Probing Nucleon Structure in Drell-Yan Production at COMPASS

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APS GHP Meeting 2021
April 14, 2021
Outline

• Nucleon structure and Transverse-Momentum Dependent (TMD) Parton Distribution Functions (PDFs)
• COMPASS Experiment and Drell-Yan data-taking
• Azimuthal Asymmetries to study TMD PDFs
• Asymmetry Results from COMPASS Drell-Yan data
• Outlook: Asymmetries in J/ψ production in pion-proton collisions
Scattering Experiments Used to Probe Nucleon Substructure

• In the infinite momentum frame of a scattering experiment, nucleon constituents appear to the incoming beam to be free, independent partons.

• Each parton carries a fraction of the longitudinal momentum of the nucleon, described by the Bjorken $x$ variable.

• Non-inclusive scattering processes must be used to probe transverse-momentum dependence.

Semi-Inclusive Deep Inelastic Scattering (SIDIS) – Lepton scatters off hadron, one or more outgoing hadrons are measured.

Drell-Yan (DY) – quark and antiquark annihilate into a virtual photon, which decays into two leptons.
Quark TMD PDFs that can be extracted from the DY and SIDIS cross-sections:

- **Boer-Mulders** – relates spin and transverse momentum of quark in unpolarized nucleon
- **Sivers** – relates transverse momentum of unpolarized quark and transverse polarization of nucleon
- **Transversity** – relates transverse polarization of quark and transverse polarization of nucleon
- **Pretzelosity** – relates transverse momentum of transversely polarized quark and transverse polarization of nucleon
Experimental studies of TMD PDFs important for verifying TMD QCD framework

- Sivers and Boer-Mulders PDFs: time-reversal odd, predicted to have opposite sign in SIDIS vs DY
- Pretzelosity and Transversity: predicted to be process independent
- COMPASS aims to verify these predictions experimentally

In SIDIS, soft gluon exchange is a final state interaction

In DY, soft gluon exchange is an initial state interaction

Courtesy: Jan Matousek
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COnmon Muon Proton Apparatus for Structure and Spectroscopy (COMPASS)

• Fixed polarized target experiment in North Area of CERN
• Beam comes from M2 beam line, originating from the SPS
COMPASS runs with polarized target:
• SIDIS – 160/200 GeV polarized muon beams
  • $d\uparrow$ ($^6$LiD): 2002-2004, $d\rightarrow(^6$LiD): 2002-2006
  • $d\uparrow$ ($^6$LiD): 2021+
• DY – 190 GeV pion beam
  • $p\uparrow$ ($\text{NH}_3$): 2015, 2018

During DY runs:
• 2 target cells filled with solid state $\text{NH}_3$
• Protons in each cell polarized in opposite directions
• Polarization flipped periodically to minimize effects of luminosity and acceptance
Azimuthal asymmetries extracted to probe TMD PDFs

Single-polarized DY Cross-section (at leading twist) in terms of azimuthal asymmetries:

\[
\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha^2}{Fq^2} \hat{\sigma}_U \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos(2\phi_{CS})} \cos(2\phi_{CS}) + S_T \left[ A_T^{\sin(\phi_S)} \sin(\phi_S) + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\phi_{CS}+\phi_S)} \sin(2\phi_{CS} + \phi_S) + A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right) \right] \right\}
\]

- **Unpolarized Asymmetry (UA)**: \( A_U^{\cos(2\phi_{CS})} \) ~ proton Boer-Mulders \( \otimes \) pion Boer-Mulders
- **Transverse Spin Asymmetries (TSAs)**:
  - \( A_T^{\sin(\phi_S)} \) ~ proton Sivers \( \otimes \) pion unpolarized PDF
  - \( A_T^{\sin(2\phi_{CS}+\phi_S)} \) ~ proton Pretzelosity \( \otimes \) pion Boer-Mulders
  - \( A_T^{\sin(2\phi_{CS}-\phi_S)} \) ~ proton Transversity \( \otimes \) pion Boer-Mulders

**Note**: negative pion-induced DY probes valence u-quark PDFs of the proton
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Dimuon Mass Distribution

- Data contains dimuons from DY scattering as well as meson decay and combinatorial background

- ‘High mass’ region used for DY analysis:
  - $4.3 \text{ GeV}/c^2 < M_{\mu\mu} < 8.5 \text{ GeV}/c^2$
  - ~96% pure

- $J/\psi$ mass region
  (used in ongoing $J/\psi$ analysis):
  - > 90% purity
COMPASS DY Boer-Mulders result

- Unpolarized asymmetry
  \[ A_U^{\cos(2\phi_{CS})} = \nu/2 \]

- Experimental results hint that there may be non-zero Boer-Mulders effects
COMPASS DY TSA Results

Sivers $\sim 1\sigma$ above zero
Transversity $\sim 2\sigma$ below zero
Pretzelosity $\sim 1\sigma$ above zero
COMPASS Sivers TSA measurements favors sign change prediction

COMPASS collected SIDIS and DY data with the same apparatus, in essentially the same kinematic region.

Note: Angles defined differently in SIDIS and DY measurements: same sign Sivers asymmetry -> Sivers PDF of opposite sign.

COMPASS, PLB **770**(2017), 138.

TSAs from SIDIS @ COMPASS

TSAs from DY @ COMPASS

Comparing experimental DY Sivers TSA with theory predictions

COMPASS, PRL **119**(2017), 112002.
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Two leading order J/ψ production processes

Quark-antiquark (q̅q) annihilation
- Sensitive to quark TMDs
- Can complement DY results

Gluon-gluon (gg) fusion
- Sensitive to gluon TMDs

Diagrams courtesy of Pietro Faccioli
Further gluon Sivers studies would be valuable

- COMPASS measured a gluon Sivers effect two sigma below zero in photon-gluon fusion.
- COMPASS measured a similar size effect in exclusive $J/\psi$ leptoproduction, but the result at lower $z$ is compatible with zero.
- PHENIX found a gluon Sivers effect compatible with zero in $\pi^0$ production in $pp$ collisions.
- The two experiments cover different kinematic regions, and the theory related to the gluon Sivers function is complicated.

COMPASS, PLB 772(2017), 854.

$J/\psi$ leptoproduction

PHENIX, PRD 103(2021) 052009.
TSAs in J/ψ production may be used to determine which production mechanism is dominant

- Anselmino et.al. predict a large Sivers asymmetry in COMPASS J/ψ production

- Calculation assumed only $q\bar{q}$ annihilation and no feed-down J/ψ

- Recent studies by Chang et.al. suggest that $gg$ fusion dominates at COMPASS

- Comparison of experiment and theory can illuminate further which production mechanism dominates at COMPASS kinematics
Summary and Outlook

• TMD PDFs describe transverse-momentum dependent behavior of partons inside a nucleon
• Azimuthal asymmetries in COMPASS Drell-Yan data give access to quark Sivers, Pretzelosity, Transversity, and Boer-Mulders TMD PDFs
• From ~70% of total DY data sample:
  • Hint of a non-zero Boer-Mulders effect
  • Sivers TSA results favor sign change prediction
• Ongoing analysis with full data sample should improve the statistical precision of results
• Ongoing TSA extraction from $J/\psi$ production in pion-proton collisions should offer insight about the $J/\psi$ production mechanism and information about the gluon Sivers function
Backup Slides
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<th>Quark Polarization</th>
<th>Nucleon Polarization</th>
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<td>Pretzelosity</td>
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COMPASS setup during DY runs (2015, 2018)

- Target cells filled with solid state \( NH_3 \)
- Protons in each cell polarized in opposite directions
- Polarization flipped periodically to minimize luminosity and acceptance effects

\( \pi^- \) beam 190 GeV/c
COMPASS Real and Monte-Carlo (MC) Data Production on Supercomputers

- Digital raw data reconstructed into physics quantities using COMPASS Reconstruction and Analysis Libraries (CORAL)
  - 2 PB of raw data from 2015/2018 DY runs
- MC simulation ‘raw data’ also reconstructed with CORAL and used to study detector performance
- High performance parallel computing resources needed for real and MC data production
- Utilize allocations on NSF-funded Blue Waters and now Frontera
Unbinned Maximum Likelihood Method of TSA Extraction

Maximize likelihood function

\[ \mathcal{L}(x, \bar{A}) = \prod_{i=1}^{N} f(x_i, \bar{A}) \]

Minimize negative log likelihood function

\[ -\ln \mathcal{L}(x, \bar{A}) = -\sum_{i=1}^{N} \ln f(x_i, \bar{A}) \]

Probability distribution function (pdf) for target cell \( i \) with polarization \( \pm \):

\[
\begin{align*}
    f_{i\pm}(\phi_S, \phi, \theta, \bar{A}) &= 1 + D_{\sin(2\theta)} A_U^{\cos(\phi)} \cos(\phi) + D_{\sin^2(\theta)} A_U^{\cos(2\phi)} \cos(2\phi) \\
    &\pm |S_T| A_T^{\sin(\phi_S)} \sin(\phi_S) \\
    &+ D_{\sin^2(\theta)} \left( A_T^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S) + A_T^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) \right) \\
    &+ D_{\sin(2\theta)} \left( A_T^{\sin(\phi + \phi_S)} \sin(\phi + \phi_S) + A_T^{\sin(\phi - \phi_S)} \sin(\phi - \phi_S) \right)
\end{align*}
\]

11 unknowns: 2 unpolarized asymmetries, 5 TSAs, 4 normalization factors (1 per pdf)
Extended UBML: add a Poissonian term to the likelihood function:

\[- \ln \mathcal{L}(\vec{A}) = \sum_{(i=1,2) \text{ (sign=+,-)}} \sum_{n=1}^{N_{i,\text{sign}}} \left[ I_{i,\text{sign}} - \ln \left( C_{i,\text{sign}} f_{i,\text{sign}}(\phi_S, \phi, \theta, \vec{A}) \right) \right] \]

\[ I_{i,\text{sign}} = \int C_{i,\text{sign}} f_{i,\text{sign}}(\phi_S, \phi, \theta) \, d\phi_S \, d\phi \, d\theta = 8\pi^2 C_{i,\text{sign}} \]

Reweight each term to account for finite statistics

\[- \ln \mathcal{L}(\vec{A}) = \sum_{(i=1,2) \text{ (sign=+,-)}} \sum_{n=1}^{\overline{N}_{i,\text{sign}}} \left[ \frac{\overline{N}}{N_{i,\text{sign}}} \left( 8\pi^2 C_{i,\text{sign}} - \sum_{n=1}^{N_{i,\text{sign}}} \ln \left( C_{i,\text{sign}} f_{i,\text{sign}}(\phi_S, \phi, \theta, \vec{A}) \right) \right) \right] \]
Left-right asymmetry $A_N$ also related to Sivers function

- Another SSA is the left-right asymmetry:
  \[ A_{lr} = \frac{1}{|S_T|} \frac{\sigma_l - \sigma_r}{\sigma_l + \sigma_r} \]

- Analyzing power $A_N$ is related to the Sivers function in a similar way to $A_T^{\sin(\phi_S)}$:
  \[ A_N = \frac{\pi}{2} A_{lr} \]