# *Polarized Drell-Yan measurements in COMPASS – a new project*

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on behalf of the COMPASS Collaboration

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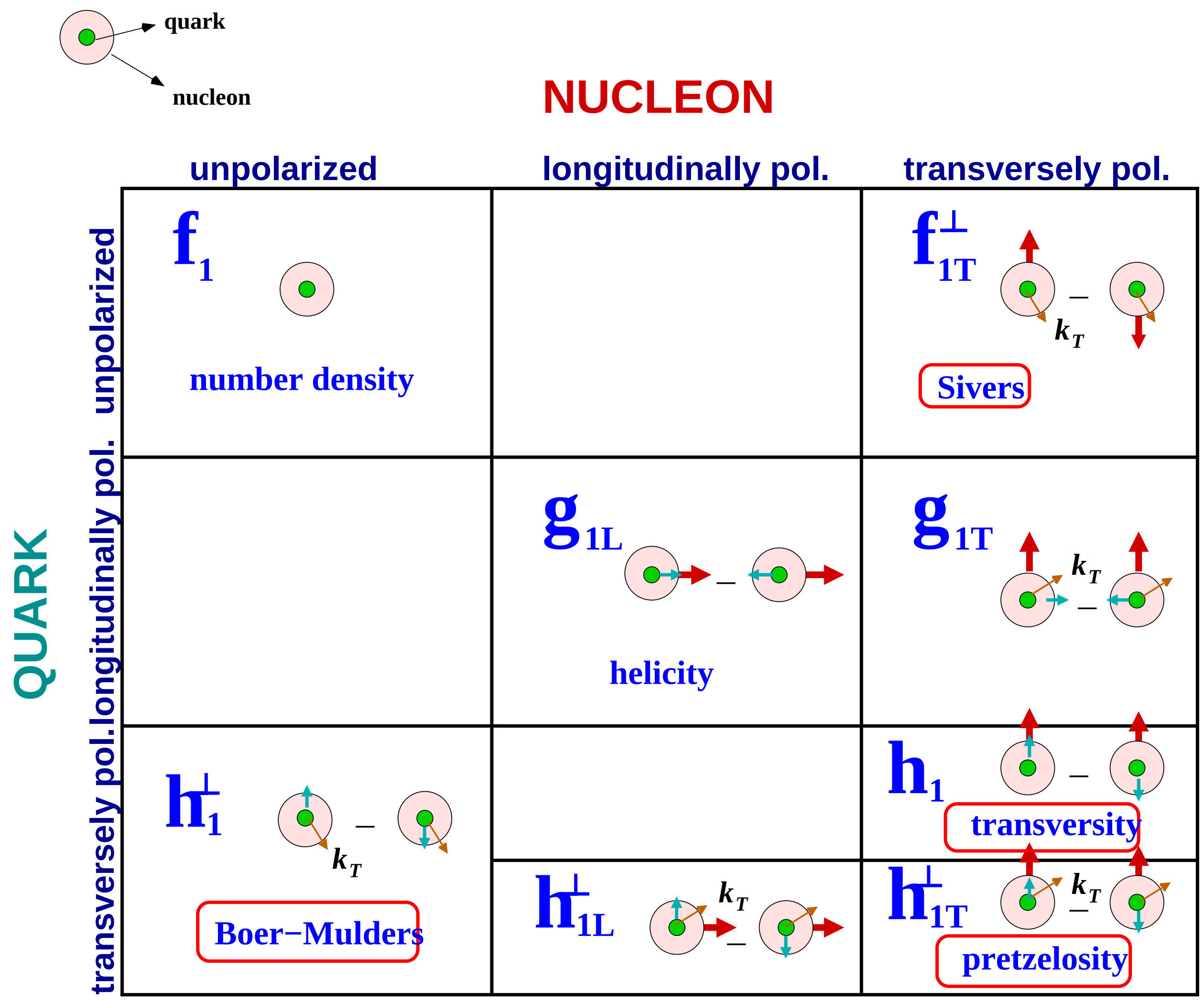
## Overview

- Transverse momentum dependent PDFs
- Polarized Drell-Yan
- Single spin asymmetries extraction
- The COMPASS experiment: present and future
- Summary

# *Parton distribution functions*

Taking into account the intrinsic transverse momentum $k_T$ of quarks, at LO **8 PDFs** are needed for a full description of the nucleon:



# Transverse momentum dependent PDFs

The transverse momentum dependent (TMD) PDFs of the nucleon carry important information about the nucleon spin dynamics:

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

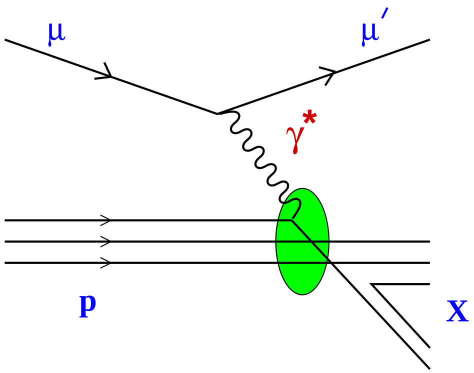
- Boer-Mulders: the $h_1^{\perp}(x, k_T^2)$ function describes the correlation between the transverse spin and the transverse momentum of a quark inside the unpolarized hadron.

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

# Accessing PDFs

TMD PDFs, like Sivers, can be accessed both from semi-inclusive DIS (SIDIS) and from the Drell-Yan process (DY).

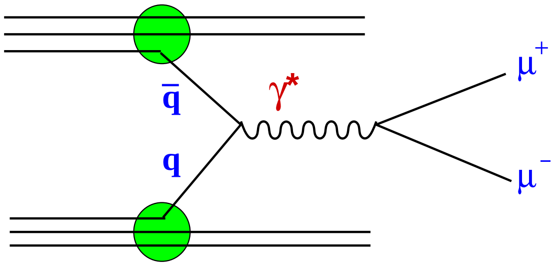
SIDIS




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

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

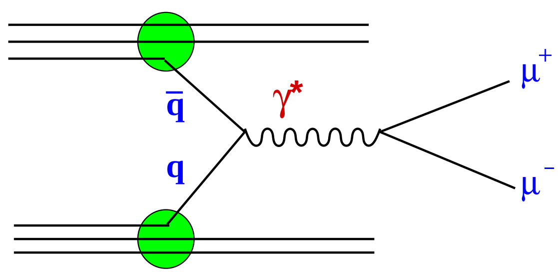
DY



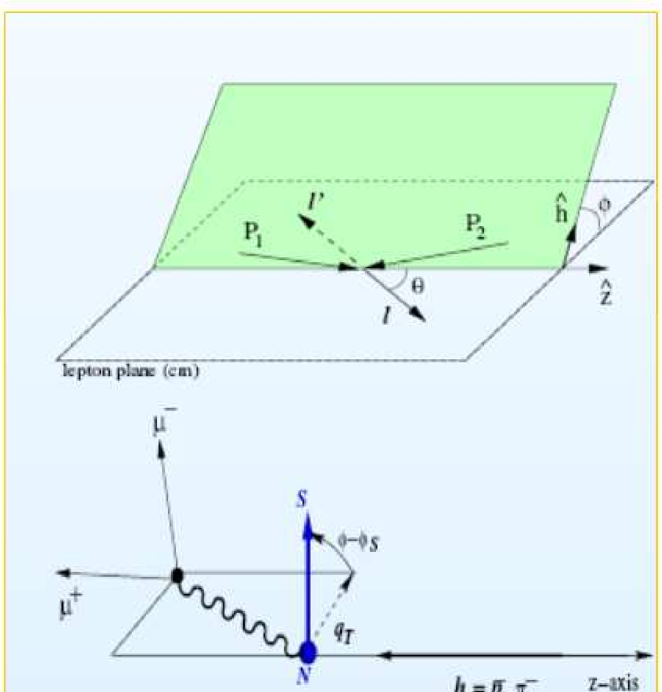

The spin asymmetry is proportional to a product of structure functions. If unpolarized beam and transversely polarized target:

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

# The Drell-Yan process




With a transversely polarized target in 2 opposite spin configurations, one can study Single Spin Asymmetries (SSA), and from these obtain the TMD PDFs.




In the Collins-Soper frame:

$\theta$, $\phi$: lepton pair wrt hadrons plane.

$\phi_{S2}$: spin-vector $S_{2T}$ wrt lepton plane, if transversely polarized hadron target.

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

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

$$\tau = M^2/s = x_1 \cdot x_2$$

# Unpolarized and Polarized DY

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

- Unpolarized DY

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

$\uparrow$ Boer-Mulders $\uparrow$

- Single polarized DY

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

$\uparrow$ Sivers

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

$\uparrow$ Boer-Mulders $\uparrow$ Transversity

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

$\uparrow$ Boer-Mulders $\uparrow$ Pretzelosity

# SIDIS versus DY

The possibility to compare Drell-Yan and SIDIS results provides an important test of non-perturbative QCD.

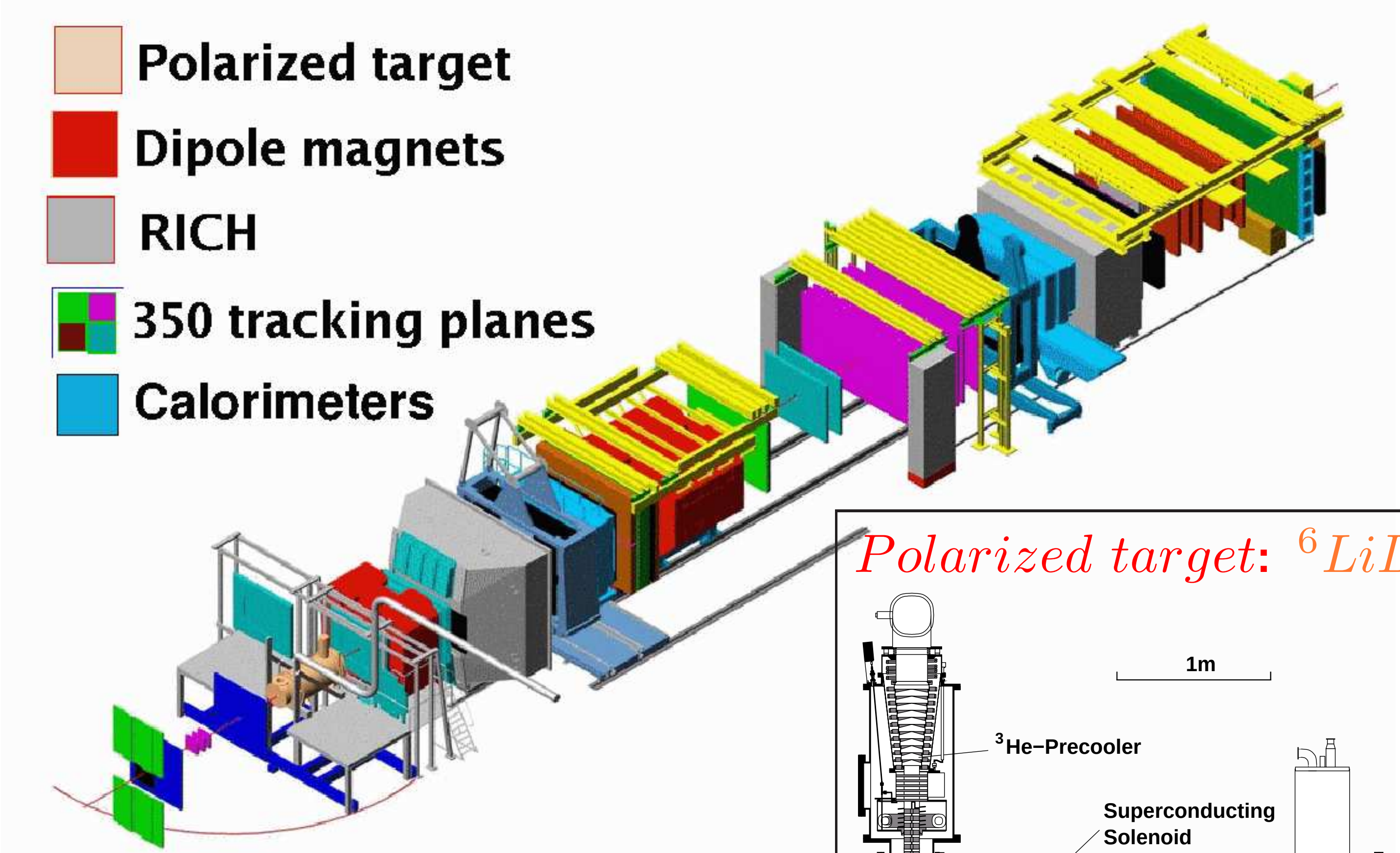
$\hookrightarrow$ Check the predictions:

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

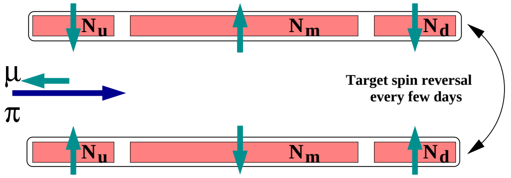
$$\boxed{h_{1}^{\perp}(DY) = -h_{1}^{\perp}(SIDIS)}$$

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

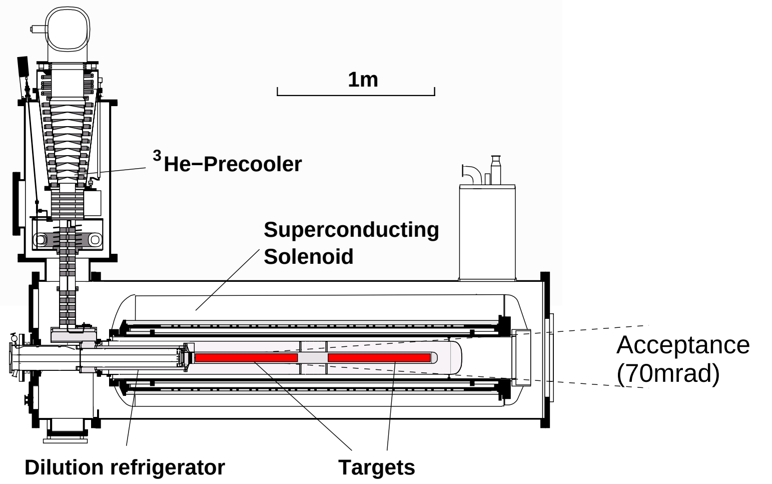
# The COMPASS Experiment at CERN




$\mu$ or $\pi$ beam




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



# *Why Drell-Yan @ COMPASS?*

Transversity and Sivers PDFs of the nucleon are addressed in COMPASS presently, from semi-inclusive DIS.

The opportunity to study, with the same spectrometer, the TMD PDFs from the Drell-Yan process is unique.

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

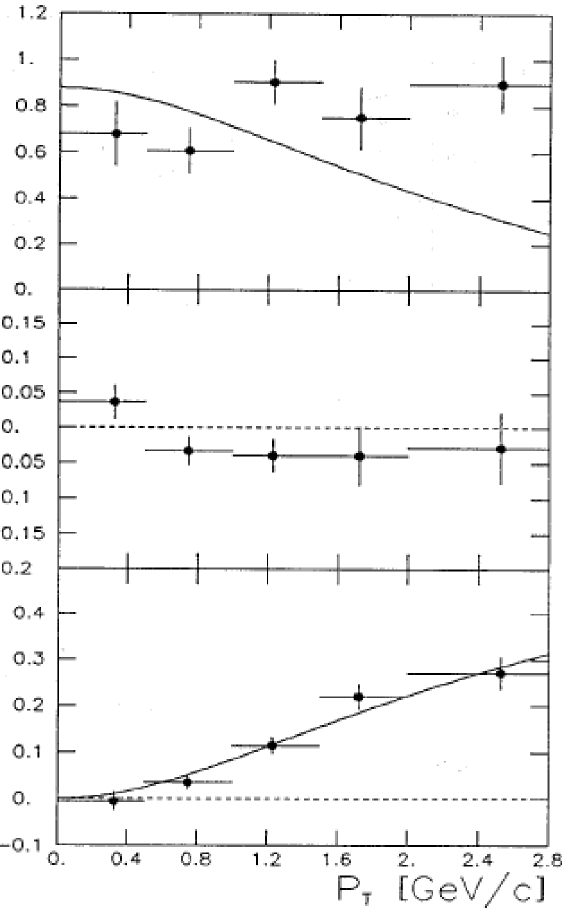
# DY in past experiments

| Experiment | Beam (GeV/c) | Targets | Physics |
|---|---|---|---|
| NA3 | $\pi^{\pm}$ 150/200/280 | $H_2$, Pt | $\pi$, $K$ PDFs |
| NA10 | $\pi^{-}$ 140/194/284 | D, W | $\pi$ PDFs, Boer-Mulders PDF |
| E615 | $\pi^{-}$ 252 | W | $\pi$, $K$ 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 | $\pi^{-}$ 160/190 | pol. $NH_3$ | Sivers, Transversity,... |

- A long history of successful unpolarized DY experiments
- Up to now, none with beam and/or polarized target – for access to the spin dependent PDFs
- COMPASS: limited beam intensity but large angular acceptance.

# DY angular distributions

NA10, $\pi^- + W$ 194 GeV/c




Z.Phys.C 31 (1986) 513

The unpolarized Drell-Yan angular distribution:

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

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

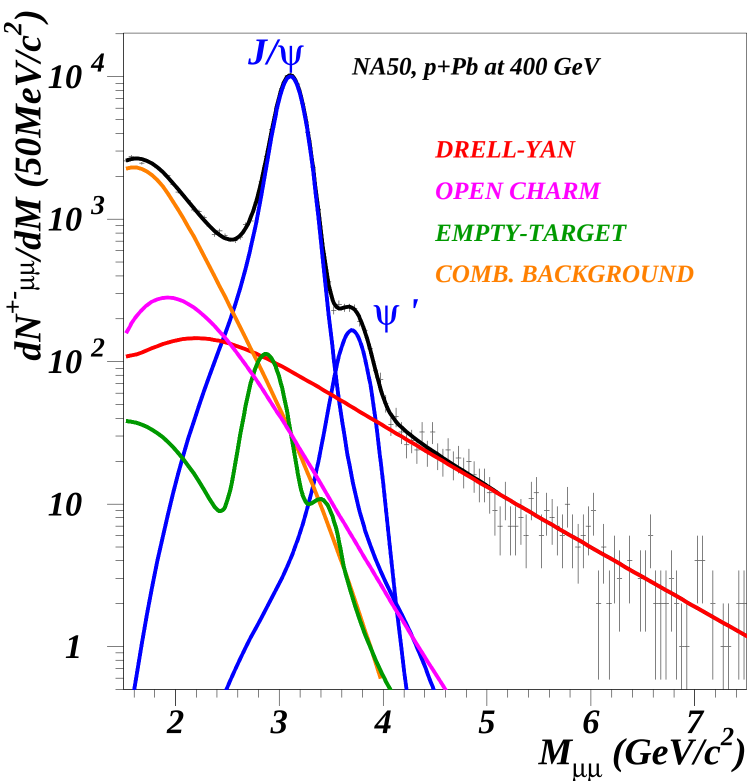
In LO and collinear approx., we get the usual:
$\lambda = 1$ and $\nu = \mu = 0$.

Important deviation seen 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).

# Signal and background

The dimuon mass spectrum is known from past DY experiments:




In the dimuon mass spectrum, 2 background sources must be considered:

- physics background:
  $D$ and $\bar{D}$ decays to $\mu^{\pm}X$;
  J/$\psi$ and $\psi$', also a subject of research.
- Combinatorial background
  $\pi$ and $K$ decaying to $\mu\nu$

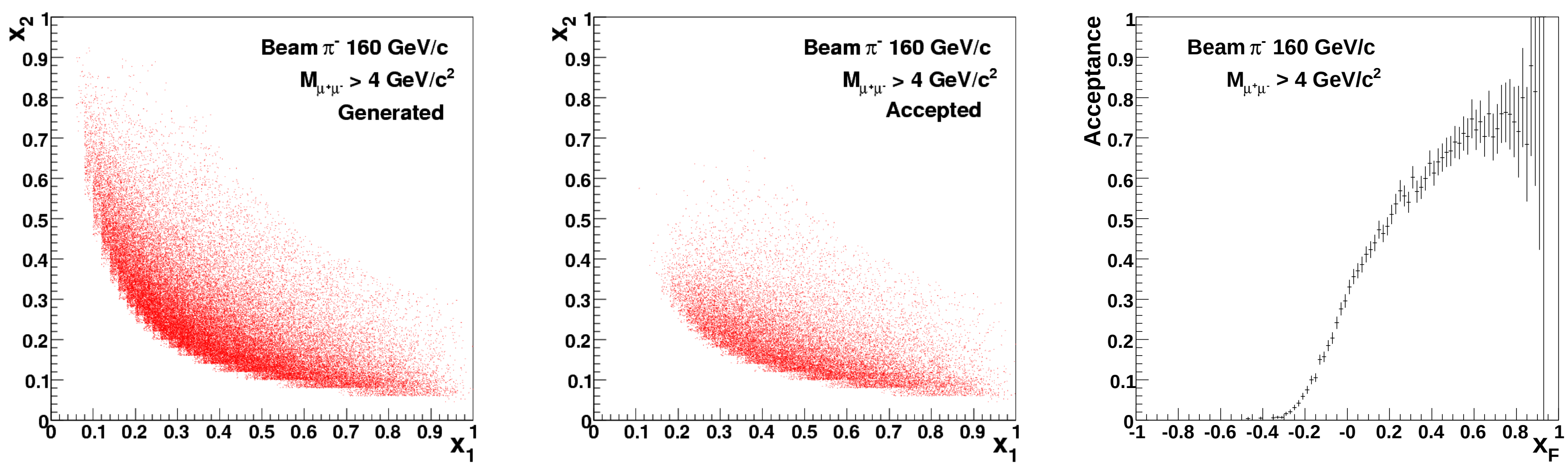
The cleanest region to study Drell-Yan is $4. < M < 9.$ GeV/c$^2$

In the region $2.0 < M < 2.5$ GeV/c$^2$ there is important contribution from background sources.

# DY cross-section and acceptance

From Pythia:

| $\sigma^{DY}$ (nb) | $2.0 < M_{\mu\mu} < 2.5$ (GeV/c$^2$) | $4. < M_{\mu\mu} < 9.$ (GeV/c$^2$) |
|---|---|---|
| s=200 GeV$^2$, $p_\pi$=106 GeV/c | 1.2 | 0.10 |
| s=300 GeV$^2$, $p_\pi$=160 GeV/c | 1.4 | 0.17 |
| s=400 GeV$^2$, $p_\pi$=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.

# Drell-Yan in $(\pi^-, p^\uparrow)$ collisions

Near future: $(\pi^-, p^\uparrow)$ $\pi^-$: $(\bar{u}d)$ $p$: $(uud)$

In the valence region: $\boxed{\sigma^{DY} \propto f_{(\bar{u}|\pi^-)} \otimes f_{(u|p)}}$

where $f = h_1^\perp, f_1, f_{1T}^\perp, h_1, h_{1T}^\perp$

The following topics can be studied:

- Sivers function $u_v$ quarks-dominance;
- Model dependent extraction of transversity and Boer-Mulders functions.

# Drell-Yan in $(\bar{p}, p^{\uparrow})$ collisions

## Longer term future: $(\bar{p}, p^{\uparrow})$

$\bar{p}$: $(\bar{u}\bar{u}\bar{d})$ $p$: $(uud)$

In this case, $f_{(\bar{u}|\bar{p})} = f_{(u|p)}$, thus

$$\boxed{\sigma^{DY} \propto f_{(u|p)} \otimes f_{(u|p)}}$$

- Model independent extraction of Sivers and transversity functions.

# Drell-Yan in $(K^-, p^\uparrow)$ collisions

Also the possibility to study $(K^-, p)$ in the future, interesting since kaon distribution functions are poorly known. Its feasibility in COMPASS is being evaluated.

$(K^-, p^\uparrow)$ $K^-$: $(\bar{u}s)$ $p$: $(uud)$

$$\sigma^{DY} \propto f_{(\bar{u}|K^-)} \otimes f_{(u|p)}$$

- Flavor separation possible, as in the $\pi^- p$ case.
- Model dependent extraction of valence Sivers, transversity and Boer-Mulders functions.
- Access to unpolarized kaon distribution functions.

# J/$\psi$-DY duality

J/$\psi$ and $\gamma$ being vector particles, the analogy between J/$\psi$ and DY production mechanisms might be of interest:

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

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

From the study of J/$\psi$ production in the dileptons decay channel:

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

Secondary hadron beam: possible to vary the beam energy (from 50 to 200 GeV), in order to study different J/$\psi$ production mechanisms.

# Dimuon trigger

In order to be efficient in measuring DY, one needs a good dimuon trigger.

For the moment COMPASS has only available a single muon trigger, based on hodoscopes stations placed in the Small Angles Spectrometer.

DY simulations show that the accepted dimuons are:

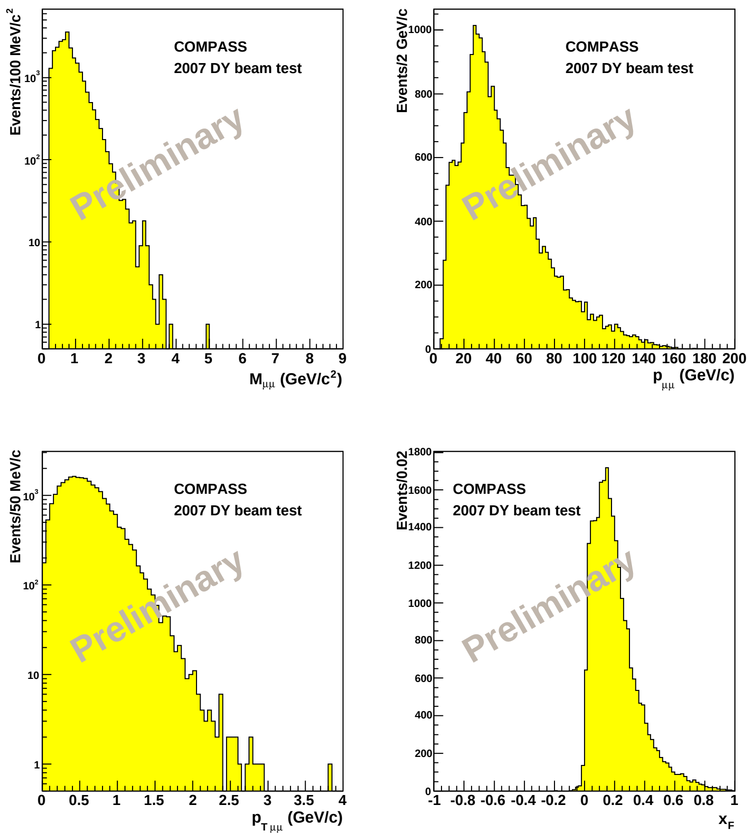
- 50% with both muons in the Large Angles Spectrometer
- 40% with 1 muon in LAS and another in SAS
- $<$ 10% with both muons in Small Angles Spectrometer

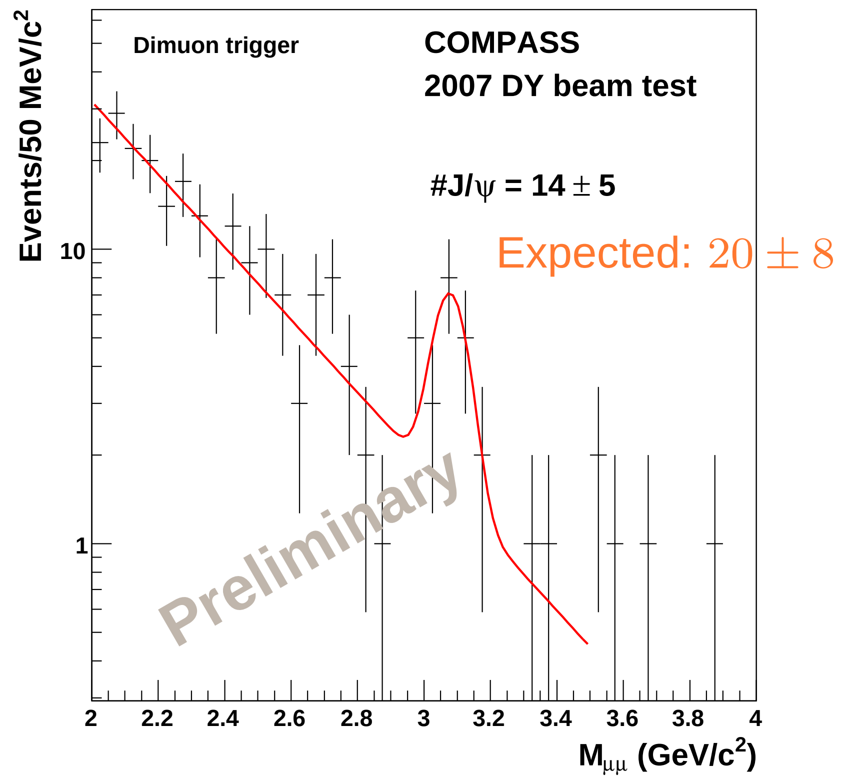
Thus, a dimuon trigger in the 1st spectrometer (LAS) is very important, it will be build from large area hodoscopes.

# Drell-Yan beam tests in COMPASS

In 2007 and 2008, short Drell-Yan beam tests were performed, to check the feasibility of the measurement.

In 2007, with a $\pi^-$ beam of 160 GeV/c on a $NH_3$ target, and without hadrons absorber: $\approx 90000$ dimuon events ($< 12$ hours data-taking).

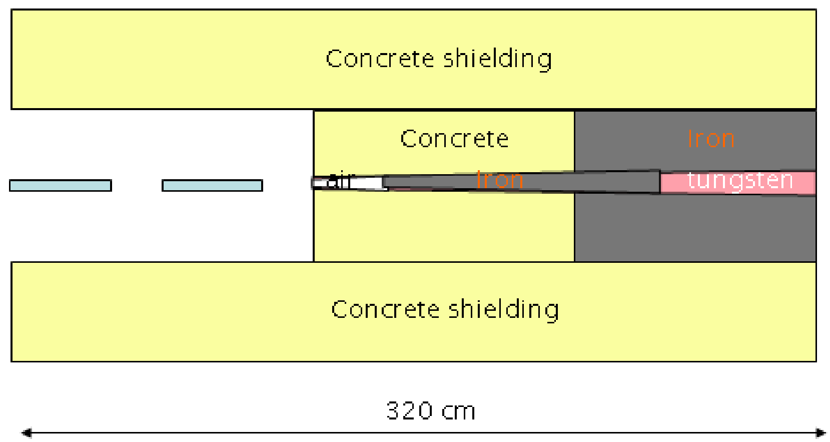


# Beam tests in COMPASS

In 2008, a test without hadron absorber and increasing the $\pi^-$ beam intensity was done $\hookrightarrow$ even at 1/4 of the proposed beam intensity, we observe too large detectors occupancy.

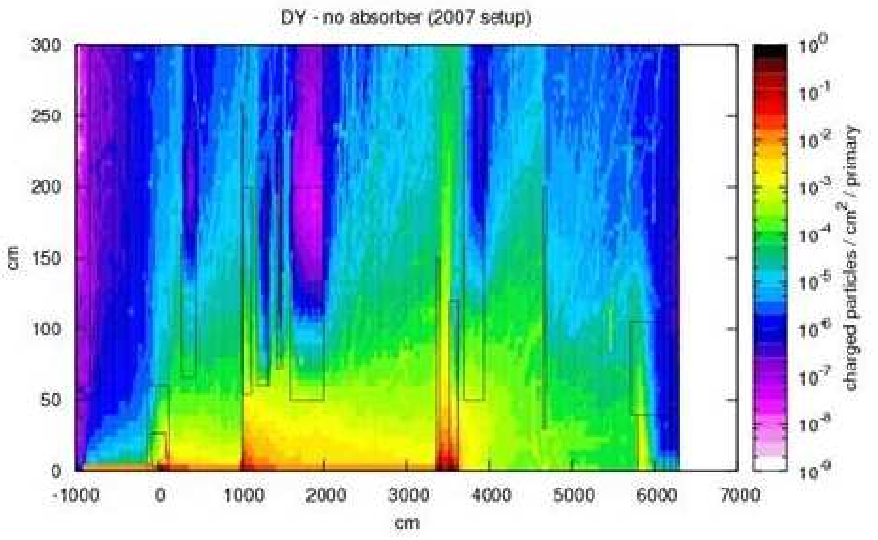
This year: An absorber will be placed after the target: check detectors occupancy, extent of the combinatorial background, mass and vertex resolution, and radiation issues.

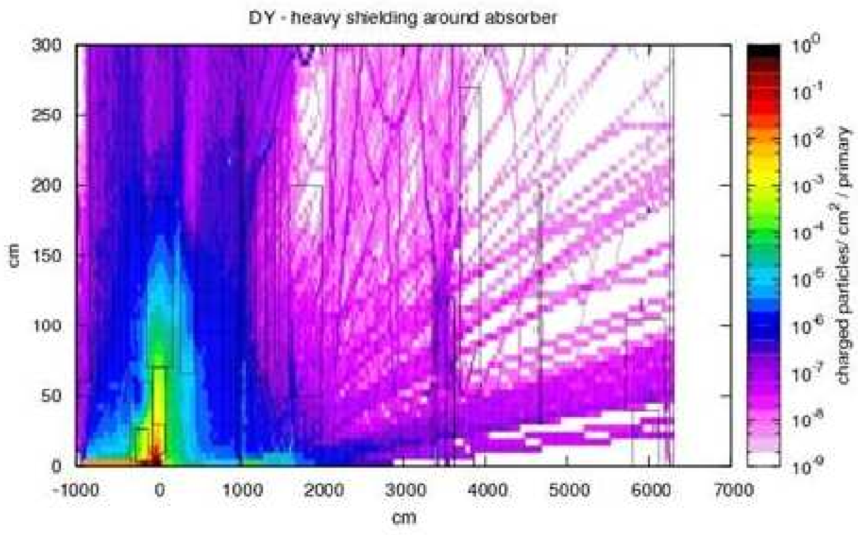



The future proposal includes a larger and improved version of absorber, for optimal background reduction.

# Radiation conditions

Since COMPASS is a ground-level experiment, the radiation conditions must be monitored carefully, and appropriate shielding must surround the target + absorber region:




FLUKA simulations, H. Vincke, CERN

# Asymmetries expected precision

With a beam intensity $I_{beam} = 6 \times 10^7$ particles/second, a luminosity of $L = 1.7 \times 10^{33}\ cm^{-2} s^{-1}$ can be obtained.

$\hookrightarrow$ Assuming 2 years of data-taking, one can collect > 200000 DY events in the region $4 < M_{\mu\mu} < 9.$ GeV/c$^2$.

In these conditions, and depending on the number of bins, the statistical error in the asymmetries measured is expected to be:

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

# Comparing with theory predictions

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 the measurement:

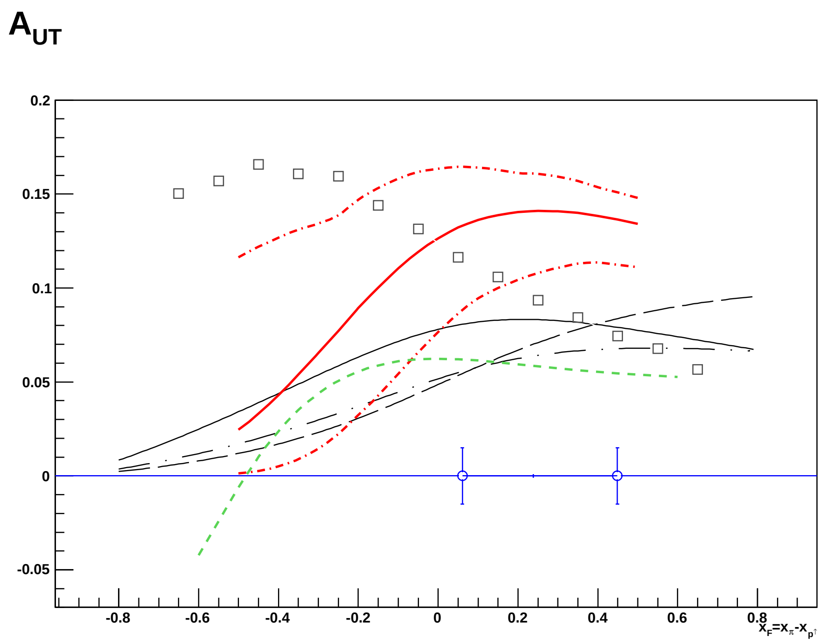
– solid and dashed: Efremov et al, PLB612(2005)233;

– 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.



# Summary

- Drell-Yan is a very well understood process.
- It provides unique information of the hadron structure and dynamics, and of transverse momentum PDFs – complementary to SIDIS.
- COMPASS experimental conditions probe the valence quarks region, where TMD effects are expected to be sizable.

- The $(\pi^-, p^\uparrow)$ part of the program can be started soon (2011 $\rightarrow$ ... )
- COMPASS can provide the first-ever Drell-Yan data on polarized target.

# SPARE: COMPASS and others

There is a strong interest in the scientific community on TMD PDFs.
Several experiments are being planned:

| 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 | $> 2015$ |
| FAIR (PAX) | collider, $\bar{p}^\uparrow$ p$^\uparrow$ | 200 | $> 2017$ |
| 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 | $> 2010$ |