Measurements of Nucleon Structure via Proton-Induced Drell–Yan Process at FNAL SeaQuest

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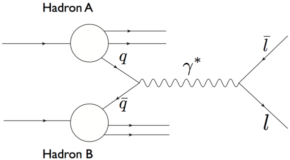
Introduction

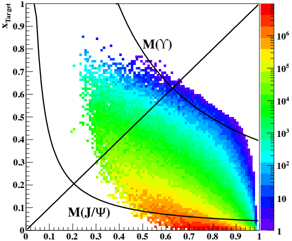
Drell–Yan Process

- Cross section ($p + p$, Leading order)

$$\frac{d^2\sigma}{dx_{\text{target}}dx_{\text{beam}}} = \frac{4\pi\alpha^2}{9x_{\text{target}}x_{\text{beam}}}\frac{1}{s}\sum_i e_i^2[q_i(x_{\text{beam}})\bar{q}_i(x_{\text{target}}) + \bar{q}_i(x_{\text{beam}})q_i(x_{\text{target}})]$$

- An antiquark is always involved
- $\bar{q}(x_{\text{beam}})q(x_{\text{target}})$ vanishes in forward detection ($x_{\text{beam}} \gg x_{\text{target}}$)
  - Access ***antiquarks in target proton*** and ***quarks in beam proton***
- No strong interaction in final state
  - Able to measure initial state effect
- Final state dimuons are measured in SeaQuest





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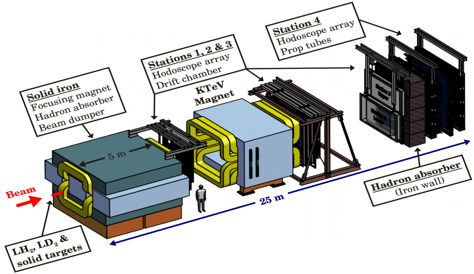
SeaQuest Experiment

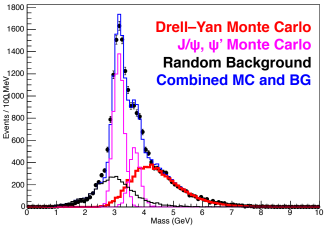
- Performed at Fermilab (Illinois, US)
  Main Injector
  - 120 GeV ($\sqrt{s} \sim 15$ GeV) proton beam
  - 5 seconds of beam is provided every 60 seconds (other 55 seconds for neutrino experiments)
  - 53 MHz beam bunch, $\sim$40k protons in a bunch

- Topics
  - **Antiquark Flavor Asymmetry**
  - **Partonic Energy Loss**
  - **Angular Distribution**
  - Dark Photon Search (analysis is in progress...)

SeaQuest Spectrometer

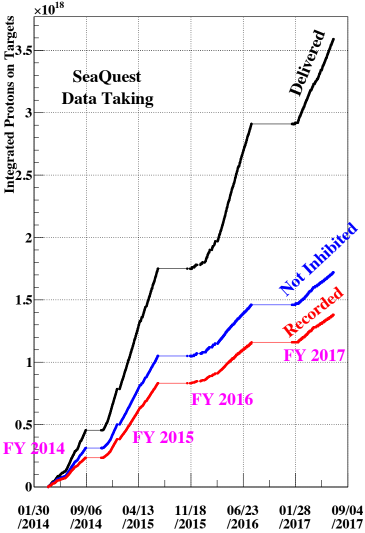


- Targets: LH_2, LD_2, C, Fe, W
- Hadron Absorbers (stop beam, muon identification)
- Magnets (focussing, momentum determination)
- 4 tracking stations, consist of
  - Hodoscopes
  - Drift Chambers (St. 1-3) or Prop. Tubes (St. 4)



- Mass distribution fitted with estimated components
- Well fitted:
  Detectors & tracking tool work as expected
- Drell–Yan can be selected with mass > 4.2 GeV$/c^2$

Timeline



Year	Month	
2011	08	Finish spectrometer construction
2012	03-04	Commissioning data taking (Run I)
	05–	Detector upgrade
2013	11–	Phys. data taking (Run II)
2014	–09	
	11–	Phys. data taking (Run III)
2015	–07	
	10-	Phys. data taking (Run IV)
2016	–08	
	11–	Phys. data taking (Run V)
2017	–07	

- Finished data taking (2017.07)
- Recorded protons on targets: 1.4×10^{18}
- Status in FY2017
  - 0.3×10^{18}
  - Wider St. 1 chamber:
    40% more effective for large x (~ 0.4)

Antiquark Flavor Asymmetry $\bar{d}/\bar{u}$

Antiquark Flavor Asymmetry

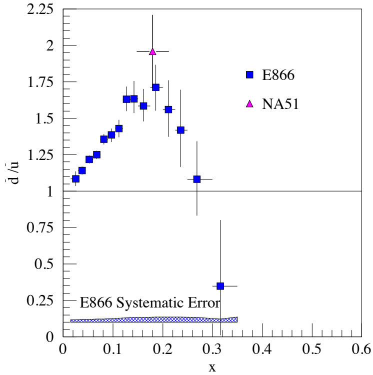
- Gluon splitting: Flavor Independent $\bar{u} = \bar{d}$
- NMC Experiment (DIS) @ CERN (1991)

$$\int_0^1 \bar{d}(x)dx > \int_0^1 \bar{u}(x)dx$$

- NA51 Experiment (Drell–Yan) @ CERN
  - **Significant Flavor Asymmetry**
    $\boldsymbol{\bar{d}/\bar{u} = 1.96 \ @ \ x = 0.18}$
- E866 Experiment (Drell–Yan) @ Fermilab
  x-dependence of $\bar{d}/\bar{u}$ @ $0.015 < x < 0.35$
  - **Significant Flavor Asymmetry**
    $\boldsymbol{\bar{d}/\bar{u} \sim 1.7 \ @ \ x \sim 0.2}$
  - $\boldsymbol{\bar{d}/\bar{u} < 1.0 \ @ \ x \sim 0.3?}$
    with large stat. uncertainty
    No theories can reproduce

x : Bjorken $x = \dfrac{P_{\text{parton}}}{P_{\text{proton}}}$

(@ high energy)



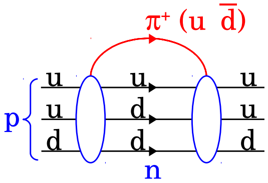
Models for $\bar{d}/\bar{u}$

- Pauli Blocking
  - $g \to u\bar{u}$ is suppressed compared to $g \to d\bar{d}$ $(p = uud)$
  - Only few % effect [NPB149, 497 (1979)]

- Statistical model [NPA948, 63 (2016)]
  - Fermi (quarks) and Bose (gluons) statistics

- Meson cloud model [PRD58, 092004 (1998)]
  - $|p\rangle = |p_0\rangle + \alpha|N\pi^+\rangle + \beta|\Delta\pi^-\rangle + \gamma|\Lambda K\rangle + \cdots$
    - ★ $N\pi^+ = (udd)(u\bar{\mathbf{d}})$
    - ★ $\Delta\pi^- = (uuu)(d\bar{\mathbf{u}})$
    - ★ $\alpha > \beta$

  $\to \bar{d} > \bar{u}$



- etc...

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

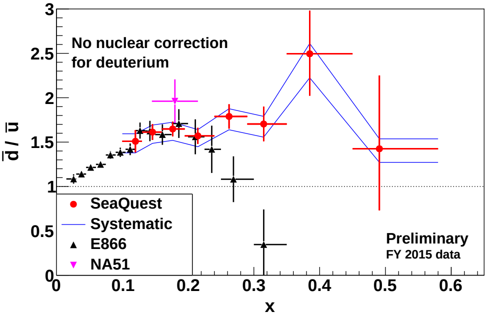
Basic Idea

$$\frac{\sigma_{pd}(x)}{2\sigma_{pp}(x)} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

Drell–Yan cross section ratio is proportional to $\bar{d}/\bar{u}$ with $x_{\text{beam}} \gg x_{\text{target}}$

- Cross section ratio: $\dfrac{\sigma_{pd}}{2\sigma_{pp}} = \dfrac{1}{2}\left(\dfrac{N_D \cdot C_D}{P_D}\right) \Big/ \left(\dfrac{N_H \cdot C_H}{P_H}\right)$
  - Cross section ratio of LD_2 to LH_2
  - Background and reconstruction efficiency corrections
- Convert $\sigma_{pd}/2\sigma_{pp}$ to $\bar{d}/\bar{u}$
  - $\dfrac{d^2\sigma}{dx_{\text{target}}dx_{\text{beam}}} = \dfrac{4\pi\alpha^2}{9x_{\text{target}}x_{\text{beam}}}\dfrac{1}{s}\sum_i e_i^2[q_i(x_{\text{beam}})\bar{q}_i(x_{\text{target}}) + \bar{q}_i(x_{\text{beam}})q_i(x_{\text{target}})]$
    LO Drell–Yan cross section is used for extracting $\bar{d}/\bar{u}$

$\bar{d}/\bar{u}$ Preliminary Result



Systematic uncertainty

- H contamination in LD_2
- background
- hit-rate dependence of reconstruction efficiency
- uncertainty from CT10 PDF (cross section ratio $\rightarrow \bar{d}/\bar{u}$)

SeaQuest Preliminary Result (LO)

- $\bar{d}/\bar{u} > 1.0$ @ $0.10 < x < 0.58$
- $\bar{d}/\bar{u} = 1.0$ @ $0.45 < x < 0.58$ within stats. error

Comparison with NA51, E866

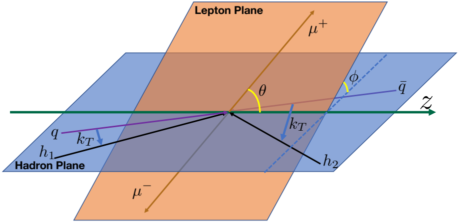
- $0.1 < x < 0.24$: well consistent
- $x > 0.24$: SeaQuest $>$ E866 !?
  - Investigation is in progress...

For the final result

- Better S/N ratio & hit-rate dependence, nuclear effect on LD_2, NLO extraction

Angular Distribution

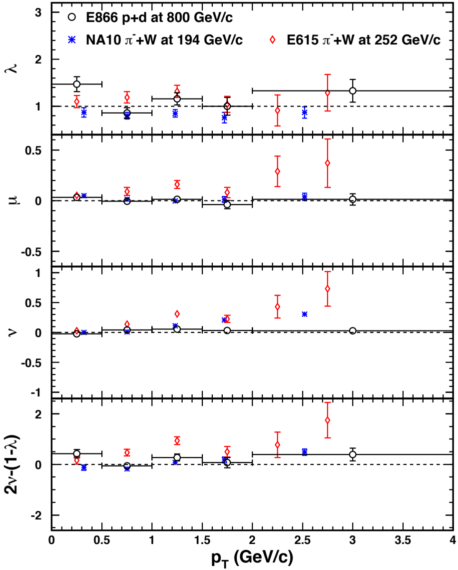
Lam–Tung Relation



Collins–Soper Frame

- Drell–Yan cross section:
$$\frac{d\sigma}{d\Omega} \propto 1 + \boldsymbol{\lambda} \cos^2\theta + \boldsymbol{\mu} \sin 2\theta \cos\phi + \frac{\boldsymbol{\nu}}{2} \sin^2\theta \cos 2\phi$$
- $q\bar{q}$ annihilation parton model: $\boldsymbol{\lambda = 1,\ \mu = \nu = 0}$
- pQCD: Lam–Tung Relation (PRD 18 (1978) 2447)
$\boldsymbol{1 - \lambda - 2\nu = 0}$

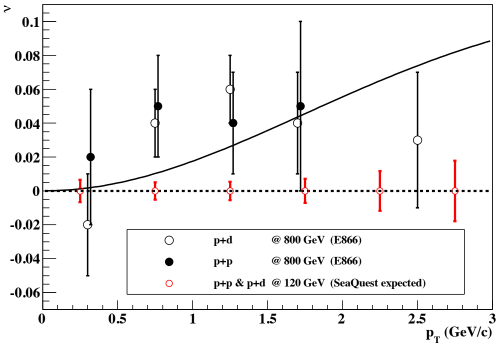
Results from Previous Experiments



PRL **99** (2007) 082301

- π beam — NA10 & E615
  - Lam–Tung relation is violated
  - Large ν : large $\cos 2\phi$ dependence
- **proton** beam — E866
  - Lam–Tung relation is satisfied?
  - Small ν : small $\cos 2\phi$ dependence
- Results indicate that the Boer–Mulders functions of sea quarks are small
  - Boer–Mulders functions may be a cause of large ν and Lam–Tung violation
  - Difference between π-beam and proton-beam results

Expected Stats. of SeaQuest

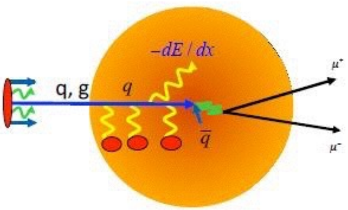


- SeaQuest is proton-induced Drell–Yan experiment
  - Better statistics than E866
  - Will show the difference from pion-induced Drell–Yan clearly
- Optimizing the method for correcting background, hit-rate dependence, trigger efficiency

Partonic Energy Loss

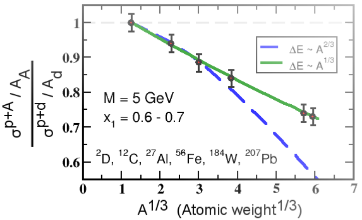
Partonic Energy Loss

- A parton loses its energy by the nuclei
  - Collision with cold nuclear matter
  - Gluon radiation
- Measurement by Drell–Yan
  $\rightarrow$ only the effect in initial-state

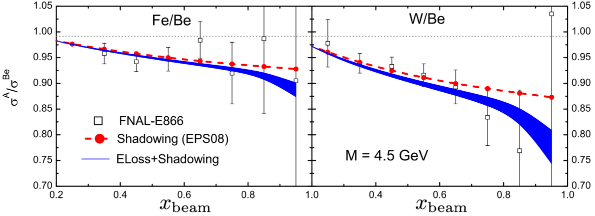


- Parton Energy Loss $\rightarrow$ smaller x_{Beam}
  ▶ Galvin and Milana : $\Delta x_1 = -\kappa_1 x_1 A^{1/3}$
  ▶ Brodsky and Hoyer: $\Delta x_1 = -\frac{\kappa_2}{s} A^{1/3}$
  ▶ Baier *et al.* : $\Delta x_1 = -\frac{\kappa_3}{s} A^{2/3}$
- Measures cross-section/Atomic number ratio

$$R_{pA} = \left(\frac{1}{A_A}\sigma(p+A)\right) \Big/ \left(\frac{1}{A_C}\sigma(p+C)\right)$$

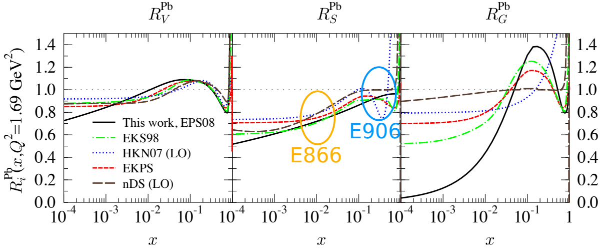


Energy Loss Measurement



Results from E866

- Cross-section ratio drop was found
- Drop can be explained by only shadowing



SeaQuest x is at minimal shadowing region

- Less affected by shadowing
- Energy loss is clearer

Energy Loss Results

(plots are deleted)

(plots are deleted)

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- 5×10^{17} PoTs
- Both Fe & W results: negative slope
- $A^{1/3}$ dependence is also observed
- Most part of systematic error is from uncertainty of tracking efficiency
- Minimizing the systematic uncertainty is in progress

Summary

- SeaQuest measures the dimuons from Drell–Yan process and investigates the structure of the proton.
- $\bar{d}/\bar{u}$: FY2015 data, preliminary result
  - $\bar{d}/\bar{u} > 1.0$ $(0.10 < x < 0.58)$
  - $\bar{d}/\bar{u}$ is consistent with 1.0 at large x $(0.45 < x < 0.58)$ within statistical uncertainty.
  - Analysis toward final results is in progress.
- Angular distribution
  - Analysis is in progress.
  - SeaQuest will show the proton-induced Drell–Yan results precisely and will show the difference between pion-induced Drell–Yan results.
- Partonic energy loss
  - $\sigma(p + A)/\sigma(p + C)$ was found
  - Minimizing systematic uncertainty. Analysis toward preliminary/final results is in progress.

Backup

Extraction of CSR

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

N : Number of dimuons, C : Correction factor,

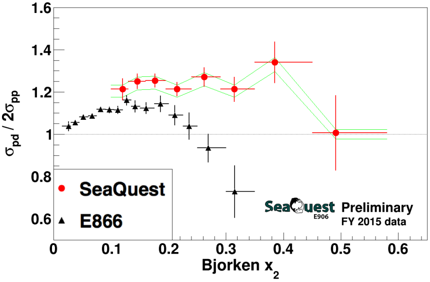
P : Number of protons in the beam, G : Number of nucleons in the target

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

Cross-Section Ratio



Systematics uncertainty

- hydrogen contamination in deuterium target
- background
- remaining rate dependence of reconstruction efficiency

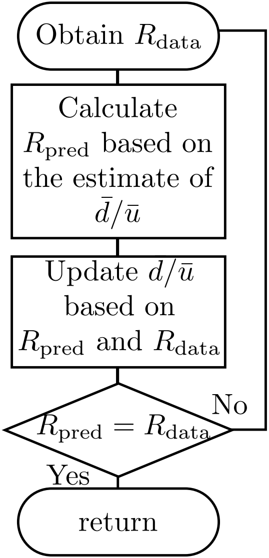
SeaQuest Preliminary Result (2016)

- $\sigma_{pd}/2\sigma_{pp} > 1.0 \; @ \; 0.10 < x < 0.58$
- $\sigma_{pd}/2\sigma_{pp} = 1.0 \; @ \; 0.45 < x < 0.58$ within stats. error

Comparison with E866

- Inconsistent??
  $\rightarrow$ Average x_1 is different

Conversion from CSR to $\bar{d}/\bar{u}$



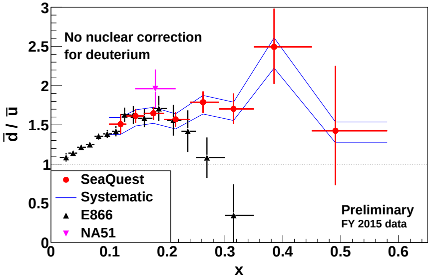
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha}{9M^2}\sum_i e_i^2[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)] \quad (1)$$

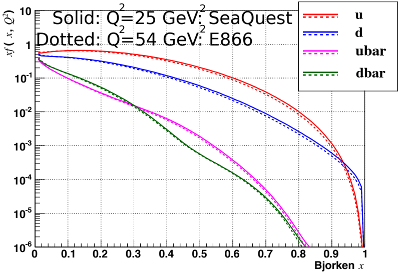
Using the Drell–Yan cross section formula, $\bar{d}/\bar{u}$ is extracted with iterative analysis in each x_2 bin.

1. Calculate cross section ratio from data ($R_{\rm data}$).
2. Set the estimate of $\bar{d}/\bar{u} = 1.0$.
3. Using Eq.(1), parton distribution functions taken from CT10LO and estimate of $\bar{d}/\bar{u}$, calculate $R_{\rm pred}$.
4. Update the estimate of $\bar{d}/\bar{u}$ based on $R_{\rm pred}$ and $R_{\rm data}$.
5. Repeat the steps 3-4 until $|R_{\rm pred} - R_{\rm data}| < 10^{-4}$.

Difference of Q^2

CT10LO: PDF at leading order calculated by CTEQ group.





- PDF difference between SeaQuest Q^2 and E866 Q^2 is small
- Difference of $\bar{d}/\bar{u}$ cannot be explained by Q^2 difference