Polarized Drell-Yan at Fermilab

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Workshop on Opportunities for Polarized Physics at Fermilab

- Single Spin Asymmetries and Sivers Function
- Sivers Function in Polarized Drell-Yan
  - fundamental QCD prediction:
    \[ f_{1T}^{\perp}_{\text{DIS}} = - f_{1T}^{\perp}_{\text{DY}} \]
- Polarized Drell-Yan at Fermilab
  - polarized Beam or Target
- Main Injector Polarization Scheme

This work is supported by NSF
Single Spin Asymmetries in $p^\uparrow p \rightarrow \pi X$

- (huge) single spin asymmetries for forward meson production in hadron-hadron interactions have been observed over a wide range of c.m. energies

- "E704 effect":
  - polarized beam at Fermilab (tertiary beam from production & decay of hyperons)
  - beam intensity too low for DY

- possible explanation for large inclusive asymmetries:
  - Sivers distribution function, or Collins fragmentation function
Transverse Momentum Distributions (Introduction)

Survive $k_T$ integration

Sivers Function
$k_T$ - dependent, Naïve T-odd

Boer-Mulders Function

$f_1$ - 

$g_1$ =

$h_1$ =

$f_{1T}^{\perp}$ =

$h_{1T}^{\perp}$ =

$h_{1L}^{\perp}$ =

$g_{1T}$ =

$k_T$ - dependent, T-even

$S_L \cdot s_L \leftrightarrow g_{1L}$

$s_T \cdot (\hat{p} \times k_T) \leftrightarrow h_{1L}^{\perp}$

$k_T \cdot (s_T \times S_L) \leftrightarrow h_{1T}^{\perp}$

$S_T \cdot (\hat{p} \times k_T) \leftrightarrow f_{1T}^{\perp}$
Sivers Function

- describes transverse-momentum distribution of unpolarized quarks inside transversely polarized proton
- captures non-perturbative spin-orbit coupling effects inside a polarized proton
- Sivers function is naïve time-reversal odd
- leads to
  - $\sin(\phi - \phi_S)$ asymmetry in SIDIS
  - $\sin\phi_b$ asymmetry in Drell-Yan
- measured in SIDIS (HERMES, COMPASS)
- future measurements at Jlab@12 GeV planned

First moment of Sivers functions:
- $u$- and $d$- Sivers have opposite signs, of roughly equal magnitude
Sivers Asymmetry in SIDIS

- Global fit to $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES (p), COMPASS (p), COMPASS (d))

Comparable measurements needed in Drell-Yan process
Polarized Drell-Yan Experiment

• Access to transverse-momentum dependent distribution (TMD) functions
  → Sivers, Boer-Mulders, etc

• Transversely Polarized Beam or Target
  → Sivers function in single-transverse spin asymmetries (sea quarks or valence quarks)
    – valence quarks constrain SIDIS data much more than sea quarks
    – global fits indicate that sea quark Sivers function is small
  → transversity $\otimes$ Boer-Mulders function
  → baryon production, incl. pseudoscalar and vector meson production, elastic scattering, two-particle correlations, J/$\psi$ and charm production

• Beam and Target Transversely Polarized
  → flavor asymmetry of sea-quark polarization
  → transversity (quark $\otimes$ anti-quark for pp collisions)
    – anti-quark transversity might be very small
**Drell Yan Process**

- **Similar Physics Goals as SIDIS:**
  - parton level understanding of nucleon
  - electromagnetic probe

  **timelike (Drell-Yan) vs. spacelike (SIDIS) virtual photon**

- **Cleanest probe to study hadron structure:**
  - hadron beam and convolution of parton distributions
  - no QCD final state effects
  - no fragmentation process
  - ability to select sea quark distribution
  - allows direct production of transverse momentum-dependent distribution (TMD) functions (Sivers, Boer-Mulders, etc)

A. Kotzinian, DY workshop, CERN, 4/10
Leading order DY Cross Section

DY cross section at LO:

\[
\frac{d\sigma}{d^4q \, d\Omega} = \frac{\alpha^2}{4q^2 \sqrt{(P_b \cdot P_t)^2 - M_p^2}} \left\{ \begin{array}{c} 
(1 + \cos^2 \theta) F_{UU}^1 + (1 - \cos^2 \theta) F_{UU}^2 \\
+ \sin 2\theta \cos \phi F_{UU}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{UU}^{\cos 2\phi}
\end{array} \right\}
\]

+ \quad S_L \left[ \sin 2\theta \sin \phi_F L \sin \phi + \sin^2 \theta \sin 2\phi F_{LU}^{\sin 2\phi} \right]

+ \quad S_T \sin \phi_b \left[ (1 + \cos^2 \theta) F_{TU}^1 + (1 - \cos^2 \theta) F_{TU}^2 \\
+ \sin 2\theta \cos \phi F_{TU}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{TU}^{\cos 2\phi} \right] \\
+ \quad \cos \phi_b \left( \sin 2\theta \sin \phi_F L \sin \phi + \sin^2 \theta \sin 2\phi F_{LU}^{\sin 2\phi} \right) \right\} 

F_{TU}^1 = -C \left[ \frac{q_T \cdot k_{T,b}}{q_T M_p} \int_{x_b}^{x_f} \langle x_f, k_{T,f}^2 \rangle f_1 (x_b, k_{T,b}^2) \right]

\Rightarrow \quad A_{TU}^{\sin \phi_b} = \frac{F_{TU}^1}{F_{UU}^1} 

with the asymmetry amplitude:
Sivers Function

- **T-odd observables**
  - SSA observable \( \sim \tilde{J} \cdot (\tilde{p}_1 \times \tilde{p}_2) \) odd under naïve Time-Reversal
  - since QCD amplitudes are T-even, must arise from interference (between spin-flip and non-flip amplitudes with different phases)

- **Cannot come from perturbative subprocess xsec at high energies:**
  - \( q \) helicity flip suppressed by \( m_q / \sqrt{s} \)
  - need \( \alpha_s \) suppressed loop-diagram to generate necessary phase
  - at hard (enough) scales, SSA’s must arise from soft physics

- **A T-odd function like** \( f_{1T}^{\perp} \) **must arise from interference (How?)**
  - and produce a T-odd effect!
  - (also need \( L_z \neq 0 \))

- **Soft gluons:** “gauge links” required for color gauge invariance
- such soft gluon re-interactions with the soft wavefunction are final (or initial) state interactions … and maybe process dependent!
- leads to sign change: \( f_{1T}^{\perp} \bigg|_{\text{SIDIS}} = - f_{1T}^{\perp} \bigg|_{\text{DY}} \)

Brodsky, Hwang & Smith (2002)
Sivers in Drell-Yan vs SIDIS: The Sign Change

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

- fundamental prediction of QCD (in non-perturbative regime)
  goes to heart of gauge formulation of field theory

- Importance of factorization in QCD:

QCD without factorization is *almost useless*

*I added this sentence after this morning comments, so it might be too strong.*
## Planned Polarized Drell-Yan Experiments

<table>
<thead>
<tr>
<th>experiment</th>
<th>particles</th>
<th>energy</th>
<th>$x_b$ or $x_t$</th>
<th>Luminosity</th>
<th>timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS (CERN)</td>
<td>$\pi^\pm + p^\uparrow$</td>
<td>160 GeV $\sqrt{s} = 17.4$ GeV</td>
<td>$x_t = 0.2 - 0.3$</td>
<td>$2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
<td>2014, 2018</td>
</tr>
<tr>
<td>PAX (GSI)</td>
<td>$p^\uparrow + p_\text{bar}$</td>
<td>collider $\sqrt{s} = 14$ GeV</td>
<td>$x_b = 0.1 - 0.9$</td>
<td>$2 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
<td>&gt;2017</td>
</tr>
<tr>
<td>PANDA (GSI)</td>
<td>$p_\text{bar} + p^\uparrow$</td>
<td>15 GeV $\sqrt{s} = 5.5$ GeV</td>
<td>$x_t = 0.2 - 0.4$</td>
<td>$2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
<td>&gt;2016</td>
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<tr>
<td>NICA (JINR)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 20$ GeV</td>
<td>$x_b = 0.1 - 0.8$</td>
<td>$1 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
<td>&gt;2014</td>
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<tr>
<td>PHENIX (RHIC)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 500$ GeV</td>
<td>$x_b = 0.05 - 0.1$</td>
<td>$2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
<td>&gt;2018</td>
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<tr>
<td>RHIC internal target phase-1</td>
<td>$p^\uparrow + p$</td>
<td>250 GeV $\sqrt{s} = 22$ GeV</td>
<td>$x_b = 0.25 - 0.4$</td>
<td>$2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
<td>&gt;2018</td>
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<td>$p^\uparrow + p$</td>
<td>250 GeV $\sqrt{s} = 22$ GeV</td>
<td>$x_b = 0.25 - 0.4$</td>
<td>$6 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>&gt;2018</td>
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<tr>
<td>SeaQuest (unpol.) (FNAL)</td>
<td>$p + p$</td>
<td>120 GeV $\sqrt{s} = 15$ GeV</td>
<td>$x_b = 0.35 - 0.85$</td>
<td>$3.4 \times 10^{35}$ cm$^{-2}$ s$^{-1}$</td>
<td>2012 - 2015</td>
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<td>polDY§ (FNAL)</td>
<td>$p^\uparrow + p$</td>
<td>120 GeV $\sqrt{s} = 15$ GeV</td>
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<td>&gt;2016</td>
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</table>

$§ L = 1 \times 10^{36}$ cm$^{-2}$ s$^{-1}$ (LH$_2$ tgt limited) / $L = 2 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ (10% of MI beam limited)
Polarized Drell-Yan at Fermilab Main Injector

- Polarize Beam in Main Injector & use SeaQuest di-muon spectrometer
  - measure Sivers asymmetry

SeaQuest di-muon Spectrometer
  - fixed target experiment, optimized for Drell-Yan
  - luminosity: \( L_{av} = 3.4 \times 10^{35} \text{/cm}^2/\text{s} \)
    - \( I_{av} = 1.6 \times 10^{11} \text{ p/s} (=26 \text{nA}) \) / \( N_p = 2.1 \times 10^{24} \text{/cm}^2 \)
  - approved for 2-3 years of running: \( 3.4 \times 10^{18} \text{ pot} \)
  - by 2015: fully understood, ready to take pol. beam
Polarized Drell-Yan at Fermilab Main Injector - II

- Polarized Beam in Main Injector
  - use SeaQuest target
    - liquid H₂ target can take about $I_{av} = 5 \times 10^{11} \text{ p/s} (=80 \text{ nA})$
  - 1 mA at polarized source can deliver about $I_{av} = 1 \times 10^{12} \text{ p/s} (=150 \text{ nA})$
    for 100% of available beam time (A. Krisch: Spin@Fermi report in (Aug 2011): arXiv:1110.3042 [physics.acc-ph])
    - 26 μs linac pulses, 15 Hz rep rate, 12 turn injection into booster, 6 booster pulses into Recycler Ring, followed by 6 more pulses using slip stacking in MI
    - 1 MI pulse = $1.9 \times 10^{12} \text{ p}$
    - using three 2-sec cycles/min (~10% of beam time):
      → $2.8 \times 10^{12} \text{ p/s} (=450 \text{ nA})$ instantaneous beam current, and $I_{av} = 0.95 \times 10^{11} \text{ p/s} (=15 \text{ nA})$
  - possible scenarios:
    - $L_{av} = 2.0 \times 10^{35} /\text{cm}^2/\text{s}$ (10% of available beam time: $I_{av} = 15 \text{ nA}$)
    - $L_{av} = 1 \times 10^{36} /\text{cm}^2/\text{s}$ (50% of available beam time: $I_{av} = 75 \text{ nA}$)
  - Systematic uncertainty in beam polarization measurement (scale uncertainty)
    $\Delta P_b/P_b < 5\%$
From 2 Siberian Snakes to 1 Snake

2 Siberian Snakes in MI
(not enough space)

1 Siberian Snake in MI
(fits well)
plus 1 solenoid snake in RR
From 2 Siberian Snakes to 1 Snake - II

2-snake design (11m long):
- 4 helical dipoles / snake
  - 2 helices: 5T / 3.1m / 6” ID
  - 2 helices: 5T / 2.1m / 6” ID (cold)

does not fit

1-snake design (5.8m long):
- 1 helical dipole + 2 conv. dipoles
  - helix: 4T / 4.2 m / 4” ID
  - dipoles: 4T / 0.62 m / 4” ID (warm)

fits

T. Roser (BNL):
- test snakes/rotators up to 5.4T
- operation not above 4T
Steady Improvements to 1 Snakes solution

8.9 GeV 4T

4-twist 4T

beam excursions shrink w/ number of twists

beam excursions shrink w/ beam energy
Acceptance for Polarized Drell-Yan - I

- **x-range:** $x_b = 0.35 - 0.85$ (valence quarks in proton beam)
  $x_t = 0.1 - 0.45$ (sea quarks in proton target)

- **Invariant mass range:** $M = 4 - 8.5$ GeV (avoid J/Ψ contamination)

- **Transverse momentum:** $p_T = 0 - 3$ GeV
Measurement at Fermilab Main Injector

• Retune 1st spectrometer magnet (FMag):
  ➡ focuses high $p_T$ muons and
  over focuses low $p_T$ muons
  ➡ we loose low $p_T$ muons when field is high!
  ➡ SeaQuest is all about going to the largest $x_t$ quarks, requiring high-$p_T$ muons

➡ Lowering FMag field
  ➡ we get back the low $p_T$ muons
  ➡ we loose the high low $p_T$ muons
  BUT

$p_T$ spectrum peaks at low $p_T$
Sivers Asymmetry at Fermilab Main Injector

- Experimental Sensitivity
  - Luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: $I_{av} = 15$ nA)
  - $3.2 \times 10^{18}$ total protons for $5 \times 10^5$ min: (= 2 yrs at 50% efficiency) with $P_b = 70$

Note:

$A_N = \frac{2}{\pi} A_{TU}^\sin \phi_b$

- Can measure not only sign, but also the size & maybe shape of the Sivers function!
E-1027 Collaboration (May 2013)

<table>
<thead>
<tr>
<th>Abilene Christian University</th>
<th>KEK</th>
<th>National Kaohsiung Normal University</th>
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<tbody>
<tr>
<td>Donald Isenhower, Tyler Hague, Rusty Towell, Shon Watson</td>
<td>Shinya Sawada</td>
<td>Ruungsheng Guo, Su-Yin Wang</td>
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<tr>
<td>Academic Sinica</td>
<td>Los Alamos National Laboratory</td>
<td>RIKEN</td>
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<tr>
<td>Wen-Chen Chang, Yen-Chu Chen, Shiu Shiuan-Hal, Da-Shung Su</td>
<td>Ming Liu, Xiang Jiang, Pat McGaughey, J. Huang</td>
<td>Yuji Goto</td>
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<tr>
<td>Argonne</td>
<td>University of Maryland</td>
<td>Rutgers University</td>
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<tr>
<td>John Arrington, Don Geesaman Kawtar Hafidi, Roy Holt, Harold Jackson, Paul E. Reimer*</td>
<td>Betsy Beise, Kaz Nakahara</td>
<td>Ron Gilman, Ron Ransome, A. Tadepalli</td>
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<td>University of Colorado</td>
<td>University of Michigan</td>
<td>Tokyo Institute of Technology</td>
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<td>Fermilab</td>
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<td>Yamagata University</td>
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<tr>
<td>Chuck Brown, David Christian, Jin-Yuan Wu</td>
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<td>Yoshiyuki Miyachi</td>
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<td>University of Basque Country†</td>
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<td>*Co-Spokespersons</td>
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<td>†new group (Aug’12)</td>
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</table>

Collaboration contains most of the E-906/SeaQuest groups and one new group (total 16 groups as of May 2013)

E-1027 collaboration working closely with SPIN@FERMI collaboration
Polarized Target at Fermilab

• Probe Sea-quark Sivers Asymmetry with a polarized proton target at SeaQuest
  
  - sea-quark Sivers function poorly known
  - significant Sivers asymmetry expected from meson-cloud model

\[ pp^\uparrow \rightarrow \mu^+\mu^- X, \ 4 < M_{\mu\mu} < 9 \text{ GeV} \]

\[ P_{\text{beam}} = 120 \text{ GeV} \]

\[ 8 \text{ cm NH}_3 \text{ target}, P_{\text{target}} = 0.8 \]

\[ A_N \]

\[ x_2 \]

– use current SeaQuest setup
– a polarized proton target, unpolarized beam

Ref: Ming Liu (ANL)
The Path to a polarized Main Injector

Stage 1 approval from Fermilab: 14-November-2012

- Detailed machine design and costing using 1 snake in MI
  → Spin@Fermi collaboration provide design
  → Fermilab (AD) does verification & costing

- Collaboration with A.S. Belov at INR and Dubna to develop polarized source

- Develop proposal to DoE NP/HEP to polarize the Main Injector
  → Cost to polarize Main Injector $10M
    → includes 15% project management & 50% contingency
  → secure funding to
    → do detailed design: $200k/yr (short-term)
    → implement modifications to MI: $10M (longer-term)
    → conversations with DoE NP & HEP, NSF NP have started
Summary

- A non-zero Sivers asymmetry has been measured both at HERMES and COMPASS
- QCD (and factorization) require sign change
  \[ f_{1T}^{\perp, \text{SIDIS}} = - f_{1T}^{\perp, \text{DY}} \]
- Fermilab is arguably best place to do this measurement
  \[ \rightarrow \text{high luminosity, large } x\text{-coverage, high-intensity polarized beam} \]
  \[ \rightarrow \text{spectrometer already setup and running} \]
- Run alongside neutrino program (10% of beam needed)
- Measure DY with both Beam or/and Target polarized
  \[ \rightarrow \text{broad spin physics program possible} \]
The END
Backup Slides
QCD Evolution of Sivers Function

- Initial global fits by Anselmino group included DGLAP evolution only in collinear part of TMDs (not entirely correct for TMD-factorization)

- Using TMD $Q^2$ evolution: agreement with data improves

\[ \text{HERMES (p)} \]

\[ \text{COMPASS (p)} \]

\[ h^+ \]

\[ h^- \]
Polarized Drell-Yan at Fermilab

- Global fit to $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES (p), COMPASS (p, d))

→ Predictions for Drell-Yan (gray error bands correspond to $\Delta\chi^2 = 20$)

Polarized beam: $E_p = 120$ GeV
\[ \sqrt{s} \sim 15 \text{ GeV} \]
\[ 4.2 < M < 8.5 \text{ GeV} \]

Hydrogen target
Fermilab: $p^+p$

Deuterium target
Fermilab: $p^+d$