Probing the antiquark distributions in the proton via unpolarized and polarized Drell-Yan experiments at Fermilab

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Outline

1. Two Drell-Yan experiments @ Fermilab
   - “SeaQuest” with unpolarized targets
   - “SpinQuest” with polarized targets

2. Spectrometer

3. Selected results of SeaQuest
   - Flavor asymmetry $\bar{d}(x)/\bar{u}(x)$ ... published on Nature 590, 561 in Feb. 2021
   - Nuclear effect on antiquarks ($R_A$ vs $x_{target}$)

4. Aim & status of SpinQuest

5. Conclusions
Access to Antiquarks via Drell-Yan Process

- **Drell-Yan process:** \( p + p \rightarrow \gamma^* \rightarrow \mu^+ + \mu^- \)
  - Invariant mass: \( M^2 = x_{\text{beam}} x_{\text{target}} s \)
  - Rapidity: \( \exp Y = \sqrt{x_{\text{beam}}/x_{\text{target}}} \)
  - Bjorken \( x_{\text{beam}} = \frac{M}{\sqrt{s}} e^Y \), \( x_{\text{target}} = \frac{M}{\sqrt{s}} e^{-Y} \)

- **Cross section at LO:**
  \[
  \frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t s} \frac{1}{s} \sum_{q=u,d} e_q^2 \left\{ q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q_t(x_t) \right\}
  \]

  - Only "\( q_b(x_b)\bar{q}_t(x_t) \)" survives @ forward rapidity
    \( \implies q \) having \( x_b \) & \( \bar{q} \) having \( x_t \) are distinguishable event-by-event
  - Lower rate because of EM interaction
    \( \implies \) Need larger luminosity & compete with more BGs

Probing the \( \bar{q} \) distributions in the proton via (un)polarized Drell-Yan experiments at Fermilab
Drell-Yan Experiments @ Fermilab

- **Beam**: Proton at 120 GeV ($\sqrt{s} = 15$ GeV) from Main Injector
  - Intensity $\sim 10^{12}$ protons/sec

- **SeaQuest/E906**
  - Target: (Unpolarized) LH2, LD2, C, Fe, W
  - Data taking: 2013-2017 (completed)
  - Physics
    - Flavor asymmetry $\bar{d}(x)/\bar{u}(x)$
    - Nuclear effects
    - Via $J/\psi$ production
    - and more

- **SpinQuest/E1039**
  - Spectrometer: Inherited from SeaQuest
  - Target: Transversely-polarized NH3, ND3
  - Data taking: 2021-2023 (planned)
  - Physics
    - Sivers asymmetry of $\bar{d}$ & $\bar{u}$
    - and more

$P > 90\%$ for NH3
SeaQuest Spectrometer

- Targets: LH$_2$, LD$_2$, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump
SeaQuest Topic #1: Flavor Asymmetry $\bar{d}(x)/\bar{u}(x)$

- Symmetric in gluon splitting ($g \to u\bar{u}$ or $d\bar{d}$)
- CERN NMC ('90): deep inelastic muon scattering
  - Gottfried Sum: $S_G = 0.235 \pm 0.026 < 1/3$
  - $\int_0^1 \bar{d}(x)dx - \int_0^1 \bar{u}(x)dx = 0.147 \pm 0.039$ ... Discovery of flavor asymmetry!
- Measurement of $x$ dependence of $\bar{d}(x)/\bar{u}(x)$: 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 $x \in (0.015, 0.35)$

- Studied actively by effective QCD models & lattice QCD
  - Precise measurement at larger $x$ was wanted

70% asymmetry!
A few % expected
• SeaQuest result (published in February 2021)

![Graph showing SeaQuest result]

Nature 590, 561 (2021)

• Systematic errors
  ○ Correction for random BG & measurement efficiency
    (via “beam-intensity extrapolation”)
  ○ Relative luminosity

• Large asymmetry at high $x$ ($\leq 0.45$) as well as low $x$
• Comparison to existing PDFs

○ Unique data to constrain anti-quark PDFs at high $x$ in global analyses (e.g. CJ15-a')
• Comparison to model calculations

○ Reasonably described by the predictions of
  ○ “Pion cloud model” (Alberg & Miller) and
  ○ “Statistical model” (Basso et al.)

○ Further studies are anticipated to understand the true mechanism
  ○ $\bar{d}(x)/\bar{u}(x)$ at higher $x$ ($\gtrsim 0.6$)
  ○ Relation to polarized distributions ($\Delta\bar{d}(x)$ & $\Delta\bar{u}(x)$)
  ○ Relation to orbital angular momenta
SeaQuest Topic #2: Nuclear Effects

- $R_A \equiv \hat{\sigma}^{p+A}/\hat{\sigma}^{p+p}$
  - Ratio of per-nucleon cross sections

1. $R_A$ vs $x_{\text{target}}$: Effect on antiquarks
   - Smaller than that on quarks? (PRL64, 2479)
   - $0.1 < x_{\text{target}} < 0.45$
   - Preliminary result in October 2019

2. Effect on quarks in beam proton
   - Parton energy loss in cold-nuclear matter
   2.1 $R_A$ vs $x_{\text{beam}}$: Energy loss
      - $x_{\text{beam}} > 0.6, x_{\text{target}} > 0.15$
      - “Preview” result at HAWAII 2018 etc.
   2.2 $R_A$ vs $p_T$: $p_T$ broadening
      - $0.1 < x_{\text{target}} < 0.45$
      - Preliminary result in April 2020

- $R_A$ should be comprehensively examined to untangle the effects of nuclear PDFs and partonic energy loss

Probing the $\bar{q}$ distributions in the proton via (un)polarized Drell-Yan experiments at Fermilab
• Result of “$R_A$ vs $x_{\text{target}}$”

○ $R_A$ deviates from 1 by 10% at max
  ○ Different from quarks ($R_A \gtrsim 1.1$)!
  ○ Close to the calculation of pion excess model by Miller (PRC 64, 022201)

○ Same trend as the EMC effect (i.e. $R_A$ decreases at middle $x$)
• Comparison with E772 result

- Agreement within measurement accuracy
- Better precision at $x_{\text{target}} \gtrsim 0.2$ by SeaQuest
Sivers distribution: $f^{\perp}_{1T}(x)$

- Correlation of parton $k_T$ with proton spin

Extraction by global analyses

- PRD 88 (2013) 114012, P. Sun & F. Yuan
- PRD 89 (2014) 074013, M. G. Echevarria et al.
- JHEP 04 (2017) 046, M. Anselmino et al.
  - Use of HERMES, COMPASS & JLab data
  - First moment of Sivers function:
    $$x\Delta^N f^{(1)}(x) \equiv -xf^{(1)}_{1T}(x)$$

$f^{\perp}_{1T}(x)$ of anti-quarks is not well known

- Since $\bar{q}$ & $q$ are mixed up in SIDIS

SpinQuest will

- Measure Sivers asymmetry of $\bar{u}$ & $\bar{d}$
- Via proton-induced Drell-Yan process
- Using new polarized targets of NH3 & ND3

Probing the $\bar{q}$ distributions in the proton via (un)polarized Drell-Yan experiments at Fermilab
Anticipated Sensitivity

- Conditions
  - Two years of data taking
  - $\text{NH}_3:\text{ND}_3 = 50\%:50\%$ in time
  - Details in the E1039 proposal

- TSSA: $A_{UT}^{\sin \phi_S} = A_N$
  - Measurement precision $\delta_{A_N} \sim 0.04$
  - Two predictions of $A_N$ of $\text{NH}_3$
    - Calculations based on SIDIS data
    - Blue line takes into account the Collins-Soper-Sterman scale evolution

- Aim to observe non-zero anti-quark Sivers asymmetry!!

**Drell-Yan Target Single-Spin Asymmetry**

$pp^{+}(d^{1}) \rightarrow \mu^{+}\mu X, 4 < M_{\mu\mu} < 9 \text{ GeV}$

$A_N$

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


## Timeline of SpinQuest

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
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| 2018 | May   | Granted Stage-2 approval from Fermilab  
Decommissioned SeaQuest components |
| 2019 | June  | Transfered the pol. target from UVA to Fermilab  
Commissioned detector components using cosmic rays |
| 2020 |       | Commissioned with limited access due to COVID-19 |
| 2021 | Spring | Commission target+detector components using beam  
Fall | Start the data taking  
↓ Run for two years |

### Other physics topics

- TSSA of $J/\psi$ production ... Later talk by C. Ayuso
- Tensor polarization of antiquarks in deuteron ... PRD 94, 054022 (2016)
Conclusions

- **Drell-Yan experiments at Fermilab**
  - Probe the antiquarks in the proton
  - Utilize the high-intensity proton beam from Main Injector

- **SeaQuest/E906 with unpolarized targets**
  - Drell-Yan events were detected successfully
  - Large $\bar{d}(x)/\bar{u}(x)$ asymmetry at large $x$ was observed firstly
    - ... Nature 590, 561 (2021)
  - Nuclear effect on antiquarks was observed smaller than quarks

- **SpinQuest/E1039 with polarized targets**
  - Data taking in 2021-2023 (planned)
  - Will measure Sivers asymmetry of $\bar{u}$ & $\bar{d}$ firstly

- **Data analyses of SeaQuest & target+detector commissioning of SpinQuest are ongoing for more physics outcomes!**