Drell-Yan processes at COMPASS

Stefano Takekawa
on behalf of the COMPASS Collaboration

INFN

14/06/2013
Structure of Nucleons and Nuclei 2013 - Como

Outline

- Introduction
- TMD PDFs and Drell-Yan
- DY@COMPASS
- COMPASS spectrometer upgrades

COmmon Muon Proton Apparatus for Structure and Spectroscopy

From COMPASS to COMPASS-II

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2010–014
SPSC-P-340
May 17, 2010

COMPASS-II Proposal

The COMPASS Collaboration

3 Pion-induced Drell–Yan muon pair production

3.1 Transverse spin-dependent structure of the nucleon

Spin and transverse momentum dependent semi-inclusive hadronic processes have attracted much interest from both experiment and theory in recent years. These processes provide more opportunities than inclusive hadronic processes to study Quantum Chromodynamics (QCD) and the internal structure of hadrons. Single transverse spin asymmetries (SSAs) were observed in various reactions, such as $H_a + H_b \to H + X$, $l + H \to H' + X$, $H_a + H_b \to l + l' + X$ and $l^+ + l^- \to H_a + H_b + X$ [88–99] where a hadron (lepton) is indicated by H (l). This stimulated remarkable theoretical developments; among them two approaches in the QCD framework have been most explored: the transverse momentum dependent approach and the higher-twist collinear factorisation approach. The first one deals with TMDs in the QCD transverse-momentum-dependent (QCD-TMD) factorisation approach that is valid at small transverse momentum $k_T \ll Q$ (see Refs. [79, 100] and references therein). Such functions generalise Feynman's original parton picture, where the partons only carry a longitudinal momentum fraction of the parent hadron's momentum. In the second approach [101] the spin-dependent differential cross sections can be calculated in terms of collinear twist-3 quark–gluon correlation functions in the formalism of collinear factorisation. This approach is applicable for large transverse momentum $k_T \gg \Lambda_{QCD}$. Recently, it was shown that the above sketched two approaches are consistent in the intermediate transverse momentum region $\Lambda_{QCD} \ll k_T \ll Q$, where both apply [101]. Since Drell–Yan events are expected to occur at COMPASS mainly at

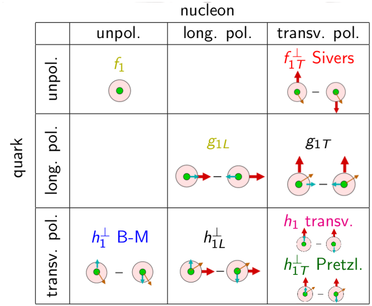
The scientific program of COMPASS-II started in 2012. It was approved by the CERN Research board on 1st December 2010.

The research covers three measurements:

- Primakoff $\rightarrow$ started in 2012
- GPD and SIDIS (2012 and 2016-17)
- Drell-Yan $\rightarrow$ *starting next year*

The structure of the nucleon at LO

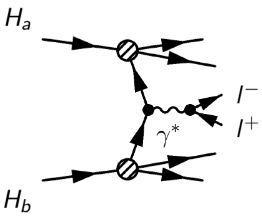
The structure of the nucleon can be described by three parton distribution functions (PDF) at leading order in collinear approximation. When the k_T dependence is taken into account, eight transverse momentum dependent (TMD) parton distribution functions are used to describe it



- $f_{1T}^{\perp}\left(x, k_T^2\right)$: the Sivers effect is related to the azimuthal asymmetry in the parton intrinsic transverse momentum distribution induced by the nucleon spin
- $h_1^{\perp}\left(x, k_T^2\right)$: the Boer-Mulders function describes the correlation between the transverse spin and the transverse momentum of a quark inside the unpolarised hadron
- $h_{1T}^{\perp}\left(x, k_T^2\right)$: the Pretzelosity function describes the polarisation of a quark along its intrisic k_T direction making accessible the orbital angular momentum information

The Drell-Yan process

The Drell-Yan process can be used to access the TMD PDFs of the proton



The Drell-Yan process is the annihilation of a quark-antiquark pair coming from two hadrons

It is a simple process, it is well understood, but it has a very small cross-section

The single polarised Drell-Yan cross-section is (at LO):

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}^4 q \mathrm{d}\Omega} &= \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \Big\{ \Big(1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi \Big) \\ &+ |\mathbf{S}_T| \Big[A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \Big(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \\ &+ A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \Big) \Big] \Big\}\end{aligned}$$

$D_{[f(\theta)]}$ = depolarisation factors, S = spin target components, F = flux of incoming hadrons and A = the azimuthal asymmetries, $\hat{\sigma}_U$ = cross section surviving the integration of ϕ and ϕ_S, θ and ϕ are the polar and azimuthal angle of the lepton in the CS frame, ϕ_S is the spin angle on the nucleon in the TF

What can be measured at COMPASS

At COMPASS, it will be possible to measure the asymmetries in single polarised Drell-Yan with the process $\pi^- + p^\uparrow \to \mu^+\mu^- + X$

Each asymmetry term in the cross section gives access to two TMD PDFs:

- $A_U^{\cos 2\phi}$: access to the Boer-Mulders functions of both incoming hadron and target nucleon
- $A_T^{\sin \phi_S}$: access to the Sivers function of the target nucleon and unpolarised pdf of beam particle
- $A_T^{\sin(2\phi+\phi_S)}$: access to the Boer-Mulders function of the beam hadron and to the pretzelosity function of the target nucleon
- $A_T^{\sin(2\phi-\phi_S)}$: access to the Boer-Mulders function of the beam hadron and the transversity function of the target nucleon

SIDIS vs DY: a crucial test of TMDs factorization

SIDIS and DY are complementary ways to access the TMD PDFs
$\rightarrow$ it is possible to perform a test of QCD

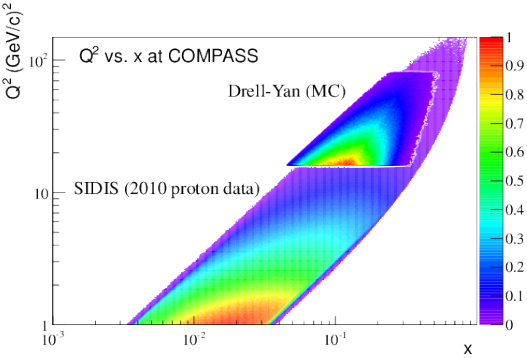
$\Rightarrow$ QCD expectation is:

$$
\begin{aligned}
f_{1T}^{\perp}(DY) &= -f_{1T}^{\perp}(SIDIS) \\
h_{1}^{\perp}(DY) &= -h_{1}^{\perp}(SIDIS)
\end{aligned}
$$

This happens because gauge links are present in the cross sections of SIDIS and Drell-Yan processes to provide the gauge invariance. The gauge link provides the possibility of existence of non-zero T-odd TMD PDFs. The Sivers and Boer-Mulders functions are T-odd and they change sign to provide the gauge invariance. This test includes not only the sign change but also the comparisons of the amplitude and the shape of the corresponding TMD PDFs.

Q^2 vs x phase space at COMPASS

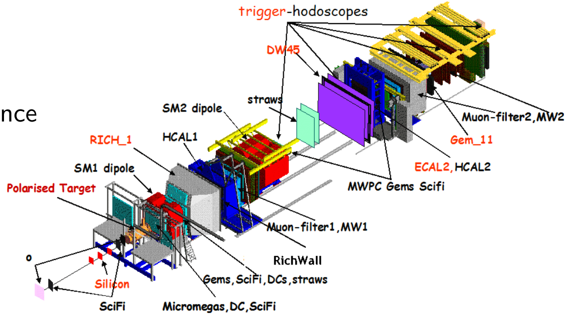
Both the Semi-Inclusive DIS and the Drell-Yan measurements allow to extract TMD PDFs

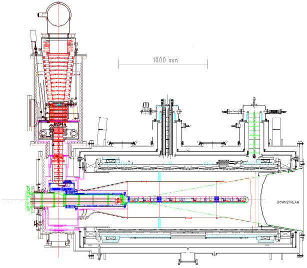


The phace spaces of the two processes overlap at COMPASS $\rightarrow$ consistent extraction of TMD PDFs in the same region!

The COMPASS spectrometer

- μ, p, π, K beam
- 50-270 GeV/c momentum
- $\pm$180 mrad angular acceptance





- NH_3 target polarisation $\sim$90%
- dilution factor 0.22 (Drell-Yan)
- three cells target

DY@COMPASS

The main characteristics of the Drell-Yan experiment:

- $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$
- the low Drell-Yan cross section requires a high intensity pion beam in order to obtain a good statistics

$\hookrightarrow$ beam intensity up to 10^8 π^- per second on the thick target ($\sim$ 1 interaction length)

$\hookrightarrow$ a hadron absorber is needed to stop secondary particles flux and a beam plug to stop the non-interacted beam

$\hookrightarrow$ rearrangement of the target area to place the absorber

- new muon trigger in the first stage of the spectrometer
- vertex detector to improve the cell separation of events

DY@COMPASS

The main characteristics of the Drell-Yan experiment:

- $\pi^- + p^\uparrow \to \mu^+\mu^- + X$
- the low Drell-Yan cross section requires a high intensity pion beam in order to obtain a good statistics

$\hookrightarrow$ beam intensity up to 10^8 π^- per second on the thick target ($\sim$ 1 interaction length)

$\hookrightarrow$ a hadron absorber is needed to stop secondary particles flux and a beam plug to stop the non-interacted beam

$\hookrightarrow$ rearrangement of the target area to place the absorber

- new muon trigger in the first stage of the spectrometer
- vertex detector to improve the cell separation of events

DY@COMPASS

The main characteristics of the Drell-Yan experiment:

- $\pi^- + p^\uparrow \to \mu^+\mu^- + X$
- the low Drell-Yan cross section requires a high intensity pion beam in order to obtain a good statistics

$\hookrightarrow$ beam intensity up to 10^8 π^- per second on the thick target ($\sim$ 1 interaction length)

$\hookrightarrow$ a hadron absorber is needed to stop secondary particles flux and a beam plug to stop the non-interacted beam

$\hookrightarrow$ rearrangement of the target area to place the absorber

- new muon trigger in the first stage of the spectrometer
- vertex detector to improve the cell separation of events

DY@COMPASS

The main characteristics of the Drell-Yan experiment:

- $\pi^- + p^\uparrow \to \mu^+\mu^- + X$
- the low Drell-Yan cross section requires a high intensity pion beam in order to obtain a good statistics

$\hookrightarrow$ beam intensity up to 10^8 π^- per second on the thick target ($\sim$ 1 interaction length)

$\hookrightarrow$ a hadron absorber is needed to stop secondary particles flux and a beam plug to stop the non-interacted beam

$\hookrightarrow$ rearrangement of the target area to place the absorber

- new muon trigger in the first stage of the spectrometer
- vertex detector to improve the cell separation of events

DY@COMPASS

The main characteristics of the Drell-Yan experiment:

- $\pi^- + p^\uparrow \to \mu^+\mu^- + X$
- the low Drell-Yan cross section requires a high intensity pion beam in order to obtain a good statistics

$\hookrightarrow$ beam intensity up to 10^8 π^- per second on the thick target ($\sim$ 1 interaction length)

$\hookrightarrow$ a hadron absorber is needed to stop secondary particles flux and a beam plug to stop the non-interacted beam

$\hookrightarrow$ rearrangement of the target area to place the absorber

- new muon trigger in the first stage of the spectrometer
- vertex detector to improve the cell separation of events

DY@COMPASS

The main characteristics of the Drell-Yan experiment:

- $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$
- the low Drell-Yan cross section requires a high intensity pion beam in order to obtain a good statistics

$\hookrightarrow$ beam intensity up to 10^8 π^- per second on the thick target ($\sim$ 1 interaction length)

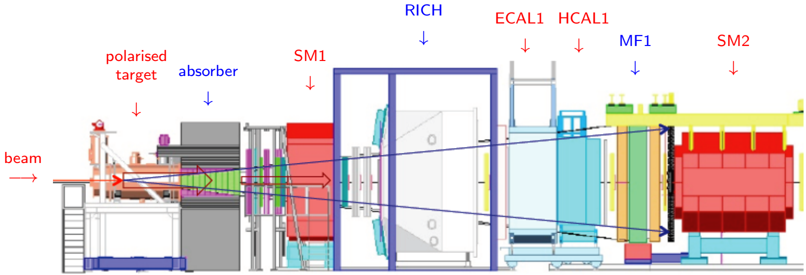
$\hookrightarrow$ a hadron absorber is needed to stop secondary particles flux and a beam plug to stop the non-interacted beam

$\hookrightarrow$ rearrangement of the target area to place the absorber

- new muon trigger in the first stage of the spectrometer
- vertex detector to improve the cell separation of events

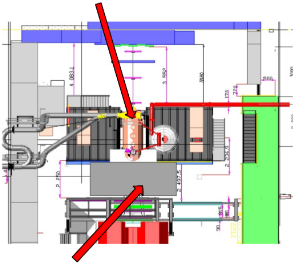
Design of the spectrometer

The first stage of the spectrometer has key importance because the main fraction of muons from Drell-Yan process is in its acceptance



View of the COMPASS Large Angle Spectrometer from CAD design

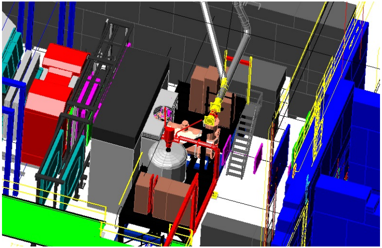
Target area



Top view of the target area

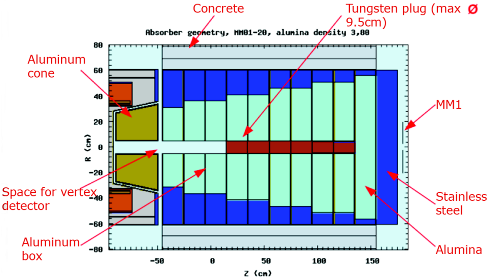
The target platform is modified and moved upstream along the beam line, so the target center will be moved of 230 cm

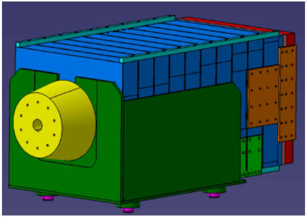
The target will be made of two 55 cm long cells spaced by 20 cm



Target area: beam comes from right bottom

Hadron absorber

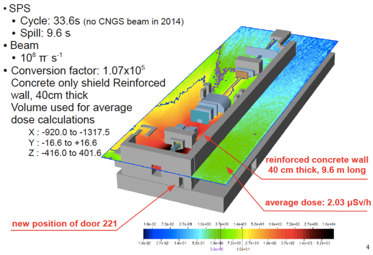




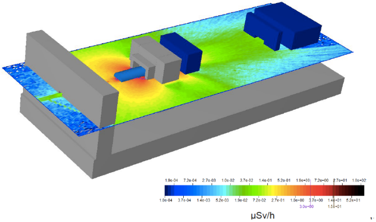
Structure of the hadron absorber:

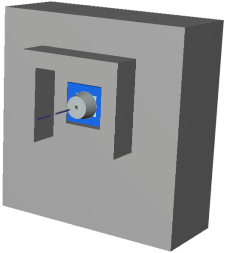
- 120 cm tungsten beam plug
- aluminium conical part
- 200 cm alumina (Al_2O_3)
- non-magnetic stainless steel peripheral part

Hadron absorber: shielding



15 minutes after the end of the run

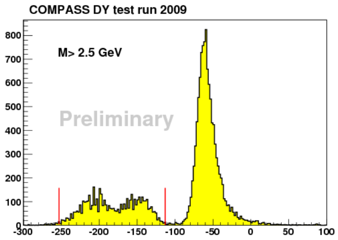




The absorber surrounded by the concrete shield

Also radioprotection rules were considered and they will be respected

Vertex detector



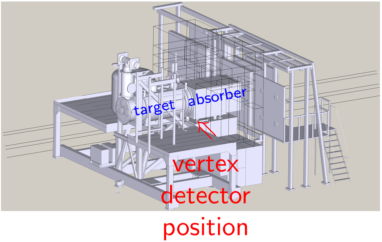
Distributions of primary vertexes along beam axis

A vertex detector has been proposed to:

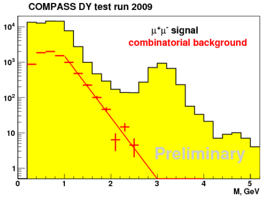
- improve mass resolution of the virtual photon
- improve resolution on the primary vertex position
  $\rightarrow$ better cell separation

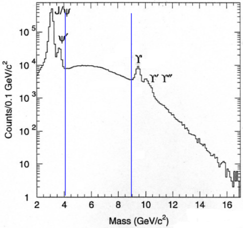
Vertex detector specs:

- SciFi detector
- U-X-Y planes
- $\sim$ 1 mm pitch
- $\sim 20 \times 15$ cm^2



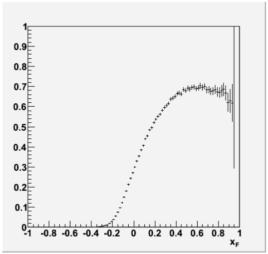
Acceptance to Drell-Yan events



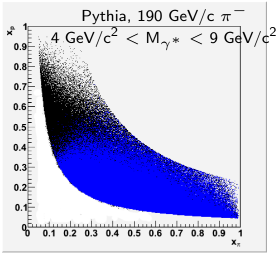


The safe mass interval is between 4 and 9 GeV/c^2

The COMPASS acceptance covers the valence quark region ($x > 0.1$)



x_F acceptance plot

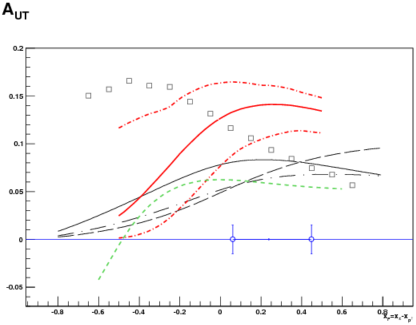


x_p vs x_π scatter plot: in black all generated events, in blue events in acceptance

Asymmetries are expected to be significant in valence quark region, up to 10%

Statistical errors and predictions

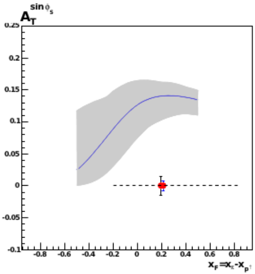
Predictions exist for the single spin asymmetry due to the Sivers effect, for the virtual photon mass range 4-9 GeV/c^2 and for the COMPASS kinematics. They are compared with the expected errors (1-2%) coming from a two bin analysis of two years of data taking. There is not TMD evolution in the predictions.

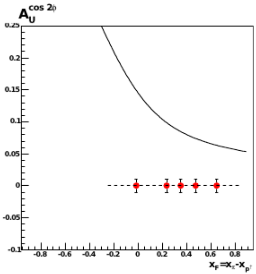


- Efremov et al., PLB612 (2005) 233 (solid and dashed)
- Collins et al., PRD73 (2006) 014021 (dot-dashed)
- Anselmino et al., PRD79 (2009) 054010 (red solid, red dot-dashed)
- Bianconi et al., PRD73 (2006) 114002 (boxes)
- Bacchetta et al., PRD78 (2008) 074010 (green short-dashed)

Predictions for asymmetries: 4-9 GeV/c^2 @ COMPASS

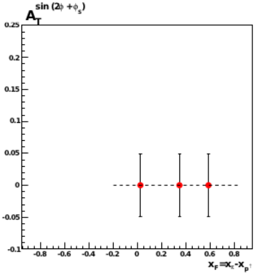
Sivers
M. Anselmino et al, Phys. Rev. D 79, 054010 (2009)

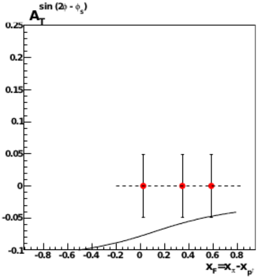




Boer-Mulders
B. Zhang et al, Phys. Rev. D 77, 054011 (2008)

BM ⊗ pretz.

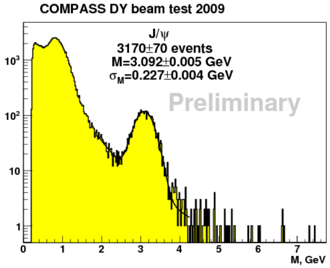


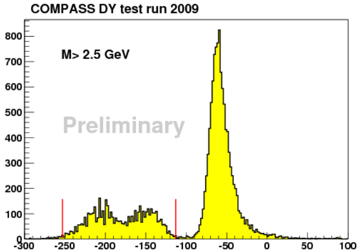


BM ⊗ transv.
A. N. Sissakian, Phys. Part. Nucl. 41, 64-100 (2010)

Drell-Yan tests

In 2007, 2008, 2009 and 2012 important tests was performed at COMPASS. The most recent one was done in the condition of the future measurement, with the hadron absorber. During the short data taking, the feasibility was proved, the J/ψ peak and Drell-Yan events were observed as expected and the two cells were distinguished.





- $\rightarrow$ target temperature ok!
- $\rightarrow$ radioprotection limits respected!

- $\rightarrow$ detector occupancies ok!
- $\rightarrow$ agreement of simulations and reality!

Time scale

There is much interest in measuring TMD PDFs with the Drell-Yan process

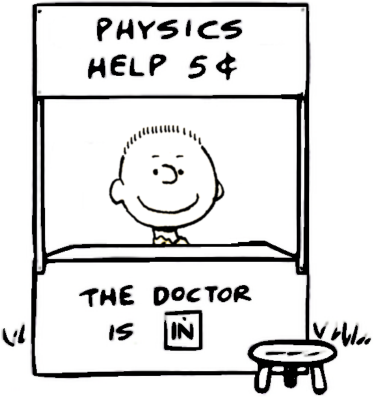
Facility	Type		s (GeV^2)	Timeline
COMPASS	fixed target	$\pi^{\pm} p^{\Uparrow}$	357	2014
RHIC (STAR,PHENIX)	collider	$p^{\Uparrow} p$	200^2	> 2016
Fermilab (SeaQuest)	fixed target	$p^{\Uparrow\Rightarrow} H$, $pH^{\Uparrow\Rightarrow}$	234	> 2015
J-PARC	fixed target	$pp^{\Uparrow}$, $\pi p^{\Uparrow}$	$60 - 100$	> 2018
Fair (PAX)	collider	$\overline{p}^{\Uparrow} p^{\Uparrow}$	200	> 2018
NICA	collider	$p^{\Uparrow} p^{\Uparrow}$, $d^{\Uparrow} d^{\Uparrow}$	144, 676	> 2018

COMPASS has the chance to be the first experiment
to collect single polarised Drell-Yan data

Summary

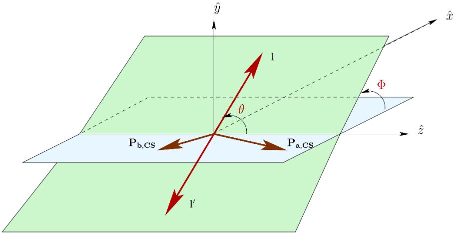
- the Drell-Yan measurement is part of the COMPASS-II Proposal
- the CERN Research board approved the COMPASS-II Proposal on 1st December 2010
- COMPASS will have first data on single polarised Drell-Yan in 2014
- COMPASS has the possibility to access TMD PDFs with SIDIS and Drell-Yan processes
- a crucial test of TMD PDFs factorization can be done by measuring the change of sign of the Boer-Mulders and the Sivers functions

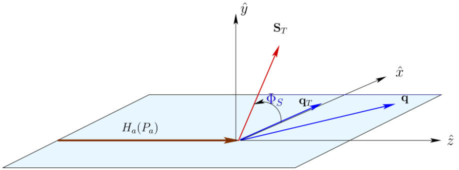
Thanks for your attention!



Backup

Definition of angles





The Collins-Soper frame: virtual photon rest frame, P_a and P_b lie in the x-z plane, z axis in the direction of $(P_a - P_b)$. The CS frame is usually choosen to study the Drell-Yan angular distribution

θ and ϕ are the angles defined by the lepton pair w. r. t. the hadrons plane

ϕ_S is the azimuthal angle of the target spin vector in the target rest frame (if target is polarised)

J/ψ-DY duality[1]

Since the J/ψ is a vector particle like the photon and the helicity structure of $\bar{q}q\,(J/\psi)$ and $(\bar{q}q)\,\gamma^*$ couplings is the same, it is possible to establish an analogy between the two processes:

$$H_a H_b \to J/\psi X \to l^+ l^- X$$
$$\Updownarrow$$
$$H_a H_b \to \gamma^* X \to l^+ l^- X$$

Studying the J/ψ production will be possible:

- check the duality hypothesis
- dramatically enlarge statistics (for region of mass around J/ψ mass)

[1] N. Anselmino, V. Barone, A. Drago and N. Nikolaev, Phys. Lett. B 594, (2004) 97
A. Sissakian, O. Shevchenko and O. Ivanov, JETP Lett. 86 (2007) 751

Expression of asymmetries

$$F_U^1 \stackrel{\mathrm{LO}}{=} \mathcal{C}\left[f_a \bar{f}_a\right]$$

$$A_U^{\cos 2\phi} \stackrel{\mathrm{LO}}{=} \mathcal{C}\left[\left(2\left(\mathbf{h}\cdot\mathbf{k}_{aT}\right)\left(\mathbf{h}\cdot\mathbf{k}_{bT}\right) - \mathbf{k}_{aT}\cdot\mathbf{k}_{bT}\right) h_1^{\perp}\bar{h}_1^{\perp}\right] \Big/ M_a M_b F_U^1$$

$$A_T^{\sin\phi_S} \stackrel{\mathrm{LO}}{=} \tilde{A}_T^{\sin\phi_S}$$

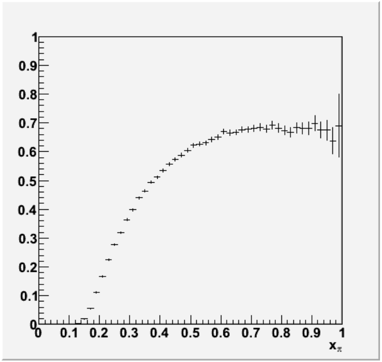
$$\stackrel{\mathrm{LO}}{=} \mathcal{C}\left[\mathbf{h}\cdot\mathbf{k}_{bT} f_1 \bar{f}_{1T}^{\perp}\right] \Big/ M_b F_U^1$$

$$A_T^{\sin(2\phi+\phi_S)} \stackrel{\mathrm{LO}}{=} -\mathcal{C}\left[\left(2\left(\mathbf{h}\cdot\mathbf{k}_{bT}\right)\left[2\left(\mathbf{h}\cdot\mathbf{k}_{aT}\right)\left(\mathbf{h}\cdot\mathbf{k}_{bT}\right) - \mathbf{k}_{aT}\cdot\mathbf{k}_{bT}\right]\right.\right.$$
$$\left.\left. -\mathbf{k}_{bT}^2\left(\mathbf{h}\cdot\mathbf{k}_{aT}\right)\right) h_1^{\perp}\bar{h}_{1T}^{\perp}\right] \Big/ 4 M_a M_b^2 F_U^1$$

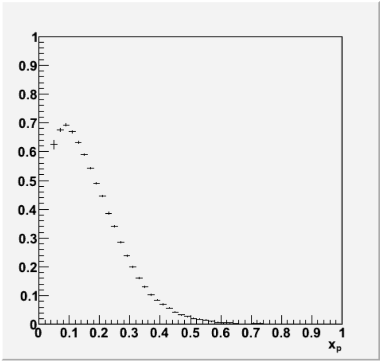
$$A_T^{\sin(2\phi-\phi_S)} \stackrel{\mathrm{LO}}{=} -\mathcal{C}\left[\mathbf{h}\cdot\mathbf{k}_{aT} h_1^{\perp}\bar{h}_1\right] \Big/ 2 M_a F_U^1$$

where $\mathbf{h} = \mathbf{q}_T / q_T$

More on acceptances



x_π acceptance plot

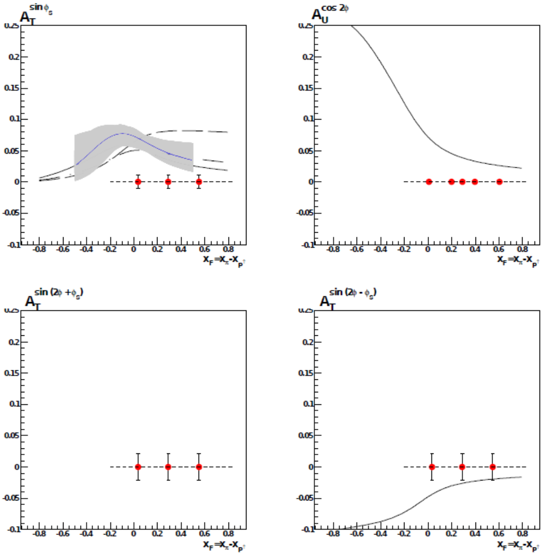


x_P acceptance plot

Predictions for asymmetries: 2-2.5 GeV/c^2 @ COMPASS

Sivers

Boer-Mulders



BM $\otimes$ pretz.

BM $\otimes$ transv.

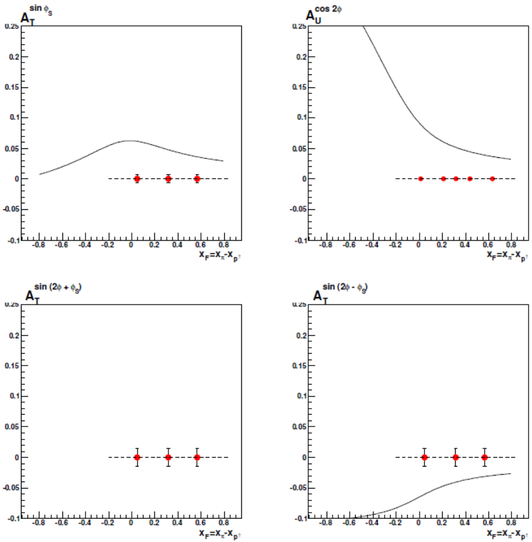
Predictions for asymmetries: 2.9-3.2 GeV/c^2 @ COMPASS

Sivers

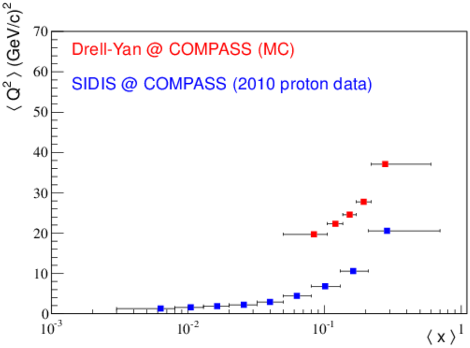
Boer-Mulders

BM $\otimes$ pretz.

BM $\otimes$ transv.



Q^2 vs x mean values

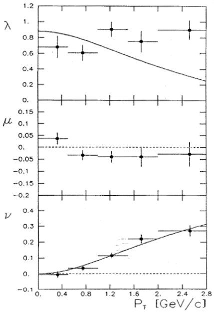


Drell-Yan angular distributions

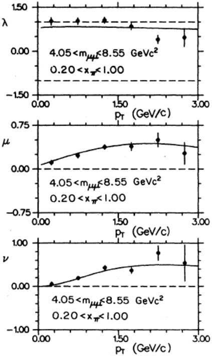
The unpolarised Drell-Yan angular distribution is:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin^2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos2\phi\right)$$

λ, μ and ν as a function of virtual photon transverse momentum



λ, μ, ν in CS frame
Falciano et al, Z. Phy. C 31, 513 (1986)



λ, μ, ν in GJ frame
Conway et al, Phys. Rev. D 39, 92 (1989)

The parameters λ, μ and ν are related by the Lam-Tung sum rule[1]:

$$1-\lambda = 2\nu$$

At LO, in collinear approximation:

$\lambda = 1$ and $\mu = \nu = 0$

but

NA10 and E615 showed non-zero values for λ, μ, ν and also a $\cos2\phi$ modulation

[1] C. S. Lam and W. K. Tung, Phys. Rev. D 21, 2712 (1980)