Probing the antiquark distributions in the proton via unpolarized and polarized Drell-Yan experiments at Fermilab

GHP 2021

14 April 2021

Kenichi Nakano

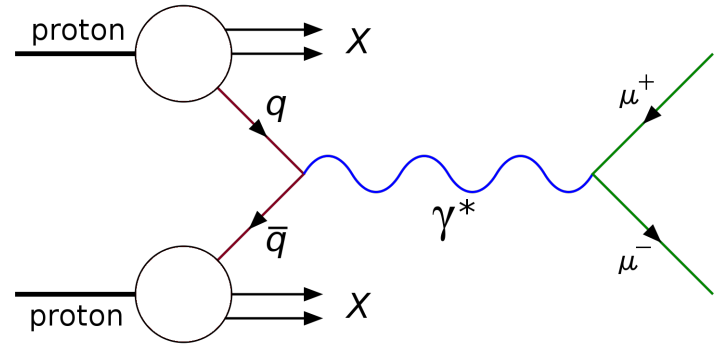
Tokyo Tech $\Longrightarrow$ University of Virginia

Outline

1. Two Drell-Yan experiments @ Fermilab
   - "SeaQuest" with unpolarized targets
   - "SpinQuest" with polarized targets
2. Spectrometer
3. Selected results of SeaQuest
   - Flavor asymmetry $\bar{d}(x)/\bar{u}(x)$ ... published on *Nature 590, 561* in Feb. 2021
   - Nuclear effect on antiquarks (R_A vs x_{target})
4. Aim & status of SpinQuest
5. Conclusions

Access to Antiquarks via Drell-Yan Process

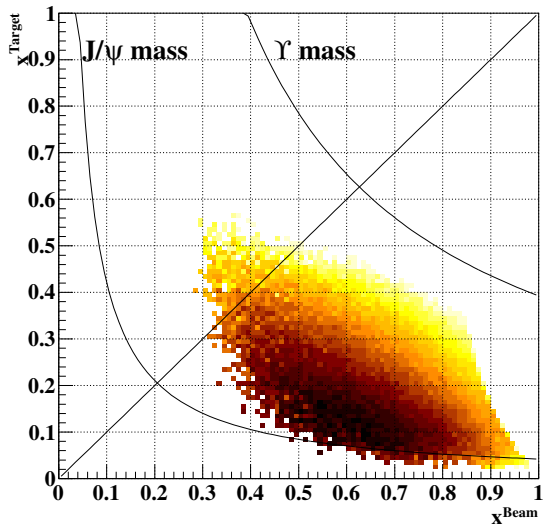
- Drell-Yan process: $p + p \to \gamma^* \to \mu^+ + \mu^-$
  - Invariant mass: $M^2 = x_{beam} x_{target} s$,
    Rapidity: $\exp Y = \sqrt{x_{beam}/x_{target}}$
  - Bjorken $x_{beam} = \frac{M}{\sqrt{s}} e^{Y}$, $\quad x_{target} = \frac{M}{\sqrt{s}} e^{-Y}$



- Cross section at LO:

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

  - Only "$q_b(x_b)\bar{q}_t(x_t)$" survives @ forward rapidity
    $\Longrightarrow$ q having x_b & $\bar{q}$ having x_t are distinguishable event-by-event
  - Lower rate because of EM interaction
    $\Longrightarrow$ Need larger luminosity & compete with more BGs

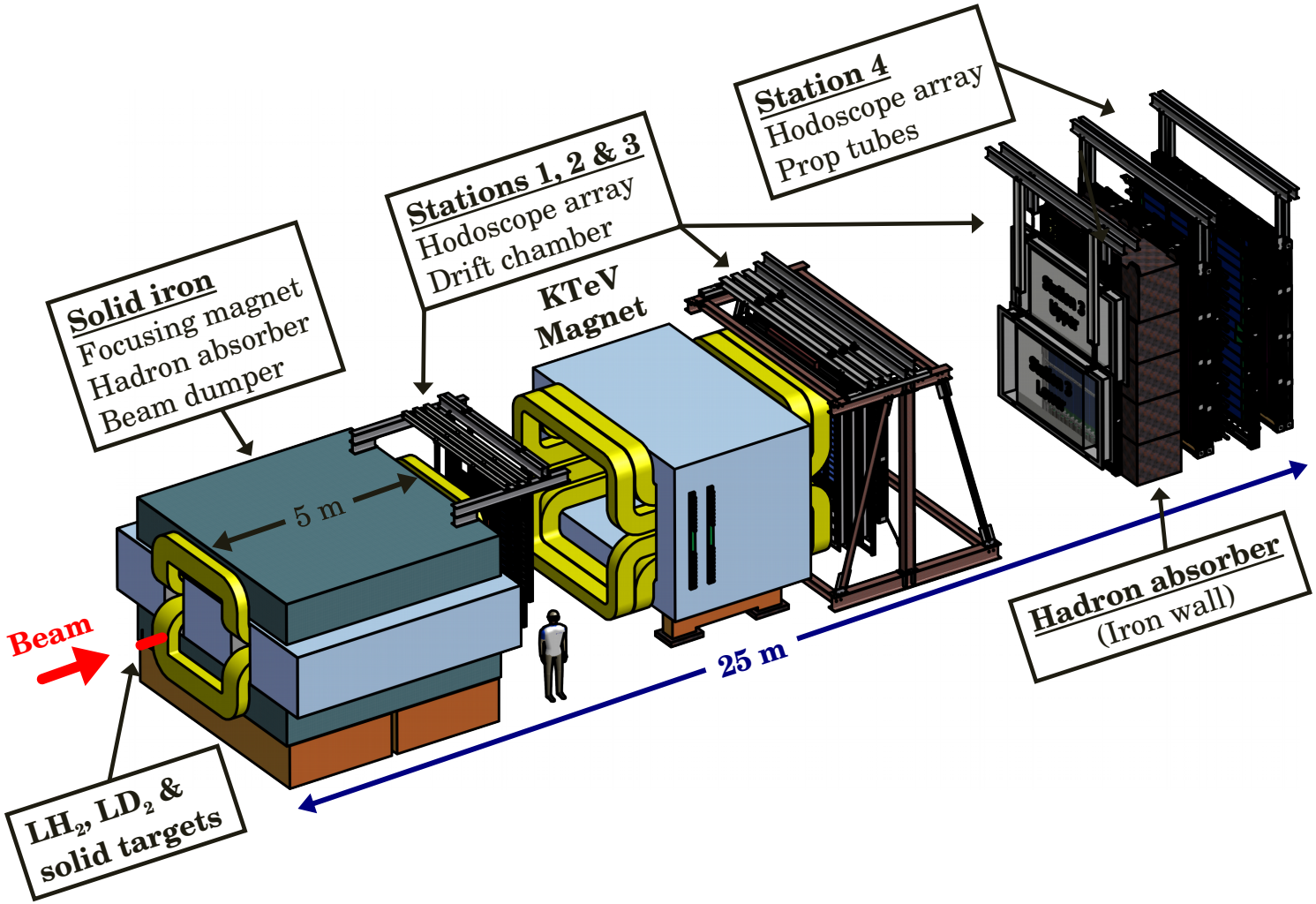


Drell-Yan Experiments @ Fermilab

- Beam: Proton at 120 GeV ($\sqrt{s} = 15$ GeV) from Main Injector
  - Intensity $\sim 10^{12}$ protons/sec
- SeaQuest/E906
  - Target: (Unpolarized) LH2, LD2, C, Fe, W
  - Data taking: 2013-2017 (completed)
  - Physics
    - Flavor asymmetry $\bar{d}(x)/\bar{u}(x)$
    - Nuclear effects
    - Via J/ψ production
    - and more
- SpinQuest/E1039
  - Spectrometer: Inherited from SeaQuest
  - Target: Transversely-polarized NH3, ND3
  - Data taking: 2021-2023 (planned)
  - Physics
    - Sivers asymmetry of $\bar{d}$ & $\bar{u}$
    - and more

$P > 90\%$ for NH3

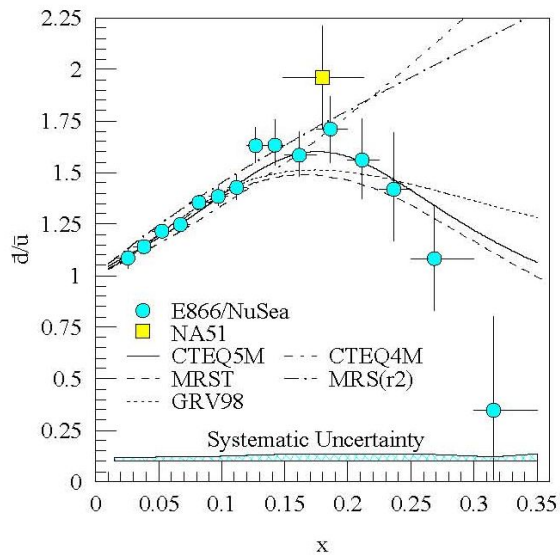
SeaQuest Spectrometer



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

SeaQuest Topic #1: Flavor Asymmetry $\bar{d}(x)/\bar{u}(x)$

- Symmetric in gluon splitting ($g \to u\bar{u}$ or $d\bar{d}$)
- 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!
- 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 $x \in (0.015, 0.35)$

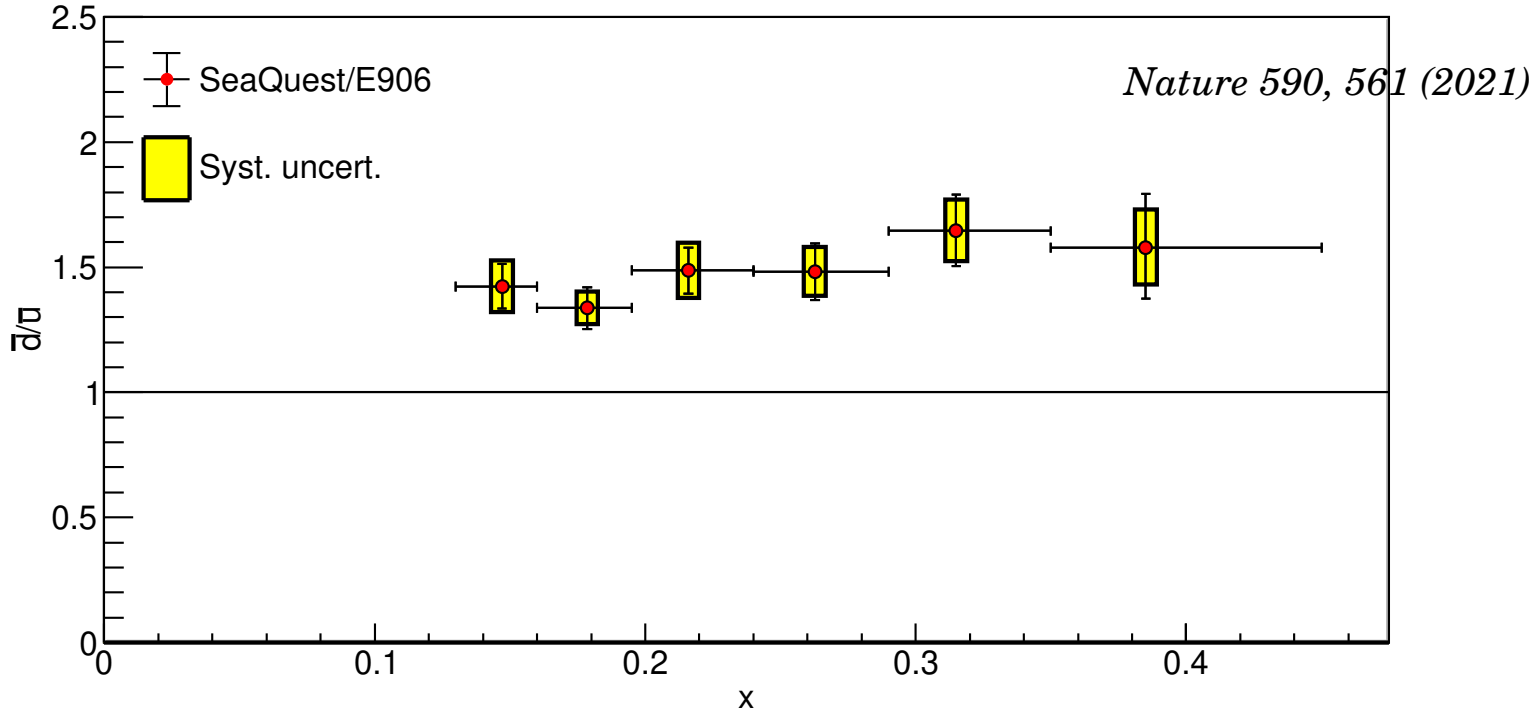


70% asymmetry!

A few % expected

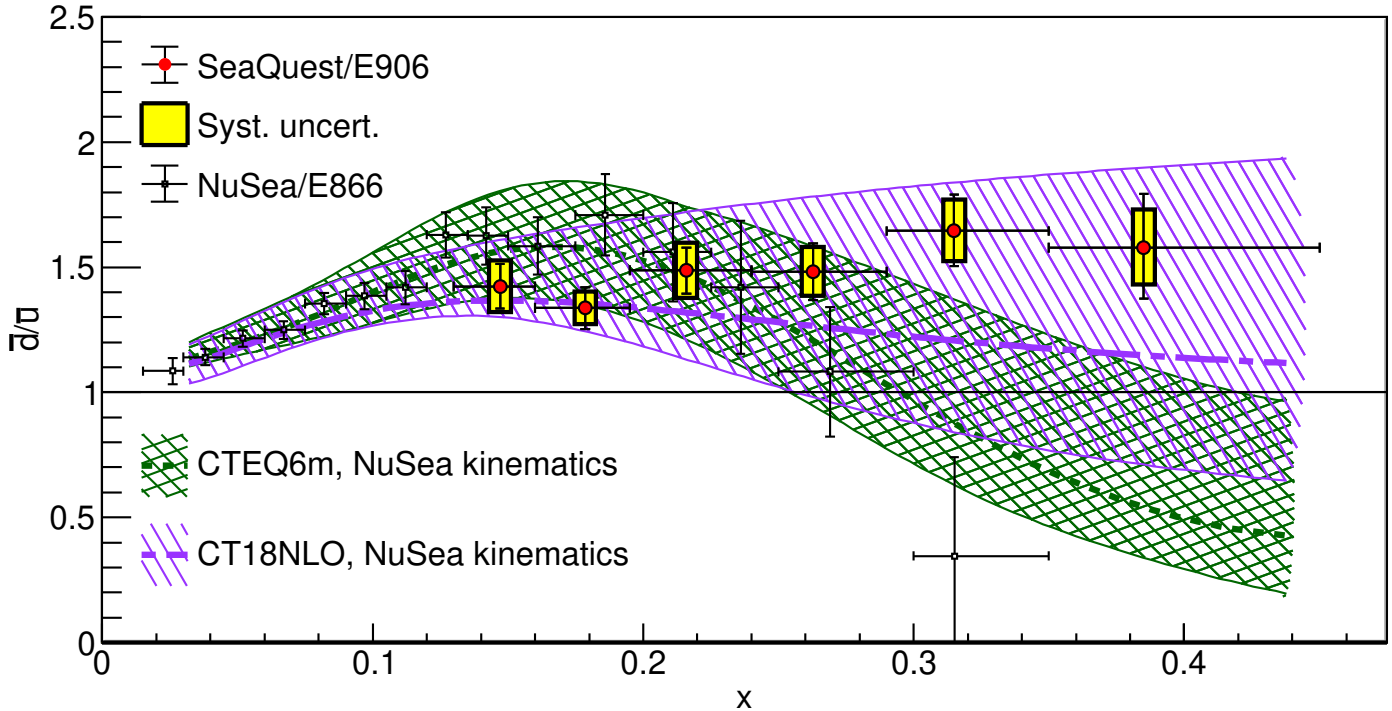
- Studied actively by effective QCD models & lattice QCD
  - Precise measurement at larger x was wanted

- SeaQuest result (published in February 2021)



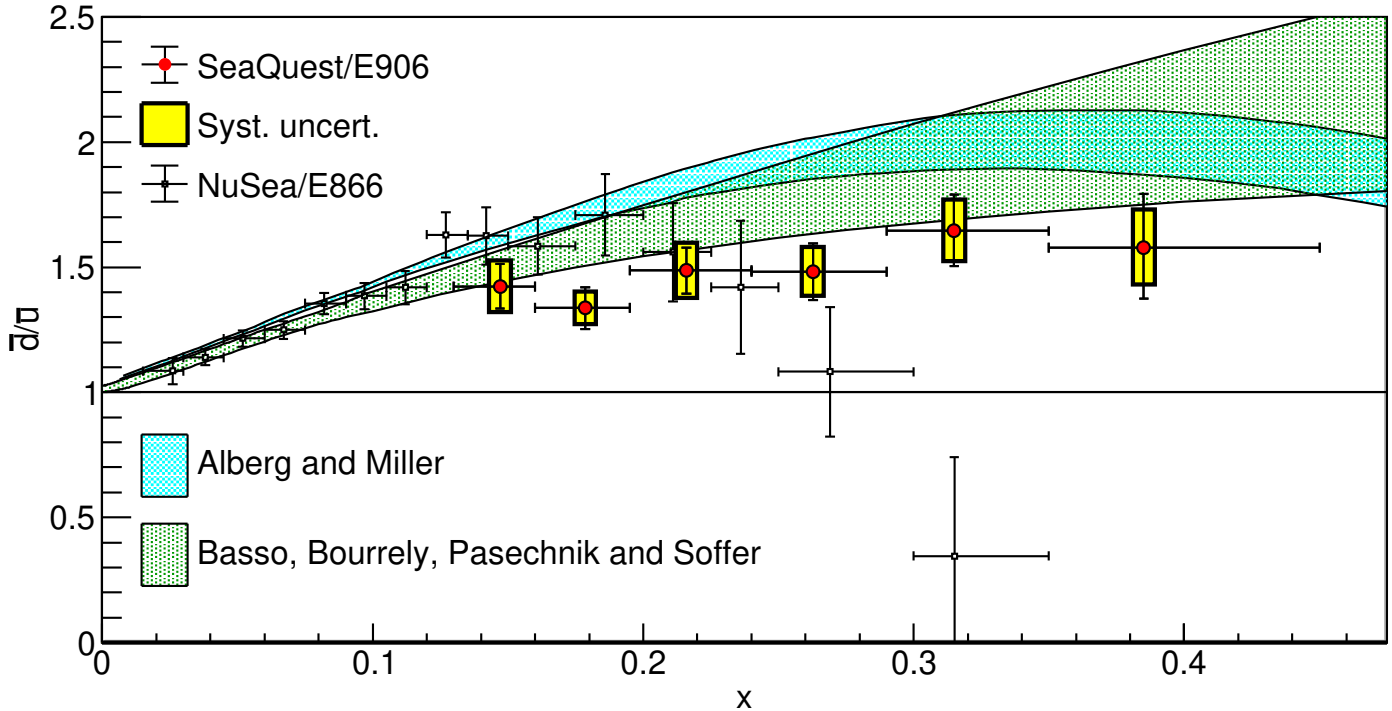
- Systematic errors
  - Correction for random BG & measurement efficiency (via “beam-intensity extrapolation”)
  - Relative luminosity
- Large asymmetry at high x (≤ 0.45) as well as low x

- Comparison to existing PDFs



  - Unique data to constrain anti-quark PDFs at high x in global analyses (e.g. CJ15-a')

- Comparison to model calculations



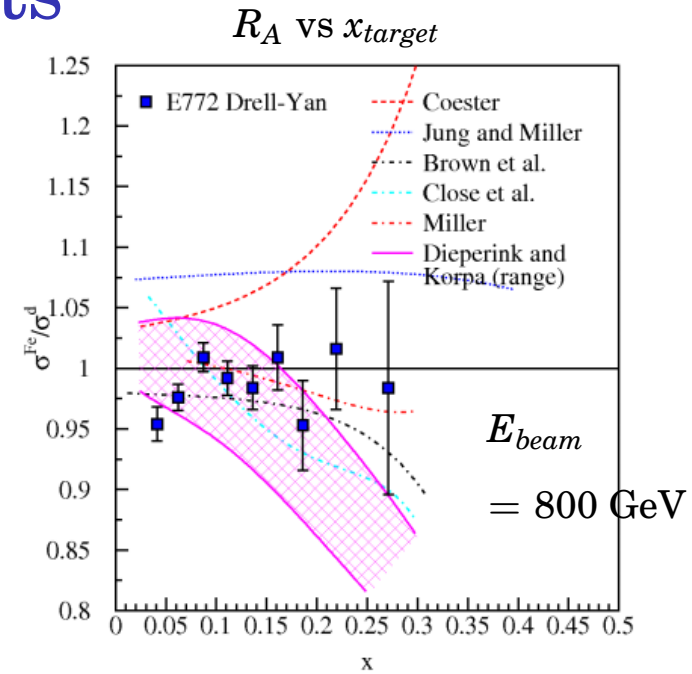
  - Reasonably described by the predictions of
    - "Pion cloud model" (Alberg & Miller) and
    - "Statistical model" (Basso et al.)
  - Further studies are anticipated to understand the true mechanism
    - $\bar{d}(x)/\bar{u}(x)$ at higher x ($\gtrsim 0.6$)
    - Relation to polarized distributions ($\Delta\bar{d}(x)$ & $\Delta\bar{u}(x)$)
    - Relation to orbital angular momenta

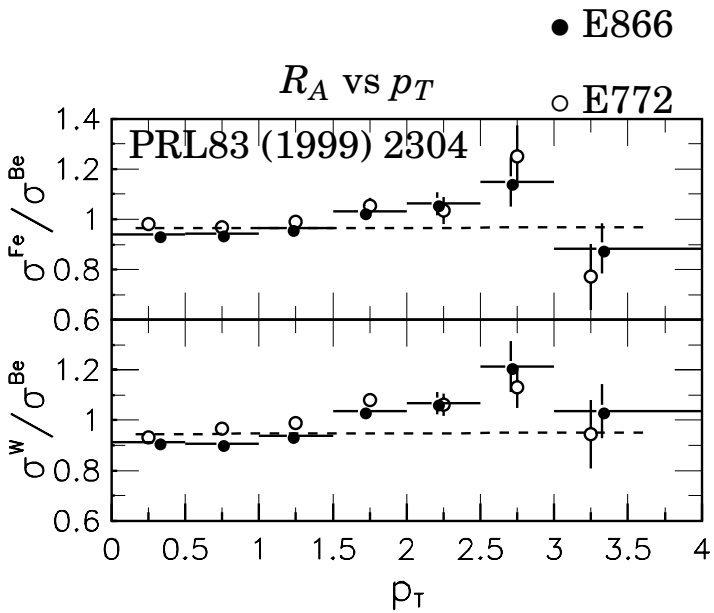
SeaQuest Topic #2: Nuclear Effects

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

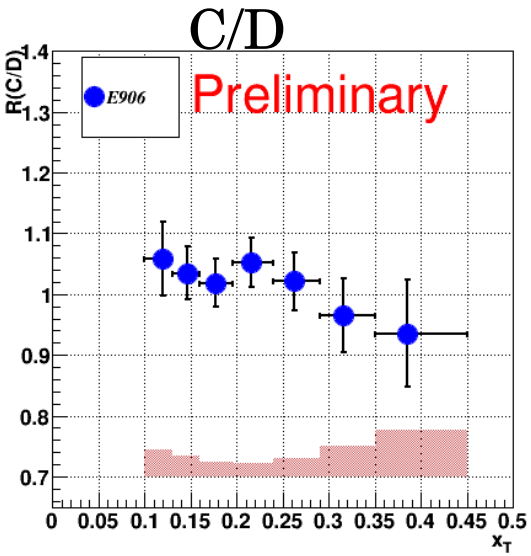
1. R_A vs x_{target}: Effect on antiquarks
   - Smaller than that on quarks? (PRL64, 2479)
   - $0.1 < x_{target} < 0.45$
   - Preliminary result in October 2019
2. Effect on quarks in beam proton
   = Parton energy loss in cold-nuclear matter
   - 2.1 R_A vs x_{beam}: Energy loss
     - $x_{beam} > 0.6, x_{target} > 0.15$
     - "Preview" result at HAWAII 2018 etc.
   - 2.2 R_A vs p_T: p_T broadening
     - $0.1 < x_{target} < 0.45$
     - Preliminary result in April 2020

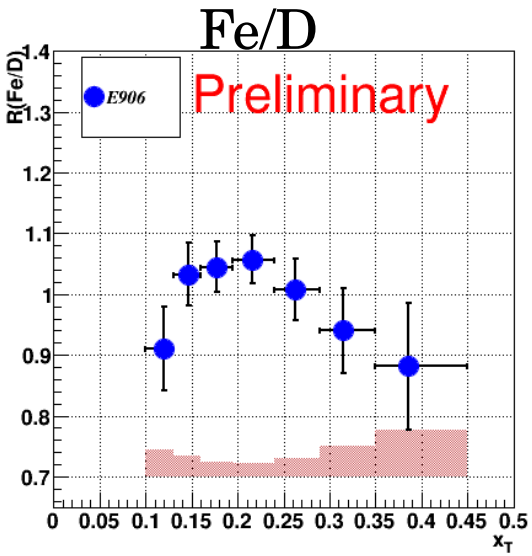
- R_A should be comprehensively examined to untangle the effects of nuclear PDFs and partonic energy loss

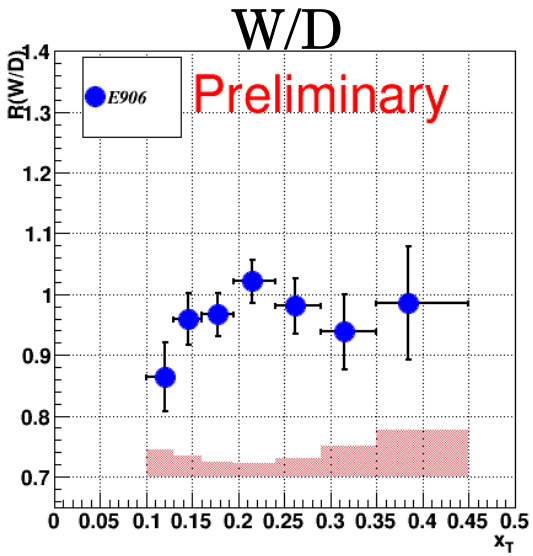




- Result of "R_A vs x_{target}"



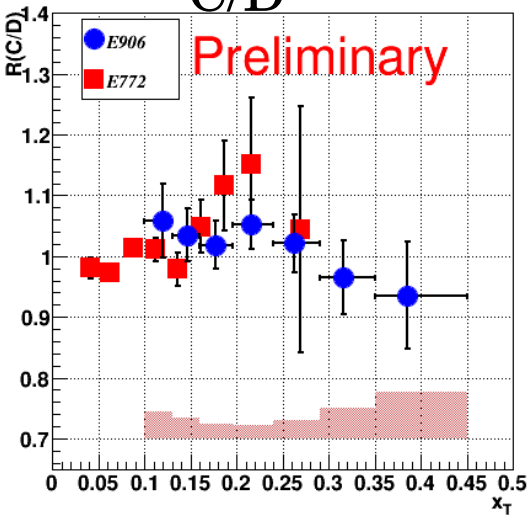




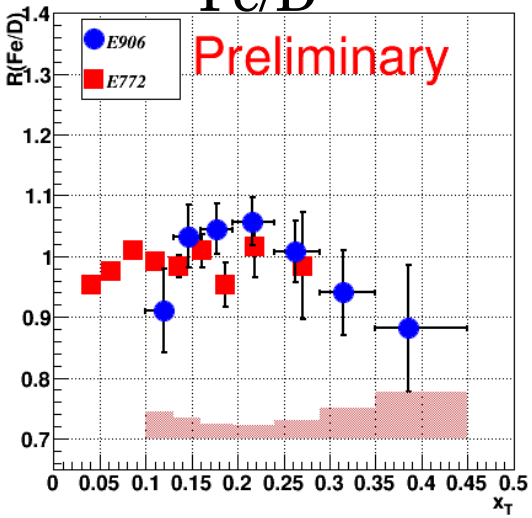
  - R_A deviates from 1 by 10% at max
    - Different from quarks ($R_A \gtrsim 1.1$)!
    - Close to the calculation of pion excess model by Miller (PRC 64, 022201)
  - Same trend as the EMC effect (i.e. R_A decreases at middle x)

- Comparison with E772 result

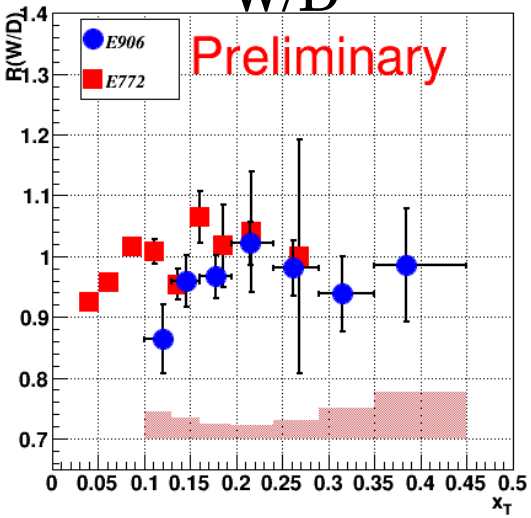
C/D



Fe/D



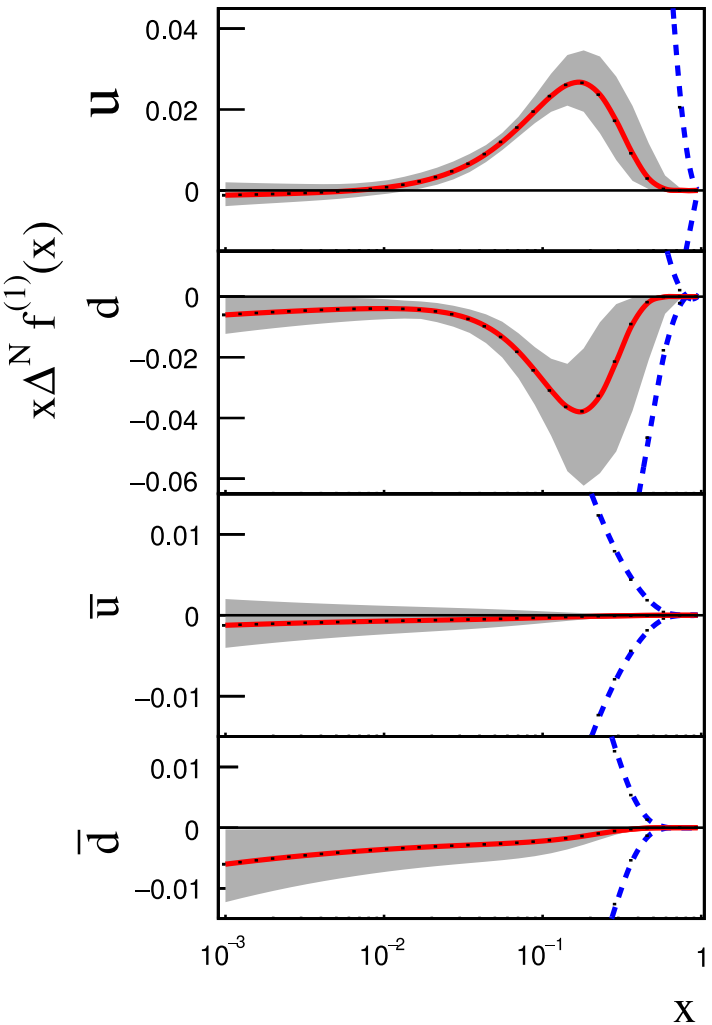
W/D



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

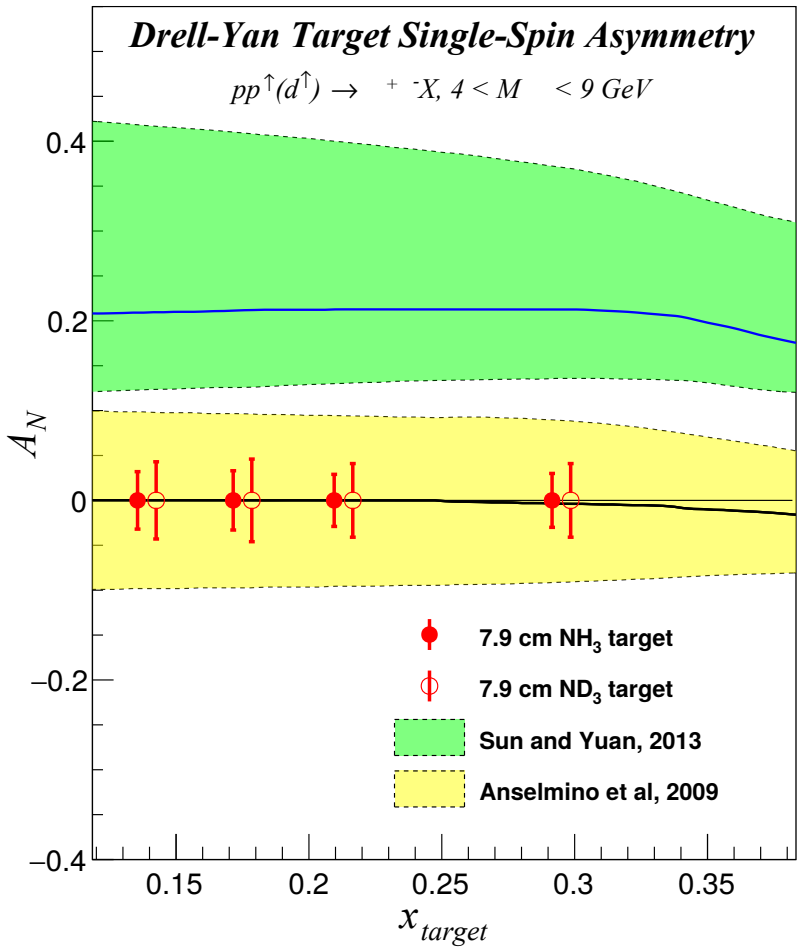
SpinQuest/E1039

- Sivers distribution: $f_{1T}^{\perp}(x)$
  - 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
- TSSA: $A_{UT}^{\sin\phi_S} = A_N$
  - Measurement precision $\delta_{A_N} \sim 0.04$
  - Two predictions of A_N of NH_3
    - Calculations based on SIDIS data
    - Blue line takes into account the Collins-Soper-Sterman scale evolution
- Aim to observe non-zero anti-quark Sivers asymmetry!!



Phys. Rev. D88, 034016 (2013)

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

Timeline of SpinQuest

Year	Month	Event
2018	May	Granted Stage-2 approval from Fermilab
		Decommissioned SeaQuest components
2019	June	Transfered the pol. target from UVA to Fermilab
		Commissioned detector components using cosmic rays
2020		Commissioned with limited access due to COVID-19
2021	Spring	Commission target+detector components using beam
	Fall	Start the data taking
		$\Downarrow$ Run for two years

- Other physics topics
  - TSSA of J/ψ production ... Later talk by C. Ayuso
  - Tensor polarization of antiquarks in deuteron ... PRD 94, 054022 (2016)

Conclusions

- Drell-Yan experiments at Fermilab
  - Probe the antiquarks in the proton
  - Utilize the high-intensity proton beam from Main Injector
- SeaQuest/E906 with unpolarized targets
  - Drell-Yan events were detected successfully
  - Large $\bar{d}(x)/\bar{u}(x)$ asymmetry at large x was observed firstly
    ... Nature 590, 561 (2021)
  - Nuclear effect on antiquarks was observed smaller than quarks
- SpinQuest/E1039 with polarized targets
  - Data taking in 2021-2023 (planned)
  - Will measure Sivers asymmetry of $\bar{u}$ & $\bar{d}$ firstly
- Data analyses of SeaQuest & target+detector commissioning of SpinQuest are ongoing for more physics outcomes!