Exploring the Antiquark Structure of Matter with Drell-Yan Scattering: Fermilab E-906/Drell-Yan

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Representing the Fermilab E-906/Drell-Yan collaboration

Why Drell-Yan?

Where will we measure it?

What will we learn?

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Why talk about Drell-Yan at JLab?

- **Similar Physics Goals**
  - Parton level understanding of nucleon
  - Electromagnetic probe

Diagram:

- **e-**
- **e-**
- **γ**
- **hadron**
- **proton**
- **X**
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- Similar Physics Goals
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- Differences
  - Timelike (Drell-Yan) vs. spacelike (DIS) virtual photon.
  - Hadron beam and convolution of parton distributions (Drell-Yan)
  - Factorization/Hadronization (SI-DIS)
  - Ability to select sea quark distributions
What’s in the proton?

Just three valence quarks?

http://www.sciencecartoonsplus.com/index.htm
What’s in the proton?

- Just three valence quarks?
- NO!!
- And quark distributions change in a nucleus

http://www.sciencecartoonsplus.com/index.htm
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
- What are the origins of the sea?
- Significant part of LHC beam.

In nuclei:
- The nucleus is not just protons and neutrons
- What is the difference?
  - Bound system
  - Virtual mesons affects antiquarks distributions
**Simple view of parton distributions: A historic approach**

- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, $Q^2$, perhaps a few hundred MeV

- It was quickly realized that some valence-like (primordial) sea was needed. Gluck, Reya, Vogt, ZPC 53, 127 (1992)
  - Driven by need to agree with BCDMS and EMC data
  - Assumption of symmetric sea remained
Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

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

Graph showing the comparison of different models (NA51, MRSr2, CTEQ4m) with data points from GSR, NMC, and NA51 experiments. The graph indicates that the NA51 Drell-Yan confirms \( \bar{d}(x) > \bar{u}(x) \).
**Light Antiquark Flavor Asymmetry: Brief History**

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

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

- Knowledge of distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD
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Proton Structure: By What Process Is the Sea Created?

- 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 1\textsuperscript{st} order in \( \alpha_s \)
  - Nonperturbative models are motivated by the observed difference

- A proton with 3 valence quarks plus glue cannot be right at any scale!!
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Models Relate Antiquark Flavor Asymmetry and Spin

- Meson Cloud in the nucleon—Sullivan process in DIS

\[ \langle P|P\rangle = (1 - a - b) \langle P_0|P_0\rangle + a \langle N_0\pi|N_0\pi\rangle + b \langle \Delta_0\pi|\Delta_0\pi\rangle \ldots \]

- Chiral Quark models—effective Lagrangians

\[ \langle q|q\rangle = \left[ 1 - \frac{3a}{2} \right] \langle q|q\rangle + \frac{3a}{2} \langle q\pi|q\pi\rangle \]

- Instantons

\[ \mathcal{L} \propto \bar{u}_R u_L \bar{d}_R d_L + \bar{u}_L u_R \bar{d}_L d_R \]

- Statistical Parton Distributions
### Models Relate Antiquark Flavor Asymmetry and Spin

- **Meson Cloud in the nucleon—Sullivan process in DIS**

  \[
  \langle P|P \rangle = (1 - a - b) \langle P_0|P_0 \rangle + a \langle N_0 \pi|N_0 \pi \rangle + b \langle \Delta_0 \pi|\Delta_0 \pi \rangle \ldots
  \]

  \[
  \int_0^1 [\bar{d}(x) - \bar{u}(x)] = \frac{2a - b}{3} = 0.10 \to a = 0.2 = 2b \quad g_A = \int_0^1 [\Delta u - \Delta d] \, dx = \frac{5}{3} - \frac{20}{27} \sqrt{2ab} \to 1.5
  \]

- **Chiral Quark models—effective Lagrangians**

  \[
  \langle q|q \rangle = \left[ 1 - \frac{3a}{2} \right] \langle q|q \rangle + \frac{3a}{2} \langle q\pi|q\pi \rangle
  \]

  \[
  \int_0^1 [\bar{d}(x) - \bar{u}(x)] = \frac{2a}{3} = 0.10 \to a = 0.14 \quad g_A = \int_0^1 [\Delta u - \Delta d] \, dx = \frac{5}{3} \cdot 3a \to 1.43
  \]

- **Instantons**

  \[
  \mathcal{L} \propto \bar{u}_R u_L \bar{d}_R d_L + \bar{u}_L u_R \bar{d}_L d_R \quad \bar{d}_I(x) - \bar{u}_I(x) = \frac{3}{5} [\Delta u_I(x) - \Delta d_I(x)]
  \]

- **Statistical Parton Distributions**

  \[
  \bar{d}(x) - \bar{u}(x) \approx \Delta \bar{u}(x) - \Delta \bar{d}(x)
  \]
**Proton Structure: By What Process Is the Sea Created?**

- **Meson Cloud in the nucleon**
  - Sullivan process in DIS
  \[ |p\rangle = |p_0\rangle + \alpha |N\pi\rangle + \beta |\Delta \pi\rangle + \ldots \]

- **Chiral Models**
  - Interaction between Goldstone Bosons and valence quarks
  \[ |u\rangle \rightarrow |d\pi^+\rangle \text{ and } |d\rangle \rightarrow |u\pi^-\rangle \]

**Perturbative sea apparently dilutes meson cloud effects at large-x, but this requires large-x gluons**
**Proton Structure: By What Process Is the Sea Created?**

- **Meson Cloud in the nucleon**
  - Sullivan process in DIS
  
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---

**Diagram:**

- **Meson Cloud**
  - Peng et al.
  - Alberg, Henley, and Miller
  - Nikolaev et al.
  - Szczurek et al.
  - Pobylitsa et al.

- **Chiral Perturbation**
  - Dorokhov and Kochelev

**Equation:**

\[ \overrightarrow{d} = \overrightarrow{d\pi} + \overrightarrow{q} \]

**Legend:**

- E866
- NA51
- HERMES
- CTEQ6
- Peng et al. Meson Cloud
- Alberg, Henley and Miller Meson Cloud
- Nikolaev et al. Meson Cloud
- Szczurek et al. Meson Cloud

**Note:**

Perturbative sea apparently dilutes meson cloud effects at large-\(x\).
Why talk about Drell-Yan at JLab?

- Other possible answer
  Make Mont feel at home?
Drell-Yan scattering: A laboratory for sea quarks

\[
\frac{d^2\sigma}{dx_1dx_2} = \frac{4\pi\alpha^2}{9x_1x_2} \frac{1}{s} \sum e^2 [\overline{q}_t(x_t)q_b(x_b) + q_t(x_t)\overline{q}_b(x_b)]
\]

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-\(x\).
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 2010
- $^1$H, $^2$H, and nuclear targets
- 120 GeV proton Beam

\[
\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1 x_2} \frac{1}{s} \sum_i e_i^2 \left[ q_{ti}(x_t) \bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t) q_{bi}(x_b) \right]
\]

- 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 detector
  - \(50 \times \) statistics!!

- Limited Phase Space
Drell-Yan Spectrometer for E-906

Solid Iron Magnet, Hadron absorber and beam dump

Station 1: Hodoscope array, MWPC tracking

Station 2 and 3: Hodoscope array, Drift Chamber tracking

Mom. Meas. (KTeV Magnet)

Station 4: Hodoscope array, Prop tube tracking

Hadron Absorber

Solid iron magnet

- Reuse SM3 magnet coils
- Sufficient Field with reasonable coils (amp-turns)
- Beam dumped within magnet

Liquid H₂, d₂, and solid targets
Extracting $d$-$\bar{d}$/$-$ubar From Drell-Yan Scattering

- E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.
Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

- Intermediate-x sea PDF's absolute magnitude set by ν-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?

- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell-Yan—Valence only effect
- What can the sea parton distributions tell us about the effects of nuclear binding?
Structure of nucleonic matter:
How do sea quark distributions differ in a nucleus?

Comparison with Deep Inelastic Scattering (DIS)

- EMC: Parton distributions of bound and free nucleons are different.
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Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

Comparison with Deep Inelastic Scattering (DIS)

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

Graph showing Drell-Yan ratios for different elements and comparison with model predictions.
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
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**E906/Drell-Yan timeline**

- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about “proton economics”
- Spectrometer upgrade funded by DOE/Office of Nuclear Physics (already received $700k by FY09)
- Fermilab PAC reaffirms earlier decision in Fall 2006
- Scheduled to run in 2010 for 2 years of data collection

- Apparatus available for future programs at, e.g. Fermilab, J-PARC or RHIC
  - Significant interest from collaboration for continued program

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<th>Expt. Funded</th>
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<td>2008</td>
<td>2009</td>
<td>2010</td>
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FNAL E866/NuSea Collaboration

Abilene Christian University
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Fermi National Accelerator Laboratory
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Georgia State University
Gus Petitt, Xiao-chun He, Bill Lee

Illinois Institute of Technology
Dan Kaplan

Los Alamos National Laboratory
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New Mexico State University
Mike Beddo, Ting Chang, Gary Kyle, Vassilios Papavassiliou, J. Seldon, Jason Webb

Oak Ridge National Laboratory
Terry Awes, Paul Stankus, Glenn Young

Texas A & M University
Carl Gagliardi, Bob Tribble, Eric Hawker, Maxim Vasiliev

Valparaiso University
Don Koetke, Paul Nord
**Additional Physics from beam parton distributions**

- High-$x_{\text{Bj}}$ Valence quark distributions
- Partonic energy loss in cold nuclear matter

![Parton Loses Energy in Nuclear Medium](image)

**Unpolarized Angular distributions**

- Lam-Tung Relation
  \[ 1 - \lambda = 2\nu \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \]
- Boer-Mulders Distributions

**Possible future programs**

- Polarized target of beam
- Pionic Drell-Yan
Drell-Yan at Fermilab

- Drell-Yan scattering is uniquely sensitive to the antiquark distributions of the target.

- The E-906/Drell-Yan Collaboration is constructing a facility to measure Drell-Yan Scattering.

- E-906/Drell-Yan will use this to measure
  - the ratio of anti-d to anti-u distributions in the proton,
  - The modifications to the quark sea in a nucleus, and
  - Many more interesting topics

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
Additional Material
I don’t have an answer, but you’ve sure given me a lot to think about
**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

![Graphs showing Drell-Yan Acceptance](image)

*Graphs showing distributions for Mass, X_{beam}, X_{target}, and X_F.*
Detector Resolution

- Triggered Drell-Yan events

**Mass Res.**

<table>
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<td>51.65 / 196</td>
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<td>Sigma</td>
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<td>$\chi^2$/ndf</td>
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<tr>
<td>Sigma</td>
<td>0.1987E-01</td>
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- 240 MeV
Drell-Yan Cross Section Ratio and $d$-bar/$u$-bar

\[
\frac{\sigma^{pd}}{2\sigma^{pp}} \bigg|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]
\]
**Drell-Yan Scattering: What we really measure**

- Measure yields of $\mu^+\mu^-$ pairs from different targets
- For each event measure 3-momentum of each $\mu$
- Assume that it is a muon to get 4-momentum

Reconstruct $M_\gamma^2, p_T^\gamma, p_{||}^\gamma$

$M_\gamma^2 = x_1x_2s,$

$x_F = 2p_{||}^\gamma/s^{1/2} \approx x_1 - x_2$

\[
\frac{d^2\sigma}{dx_1dx_2} = \frac{4\pi\alpha^2}{9x_1x_2s} \frac{1}{s} \sum e^2 [\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)]
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\frac{\sigma_{pd}}{2\sigma_{pp}} \bigg|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]
\]
Next-to-Leading Order Drell-Yan

- Next-to-leading order diagrams complicate the picture
- These diagrams are responsible for **50% of the measured cross section**
- Intrinsic transverse momentum of quarks (although a small effect, $\lambda > 0.8$)
Drell-Yan Mass Spectra

Data From Fermilab E-866/NuSea
800 GeV proton beam on hydrogen target

Counts/0.1 GeV

Edge of Spectrometer Acceptance

DiMuon Mass (GeV)