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Drell–Yan Measurements at SeaQuest and SpinQuest at Fermilab

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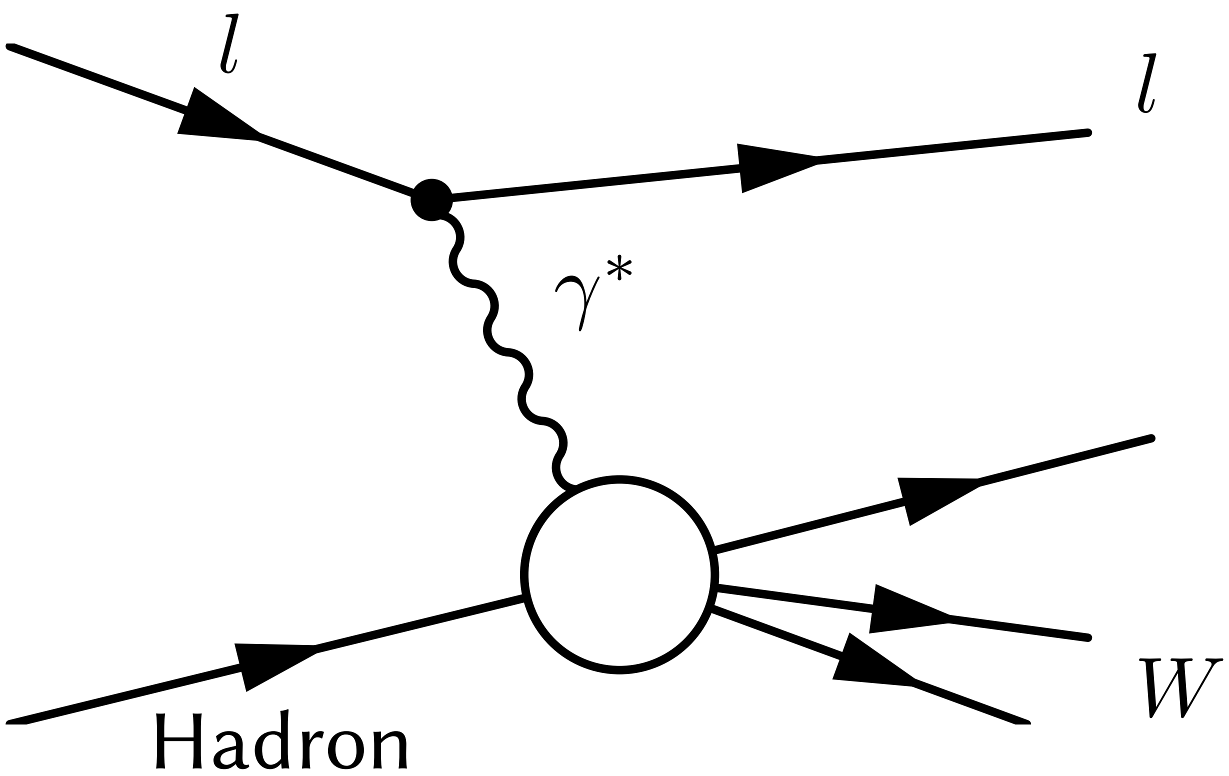
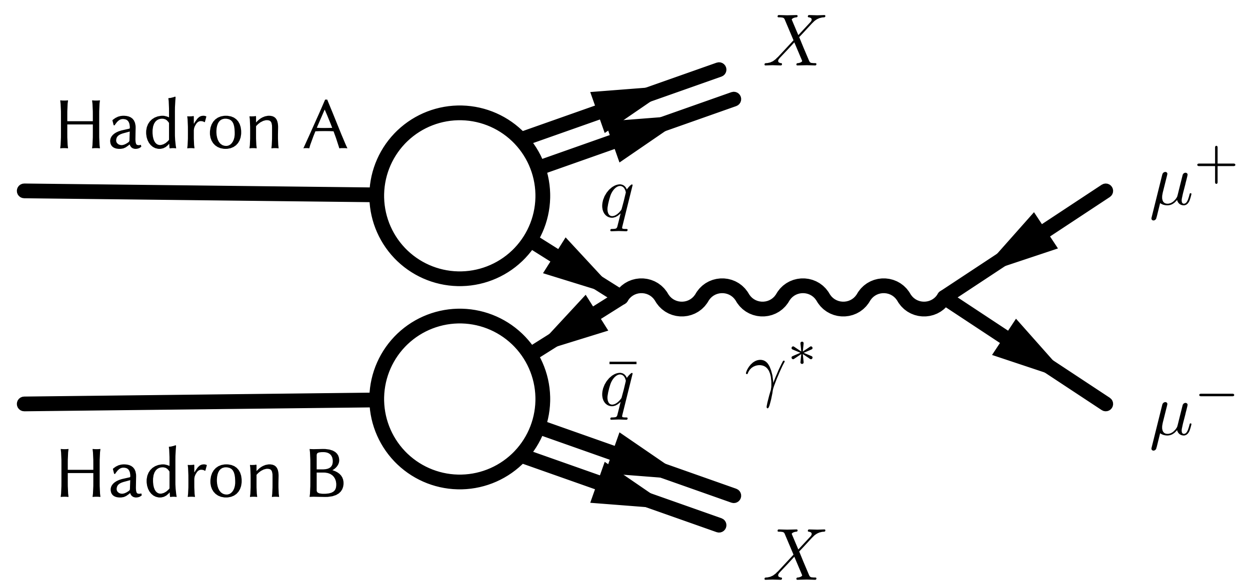
International Workshop on Hadron Structure and Spectroscopy 2023

Contents

1. Drell–Yan process and proton structure

Access proton structure



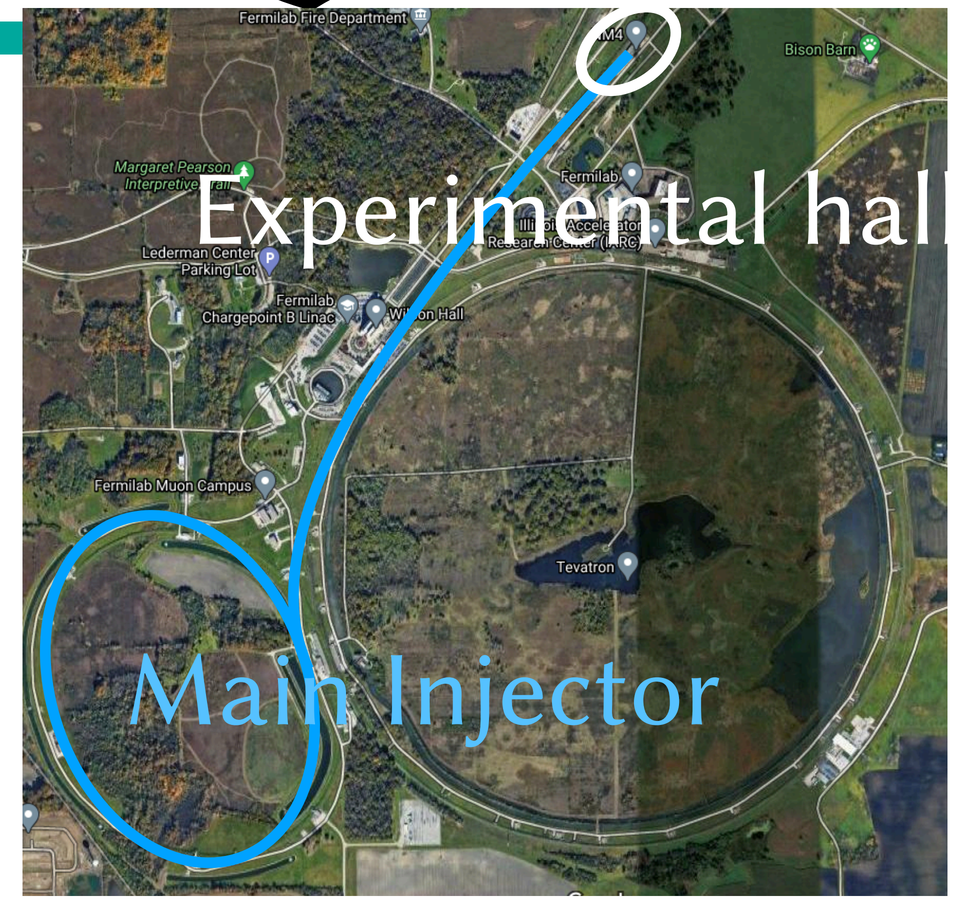


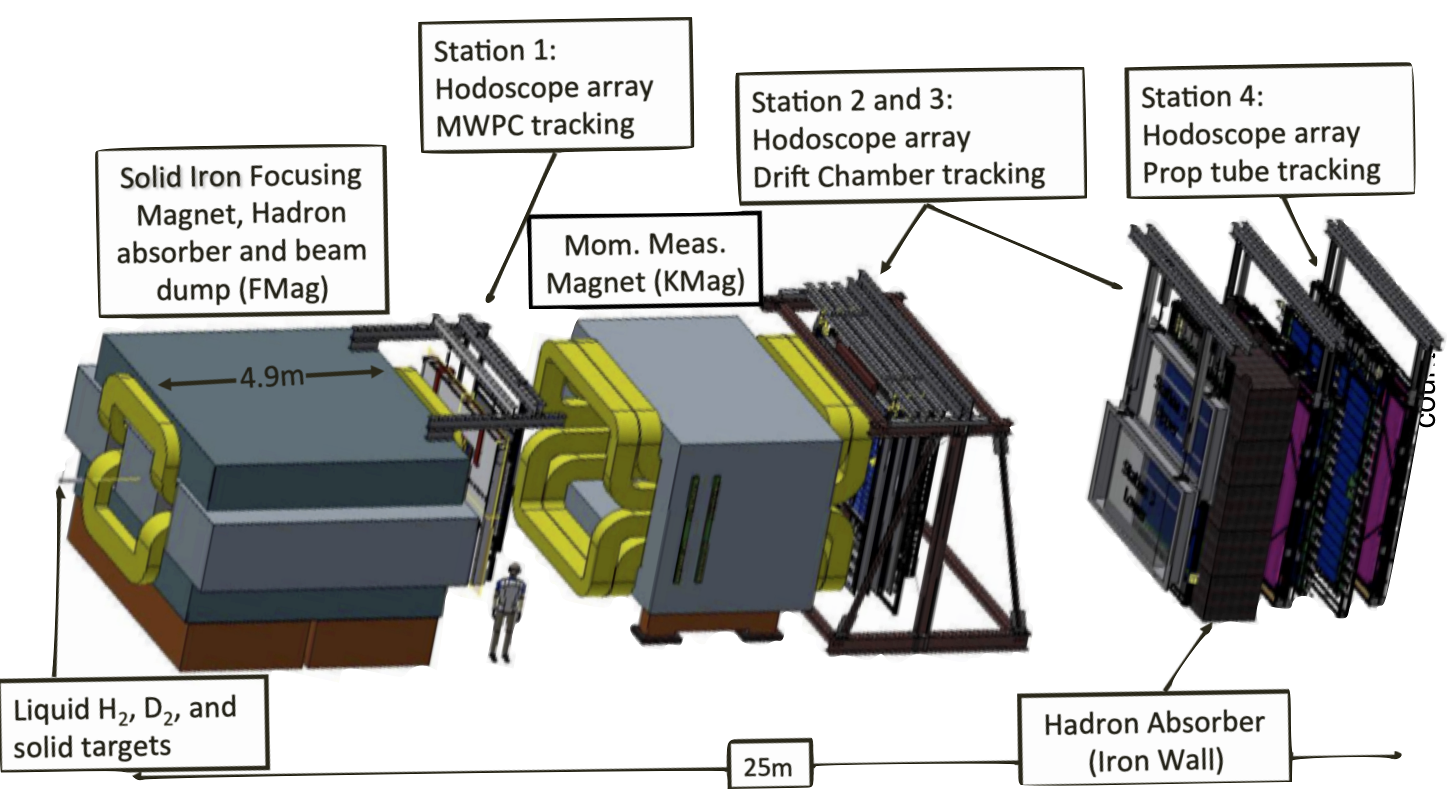
- Deep Inelastic scattering experiments have investigated the proton structure
  - Scattering with all charged partons (u, d, $\bar{u}$, $\bar{d}$, $\cdots$)
  - Great achievement for u, d quarks PDFs

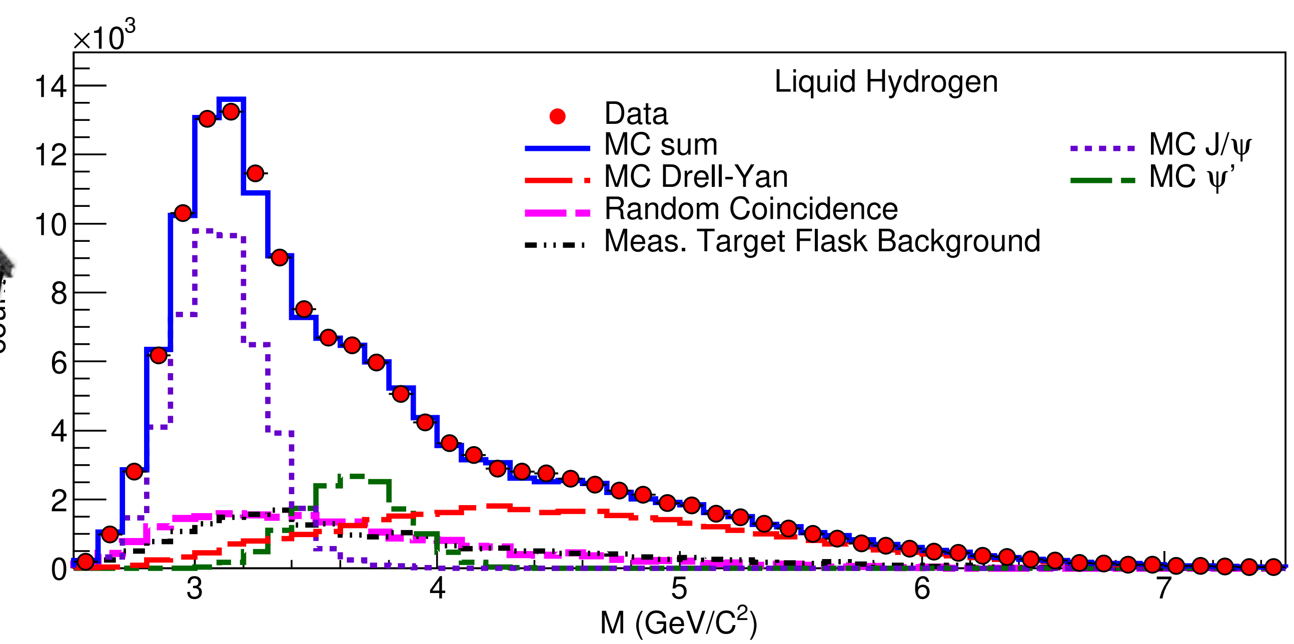
- Drell–Yan process
  - $q + \bar{q} \rightarrow \gamma^* \rightarrow l + \bar{l}$
  - Antiquark is always involved in the reaction
  - Access antiquarks PDFs
  - If the hadron is the proton, antiquark is always sea quark

SeaQuest & SpinQuest

- Fermi National Accelerator Laboratory (FNAL)
  - 120 GeV proton beam provided by Main Injector
- Fixed target Drell–Yan experiment
  - Typical momentum of the muon ~ 40 GeV
- Four tracking stations
  - Drift chamber (St.1-3) or proportional tube (St.4)
  - Hodoscopes
- Data acquisition:
  - SeaQuest: 2014-2017 8.6×10^{17} POT
  - SpinQuest: Beam commissioning will start this year

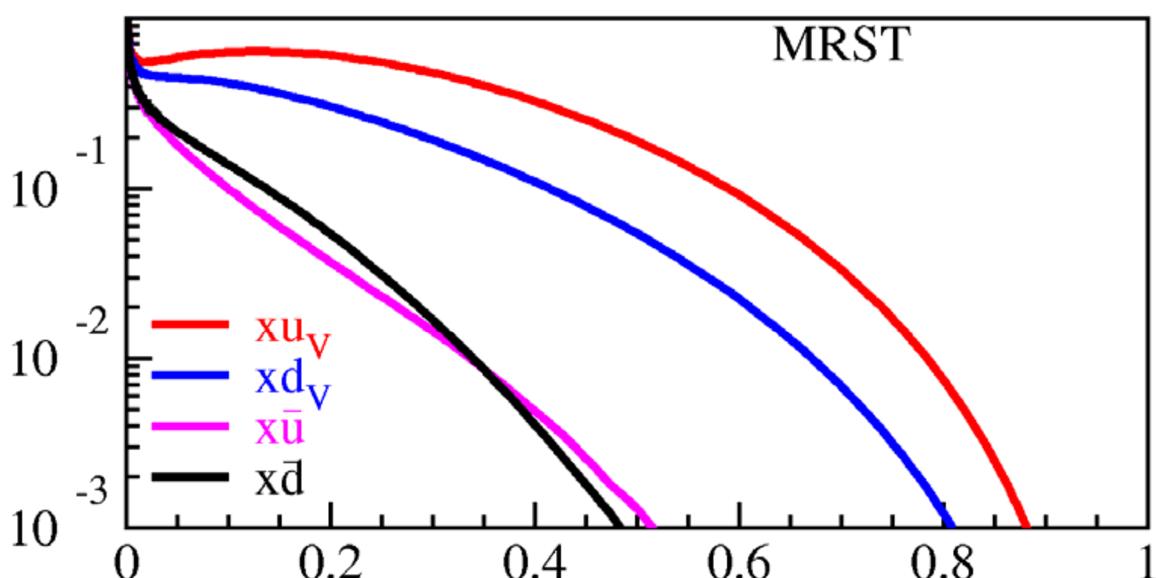






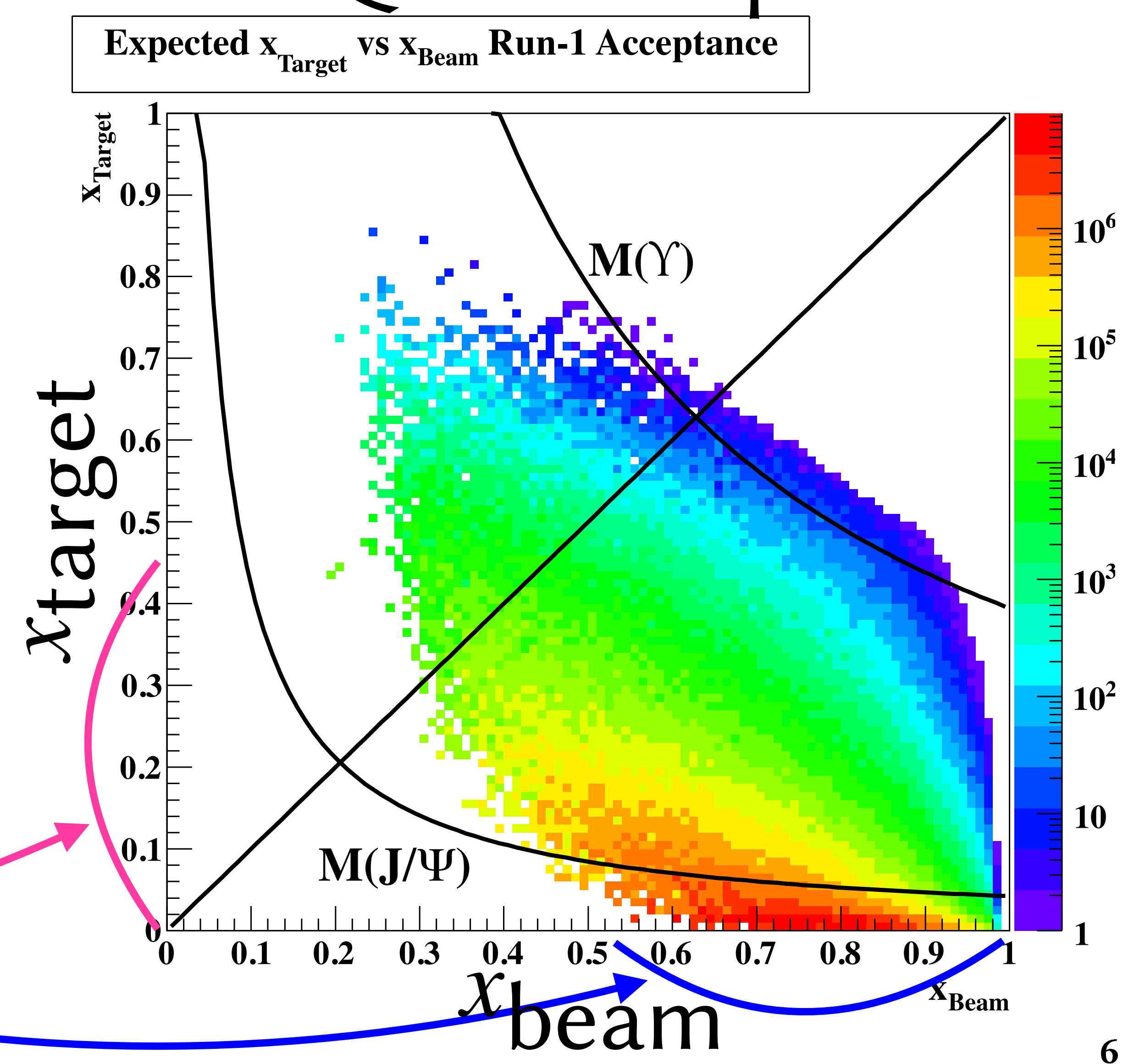
p-p Drell–Yan Process

- $$\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_t x_b}\frac{1}{s}\sum e^2[\bar{q}_t(x_t)q_b(x_b) + \bar{q}_b(x_b)q_t(x_t)]$$
  - $x_t \ll x_b$: Forward detection
  - $\bar{q}$ at large x is small
    - ★ Second term $\bar{q}_b(x_b)q_t(x_t)$ can be ignored
  - *Access sea-antiquarks in target proton*
  - Cross section ratio $\propto 1/s$
    - ★ 800 GeV (E866) ⟶ 120 GeV (E906)



x_{target} x_{beam}

SeaQuest acceptance



Physics Topics

TMDs

		Quarks		
		Unpolarized	Longitudinally Polarized	Transversally Polarized
Nucleon	U	f_1		$h_1^{\perp}$ (Boer-Mulders)
	L		g_{1L}	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$ (Sivers)	$g_{1T}^{\perp}$	h_{1T} $h_{1T}^{\perp}$

- SeaQuest (Unpolarized Drell–Yan)
  - Antiquark flavor asymmetry (PDFs)
  - Drell–Yan angular distribution (Boer–Mulders Function)
- SpinQuest (Polarized Drell–Yan)
  - Single spin asymmetry (Sivers Function)

2.Recent Progress on SeaQuest Analyses

Antiquark Flavor Asymmetry

- Gluon splitting (perturbative QCD)

$$\bar{u}(x) = \bar{d}(x), \quad \int_0^1 dx \bar{u}(x) = \int_0^1 dx \bar{d}(x)$$

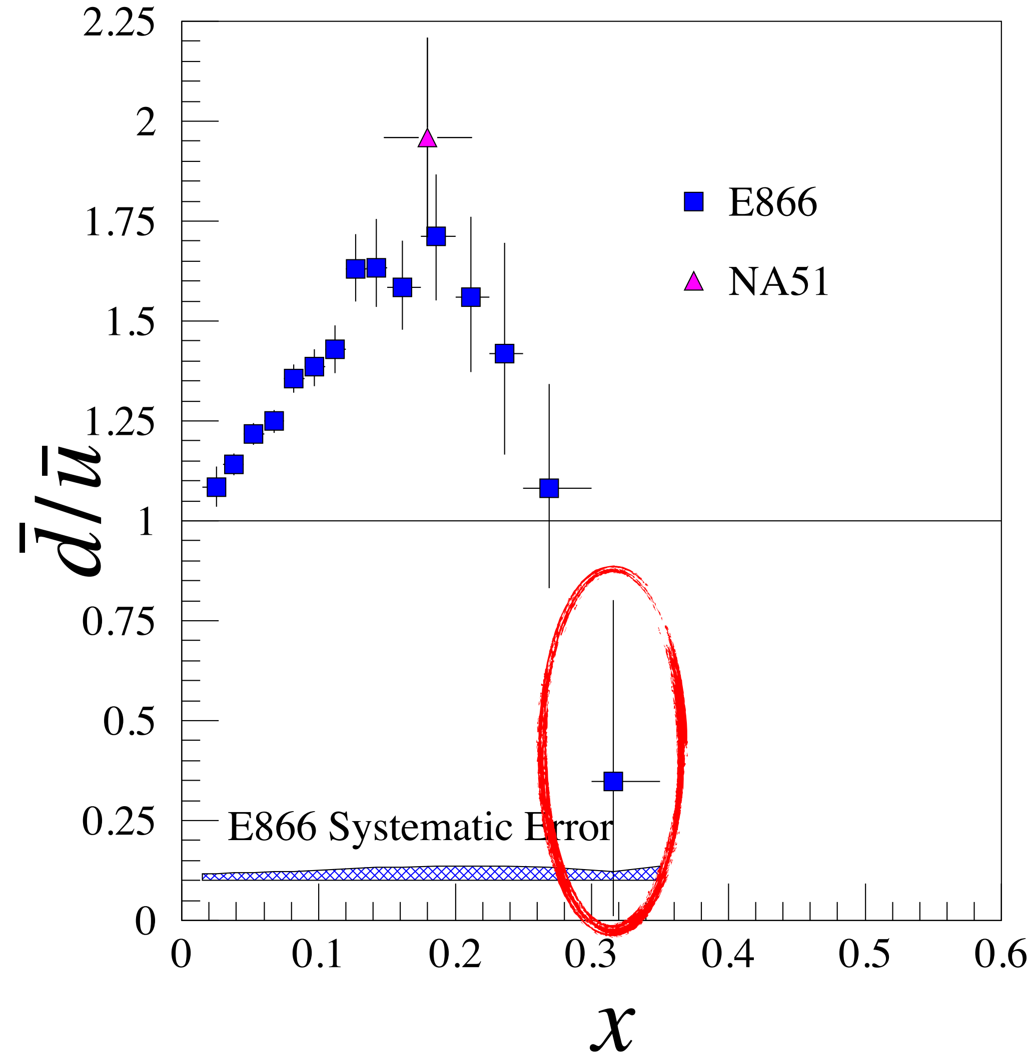
- Gottfried sum rule: PRL 18 (1967) 1174

$$S_G = \int dx \frac{F_2^p - F_2^n}{x} = \frac{1}{3} + \frac{2}{3} \int_0^1 dx(\bar{u}(x) - \bar{d}(x)) = \frac{1}{3}$$

- NMC Experiment (DIS) @ CERN
  $S_G = 0.235 \pm 0.026 < 1/3$

$$\rightarrow \int_0^1 \bar{d}(x)\ dx - \int_0^1 \bar{u}(x)\ dx = 0.147 \pm 0.039$$

- NA51 (Drell–Yan) @ CERN: $\bar{d}/\bar{u} \sim 1.7$
- E866 Experiment (Drell–Yan) @ Fermilab
  x-dependence of $\bar{d}/\bar{u}$ @ $0.015 < x < 0.35$
  - Significant Flavor Asymmetry
    $\bar{d}/\bar{u} \sim 1.7$ @ $x \sim 0.2$
  - $\bar{d}/\bar{u} < 1.0$ @ $x \sim 0.3$??
    with large statistical uncertainty



Theoretical Models

- Pauli blocking – Only a few %
- Meson Cloud Model – $\bar{d}/\bar{u} > 1.0$
- Statistical Model – $\bar{d}/\bar{u} > 1.0$

E906/SeaQuest aims at measuring $\bar{d}/\bar{u}$ in a large and wide x range

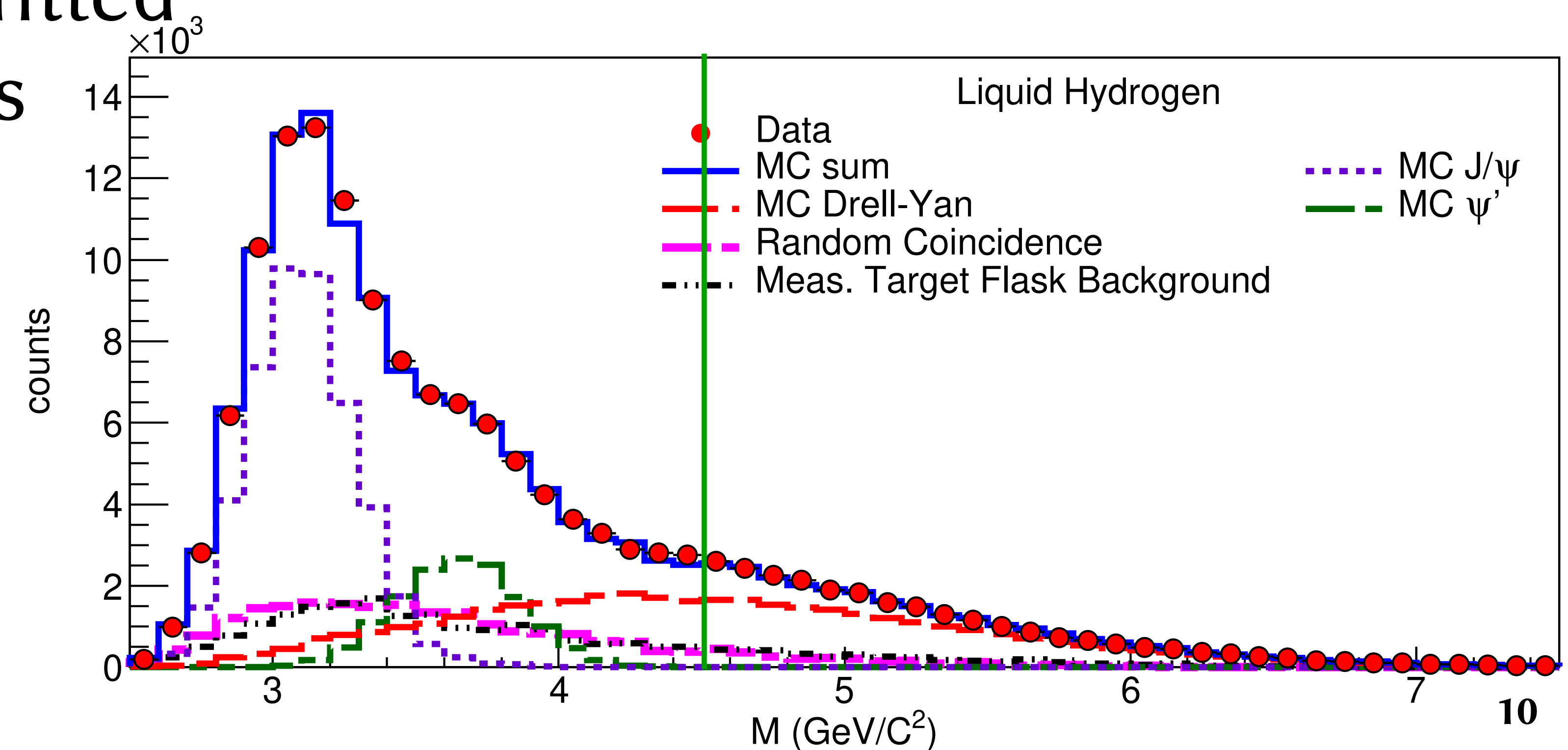
Measurement

- Cross section ratio of p–d to p–p Drell–Yan process

$$\frac{1}{2}\frac{\sigma^{pd}}{\sigma^{pp}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]\Bigg|_{x_b \gg x_t}$$

  - Measure p-d and p-p Drell–Yan dimuons
  - Extract cross section ratio
  - Convert cross section ratio to antiquark flavor asymmetry $\bar{d}/\bar{u}$

- Dimuon mass distribution fitted with estimated components
  - Well fitted: Detectors & reconstruction work as expected
  - Drell–Yan dimuons: Mass > 4.5 GeV/c^2

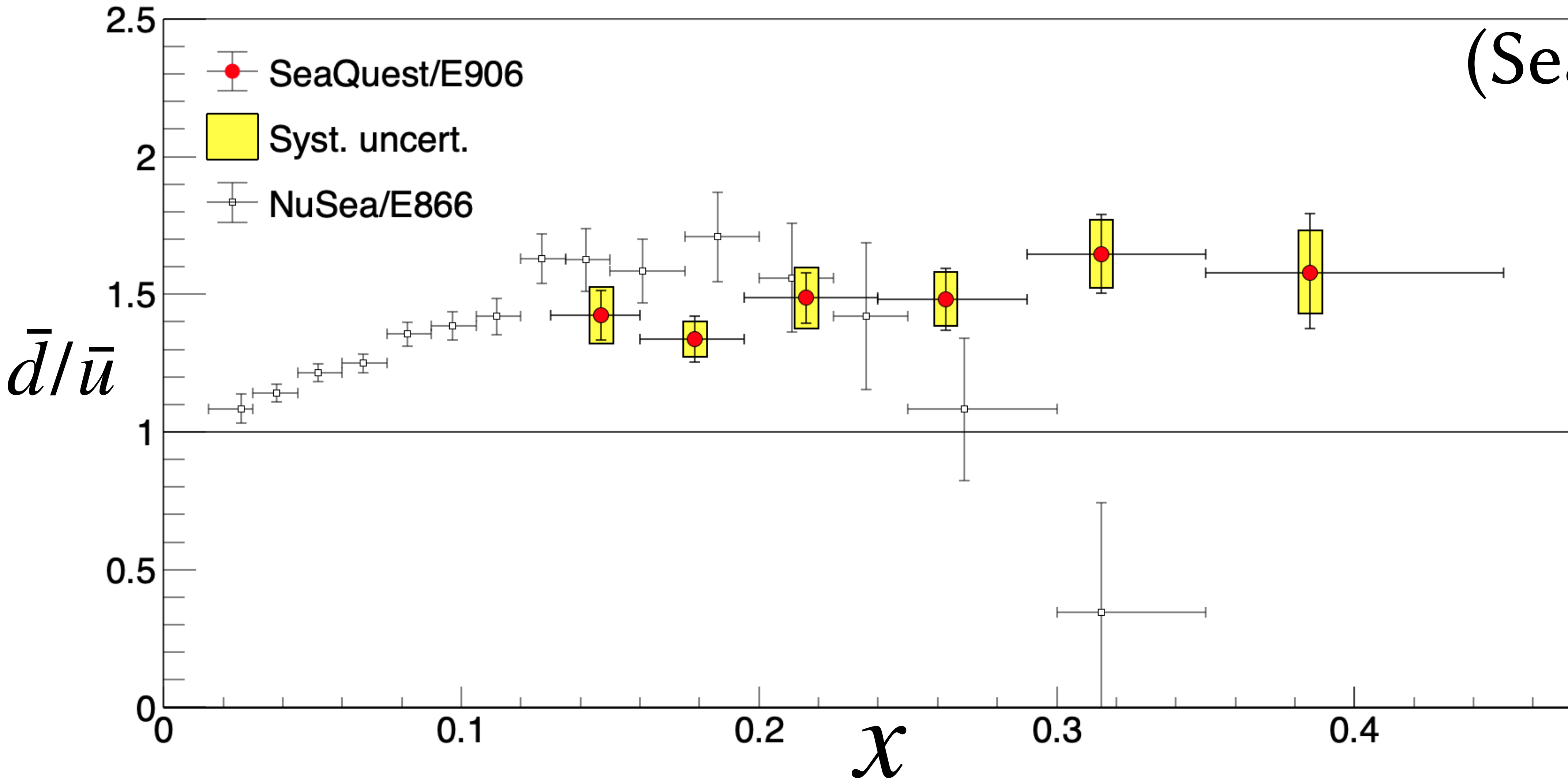


Proton antiquark flavor asymmetry $\bar{d}/\bar{u}$

February 2021: The asymmetry of antimatter in the proton

Nature **590**, 561 (2021)

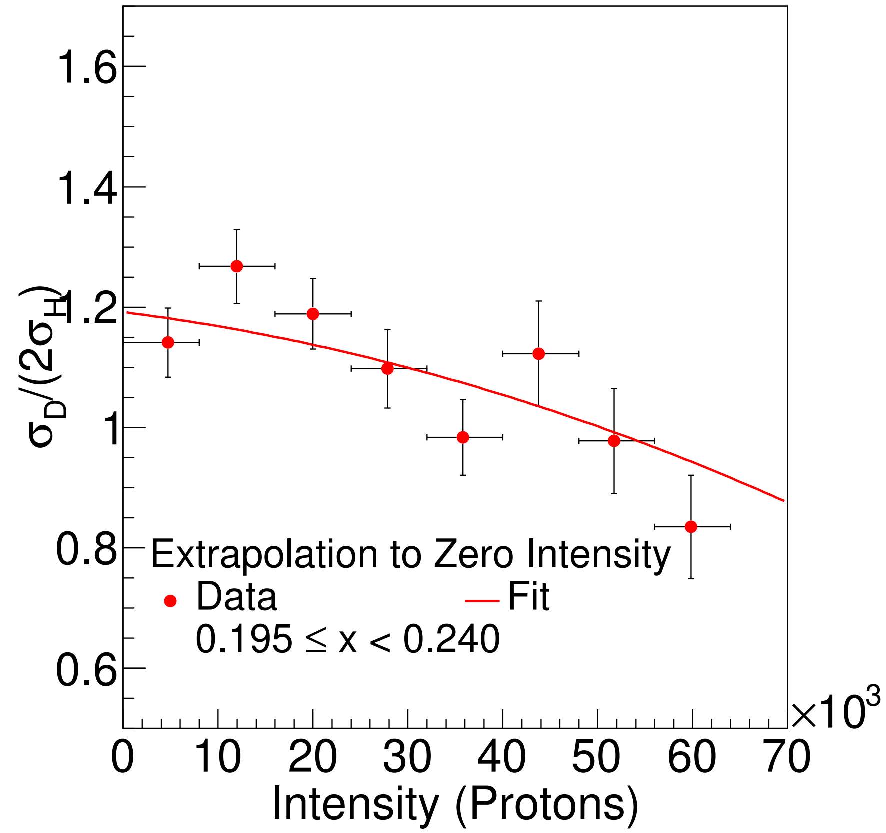
(SeaQuest)

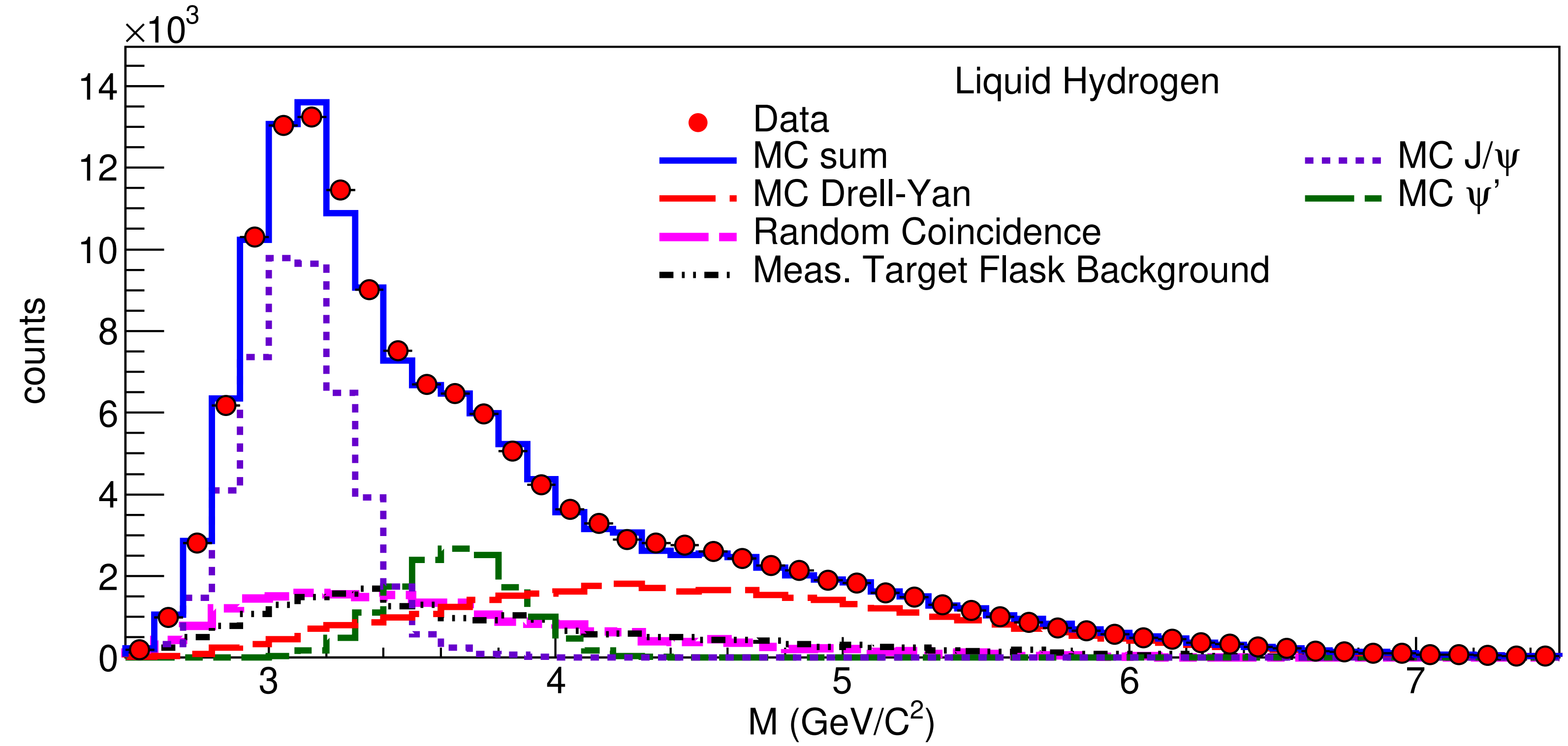


- Antiquark flavor asymmetry $\bar{d}/\bar{u}$ (antiquark PDF) of the proton at large x $(0.13 < x < 0.45)$
- $\bar{d}/\bar{u} > 1.0$ in all measured ranges

Two Methods Comparison

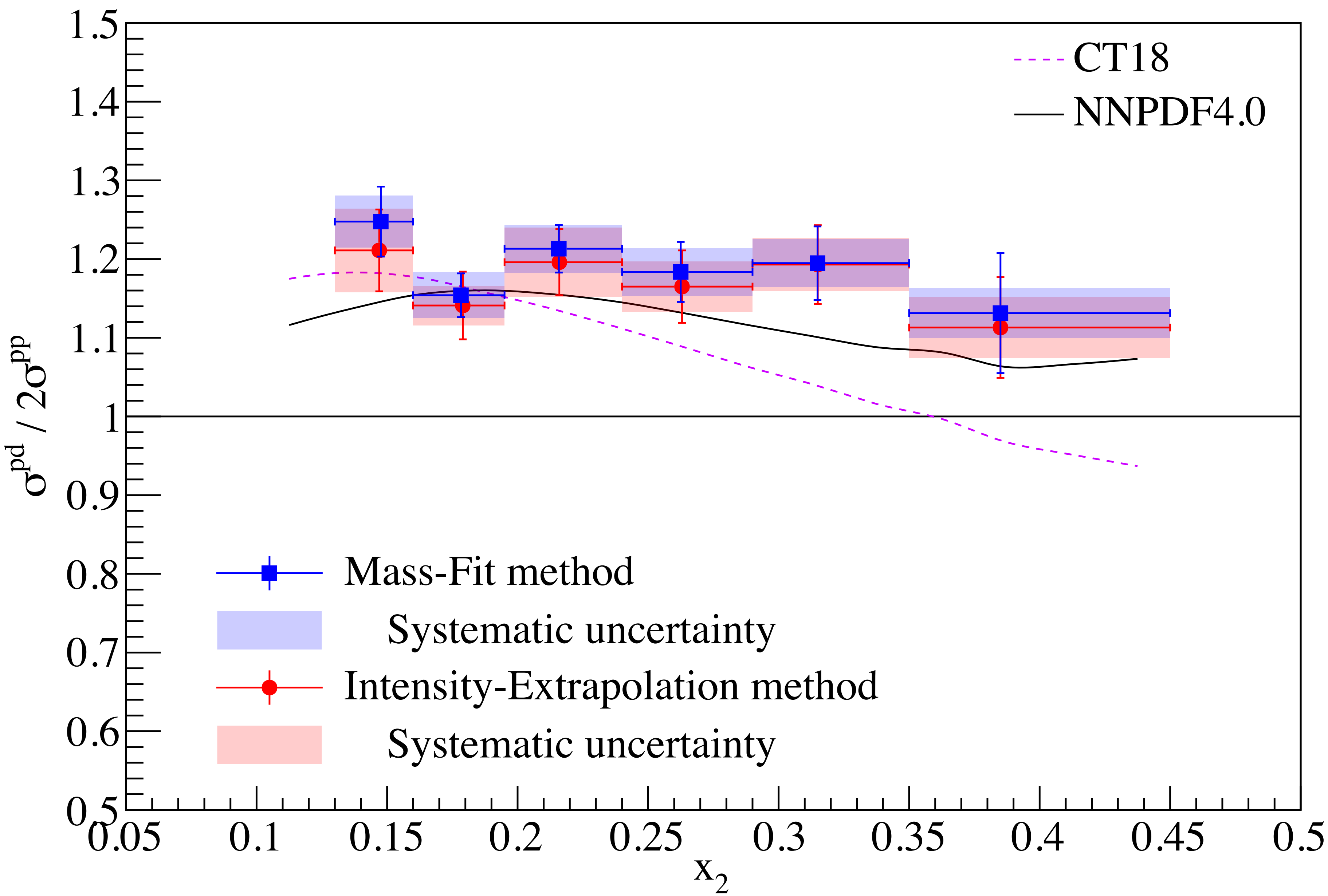
$0.195 \leq x < 0.240$





- Intensity-Extrapolation Method (Nature)
  - Extrapolate the cross-section ratio to zero-intensity
    - ★ Suppose no background and rate dependence at zero-intensity
- Mass-Fit Method
  - Subtract the background
  - Rate dependence correction using efficiency curve by simulation

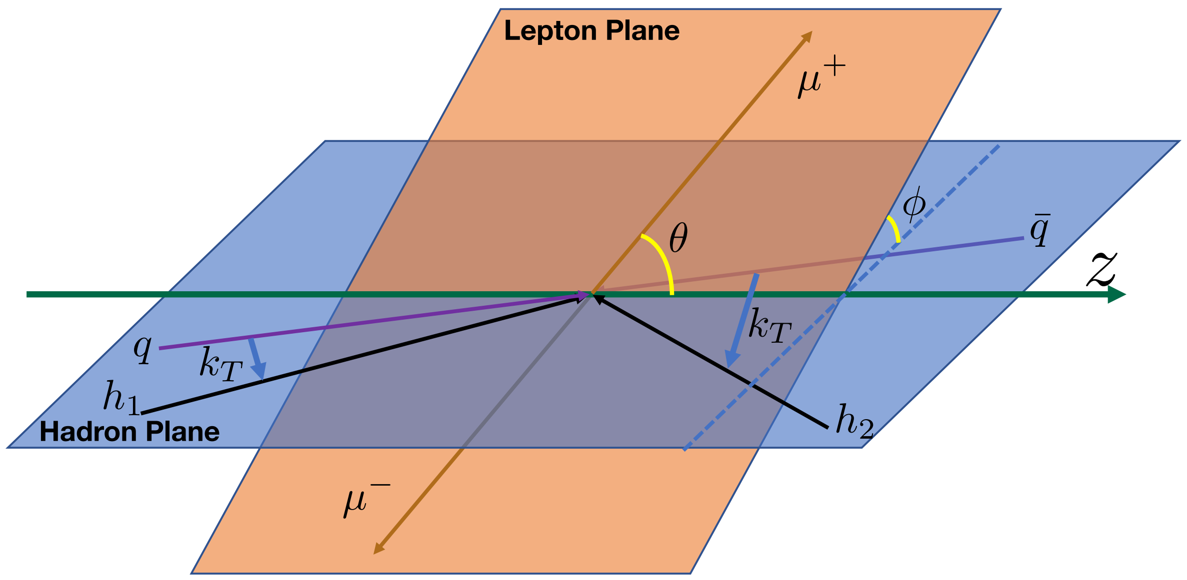
Another $\bar{d}/\bar{u}$ paper



- Submitted to Phys. Rev. C. (https://arxiv.org/abs/2212.12160)
- Cross-check with another method and analysis details
- Results from two methods agree well

Angular distribution of Drell–Yan

- Collins–Soper frame
  - Virtual photon rest frame
  - θ: polar angle of positive lepton
  - ϕ: azimuthal angle of positive lepton



- Drell–Yan cross section

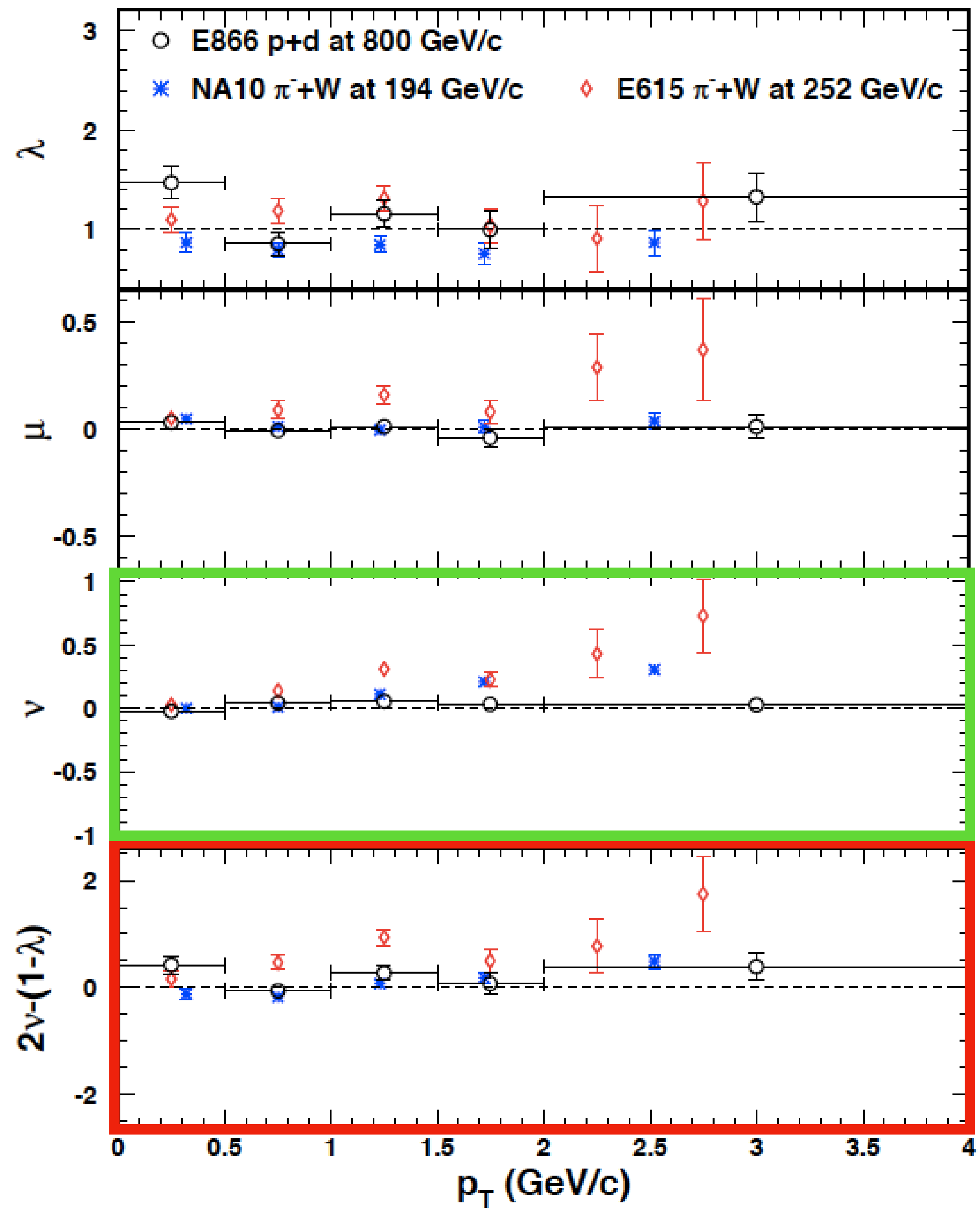
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

  - Naively, $\lambda = 1$, $\mu = \nu = 0$ ($d\sigma \propto 1 + \cos^2\theta$) at leading order
    - ★ No transverse momentum on quarks
    - ★ No gluon emission
  - NLO: $\lambda \neq 1$, μ, $\nu \neq 0$, but λ and ν still satisfy $1 - \lambda = 2\nu$ (**Lam–Tung relation**)

- Lam–Tung relation
  - Analogue of Callan–Gross relation (scattering of spin 1/2 particles)
  - Satisfied when the quark-antiquark axis is coplanar to hadron plane

Past Experiments

- NA10 (CERN), E615 (Fermilab)
  - $\pi^-(\bar{u}d)$+W
  - NA10: 194 GeV, E615: 252 GeV beam
  - L–T violation @ large p_T
  - Strong p_T dependence of ν
- E866 (Fermilab)
  - p+d (p+p), 800 GeV beam
  - Smaller L–T violation than π beam experiments
  - Weak p_T dependence of ν



Size of L–T violation depends on beam type

Boer–Mulders function $h_1^\perp$:

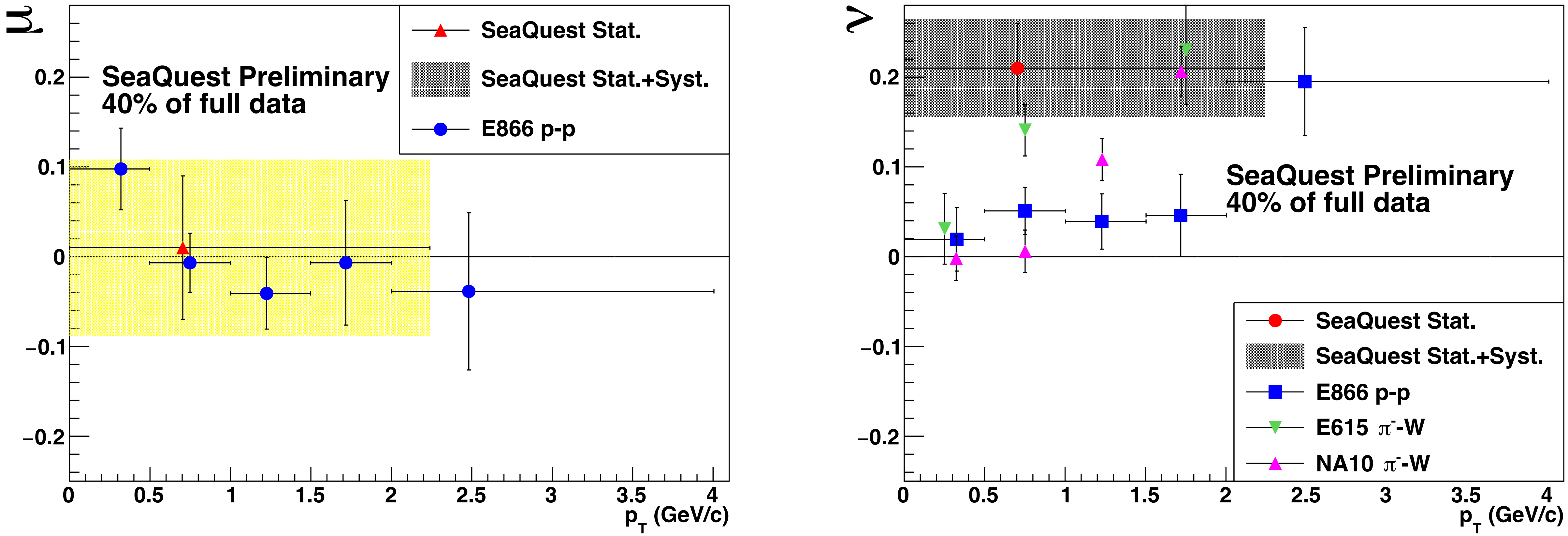
$$\nu/2 \propto h^\perp_{1,\text{beam}} h^\perp_{1,\text{target}}$$

Small B-M of sea quark $\longrightarrow$ Small ν in P-beam

Phys. Rev. Lett. 99, 082301, (2007)

Preliminary Results

SeaQuest: 120 GeV proton beam
E866 : 800 GeV proton beam
E615 : 252 GeV π^- beam
NA10 : 194 GeV π^- beam

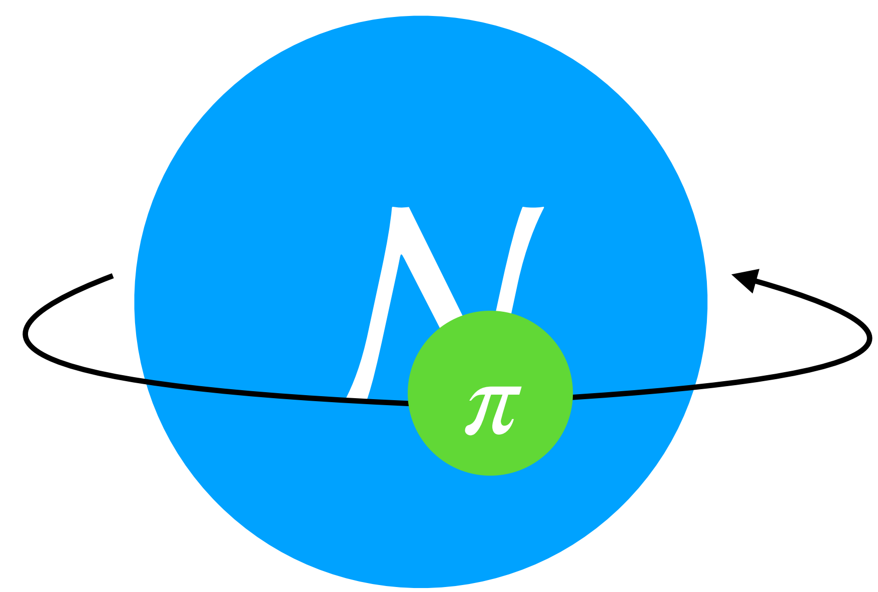


- The SeaQuest ν result is larger than E866 p-p results.
  - March 2023
- Similar level as pion-induced Drell–Yan results.
  - Further analysis with full data will give accurate results.
  - p-d analysis will also be performed.

3. Recent Progress on SpinQuest

Orbital Angular Momentum

- Is the π cloud model the cause of $\bar{d}/\bar{u}$ asymmetry?
  - $|p\rangle = \alpha|p_0\rangle + \beta|N\pi^+\rangle + \gamma|\Delta^{++}\pi^-\rangle + \cdots$
    - ★ Superposition of baryon-meson state
    - ★ $\bar{d}$ is in π^+ of $|N\pi^+\rangle$
      - ✦ Naively imagine that π^+ floats around the neutron
    - ★ $\bar{u}$ is in π^- of $|\Delta^{++}\pi^-\rangle$
  - The orbital angular momentum of antiquarks should be large

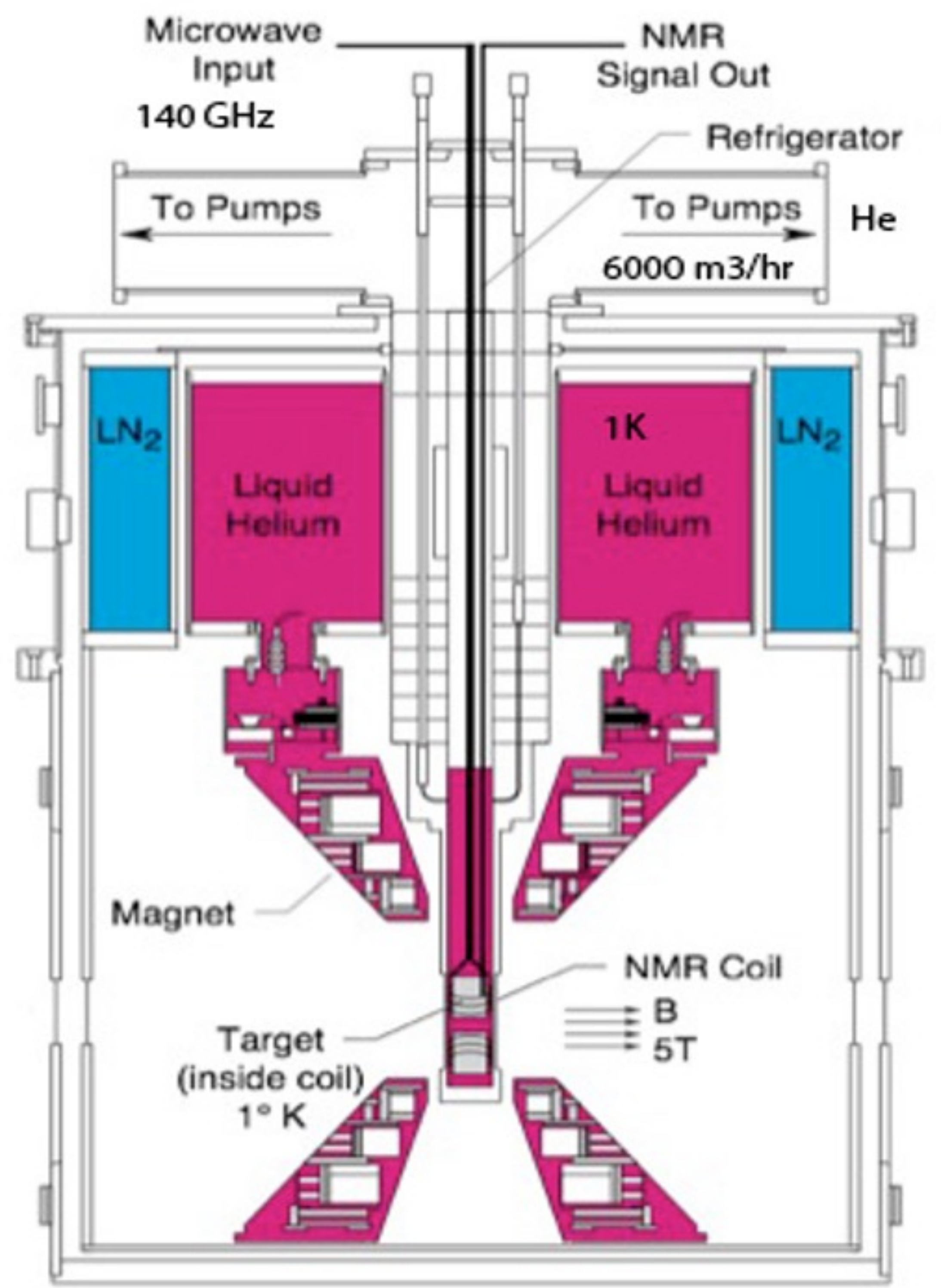


The source of the flavor asymmetry can be investigated by measuring the contribution of OAM to proton spin

Non-zero Sivers function $\longrightarrow$ Non-zero OAM

SpinQuest Experiment

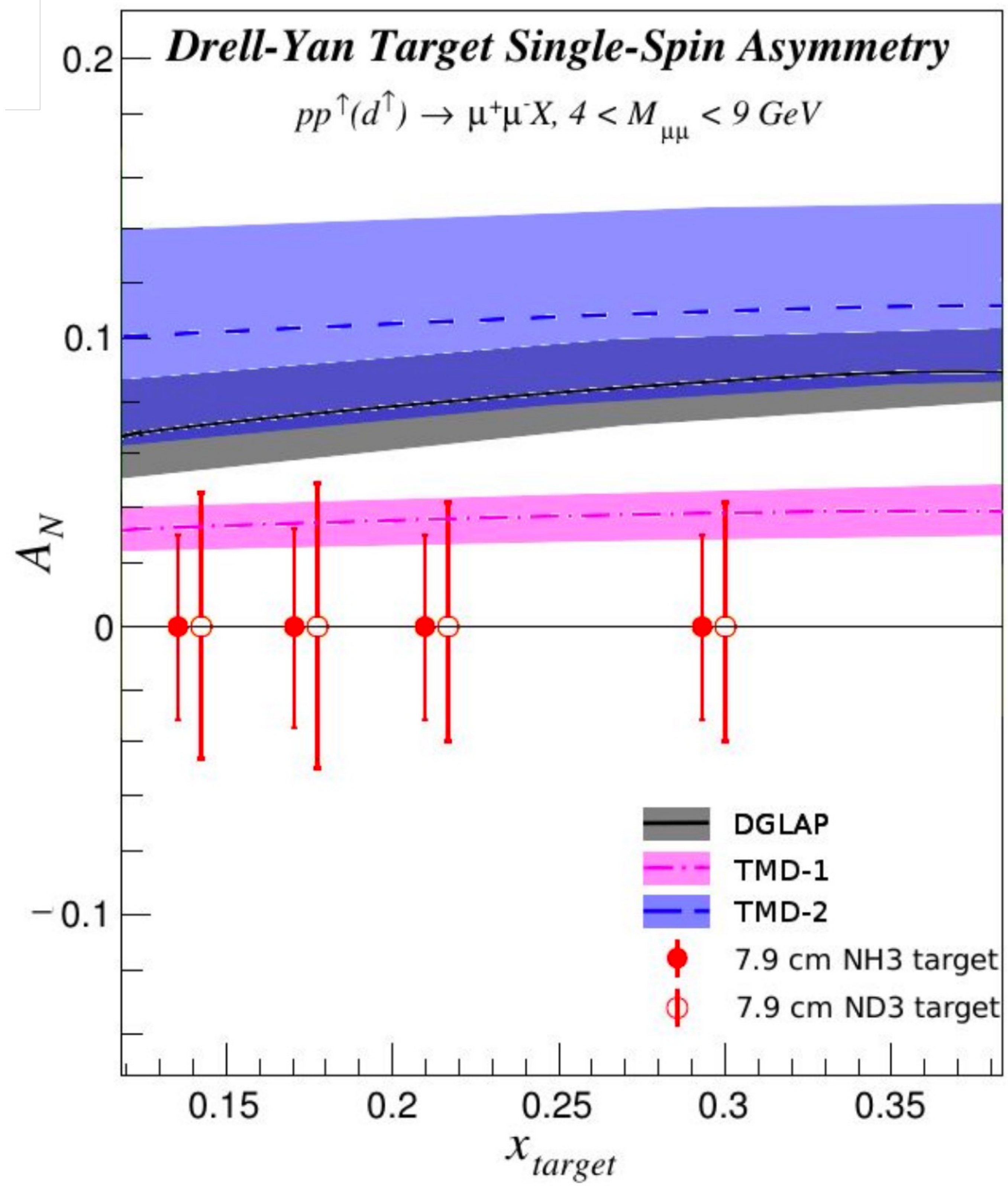
- Sivers asymmetry is accessible by polarized Drell–Yan process
  - First accurate measurement of antiquarks Sivers function
- Difference from SeaQuest: Polarized target instead of un-polarized target
  - NH_3 , ND_3
- Dynamic nuclear polarization
  - 80-90% polarization (NH_3)
- Polarization flips every 8hrs



SpinQuest Projection

- Single spin asymmetry A_N
  - $0.1 < x_{\text{target}} < 0.3$
  - Accuracy: $\delta_{A_N} \sim 0.04$

- Current Status:
  - Polarized targets and detectors are ready for the data acquisition
  - Beam commissioning will start late this year
  - 2-year data acquisition is planned



Summary

- The sea-quarks and antiquarks structure of the proton is probed by Drell–Yan process accurately.
  - Access antiquark PDFs (SeaQuest)
    - ★ $\bar{d}/\bar{u}$ results were published in Nature.
    - ★ Two methods comparison and analyses details are discussed in a new long paper. They agree really well.
    - ★ $\bar{d}/\bar{u} > 1.0$ in all measured ranges.
  - Access sea-quark Boer–Mulders function (SeaQuest)
    - ★ Released the SeaQuest preliminary results (μ and ν), and large ν is obtained.
    - ★ Further investigation toward final results.
  - Access antiquark Sivers function (SpinQuest)
    - ★ Contribution of antiquarks OAM to the proton spin.
    - ★ First direct measurement of antiquark Sivers function.
    - ★ Beam commissioning will start late this year

Backup

Antiquarks PDFs

- Gluon splitting: Flavor Independent

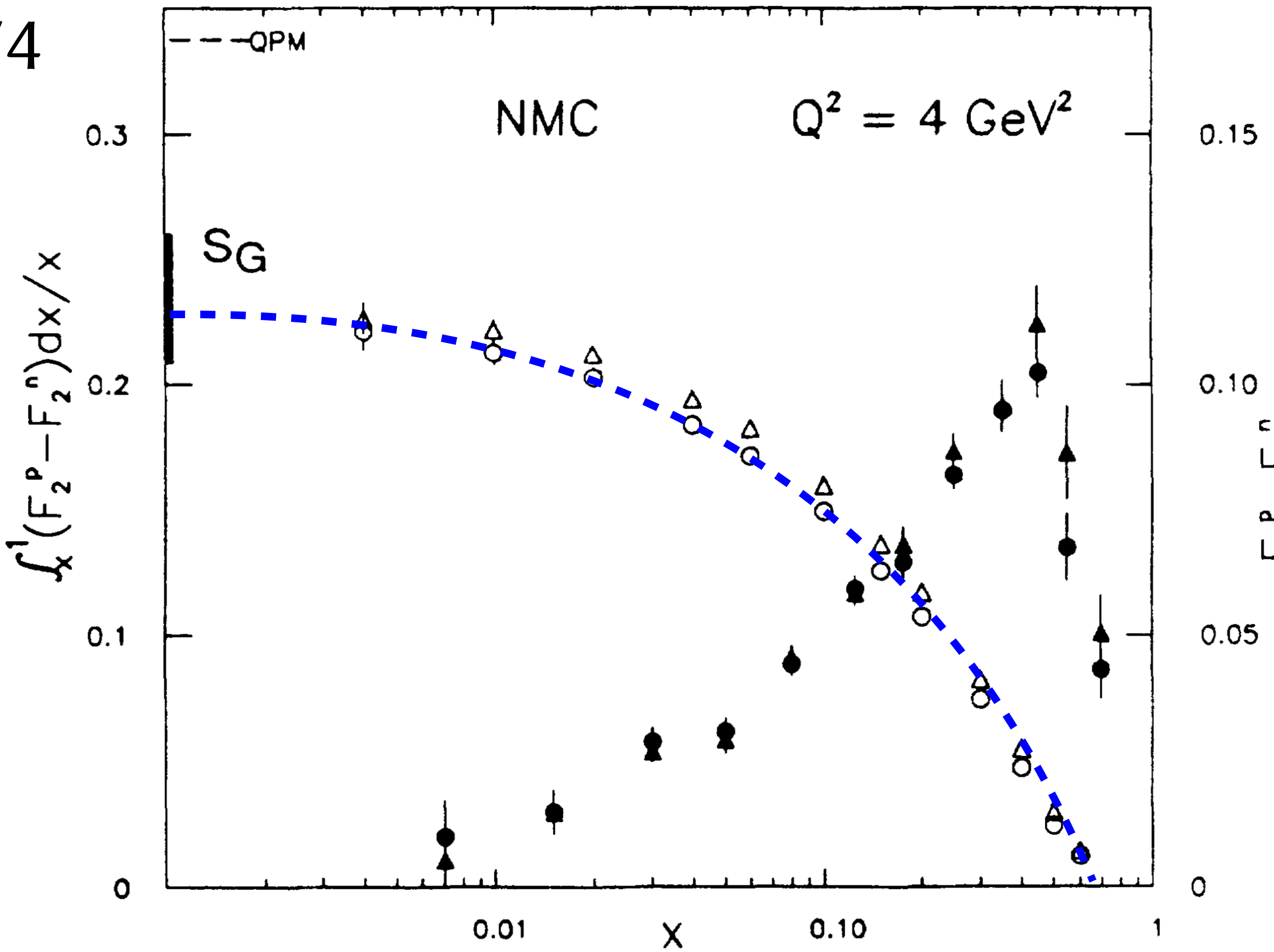
$$\bar{u} = \bar{d}$$

- Gottfried sum rule: PRL 18 (1967) 1174

$$S_G = \int_0^1 dx \frac{F_2^p - F_2^n}{x}$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 dx(\bar{u}(x) - \bar{d}(x)) = \frac{1}{3}$$

$= 0$ if $\bar{d} = \bar{u}$



- NMC Experiment (DIS) @ CERN

$$S_G = 0.235 \pm 0.026 < 1/3$$

$$\rightarrow \int_0^1 \bar{d}(x)\, dx > \int_0^1 \bar{u}(x)\, dx$$

Antiquark Flavor Asymmetry

x-dependence

- NA51 Experiment (Drell–Yan) @ CERN
  x-dependence of $\bar{d}/\bar{u}$ @ $x = 0.17$
  - Significant Flavor Asymmetry
    $\bar{d}/\bar{u} = 1.9$ @ $x = 0.17$
- E866 Experiment (Drell–Yan) @ Fermilab
  x-dependence of $\bar{d}/\bar{u}$ @ $0.015 < x < 0.35$
  - Significant Flavor Asymmetry
    $\bar{d}/\bar{u} \sim 1.7$ @ $x \sim 0.2$
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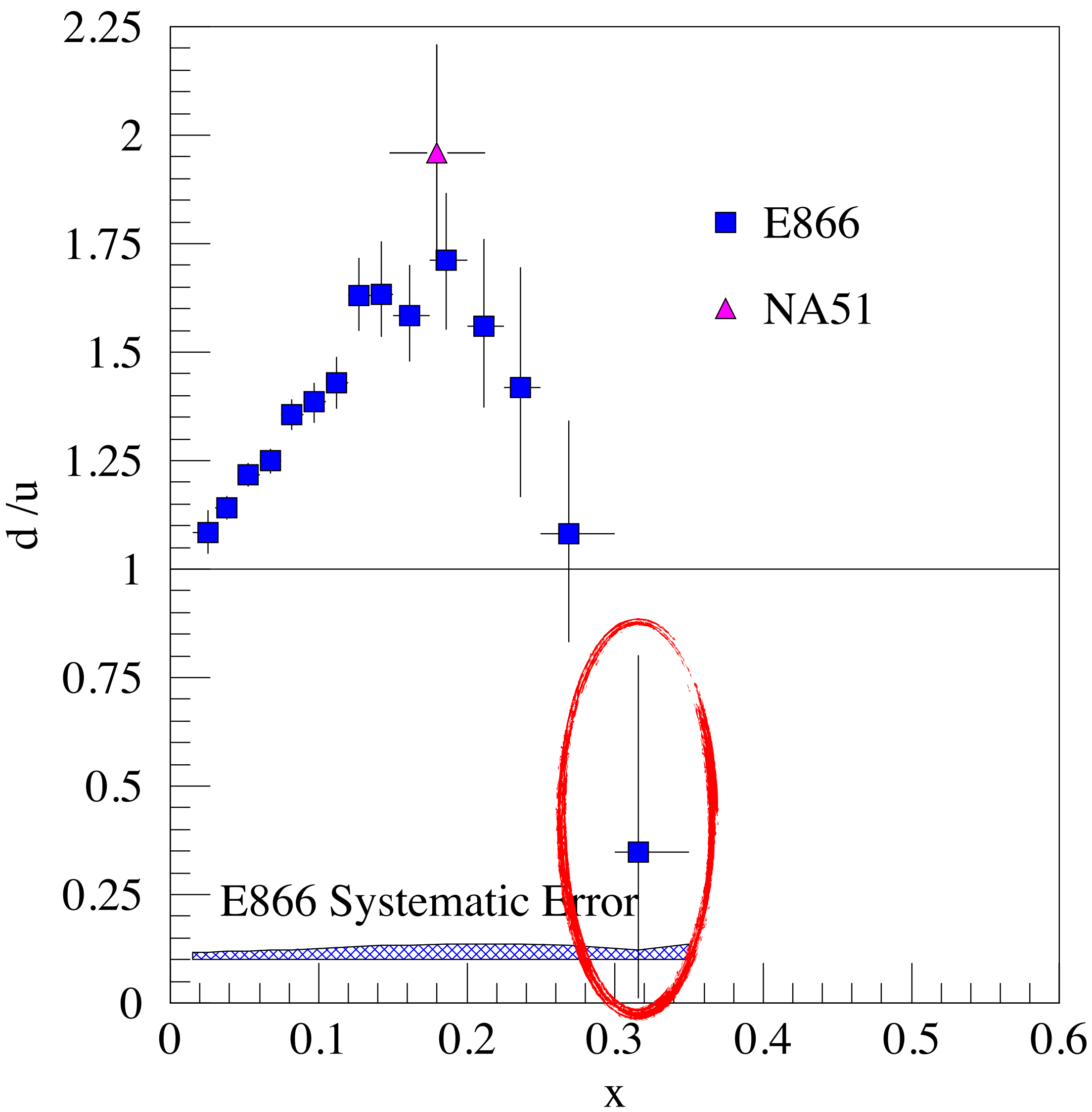
    with large statistical uncertainty

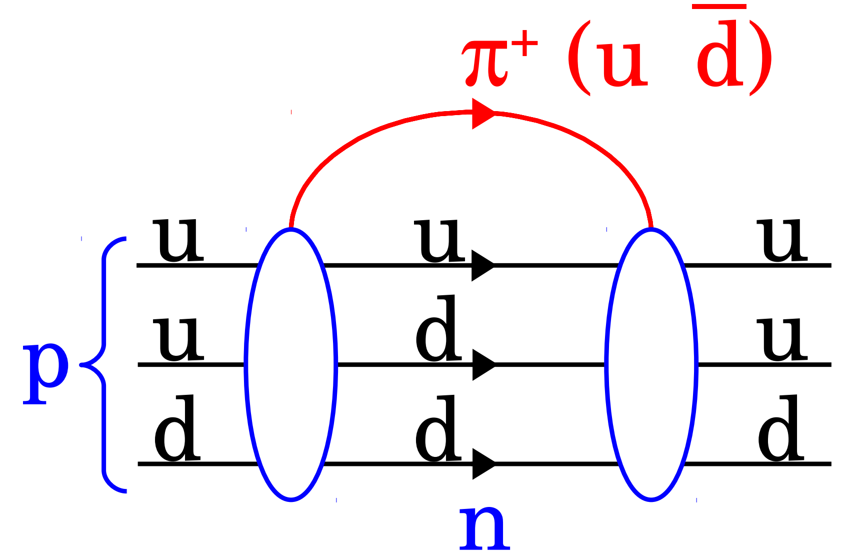


E906/SeaQuest aims to measure $\bar{d}/\bar{u}$ in a large and wide x range

Models

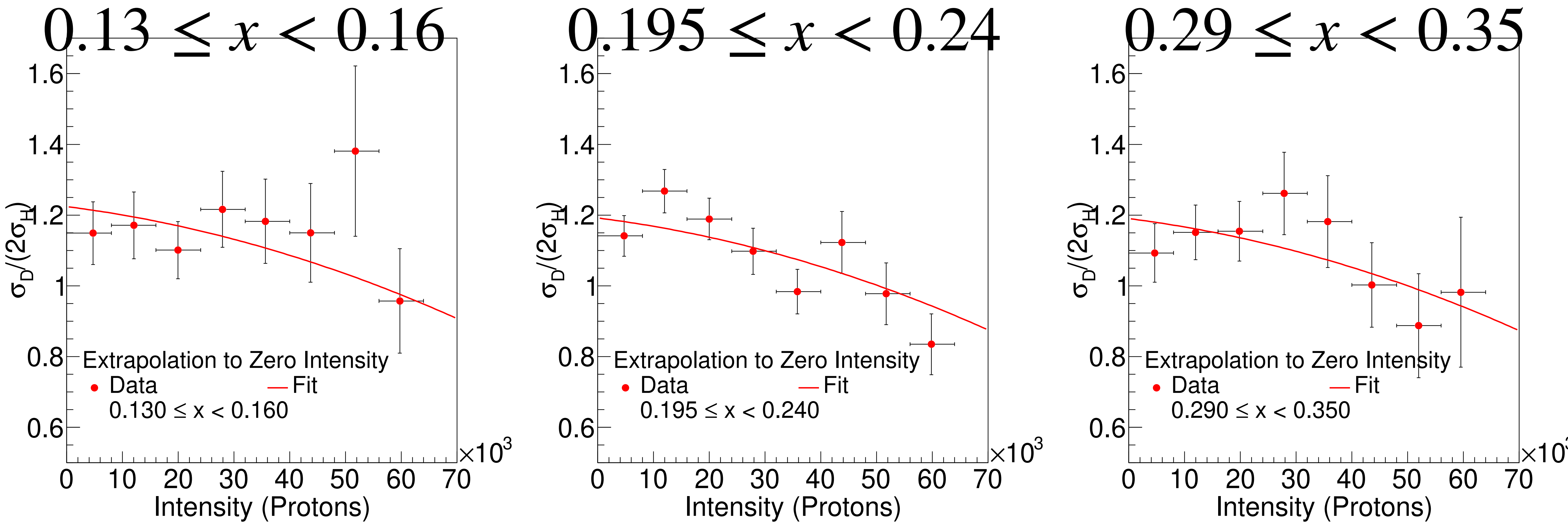
- Pauli blocking: small effect (few %)

- Pion Cloud model (Phys. Rev D 58 (1998) 092004)
  - $|p\rangle = |p_0\rangle + \alpha\,|N(udd)\pi^+(u\bar{d})\rangle + \beta\,|\Delta(uuu)\pi^-(\bar{u}d)\rangle + \gamma\,|\Lambda K\rangle + \cdots$
  - $\alpha > \beta \rightarrow \bar{d} > \bar{u}$



- Statistical Parton Distributions (Nucl. Phys. A 948 (2016) 63)
  - Parton distribution calculated under the assumption of
    - ★ Quarks obey Fermi-Dirac function
    - ★ Gluons obey Bose-Einstein function
  - $\bar{d} > \bar{u}$

Beam Intensity Dependence



- Cross section ratio ($\sigma^{pd}/2\sigma^{pp}$) has beam intensity dependence
  - Higher beam intensity $\longrightarrow$ More hits on detectors
    - ★ Random background
    - ★ Lower reconstruction efficiency

- Instead of figuring out the effect separately, fit [Cross section ratio] vs [Beam Intensity] as a function of beam intensity (extrapolation method)

$$f(I) = R_x + aI + bI^2$$

Proton antiquark flavor asymmetry $\bar{d}/\bar{u}$

February 2021: The asymmetry of antimatter in the proton

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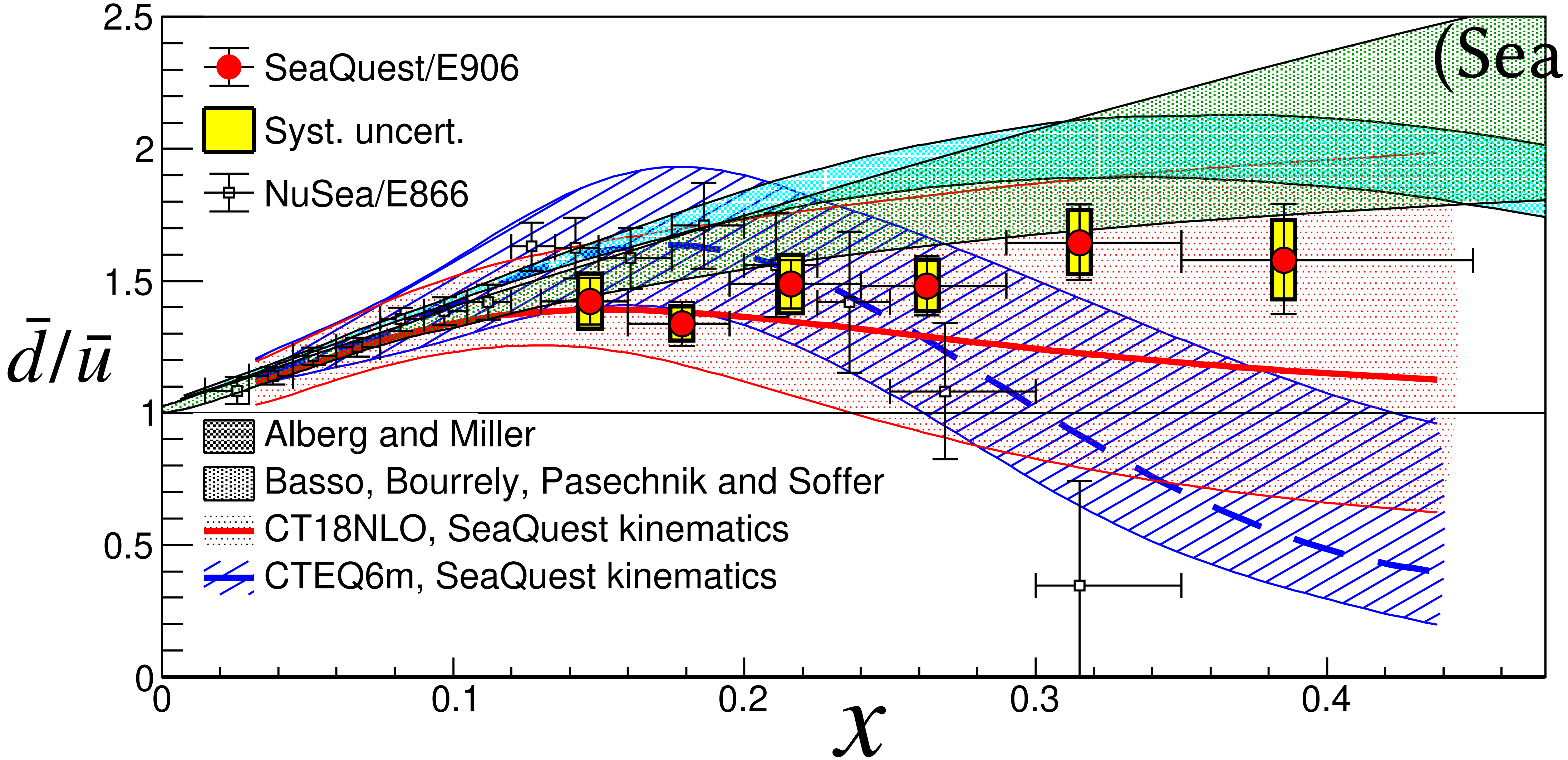
(SeaQuest)

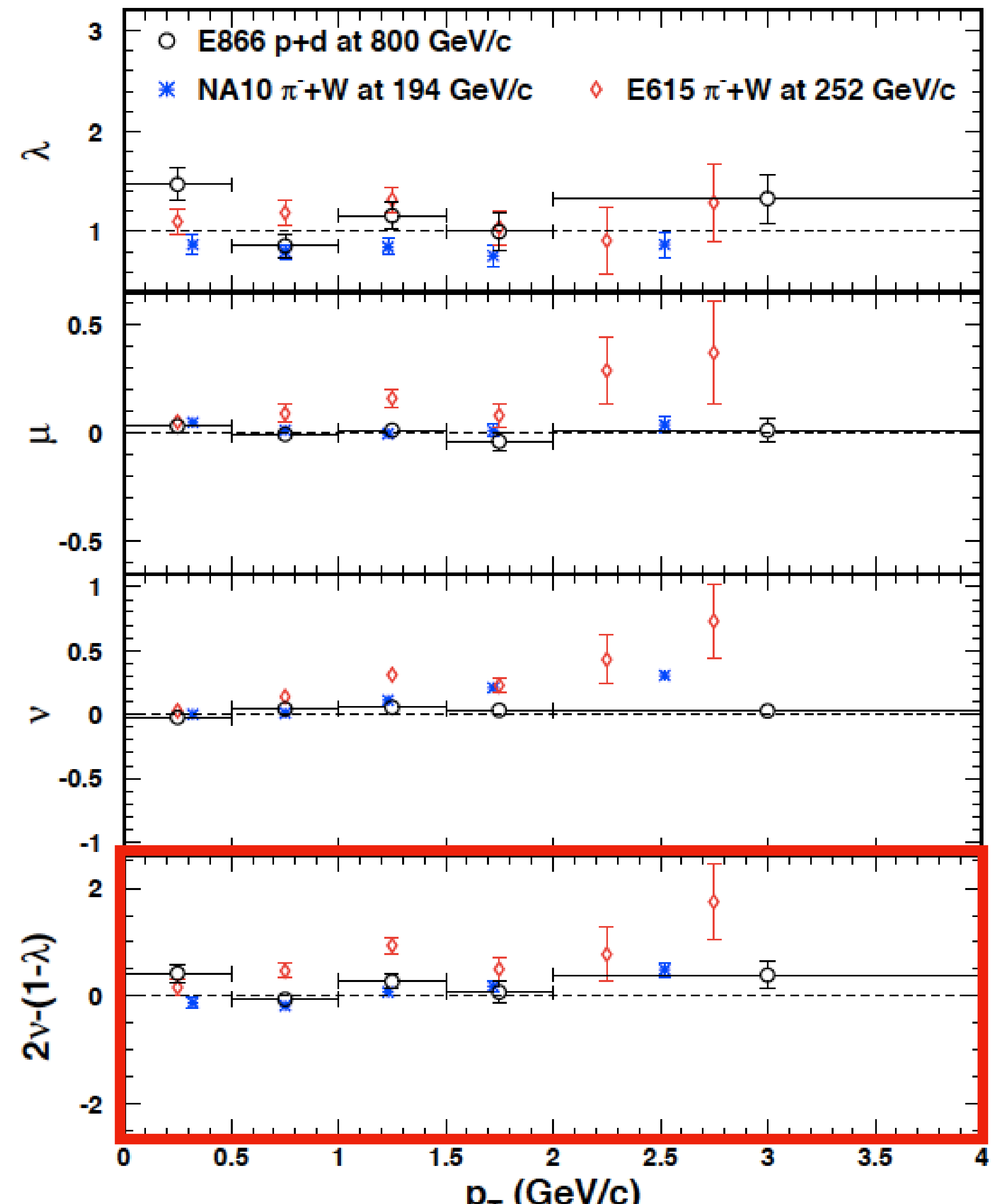


- Antiquark flavor asymmetry $\bar{d}/\bar{u}$ (antiquark PDF) of the proton at large x $(0.13 < x < 0.45)$
- $\bar{d}/\bar{u} > 1.0$ in all measured range

Lam–Tung violation

- NA10 (CERN), E615 (Fermilab)
  - $\pi^-(\bar{u}d)$+W
  - NA10: 194 GeV, E615: 252 GeV beam
  - L–T violation @ large p_T
- E866 (Fermilab)
  - p+d (p+p), 800 GeV beam
  - Smaller L–T violation than π beam experiments

Size of L–T violation depends on beam type

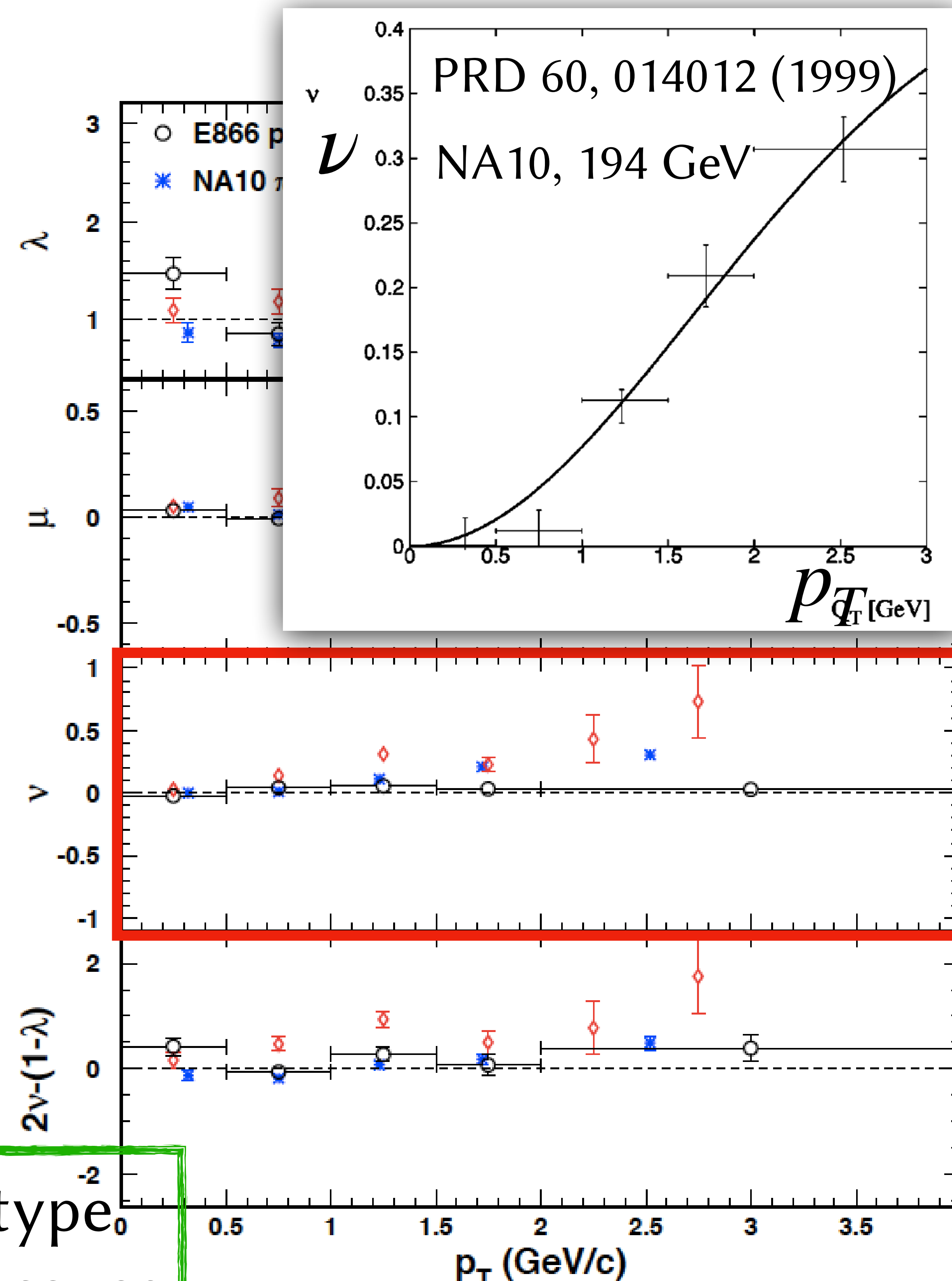


Phys. Rev. Lett. 99, 082301, (2007)

Boer–Mulders function

- Boer-Mulders function and ν
  - $\nu/2 \propto h_1^{\perp}(\text{beam}) h_1^{\perp}(\text{target})$

- <u>B–M function of sea quarks doesn't have to be the same as that of valence quarks</u>
  - π beam: antiquark as valence quark, valence quark-valence antiquark reaction is dominant
  - proton beam: no antiquarks as valence quarks, sea quarks are always involved in the reaction



Phys. Rev. Lett. 99, 082301, (2007)

L–T violation and ν depend on beam type
→ B–M is one of the candidates of the cause

Motivation of angular distribution measurement by SeaQuest

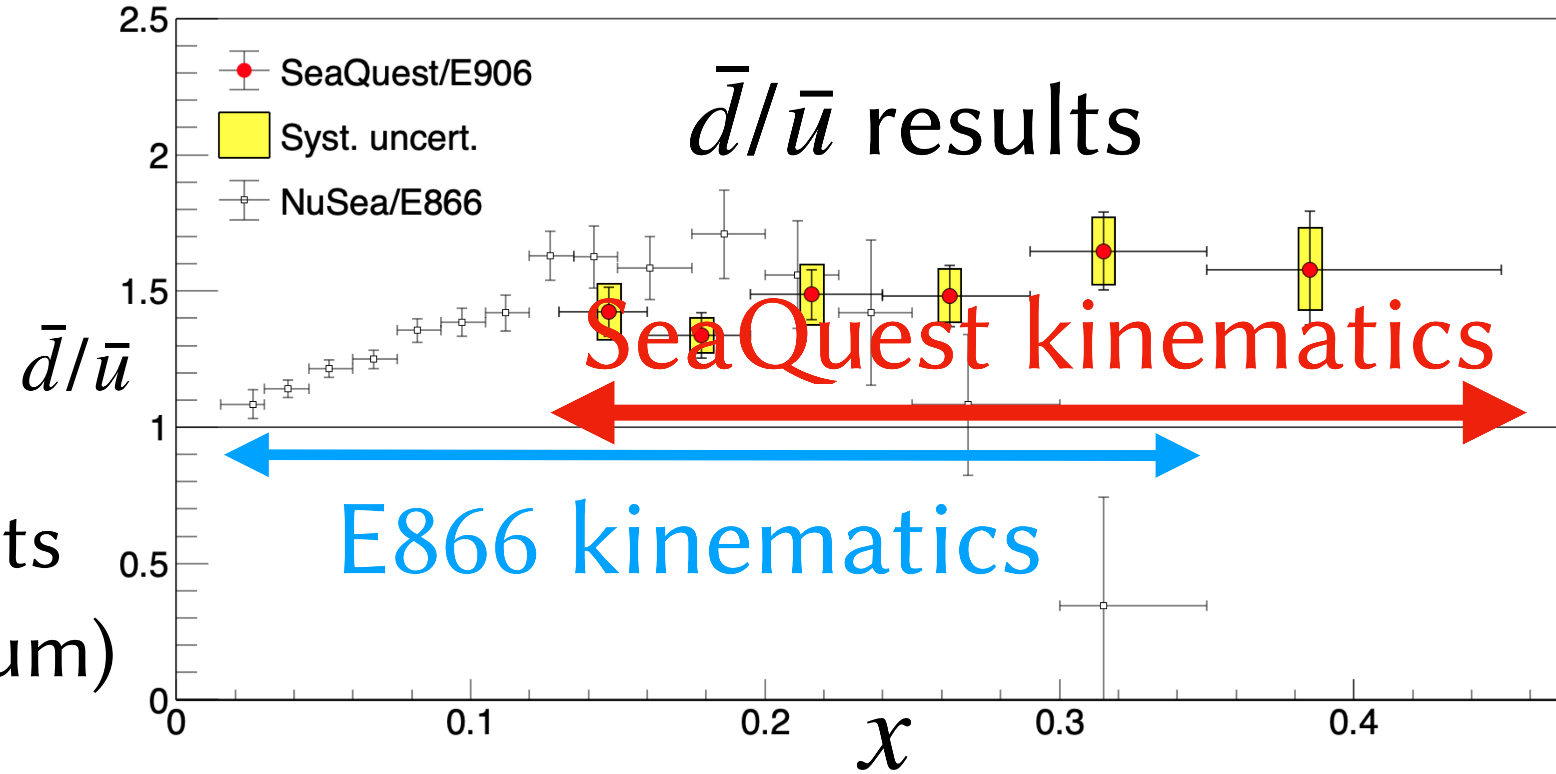
- Angular distribution results by fixed-target x proton beam are only by E866 at this present
  - SeaQuest will give another set of results

- Different kinematics of E866
  - Gives Boer–Mulders function at a larger x region

- Full ϕ range measurement
  - Suitable to extract μ and ν
  - λ is currently fixed to 1.0

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

- Baseline of E1039
  - E1039: polarized targets
    SeaQuest: unpolarized targets
  - Pure hydrogen (and deuterium) angular distribution



Analysis Procedure

- Prepare correction factors – 2-dimensional histograms
  - Accepted simulation / 4pi simulation – acceptance factor
  - Realistic simulation / accepted simulation – reconstruction efficiency factor

- 2-dimensional un-binned p-p data
  - p-p data / acceptance factor / reconstruction efficiency factor

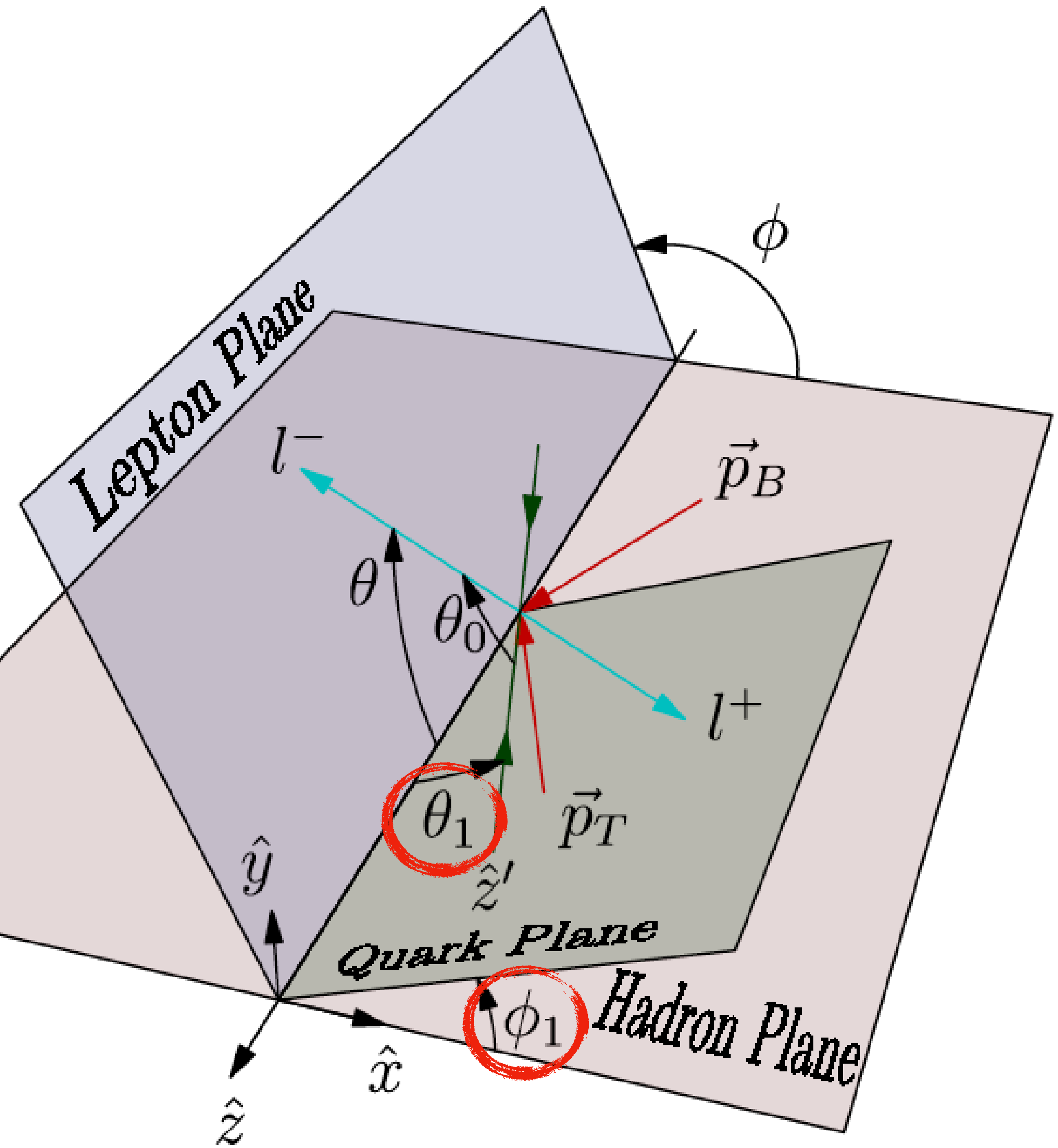
- Subtract background from p-p data

- Fit with

$$A \times \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

  - $\lambda = 1$ (FIXED) and extracted μ and ν

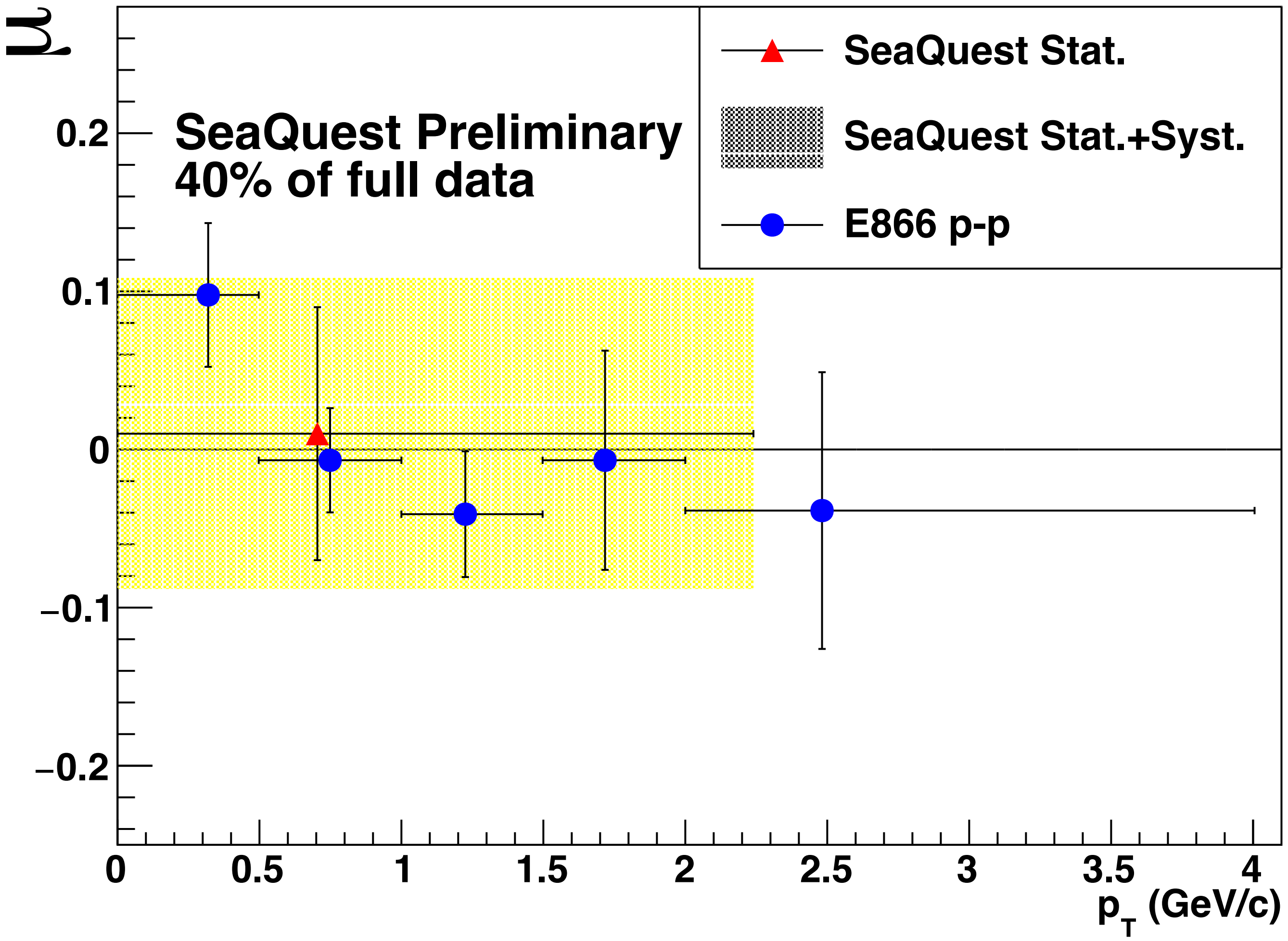
Condition of Lam–Tung Relation



- Introduce quark plane in Collins–Soper frame
  - θ_1: polar angle of quark
  - ϕ_1: azimuthal angle of quark

- Lam–Tung relation:
  - $\langle \sin^2\theta_1 \rangle = \langle \sin^2\theta_1 \cos 2\phi_1 \rangle$
  - Lam–Tung relation is satisfied when $\phi_1 = 0$
    → Quark plane and hadron plane are common

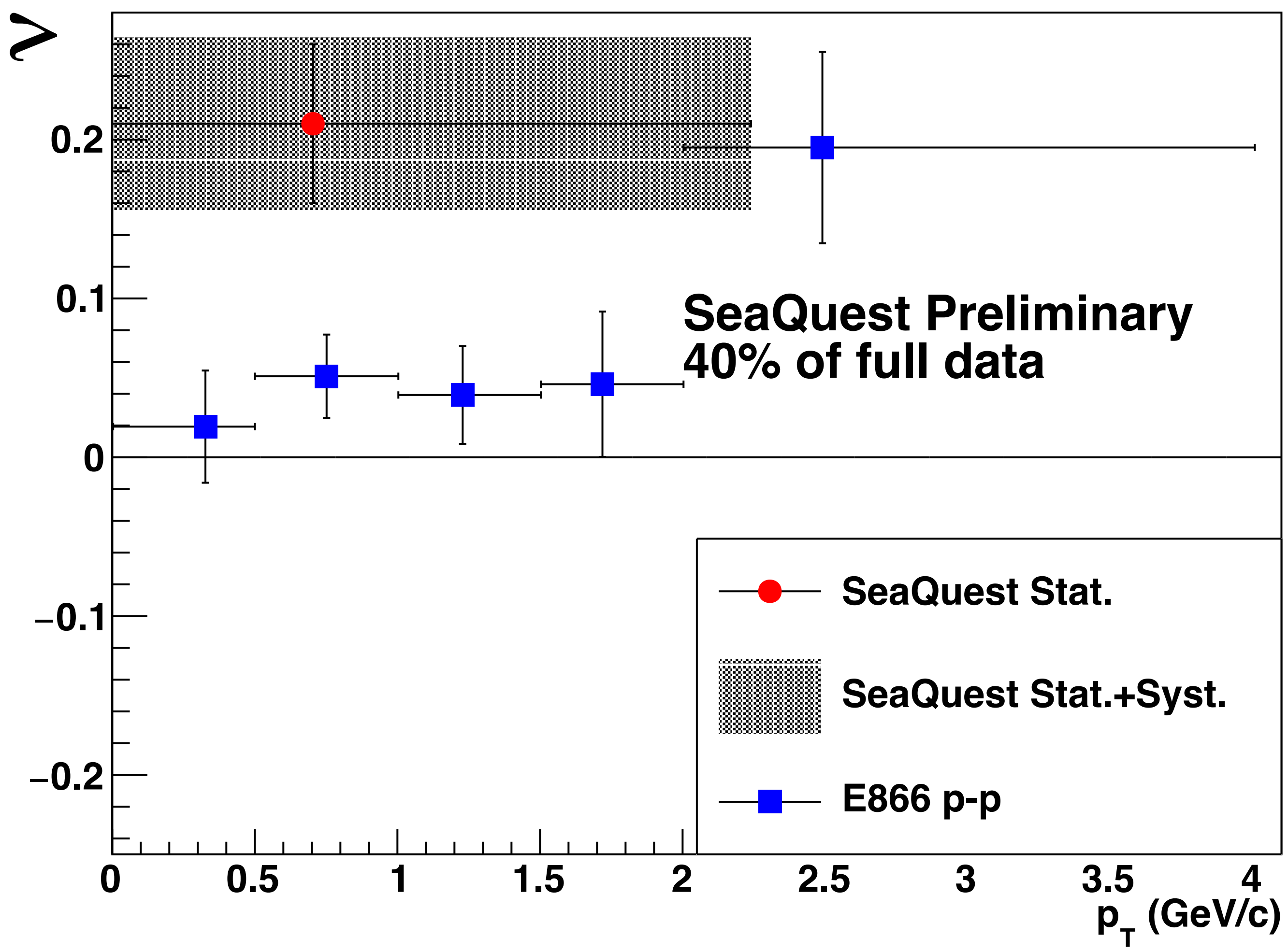
Preliminary Results



SeaQuest: 120 GeV proton beam
E866 : 800 GeV proton beam

- μ is consistent with 0.0 within the uncertainty.
- Consistent with E866 p-p results.

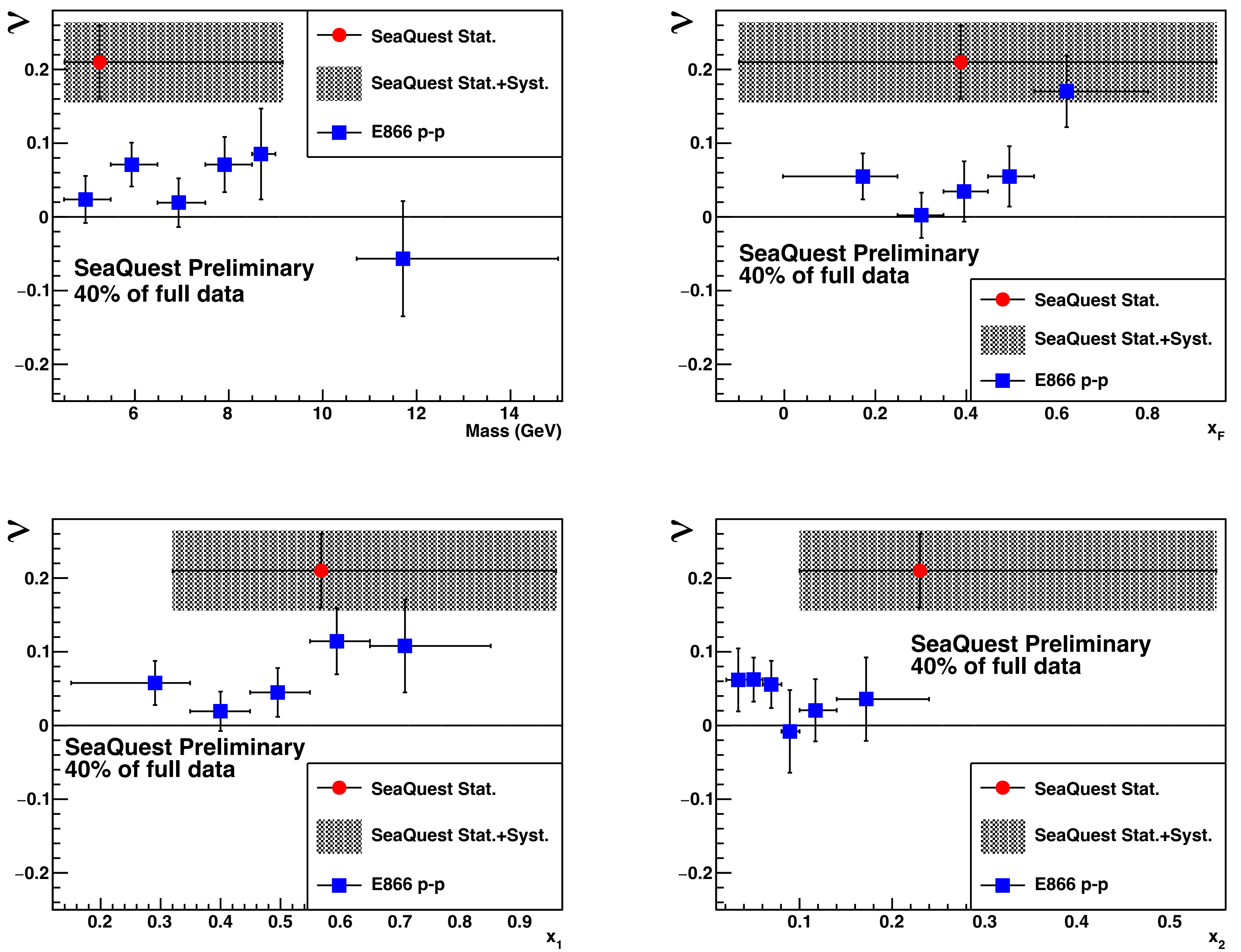
Preliminary Results



SeaQuest: 120 GeV proton beam
E866 : 800 GeV proton beam

- Non-zero ν is obtained.

Preliminary Results



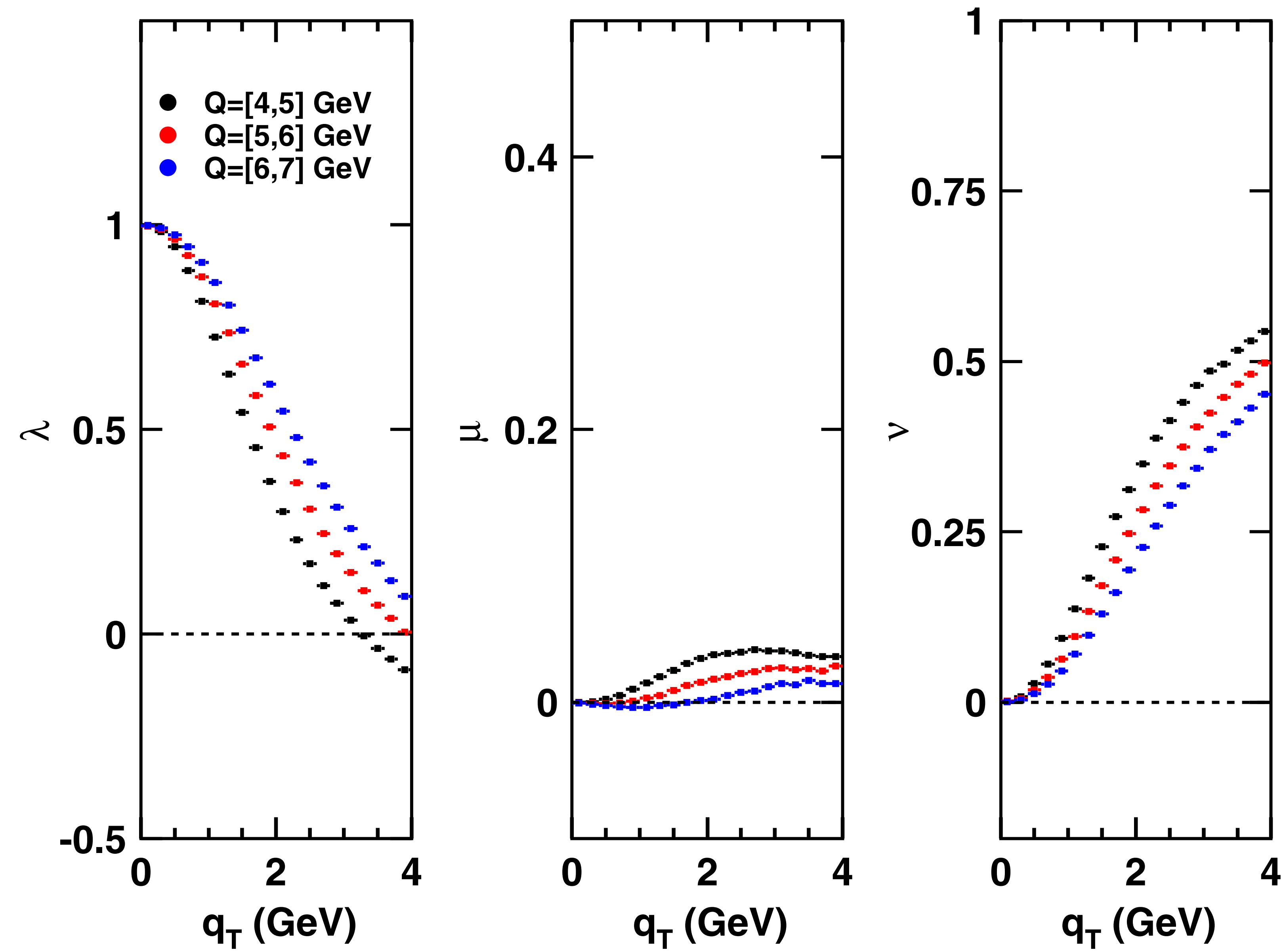
SeaQuest: 120 GeV proton beam
E866 : 800 GeV proton beam

- SeaQuest provides the data at a large x_2 range

p_T dependence of ν in pQCD

- SeaQuest p+p 120 GeV, NLO Drell–Yan
- Boer-Mulders function is not included (pure pQCD)
- Large ν is expected even without Boer–Mulders function
  - Difference between experimental results and pQCD results is important

PHYS. REV. D **99,** 014032 (2019)



Proton Spin Puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma\,?$$

-1980s

RHIC

gluon spin 30-50%

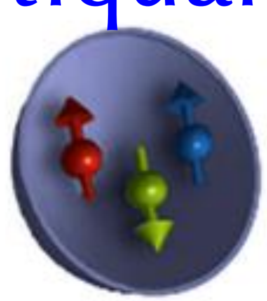
from $x = 0.05$ to $x = 0.2$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

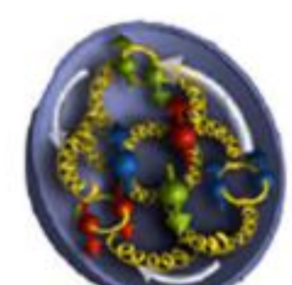
spin of quarks and antiquarks

~25%

EMC at CERN (1989)



Orbital Angular Momentum



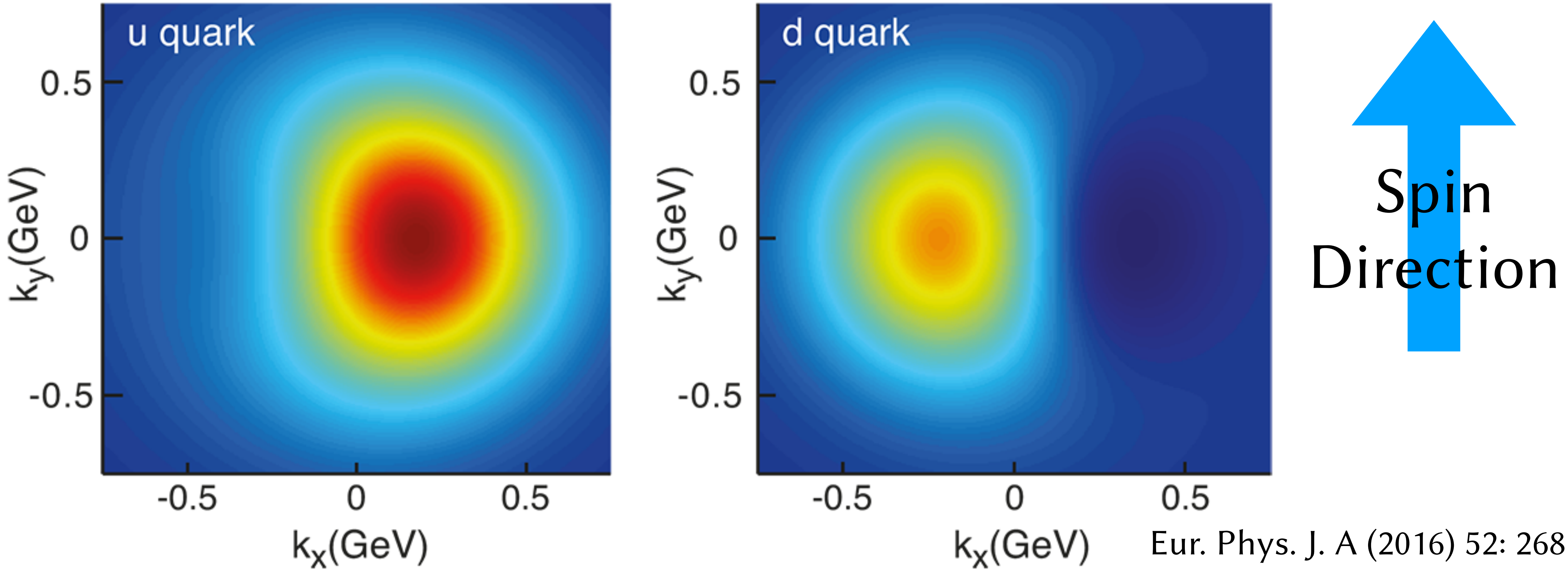
TMDs

TMDs (highlighted)

		Quarks		
		Unpolarized	Longitudinally Polarized	Transversally Polarized
Nucleon	U	f_1		$h_1^\perp$ −
	L		g_{1L} −	$h_{1L}^\perp$ −
	T	$f_{1T}^\perp$ − Sivers	$g_{1T}^\perp$ −	h_{1T} − $h_{1T}^\perp$ −

- **<u>Sivers function</u>**
  - Transversely polarized target and unpolarized beam
  - Represent the relation between quark transverse momentum and nucleon spin
  - The non-zero Sivers function indicates the non-zero orbital motion of the parton
    - ★ Orbital angular momentum contribution on the proton spin

Sivers Effect



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- Demonstration of Sivers effect at $x = 0.1$
- The transverse momentum distribution is distorted due to the Sivers function (Sivers effect)

Measurements of Sivers Function

- Global analysis results of the experimental data
  - HERMES, COMPASS, JLab
- Sivers functions of u and d quarks are non-zero
  - Contribute to the proton spin
- Antiquarks Sivers functions are zero?
  - Reveal by the direct measurement – Drell–Yan process

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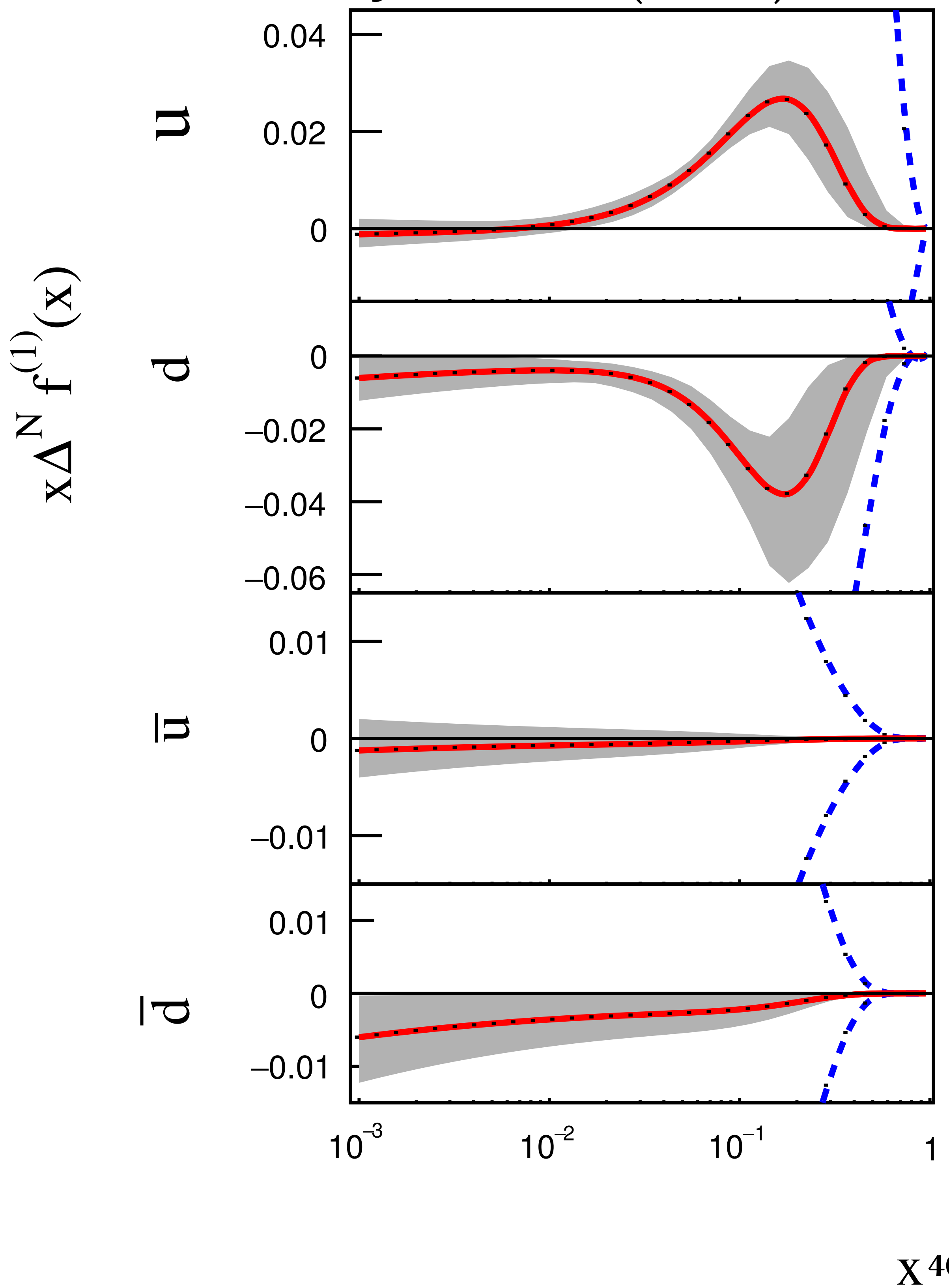
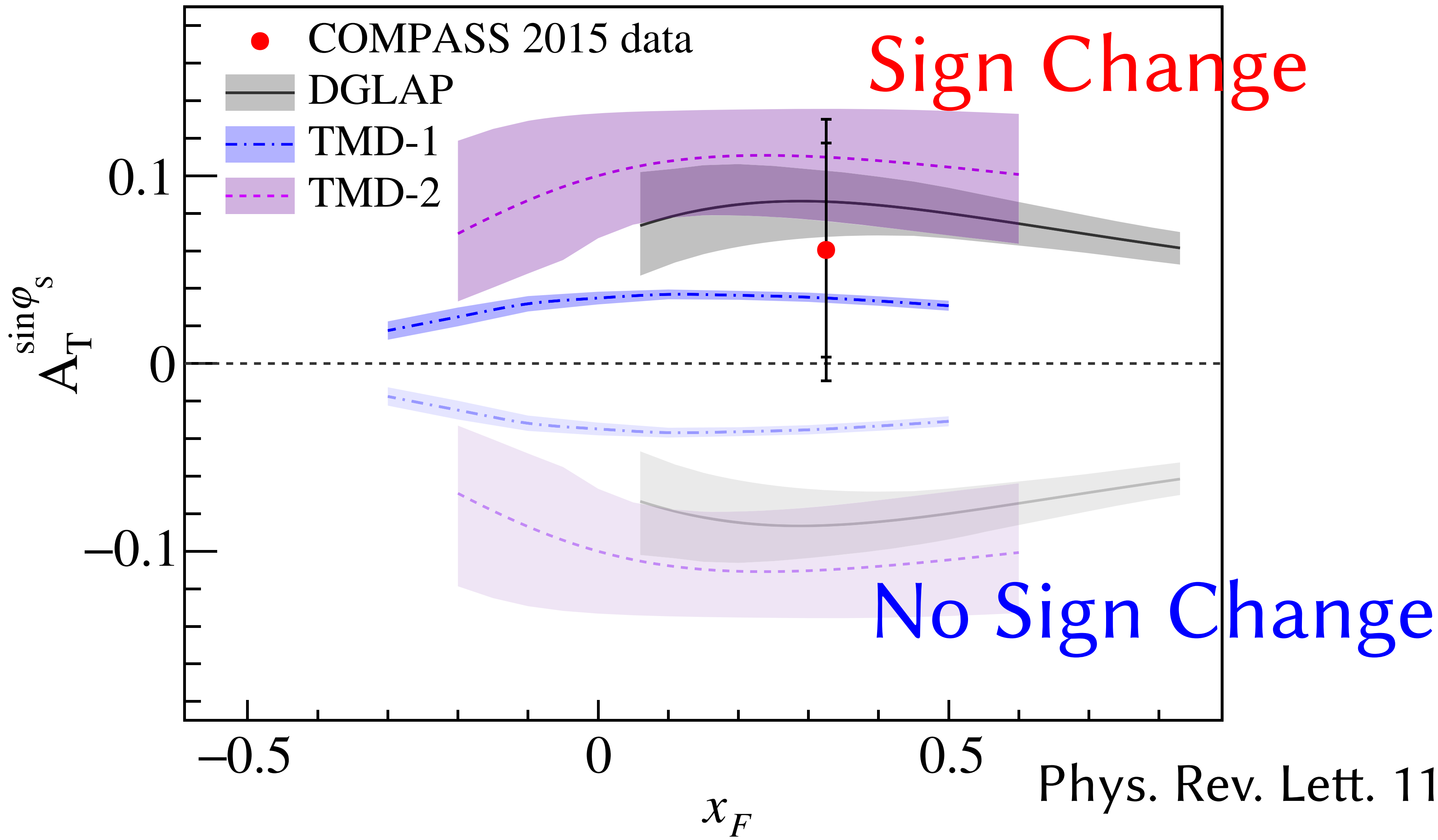


Sign Change of Sivers Asymmetry



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- COMPASS has measured the Sivers asymmetry in Drell–Yan and indicated the sign of the asymmetry is opposite of that of SIDIS.
- <u>Sign change of Sivers asymmetry of antiquarks may be investigated with SpinQuest results and future experiments results.</u>