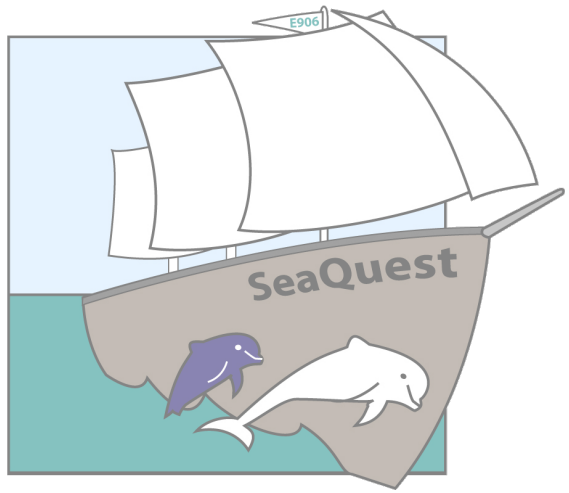
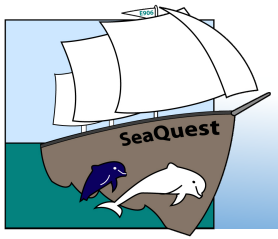
Recent updates of $\bar{d}/\bar{u}$ analysis by SeaQuest experiment

Kei Nagai
Academia Sinica

10th July, 2020



Taiwan Hadronic Physics Meeting @ 中原大學



Introduction

Antiquark Flavor Asymmetry

- Gluon splitting: Flavor Independent $\bar{u} = \bar{d}$
- Gottfried sum

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

x : Bjorken $x = P_{\text{parton}}/P_{\text{proton}}$ @ high-energy

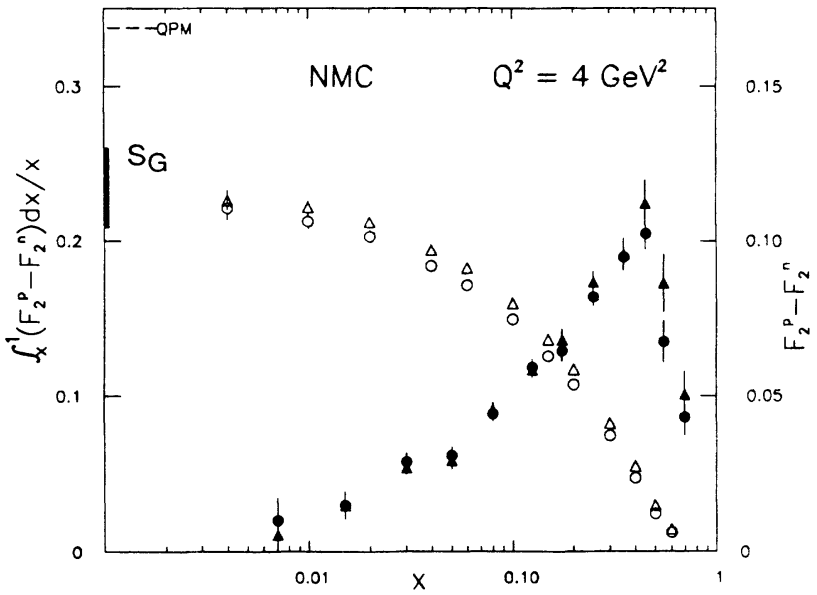
Assumption: PDFs in neutron and proton are isospin symmetric:

$$\int_0^1 u_p(x)dx = \int_0^1 d_n(x)dx, \ldots$$

- NMC experiment at CERN (1990, DIS)

$$S_G = 0.235 \pm 0.026 < 1/3$$

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



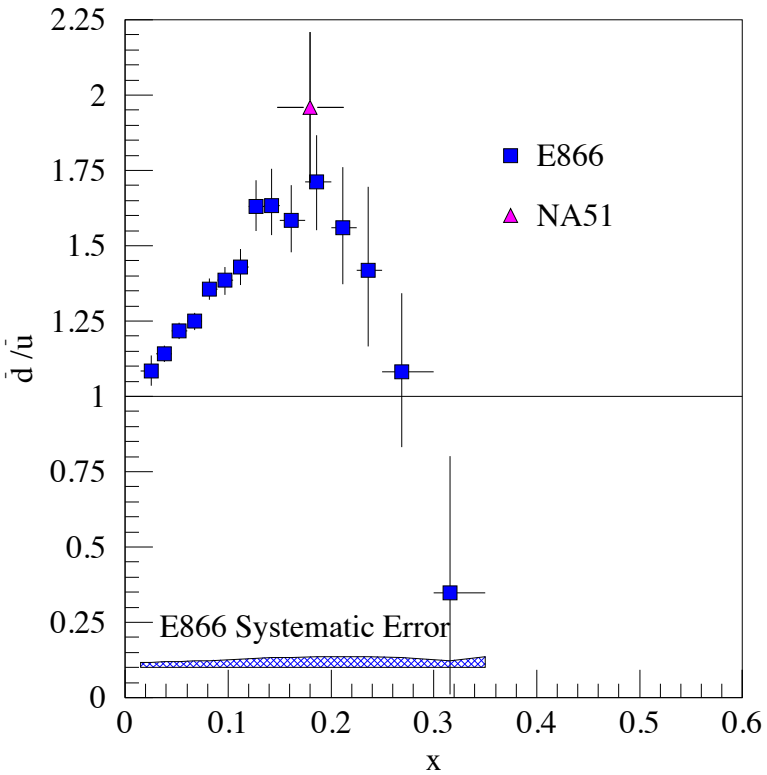
Antiquark Flavor Asymmetry

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

(@ high energy)

- NA51 Experiment (Drell–Yan) @ CERN
  - **Significant Flavor Asymmetry**
    $\bar{d}/\bar{u} = 1.96$ @ $x = 0.18$

- E866 Experiment (Drell–Yan) @ Fermilab
  x-dependence of $\bar{d}/\bar{u}$ @ $0.015 < x < 0.35$
  - **Significant Flavor Asymmetry**
    $\bar{d}/\bar{u} \sim 1.7$ @ $x \sim 0.2$
  - **$\bar{d}/\bar{u} < 1.0$ @ $x \sim 0.3$?**
    with large stat. uncertainty

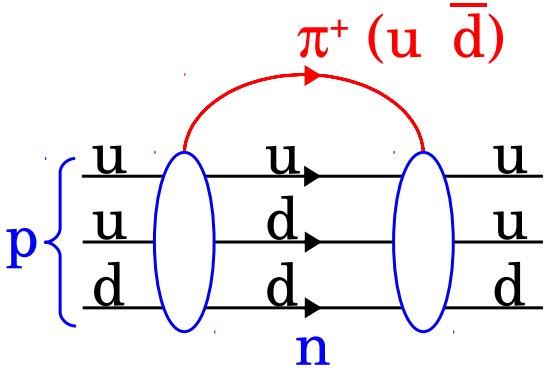


Models for $\bar{d}/\bar{u}$

$\bar{d}/\bar{u} > 1.0$: Proposed several theories

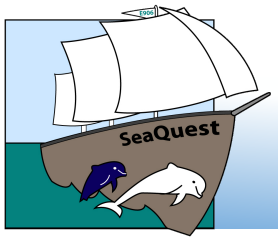
- Pauli Blocking
  - $g \to u\bar{u}$ is suppressed compared to $g \to d\bar{d}$ $(p = uud)$
  - Only few % effect [NPB149, 497 (1979)]
- Statistical model [NPA948, 63 (2016)]
  - Fermi (quarks) and Bose (gluons) statistics
- Meson cloud model [PRD58, 092004 (1998)]
  - $|p\rangle = |p_0\rangle + \alpha|N\pi^+\rangle + \beta|\Delta\pi^-\rangle + \gamma|\Lambda K\rangle + \cdots$
    - ★ $N\pi^+ = (udd)(u\bar{d})$
    - ★ $\Delta\pi^- = (uuu)(d\bar{u})$
    - ★ $\alpha > \beta$

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



$\bar{d}/\bar{u} < 1.0$: No theories can reproduce

SeaQuest will provide the new data points $(0.1 < x < 0.45)$
and it is important to understand the structure of the proton!



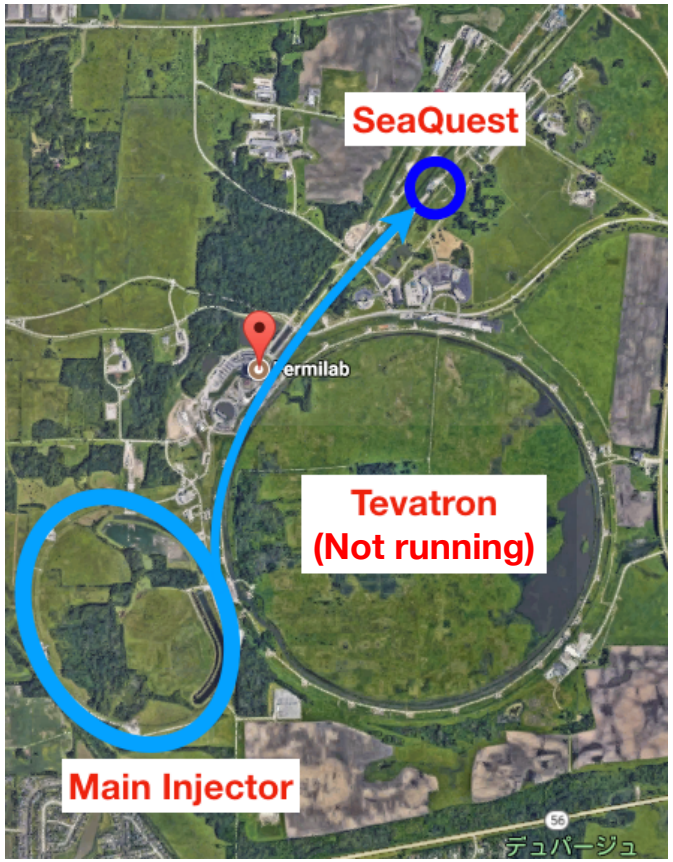
SeaQuest Experiment

SeaQuest Experiment

Drell–Yan 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, ∼40k protons in a bunch

- Topics
  - **Antiquark Flavor Asymmetry**
  - Nuclear dependence
  - Angular Distribution
  - Dark Photon Search



Collaboration List

Abilene Christian University
A. Boles, B. Bowen, K. Bowling, A.T. Brown, A.W. Brown, E. Carlisle, P. Carstens, R. Castillo, M. Crowder, M. Daugherity, B. Edlund, T. Hague, L.D. Isenhower, N. Kitts, S. Marshall, L. Medlock, A. Miller, B. Miller, L. Selensky, T. Sipos, R. Towell, S. Watson, Z. Xi

Academia Sinica
T.-H. Chang, W.-C. Chang, K. Nagai, S.-H. Shiu, D.-S. Su, M. Quaresma

Argonne National Laboratory
J. Arrington, C. Durandet, J. Ferreri, D.F. Geesaman*, R.J. Holt, M.M. Medeiros, P.E. Reimer*, B.G. Tice, Z. Ye

University of Colorado
E. Erdos, J. Katich, E. Kinney, P.-J. Lin, B. McDonald

Fermi National Accelerator Laboratory
C. Brown, D. Christian, J.-Y. Wu

University of Illinois
B. Dannowitz, A. Chen, M. Diefenthaler, B. Kerns, J. Kras, H. Li, D. Liu, N.C.R. Makins, R.E. McClelland, J.-C. Peng, S. Prasad, M.H. Teo, M. Witek, Y. Yin

KEK
S. Sawada

Los Alamos National Laboratory
G.T. Garvey, L. Guo, X. Jiang, A. Klein, D. Kleinjan, M. Leitch, H. Liu, K. Liu, M. Liu, P. McGaughey, A. Puckett

Mississippi State University
L. El Fassi

University of Maryland
S. Bastola, E. Beise, K. Nakahara

University of Michigan
C.A. Aidala, C. Ayuso, C. Culkin, C. Dutta, V.R. Logins, W. Lorenzon, I.A. Mooney, D. Morton, B. Nadim, B.J. Ramson, R. Raymond, J.G. Rubin, T. Sawada, M. Scott, M. Stewart, M.R. Wood

National Kaohsiung Normal University
R. Guo, S.-Y. Wang

RIKEN
Y. Goto

Rutgers University
R. Gilman, R. Ransome, A.S. Tadepalli, Y. Zhang

Tokyo Institute of Technology
S. Miyasaka, K. Nakano, S. Obata, F. Sanftl, T.-A. Shibata, S. Takeuchi

Yamagata University
Y. Kudo, Y. Miyachi, S. Nara

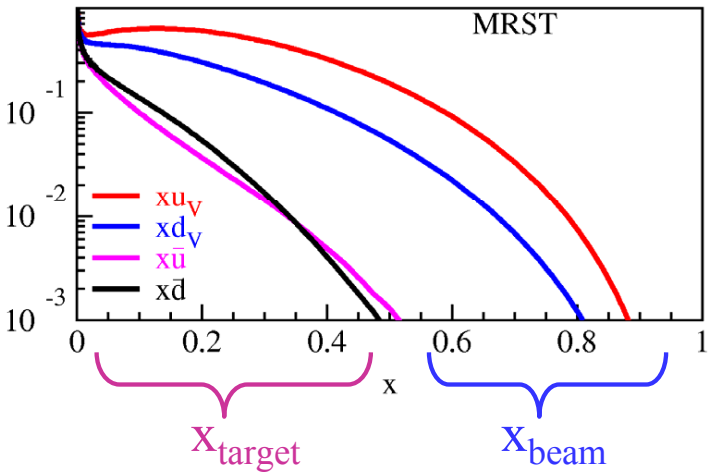
* Co-Spokespersons

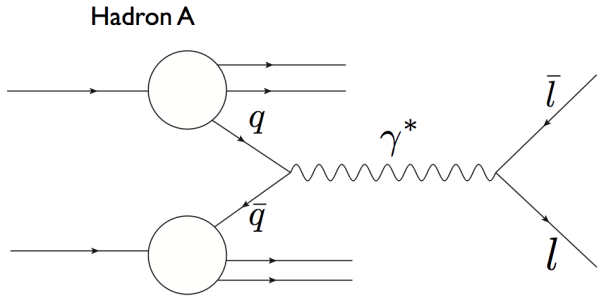
Drell–Yan Process

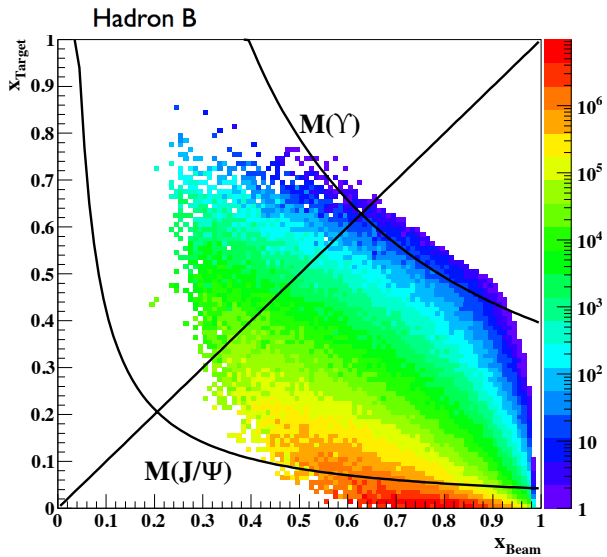
- Cross section ($p + p$, Leading order)

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

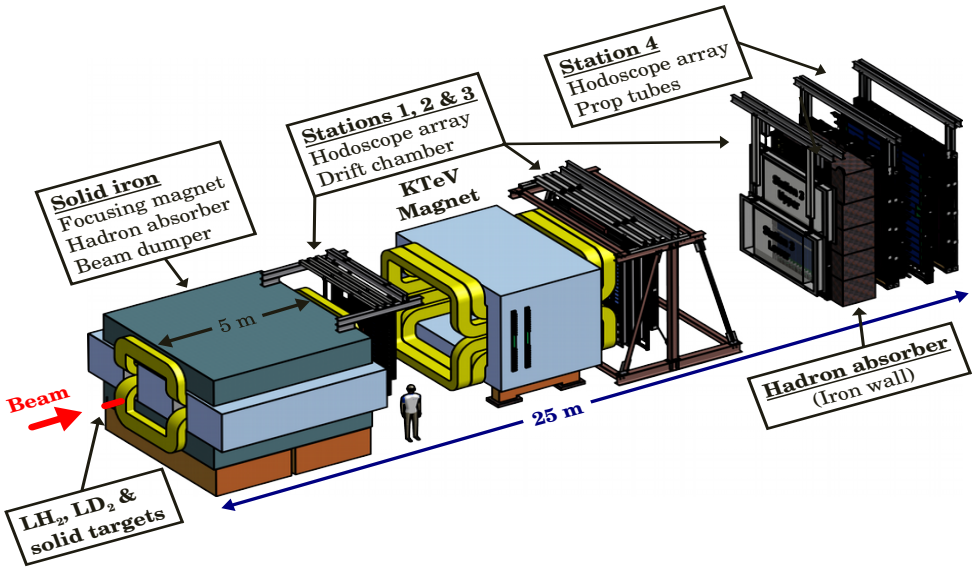
- An antiquark is always involved
- $\bar{q}(x_{\text{beam}})q(x_{\text{target}}) \sim 0$ @ $x_{\text{beam}} \gg x_{\text{target}}$
  - Access ***antiquarks in target proton*** and ***quarks in beam proton***
- Final state dimuons are measured



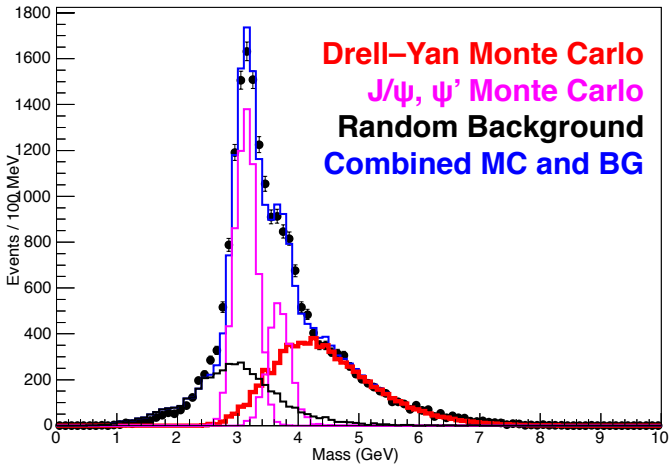




SeaQuest Spectrometer

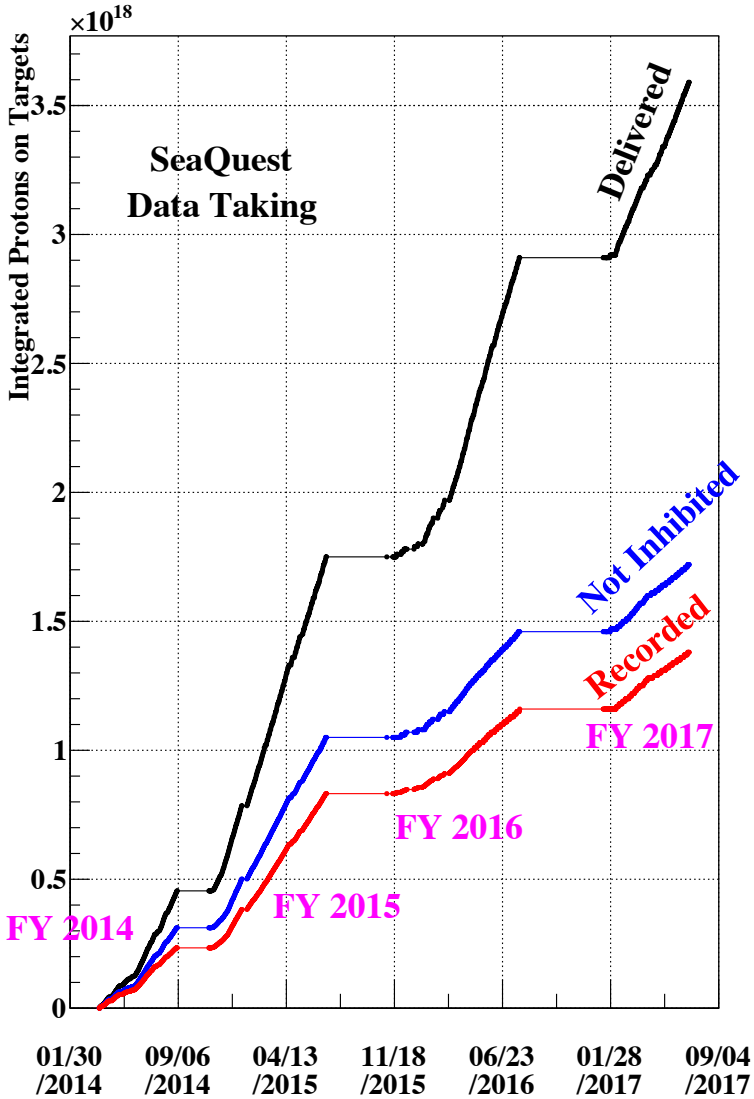


- Targets: LH_2, LD_2, C, Fe, W
- Hadron Absorbers (stop beam, muon identification)
- Magnets (focussing, momentum determination)
- 4 tracking stations, consist of
  - Hodoscopes
  - Drift Chambers (St. 1-3) or Prop. Tubes (St. 4)



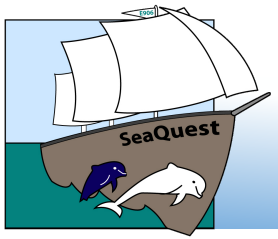
- Mass distribution fitted with estimated components
- Well fitted:
  Detectors & tracking tool work as expected
- Drell–Yan can be selected with
  mass > 4.2 GeV$/c^2$

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}



Data Analysis

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

Basic Idea

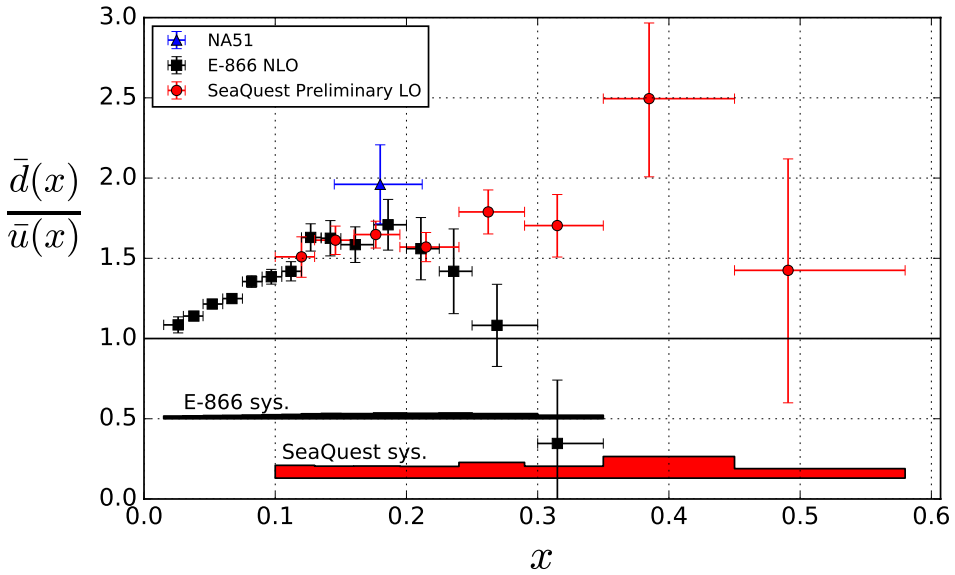
$$\frac{\sigma_{pd}(x)}{2\sigma_{pp}(x)} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

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

- Cross section ratio: $\dfrac{\sigma_{pd}}{2\sigma_{pp}} = \dfrac{1}{2}\left(\dfrac{N_D \cdot C_D}{P_D}\right) \Big/ \left(\dfrac{N_H \cdot C_H}{P_H}\right)$
  - Number of dimuons (N)
  - Background and reconstruction efficiency corrections (C)
  - Normalization with number of nucleons in beam and target (P)

- 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 $\rightarrow \bar{d}/\bar{u}$)

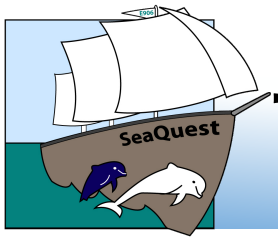
Note: Nuclear corrections for deuterium have not yet been applied.

SeaQuest Preliminary Result (LO)

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

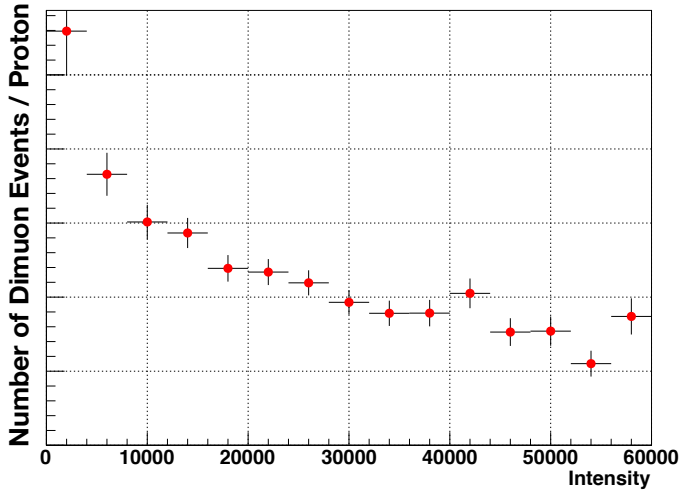
Comparison with NA51, E866

- $0.1 < x < 0.24$: well consistent
- $x > 0.24$: SeaQuest $>$ E866 !?
  - Difference of Q^2? – No effect
  - Difference of PDF sets? – No effect



Toward Final Results

Difficulties in Current Analysis?



- Reconstruction efficiency effect
  - Reconstruction efficiency decreases as intensity increases (rate-dependent)

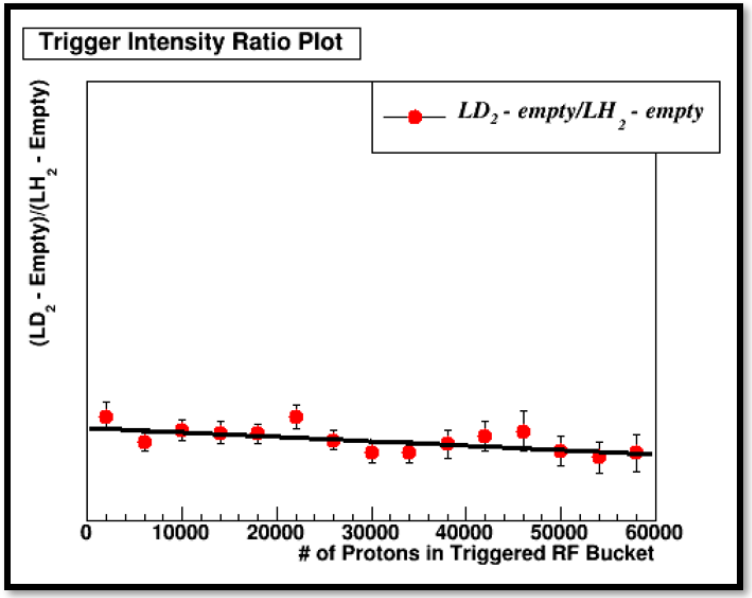
- Combinatorial background
  - Example: Single muon coming from π + single muon from Drell–Yan
  - Estimated with event mixing method
    - ★ Mix muons from different events
  - Background would be rate-dependent

How to remove these effects?

- Basic Idea: These effects should vanish at "zero" intensity

Extrapolation Method

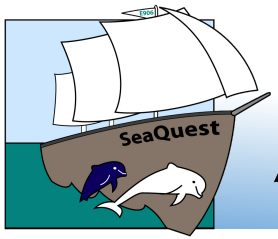
- Cross-section ratio as a function of intensity
- Extrapolate the data to “Zero” intensity
- **Intercept value is “correct” cross-section ratio**
  - No reconstruction efficiency effect
  - No combinatorial background



Difficulties of this method?

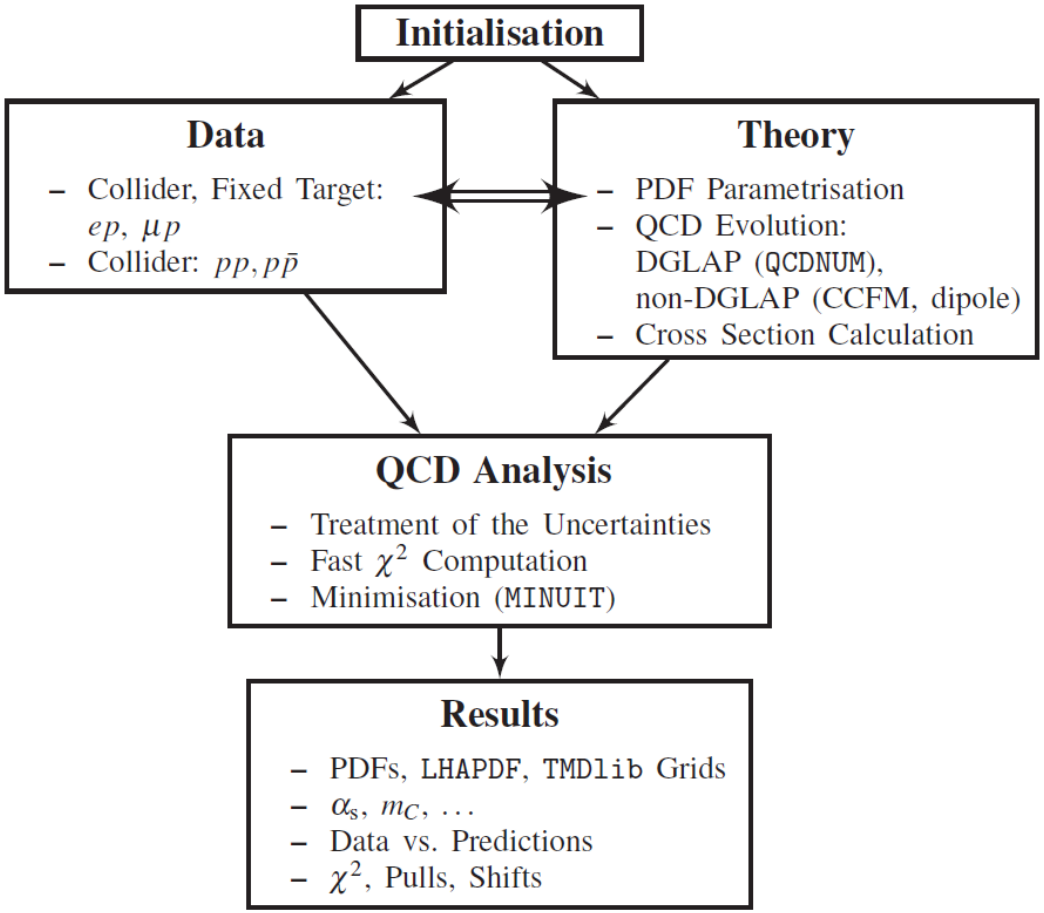
- Fitting shape?
- Validity of the method?
- How to extract $\bar{d}/\bar{u}$?

We have already resolved them
and the new results are expected to be released soon!



Another Method — xFitter —

xFitter



Global analysis tool for **proton** parton distribution functions

- Modules of several analysis methods are prepared
- It gives parton distribution functions with experimental input

Thanks to theorists and developers, experimentalists can also do global analysis with less effort ☺

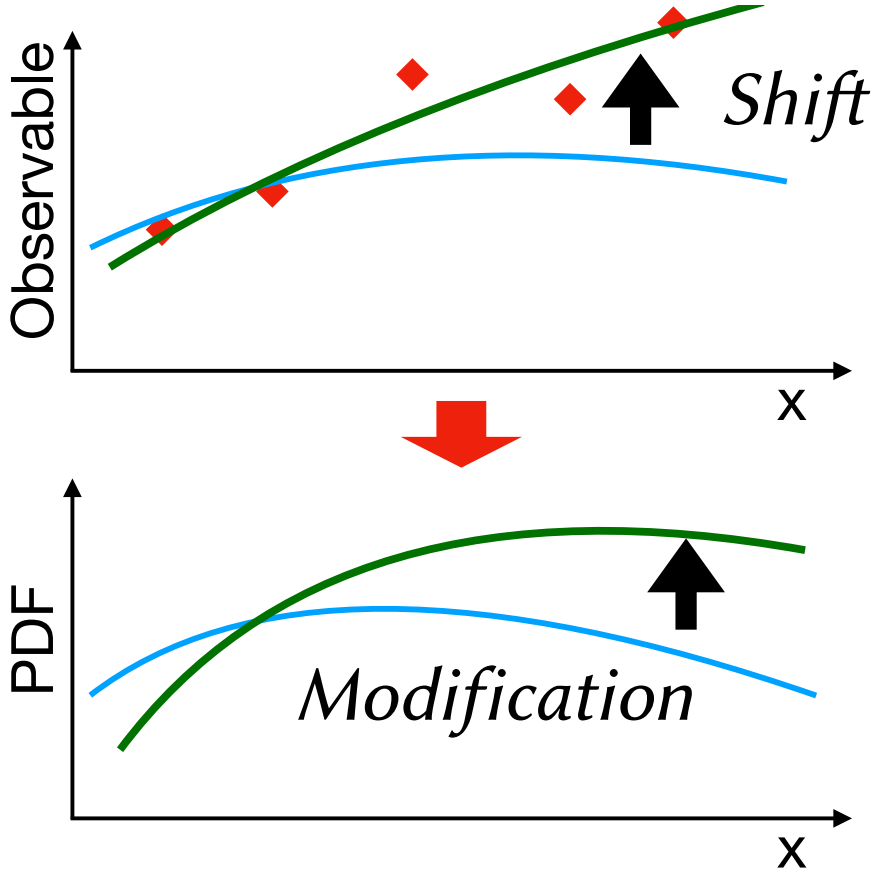
Profiling Method

- Not a full global analysis fitting
- Shows the impact of the input data set to the PDFs
  - This method modifies existing PDFs – Makes PDFs shifted
- Performed with each PDF members

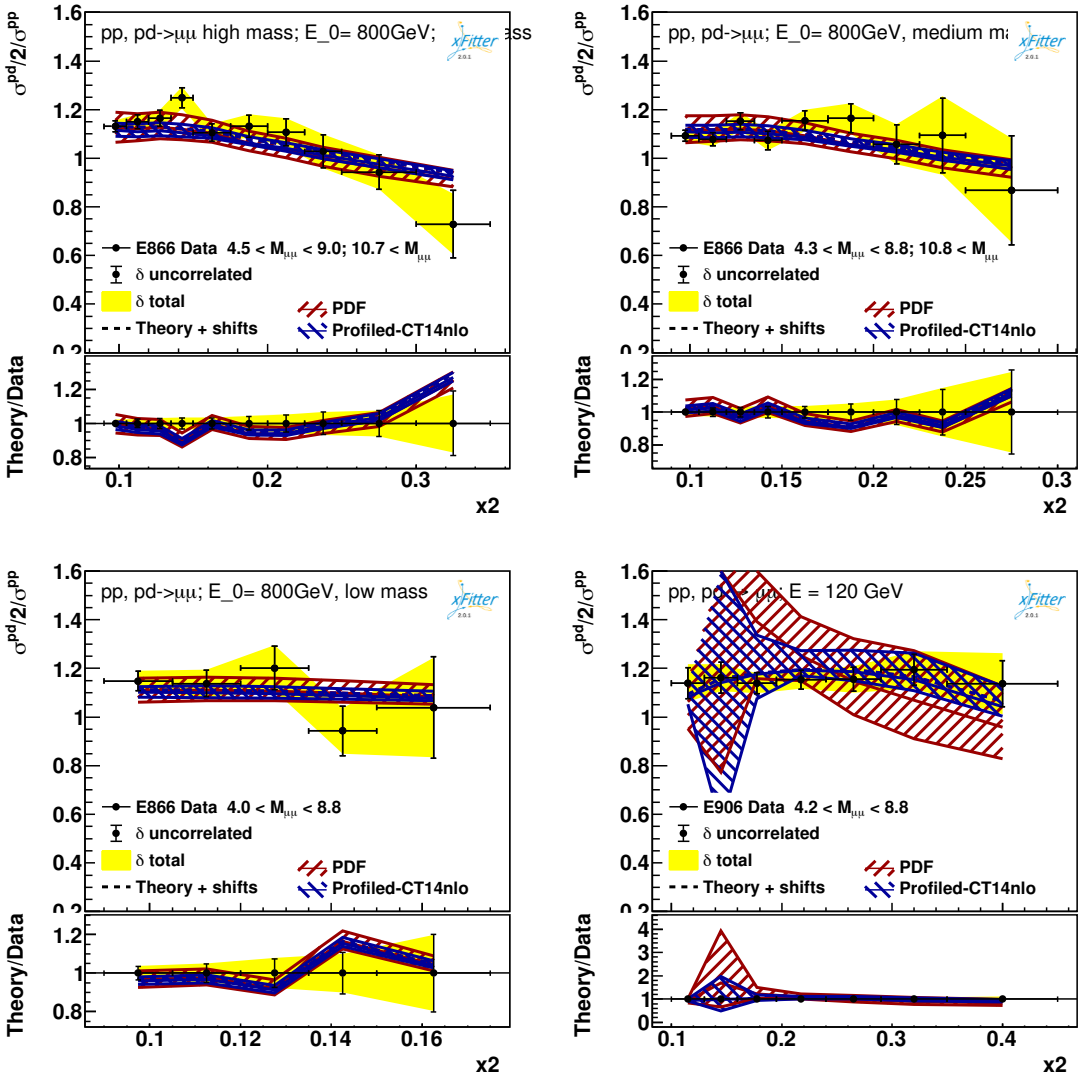
$$\chi^2(\boldsymbol{b}_{\mathbf{exp}}, \boldsymbol{b}_{\mathbf{th}}) = \sum_{i=1}^{N_{\text{data}}} \frac{\left(\sigma_i^{\text{exp}} + \sum_\alpha \Gamma_{i\alpha}^{\text{exp}} b_{\alpha,\text{exp}} - \sigma_i^{\text{th}} - \sum_\beta \Gamma_{i\beta}^{\text{th}} b_{\beta,\text{th}}\right)^2}{\Delta_i^2} + \sum_\alpha b_{\alpha,\text{exp}}^2 + \sum_\beta b_{\beta,\text{th}}^2 .$$

$$f_0' = f_0 + \sum_\beta b_{\beta,\text{th}}^{\min} \left(\frac{f_\beta^+ - f_\beta^-}{2} - b_{\beta,\text{th}}^{\min} \frac{f_\beta^+ + f_\beta^- - 2f_0}{2} \right)$$

Observable (NLO)
= PDFs × *Look-up Table*

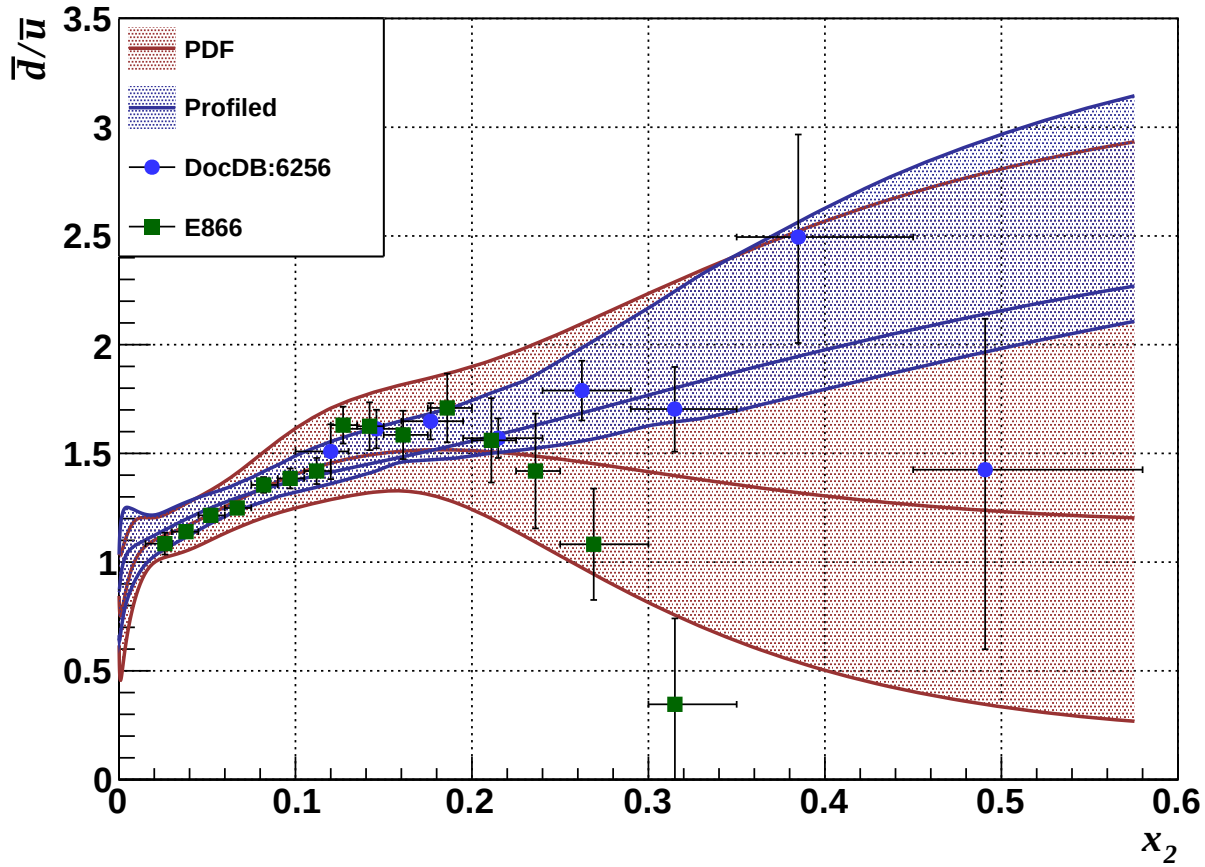


Fitting

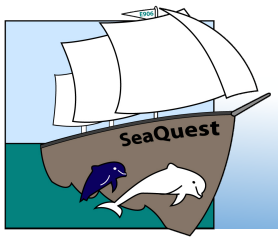


- Data: E866 & E906
- PDF: CT14 NLO
- $\chi^2/\text{ndf} = 39/31 = 1.25$
  Probability: $\sim 15\%$
  - Consistency between two experiments

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

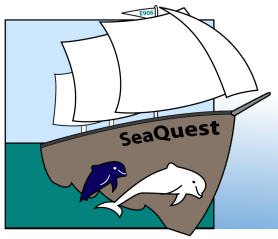


- Profiled PDF covers both E906 & E866 data as shown in previous page
- This analysis is repeated with the new results



Summary

- SeaQuest aims to investigate the structure of the proton using Drell–Yan process.
- Drell–Yan process is sensitive to the antiquark distributions. Suitable for the investigation of the antiquark flavor asymmetry.
- Antiquark flavor asymmetry is important to understand the structure of the proton.
- SeaQuest finished the data taking (2012-2017).
- The preliminary results were released.
  - $\bar{d}/\bar{u} > 1.0$ @ $0.10 < x < 0.45$,
    $\bar{d}/\bar{u} = 1.0$ @ $0.45 < x < 0.58$
  - According to the xFitter analysis, it seems that the discrepancy between E866 is coming from the $\bar{d}/\bar{u}$ extraction method.
- Works for final results are in progress.
  - New method: Extrapolation method
  - Resolving the difficulties of this method. Final results will be released soon!
- Using xFitter, the global analysis is also in progress.



Backup