Measurement of angular distribution of Drell–Yan dimuons by the SeaQuest experiment at Fermilab

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on behalf of the SeaQuest Collaboration

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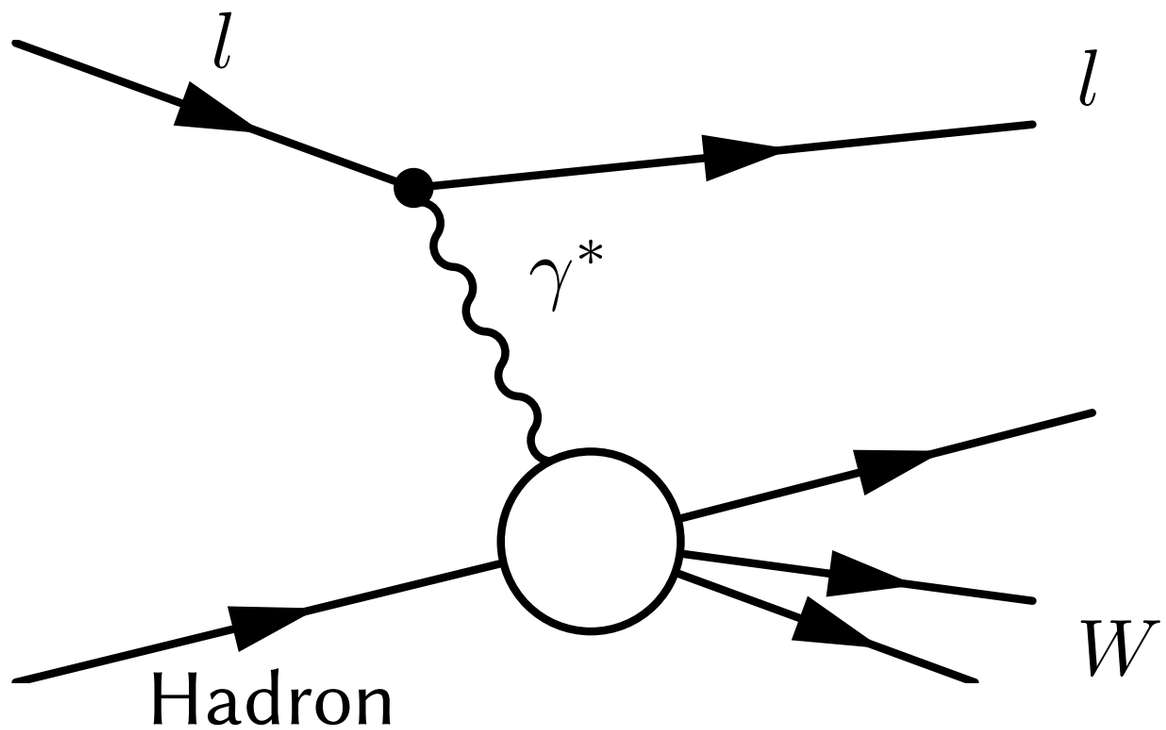
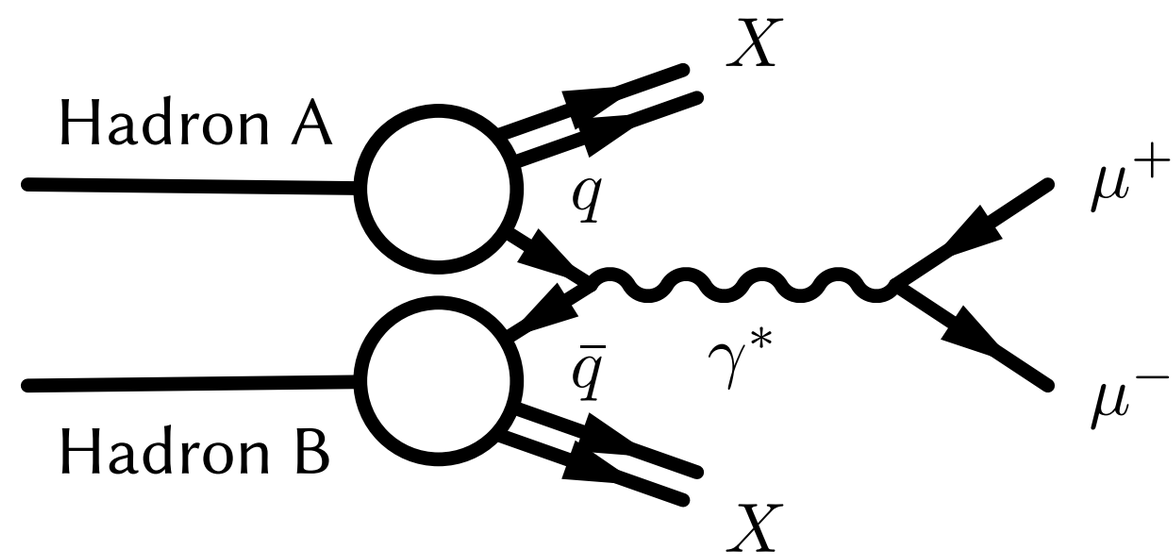
1. Drell–Yan process and proton structure

Access proton structure





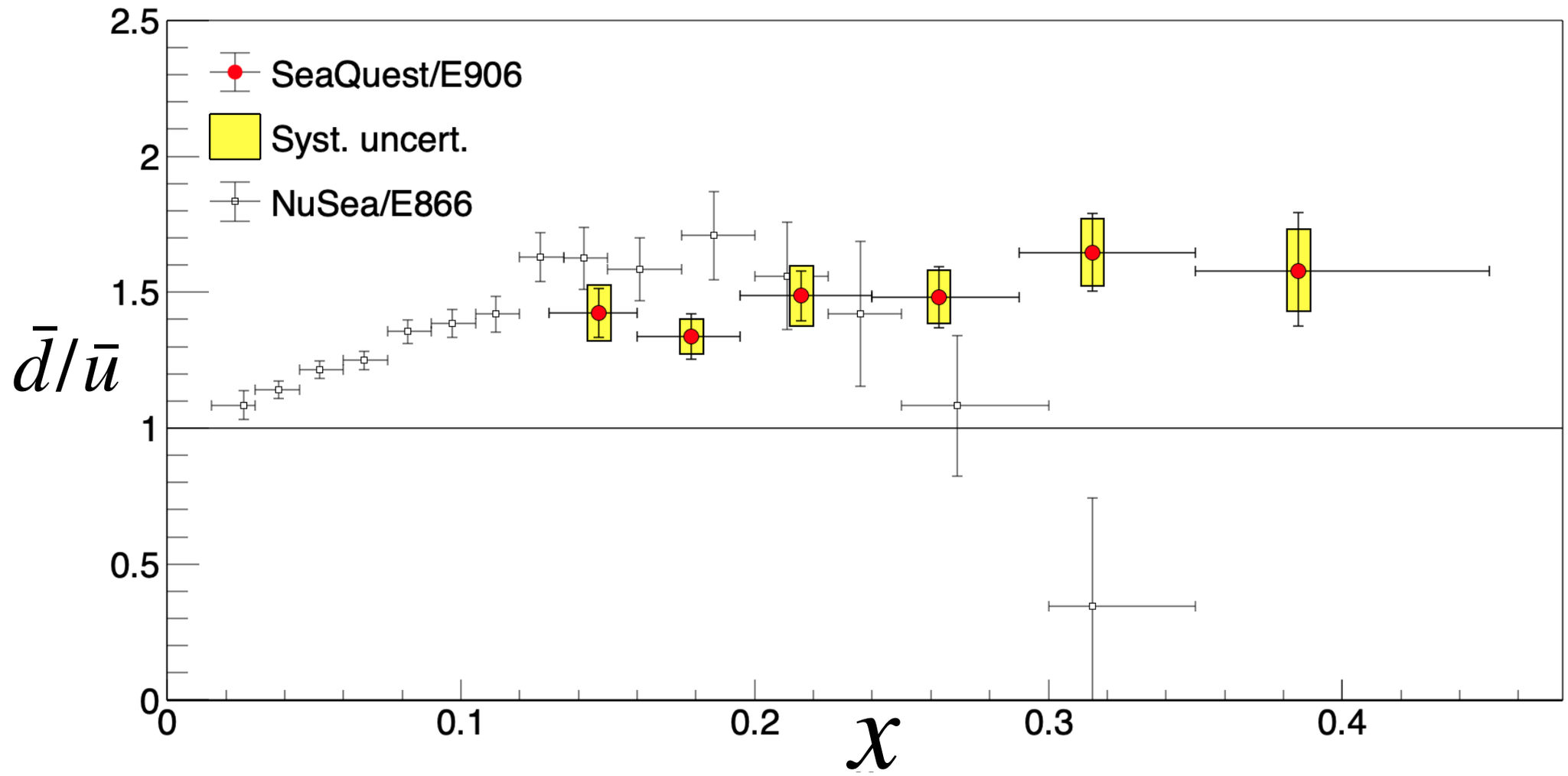
- Deep Inelastic scattering experiments have investigated the proton structure
  - Scattering with all charged partons (u, d, $\bar{u}$, $\bar{d}$, $\cdots$)
  - Great achievement for u, d quarks PDFs

- 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 <u>sea quark</u>

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

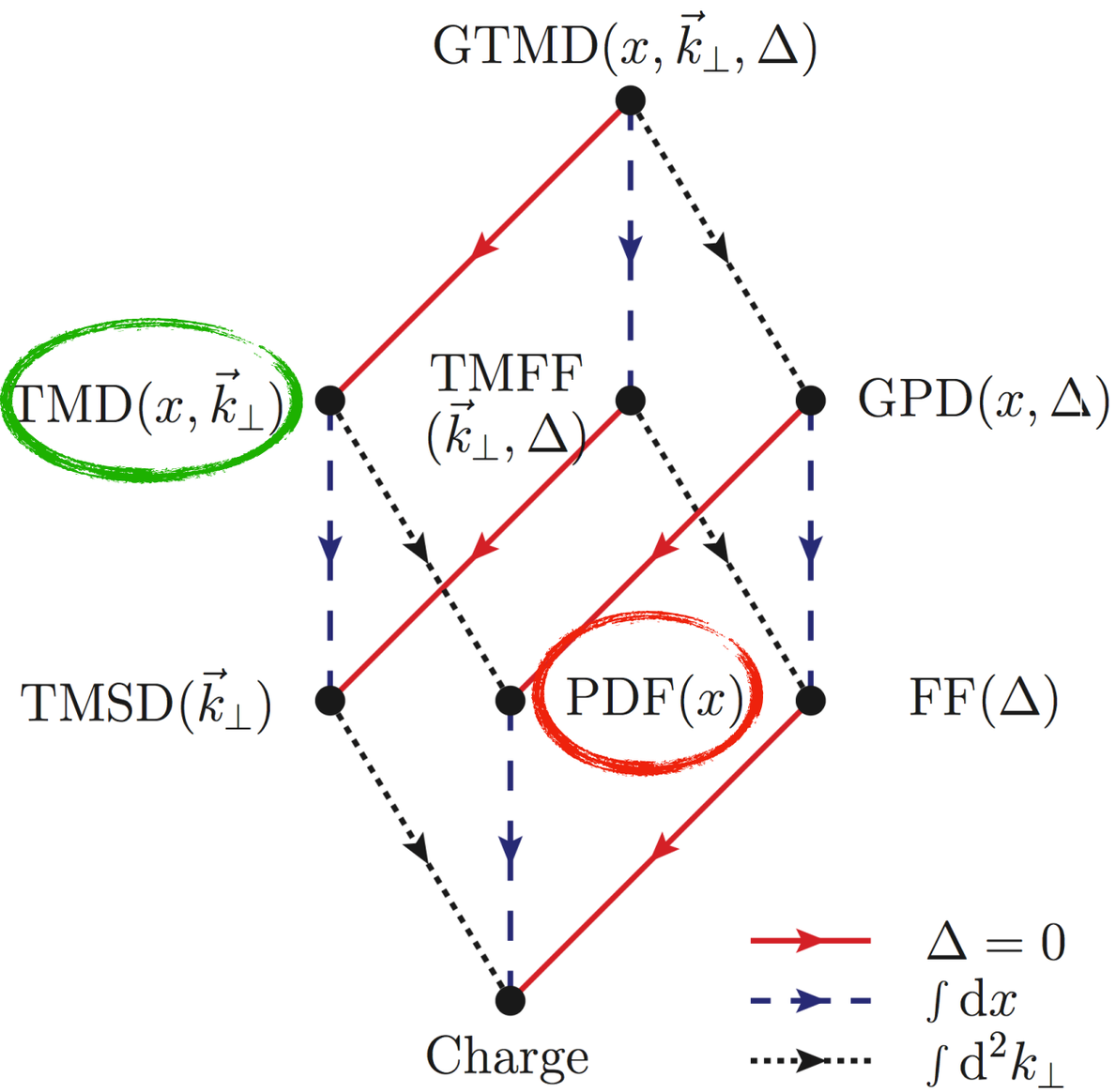
February 2021: The asymmetry of antimatter in the proton

Nature **590**, 561 (2021)



- Antiquark flavor asymmetry $\bar{d}/\bar{u}$ of the proton at large x ($0.13 < x < 0.45$)
  - x: Bjorken x, momentum fraction of parton to the proton
- $\bar{d}/\bar{u} > 1.0$ in all measured range

3D Structure



- PDF
  - Function of longitudinal momentum x (1-dim)

- TMD (Transverse-momentum dependent parton distribution function)
  - Longitudinal momentum x + transverse momentum $\vec{k}_\perp$ (3-dim)
  - Research on the effect of spin

TMDs

TMDs

		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}
				$h_{1T}^\perp$

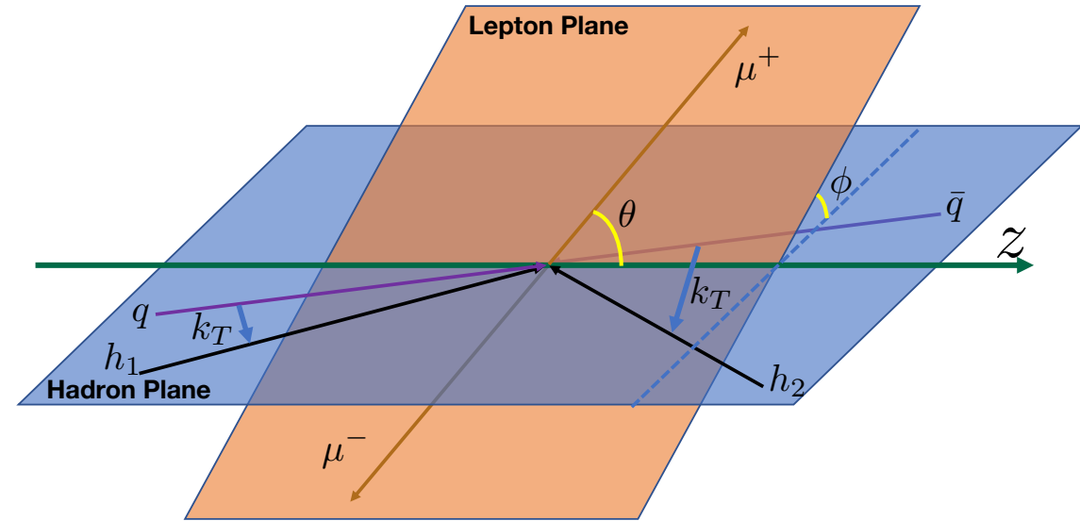
Boer-Mulders

- Sivers function: SpinQuest experiment
  - Transversally polarized target and unpolarized beam
  - Represent the relation between quark transverse momentum and nucleon spin
  - Contribution of orbital angular momentum of the quarks on proton spin
- **Boer–Mulders function**
  - Unpol. target and unpol. beam
  - Relation between quark transverse spin and transverse momentum
  - Research on Lam–Tung relation

2.Angular Distribution

Angular distribution of Drell–Yan

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



- Drell–Yan cross section

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

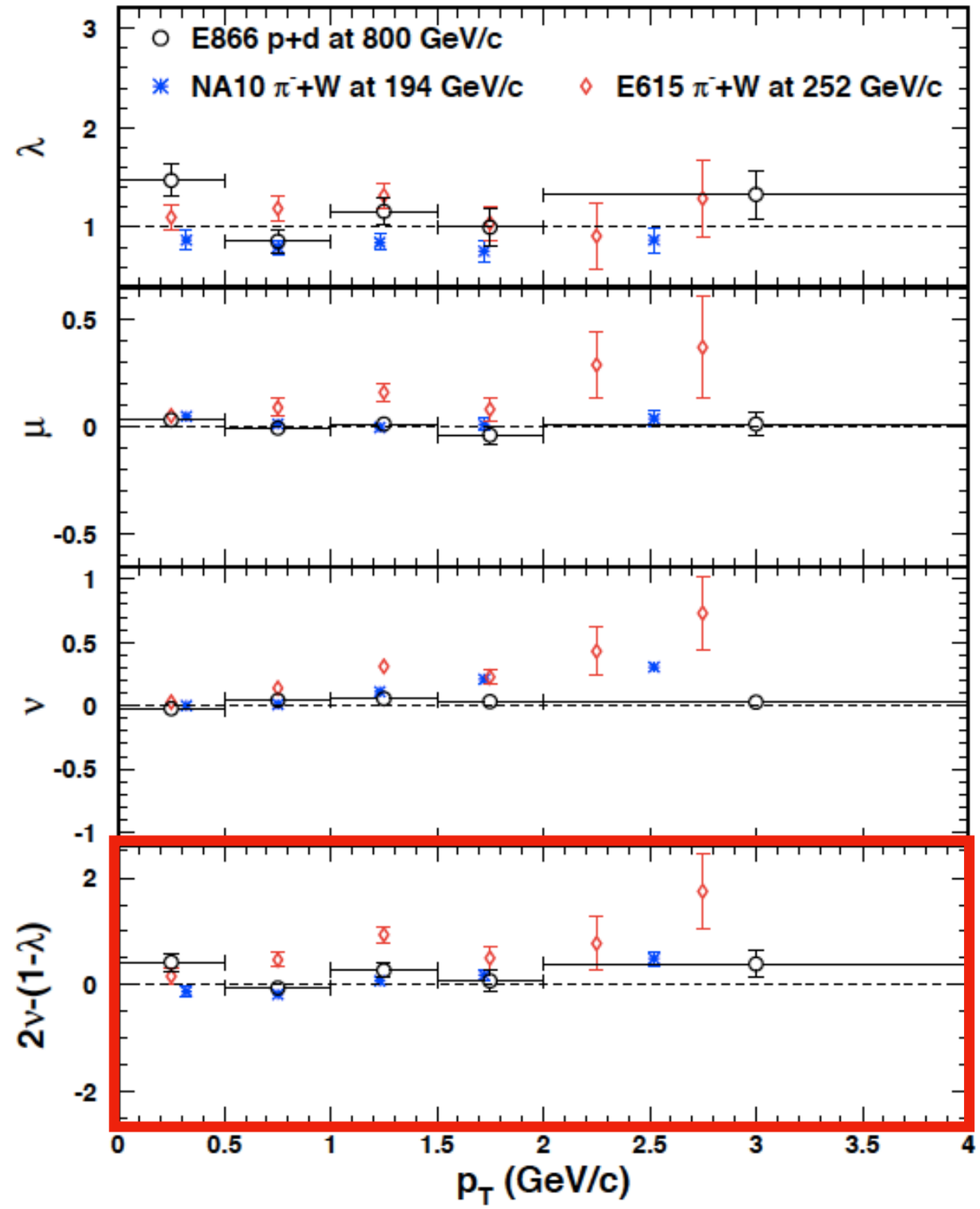
  - Naively, $\lambda = 1$, $\mu = \nu = 0$ ($d\sigma \propto 1 + \cos^2\theta$) at leading order
    - ★ No transverse momentum on quarks
    - ★ No gluon emission
  - NLO: $\lambda \neq 1$, μ, $\nu \neq 0$, but $1 - \lambda = 2\nu$ is held (**Lam–Tung relation**)

- Lam–Tung relation
  - Analogue of Callan–Gross relation (scattering of spin 1/2 particles)
  - Held when q-$\bar{q}$ axis is coplanar to hadron plane

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

L–T violation is different in different beam type

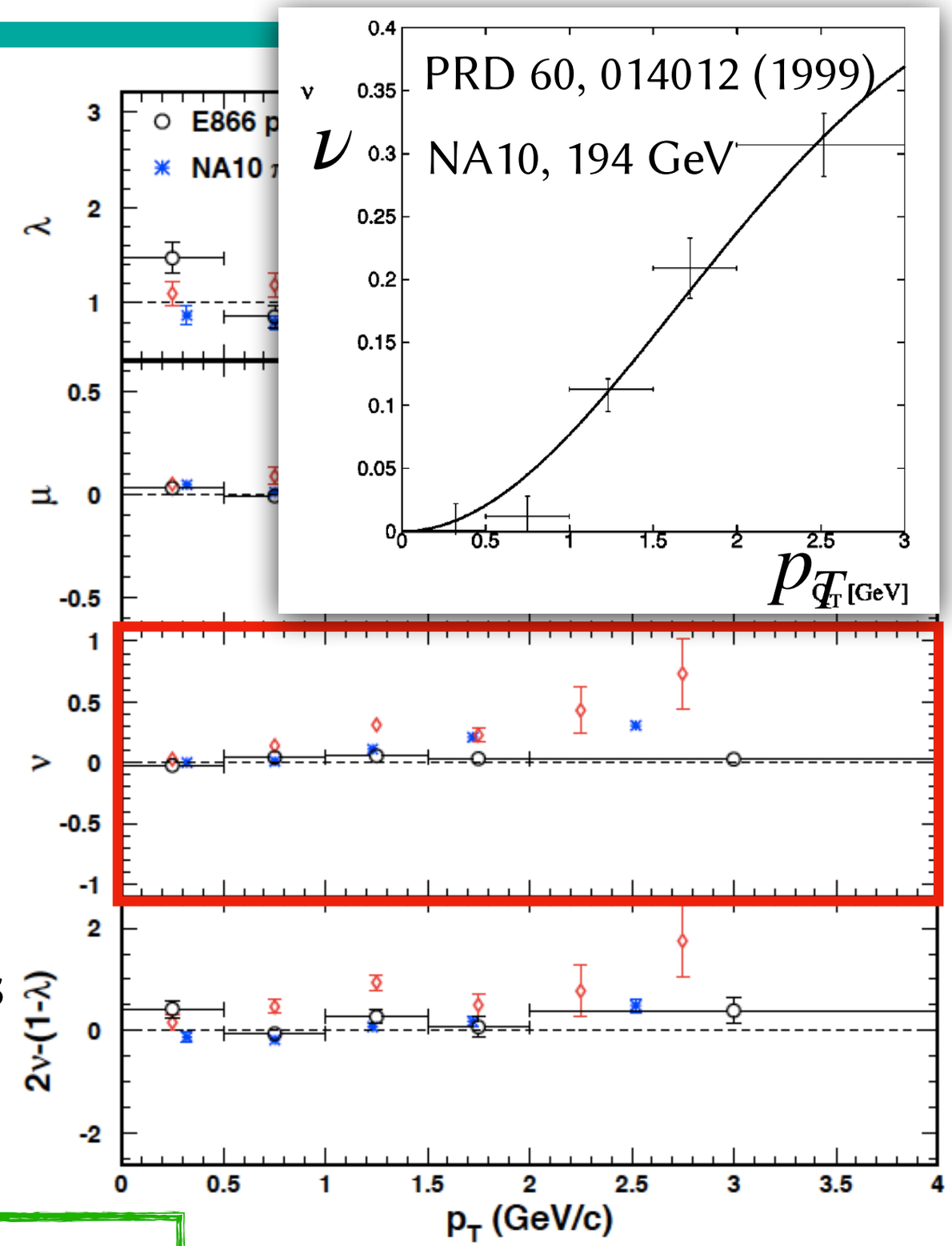


Phys. Rev. Lett. 99, 082301, (2007)

Boer–Mulders function

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

- <u>B–M functions of sea quarks don'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



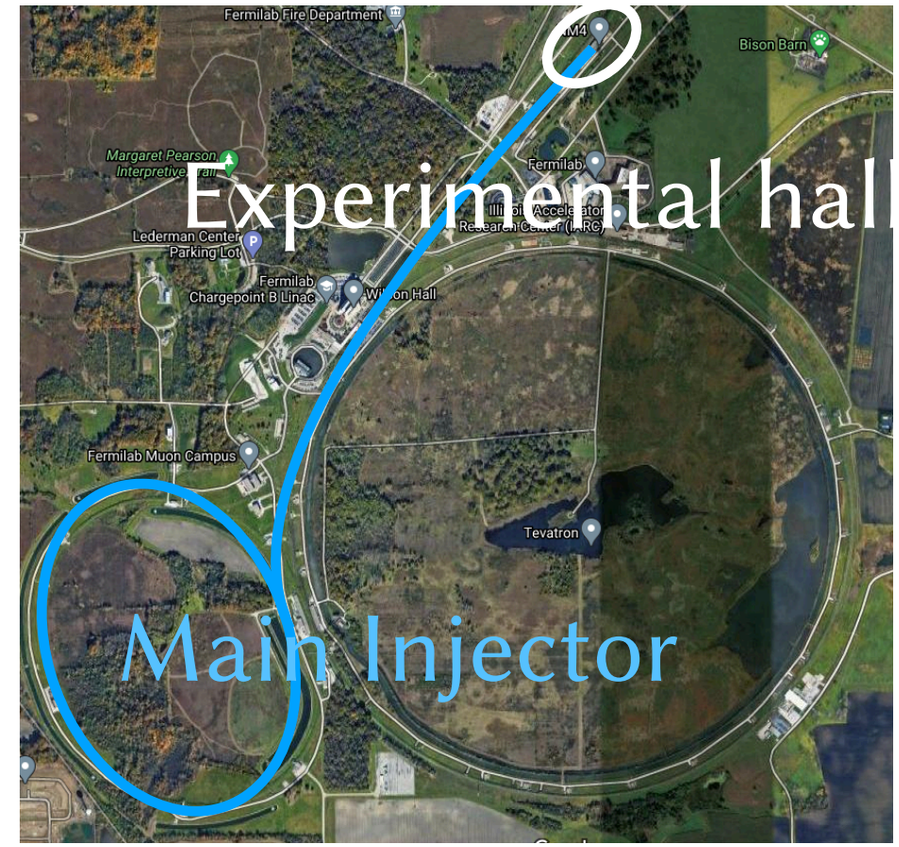
L–T violation and ν depend on beam type
$\longrightarrow$ B–M is one of the candidates of the cause

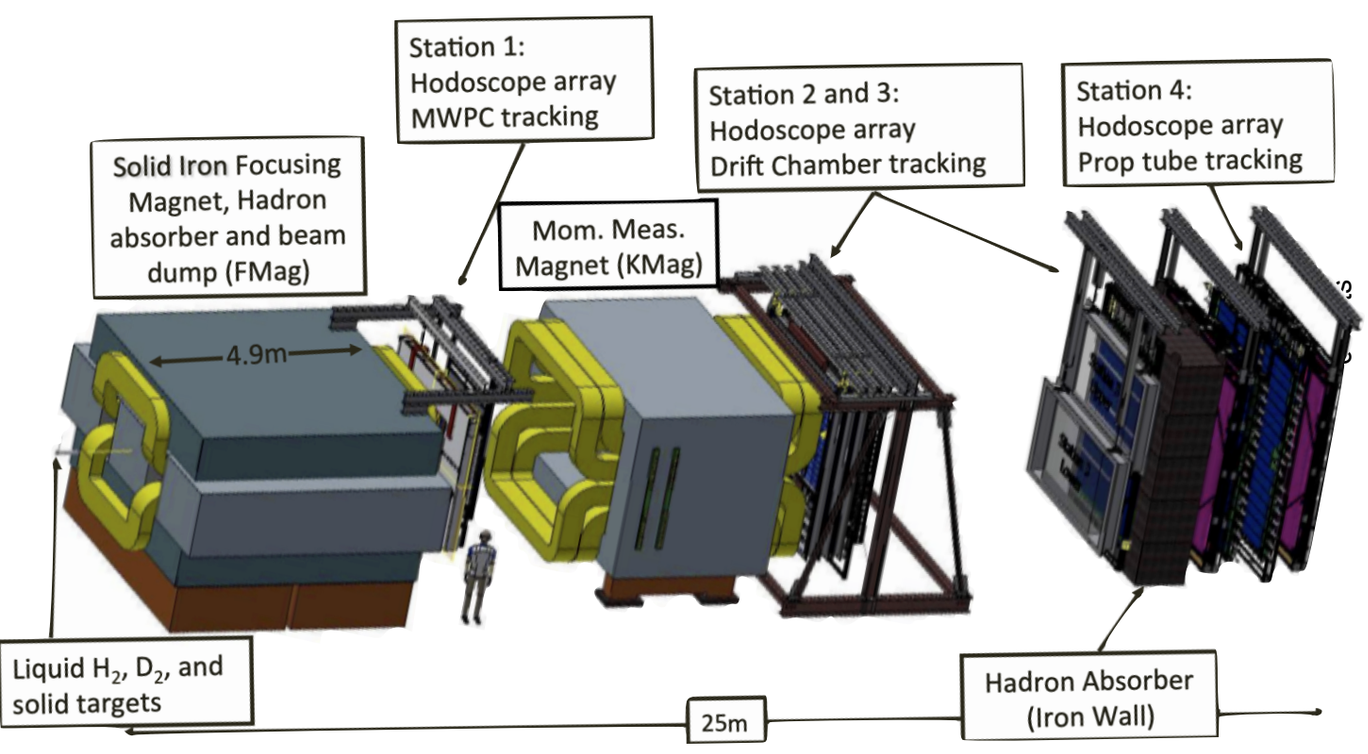
Phys. Rev. Lett. 99, 082301, (2007)

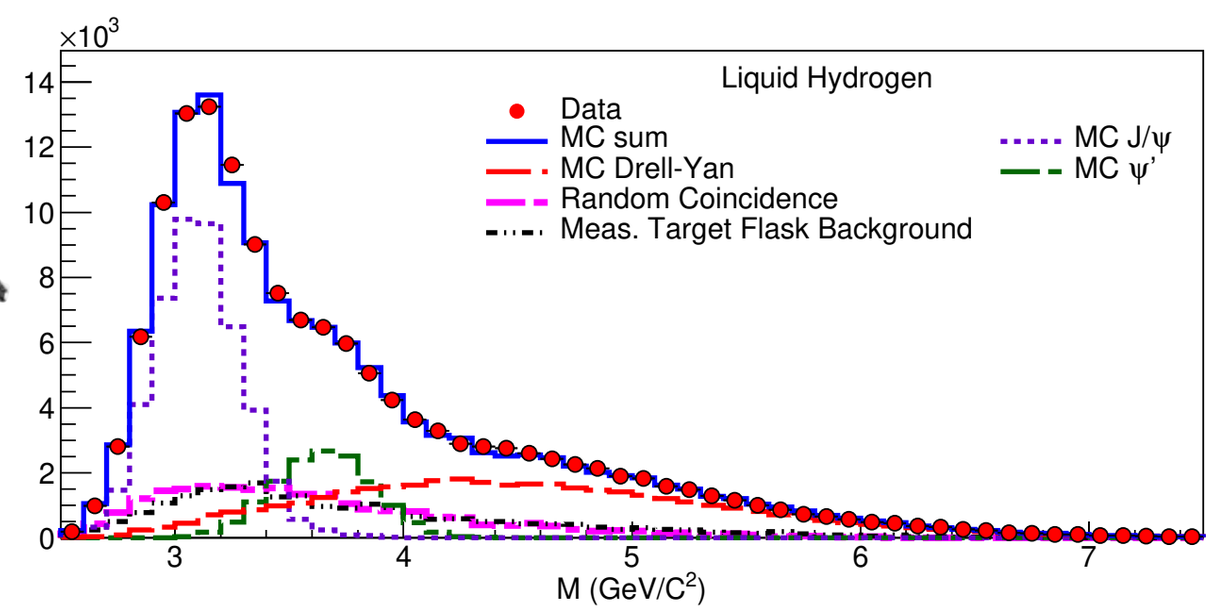
3.Measurement of angular distribution by SeaQuest

E906/SeaQuest experiment

- 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: 2014-2017
  - 8.6×10^{17} protons on target





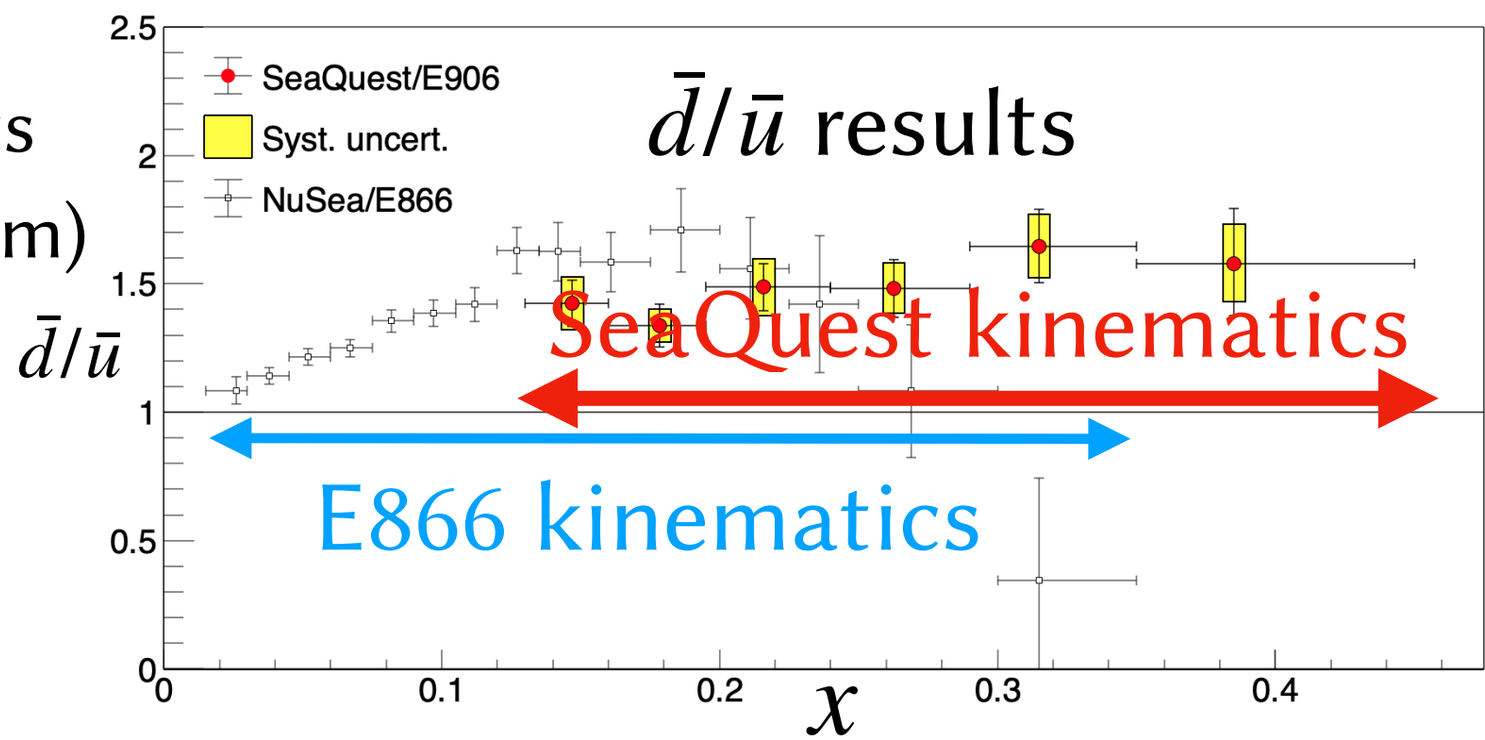


Motivation of angular distribution measurement by SeaQuest

- 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 larger x region

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



Analysis Procedure

- Plot $\cos\theta$ vs ϕ of data, background, and simulation
  - data: $(\sigma_{DY} + \sigma_{BG}) \times$
    [trigger efficiency] $\times$ [detector acceptance] $\times$ [detector efficiency] (A)
    - ★ Subscripts DY and BG stand for Drell–Yan and background
  - background: $\sigma_{BG} \times$
    [trigger efficiency] $\times$ [detector acceptance] $\times$ [detector efficiency] (B)
  - Simulation:
    [trigger efficiency] $\times$ [detector acceptance] $\times$ [detector efficiency] (C)
    - ★ Obtained by [Accepted simulation / 4pi simulation]

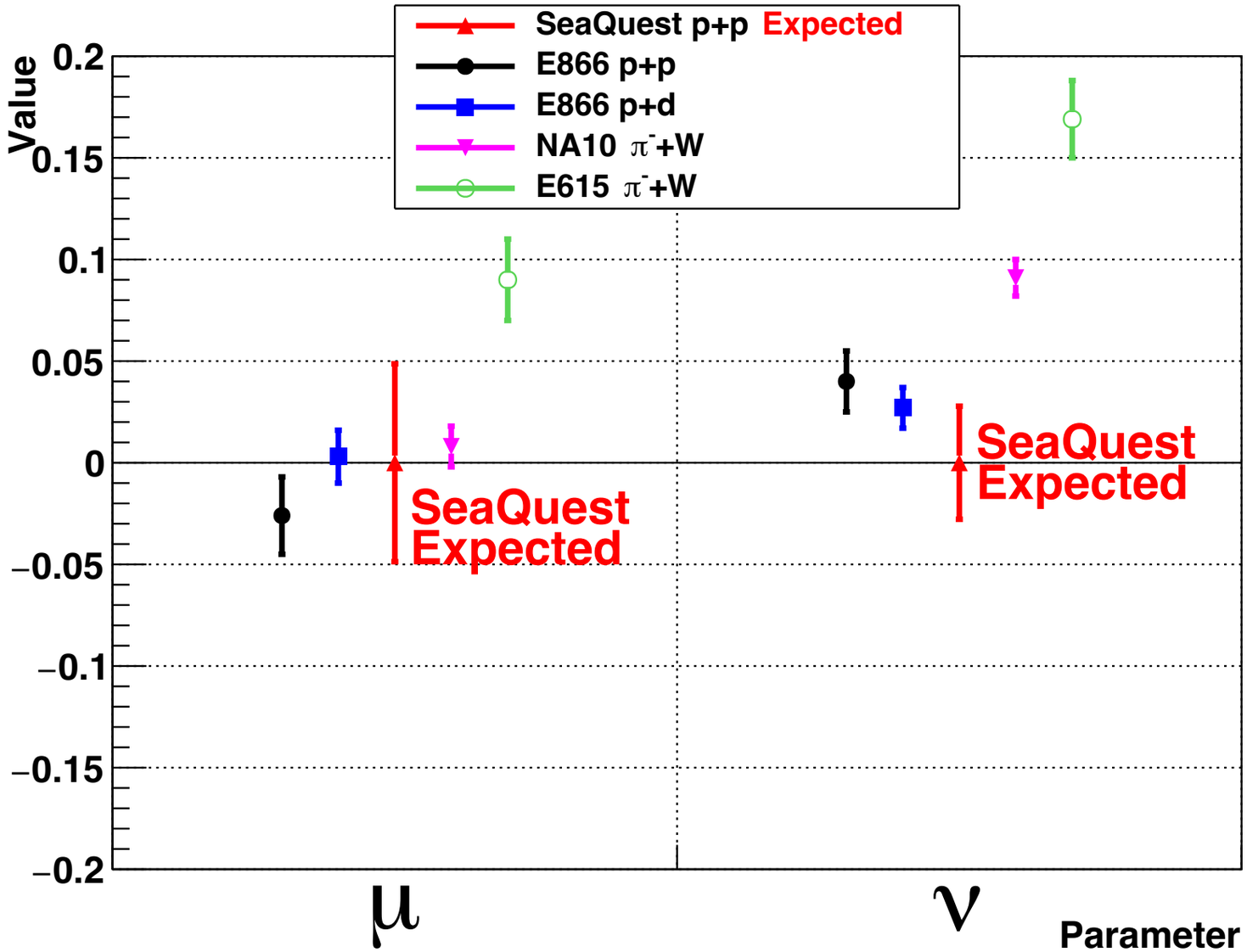
- Subtract background from data – (A)−(B) = (D)

- Correct efficiencies and acceptance
  - (D) / (C) = (E)

- Fit (E) with

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

Expected Accuracy



E866 p+d, NA10, E615 data
Phys. Rev. Lett. 99, 082301 (2007)
E866 p+p data
Phys. Rev. Lett. 102, 182001 (2009)

- Expected accuracy based on SeaQuest real data
- ν: important factor to determine Boer–Mulders function
  - Enough accuracy to see the difference of pion- and proton-induced Drell–Yan
- Different x_2 coverage of E866

Summary & Outlook

- The structure of proton is probed by Drell–Yan process accurately.
- SeaQuest experiment measured $\bar{d}/\bar{u}$ in the proton at high x_2 (Feb. 2021).
- Proton-induced Drell–Yan angular distribution analysis is in progress.
  - Measurement of Boer–Mulders function (represents relation of transverse momentum and spin)
- Boer–Mulders function is one of the candidates causing Lam–Tung violation.
  - The E866 results are only the results of proton-induced Drell–Yan angular distribution measurement at this present.
  - SeaQuest will give another set of proton-induced Drell–Yan angular distribution in different x_2 coverage.

- Detector efficiencies, rate effect are not considered for now. Take these effect into account to finalize.

Backup