Measurement of Boer-Mulders Function via Drell-Yan Process by SeaQuest Experiment at Fermilab

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Kenichi Nakano for E906/SeaQuest Collaboration

Tokyo Tech

Outline

- Motivation
  - Drell-Yan process as probe to nucleon structure
  - Sea-queark flavor asymmetry ($\bar{d}/\bar{u}$)
  - Boer-Mulders function ($h_1^\perp$)
  - And more...
- Experiment setup & timeline
  - First physics run (Run-2) has finished
- Status & prospect
  - Based on analyses of Run-2 data
- Summary

Drell-Yan Process @ Forward

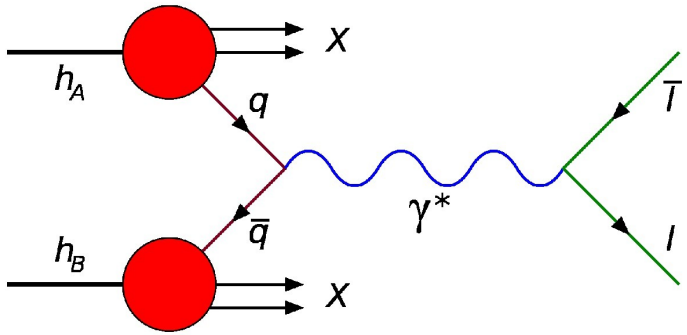
- Cross section @ LO

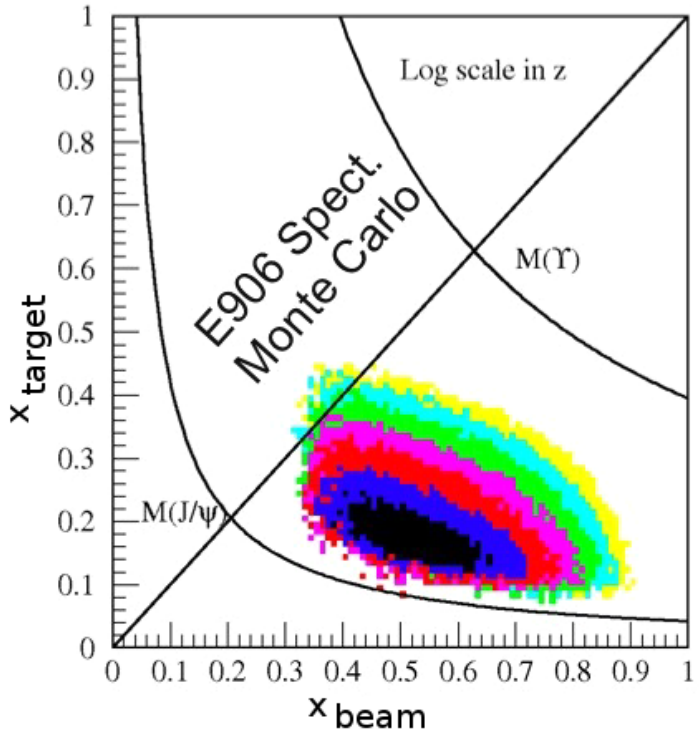
$$\frac{d^2\sigma}{dx_B dx_T} = \frac{4\pi\alpha^2}{9x_B x_T}\frac{1}{s}\sum_i {e_i}^2$$
$$\times \left\{ q_i^{\mathrm{B}}(x_B)\bar{q}_i^{\mathrm{T}}(x_T) + \bar{q}_i^{\mathrm{B}}(x_B) q_i^{\mathrm{T}}(x_T) \right\}$$

(B: beam, T: target)

  - Always involve anti quark ... cf. DIS
  - Quark @ beam & anti-quark @ target since $x_{\mathrm{B}} \gg x_{\mathrm{T}}$ & $q(x) \gg \bar{q}(x)$ at large x

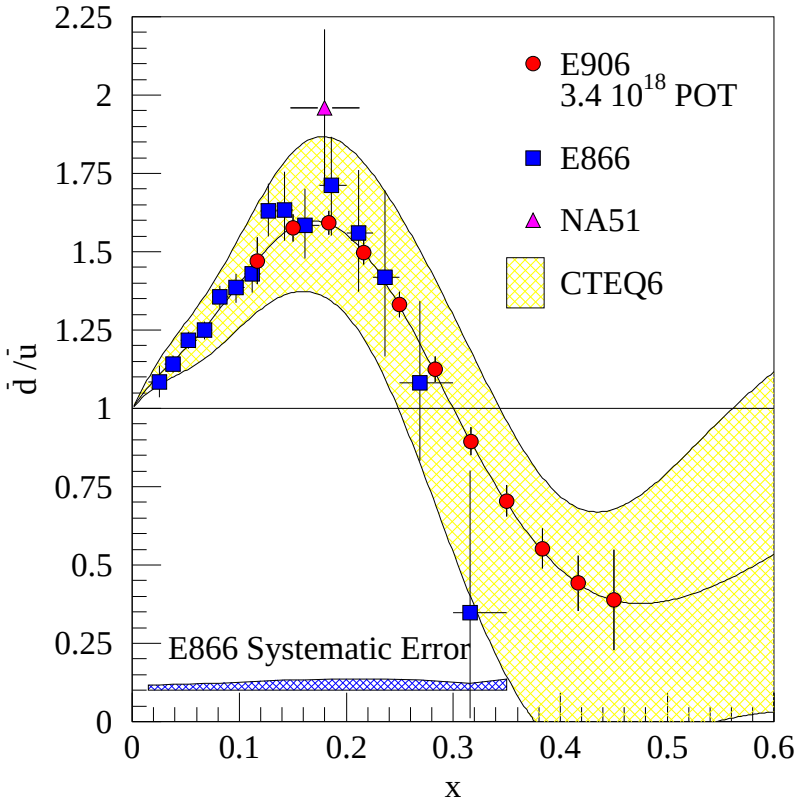
$$q + \bar{q} \to \gamma^* \to \mu^+ + \mu^-$$





Sea-Quark Flavor Asymmetry ($\bar{d}/\bar{u}$)

- Dependence on x first measured by FNAL E866/NuSea



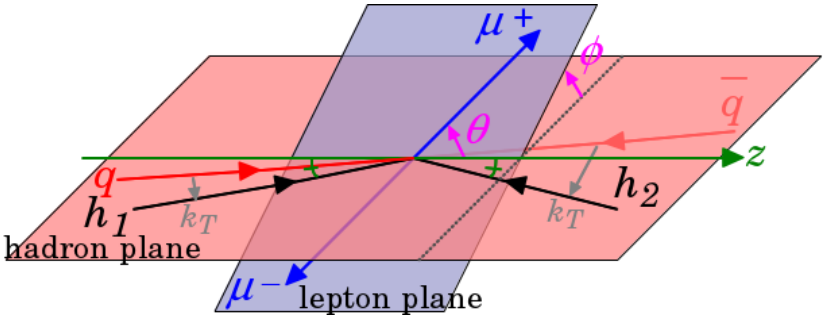
  - Examined with theory models (meson cloud model etc.)
  - Unique data on $\bar{u} \neq \bar{d}$

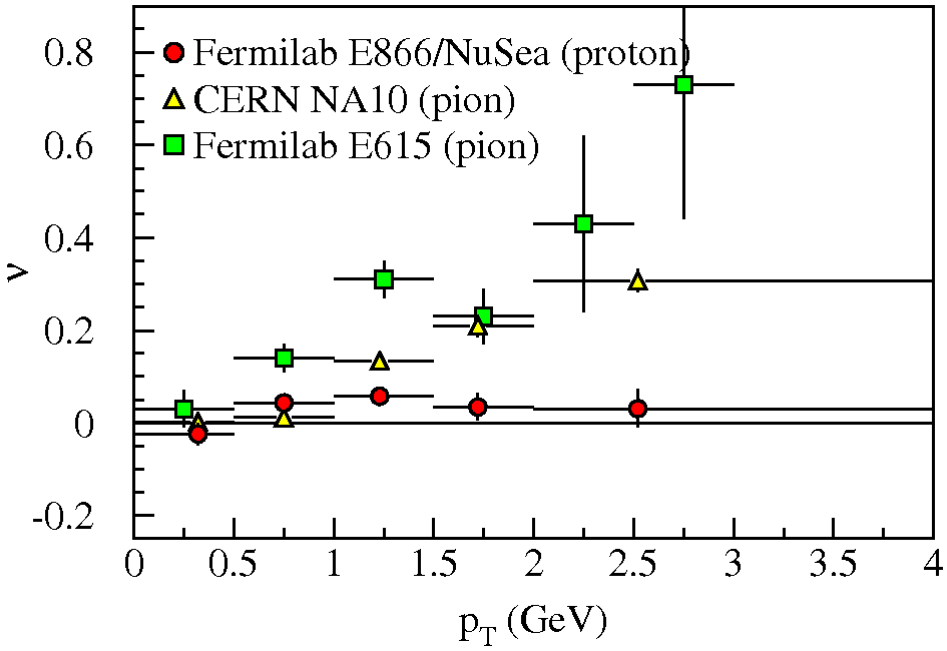
- SeaQuest will measure $\bar{d}/\bar{u}$ @ $0.2 \lesssim x_{Bj} \lesssim 0.4$ w/ $p+p$ & $p+d$
  - x_{Bj} dependence is the key to understand $\bar{d}/\bar{u}$ asym.
  - Particularly $\bar{d} \gtrless \bar{u}$ @ $x_{Bj} \sim 0.3$??

Boer-Mulders Function ($h_1^\perp(x, k_T)$)

- Via measurement of angular distribution with $p + p$ & $p + d$

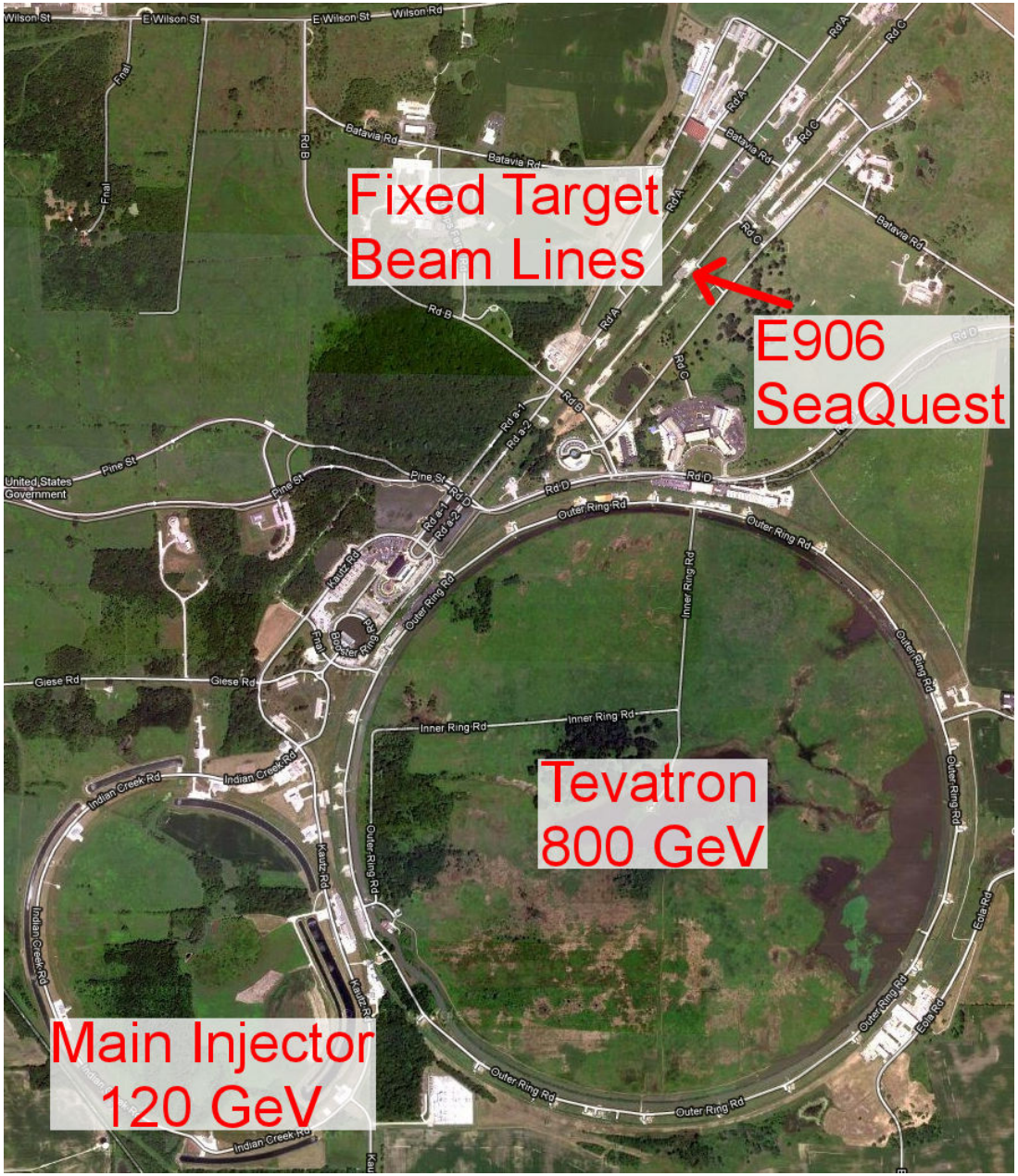
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$





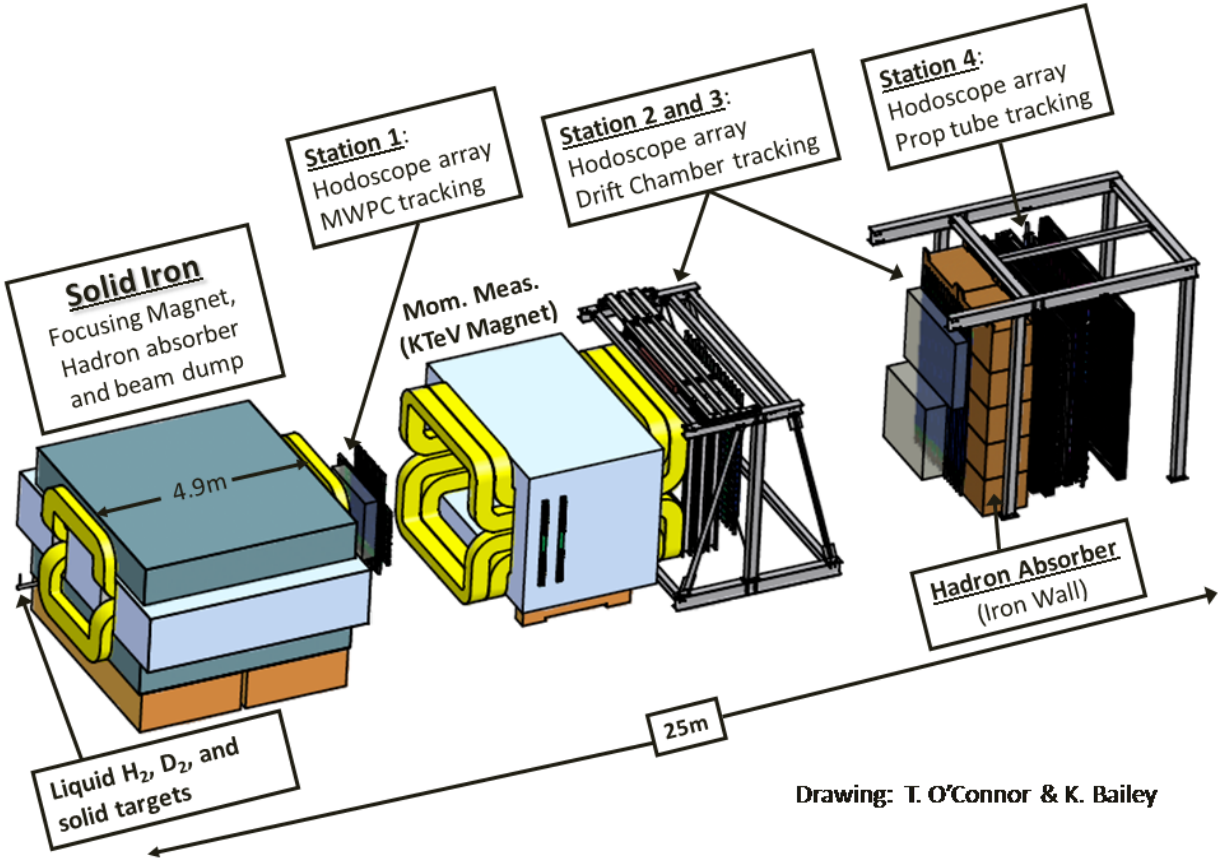
  - $\nu \equiv$ size of $\cos(2\phi)$ modulation
  - Break of Lam-Tung relation: $1 - \lambda \neq 2\nu$
- Convolution of two $h_1^\perp$
  - $\nu \propto \left[\, h_1^\perp \text{ of } \bar{q}\right] \times \left[\, h_1^\perp \text{ of } q\right]$
  - $h_1^\perp$ of q @ $x \sim 0.5$
  - $h_1^\perp$ of $\bar{q}$ @ $x \sim 0.3$
  - Extraction of $h_1^\perp$ from E866/NuSea data ... PRD 81, 034023 (2010), PRD 82, 114025 (2010)

Fermilab Proton Beam



- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 60 sec per cycle
  - 5 sec for E906 with slow extraction
  - The rest for neutrino exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec in spot size

E906/SeaQuest Spectrometer



- Targets ... LH_2, LD_2, C, Fe, W (& empty flask, none) in rotation
- Di-muon trigger with hodoscopes @ St. 1...4
- Tracking with drift chambers @ St. 1...4
- Detect $\mu^{+/-}$ with $p \sim 40$ GeV/c

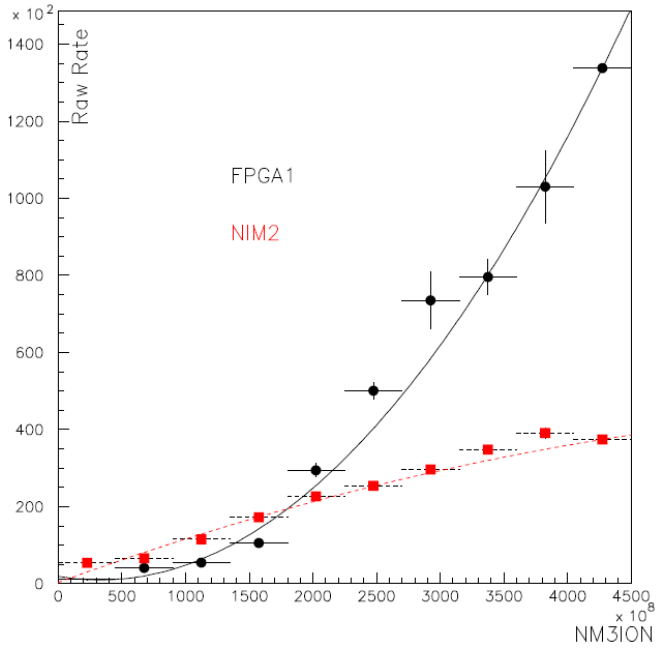
SeaQuest Schedule

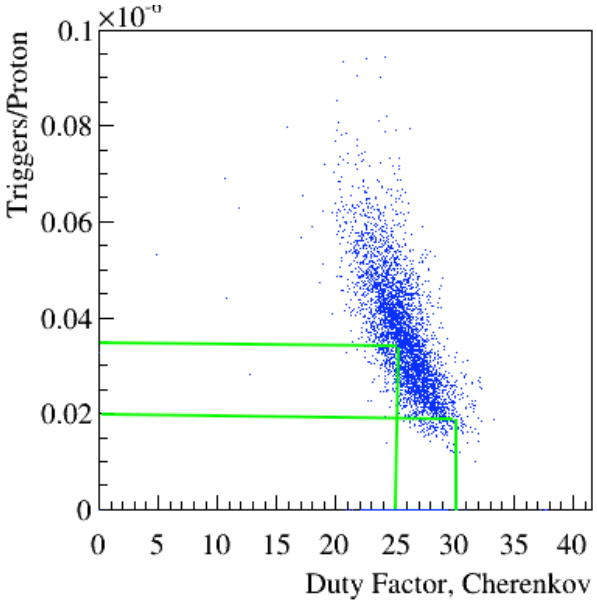
Year	Month	Event
2009	04	Start of building spectrometer
2011	08	Complete spectrometer
2012	03-04	Commissioning run (Run 1)
		(1st beam on March 08)
2012	05...	Detector & DAQ upgrade
2013	11	Start of Physics run (Run 2)
		(1st beam on November 08)
2014	09-10	Accelerator maintenance $\leftarrow$ Now
2014	11	Re-start of Physics run (Run 3)
2016	X	End

- Two years for 10^{19} protons delivered
  (10^{13} protons/spill $\times$ 1 spill/min $\times$ 2 years)

Trigger Rate (R) & Beam Intensity (I)

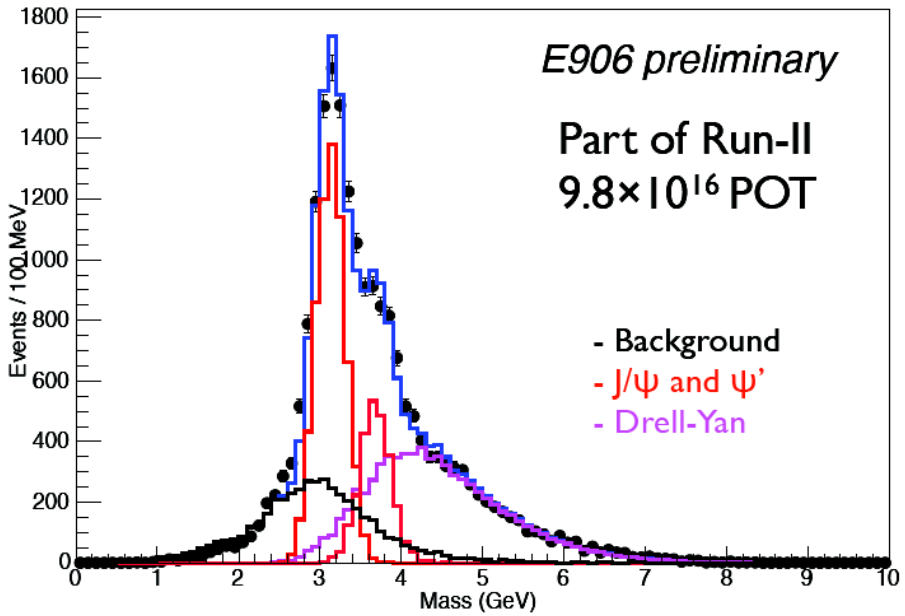
- Primary issue at Run-2 start
- R was much higher (>10 kHz) than DAQ bandwidth (5 kHz)
  - Observed $R \propto I^2$
  - Due to fake high-p tracks
- Solution
  - Measured & improved beam duty factor ($\langle I \rangle^2 / \langle I^2 \rangle$)
  - Found & removed "hot" trigger patterns in real data & simulation
- 4×10^{12} delivered protons/spill at Run-2 end (to be 1×10^{13} in Run 3)





Status of Run-2 Data Analysis

- Di-muon mass distribution (preliminary)

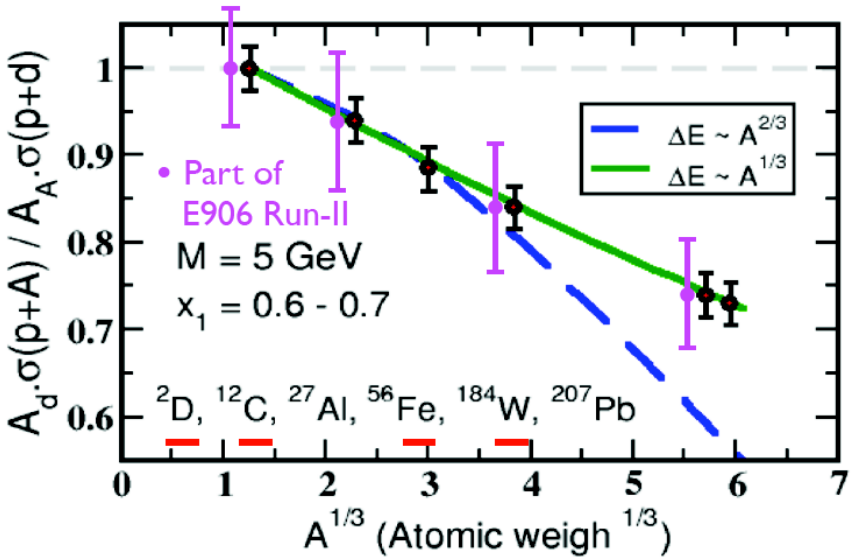


  - With ∼1/3 of Run-2 data
  - Events on all targets (LH_2, LD_2, C, Fe & W) are summed up here
  - Detectors work nicely as expected
  - Good J/ψ mass resolution (∼180 MeV)
    - Drell-Yan dominates @ $M \gtrsim 4$ GeV
    - Can separate J/ψ & ψ'
  - Resonable MC/data agreement on mass dependence of acceptance

Measurement Precision at Present

- With part of Run-2 data = ~5% of expected luminosity
- Flavor asymmetry ($\bar{d}/\bar{u}$) → & nuclear dependence ↓
- The anticipated precision is achievable!

(error size only)



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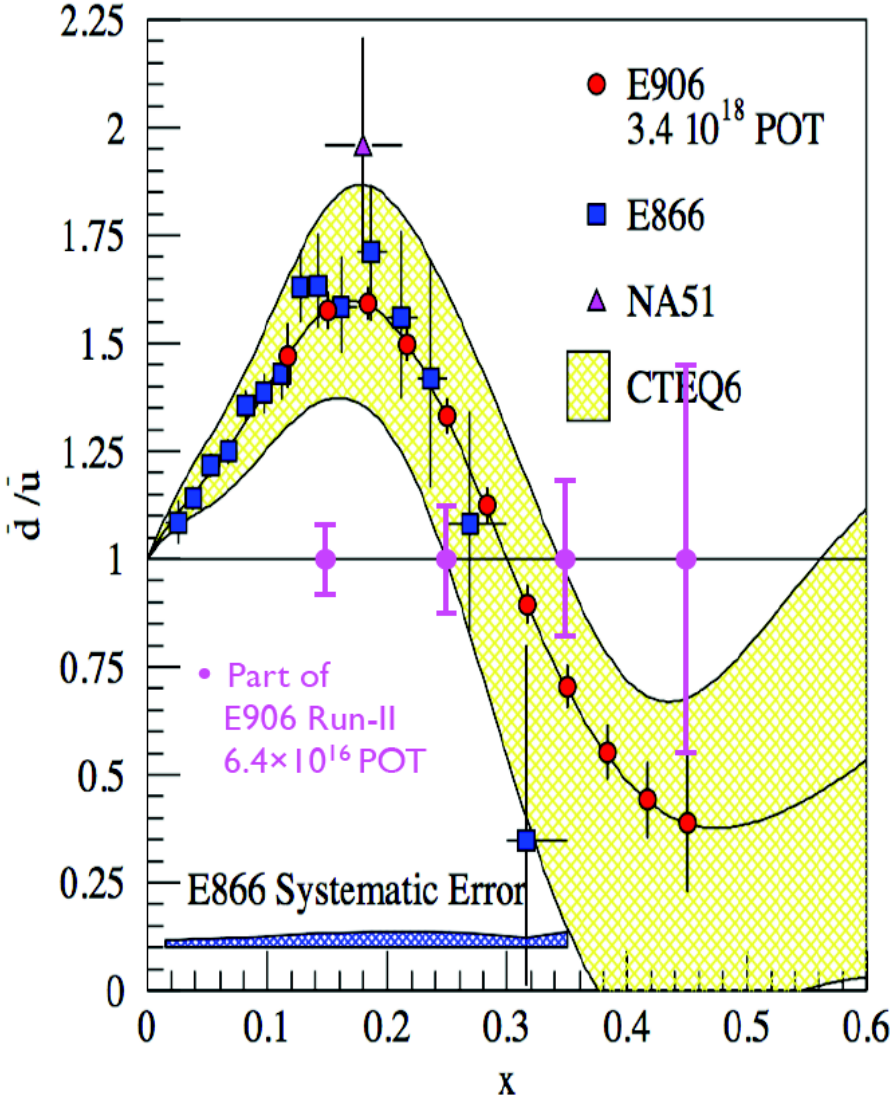
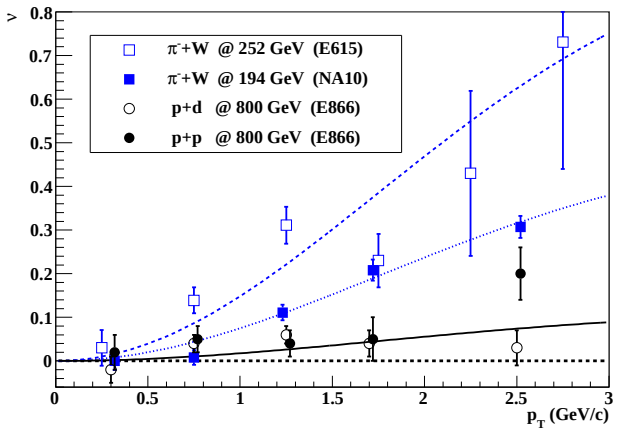
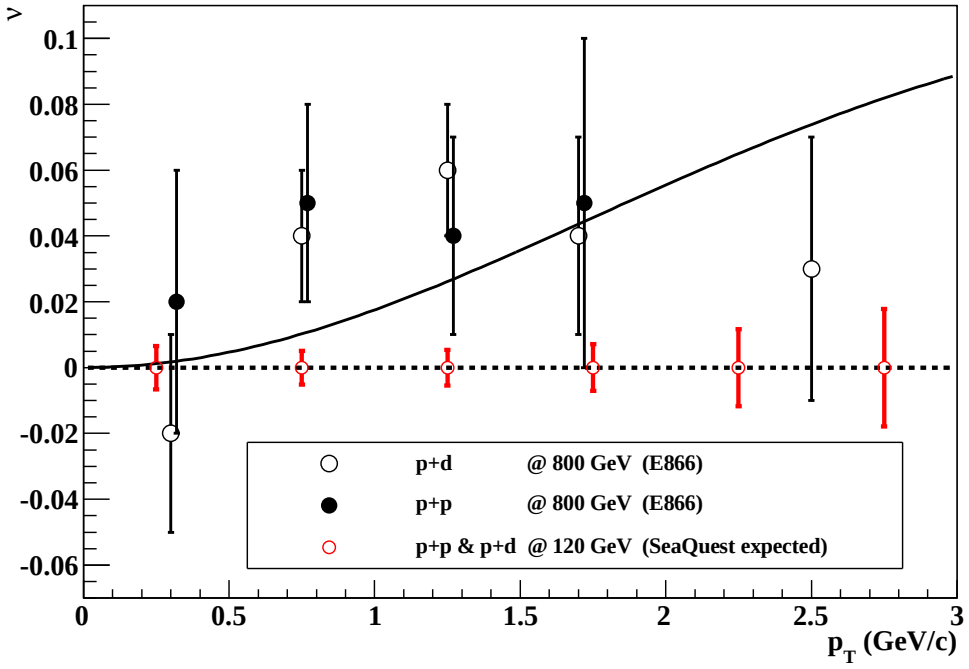


Expected Precision on Angular Distribution

- Data analysis is ongoing
- Estimate with MC
  - Assuming the full luminosity (3.4×10^{18} recorded protons)
  - $\nu \equiv$ size of $\cos(2\phi)$ modulation $\propto \left[\, h_1^\perp \text{ of } \bar{q}\right] \times \left[\, h_1^\perp \text{ of } q\right]$





  - Probably $h_1^\perp$ of $\bar{q}$ is smaller than q,
    but E906/SeaQuest will measure it with enough accuracy

Summary

- Purpose of E906/SeaQuest @ Fermilab
  - Investigate the nucleon structure with the Drell-Yan process
  - Measure the sea-quark flavor asymmetry, $\bar{d}/\bar{u}$
  - Measure the Boer-Mulders function, $h_1^{\perp}(x, k_T)$
  - Measure the nuclear dependence, $\sigma_{p+A}/\sigma_{p+d}$
    - Not only physics but also to limit the nuclear correction on $\bar{d}/\bar{u}$.
- First physics run (Run-2) has finished
  - Data analyses are on-going
  - Preliminary result has confirmed that
    the data are being accumulated as anticipated
- Second physics run (Run-3) will start in November 2014
- (W. Lorenzon is talking in Session 12 about future polarized Drell-Yan experiments at Fermilab, i.e. E-1027 & E-1039)