Transverse spin physics from the Drell-Yan process in COMPASS

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on behalf of the COMPASS Collaboration

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ECT Workshop on Drell-Yan Scattering

and the Structure of Hadrons

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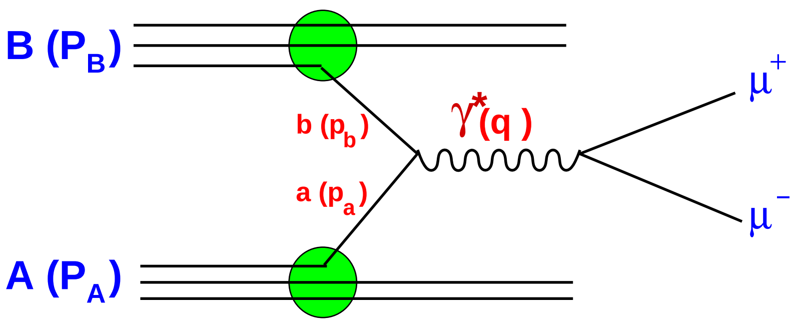
Outline

- 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

$\hookrightarrow$ Unpolarized Drell-Yan measurements: covered in Wen-Chen Chang's talk

Drell-Yan process

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 $q_T = k_{Ta} + k_{Tb}$.

The Drell-Yan angular distribution is:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

Past experiments NA10 (CERN) and E615 (Fermilab) have observed important $\cos 2\phi$ dependence, with ν up to 30%.

$\hookrightarrow$ a correlation between the quarks k_T and their transverse spin (i.e. the Boer-Mulders TMD PDF) may lead to the observed modulation.

Polarized Drell-Yan

With a transversely polarized target, one can calculate the cross-sections asymmetry between the 2 possible spin configurations, and cancel part of the systematic errors involved.

Written in terms of the azimuthal asymmetries, 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.

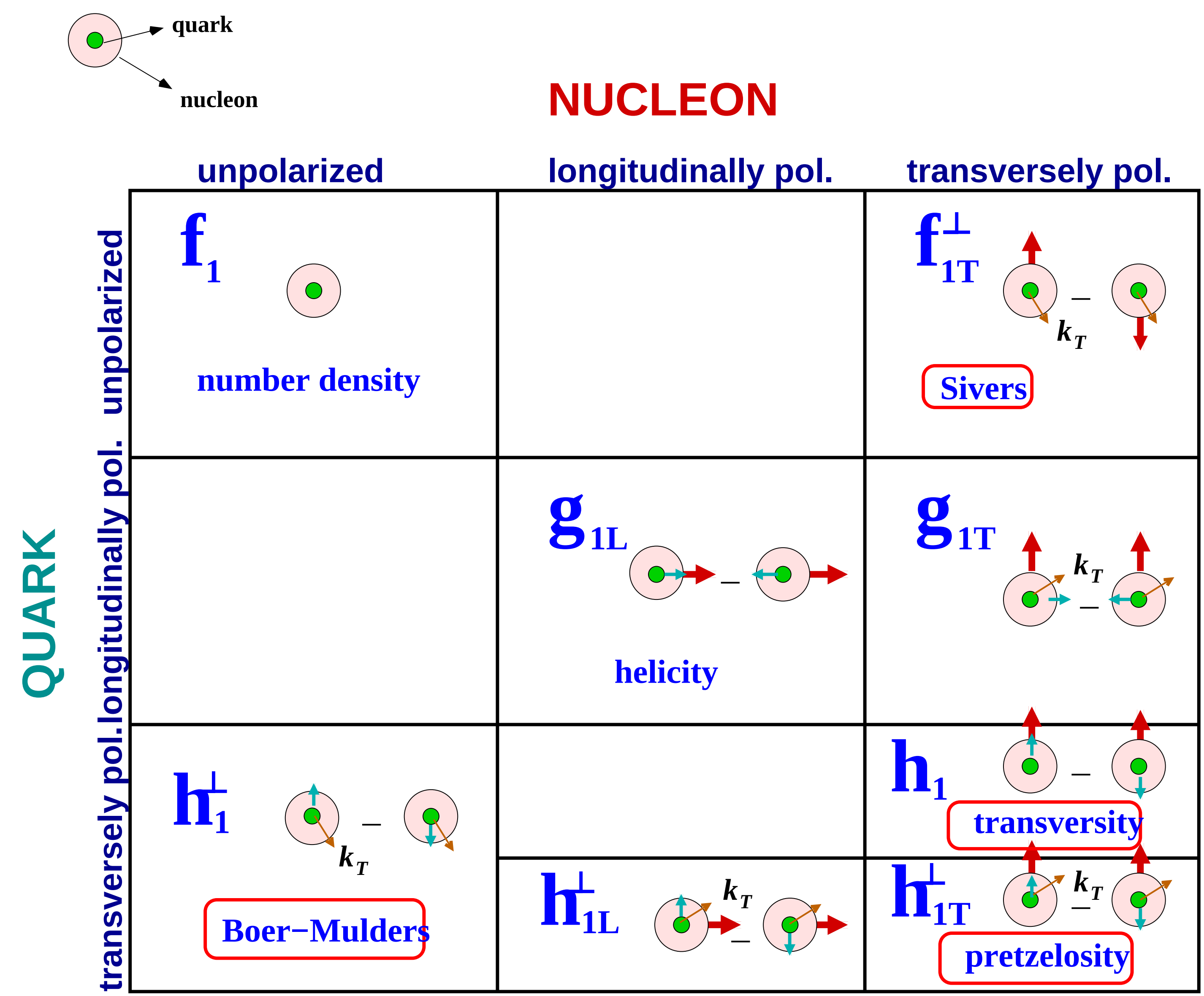
Azimuthal asymmetries

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

- $A_U^{\cos 2\phi}$: the Boer-Mulders functions of incoming hadrons ($h_1^\perp(\pi) \otimes h_1^\perp(p)$);
- $A_T^{\sin \phi_S}$: density number of beam hadron with the Sivers function of target nucleon ($f_1(\pi) \otimes f_{1T}^\perp(p)$);
- $A_T^{\sin(2\phi+\phi_S)}$: Boer-Mulders function of beam hadron with pretzelosity of target nucleon ($h_1^\perp(\pi) \otimes h_{1T}^\perp(p)$);
- $A_T^{\sin(2\phi-\phi_S)}$: Boer-Mulders function of beam hadron with transversity of target nucleon ($h_1^\perp(\pi) \otimes h_1(p)$).

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

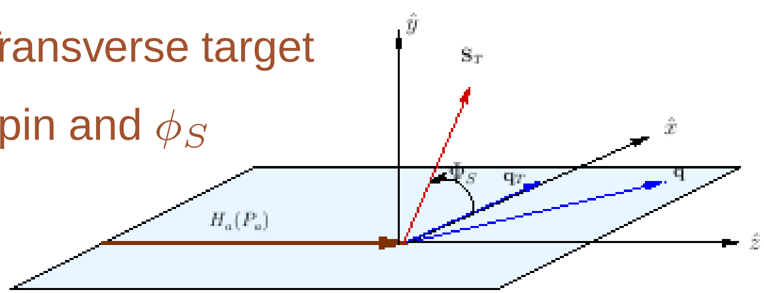

quark
nucleon
NUCLEON
unpolarized
longitudinally pol.
transversely pol.
QUARK
unpolarized
longitudinally pol.
transversely pol.
f_1
number density
$f_{1T}^{\perp}$
k_T
Sivers
g_{1L}
helicity
g_{1T}
k_T
h_1
transversity
$h_1^{\perp}$
k_T
Boer−Mulders
$h_{1L}^{\perp}$
k_T
$h_{1T}^{\perp}$
k_T
pretzelosity

Reference frame

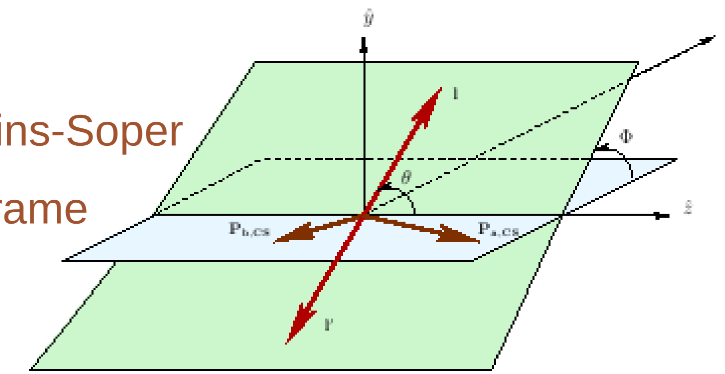
When measuring azimuthal spin asymmetries, the choice of reference frame is important.

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



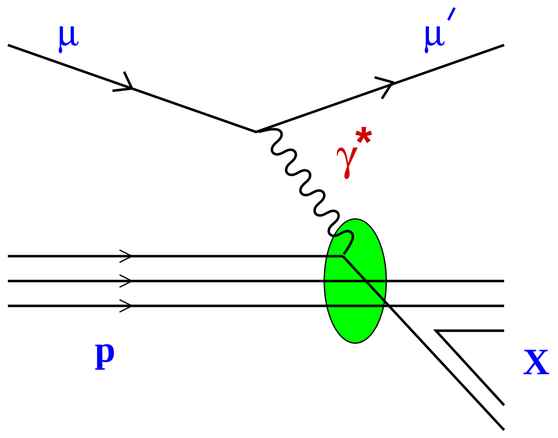
Collins-Soper frame



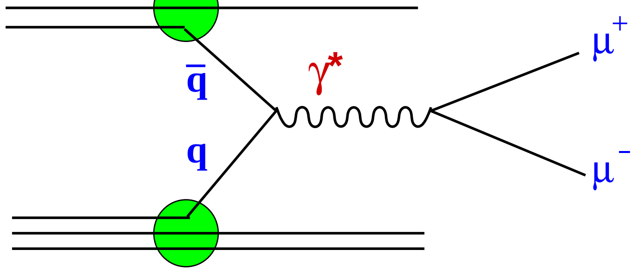
The advantage of this Collins-Soper Z-axis as optimal spin quantization axis is partly "diluted" when including transverse effects.

(Non-)Universality of TMD PDFs

SIDIS



DY



Because the Sivers and Boer-Mulders PDFs are naive time-reversal odd, a sign change of these TMDs when measured from Semi-inclusive DIS (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.

DY versus SIDIS in COMPASS

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

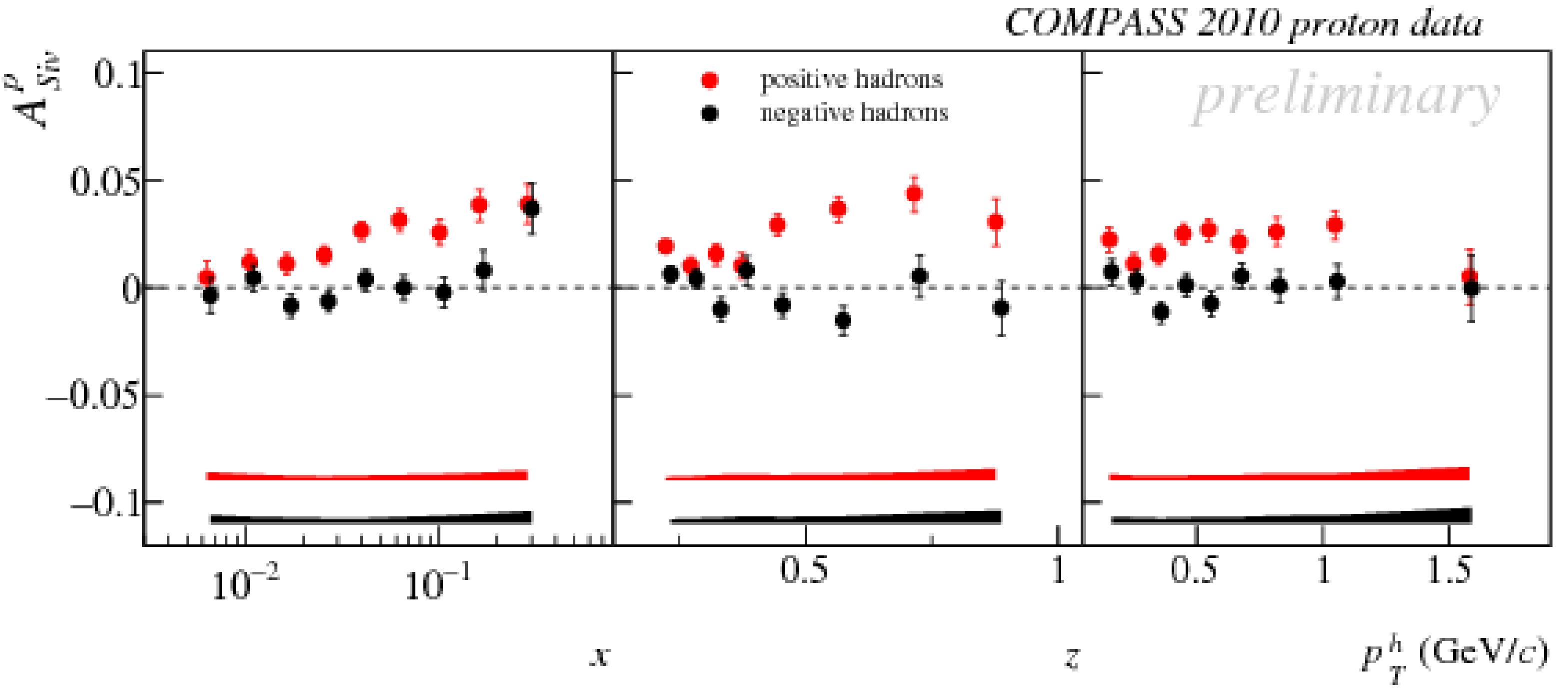
- COMPASS has accessed the Sivers PDF from SIDIS.
- In COMPASS-II this will also be done via the Drell-Yan process.

SIDIS	DY
Asymmetry is convolution of a structure function with a fragmentation function: $A_{Sivers} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp(1)}(x) D_q^h(z)}{\sum_q e_q^2 f_1(x) D_q^h(z)}$	Asymmetry is convolution of structure functions. If unpolarized beam and transversely polarized target: $A_{Sivers} \propto 2\frac{\sum_q e_q^2 \bar{f}_{1q}(x_1) f_{1Tq}^{\perp(1)}(x_2)}{\sum_q e_q^2 \bar{f}_{1q}(x_1) f_{1q}(x_2)}$

Sivers from SIDIS (I)

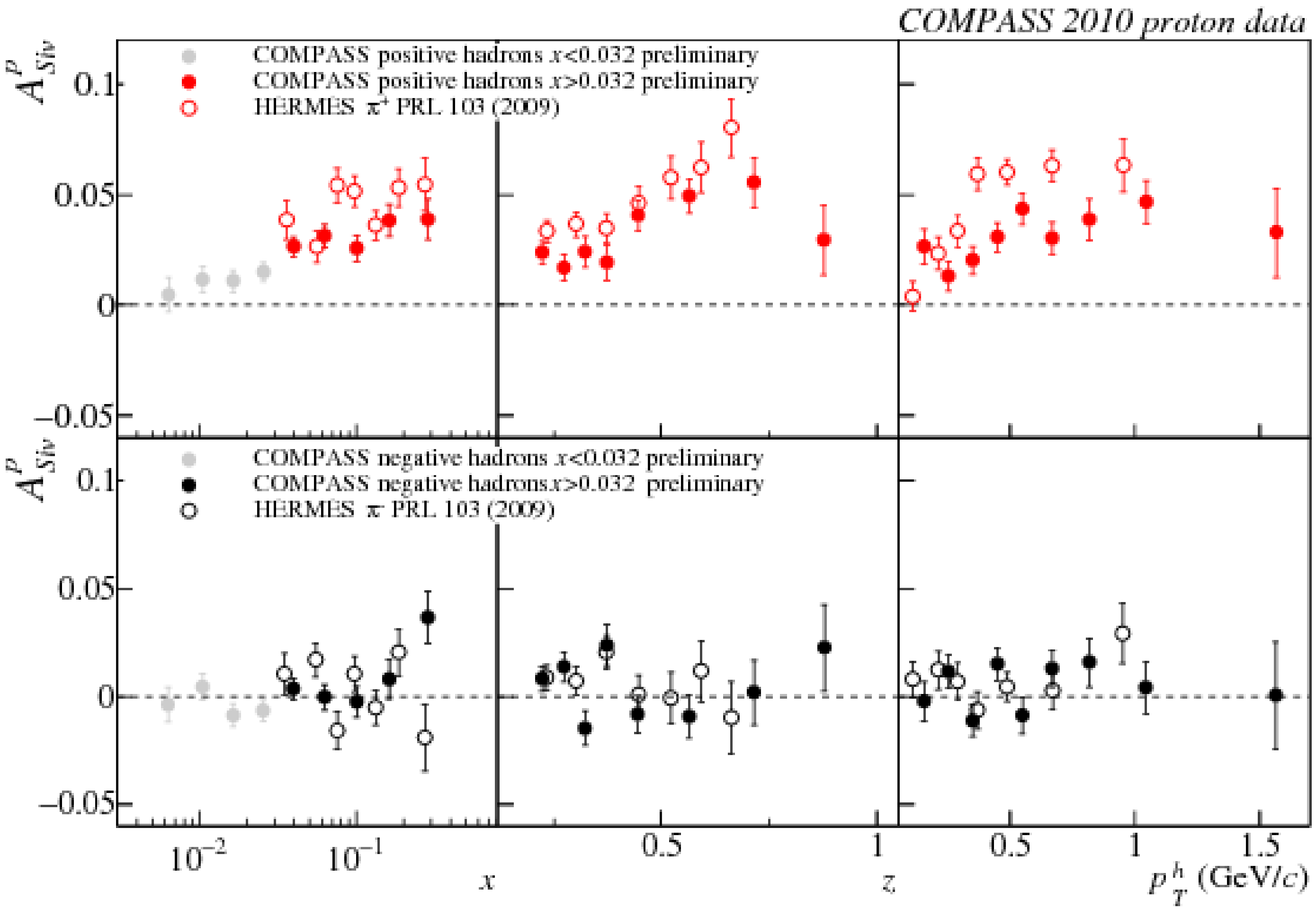
With transversely polarized proton target, the COMPASS SIDIS measurements give:

- a positive Sivers asymmetry for positive hadrons
- an asymmetry compatible with zero for negative hadrons



Sivers from SIDIS (II)

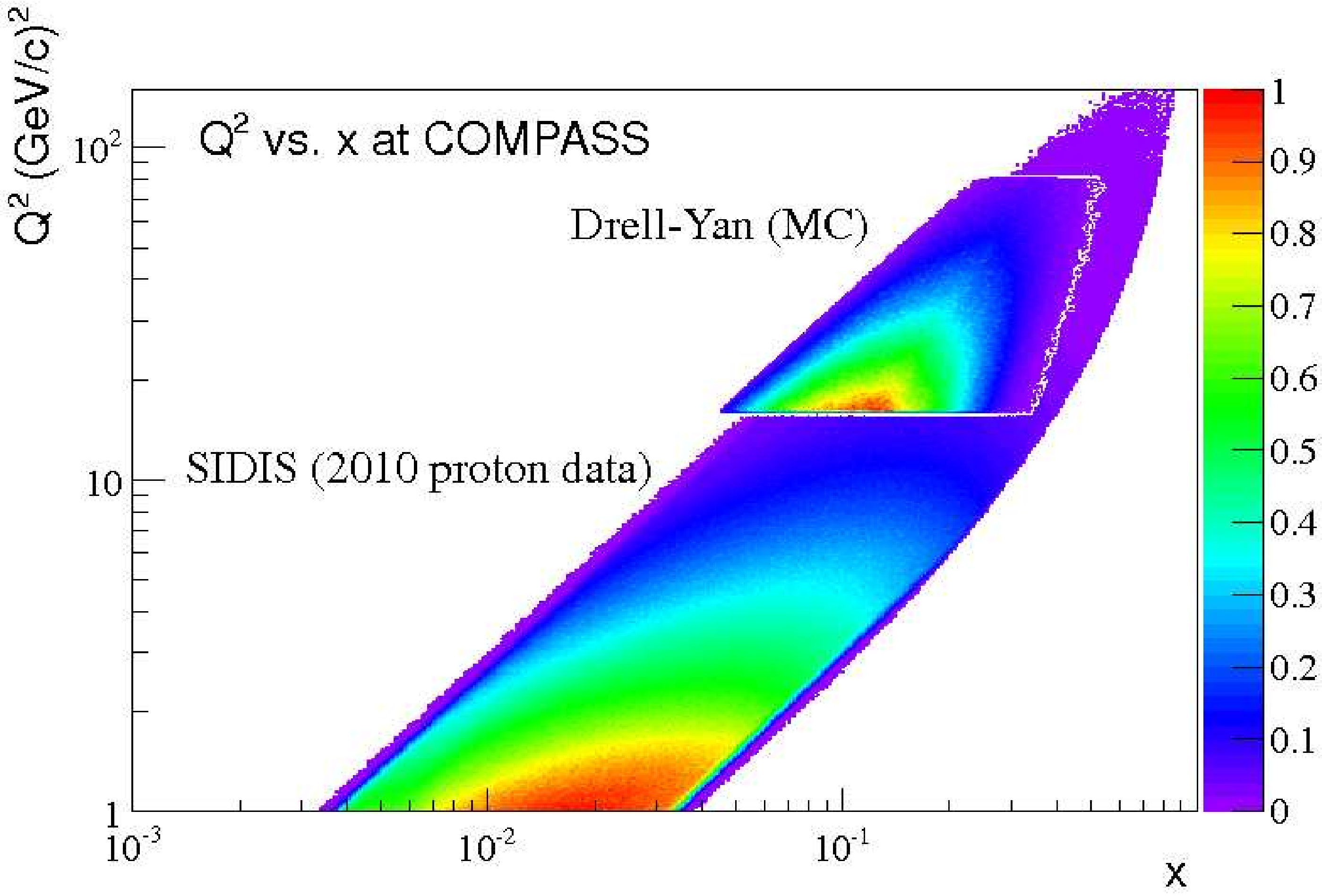
Qualitative agreement with HERMES results (PRL 103(2009)):



$\hookrightarrow$ Recent suggestions that difference may be due to TMD evolution:

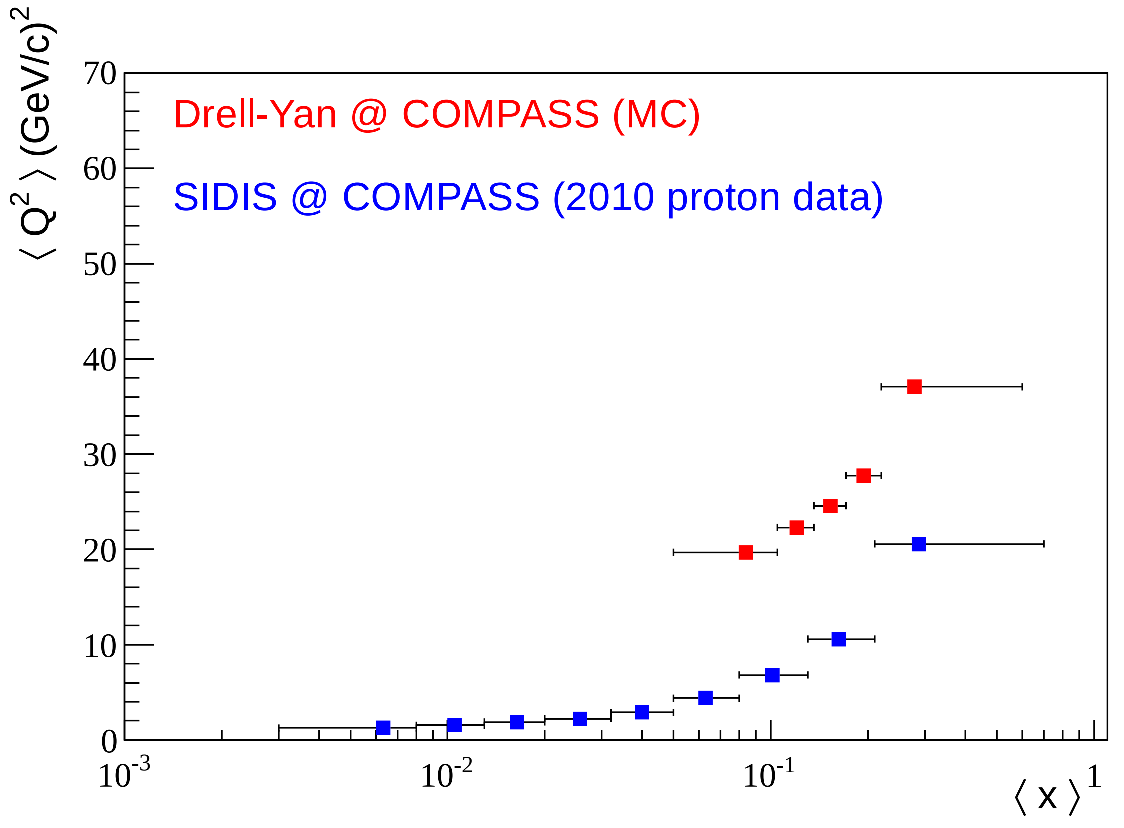
M. Aybat (2011), T. Rogers, A. Prokudin

SIDIS and DY



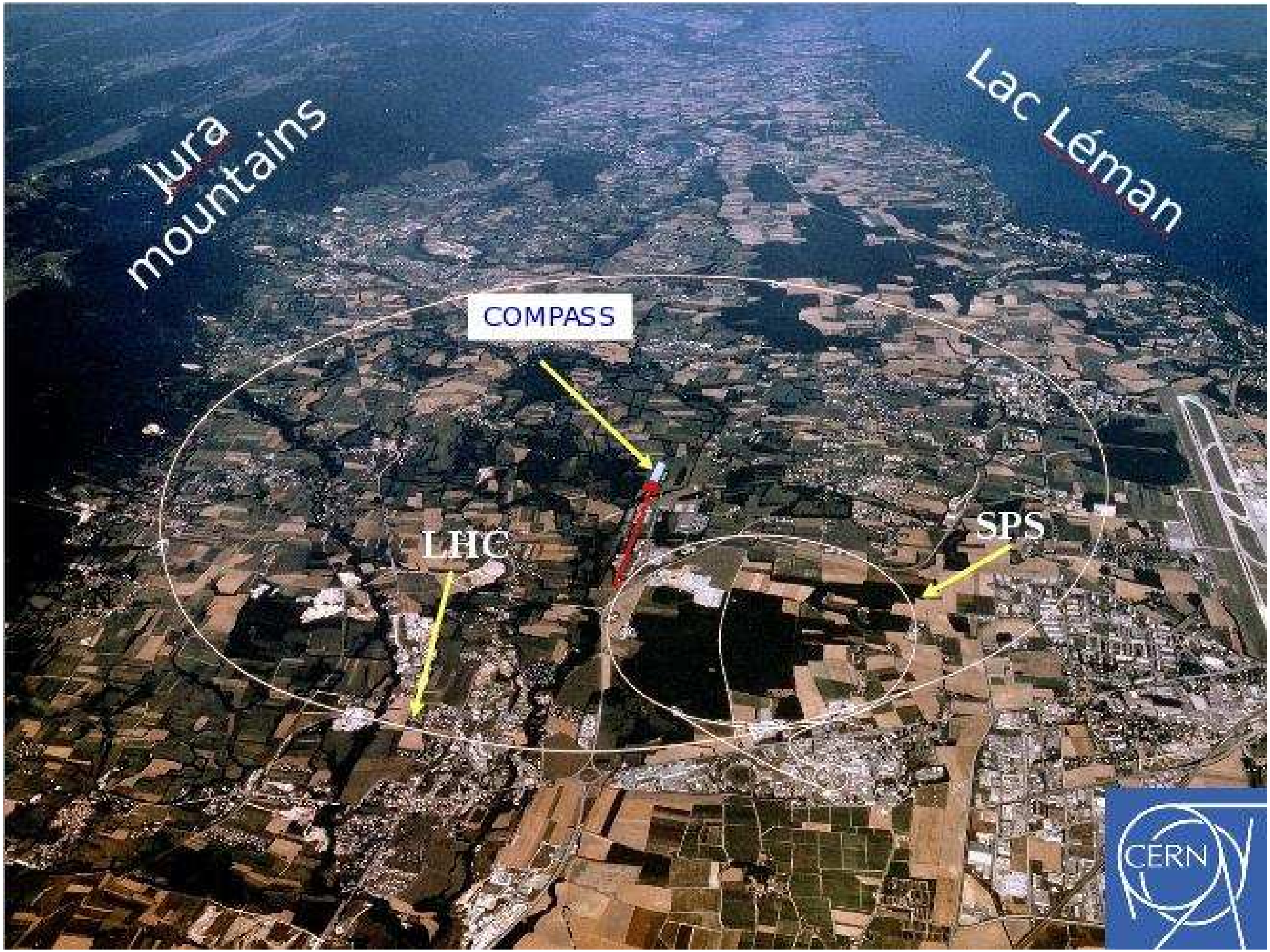
The COMPASS SIDIS and DY experimental measurements have an overlapping region.

Mean values comparison

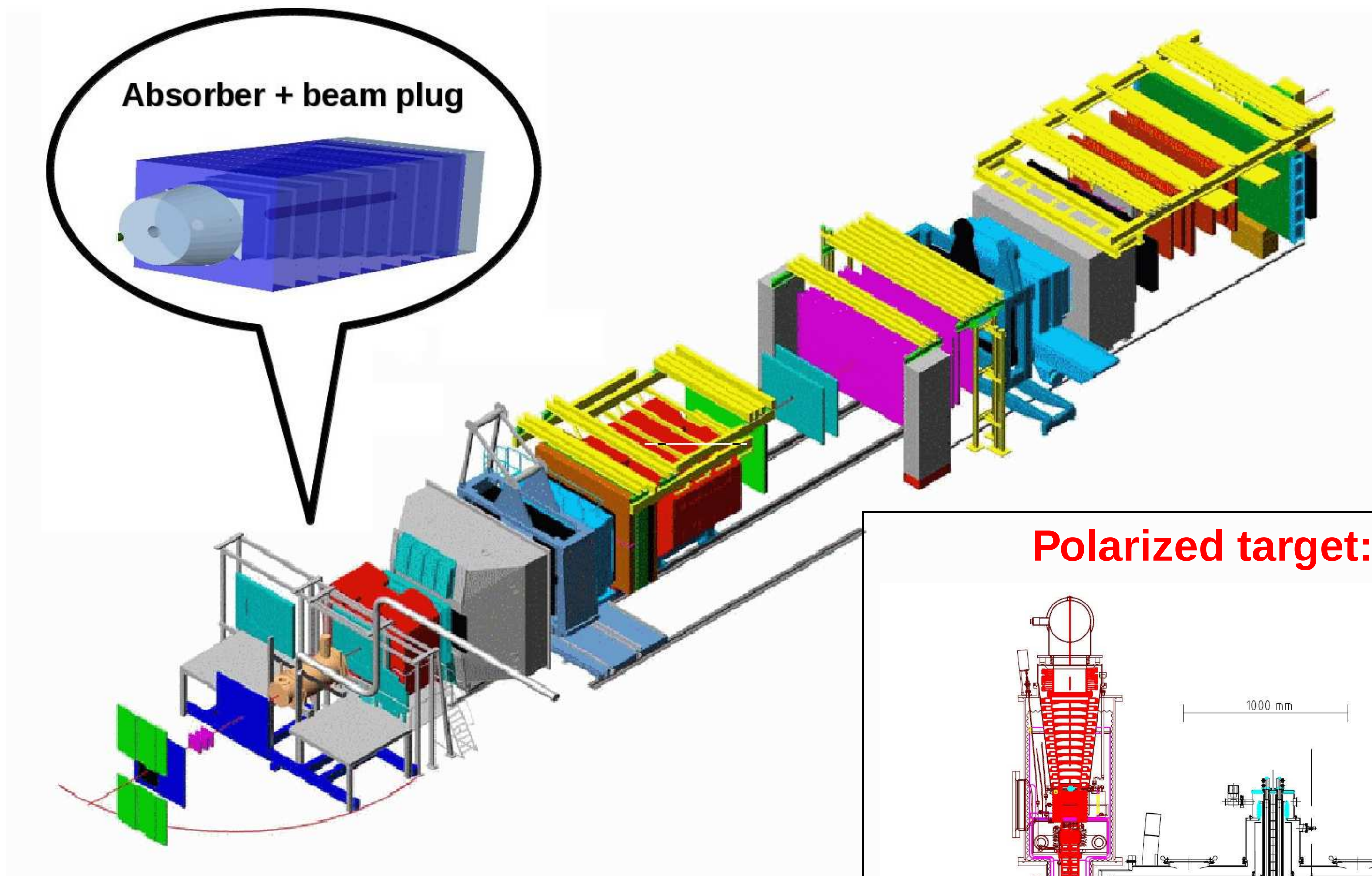


There is overlap in the phase-space accessed by the 2 measurements. Nevertheless, when comparing the TMDs extracted, the QCD evolution of the TMDs must be properly taken into account.

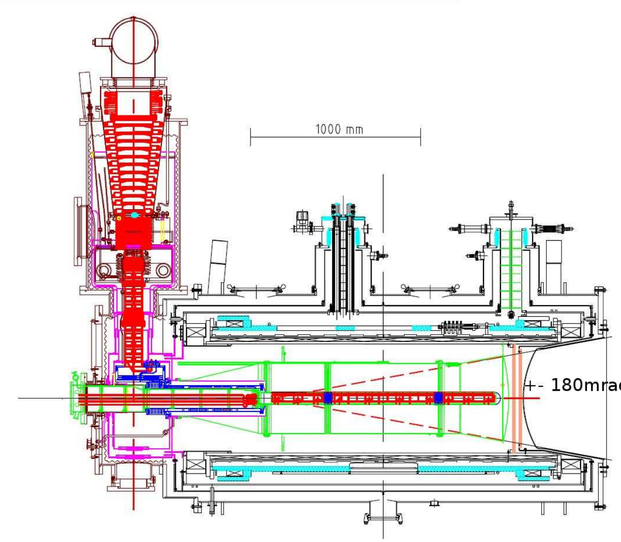
The COMPASS Experiment at CERN



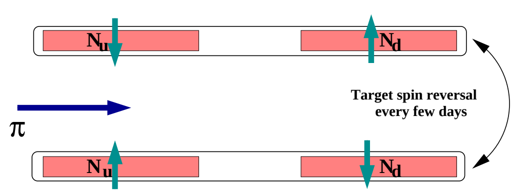
COMPASS set-up



Polarized target: NH_3



π^- beam

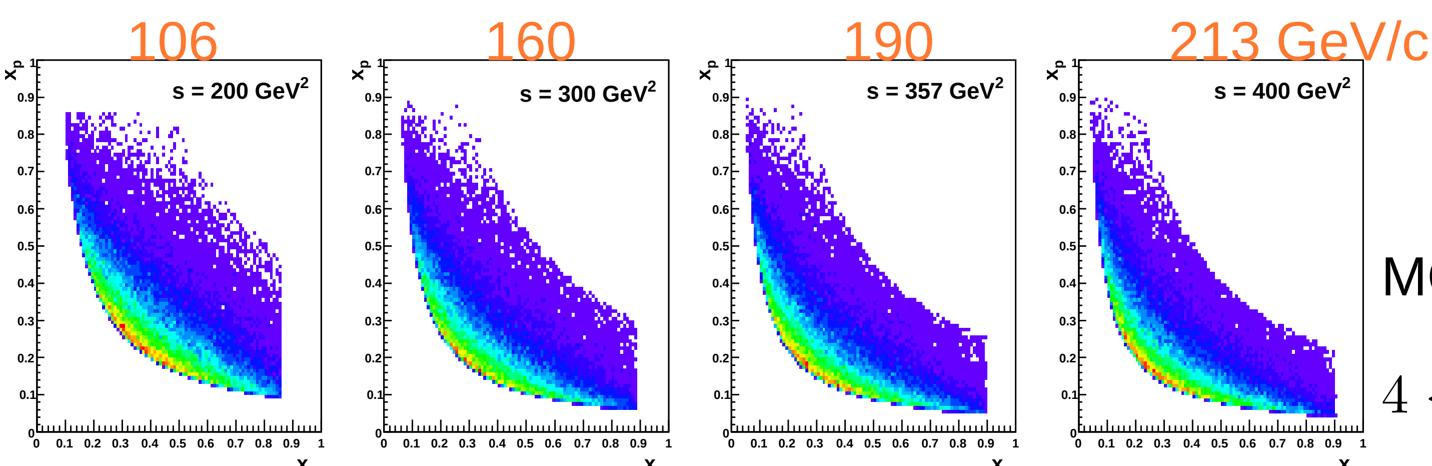


Choice of beam (I)

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

COMPASS uses the M2 SPS beam line. A secondary hadron beam is produced from SPS protons at 400 GeV/c colliding in a Be target.

- Beam momentum can be in the range 100 - 280 GeV/c
- Experience namely with π^- beam at 190 GeV/c ($\pm$ 1-2% RMS)
- 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.



MC Drell-Yan

$4 < M < 9$ GeV

Choice of beam (II)

- MC simulation shows that with higher beam momentum the phase space accessible for DY dimuons with $4 \leq M_{\mu\mu} < 9$ GeV/c^2 is extending towards the lower-x region.

- On the other hand, the DY cross-section is higher for higher beam momentum (for $4 \leq M_{\mu\mu} < 9$ GeV/c^2, K^{exp} factor=2):

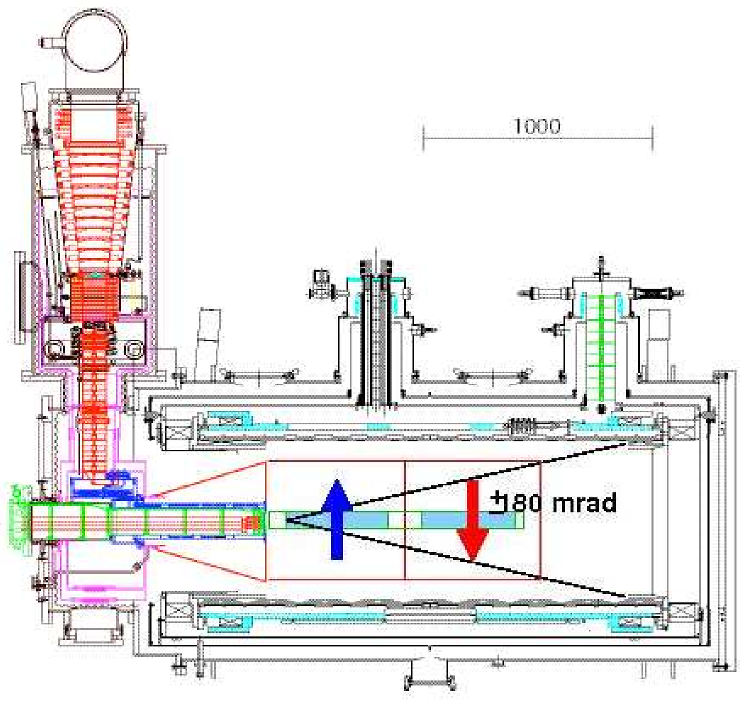
p^{π} (GeV/c)	106	160	190	213
$\sigma_{\pi p}^{DY \rightarrow \mu\mu} * K$ (nb)	0.164	0.252	0.290	0.318

$$\Downarrow$$

The π^- beam at 190 GeV/c seems to be a good compromise

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.



- With 2 cells oppositely polarized, part of the systematics in the asymmetries measurement cancel.
- The spacing between cells is important to correctly assign the events to one of the cells (Vertex resolution limited by the presence of the hadron absorber).

Polarized target (II)

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

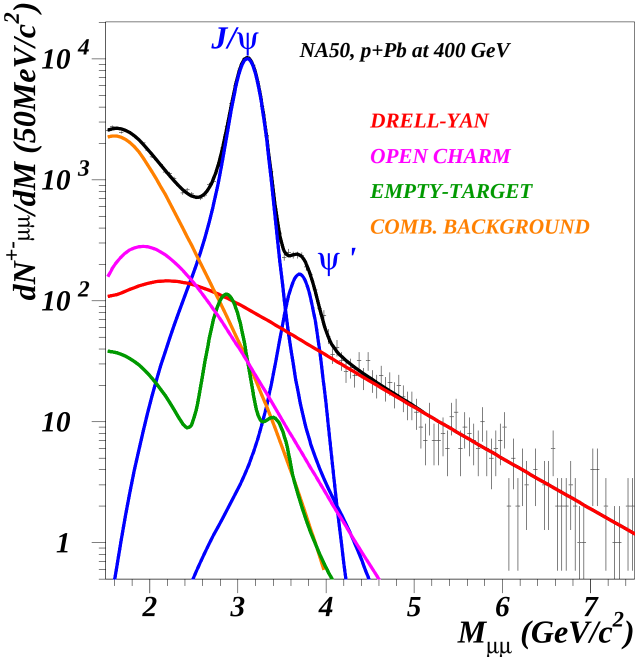
material	polarization	dilution factor
^{6}LiD	50%	0.4
NH_3	90%	0.22

- For the unpolarized DY, long LH_2 and LD_2 targets will be used
  $\hookrightarrow$see Wen-Chen Chang talk
- The 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.

- With beam intensity 6×10^{7} pions/s, the heat input in the target is $\approx$ 2 mW – not a problem, since the cooling power of the system is 5 mW at 70 mK.

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.

Additionally, the region $2 \leq M_{\mu\mu} < 2.5$ GeV/c^2 could also be studied, although the background here cannot be neglected.

Also the J/ψ region may be of interest, but less simple to interpret.

Absorber and beam plug (I)

- A hadron absorber made of low Z material allows to minimize the multiple scattering suffered by the muons. Additionally, we need to maximize the stopping power for produced hadrons.

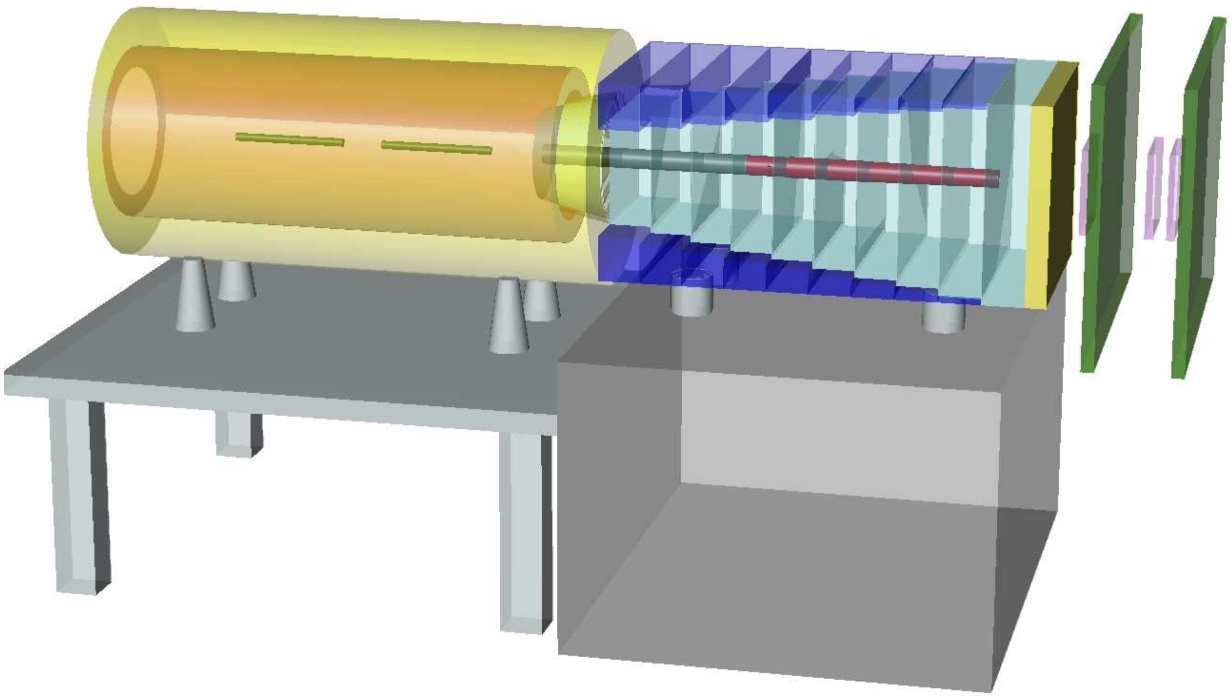
- A tungsten beam plug allows to efficiently stop the beam which does not interact in the target. Its shape is optimized to contain the Molière cascades, reducing the probability of crossing by Drell-Yan muons.

- Different combinations of materials are being studied: Al_2O_3 with borated polyethylene; Al_2O_3 with steel; graphite with copper;...

$$\Downarrow$$

The present reference absorber we use in simulations is 240 cm of Al_2O_3.

Absorber and beam plug (II)



Present configuration
(still undergoing optimization):

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

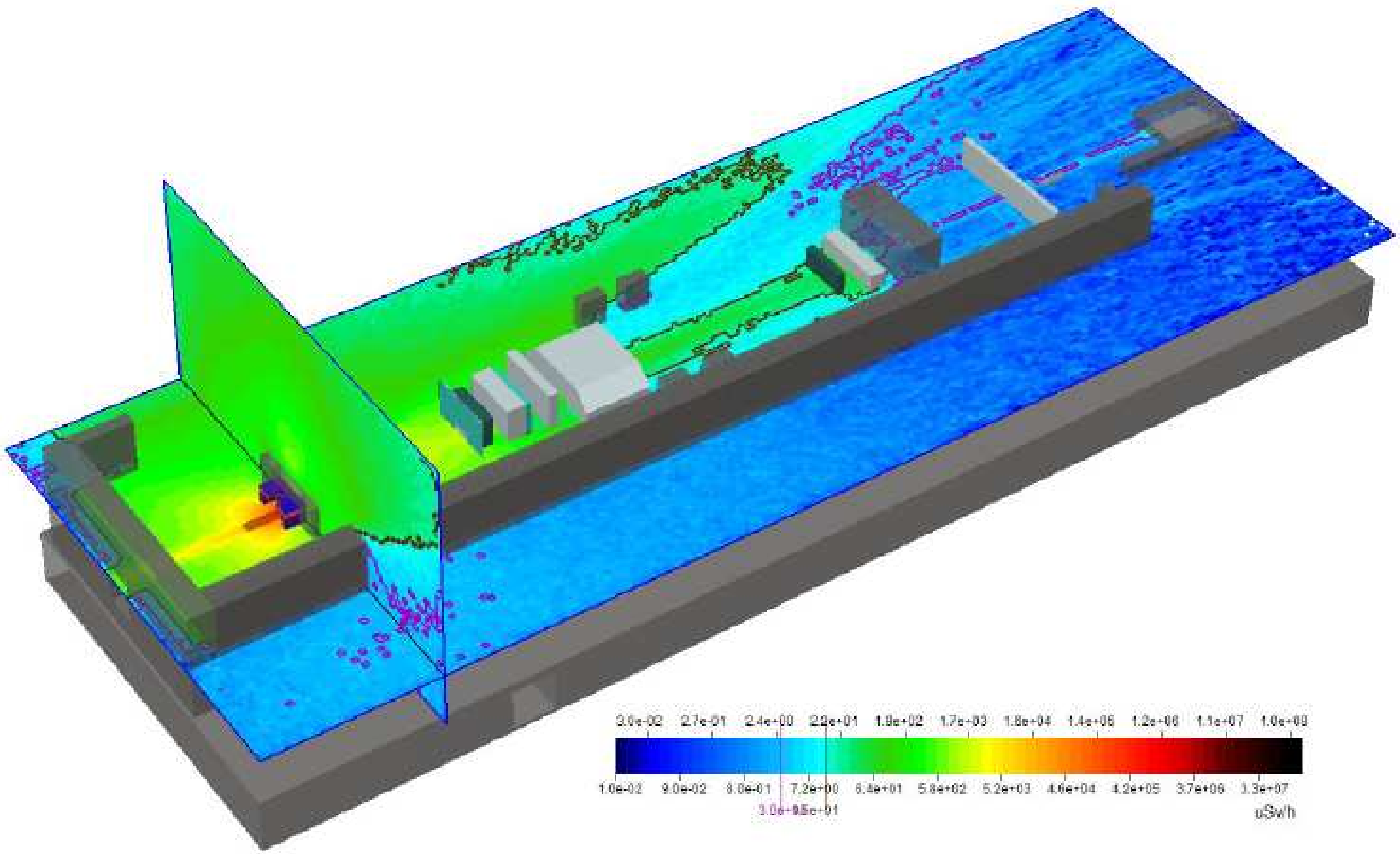
Radiation conditions (I)

- COMPASS is a ground level experiment
  $\hookrightarrow$ the whole target area including the absorber needs proper shielding.
- Several options for shielding are being considered: concrete; concrete and borated polyethylene; concrete and steel.
- Higher the beam intensity $\Rightarrow$ increase of radiation dose
  $\hookrightarrow$ modularity of the absorber, and a shielding with good margin.
- The control room must be moved to a remote location
- The radiation conditions must be carefully monitored online

$\Rightarrow$ Radioprotection CERN group $+$ detailed COMPASS simulations

Radiation conditions (II)

With a radiation screen of steel, borated polyethylene (neutrons absorption) and concrete, also on top, to avoid important skyshine.



$\hookrightarrow$ With a beam intensity up to $1 \times 10^8\ \pi^-$/second, the radiation levels are within safety limits.

COMPASS Spectrometer

The 2-stage spectrometer remains practically unchanged:

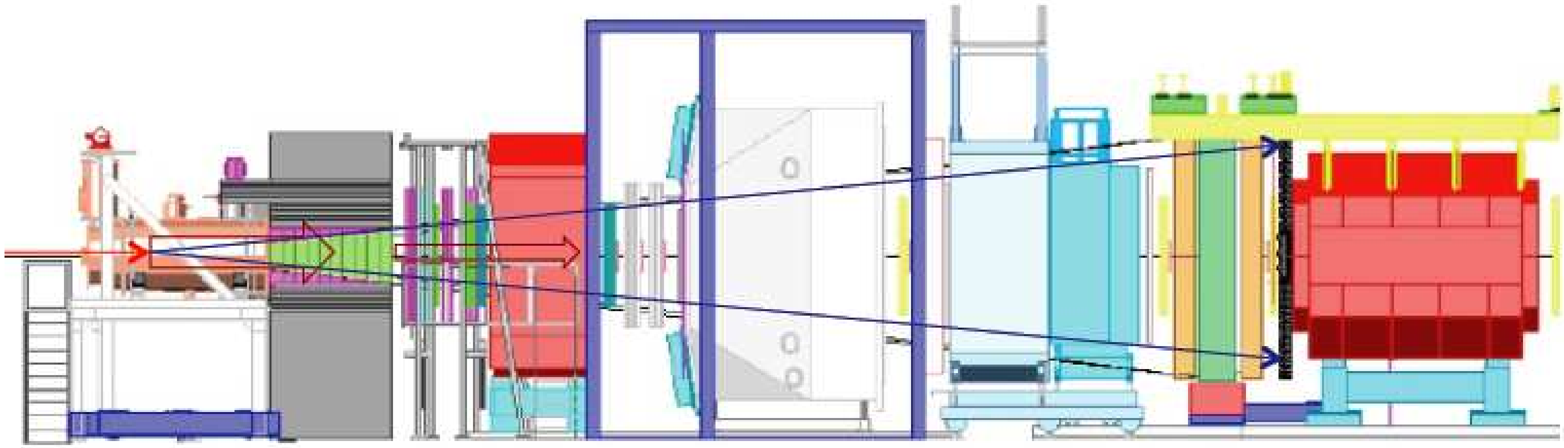
- More than 300 tracking planes
- Replace less efficient large angle trackers by new drift chambers
- 3 absorbers along the spectrometer, to ensure muon identification
- Capability to identify muons with angles $18 < \theta_\mu < 180$ mrad
- Possibility to place a scintillator fibers detector in between 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.

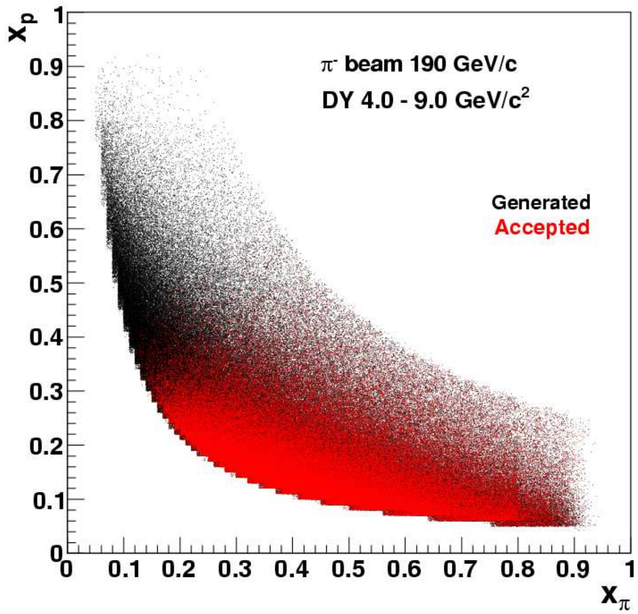
- a Large Angle Spectrometer trigger: 2 large area hodoscopes, the second placed downstream of a hadrons absorber (LAST);
- a Small Angle Spectrometer trigger: 2 hodoscopes (modified Outer System), complemented with smaller angle hodoscopes (with absorber upstream of the second hodoscope) (OT);
- The 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 in a dipole field 0.6 T.
- 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.

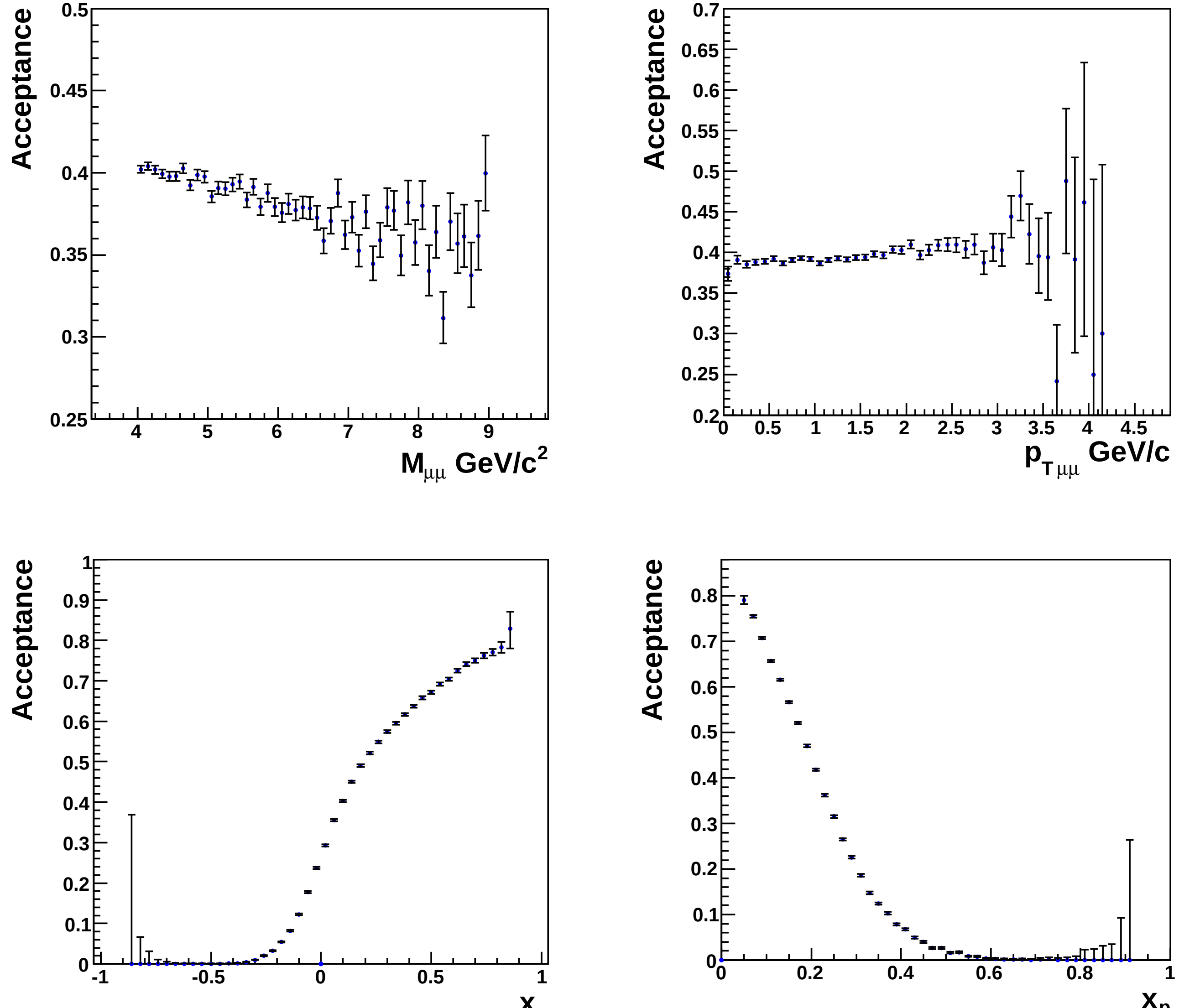
Global acceptance for high mass dimuons: $\approx$ 39% :

- 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)

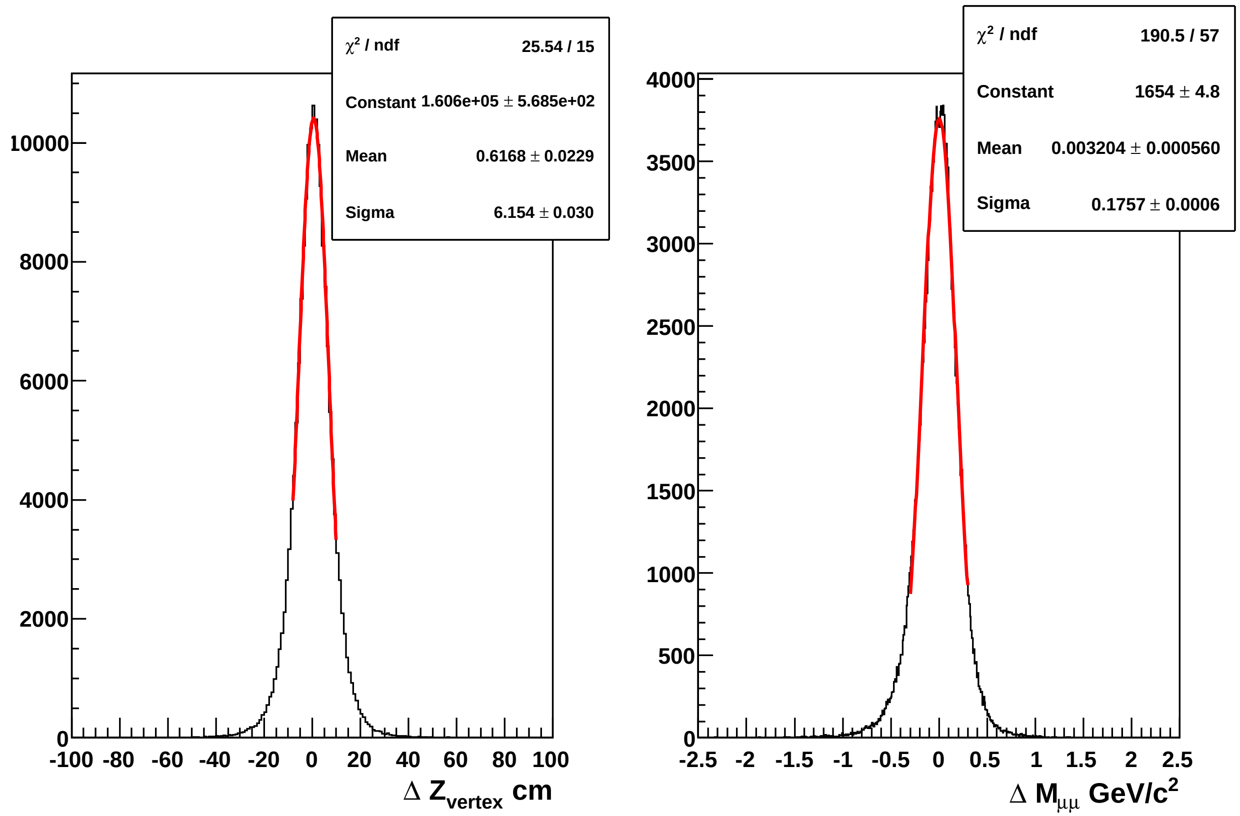
Acceptances

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



Resolutions

MC simulation of Drell-Yan events with $4 < M_{\mu\mu} < 9$ GeV/c^2



- Z_{vertex} resolution is 6 cm: allows to distinguish well events from each cell.
- Dimuon mass resolution is 180 GeV/c^2: as expected taking into account the absorber.

J/ψ-DY duality

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

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

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 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.

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

- 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.
  (≈ 420 000 events if $I_{beam} = 1 \times 10^8$ particles/second)

- expect 4300/day DY events with $2 < M_{\mu\mu} < 2.5$ GeV/c^2.

  In 2 years of data-taking, collect 1 190 000 events in the DY IMR
  (contamination from open charm decays is estimated ≈ 15%)

- expect 13700/day DY + J/$\psi^{q\bar{q}}$ events in $2.9 < M_{\mu\mu} < 3.2$ GeV/c^2.

  In 2 years, collect 3 845 000 events in the J/ψ region
  (assuming J/ψ-DY duality and a fraction of J/ψ from $q\bar{q}$ of 60%)

Asymmetries statistical error

The expected statistical errors in the asymmetries are given by:

$$\delta\, A_U^{\cos 2\phi} = 2\sqrt{\frac{2}{N}}; \quad \delta\, A_T^{\sin \phi_S} = \frac{1}{f S_T}\sqrt{\frac{2}{N}}; \quad \delta\, A_T^{\sin(2\phi \pm \phi_S)} = \frac{2}{f S_T}\sqrt{\frac{2}{N}}$$

Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta\, A_U^{\cos 2\phi}$	0.0026	0.0014	0.0056
$\delta\, A_T^{\sin \phi_S}$	0.0065	0.0036	0.0142
$\delta\, A_T^{\sin(2\phi+\phi_S)}$	0.0131	0.0073	0.0284
$\delta\, A_T^{\sin(2\phi-\phi_S)}$	0.0131	0.0073	0.0284

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

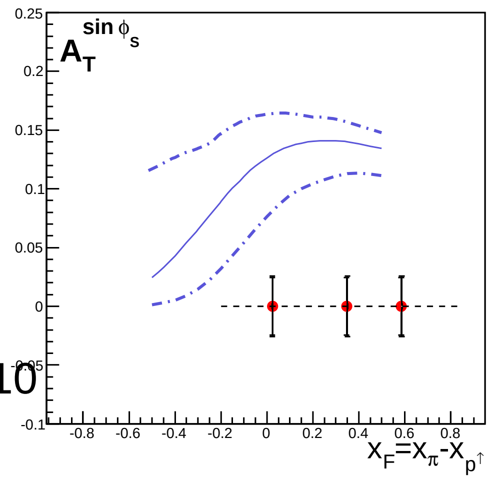
Comparing with theory predictions

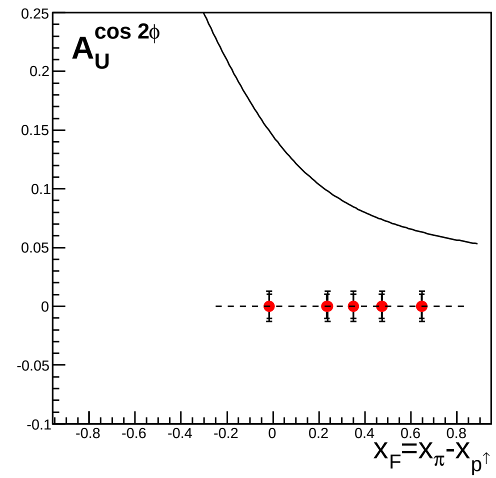
...but: Q^2 evolution not properly accounted for in the predictions...

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

$f_1^\pi \otimes$ Sivers^p

Anselmino et al, PRD79(2009)054010



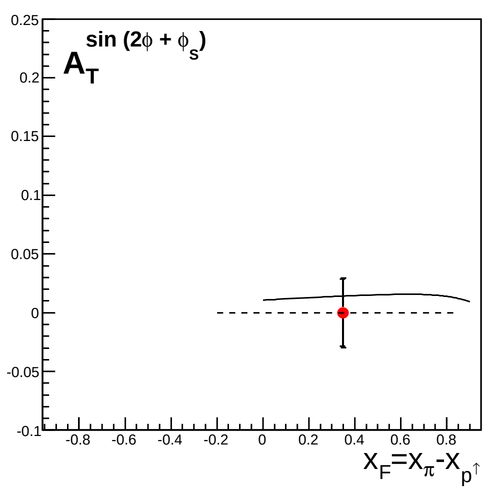


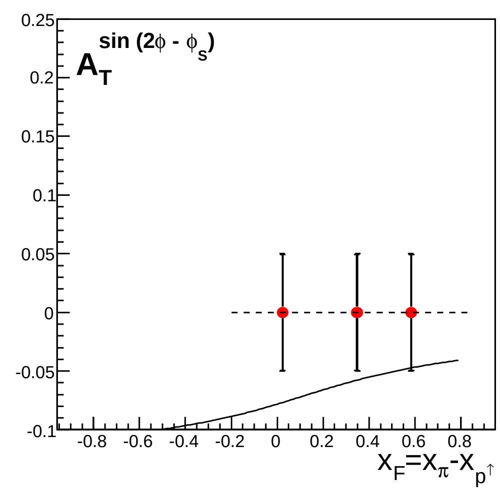
BM$^\pi \otimes$ BM^p

B. Zhang et al, PRD77(2008)054011

BM$^\pi \otimes$ pretzel.^{p}

Zhun Lu et al, arXiv:1101.2702v2





BM$^\pi \otimes$ transv.^{p}

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

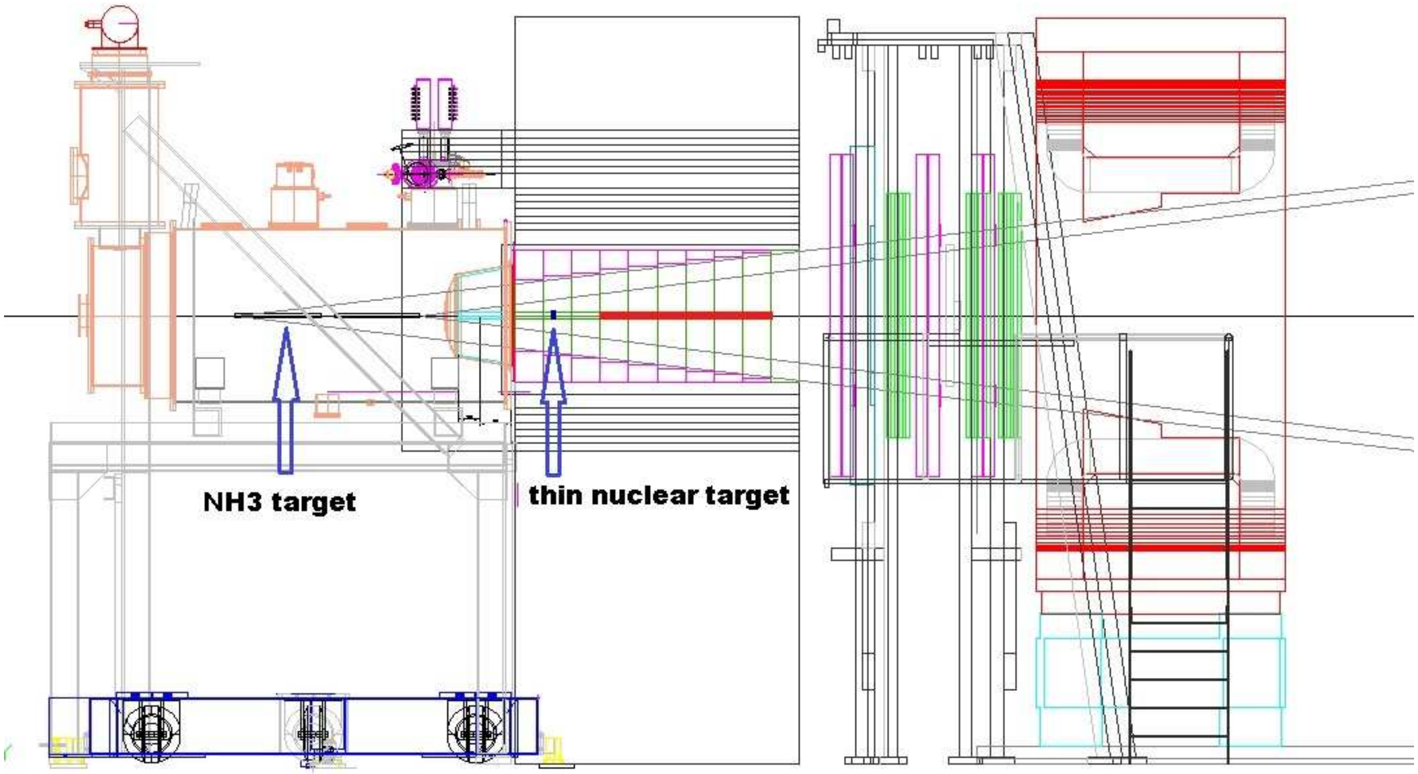
Timeline

The COMPASS Drell-Yan project is one of the topics addressed in the COMPASS-II proposal, which was submitted and approved in 2010.

- 2004: First ideas for Drell-Yan at COMPASS were expressed after the Villars meeting
- 2007, 2008: short DY beam tests with open spectrometer
- 2009: 3 days beam test with a prototype hadron absorber and a simplified dimuon trigger
- 2008-2012: Conceptual design and optimization of absorber and beam plug, radiation shielding, vertex and beam telescope detectors, large area hodoscopes and new large area trackers
- 2013: production and installation of the new elements needed
- 2014: long run dedicated to DY measurement with transversely polarized NH_3 target

2014: DY measurement

2014:first year of Drell-Yan measurement with transversely polarized NH_3 target



In parallel, the study of unpolarized Drell-Yan nuclear effects (like EMC effect) can be performed, with the insertion of an additional thin nuclear target in the region upstream of the beam plug.

How it may continue

According to latest schedules, two long shutdown periods of the SPS and LHC are planned, in 2013 and in 2018.

From 2017 and beyond, COMPASS-II should continue its physics program (still requires approval):

- second year of Drell-Yan data-taking with transversely polarized NH_3 target.
- unpolarized DY measurements with liquid H_2 target.
- possibility to measure DY with polarized ^{6}LiD target.
- possibility to vary the beam energy in the range 100-280 GeV, to study J/ψ polarization and production mechanisms
- ...

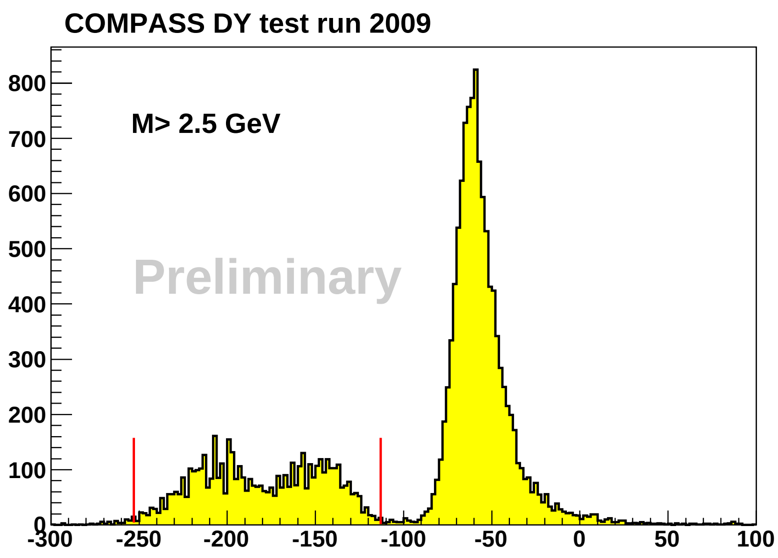
Feasibility studies

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

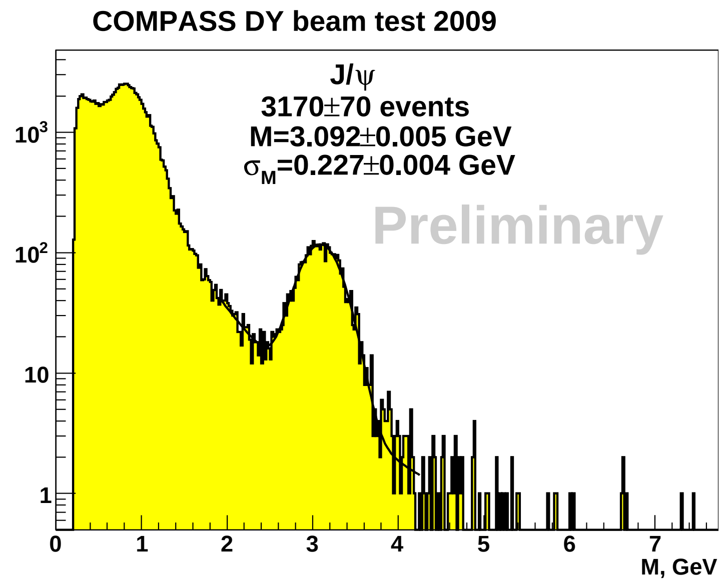
- The target temperature does not seem to increase significantly with the hadron beam, long polarization relaxation times measured (2007 beam test).
- Reasonable occupancies in the detectors closer to the target can only be achieved if a hadron absorber and beam plug is used (2008 beam test).
- Radiation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

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. J/ψ events match the expected yield.

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.

Competition and complementarity

The Drell-Yan way of accessing TMDs has raised a lot of interest in recent years.

Several experimental proposals appeared. Meanwhile, some are on hold due to lack of funding, some waiting for R&D break-through, some waiting for a time opportunity.

Facility	type	s (GeV^2)	timeline
RHIC (STAR, PHENIX)	collider, p$^{\uparrow}$p	200^2	> 2016
J-PARC	fixed target, p$^{\rightarrow\uparrow}$ D	60 – 100	> 2018
FAIR (PAX)	collider, $\bar{p}^{\uparrow}$ p$^{\uparrow}$	200	> 2018
NICA	collider, p$^{\uparrow}$ p$^{\uparrow}$, D$^{\uparrow}$ D$^{\uparrow}$	676, 144	> 2018
COMPASS	fixed target, $\pi^{\pm}$ H$^{\rightarrow\uparrow}$, $\pi^{\pm}$ D$^{\rightarrow\uparrow}$	357	2014

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 will be done in 2014. It will be the first of its kind in the world. A second year of DY data-taking in 2017.
- 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 COMPASS measurements will contribute to the common effort of extracting the TMD PDFs, namely Sivers, Boer-Mulders and Pretzelosity, as well as the transversity PDF.