Probing Parton Distributions and Nucleon Structure in the SeaQuest and SpinQuest Experiments at Fermilab

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Outline

• Drell-Yan (DY) Fixed Target Experiments at Fermilab
  - E-906/SeaQuest (unpolarized targets)
  - E-1039/SpinQuest (polarized targets)
  - The Spectrometer

• Highlight of SeaQuest Physics Topic
  - Anti-quark Asymmetry

• Highlight of SpinQuest Physics Topics and Status

• Summary and Outlook
The Drell-Yan Process

**DY process:** $p + p \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$

Cross section at Leading Order (LO):

$$\frac{d^2\sigma}{dM^2dx_F} = \frac{4\pi\alpha^2}{9M^4} \frac{x_{beam}x_{target}}{x_{beam} + x_{target}} \sum_{i \in \{u,d,s,\ldots\}} e_i^2 \left[ f_i(x_{beam})\bar{f}_i(x_{target}) + \bar{f}_i(x_{beam})f_i(x_{target}) \right]$$

Definitions:

- $x_F \approx x_{beam} - x_{target}$
- $\alpha = \text{fine structure constant}$
- $M = \text{mass of dimuon pair}$
- $e_i = \text{charge of quark}$
- $\tau = M^2 / s = x_{beam}x_{target}$
- $\sqrt{s} = E_{CM} = \sqrt{2E_{beam}m_p}$
DY Fixed-Target Experiments at Fermilab

- 120 GeV proton beam ($\sqrt{s} = 15$ GeV) from Main Injector
  - Intensity $\sim 10^{12}$ protons/sec
- E-906/SeaQuest
  - Targets (unpolarized):
    - Liquid hydrogen and deuterium (LH2, LD2)
    - Solid carbon, iron, tungsten
  - Data taking: 2013-2017
- Some physics topics
  - Flavor asymmetry in the proton sea*
  - Nuclear effects via DY process
  - Nuclear effects via J/$\psi$ production

AND MORE!
DY Fixed-Target Experiments at Fermilab

• 120 GeV proton beam ($\sqrt{s} = 15$ GeV) from Main Injector
  ▪ Intensity $\sim 10^{12}$ protons/sec

• E-1039/SpinQuest
  ▪ Targets (transversely-polarized):
    • NH$_3$ and ND$_3$
  ▪ Expected data taking: 2021-2023
  ▪ Some physics topics
    • Anti-quarks Sivers asymmetry
    • Gluonic Sivers asymmetry*

AND MORE!
The Spectrometer

- Employed by both SeaQuest and SpinQuest

- SpinQuest polarized cryogenic targets:
  - Dynamic nuclear polarization (~ 80% target polarization at 4% uncertainty)
  - Kept at 1K in 5 T field, polarization flip every 8 hours

Located in NM4 enclosure at Fermilab
Highlight of
SeaQuest Physics Topics:

Anti-quark Asymmetry
Nucleon Sea

- Nucleon sea naively assumed to be flavor symmetric
  - Gluons don’t couple to flavor
  - Masses of u and d quarks are similar and small, compared to QCD scale

Perturbative contributions calculated to be small!

NMC (1991)

- Gottfried Sum Rule:
  \[ S_G = \frac{1}{3} + \int_0^1 \frac{2}{3} (\bar{u}^p(x) - \bar{d}^p(x)) \, dx \]

- Symmetric sea implies \( S_G = 1/3 \)

- NMC experiment (LD2, LH2, 90 GeV and 280 GeV \( \mu \)-beam)

\[ S_G = \int_0^1 (F_2^p - F_2^n) \, dx / x = 0.235 \pm 0.026 \]
More Evidence of Flavor Asymmetry

- **CERN NA51** (1994): 450 GeV p-beam, LD2, LH2 targets
  \[ \frac{d}{u} \langle x \rangle = 1.96 \pm 0.15 \pm 0.05 \]

- **FNAL E866/NuSea** (1998): 800 GeV p beam LD2, LH2 targets

- Studied actively by effective QCD models & lattice QCD
  - Precise measurement at large x was needed

R.S. Towell *et. al.* Phys. Rev. D 64, 244-250
SeaQuest Result

- Large asymmetry over entire range measured
- Discrepancy with NuSea could be due to: different beam energy, acceptance and kinematic coverage
  - Discrepancy at high x is not well understood

Model Calculation Comparison

- Reasonably described by the predictions of
  - “Pion cloud model” (Alberg & Miller)
    \[ |p \rangle = (1 - \sum a_i) |p_0 \rangle + a_{|N\pi\rangle} |N\pi \rangle + a_{|\Delta\pi\rangle} |\Delta\pi \rangle + a_{|\Lambda K\rangle} |\Lambda K \rangle + \ldots \]
  - “Statistical model” (Basso et al.)
SpinQuest Motivation

- Explore the **anti-quark** and **gluon Sivers functions**, $f_{1T}^\perp$:

  - Large transverse single spin asymmetries (TSSAs), $A_N (\propto f_{1T}^\perp)$, observed in polarized pp-collisions
  - Study/constrain antiquark and gluon orbital angular momentum contributions to proton spin
Sivers Function at SpinQuest

- Measure azimuthal asymmetry in:
  - DY dimuon production → study anti-quark Sivers
  - \( J/\psi \) meson dimuon decay → study gluon Sivers

\[
A_n = \frac{N_u}{L_u} - \frac{N_d}{L_d} \div \frac{N_u}{L_u} + \frac{N_d}{L_d}
\]

where

- \( x_{Bjorken} = x = \frac{p_{\text{parton}}}{p_{\text{proton}}} \)
- \( x_2 = x_{\text{target}}, \ x_1 = x_{\text{beam}} \)
- \( x_F = x_1 - x_2 \)

- \( N_{u (or \ d)} \) = # of dimuons for spin \( \uparrow (\downarrow) \)
- \( L_{u (or \ d)} \) = live protons for spin \( \uparrow (\downarrow) \)

Small due to SpinQuest acceptance!
J/ψ Production

- The SpinQuest experiment: access to dimuon decay of the J/ψ meson (charm, anti-charm bound state)
- Mechanisms:
  1. gluon-gluon (g-g) fusion
  2. quark anti-quark (q-q-) annihilation

\[
H_{\text{beam,target}}(x_{\text{target}}, x_{\text{beam}}; M^2) = g(x_{\text{beam}})g(x_{\text{target}})\sigma(gg \rightarrow c\bar{c}; M^2) \\
+ \sum_{i \in \{u,d,s,\ldots\}} \left[ f_i(x_{\text{beam}})\bar{f}_i(x_{\text{target}}) + \bar{f}_i(x_{\text{beam}})f_i(x_{\text{target}}) \right] \sigma(q\bar{q} \rightarrow c\bar{c}; M^2)
\]

\[
\frac{d^2 \sigma}{d\tau dx_F} = \frac{2\tau}{\sqrt{x_F^2 + 4\tau^2}} H_{\text{beam,target}}(x_{\text{target}}, x_{\text{beam}}; x_{\text{target}} x_{\text{beam}} s)
\]
**J/ψ TSSAs**

- TSSAs (up to ~40%) observed in light hadron production in $0.1 < x < 0.5$
- **g-g fusion**: dominant mechanism for J/ψ production at SpinQuest
  - Acceptance $x_F \gg 0$ at J/ψ mass
  - q-q- vs. g-g / Σ cross sections → gg mechanism dominant at SpinQuest’s $E_{cm} (=15\text{GeV})$ for $x_F > 0.42$
- J/ψ TSSA: study of gluon Sivers and QCD dynamics in hadron production with **improved statistics** in higher $x_F$ region!
Anticipated Uncertainty for J/ψ TSSAs

• Rate of in-acceptance dimuons estimated by GMC:
  - PYTHIA8 charmonium production
  - Geometric acceptance considered

• **One week** of dedicated data taking was assumed
  - Integrated luminosity: \( L_{1w} = 1.75 \times 10^4 \text{ pb}^{-1} \) & \( L_{\text{sim}} = 6567 \text{ pb}^{-1} \)
  - Dilution factor: \( f = 0.176 \)
  - Polarization: \( P = 0.8 \)

\[ A_N = \frac{2 \sum_i N(x_T, \Phi_{S_i}) \sin \Phi_{S_i}}{f \sum_i N(x_T, \Phi_{S_i})} \]

\[ \delta_{AN}^{1w} = 1/f \cdot 1/P \cdot \delta_{AN}^{\text{sim}} \cdot \sqrt{L_{\text{sim}}/L_{1w}} = 3.3 \cdot \delta_{AN}^{\text{sim}} \]

\[ \delta_{AN}^{\text{sim}} \sim 1/\sqrt{N_{\text{measured}}} \]

\( \Phi_\varphi = \) azimuthal angle b/t target spin & hadron plane

"Day-One Physics" program at SpinQuest
# Timeline for SpinQuest

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
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<tbody>
<tr>
<td>2018</td>
<td>May</td>
<td>Granted Stage-2 approval from Fermilab Decommissioned SeaQuest components</td>
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<tr>
<td>2019</td>
<td>June</td>
<td>Transferred the pol. target from UVA to Fermilab Sanity checking/debugging detector components using cosmic rays</td>
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<tr>
<td>2020</td>
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<td>Testing spectrometer components with cosmic ray data (limited access due to COVID-19)</td>
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<tr>
<td>2021</td>
<td>January</td>
<td>Testing/debugging spectrometer components</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>Commission target and detector</td>
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<tr>
<td>December</td>
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<td>Production runs</td>
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<tr>
<td>2021-2023</td>
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Summary and Outlook

- SeaQuest and SpinQuest aim to probe nucleonic structure and parton distributions in newer kinematic regions and higher accuracy.
- E-906/SeaQuest with unpolarized targets
  - Large anti-down vs. anti-up asymmetry at high x was observed.
  - Also investigating nuclear effects via DY and J/ψ and more topics!
- SpinQuest polarized DY and J/ψ data will constrain anti-quark and gluon Sivers functions.
  - SpinQuest measurement on J/ψ TSSA is anticipated to be the first published results.

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Backup Slides
Importance of Gluons and Seaquarks

- Proton spin puzzle:

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + J_G + L_q + L_{\bar{q}} \]

Lattice QCD
(PoS LATTICE2011, 164)