SeaQuest Experiment at Fermilab

Spinfest 2015

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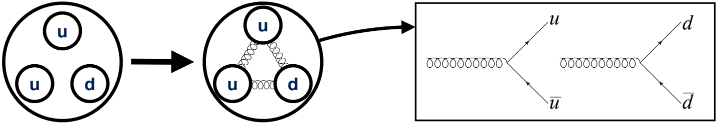
1. Introduction

Structure of the Proton



- The quarks in the proton exchange gluons.
- Anti-quarks are created by gluon splitting.

$$g \to u + \bar{u}, \quad g \to d + \bar{d}$$

- The amount of $\bar{d}$ in the proton has been thought to be the same as that of $\bar{u}$ since the masses of d and u are almost the same.

$$\bar{d} = \bar{u}$$

  - "Flavor Symmetry"

Gottfried Sum

- Gottfried sum is the first experimental approach to test flavor symmetry.

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

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

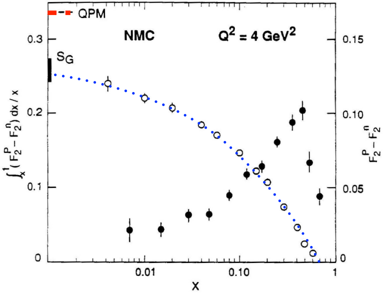
  - Assuming that parton distribution functions in neutron and proton have flavor symmetry:

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

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

$$S_G = 0.235 \pm 0.026 < 1/3$$
$$\rightarrow\ \bar{d} \neq \bar{u}$$

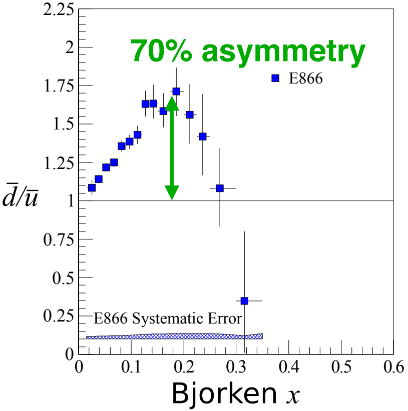
Discovery of "Flavor Asymmetry"



x Dependence of Flavor Asymmetry

E866 experiment at Fermilab measured Bjorken x dependence of $\bar{d}/\bar{u}$.
$(0.015 < x < 0.35)$

- The first measurement of x dependence of flavor asymmetry.
- 70% asymmetry at maximum has been measured at $x \sim 0.2$.
  - Some theories are proposed for explaining this result (discuss one of them later).
  - They can reproduce this shape of asymmetry.
- $\bar{d} < \bar{u}$ at $x \sim 0.3$?
  - No theory can explain it.
  - Statistical errors are very large. More accurate measurement is needed.



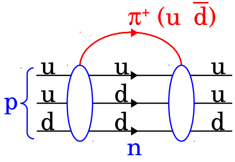
Meson Cloud Model

Meson Cloud Model can reproduce the flavor asymmetry best at present.

- A proton wave function contains virtual meson wave functions.

  $|\mathrm{p}\rangle = |\mathrm{p}_0\rangle + \alpha|\mathrm{n}\pi^+\rangle + \beta|\Delta^{++}\pi^-\rangle + \cdots$

  - $\mathrm{p} \to \mathrm{n} + \pi^+$: 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 $\bar{d} > \bar{u}$.

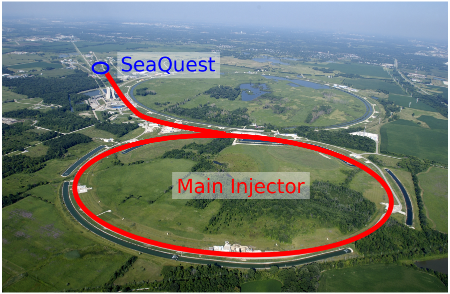


- SeaQuest experiment will provide the new data points.
  - It will be helpful for understanding the theory of proton structure.

2. SeaQuest Experiment

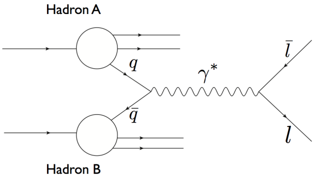
2. SeaQuest Experiment

- SeaQuest is a Drell–Yan experiment at Fermi National Accelerator Laboratory (Fermilab).
- Collaboration: Japan, USA, Taiwan
- 120 GeV proton beam extracted from Main Injector is used.
- SeaQuest measures $\bar{d}/\bar{u}$ in the region $0.1 < x < 0.45$ by Drell–Yan Process.
  - Only one experiment which measures $\bar{d}/\bar{u}$ at large Bjorken x.



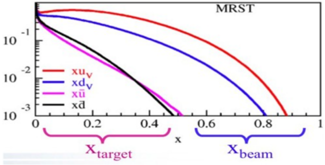
Drell–Yan Process

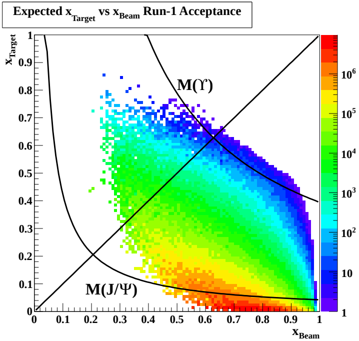
- Drell–Yan process can directly access anti-quarks in the proton.
  - $q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$



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

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



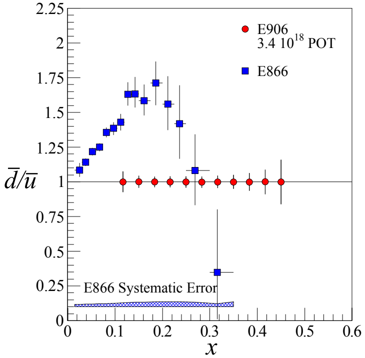


Goal

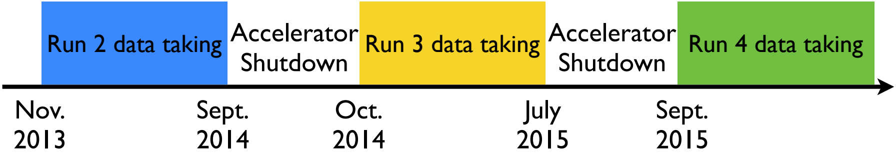
Clarify the behavior of $\bar{d}/\bar{u}$ at large Bjorken x.

- Red points show the expected statistical errors of all the data of SeaQuest.

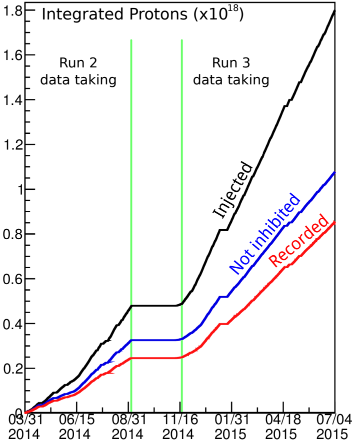
  (Magnitudes are set to 1.)
- SeaQuest will obtain $\times 50$ more statistics than E866 experiment.
  - Beam energy: 800 GeV (E866) $\rightarrow$ 120 GeV (SeaQuest)
    - ★ $\sigma_{\mathrm{DY}} \propto 1/s \; \cdots \; \times 7$ signals
    - ★ $\sigma_{J/\psi} \propto s \; \cdots \; \times 1/7$ main backgrounds



Schedule



- First long run of data taking was done (Run 2).
  - Data analyzed and shown in this presentation are taken in Run 2.
- Integrated number of protons: $\sim 0.8 \times 10^{18}$
  It is $\sim 20\%$ of final number of protons.
- SeaQuest will take 3.8×10^{18} protons by July 2016.



3. Experimental Setup

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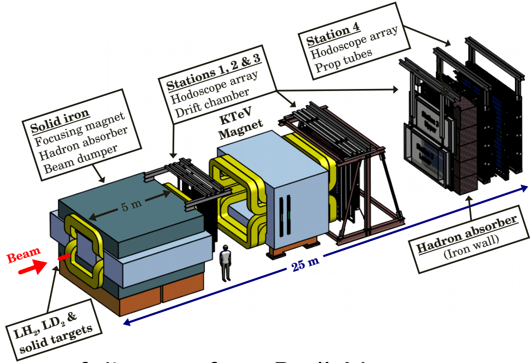
Proton Beam

- 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.
- 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 2 $\rightarrow$ 45% in Run 3

Spectrometer

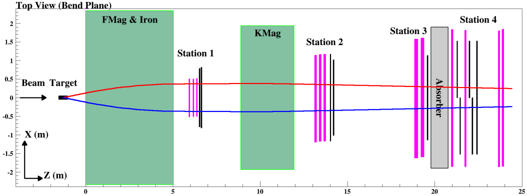
25 m long



Measures momenta of dimuons from Drell–Yan process.

- Targets: proton, deuteron, carbon, iron and tungsten
- Four Tracking "Stations"
  - Hodoscopes for Trigger.
  - Drift Chambers or Proportional Tubes for Tracking.
- Two Dipole Magnets
  - Focuses the muons and dumps the beam (1st magnet).
  - Determines muon momenta (2nd magnet).

Trigger

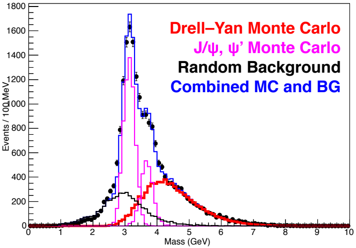


- "Trigger Road"
  - A rough decision on the Drell–Yan muons pass.
  - It is determined by Hodoscopes of St. 1, 2, 3 and 4.
    ex. (H1, H2, H3, H4)=(13, 13, 15, 15) $\cdots$ each number is paddle ID
- "Trigger Road Set"
  - A set of trigger roads enabled in trigger decision.
- Dimuon Trigger
  - At least one accepted positive muon and one accepted negative muon are required.
  - Drell–Yan rate (mass $\geq 4\ \mathrm{GeV}/c^2$): a few Hz
  - Random coincidence is dominant: $\sim 1\ \mathrm{kHz}$

4. Analysis and Results

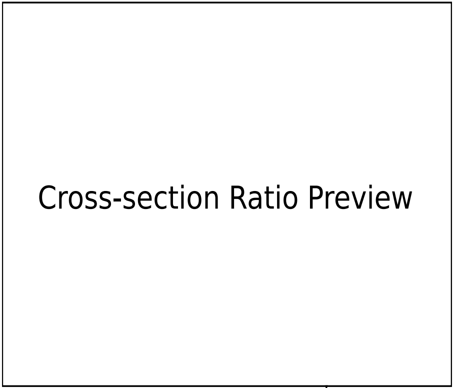
Dimuon Mass

- Data set: approximately 5% of final data set are analyzed
  - July 25th - Sept. 3rd, 2014
- The distribution shapes of Drell–Yan, J/ψ and ψ' events were estimated with simulation.



- Shape of random backgrounds was estimated using real data.
- Experimental data were reasonably well fitted.
  - Detectors and tracking tools work as expected.
- Drell–Yan events are dominant at mass ≥ 4.2 GeV

Cross-section Ratio



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

- dimuon mass ≥ 4.2 GeV
- The result of cross-section ratio is consistent with the E866 result at small x.
- Systematic error is being investigated and reduced.
  - Main cause of this is beam intensity dependence.

Flavor Asymmetry

- $\bar{d}/\bar{u}$ is derived from cross-section ratio using the formula
$$\frac{1}{2}\frac{\sigma^{pd}}{\sigma^{pp}}\bigg|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Flavor Asymmetry Preview

- Systematic error of $\bar{d}/\bar{u}$ is still large but is being investigated and reduced.
- The results of $\bar{d}/\bar{u}$ are consistent with the E866 results at small Bjorken x.
- We need more statistics to clarify the behavior at large Bjorken x.
  - 20 times more data will be used finally.
  - Data taking and quality assurance of the data are in progress.

5. Summary

- Bjorken x dependence of flavor asymmetry of anti-quark is important to understand the structure of the proton.
- SeaQuest measures flavor asymmetry of anti-quarks in the proton at large x $(0.1 < x < 0.45)$.
- 20% of final number of protons have already been taken.
- 5% of final data set were analyzed.
- Dimuon mass was reconstructed well.
  - Detectors and tracking tools work as expected.
- Cross-section ratio is consistent with that of E866 at small x.
  - Systematic error is large because of beam intensity dependence of cross-section ratio.
  - We are investigating it and reducing the systematic error.
- Flavor asymmetry is consistent with that of E866 at small x.
  - In order to clarify the behavior at large x, we need more data. It is in progress.