Drell-Yan measurements in COMPASS

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12th April 2011, DIS 2011
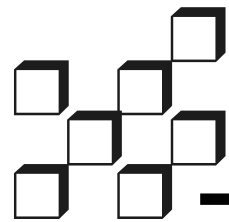
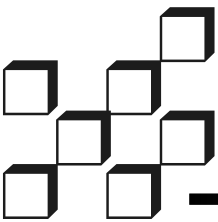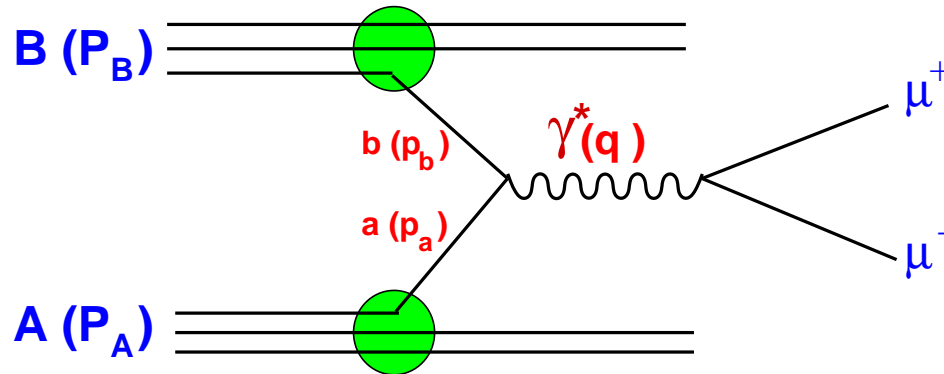- ◆ The Drell-Yan process

- ◆ Drell-Yan with transversely polarized target

- ◆ Drell-Yan at COMPASS: why and how

- ◆ COMPASS sensitivity to TMD PDFs

- ◆ Summary

Quark-antiquark annihilation, with dilepton production:

$$p_a = \sqrt{s}/2 \; x_a(1,0,1)$$

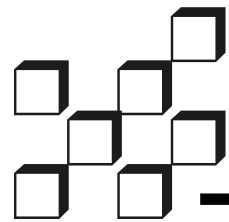$$p_b = \sqrt{s}/2 \; x_b(1,0,-1)$$

$$q = p_a + p_b = (q_0, 0, q_L)$$

(massless quarks, collinear γ^*)

$$s = (P_A + P_B)^2 = \frac{\hat{s}}{x_a x_b} = \frac{\hat{s}}{\tau} \quad \Rightarrow \quad \tau = x_a x_b = \frac{\hat{s}}{s} = \frac{Q^2}{s} = \frac{M_{\mu\mu}^2}{s}$$

The hadronic cross-section is given by a convolution of parton distribution functions:

$$\frac{d\sigma}{dQ^2} = \sum_{q=u,d,s} \int dx_a \int dx_b \left(q(x_a)\bar{q}(x_b) + \bar{q}(x_a)q(x_b) \right) \hat{\sigma}_0 \; \delta(Q^2 - \hat{s})$$
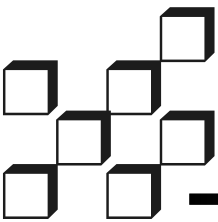
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi(\lambda+3)}[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi]$$

The collinearity hypothesis would imply $\lambda = 1$ and $\mu = \nu = 0$.

But experiments at CERN (NA10) and Fermilab (E615) measured important deviations from the collinearity hypothesis, with a modulation of $\cos 2\phi$ up to 30%!

This means we cannot neglect the intrinsic transverse momentum k_T of quarks inside hadrons. Taking this into account, the γ^* transverse momentum is $q_T = k_{Ta} + k_{Tb}$.

Nowadays the $\cos 2\phi$ modulation is believed to naturally arise from a product of 2 transverse momentum dependent (TMD) PDFs – the so-called Boer-Mulders PDFs of target and beam quarks interacting.

Parton distribution functions

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 k_T, 8 PDFs are needed.

This TMD PDFs approach is valid when $Q \gg q_T \gtrsim \Lambda_{QCD}$:
like in Drell-Yan at relatively small q_T, where we have $M_{\mu\mu} \gg p_T^{\mu\mu}$.

In the region $Q, q_T \gg \Lambda_{QCD}$, the collinear twist-3 approach should be used instead.
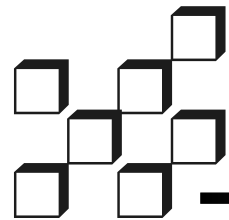
In the single polarized DY case, the general expression of the Drell-Yan cross-section (LO) is:

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \{(1 + D_{[\sin^2\theta]}A_U^{\cos 2\phi}\cos 2\phi)$$

$$+ |\vec{S}_T|[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)$$
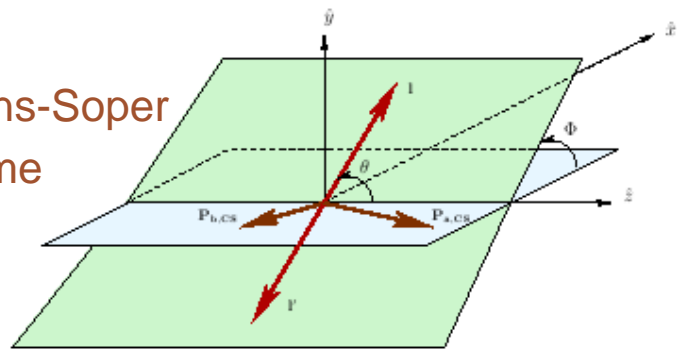
$$+ A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S))]\}$$

◆ A: azimuthal asymmetries – $A_U^{\cos 2\phi}$, $A_T^{\sin\phi_S}$, $A_T^{\sin(2\phi+\phi_S)}$ and $A_T^{\sin(2\phi-\phi_S)}$

◆ D: depolarization factor

◆ S: target spin components

◆ $F = 4\sqrt{(P_a \cdot P_b)^2 - M_a^2 M_b^2}$

◆ $\hat{\sigma}_U$: part of the cross-section surviving integration over ϕ and ϕ_S.
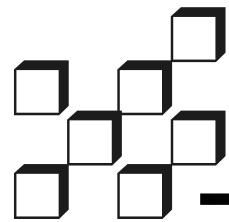
Transverse target spin and ϕ_S
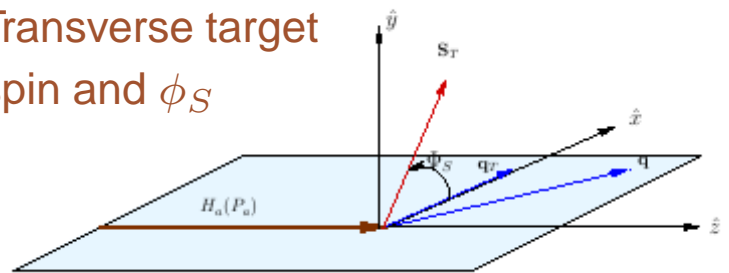
Collins-Soper frame

Each asymmetry contains a convolution of 2 PDFs, one from target and another from beam quarks.

- ♦ $A_U^{\cos 2\phi}$: access to Boer-Mulders functions of incoming hadrons;

- ♦ $A_T^{\sin \phi_S}$: access to the Sivers function of target nucleon;

- ♦ $A_T^{\sin(2\phi+\phi_S)}$: access to Boer-Mulders function of beam hadron and to pretzelosity of target nucleon;

- ♦ $A_T^{\sin(2\phi-\phi_S)}$: access to Boer-Mulders function of beam hadron and to transversity of the target nucleon.

$\hookrightarrow$all to be measured experimentally

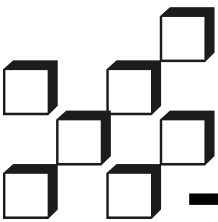All these azimuthal asymmetries are expected to be sizable in the valence quarks region – where we measure.
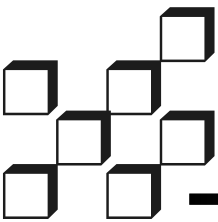
Theory predictions: $A_T^{\sin\phi_S}$

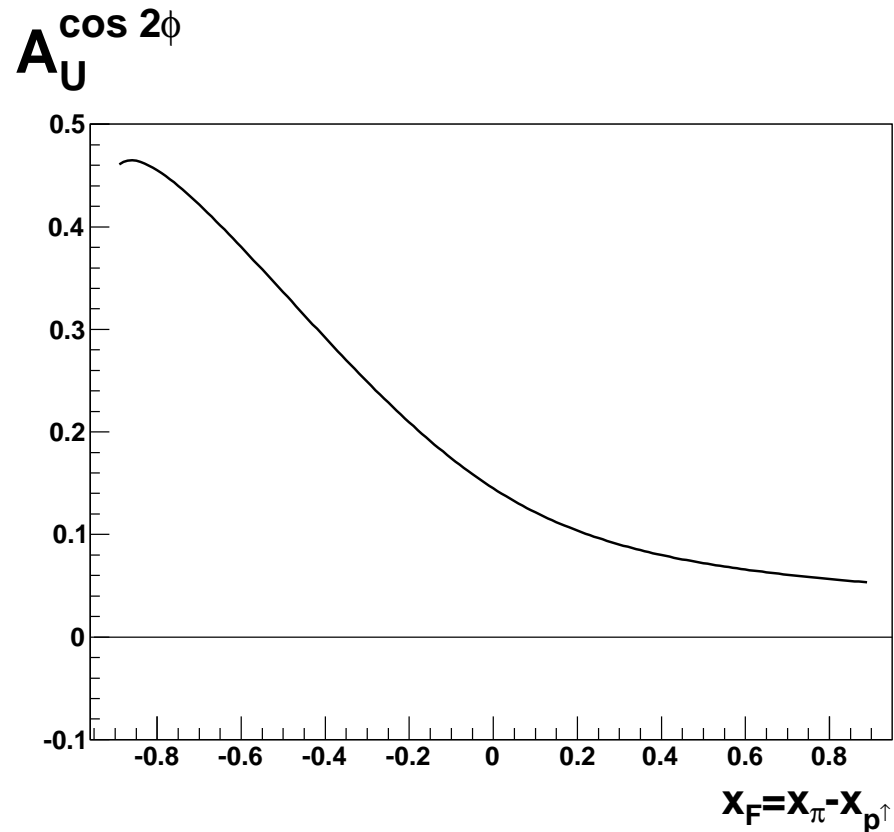## Sivers for DY 4.0 - 9.0 GeV/c^2, from π^- (190 GeV/c) $p^\uparrow$ collisions

– solid and dashed: Efremov et al,

    PLB612(2005)233;

– dot-dashed: Collins et al,

    PRD73(2006)014021;

– solid,dot-dashed: Anselmino et al,

    PRD79(2009)054010;

– boxes: Bianconi et al, PRD73(2006)114002;

– short-dashed: Bacchetta et al,

    PRD78(2008)074010.
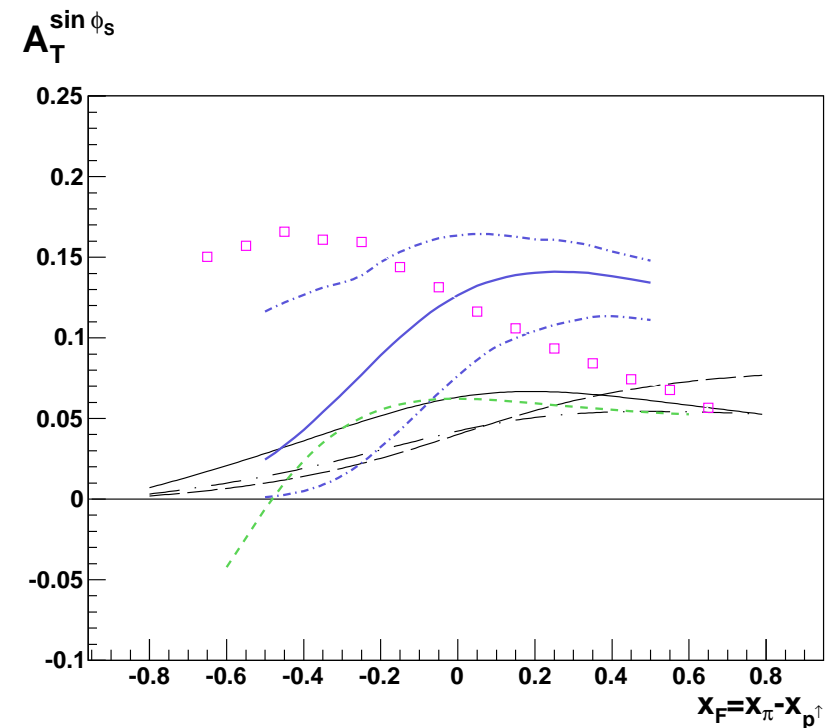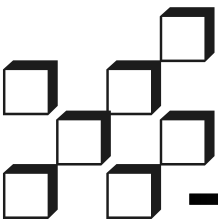
Theory predictions: $A_U^{\cos 2\phi}$

Boer-Mulders for DY 4.0 - 9.0 GeV/c^2,
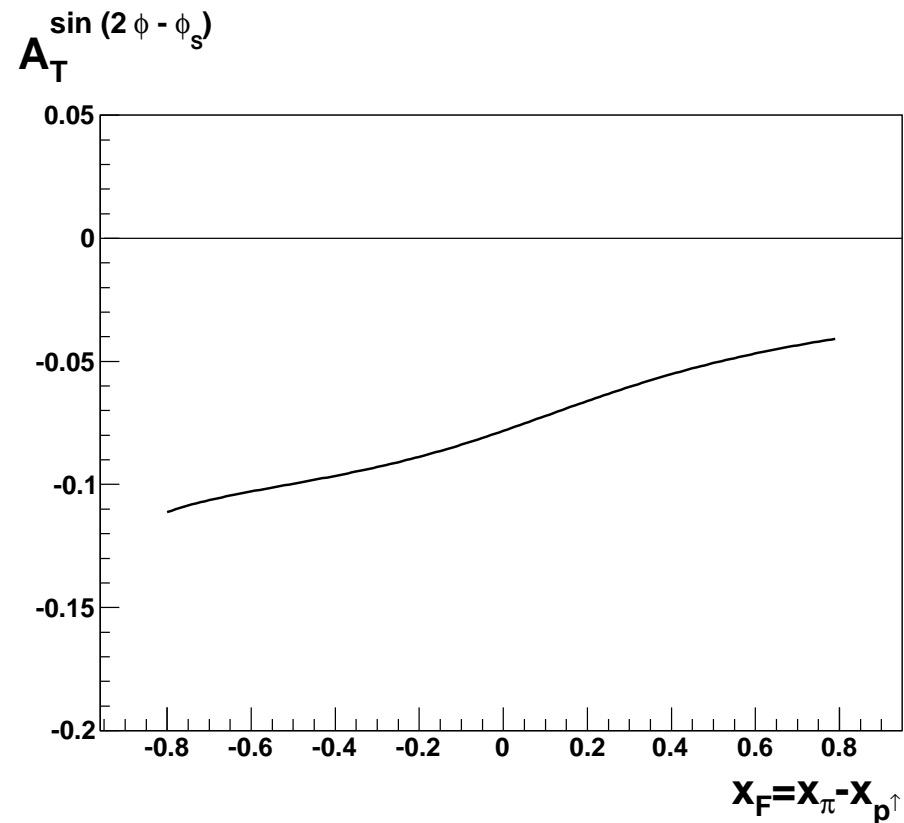from π^- (190 GeV/c) $p^\uparrow$ collisions

B. Zhang et al, Phys. Rev. D77 (2008) 054011; with π BM parametrization from D. Boer, Phys. Rev. D60 (1999) 014012 on NA10 data.
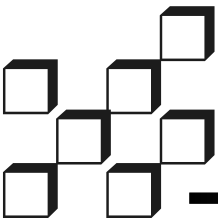
Theory predictions: $A_T^{\sin(2\phi-\phi_S)}$

BM $\otimes$ transversity, for DY 4.0 - 9.0 GeV/c^2,
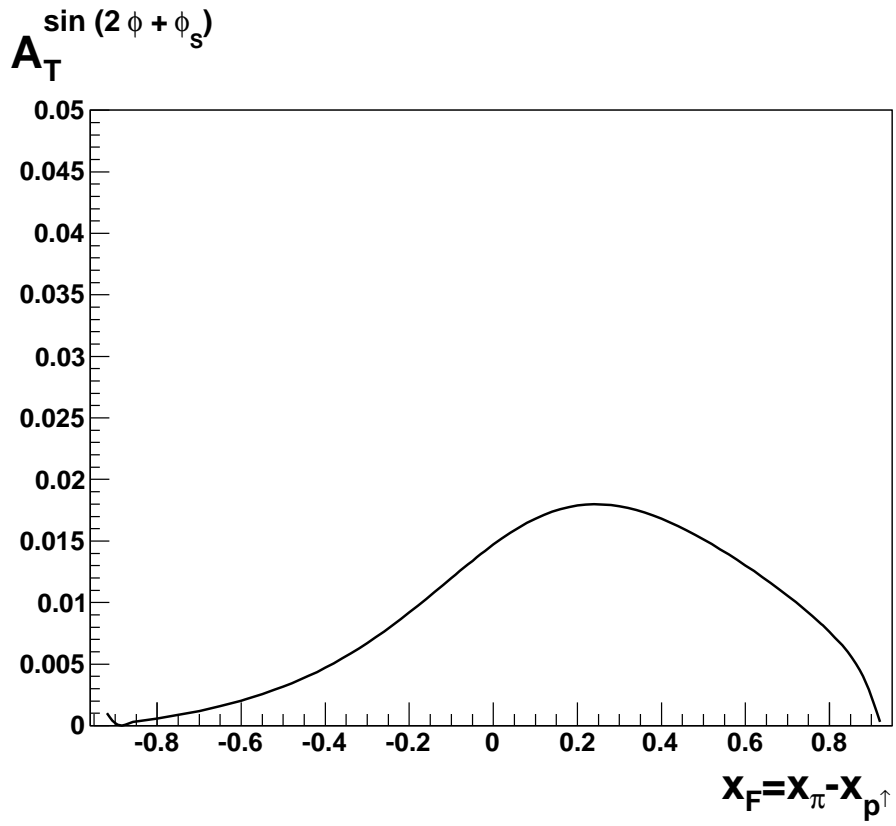from π^- (190 GeV/c) $p^\uparrow$ collisions

A.N. Sissakian, O.Yu. Shevchenko, A.P. Nagaitsev, O.N. Ivanov,
Phys.Part.Nucl.41:64-100,2010.

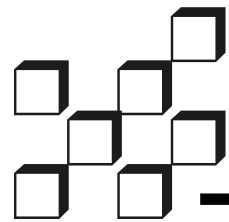# **Theory predictions:** $A_T^{\sin(2\phi+\phi_S)}$

BM $\otimes$ pretzelosity, for DY 4.0 - 9.0 GeV/c^2,
from π^- (190 GeV/c) $p^\uparrow$ collisions
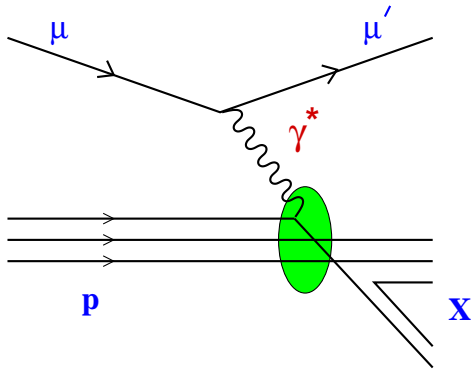

A. Efremov, B. Pasquini, P. Schweitzer, F. Yuan, in preparation.
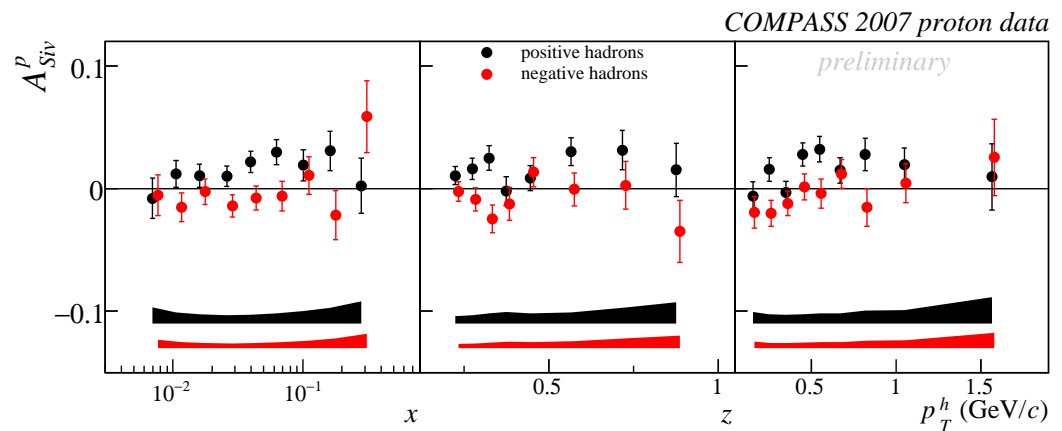
Presently, our knowledge of PDFs in transversely polarized nucleons comes from SIDIS measurements (COMPASS and HERMES).
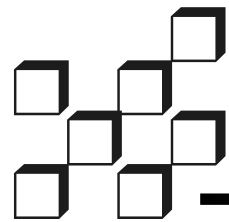

In semi-inclusive deep inelastic scattering the measured asymmetry results from the convolution of a nucleon PDF with a fragmentation function for the final state hadron.

The Sivers asymmetry was measured in COMPASS and HERMES.

The asymmetry is positive for h^+ on proton target (the effect in HERMES is larger by a factor 2 than in COMPASS).
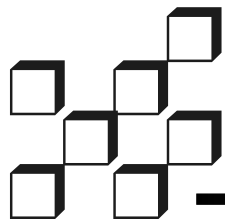
Because the Sivers and Boer-Mulders PDFs are "time-reversal odd", they are expected to change sign when measured from SIDIS or from Drell-Yan:

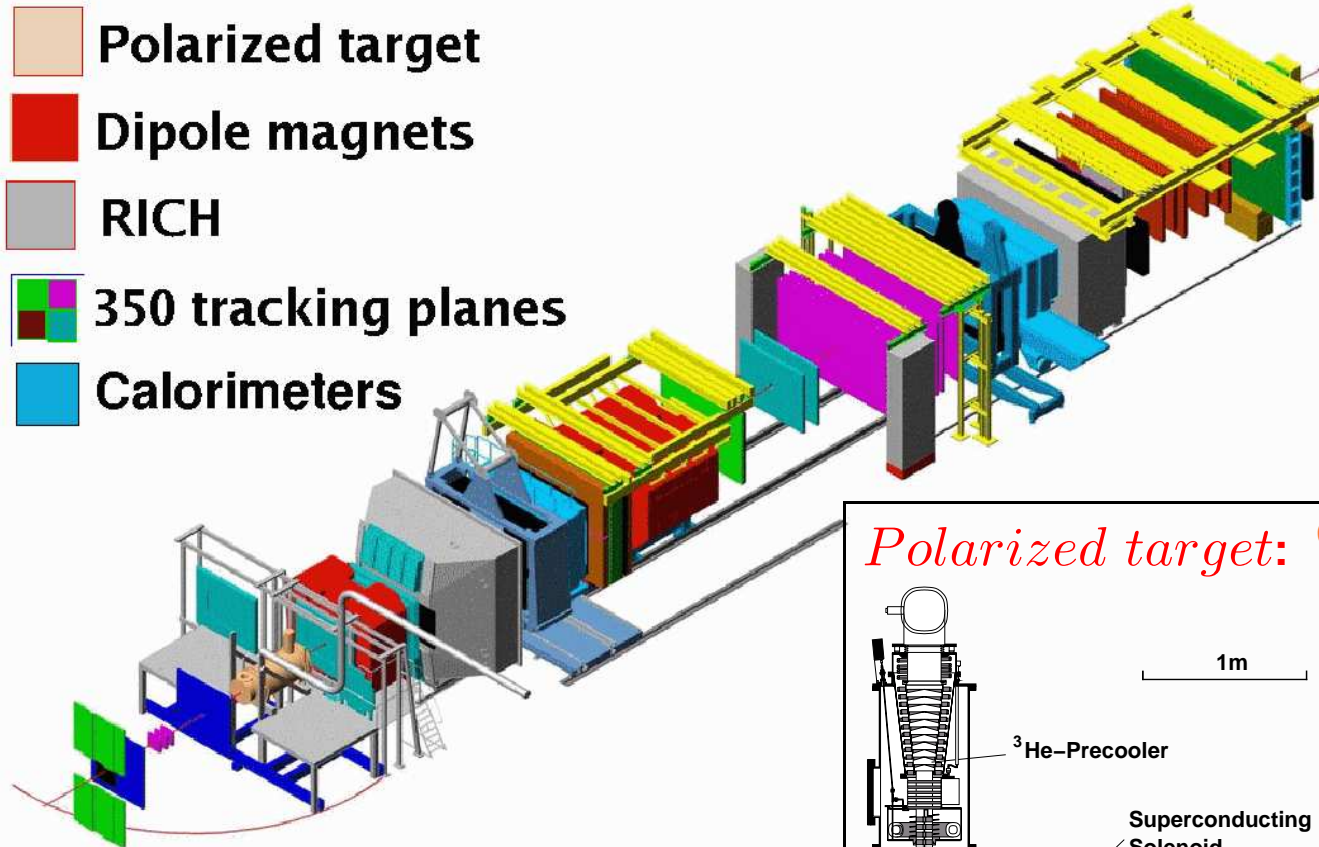$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$$

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

This sign change is considered a crucial test of non-perturbative QCD: the QCD TMD factorization and the TMD approach itself.

In COMPASS, we have the opportunity to test this sign change using the same spectrometer and transversely polarized target.

Polarized target

Dipole magnets

RICH

350 tracking planes

Calorimeters

μ or π beam

N_u N_m N_d

μ

π

Target spin reversal every few days

N_u N_m N_d

Polarized target: ^6LiD **or** NH_3

1m

^{3}He−Precooler

Superconducting Solenoid

Acceptance (180mrad)
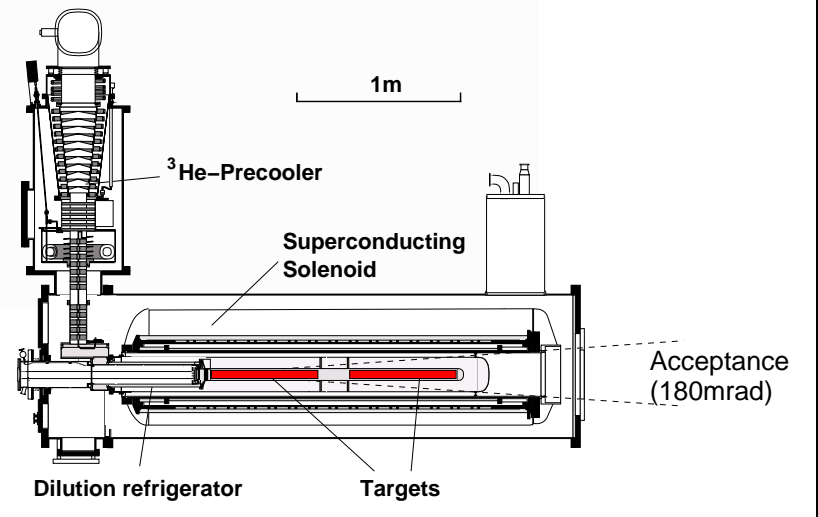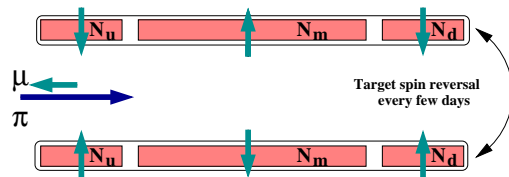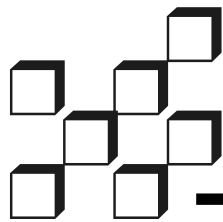
Dilution refrigerator   **Targets**

♦ Availability of hadron beams (100 - 280 GeV/c):
π^- beam @190 GeV/c (4% kaons contamination, $<$1% $\bar{p}$).

♦ A longitudinal/transversely polarized target system:

material	^6LiD	NH_3
polarization	50%	90%
dilution factor	0.4	0.22

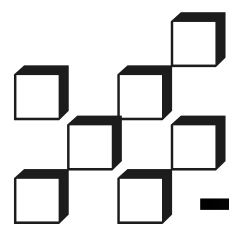♦ Long hadron absorber and beam plug downstream of the target.

♦ Muons angular acceptance: $30 < \theta < 140$ mrad.

♦ Dimuon trigger based on hodoscope signals coincidence, homothetic and pointing to the target.

♦ Long relaxation time of target polarization guaranteed by larger beam spot ($\sigma \approx$ 1cm) $\Rightarrow$ loose very small angle muons.
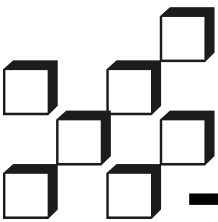
Detailed simulations using PYTHIA and GEANT. Results were compared with published cross-sections from past Drell-Yan experiments – good agreement.

$\sigma_{\mu\mu}^{DY}$ (nb)	$2 < M_{\mu\mu} < 2.5$	$4 < M_{\mu\mu} < 9$ (GeV/c^2)
π^-p @190 GeV/c: PYTHIA (LO)	0.63	0.14
π^-p @190 GeV/c: PYTHIA*K-factor	1.26	0.28
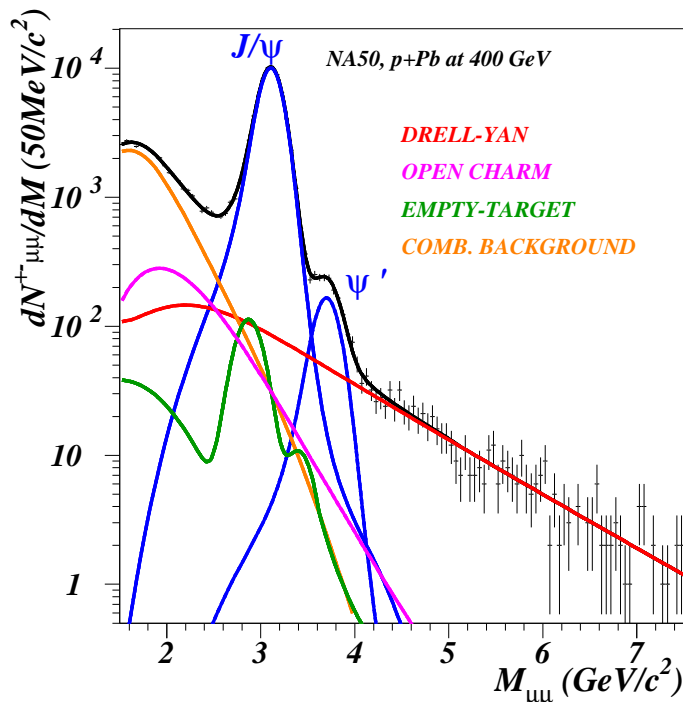
Even if the cross-section is low, dimuons with $4. \leq M_{\mu\mu} < 9.$ GeV/c^2 are the ideal sample to study azimuthal asymmetries in Drell-Yan, due to negligible background contamination.
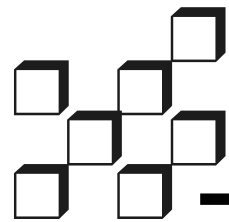
π^- (190GeV/c) on $p^\uparrow$ interactions: u-quark dominance.
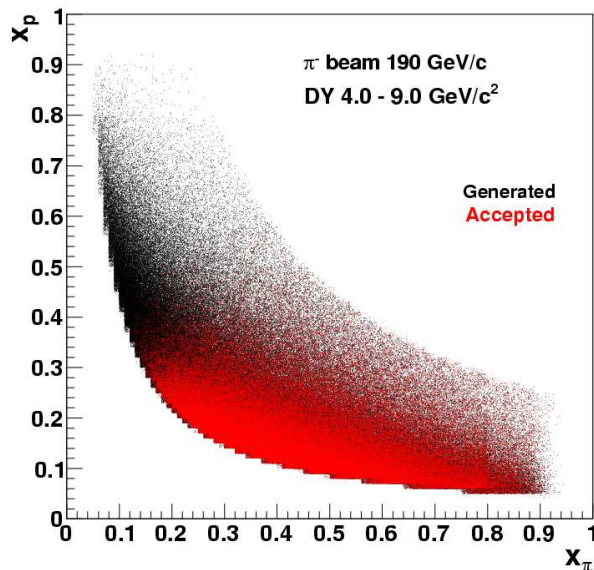
Valence quarks in the nucleon are probed $x_p > 0.1$: also the most favorable region to measure asymmetries, according to theory predictions.

Global acceptance for high mass dimuons: $\approx$ 35%

With a beam intensity $I_{beam} = 6 \times 10^7$ particles/second,

a luminosity of $L = 1.2 \times 10^{32} \ cm^{-2} s^{-1}$ can be obtained

$\Longrightarrow$ expect 800/day DY events with $4 < M_{\mu\mu} < 9$ GeV/c^2.

Assuming 2 years of data-taking (140 days/year), one can collect:

♦ 230 000 events in DY HMR

This will translate into a statistical error in the asymmetries:

Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285

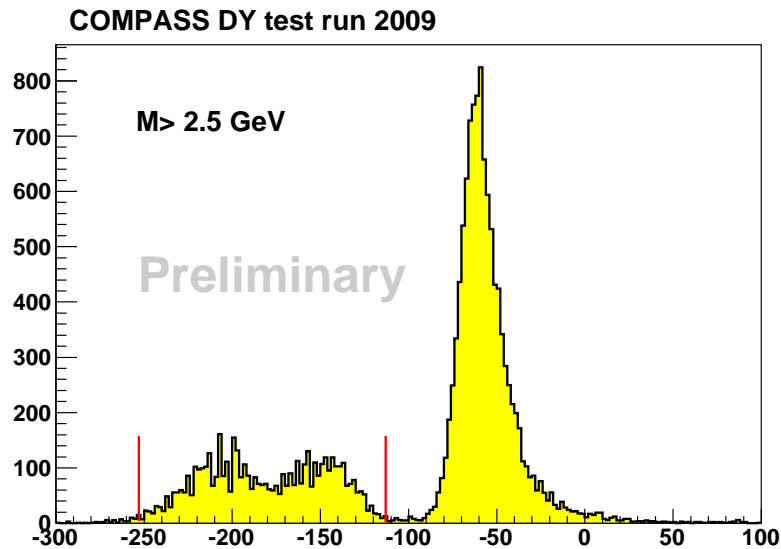$\hookrightarrow$ Possibility to study the asymmetries in several x_F bins.
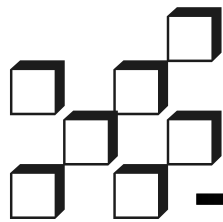
Beam tests were done in 2007, 2008 and 2009 to study the feasibility of the measurement.

◆ The target temperature does not seem to increase significantly with the hadron beam, long polarization relaxation times measured (2007 beam test).

◆ Reasonable occupancies in the detectors closer to the target can only be achieved if a hadron absorber and beam plug is used (2008 beam test).

◆ Radiation conditions are within safety limits up to a beam intensity of $6 \times 10^7 \ \pi^-$/second (measurements during all beam tests)

◆ Physics simulation were validated, within statistical errors (J/ψ peak and combinatorial background, in 2007 and 2009 beam tests).
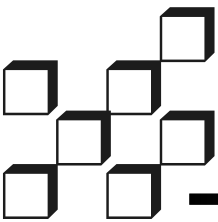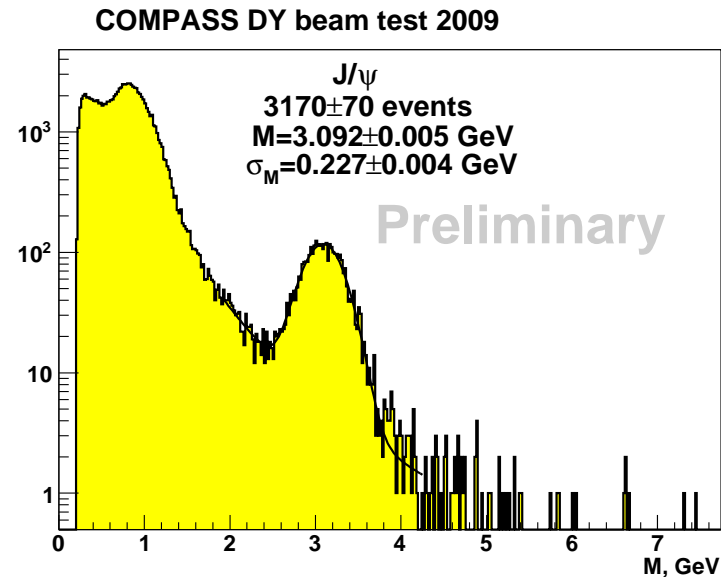
π^- beam 190 GeV/c on a plastic 2-cells target. A hadron absorber and a beam plug were used. The test lasted ≈ 3 days.

COMPASS DY test run 2009

M> 2.5 GeV

Preliminary

COMPASS DY beam test 2009

J/ψ
3170$\pm$70 events
M=3.092$\pm$0.005 GeV
σ_M=0.227$\pm$0.004 GeV

Preliminary

M, GeV

Reasonable Z_{vertex} separation, allowing to distinguish the 2 target cells and the absorber.

Mass resolution as expected, but worse than in previous experiments $\Rightarrow$ reconstruction program still needs optimization.
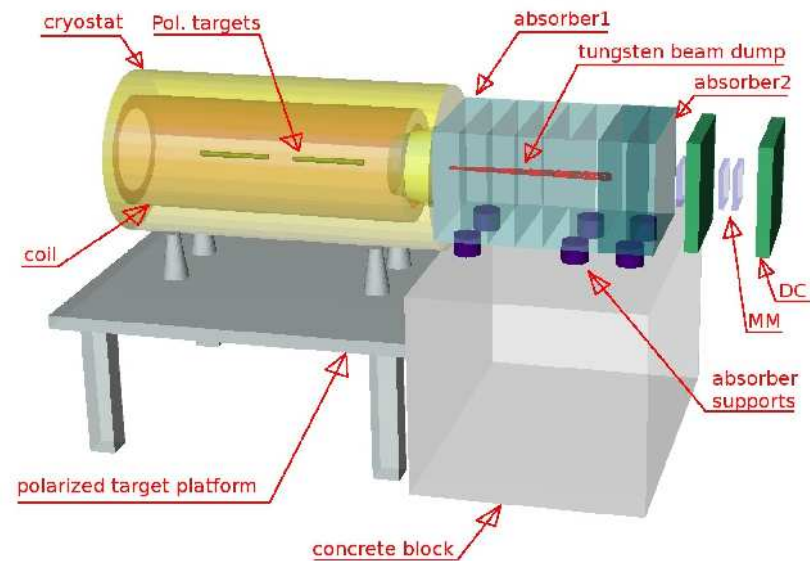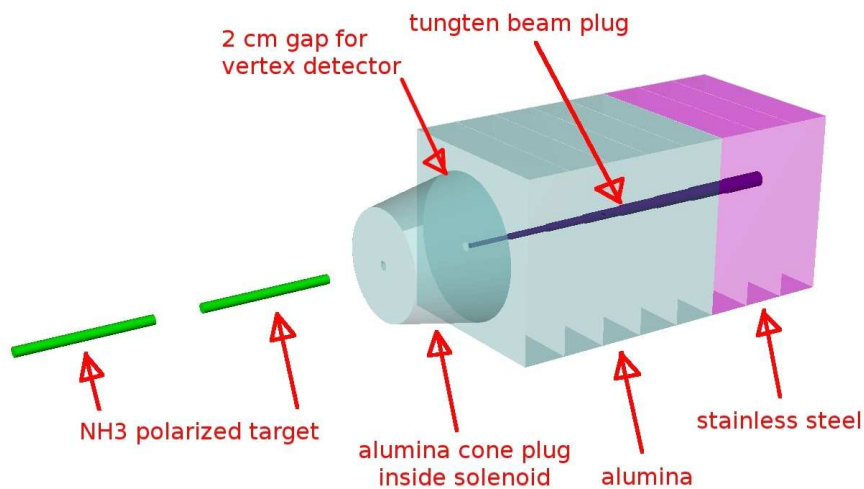
Combinatorial background (from uncorrelated π decays) is estimated using the measured like-sign $\mu\mu$ distributions: the presence of the absorber reduces the background by a factor ≈ 10 at $M_{\mu\mu} = 2$ GeV/c^2.
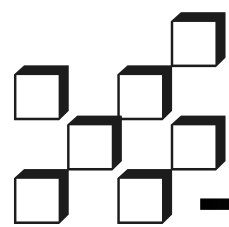
Hadron absorber, beam plug and large area dimuon trigger are the main new components of the project. Optimization studies are ongoing.
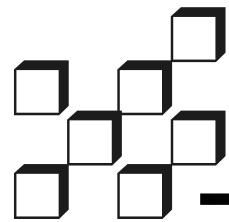
Possible setup

- ♦ 2 target cells (55 + 55 cm), spaced by 20 cm, filled with NH_3, inside a 0.4T dipole.

- ♦ Absorber of Al_2O_3, 2.4 m long (+ steel), with beam plug (W) inside, 1.2 m long.

- ♦ 2 large area hodoscopes, for dimuon trigger in the 1st spectrometer.

- ♦ Possibility to add a vertexing detector between target and absorber.
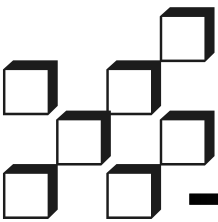
♦ The polarized Drell-Yan measurement is part of the COMPASS-II new physics proposal.

♦ Proposal recommended for approval by SPSC/CERN for a first period of 3 years (2012 to 2014) including 1 year for Drell-Yan.

♦ Feasibility of the measurement shown by beam tests already performed.

♦ The expected statistical accuracy reached in 2 years will allow to check theory predictions and extract TMD PDFs, namely Sivers and Boer-Mulders, as well as the transversity PDF.

♦ Sivers and Boer-Mulders PDFs sign change when measuring in Drell-Yan versus SIDIS will be checked. This is considered to be a fundamental test of the TMDs approach.

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

♦ **Boer-Mulders**: the $h_1^{\perp}(x, k_T^2)$ function
describe$correlation between the transverse spin and the transverse mome$
unpolarized hadron.

♦ **Pretzelosity**: the $h_{1T}^{\perp}(x, k_T^2)$ function
descr$the transverse polarization of a quark, along its intrinsic$k$_T$
direction.
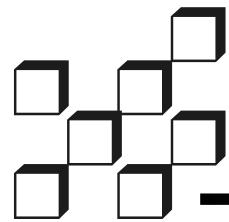
J/ψ and γ being vector particles, the analogy between J/ψ and DY production mechanisms might be of interest:
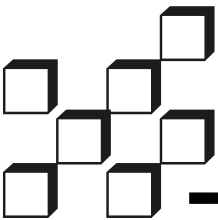
$$\pi^- p^\uparrow \to J/\psi X \to \mu^+ \mu^- X \qquad\qquad \pi^- p^\uparrow \to \gamma^* X \to \mu^+ \mu^- X$$

J/ψ production via $q\bar{q}$ annihilation dominates at low-energies, justifying such analogy – J/ψ-DY duality.

From the study of J/ψ production in the dileptons decay channel:

◆ Check duality hypothesis – polarized J/ψ production cross-section

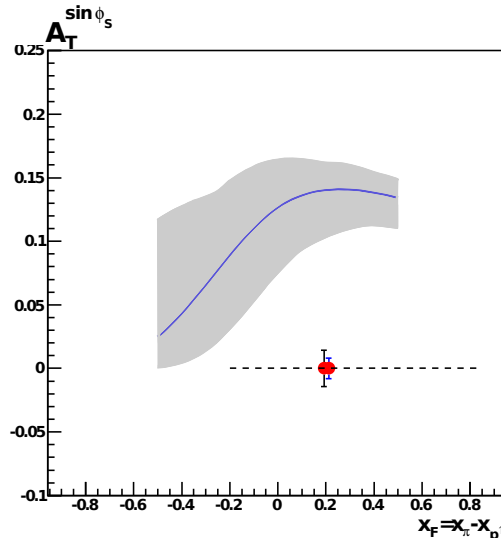◆ Access PDFs from J/ψ events – larger statistics available

Using secondary hadron beams it is possible to vary the beam energy (from 50 to 200 GeV), to study different J/ψ production mechanisms.
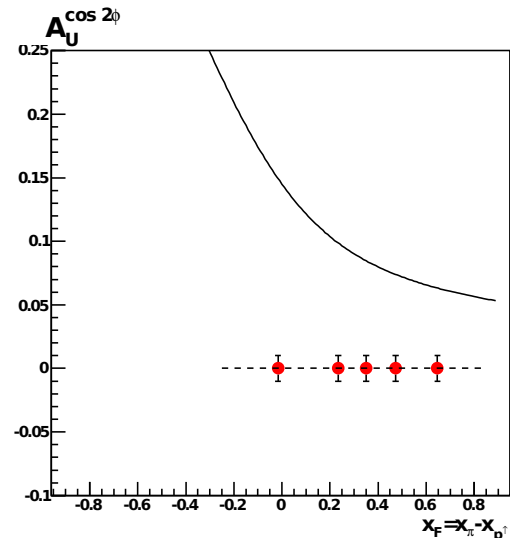
DY $4. - 9.$ GeV/c^2

Sivers

Boer-Mulders

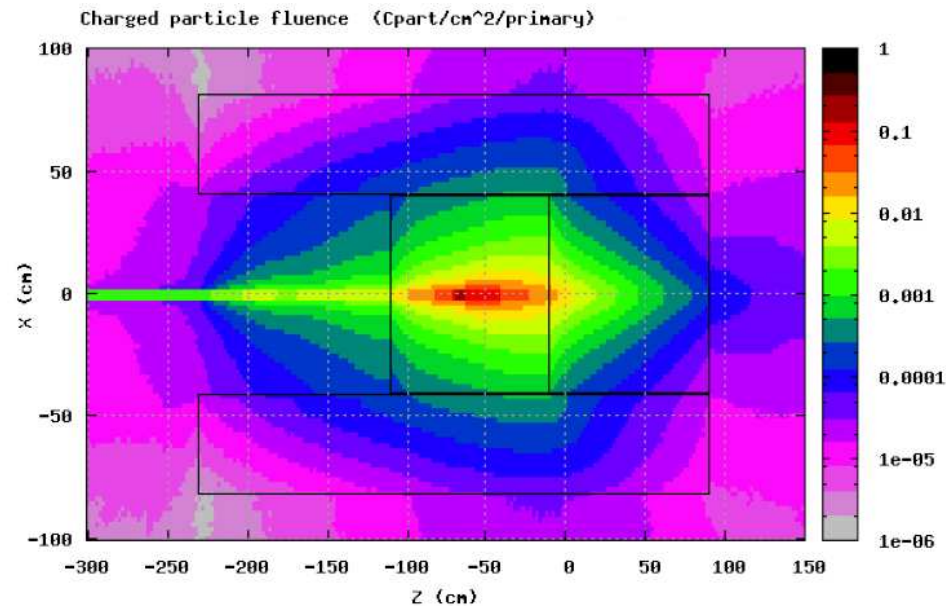BM $\otimes$ pretzelosity
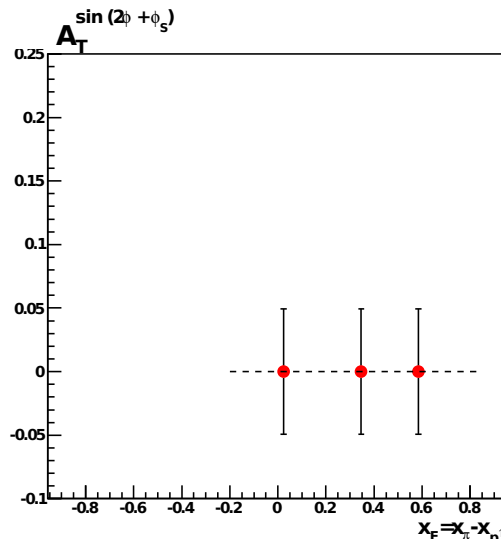
BM $\otimes$ transversity
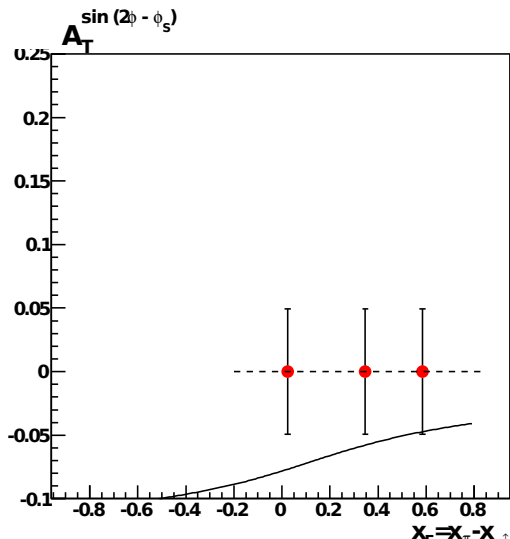
COMPASS is a ground-level experiment, thus radiation conditions must be monitored, with appropriate shielding surrounding the target $+$ absorber region:

FLUKA simulations describing the polarized target, absorber, beam plug and shielding, and the spectrometer, show that with beam intensity 6×10^8 to 1×10^9 π^-/spill the particles fluence is still below radio-protection limits, and safe for the detectors downstream.