Measurements of Parton Structure of Nucleons and Nuclei via Drell-Yan Process at Fermilab

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Outline

1. Drell-Yan process for studying nucleon structure

2. Measurements at Fermilab
   - SeaQuest with $p + p(d)$ & $p + A$ in 2013-2017
   - E1039 with $p + \bar{p}(\vec{d})$ in 2019-2021

3. Status & prospect of physics topics
   - Flavor asymmetry of anti-quarks ($\bar{d}(x)/\bar{u}(x)$)
   - Boer-Mulders function of anti-quarks
   - Nuclear effects
   - Sivers function of anti-quarks

4. Summary
Drell-Yan Process for PDF Measurements

- Cross section of $p + p$ D-Y @ LO

$$\frac{d^2 \sigma}{dx_{\text{Beam}} dx_{\text{Target}}} = \frac{4\pi\alpha^2}{9x_{\text{Beam}}x_{\text{Target}} s} \sum_i e_i^2 \left\{ q_i(x_{\text{Beam}}) \bar{q}_i(x_{\text{Target}}) + \bar{q}_i(x_{\text{Beam}}) q_i(x_{\text{Target}}) \right\}$$

- “$q_i(x_{\text{Beam}}) \bar{q}_i(x_{\text{Target}})$” survives @ forward rapidity
- $q$ w/ $x_{\text{Beam}}$ & $\bar{q}$ w/ $x_{\text{Target}}$ are distinguishable event-by-event

- Specialty
  - Sensitivity to $\bar{q}$
  - Similarity to SIDIS
    - Complementary measurements
    - TMD sign change
  - No strong interaction in final state (vs heavy-ion collision)
Fermilab Proton Beam

- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for SeaQuest
  - 55 sec for $\nu$ exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - $10^{13}$ protons in 5 sec
E906/SeaQuest Spectrometer

- Targets: LH$_2$, LD$_2$, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump
- A typical Drell-Yan event (top view) ... mass = 6 GeV, $\theta_{\mu^+} = 90^\circ$, $\phi_{\mu^+} = 0^\circ$

- Detection of dimuons
  - Station 1-3 : Tracking with drift chambers
  - Station 4 : Particle identification with drift tube
  - Momenta of detected muons are 40 GeV/c on average
SeaQuest Data Taking

- **Data-taking periods**
  
<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
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<tbody>
<tr>
<td>2012</td>
<td>03-04</td>
<td>1st data taking (commissioning)</td>
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<tr>
<td>2013</td>
<td>11-</td>
<td>2nd data taking (10 months)</td>
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<tr>
<td>2014</td>
<td>11-</td>
<td>3rd data taking (8 months)</td>
</tr>
<tr>
<td>2015</td>
<td>10-</td>
<td>4th data taking (10 months)</td>
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<tr>
<td>2016</td>
<td>12-</td>
<td>5th data taking (7 months)</td>
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- **Beam protons on targets**
  - $1.4 \times 10^{18}$ recorded
  - $0.6 \times 10^{18}$ analyzed for preliminary $\bar{d}/\bar{u}$

- **Last data taken in FY2017**
  - Wider chamber acceptance at St. 1
    $\implies 40\%$ more events at high $x$ ($\sim 0.4$)
  - Top+Top & Bottom+Bottom events
    (thanks to faster DAQ)
    $\implies 30\%$ more events
SeaQuest Data Analysis

- Dimuon invariant mass

  - Have understood the origins of dimuons
    - Drell-Yan, $J/\psi$ & $\psi'$ ... evaluated with simulation
    - Combinatorial pairs ... evaluated with real-data event mixing
    - Drell-Yan dominates @ $M > 4.2$ GeV
  - Sufficient resolution (~0.18 GeV)

- Dependence of tracking performance on beam intensity
  - Intenser beam → more detector hits → more fake tracks & less true tracks
  - Tighter track selection & inefficiency correction are being studied
Anti-Quark Flavor Asymmetry:

$\frac{\bar{d}(x)}{\bar{u}(x)}$
Past Measurements of Flavor Asymmetry

- Symmetric in gluon splitting \((g \rightarrow u\bar{u} \text{ or } d\bar{d})\)
- CERN NMC ('90): deep inelastic muon scattering
  - Gottfried Sum: \(S_G = 0.2281(65) < 1/3\)
  - \(\int \bar{d}(x)dx > \int \bar{u}(x)dx\) ... discovery of flavor asymmetry of anti-quarks in proton
- Measurement of \(x\) dependence of \(\bar{u}(x) \& \bar{d}(x)\): Drell-Yan process
  - CERN NA51 ('94): \(\bar{d} > \bar{u}\) at \(x \sim 0.18\)
  - FNAL E866/NuSea ('98): \(\bar{d}(x)/\bar{u}(x)\) for \(x \in (0.015, 0.35)\)

![Graph showing 70% asymmetry!](image)
Theories of $\bar{d}/\bar{u}$ Asymmetry (1)

- Mass difference between $u$ & $d$ ($\sim 2$ & $5$ MeV) in $g \rightarrow q\bar{q}$
  - Very small and even results in $\bar{d} < \bar{u}$

- Pauli blocking ... *PRD15*, 2590 (1977)
  - $\text{Prob}(g \rightarrow u\bar{u}) < \text{Prob}(g \rightarrow d\bar{d})$ since $p = uud$
  - Cannot explain the measured size ... *NPB149*, 497 (1979)
  - Even $\bar{d} < \bar{u}$ via connected sea (at high $x$)? ... *PLB736*, 411 (2014)

- Lattice-QCD calculation with LaMET ... *PRD91*, 054510 (2015)
  - As large as the measured size
  - Room to improve pion mass & lattice size
Theories of $\bar{d}/\bar{u}$ Asymmetry (2)

- **Statistical model ... NPA941, 307 (2015)**
  - Based on the Fermi & Bose statistics
  - Predicts $\bar{d}(x) - \bar{u}(x) = \Delta\bar{u}(x) - \Delta\bar{d}(x)$

- **Meson cloud model ... PRD58, 092004 (1998)**
  - $|p\rangle = (1 - a - b)|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$
  - **More** $\bar{d}$ in $\pi^+$ as $|n\pi^+\rangle$ etc.
  - **Less** $\bar{u}$ in $\pi^-$ as $|\Delta^{++}\pi^-\rangle$ etc.
  - Predict non-zero $L_{q\bar{q}}$ like “meson tornado”
    (need $L = 1$ of $\pi$ to make $J^P = 1/2^+$ of proton, as parity of $\pi$ is $J^P = 0^-$)
Comparison of Theories to Measurements

The $x$ dependence of $d(x) = u(x)$ is the key to develop/examine models:
- Drop sharply at $x \sim 0.3$? Go down to $d < u$?
SeaQuest Result of $\bar{d}/\bar{u}$

- Preliminary result with $6 \times 10^{17}$ PoTs, $M > 4.2$ GeV

\[
\frac{\sigma_{pd}(x_{ta})}{2\sigma_{pp}(x_{ta})} \approx \frac{1}{2} \left(1 + \frac{\bar{d}(x_{ta})}{\bar{u}(x_{ta})}\right)
\]

- $\bar{d}/\bar{u} > 1$ at high $x$ also
SeaQuest Result of $\bar{d}/\bar{u}$

- Comparison with other measurements

- All agree at small $x$
- $\bar{d}/\bar{u}$ at $x \sim 0.3$ seems higher by SeaQuest
  ... Physical reasons for this difference are being investigated

- Systematic errors are being examined & reduced for final result
Boer-Mulders Function of Anti-Quark

(Parton Spin $\leftrightarrow$ Parton $k_T$)
Angular Distribution of Drell-Yan Process

- Drell-Yan angles in Collins-Soper frame

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

- Lam-Tung relation:

\[1 - \lambda = 2\nu\]

- Spin-1/2 nature of quarks ... analogous to Callen-Gross relation in DIS
- No NLO corrections \((\mathcal{O}(\alpha_s))\)
- Small NNLO corrections \((\mathcal{O}(\alpha_s^2))\) ... sometimes sizable [PRD 93, 114013 (2016)]
Measurements @ Fixed-Target Experiments

- $2 \nu - (1 - \lambda)$

- $\nu \ldots \cos 2\phi$ dependence

- With $\pi$ beam
  - Lam-Tung relation violated!
  - Large $\nu$

- Boer-Mulder function ($h_1^\perp$) can be extracted from $\nu$
  - Large for $q$ & small for $\bar{q}$??

- With $p$ beam
  - Lam-Tung relation violated weakly?
  - Small $\nu$
Anticipated Result by SeaQuest

- **SeaQuest** measures the Drell-Yan angular distribution in $p+p \& p+d$
  - $\nu = \text{size of } \cos(2\phi) \text{ modulation}$

- Probably small as past measurements indicate small $h_1^\perp$ of $q$
- Better accuracy is anticipated

- Convolution of two Boer-Mulders functions:
  $$\nu \propto \left[ h_1^\perp \text{ of } \bar{q} \right] \times \left[ h_1^\perp \text{ of } q \right]$$
  - Extraction of $h_1^\perp$ from $p+p \& p+d$ Drell-Yan (E866)
    - ... PRD 81, 034023 (2010), PRD 82, 114025 (2010)
Nuclear Effects
Nuclear Effects in $p + A$ Drell-Yan

- **Observable:** $\hat{\sigma}^{p+A}(x)/\hat{\sigma}^{p+p}(x) \equiv$ Ratio of per-nucleon D-Y cross sections

- **Modification mechanisms**
  - Modification of PDF inside nucleus
    - “Nuclear effects” as observed in DIS:
      $R_i^A(x) \equiv f_i^A(x)/f_i^p(x)$
    - Shadowing & anti-shadowing
    - EMC effect … PLB 123, 275 (1983)
    - Fermi motion
  - “Parton energy loss in cold nuclear matter”
    - Soft interaction of parton in beam proton with nuclear matter
    - Collisional or radiative

- **Various conditions of measurements are needed to disentangle the modification mechanisms**
  - Quark-Gluon Plasma at RHIC/LHC
  - Nuclear effects on $\bar{q}$

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Measurement by SeaQuest

- Direct extraction of parton energy loss in cold nuclear matter
  - Choice of proper $\sqrt{s} (= 15 \text{ GeV}) \& x (\gtrsim 0.3)$
  - Parton energy loss $\gg$ shadowing (unlike past experiments like E866)

- Theory prediction: Change of $x$ by parton energy loss
  - $\Delta x = -\kappa_1 x A^{1/3}$ ... Gavin & Milana (PRL68, 1834)
  - $\Delta x = -\frac{\kappa_2}{s} A^{1/3}$ ... Brodsky & Hoyer (PLB298, 165)
  - $\Delta x = -\frac{\kappa_2}{s} A^{2/3}$ ... Baier et al. (NPB531, 403)
  - Measure with several targets ($A$) to select the right model
Present SeaQuest Result

- Select where parton energy loss dominates ... \( x_{\text{Target}} > 0.15, x_{\text{Beam}} > 0.6 \)
- With \( 5 \times 10^{17} \) PoTs

- Systematic error \( \approx \) uncertainty of tracking efficiency
Other Quantities from $p + A$ Drell-Yan

- Transverse-Momentum (pT) Broadening
  - D-Y : SeaQuest (■) $\sim$ E772 (○) $\sim$ 1
  - $J/\psi$ & $\psi'$ : SeaQuest (■) $\sim$ E866 (□) $\ll$ 1

- Nuclear effects to anti-quarks
  - No sizable effect at $x \gtrsim 0.1$ by E772
  - Will measure “anti-quark $\neq$ quark” (or not) precisely

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**Fe / C**

- DY, Fe
- J/$\psi$, Fe
- $\Psi'$, Fe

**W / C**

- DY, W
- J/$\psi$, W
- $\Psi'$, W

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Sivers Function of Anti-Quark
by E1039
(Proton Spin $\leftrightarrow$ Parton $k_T$)
E1039 ≈ SeaQuest + Polarized Target

- Experimental design
  - SeaQuest spectrometer (almost as it is)
  - Polarized target
    - NH₃ & ND₃ with $L = 8$ cm, $B = 5$ T
    - Called “Hall-C” target in past
    - Refurbished for transverse polarization
    - $dB/B < 10^{-4}$ & $P \geq 90\%$ achieved!!

- Status
  - Stage-2 approval was granted from Fermilab in May 2018
  - SeaQuest decommissioning is ongoing, particularly a reconfiguration of the radiation shielding
  - Data taking will start likely in 2019 for two years

During cool-down test in 2018
Prospect of E1039 Measurement

- **Sivers** TMD PDF of anti-quark
  - $\bar{u} & \bar{d}$ separately from $p + \bar{p} & p + \bar{d}$

- Observable: single-spin asymmetry $A_N$

$$A_N(\phi_S) \equiv \frac{\sigma^{\uparrow}(\phi_S) - \sigma^{\downarrow}(\phi_S)}{\sigma^{\uparrow}(\phi_S) + \sigma^{\downarrow}(\phi_S)} \approx \frac{f(x_B) \cdot f_{1T}^{-}(x_T)}{f(x_B) \cdot f(x_T)}$$

- Measurement accuracy $\delta_{A_N} \approx 0.04$
- Compare with two calculations based on SIDIS data
  - Blue line takes into account the Collins-Soper-Sterman scale evolution

![Drell-Yan Target Single-Spin Asymmetry](image)

- $pp^{\uparrow}(d^{\uparrow}) \rightarrow \mu^+\mu X, 4 < M_{\mu\mu} < 9 \text{ GeV}$


Measurements of Parton Structure of Nucleons and Nuclei via Drell-Yan Process at Fermilab
Summary

- The Drell-Yan process is a sharp tool to explore the parton structure
- SeaQuest & E1039 are running at Fermilab

\[ d(x)/u(x) \]
  - SeaQuest found \( d(x)/u(x) > 1 \) possibly at high \( x \) as well

- Boer-Mulders function of anti-quark
  - SeaQuest will extract \( h_1^+ \) of \( \bar{q} \) from angular distribution

- Parton-energy loss in cold nuclear matter
  - SeaQuest found \( \sigma_{p+A}/\sigma_{p+p} < 1 \) at high \( x \)
  - The \( A \) dependence will distinguish the energy-loss mechanism

- Sivers function of anti-quark (via SSA)
  - E1039 will start the 1st data taking in 2019

### SeaQuest/E1039 Presentations @ HAWAII 2018

**25 (Th) 7 PM**
- A. Wickes
  - Unambiguous Observation of Initial-State Energy Loss in Cold Nuclear Matter at E906 SeaQuest

**26 (Fr) 2 PM**
- J. Marsden
  - Using Machine Learning to Differentiate Signals from Background Events for SeaQuest
- R. Salinas
  - Experiment 1039 at Fermi National Accelerator Laboratory

**27 (Sa) 9 AM**
- A. Tadepalli
  - Studies on Light Quark Flavor Asymmetry in the Nucleon Sea at SeaQuest Experiment
- D. Morton
  - Machine Learning and the Drell-Yan Cross-Section Ratios at E906 SeaQuest
- D. Isenhower
  - Fermilab E1039 polarized target experimental apparatus and changes from SeaQuest/E906
- H. Yu
  - Simulation and Reconstruction Effort for the E1039 Polarized Drell-Yan Experiment
- M. Yurov
  - The Measurement of the Seaquark Sivers Asymmetry in Fermilab E1039 Polarized Drell-Yan Experiment
- M. Daugherity
  - Fermilab E1039 Beyond Sea Quark Sivers

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