Polarized Drell-Yan at Fermilab MI

Fermilab PAC Meeting
Aspen, CO
(21-June-2012)

Wolfgang Lorenzon (U Michigan), Paul Reimer (Argonne)

- Polarized Drell-Yan at FNAL
  - Measure Sivers Function
    \[ f_{1T}^{\perp q} \bigg|_{DIS} = - f_{1T}^{\perp q} \bigg|_{D-Y} \]
  - Address major milestone in hadronic physics (HP13)
Polarized Drell-Yan Experiment

- Access to transverse momentum dependent distributions (TMD) functions
  - Sivers, Boer-Mulders, etc
- Transversely Polarized Beam or Target
  - Sivers function in single-transverse spin asymmetries (SSA) (sea quarks or valence quarks)
    - valence quarks constrain SIDIS data much more than sea quarks
  - 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 (DIS) 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:

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

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

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

\[ \left. + \cos \phi_b \left( \sin 2\theta \sin \phi F_{TU}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{TU}^{\sin 2\phi} \right) \right] \]

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

\[ A_{TU}^{\sin \phi_b} = \frac{F_{TU}^1}{F_{UU}^2} \]
Transverse Momentum Distributions (Introduction)

Survive $k_T$ integration

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

Boer-Mulders Function
- $k_T$ - dependent, $T$-even

$f_1 \leftrightarrow S_L \cdot S_L \leftrightarrow g_{1L}$

$g_1 \rightarrow$

$h_1 \rightarrow$

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

$h_{1T} \rightarrow$

$h_{1L} \rightarrow$

$k_T \cdot (S_T \times S_L) \leftrightarrow h_{1L}^\perp$
Inclusive Pion Asymmetry in $p$-$p$ Collisions

- “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

C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009
Sivers Function

- described by transverse-momentum dependent distribution function
- captures non-perturbative spin-orbit coupling effects inside a polarized proton
- leads to a \( \sin(\phi - \phi_S) \) asymmetry in SIDIS and a \( \sin\phi_b \) asymmetry Drell-Yan
- done in SIDIS (HERMES, COMPASS)
- Sivers function is time-reversal odd
  - leads to sign change
    \[
    f_{1T}^{q} \bigg|_{DIS} = - f_{1T}^{q} \bigg|_{D-Y}
    \]
  - fundamental prediction of QCD
    (goes to heart of gauge formulation of field theory)

Predictions based on fit to SIDIS data

Anselmino et al. priv. comm. 2010

FNAL 120 GeV polarized beam \( \sqrt{s} \sim 15 \text{ GeV} \) (hydrogen)

FNAL 120 GeV polarized beam \( \sqrt{s} \sim 15 \text{ GeV} \) (deuterium)
Sivers Asymmetry Measurements

HERMES (p)

COMPASS (p)

- Global fit to $\sin (\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES, COMPASS)
  - $u$- and $d$- Sivers have opposite signs
- Future measurements at Jlab (12 GeV) will have dramatically better statistics
  Comparable measurements needed in Drell-Yan process
**Sivers Function Measurements**

- **T-odd observables**
  - SSA observable $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2)$ 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 $f_{1T}^{\perp q}$ must arise from interference (How?)
  - can interfere with
  - 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: $f_{1T}^{\perp q}|_{\text{DIS}} = - f_{1T}^{\perp q}|_{\text{D–Y}}$

Brodsky, Hwang & Smith (2002)

and produce a T-odd effect! (also need $L_z \neq 0$)

e.g. Drell-Yan)}
Hadronic Physics Milestone #13

- Report to NSAC, 11-Aug-2008 (by subcommittee on performance measures)
  - Table 11: New, Updated and Continuing Milestones for Hadronic Physics SeaQuest spectrometer
    - ✓ 2015 | HP13 (new) | Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering
  - New Milestone HP13 reflects the intense activity and theoretical breakthroughs of recent years in understanding the parton distribution functions accessed in spin asymmetries for hard-scattering reactions involving a transversely polarized proton. This leads to new experimental opportunities to test all our concepts for analyzing hard scattering with perturbative QCD.
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>
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</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) (x_t \sim 0.05) (low mass)</td>
<td>(2 \times 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1})</td>
<td>(2014)</td>
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<tr>
<td>PAX (GSI)</td>
<td>(p^\uparrow + p_{\text{par}})</td>
<td>collider (\sqrt{s} = 14\ GeV)</td>
<td>(x_b = 0.1 - 0.9)</td>
<td>(2 \times 10^{30}\ \text{cm}^{-2}\ \text{s}^{-1})</td>
<td>(&gt;2017)</td>
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<tr>
<td>PANDA (GSI)</td>
<td>(p_{\text{par}} + 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}\ \text{cm}^{-2}\ \text{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}\ \text{cm}^{-2}\ \text{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}\ \text{cm}^{-2}\ \text{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}\ \text{cm}^{-2}\ \text{s}^{-1})</td>
<td>(&gt;2018)</td>
</tr>
<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>(6 \times 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1})</td>
<td>(&gt;2018)</td>
</tr>
<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) (x_t = 0.1 - 0.45)</td>
<td>(3.4 \times 10^{35}\ \text{cm}^{-2}\ \text{s}^{-1})</td>
<td>(2012)</td>
</tr>
<tr>
<td>pol. SeaQuest§ (FNAL)</td>
<td>(p^\uparrow + p)</td>
<td>(120\ GeV) (\sqrt{s} = 15\ GeV)</td>
<td>(x_b = 0.35 - 0.85)</td>
<td>(1 \times 10^{36}\ \text{cm}^{-2}\ \text{s}^{-1})</td>
<td>(&gt;2015)</td>
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</table>

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

- Polarize Beam in Main Injector

  - Use SeaQuest dimuon Spectrometer
    - fixed target experiment
    - 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, optimized for Drell-Yan, and ready to take pol. beam
Polarized Drell-Yan at Fermilab Main Injector - II

• Polarized Beam in Main Injector
  ➡ use SeaQuest spectrometer
  ➡ use SeaQuest target
  ✓ liquid H₂ target can take Iav = ~5 x 10¹¹ p/s (=80 nA)
  ➡ 1 mA at polarized source can deliver about Iav = ~1 x 10¹² p/s (=150 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 x 10¹² p
  ✓ using three 2-s cycles (1.33-s ramp time, 0.67-s slow extraction) /min (=10% of beam time):
    → 2.8 x 10¹² p/s (=450 nA) instantaneous beam current , and Iav = ~0.95 x 10¹¹ p/s (=15 nA)
  ➡ Scenarios:
    ✓ L = 2.0 x 10³⁵ /cm²/s (10% of available beam time: Iav = 15 nA)
    ✓ L = 1 x 10³⁶ /cm²/s (50% of available beam time: Iav = 75 nA)
  ➡ x-range:
    ✓ xb = 0.35 – 0.85 (valence quarks)   xt = 0.1 – 0.35 (sea quarks)

• Systematic uncertainty in beam polarization measurement (scale uncertainty)
  ΔPb/Pb <5%
Fermilab E906/SeaQuest Collaboration (June 2012)

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*Co-Spokespersons

Collaboration contains many of the E-866/NuSea groups and several new groups (total 17 groups as of April 2012)
Drell-Yan Spectrometer for SeaQuest
(25m long)

Station 1
(hodoscope array, MWPC track.)

Station 2
(hodoscope array, prop tube track.)

Station 3
(Hodoscope array, drift chamber track.)

Station 4
(hodoscope array, drift chamber track.)

Targets
(liquid H₂, D₂, and solid targets)

Solid Iron Magnet
(focusing magnet, hadron absorber and beam dump)

KTeV Magnet
(Mom. Meas.)

Iron Wall
(Hadron absorber)
Mirror image of previous page—beam enters from upper right
SeaQuest Status

- Commissioning Run (Late Feb. 2012 – April 30th, 2012)
- First beam in E906 on March 8th, 2012
- Extensive beam tuning by the Fermilab accelerator group
  - $1 \times 10^{12}$ protons/s (5 s spill/min)
  - 120 GeV/c
- Cryogenic target systems (LH$_2$ and LD$_2$) worked smoothly
- All the detector subsystems worked reliably
  - Improvements for the production run underway
- Reconstructable dimuon events seen
- Preliminary analysis underway
- Main Injector shut down began on May 1st, 2012 (11 months)

A successful commissioning run
GOOD single muon event:
Clean Track in all but one plane
w/wire chamber hits and
hodoscopes

Working to have all events this clean
Fermilab Seaquest Timelines

<table>
<thead>
<tr>
<th></th>
<th>Expt. Funded</th>
<th>Experiment Construction</th>
<th>Exp. Runs</th>
<th>Shutdown</th>
<th>Experiment Runs</th>
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<tbody>
<tr>
<td>2009</td>
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<td>2014</td>
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<td>Beam: low intensity</td>
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<td>high intensity</td>
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<td>2013</td>
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<td>2015</td>
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</table>

Apparatus available for future programs at, e.g. Fermilab, (J-PARC or RHIC)

- significant interest from collaboration for continued program:
  - Polarized beam in Main Injector
  - Polarized Target at NM4

May 2012
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 $J/\Psi$ contamination)

- Transverse momentum: $p_T = 0 - 3$ GeV
Acceptance for Polarized Drell-Yan - II

![Graphs showing acceptance distributions for different variables](image)
## Polarized Drell-Yan Rate Estimates

<table>
<thead>
<tr>
<th>LH₂</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>( \rho_{H_2} )</td>
<td>50.8 cm</td>
</tr>
<tr>
<td>( I_{av} )</td>
<td>0.0678 g/cm³</td>
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<tr>
<td></td>
<td>9.5 ( \times 10^{10} ) p/s (= 15 nA)</td>
</tr>
</tbody>
</table>

| \( L_{av} \) | 2 \( \times 10^{35} \) cm\(^{-2}\) s\(^{-1}\) |
| \( \Omega \) (acceptance) | 0.02 |
| \( \varepsilon_t \) (trigger) | 0.8 |
| \( \varepsilon_r \) (reconstruction) | 0.5 |
| \( t_{spill} \) | 2 sec |
| \( n_{spill} \) | 3/min |
| Number of DY events | 3730 /day |
| \( \varepsilon_{exp} \) (experimental) | 0.5 |

\[
\text{Rate} = (\text{DY events/min}) \times \varepsilon_{exp} = 1865/\text{day}
\]
Sivers Asymmetry at Fermilab Main Injector - I

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

Note:
- Can measure not only sign, but also the size & maybe shape of the Sivers function!

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

~650k DY events

FNAL pol DY
3.2 $10^{13}$ POT
Sivers Asymmetry at Fermilab Main Injector - II

- Statistics can be improved
  - F Mag focuses high $p_T$ muons and over focuses low $p_T$ muons
    - we loose low $p_T$ muons when field is high!
  - Lowering F Mag field
    - we get back the low $p_T$ muons
    - we loose the high low $p_T$ muons

BUT

$p_T$ spectra peak at low $p_T$

Overall gain in the statistics!
Sivers Asymmetry at Fermilab Main Injector - III

- 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 $P_b = 70$

- Can measure not only sign, but also the size & maybe shape of the Sivers function!

- 75% FMag focusing!

- Increase statistics by a factor of 2!

- $\sim 1,288k$ DY events

- FNAL pol DY
  - $3.2 \times 10^{16}$ POT

- Anselmino et al.
# Polarized Drell-Yan at FNAL

## Possible Polarized Beam Project Chart

### Needs More Study

<table>
<thead>
<tr>
<th>Calendar Years</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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</thead>
<tbody>
<tr>
<td>Fermilab Shut-Down Schedule</td>
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<tr>
<td>1. Polarized Ion Source</td>
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<td>2. 35 keV Transport Line: PIS - RFQ</td>
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<td>3. RFQ</td>
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<td>4. 750 keV Transport Line: RFQ - LINAC</td>
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<td>5. 35 keV Polarimeter</td>
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<td>400 MeV Polarimeter</td>
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<td>6. Beam Stacking</td>
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<td>7. 400 MeV LINAC</td>
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<tr>
<td>8. 400 MeV Transport Line: LINAC - Booster</td>
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<tr>
<td>9. 8.9 GeV/c Booster Siberian Snake</td>
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<tr>
<td>10. 8.9 GeV/c Booster Pulsed Quads</td>
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<tr>
<td>11. 8.9 GeV/c Polarimeter</td>
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<tr>
<td>12. 8.9 GeV/c Transport Lines: Booster - RR</td>
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<tr>
<td>8.9 GeV/c Transport Lines: RR - MI</td>
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<tr>
<td>13. 8.9 GeV/c Recycler Ring</td>
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<tr>
<td>14. 120 GeV/c Main Injector Siberian Snakes</td>
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<td>15. 120 GeV/c Polarimeters</td>
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<td>16. 120 GeV/c Transport Line Spin Rotator</td>
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<td>17. Computer Controls</td>
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Legend: **Fermilab Shut-Downs**, **Decision**, **Obtain or Fabricate**, **Install**, **Final Design**, **Commission**

16 May 2012

A.D. Kirsch / D.A. Nees / M.A. Leonova
Requests to Fermilab

- SeaQuest spectrometer and experimental hall
  => continue to use NM3/4; counting house plus infrastructure
- Provide polarized beam in slow extraction mode (assumed 70% in stat. analysis)
  => continue to study issues with space limitations and work-arounds

Funding Model

- Investment of funds from NP and HEP
  => most groups funded through NP DOE or NSF
  => also funding from Japan and Taiwan
- Indications that both NP and HEP need to provide funding (similar to SeaQuest)
  => Phase I approval needed to pursue cooperative funding between agencies
Conclusions

• Extraordinary opportunity at Fermilab
  ➡ set up best polarized DY experiment to measure sign change in Sivers function
    ➔ high luminosity, large x-coverage, high-intensity polarized beam
    ➔ spectrometer already setup and running
  ➡ with (potentially) minimal impact on neutrino program
    ➔ 10% of available beam time at MI

• Cost to polarize Main Injector $20M - $30M
  ➡ Includes 50% contingency

• Several hurdles to take
  ➡ investigating using 1 snake in MI
    ➔ never been done at high energy
    ➔ but successfully at low energies (IUCF, Bates, AMPS)
  ➡ Investigating no partial snake in Booster
    ➔ polarization loss might be small (<10%)