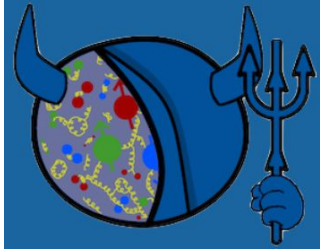
The 25th International Spin Symposium (Spin2023)



Angular distribution analysis in the Drell-Yan process with 120 GeV proton beam and LH_2 target at SeaQuest experiment

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For SeaQuest collaboration

SeaQuest E906

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Outline

- Physics motivation
- SeaQuest experiment
- Measurement of the angular distribution
- Preliminary results

Drell-Yan process and its angular distribution functions

- Drell-Yan process: $q + \bar{q} \rightarrow \gamma^* \rightarrow l + \bar{l}$
  - Anti-quark is always involved
    (If hadron is the proton, anti-quark is sea quark)
- Cross-section:

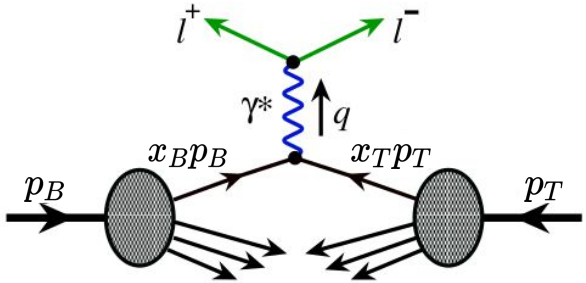
$$\left(\frac{d^2\sigma}{dx_B x_T}\right)_{D-Y} = \frac{4\pi\alpha^2}{9 s x_B x_T} \sum_n e_n^2 [q_n(x_B)\bar{q}_n(x_T) + \bar{q}_n(x_B) q_n(x_T)]$$

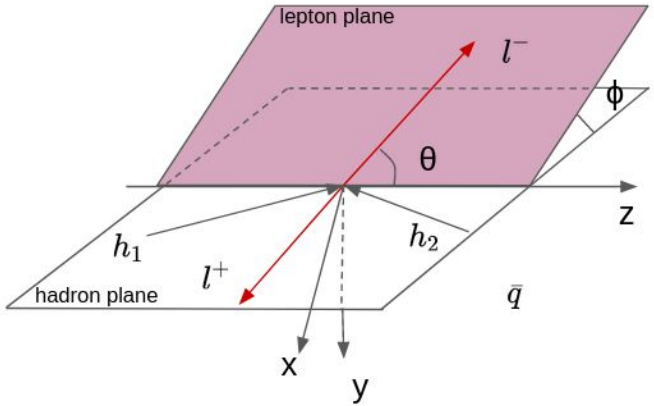
- Angular distribution in Drell-Yan process (general expression)

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

C. S. Lam and W. K. Tung, Phys. Rev. D 18, 2447 (1978).

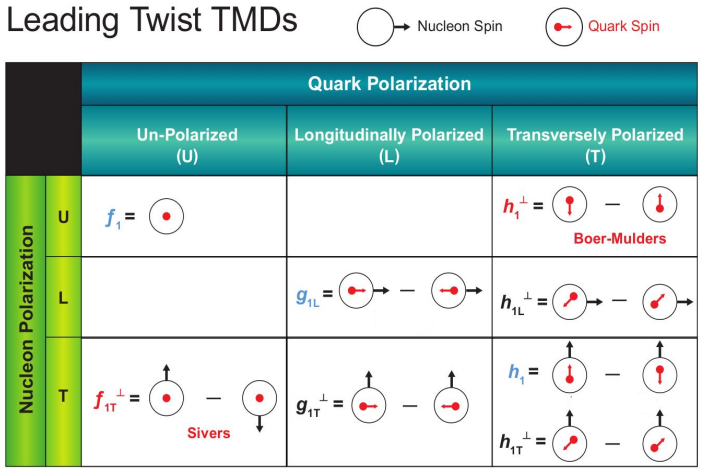
  - LO, $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto 1 + \cos^2\theta$, $\lambda = 1, \mu = \nu = 0.$
    - No quark transverse momenta
    - No gluon emissions
  - NLO,
    $\lambda \neq 1, \mu \neq \nu \neq 0,$
    $1 - \lambda = 2\nu$ (Lam-Tung relation)





Collins Soper frame (dilepton center of mass frame)
θ: polar angle of l^- ϕ: azimuthal angle of l^-

Transverse momentum dependent distribution functions



- Three dimensional momentum densities of the patronic structure: x (longitudinal) + $k_\perp$(transverse)
- Carry information on transverse parton momenta and spin-orbit correlations.
- Sivers function:
  - SpinQuest,
  - Sea quark contribution to the orbital angular momentum.
- Boer-Mulders function:
  - SeaQuest,
  - Contribution to the cos2ϕ dependence.

Boer-Mulders function $h_1^\perp(x, k_\perp)$

- Boer pointed out that the $\cos 2\phi$ dependence can be caused by the presence of the Boer-Mulders function.

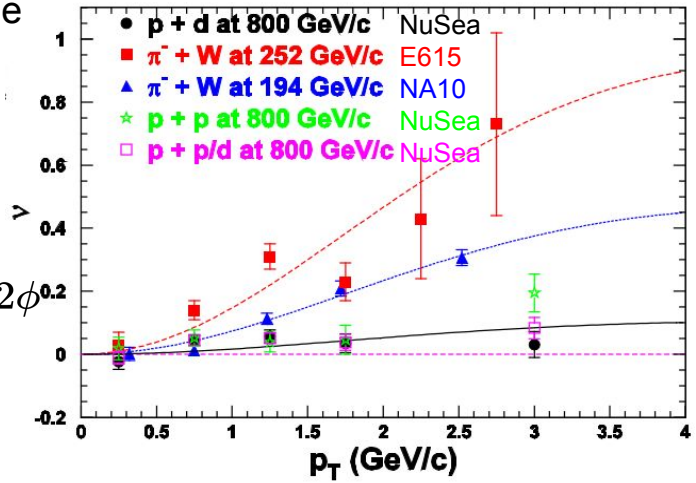
$$\nu \propto h_1^\perp(x_q, k_{\perp q}) h_1^\perp(x_{\bar{q}}, k_{\perp \bar{q}})$$

D. Boer, Phys. Rev. D 60, 014012 (1999).

- Research status:
  - Pion induced Drell-Yan in NA10 and E615, pronounced $\cos 2\phi$ dependence was observed.
  - Proton induced Drell-Yan in NuSea, significantly smaller (nonzero) $\cos 2\phi$ dependence were observed.

$$\nu\left(\pi^- W \to \mu^+\mu^-\right) \propto \left[valence\, h_1^\perp(\pi)\right]\left[valence\, h_1^\perp(p)\right]$$

$$\nu\left(pp(d) \to \mu^+\mu^-\right) \propto \left[valence\, h_1^\perp(p)\right]\left[sea\, h_1^\perp(p)\right]$$



Cited from Jen-Chieh Peng's slides reported at IWHSS 2016

  - The comparison among NuSea and NA10/E615 experiments indicate Boer-Mulders functions for sea quarks are significantly smaller than those for valence quarks.

Motivation for angular distribution measurement at SeaQuest

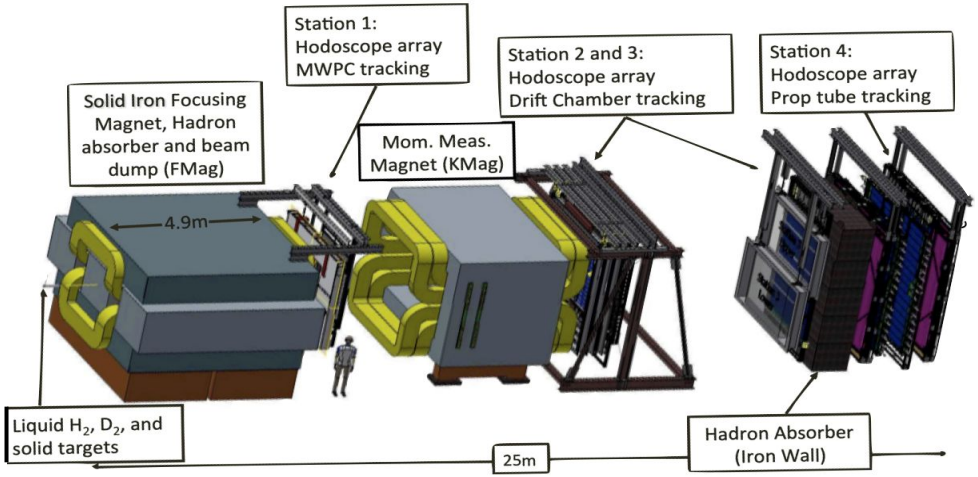
- Angular distribution results by proton induced Drell-Yan process are only by NuSea by far.
  - SeaQuest present another set of data.
  - Different kinematics: SeaQuest cover Boer-Mulders function at larger x region.
    NuSea: 0.015 < x <0.35, SeaQuest: 0.15 < x < 0.45. *J.Dove, etc. Nature 590, 561 (2021)*
- SeaQuest provides full a ϕ range measurement, suitable to extract μ and ν:

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

- SeaQuest provides a stringent verification of the sea quark Boer-Mulders function magnitude:

$$h_1^{\perp}(sea) < h_1^{\perp}(valence)\,?$$

SeaQuest experiment setup

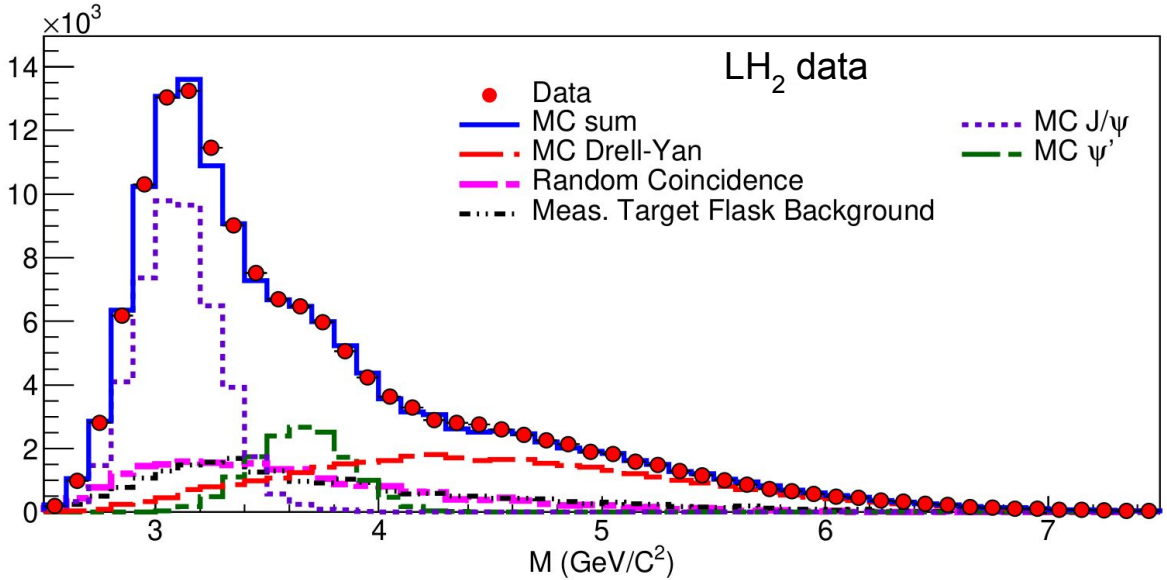


SeaQuest Spectrometer

- 120 GeV proton beam, $2x10^{12}$ protons per second.
- Fixed target: 7 kinds, LH_2 in use.
- Four tracking stations:
  - Hodoscopes — trigger
  - drift chambers — tracking
  - proportional tubes — muon identification.
- Data acquisition: year 2013 - 2017.
  - Data in year 2014 is in use, accounting for 40% of whole acquired data.

Drell-Yan produced dimuon selection

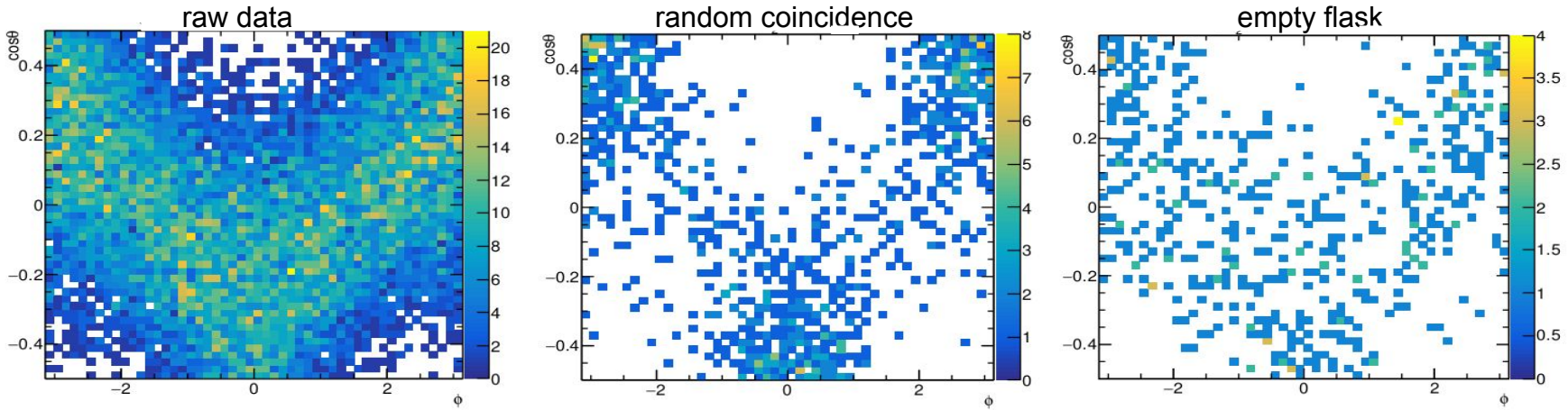
- After track reconstructions, selection criteria is applied to select dimuons:
  - track cuts
  - dimuon cuts
  - physics cuts
  - occupancy and intensity cuts
- Mass fitting method to subtract dimuons from non Drell-Yan process



  - Sources: J/ψ, ψ', Drell-Yan, random coincidence and empty flask.
  - 4.4 GeV/c^2 mass cut is applied to separate J/ψ and ψ' from Drell-Yan, leaving Drell-Yan data (87%), random coincidence data (8%) and empty flask data (5%) .

Background subtraction

- The angular distributions in $(\cos\theta, \phi)$ two dimensions:

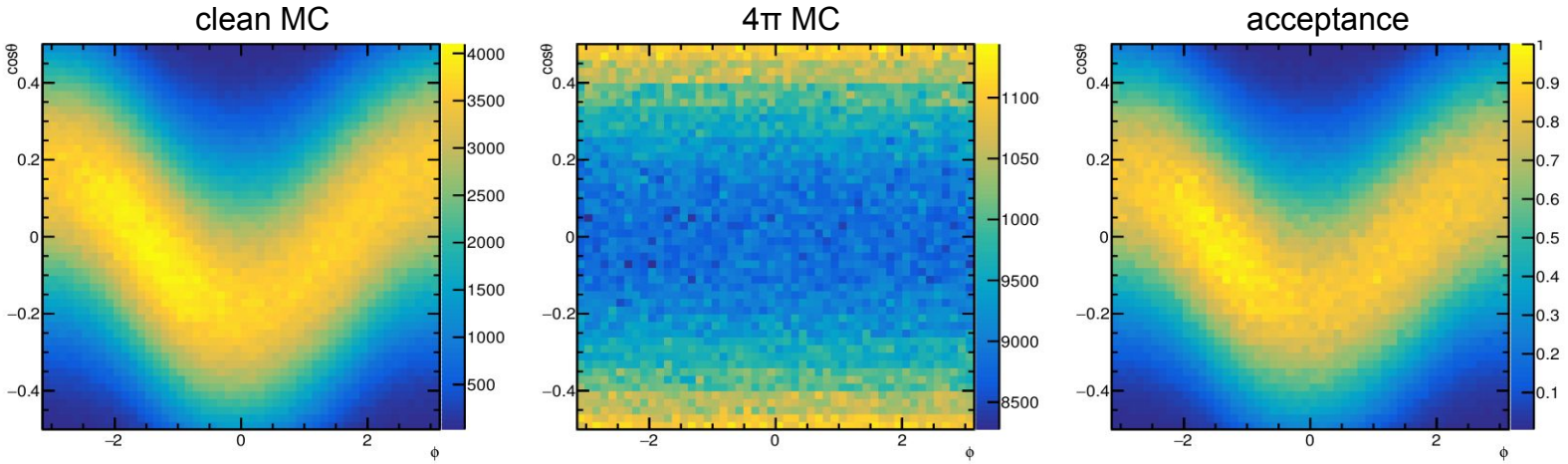


  - In the selected mass region, dimuons from Drell-Yan process are obtained via:

$$s_k = (n_k - r_f \cdot f_k - r_b \cdot b_k) \cdot \frac{1}{A(\cos\theta, \phi)} \cdot \frac{1}{E(\cos\theta, \phi, occ)}$$

    - Random coincidence and empty flask events are subtracted from raw data bin by bin.
    - Data are corrected by acceptance $A(\cos\theta, \phi)$ and rate dependent efficiency $E(\cos\theta, \phi, occ)$ to obtain physics distributions.

Acceptance correction



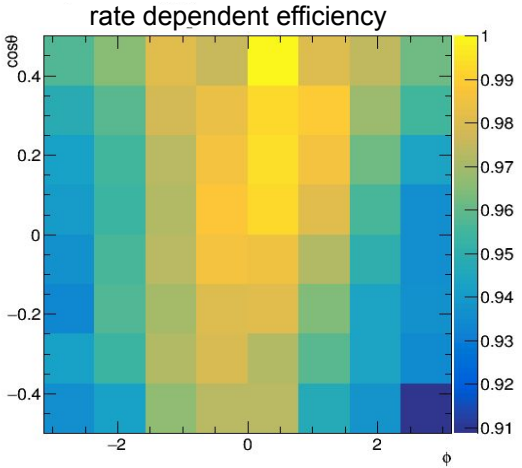
- Spectrometer acceptance:
  - spectrometer geometry acceptance
  - detector efficiency
  - detector resolution

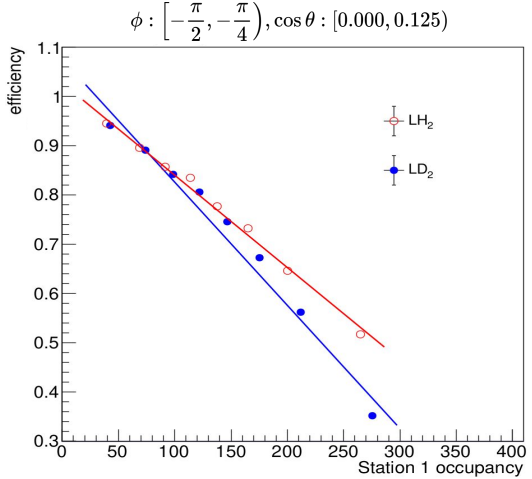
$$A(\cos\theta, \phi) = \frac{MC_{clean}}{MC_{4\pi}}$$

MC_{clean}: detector level MC

$MC_{4\pi}$: generator level MC

Rate dependent efficiency





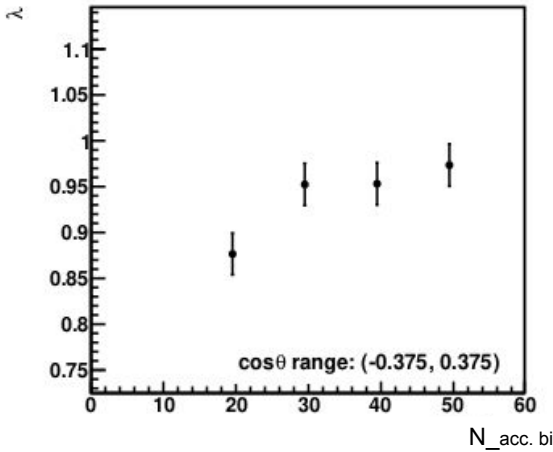
$$E(\cos\theta, \phi) = \frac{MC_{messy}}{MC_{clean}}$$

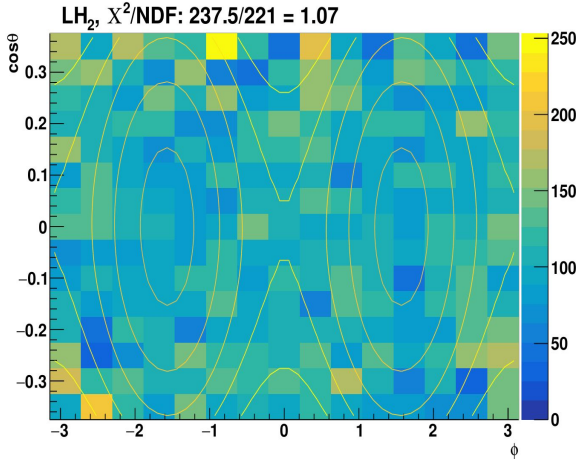
MC_{messy}: Detector level MC with random hits embedded

MC_{clean}: another set of detector level MC data

- Tracking efficiency $\propto$ beam intensity $\propto$ station 1 chamber occupancy.
- In each $(\cos\theta, \phi)$ bin, efficiency has a linear dependence on station 1 chamber occupancy.

Angular distribution fitting

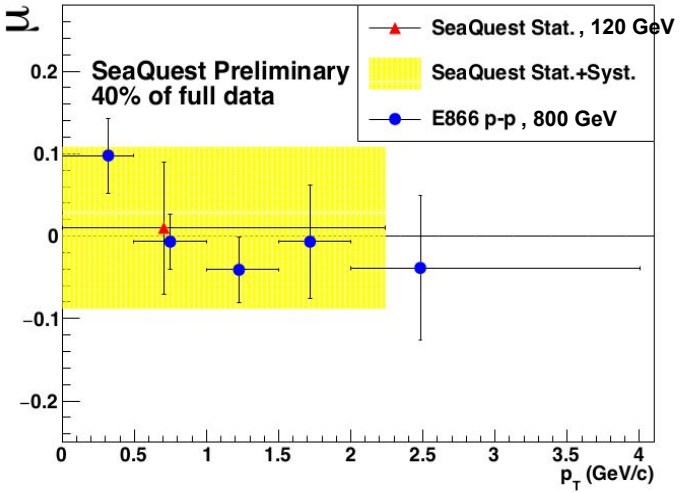




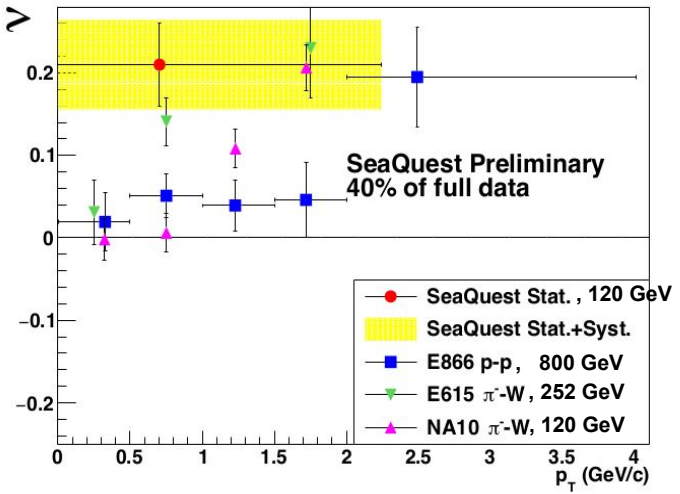
Parameters	fitting results LH_2
λ	1.00 ± 0.00
μ	0.007 ± 0.080
ν	0.208 ± 0.050

- Fitting function: $\frac{d\sigma}{d\Omega} = 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi$
- Fitting method:
  - maximum likelihood
  - unbinned fitting by RooFit package
- Fitting conditions:
  - -0.375 < $\cos\theta$ <0.375
  - 50 x 50 bins of $(\cos\theta, \phi)$
  - $\lambda = 1$ fixed, the different λ setting values are one of sources of systematic uncertainties.
- Fittings are iterated until resulting μ and ν are converged.

Preliminary results

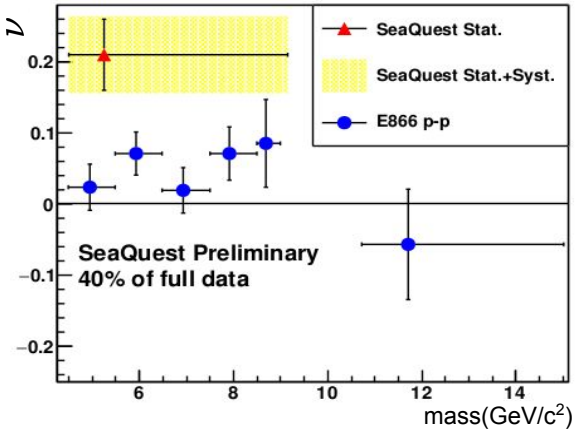


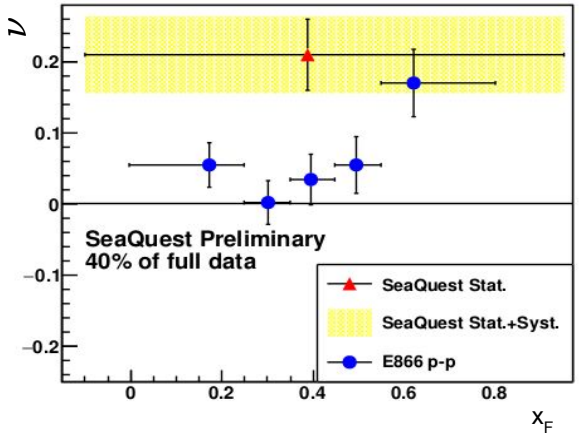
μ = 0.01±0.08(stat.)± 0.06(syst.)

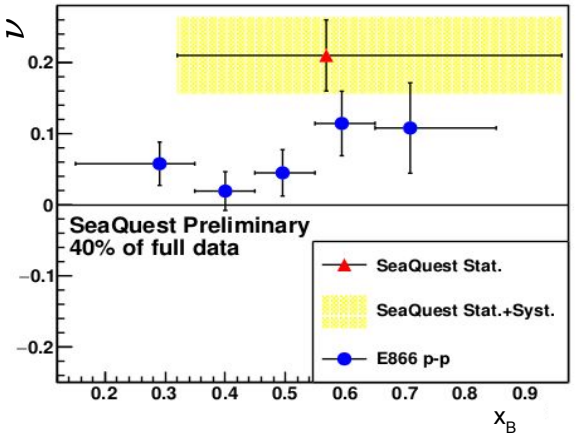


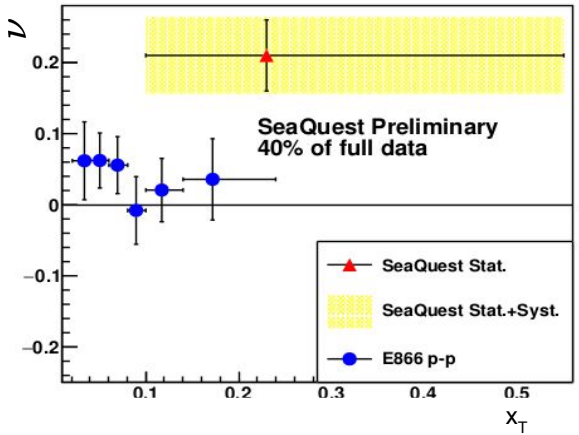
ν = 0.21±0.05(stat.)± 0.02(syst.)

- μ is consistent with zero within uncertainties, in agreement with E866/NuSea results.
- ν is obtained non-zero, larger than those from E866/NuSea, at similar level as the pion induced Drell-Yan results.
  - Other mechanism might be involved for the $\cos 2\phi$ dependence origin.







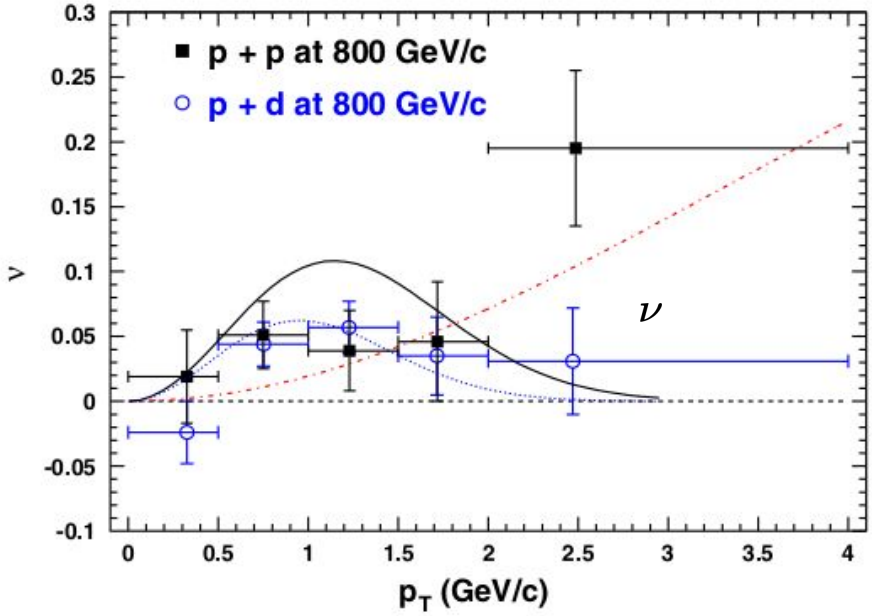


- SeaQuest: Provide data at larger x_T range.

Summary and outlook

- Angular distribution measurement in proton induced Drell-Yan process is a good tool to access sea quark Boer-Mulders Function.
- Release SeaQuest preliminary results for μ and ν:
  - μ is consistent with zero.
  - Large ν is obtained, indicating there might be other mechanism involved in the origin of the $\cos 2\phi$ dependence.
- Results are obtained with 40% of full SeaQuest data. Full statistics will be used in the final results.
- Study of the LD_2 data is ongoing. The results will be compared to the LH_2 data to investigate quark flavor dependence.

Backup



L. Y. Zhu et al., Phys. Rev. Lett. 102, 182001 (2009)

- The solid curve/dotted curve: the calculation using Boer-Mulders function parametrizations deduced from a fit to the p + d data.
- The dot-dashed curve is the contribution from the QCD process.
- At lower p_T: QCD contribution < Boer-Mulders functions contribution.
  At high p_T: QCD contribution > Boer-Mulders functions contribution.