Measurements of Antiquark Distributions in Proton via Unpolarized/Polarized Drell-Yan Process at FNAL-SeaQuest/SpinQuest Experiments

JAEA Seminar

2022/09/14

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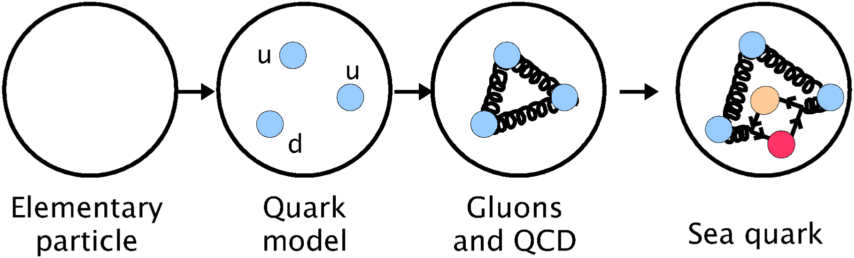
Outline

1. Introduction
   - Partonic (quark, antiquark & gluon) structure of proton
   - Drell-Yan process for measurements of parton distribution function (PDF)
2. SeaQuest experiment
   - Beam & spectrometer
   - Unpolarized targets
   - Flavor asymmetry of light anti-quarks: $\bar{d}(x)/\bar{u}(x)$
   - Nuclear effects
3. SpinQuest experiment
   - Polarized targets
   - Sivers function
   - Spin asymmetry of J/ψ productions
   - Schedule
4. Summary

Internal Structure of Proton (Nucleon)

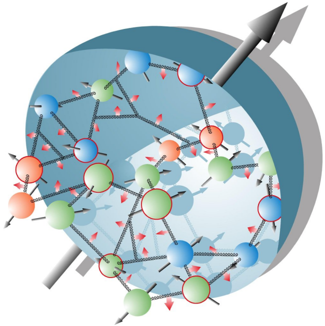
- Representations at various scale

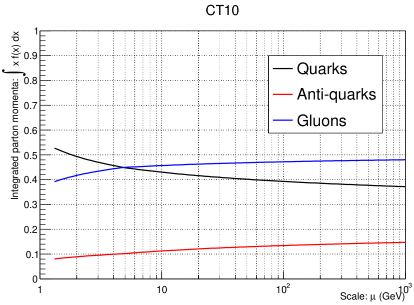
Shorter distance, higher energy $\Longrightarrow$



  - Proton structure at energy scale $\mu \gtrsim 1$ GeV will be discussed
  - Dynamical creation of anti-quarks from gluons ... $g \to q\bar{q}$

Proton @ Short Distance

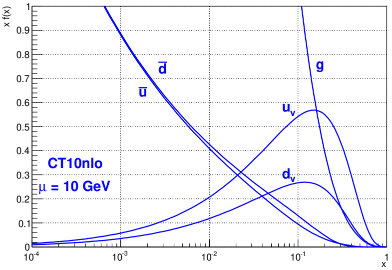




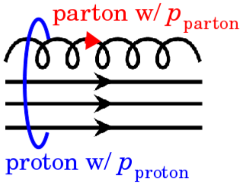
- Valence quarks, sea quarks & gluons
- Breakdown of proton momentum
  ... $q : \bar{q} : g \sim 45\% : 10\% : 45\%$ @ $\mu \sim 10$ GeV

Parton Distribution Function: PDF

- Quarks, anti-quarks & gluons

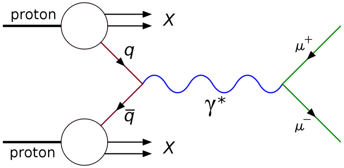


- Global analyses of multiple experimental data
  $\Longrightarrow$ Practical understanding of PDFs
  - Cf.: QCD-based models/calculations
    $\Longrightarrow$ Theoretical understanding



Access to Antiquarks via Drell-Yan Process

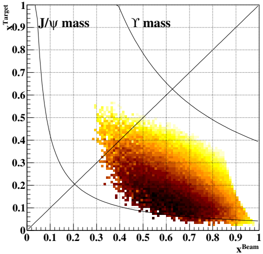
- Drell-Yan process: $p + p \to \gamma^* \to \mu^+ + \mu^-$
  - Invariant mass: $M^2 = x_{beam} x_{target} s$,
    Rapidity: $\exp Y = \sqrt{x_{beam}/x_{target}}$
  - Bjorken $x_{beam} = \frac{M}{\sqrt{s}} e^Y, \quad x_{target} = \frac{M}{\sqrt{s}} e^{-Y}$



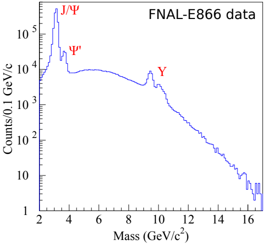
- Cross section @ LO

$$\frac{d^2\sigma}{dx_{Beam} dx_{Target}} = \frac{4\pi\alpha^2}{9x_{Beam}x_{Target}} \frac{1}{s} \sum_i e_i{}^2 \cdot$$
$$\{q_i(x_{Beam})\bar{q}_i(x_{Target}) + \bar{q}_i(x_{Beam})q_i(x_{Target})\}$$

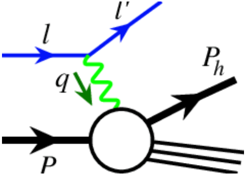
  - Only "$q(x_{Beam})\bar{q}(x_{Target})$" survives @ forward rapidity
    $\Longrightarrow$ q having x_{Beam} & $\bar{q}$ having x_{Target} are distinguishable event-by-event
  - Larger invariant mass
    $\Longrightarrow$ Larger x_{Target} (and x_{Beam})
  - Lower rate because of EM interaction
    $\Longrightarrow$ Need larger luminosity
    & compete with more BGs



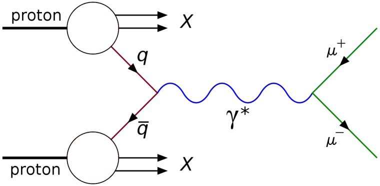
- For PDF measurements
  - Cross section $\Longrightarrow$ Unpolarized PDFs
  - Angular distribution $\Longrightarrow$ Boer-Mulders
  - With polarization $\Longrightarrow$ Sivers, Transversity, etc.
  - Nuclear targets $\Longrightarrow$ Nuclear effects
- Specialty w.r.t. SIDIS
  - Sensitivity to $\bar{q}$
  - TMD sign change



Semi-Inclusive DIS



Drell-Yan



Aim to Research Antiquarks in Proton

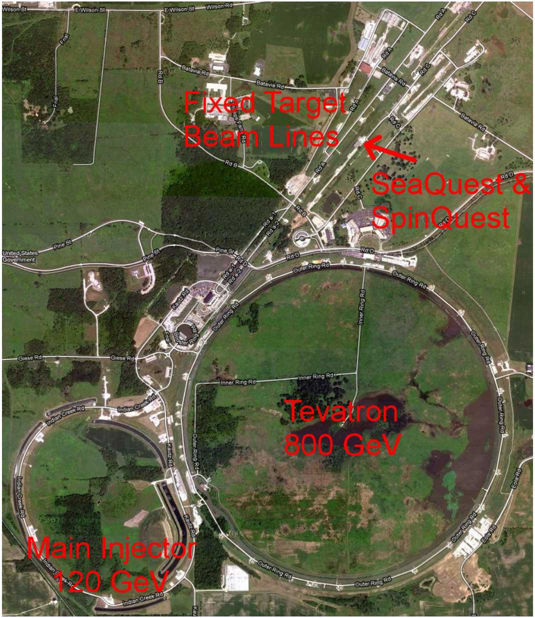
- Proton is simplest stable object bound by strong force (QCD)
  - Best system to study QCD
  - Antiquarks are sensitive to QCD dynamics in proton
    (because quarks are diluted with valence component)
- Ex.: Antiquark flavor asymmetry ($\bar{d}(x)/\bar{u}(x)$)?
  - Non-perturbative (i.e. low-energy) QCD effect?
  - Behavior at large x?

$\Downarrow$

1. Improve the accuracy of antiquark PDFs
   - $\bar{q}(x)$ is an input of hadron-induced processes (ex: $u + \bar{d} \to W^+$)
2. Understand "how the hadrons are constructed by QCD"
   - Together with spin polarization and orbital angular momentum
   - Relation/unification with hadron models based on QCD effective theory

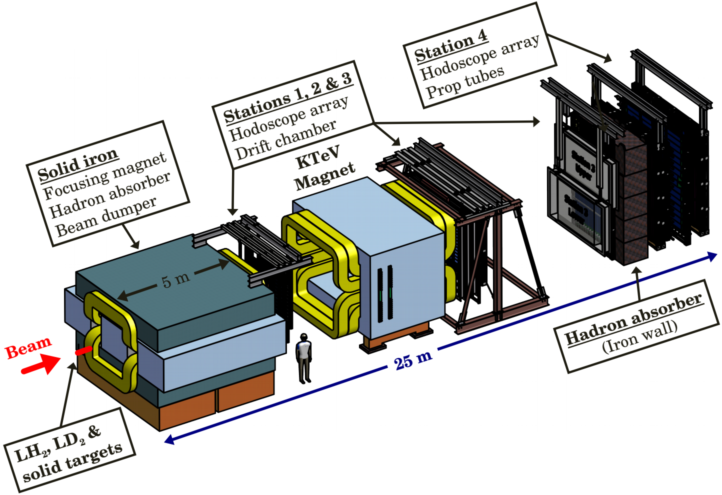
SeaQuest Experiment (Unpolarized Targets)

Proton Beam @ FNAL



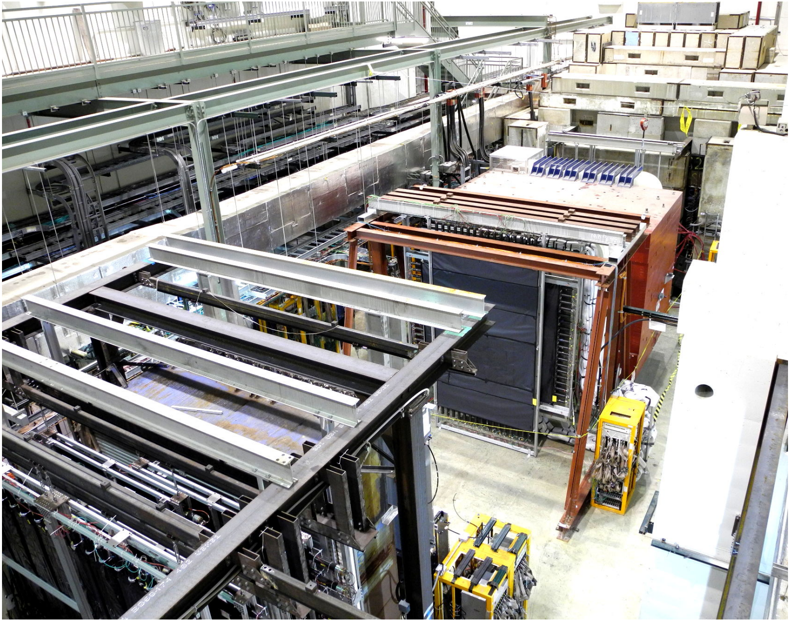
- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for Sea/SpinQuest
  - 55 sec for ν exp.
- Bunch
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec

SeaQuest Spectrometer



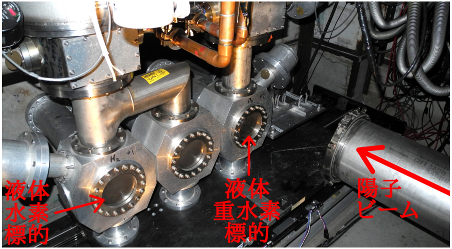
- Targets: LH_2, LD_2, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump

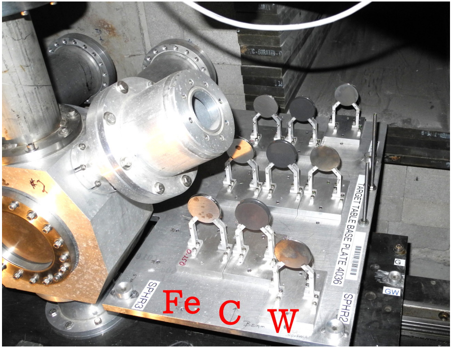
SeaQuest Hall — 2015-July-27



SeaQuest Targets

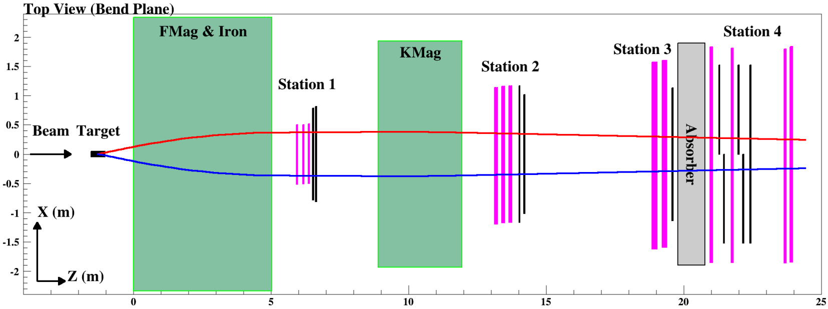
- LH_2, LD_2
  - 50.8 cm $\sim$ 0.1 interaction lengths
- Iron, Carbon, Tungsten





Signal Event

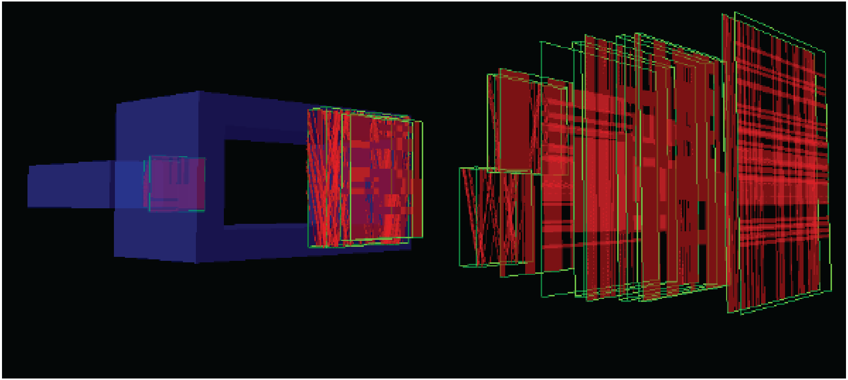
- A typical Drell-Yan event (top view) ... mass = 6 GeV, θ_{μ^+} = 90°, ϕ_{μ^+} = 0°



- 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

Background Event

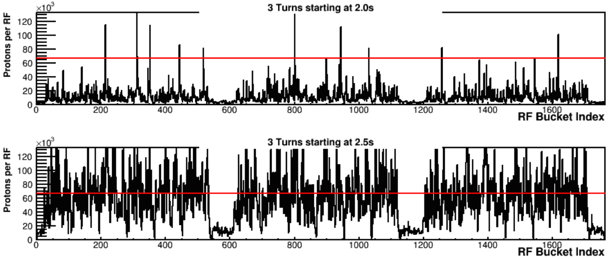
- Typical BG event during commissioning



  - Detector occupancy $\sim 100\%$!!

Intensity of Beam RF-Buckets

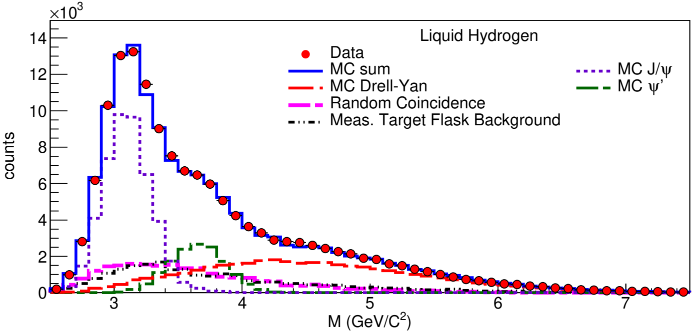
- Example in Run 2



  - 1 RF = 19 ns
  - Supposed intensity = 40k protons/RF at max
  - As high as $\times 5$!!
    - Improvement at accelerator
    - Veto in trigger (and analysis)

Reconstruction & Identification of Drell-Yan Events

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

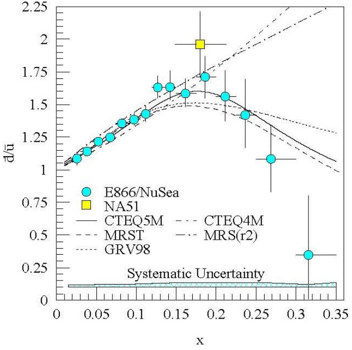


  - Drell-Yan, J/ψ & ψ' events from simulation
  - Non-target events from empty target
  - Random-coincidence BGs from real data via event mixing
- Origins of measured dimuons well understood
- Dominated by Drell-Yan at $M > 4.5$ GeV

Flavor Asymmetry of Light Antiquarks ($\bar{d}(x)/\bar{u}(x)$) @ SeaQuest

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

- CERN NMC ('90): deep inelastic muon scattering
  - Gottfried Sum: $S_G = 0.235 \pm 0.026 < 1/3$
  - $\int_0^1 \bar{d}(x)dx - \int_0^1 \bar{u}(x)dx = 0.147 \pm 0.039$ ... discovery of flavor asymmetry of anti-quarks in the proton (more $\bar{d}$ than $\bar{u}$)
- 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 $x \in (0.015, 0.35)$

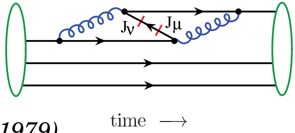


70% asymmetry!

A few % expected

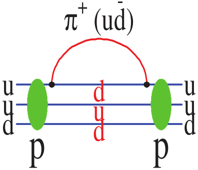
Theories of $\bar{d}/\bar{u}$ Asymmetry (1)

- 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)*

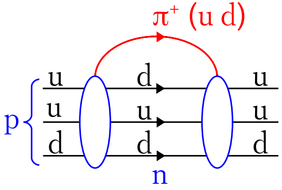
- Chiral quark model ... *PRD59, 034024 (1999)*
  - Effective interaction between Goldstone boson (π) & constituent quark
  - $|q_{\text{constituent}}\rangle = \left(1 - \frac{3a}{2}\right)|q\rangle + \frac{3a}{2}|q\pi\rangle$



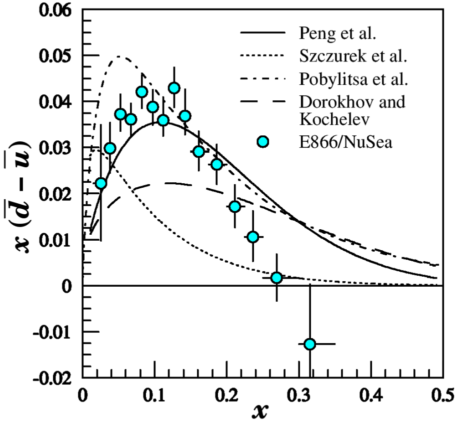
Theories of $\bar{d}/\bar{u}$ Asymmetry (2)

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

- 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 $J^P = 0^-$)



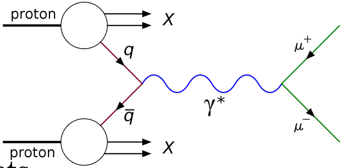
Comparison of Theories to Measurements



Meson cloud model: PRD58, 092004
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 $\bar{d} < \bar{u}$?

Method of Measuring $\bar{d}(x)/\bar{u}(x)$



- Drell-Yan process @ forward rapidity

$$\frac{d^2\sigma}{dx_b dx_t} \approx \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum_i e_i{}^2 q_i(x_b)\bar{q}_i(x_t)$$

- Ratio of cross sections with LH2 & LD2 targets

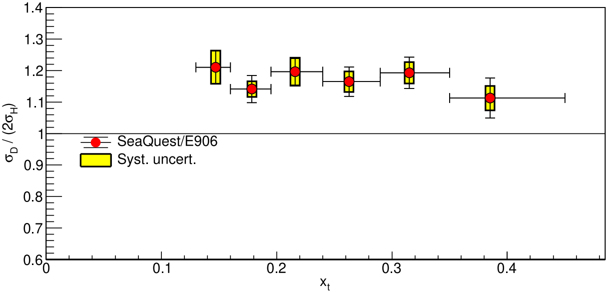
$$\frac{\sigma_{pd}(x_t)}{2\sigma_{pp}(x_t)} = \frac{\sigma_{pp}(x_t) + \sigma_{pn}(x_t)}{2\sigma_{pp}(x_t)} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$

- Larger invariant mass $\Longrightarrow$ Larger x_{Target} (and x_{Beam})

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

- SeaQuest result

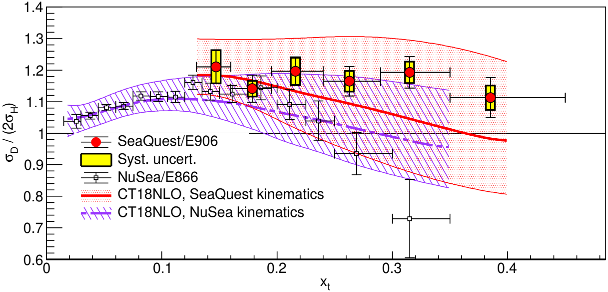
Nature 590, 561 (2021)



- 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

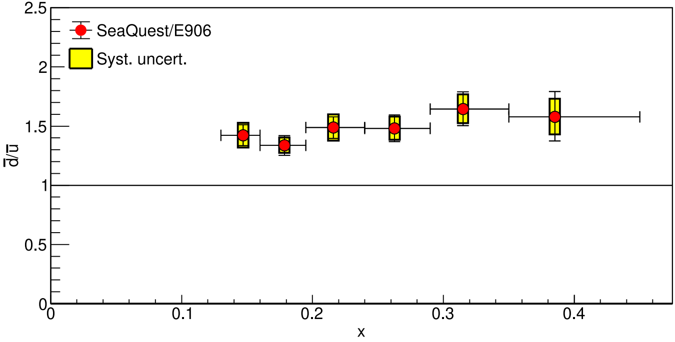


- Effects of experimental kinematics
  - Shown by the calculations using CT18 NLO
  - Account for the difference at $x_t \sim 0.15$

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

- SeaQuest result

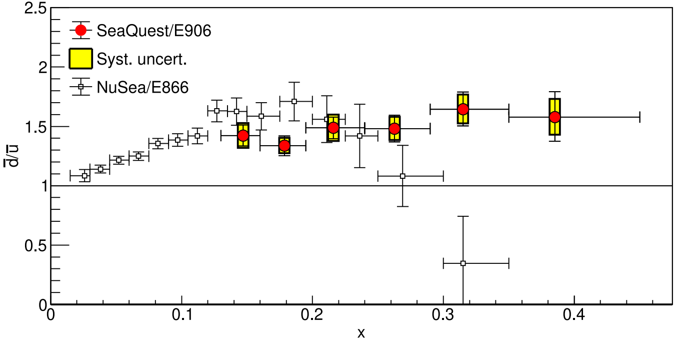
Nature 590, 561 (2021)



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

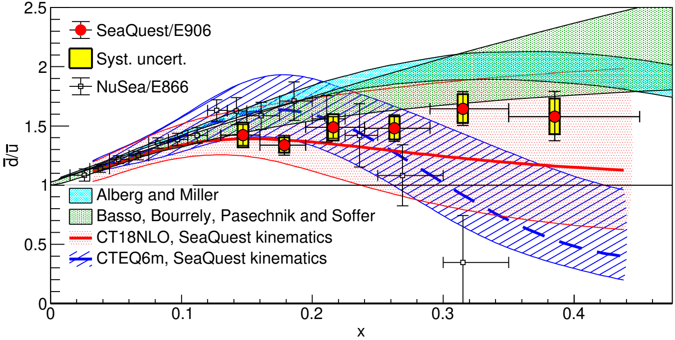
- Comparison to NuSea/E866 result



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

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

- Comparison to theory calculations



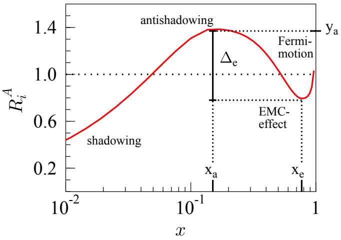
- Reasonably described by the predictions of
  - "Pion cloud model" (Alberg & Miller) and
  - "Statistical model" (Basso et al.)
- Unique data to constrain anti-quark PDFs at high x in global analyses

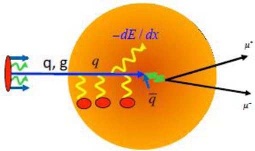
Nuclear Effects @ SeaQuest

Nuclear Effects in Drell-Yan Process

- Observable: $R_A \equiv \hat{\sigma}^{p+A}(x)/\hat{\sigma}^{p+p}(x)$
  = Ratio of per-nucleon D-Y cross sections
- Mechanism for $R_A \neq 1$
  - Change of PDF in nucleus
    = "Nuclear effects" observed in DIS
    - Shadowing & anti-shadowing
    - EMC effect — PLB 123, 275 (1983)
    - Fermi motion
  - Parton energy loss in cold nuclear matter
    - Soft interaction between beam-side parton & nuclear matter
    - Collisional or radiative?
  - No final-state interaction
- R_A should be comprehensively examined to untangle the mechanisms

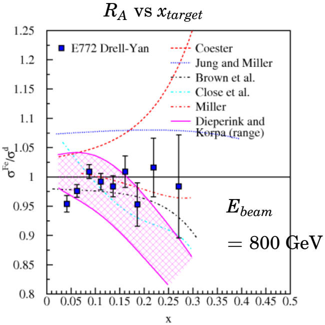
JHEP 0807, 102 (2008)

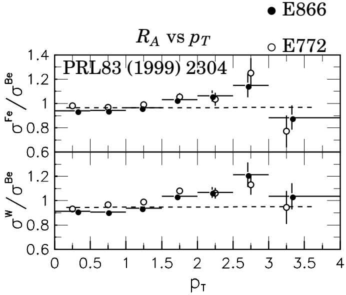




Measurements @ SeaQuest

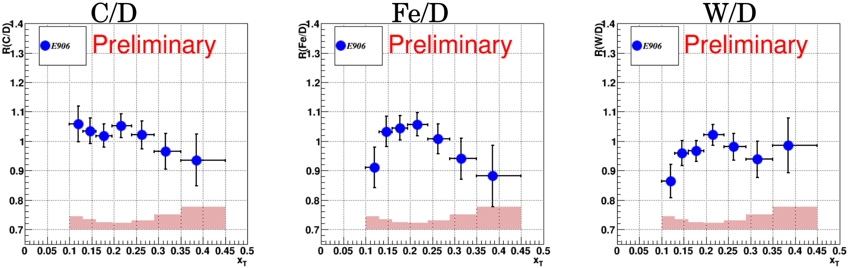
- Drell-Yan process at forward rapidity
- R_A vs x_{target}: Effect on antiquarks
  - Smaller than that on quarks? (PRL64, 2479)
  - $0.1 < x_{target} < 0.45$
- Effect on quarks in beam proton
  = Parton energy loss in cold-nuclear matter
  - R_A vs x_{beam}: Energy loss
    - $x_{beam} > 0.6, x_{target} > 0.15$
  - R_A vs p_T: p_T broadening
    - $0.1 < x_{target} < 0.45$





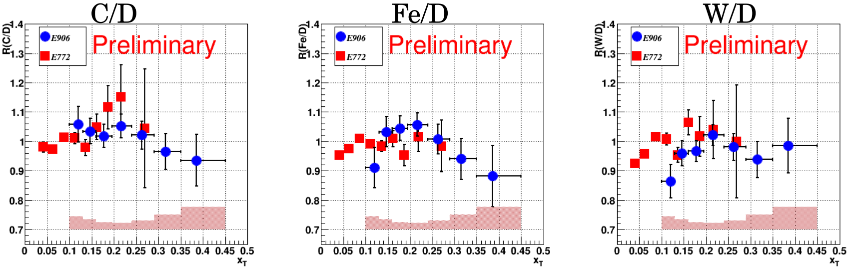
R_A vs x_{target} by SeaQuest

- Preliminary result



  - 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



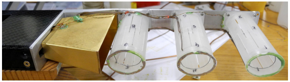
  - Agreement within measurement accuracy
  - Better precision at $x_{target} \gtrsim 0.2$ by SeaQuest

SpinQuest Experiment (Polarized Targets)

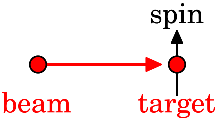
SpinQuest Hall — 2022-August-26

Polarized Targets of SpinQuest

- Solid NH_3 & ND_3 beads
  - L 80 mm, ϕ 40 mm



- Transverse polarization



- Cryostat in “Target Cave”
  - Standalone test completed in 2018 at UVA
  - Piping & safety test ongoing in Target Cave

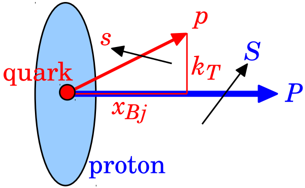
Sivers Function @ SpinQuest

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

- One of the eight Transverse-Momentum-Dependent (TMD) PDFs

		Parton spin		
		U	L	T
Nucleon	U	Density f_1		Boer-Mulders $h_1^{\perp}$
spin	L		Helicity g_1	Worm gear #2 $h_{1L}^{\perp}$
	T	Sivers $f_{1T}^{\perp}$	Worm gear #1 g_{1T}	Transversity h_1 & Pretzelosity $h_{1T}^{\perp}$

  - Proposed in 1990s already
  - Nucleon structure can be rich
    $\Longleftrightarrow$ Can be simple (i.e TMD PDFs = 0) if k_T doesn't correlate with spins

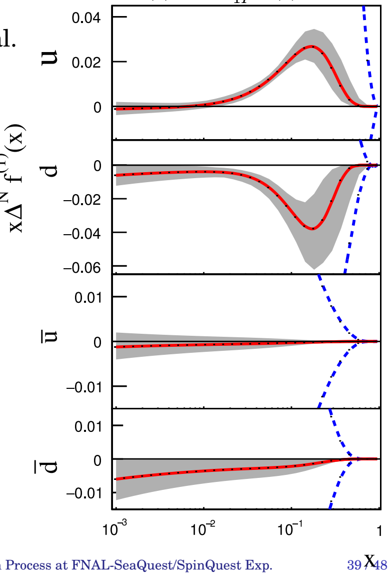


- Correlation between the nucleon spin (S) & the parton transverse momentum (k_T)

Sivers Function of Anti-Quarks

- Extraction by global analyses
  - PRD88 (2013) 114012, P. Sun & F. Yuan
  - PRD89 (2014) 074013, M. G. Echevarria et al.
  - JHEP 04 (2017) 046, M. Anselmino et al.
    - Use of HERMES, COMPASS & JLab data
- $f_{1T}^{\perp}(x)$ 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

First moment of Sivers function:
$x\Delta^N f^{(1)}(x) \equiv -x f_{1T}^{\perp(1)}(x)$

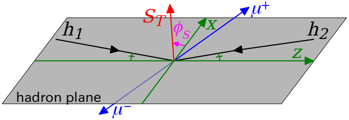


Measurement Method @ SpinQuest

- Proton beam $+$ Transversely-polarized NH_3 & ND_3 targets
- Drell-Yan processes in $p+\vec{p}$ & $p+\vec{d}$
- Observable: Transverse Single-Spin Asymmetry A_N

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

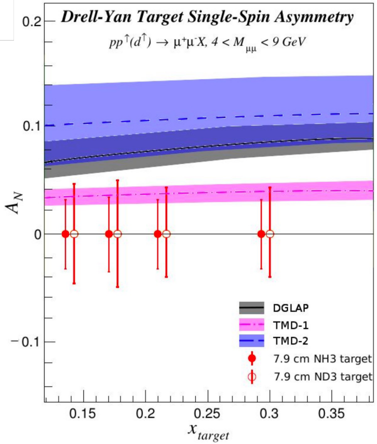
  - ϕ_S: Angle of proton spin w.r.t. transverse momentum of quarks



  - Sivers function = correlation between proton spin & quark k_T
  - Non-zero correlation $\Longrightarrow$ Momentum bias in angle $\Longrightarrow$ Non-zero TSSA
- Sivers function of antiquarks
  - Combined analysis of TSSAs in $p+\vec{p}$ & $p+\vec{d}$ $\Longrightarrow$ Seperation of $\bar{u}$ & $\bar{d}$

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): $A_{UT}^{\sin \phi_S}$
  - $0.1 \lesssim x_{Target} \lesssim 0.3$
  - Measurement precision $\delta_{A_N} \sim 0.04$
- Aim to observe non-zero anti-quark Sivers asymmetry!!



SpinQuest Timeline

- Schedule for data taking

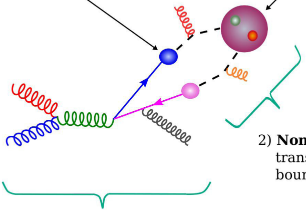
Year	Month	Event
2022	12	Commission target & spectrometer using beam
2023	02	Start the 1st data taking
		$\Downarrow$ 4.5 months
	07	Accelerator summer shutdown
	12	Start the 2nd data taking

- "Day-One" Physics
  - TSSA of J/ψ production
  - Sufficient statistics with first one month
- SpinQuest Upgrades?
  - Tensor polarization of antiquarks in deuteron — PRD 94, 054022 (2016)
  - Polarized nuclear effects
  - "DarkQuest": Dark-photon search

Spin Asymmetry of J/ψ Productions @ SpinQuest

J/ψ Productions in $p+p$

- $p+p \to J/\psi + X$

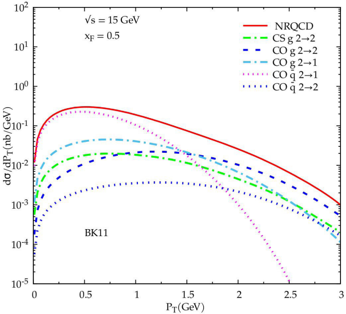


  - $g+g \to c+\bar{c}+X$
  - $q+\bar{q} \to c+\bar{c}+X$

  - Color Evaporation Model (CEM) ... NPB 405, 507 (1993)
    - $$\frac{d\sigma_{J/\psi}}{dx_F} = F_{J/\psi} \sum_{i,j=q,\bar{q},G} \int_{2m_c}^{2m_D} dM \frac{2M}{s\sqrt{x_F^2 + 4M^2/s}} f_i(x_1) f_j(x_2) \sum_n \hat{\sigma}_{ij\to c\bar{c}[n]}(x_1,x_2)$$
  - Non-Relativistic QCD (NRQCD) ... arXiv:2103.11660
    - $$\frac{d\sigma_{J/\psi}}{dx_F} = \sum_{i,j=q,\bar{q},G} \int_0^1 dx_1 dx_2 \delta(x_F - x_1 + x_2) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij\to J/\psi}(x_1,x_2)$$
    - $\hat{\sigma}_{ij\to J/\psi} = \sum_n C^{ij}_{c\bar{c}[n]} \left\langle \mathcal{O}_n^{J/\psi} \right\rangle$

J/ψ @ SpinQuest

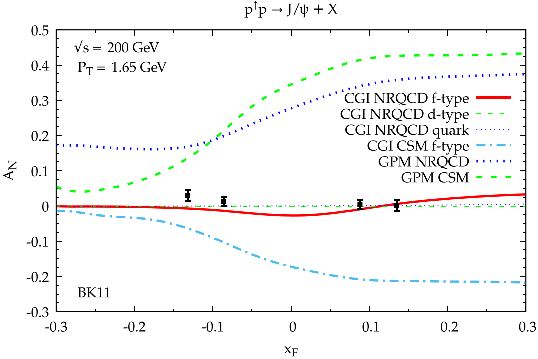
- Cross section
  - Based on NRQCD (`https://confluence.its.virginia.edu/display/twist/Seminars`)



  - Subprocess fractions vary with p_T largely
  - Sensitive to distributions of anti-quarks and gluons (at target side)
  - All depend on theoretical parameters (LDMEs & $\langle k_\perp^2 \rangle^{quark,gluon}$)
- Unique in terms of $\sqrt{s}$ & x_F

Transverse Single Spin Asymmetry of J/ψ

- Sensitive to the Sivers functions of antiquark & gluon
- Measurement at RHIC-PHENIX — PRD 98, 012006 (2018)
  - $\sqrt{s} = 200$ GeV, $x_F \sim 0.1$
- Theoretical estimate
  - Maximum TSSA — PRD 102, 094011

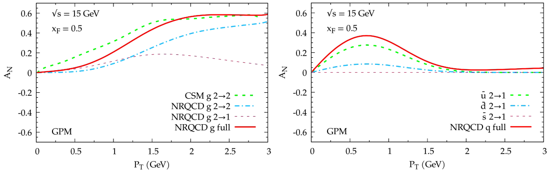


- Wide ranges of explorable asymmetry sizes & kinematic regions

Anticipated J/ψ TSSA @ SpinQuest

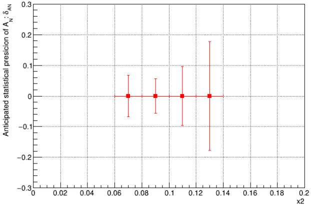
- Theoretical estimate of max Sivers asymmetry
  - $\sqrt{s} = 15$ GeV, $x_F \sim 0.5$

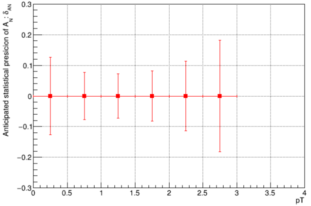
by Rajesh Sangem



- Anticipated statistical precision: δ_{AN}
  - Based on PYTHIA8
  - In case of one-week data taking

δ_{AN} of J/ψ vs x_2 and p_T (GeV)





Summary

- Drell-Yan process
  - Simplest/cleanest process in p+p scatterings
  - Becoming more important in measuring (TMD) PDFs of antiquarks
- SeaQuest experiment
  - Unpolarized Drell-Yan process
  - Flavor asymmetry of light anti-quarks: $\bar{d}(x)/\bar{u}(x)$
  - Nuclear effects
- SpinQuest experiment
  - Transversely-polarized Drell-Yan process
  - Sivers function
  - TSSA of J/ψ productions
- SpinQuest is starting the beam commissioning & the 1st data taking in December 2022. Please contact the spokespersons if interested:
  Dustin Keller (UVA, dustin@virginia.edu) & Kun Liu (LANL, liuk@lanl.gov)