The Drell-Yan program at COMPASS

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on behalf of the COMPASS Collaboration

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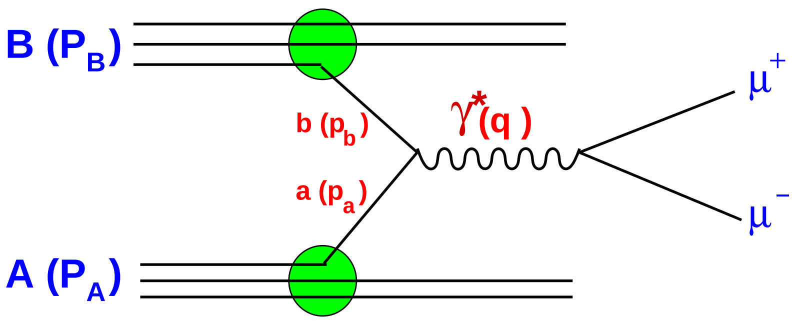
Outline

- Polarized Drell-Yan process
- TMD PDFs
- TMDs in COMPASS: SIDIS and DY
- Drell-Yan at COMPASS: why and how
- COMPASS sensitivity to TMD PDFs
- Summary

Polarized Drell-Yan

Quark-antiquark annihilation, with dilepton production:



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

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

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

If the quarks intrinsic transverse momentum $\neq 0$, the dimuon has also $q_T = k_{Ta} + k_{Tb}$.

If transversely polarized target, 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
- D: depolarization factor
- S: target spin components

- $F = 4\sqrt{(P_a\cdot P_b)^2 - M_a^2 M_b^2}$
- $\hat{\sigma}_U$: cross-section surviving integration over ϕ and ϕ_S.

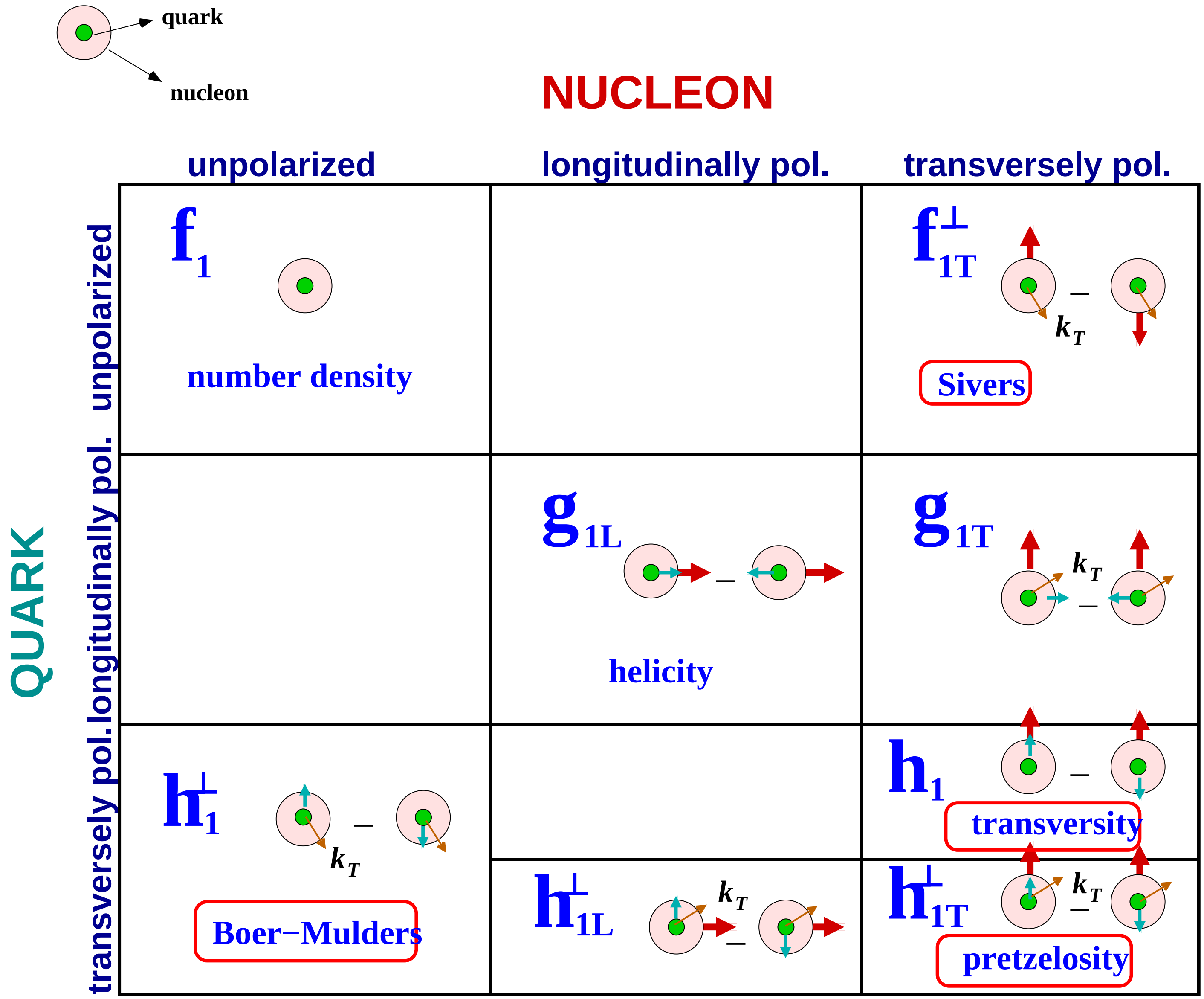
Azimuthal asymmetries

Each one of these asymmetries contains a convolution of 2 PDFs:

- $A_U^{\cos 2\phi}$: the Boer-Mulders functions of incoming hadrons ($h_1^{\perp}$);
- $A_T^{\sin \phi_S}$: the Sivers function of target nucleon ($f_{1T}^{\perp}$);
- $A_T^{\sin(2\phi+\phi_S)}$: the Boer-Mulders function of beam hadron ($h_1^{\perp}$) and the pretzelosity of target nucleon ($h_{1T}^{\perp}$);
- $A_T^{\sin(2\phi-\phi_S)}$: the Boer-Mulders function of beam hadron ($h_1^{\perp}$) and the transversity of the target nucleon (h_1).

These Transverse Momentum Dependent PDFs (TMDs) are part of the 8 TMDs needed to describe the nucleon structure when the intrinsic transverse momentum is also taken into account.

TMD PDFs

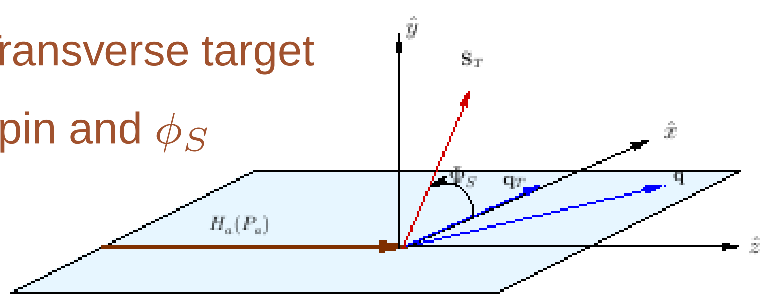

quark
nucleon
NUCLEON
unpolarized
longitudinally pol.
transversely pol.
QUARK
unpolarized
longitudinally pol.
transversely pol.
f_1
number density
$f_{1T}^{\perp}$
k_T
Sivers
g_{1L}
helicity
g_{1T}
k_T
$h_1^{\perp}$
k_T
Boer−Mulders
h_1
transversity
$h_{1L}^{\perp}$
k_T
$h_{1T}^{\perp}$
k_T
pretzelosity

Reference frame

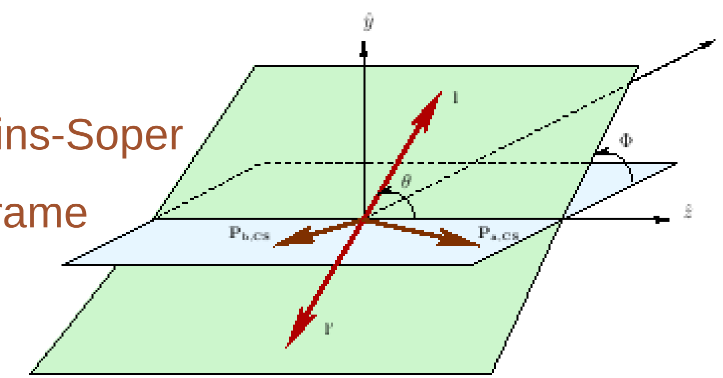
When measuring azimuthal spin asymmetries, the choice of reference frame is important.

The Collins-Soper frame is usually used in Drell-Yan: a special rest frame of the dimuon, where the Z-axis is along the bissector of initial hadron momenta.

Transverse target spin and ϕ_S



Collins-Soper frame



The advantage of this Collins-Soper Z-axis as optimal spin quantization axis is partly "diluted" when including transverse effects.

(Non-)Universality of TMD PDFs

Because the Sivers and Boer-Mulders PDFs are "time-reversal odd", a sign change of these TMDs when measured from SIDIS or from Drell-Yan is predicted:

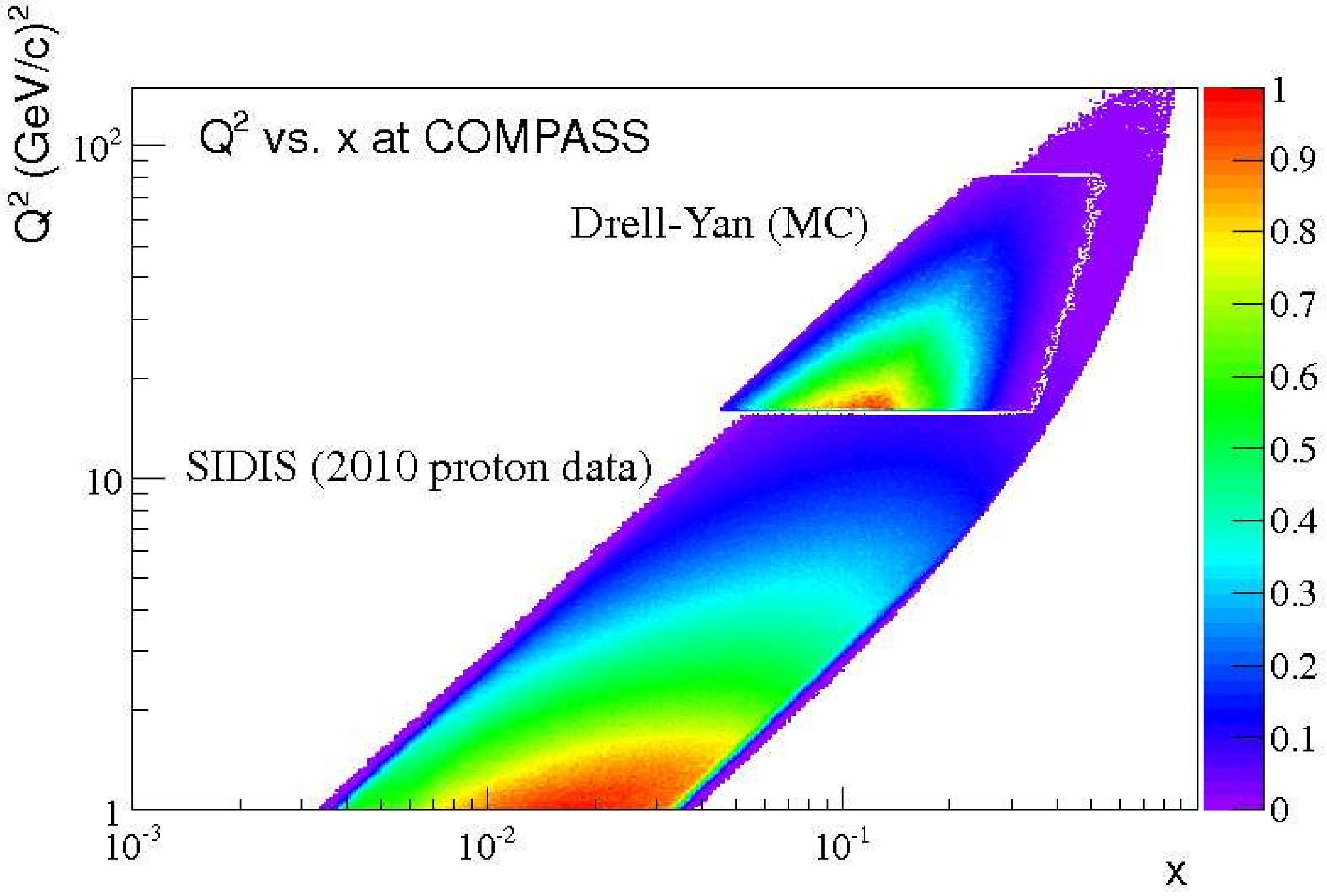
$$\boxed{f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)} \qquad \boxed{h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)}$$

$$\Downarrow$$

Test the QCD TMD factorization and the TMD approach itself.

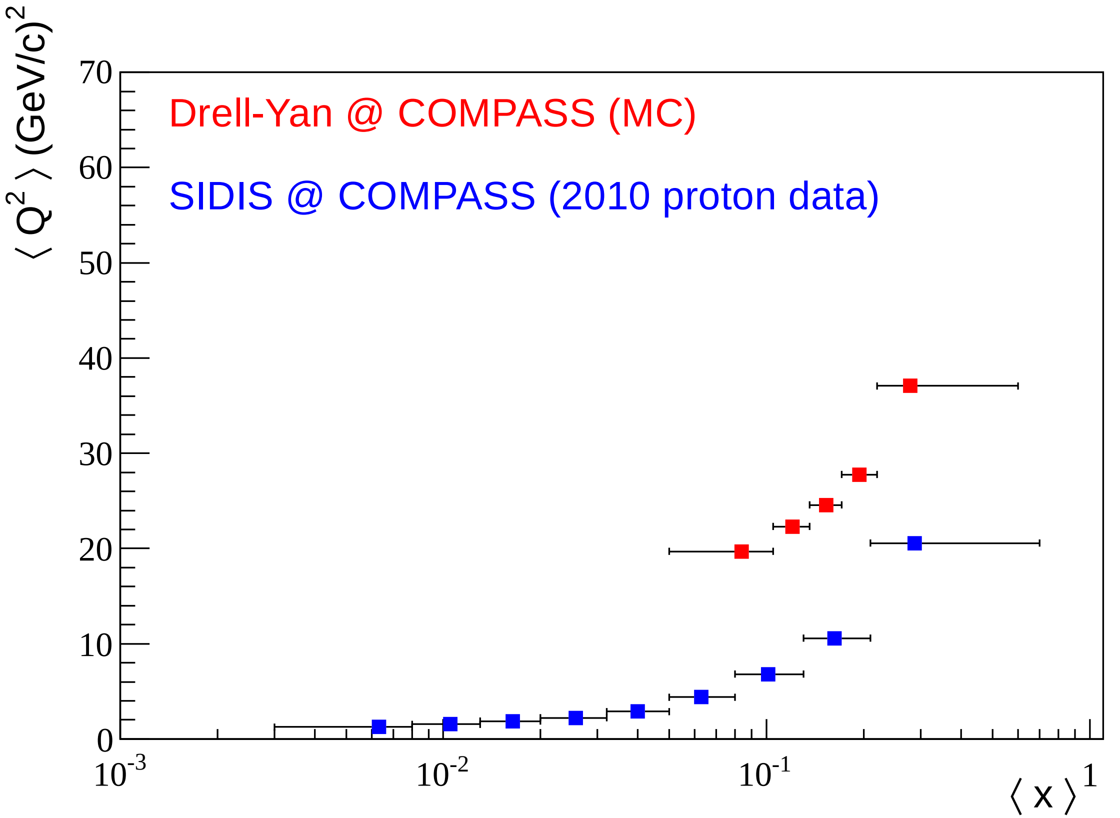
In COMPASS, we have the opportunity to test this sign change using the same spectrometer and a transversely polarized target.

DY versus SIDIS in COMPASS



The 2 experimental measurements have an overlapping region.

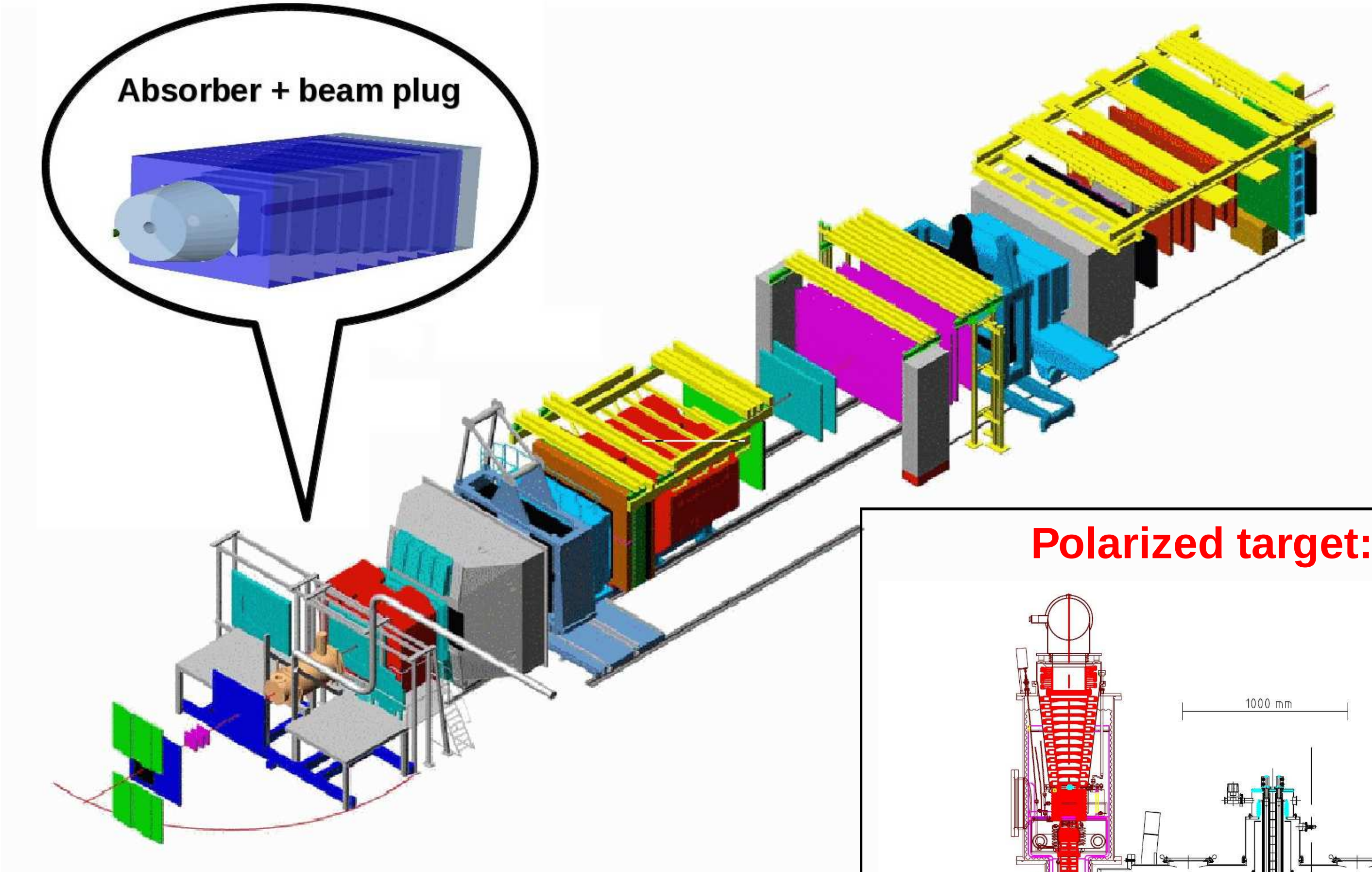
DY versus SIDIS

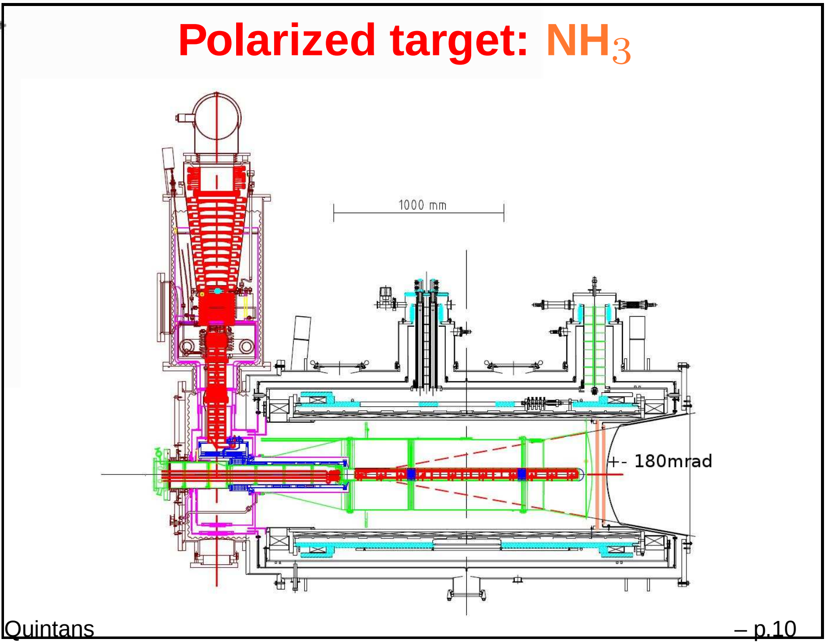


There is overlap in the phase-space accessed by the 2 measurements. Nevertheless, when comparing the TMDs extracted, the QCD evolution of the TMDs must be properly taken into account.

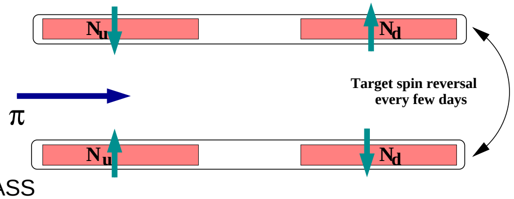
$\hookrightarrow$A. Prokudin's talk

The COMPASS Experiment at CERN





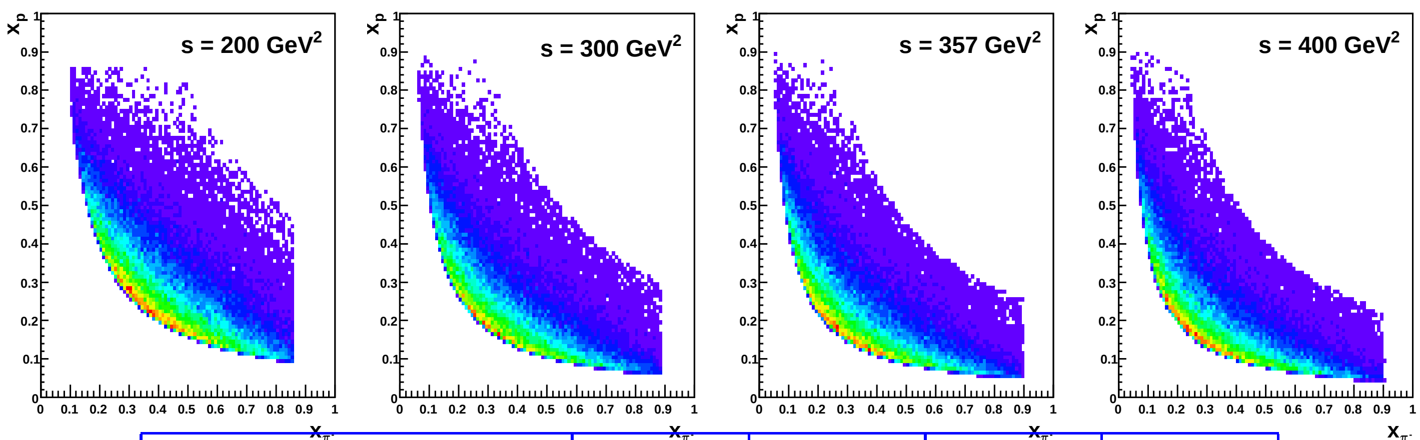
π^- beam



Choice of beam

Drell-Yan with π^- beam: u-quark dominance.

- π^- beam with small contamination from other particles: 2% kaons, $<$1% $\bar{p}$. Muon halo contamination $<$1%.
- High intensity beam, up to 1×10^8/second possible, limited by the radiation levels allowed.
- Beam momentum can be in the range 100 - 280 GeV/c



p^{π} (GeV/c)	106	160	190	213
$\sigma_{\pi p}^{DY\rightarrow\mu\mu} * K$ (nb)	0.164	0.252	0.290	0.318

Polarized target

The polarized target system comprises:

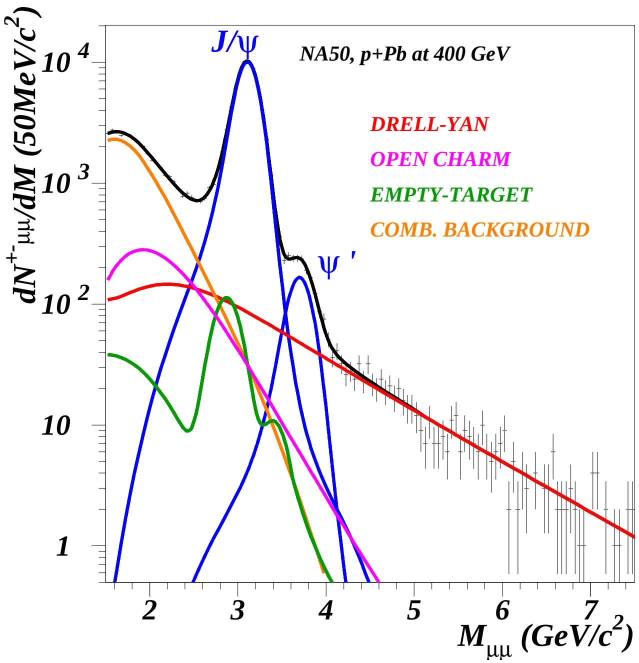
- a cryogenic part to cool the target material down to 50 mK;
- a solenoid to build-up polarization in the target material;
- a dipole to keep the polarization when in transverse mode.

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

Ammonia is the ideal material to study the proton spin, while ^{6}LiD may be of interest to study deuteron spin.

The target cells $\varnothing$ must be large enough for uniform filling.
Correct polarization measurement requires beam spot dimensions similar to target $\varnothing$ ($\approx$ uniform irradiation).
$\hookrightarrow$ target cells with 4 cm diameter; beam spot $\sigma_{x,y}$=1 cm.

Signal and background

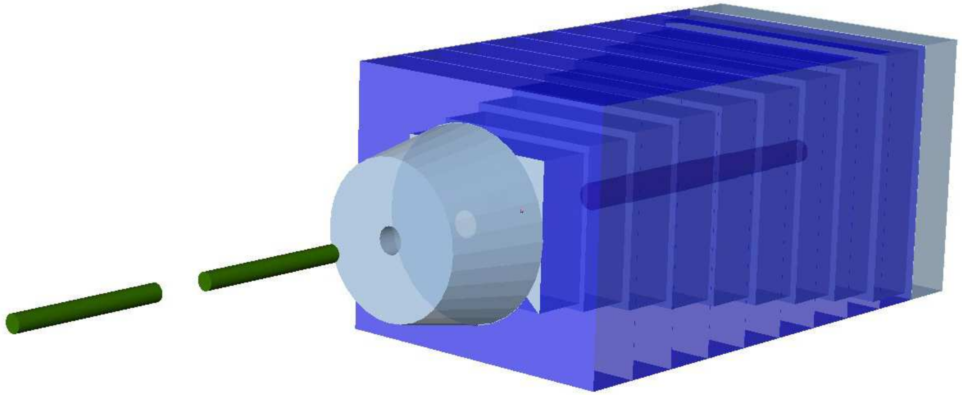


Even if the cross-section is low, dimuons with $4 \leq M_{\mu\mu} < 9$ GeV/c^2 are the ideal sample to study azimuthal asymmetries in Drell-Yan, due to negligible background contamination.

The combinatorial background is kept under control by the presence of a hadron absorber downstream of the target.

Absorber and beam plug

- A hadrons absorber made of Al_2O_3 allows to minimize the multiple scattering suffered by the muons, while maximizing the stopping power of produced hadrons.
- A tungsten beam plug allows to efficiently stop the beam which does not interact in the target. Its shape is optimized to contain the Molière cascades, reducing the probability of crossing by Drell-Yan muons.



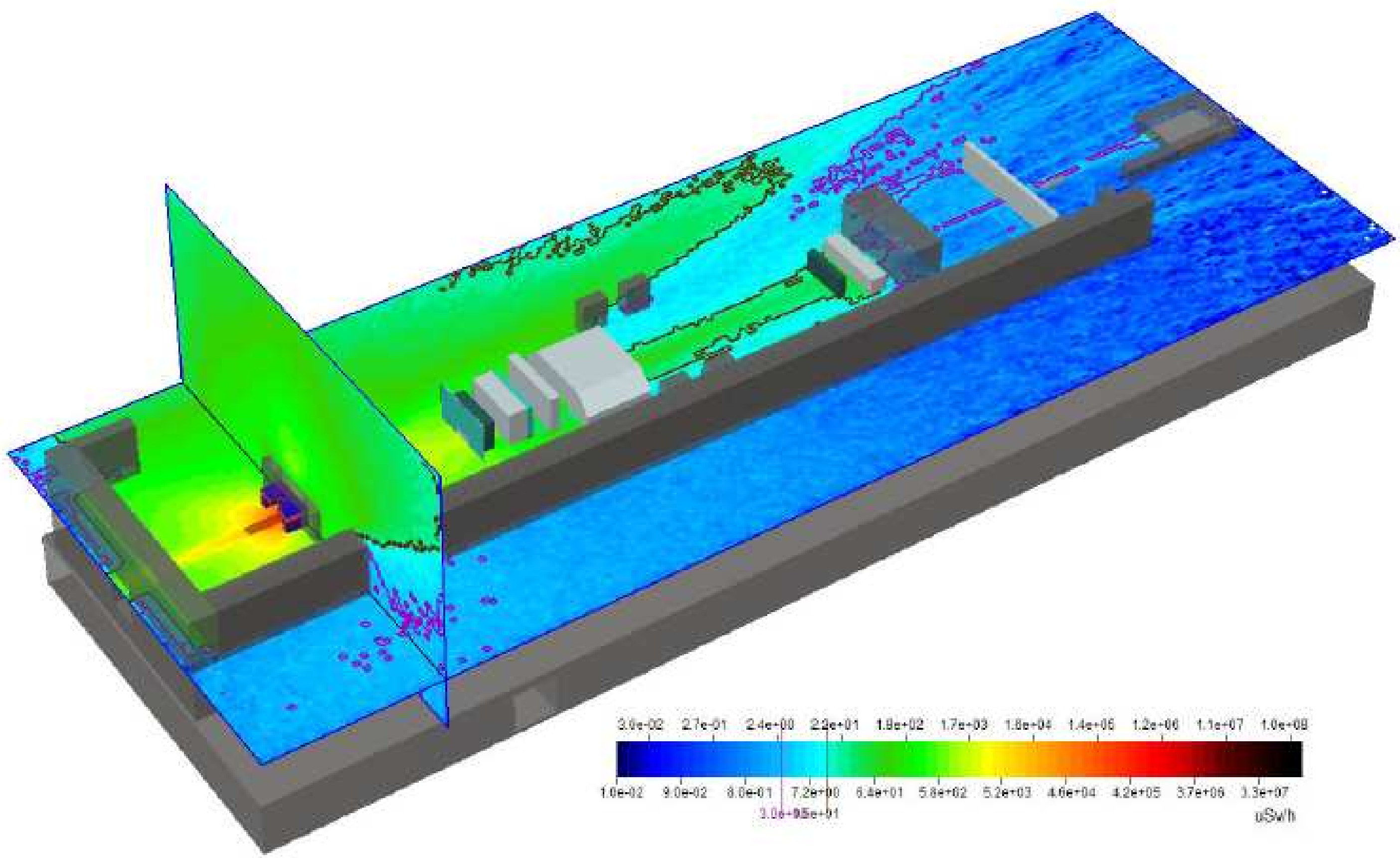
Present configuration
(still undergoing optimization):

	Absorber	Beam plug
X/X0	34	343
X/λ^{π}_{int}	7.2	10.6

Radiation conditions

Higher beam intensity implies also the increase of radiation doses, thus requires larger absorber and shielding.

The control room must be moved to a remote location and the radiation conditions must be carefully controlled $\Rightarrow$ Radioprotection CERN group $+$ detailed COMPASS simulations



COMPASS Spectrometer

The 2-stage spectrometer remains practically unchanged:

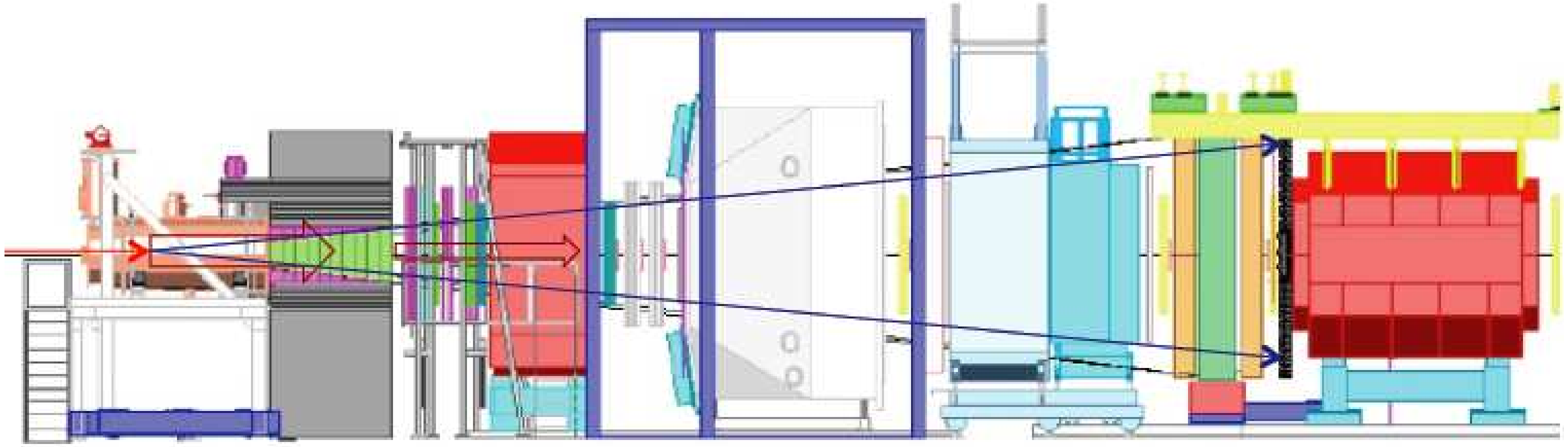
- More than 300 tracking planes
- Replace less efficient large angle trackers by new drift chambers
- 3 absorbers along the spectrometer, to ensure muon identification
- Capability to identify muons with angles $18 < \theta_\mu < 180$ mrad
- Calorimeters and RICH are not used, and act as additional absorbers
- Possibility to place a scintillator fibers detector in between the absorber parts is under study $\Rightarrow$ improve vertexing
- A beam telescope with minimal material in the beam path, based on scintillating fiber detectors
- The beam momentum is assumed to be $p_\mu = 190$ GeV/c; the beam particles are assumed as pions (small contamination).

Dimuon trigger

The design of the dimuon trigger system is under study. It will be based in coincidences of the single muon signals, with logics implemented in FPGAs.

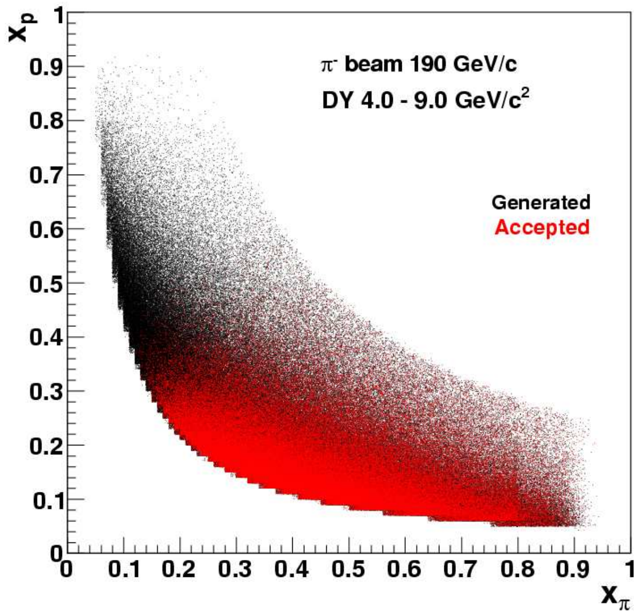
- a Large Angle Spectrometer trigger: 2 large area hodoscopes, the second placed downstream of a hadrons absorber (LAST);
- a Small Angle Spectrometer trigger: 2 hodoscopes (modified Outer System), complemented with smaller angle hodoscopes (with absorber upstream of the second hodoscope) (OT);
- The hodoscopes have target pointing capability, ensured by horizontal scintillator slabs coincidence matrix;
- Dimuon coincidences for 2 muons in LAST OR one muon in LAST and another in OT;
- A veto system to reject near halo muons.

Drell-Yan at COMPASS



- π^- beam @190 GeV/c, I_{beam} up to 1×10^8 particles/second.
- A transversely polarized target of NH_3, with dipole field 0.5 T.m
- Hadron absorber of Al_2O_3, 240 cm long; and tungsten beam plug of 120 cm.
- 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) $\Rightarrow$ lose very small angle muons.

COMPASS acceptance



Valence quarks in the nucleon are probed.

For DY $4 \leq M_{\mu\mu} \leq 9$ GeV/c^2, we have $x_p > 0.05$
$\hookrightarrow$ also the most favorable region to measure asymmetries, according to theory predictions.

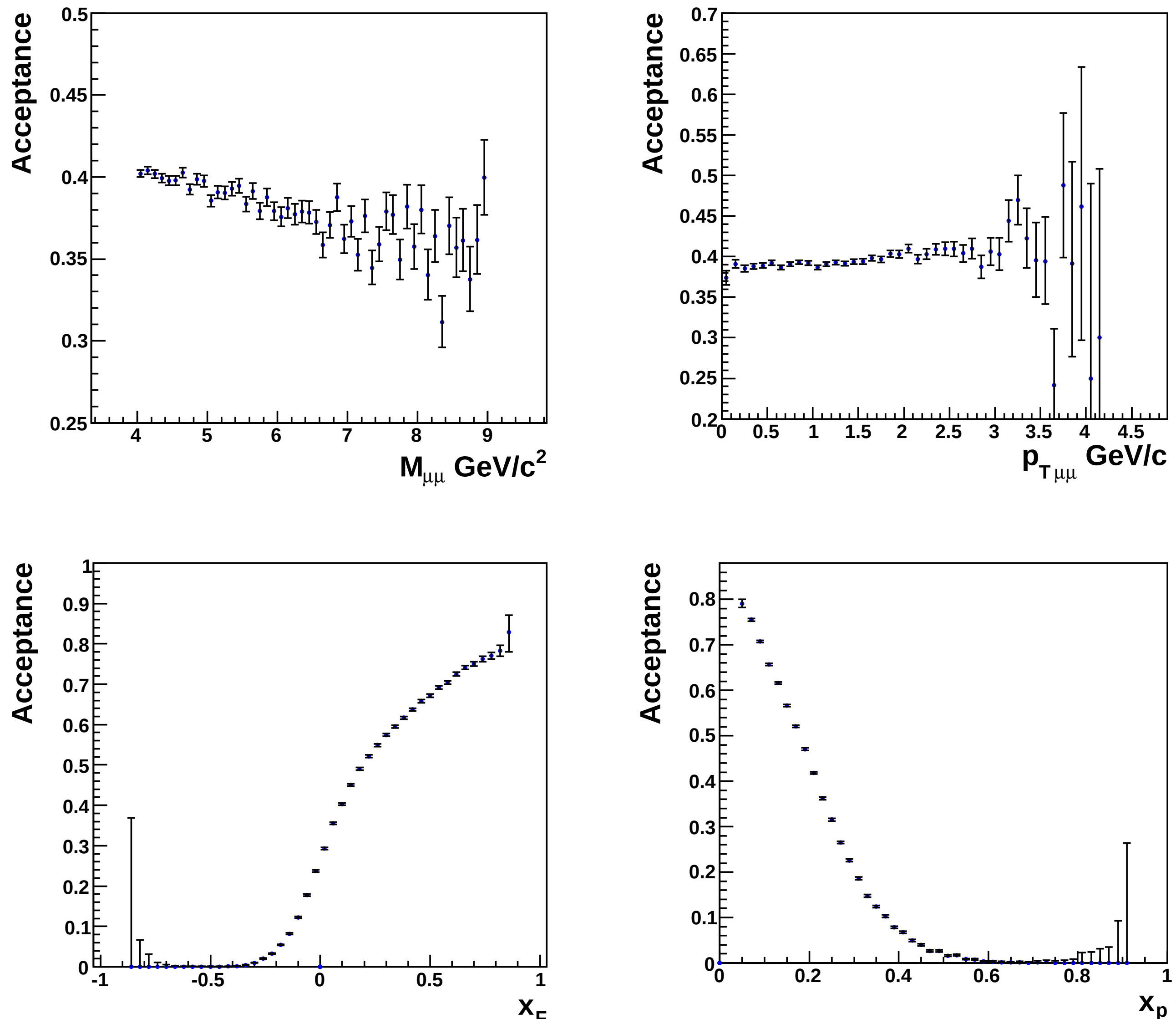
Global acceptance for high mass dimuons: $\approx$ 39% :

- both muons in the Large Angle Spectrometer: 22%
- one in Large Angle, another in Small Angle Spectrometer: 18%
- both muons in the Small Angle Spectrometer: 2% (no trigger)

(some superposition between LAS and SAS)

Acceptances

DY: $4 < M_{\mu\mu} < 9$ GeV/c^2



Expected event rates

With a beam intensity of $I_{beam} = 6 \times 10^7$ particles/second,
a luminosity of $L = 1.2 \times 10^{32}\ cm^{-2}s^{-1}$ can be obtained
$\Longrightarrow$ expect 900/day DY events with $4 < M_{\mu\mu} < 9$ GeV/c^2.

In 280 days one can collect 250 000 events in the DY HMR.
($\approx$ 420 000 events if $I_{beam} = 1 \times 10^8$ particles/second)

The expected statistical error in the asymmetries is:

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	0.0080	0.0285
$\delta\, A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.0080	0.0285

$\hookrightarrow$ Possibility to study the asymmetries in several x_F bins.

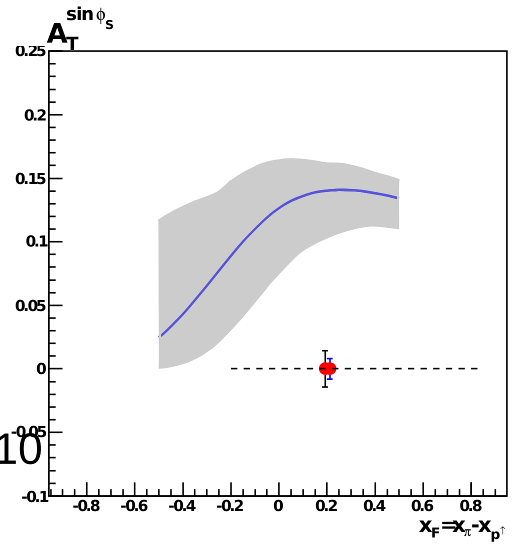
Comparing with theory predictions

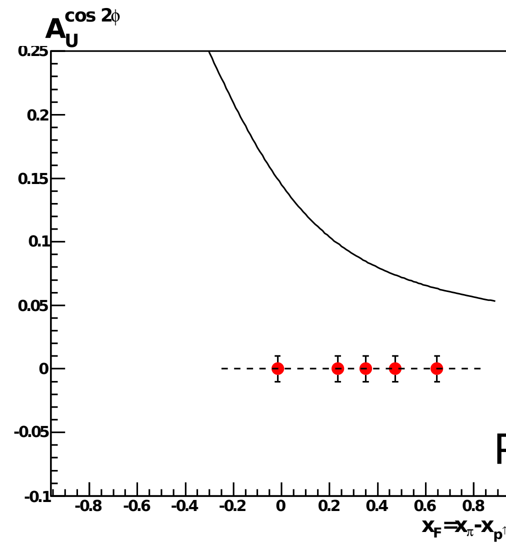
...but: Q^2 evolution not properly accounted for in the predictions...

DY: $4 < M_{\mu\mu} < 9$ GeV/c^2

Sivers

Anselmino et al, PRD79(2009)054010

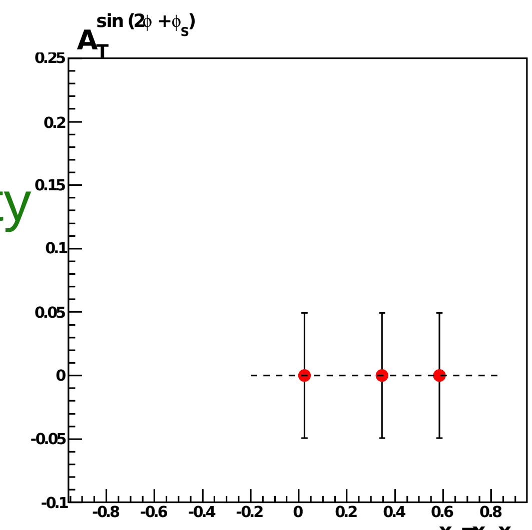


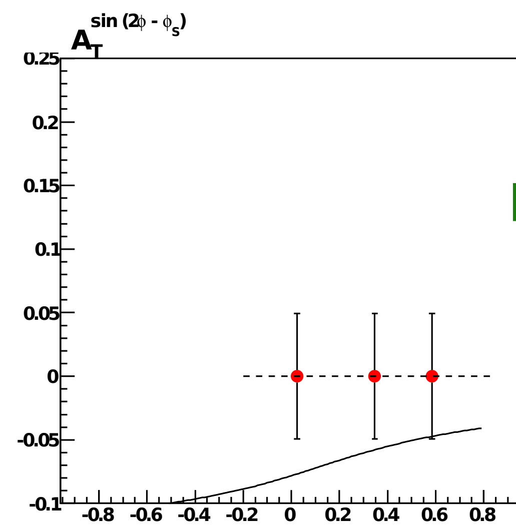


Boer-Mulders

B. Zhang et al, PRD77(2008)054011

BM $\otimes$ pretzelosity





BM$\otimes$transversity

A.N. Sissakian et al, Phys.Part.Nucl.41: 64-100,2010

J/ψ-DY duality

J/ψ and γ being vector particles, the analogy between J/ψ and DY production mechanisms might be of interest:

$$\pi^- p^\uparrow \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X \qquad\qquad \pi^- p^\uparrow \rightarrow \gamma^* X \rightarrow \mu^+ \mu^- X$$

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 dimuon decay channel:

- Check duality hypothesis – polarized J/ψ production cross-section
- Access PDFs from J/ψ events – larger statistics available

Varying the beam energy (between 100 and 280 GeV), one can study the different J/ψ production mechanisms.

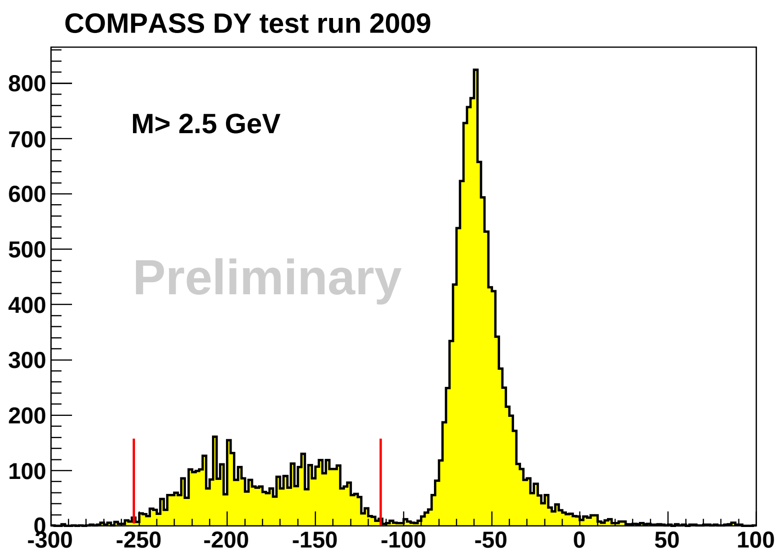
Feasibility studies

Beam tests were done in 2007, 2008 and 2009 to study the feasibility of the measurement.

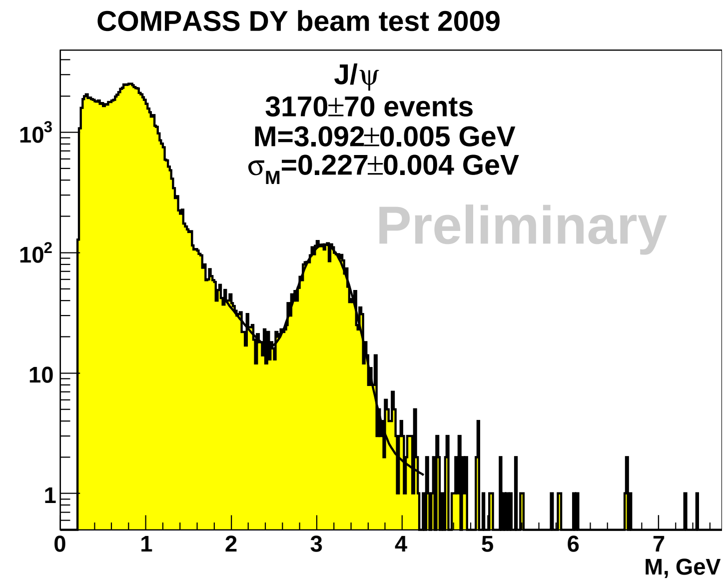
- The target temperature does not seem to increase significantly with the hadron beam, long polarization relaxation times measured (2007 beam test).
- Reasonable occupancies in the detectors closer to the target can only be achieved if a hadron absorber and beam plug is used (2008 beam test).
- Radiation conditions should be within safety limits up to a beam intensity of 1×10^8 π^-/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).

2009 feasibility studies

2009: π^- beam 190 GeV/c on a 2-cells polyethylene target. Setup including hadron absorber and a beam plug. 3 days of data-taking.



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



Mass resolution as expected, but reconstruction program still needs optimization.

Combinatorial background (from uncorrelated π decays) is estimated using the measured like-sign $\mu^\pm\mu^\pm$ distributions: the absorber reduces the background by a factor $\approx$ 10 at $M_{\mu\mu} = 2$ GeV/c^2.

Summary

- The new COMPASS Proposal was approved by CERN for a first period of 3 years (starting now), including 1 year for Drell-Yan.
- The polarized Drell-Yan measurement, now planned for 2014, will be the first of its kind in the world.
- Feasibility of the measurement was shown in the beam tests already performed.
- Sivers and Boer-Mulders PDFs sign change when measuring in Drell-Yan or in SIDIS will be checked.
- The expected statistical accuracy reached in 2 years will allow to check theory predictions and extract TMD PDFs, namely Sivers, Boer-Mulders and Pretzelosity, as well as the transversity PDF.

$\hookrightarrow$ Exciting times ahead of us!