Future Drell-Yan fixed target experiments at Fermilab

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on behalf of the SeaQuest Collaboration

• Introduction
• SeaQuest: Fermilab Experiment E906
  ➡ What will we learn?
  ➡ What will we measure?
  ➡ How will we measure it?
  ➡ When we will do it?
• Beyond SeaQuest

This work is supported by

• QCD
  ➡ What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
  ➡ What is the internal landscape of the proton?
  ➡ What does QCD predict for the properties of strongly interacting matter?
  ➡ What governs the transition of quarks and gluons into pions and nucleons?
  ➡ What is the role of gluons and gluon self-interactions in nucleons and nuclei?
  ➡ What determines the key features of QCD, and what is their relation to the nature of gravity and spacetime?

• Nuclei and Nuclear Astrophysics

• Fundamental Symmetries and Neutrinos
Internal Landscape of the Proton

- Just three valence quarks?

http://www.sciencecartoonsplus.com/index.htm
Internal Landscape of the Proton

• Just three valence quarks?
• No!!
• And, quark distributions change in the nucleus

http://www.sciencecartoonsplus.com/index.htm
Constituent Quark Model
Pure valence description: proton = 2u + d

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

What is the origin of the sea?

Significant part of the LHC beam

\[ d \rightarrow W' \rightarrow u \]
Flavor Structure of the Proton - II

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

- \[\bar{d} - \bar{u}\]
  - Symmetric sea via pair production from gluons subtracts off
  - No gluon contribution at 1st 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 - III

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

Meson Cloud Models

- Quark sea from cloud of $0^-$ mesons:
  - $\pi^+$ meson
  - 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

- Quark d.o.f. in a pion
  - Mean-field: $u \rightarrow d + \pi^+$
  - Nucleon = chiral soliton
  - One parameter: dynamically generated quark mass
  - Expand in $1/N_c$:

  $\rightarrow \bar{d} > \bar{u}$

Statistical Model

- Nucleon = gas of massless partons
  - Few parameters: generate parton distribution functions
  - Input:
    - QCD: chiral structure
    - DIS: $u(x)$ and $d(x)$

$\rightarrow \bar{d} > \bar{u}$

$\Rightarrow$ Important constraints on flavor asymmetry for polarization of light sea

- $\Delta \bar{q} = 0$
- $\Delta \bar{u} \approx -\Delta \bar{d} > 0$
- $\Delta \bar{d} < 0$, $\Delta \bar{u} < 0$
Flavor Structure of the Proton - IV

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?
Fermilab Experiment E906

• E906 will extend Drell-Yan measurements of E866 (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 $J/\Psi$ and similar resonances decreases as $s$

• Use many components from E866 to save money/time, in NM4 Hall

• Hydrogen, Deuterium and Nuclear Targets
Fermilab E906/Drell-Yan Collaboration

Collaboration contains many of the E-866/NuSea groups and several new groups (total 17 groups)
Drell-Yan Spectrometer for E-906
(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.)

Mom. Meas.

KMag

Borated Neutron Absorber

Muon ID Absorber

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

Targets
(liquid H₂, D₂, and solid targets)

4.9m
Fixed Target Drell-Yan: What we really measure

- Measure yields of $\mu^+\mu^-$ pairs from different targets
- Reconstruct $p_\gamma$, $M_\gamma^2 = x_b x_t s$
- Determine $x_b, x_t$
- Measure differential cross section

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 [\bar{q}_t(x_t) q_b(x_b) + q_t(x_t) \bar{q}_b(x_b)]$$

- Fixed target kinematics and detector acceptance give $x_b > x_t$
  - $x_F = 2p_{||}/s^{1/2} \approx x_b - x_t$
  - 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
  - $1 \times 10^{13}$ protons/spill
SeaQuest Projections for absolute cross sections

- Reach high $x$ through beam proton
  - large $x_F$ gives large $x_{\text{beam}}$
- High $x$ distributions poorly understood
  - nuclear corrections are large, even for deuterium
  - lack of proton data
- In $pp$ cross section, no nuclear corrections
  - direct measure of $4u+d$
- Measure convolution of beam and target PDF
  - absolute magnitude of high $x$ valence distributions
  - absolute magnitude of the sea in target $(\bar{d} + \bar{u})$
  (currently determined by $\nu$-Fe DIS)
Sea quark distributions in Nuclei

- EMC effect from DIS is well established
- But 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
Partonic Energy Loss in Cold Nuclear Matter

- An understanding of partonic energy loss in both cold and hot nuclear matter is paramount to elucidating RHIC data.
- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic value ($x_1$ or $x_F$) is shifted.
- Fit shift in $x_1$ relative to deuterium

\[ \text{shift in } \Delta x_1 \propto 1/s \text{ (larger at 120 GeV)} \]

- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample.
Fermilab Seaquest Timelines

- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about “proton economics”
- Stage II approval in December 2008
- Scheduled to run in 2010 for 2 years of data collection

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Apparatus available for future programs at, e.g. Fermilab, J-PARC or RHIC

→ significant interest from collaboration for continued program
Future Possibilities

- **Transversely Polarized Target**
  - Single spin asymmetries → Sivers distribution
  - Check: \[ f_{1T}^{\perp q}(x, k_T)_{\text{DIS}} = - f_{1T}^{\perp q}(x, k_T)_{\text{D-Y}} \]
  - Transversely polarized beam at JPARC???

- **Pionic Drell-Yan**
  - Measure high-x pionic parton distributions
  - Test charge symmetry violation
    - \( \pi^+\pi^- \) comparison on deuterium target
    - Difficulty producing pure \( \pi^+ \) beam
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 high $x$ structure of the proton?

- What is the structure of nucleonic matter?
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?

- Do colored partons lose energy in cold nuclear matter?

- SeaQuest: 2010 - 2012
  - significant increase in physics reach

- Beyond SeaQuest
  - Polarized Drell-Yan
  - Pionic Drell-Yan