I. AntiQuarks and Proton Structure
II. Proton and Nucleon Structure
III. Drell-Yan and Spin

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
What are the origins of the Sea?

- 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
What are the origins of the Sea?

- 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

Great idea but it didn’t agree with the data
Sea is a fundamental part of the proton

Parton distributions for high energy collisions

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Received 10 June 1991

Abstract. Recent data from deep inelastic scattering experiments at $x > 10^{-2}$ are used to fix the parton distributions down to $x = 10^{-4}$ and $Q^2 = 0.3 \text{ GeV}^2$. The predicted extrapolations are uniquely determined by the requirement of a valence-like structure of all parton distributions at some low resolution scale . . . .
Light Antiquark Flavor Asymmetry: Brief History

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

- NMC (Gottfried Sum Rule)
  \[ \int_0^1 \left[ \bar{d}(x) - \bar{u}(x) \right] dx \neq 0 \]
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- Naïve Assumption:
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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 sea dist. are data driven
  - Sea quark distributions are difficult for Lattice QCD

- Non perturbative QCD models can explain excess d-bar quarks, but not return to symmetry or deficit of d-bar quarks
Models Relate Antiquark Flavor Asymmetry and Spin

- Meson Cloud in the nucleon—Sullivan process in DIS

\[ |p\rangle = (1 - a - b) |p_0\rangle + a |N\pi\rangle + b |\Delta\pi\rangle \]

Antiquarks in spin 0 object → No net spin

- Chiral Quark models—effective Lagrangians

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

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

- Instantons

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

- Statistical Parton Distributions

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

- There is a gluon splitting component which is symmetric.

\[ \bar{d}(x) = \bar{d}_{\text{pQCD}}(x) + \bar{d}_{\pi}(x) \]
\[ \bar{u}(x) = \bar{u}_{\text{pQCD}}(x) + \bar{u}_{\pi}(x) \]
\[ \bar{q}_{\text{pQCD}}(x) = \bar{d}_{\text{pQCD}}(x) = \bar{u}_{\text{pQCD}}(x) \]

- Symmetric sea via pair production from gluons subtracts away.
- No Gluon contribution at 1st order in \( \alpha_s \).
- Nonperturbative models are motivated by the observed difference.
Proton Structure: By What Process Is the Sea Created?

- Lattice weighs in!!
How can we measure the sea distributions?

Need a process that can isolate sea contributions:

\[
F_{2}^{\mu p}(x) \propto \sum_{q \in \{u,d,\ldots\}} e_{q}^{2} x [q(x, Q^{2}) + \bar{q}(x, Q^{2})]
\]

\[
F_{2}^{\nu p}(x) + F_{2}^{\nu n} \propto \sum_{q \in \{u,d,\ldots\}} x [q(x, Q^{2}) + \bar{q}(x, Q^{2})]
\]

\[
x F_{3}^{\nu N}(x) \propto \sum_{q \in \{u,d,\ldots\}} x [q(x, Q^{2}) - \bar{q}(x, Q^{2})]
\]

\[
N^{\pi \pm} \propto \sum_{q \in \{u,d,\ldots\}} [q(x, Q^{2}) D^{\pi \pm} + \bar{q}(x, Q^{2}) D^{\pi \pm}]
\]

\[
A_{W}(y) \propto \frac{u(x_{1}) \bar{d}(x_{2}) - d(x_{1}) \bar{u}(x_{2})}{u(x_{1}) \bar{d}(x_{2}) + d(x_{1}) \bar{u}(x_{2})}
\]

\[
\frac{d\sigma}{dx_{1}dx_{2}} \propto \sum_{q \in \{u,d,\ldots\}} e_{q}^{2} [q(x_{1}) \bar{q}(x_{2}) + \bar{q}(x_{1}) q(x_{2})]
\]
How can we measure the sea distributions?

Need a process that can isolate sea contributions:

- **SIDIS**
  - Low statistics
  - \( K/\pi \) identification
  - Knowledge of fragmentation functions (\( D^\pi \))
- **HERMES, COMPASS, JLab 12 GeV**
- **Collider W production**
  - Fermilab Tevatron, CERN LHC, **RHIC**
- **Drell-Yan**
  - Fermilab, COMPASS, **RHIC**

\[
N^{\pi \pm} \propto \sum_{q \in \{u,d,\ldots\}} \left[ q(x, Q^2) D^{\pi \pm} + \bar{q}(x, Q^2) D^{\pi \pm} \right]
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\]

\[
\frac{d\sigma}{dx_1 dx_2} \propto \sum_{q \in \{u,d,\ldots\}} e_q^2 \left[ q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2) \right]
\]
The Drell-Yan reaction:

\[
\frac{d^2 \sigma}{dx_b dx_t} = \frac{4\pi \alpha^2}{x_b x_t s} \sum_{q \in \{u, d, s, \ldots \}} e_q^2 q_t (x_t) q_b (x_b) + \bar{q}_b (x_b) q_t (x_t)
\]

Calculate the probability of finding two quarks with momentum in the range \([x_t, x_t + dx_t]\) and \([x_b, x_b + dx_b]\)

Start with point cross section for two annihilating Fermions (See Halzen and Martin or Perkins)
Drell-Yan Cross Section

- Cross section is a convolution of beam and target parton distributions

\[
\frac{d^2 \sigma}{dx_b dx_t} = \frac{4 \pi \alpha^2}{x_b x_t s} \sum_{q \in \{u,d,s,...\}} e_q^2 \left[ \bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t) \right]
\]

- u-quark dominance \((2/3)^2\) vs. \((1/3)^2\)

<table>
<thead>
<tr>
<th>Beam</th>
<th>Sensitivity</th>
<th>Experiment</th>
</tr>
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<tr>
<td>Hadron</td>
<td>Beam quarks</td>
<td>Fermilab, J-PARC RHIC (forward acpt.)</td>
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<tr>
<td></td>
<td>target antiquarks</td>
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</tr>
<tr>
<td>Anti-Hadron</td>
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<td>Meson</td>
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\]

- u-quark dominance
  \((2/3)^2\) vs. \((1/3)^2\)

\[
\frac{\sigma_{pd}}{2\sigma_{pp}} = \frac{1}{2} \left[ 1 + \frac{\bar{d}(x)}{\bar{u}(x)} \right]
\]
Drell-Yan Cross Section—Next-to-leading order $\alpha_s$

- These diagrams are responsible for approximately 50% of the measured cross section
SeaQuest Experiment

Main Injector 120 GeV

Fixed Target beam lines

Tevatron 800 GeV

Paul E Reimer, SeaQuest

4 September 2016
Solid Iron
Focusing Magnet, Hadron absorber and beam dump

Liquid $H_2$, $d_2$, and solid targets (Fe, C, W)

Mom. Meas. (KTeV Magnet)

Station 1: Hodoscope array MWPC tracking

Station 2 and 3: Hodoscope array Drift Chamber tracking

Station 4: Hodoscope array Prop tube tracking

Hadron Absorber (Iron Wall)

Drawing: T. O’Connor and K. Bailey

Paul E Reimer, SeaQuest

4 September 2016
Data From FY2014—target-dump separation

- Entire beam interacts upstream of SeaQuest Spectrometer
- Pointing resolution very poor along beam axis
Data From FY2014

- SeaQuest Data
- J/ψ Monte Carlo
- ψ' Monte Carlo
- Drell-Yan Monte Carlo
- Random Background
- Combined MC and bg

0.05 × 10^{18} protons
- approximately 2% of final data set
- 10 × more data recorded or approx. 0.5 × 10^{18}
Data From FY2014

- Monte Carlo describe data well
- Resolution better than expected
  - $\sigma_M(J/\psi) \sim 180$ MeV  $\sigma_M(D-Y) \sim 220$ MeV
  - Clever postdocs and students
  - $J/\psi \psi'$ separation
  - Lower $J/\psi$ mass cut (more Drell-Yan events)
- Target/Beam Dump separation w/o $0^\circ$ muon cut
Data From FY2014

- SeaQuest Data
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**E906 preliminary**

- Monte Carlo describe data well
- Resolution better than expected
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- J/ψ ψ’ separation
- Lower J/ψ mass cut (more Drell-Yan events)
- Target/Beam Dump separation w/o $0^\circ$ muon cut

- Reconstruction efficiency
  - Improved Beam Duty Factor—less noise
  - Optimizing tracker cuts
    - Previous optimization valued processing speed
  - Spectrometer Rate Dependence
SeaQuest Cross Section Ratio

- Low-x overlap region consistency?
- There is a kinematic difference between SeaQuest and E866
- $x_1^{SQ} > x_1^{866}$

3.5 x 10^{17} live protons, 17% of final data set
There is a kinematic difference between SeaQuest and E866

\( x_1^{SQ} > x_1^{866} \)

LO calculations still slightly low

3.5 \( \times 10^{17} \) live protons, 17% of final data set
SeaQuest LO dbar/ubar extraction

- Iteratively ask, “What ratio of dbar/ubar is needed to reproduce the observed cross section ratio.
- Caveats:
  - Leading order only—so far
  - Correct method -> global fit
  - Large $x_{beam}$ dbar/ubar
  - ...
- Low-x overlap region consistency?

3.5 x $10^{17}$ live protons, 17% of final data set
3.5 x 10^{17} live protons, 17% of final data set
SeaQuest Cross Section Ratio

Caveat emptor:
1. These data are preliminary
2. May have random coincidences
3. May have spectrometer rate dependence issues

3.5 x 10^{17} live protons, 17\% of final data set
SeaQuest Seaquark EMC Effect

- 10% of anticipated statistical precision
- Increased detector acceptance at large-x to come.
- No antiquark modification apparent.

SeaQuest Preview

- C/D
- Fe/D
- W/D

SeaQuest <10% of anticipated data
E-772

Preview Systematic:
~1% LD2 Comp., ~6% rate dep.
Final systematic error < 2% expected
Now add Spin

- Dynamics make things messy
- ... Or more interesting?
Leading order Single Spin Drell-Yan Cross Section

\[
\frac{d\sigma^{\text{LO}}}{d^4 q d\Omega} = \frac{\alpha^2}{F q^2} \hat{\sigma}^{\text{LO}} \left[ 1 + D^{\text{LO}}_{\sin^2\theta} A^{\cos 2\phi}_U \cos 2\phi \\
+ S_L D^{\text{LO}}_{\sin^2\theta} A^{\sin 2\phi}_L \sin 2\phi \\
+ \left| \vec{S}_T \right| A^{\sin \phi_S}_T \sin \phi_S \\
+ \left| \vec{S}_T \right| D^{\text{LO}}_{\sin^2\theta} A^{\sin(2\phi+\phi_S)}_T \sin (2\phi + \phi_S) \\
+ \left| \vec{S}_T \right| D^{\text{LO}}_{\sin^2\theta} A^{\sin(2\phi-\phi_S)}_T \sin (2\phi - \phi_S) \right]
\]

\( A^{\cos 2\phi}_U \) Boer-Mulders of target hadron

\( A^{\sin \phi_S}_T \) Sivers for beam nucleon

\( A^{\sin (2\phi+\phi_S)}_T \) Boer-Mulders of target and \( h_1^\perp \) and pretzelosity of beam

\( A^{\sin (2\phi-\phi_S)}_T \) Boer-Mulders of target and \( h_1 \) and transversity of beam

*(with polarized beam and unpolarized target)*
Sivers Function and the Spin Crisis

- Correlation between unpolarized quarks and a nucleon’s transverse polarization

\[ f_{1T} = \begin{array}{c}
\end{array} \]

- Non-zero Sivers distribution \( \Rightarrow \) non-zero quark orbital momentum

\[
\frac{1}{2} = \Delta \Sigma + \Delta G + L
\]

\[
\Delta \Sigma = \Delta u + \Delta d + \Delta s
\]

\(
\frac{1}{2} \Delta \Sigma \approx 25\%
\)

\(
\Delta G \approx 0-15\%
\)

\( L \approx \) unmeasured

- SeaQuest will measure antiquark Sivers
  - Orbital angular momentum of sea quarks
  - Or pionic cloud
“Naïve” T-odd observables

- Naïve T-odd effect ($F_{1T}^{\perp q}$) must arise from interference between spin-flip and non-flip amplitudes w/different phases

- Soft gluons “gauge links” required for color gauge invariance

- Soft gluon re-interactions are final (or initial) state interactions ... and may be process dependent!

$$f_{1T}^{\perp T} \bigg|_{\text{SIDIS}} = - f_{1T}^{\perp T} \bigg|_{\text{DY}}$$
Projected Statistical Precision with a Polarized Target at SeaQuest

Polarized target
• Installation in Summer 2017
• Supported with Los Alamos LDRD funds
• Operation funds expected from DOE HEP & NP

Statistics precision shown for two calendar years of running:
Protons on target = $2.7 \times 10^{18}$
$\mathcal{L} = 7.2 \times 10^{42} \text{/cm}^2$

Drell-Yan Target Single-Spin Asymmetry

$pp^\uparrow \rightarrow \mu^+\mu^-X$, $4<M_{\mu\mu}<9 \text{ GeV}$
The Plan:

- Use fully understood SeaQuest Spectrometer
- Add polarized beam.
Polarized Beam Drell-Yan at Fermilab

The Plan:
- Use fully understood SeaQuest Spectrometer
- Add polarized beam.

Polarized Target:
- Installation costs $1.9M

Polarized Main Injector:
- Cost Est.: $6M +$4M Contingency & Management = $10M (in 2013)
Expected Precision from E-1027 at Fermilab

- Experimental Conditions
  - Same as SeaQuest
  - luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: $I_{av} = 15 \text{ nA}$)
  - $3.2 \times 10^{18}$ total protons for $5 \times 10^5 \text{ min}$: (= 2 yrs at 50% efficiency) with $P_b = 70$

Can measure not only sign, but also the size & maybe shape of the Sivers function!
Drell-Yan Physics Program

- Sea Quarks of the Target
  - $\bar{d}b/ubar$
  - Sea quark EMC effect

- Transverse Spin Physics
  - Sivers and OAM of Sea Quarks
  - Sivers and QCD on Valence Quarks (COMPASS and SeaQuest)

- Not discussed:
  - Boer Mulders from un-polarized D-Y
  - Quark sea absolute magnitude
  - Partonic Energy Loss
  - $J/\psi$ Nuclear Dependence
  - Dark Photons

4 September 2016
Sea Quark EMC Effect

Guggenheim, Bilbao, Spain

Paul E Reimer, SeaQuest

4 September 2016
The European Muon Collaboration (EMC) Effect

Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Is there a difference between hitting a proton in a nucleus and a free proton?
- Hard scattering makes an implicit assumption that the interaction is energetic enough so that the binding of quarks in a proton is small so surely, the binding of protons in the nucleus is also small?
- Do the quarks change configuration?
The European Muon Collaboration (EMC) Effect

Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Experimentally—No
- EMC measured the DIS $F_2$ ratio for Iron to Deuterium

$$F_2(x) = \sum_{q \in \{u,d,\ldots\}} e_q^2 \left[ q(x) + \bar{q}(x) \right]$$

Why?

- Shadowing
- Nuclear binding effects
The European Muon Collaboration (EMC) Effect

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Why?

- Shadowing
- Nuclear binding effects

Do quarks and antiquarks experience the same modifications?
Aside: Problem for PDF fits

- Many experiments used nuclear targets

- Does this data need to be thrown out now?
  - Information of d-quark distributions comes from Deuterium and isospin symmetry

  \[ F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q \in \{u,d,...\}} x \left[ q(x, Q^2) + \bar{q}(x, Q^2) \right] \]

  - Neutrino DIS data?
    - Old $H_2$ bubble chamber data OK
    - Modern experiments use iron target
    - Magnitude of Sea Quark distributions dominated by neutrino data

- Parameterize measurements?
Structure of nucleonic matter: How do DIS and Drell-Yan data compare?

- Shadowing present in Drell-Yan
- Antishadowing not seen in Drell-Yan —Valence only effect

Kulagin and Petti sea vs. valence nuclear effects

FMB—Fermi Motion and Nuclear Binding
OS—Off shell effects
NS—nuclear shadowing
PI—nuclear pions
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.
Structure of nucleonic matter: Where are the nuclear pions?

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- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
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
Fermilab E906/SeaQuest Collaboration

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**Polarized Target:**
Argonne National Laboratory
Fermi National Accelerator Laboratory
Institute of Physics, Academia Sinica
KEK
Ling-Tung University
Los Alamos National Laboratory
University of Maryland
University of Michigan
University of New Hampshire
National Kaohsiung Normal University
RIKEN
Rutgers University
Thomas Jefferson National Accelerator Facility
Tokyo Tech
University of Virginia

Andi Klein and Xiaodong Jiang
Co-Spokespersons

**Polarized Beam:**
Abilene Christian University
Argonne National Laboratory
University of Basque Country
University of Colorado
Fermi National Accelerator Laboratory
University of Illinois
KEK
Los Alamos National Laboratory
University of Maryland
University of Michigan
RIKEN
Rutgers
Tokyo Tech
Yamagata University

Wolfgang Lorenzon and Paul E Reimer
Co-Spokespersons
Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment

- Minimal impact on Drell-Yan program

\[ \mathcal{L} \propto - \frac{1}{4} F_{\mu\nu}^{SM} F_{\mu\nu}^{SM} - \frac{1}{4} F_{\mu\nu}^{hidden} F_{\mu\nu}^{hidden} + \frac{1}{2} \epsilon F_{\mu\nu}^{SM} F_{\mu\nu}^{hidden} + m_A^2 A_\mu^{hidden} A_\mu^{hidden} \]
Proton Structure: By What Process Is the Sea Created?

\[
\frac{d\bar{d}}{du} = \frac{d\bar{d}^\pi}{u^\pi} + \bar{q}
\]

Perturbative sea apparently dilutes meson cloud effects at large-x.
Non-perturbative Models: Pion Cloud

- Meson Cloud in the nucleon Sullivan process in DIS

\[ |p\rangle = |p_0\rangle + \alpha |N\pi\rangle + \beta |\Delta\pi\rangle + \gamma |\Lambda K\rangle + \ldots \]

- In its simplest form, Clebsch-Gordon Coefficients and \(\pi N, \pi \Lambda\) couplings

\[
\begin{align*}
\alpha: & \quad |N\pi\rangle = \begin{cases} 
|p, \pi^0\rangle & \frac{u\bar{u} + d\bar{d}}{2} - \sqrt{\frac{1}{3}} \\
|n, \pi^+\rangle & u\bar{d} \quad \sqrt{\frac{2}{3}} 
\end{cases} \\
\beta: & \quad |\Delta\pi\rangle = \begin{cases} 
|\Delta^{++}, \pi^-\rangle & d\bar{u} \quad \sqrt{\frac{1}{2}} \\
|\Delta^+, \pi^0\rangle & \frac{u\bar{u} + d\bar{d}}{2} - \sqrt{\frac{1}{3}} \\
|\Delta^0, \pi^+\rangle & u\bar{d} \quad \sqrt{\frac{1}{6}} 
\end{cases}
\end{align*}
\]

- Predicts

\[ \bar{d} \geq \bar{u} \]

- Cannot have

\[ \bar{d} \leq \bar{u} \]