Measurement of the Polarised Drell-Yan process at COMPASS

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on behalf of the COMPASS Collaboration

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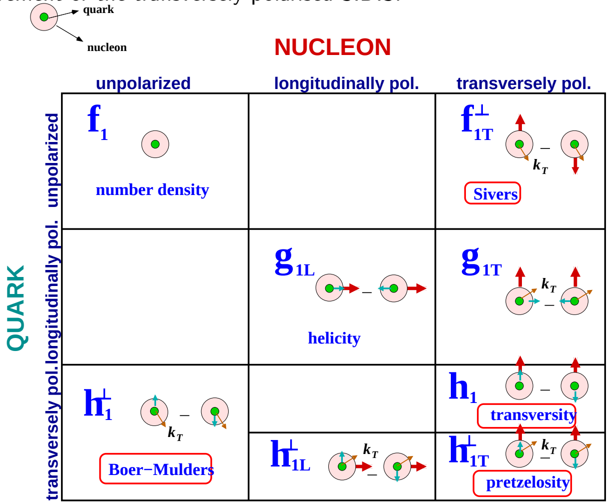
Transverse Momentum Dependent Parton Distribution Functions - TMD PDFs

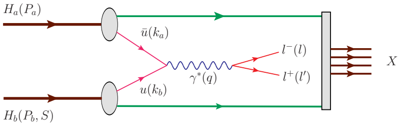
The nucleon structure in leading order QCD, taking into account k_T, is described by 8 PDFs for each quark flavour.

Sivers, Boer-Mulders, transversity and pretzelosity are accessible via either the single polarised Drell-Yan measurement or the transversely polarised SIDIS.



Polarised Drell-Yan process

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

This process is an excellent tool to access TMD PDFs:

- No fragmentation functions involved, but the convolution of two PDFs.
- The use of a negative pion beam allows the annihilation between the valence quark $\bar{u}$ from π^- with a valence quark u from proton to be dominant.
  $\hookrightarrow$ All the TMD PDFs are expected to be sizeable in the valence quark region
- The QCD TMD approach is valid in the region Q ($M_{\mu\mu} > 4$ GeV/c^2) $\gg \langle p_T \rangle \sim 1$ GeV/c

A drawback of this process is its very low cross-section (fraction of nb for $M_{\mu\mu} > 4$ GeV/c^2)
$\hookrightarrow$ Imposing an experiment with high luminosity

Considering an unpolarised π^- beam and a transversely polarised proton target the σ_{DY} at LO can be written as:

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

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

Each angular modulation present in the DY cross-section has an amplitude that contains the convolution of two TMD PDFs. These amplitudes are accessed via the measurement of the angular azimuthal asymmetries between the two oppositely transversely polarised target cells.

Each asymmetry relates to:

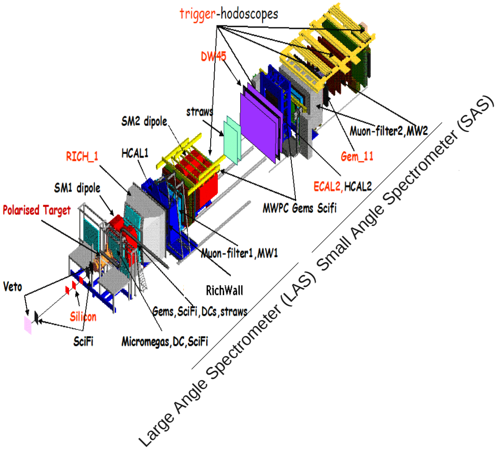
- $\boxed{A_U^{\cos 2\phi}}$ Boer-Mulders $h_1^\perp(\pi)$ $\otimes$ Boer-Mulders $h_1^\perp(p)$
- $\boxed{A_T^{\sin\phi_S}}$ unpolarised PDF $f_1(\pi)$ $\otimes$ Sivers $f_{1T}^\perp(p)$
- $\boxed{A_T^{sin(2\phi+\phi_S)}}$ Boer-Mulders $h_1^\perp(\pi)$ $\otimes$ pretzelosity $h_{1T}^\perp(p)$
- $\boxed{A_T^{sin(2\phi-\phi_S)}}$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

COMPASS @ CERN

COmmon Muon Proton Apparatus for Structure and Spectroscopy

- Fixed target experiment at the end of M2 SPS beam line
- Around 240 collaborators from 13 countries and 23 institutes

Experimental setup



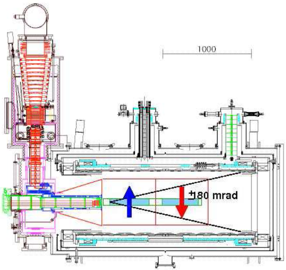
Beam

π^- @ 190 GeV/c

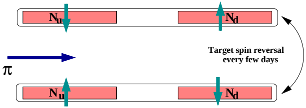
Polarised target, NH_3

dilution factor 22%

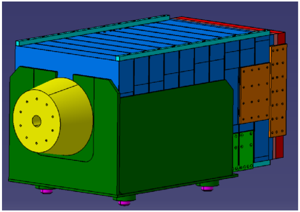
polarisation up to 90%



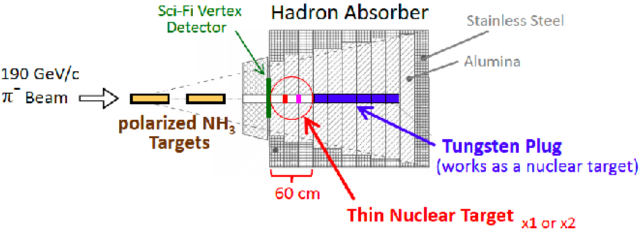
- Large angular acceptance (±180 mrad)
- Two target cells (NH_3) with opposite polarisations transverse to the beam



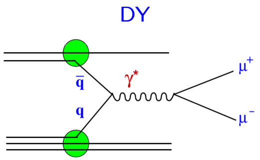
- A hadron absorber made of alumina will be placed downstream of the target to stop the hadrons and with a beam plug in the centre to stop the non-interacting beam.
- The hadron absorber will introduce multiple scattering on muons and there will be a degradation of the resolutions. To partially solve this problem a vertex detector is introduced in the first part of the absorber.

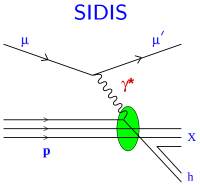


In parallel to the polarised DY measurements, unpolarised DY measurements will also be performed using nuclear targets, W and some thin lighter materials:



There is a theoretical prediction that Sivers ($f_{1T}^{\perp}$) and Boer-Mulders ($h_1^{\perp}$) functions must change sign when accessed from DY or SIDIS due to the fact that these functions are time-reversal odd functions.

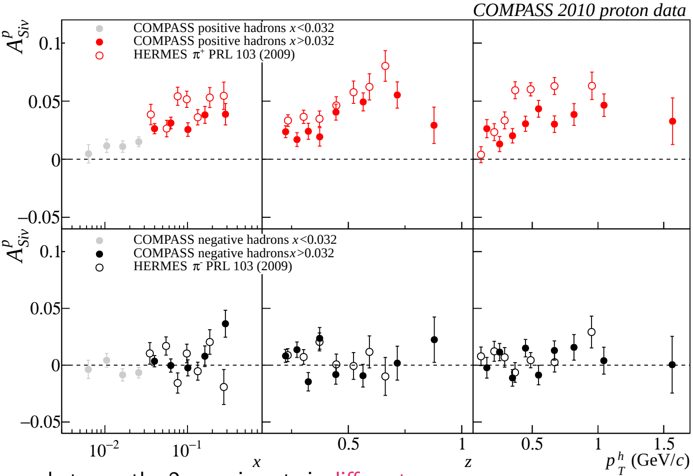




$$f_{1T}^{\perp}(x,k_T)|_{DY} = -f_{1T}^{\perp}(x,k_T)|_{SIDIS}$$

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

The experimental confirmation of this sign change is considered a crucial test of the QCD TMD approach.

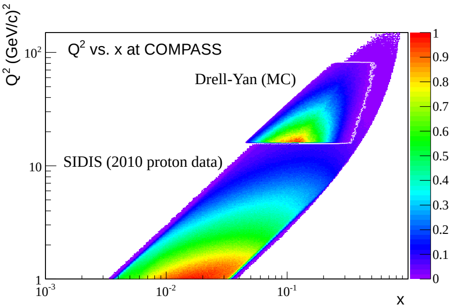


The Q^2 coverage between the 2 experiments is different:

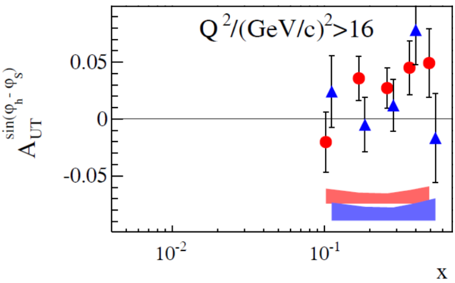
- COMPASS: $x > 0.032$, $\langle Q^2 \rangle = 8.7$ GeV/c^2 (PLB 717 2012)
- HERMES: $x > 0.032$, $\langle Q^2 \rangle = 2.4$ GeV/c^2 (PRL 103 2009)

For h^- the asymmetry is zero, for h^+ the asymmetry is positive and slightly different between the two experiments, being the difference assigned to the Q^2 coverage.

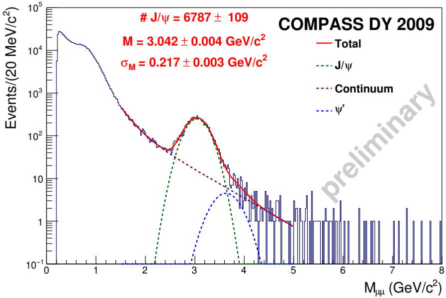
In COMPASS we have the opportunity to access the TMD PDFs from both DY and SIDIS processes.

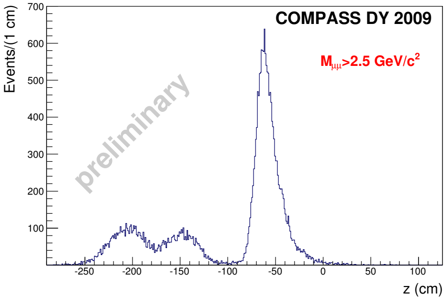


Sivers asymmetry from SIDIS - h^+ and h^-



- 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.
- Recently the SIDIS analysis was performed in 4 Q^2 bins, one of the bins being $Q^2 > 16$ $(\mathrm{GeV}/c)^2$, the so-called DY range.
- $\delta A_{UT}^{\sin(\phi_h-\phi_S)} \approx 0.01$ for both h^+ and h^- in SIDIS for $Q^2 > 16$ $(\mathrm{GeV}/c)^2$, same statistical error as expected for Sivers from DY.



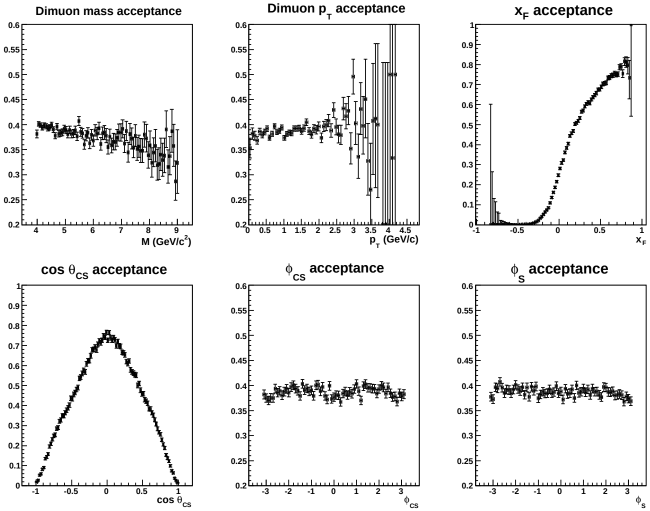


In 2009 a 3 days data taking beam test was done using a hadron absorber prototype, two polyethylene target cells and a negative pion beam at 190 GeV/c with an intensity of $1.5 \times 10^7 \pi/s$. A double trigger based on calorimeter signals was also used.

- The analysis confirmed the expectations. The J/ψ yields were confirmed considering the low efficiencies involved. The mass and the mass resolution were in agreement with the MC simulations.
- In the future the trigger will be based on hodoscopes with a high efficiency, purity and target pointing capability.
- The two target cells and the beam plug are distinguishable even if the absorber was not ideal. For the future the Z_{vtx} resolution will be better because of the better absorber and of the inclusion of the vertex detector.

2014/2015 Geometrical acceptance

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



For the extraction of the asymmetries the differential acceptance must be taken into account and to be well known.

Event rates and statistical accuracy

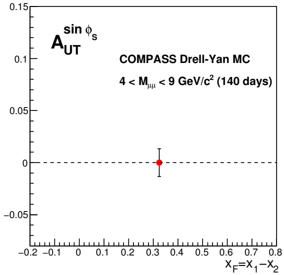
For a π^- beam at 190 GeV/c, $I_{beam} = 10^8 \pi$/s and $\mathcal{L} = 2.3 \times 10^{33}\ cm^{-2}\ s^{-1}$ the DY rate in the mass region $4 < M_{\mu\mu} < 9$ GeV/c^2 is:

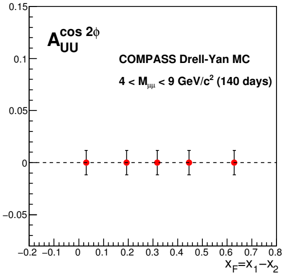
- 2000 events/day considering 9.6 s of beam spill and a 34 s SPS super cycle.
- 285000 events after one year of data taking ($\approx$ 140 days)

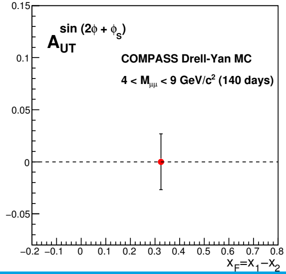
The expected statistical errors of the asymmetries, considering 285000 events, are:

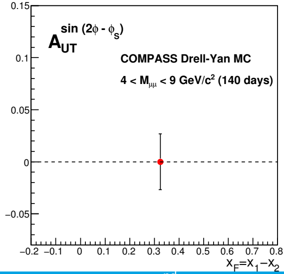
Asymmetry	Statistical error ($4 < M_{\mu\mu} < 9$ GeV/c^2)
$\delta\, A_{UU}^{\cos 2\phi}$	0.005
$\delta\, A_{UT}^{\sin \phi_S}$	0.013
$\delta\, A_{UT}^{\sin(2\phi+\phi_S)}$	0.027
$\delta\, A_{UT}^{\sin(2\phi-\phi_S)}$	0.027

Asymmetries precision projections





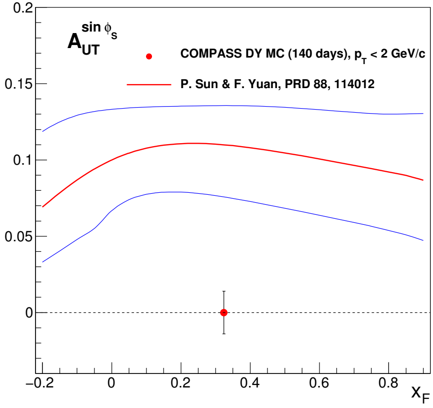


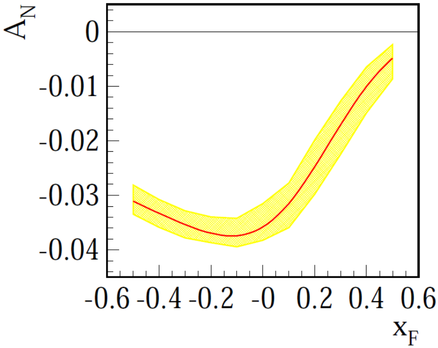


Asymmetries theoretical predictions

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

Two predictions for the Sivers asymmetry are shown:





Echevarria *et al*, arXiv: 1401.5078

$x_F = x_p - x_\pi$

Final remarks

- The Pilot Drell-Yan run will start in mid-October 2014 for 2 months. This pilot run will be the opportunity to test and check everything before next year physics data taking.
- The Sivers function sign change is expected to be checked based on the COMPASS SIDIS and DY results.
- The nuclear targets will give the opportunity to perform some unpolarised DY studies such as the flavour dependence EMC effect.
- Dedicated J/ψ studies will be performed.
- The possibility to have a 2^{nd} year of DY data taking after 2017 was proposed, but this still requires approval.

We are looking forward to have the first ever DY polarised data.

BACKUP SLIDES

The expected DY rate for the future is given by:

$$R = \mathcal{L}\ \sigma_{\pi N}\ d_{spill}\ n_{spill}\ \varepsilon_{tot}\ = 2.3 \cdot 10^{33} \times 2.136 \cdot 10^{-34} \times 9.6 \times 2464 \times 0.175\ = \\ = 2034/day$$

being the Luminosity given by:

$$\mathcal{L} = I_{beam} \times L_{eff}\ \frac{\rho \times F_f \times N_A}{A_{mol}}\ A\ = 10^8 \times 89.85\ \frac{0.85 \times 0.5 \times 6.022 \cdot 10^{23}}{17}\ 17\ = \\ = 2.3 \cdot 10^{33}\ cm^{-2}\ s^{-1}$$

and the effective target length for a target of 55+55 cm of NH_3:

$$L_{eff} = \frac{\lambda_{int}}{\rho\ F_f}\ (1\ -\ exp(-L\rho/\lambda_{int})) = 89.85\ cm$$

Update on expected Drell-Yan rates (cont.)

The expected DY rate for the future is given by:

$$R = \mathcal{L}\ \sigma_{\pi N}\ d_{spill}\ n_{spill}\ \varepsilon_{tot}\ = 2.3 \cdot 10^{33} \times 2.136 \cdot 10^{-34} \times 9.6 \times 2464 \times 0.175\ = \\ = 2034/day$$

The cross-section for pion nucleon is obtained taking into account the pion-proton and pion-neutron cross-sections from PYTHIA:

$$\sigma_{\pi N} = \frac{10}{17}\sigma_{\pi p} + \frac{7}{17}\sigma_{\pi n} = 2.316 \cdot 10^{-34} cm^2$$

The duration of the spill is:

$$d_{spill} = 9.6s$$

The number of spills is:

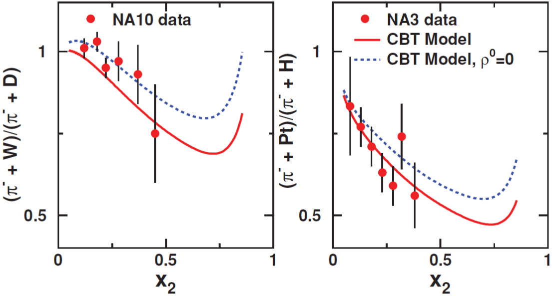
$$n_{spill} = \frac{23 \times 60 \times 60}{33.6} = 2464$$

And the expected total efficiency is:

$$\varepsilon_{tot} = \Omega\ \varepsilon_{rec}\ \varepsilon_{trig}\ \varepsilon_{SPS}\ \varepsilon_{spec}\ = 0.387 \times 0.8 \times (0.95^2 \times 0.92) \times 0.8 \times 0.85\ = \\ = 0.175$$

Flavour dependent EMC effect

- The EMC effect corresponds to the modification of the quark distributions in nuclei.
- Several models try to explain this effect. Some of them considering a flavour dependence. For a nucleus with different number of protons and neutrons u and d quarks will have different nuclear effects.
- One way to study the flavour dependence is via the A dependence, where the ratios proton/neutron and so u/d are different.
- The existing data are not sufficiently accurate to draw any firm conclusion.



PHYSICAL REVIEW C 83, 042201 (R) (2011)

J/ψ studies

- Measurement of the J/ψ cross-section
- Measurement of the J/ψ polarisation
- J/ψ production mechanisms:
  - In case of duality DY $\leftrightarrow$ J/ψ ($q\bar{q} \to \gamma^*/\mathrm{J}/\psi \to \mu^+\mu^- X$):
    Possibility to extract the TMD PDFs with much larger statistics
  - If gg production mechanism is dominating ($gg \to \mathrm{J}/\psi \to \mu^+\mu^- X$):
    Possibility to extract the gluon Sivers TMD (related with gluons OAM)