Drell-Yan Experiments at Fermilab: SeaQuest and Beyond

Wolfgang Lorenzon

SeaQuest: Fermilab Experiment E906

- Status and Plans

Beyond SeaQuest

- Polarized Drell-Yan at Fermilab (E1027)

\[ f_{1T}^{q} \bigg|_{DIS} = - f_{1T}^{\bar{q}} \bigg|_{D-Y} \]

This work is supported by...
What is the Structure of the Nucleon?

Flavor Structure of the Proton

- Constituent Quark Model
  Pure valence description: proton = 2u + d

- Perturbative Sea
  sea quark pairs from \( g \rightarrow q\bar{q} \)
  should be flavor symmetric: \( \bar{d} = \bar{u} \)

What does the data tell us?

- Are there more gluons and thus symmetric anti-quarks at higher x?
- Unknown other mechanisms with unexpected x-dependence?
SeaQuest Projections for d-bar/u-bar Ratio

- SeaQuest will extend E866 measurements and reduce statistical uncertainty.
- SeaQuest expects systematic uncertainty to remain at ≈1% in cross section ratio.
- 5 s slow extraction spill each minute.
- Intensity:
  - $2 \times 10^{12}$ protons/s ($I_{\text{inst}} = 320$ nA)
  - $1 \times 10^{13}$ protons/spill.
SeaQuest: what else …

- **What is the structure of the nucleon?**
  - What is \( \bar{d}/\bar{u} \)? What is the origin of the sea quarks?
  - What is the high \( x \) structure of the proton?

- **What is the structure of nucleonic matter?**
  - Is anti-shadowing a valence effect?
  - Where are the nuclear pions?

- **Do colored partons lose energy in cold nuclear matter?**
  - How large is energy loss of fast quarks in cold nuclear matter?
A simple Spectrometer for SeaQuest

Optimized for Drell-Yan (25m long)

Station 1
(hodoscope array, MWPC track.)

Station 2
(hodoscope array, drift chamber track.)

Station 3
(Hodoscope array, drift chamber track.)

Station 4
(hodoscope array, prop tube 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)
The SeaQuest Collaboration

Abilene Christian University
Andrew Boles, Kyle Bowling, Ryan Castillo, Michael Daughetry, Donald Isenhower, Hoah Kitts, Rusty Towell, Shon Watson

Academia Sinica
Wen-Chen Chang, Yen-Chu Chen, Jai-Ye Chen, Shiu Shiuan-Hal, Da-Shung Su, Ting-Hua Chang

Argonne National Laboratory
John Arrington, Don Geesaman*

University of Illinois
Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Naomi C.R Makins, R. Evan McClellan, Jen-Chieh Peng, Shivangi Prasad, Mae Hwee Teo

KEK
Shinya Sawada

Los Alamos National Laboratory
Gerry Garvey, Andi Klein, Mike Leitch, Ming Liu, Pat

University of Michigan
Christine Aidala, Catherine Culkin, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh Rubin

National Kaohsiung Normal University
Rurngsheng Guo, Su-Yin Wang

RIKEN
Yoshinori Fukao, Yuji Goto, Atsushi Taketani, Manabu Togawa

Rutgers University
Ron Gilman, Ron Ransome, Arun

*Co-Spokespersons

Oct, 2013
(70 collaborators)
From Commissioning Run to Science Run

- 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
- All the detector subsystems worked
  - improvements for the production run completed
- Main Injector shut down began on May 1st, 2012
- Reconstructable dimuon events seen:
  - $M_{J/\Psi} = 3.12 \pm 0.05$ GeV
  - $\sigma = 0.23 \pm 0.07$ GeV

  A successful commissioning run

- Science Run start in Nov. 2013 for 2 years
The long Path towards the Science Run

- Stage I approval in 2001
- Stage II approval in December 2008
- Commissioning Run (March - April 2012)
- Expect beam again in November 2013 (for 2 years of data collection)

![Timeline Diagram]

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
Let’s Add Polarization

- **Polarize Beam** in Main Injector & use SeaQuest dimuon Spectrometer
  - measure Sivers asymmetry

- **Sivers function**
  - captures non-perturbative spin-orbit coupling effects inside a polarized proton
  - is naïve time-reversal odd:
    - leads to sign change:
      - Sivers function in SIDIS = - Sivers function in Drell-Yan:
        \[ f_{1T}^{\perp} \bigg|_{SIDIS} = - f_{1T}^{\perp} \bigg|_{DY} \]
    - fundamental prediction of QCD (in non-perturbative regime)
Polarized Drell-Yan at Fermilab Main Injector - II

• Polarized Drell-Yan:  
  ➡ major milestone in hadronic physics (HP13)

• 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
    ➡ (SeaQuest) spectrometer already setup and running
  ➡ with (potentially) minimal impact on neutrino program
    ➡ run alongside neutrino program (10% of beam needed)

  ➡ experimental sensitivity:
    ➡ 2 yrs at 50% eff, \( P_b = 70\% \)
    ➡ luminosity: \( \mathcal{L}_{av} = 2 \times 10^{35} \text{ /cm}^2\text{/s} \)

• Cost estimate to polarize Main Injector $10M (total)
  ➡ includes 15% project management & 50% contingency
# 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>$p^\pm + p^\uparrow$</td>
<td>$160 \text{ GeV}$ $\sqrt{s} = 17.4 \text{ GeV}$</td>
<td>$x_t = 0.2 – 0.3$</td>
<td>$2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>2014, 2018</td>
</tr>
<tr>
<td>PAX (GSI)</td>
<td>$p^\uparrow + p_{\bar{\text{p}}}$</td>
<td>collider $\sqrt{s} = 14 \text{ GeV}$</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>
</tr>
<tr>
<td>PANDA (GSI)</td>
<td>$p_{\bar{\text{p}}} + p^\uparrow$</td>
<td>$15 \text{ GeV}$ $\sqrt{s} = 5.5 \text{ GeV}$</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>
</tr>
<tr>
<td>NICA (JINR)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 20 \text{ GeV}$</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>
</tr>
<tr>
<td>PHENIX (RHIC)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 500 \text{ GeV}$</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>
</tr>
<tr>
<td>RHIC internal target phase-1</td>
<td>$p^\uparrow + p$</td>
<td>$250 \text{ GeV}$ $\sqrt{s} = 22 \text{ GeV}$</td>
<td>$x_b = 0.25 – 0.4$</td>
<td>$2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>RHIC internal target phase-1</td>
<td>$p^\uparrow + p$</td>
<td>$250 \text{ GeV}$ $\sqrt{s} = 22 \text{ GeV}$</td>
<td>$x_b = 0.25 – 0.4$</td>
<td>$6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>SeaQuest (unpol.) (FNAL)</td>
<td>$p + p$</td>
<td>$120 \text{ GeV}$ $\sqrt{s} = 15 \text{ GeV}$</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 - 2015</td>
</tr>
<tr>
<td>polDY§ (FNAL)</td>
<td>$p^\uparrow + p$</td>
<td>$120 \text{ GeV}$ $\sqrt{s} = 15 \text{ GeV}$</td>
<td>$x_b = 0.35 – 0.85$</td>
<td>$2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>&gt;2016</td>
</tr>
</tbody>
</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)
A Novel Siberian Snake for the Main Injector

Single 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
- use 2-twist magnets
  - $4\pi$ rotation of B field
- never done before in a high energy ring
  - RHIC uses snake pairs
  - single-twist magnets ($2\pi$ rotation)
Siberian Snake Studies

8.9 GeV 4T

beam excursions shrink w/ number of twists

4-twist 4T

beam excursions shrink w/ beam energy
x, y, z spin components vs distance

- transport matrix formalism (E.D. Courant): fringe field not included, $\beta = 1$ (fixed)
- spin tracking formalism (Thomas-BMT): fringe field included, $\beta$ variable

fringe fields have <0.5% effect at 8.9 GeV and <<0.1% effect at 100 GeV [arXiv: 1309.1063]
Spin direction control for extracted beam

- Spin rotators used to control spin direction at BNL
- Spin@Fermi collaboration recent studies (to save $$)
  ➡ rotate beam at experiment by changing proton beam energy around nominal 120 GeV

radial ("sideways") / vertical ("normal")
The Path to a polarized Main Injector

**Stage 1 approval** from Fermilab: 14-November-2012

- Collaboration with A.S. Belov at INR and Dubna to develop polarized source
- Detailed machine design and costing using 1 snake in MI
  - Spin@Fermi collaboration provide design
  - Get latest lattice for NOVA:
    - translate “mad8” optics file to spin tracking code (“zgoubi”)
    - determine intrinsic resonance strength from depolarization calculations
  - do single particle tracking with “zgoubi” with novel single-snake
  - set up mechanism for adding errors into the lattice:
    - orbit errors, quadrupole mis-alignments/rolls, etc.
  - perform systematic spin tracking
    - explore tolerances on beam emittance
    - explore tolerances on various imperfections: orbit / snake / etc

Fermilab (AD) does verification & costing
Intrinsic Resonance Strength in Main Injector

Depol calculations: single particle at $10\pi$ mm-mrad betatron amplitude

- 1995 Spin@Fermi report
  - before MI was built

- using NOVA lattice (July 2013)

- very similar: largest resonance strength just below 0.2
  - → one snake sufficient (E. Courant rule of thumb)
Another Way to Add Polarization: E1039

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

Proton Beam 120 GeV/c

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

Ref: Andi Klein (ANL)
Summary

• **SeaQuest (E906):**
  ➡ What is the structure of the nucleon? $\bar{d} / \bar{u}$?
  ➡ How does it change in the nucleus?
    → provide better understanding on the physical mechanism which generates the proton sea

• **Polarized Drell-Yan (E1027):**
  ➡ QCD (and factorization) require sign change in Sivers asymmetry:
    \[
    f_{1T}^{1/2} \text{SIDIS} = -f_{1T}^{1/2} \text{DY}
    \]
    → test fundamental prediction of QCD (in non-perturbative regime)
  ➡ Measure DY with both Beam or/and Target polarized
    → broad spin physics program possible
  ➡ Path to polarized proton beam at Main Injector
    → perform detailed machine design and costing studies
      › proof that single-snake concept works
      › applications for JPARC, NICA, ....
    → Secure funding
Thank You