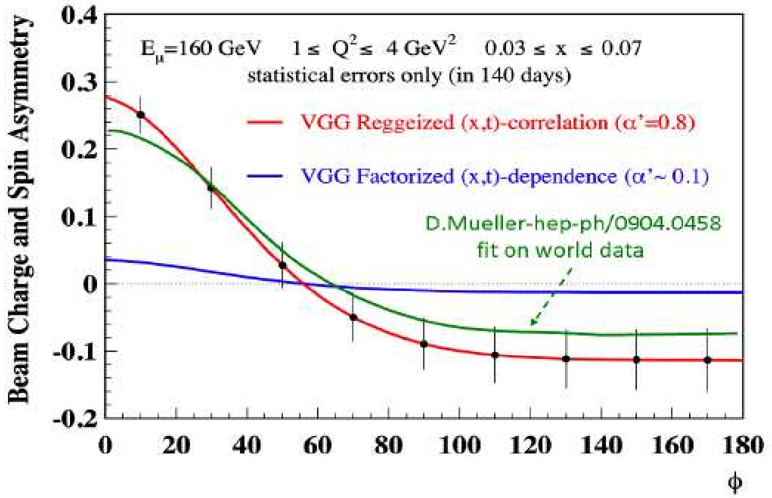
The measurement requires a recoil proton detector, and large coverage electromagnetic calorimetry.

DVCS: Projections

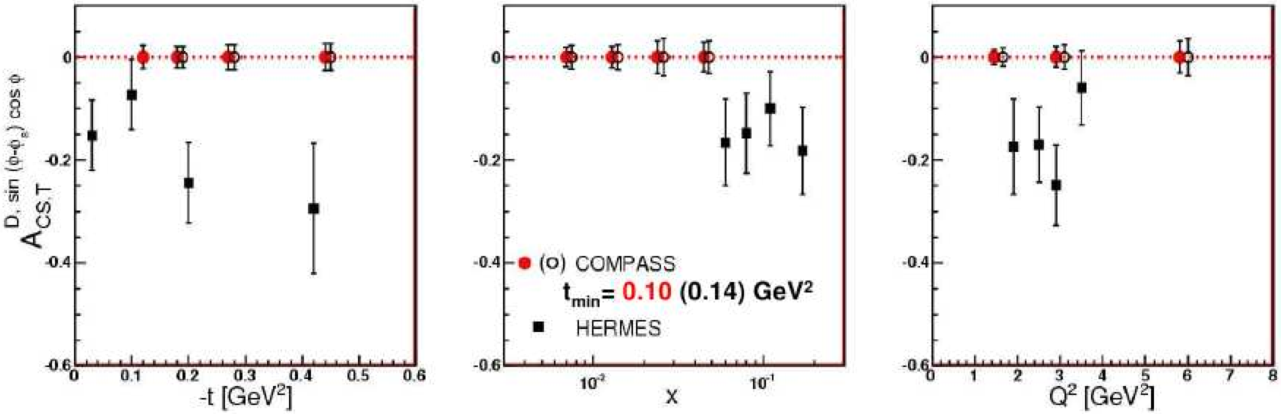
Phase 1: B=<r$^2_\perp$>/2



$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow})$$



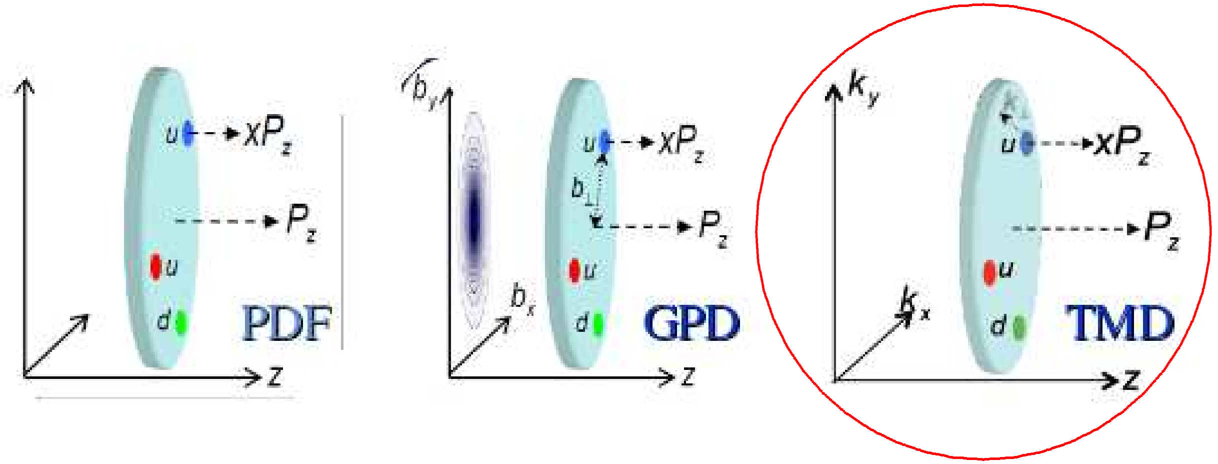
Phase 2: Azimuthal asymmetries



TMD PDFs

TMDs: dynamic picture of the nucleon, by considering also the partons intrinsic transverse momentum k_T.

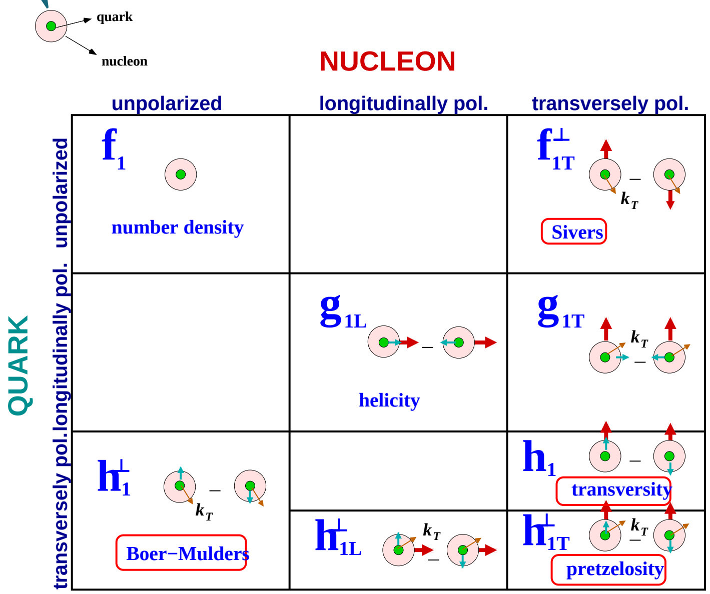
They also allow to access information on the quarks orbital angular momentum.



In COMPASS TMD PDFs can be studied in 2 complementary ways:

- Semi-inclusive DIS
  - $\hookrightarrow$ polarized muon beam on unpolarized/transversely polarized target;
- Drell-Yan process
  - $\hookrightarrow$ pion beam on unpolarized/transversely polarized target.

TMDs approach

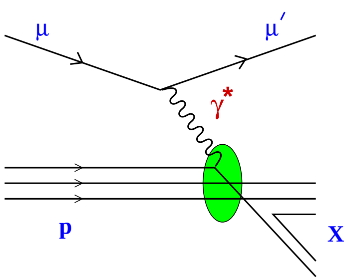


In LO and considering the quarks k_T, 8 PDFs are needed to fully describe the nucleon.

The TMDs approach is valid when $Q \gg q_T \gtrsim \Lambda_{QCD}$.

TMDs are accessed by measuring azimuthal asymmetries.

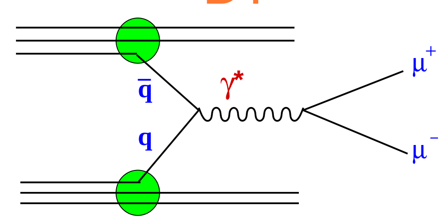
SIDIS



The spin asymmetry is proportional to PDF ⊗ FF:

$$A_{Sivers} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp(1)}(x) D_q^h(z)}{\sum_q e_q^2 f_1(x) D_q^h(z)}$$

DY

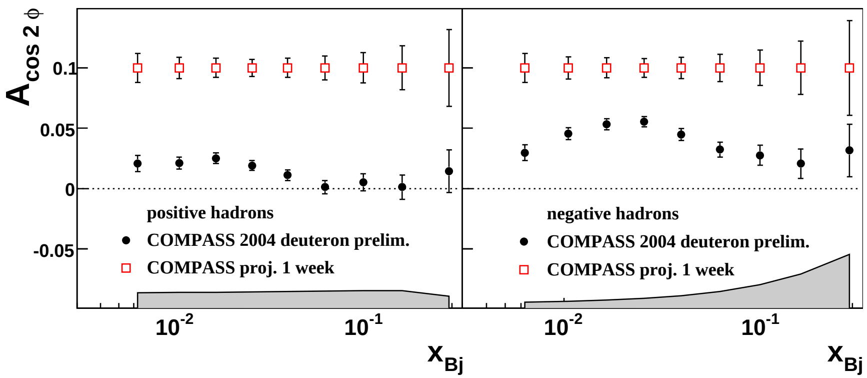


The spin asymmetry is proportional to PDF^b ⊗ PDF^t. If unpolarized beam and transversely polarized target:

$$A_{Sivers} \propto 2\frac{\sum_q e_q^2 \bar{f}_{1q}(x_1) f_{1Tq}^{\perp(1)}(x_2)}{\sum_q e_q^2 \bar{f}_{1q}(x_1) f_{1q}(x_2)}$$

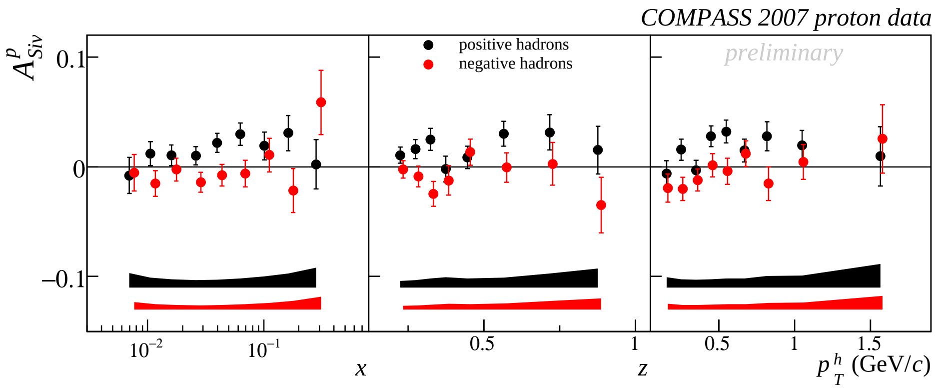
Boer-Mulders and Sivers in SIDIS

We look at the azimuthal modulations of produced hadrons, ϕ being the angle of the hadron in the γ^*-nucleon reference frame.



2004-2006 data on deuteron target: non-zero Boer-Mulders asymmetry ($A_{LU}^{\cos 2\phi}$).

The Boer-Mulders TMD in the proton can be measured in parallel with DVCS.



The Sivers asymmetry ($A_{LT}^{\sin \phi_S}$) was measured in COMPASS in deuteron and proton targets.

Positive asymmetry for h^+ on proton, but effect seen in HERMES is a factor 2 larger.

As Sivers and Boer-Mulders are T-odd PDFs:

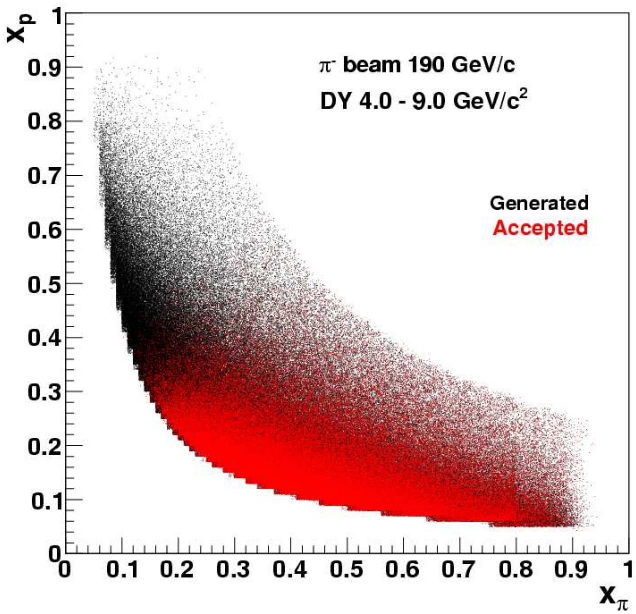
$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$$

$$h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

$\hookrightarrow$A crucial test of non-perturbative QCD and of TMDs approach.

TMDs in Drell-Yan

Drell-Yan events from π^- @190 GeV/c collisions on a NH_3 target transversely polarized $\Rightarrow$ access 4 azimuthal modulations related to Boer-Mulders, Sivers, pretzelosity and transversity PDFs.

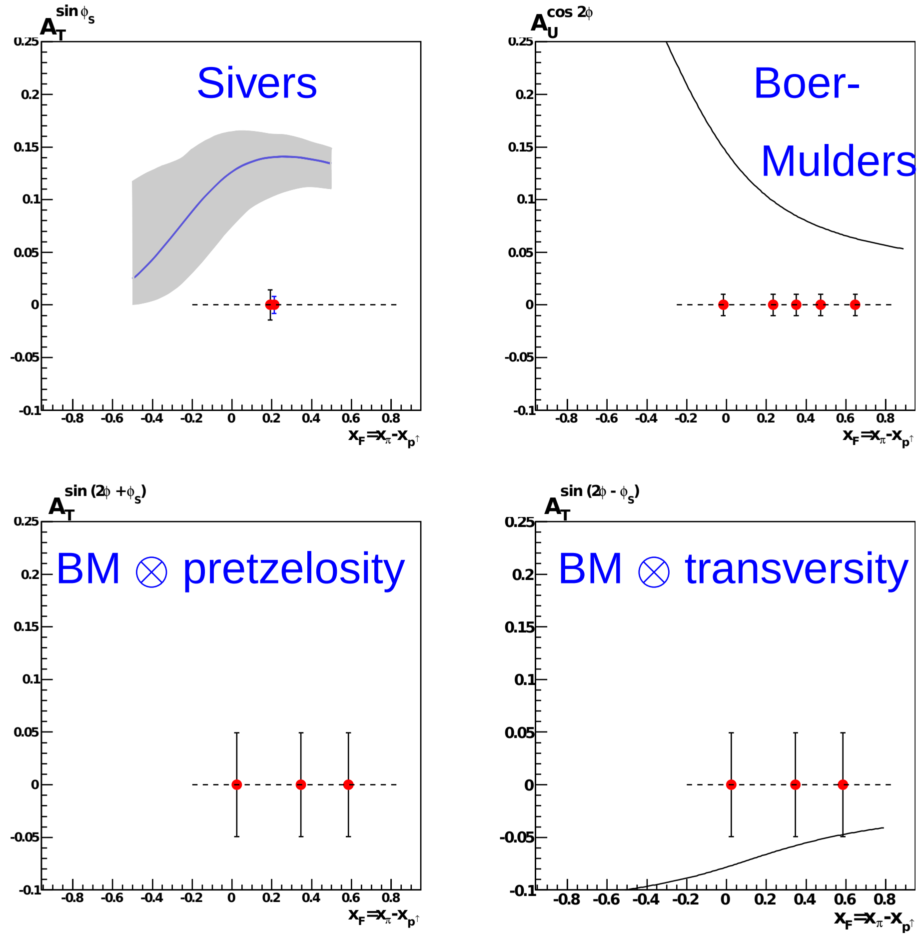


- All 4 asymmetries predicted to be sizable in the valence quarks region.
- COMPASS acceptance is very favorable: $x_p > 0.05$.
- Study Drell-Yan in $4 < M_{\mu\mu} < 9$ GeV/c^2, where background is negligible.
- TMD approach validity guaranteed by $M_{\mu\mu} \gg p_T^{\mu\mu} \approx 1$ GeV.

The measurement requires a hadron absorber downstream the target, and a dimuon trigger system.

Drell-Yan: projections

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

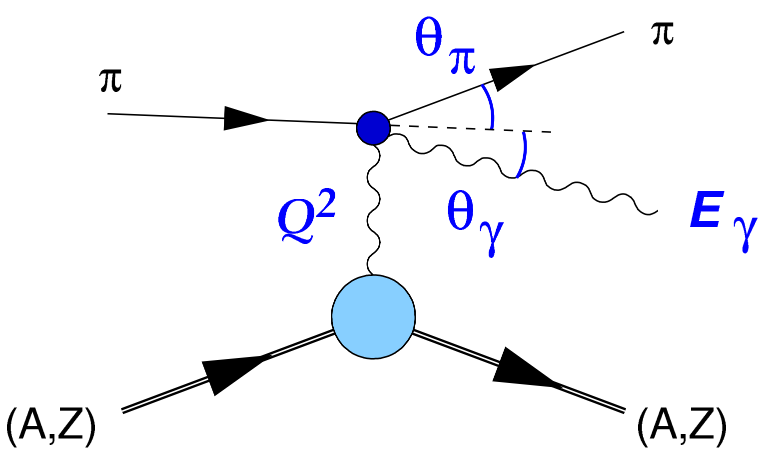


Assuming 2 years of data-taking, it will be possible to check the sign change between SIDIS and DY, and test PDF predictions.

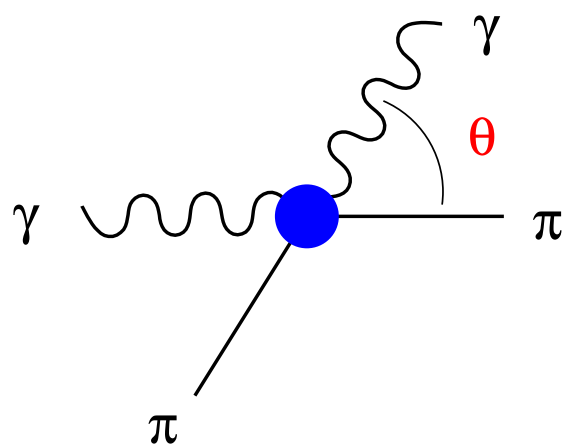
Testing ChPT

Chiral Perturbation Theory predicts the strong interaction dynamics of Goldstone bosons.

$\hookrightarrow$the internal structure of the pion is revealed by its response in presence of an electromagnetic field, i.e. pion polarizabilities.



Primakoff

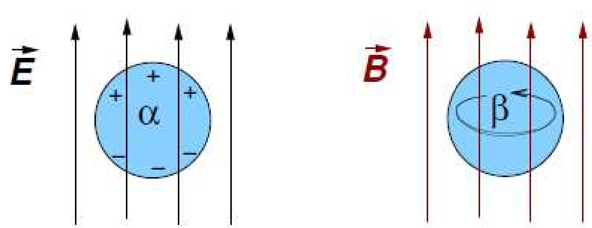


Inverse Compton

Studying the π induced Primakoff reaction and the embedded inverse Compton scattering, one can measure the π polarizabilities and check ChPT predictions.

Pion polarizabilities

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}}\right]_{point-like} + C\,\frac{s-m_\pi^2}{s^2}\,\mathcal{P}(\alpha_\pi, \beta_\pi)$$



Polarizability:

$$\mathcal{P} = (1-\cos\theta_{cm})^2\,(\alpha_\pi - \beta_\pi) + (1+\cos\theta_{cm})^2\,(\alpha_\pi + \beta_\pi)\,\frac{s^2}{m_\pi^4} + (1-\cos\theta_{cm})^3\,(\alpha_2 - \beta_2)\,\frac{(s-m_\pi^2)^2}{24s}$$

In 120 days (90 with π, 30 with μ beams)	$\alpha_\pi - \beta_\pi$ (10^{-4} fm^3)	$\alpha_\pi + \beta_\pi$ (10^{-4} fm^3)	$\alpha_2 - \beta_2$ (10^{-4} fm^3)
2-loop ChPT prediction	5.7 $\pm$ 1.0	0.16 $\pm$ 0.10	16
COMPASS sensitivity	$\pm$ 0.66	$\pm$ 0.025	$\pm$ 1.94

Measurement with muon beam will allow to cross-check systematics.

Up to now, experiments measured $\alpha_\pi - \beta_\pi$ from 4 to 14 $\times 10^{-4}$ fm^3.

In addition COMPASS will measure for the first time kaon polarizabilities.

Timeline and Conclusions

COMPASS new proposal (May 2010), with physics program including:

- Unpolarized SIDIS measurements to access the strange quark PDF, FFs and TMD PDFs with unprecedented precision;
- DVCS and DVMP for GPDs studies in a phase-space region not yet covered by other past or near-future experiments;
- First-ever polarized Drell-Yan experiment for TMDs studies;
- Primakoff reactions for pion polarizabilities (improved accuracy) and first measurement of kaon polarizabilites.

$\hookrightarrow$at least 5 years of data-taking, which can start from 2012.

Program approved by the SPSC/CERN for a first period of 3 years.

COMPASS will continue playing a major role in QCD physics for the next 5 to 10 years.

Stay tuned!