Drell-Yan Scattering at Fermilab: SeaQuest and Beyond

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(1-September-2011)
Transversity-2011 Workshop

• Introduction

• SeaQuest: Fermilab Experiment E906
  ➔ Sea quarks in the proton
  ➔ Sea quarks in the nucleus
  ➔ other topics

• Beyond SeaQuest
  ➔ Polarized Drell-Yan at FNAL?

\[ \left. f_{1T}^{\perp} \right|_{DIS} = - \left. f_{1T}^{\perp} \right|_{D-Y} \]

With help from Chiranjib Dutta (U-M), and Paul Reimer (Argonne)

This work is supported by
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
Flavor Structure of the Proton

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

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

- **What does the data tell us?**

  ![Graph showing No Data, \( \bar{d} = \bar{u} \) with the x-axis ranging from 0 to 0.6 and the y-axis from 0 to 2.25]
Flavor Structure of the Proton: Brief History

- Perturbative Sea
  \[ \bar{d}(x) = \bar{u}(x) \]

- NMC (inclusive DIS)
  \[ \int_0^1 \left[ \bar{d}(x) - \bar{u}(x) \right] dx \neq 0 \]

- NA51 (Drell-Yan)
  \[ \bar{d}(x) > \bar{u}(x) \]

- E866/NuSea (Drell-Yan)
  \[ \bar{d}(x) > \bar{u}(x) \]

- What is the origin of the sea

E866: \[ \bar{d} > \bar{u} \]

Knowledge of parton distributions is data driven
- Sea quark distributions are difficult for Lattice QCD
Flavor Structure of the Proton: What creates Sea?

- There is a gluon splitting component which is symmetric
  \[ \overline{d}(x) = \overline{u}(x) = \overline{q}(x) \]

- \( \overline{d} - \overline{u} \)
  - Symmetric sea via pair production from gluons subtracts off
  - No gluon contribution at 1\textsuperscript{st} order in \( \alpha_s \)
  - Non-perturbative models are motivated by the observed difference

- A proton with 3 valence quarks plus glue cannot be right at any scale!!
Flavor Structure of the Proton: Models

Non-perturbative models: alternate d.o.f.

Meson Cloud Models

- quark d.o.f. in a pion mean-field: \( u \rightarrow d + \pi^+ \)
- nucleon = chiral soliton
- one parameter: dynamically generated quark mass
- expand in \( 1/N_c \):

\[ \rightarrow \bar{d} > \bar{u} \]

Chiral-Quark Soliton Model

- nucleon = gas of massless partons
- few parameters: generate parton distribution functions
- input:
  - QCD: chiral structure
  - DIS: \( u(x) \) and \( d(x) \)

\[ \rightarrow \bar{d} > \bar{u} \]

Statistical Model

- quark d.o.f. in a pion
- nucleon = chiral soliton
- one parameter: dynamically generated quark mass
- expand in \( 1/N_c \):

\[ \rightarrow \bar{d} > \bar{u} \]

\[ \Rightarrow \text{important constraints on flavor asymmetry for polarization of light sea} \]

\[ \Delta \bar{q} = 0 \quad \Delta \bar{u} \cong -\Delta \bar{d} > 0 \quad \Delta \bar{d} < 0, \Delta \bar{u} > 0 \]
Flavor Structure of the Proton: What creates Sea?

Comparison with models

- High x behavior is not explained
- Perturbative sea seems to dilute meson cloud effects at large x (but this requires large-x gluons)

Measuring the ratio is powerful

Are there more gluons and thus symmetric anti-quarks at higher x?

Unknown other mechanisms with unexpected x-dependence?
SeaQuest: Fermilab Experiment E906

- E906 will extend Drell-Yan measurements of E866/NuSea (with 800 GeV protons) using upgraded spectrometer and 120 GeV proton beam from Main Injector
- Lower beam energy gives factor 50 improvement “per proton”!
  - ✔️ Drell-Yan cross section for given x increases as 1/s
  - ✔️ Backgrounds from J/Ψ and similar resonances decreases as s
- Use many components from E866 to save money/time, in NM4 Hall
- Hydrogen, Deuterium and Nuclear Targets
Collaboration contains many of the E-866/NuSea groups and several new groups (total 17 groups as of Aug 2011)
Drell-Yan Spectrometer for E906
(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.)

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

KTeV Magnet
(Mom. Meas.)

Iron Wall
(Hadron absorber)

Targets
(liquid H₂, D₂, and solid targets)
Drell-Yan Spectrometer for E906
(Reduce, Reuse, Recycle)

• St. 4 Prob Tubes: Homeland Security via Los Alamos
• St. 3 & 4 Hodo PMTs: E866, HERMES, KTeV
• St. 1 & 2 Hodoscopes: HERMES
• St. 2 Support Structure: KTeV
• St. 2 & 3 tracking: E866
• Target Flasks: E866
• Cables: KTeV

• Hadron Absorber: FNAL
  • Shielding blocks: FNAL old beamline
  • 2nd Magnet: KTeV mom analysis magnet
• Solid Fe Magnet Coils: E866 SM3 Magnet
• Solid Fe Magnet FLUX Return Iron: E866 SM12 Magnet

Expect to start collecting data: November 2011
Fixed Target Drell-Yan: What we really measure

- Measure yields of $\mu^+\mu^-$ pairs from different targets
- Reconstruct $p_\gamma$, $M^2_\gamma = x_b x_t s$
- Determine $x_b$, $x_t$
- Measure differential cross section
  $$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q \in \{u, d, s, \ldots\}} e_q^2 \left[ \bar{q}_i(x_t)q_b(x_b) + q_i(x_t)\bar{q}_b(x_b) \right]$$
- Fixed target kinematics and detector acceptance give $x_b > x_t$
  - $x_F = 2p_{||}\gamma/s^{1/2} \approx x_b - x_t$
  - Beam valence quarks probed at high $x$
  - Target sea quarks probed at low/intermediate $x$
Fixed Target Drell-Yan: What we really measure - II

- Measure cross section ratios on Hydrogen, Deuterium (and Nuclear) Targets

\[ \frac{\sigma^{pd}}{2\sigma^{pp}} \bigg|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right] \]
SeaQuest Projections for d-bar/u-bar Ratio

- SeaQuest will extend these 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
Sea quark distributions in Nuclei

- EMC effect from DIS is well established
- Nuclear effects in sea quark distributions may be different from valence sector
- Indeed, Drell-Yan apparently sees no Anti-shadowing effect (valence only effect)
Sea quark distributions in Nuclei - II

- SeaQuest can extend statistics and x-range
- Are nuclear effects the same for sea and valence distributions?
- What can the sea parton distributions tell us about the effects of nuclear binding?
Where are the exchanged pions in the nucleus?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.

- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.

- Contemporary models predict large effects to antiquark distributions as $x$ increases.

- Models must explain both DIS-EMC effect and Drell-Yan

- SeaQuest can extend statistics and $x$-range

If large nuclear effects were found → nuclear effects may be important in D/H
Fermilab Seaquest Timelines

- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about “proton economics”
- Fermilab Stage II approval in December 2008
- Expect first beam in November 2011 (for 2 years of data collection)

<table>
<thead>
<tr>
<th>Year</th>
<th>Expt. Funded</th>
<th>Experiment Construction</th>
<th>Exp. Runs</th>
<th>Shutdown</th>
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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
Beyond SeaQuest

• **Polarized Drell-Yan Experiment**

  ➡ Not yet done!
  ➡ transverse momentum dependent distributions functions (Sivers, Boer-Mulders, etc)
  ➡ Transversely Polarized **Beam** or **Target**

  ✓ Sivers function in single-transverse spin asymmetries (SSA) (sea quarks or valence quarks)
    – valence quark effects expected to be large
    – sea quark effects might be 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
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 Drell-Yan
- done in SIDIS (HERMES, COMPASS)
- Sivers function is time-reversal odd
  - leads to sign change
  \[
  f_{1T}^\perp q \bigg|_{\text{DIS}} = - f_{1T}^\perp q \bigg|_{\text{D-Y}}
  \]
  - 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
Sivers Asymmetry Measurements

**HERMES (p)**

- Global fit to $\sin (\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES, COMPASS)
  - $u$- and $d$-Sivers DF almost equal size, but different sign ($d$ slightly larger)

**COMPASS (d)**

- Comparable measurements needed for single spin asymmetries in Drell-Yan process
- BUT: COMPASS (p) data (2007 & 2100) smaller Sivers asym. than HERMES
  - maybe due to $y$ or $z$ dependence?
  - do global fits with all available data

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Anselmino et al. EPJA 39, 89 (2009)
Polarized Drell-Yan at Fermilab Main Injector

- Polarize Beam in Main Injector (A. Krisch’s talk)

- Use SeaQuest di-muon 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: \( 3.4 \times 10^{18} \) pot
  - by 2015: fully understood, optimized for Drell-Yan, and ready to take pol. beam
Polarized Drell-Yan at Fermilab Main Injector - II

• **SeaQuest di-muon Spectrometer**
  - **luminosity**: \( L_{\text{av}} = 3.4 \times 10^{35} \text{ /cm}^2\text{/s} \) \( \text{[} I_{\text{av}} = 1.6 \times 10^{11} \text{ p/s (26 nA)} / N_p = 2.1 \times 10^{24} \text{ /cm}^2 \text{]} \)
  - approved for \( 3.4 \times 10^{18} \text{ pot} \)

• **Polarized Beam in Main Injector**
  - use Seaquest spectrometer
  - use SeaQuest target
    ✓ liquid H\(_2\) target can take \( I_{\text{av}} = \sim 5 \times 10^{11} \text{ p/s (80 nA)} \)
  - 1 mA at polarized source can deliver about \( I_{\text{av}} = \sim 1 \times 10^{12} \text{ p/s (150 nA)} \) for 100% of available beam time (A. Krisch: Spin@Fermi report in (Aug 2011))
    ✓ 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-s cycles (1.33-s ramp time, 0.67-s slow extraction) /min (=10% of beam time):
    \( \rightarrow 2.8 \times 10^{12} \text{ p/s (450 nA) instantaneous beam current}, \text{ and } I_{\text{av}} = \sim 0.95 \times 10^{11} \text{ p/s (15 nA)} \)

  ➤ **Scenarios:**
    ✓ \( L = 2.0 \times 10^{35} \text{ /cm}^2\text{/s} \) (10% of available beam time: \( I_{\text{av}} = 15 \text{ nA} \))
    ✓ \( L = 1 \times 10^{36} \text{ /cm}^2\text{/s} \) (50% of available beam time: \( I_{\text{av}} = 75 \text{ nA} \))

  ➤ **x-range:**
    ✓ \( x_b = 0.3 – 0.9 \) (valence quarks) \( x_l = 0.1 – 0.4 \) (sea quarks)
SeaQuest: Drell-Yan Acceptance

- Programmable trigger removes likely $J/\psi$ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for $J/\psi$, $\psi'$ studies
SeaQuest: Detector Resolution

- Triggered Drell-Yan events
Experimental Sensitivity

- Luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: $I_{av} = 15$ nA)
- 100 fb$^{-1}$ for $5 \times 10^5$ min: (= 2 yrs at 50% efficiency)

**Note:**

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

$$A_N = \frac{2}{\pi} A_{TU}^{\sin(\phi - \phi_S)}$$
Polarized Drell-Yan at Fermilab Main Injector - III

What if?

- Luminosity: $L_{av} = 2 \times 10^{34}$ (10x lower than expected)
- 10 fb$^{-1}$ for $5 \times 10^5$ min: (2 yrs at 50% efficiency)

Can still measure sign, AND shape of the Sivers function, with 10x less $L_{int}$!

What if the sign changes, BUT $f_{1T}^{q \perp}_{DIS} \neq f_{1T}^{q \perp}_{D-Y}$? 
## Planned Polarized Drell-Yan Experiments

<table>
<thead>
<tr>
<th>experiment</th>
<th>particles</th>
<th>energy</th>
<th>$x_1$ or $x_2$</th>
<th>luminosity</th>
<th>timeline</th>
</tr>
</thead>
</table>
| COMPASS (CERN)              | $\pi^\pm + p^\$ | 160 GeV $\sqrt{s} = 17.4$ GeV | $x_2 = 0.2 - 0.3$  
                      ~ $0.05$ (low mass) | $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ | 2014 |
| PAX (GSI)                   | $p^\$ + $p_{par}$ | collider $\sqrt{s} = 14$ GeV | $x_1 = 0.1 - 0.9$ | $2 \times 10^{30}$ cm$^{-2}$ s$^{-1}$ | >2017 |
| PANDA (GSI)                 | $p_{par} + p^\$ | 15 GeV $\sqrt{s} = 5.5$ GeV | $x_2 = 0.2 - 0.4$ | $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ | >2016 |
| J-PARC                      | $p^\$ + $p$ | 50 GeV $\sqrt{s} = 10$ GeV | $x_1 = 0.5 - 0.9$ | $1 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ | >2015 |
| NICA (JINR)                 | $p^\$ + $p$ | collider $\sqrt{s} = 20$ GeV | $x_1 = 0.1 - 0.8$ | $1 \times 10^{30}$ cm$^{-2}$ s$^{-1}$ | >2014 |
| PHENIX (RHIC)               | $p^\$ + $p$ | collider $\sqrt{s} = 500$ GeV | $x_1 = 0.05 - 0.1$ | $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ | >2018 |
| RHIC internal target phase-1| $p^\$ + $p$ | 250 GeV $\sqrt{s} = 22$ GeV | $x_1 = 0.25 - 0.4$ | $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ | >2015 |
| RHIC internal target phase-1| $p^\$ + $p$ | 250 GeV $\sqrt{s} = 22$ GeV | $x_1 = 0.25 - 0.4$ | $3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ | >2018 |
| $A_{\pi,\text{DY}}$ RHIC (IP-2) | $p^\$ + $p$ | collider $\sqrt{s} = 500$ GeV | $x_1 = 0.1 - 0.3$ | $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ | 2013 |
| SeaQuest (unpol.) (FNAL)    | $p + p$   | 120 GeV $\sqrt{s} = 15$ GeV | $x_1 = 0.3 - 0.9$  
                      $X_2 = 0.1 - 0.45$ | $3.4 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ | 2011 |
| pol. SeaQuest (FNAL)        | $p^\$ + $p$ | 120 GeV $\sqrt{s} = 15$ GeV | $x_1 = 0.3 - 0.9$ | $1 \times 10^{36}$ cm$^{-2}$ s$^{-1}$ | >2014 |
Drell-Yan fixed target experiments at Fermilab

- What is the structure of the nucleon?
  - What is \( \bar{d} / \bar{u} \)?
  - What is the origin of the sea quarks?
- What is the structure of nucleonic matter?
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?
- SeaQuest: 2011 - 2014
  - significant increase in physics reach
- Beyond SeaQuest
  - Polarized beam at Fermilab Main Injector
  - Polarized target at Main Injector
  - high-luminosity Drell-Yan program: complementary to spin programs at RHIC and JLAB