Study of Transverse Momentum Dependent Distributions from Polarised Drell-Yan at COMPASS

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on behalf of the COMPASS/CERN Collaboration

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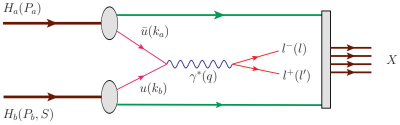
Quark-antiquark annihilation, with dilepton production



- $P_{a(b)}$, beam (target) hadron momentum
- $s = (P_a + P_b)^2$, centre of mass energy squared
- $x_{a(b)} = q^2/(2P_{a(b)} \cdot q)$, momentum fraction carried by the quark from $H_{a(b)}$
- $x_F = x_a - x_b$, Feynman x
- $Q^2 = q^2 = {M_{\mu\mu}}^2 = s x_a x_b$, dimuon invariant mass squared
- $k_{T\,a(b)}$, quark intrinsic transverse momentum

If $k_{T\,a(b)} \neq 0$, the dimuon has also transverse momentum:

$$q_T = P_T = k_{T\,a} + k_{T\,b}$$

An experimental evidence of $k_T \neq 0$:

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

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

If quarks do not have transverse momentum (collinear hypothesis): $\lambda = 1,\ \mu = 0,\ \nu = 0$.

NA10 (CERN) and E615 (Fermilab) experiments measured a modulation of $\cos 2\phi$ up to 30%.

Why polarised Drell-Yan process to access TMD PDFs

The Drell-Yan process is an excellent tool to study PDFs:

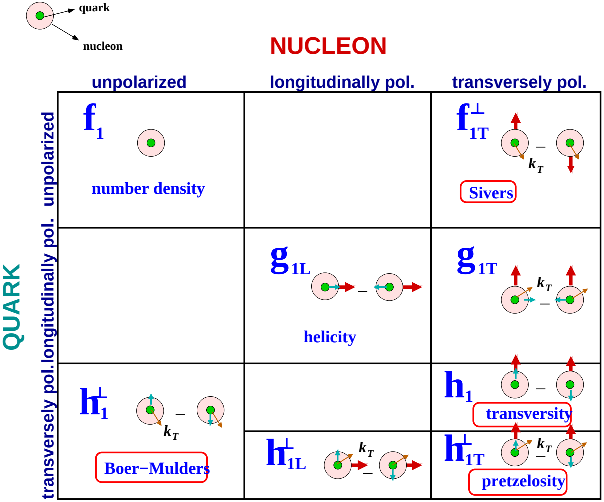
- well calculable process (W. Vogelsang et al, Phys. Rev. Lett. 105 (2010) 252003 and Phys. Rev. D83 (2011) 114023)
- no fragmentation functions involved (contrary to SIDIS)
- convolution of two PDFs ($\sigma_{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$)
  $\hookrightarrow$ dominated by annihilation of valence $\bar{u}$ from π^- and valence u from p
- All TMD PDFs are expected to be sizeable in the valence quark region ($x > 0.1$)
- QCD TMD approach is applied in the region: Q ($\geq$ 4 GeV/c^2) $\gg$ p_T ($\simeq$ 1 GeV/c)

$\hookrightarrow$ Very clean signal to access initial parton distribution functions

However there is a price to pay $\Rightarrow$ The DY process has a very low cross-section
$\hookrightarrow$ High luminosity needed $\Rightarrow$ High intense beam

TMD PDFs

The nucleon structure in QCD leading order, taking into account k_T, is described by 8 PDFs.



In the DY COMPASS programme we will access 4 PDFs via the measurement of transverse spin asymmetries:

- **Boer-Mulders** $h_1^{\perp}$
- **Sivers** $f_{1T}^{\perp}$
- **transversity** h_1
- **pretzelosity** $h_{1T}^{\perp}$

Considering an unpolarised beam and a transversely polarised target the σ_{DY} in LO can be written as:

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

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

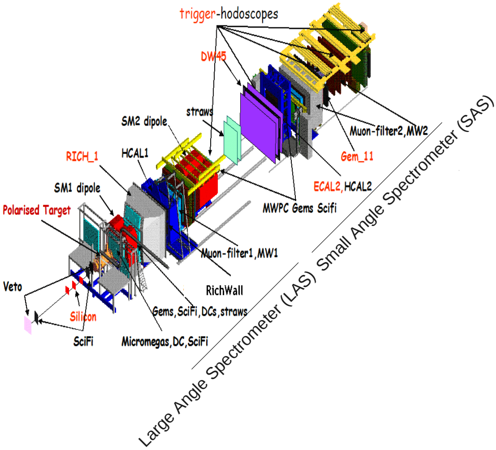
The azimuthal asymmetries A contain a convolution of 2 PDFs of the beam and target hadrons:

- $\boxed{A_U^{\cos 2\phi}}$ Boer-Mulders of beam ($h_1^\perp(\pi)$) $\otimes$ Boer-Mulders of target ($h_1^\perp(p)$)
- $\boxed{A_T^{\sin\phi_S}}$ unpolarised PDF of beam ($f_1(\pi)$) $\otimes$ Sivers of target ($f_{1T}^\perp(p)$)
- $\boxed{A_T^{sin(2\phi+\phi_S)}}$ Boer-Mulders of beam ($h_1^\perp(\pi)$) $\otimes$ pretzelosity of target ($h_{1T}^\perp(p)$)
- $\boxed{A_T^{sin(2\phi-\phi_S)}}$ Boer-Mulders of beam ($h_1^\perp(\pi)$) $\otimes$ transversity of target ($h_1(p)$)

↪ These asymmetries will be measured by fitting the corresponding (ϕ, ϕ_S) distributions.

COmmon Muon Proton Apparatus for Structure and Spectroscopy

Experimental setup



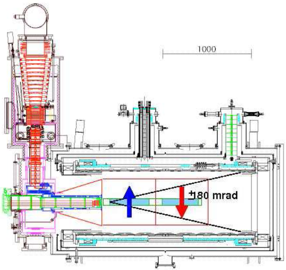
Beam

π^- @ 190 GeV/c

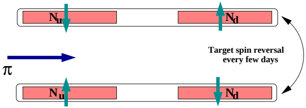
Polarised target, NH_3

dilution factor 22%

polarisation up to 90%



- Large angular acceptance (±180 mrad)
- Two target cells (NH_3) with opposite polarisations transverse to the beam



1. Large angular acceptance spectrometer
2. High intensity (up to 10^8 particles/s) hadron beam
3. Very good resolution beam telescope
4. Transversely polarised proton target (NH_3)
5. Possibility to include a hadron absorber downstream of the target
6. Possibility to include a vertex detector upstream of the hadron absorber to improve the vertex resolution
7. Dimuon trigger based on hodoscope signal coincidences and with target pointing capability

↪ The COMPASS II Proposal was approved by CERN for a first period of 3 years including 1 year for Drell-Yan.

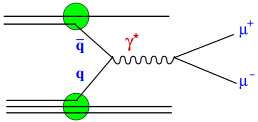
TMDs (Non-)Universality – DY <> SIDIS

The Sivers ($f_{1T}^{\perp}$) and the Boer-Mulders ($h_1^{\perp}$) functions are time-reversal odd functions

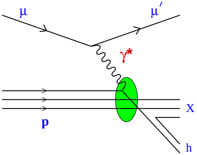
$\hookrightarrow$ they are process dependent

This leads to the prediction that they must change sign when accessed from DY or SIDIS[1].

DY



SIDIS



$$f_{1T}^{\perp}(x, k_T)|_{DY} = -f_{1T}^{\perp}(x, k_T)|_{SIDIS}$$

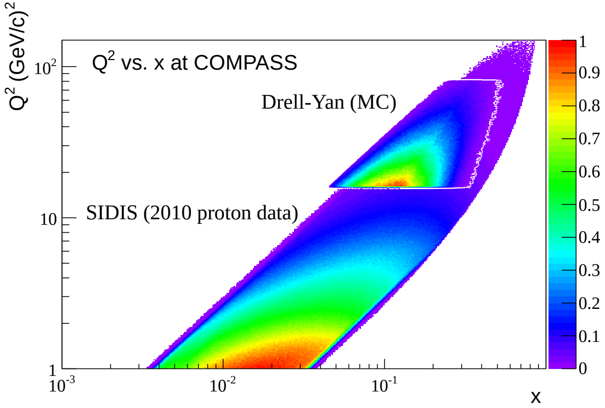
$$h_1^{\perp}(x, k_T)|_{DY} = -h_1^{\perp}(x, k_T)|_{SIDIS}$$

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

[1] J.C. Collins, Phys. Lett. B536 (2002) 43

Q^2 vs x domain in COMPASS

In COMPASS we have the opportunity to access these TMD PDFs from both DY and SIDIS processes.

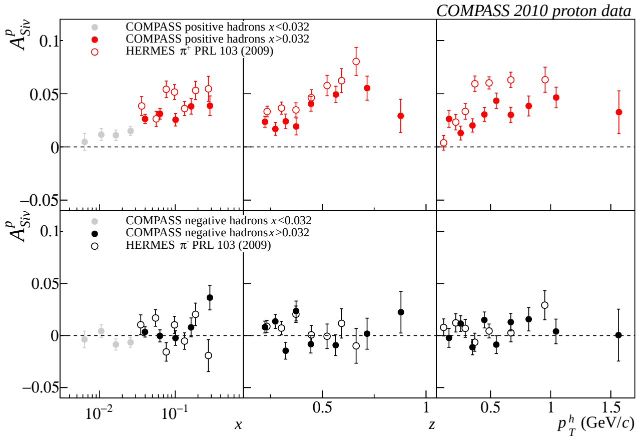


There is a phase space overlap between the two measurements.
⟶ However to properly compare the extracted TMDs, their Q^2 evolution must be taken into account.

From SIDIS:

COMPASS (PLB 717 2012)
If $x > 0.032$
$\hookrightarrow \langle Q^2 \rangle = 8.7\ \mathrm{GeV}/c^2$

HERMES (PRL 103 2009)
$\langle Q^2 \rangle = 2.4\ \mathrm{GeV}/c^2$



- $h^- \Rightarrow A^p_{Siv} \sim 0$
- $h^+ \Rightarrow A^p_{Siv} > 0$
- A^p_{Siv}(COMPASS)$<A^p_{Siv}$(HERMES) $\longrightarrow$ The difference may be due to TMD Q^2 evolution.

J/ψ studies

$$q\bar{q} \rightarrow J/\psi\ X \rightarrow \mu^+\mu^- X \quad \textbf{vs} \quad gg \rightarrow J/\psi\ X \rightarrow \mu^+\mu^- X$$

In case of duality DY $\leftrightarrow$ J/ψ ($q\bar{q} \rightarrow \gamma^*/J/\psi\ X \rightarrow \mu^+\mu^- X$), that is, the $q\bar{q}$ annihilation J/ψ production is dominating over gg fusion J/ψ production in the COMPASS phase space:

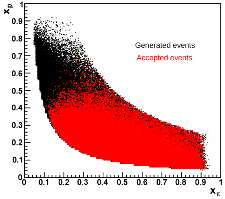
- Possibility to study the polarised J/ψ cross-section
- Possibility to extract the TMD PDFs with much larger statistics

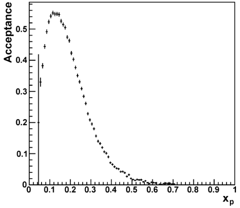
If gg production mechanism is dominating:

- Possibility to extract the gluon Sivers TMD (related with gluons OAM)

Geometrical acceptance

Valence range ($x \gtrsim 0.1$) for both quarks



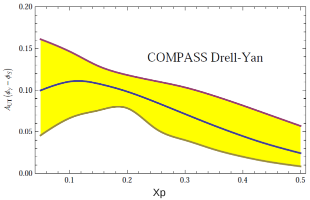


The dimuons acceptance in the HMR ($M_{\mu\mu} > 4$ GeV$/c^2$) is 39%.

The accepted dimuons are:

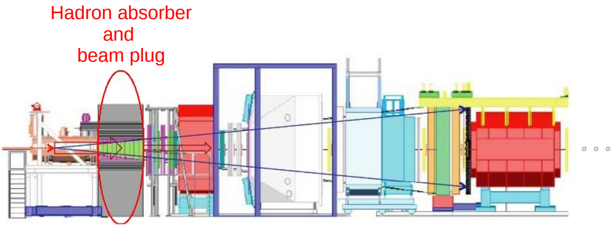
μ_1 (1st spectrometer) & μ_2 (1st spectrometer)	–	22 %
μ_1 (1st spectrometer) & μ_2 (2nd spectrometer)	–	18 %
μ_1 (2nd spectrometer) & μ_2 (2nd spectrometer)	–	2 %

Sivers prediction
Sun & Yuan, http://arxiv.org/abs/arXiv:1308.5003



The acceptance is larger in the region in which Sivers is expected to be larger ($\sim 10\%$)

Experimental setup - Absorber



- The main goal of the hadron absorber is to stop the hadrons produced in the primary interaction.
- The task of the beam plug is to stop the non-interacting beam.

The hadron absorber also introduces multiple scattering on muons

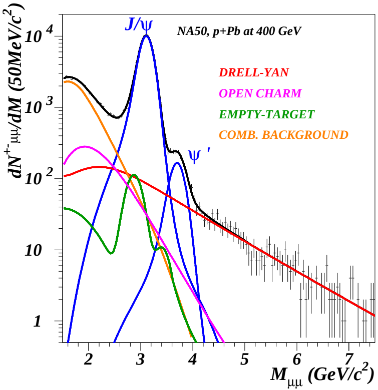
$\Rightarrow$ It is important to minimise the number of radiation lengths crossed by the muons in the absorber, while maximising the number of pion interaction lengths $\rightarrow Al_2O_3$.

Signal/Background

- Strong decrease of σ_{DY} with $M_{\mu\mu}$
- The Drell-Yan signal is very clean (background free) for $M_{\mu\mu} > 4$ GeV/c^2

We will study DY in the HMR, nevertheless there is the possibility to use also the regions $2 < M_{\mu\mu} < 2.5$ GeV/c^2 and J/ψ ($J/\psi \leftrightarrow$ DY duality) for TMDs.

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



- The combinatorial background comes from uncorrelated pion and kaon decays and it is controlled using an optimised hadron absorber and a beam plug.
- $I_{beam} \leq 10^8$ π^-/s $\sim$ 10 times lower than the NA50 beam intensity.
- The combinatorial background ($\propto I^2_{beam}$) $\sim$ 100 times lower than in NA50.
- The open charm background comes from $D\bar{D}$ mesons semileptonic decays

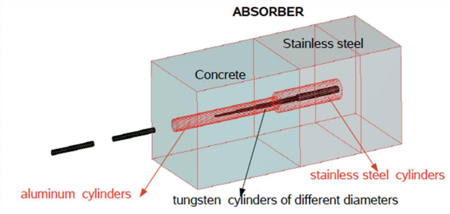
Feasibility of the measurement

The feasibility of the measurement was proved by several beam tests done so far.

- verification of the absorber effect and the spectrometer response ✓
- verification of the radiation doses ✓
- verification of the detector occupancies ✓
- verification of the trigger rates ✓
- validation of the dimuon trigger ✓

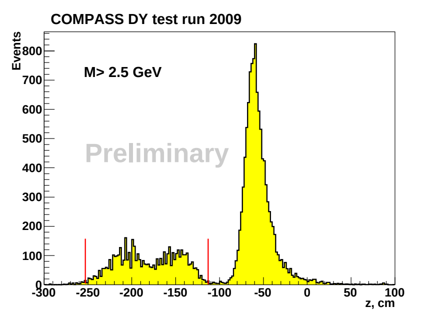
In 2009 we did a 3 days test using:

- A hadron absorber prototype
- A beam plug, inside the central part of absorber
- π^- beam @ 190 GeV/c up to $I_{beam} = 1.5 \times 10^7$ π/s
- Two unpolarised target cells (polyethylene)



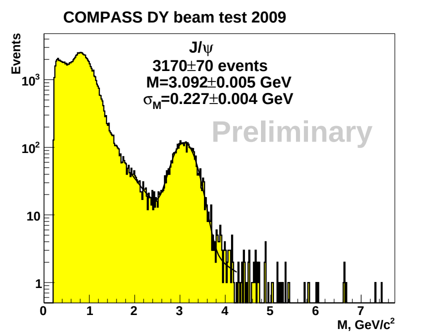
2009 DY beam test - z vertex and dimuon mass distributions

z vertex distribution



Enough Z_{vtx} resolution to distinguish the target cells and the absorber

Dimuon mass distribution



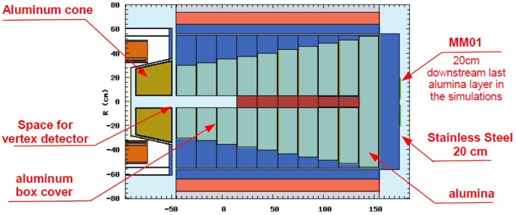
J/ψ yields as expected ✓

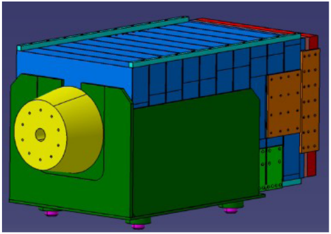
Mass resolution as expected from MC ✓

DY setup design for 2014-15 Run

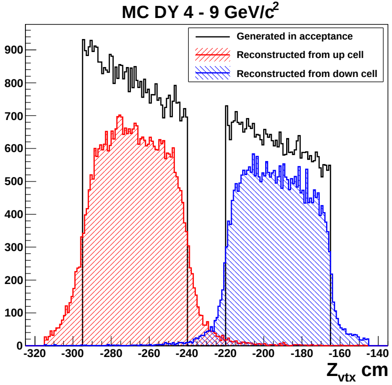
The setup for DY experiment is being optimised:

- Polarised target:
  - modified microwave cavity
  - two target cells of NH_3 (55 cm length, 4 cm diameter, spaced by 20 cm)
  - moved $\sim$ 2.3 m upstream in order to have space for the hadron absorber
- Radioprotection shielding
- New SciFi based beam telescope - high rate capability
- Trigger hodoscopes modifications
- Vertex detector
- New large area tracking station in the 1[st] spectrometer
- Hadron absorber and beam plug

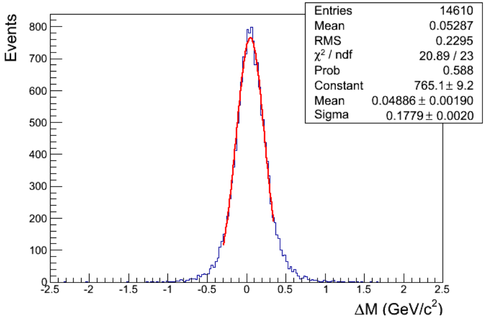




z vertex distribution



Dimuon mass resolution



- $\Delta z \simeq 6$ cm ($4 < M_{\mu\mu} < 9$ GeV/c^2)
- A very low level of contamination

- $\Delta M \simeq 180$ MeV/c^2 ($4 < M_{\mu\mu} < 9$ GeV/c^2)

Event rates and experimental accuracy

For a π^- beam of 190 GeV/c, $I_{beam} = 6 \times 10^7$ particles/s and $L = 1.2 \times 10^{32}$ cm^{-2}s^{-1} one expects:

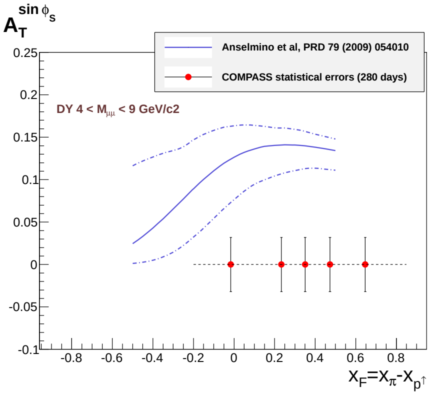
- A DY event rate of 4300 events/day in $2 < M_{\mu\mu} < 2.5$ GeV/c^2
- A DY+J/ψ event rate of 25900 events/day in $2.9 < M_{\mu\mu} < 3.2$ GeV/c^2
- A DY event rate of 900 events/day in the $4 < M_{\mu\mu} < 9$ GeV/c^2

Considering two years of data taking (about 280 days) we expect 250k events in the HMR and the following statistical errors in azimuthal asymmetries:

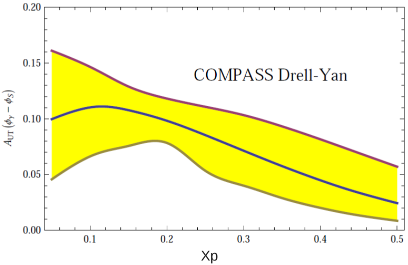
Asymmetry error	$2 < M_{\mu\mu} < 2.5$ GeV/c^2	$2.9 < M_{\mu\mu} < 3.2$ GeV/c^2	$4 < M_{\mu\mu} < 9$ GeV/c^2
$\delta A_U^{\cos 2\phi}$	0.0026	0.0011	0.0057
$\delta A_T^{\sin \phi_S}$	0.0065	0.0027	0.0143
$\delta A_T^{sin(2\phi+\phi_S)}$	0.0130	0.0053	0.0285
$\delta A_T^{sin(2\phi-\phi_S)}$	0.0130	0.0053	0.0285

Different theory predictions for the spin asymmetries in COMPASS are available.

Sivers prediction at the time of the proposal



Most recent Sivers prediction
Sun & Yuan,
http://arxiv.org/abs/arXiv:1308.5003



After 2 years of data taking our statistical accuracy is enough to have the asymmetry in bins of x_p.

Worldwide plans to study TMD PDFs via the polarised DY process

Facility	type	s (GeV^2)	timeline
COMPASS	fixed target, $\pi^{\pm} H^{\uparrow\rightarrow}$, $\pi^{\pm} D^{\uparrow\rightarrow}$	357	end of 2014
Fermilab (SeaQuest)	fixed target, $p^{\uparrow\rightarrow} H$, $pH^{\uparrow\rightarrow}$	234	$>$ 2015
RHIC (STAR, PHENIX)	collider, $p^{\uparrow} p$	200^2	$>$ 2016
J-PARC	fixed target, $p^{\uparrow\rightarrow} D$	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 aims to perform the first polarised DY experiment in the world

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 in 1^{st} year of data taking.
- Joining two years of data taking there will be enough statistics to study the asymmetries in terms of x_F (x_p) and p_T.
- The feasibility of the measurement has been proven after several performed tests.
- Polarised Drell-Yan data taking will start in the end of 2014 and continue during 2015. A second year of DY data taking is planned, possibly in 2018.