Polarized Drell-Yan in the COMPASS Experiment

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on behalf of the COMPASS Collaboration

Mainz, 31 March 2009

Outline

- Transverse Momentum Dependent PDFs
- Accessing PDFs from Drell-Yan process
- Polarized Drell-Yan in COMPASS
- DY@COMPASS wrt past and future experiments

Structure functions of the nucleon

The nucleon is fully described by a set of structure functions that can be built from the knowledge of the parton distribution functions (PDFs) – in a given constituents model of the nucleon.

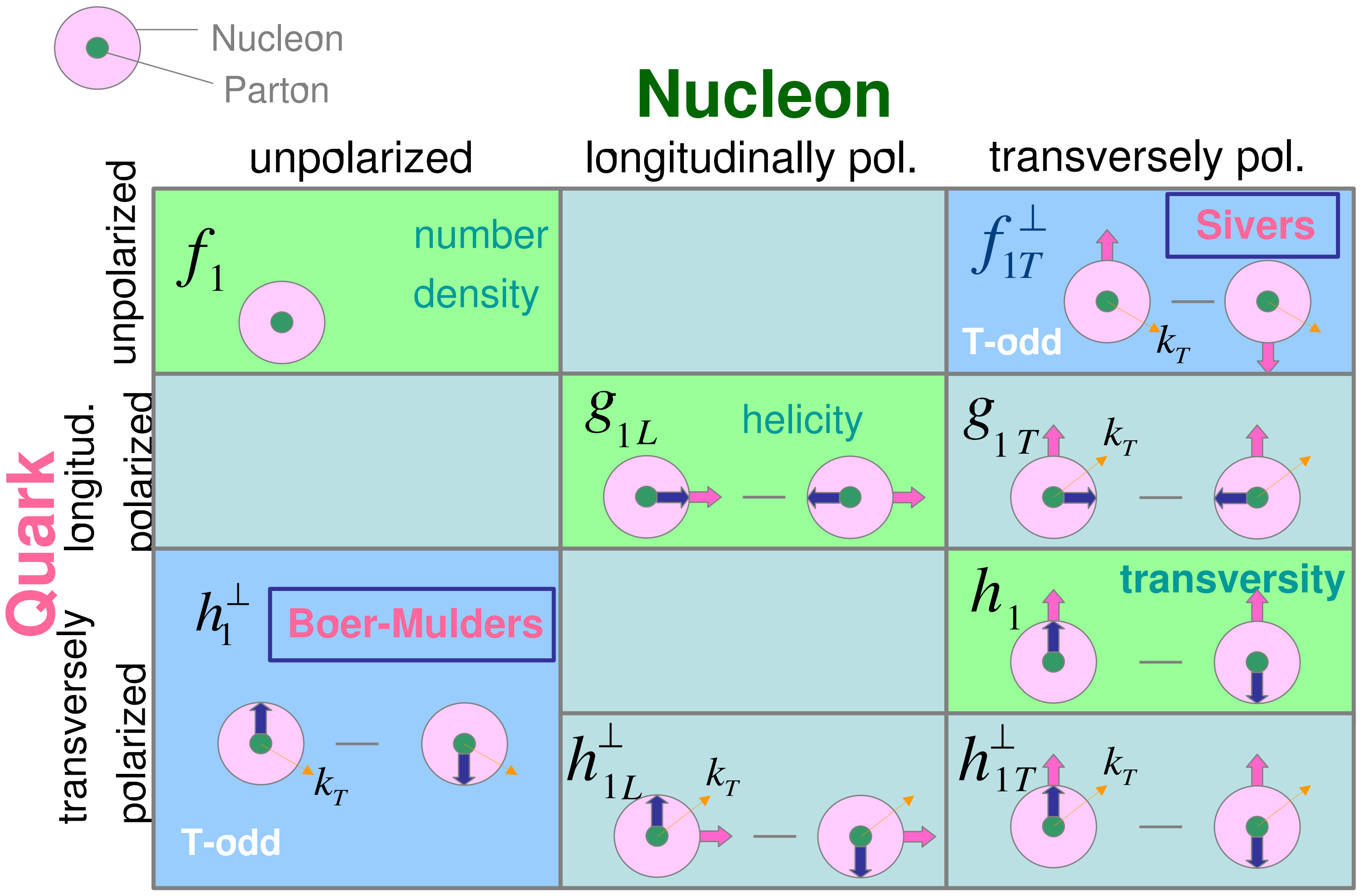
In the parton model in LO, if the transverse momentum of partons is neglected (k_T integrated):

- 3 parton distribution functions dependent on (x)

If the transverse momentum of partons is also considered (k_T dependence):

- 8 parton distribution functions dependent on (x, k_T^2)

A catalog of PDFs



- $f_1(x, k_T^2)$: unpolarized. Integrated in k_T^2 gives the usual $f_1(x)$.

- $g_{1L}(x, k_T^2)$: longitudinally polarized. When integrated over k_T^2 it is the helicity function $g_1(x)$. From its 1st moment one can obtain $\Delta\Sigma = \Delta u + \Delta d + \Delta s$

  $\hookrightarrow$COMPASS DIS and SIDIS results:
  PLB647(2007)8-17;
  PLB647(2007)330-340;
  PLB660(2008)458-465.

- $h_1(x, k_T^2)$: transversely polarized. When integrated over k_T^2 it survives, giving the transversity function $h_1(x)$.

  $\hookrightarrow$COMPASS SIDIS results:
  PRL94(2005)202002;
  NPB765(2007)31-70;
  PLB673(2009)127-135.

Interpreting the PDFs (II)

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

  $\hookrightarrow$COMPASS DIS results:

  PRL94(2005)202002;
  NPB765(2007)31-70;

  PLB673(2009)127-135.

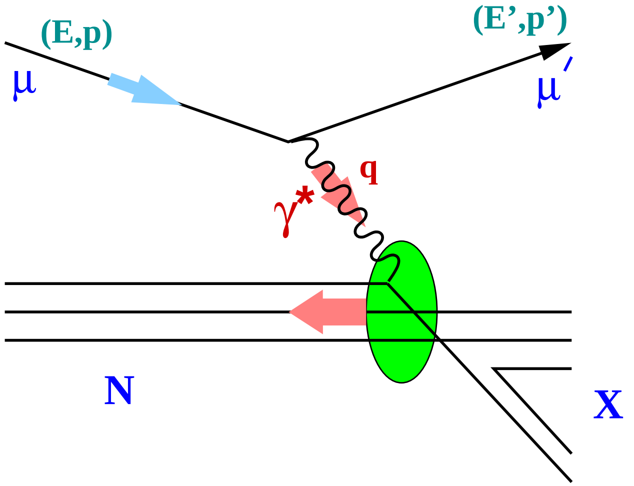
- $h_1^{\perp}(x, k_T^2)$: Boer-Mulders function. It describes the correlation between the transverse spin and the transverse momentum of a quark inside the unpolarized hadron.

- $h_{1T}^{\perp}(x, k_T^2)$: Pretzelosity function. It describes the transverse polarization of a quark, along its intrinsic k_T direction. It allows to access the orbital angular momentum information.

These 3 PDFs are Transverse Momentum Dependent (TMD). The first 2 are also time reversal odd (T-odd).

Polarized structure functions can be accessed from spin asymmetries.

In deep inelastic scattering (DIS) experiments, like COMPASS, with beam and target polarized:



$$Q^2 = -q^2 \quad \nu = E - E'$$

$$x = \frac{Q^2}{2M\nu}$$

$$z = \frac{E_h}{\nu}$$

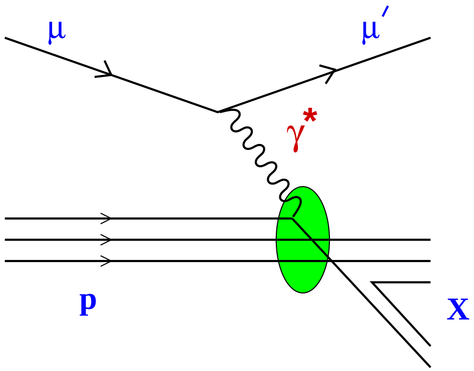
The μ-deuteron asymmetry is measured from the difference between cross-sections from 2 oppositely polarized target cells:

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

f: target dilution factor
P_T: target polarization
P_B: beam polarization.

COMPASS accesses the Sivers PDF from semi-inclusive DIS (SIDIS).
Another possible way to do it is via the Drell-Yan process (DY)

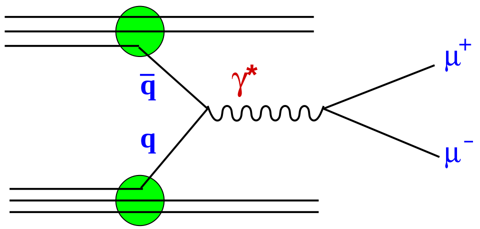
SIDIS



The physics asymmetry is given by the convolution of structure functions with fragmentation functions:

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

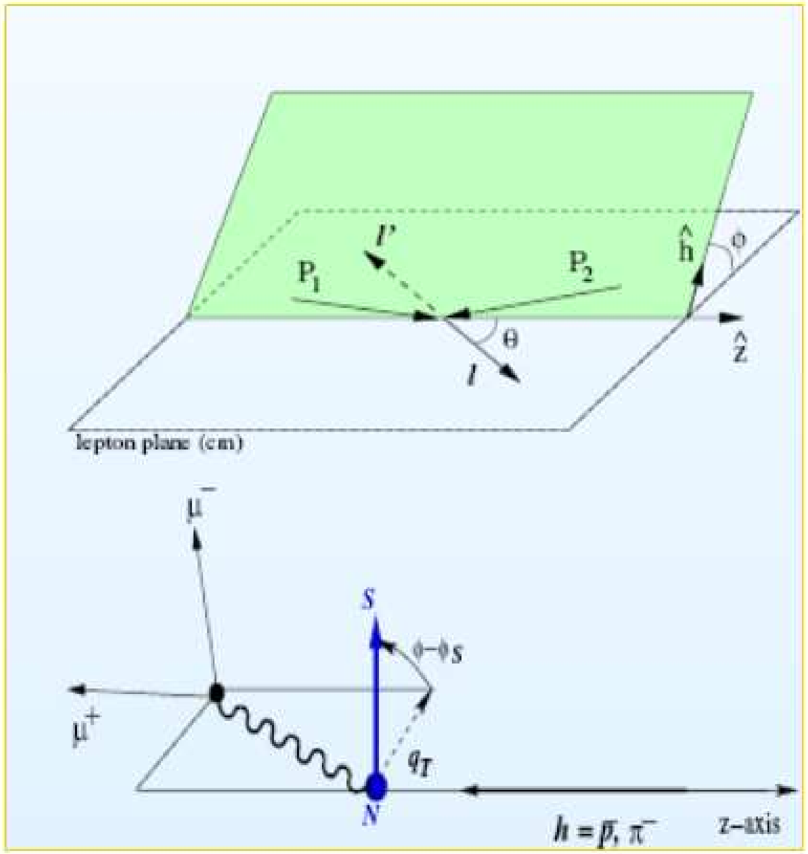
DY



The spin asymmetry is proportional to a product of structure functions. If unpolarized beam and transversely polarized target:

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

$$q\bar{q} \rightarrow \gamma^* \rightarrow l^+ l^-$$



In the Collins-Soper frame:
θ, ϕ: lepton pair wrt hadrons plane.
ϕ_{S2}: spin-vector S_{2T} wrt lepton plane, if transversely polarized hadron target.

The phase-space is defined by the variables x_1 and x_2:

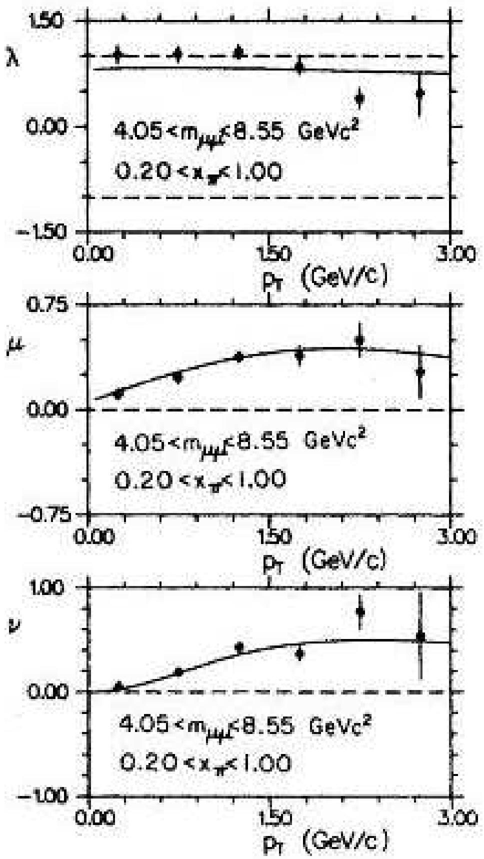
$$x_F = x_1 - x_2 = \frac{2p_L}{\sqrt{s}}$$

$$\tau = \frac{M^2}{s} = x_1 \cdot x_2$$

Drell-Yan is purely electromagnetic process. Its cross-section is exactly calculable.

Drell-Yan angular distribution (unpolarized):

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



E615, Conway et al (1989)

Lam-Tung sum rule: $\boxed{1-\lambda-2\nu=0}$

In LO and collinear approx., we get the usual: $\lambda=1$ and $\nu=\mu=0$.

This sum rule was seen to be violated in past experiments at CERN (NA10) and FERMILAB (E615) – $\cos 2\phi$ modulation, up to 30%!

Such modulation amplitude can arise from the product of 2 Boer-Mulders functions: (beam PDF $\otimes$ target PDF).

What we can learn from Drell-Yan

Having a **transversely polarizable** target available, one can study **both unpolarized and polarized Drell-Yan**:

- Unpolarized DY

$$d\sigma^{DY} \propto \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_1^{\perp}(x_2, k_{T2}^2) \cos 2\phi$$

↑ Boer-Mulders ↑

- Single polarized DY

$$d\sigma^{DY} \propto \bar{f}_1(x_1, k_{T1}^2) \otimes f_{1T}^{\perp}(x_2, k_{T2}^2) \sin(\phi - \phi_{S2}) +$$

↑ Sivers

$$+ \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_1(x_2, k_{T2}^2) \sin(\phi + \phi_{S2}) +$$

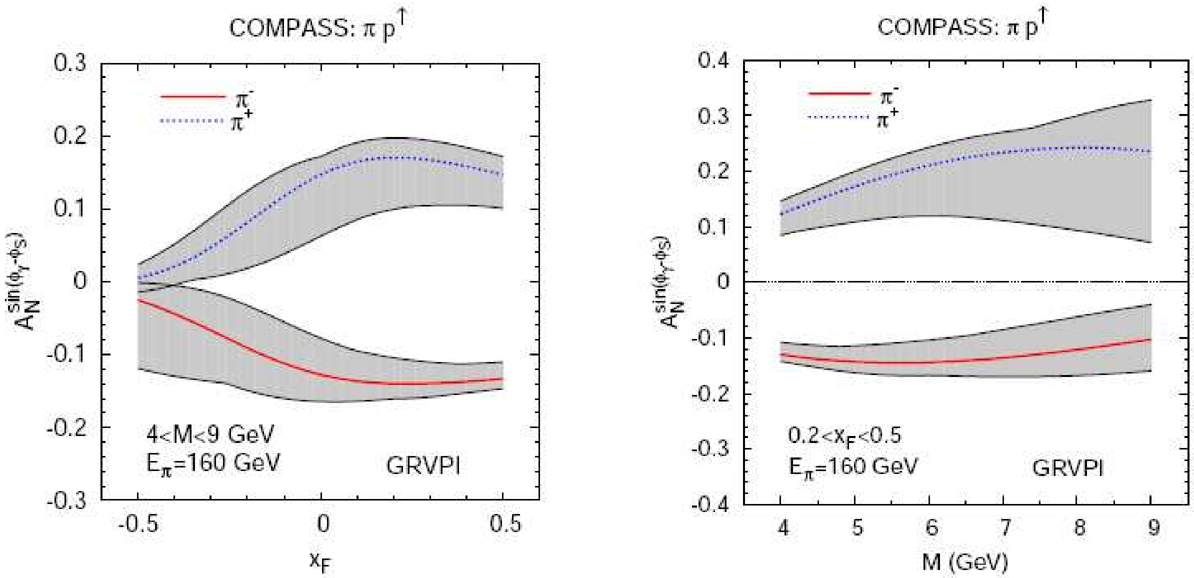
↑ Boer-Mulders ↑ Transversity

$$+ \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_{1T}^{\perp}(x_2, k_{T2}^2) \sin(3\phi - \phi_{S2}) +$$

↑ Boer-Mulders ↑ Pretzelosity

In practice, to access the polarized PDFs, like for example Sivers, in the experiment we measure a single spin asymmetry:

$$A_N^{\sin(\phi_{S2}-\phi)} = \frac{\int_0^{2\pi}(d\sigma^\uparrow - d\sigma^\downarrow)\sin(\phi_{S2}-\phi)d\phi}{\frac{1}{2}\int_0^{2\pi}(d\sigma^\uparrow + d\sigma^\downarrow)d\phi}$$



Anselmino et al., Phys.Rev.D 79:054010, 2009

- Sizable spin asymmetries are expected

Testing non-perturbative QCD

Confronting Drell-Yan and SIDIS results provides a crucial test of non-perturbative QCD

$\hookrightarrow$ Check the predictions:

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

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

due to the T-odd character of the Sivers and Boer-Mulders functions.

J/ψ-DY duality

J/ψ production mechanisms are still nowadays a subject of research.

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

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

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

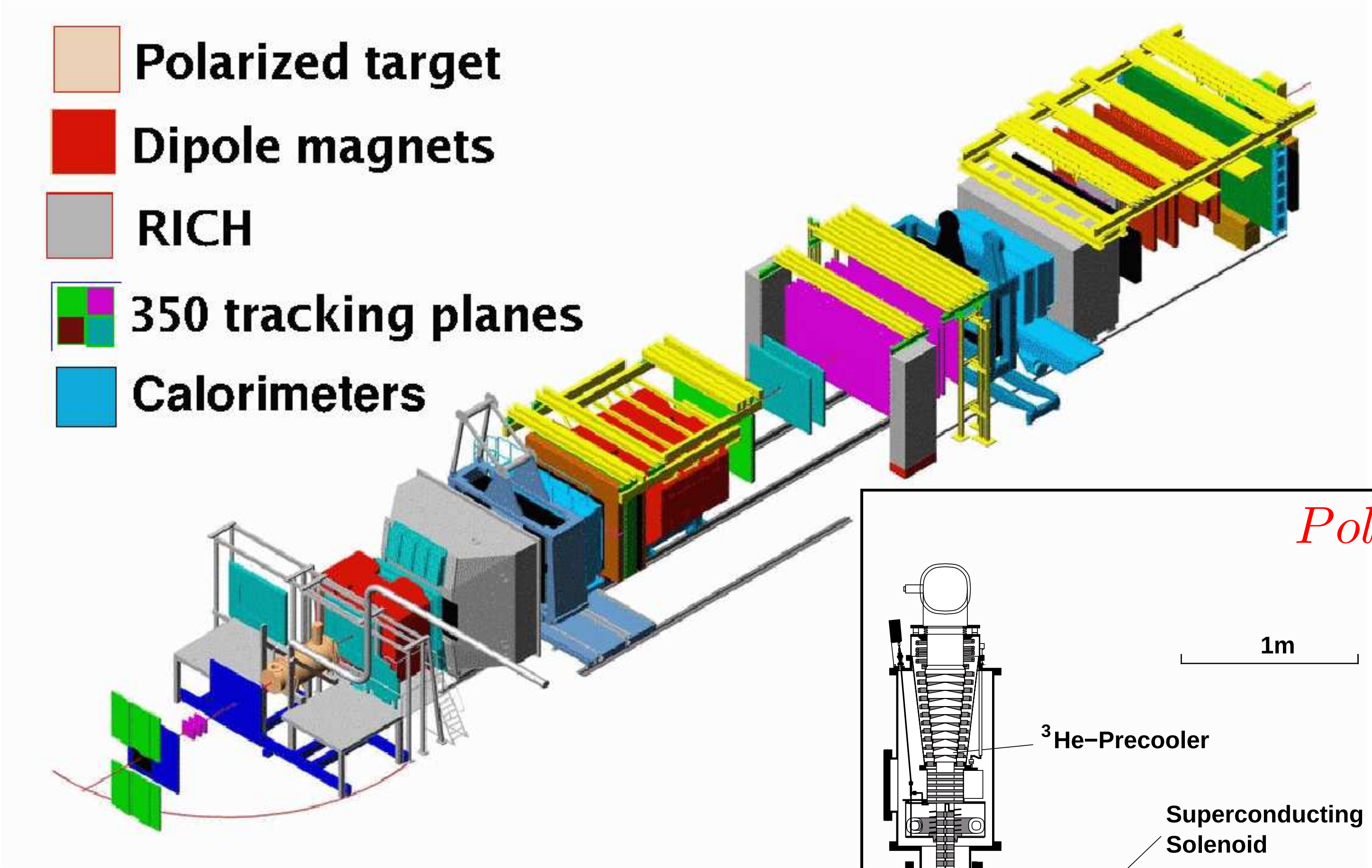
Why Drell-Yan @ COMPASS?

COMPASS has a multipurpose spectrometer:

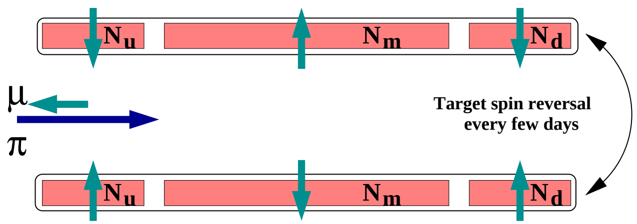
- Availability of both muon and pion beams
- Unique polarized target, well suited for transversity studies
- 2-stage spectrometer with wide angular acceptance
- A muon detection system
- Physicists community with know-how on both Drell-Yan physics and transversity physics

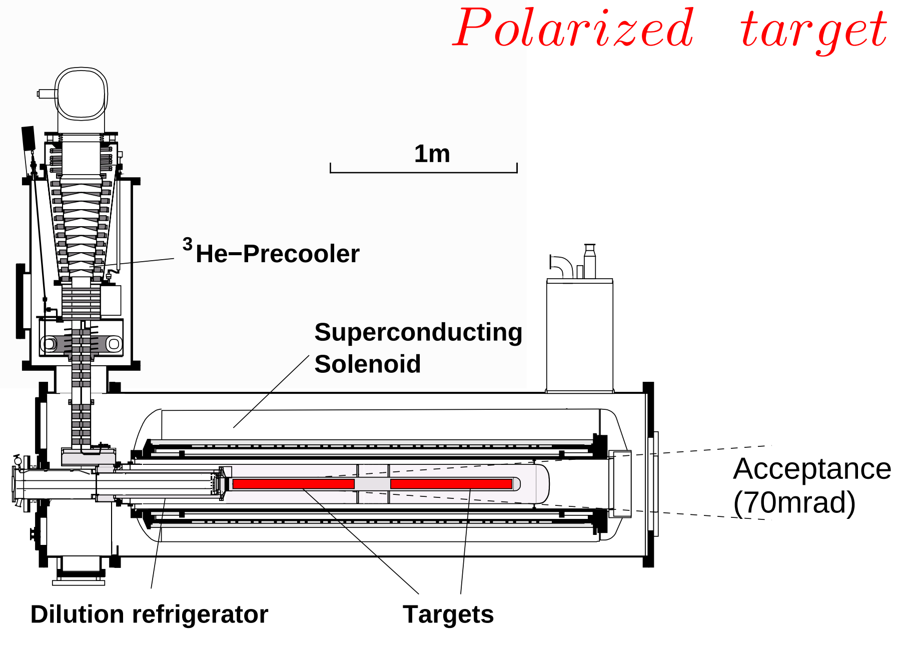
Experimentally, there is **a window of opportunity** for COMPASS to perform this measurement.

The COMPASS spectrometer (2007)



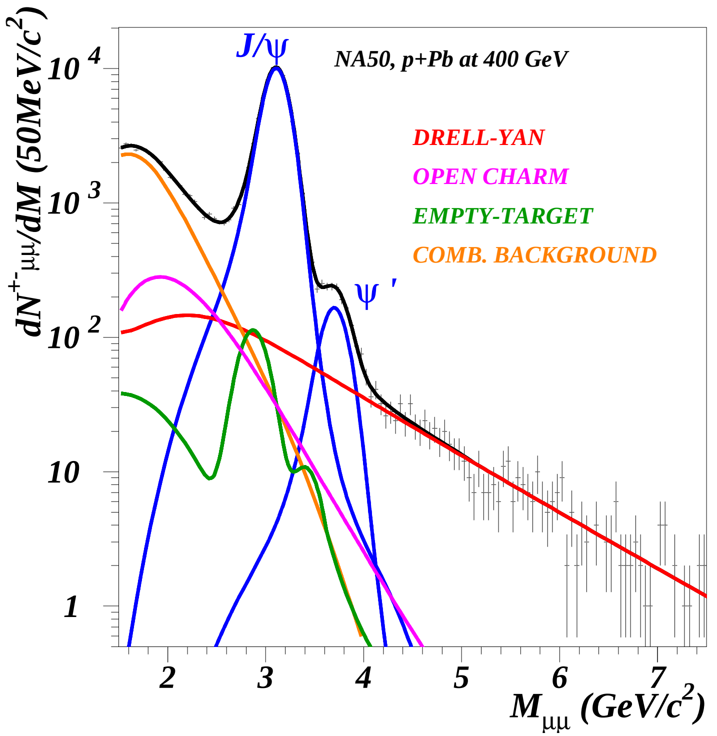
μ or π beam





^6LiD or NH_3 target

The dimuon mass spectrum is known from past DY experiments:



- $M < 2.5$ GeV/c^2:
  Large physics background
  from decays $D \rightarrow \mu^{\pm} X$

  Combinatorial background
  π and K decaying to $\mu\nu$
  - Absorber option
- J/ψ and ψ' region: the charmonium polarization is itself a subject of research.
- $M > 4.$ GeV/c^2: safe region to study Drell-Yan

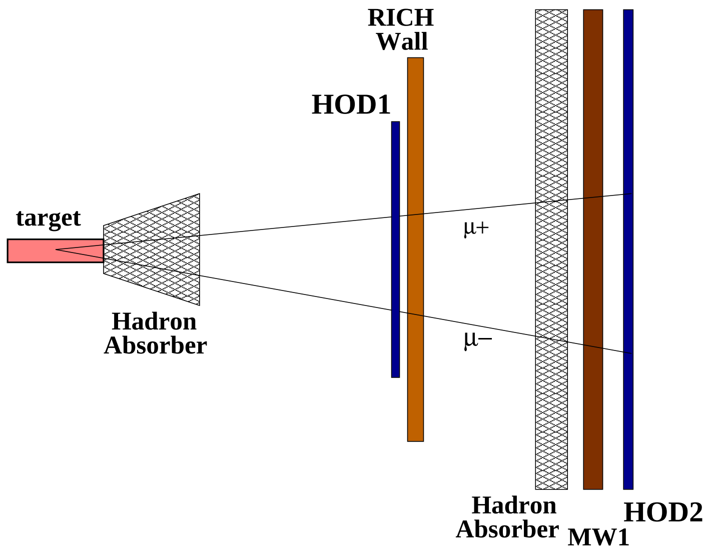
Absorber and Trigger

In 2007 and 2008, short Drell-Yan beam tests were performed.
↪without an hadron absorber, the detectors occupancy is too large.

By adding an absorber between the target and the 1st spectrometer detectors, one can reduce drastically the combinatorial background.

But:

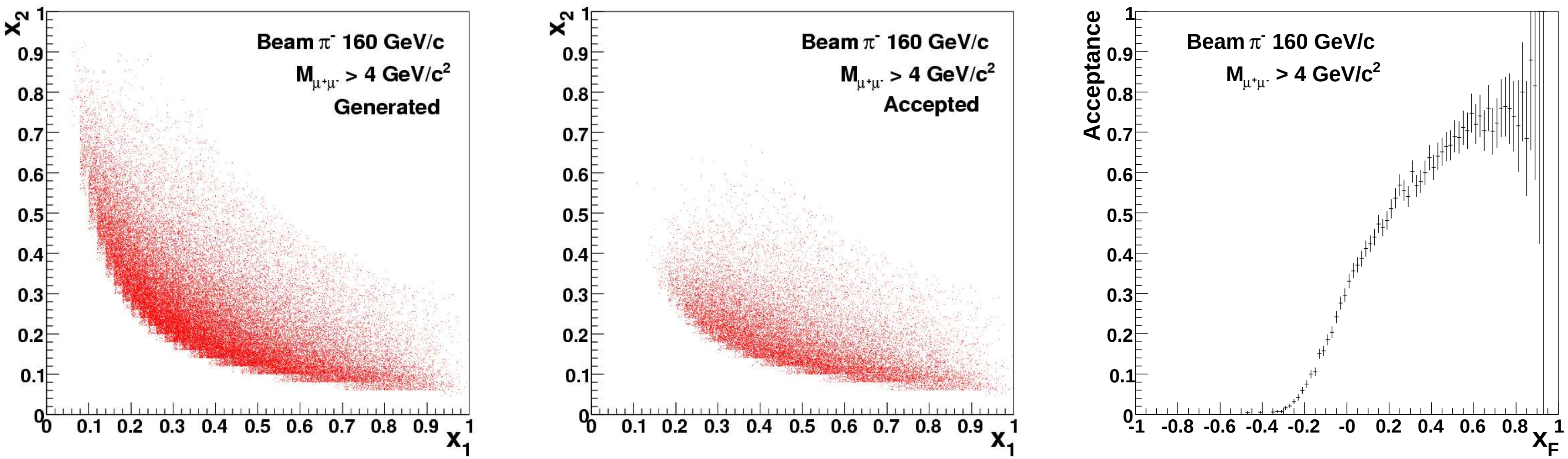
- Only $DY \to \mu^+\mu^-$ channel remains accessible
- The vertex resolution is degraded.



DY cross-section and acceptance

From Pythia:

σ^{DY} (nb)	$2.0 < M_{\mu\mu} < 2.5$ (GeV/c^2)	$4. < M_{\mu\mu} < 9.$ (GeV/c^2)
s=100 GeV^2, p_π=73 GeV/c	0.9	0.03
s=200 GeV^2, p_π=106 GeV/c	1.2	0.10
s=300 GeV^2, p_π=160 GeV/c	1.4	0.17
s=400 GeV^2, p_π=213 GeV/c	1.6	0.24



COMPASS acceptance is in the valence quarks region ($x > 0.1$). This is also the best region to measure the spin asymmetries, as expected from theory predictions.

Dimuons geometrical acceptance

For the moment, the COMPASS spectrometer has only a single muon trigger, from hodoscope stations (in the SAS).

DY simulations show, for the accepted dimuons, that:

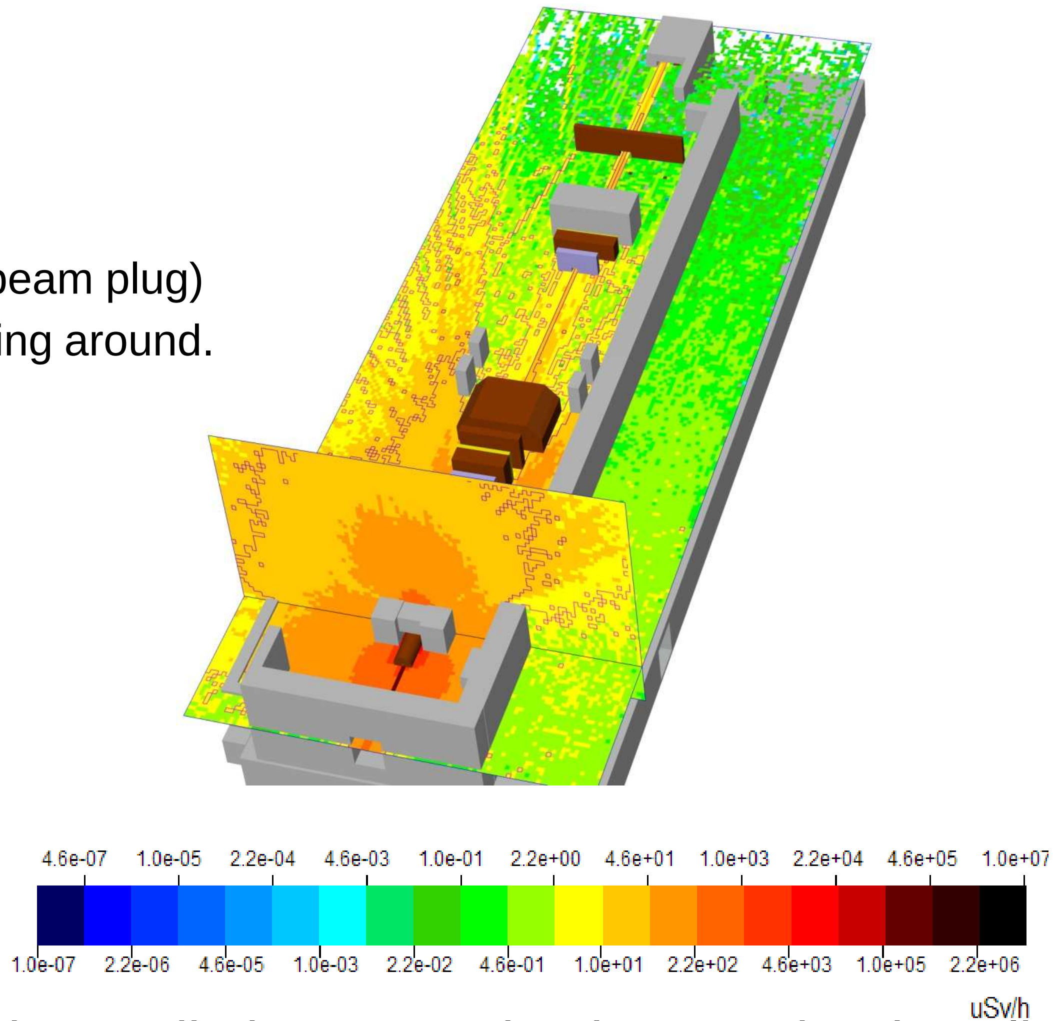
- $\approx$ 50% have both muons in the 1st spectrometer
- $\approx$ 40% have one muon in 1st and another in 2nd spectrometer
- $<$10% have both muons in the 2nd spectrometer

A dimuon trigger in the 1st spectrometer will be build, from large area hodoscopes.

Radiation conditions

Simulations from Heinz Vincke (Rad-Prot/CERN)

Beam I=8×10^7 π^-/s
Absorber (Al_2O_3 with W beam plug) of 1.5 m. Concrete shielding around.



COMPASS is a radiation supervised area. The dose limits in the control room must stay $\leq 3\mu$Sv/h

$\hookrightarrow$All the region around target and absorber must be shielded.

Expected event rates

With maximum target length (120cm) and a π^- beam of 190 GeV/c with maximum intensity (6×10^7 π^-/s):

Luminosity: $L = l_{eff}\ \rho_{NH3}\ F_f\ N_A\ I_{beam} \approx 1.7 \times 10^{33}\ cm^{-2}s^{-1}$

DY event rate per day: $R = L\ \sigma_{\pi p}\ t_{spill}\ n_{spill}\ \epsilon_{tot}$
with $t_{spill} = 9.6s$; $n_{spill} = 1800$/day; $\epsilon_{tot} = 0.14$ includes all efficiencies and acceptance

- Event rate (/day): 1000 with $4. < M < 9.$ GeV/c^2; and 6500 with $2. < M < 2.5$ GeV/c^2.
- In 2 years of data-taking (assuming 140 run days/year), one can collect $>$ 200000 DY events with $4. < M < 9.$ GeV/c^2

Asymmetries expected precision

Depending on the number of bins, the statistical error in the asymmetry is expected to be:

$$\delta A^{\sin(\phi_{S2}-\phi)} \approx 1-2\%$$

Predictions for the Sivers asymmetry in the COMPASS phase-space, for the mass region $4. < M < 9.$ GeV/c^2, compared to the expected statistical errors of DY@COMPASS:

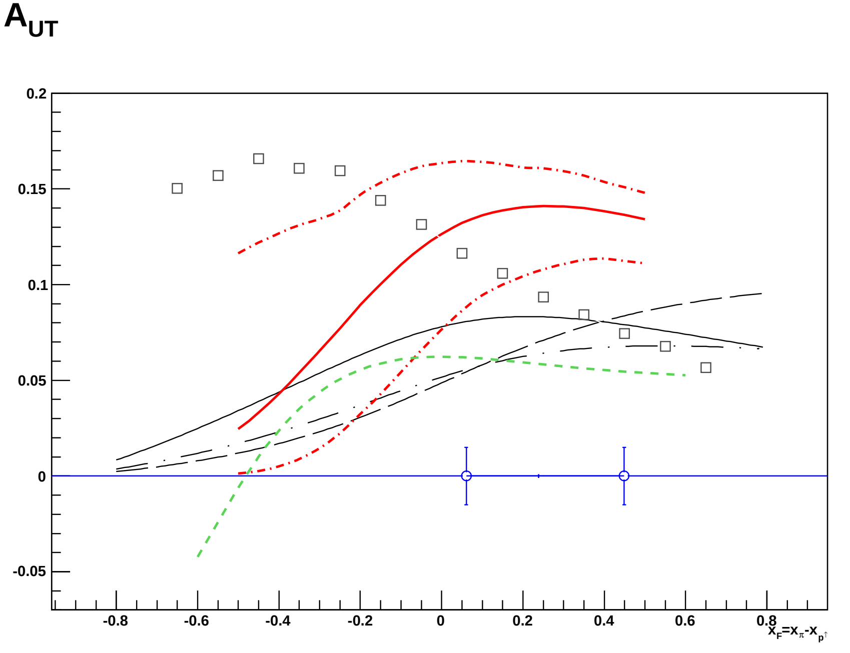
– solid and dashed: Efremov et al, PLB612(2005)233;

– 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.



COMPASS and past experiments

Experiment	Beam (GeV/c)	Targets	Physics
NA3	$\pi^{\pm}$ 150/200/280	H_2, Pt	π, K PDFs
NA10	π^{-} 140/194/284	D, W	π PDFs, Boer-Mulders PDF
E615	π^{-} 252	W	π, K PDFs, Boer-Mulders PDF
NA51	p 450	H_2, D	$\bar{d}/\bar{u}$ asymmetry in proton
E866	p 800	H_2, D	$\bar{d}/\bar{u}$ asymmetry in proton
COMPASS	π^{-} 160/190	NH_3	Sivers, Boer-Mulders, Transversity

- A long history of successful DY experiments
- Up to now, none with beam and/or polarized target – for access to the spin dependent PDFs
- Limited I_{beam} in COMPASS, but large angular acceptance.
- The critical issue being the small σ_{DY}, to have significant integrated luminosity one needs considerable running period.

Competition and complementarity

Several experiments are being planned, to study polarized Drell-Yan:

Facility	type	s (GeV^2)	timeline
RHIC (STAR)	collider, $p^{\uparrow}p$	200^2	> 2013
J-PARC	fixed target, $p^{\rightarrow\uparrow}$ D	60 – 100	> 2014
FAIR (PAX)	collider, $\bar{p}^{\uparrow}$ $p^{\uparrow}$	200	> 2016
NICA	collider, $p^{\uparrow}$ $p^{\uparrow}$, $D^{\uparrow}$ $D^{\uparrow}$	676	> 2014
COMPASS	fixed target, $\pi^{\pm}$ $H^{\rightarrow\uparrow}$, $\pi^{\pm}$ $D^{\rightarrow\uparrow}$	300 – 400	> 2010

Summary

- The COMPASS spin physics program is presently addressing the transversity and Sivers PDFs of the nucleon, among other topics.
- A natural sequence to this program is to study the Transverse Momentum Dependent PDFs of nucleon and pion.
- These can be accessed from the polarized Drell-Yan process.
- It allows an important test of non-perturbative QCD, by comparing the Sivers PDF obtained by SIDIS and by DY processes.

- 2 tests beams have been performed in COMPASS, demonstrating the feasibility of the DY measurement in COMPASS.
- The radiation conditions, and the necessary modifications to the spectrometer are being studied.
- COMPASS has good prospects to make this measurement for the first time.

The end