Study of nucleon spin structure by the Drell-Yan process in the COMPASS experiment

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Excited QCD 2012

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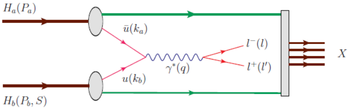
Outline

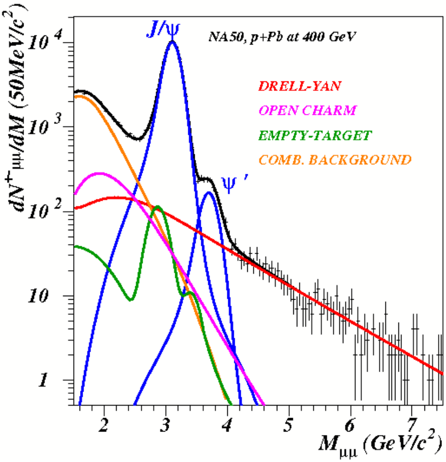
- Introduction to the Drell-Yan (DY) process
- Goals of the DY measurement @ COMPASS
- COMPASS Experiment – Spectrometer description
- Feasibility of the measurement
- Acceptances, event rates and statistical errors

Drell-Yan process

Annihilation of a $q\bar{q}$ pair from a 2 hadrons collision, producing a lepton pair



Dimuon mass distribution for p @ 400 GeV/c in a Pb target (NA50 Collaboration)



- Strong σ_{DY} decreases with the dimuon mass ($\sigma_{DY} \propto M_{\mu\mu}^{-4}$).
- The Drell-Yan signal is very clean above 4 GeV/c^2 dimuon mass. It is the region where we are interested in, the High Mass Region (HMR).

The angular distribution of the DY events can be written as:

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

The Lam-Tung sum rule $\boxed{1-\lambda-2\nu=0}$ relates the modulation amplitudes of the DY process.

The collinear hypothesis implies: $\boxed{\lambda=1,\ \mu=0,\ \nu=0}$.

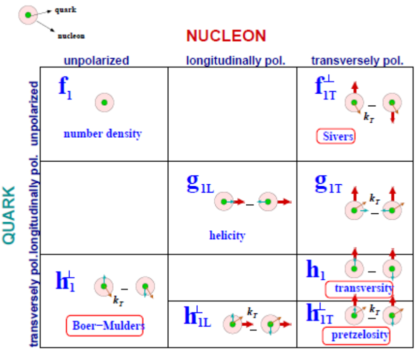
It was shown by the NA10 (CERN) and E615 (Fermilab) experiments that this hypothesis is violated.

They measured a modulation of $\cos 2\phi$ up to 30%

This means we cannot neglect the intrinsic transverse momentum k_T of quarks inside hadrons.

The nucleon structure in first order QCD is described by:

- 3 PDFs in the collinear approximation
- 8 PDFs taking into account the quark intrinsic transverse momentum, k_T



In the DY COMPASS program we will access 4 of them:

- **Transversity** h_1: describes the difference between the number density of quarks with parallel and anti-parallel spin w.r.t. the transversely polarised, relatively to the beam direction, father hadron
- **Boer-Mulders** $h_1^{\perp}$: describes the correlation between the transverse spin and the transverse momentum of a quark in an unpolarised nucleon
- **Sivers** $f_{1T}^{\perp}$: describes the influence of the nucleon transverse spin in the transverse momentum distribution of the quark
- **Pretzelosity** $h_{1T}^{\perp}$: describes the transverse polarization of a quark, along its intrinsic transverse momentum direction

Arnold *et al.*[1] derived the full expression of the σ_{DY}, for arbitrarily polarized beam and target.

Having an unpolarized beam and a transversely polarized target the σ_{DY} in LO can be written as:

$$\frac{d\sigma}{d^4 q d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U\{(1 + D_{[\sin^2\theta]}\boxed{A_U^{\cos 2\phi}}\cos 2\phi) + |\vec{S}_T|[\boxed{A_T^{\sin\phi_S}}\sin\phi_S$$

$$+ D_{[sin^2\theta]}(\boxed{A_T^{sin(2\phi+\phi_S)}}sin(2\phi + \phi_S) + \boxed{A_T^{sin(2\phi-\phi_S)}}sin(2\phi - \phi_S))]\}$$

where:

- θ and ϕ are the polar and azimuthal angles of μ^+ in the Collins-Soper reference frame
- ϕ_S is the angle between the transverse spin of the target nucleon and the transverse momentum of the γ^*
- F is given by $F = 4\sqrt{(P_\pi \cdot P_p)^2 - M_\pi^2 M_p^2}$
- q is the γ^* four-momentum
- $\hat{\sigma}_U$ is the part of the cross-section surviving the integration over the angles ϕ and ϕ_S
- $|\vec{S}_T|$ is the target polarization value
- $D_{[sin^2\theta]}$ is the virtual photon depolarization factor

[1] S. Arnold et al, Phys.Rev. D79 (2009)034005

$$\frac{d\sigma}{d^4qd\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U\{(1 + D_{[\sin^2\theta]}\boxed{A_U^{\cos 2\phi}}\cos 2\phi) + |\vec{S}_T|[\boxed{A_T^{\sin\phi_S}}\sin\phi_S$$
$$+ D_{[sin^2\theta]}(\boxed{A_T^{sin(2\phi+\phi_S)}}sin(2\phi+\phi_S) + \boxed{A_T^{sin(2\phi-\phi_S)}}sin(2\phi-\phi_S))]\}$$

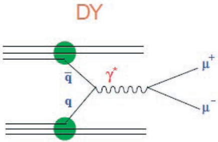
The azimuthal asymmetries A contain a convolution of 2 PDFs of the target and beam hadrons:

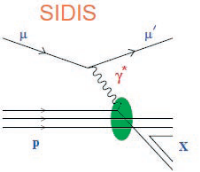
- $\boxed{A_U^{\cos 2\phi}}$ gives access to the Boer-Mulders functions of both hadrons.
- $\boxed{A_T^{\sin\phi_S}}$ gives access to the unpolarised PDF of beam hadron and the Sivers function of the target nucleon.
- $\boxed{A_T^{sin(2\phi+\phi_S)}}$ gives access to the Boer-Mulders function of the beam hadron and to the pretzelosity function of the target nucleon.
- $\boxed{A_T^{sin(2\phi-\phi_S)}}$ gives access to the Boer-Mulders function of the beam hadron and to the transversity function of the target nucleon.

We need to disentangle the PDFs in each of these asymmetries $\Rightarrow$ it requires some input.

DY vs SIDIS

The Sivers ($f_{1T}^{\perp}$) and the Boer-Mulders ($h_1^{\perp}$) functions are time-reversal odd functions. This leads to the prediction that they must change sign when accessed from DY or SIDIS[2].





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

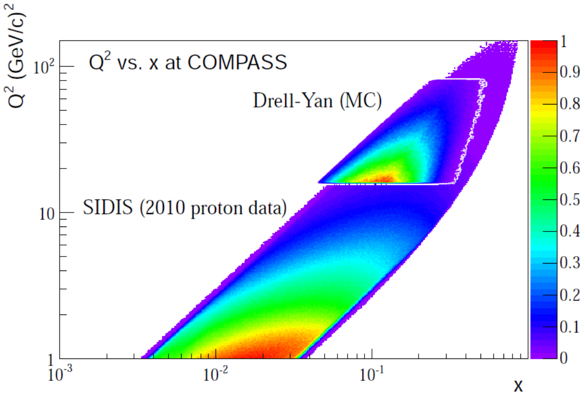
$$\boxed{h_1^{\perp}{}_{DY} = -h_1^{\perp}{}_{SIDIS}}$$

The experimental confirmation of this sign change is considered a crucial test of non-perturbative QCD.

[2] J.C. Collins, Phys. Lett. B536 (2002) 43, J.C. Collins, talk at LIGHT CONE 2008

DY vs SIDIS

Phase space overlapping



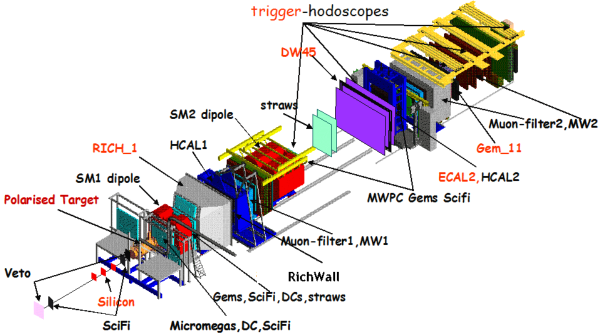
The J/ψ duality corresponds to consider a possible analogy in the production mechanisms of both J/ψ ($q\bar{q} \rightarrow J/\psi + X$) and γ^*.

Studying the charmonium mass region in the dilepton decay channel:

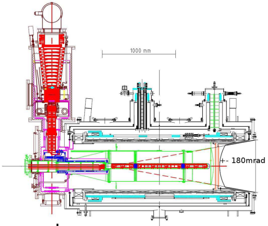
1. Check duality hypothesis - polarized J/ψ production cross-section
2. Access PDFs from J/ψ events - larger statistics available

COmmon Muon Proton Apparatus for Structure and Spectroscopy

Beam: π^- @ 190 GeV/c



Polarized target – NH_3



- Beam telescope:
  - SciFis
- Large Angle Spectrometer (LAS):
  - SM1 magnet
  - Tracking detectors
  - RICH
  - ECAL1
  - HCAL1
  - Muons Filter 1
- Small Angle Spectrometer (SAS):
  - SM2 magnet
  - Tracking detectors
  - ECAL2
  - HCAL2
  - Muons Filter 2

Feasibility of the measurement

In 2007, 2008 and 2009 short Drell-Yan beam tests were performed, to check the feasibility of the measurement.

2007 test:

- open spectrometer (without hadron absorber)
- π^- beam @ 160 GeV/c ($I_{beam} = 4 \times 10^6\ \pi/s$) and an unpolarized NH_3 target
- we collected $\simeq$ 90000 dimuons in $\lesssim$ 12 hours
- validation of the J/ψ yields expected

2008 test:

- open spectrometer (without hadron absorber)
- increase of the beam intensity up to $6.5 \times 10^6\ \pi/s$
- high occupancy of detectors closer to the target region $\Rightarrow$ confirmed that is mandatory the use of a hadron absorber
- verification of the spectrometer response and radiation doses

2009 test was done using:

- π^- beam @ 190 GeV/c
- Two target cells (polyethylene) with 40 cm length and 5 cm diameter, spaced by 20 cm
- A prototype of an absorber:
  - Two blocks, of concrete and stainless steel, 100 cm length each, and 80×80 cm^2 in transverse dimensions each
  - A beam plug, inside the central part of absorber, made of W and steel disks.

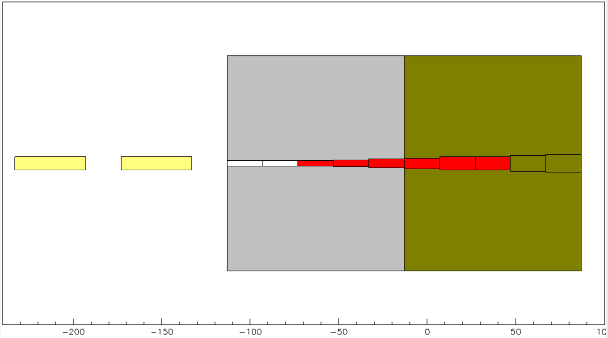
Number of radiation lengths (multiple scattering for muons):

$x/X_0 = 66.17$

Number of interaction lengths (stopping power for pions):

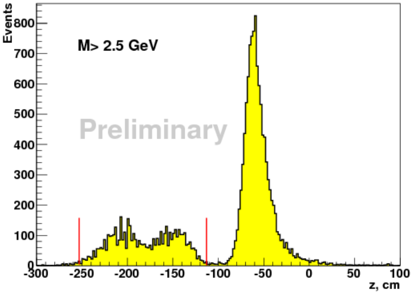
$x/\lambda_{int} = 6.69$

Target + Absorber region

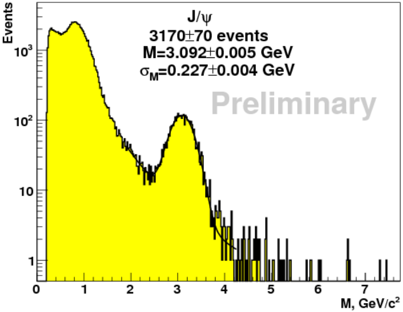


- 3 days test

z vertex distribution

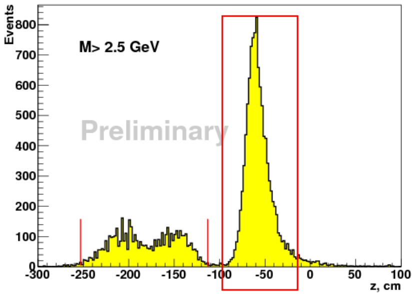


Dimuon mass distribution

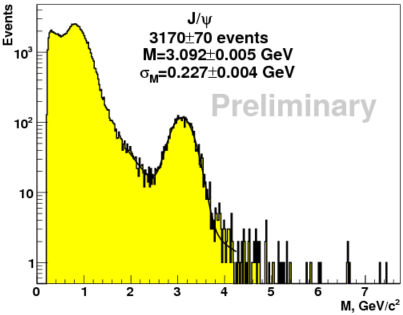


- 3 days test

z vertex distribution



Dimuon mass distribution



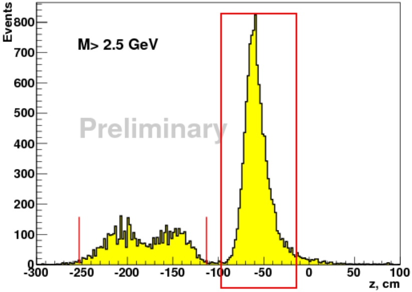
$\Downarrow$

Huge number of events due to the fact we didn't have a dimuon trigger.

2009 DY beam test - results

- 3 days test

z vertex distribution



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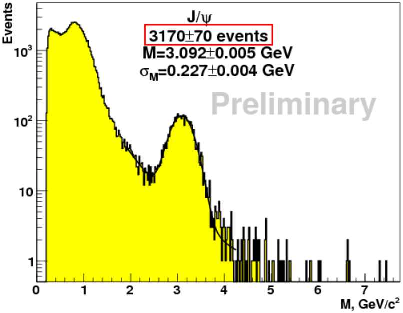
Huge number of events due to the fact we didn't have a dimuon trigger.

Dimuon mass distribution



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The number of expected J/ψ was reached.

Current DY setup status

The proposal setup was in the meanwhile optimized. The newer version is:

- Two target cells (NH_3) inside the dipole with 55 cm length and 4 cm diameter, spaced by 20 cm;
- The absorber is 236 cm long, made of Al_2O_3;
- The plug inside the absorber is made of 6 disks of W, 20 cm long each and 20 cm of Alumina in the most downstream part (total of 140 cm).

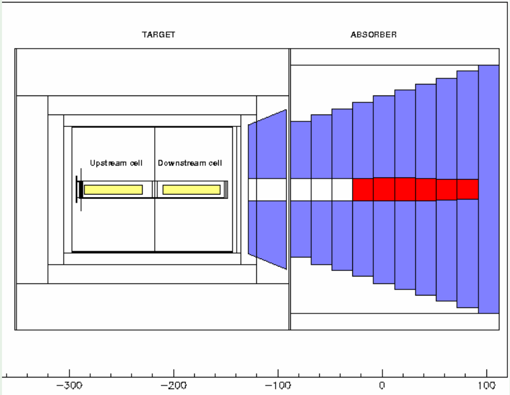
Number of radiation lengths (multiple scattering for muons):

$x/X_0 = 33.53$
(66.17 for 2009 test absorber)

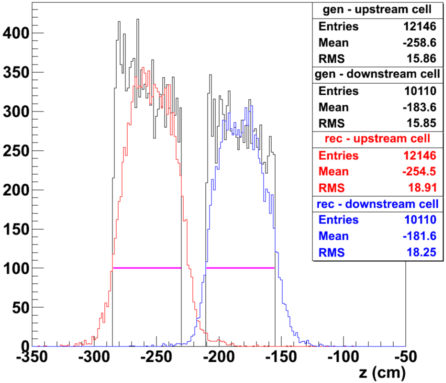
Number of interaction lengths (stopping power for pions):

$x/\lambda_{int} = 7.25$
(6.69 for 2009 test absorber)

Polarised Target + Absorber region



z vertex distribution



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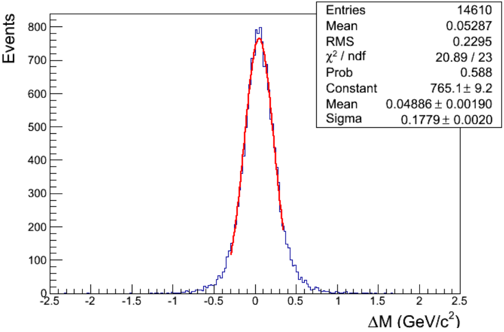
$\Delta z = 6\ cm$ in HMR ($M_{\mu\mu} > 4\ GeV/c$)

Dimuon mass resolution



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$\Delta M = 178\ MeV/c^2$ in HMR ($M_{\mu\mu} > 4\ GeV/c$)

Contamination:

Upstream cell — 0.29 %

Downstream cell — 1.16 %

⇒ A very low level of contamination.

Acceptances, event rates and statistical errors

The dimuons acceptance in the HMR ($M_{\mu\mu} > 4$ GeV/c) is 39%.

The accepted dimuons are:

- μ_1 (1^{st} spectrometer) & μ_2 (1^{st} spectrometer) - 22%
- μ_1 (2^{nd} spectrometer) & μ_2 (2^{nd} spectrometer) - 2%
- μ_1 (1^{st} spectrometer) & μ_2 (2^{nd} spectrometer) - 18%

We expect an DY event rate of 900 events/day in the HMR assuming:

- π^- beam with 190 GeV/c
- $I_{beam} = 6 \times 10^7$ $particles/s$
- $L = 1.2 \times 10^{32}$ $cm^{-2}s^{-1}$

Assuming two years of data taking we expect the following statistical errors in azimuthal asymmetries:

Asymmetry	Uncertainty in HMR (%)
$\delta A_U^{\cos 2\phi}$	0.43
$\delta A_T^{\sin \phi_S}$	1.34
$\delta A_T^{sin(2\phi+\phi_S)}$	2.70
$\delta A_T^{sin(2\phi-\phi_S)}$	2.70

Azimuthal asymmetries and statistical errors (2010 status)

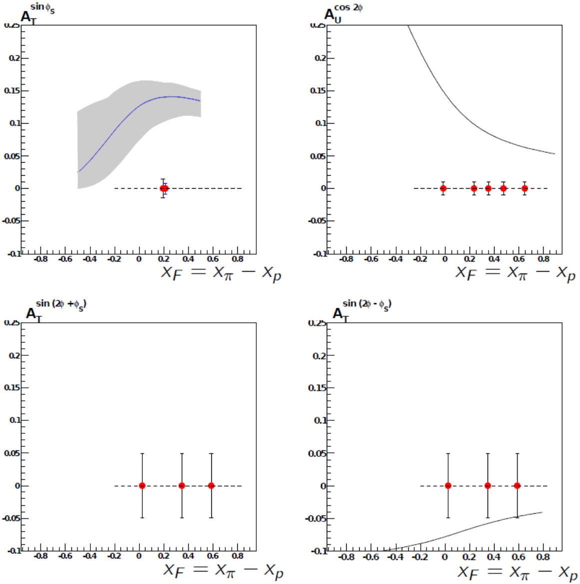
Theory update is needed to take into account the Q^2 evolution.

Unpolarized PDF
$\otimes$
Sivers

M. Anselmino *et al*, Phys. Rev. D 79 (2009) 054010

Boer-Mulders
$\otimes$
Boer-Mulders

B. Zhang *et al*, Phys. Rev. D 77 (2008) 054011



Boer-Mulders
$\otimes$
Pretzelosity

Boer-Mulders
$\otimes$
Transversity

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

Summary

- The opportunity to study, in the same experiment, the TMD PDFs from both SIDIS and the DY processes is unique.
- The sign change in Sivers and Boer-Mulders functions when accessed by DY and SIDIS will be checked.
- The feasibility of the measurement was proven after three past beam tests.
- The COMPASS II Proposal was approved by CERN for a first period of 3 years including 1 year for Drell-Yan.
- Drell-Yan data taking will start in 2014 and the second year of data taking is expected in 2017.