Measurement of Boer-Mulders Function via Drell-Yan Process by SeaQuest Experiment at Fermilab

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Outline

▶ Motivation
  ▷ Drell-Yan process as probe to nucleon structure
  ▷ Sea-queark flavor asymmetry ($\bar{d}/\bar{u}$)
  ▷ Boer-Mulders function ($h_1^\perp$)
  ▷ And more...

▶ Experiment setup & timeline
  ▷ First physics run (Run-2) has finished

▶ Status & prospect
  ▷ Based on analyses of Run-2 data

▶ Summary
Drell-Yan Process @ Forward

- Cross section @ LO

\[
\frac{d^2\sigma}{dx_Bdx_T} = \frac{4\pi\alpha^2}{9x_Bx_T}s \sum_i e_i^2 \times \left\{ q_i^B(x_B)\bar{q}_i^T(x_T) + \bar{q}_i^B(x_B)q_i^T(x_T) \right\}
\]

(B: beam, T: target)

- Always involve anti quark ... cf. DIS
- Quark @ beam & anti-quark @ target since \( x_B \gg x_T \) & \( q(x) \gg \bar{q}(x) \) at large \( x \)
Sea-Quark Flavor Asymmetry ($\bar{d}/\bar{u}$)

- Dependence on $x$ first measured by FNAL E866/NuSea

- Examined with theory models (meson cloud model etc.)

- Unique data on $\bar{u} \neq \bar{d}$

- SeaQuest will measure $\bar{d}/\bar{u}$ @ $0.2 \lesssim x_{Bj} \lesssim 0.4$ w/ $p+p$ & $p+d$

  - $x_{Bj}$ dependence is the key to understand $\bar{d}/\bar{u}$ asym.
  - Particularly $\bar{d} \gtrsim \bar{u}$ @ $x_{Bj} \sim 0.3$??

Meas. of Boer-Mulders Function via Drell-Yan Process by SeaQuest Exp. at Fermilab
Boer-Mulders Function \( (h_1^\perp(x, k_T)) \)

- Via measurement of angular distribution with \( p + p \) & \( p + d \)

\[
\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left( 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right)
\]

- Size of \( \cos(2\phi) \) modulation
- Break of Lam-Tung relation:
  \( 1 - \lambda \neq 2\nu \)

- Convolution of two \( h_1^\perp \)
  - \( \nu \propto [h_1^\perp \text{ of } q] \times [h_1^\perp \text{ of } \bar{q}] \)
  - \( h_1^\perp \text{ of } q @ x \sim 0.5 \)
  - \( h_1^\perp \text{ of } \bar{q} @ x \sim 0.3 \)
  - Extraction of \( h_1^\perp \) from E866/NuSea data
    ... PRD 81, 034023 (2010), PRD 82, 114025 (2010)
Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)

Duty cycle
- 60 sec per cycle
- 5 sec for E906 with slow extraction
- The rest for neutrino exp.

Bunch
- Length: 1 nsec
- Interval: 19 nsec (53 MHz)
- $10^{13}$ protons in 5 sec in spot size
E906/SeaQuest Spectrometer

- Targets ... LH$_2$, LD$_2$, C, Fe, W (& empty flask, none) in rotation
- Di-muon trigger with hodoscopes @ St. 1...4
- Tracking with drift chambers @ St. 1...4
- Detect $\mu^+/\mu^-$ with $p \sim 40$ GeV/c

Meas. of Boer-Mulders Function via Drell-Yan Process by SeaQuest Exp. at Fermilab
## SeaQuest Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>04</td>
<td>Start of building spectrometer</td>
</tr>
<tr>
<td>2011</td>
<td>08</td>
<td>Complete spectrometer</td>
</tr>
<tr>
<td>2012</td>
<td>03-04</td>
<td><strong>Commissioning run</strong> (Run 1) (1st beam on March 08)</td>
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<tr>
<td>2012</td>
<td>05...</td>
<td>Detector &amp; DAQ upgrade</td>
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<tr>
<td>2013</td>
<td>11</td>
<td>Start of <strong>Physics run</strong> (Run 2) (1st beam on November 08)</td>
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<tr>
<td>2014</td>
<td>09-10</td>
<td>Accelerator maintenance</td>
</tr>
<tr>
<td>2014</td>
<td>11</td>
<td>Re-start of <strong>Physics run</strong> (Run 3)</td>
</tr>
<tr>
<td>2016</td>
<td>X</td>
<td>End</td>
</tr>
</tbody>
</table>

- Two years for $10^{19}$ protons delivered
  
  $(10^{13}$ protons/spill $\times$ 1 spill/min $\times$ 2 years)
Trigger Rate ($R$) & Beam Intensity ($I$)

- Primary issue at Run-2 start
- $R$ was much higher ($>10$ kHz) than DAQ bandwidth (5 kHz)
  - Observed $R \propto I^2$
  - Due to fake high-$p$ tracks
- Solution
  - Measured & improved beam duty factor ($\langle I \rangle^2 / \langle I^2 \rangle$)
  - Found & removed “hot” trigger patterns in real data & simulation
- $4 \times 10^{12}$ delivered protons/spill at Run-2 end (to be $1 \times 10^{13}$ in Run 3)
Status of Run-2 Data Analysis

- Di-muon mass distribution (preliminary)

- With $\sim 1/3$ of Run-2 data
- Events on all targets (LH$_2$, LD$_2$, C, Fe & W) are summed up here
- Detectors work nicely as expected
- Good $J/\psi$ mass resolution ($\sim 180$ MeV)
  - Drell-Yan dominates @ $M \gtrsim 4$ GeV
  - Can separate $J/\psi$ & $\psi'$
- Resonable MC/data agreement on mass dependence of acceptance

![Di-muon mass distribution graph](image-url)
Measurement Precision at Present

- With part of Run-2 data
  - $\sim 5\%$ of expected luminosity
- Flavor asymmetry ($\bar{d}/\bar{u}$) $\rightarrow$
  - & nuclear dependence $\downarrow$
- The anticipated precision is achievable!

(error size only)

![Graph showing the measurement precision at present](image)
Expected Precision on Angular Distribution

- Data analysis is ongoing
- Estimate with MC
  - Assuming the full luminosity \((3.4 \times 10^{18} \text{ recorded protons})\)
  - \(\nu \equiv \text{size of } \cos(2\phi) \text{ modulation } \propto \left[ h_{1/2} \text{ of } \bar{q} \right] \times \left[ h_{1/2} \text{ of } q \right]\)

- Probably \(h_{1/2} \text{ of } \bar{q}\) is smaller than \(q\), but E906/SeaQuest will measure it with enough accuracy
Summary

- **Purpose of E906/SeaQuest @ Fermilab**
  - Investigate the nucleon structure with the Drell-Yan process
  - Measure the sea-quark flavor asymmetry, $\bar{d}/\bar{u}$
  - Measure the Boer-Mulders function, $h_1^+(x, k_T)$
  - Measure the nuclear dependence, $\sigma_{p+A}/\sigma_{p+d}$
  - Not only physics but also to limit the nuclear correction on $\bar{d}/\bar{u}$.

- **First physics run (Run-2) has finished**
  - Data analyses are on-going
  - Preliminary result has confirmed that the data are being accumulated as anticipated

- **Second physics run (Run-3) will start in November 2014**

- (W. Lorenzon is talking in Session 12 about future polarized Drell-Yan experiments at Fermilab, i.e. E-1027 & E-1039)