Measurement of Antiquark Flavor Asymmetry in the Proton by the Drell–Yan Experiment SeaQuest at Fermilab

MENU 2016, Meson-Nucleon Physics and the Structure of the Nucleon

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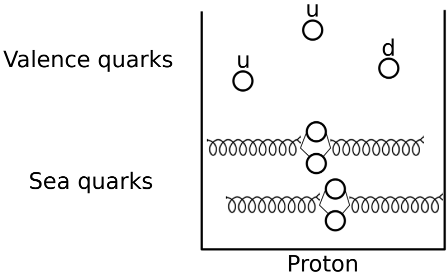
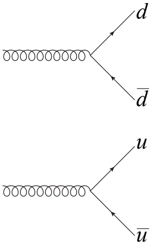
1. Introduction

Valence Quarks and Sea Quarks

- Valence quarks carry the quantum numbers such as the electric charge and isospin.
- Sea quarks are generated from gluon splitting.





- Probability of gluon splitting is independent of quark flavors.
  - Coupling constant is the same.

$\rightarrow$ The amounts of $u\bar{u}$ and $d\bar{d}$ should be the same. "Flavor Symmetry"

Here, the quarks are current quarks: m_u and m_d are a few MeV/c^2.

What is "Flavor Asymmetry"?

- Gottfried sum was measured by Deep Inelastic Muon Scattering to test flavor symmetry.

  $$S_G \equiv \int_0^1 \frac{dx}{x}\left[F_2^p(x) - F_2^n(x)\right] = \frac{1}{3} + \frac{2}{3}\left(\int_0^1 \bar{u}_p(x)dx - \int_0^1 \bar{d}_p(x)dx\right)$$

  $F_2^p(x),\ F_2^n(x)$: structure functions of proton and neutron, respectively

  x : Bjorken x, which is the momentum fraction of parton to proton

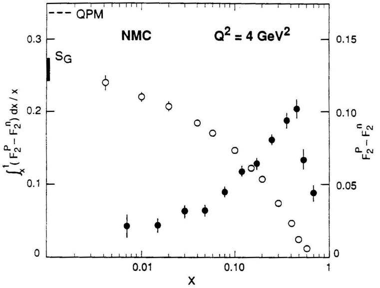
  - Assuming that the parton distribution functions in neutron and proton have isospin symmetry:

    $$\int_0^1 u_p(x)dx = \int_0^1 d_n(x)dx,\ \int_0^1 d_p(x)dx = \int_0^1 u_n(x)dx$$
    $$\int_0^1 \bar{u}_p(x)dx = \int_0^1 \bar{d}_n(x)dx,\ \int_0^1 \bar{d}_p(x)dx = \int_0^1 \bar{u}_n(x)dx$$

- If $\bar{d}$ and $\bar{u}$ in the proton are symmetric, Gottfried Sum is $1/3$.
- NMC experiment at CERN (1990)

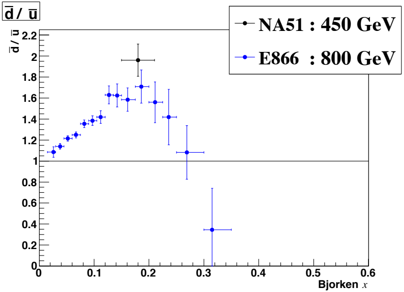
  $$S_G = 0.235 \pm 0.026 < 1/3$$
  $$\rightarrow\ \int_0^1 \bar{d}(x)dx > \int_0^1 \bar{u}(x)dx$$

  Discovery of "Flavor Asymmetry"



x Dependence of Flavor Asymmetry

E866 experiment ($0.015 < x < 0.35$) and NA51 experiment ($x \sim 0.2$) measured Bjorken x dependence of $\bar{d}/\bar{u}$ in the proton using Drell–Yan process.



- $\bar{d}/\bar{u}$ is the ratio of antiquark PDFs of $\bar{d}$ and $\bar{u}$
- $\bar{d}/\bar{u}$ deviates from 1.0 $\rightarrow$ "Flavor Asymmetry"

- 70% asymmetry at maximum has been measured at $x \sim 0.2$.
  - Several models are proposed for explaining this result.
- $x \gtrsim 0.3$: More accurate measurement is needed.
  - Statistical error is large.

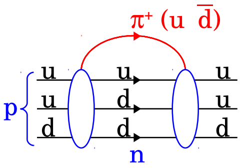
SeaQuest is measuring $\bar{d}/\bar{u}$ at large x ($0.1 < x < 0.45$) accurately!!

Understanding the flavor asymmetry of the antiquarks in the proton is a challenge in QCD.

- It is important to measure with higher accuracy and in wider Bjorken x range.
- Theoretical investigation from the first principle of QCD such as lattice QCD calculation is important.
- QCD effective models and hadron models can also be tested with the flavor asymmetry of antiquarks.

Meson Cloud Model, for example

- A proton wave function contains virtual meson wave functions;
  $|\mathrm{p}\rangle = \alpha|\mathrm{p}_0\rangle + \beta|\mathrm{n}\pi^+\rangle + \gamma|\Delta^{++}\pi^-\rangle + \cdots$
  - $\mathrm{p} \to \mathrm{n} + \pi^+$: π^+ includes $\bar{d}$.
  - $\mathrm{p} \to \Delta^{++} + \pi^-$: π^- includes $\bar{u}$.
    - ★ Probability of $\mathrm{p} \to \mathrm{n} + \pi^+$ is higher than that of $\mathrm{p} \to \Delta^{++} + \pi^-$.
    - ★ It leads to $\bar{d} > \bar{u}$.



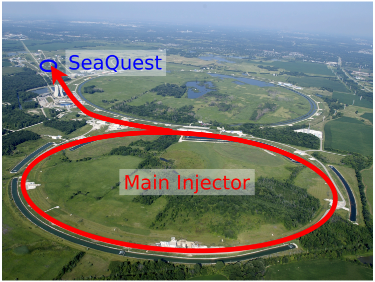
SeaQuest experiment provides the new data points.

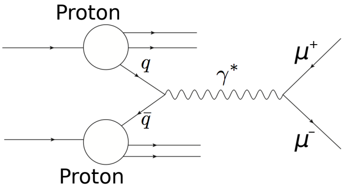
▶ It will be useful for understanding the structure of the proton.

2. SeaQuest Experiment: Drell–Yan Process

SeaQuest Experiment

- Fermi National Accelerator Laboratory (Fermilab)
  - Main Injector:
    120 GeV ($\sqrt{s} = 15$ GeV) proton beam
- Collaboration: Japan, USA, Taiwan
- Drell–Yan experiment
  - $q\bar{q} \to \gamma \to \mu^+\mu^-$
  - An antiquark is always involved in the interaction. $\rightarrow$ Drell–Yan process can directly access antiquarks
  - We measure the momenta of muons in the final state
    - ★ Typical momentum of the muon $\sim$ 40 GeV
- Measurements with Drell–Yan Process
  - **Antiquark Flavor Asymmetry**
  - Boer–Mulders Function
  - Partonic Energy Loss





Collaboration

- Abilene Christian University
- Academia Sinica
- Argonne National Laboratory
- University of Colorado
- Fermi National Accelerator Laboratory
- University of Illinois
- **KEK**
- Los Alamos National Laboratory
- University of Maryland
- University of Michigan
- National Kaohsiung Normal University
- **RIKEN**
- Rutgers University
- **Tokyo Institute of Technology**
- **Yamagata University**

Japanese Group

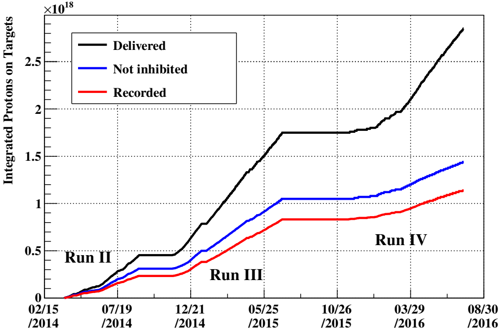
- In charge of running and managing drift chambers
- Two of the drift chambers (St. 3 chambers) are built with JSPS KAKENHI

Timeline

Year	Month	
2009	04	Building detectors
2011	08	
2012	03-04	Commissioning Run (Run I)
	05–	Upgrade detectors
2013	11–	Run II

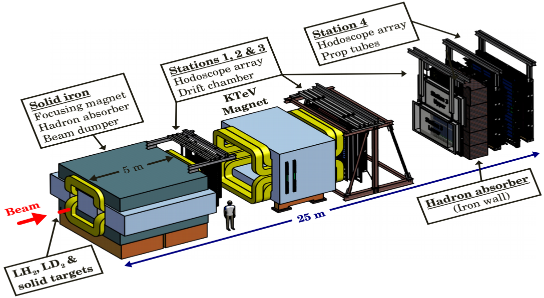
Year	Month	
2014	09-10	Accelerator Shutdown
	11–	Run III
2015	07-09	Accelerator Shutdown
	10-	Run IV
2016	08-11?	Accelerator Shutdown
2016	11?	Run V

- Run IV is about to finish
  - obtained: 1.1×10^{18} protons
  - Proposal: 3.4×10^{18} protons
- Run V will start later this year.
  - Total with Run V will be 1.5×10^{18}.
  - Reach 50% of proposal.



Spectrometer

25 m long



Measures momenta of dimuons from Drell–Yan process.

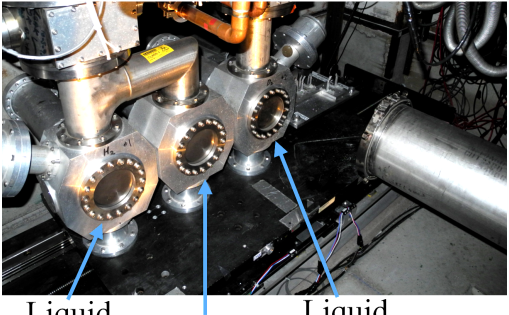
- Targets:
  - proton, deuteron, carbon, iron and tungsten
- Hadron absorbers:
  - Downstream the targets, to stop the proton beam
  - Between St. 3 and St. 4 for muon identification
- Four Tracking "Stations":
  - Hodoscopes for Trigger.
  - Drift Chambers or Proportional Tubes for Tracking.
- Two Dipole Magnets:
  - Focuses the muons and dumps the beam.
  - Determines muon momenta.

Proton Beam

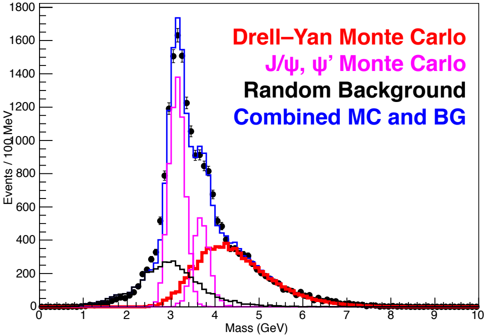
- Beam energy: 120 GeV
  - Center of mass energy $\sqrt{s} = 15\ \mathrm{GeV}$
- 5 seconds of the beam is provided every 60 seconds.
  - The other 55 seconds of the beam is used for a neutrino experiment at Fermilab. The targets of SeaQuest are swapped during this 55 seconds.
- Beam bunch
  - Frequency: 53 MHz (comes every 19 ns)
  - One bunch contains 40k protons on average.
  - Duty Factor (indicates stability of beam intensity I) $\equiv \langle I \rangle^2 / \langle I^2 \rangle$: 30% in Run II $\rightarrow$ 45% after Run III

Targets

- Liquid Targets: LH2, LD2
- Solid Targets: Iron, Carbon, Tungsten
- Move the target table during beam off



Dimuon mass



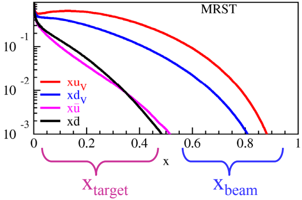
- Data set:
  - approximetely 5% of final data set taken in Run II
- Succeeded in reconstructing the mass distributions.
  - Drell–Yan, J/ψ, ψ': estimated with simulation
  - Random Background: estimated using real data
  - Experimental data were well fitted
    - ★ Detectors and tracking tools work as expected
    - ★ Drell–Yan events are dominant at mass ≥ 4.2 GeV

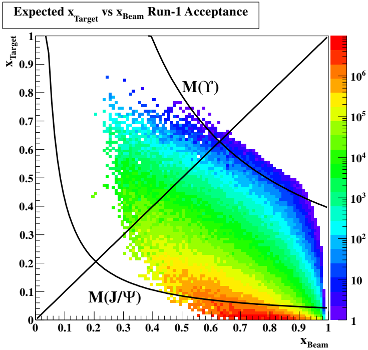
3. Data Analysis and Results

Analysis Method

- SeaQuest uses proton-proton and proton-deuteron Drell–Yan process.
- $\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_t x_b}\frac{1}{s}\sum e^2[\bar{q}_t(x_t)q_b(x_b) + \cancel{\bar{q}_b(x_b)q_t(x_t)}]$
  - $x_t \ll x_b$ in SeaQuest acceptance.
  - $\bar{q}_b(x_b)q_t(x_t)$ can be ignored.
  - Cross section ratio provides $\bar{d}/\bar{u}$:

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





Extracting the Cross Section Ratio

$$\frac{\sigma^{pd}}{2\sigma^{pp}} = \frac{1}{2}\left(\frac{N_D \cdot C_D}{P_D \cdot G_D}\right) \Big/ \left(\frac{N_H \cdot C_H}{P_H \cdot G_H}\right)$$

N : Number of dimuons, C : Correction factor,

P : Number of protons in the beam, G : Number of nucleons in the target

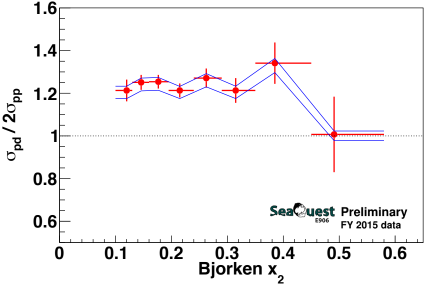
1. Count dimuon yields of each LH2 and LD2 target as a function of x (N)
2. Correct dimuon yields ($N \cdot C$)
   - Background subtraction
   - Tracking efficiency correction
     - ⋆ Tracking efficiency depends on beam intensity or chamber hit rate
3. Normalize the corrected dimuon yields ($N \cdot C/P \cdot G$)
   - $G_D \sim 2 \cdot G_H$
4. Take ratio of them
   - Cross section ratio is obtained!

Benefit of taking the ratio

- Don't have to require the absolute value of cross section
- Cancel out the systematics
  - detector acceptance
  - intensity of the beam
  - efficiency

Cross Section Ratio

Released preliminary result in April 2016.



Systematics

- Hydrogen contamination of deuterium target
- Background subtraction
- Remaining hit rate dependence of dimuon yields
  - Most of it was corrected by tracking efficiency correction.

Cross section ratio of σ^{pd} and σ^{pp}

- Data analysis was done with $\sim$70% of FY 2014 and FY 2015 data.
- Cross section ratio at $0.1 < x < 0.58$ is obtained
- Cross section ratio at each bin > 1

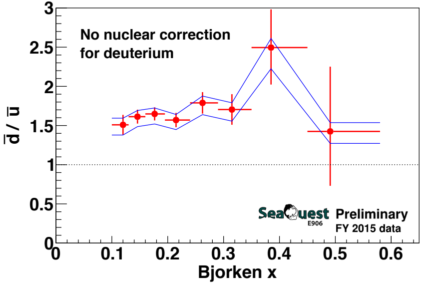
Extracting $\bar{d}/\bar{u}$

Iterative analysis has been done at each x bin

1. obtain R_{data} from data
   - R_{data}: cross section ratio obtained from data
2. set $\bar{d}/\bar{u} = 1$
3. calculate R_{pred} at leading order based on estimate of $\bar{d}/\bar{u}$
   - R_{pred}: cross section ratio predicted from CT10NLO PDF
     - ⋆ CT10NLO: PDF at next to leading order calculated by CTEQ group.
     - ⋆ $u(x),\ d(x),\ c(x),\ s(x)$, and $\bar{u}(x) + \bar{d}(x)$ are taken from CT10NLO
   - $\sigma^{pp} \propto \sum e_i^2 q_i(x_1)\bar{q}_i(x_2)$
     $q_i = u,\ d,\ s,\ c$
4. update estimate of $\bar{d}/\bar{u}$ based on R_{pred} and R_{data}
5. repeat the step 3 and step 4 until $R_{\mathrm{pred}} = R_{\mathrm{data}}$ is reached.

Flavor Asymmetry

Released preliminary result in April 2016.

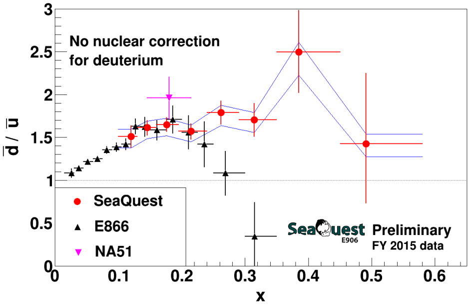


Systematics

- (The same sources as cross section ratio)
- Uncertainties from PDFs

- $\bar{d}/\bar{u}$ at $0.1 < x < 0.58$ is obtained based on the cross section ratio
  - The same trend as cross section ratio
- $\bar{d}/\bar{u} > 1$ at each bin
  $\rightarrow$ Antiquark flavor asymmetry has been found at high Bjorken x.
- We are taking data in FY 2016 with updated detector with a wider Bjorken x acceptance.
  - More statistics at higher x

Flavor Asymmetry (Compared with E866, NA51)



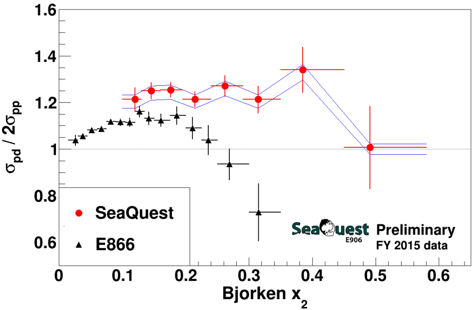
- Comparison with the previous experiments (E866, NA51)
- SeaQuest and the previous experiments agree well at small x
- $\bar{d}/\bar{u}$ around $x = 0.3$ is higher than that of E866 beyond statistical and systematic errors.
    - Physical reasons for the difference between the SeaQuest result and the E866 results are being investigated.

4. Summary

- The proton consists of quarks, antiquarks and gluons.
- Bjorken x dependence of flavor asymmetry of antiquarks ($\bar{u}$ and $\bar{d}$) is important to understand the structure of the proton.
- SeaQuest measures flavor asymmetry of antiquarks in the proton at large x $(0.1 < x < 0.45)$ using Drell–Yan process.
- We constructed a dimuon spectrometer.
- We analyzed FY 2015 data.
- Dimuon mass was reconstructed well.
  - Detectors and tracking tools work as expected.
- We obtained cross setion ratio and $\bar{d}/\bar{u}$ at $0.1 < x < 0.58$.
  - Cross section ratio and $\bar{d}/\bar{u} > 1$ at each bin
    $\rightarrow$ Antiquark flavor asymmetry has been found at high Bjorken x.
- Understanding the flavor asymmetry of the antiquarks in the proton is a challenge in QCD.

Backup

Cross Section Ratio (Compared with E866)

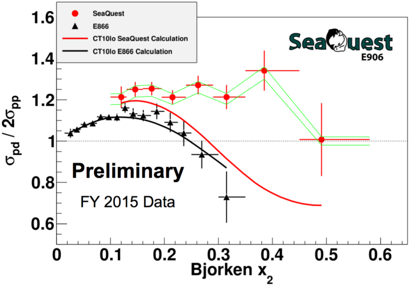


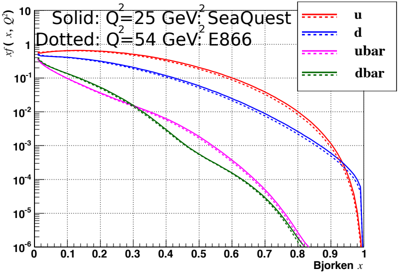
Cross section ratio of σ^{pd} and σ^{pp}

- Comparison with the previous experiment (E866)
  - Obtained cross section ratio at larger Bjorken x
  - SeaQuest data are larger than those of E866

Difference of Cross Section Ratio?

CT10NLO: PDF at next to leading order calculated by CTEQ group. Fitted with E866 results.





- CT10NLO cross section ratio with SeaQuest kinematics is larger than that with E866 kinematics
  - Difference of Q^2 doesn't make the difference of PDF
  - Bjorken x in beam of SeaQuest is higher than that of E866
    $\rightarrow$ PDFs of antiquarks and quarks are not the same
  - Cross section ratio difference at $x \lesssim 0.2$ can be explained by difference of beam Bjorken x, but not at higher x