Measurement of flavor asymmetry of light antiquarks in proton via Drell-Yan process at Fermilab SeaQuest

CNS + Radiation Lab Seminar

2019/01/29 @ RIKEN

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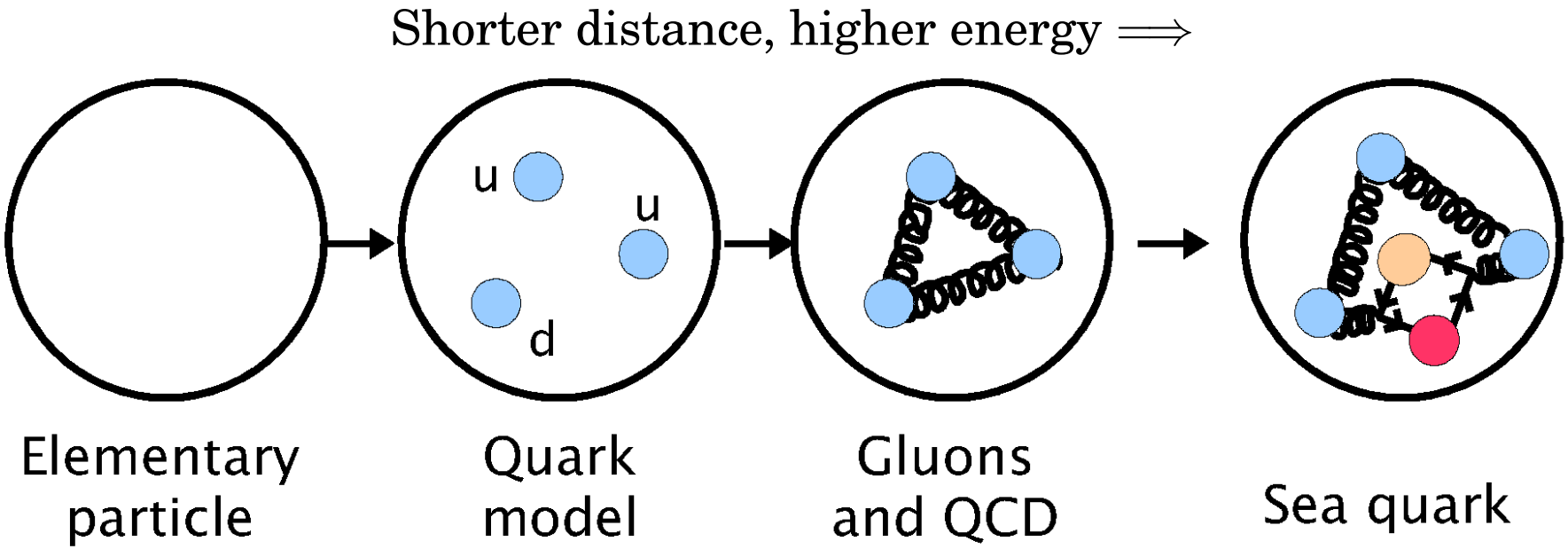
Outline

1. Research motivation
   - Partonic structure of proton (nucleon)
   - Experimental & theoretical understandings on $\bar{d}(x)/\bar{u}(x)$
   - Drell-Yan process for $\bar{d}(x)/\bar{u}(x)$
2. Experimental setup
   - Beam, target & spectrometer
   - Data taking
3. Method & result of $\bar{d}(x)/\bar{u}(x)$ measurement
   - Extraction method
   - Preliminary result
   - Recent progress
4. "E1039/SpinQuest", the successor with polarized target
5. Summary

1. Research Motivation

Internal Structure of Proton (Nucleon)

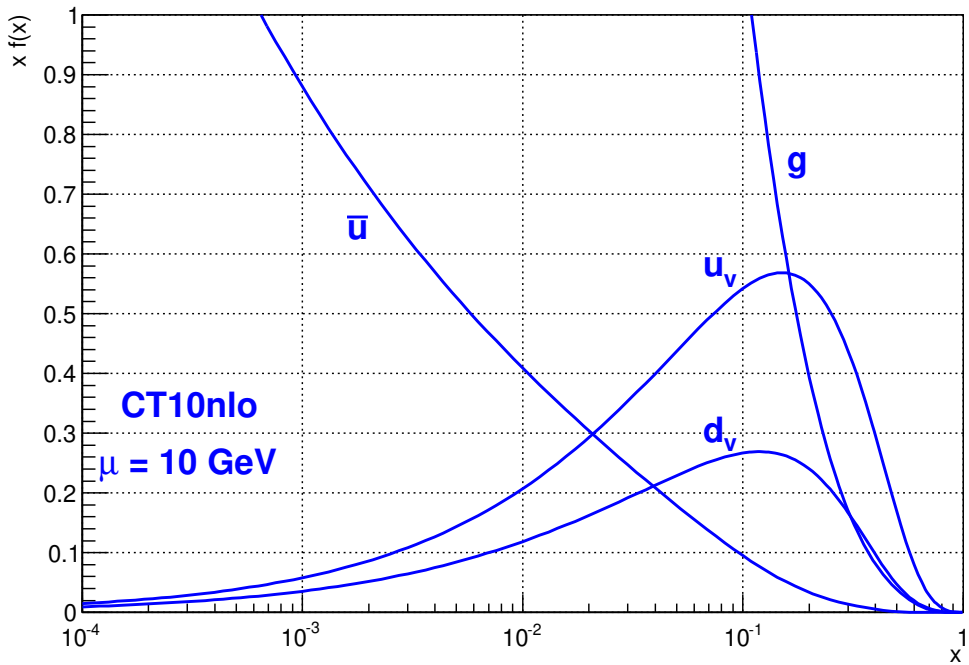
- Representations at various probing scale



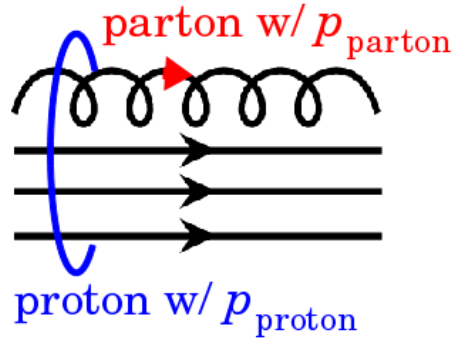
  - Proton structure at energy scale $\mu \gtrsim 1$ GeV ($\lambda \lesssim 1$ fm) will be discussed
  - Dynamical creation of anti-quarks from gluons ... $g \to q\bar{q}$
    - Breakdown of proton momentum: $q : \bar{q} : g \sim 45\% : 10\% : 45\%$ @ $\mu \sim 10$ GeV

Internal Structure of Proton (Nucleon)

- Parton distribution function: $f(x, \mu^2)$



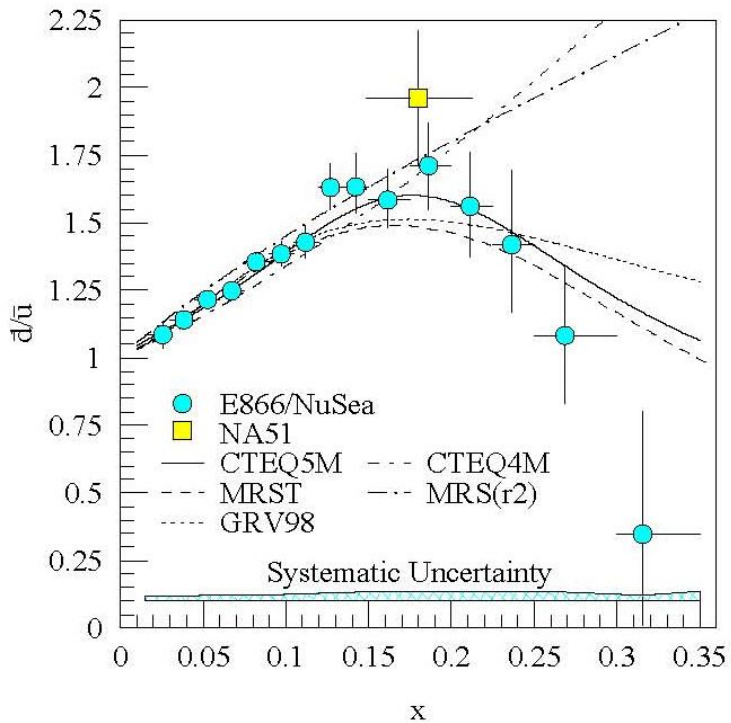
Bjorken-$x \approx \dfrac{p_{parton}}{p_{proton}}$



- The anti-quark distribution is flavor symmetric?
  - Strong force is independent of flavor
  - Splittings of $g \to u\bar{u}$ & $g \to d\bar{d}$ occur equally

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

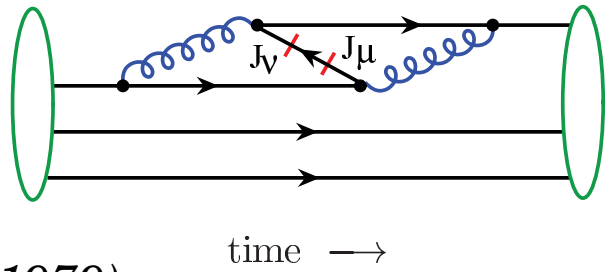
- CERN NMC ('90): deep inelastic muon scattering
  - Gottfried Sum: $S_G = 0.2281(65) < 1/3$
  - $\int \bar{d}(x)dx > \int \bar{u}(x)dx$ ... discovery of flavor asymmetry of anti-quarks in proton
- Measurement of x dependence of $\bar{u}(x)$ & $\bar{d}(x)$: Drell-Yan process
  - CERN NA51 ('94): $\bar{d} > \bar{u}$ at $x \sim 0.18$
  - FNAL E866/NuSea ('98): $\bar{d}(x)/\bar{u}(x)$ for $x \in (0.015, 0.35)$



70% asymmetry!

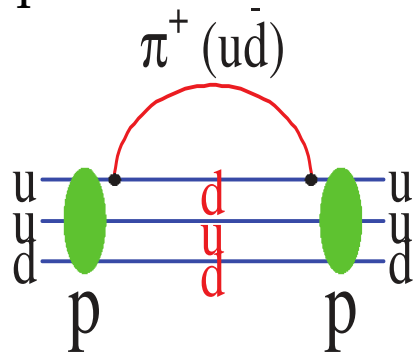
Theories of $\bar{d}/\bar{u}$ Asymmetry (1)

- Mass difference between u & d ($\sim$2 & 5 MeV) in $g \to q\bar{q}$
  - Very small and even results in $\bar{d} > \bar{u}$



- Pauli blocking ... *PRD15, 2590 (1977)*
  - $Prob(g \to u\bar{u}) < Prob(g \to d\bar{d})$ since $p = uud$
  - Cannot explain the measured size ... *NPB149, 497 (1979)*
  - Even $\bar{d} < \bar{u}$ via connected sea (at high x)? ... *PLB736, 411 (2014)*

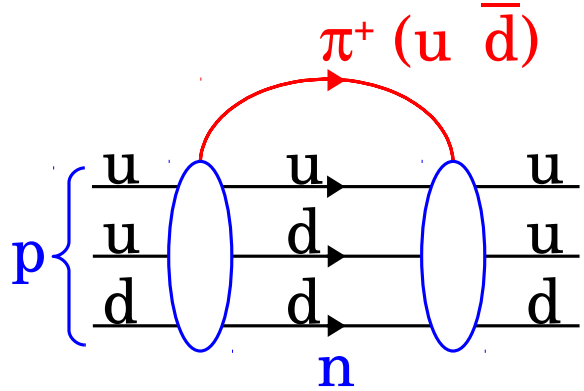
- Chiral quark model ... *PRD59, 034024 (1999)*
  - Effective interaction between Goldstone boson (π) & valence quark
  - $|q_{\text{constituent}}\rangle = \left(1 - \frac{3a}{2}\right)|q\rangle + \frac{3a}{2}|q\pi\rangle$



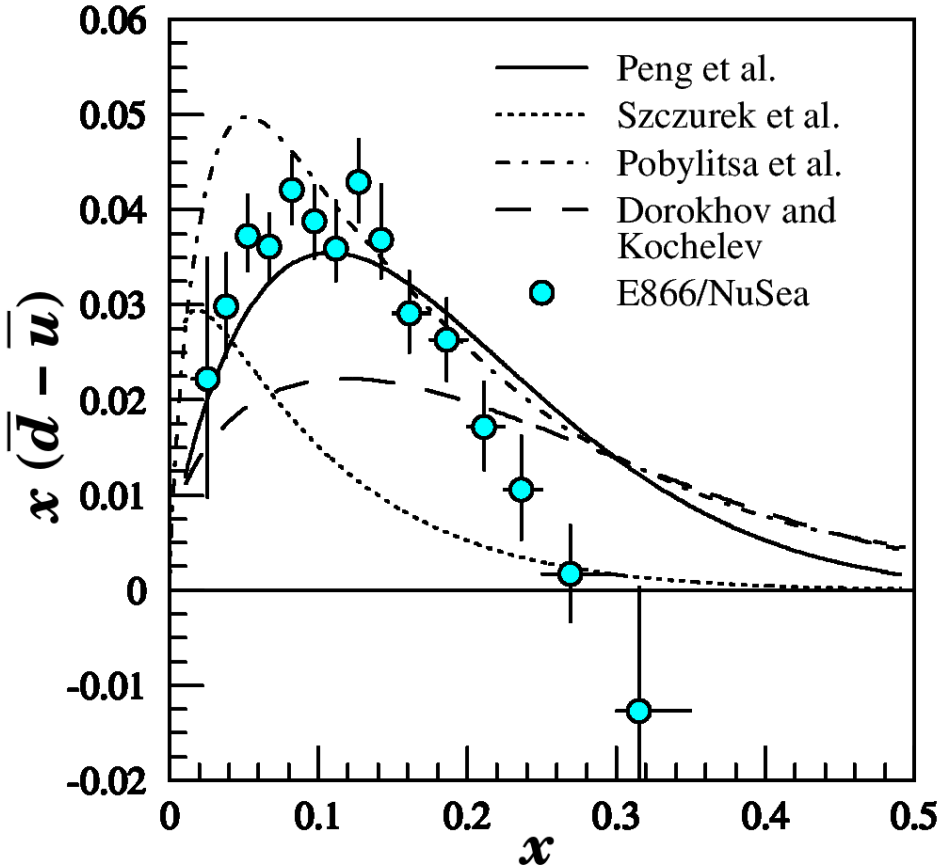
Theories of $\bar{d}/\bar{u}$ Asymmetry (2)

- Statistical model ... *NPA941, 307 (2015)*
  - Based on the Fermi & Bose statistics
  - Predicts $\bar{d}(x) - \bar{u}(x) = \Delta\bar{u}(x) - \Delta\bar{d}(x)$

- Meson cloud model ... *PRD58, 092004 (1998)*
  - $|p\rangle = (1-a-b)|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$
  - More $\bar{d}$ in π^+ as $|n\pi^+\rangle$ etc.
  - Less $\bar{u}$ in π^- as $|\Delta^{++}\pi^-\rangle$ etc.
  - Predict non-zero $L_{q,\bar{q}}$ like "meson tornado" (need $L = 1$ of π to make $J^P = 1/2^+$ of proton, as parity of π is $J^P = 0^-$)



Comparison of Theories to Measurements

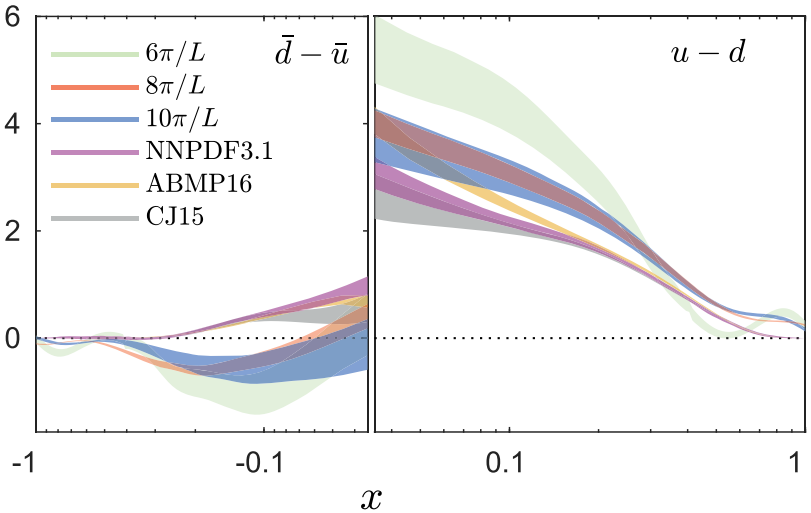


Meson cloud model: PRD58, 092004
Chral quark model: NPA596, 397
Chral quark model: PRD59, 034024
Instanton model: PLB304, 167
(Updated calculations exist)

- The x dependence of $\bar{d}(x)/\bar{u}(x)$ is the key to develope/examine models
  - Sharp drop at $x \sim 0.3$. Even go down to $\bar{d} < \bar{u}$?

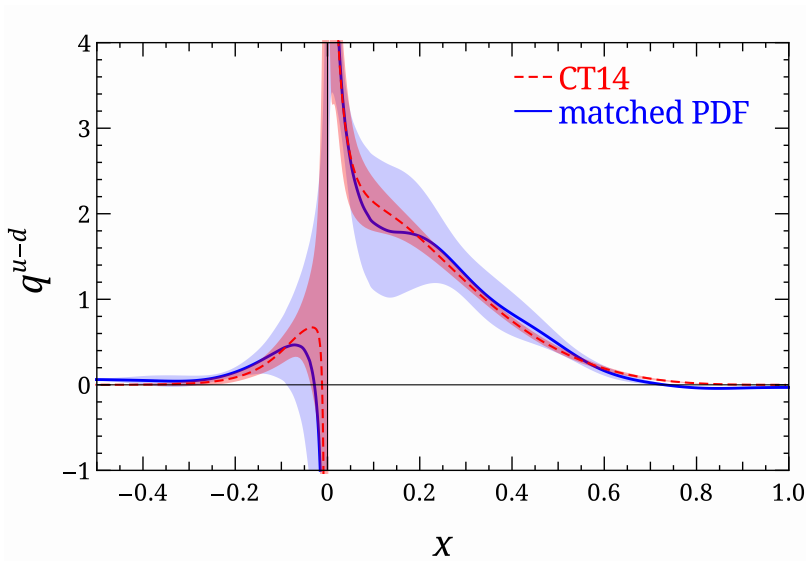
Flavor Asymmetry by Lattice QCD

- Direct calculation of PDF (not Mellin moment)
  - With large-momentum effective theory (LaMET)
  - ETM collaboration



PRL 121, 112001 (2018)

  - LP^3 collaboration

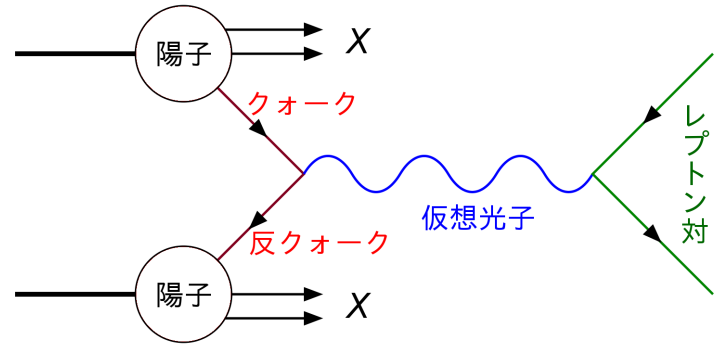


arXiv:1803.04393 (2018)

- $\bar{d}(x)/\bar{x}(x)$ is an attractive object on lattice as well

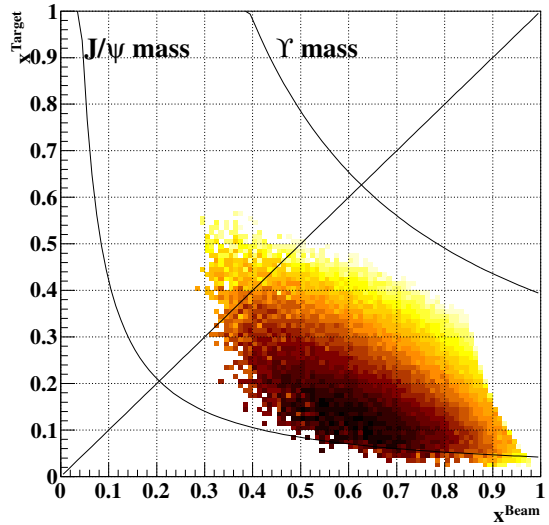
Measurement of $\bar{d}(x)/\bar{u}(x)$ with Drell-Yan Process

- Drell-Yan process: $p + p \to \gamma^* \to \mu^+ + \mu^-$
  - Invariant mass: $M^2 = x_{beam} x_{target} s$,
    Rapidity: $\exp Y = \sqrt{x_{beam}/x_{target}}$
  - $x_{beam} = \frac{M}{\sqrt{s}} e^{Y}, \quad x_{target} = \frac{M}{\sqrt{s}} e^{-Y}$
  - Cross section at LO:



$$\frac{d^2\sigma}{dx_{be}dx_{ta}} = \frac{4\pi\alpha^2}{9x_{be}x_{ta}} \frac{1}{s} \sum_{q=u,d} {e_q}^2 \{q_{be}(x_{be})\bar{q}_{ta}(x_{ta}) + \bar{q}_{be}(x_{be})q_{ta}(x_{ta})\}$$

  - Only "$q_{be}(x_{be})\bar{q}_{ta}(x_{ta})$" survives @ forward rapidity, i.e. quark in beam & anti-quark in target



- Ratio of cross sections with LH2 & LD2 targets

$$\frac{\sigma_{pd}(x_{ta})}{2\sigma_{pp}(x_{ta})} = \frac{\sigma_{pp}(x_{ta}) + \sigma_{pn}(x_{ta})}{2\sigma_{pp}(x_{ta})} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_{ta})}{\bar{u}(x_{ta})}\right)$$

- SeaQuest measures the x dependence of $\bar{d}(x)/\bar{u}(x)$ particularly at high x ($0.15 \lesssim x \lesssim 0.45$)

Aim to Research Anti-Quark in Proton

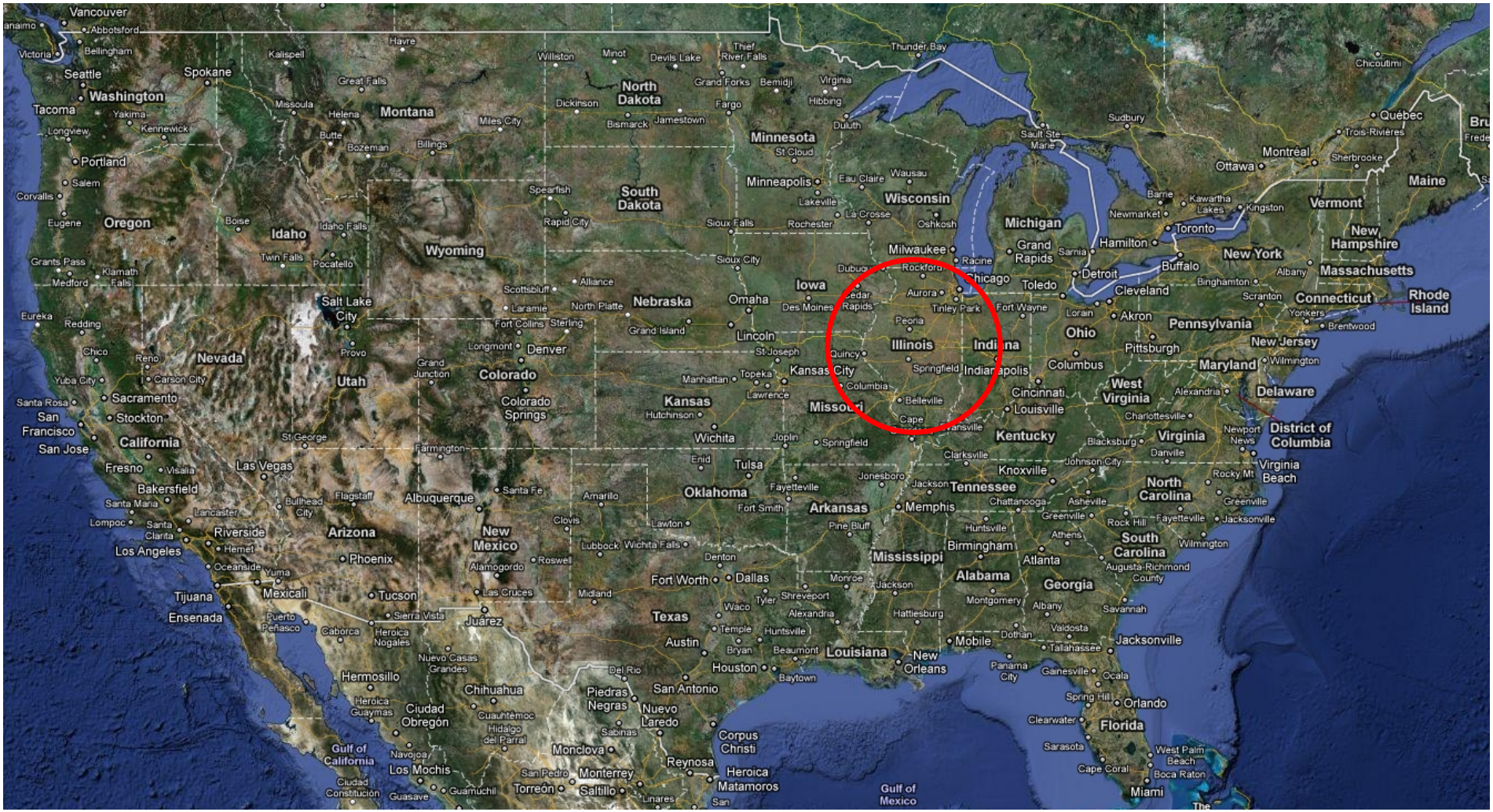
1. Improve the accuracy of anti-quark PDFs
   - Proton is widely used in various research
   - $\bar{q}(x)$ is an input of hadron-reaction simulations (ex: $u + \bar{d} \to W^+$)

2. Investigate QCD effects on the proton structure
   - All anti-quarks are dynamically created by QCD

3. Examine hadron models based on QCD effective theory
   - Each model represents an aspect of hadrons
   - Can it well describe antiquarks also?

2. Experimental Setup

USA


Vancouver
Abbotsford
Victoria
Bellingham
Seattle
Washington
Spokane
Tacoma
Yakima
Kennewick
Longview
Portland
Salem
Corvallis
Eugene
Oregon
Boise
Idaho
Idaho Falls
Twin Falls
Pocatello
Grants Pass
Klamath Falls
Medford
Eureka
Redding
Chico
Reno
Nevada
Carson City
Yuba City
Sacramento
Santa Rosa
San Francisco
Stockton
San Jose
California
Fresno
Visalia
Las Vegas
Bakersfield
Santa Maria
Lancaster
Lompoc
Santa Clarita
Riverside
Hemet
Los Angeles
Oceanside
Yuma
Mexicali
Tijuana
Ensenada
Puerto Peñasco
Caborca
Heroica Nogales
Hermosillo
Heroica Guaymas
Ciudad Obregón
Navojoa
Los Mochis
Ciudad Constitución
Guasave
Guamuchil
Gulf of California
Havre
Kalispell
Great Falls
Missoula
Helena
Montana
Butte
Bozeman
Billings
Miles City
Wyoming
Salt Lake City
Provo
Utah
Grand Junction
Colorado
Denver
Colorado Springs
Farmington
Albuquerque
Santa Fe
Flagstaff
Bullhead City
Arizona
Phoenix
Tucson
Sierra Vista
Juárez
Nuevo Casas Grandes
Chihuahua
Cuauhtémoc
Hidalgo del Parral
Monclova
Monterrey
San Pedro
Torreón
Saltillo
Linares
Piedras Negras
Nuevo Laredo
Sabinas
Del Rio
San Antonio
Corpus Christi
Reynosa
Heroica Matamoros
Gulf of Mexico
Williston
Minot
Devils Lake
Thief River Falls
Grand Forks
Bemidji
Virginia
Hibbing
Duluth
Fargo
Jamestown
Bismarck
Dickinson
North Dakota
Minnesota
St Cloud
Minneapolis
Eau Claire
Wausau
Lakeville
La Crosse
Rochester
Oshkosh
Wisconsin
Sioux Falls
Sioux City
Spearfish
Rapid City
South Dakota
Alliance
Scottsbluff
Laramie
North Platte
Nebraska
Omaha
Iowa
Des Moines
Cedar Rapids
Lincoln
Grand Island
Fort Collins
Sterling
Longmont
St Joseph
Quincy
Kansas City
Topeka
Manhattan
Lawrence
Kansas
Hutchinson
Wichita
Joplin
Springfield
Enid
Tulsa
Oklahoma
Fayetteville
Fort Smith
Arkansas
Pine Bluff
Lawton
Clovis
Amarillo
Lubbock
Wichita Falls
Denton
Fort Worth
Dallas
Monroe
Jackson
Shreveport
Tyler
Waco
Alexandria
Texas
Temple
Huntsville
Austin
Bryan
Beaumont
Houston
Baytown
Louisiana
New Orleans
Mississippi
Hattiesburg
Alabama
Montgomery
Mobile
Dothan
Panama City
Tallahassee
Valdosta
Jacksonville
Gainesville
Ocala
Spring Hill
Orlando
Clearwater
Florida
Sarasota
West Palm Beach
Cape Coral
Boca Raton
Miami
Georgia
Albany
Savannah
Augusta-Richmond County
Atlanta
Birmingham
Huntsville
Athens
South Carolina
Wilmington
Greenville
Rock Hill
Fayetteville
Jacksonville
North Carolina
Rocky Mt
Virginia Beach
Greenville
Asheville
Chattanooga
Knoxville
Johnson City
Tennessee
Jonesboro
Jackson
Memphis
Kentucky
Clarksville
Louisville
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Columbus
Ohio
Cape
Evansville
Indianapolis
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Illinois
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Tinley Park
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Delaware
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Yonkers
Scranton
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Buffalo
Toronto
Hamilton
Sarnia
Grand Rapids
Michigan
Sault Ste Marie
Sudbury
Barrie
Newmarket
Kawartha Lakes
Kingston
Vermont
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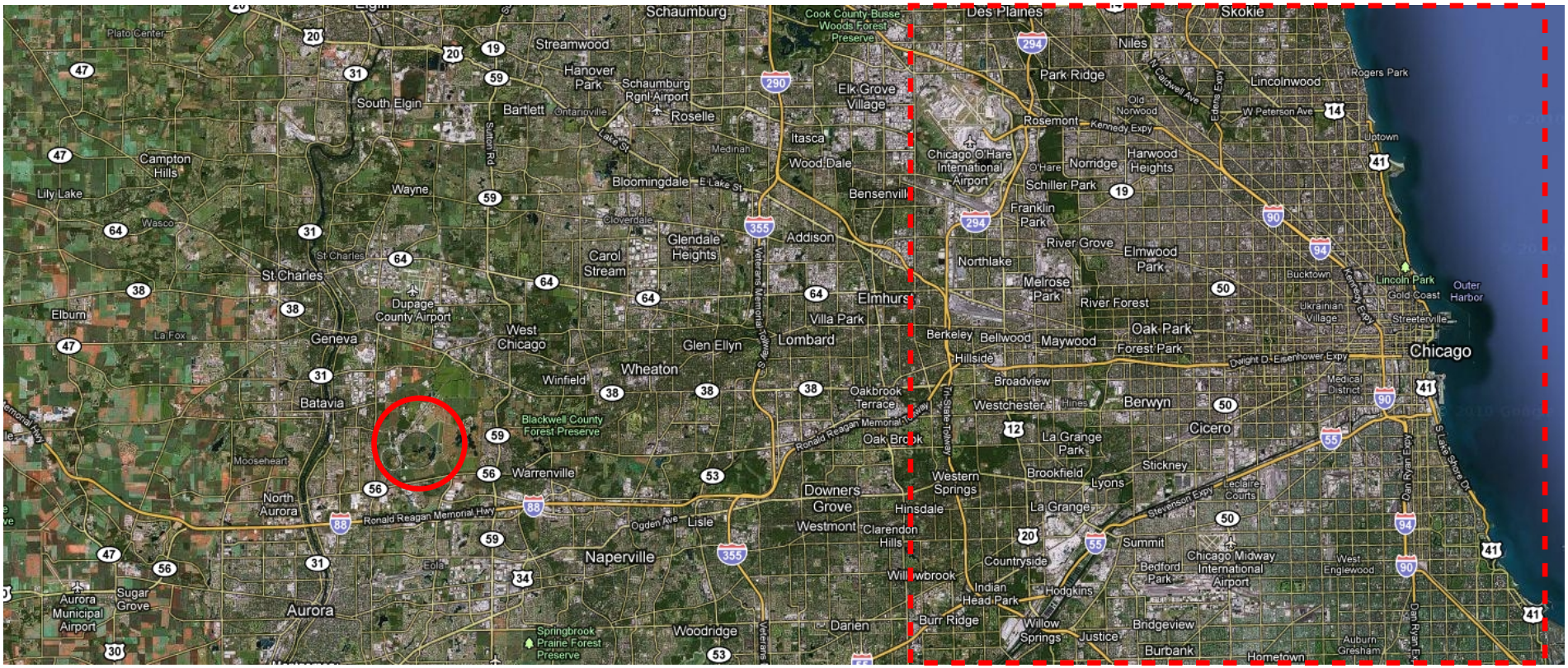
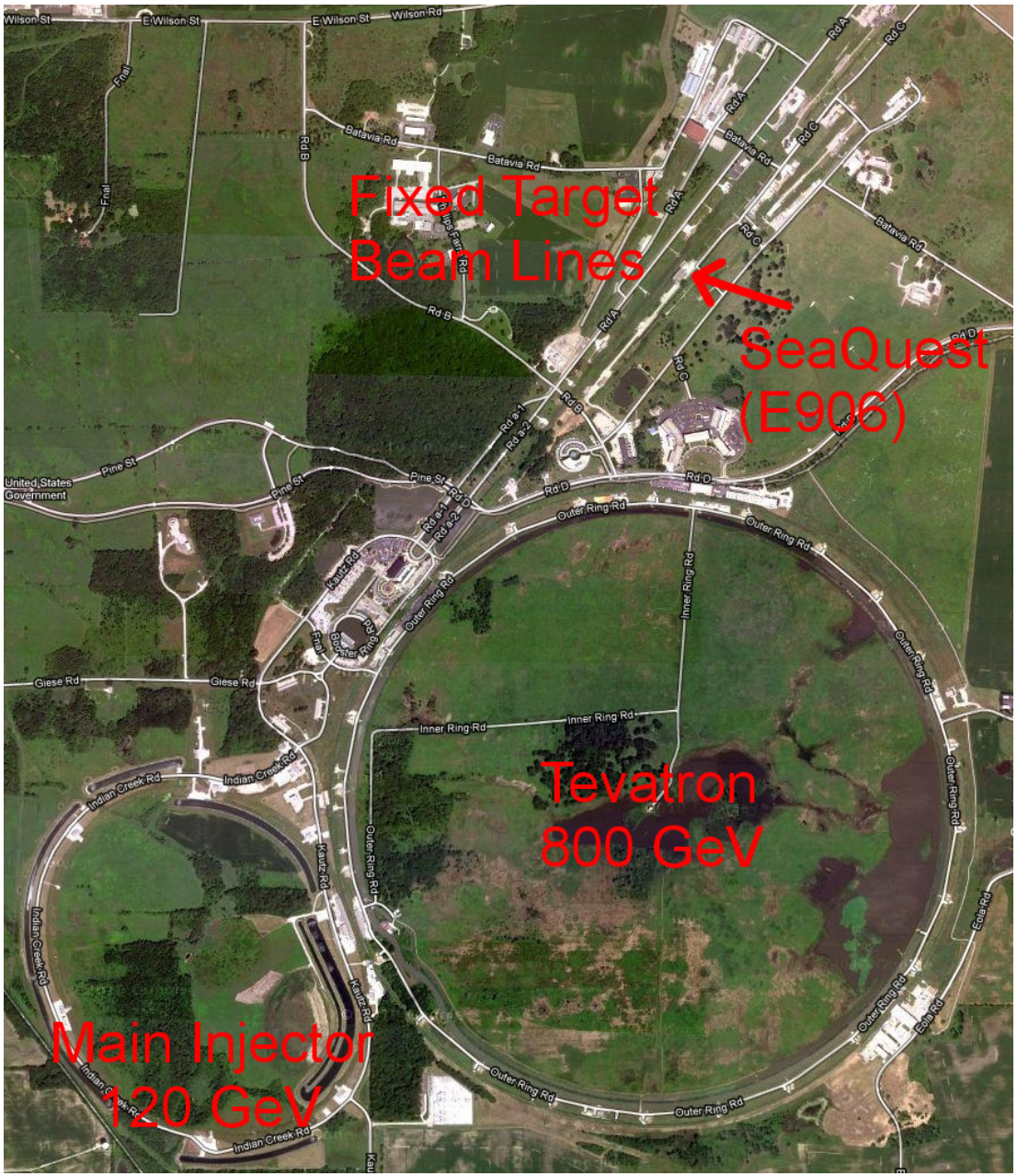
Frede

Fermi National Accelerator Lab



Fermilab Proton Beam

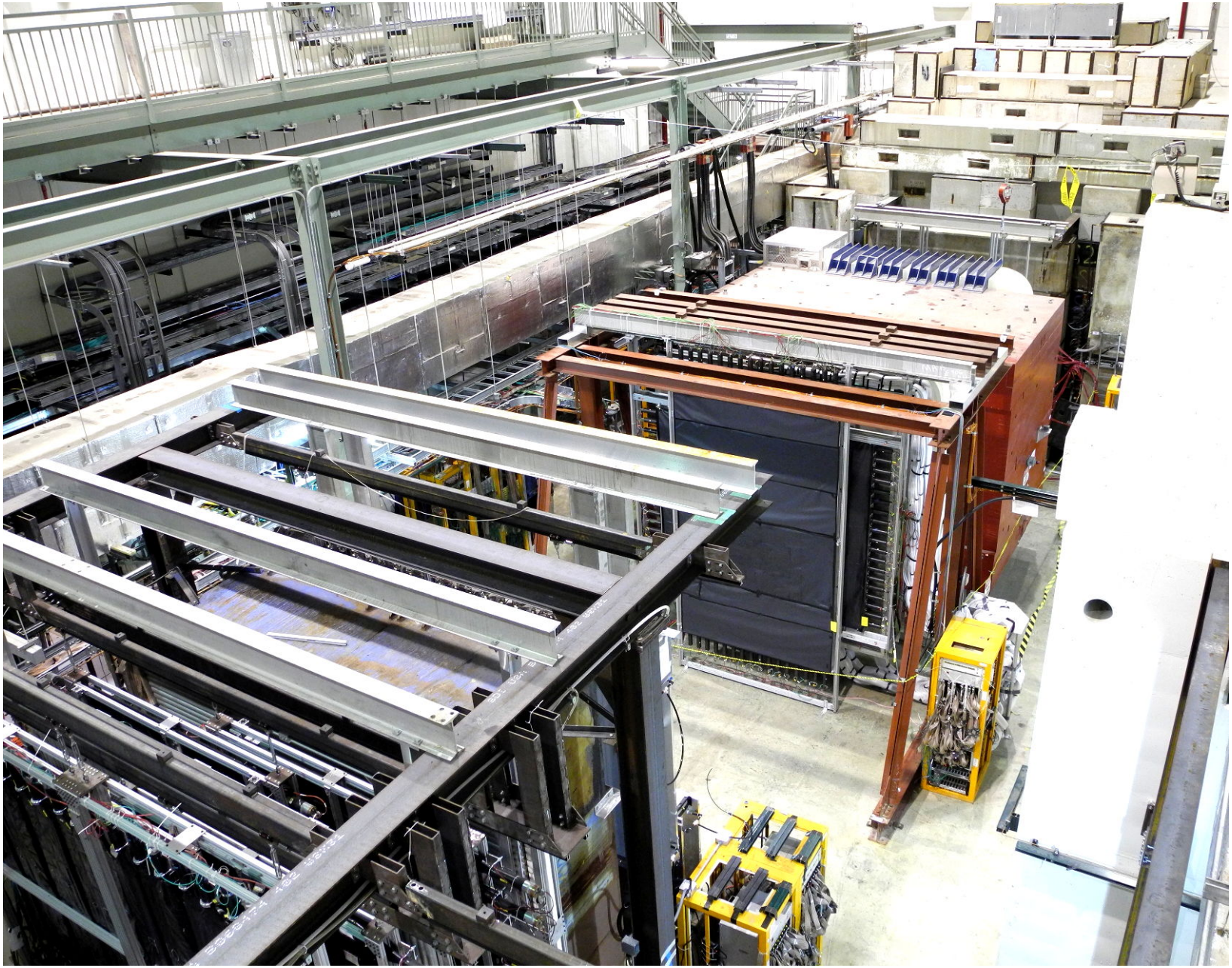


- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for E906
  - 55 sec for ν exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec in spot size

FNAL-SeaQuest Collaboration

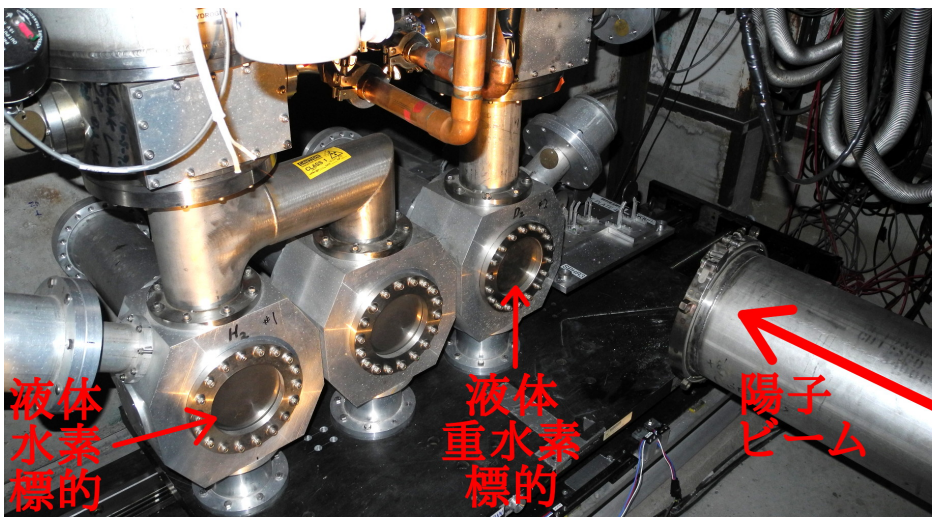
- Institutes
  - Abilene Christian Univ.
  - Argonne National Lab
  - Fermi National Accelerator Lab
  - KEK Jp
  - Los Alamos National Lab
  - Univ. of Michigan
  - RIKEN Jp
  - Tokyo Tech Jp
  - Academia Sinica Tw
  - Univ. of Colorado
  - Univ. of Illinois
  - Ling-Tung Univ. Tw
  - Univ. of Maryland
  - National Kaohsiung Normal Univ.
  - Rutgers Univ.
  - Yamagata Univ. Jp

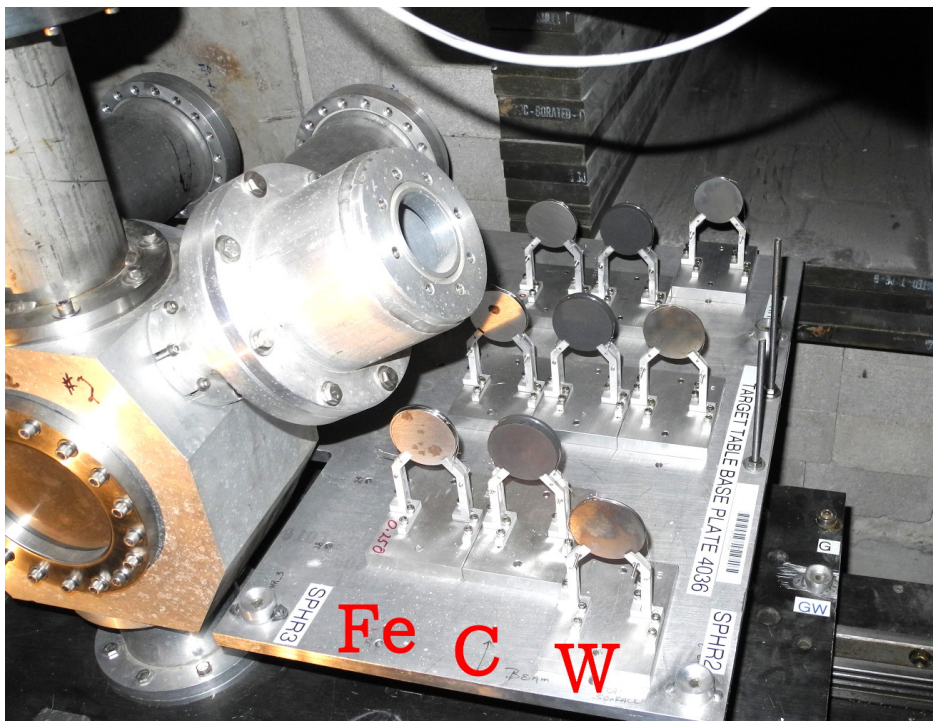
SeaQuest Hall — 2015-July-27



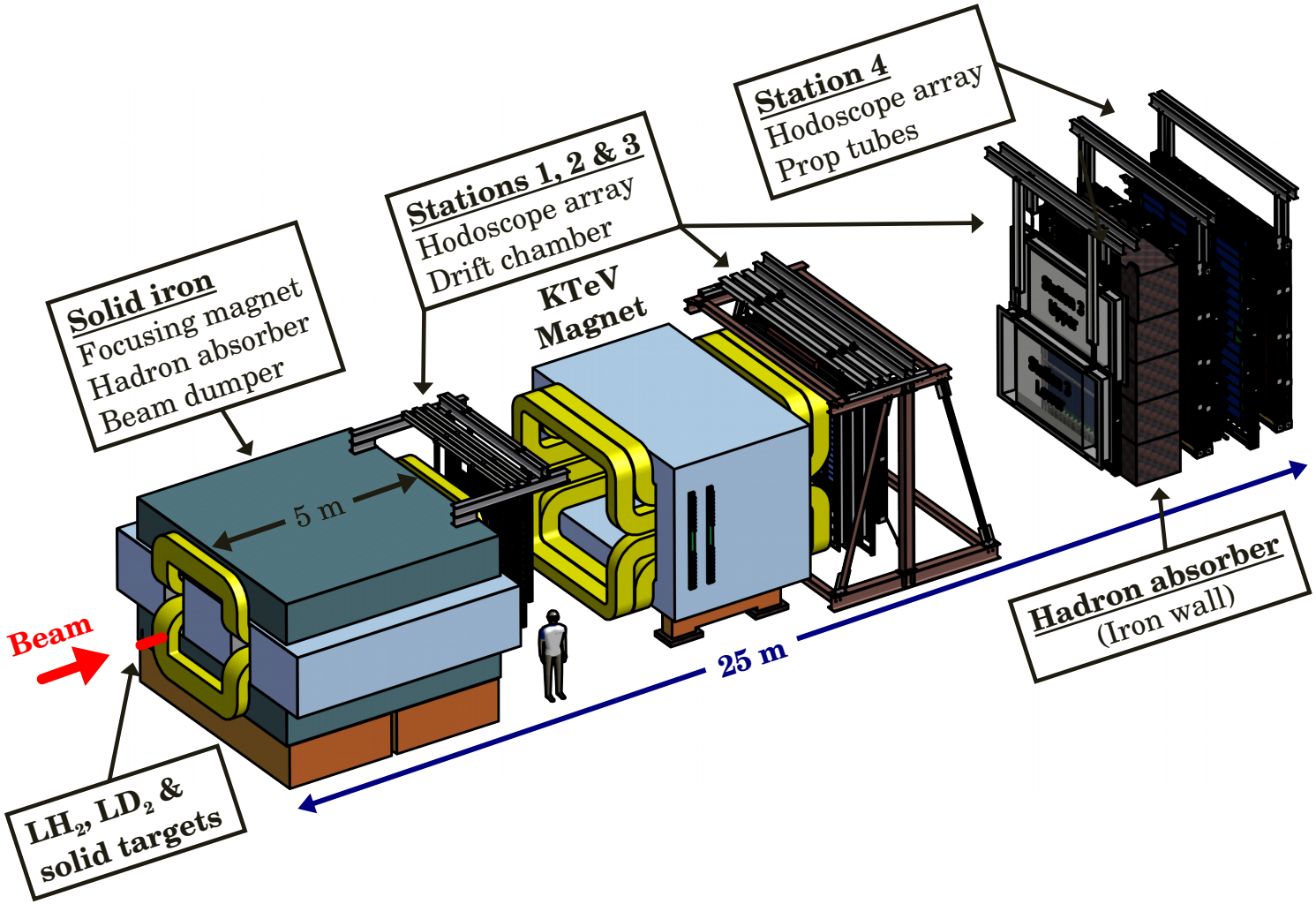
SeaQuest Targets

- LH_2, LD_2
  - 50.8 cm $\sim$ 0.1 interaction lengths
- Iron, Carbon, Tungsten



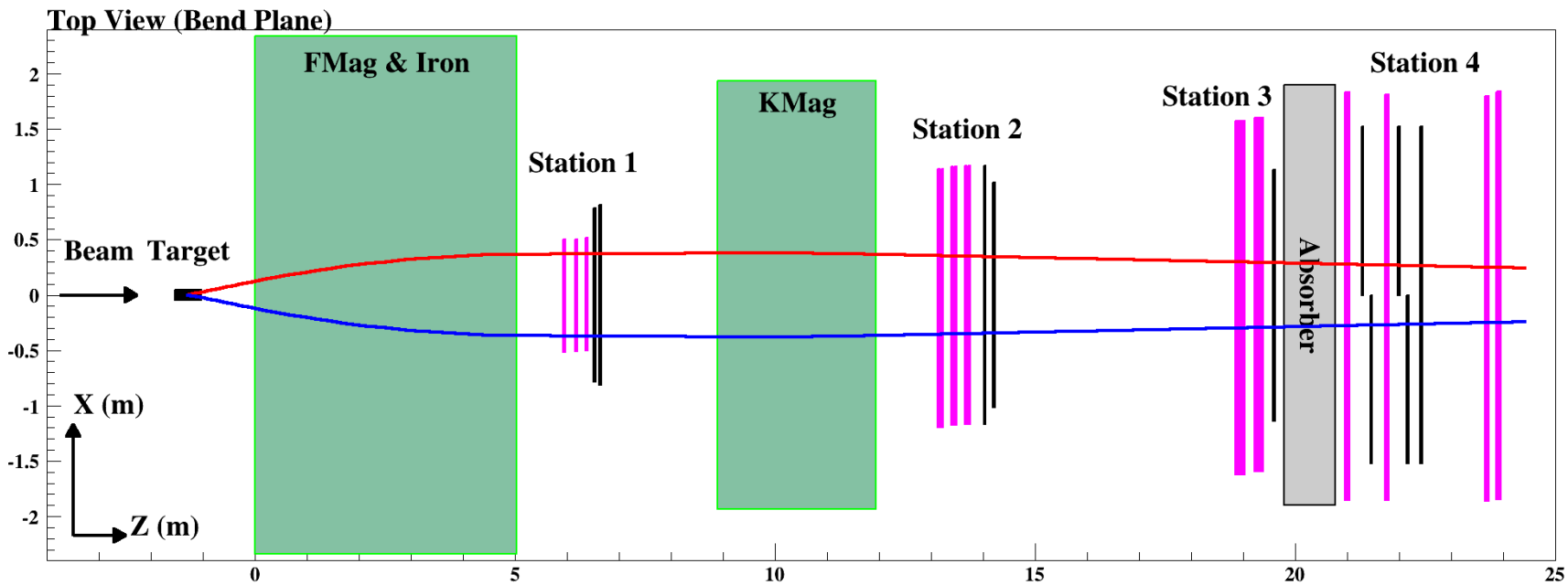


E906/SeaQuest Spectrometer



- Targets: LH_2, LD_2, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump

- A typical Drell-Yan event (top view) ... mass = 6 GeV, $\theta_{\mu+}$ = 90°, $\phi_{\mu+}$ = 0°



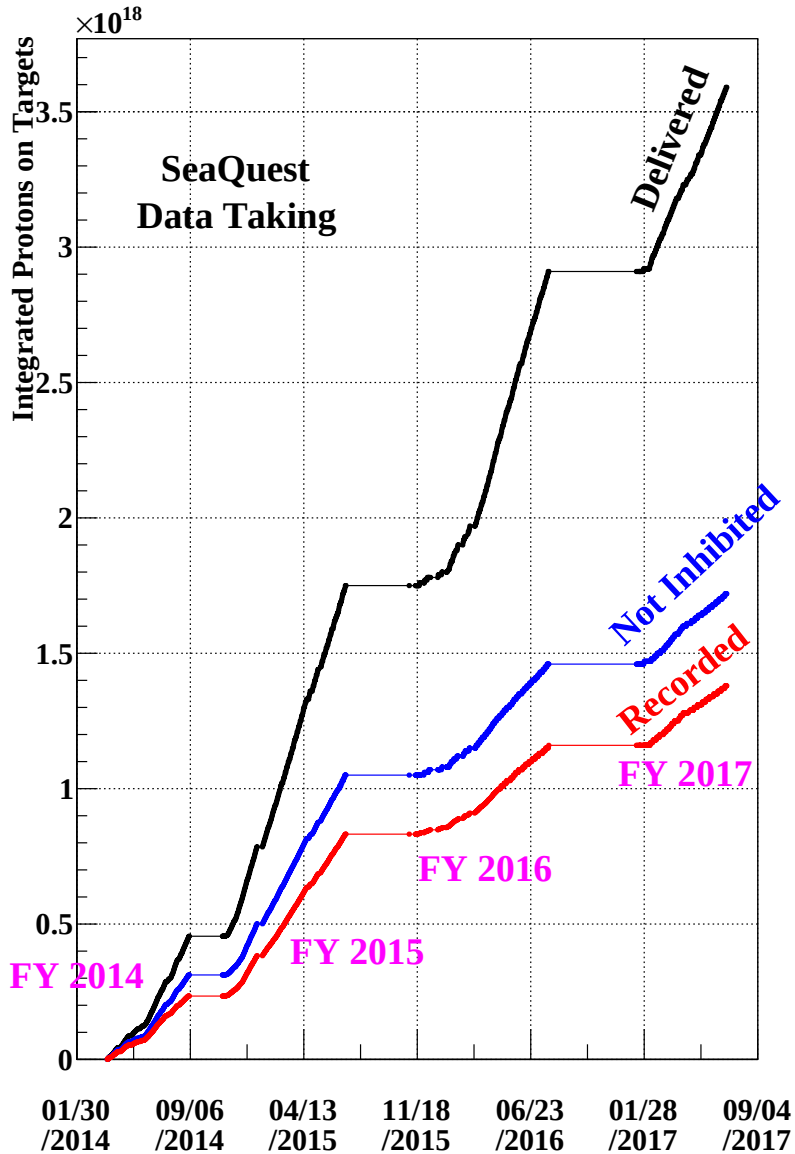
- Detection of dimuons
  - Station 1-3 : Tracking with drift chambers
  - Station 4 : Particle identification with drift tube
  - Momenta of detected muons are 40 GeV/c on average

SeaQuest Data Taking

- Data-taking periods

Year	Month	Event
2012	03-04	1st data taking (commissioning)
2013	11-	2nd data taking (10 months)
2014	11-	3rd data taking (8 months)
2015	10-	4th data taking (10 months)
2016	12-	5th data taking (7 months)

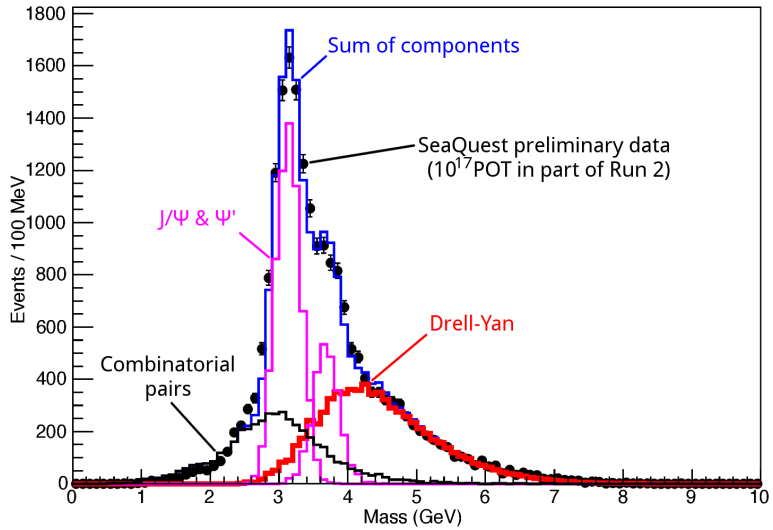
- Beam protons on targets
  - 1.4×10^{18} recorded
  - 0.6×10^{18} analyzed for preliminary $\bar{d}/\bar{u}$
- Last data taken in FY2017
  - Wider chamber acceptance at St. 1
    $\Longrightarrow$ 40% more events at high x (~ 0.4)
  - Top+Top & Bottom+Bottom events
    (thanks to faster DAQ)
    $\Longrightarrow$ 30% more events



3. Method & Result of $\bar{d}(x)/\bar{u}(x)$ Measurement

Extraction of $\bar{d}(x)/\bar{u}(x)$ — Step 1

- Measure Drell-Yan events with two targets
  - LH2 & LD2 targets
  - Invariant mass > 4.2 GeV
- Correct Drell-Yan yields for
  - Backgrounds
  - Reconstruction efficiency
    (due to detector hit rates)
- Normalize with relative luminosity
- Take the ratio of normalized yields

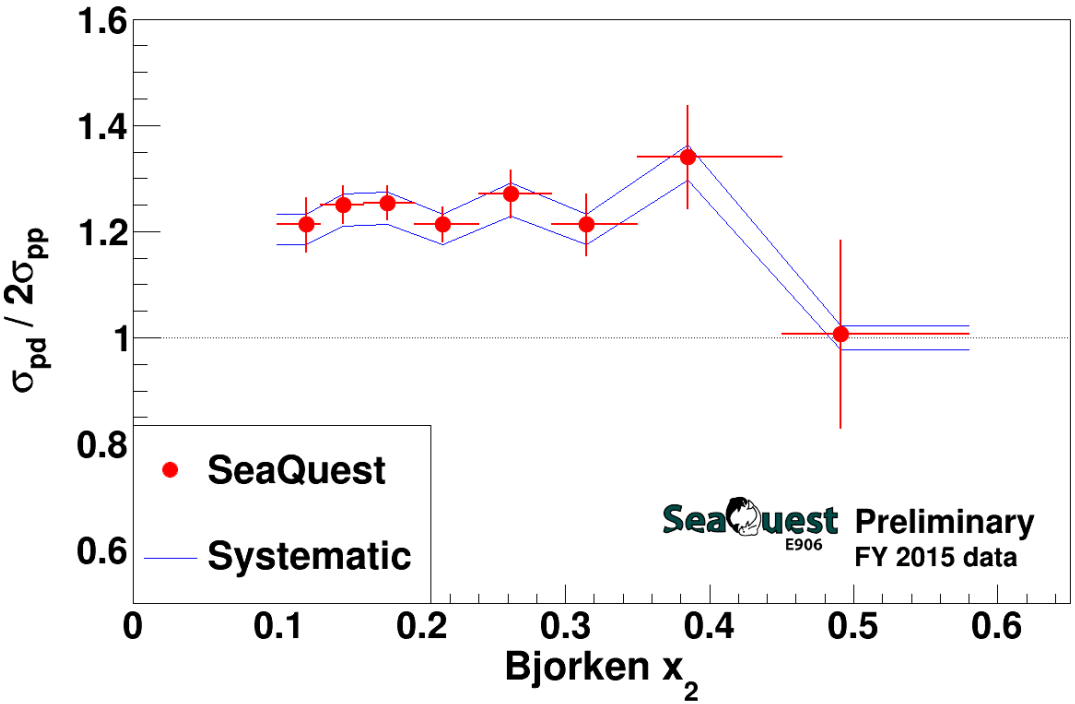


$$\frac{\sigma_{pd}(x_{ta})}{2\sigma_{pp}(x_{ta})} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_{ta})}{\bar{u}(x_{ta})}\right)$$

  - Systematic errors cancel out between σ_{pd} & σ_{pp}
  - Direct observable in experiment

Cross-Section Ratio: $\sigma_{pd}/2\sigma_{pp}$

- Preliminary result with ~70% of FY 2014 & 2015 data



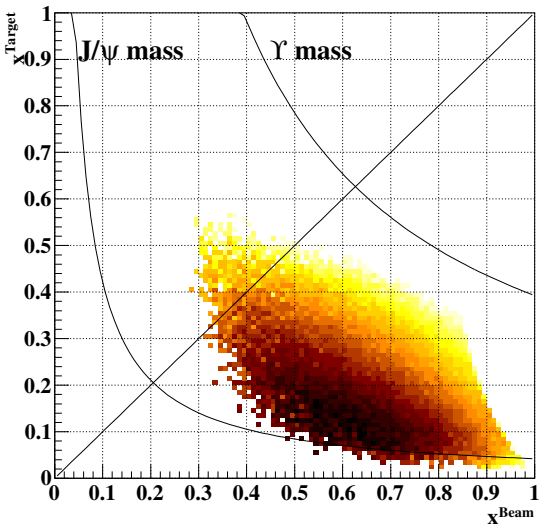
- Systematic errors
  - H contamination of LD2 target
  - Background subtraction
  - Tracking efficiency correction
- $\sigma_{pd}/2\sigma_{pp}$ always > 1 in measured x range

Extraction of $\bar{d}(x)/\bar{u}(x)$ — Step 2

- Derive $\bar{d}(x)/\bar{u}(x)$ from $\sigma_{pd}/2\sigma_{pp}$
  - This relation is not accurate at high x_{ta}

$$\frac{\sigma_{pd}(x_{ta})}{2\sigma_{pp}(x_{ta})} \approx \frac{1}{2}\left(1+\frac{\bar{d}(x_{ta})}{\bar{u}(x_{ta})}\right)$$

  because the assumption "$x_{be} \gg x_{ta}$" breaks
  - Iterative calculation from $\bar{d}/\bar{u}$ to $\sigma_{pd}/2\sigma_{pp}$



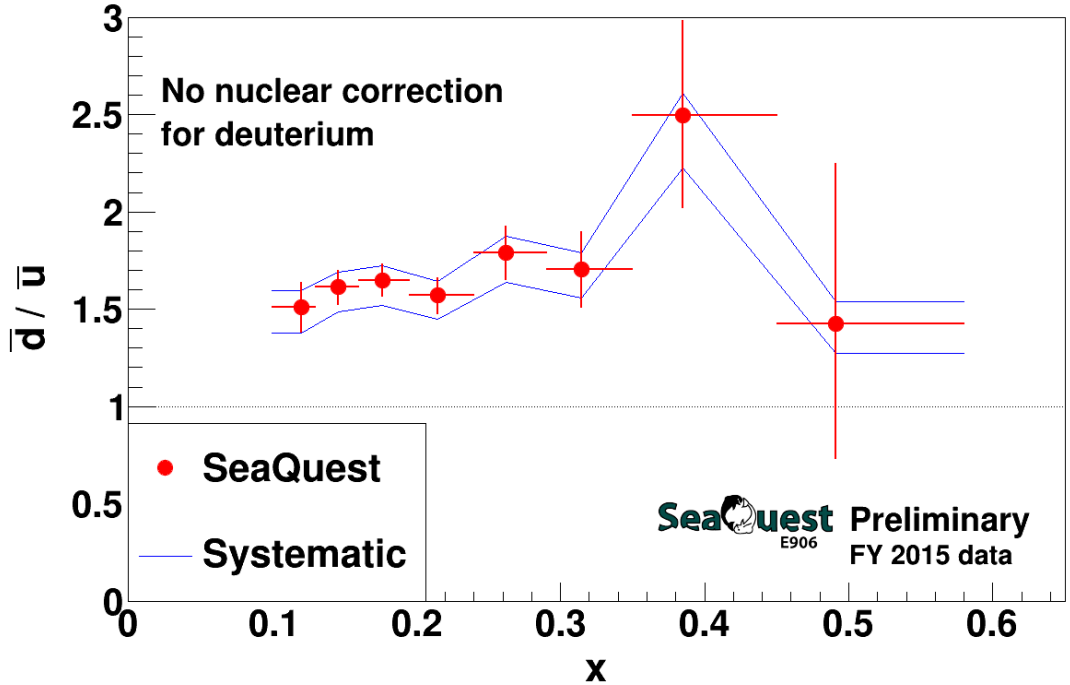
1. Have the measured $\sigma_{pd}/2\sigma_{pp}$ ($\equiv R_{meas}$)
2. Initialize $\bar{d}(x)/\bar{u}(x) = 1$
3. Calculate the cross-section ratio ($\equiv R_{pred}$) without assuming $x_{be} \gg x_{ta}$:

$$\sigma \propto \sum_{q=u,d} {e_q}^2 \{q_{be}(x_{be})\bar{q}_{ta}(x_{ta}) + \bar{q}_{be}(x_{be})q_{ta}(x_{ta})\}$$

   - Use event-by-event measured kinematics (x_{be} & x_{ta})
   - Take $u(x)$, $d(x)$ & $\bar{u}(x)+\bar{d}(x)$ from CT10 PDF
4. Adjust $\bar{d}(x)/\bar{u}(x)$ to reduce $R_{pred} - R_{meas}$
5. Go back to #3 until $R_{pred} \approx R_{meas}$

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

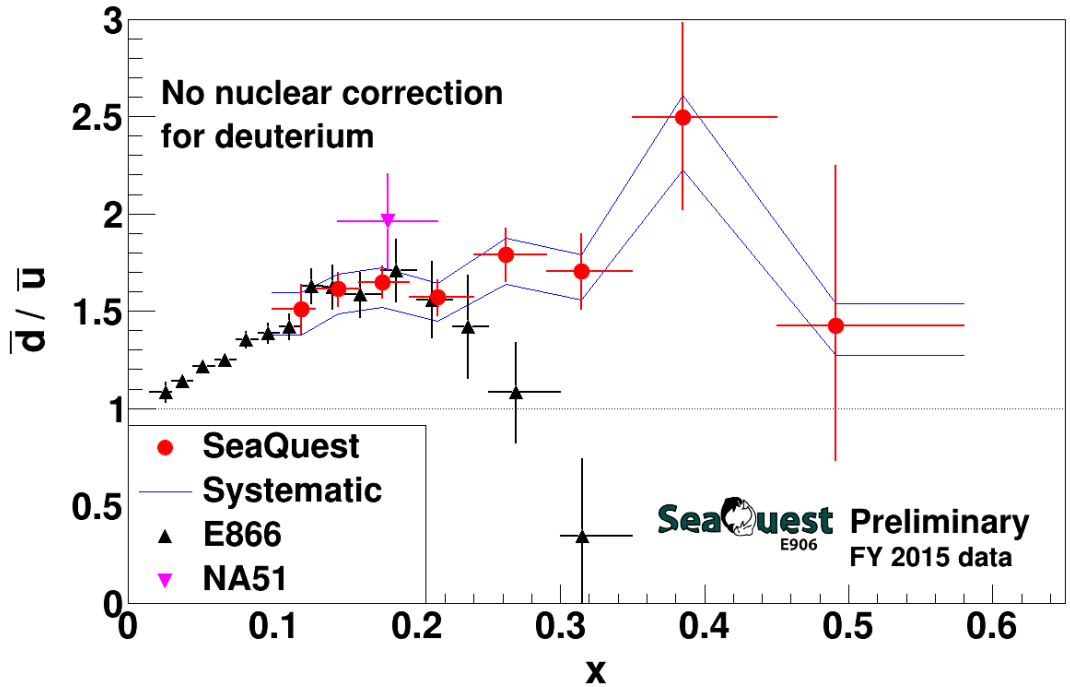
- Preliminary result



- Systematic errors
  - Errors of cross-section ratio
  - Errors of CT10 PDF
  - $\bar{d}/\bar{u}$ outside the measured x range
- $\bar{d}/\bar{u} > 1$ at high x also

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

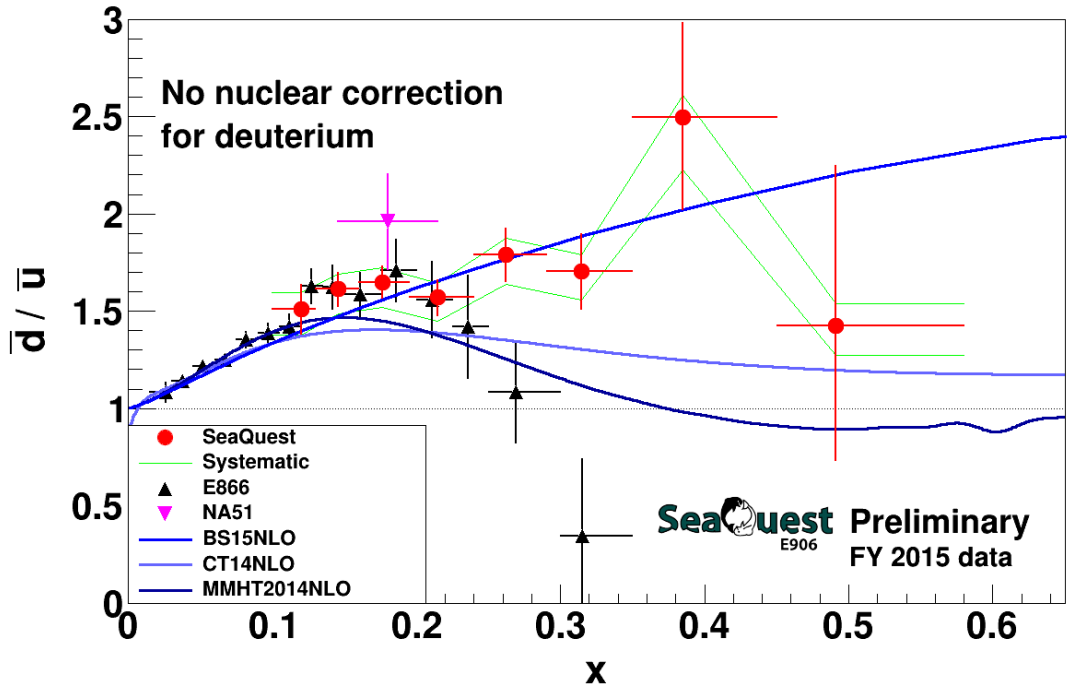
- Comparison with other measurements



  - All agree at small x
  - $\bar{d}/\bar{u}$ at $x \sim 0.3$ seems higher by SeaQuest
    ... Physical reasons for this difference are being investigated

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

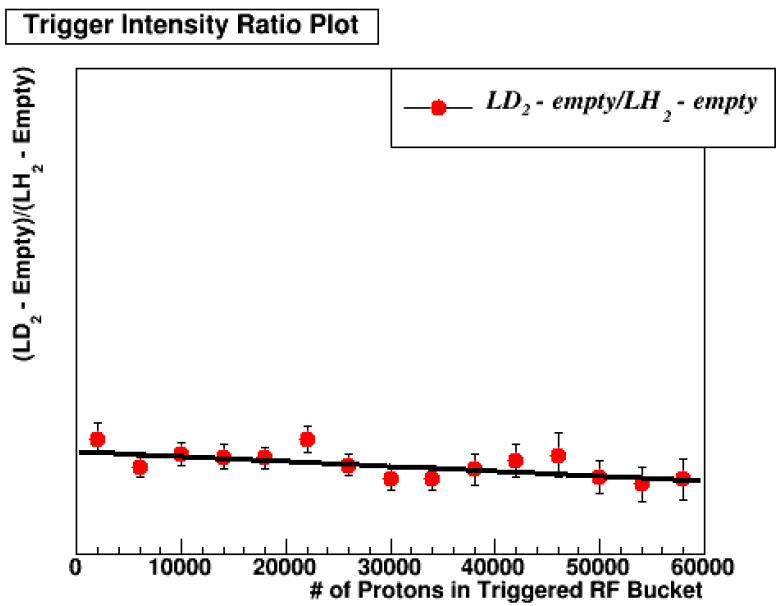
- Comparison with PDF models



- The key region is definitely $x \sim 0.3$

Recent Progress in Analysis

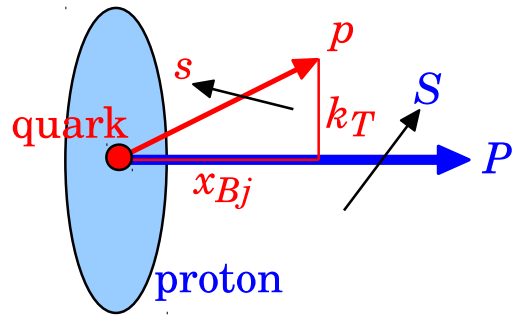
- Improvement in detector alignments
  - More parameters and finer time periods
- Increase of statistics
  - Detailed QAs and better calibrations $\Longrightarrow$ 50% more analyzable events
  - Optimized dimuon selection for better S/N
- New correction method
  - Key effect = beam-intensity dependence
    - Efficiency of event reconstruction
    - Amount of random background
  - Past: "realistic" GMC simulation
  - New: intensity extrapolation
    - Cross-section ratio vs intensity
    - Extrapolation to "intensity = 0"



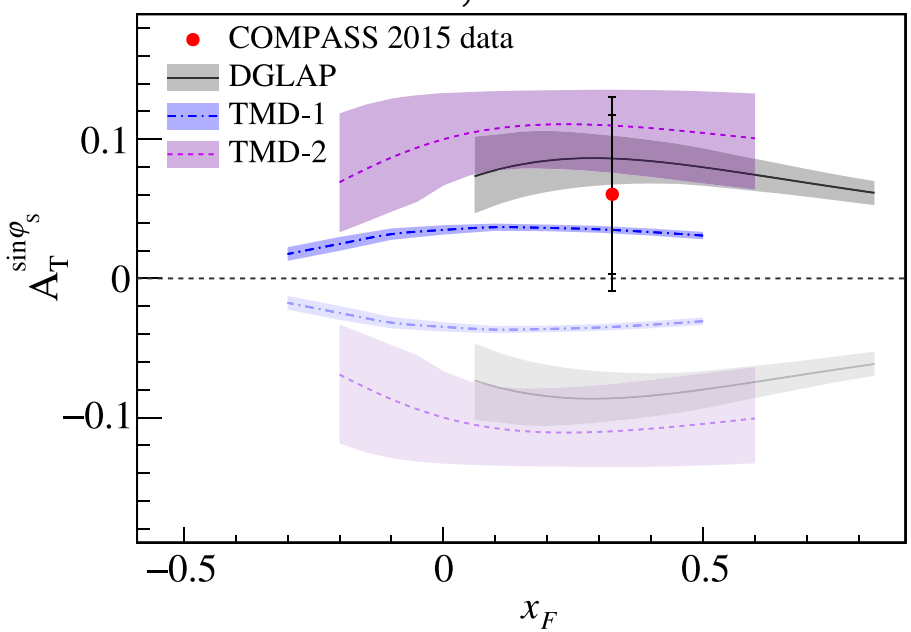
4. E1039/SpinQuest: Successor with Polarized Target

Sivers Distribution Function: $f_{1T}^{\perp}(x_{Bj}, k_T)$

- One of the eight transverse momentum dependent (TMD) PDFs
  - Correlation between nucleon spin (S) & quark transverse momentum (k_T)
- Of quarks
  - Rather well constrained by measurements of SIDIS, $p^{\uparrow} + p \to W^{\pm}/Z$ & $\pi + p^{\uparrow}$ Drell-Yan
- Of antiquarks
  - Uncertain
  - Accessible by $p + p^{\uparrow}$ Drell-Yan



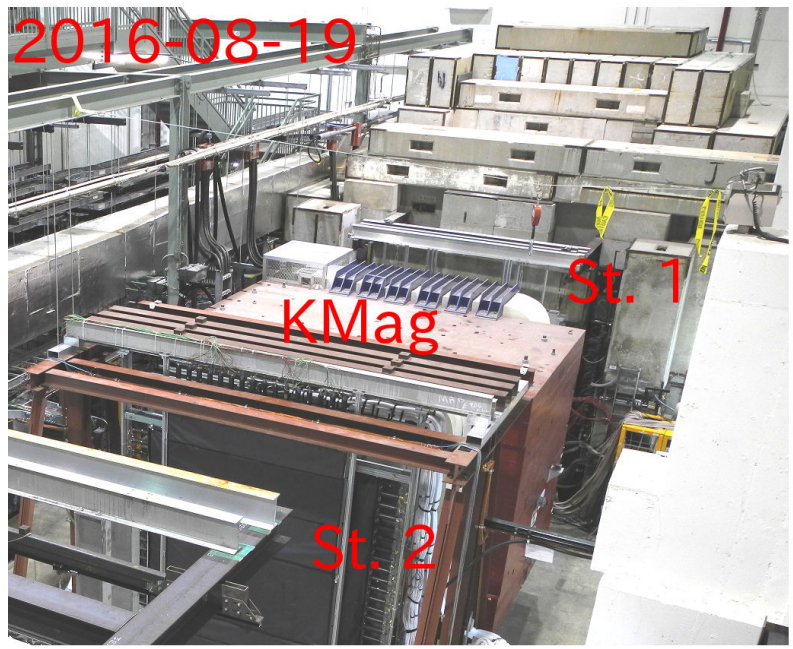
PRL 119, 112002



E1039/SpinQuest ≈ Polarized Target + SeaQuest

- Experimental design
  - SeaQuest spectrometer (almost as it is)
  - Polarized target
    - NH_3 & ND_3 with $L = 8$ cm, $B = 5$ T
    - Called “Hall-C” target in past
    - Refurbished for transverse polarization
    - $dB/B < 10^{-4}$ & $P \gtrsim 90\%$ achieved!!
- Status
  - Stage-2 approval was granted from Fermilab in May 2018
  - SeaQuest decommissioning is ongoing, particularly a reconfiguration of the radiation shielding
  - Data taking will start likely in 2019 for two years

During cool-down test in 2018

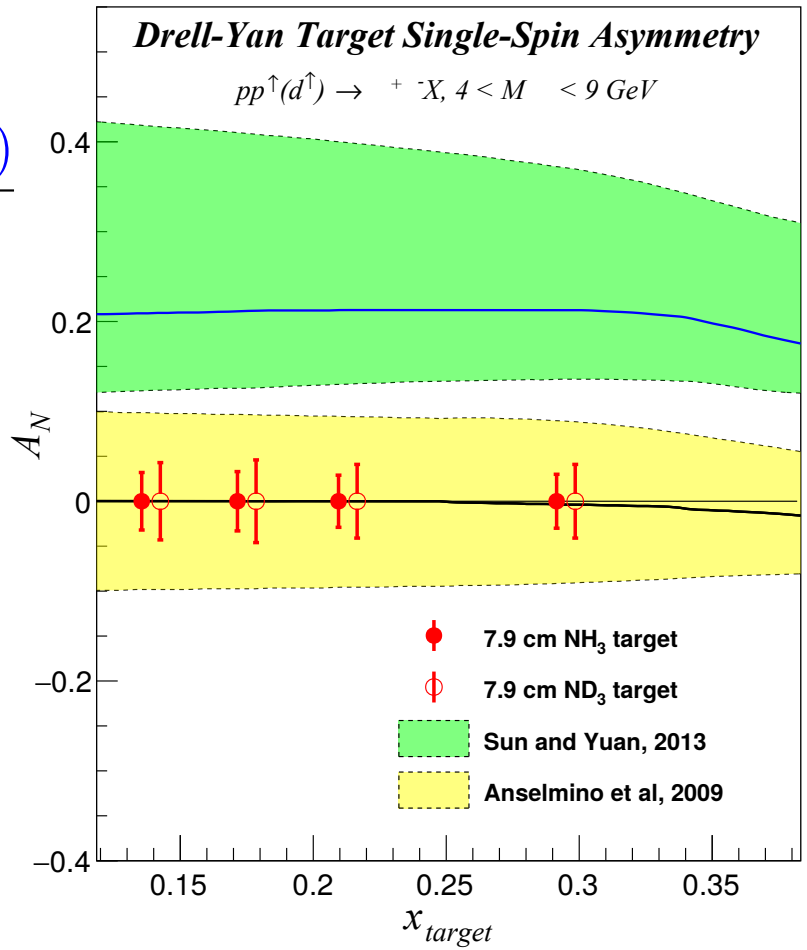


Prospect of E1039 Measurement

- Sivers TMD PDF of anti-quark
  - $\bar{u}$ & $\bar{d}$ separately from $p + \vec{p}$ & $p + \vec{d}$
- Observable: single-spin asymmetry A_N

$$A_N(\phi_S) \equiv \frac{\sigma^{\uparrow}(\phi_S) - \sigma^{\downarrow}(\phi_S)}{\sigma^{\uparrow}(\phi_S) + \sigma^{\downarrow}(\phi_S)} \sim \frac{f(x_B) \cdot f_{1T}^{\perp,\bar{f}}(x_T)}{f(x_B) \cdot \bar{f}(x_T)}$$

  - Measurement accuracy $\delta_{A_N} \sim 0.04$
  - Compare with two calculations based on SIDIS data
    - Blue line takes into account the Collins-Soper-Sterman scale evolution



Phys. Rev. D88, 034016 (2013)

Eur. Phys. J. A39, 89 (2009)

5. Summary

- Internal structure of proton
  - Large flavor asymmetry $\bar{d}(x)/\bar{u}(x)$ was observed
  - SeaQuest measures the x dependence of $\bar{d}(x)/\bar{u}(x)$ with Drell-Yan process
  - Various aspects (like $\bar{d}(x)$ vs $\bar{u}(x)$, $\Delta\bar{d}(x)$ vs $\Delta\bar{u}(x)$ & $L_{q,\bar{q}}$) are being studied together by experiments & theories
- SeaQuest experiment @ Fermilab
  - Recorded 1.4×10^{18} protons on targets by July 2017
  - Analyzed 0.6×10^{18} protons for preliminary $\bar{d}/\bar{u}$
- Method & results of $\bar{d}(x)/\bar{u}(x)$ measurement
  - Cross-section ratio $\sigma_{p+d}/2\sigma_{p+p}$ was measured
  - $\bar{d}(x)/\bar{u}(x)$ was extracted with LO calculation
  - $\bar{d}(x)/\bar{u}(x) > 1$ was found up to $x = 0.58$
  - Analyses toward final result with better statistics & systematics
- E1039/SpinQuest $\approx$ polarized target + SeaQuest
  - Measure the antiquark Sivers function
  - Start this year for two-year data taking