Measurement of the anti-quark flavor asymmetry in the proton at FNAL-SeaQuest

JLUO Annual Meeting 2022

2022/June/15

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for the SeaQuest Collaboration

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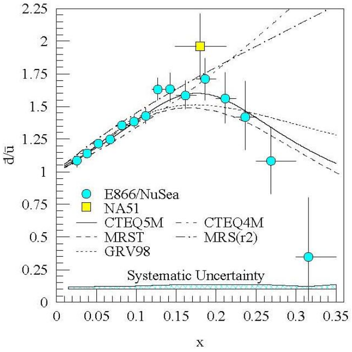
Outline

1. Flavor asymmetry of light anti-quarks in the proton: $\bar{d}(x)/\bar{u}(x)$
2. SeaQuest experiment
   - Measurement method
   - Beam, target & spectrometer
   - Data taking & analysis procedure
3. Measured results
   - Cross-section ratio ($\sigma^{pd}/2\sigma^{pp}$) & $\bar{d}(x)/\bar{u}(x)$
   - Nuclear ratio (R_A) — Another SeaQuest result
4. SpinQuest — Successor with polarized targets
5. Conclusions

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

- CERN NMC ('90): deep inelastic muon scattering
  - Gottfried Sum: $S_G = 0.235 \pm 0.026 < 1/3$
  - $\int_0^1 \bar{d}(x)dx - \int_0^1 \bar{u}(x)dx = 0.147 \pm 0.039$

    ... Clear signature of anti-quark flavor asymmetry
- Measurement of x dependence of $\bar{d}(x)/\bar{u}(x)$: 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 $x \in (0.015, 0.35)$

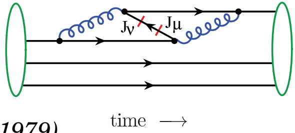


70% asymmetry!

A few % expected

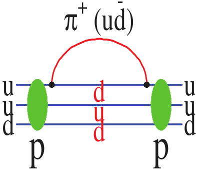
Theories of $\bar{d}/\bar{u}$ Asymmetry (1)

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

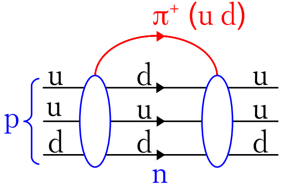


- Pauli blocking ... *PRD15, 2590 (1977)*
  - $Prob(g \to u\bar{u}) < Prob(g \to d\bar{d})$ since $p = uud$
  - Cannot explain the measured size ... *NPB149, 497 (1979)*
  - Even $\bar{d} < \bar{u}$ via connected sea (at high x)? ... *PLB736, 411 (2014)*

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



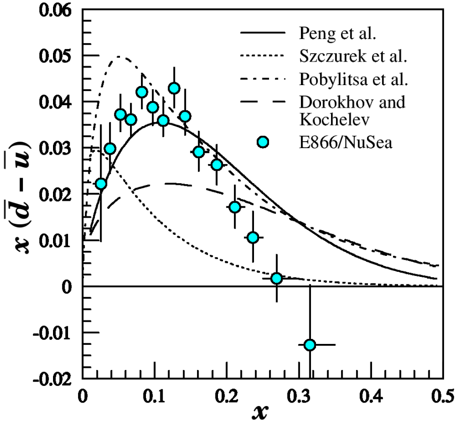
Theories of $\bar{d}/\bar{u}$ Asymmetry (2)



- 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 $J^P = 0^-$)

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

Comparison of Theories to Measurements

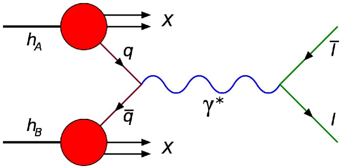


Meson cloud model: PRD58, 092004
Chiral quark model: NPA596, 397
Chiral quark model: PRD59, 034024
Instanton model: PLB304, 167
(Updated calculations exist)

- 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 $\bar{d} < \bar{u}$?
- Reveal what QCD mechanism generates the asymmetric sea!

2. SeaQuest Experiment

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

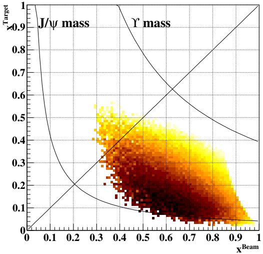


- Drell-Yan process: $p + p \to \gamma^* \to \mu^+ + \mu^-$
  - Virtual photon
    - Invariant mass: $M^2 = x_{beam} x_{target} s$
    - Rapidity: $\exp Y = \sqrt{x_{beam}/x_{target}}$
  - $x_{beam} = \frac{M}{\sqrt{s}} e^{Y}, \quad x_{target} = \frac{M}{\sqrt{s}} e^{-Y}$
  - Cross section at LO:

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum_{q=u,d} {e_q}^2 \left\{ q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b) q_t(x_t) \right\}$$

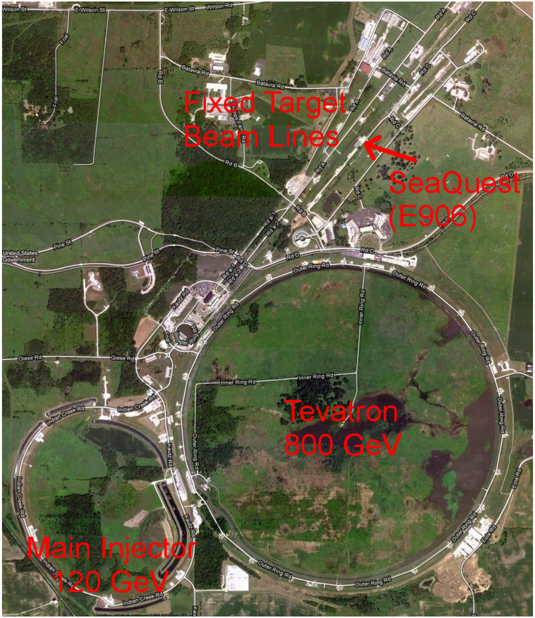
  - Only "$q_b(x_b)\bar{q}_t(x_t)$" survives @ forward rapidity, i.e. quark in beam & anti-quark in target
- Ratio of cross sections with LH2 & LD2 targets

$$\frac{\sigma_D(x_t)}{2\sigma_H(x_t)} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$



- 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

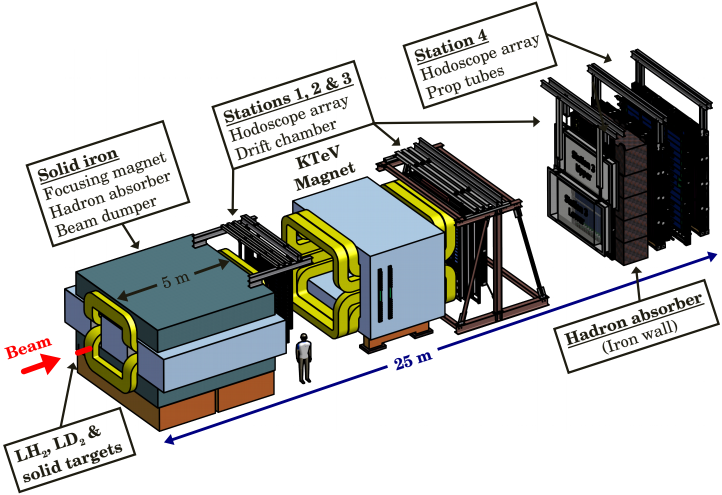


- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for E906
  - 55 sec for ν exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec in spot size

FNAL-SeaQuest Collaboration

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

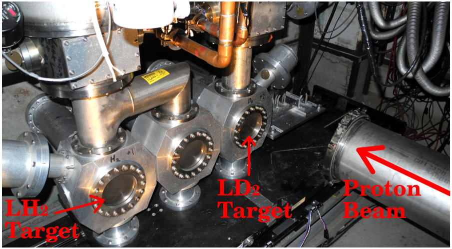
E906/SeaQuest Spectrometer

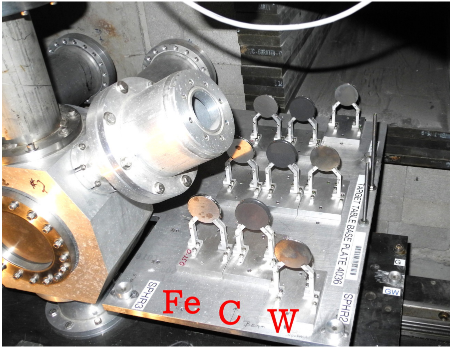


- Targets: LH_2, LD_2, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump

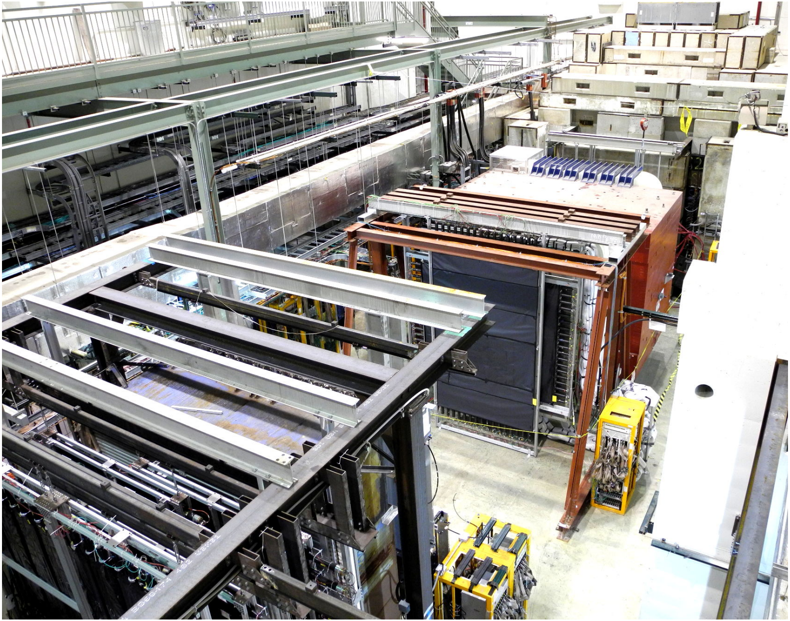
SeaQuest Targets

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





SeaQuest Hall — 2015-July-27

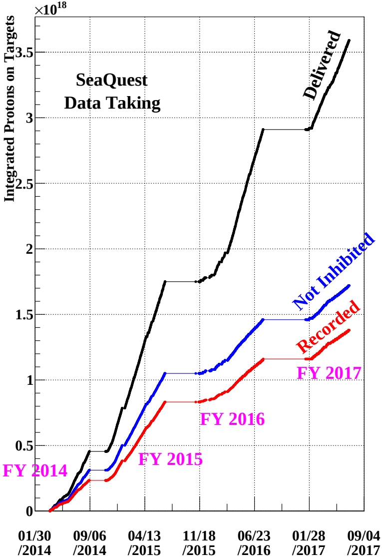


SeaQuest Data Taking

- Data-taking periods

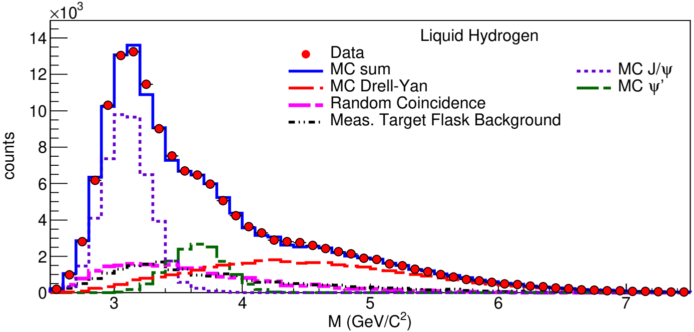
Year	Month	Event
2012	03-04	1st data taking (commissioning)
2013	11-	2nd data taking (10 months)
2014	11-	3rd data taking (8 months)
2015	10-	4th data taking (10 months)
2016	12-	5th data taking (7 months)

- Beam protons on targets
  - 1.4×10^{18} recorded
  - 0.6×10^{18} analyzed for the 1st $\bar{d}/\bar{u}$ result & others



Reconstruction & Identification of Drell-Yan Events

- Unlike-sign muon pairs were triggered and reconstructed
- Distribution of dimuon mass



  - Drell-Yan, J/ψ & ψ' events from simulation
  - Non-target events from empty target
  - Random-coincidence BGs from real data via event mixing
- Origins of measured dimuons well understood
- Dominated by Drell-Yan at $M > 4.5$ GeV

3. Measured Results

Extraction of $\bar{d}(x)/\bar{u}(x)$ — Analysis Outline

- Dimuon yields
  - With LH2 & LD2 targets for σ_H & σ_D
  - At invariant mass > 4.5 GeV

$\Downarrow$

- Cross-section ratio: $\sigma_D/2\sigma_H$ vs x_t
  - Normalized by relative beam luminosity
  - Corrected for backgrounds & efficiencies

$\Downarrow$

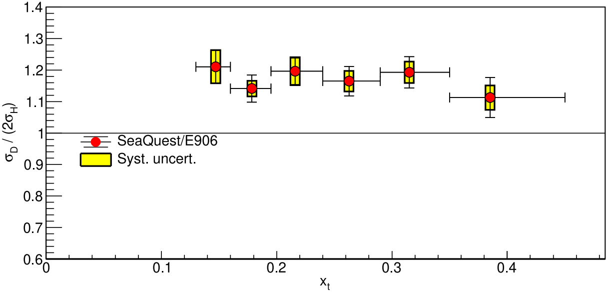
$$\frac{\sigma_D(x_t)}{2\sigma_H(x_t)} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$

- $\bar{d}(x)/\bar{u}(x)$ vs x
  - Iterative computations of $\sigma_D/2\sigma_H$ from $\bar{d}/\bar{u}$
  - Using the SeaQuest data alone to demonstrate its impact
  - Anticipating global analyses for more-accurate extractions

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

- SeaQuest result

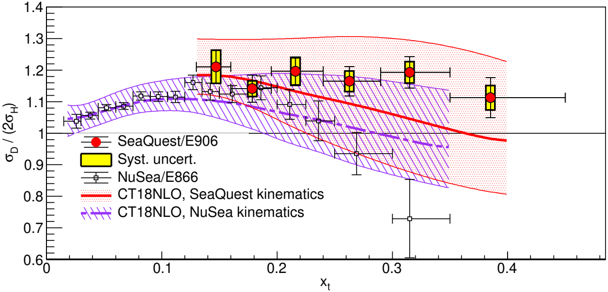
Nature 590, 561 (2021)



- Systematic errors
  - Beam-intensity extrapolation
  - Relative luminosity
- $\sigma_{pd}/2\sigma_{pp}$ always > 1 in measured x range

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

- Comparison to NuSea/E866 result



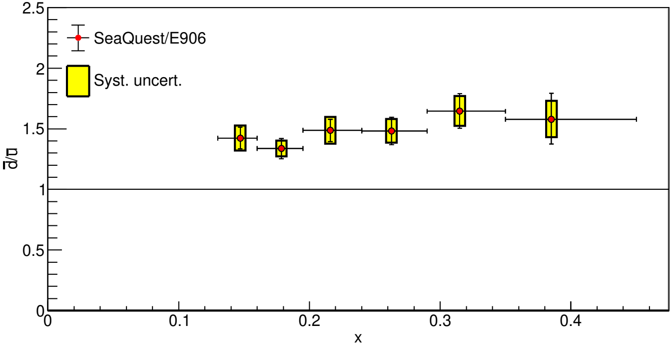
- Effects of experimental kinematics
  - Shown by the calculations using CT18 NLO
  - Account for the difference at $x_t \sim 0.15$

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum_{q=u,d} e_q{}^2 \{q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q_t(x_t)\}$$

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

- SeaQuest result

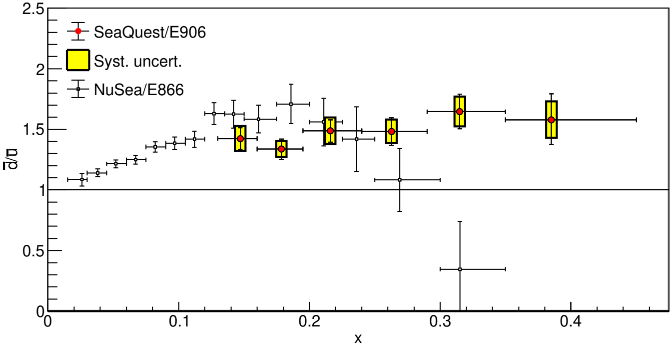
Nature 590, 561 (2021)



- Systematic errors
  - Errors of cross-section ratio
  - $\bar{d}/\bar{u}$ above measured x region (> 0.45)
  - Nuclear effect for deuterium
- Large asymmetry at high x as well as low x

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

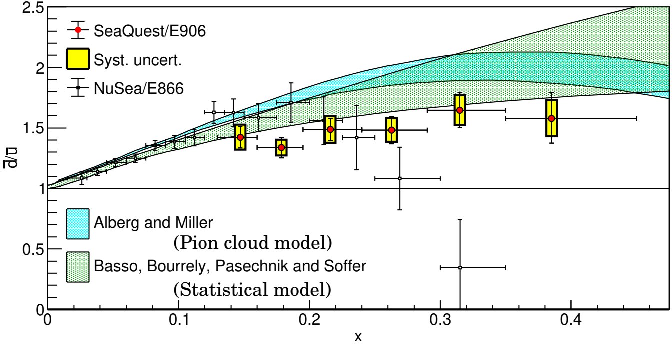
- Comparison to NuSea/E866 result



- Agreement at low x (~ 0.2)
- The trends at high x are quite different
  - No explanation has been found for the difference

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

- Comparison to theory calculations

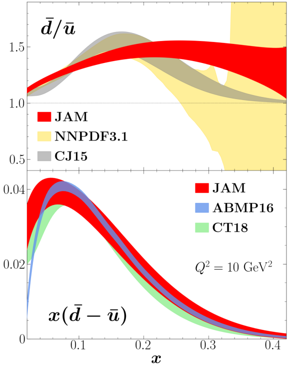


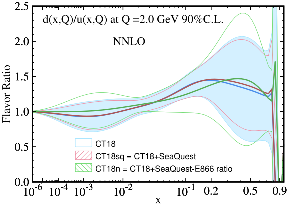
- Reasonably described by two theoretical predictions
- Improved analyses are ongoing
  - Better statistics with full dataset
  - Better systematics with fine-tuned simulation

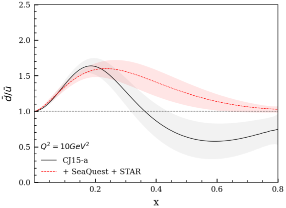
Therotical Calculations about $\bar{d}/\bar{u}$

- The SeaQuest data have been analyzed, together with the RHIC-STAR $W^{\pm}$ data, including but not limited to

- JAM
  PRD 104, 074031
- CT18sq
  arXiv:2108.06596
- CJ15-a+
  arXiv:2108.05786







Nuclear Effects by SeaQuest

- $R_A \equiv \hat{\sigma}^{p+A} / \hat{\sigma}^{p+p}$
  $=$ Ratio of per-nucleon cross sections

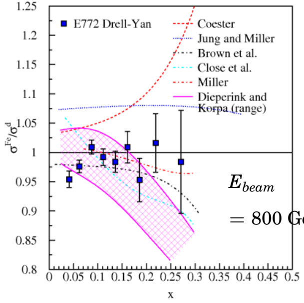
1. R_A vs x_{target}: Effect on antiquarks
   - Smaller than that on quarks? (PRL64, 2479)
   - $0.1 < x_{target} < 0.45$
2. Effect on quarks in beam proton
   = Parton energy loss in cold-nuclear matter

   2.1 R_A vs x_{beam}: Energy loss
   - ◦◦ $x_{beam} > 0.6, x_{target} > 0.15$

   2.2 R_A vs p_T: p_T broadening
   - ◦◦ $0.1 < x_{target} < 0.45$

- R_A should be comprehensively examined to untangle the effects of nuclear PDFs and partonic energy loss

R_A vs x_{target}

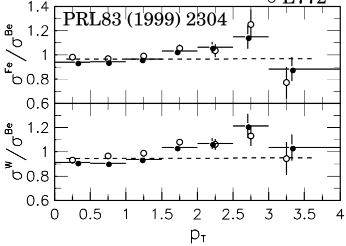


E_{beam} $= 800$ GeV

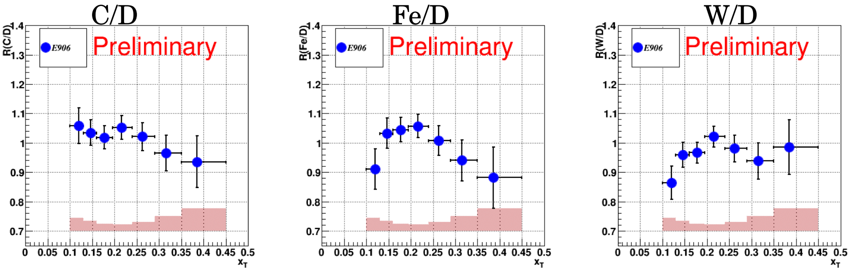
● E866

○ E772

R_A vs p_T

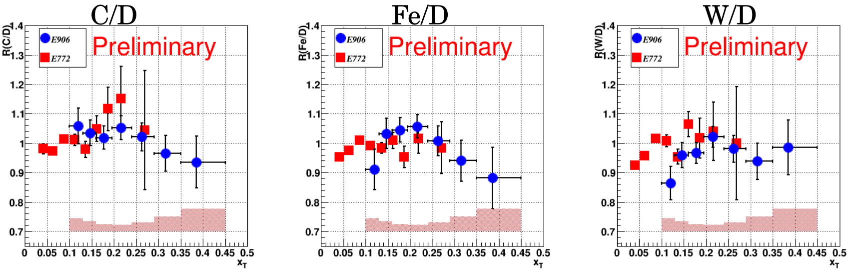


- Result of "R_A vs x_{target}"



  - R_A deviates from 1 by 10% at max
    - Different from quarks ($R_A \gtrsim 1.1$)!
    - Close to the calculation of pion excess model by Miller (PRC 64, 022201)
  - Same trend as the EMC effect (i.e. R_A decreases at middle x)

- Comparison with E772 result

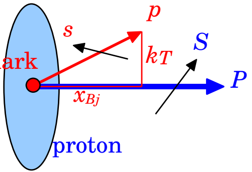


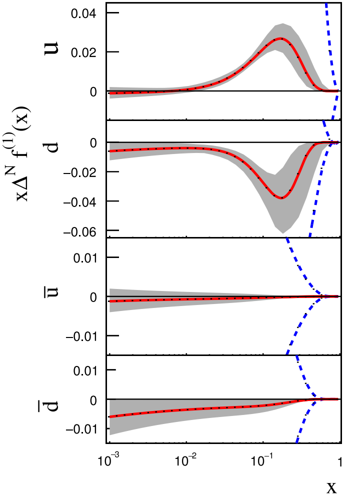
  - Agreement within measurement accuracy
  - Better precision at $x_{target} \gtrsim 0.2$ by SeaQuest

4. SpinQuest
∼Successor with Polarized Targets∼

SpinQuest/E1039

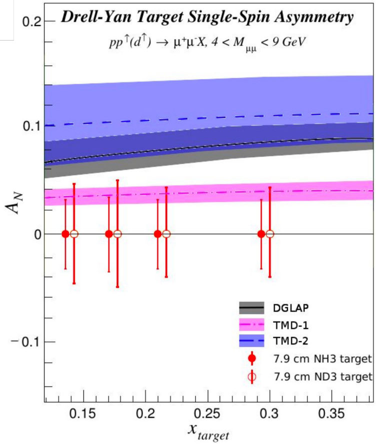
- Sivers distribution: $f_{1T}^{\perp}(x)$
  - One of eight TMD PDFs
  - Correlation of parton k_T with proton spin
- Extraction by global analyses
  - PRD 88 (2013) 114012, P. Sun & F. Yuan
  - PRD 89 (2014) 074013, M. G. Echevarria et al.
  - JHEP 04 (2017) 046, M. Anselmino et al.
    - Use of HERMES, COMPASS & JLab data
    - First moment of Sivers function: $x\Delta^N f^{(1)}(x) \equiv -x f_{1T}^{\perp(1)}(x)$
- $f_{1T}^{\perp}(x)$ of anti-quarks is not well known
  - Since $\bar{q}$ & q are mixed up in SIDIS
- SpinQuest will
  - Measure Sivers asymmetry of $\bar{u}$ & $\bar{d}$
  - Via proton-induced Drell-Yan process
  - Using new polarized targets of NH3 & ND3





Anticipated Sensitivity

- Conditions
  - Two years of data taking
  - NH_3:ND_3 = 50%:50% in time
  - Details in the E1039 proposal
- Transverse Single-Spin Asymmetry (TSSA): $A_{UT}^{\sin\phi_S}$
  - Measurement precision $\delta_{A_N} \sim 0.04$
- Aim to observe non-zero anti-quark Sivers asymmetry!!

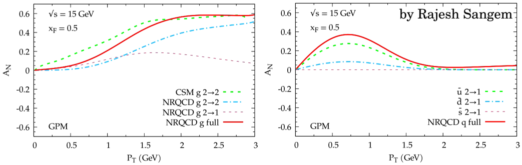


Preparations toward Data Taking

- Will start the commissioning *in Fall 2022*, using the proton beam
- Polarized target
  - Target with cryostat
    - Standalone tests were already completed
    - Being assembled in cave

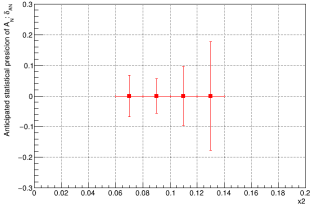
  - Roots pump & Helium liquefier
    - High capacity for high beam intensity
    - Being tested for full He circulation

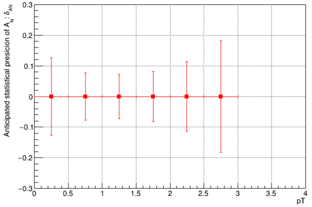
- Examination of J/ψ TSSA measurement, as "Day-One" physics
  - Maximum Sivers asymmetry
    - Based on NRQCD — PRD 102, 094011



  - Anticipated statistical precision: δ_{AN}
    - Based on PYTHIA8
    - In case of one-week data taking
- Optimizations of run configuration
  - Dimuon trigger for J/ψ and/or Drell-Yan
  - Magnetic field
  - Realistic detector response in simulation tests

δ_{AN} of J/ψ vs x_2 and p_T (GeV)





Conclusions

- SeaQuest
  - Designed to measure Drell-Yan process at high x
  - $\bar{d}(x)/\bar{u}(x) \sim 1.5$ up to $x = 0.45$
  - Reasonably described by “meson cloud model” & “statistical model”
  - Improved analyses are ongoing
    - Better statistics with full dataset
    - Better systematics with fine-tuned simulation
  - Nuclear effects, J/ψ production, Drell-Yan angular distribution, etc.
- SpinQuest
  - Measurement of Sivers functions ($f_{1T}^{\perp}(x)$) of anti-quarks
  - Via Drell-Yan process with polarized NH3 & ND3 targets
  - In final preparation and then data taking in Fall 2022.

    Please contact spokespersons if interested:

    Dustin Keller (UVA, dustin@virginia.edu) & Kun Liu (LANL, liuk@lanl.gov)

Backup Slides

Analysis Step 1 — Cross-Section Ratio

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

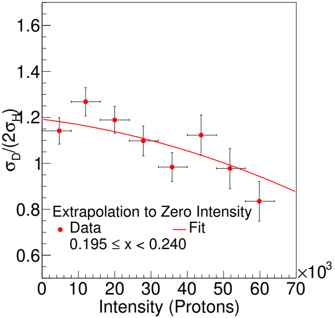
- Measure dimuon events
  - With LH2 & LD2 targets
  - At $M > 4.5$ GeV
- Take the ratio of dimuon yields in p+p & p+d

$$\frac{Y_D(x_t, I)}{2Y_H(x_t, I)} \quad \text{with} \quad Y_{H,D}(x_t, I) = \frac{N_{H,D}(x_t, I)}{L_{H,D}} - \frac{N_{Empty}(x_t, I)}{L_{Empty}}$$

  - Normalized by relative beam luminosity
  - Corrected for non-target events
- Correct the yield ratio
  - For random BGs and reconstruction efficiency
  - Via "beam-intensity extrapolation"

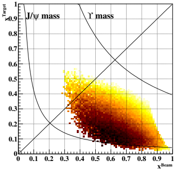
$$\frac{Y_D(x_t, I)}{2Y_H(x_t, I)} = \frac{\sigma_{pd}(x_t)}{2\sigma_{pp}(x_t)} + a\,I + b\,I^2$$

- Obtain $\sigma_{pd}/2\sigma_{pp}$ vs x_t



Analysis Step 2 — $\bar{d}/\bar{u}$

- Derivation of $\bar{d}(x)/\bar{u}(x)$ from $\sigma_{pd}/2\sigma_{pp}$
  - Using the SeaQuest data alone to demonstrate its impact
  - Anticipating global analyses for more-accurate extractions



- Procedure
  - "$\sigma_{pd}/2\sigma_{pp} \approx (1 + \bar{d}/\bar{u})/2$" is not valid at high x_t because the assumption "$x_b \gg x_t$" breaks
  - Iterative computations of $\sigma_{pd}/2\sigma_{pp}$ from $\bar{d}/\bar{u}$

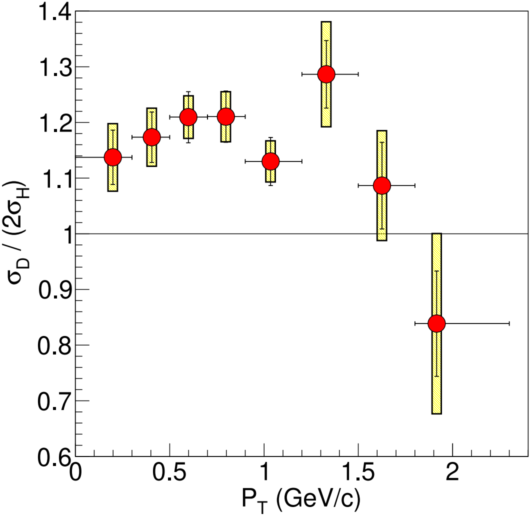
1. Have the measured $\sigma_{pd}/2\sigma_{pp}$ ($\equiv R_{meas}$)
2. Initialize $\bar{d}(x)/\bar{u}(x) = 1$
3. Calculate the cross-section ratio ($\equiv R_{pred}$) without assuming $x_b \gg x_t$:

$$\sigma(x_b, x_t) \propto \sum_{q=u,d,s,c} {e_q}^2 \{q_b(x_b)\bar{q}_t(x_t) + \bar{q}_b(x_b)q_t(x_t)\}$$

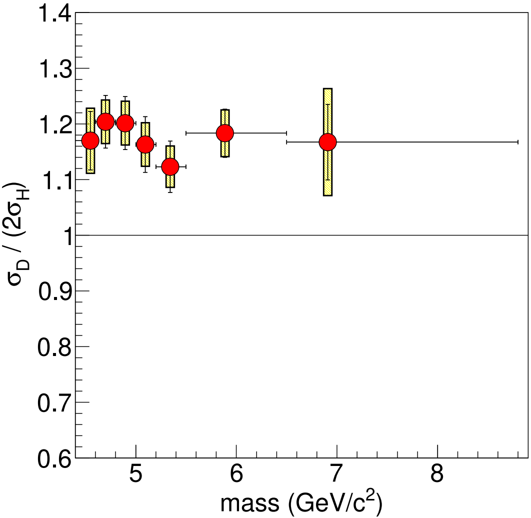
   - At NLO
   - Take $u(x)$, $d(x)$, $s(x)$, $c(x)$ & $\bar{u}(x) + \bar{d}(x)$ from CT18 PDF
   - Apply the measured kinematic region (i.e. x_b & x_t) evaluated by simulation

4. Adjust $\bar{d}(x)/\bar{u}(x)$ to reduce $R_{pred} - R_{meas}$
5. Go back to #3 until $R_{pred} \approx R_{meas}$

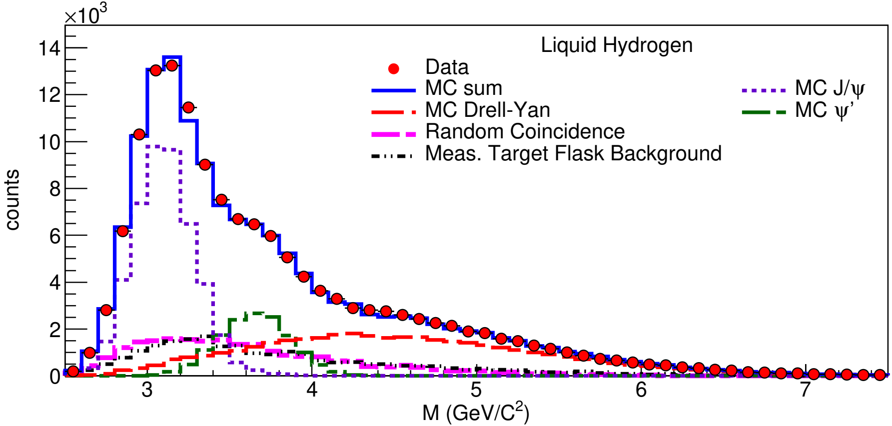
Cross-Section Ratio ($\sigma_{pd}/2\sigma_{pp}$) vs Dimuon p_T



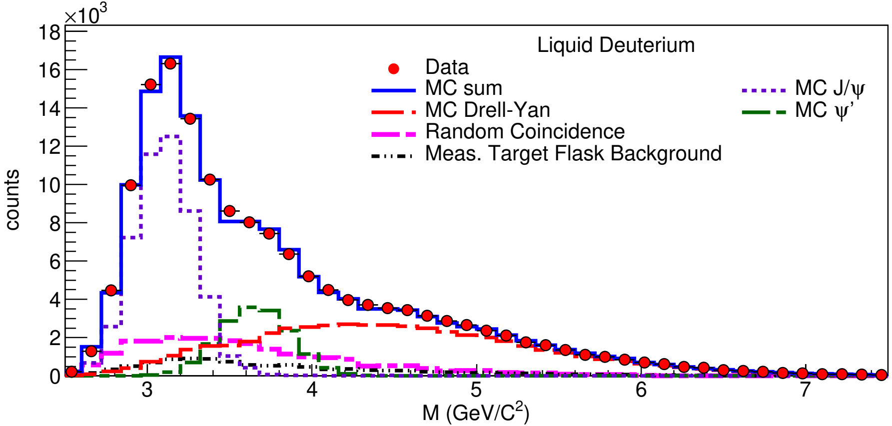
Cross-Section Ratio ($\sigma_{pd}/2\sigma_{pp}$) vs Dimuon Mass



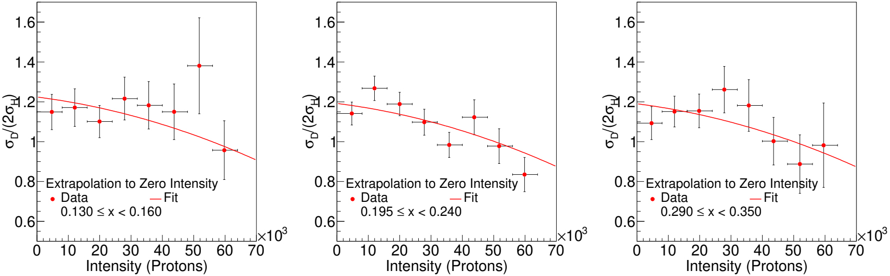
Mass Distribution — LH2



Mass Distribution — LD2

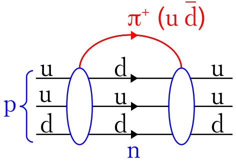


Beam-Intensity Extrapolation

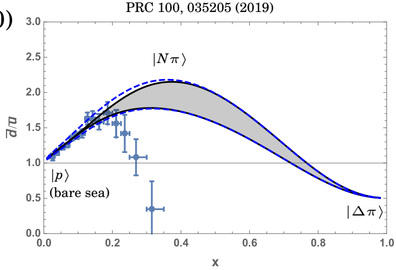


Comparison to Theory Calculations

- Pion Cloud Model
  - $|p\rangle = (1-a-b)|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$
    - $\bar{d}$ in π^+ as $|n\pi^+\rangle$ etc.
    - $\bar{u}$ in π^- as $|\Delta^{++}\pi^-\rangle$ etc.



  - $\bar{u}_p(x) \sim \bar{u}_{p0}(x) + f_{\pi N} \otimes \bar{u}_\pi(x) + f_{\pi\Delta} \otimes \bar{u}_\pi(x)$
    $\bar{d}_p(x) \sim \cdots$
    - $f_{\pi N}$ & $f_{\pi\Delta}$: pion-splitting functions (indendent of SeaQuest nor NuSea data)
    - $\bar{d}/\bar{u} \to 1$ @ $x \to 0$
    - $\bar{d}/\bar{u} > 1$ @ middle x
    - $\bar{d}/\bar{u} \to 1/2$ @ $x \to 1$
  - Predicts no spin polarization ($\Delta\bar{d} = \Delta\bar{u} = 0$)
    - When only scalar mesons are considered
    - Inconsistent with A_L of $W^\pm$ at RHIC??
  - Predicts non-zero orbital angular momentum ($L_{q,\bar{q}}$)
    - Needs $L = 1$ of π to make $J^P = 1/2^+$ of proton, as parity of π is $J^P = 0^-$



- Statistical model ... *NPA948, 63 (2016)*
  - Based on the Fermi-Dirac statistics:

$$xq^h(x) = \frac{A_q X_{0q}^h x^{b_q}}{\exp\left[(x - X_{0q}^h)/\bar{x}\right] + 1} + \frac{\tilde{A}_q x^{\tilde{b}_q}}{\exp(x/\bar{x}) + 1}$$

$$x\bar{q}^h(x) = \frac{\bar{A}_q \left(X_{0q}^{-h}\right)^{-1} x^{b_{\bar{q}}}}{\exp\left[(x + X_{0q}^{-h})/\bar{x}\right] + 1} + \frac{\tilde{A}_q x^{\tilde{b}_q}}{\exp(x/\bar{x}) + 1}$$

    - $X_{\bar{q}}^{+h} = -X_q^{-h}$ due to QCD chiral structure
  - Fitted to only DIS data
    - $\bar{d}/\bar{u} \to 2.5$ as $x \to 1$
  - Expects opposite spin polarization: $\Delta\bar{d}(x) - \Delta\bar{u}(x) \approx -\left[\bar{d}(x) - \bar{u}(x)\right]$
    - Compatible with A_L of $W^{\pm}$ at RHIC
  - Considers no orbital angular momentum