Measurement of Target Spin (in)dependent Asymmetries in Dimuon Production in Pion-Nucleon Collisions at COMPASS

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Multi-dimensional Partonic Structures

Wigner Distributions $(x, k_\perp, r_\perp)$

Generalized Parton Distributions $(x, r_\perp)$

Transverse Momentum Distributions $(x, k_\perp)$

Parton Distribution Functions $(x)$

Momentum Tomography

Spatial Tomography

TMDs

GPDs

3+2D Map

3D Map

1+2D Map
The TMD PDFs are sorted according to the nucleon polarization and individual polarization of partons.
Drell–Yan (DY) Angular Distributions

- The angular distribution of DY process is an important source of information to probe the spin and transverse momentum of partons.

- The LO differential cross-section for single-polarized DY angular distribution is:

\[
\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \left\{ 1 + A_U^1 \cos^2 \theta_{CS} + \sin 2\theta_{CS} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} + \sin^2 \theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} 
\right. \\
+ S_T \left[ (A_T^{\sin \varphi_S} + \cos^2 \theta_{CS} \tilde{A}_T^{\sin \varphi_S}) \sin \varphi_S \\
+ \sin 2\theta_{CS} \left( A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS} + \varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS} - \varphi_S) \right) \\
+ \sin^2 \theta_{CS} \left( A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS} + \varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right) \right] \right\}
\]

Spin independent

\[ A_U^1 = \lambda \]
\[ A_U^{\cos \varphi_{CS}} = \mu \]
\[ A_U^{\cos 2\varphi_{CS}} = \nu \]

Spin Independent

Transverse spin dependent

- In case of COMPASS the subprocess of the annihilation of quark and antiquark into the lepton-pair goes through an intermediate virtual photon production (Drell–Yan lepton-pair production so that both longitudinal and transverse components of the momentum of the virtual photon vanish. The Drell–Yan azimuthal asymmetries are commonly defined using two coordinate systems:

\[ P_{\pi} \times P_{\pi} = 0 \]
\[ P_{\pi} \cdot P_{\pi} = s \]

\[ \chi_{p_{\pi} \cdot P_{\pi}} = 0 \]
\[ \chi_{P_{\pi} \cdot P_{\pi}} = 1 \]

1 INTRODUCTION

13 Apr 2021
SIDIS and Single-Polarized Drell–Yan

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

\[
\frac{d\sigma^{LO}}{dxdydzdp_T^2d\phi_hd\phi_s} \propto \left( F_{UU,T} + \varepsilon F_{UU,L} \right)
\]

\[
= 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL}
\]

\[
\times \left[ A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) + \varepsilon A_{UL}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \right]
\]

\[
+ S_T \lambda \left[ \sqrt{1 - \varepsilon^2} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right]
\]

Drell–Yan process (DY)

\[
\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left( 1 + \cos^2 \theta_{CS} \right)
\]

\[
= 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}
\]

\[
\times \left[ A_T^{\sin \varphi_S} \sin \varphi_S + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \right]
\]

where \( D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / \left( 1 + \cos^2 \theta_{CS} \right) \)

- Boer-Mulders
- Sivers
- Transversity
- Pretzelosity
- Worm-gear L

Double polarized DY only
Unpolarized Asymmetries

\[ \frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[ 1 + \lambda \cos^2 \theta_{CS} + \mu \sin 2\theta_{CS} \cos \varphi_{CS} + \frac{\nu}{2} \sin^2 \theta_{CS} \cos 2\varphi_{CS} \right] \]

- The angular coefficients \(\lambda, \mu, \nu\) are often referred to as **Unpolarized Asymmetries (UAs)**.

- **[LO]** In the naïve DY model, virtual photon is produced by the electromagnetic quark-antiquark annihilation. (\(\lambda = 1, \mu = 0, \nu = 0\), because of \(\bar{s}_{q,\bar{q}} = \frac{1}{2}\))

- **[NLO]** The **Lam–Tung relation** (\(1 - \lambda = 2\nu\)) [PRD 18(1978) 2447], valid in NLO(\(\alpha_s\)) QCD corrections \(\Rightarrow\) non-zero \(\cos 2\varphi\) dependence.

NLO(\(\alpha_s\))

annihilation diagram

NLO(\(\alpha_s\))

Compton diagram
The Lam–Tung relation was found to be violated in past pion-induced DY experiments.

Significant discrepancy between pQCD calculations and experimentally measured $\nu$ as a function of dimuon transverse momentum $q_T$. 

NA10 $\pi^-+W$ at 194 GeV

E615 $\pi^-+W$ at 252 GeV
Including NNLO contributions in pQCD violates Lam-Tung relation.

Opposite sign for Lam-Tung relation from NNLO pQCD calculations and experiments.
An explanation to the $\cos 2\phi$ dependence observed in the DY process was proposed, by introducing a non-perturbative TMD **Boer–Mulders function**.

The Boer–Mulders function $h_{1\perp}$ represents a correlation between quark’s intrinsic transverse momentum $k_T$ and transverse spin $S_T$ (transversely polarized quark) in an unpolarized hadron.

$$A_{U}^{\cos 2\phi_{CS}} = \frac{\nu}{2} \propto h_{1\perp}(N)\bar{h}_{1\perp}(\pi)$$
Non-Universality of TMD Functions

To be tested by COMPASS experiment!

\[ \text{Sivers}_{\text{DY}} = -\text{Sivers}_{\text{SIDIS}} \]

- QCD gluon gauge link (Wilson line) in the initial state (DY) v.s. final state interactions (SIDIS).
- Fundamental predictions from TMD framework of QCD.

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<th>Quark</th>
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<tbody>
<tr>
<td>Nucleon</td>
<td>spin of the nucleon</td>
<td>number density $f_1^{u,d}(x, k_T^2)$</td>
<td>Boer-Mulders $h_1^{u,d}(x, k_T^2)$</td>
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<tr>
<td>spin of the parton</td>
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<td>$k_T$ of the parton</td>
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A fixed-target experiment at SPS north area.

24 participating institutions from 13 countries.

Physics programs:
- Nucleon spin and partonic structure.
- Hadron spectroscopy
- TMDs + pion structure

Taking data since 2002.

Last run will take place in 2022.

To be superseded by AMBER experiment.
First ever polarized DY measurements were performed by COMPASS in 2015 and 2018.

- $\pi^-$ beam at 190 GeV/c with average beam intensity $7 \times 10^7$ s$^{-1}$ from CERN SPS M2 beam line.
- Transversely polarized NH$_3$ target cells (55+55 cm) + Al target (7 cm) + W beam plug (120 cm)
**Hadron Absorber**

- The total length of the hadron absorber is 240 cm
- It incorporates 120 cm W beam plug and 7 cm Al target.
Dimuons produced via **DY process** are mixed with muon pairs from **open-charm**, $J/\psi$, $\psi'$ channels and **combinatorial background**.

96% purity of **DY** in the selected mass region is concluded based on MC studies.
Good data/MC agreement is achieved for all key kinematic distributions!
Unpolarized Asymmetries

\[ \frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[ 1 + \frac{1}{2} \cos^2 \theta_{CS} + \mu \sin 2\theta_{CS} \cos \varphi_{CS} + \nu \sin^2 \theta_{CS} \cos 2\varphi_{CS} \right] \]

- Preliminary COMPASS results for \( \nu \) tend to deviate from pQCD calculation at large \( q_T \). An indication for a presence of a non-zero TMD Boer-Mulders effect.
- Preliminary results are based on \(~70\%\) of COMPASS tungsten data collected in 2018.
COMPASS preliminary results indicate possible violation of the Lam-Tung relation.

Consistent with results obtained by past pion-induced DY experiments.
Sivers Asymmetry in Drell-Yan

COMPASS, PRL 119 (2017) 112002

\[ A_T^{\sin\phi_s} = 0.060 \pm 0.057\text{(stat.)} \pm 0.040\text{(sys.)} \]

- First COMPASS published results from 2015 run and preliminary results from 2018 favor the sign change hypothesis!
- Final analysis of combined 2015-2018 data is ongoing.

COMPASS 2015 + 2018 (~50%)
Summary and Outlook

- COMPASS study the spin and partonic structure of the nucleon via SIDIS and Drell-Yan channels employing muon and pion beams impinging on different polarized and unpolarized targets.

- In 2017 COMPASS has published the results of Sivers asymmetry from the first ever polarized DY measurements. [PRL 119, 112002 (2017)]

- The preliminary results of DY angular distributions from COMPASS tungsten data may indicate the presence of TMD Boer-Mulders function.

- Various ongoing analyses: cross-section and EMC-effect, polarization (in)dependent asymmetries, J/ψ asymmetries etc.

Thank you for your attention!
Back Up
Rotational invariant quantities (rotated along the y axis):

\[ \tilde{\lambda} = \frac{2\lambda + 3\nu}{2 - \nu} \]

\[ \mathcal{F} = \frac{1 + \lambda + \nu}{3 + \lambda} \]

Rotational invariant quantities is a good testing ground of overall systematic uncertainties of angular analysis.