Recent Progress on Flavor Asymmetry of Anti-Quarks in the Proton by Drell-Yan Experiement at SeaQuest

第 10 回 高エネルギー QCD・核子構造 勉強会

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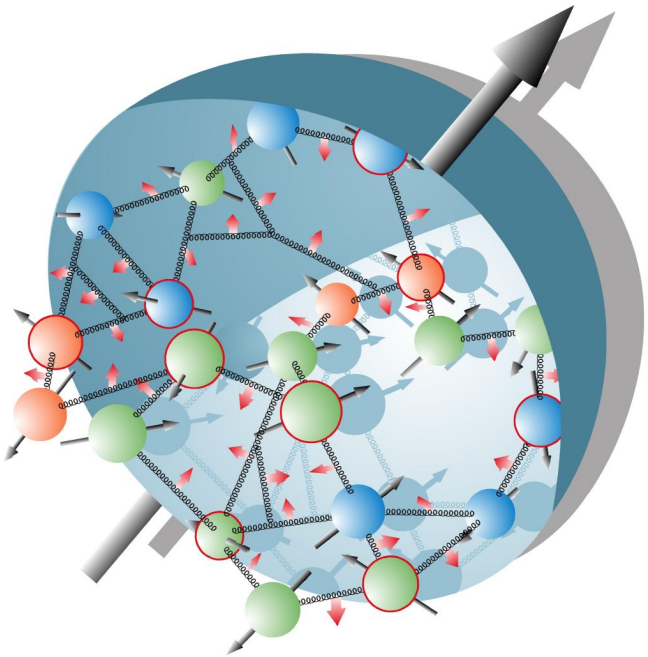
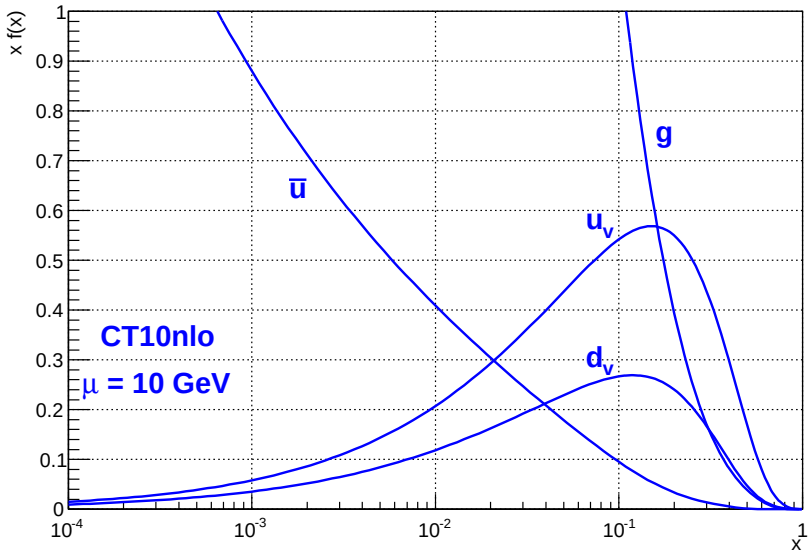
Outline

1. Purpose & technique of measurement
   - Flavor asymmetry of anti-quarks ($\bar{d}(x)/\bar{u}(x)$) in nucleon
   - Understandings of $\bar{d}(x)/\bar{u}(x)$ by measurements & theories
   - Technique to measure $\bar{d}(x)/\bar{u}(x)$ with Drell-Yan process
2. Setup & status of SeaQuest experiment
   - Beam, target & spectrometer
   - Data taking
3. Measurement of $\bar{d}(x)/\bar{u}(x)$
   - Analysis procedure
   - Preliminary result
4. Summary

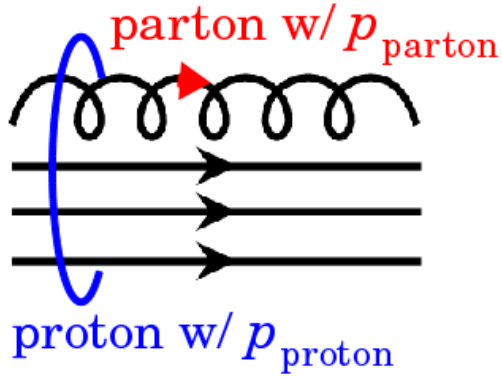
Internal Structure of Proton (Nucleon)

- Quarks, anti-quarks & gluons



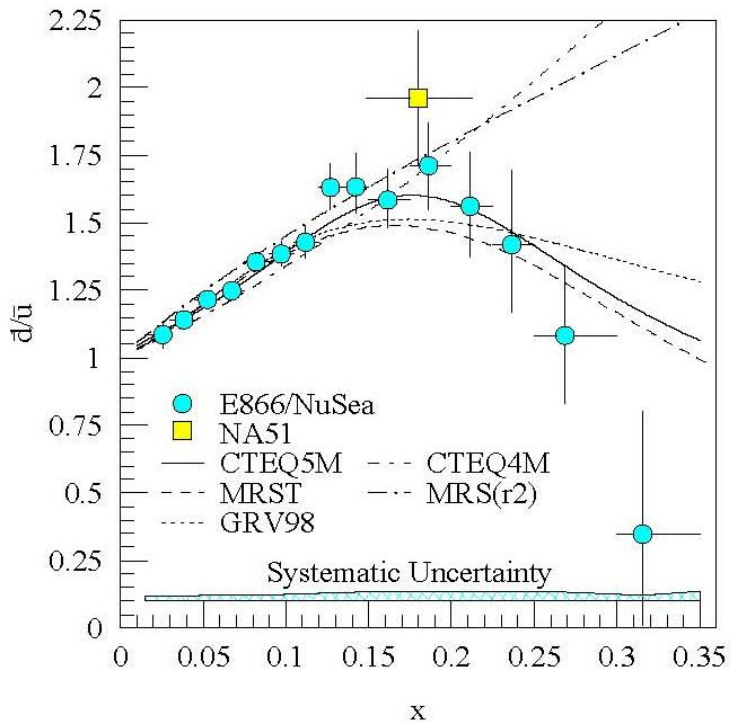


- The anti-quark distribution is flavor symmetric?
  - Strong force is independent of flavor
  - Splittings of $g \to u\bar{u}$ & $g \to d\bar{d}$ occur equally



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!

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: $u + \bar{d} \rightarrow W^+$)

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

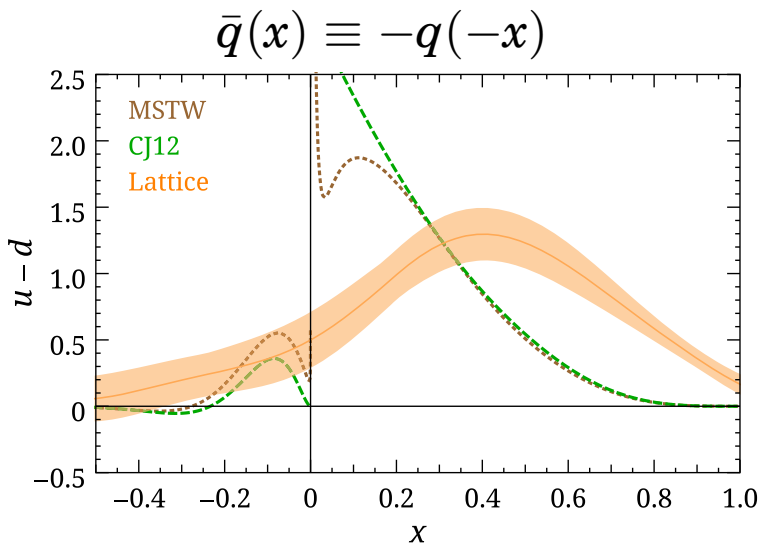
3. Examine hadron models based on QCD effective theory

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)*

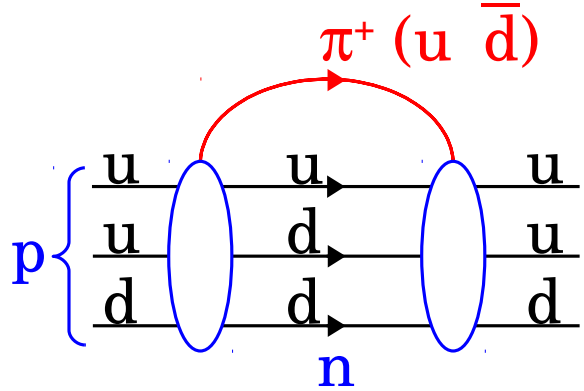
- Lattice-QCD calculation with LaMET ... *PRD91, 054510 (2015)*
  - As large as the measured size
  - Room to improve pion mass & lattice size



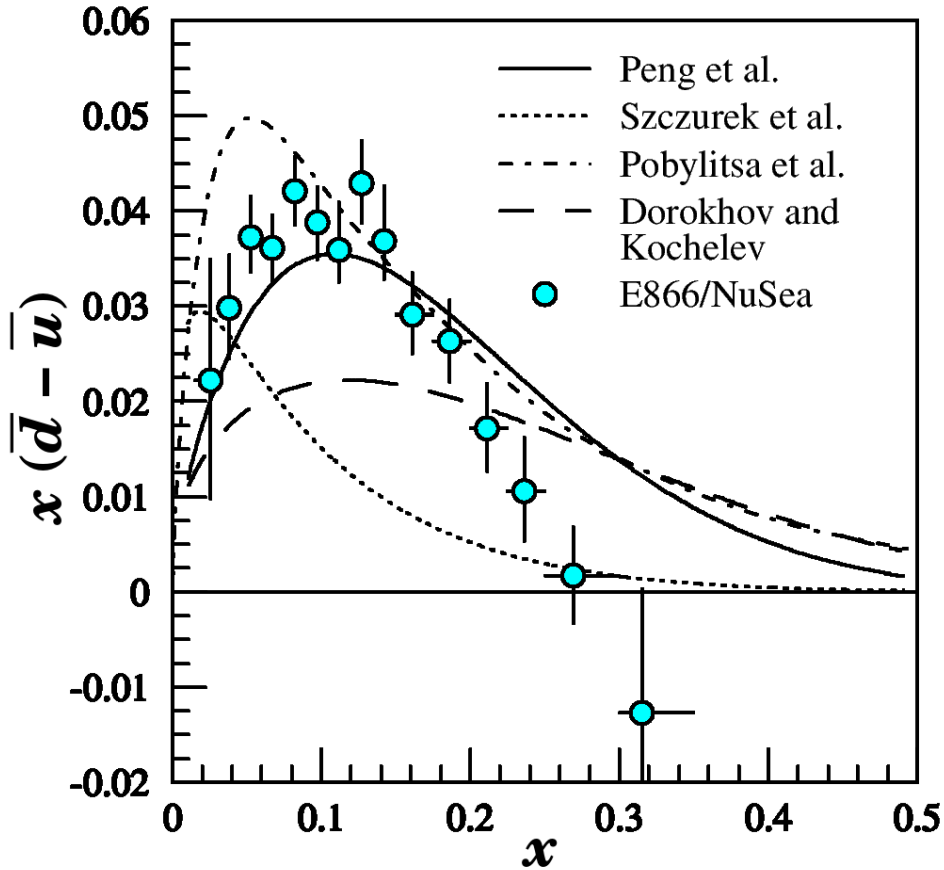
Theories of $\bar{d}/\bar{u}$ Asymmetry (2)

- 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 $J^P = 0^-$)



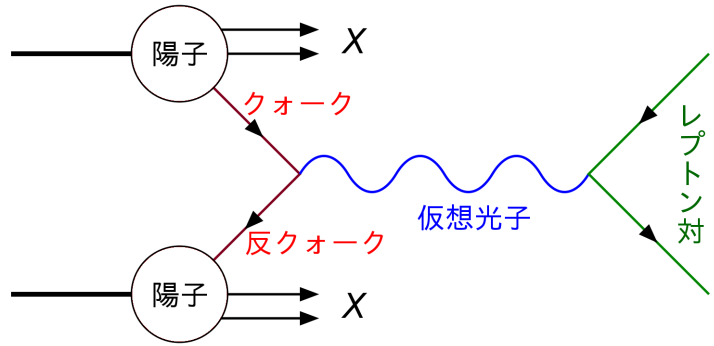
Comparison of Theories to Measurements



- The x dependence of $\bar{d}(x)/\bar{u}(x)$ is the key to develope/examine models
  - Drop sharply at $x \sim 0.3$? Go down to $\bar{d} < \bar{u}$?

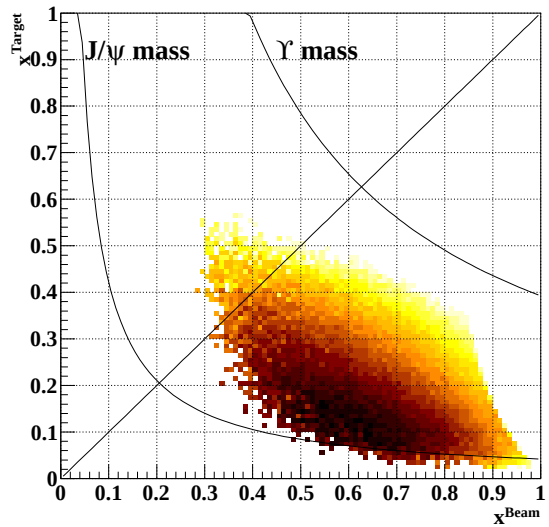
Measurement of $\bar{d}(x)/\bar{u}(x)$ with Drell-Yan Process

- Drell-Yan process: $p + p \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$
  - 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

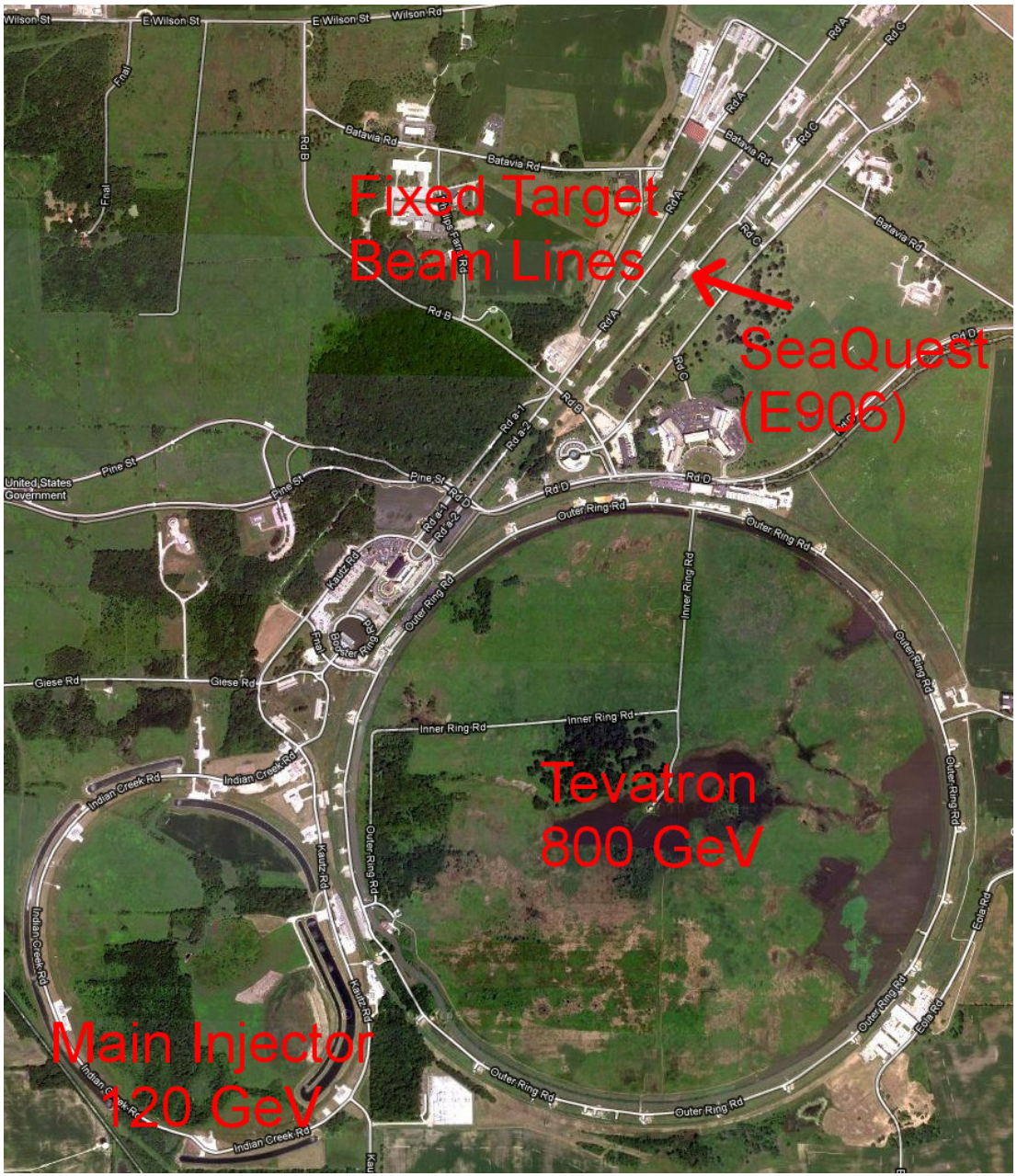


- Ratio of cross sections with LH2 & LD2 targets

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

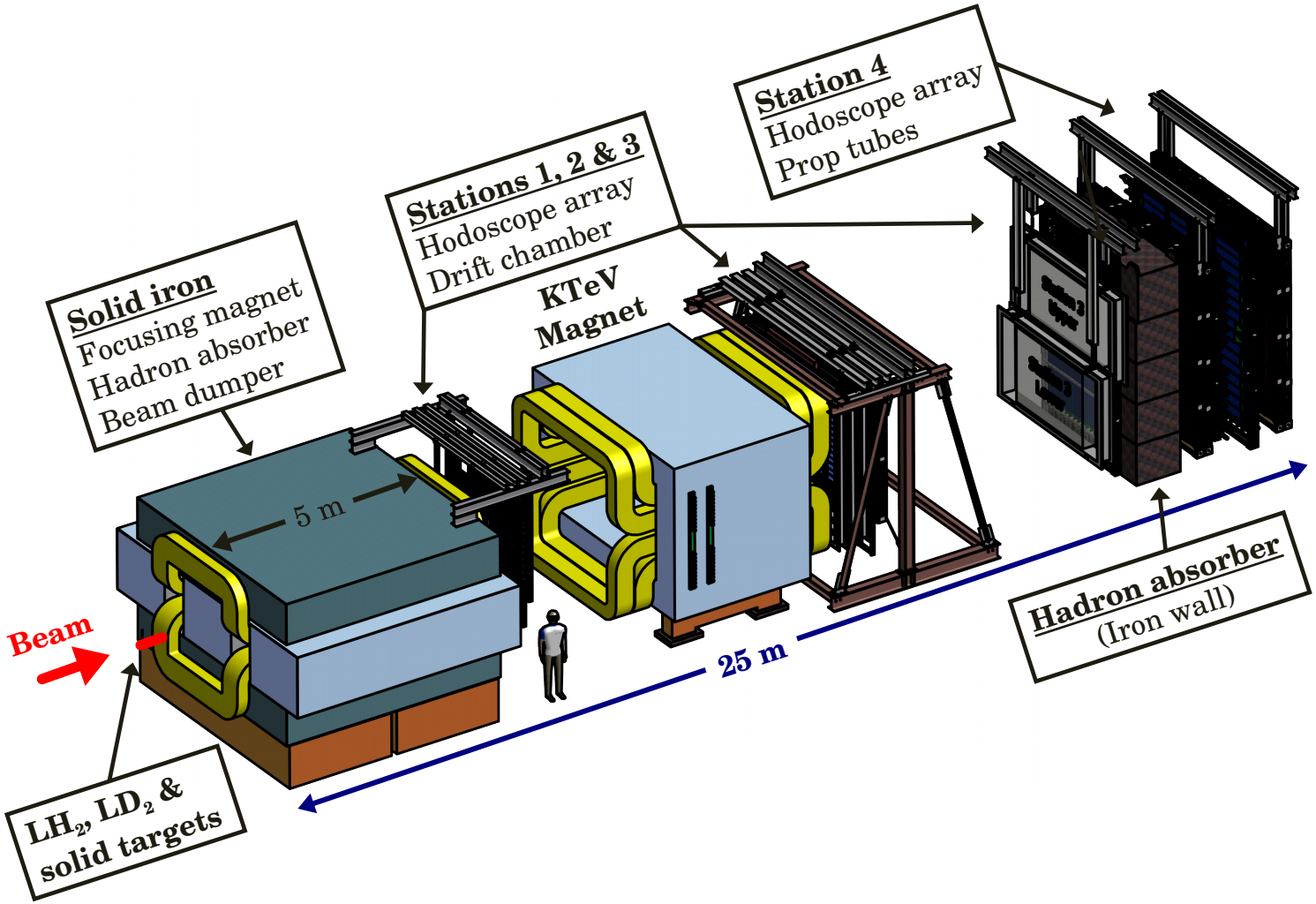
- SeaQuest measures the x dependence of $\bar{d}(x)/\bar{u}(x)$ particularly at high x ($0.15 \lesssim x \lesssim 0.45$)

Fermilab Proton Beam



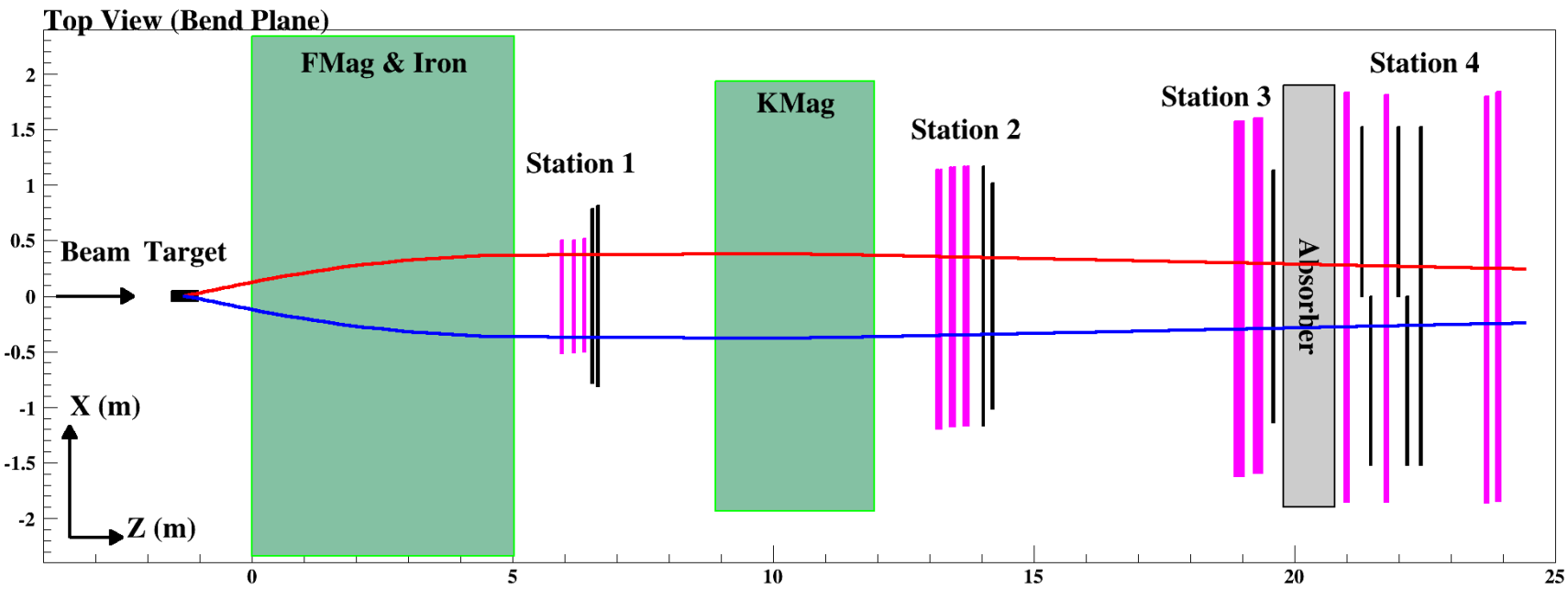
- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for E906
  - 55 sec for ν exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec in spot size

E906/SeaQuest Spectrometer



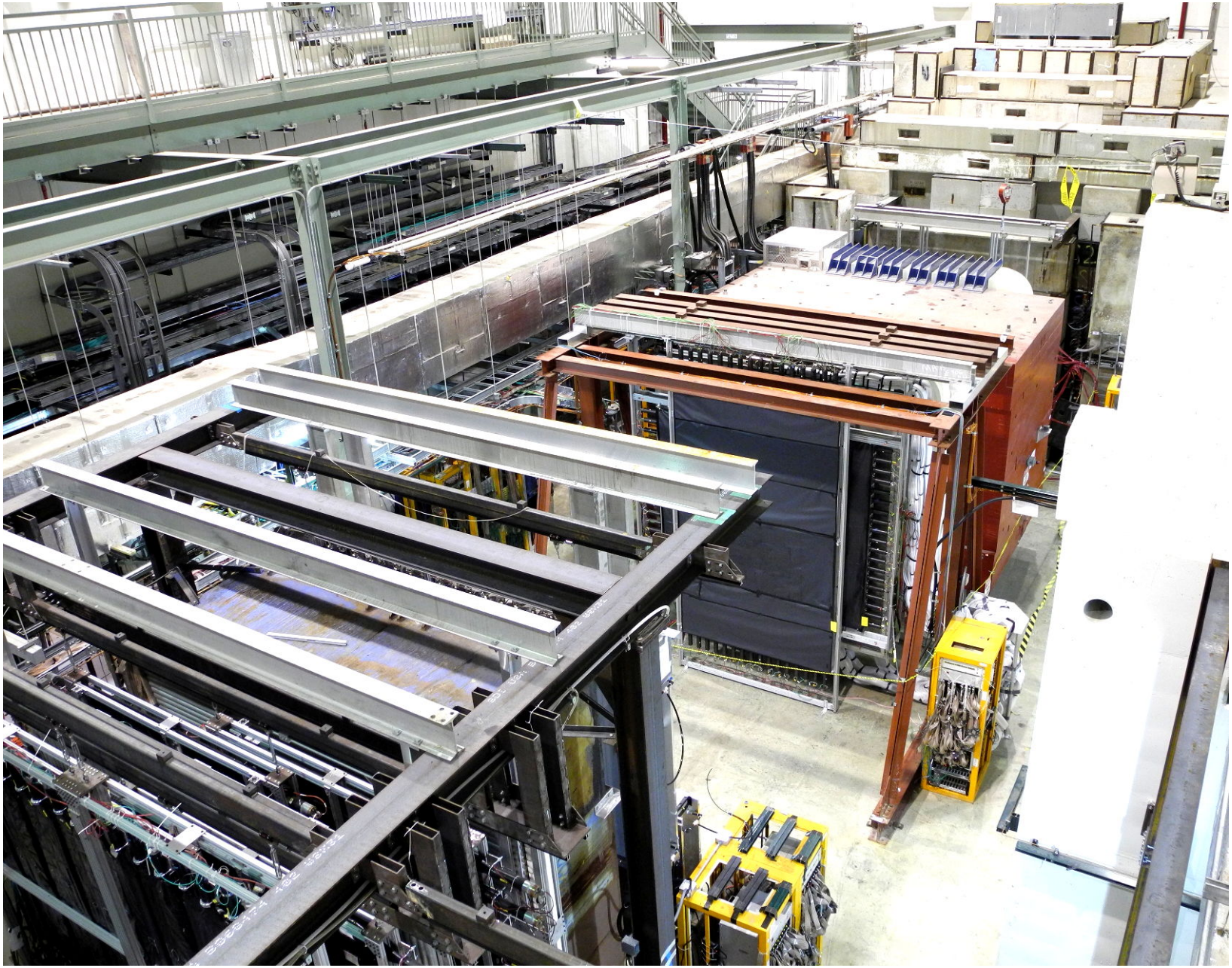
- Targets: LH_2, LD_2, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump

- 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 Hall — 2015-July-27

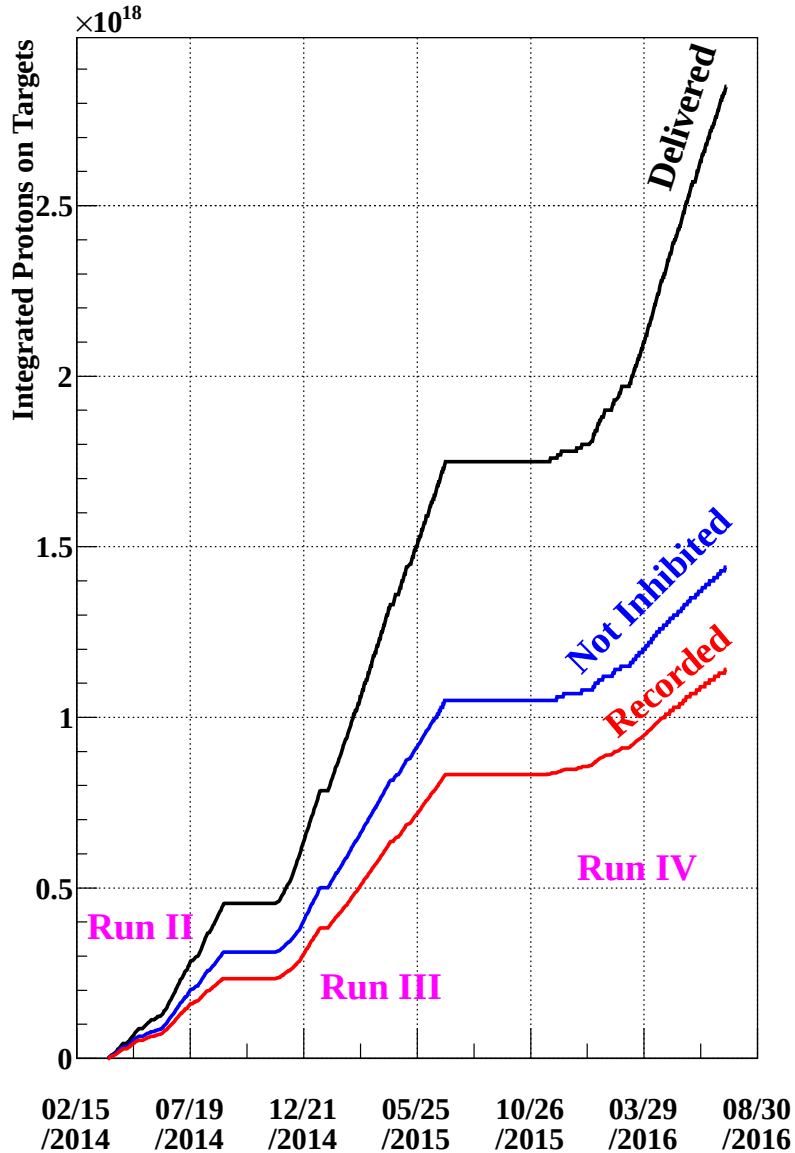


Status of SeaQuest Data Taking

- Events

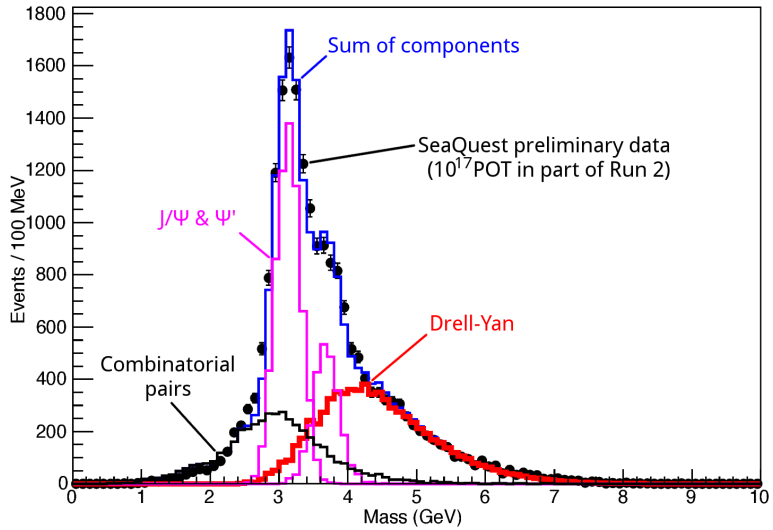
Year	Month	Event
2008	12	Fermilab Stage-2 approval
2011	08	End of spectrometer construction
2012	03-04	1st data taking (commissioning)
	05-	Detector & DAQ upgrade
2013	11-	2nd data taking (10 months)
2014	11-	3rd data taking (8 months)
2015	10-	4th data taking (10 months)
2016	08	First PhD thesis on $\bar{d}/\bar{u}$ (宮坂, 東工大)
2016	11-	5th data taking (plan)

- Beam protons on targets
  - 1.1×10^{18} recorded up to now
  - 0.6×10^{18} analyzed for preliminary $\bar{d}/\bar{u}$
- Data taking continues in FY2017
  - Another 0.4×10^{18} to be recorded (1.5×10^{18} in total)
  - Wider chamber acceptance at St. 1
  - Faster DAQ
  - Smarter trigger logic



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

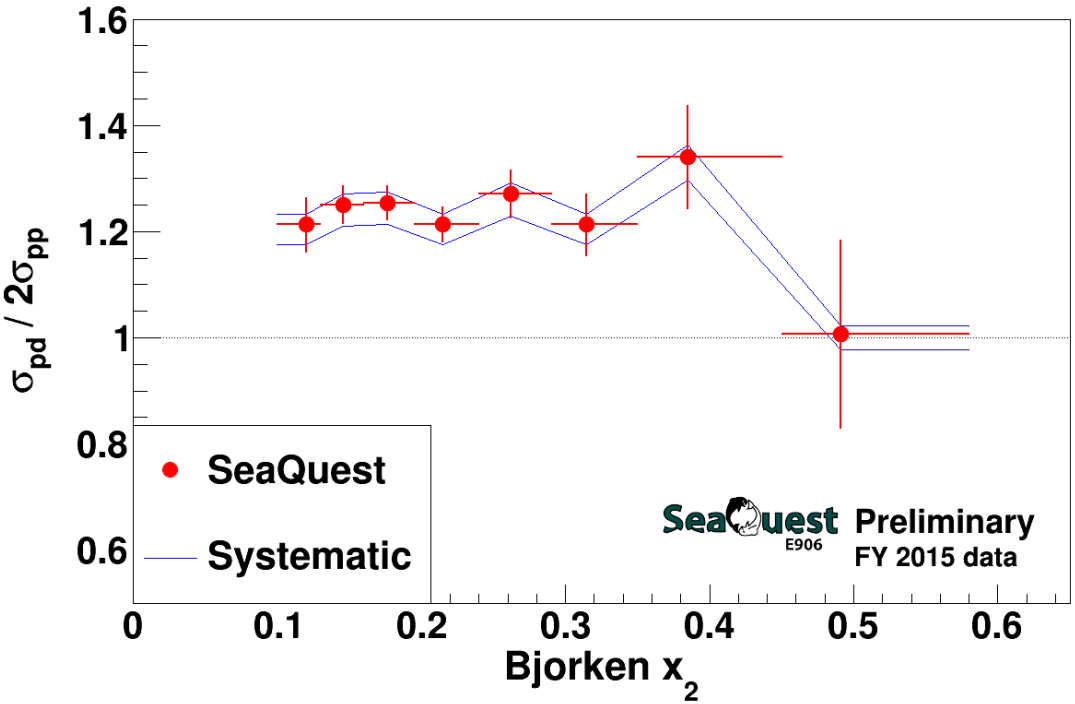


$$\frac{\sigma_{pd}(x_{ta})}{2\sigma_{pp}(x_{ta})} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_{ta})}{\bar{u}(x_{ta})}\right)$$

  - 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



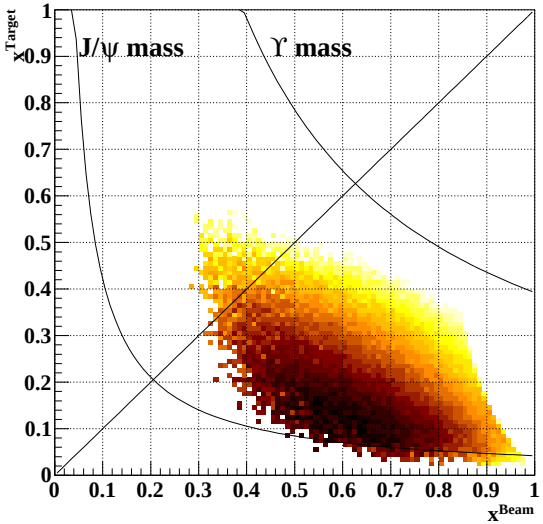
- Systematic errors
  - H contamination of LD2 target
  - Background subtraction
  - Tracking efficiency correction
- $\sigma_{pd}/2\sigma_{pp}$ always > 1 in measured x range

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 $\sigma_{pd}/2\sigma_{pp}$



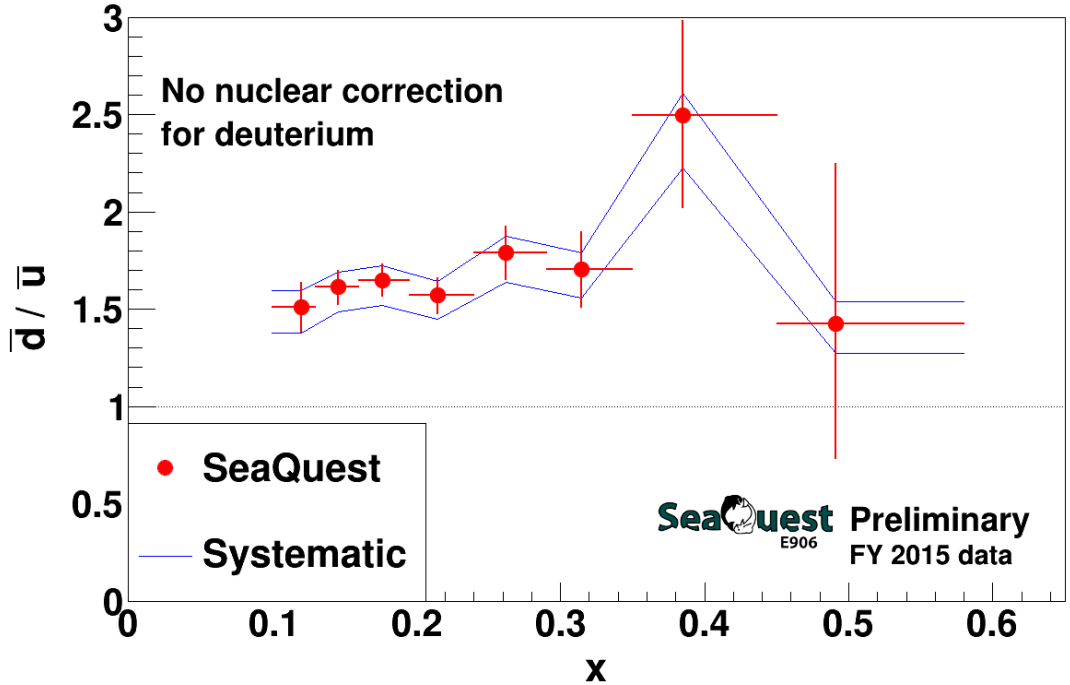
1. Have the measured $\sigma_{pd}/2\sigma_{pp}$ ($\equiv R_{meas}$)
2. Initialize $\bar{d}(x)/\bar{u}(x) = 1$
3. Calculate the cross-section ratio ($\equiv R_{pred}$) without assuming $x_{be} \gg x_{ta}$:

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

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

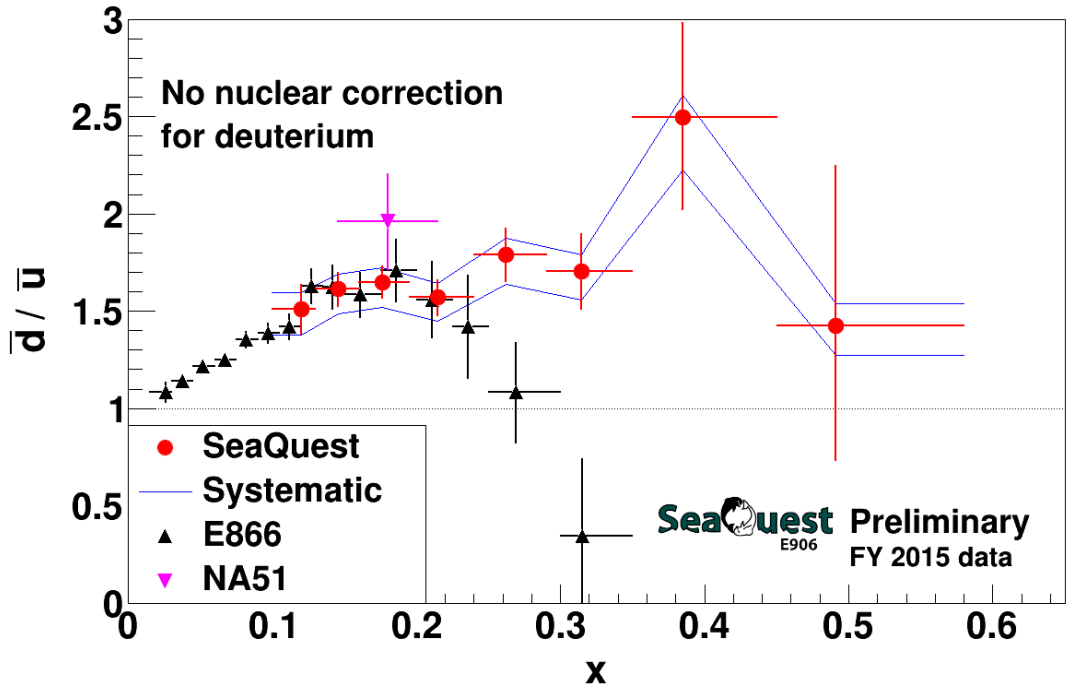
- Preliminary result



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

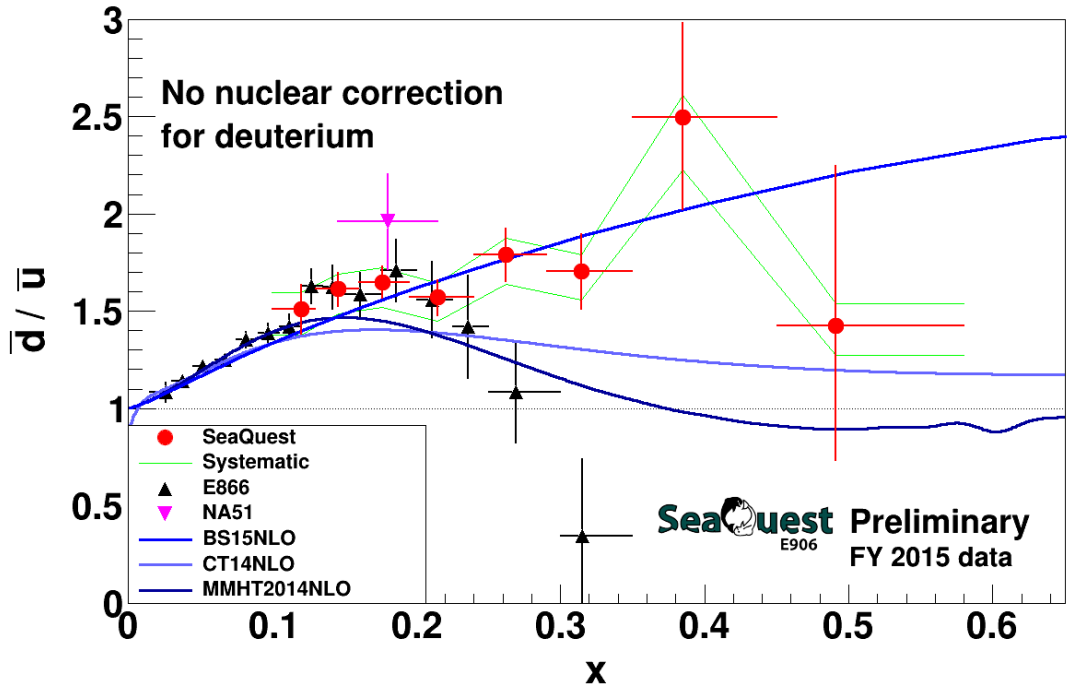
- Comparison with other measurements



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

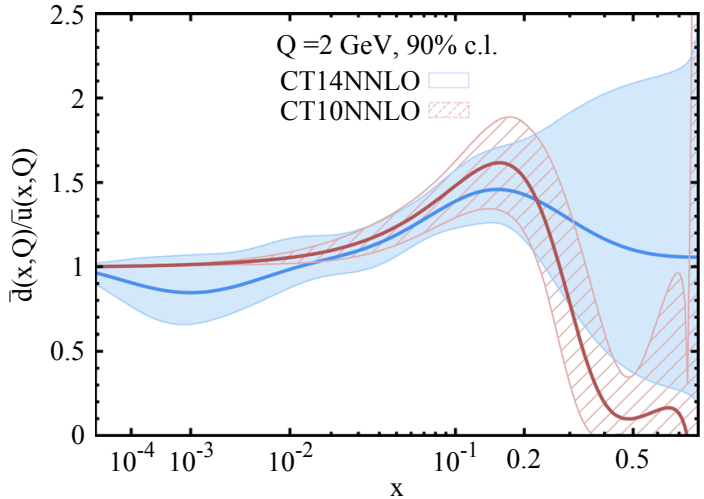
- Comparison with PDF models

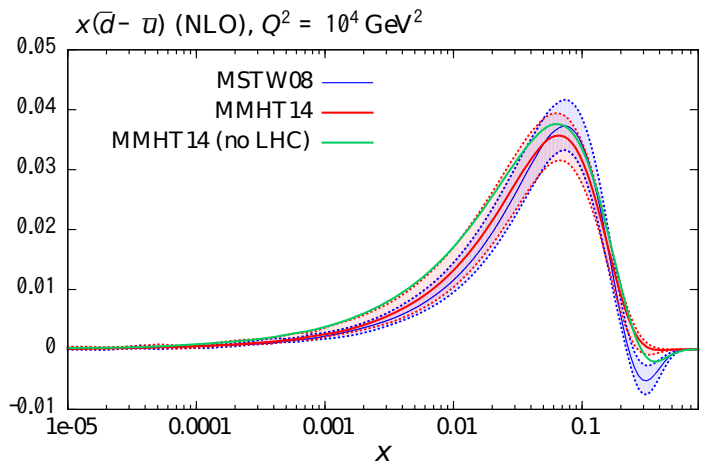


- Will take data in FY 2017 with upgraded detectors to increase the statistics

Recent Unpolarized PDFs & $\bar{d}/\bar{u}$

- CT14 (*PRD93, 033006, 2016*)
  $\Longleftarrow$ CT10 $\Longleftarrow$ CTEQ6
  - DIS, ν(SI)DIS, E866 D-Y, Tevatron, LHC
  - $xf(x) = A \cdot x^{\alpha} \cdot (1-x)^{\beta} \cdot$ (4th-order polynomial)
    ... more flexible than CT10
- MMHT 2014 (*EPJC75, 204, 2015*)
  $\Longleftarrow$ MSTW 2008 $\Longleftarrow$ MRST 2004
  - DIS, ν(SI)DIS, E866 D-Y, Tevatron, LHC
  - $xf(x) = A \cdot x^{\alpha} \cdot (1-x)^{\beta} \cdot$ (4th-order polynomial) for u_v, d_v, $\bar{u}+\bar{d}$, $s+\bar{s}$,
    $x(\bar{d}-\bar{u}) = A \cdot x^{\alpha} \cdot (1-x)^{\beta} \cdot$ (2th-order polynomial)
- BS15 (*NPA941, 307, 2015*) ... statistical model
  - DIS only
  - $xq(x) = \frac{AX_0x^b}{\exp[(x-X_0)/\bar{x}]+1} + \frac{\tilde{A}x^{\tilde{b}}}{\exp(x/\bar{x})+1}$
- JR09 (*PRD79, 074023, 2009*)
  $\Longleftarrow$ GJR08 $\Longleftarrow$ GRV98
- HERAPDF2.0 (*EPJC 75, 580, 2015*)
- NNPDF3.0 (*JHEP04, 040, 2015*)





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 1.1×10^{18} protons on targets by July 2016
  - Data taking continues in FY2017 with upgraded hardware
  - 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 $x = 0.58$
  - The difference from E866 result is being investigated