Angular distribution measurement of proton-induced Drell–Yan process by the SeaQuest experiment at Fermilab

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on behalf of the SeaQuest Collaboration

March 30th, 2023

XXX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2023)
Michigan

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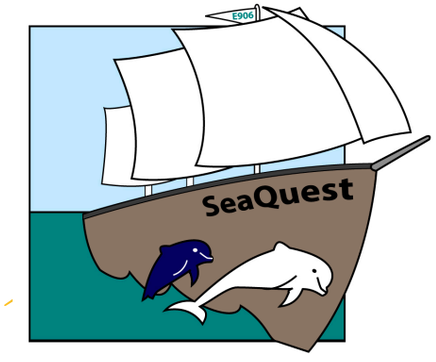
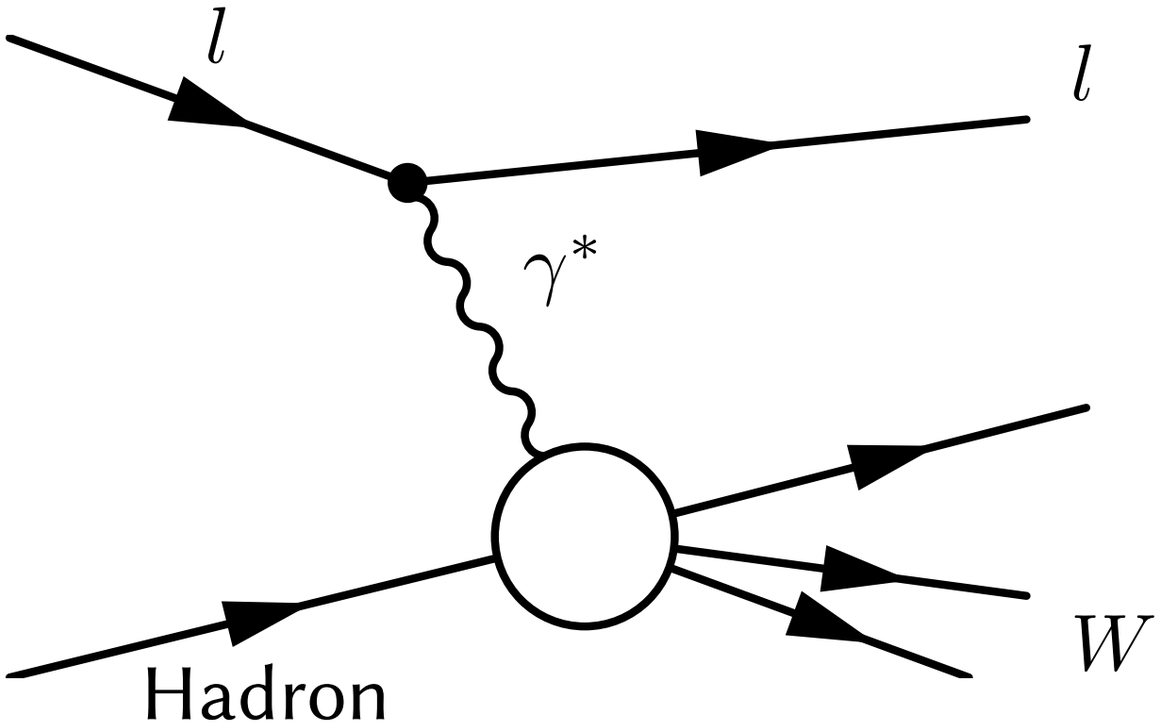
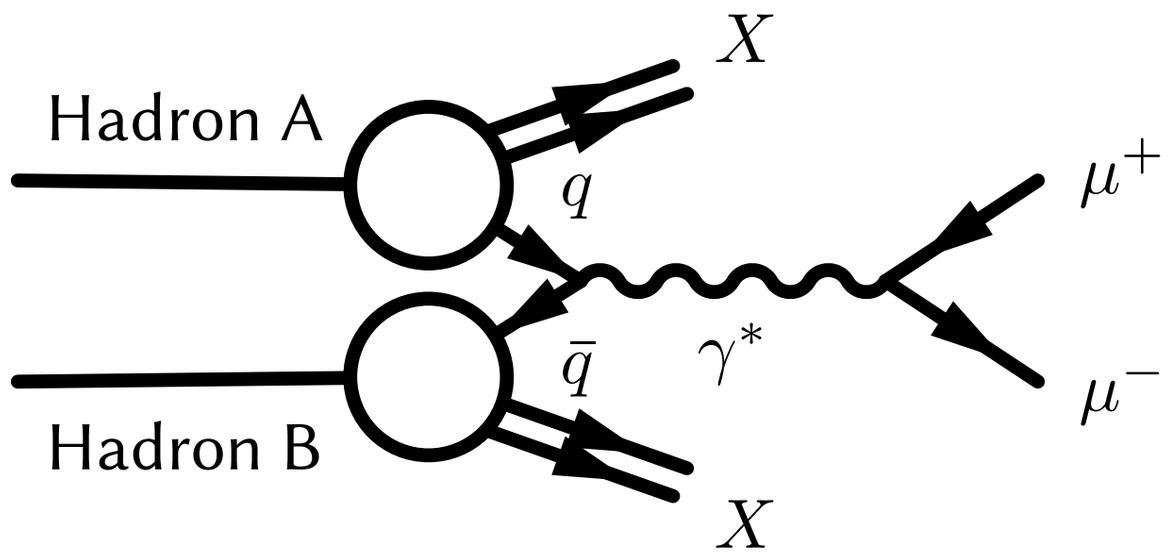


1. Drell–Yan process and proton structure

Access proton structure





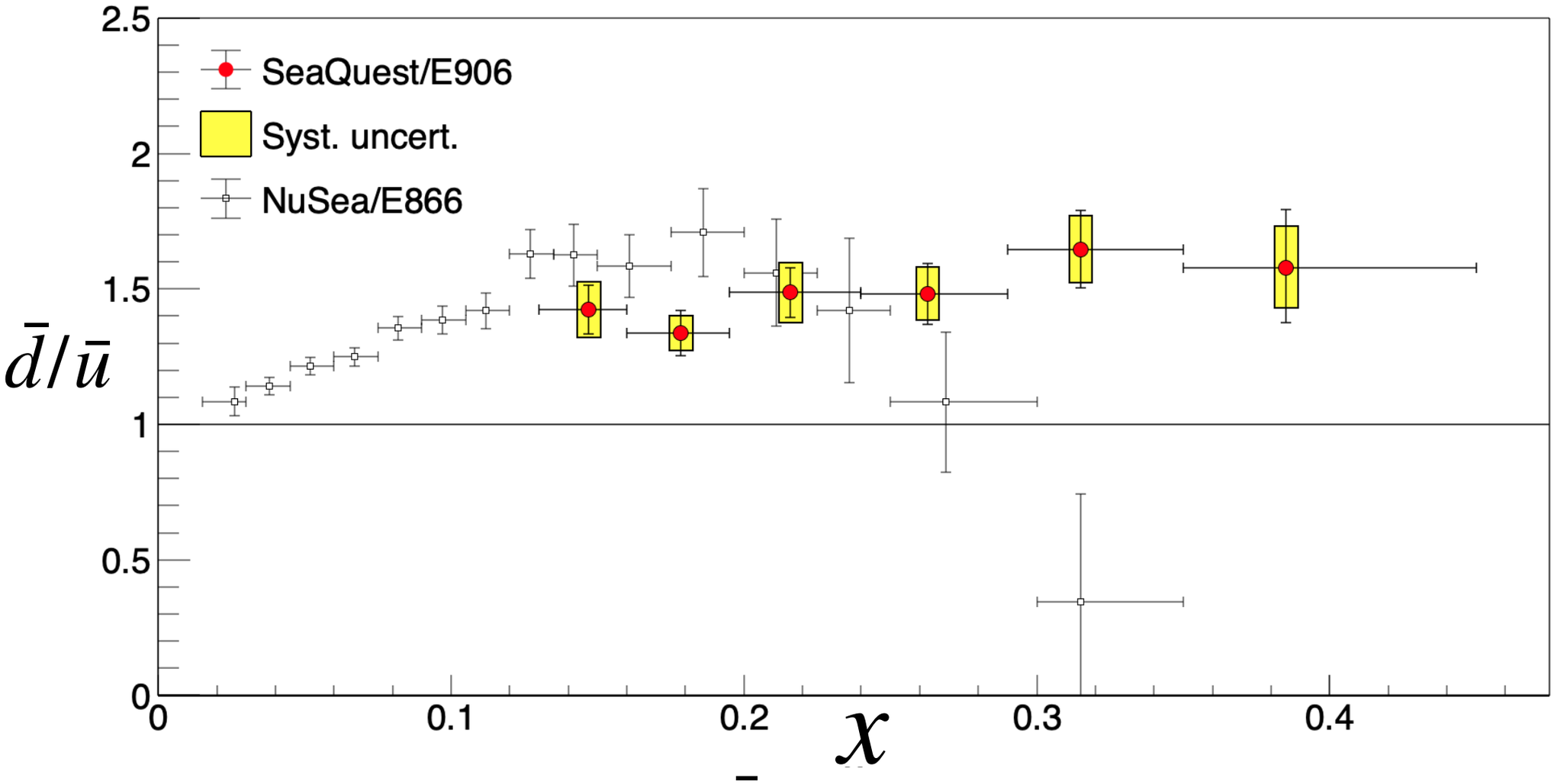
- Deep Inelastic scattering experiments have investigated the proton structure
  - Scattering with all charged partons (u, d, $\bar{u}$, $\bar{d}$, $\cdots$)
  - Great achievement for u, d quarks PDFs

- 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 sea quark

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

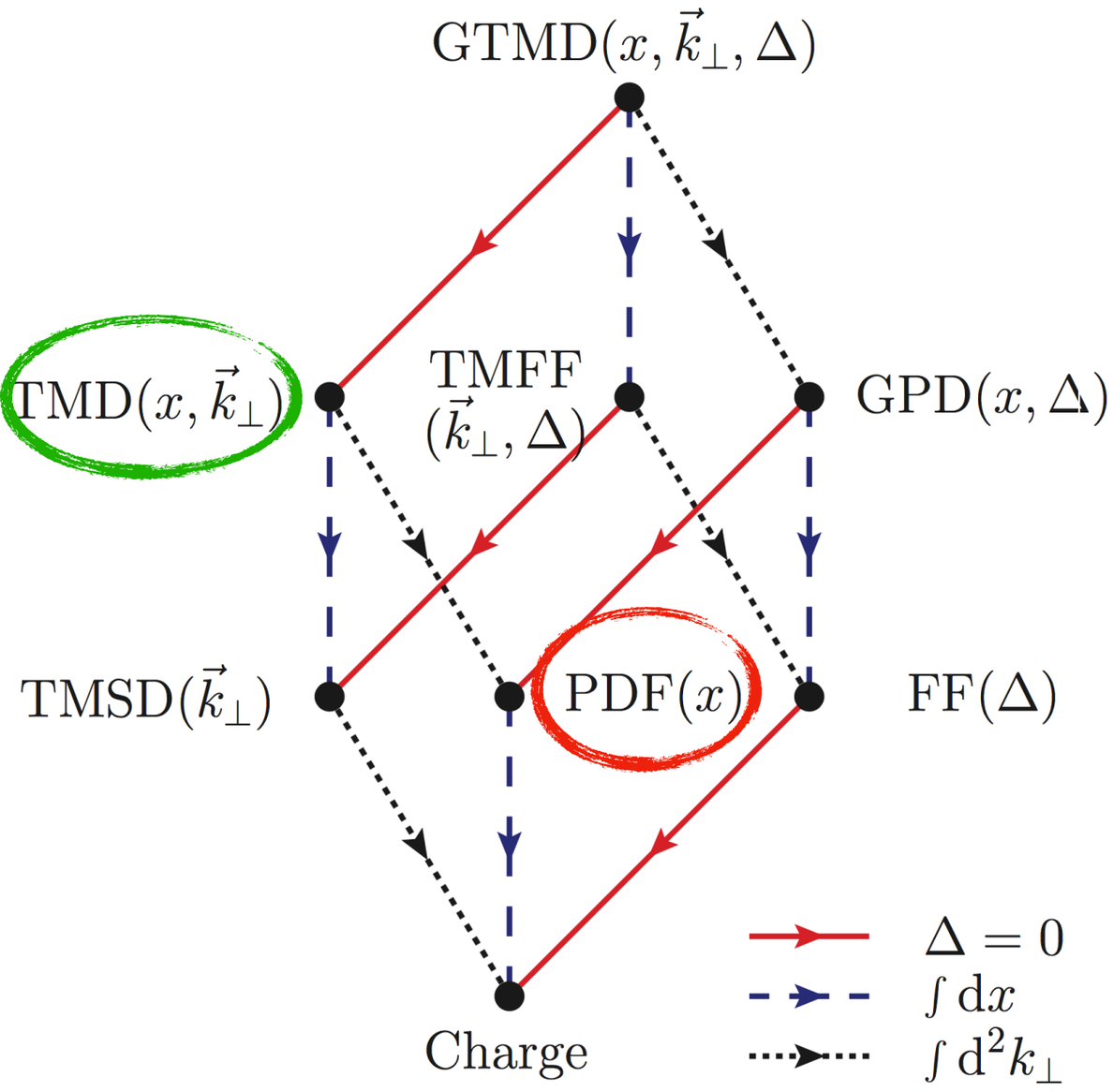
February 2021: The asymmetry of antimatter in the proton

Nature **590**, 561 (2021)



- Antiquark flavor asymmetry $\bar{d}/\bar{u}$ (antiquark PDF) 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

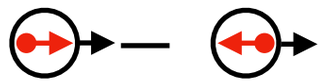
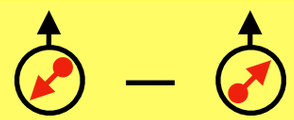


- PDF
  - Function of longitudinal momentum x (1-dim)

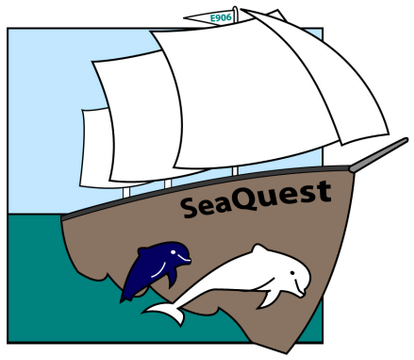
- TMD (Transverse-momentum dependent parton distribution function)
  - Longitudinal momentum x + transverse momentum $\vec{k}_\perp$ (3-dim)
  - Research on the effect of spin

TMDs

TMDs

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

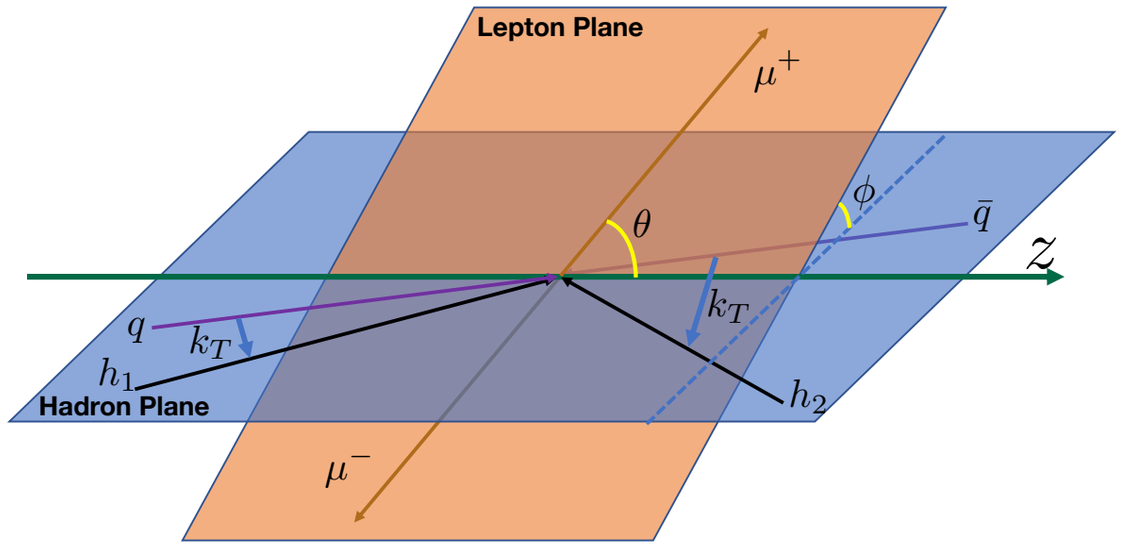
- **Boer–Mulders function**
  - Unpol. target and unpol. beam
  - Relation between quark transverse spin and transverse momentum
  - Research on Lam–Tung relation



2.Angular Distribution

Angular distribution of Drell–Yan

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



- Drell–Yan cross section

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

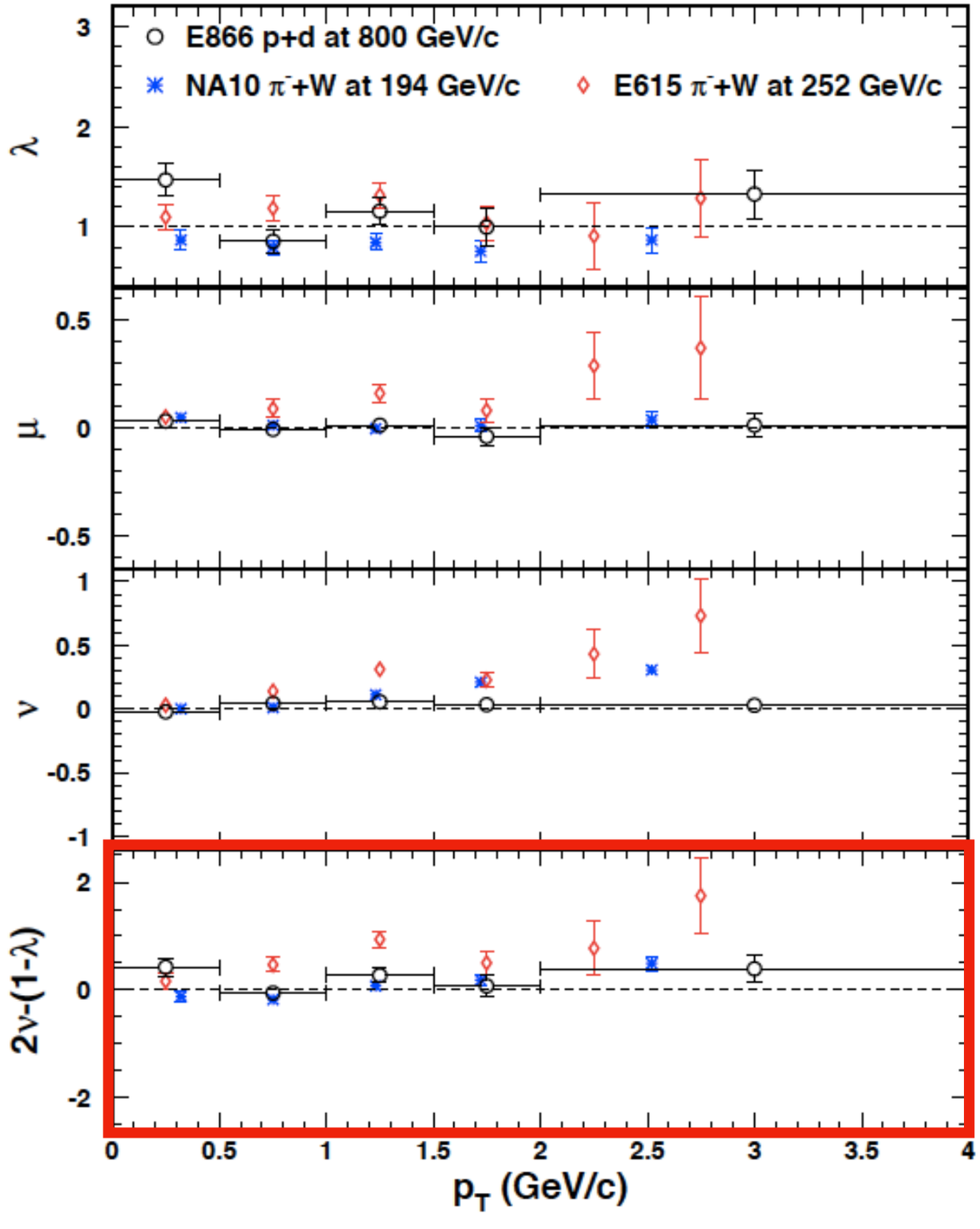
  - Naively, $\lambda = 1,\ \mu = \nu = 0$ ($d\sigma \propto 1 + \cos^2\theta$) at leading order
    - ★ No transverse momentum on quarks
    - ★ No gluon emission
  - NLO: $\lambda \neq 1,\ \mu,\ \nu \neq 0,$ but λ and ν still satisfy $1 - \lambda = 2\nu$ (**Lam–Tung relation**)

- 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

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

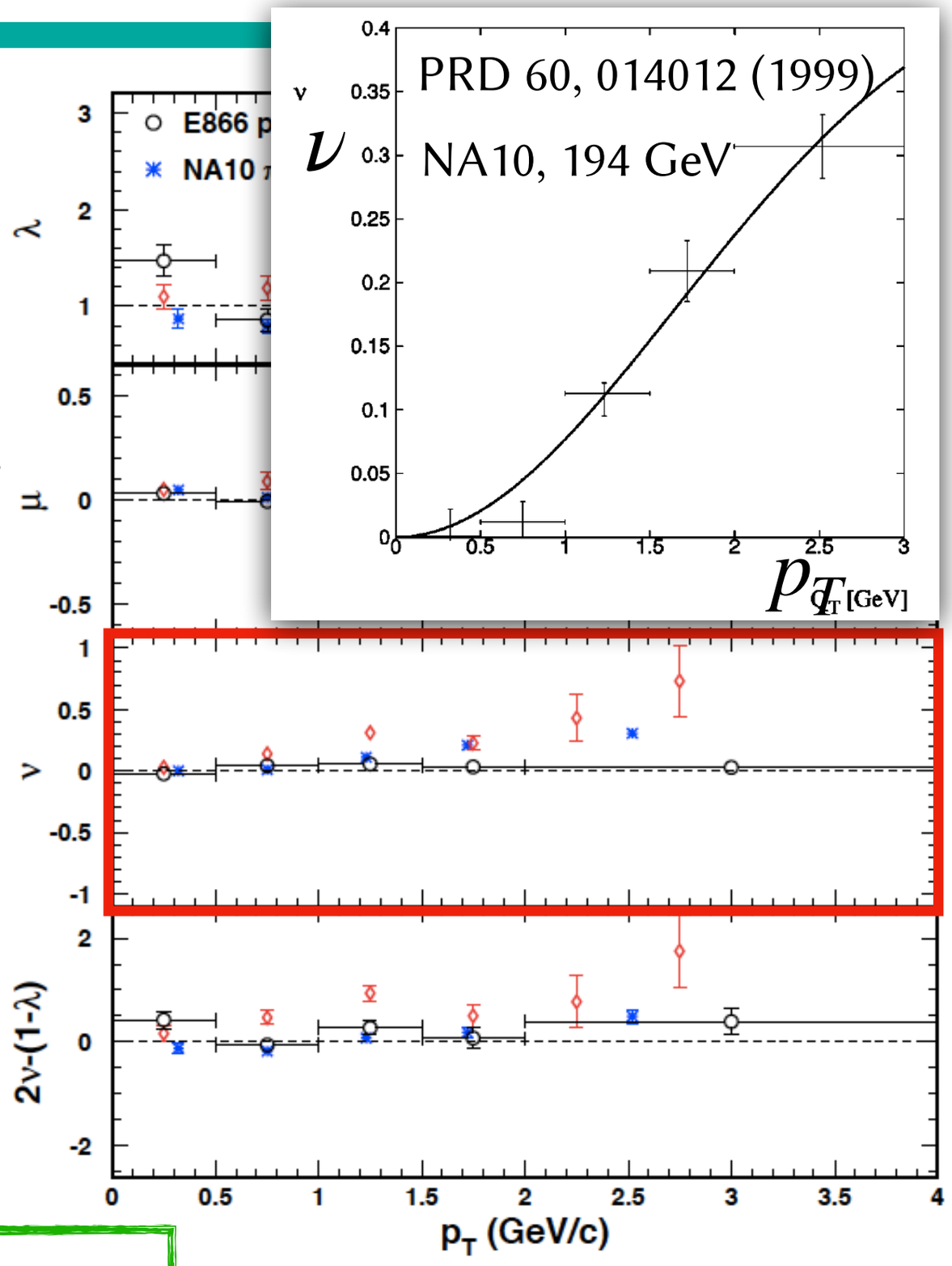


Phys. Rev. Lett. 99, 082301, (2007)

Boer–Mulders function

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

- B–M function of sea quarks doesn't have to be the same as that of valence quarks
  - 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



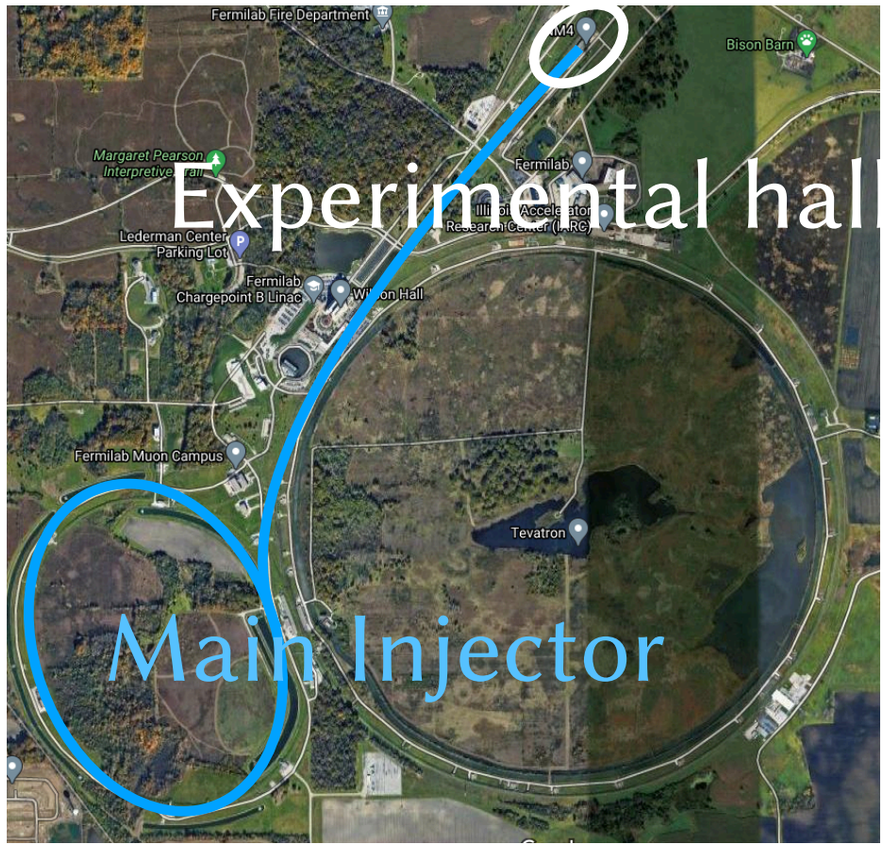
L–T violation and ν depend on beam type
$\longrightarrow$ B–M is one of the candidates of the cause

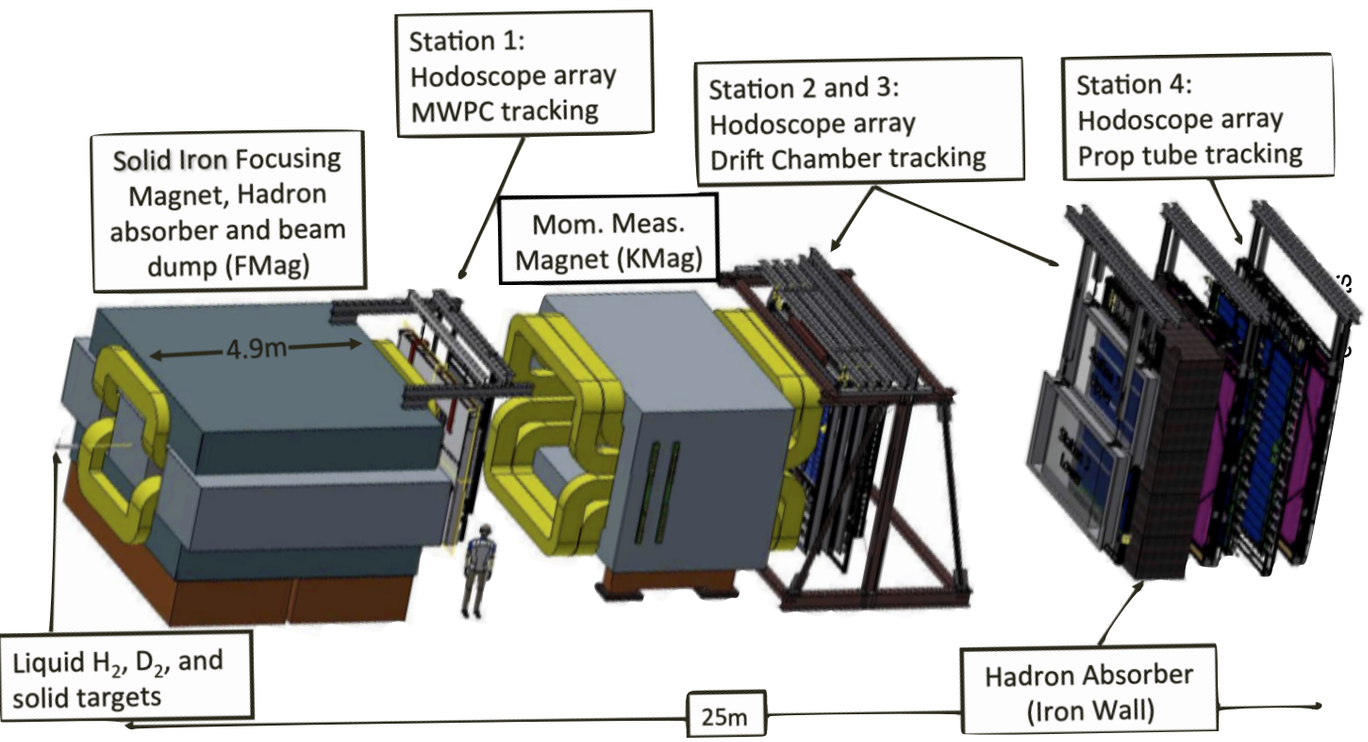
Phys. Rev. Lett. 99, 082301, (2007)

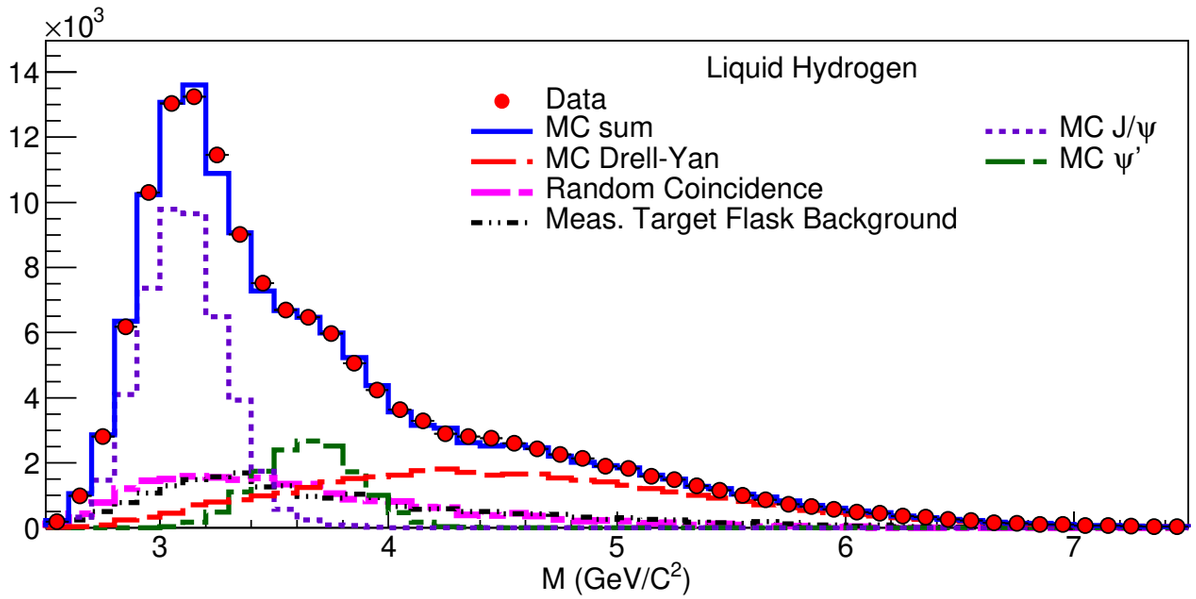
3.Measurement by SeaQuest

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

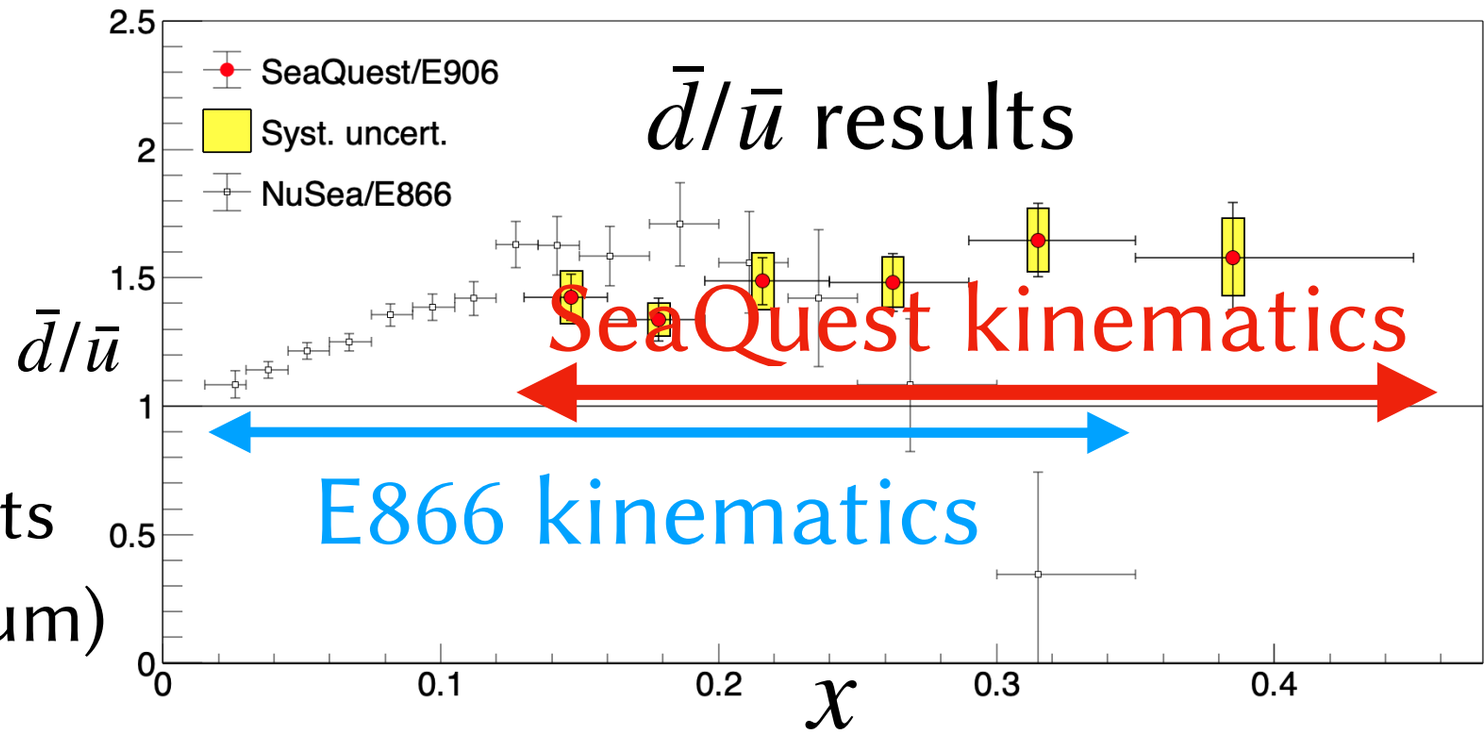
- Angular distribution results by fixed-target x proton beam are only by E866 at this present
  - SeaQuest will give another set of results

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

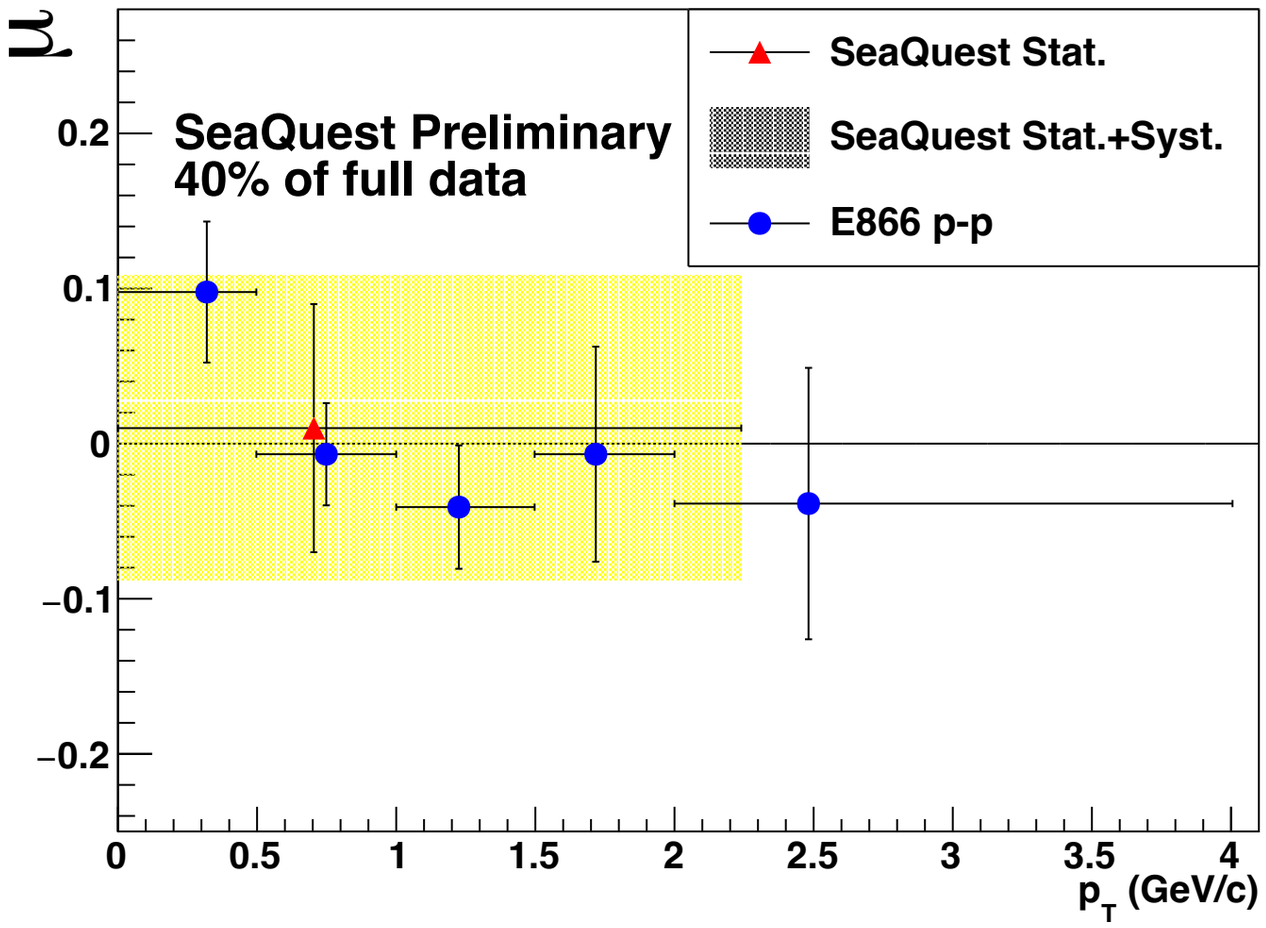
- Full ϕ range measurement
  - Suitable to extract μ and ν
  - λ is currently fixed to 1.0

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

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



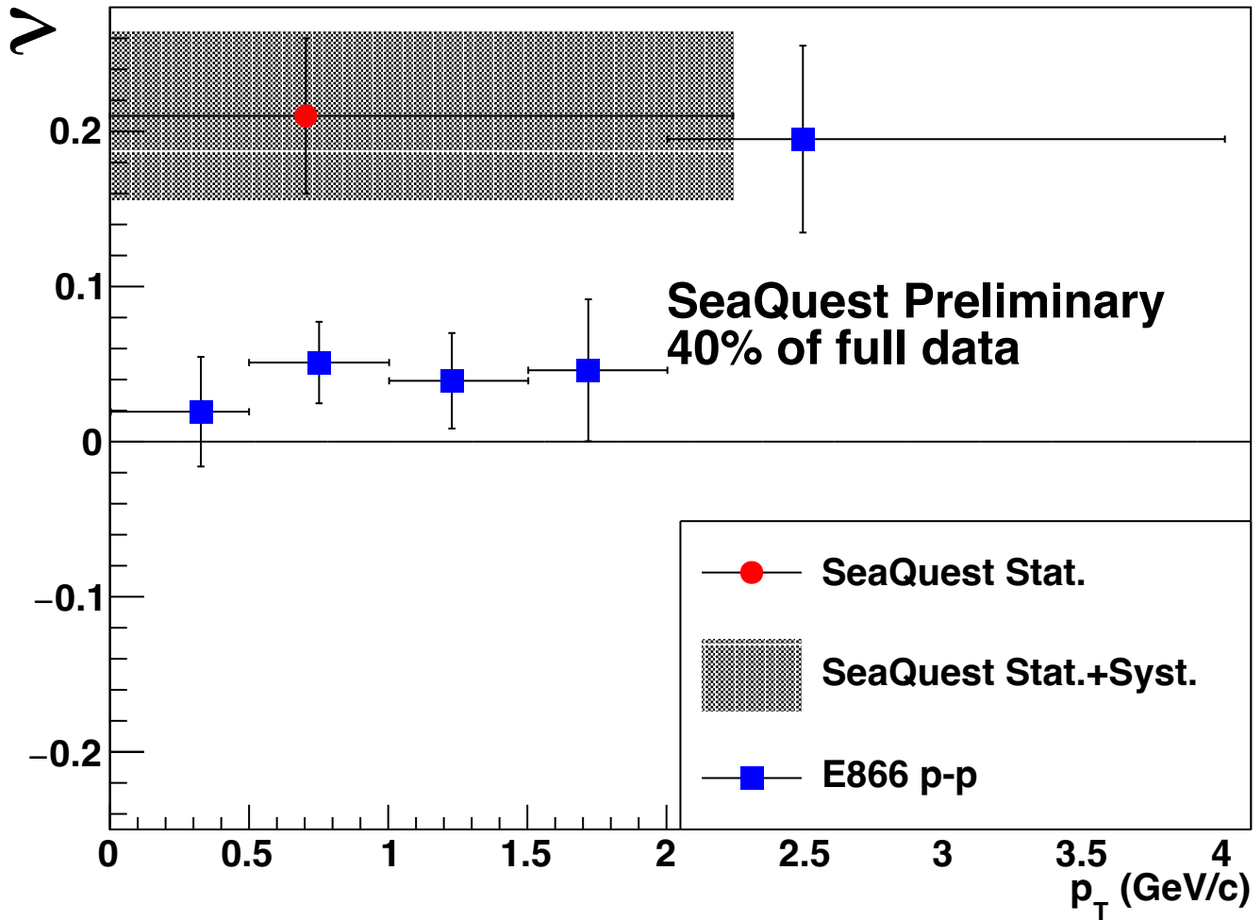
Preliminary Results



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.

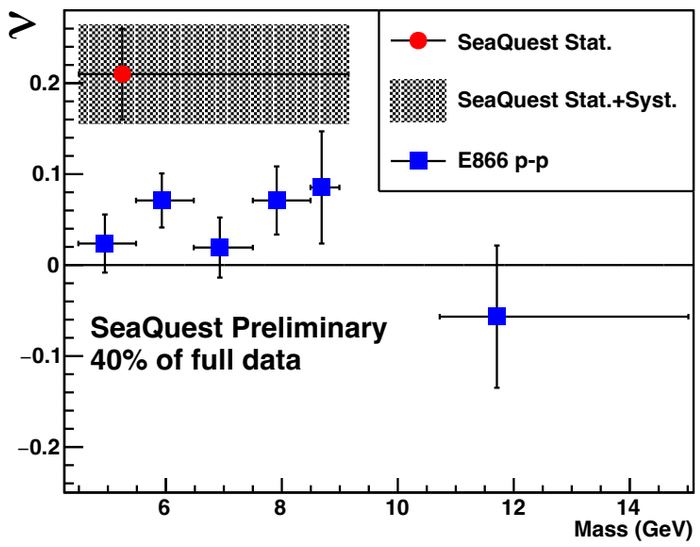
Preliminary Results

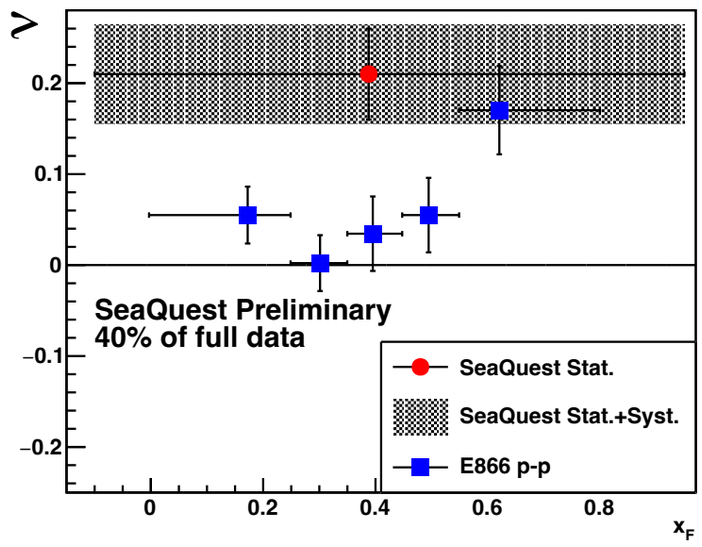


SeaQuest: 120 GeV proton beam
E866 : 800 GeV proton beam

- Non-zero ν is obtained.

Preliminary Results





SeaQuest: 120 GeV proton beam

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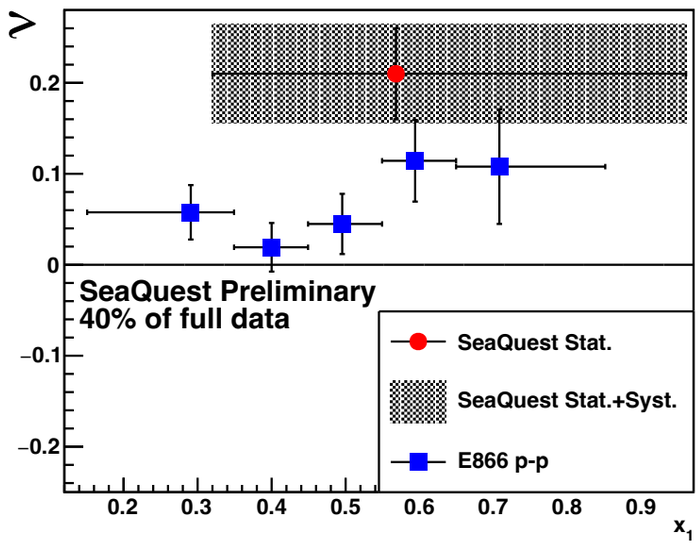
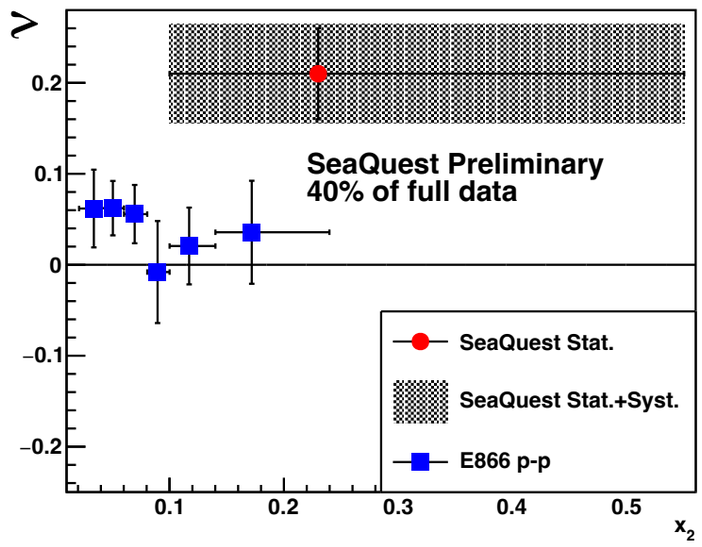
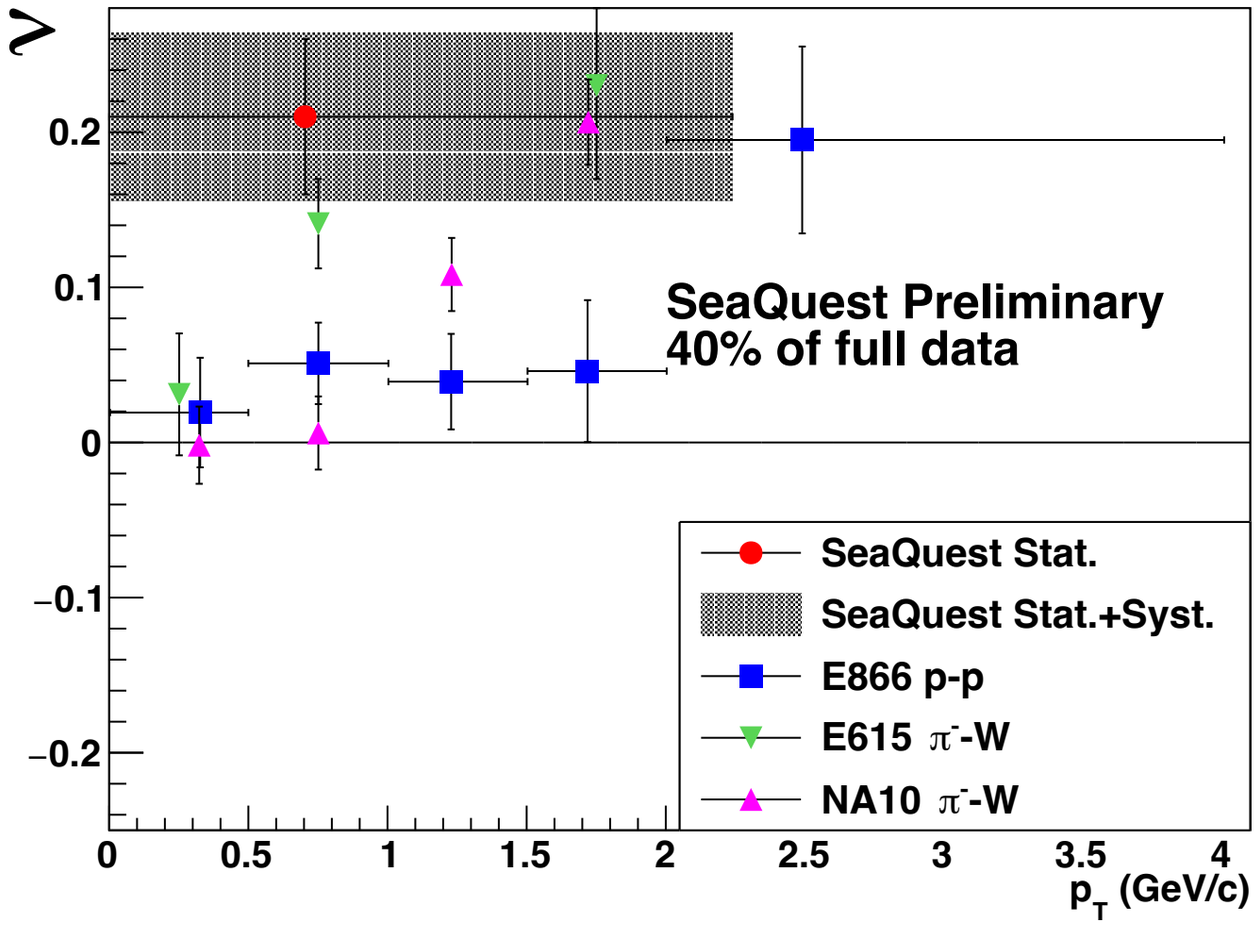




- SeaQuest provides the data at a large x_2 range

Preliminary Results



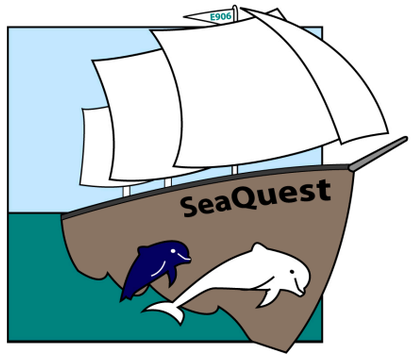
SeaQuest: 120 GeV proton beam
E866 : 800 GeV proton beam
E615 : 252 GeV π^- beam
NA10 : 194 GeV π^- beam

- The SeaQuest ν result is larger than E866 p-p results.

- Similar level as pion-induced Drell–Yan results.
  - Further analysis with full data will give accurate results.
  - p-d analysis will also be performed.

Summary & Outlook

- The sea-quarks and antiquarks structure of the proton is probed by Drell–Yan process accurately.
  - Access sea-quark Boer–Mulders function (represents the relation of transverse momentum and spin)
- Boer–Mulders function is one of the candidates causing Lam–Tung violation.
- Release SeaQuest preliminary results of μ and ν
  - μ is consistent with 0.0.
  - Large ν is obtained.
  - Results are obtained with 40% of full SeaQuest data. Statistics will be doubled in the final results.
  - Results on p-p Drell–Yan angular distribution are reported here. The results on p-d Drell–Yan angular distribution will be released soon.



Backup

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

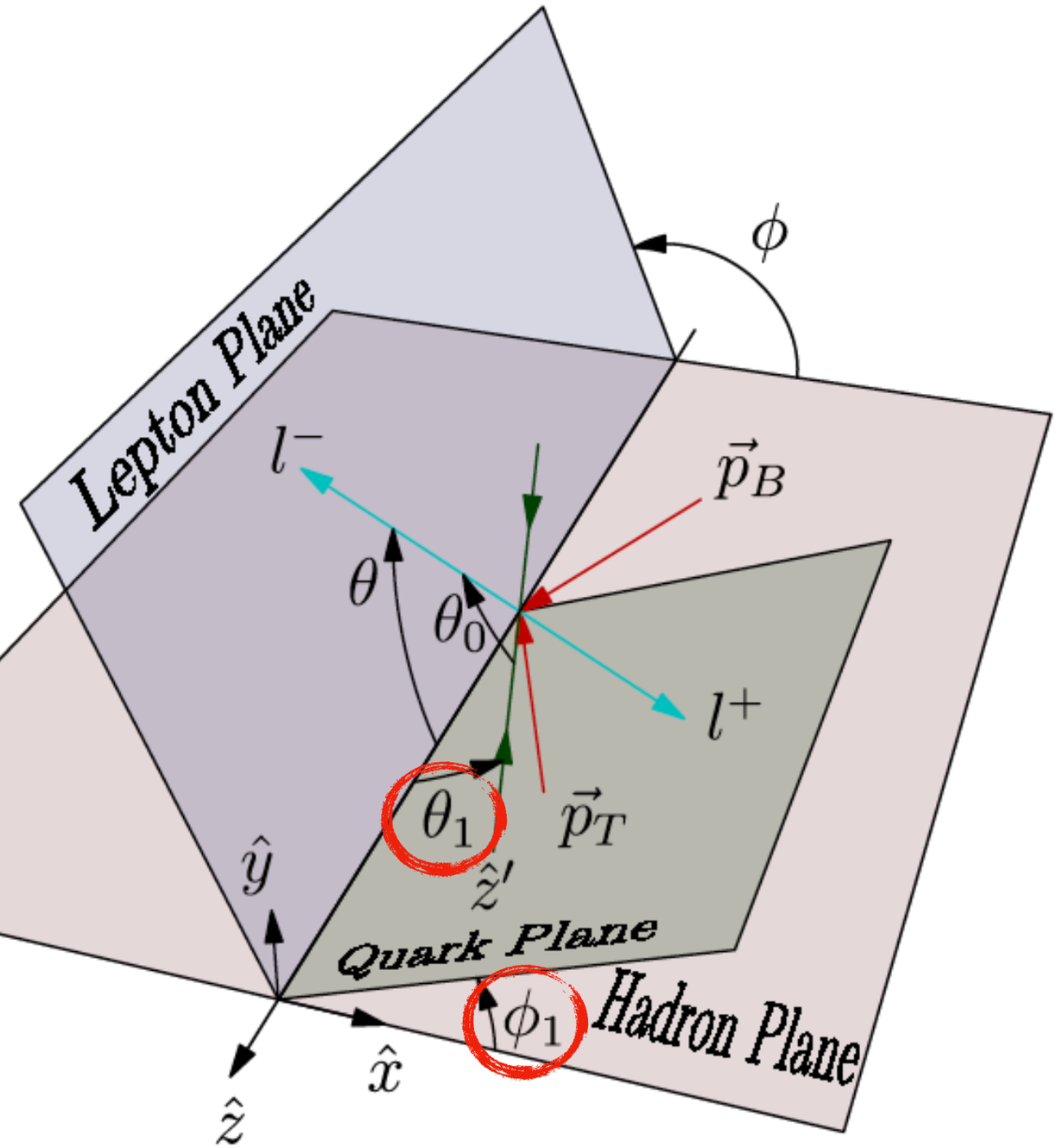
- Subtract background from p-p data

- 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

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)