E906 Update: Drell-Yan Measurements of Nucleon and Nuclear Structure with the Fermilab Main Injector

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What will we learn?
- d-bar/u-bar in the proton
- Nuclear effects in the sea quark distributions
- High-x valence distributions
- Partonic energy loss in cold nuclear matter

What will we measure?

How will we measure it?
- Spectrometer upgrade
What is the distribution of sea quarks?

In the nucleon:

- Sea and gluons are important:
  - 98% of mass; 60% of momentum at $Q^2 = 2 \text{ GeV}^2$
- Not just three valence quarks and QCD. Shown by E866/NuSea d-bar/u-bar data
- Significant part of LHC beam.
- What are the origins of the sea?

In nuclei:

- The nucleus is not just a sum of protons and neutrons
- What distinguishes this?
  - Bound system
  - Binding via virtual mesons affects antiquarks distributions
Light Antiquark Flavor Asymmetry: Brief History

Naïve Assumption:
\[ \bar{d}(x) = \bar{u}(x) \]

NMC (Gottfried Sum Rule)
\[ \int_0^1 \left[ \bar{d}(x) - \bar{u}(x) \right] dx \neq 0 \]

GSR, NMC
\[ Q^2 = 4 \text{ GeV}^2 \]
**Light Antiquark Flavor Asymmetry: Brief History**

- **Naïve Assumption:**
  \[ \bar{d}(x) = \bar{u}(x) \]

- **NMC (Gottfried Sum Rule)**
  \[ \int_0^1 \left[ \bar{d}(x) - \bar{u}(x) \right] dx \neq 0 \]

**Graph:**

- **NA51 Drell-Yan** confirms \( \bar{d}(x) > \bar{u}(x) \)
**Light Antiquark Flavor Asymmetry: Brief History**

- **Naïve Assumption:**
  \[ \bar{d}(x) = \bar{u}(x) \]

- **NMC (Gottfried Sum Rule)**
  \[ \int_0^1 \left[ \bar{d}(x) - \bar{u}(x) \right] dx \neq 0 \]

- **NA51 (Drell-Yan)**
  \[ \bar{d} > \bar{u} \text{ at } x = 0.18 \]

- **E866/NuSea (Drell-Yan)**
  \[ \frac{\bar{d}(x)}{\bar{u}(x)} \text{ for } 0.015 \leq x \leq 0.35 \]

- **Knowledge of distributions is data driven**
  - Sea quark distributions are difficult for Lattice QCD

- **E906 extends this knowledge**
Drell-Yan scattering: A laboratory for sea quarks

\[ \frac{d^2 \sigma}{dx_1 dx_2} = \frac{4\pi \alpha^2}{9x_1 x_2} \frac{1}{s} \sum e^2 [\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)] \]

Detector acceptance chooses \( x_{\text{target}} \) and \( x_{\text{beam}} \):
- Fixed target \( \Rightarrow \) high \( x_F = x_{\text{beam}} - x_{\text{target}} \)
- Valence Beam quarks at high-\( x \).
- Sea Target quarks at low/intermediate-\( x \).
Extracting $d$-bar/-$ubar$ From Drell-Yan Scattering

Ratio of Drell-Yan cross sections

\[
\left. \frac{\sigma^{pd}}{2\sigma^{pp}} \right|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]
\]

(in leading order—E866 data analysis confirmed in NLO)

- Global NLO PDF fits which include E866 cross section ratios agree with E866 results
- Fermilab E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.
Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- \(^1\)H, \(^2\)H, and nuclear targets
- 800 GeV proton beam

The future:

Fermilab E906

- Data in 2009
- \(^1\)H, \(^2\)H, and nuclear targets
- 120 GeV proton beam

Cross section scales as \(1/s\)
- \(7 \times\) that of 800 GeV beam

Backgrounds, primarily from J/\(\psi\)
decays scale as \(s\)
- \(7 \times\) Luminosity for same

\[\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2} \frac{1}{s} \times \sum_i e_i^2 [q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)]\]

detector rate as 800 GeV beam

\(50 \times\) statistics!!
Proton Structure: By What Process Is the Sea Created?

- A proton with 3 valence quarks plus glue cannot be right at any scale!!

\[ \bar{d}(x) = \bar{u}(x) = \bar{q}(x) \]

- \( \bar{d} - \bar{u} \)
  - Symmetric sea via pair production from gluons subtracts off
  - No Gluon contribution at 1st order in \( \alpha_s \)
  - Nonperturbative models are motivated by the observed difference

![Graph showing the difference between \( \bar{d} \) and \( \bar{u} \) over a range of \( x \) values]
**Proton Structure: By What Process Is the Sea Created?**

- **Meson Cloud in the nucleon**
  - Sullivan process in DIS
  - \(|p⟩ = |p₀⟩ + \alpha |Nπ⟩ + \beta |\Delta π⟩ + \ldots\)

- **Chiral Models**
  - Interaction between Goldstone Bosons and valence quarks
  - \(|u⟩ \rightarrow |dπ⁺⟩ \) and \(|d⟩ \rightarrow |uπ⁻⟩\)

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**Perturbative sea apparently dilutes meson cloud effects at large-\(x\)**
Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell-Yan—Valence only effect

- Intermediate-x sea PDF’s absolute magnitude set by $\nu$-DIS on iron.
  - Are nuclear effects the same for the sea as for valence?
  - Are nuclear effects with the weak interaction the same as electromagnetic?

- What can the sea parton distributions tell us about the effects of nuclear binding?
Structure of nucleonic matter: Where are the nuclear pions?

- 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
**Drell-Yan Absolute Cross Sections: \( x_{\text{target}} \)**

Measures a convolution of beam and target PDF

- absolute magnitude of high-x valence beam distributions
- absolute magnitude of the sea in the target
  - *Currently determined by \( \nu-\text{Fe DIS} \)

![Graph showing Drell-Yan cross sections](image)
**Drell-Yan Absolute Cross Sections:** $x_{\text{target}}$

- Reach high-$x$ through *beam proton*—Large $x_F \Rightarrow$ large $x_{\text{beam}}$.

- High-$x$ distributions poorly understood
  - Nuclear corrections are large, even for deuterium
  - Lack of proton data

- Proton-Proton—no nuclear corrections—$4u(x) + d(x)$
What will these measurement tell us?

- Better knowledge of parton distributions
  - Input to LHC: Consider 5 TeV Vector Boson
    \[ \bar{u}(x)d(x) \rightarrow W' \text{ with } M_{W'}^2 = x_1 x_2 s \]
    \[ x_1 \approx x_2 \approx 0.35 \Rightarrow \text{d-bar/u-bar} = 1 \text{ or } 0? \]

- Gluon distributions form symmetric sea

- Absolute magnitude of sea quark distributions
  - Absolute cross sections
  - Nuclear effects in sea quarks relevant interpretation of νDIS data

- Absolute magnitude of high-x distributions
**Partonic Energy Loss**

- 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 loses energy.
- Apparent (reconstructed) kinematic values ($x_1$ or $x_F$) is shifted.
- Fit shift in $x_1$ relative to deuterium.

Models:
- Galvin and Milana: $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
- Brodsky and Hoyer: $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
- Baier et al.: $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$
Partonic Energy Loss

- E866 data are consistent with NO partonic energy loss for all three models.
- Caveat: A correction must be made for shadowing because of $x_1 - x_2$ correlations.
  - E866 used an empirical correction based on EKS fit do DIS and Drell-Yan.

- Treatment of parton propagation length and shadowing are critical.
  - Johnson et al. find 2.2 GeV/fm from the same data with different shadowing correction.
- Better data outside of shadowing region are necessary.
**Parton Energy Loss**

- Energy loss $\propto 1/s$
  - larger at 120 GeV
- Ability to distinguish between models
- Measurements rather than upper limits

- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample.
Other Possible Measurements of $d$-bar—$u$-bar asymmetry

- Semi-Inclusive DIS—HERMES, JLab, JLab 12 GeV
  - Tag struck quark through leading hadron
  - Must understand fragmentation
  - HERMES will reduce statistical uncertainty but will still have significant systematic uncertainty
  - Dominated by systematic uncertainties

- Drell-Yan—JPARC
  - Initial phase of JPARC is 30 GeV—sufficient only for $J/\psi$ studies, no Drell-Yan (no phase space for events above $J/\psi$)
  - JPARC Phase II—50 GeV
    - great possibilities for polarized Drell-Yan
    - Berger criteria for nuclear targets—insufficient energy for heavy A
    - No partonic energy loss studies—$x_{beam}$-$x_{target}$ correlations
    - Experimental issues: $p_T$ acceptance, $\pi^\pm$ decay in flight background
  - **Physics Program cannot be reached by 30 GeV machine (physics program strongly endorsed)**
Fermilab E906/Drell-Yan Collaboration

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**Drell-Yan Spectrometer Guiding Principles**

- Follow basic design of MEast spectrometer (don’t reinvent the wheel):
  - Two magnet spectrometer
  - Hadron absorber within first magnet
  - Beam dump within first Magnet
  - Muon-ID wall before final elements

- Where possible and practical, reuse elements of the E866 spectrometer.
  - Tracking chamber electronics (and electronics from E871)
  - Hadron absorber, beam dump, muon ID walls
  - Station 2 and 3 tracking chambers
  - Hodoscope array PMT’s
  - SM3 Magnet

- New Elements
  - 1st magnet (different boost)
    Experiment shrinks from 60m to 26m
  - Sta. 1 tracking (rates)
  - Scintillator (age)
  - Trigger (flexibility)
E906 Spectrometer: Bend Plane View

Bend plane view
Mass = 7.0 GeV  \( X_f = 0.0, 0.2, 0.4 \)

SM3

station 1

Target

Absorber

DUMP

\( X_f = 0.0 \)

\( X_f = 0.4 \)

Station 2

Station 3

Station 4 and Micron TD wall

100 inches

10 inches
E906 Spectrometer: Non-bend plane view
Spectrometer Upgrade Budget and Schedule

- **Approximate Cost:**
  - Magnet coil fabrication: US$1.4M
  - US$0.8M for Spectrometer upgrades

- **Funding sources**
  - US DOE-Office of Nuclear Physics US$2.0M
  - US NSF US$0.3M

- Two timelines have been proposed to DOE/ONP, both starting FY07—**schedule is funding driven**
  - Realistic: Funds over three years, coil purchase in FY08, spectrometer completion in early FY09
  - Optimistic: Funds over two years, coil purchase in FY07

- DOE/ONP has asked Argonne to hold a cost/schedule review before receiving any funds
  - Tentatively scheduled for December
  - **Need Phase II approval and draft MOU with Fermilab**
Proton Economics

- Total of $5.2 \times 10^{18}$ protons (over 2 years)

- Maximum instantaneous rate of $2 \times 10^{12}$ proton/sec
  - Based on E866 experience with target related rate dependence—balance systematic and statistical uncertainties
  - Station 1 chamber rates.

- Possible delivery scenario:
  - 5 sec spill of $1 \times 10^{13}$ protons each minute
  - Longer spill (5 sec) desirable over 5-1 sec spills
Experimental Location

- Originally proposed MEast was ideal
  - Superconducting Cryo-Module Test Facility (SMTF) now in MEast
- MWest provides a suitable location (adds additional burden to Fermilab)
  - Complete Switchyard
  - 120 Upgrade
  - MWest beam line must be rebuilt
  - Magnet assembly difficult—need 30 t crane
- KTeV’s Hall—New possibility being studied

Bottom line:

Experiment has will moved to accommodate Fermilab’s space needs, but the move from Meson East increased the impact on Fermilab resources
**Request of Fermilab and Impact**

**Accelerator Division**

Provide a slow extracted beam of 120 GeV protons at a rate of no more than $2 \times 10^{12}$/s for a total of $5.2 \times 10^{18}$ protons on target in two years

- Assuming MWest location, the Switchyard 120 upgrade (or another solution to reduce beam losses) must be implemented.
- Spill cycle with 5 sec $1 \times 10^{13}$ protons each minute will provide desired instantaneous and total luminosity

**Provide beam line and instrumentation**

- Beam line must be rebuilt

**Provide utilities (power and cooling water) for magnets and power supplies**

- Minor impact on other operations

**Computing Division**

Provide PREP electronics, including 1700 channels of multi-hit TDC’s

- Collaboration could take on testing of modules as requested by PREP
- Additional solutions (other sources) are being investigated

**DAQ and data logging suggestions are reasonable**
Request of Fermilab and Impact
Research Division

Assembly of new M1 magnet
- Requires 30-ton crane to for yoke pieces. This was available in MEast, but not in MWest. A crane would need to be rented for assembly.
- Modification of existing yoke on top and bottom, modification of existing copper beam dump
- Additional foundation pits must be excavated for magnets (again these were available in MEast location).

Installation of SM3 in spectrometer location
- Again requires use of 30-ton crane

Provide liquid hydrogen and deuterium targets and drive mechanism
- If still available, reuse e866 target system

Additional “minor” requests—see appendix of proposal for complete list
**Drell-Yan at Fermilab**

- **What is the structure of the nucleon?**
  - What is $d$-bar/$u$-bar?
  - What are the origins 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?**

- **Answers from Fermilab E906/Drell-Yan**
  - Significant increase in physics reach over previous Drell-Yan experiments
  - DOE/ONP funding of spectrometer likely this year
    
    **E906 needs Phase II approval for this to happen**
Additional Material
Drell-Yan Cross Section Ratio and d-bar/u-bar

\[ \frac{\sigma^{pd}}{2\sigma^{pp}} \bigg|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{d(x_t)}{\bar{u}(x_t)} \right] \]
Drell-Yan Acceptance

- Programmable trigger removes likely J/ψ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for J/ψ, ψ′ studies
Kulagin and Petti sea vs. valence nuclear effects

Proton Valence Structure: Unknown as $x \to 1$

**Theory**
- Exact SU(6): $d/u \to 1/2$
- Diquark $S=0$ dom.: $d/u \to 0$
- pQCD: $d/u \to 3/7$

**Data**
- Binding/Fermi Motion effects in deuterium—choice of treatments.
- **Proton data is needed.**

**Reality:**
We don’t even know the $u$ or $d$ quark distributions—there really is very little high-$x$ proton data.
Detector Resolution

- Triggered Drell-Yan events

\[
\begin{align*}
\chi^2/\text{ndf} & \quad 51.65 / 196 \\
\text{Constant} & \quad 83.33 \\
\text{Mean} & \quad -0.6719\times10^{-3} \\
\text{Sigma} & \quad 0.2370
\end{align*}
\]

\[
\begin{align*}
\chi^2/\text{ndf} & \quad 73.73 / 196 \\
\text{Constant} & \quad 99.02 \\
\text{Mean} & \quad 0.3957\times10^{-2} \\
\text{Sigma} & \quad 0.1987\times10^{-1}
\end{align*}
\]

240 MeV Mass Res.

0.04 $x_2$ Res.
## Detector Rates

<table>
<thead>
<tr>
<th></th>
<th>$LH_2$ Target</th>
<th>$LD_2$ Target</th>
<th>Copper Beam Dump</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$’s</td>
<td>Trks.</td>
<td>$\mu$’s</td>
</tr>
<tr>
<td>$\pi^+$ decay-in-flight</td>
<td>81 k</td>
<td>12 k</td>
<td>195 k</td>
</tr>
<tr>
<td>$\pi^-$ decay-in-flight</td>
<td>35 k</td>
<td>8 k</td>
<td>84 k</td>
</tr>
<tr>
<td>$K^+$ decay-in-flight</td>
<td>63 k</td>
<td>13 k</td>
<td>151 k</td>
</tr>
<tr>
<td>$K^-$ decay-in-flight</td>
<td>6 k</td>
<td>3 k</td>
<td>15 k</td>
</tr>
<tr>
<td>Total $\mu^+$</td>
<td>144 k</td>
<td>25 k</td>
<td>346 k</td>
</tr>
<tr>
<td>Total $\mu^-$</td>
<td>41 k</td>
<td>11 k</td>
<td>99 k</td>
</tr>
</tbody>
</table>

Expected single muon rates per $2 \times 10^{12}$ protons from decay-in-flight mesons which pass through the detector ($\mu$'s) and satisfy trigger matrix tracking requirements (Trks.) from liquid hydrogen and deuterium targets and the copper beam dump.
Publications of the Fermilab Drell-Yan Program

E866/NuSea


E789 Publications:

Publications of the Fermilab Drell-Yan Program

E789 Publications (Cont.):


E772 Publications: