Drell-Yan Angular Distributions at Fermilab E906/SeaQuest

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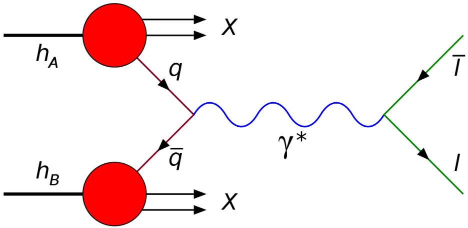
February 15, 2018

The Drell-Yan Process

Drell-Yan angular distributions have information about parton dynamics:



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

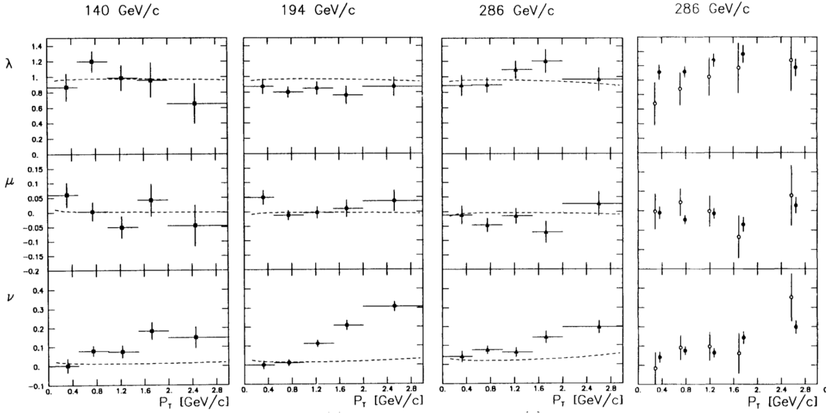
Where λ, μ, and ν are proportional to polarized hadronic tensor elements

If quarks and leptons are fermions:

$$1-\lambda = 2\nu \text{ with } \lambda = 1 \qquad \& \qquad \nu = 0$$

Previous Drell-Yan Measurements

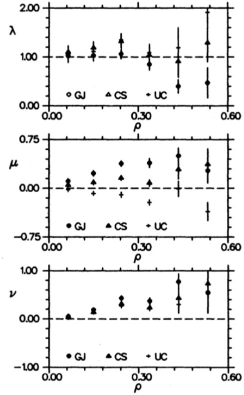
CERN-NA10, π^{-}+W,D @ 140, 194, and 286 GeV

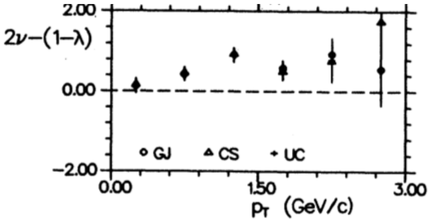


ν-modulation major driver of violation!

Previous Drell-Yan Measurements

Fermilab E615, $\pi^{\pm}$+W @ 80, 252 GeV

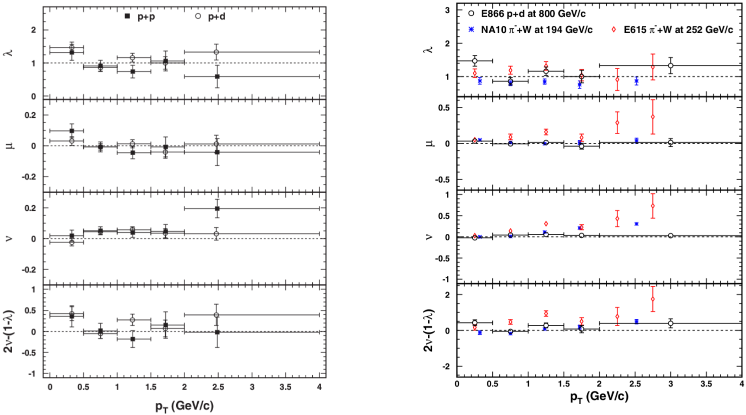




ν-modulation major driver of violation!

Previous Drell-Yan Measurements

Fermilab E866, p+H,D @ 800 GeV



Suppressed ν-modulation driver of violation!

TMD Distributions: Origin of Violation?

Transverse-Momentum-Dependent Distributions (TMDs) responsible for violation? If $Q_T \ll Q$:

$$\Phi^{[\gamma^+]} = f_1 - \frac{\epsilon_T^{ij} k_\perp^i S_\perp^j}{M} f_{1T}^\perp$$

$$\Phi^{[\gamma^+\gamma_5]} = S_z g_1 + \frac{k_\perp \cdot S_\perp}{M} g_{1T}$$

$$\Phi^{[i\sigma^{i+}\gamma_5]} = S_\perp^j h_1 + S_z \frac{k_\perp^j}{M} h_{1L}^\perp + \frac{\epsilon_T^{ji} k_\perp^i}{M} h_1^\perp + S_\perp^i \frac{2k_\perp^i k_\perp^j - k^2 \delta^{ij}}{2M^2} h_{1T}^\perp$$

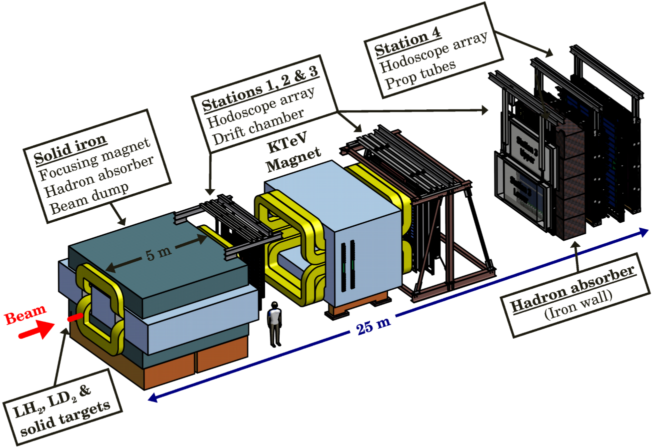
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Unpolarized Drell-Yan cross section contains Boer-Mulders:

$$\sigma_{UU} \propto f_1 f_1 + \cos(2\phi) h_1^\perp h_1^\perp$$

How to Observe Drell-Yan?

The E906/SeaQuest spectrometer was designed to observe the Light Quark Flavor Asymmetry:



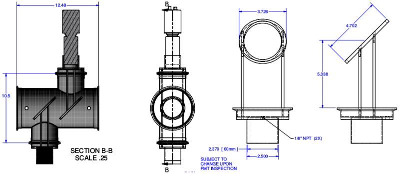
Charmonia are major sources of background!

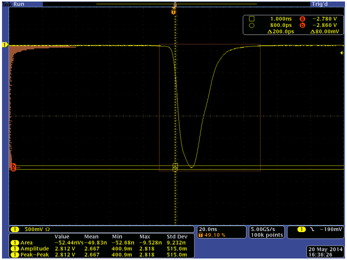
E906/SeaQuest Service and Support

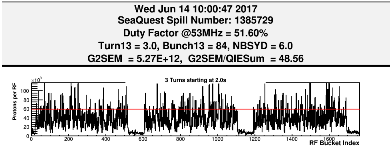
Hardware Contribution: E906/SeaQuest Beam Intensity Monitor

Commissioning Tasks:

- Installed and tested iterative versions of chamber
- PMT voltage sag measurements
- Charge Integrating and Encoding (QIE) Sum-Checks



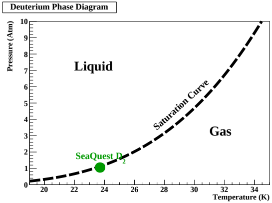




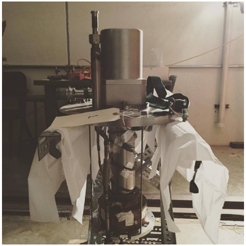
Led to pulse-by-pulse resolution (∼19ns) of proton intensity!

E906/SeaQuest Service and Support

Hardware Contribution: E906/SeaQuest Nuclear Target

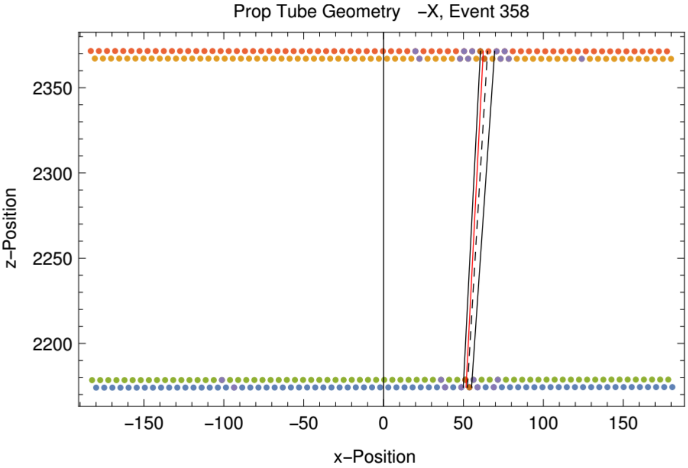


- Inherited Operational Lead in 2015
- Coordinated Various Maintenance Schedule Tasks



E906/SeaQuest Service and Support

Software Contribution: Muon ID Tracker Module (SQERP)



Thesis: How to Extract Angular Modulations

This equation defines calculation of estimated DY yields from measured yields as a function of intensity, $\mathcal{I}(t)$ and dimuon observable, X:

$$N_{Est.}^{q\bar{q}\to l\bar{l}}(X) = \int_T \int_{10^3}^{10^5} \left[\frac{N_{Meas.}(\mathcal{I}(t), X)}{\Gamma(X)\cdot\epsilon(\mathcal{I}(t), X)}\right] d\mathcal{I}(t)dt$$

$$\approx \sum_T \sum_{10^3}^{10^5} \left[\frac{N_{Meas.}(\mathcal{I}(t), X)}{\Gamma(X)\cdot\epsilon(\mathcal{I}(t), X)}\right] \Delta\mathcal{I}(t)\Delta t$$

- $\Gamma(X)$ are Acceptance Corrections
- $\epsilon(\mathcal{I}(t), X)$ are Efficiency Corrections
- $N_{Meas.}(\mathcal{I}(t), X)$ is the Measured Sample

Acceptance Corrections

$$\Gamma(X) = \frac{\sigma_{MC}^{Geom.}(X)}{\sigma_{MC}^{q\bar{q}\to l\bar{l}}(X)} \cdot \frac{\sigma_{MC}^{Trig.}(X)}{\sigma_{MC}^{Geom.}(X)} \cdot \frac{\sigma_{MC}^{Recon.}(X)}{\sigma_{MC}^{Trig.}(X)} = \frac{\sigma_{MC}^{Recon.}(X)}{\sigma_{MC}^{q\bar{q}\to l\bar{l}}(X)}$$

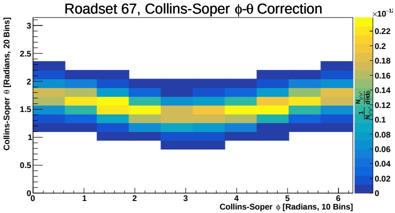
Equation was evaluated with guidance from collected data.

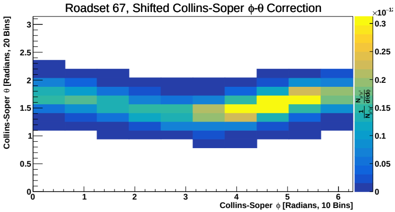
Important Highlights:

- *Ab initio* calculations of spectrometer geometric acceptance showed great agreement with simulated and collected data
- A beam-spectrometer offset was identified in the y-direction and corrected using minimum bias data
- Spectrometer acceptance and angular mixing motivated fiducial cuts in θ at $|\cos\theta| < 0.462$
- Dimuon trigger rejection factor $\sim 5.0 \times 10^{-7}$
- Res. : $\Delta\theta = 0.023$ radians, $\Delta\phi = .146$ radians, $\Delta p_T = .402$ GeV/c

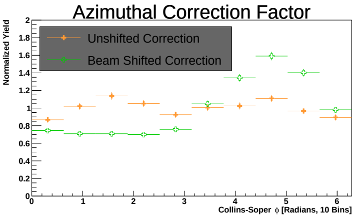
Acceptance Correction Factors

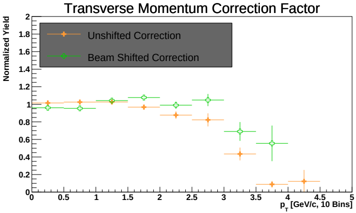
2D Angular Corrections:





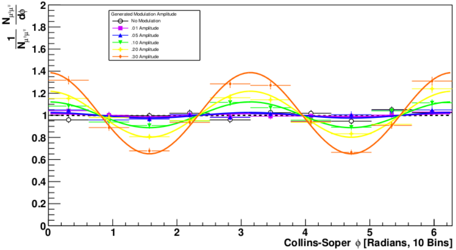
1D Angular Corrections:





Extractions from MC

Azimuthal Moment:



$[\kappa] + [\nu\kappa]\cos(2\phi)$ Extractions				
Generated ν	$\chi^2/n.d.f$	ν	$[\kappa]$	$[\nu\kappa]$
None	$12.025/8 \approx 1.503$	0.002 ± 0.014	0.998 ± 0.0094	0.002 ± 0.014
.01	$3.634/8 \approx 0.454$	0.015 ± 0.013	1.000 ± 0.0089	0.015 ± 0.013
.05	$12.755/8 \approx 1.594$	0.025 ± 0.014	1.000 ± 0.0090	0.025 ± 0.014
.10	$9.623/8 \approx 1.203$	0.116 ± 0.014	1.000 ± 0.0092	0.117 ± 0.014
.20	$7.814/8 \approx 0.977$	0.206 ± 0.015	1.010 ± 0.0097	0.208 ± 0.015
.30	$3.404/8 \approx 0.425$	0.361 ± 0.015	1.020 ± 0.0103	0.368 ± 0.015

Azimuthal moment extractions are within 2σ up to a thrown $\nu = .30$

Event Reconstruction Efficiency

Intensity dependence can be corrected in dimuon pair reconstruction.

$$\epsilon(\mathcal{I}(t), X) = \epsilon_{Data}^{Trig}(\mathcal{I}(t), X) \times \epsilon_{Embed.}^{Recon.}(\mathcal{I}(t), X)$$

Trigger Efficiency:

$$\epsilon_{Data}^{Trig}(\mathcal{I}(t), X)$$

Intensity dependent "Pseudo-Efficiency" evaluated using single muon (FPGA4) and minimum bias (NIM3) triggered data.

Track Reconstruction Efficiency:

$$\epsilon_{Embed}^{Recon.}(\mathcal{I}(t), X)$$

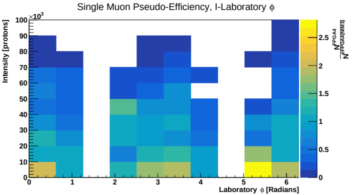
Intensity dependent reconstruction efficiency evaluated using simulation with embedded minimum bias (NIM3) triggered data

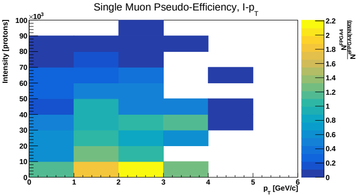
Trigger (Pseudo) Efficiency

Explicit Goal of Pseudo-Efficiency:

$$\frac{N(Muon(FPGA4), Y)}{N(eMuon(NIM3), Y)} \stackrel{?}{=} 1$$

where *eMuon* means emulated muon trigger applied to minimum bias (NIM3) data.





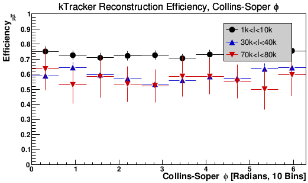
Singles trigger dependent on intensity and observable for angular variables and transverse momentum $\implies$ Dimuon trigger is as well.

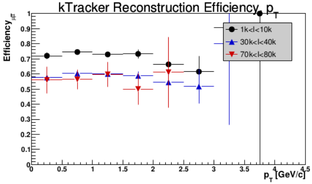
Track Reconstruction Efficiency

Dimuon reconstruction efficiency was evaluated by comparing simulation event reconstruction efficiency with and without embedded minimum bias data:

Event reconstruction as a function of intensity and dimuon observable X:

$$\frac{N(MC^{DY} + Min.Bias, \mathcal{I}, X)}{N(MC^{DY}, X)} < 1$$

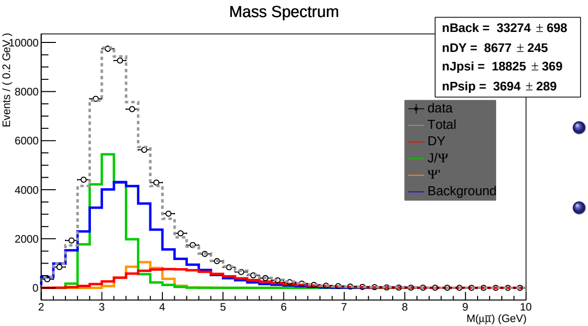




Event reconstruction efficiency due to tracker is manageable.

Sample Curation

Analyzed Deuterium data from Roadset 67 $< 50\%$ of available data.

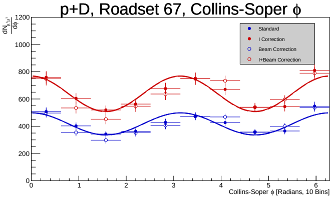


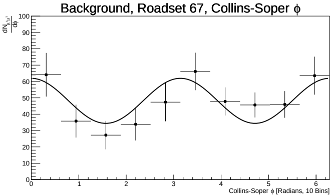
- Background modeled with *Empty* and *No Target* Data
- reduced $\chi^2 \approx 6.1$
- Yields 4,100 Drell-Yan ($M_{\mu\bar{\mu}} > 4.2$ GeV) events after standard cuts

Calculated background percentage is 39.3% with $M_{\mu\bar{\mu}} > 4.2$ GeV

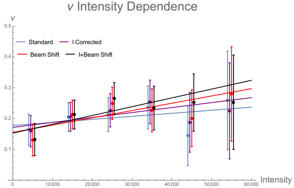
Azimuthal Extractions

Azimuthal Moment Extractions





Intensity Dependence



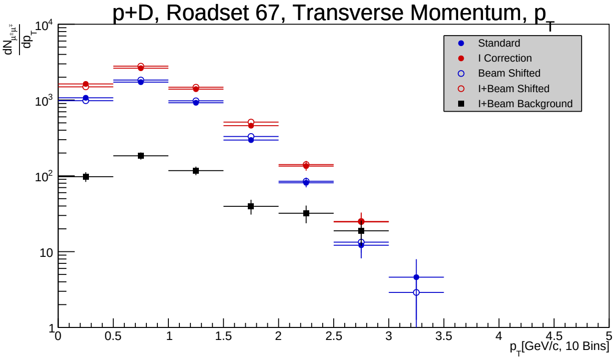
Extraction Values

$[\kappa] + [\nu\kappa] \cos 2\phi$ Extractions				
Sample Class	$\chi^2/n.d.f$	ν	$[\kappa]$	$[\nu\kappa]$
Standard	$14.355/8 \approx 1.794$	0.194 ± 0.030	417.0 ± 8.24	80.8 ± 12.4
I	$11.494/8 \approx 1.437$	0.203 ± 0.030	639.0 ± 12.7	130.0 ± 19.0
Beam	$29.649/8 \approx 3.706$	0.195 ± 0.029	417.0 ± 8.08	81.5 ± 12.0
I+Beam	$27.889/8 \approx 3.486$	0.204 ± 0.029	637.0 ± 12.4	130.0 ± 18.4
Background	$6.4192/8 \approx 0.802$	0.286 ± 0.103	38.5 ± 2.57	11.0 ± 3.89

Yields: $\nu^{Sa.} = 0.204 \pm 0.029$ & $\nu^{Bg.} = 0.286 \pm 0.103$

Transverse Momentum

Transverse Momentum calculated using same method, but no fit function to verify.



Average transverse momentum of the dataset is 0.87 ± 0.50 GeV/c.

Result Calculation

Background substraction method done mathematically using PHENIX asymmetry models:

$$x^{DY} = \frac{x^{Sa} - rx^{Bg}}{1 - r}$$

with error propagation:

$$\sigma_{x^{DY}} = x^{DY} \sqrt{\frac{(1-r^2)\left[(rx^{Bg})^2\left[\left(\frac{\sigma_r}{r}\right)^2 + \left(\frac{\sigma_{x^{Bg}}}{x^{Bg}}\right)^2\right] + \sigma^2_{x^{Sa}}(x^{Sa} - rx^{Bg})\right]}{(x^{Sa} - rx^{Bg})^2(1-r)^2}}$$

where

- x is the extracted parameter
- r is the background percentage
- *Sa.* is the extraction from the Deuterium target sample
- *Bg*. is the extraction from the background sample
- σ is the uncertainty

Final Result

Final Azimuthal Moment:

$$\nu = 0.151 \pm 0.088(stat.) \pm 0.346(syst.)$$

- With statistical uncertainty, Deuterium azimuthal extraction < 1.41 standard deviations from E866 values
- Systematic range is about the size of the difference between pion and proton induced Drell-Yan experiments
- Largest sources of uncertainty are intensity dependence and background contamination

Next Steps

This *angular distributions* analysis was current as of September 2017.

E906/SeaQuest has significantly progressed in 6 months:

- Trigger discrepancy identified and corrected in December (FPGA4 $\sim$ 90% efficiency)!
- Two tracking revisions (now R008), significantly improving underlying track finding!
- Reduced χ^2 of most recent mass fits approaching unity!
- Converging models for background mixing!

Analysis Coordinator Announcement:

"We have understood the dimuons measured!"

Light Quark Flavor Asymmetry Publication on the Horizon!

How to Improve Angular Analysis?

Angular Analysis requires *"pure"* signal or high accuracy of reconstructed tracks

- Tight cuts on new tracking revision may yield enough statistics for a preliminary result
- Improved Background models may be useful for angular analysis
- Introduction of machine learning on GPUs (Tensorflow, CUDAS, PyKeras) may allow for background simulation and optimized signal cuts

Low hanging fruit includes Charmonium polarization...

Backup

Angular Distributions Explained

Drell-Yan angular distributions have information about parton dynamics.

$$\frac{d\sigma}{d^4q d\Omega} = \frac{1}{32\pi^4}\left(\frac{\alpha}{Ms}\right)^2 [W_T(1+\cos^2\theta) + W_L(1-\cos^2\theta) + W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi],$$

Initial derivation depends only on dynamics of a two-to-two process mediated by a virtual photon.

$$W^{\mu\nu}(P,S) = \int d^4x e^{ik\cdot x}\langle P,S|[J^\mu(x),J^\nu(0)]|P,S\rangle,$$

$$\begin{aligned} W_T =& \epsilon_1^\mu(q) W_{\mu\nu}(P,S)\epsilon_1^{*\nu}(q),\\ W_L =& \epsilon_0^\mu(q) W_{\mu\nu}(P,S)\epsilon_0^{*\nu}(q),\\ W_\Delta =& \frac{1}{\sqrt{2}}[\epsilon_1^\mu(q) W_{\mu\nu}(P,S)\epsilon_0^{*\nu}(q) + \epsilon_0^\mu(q) W_{\mu\nu}(P,S)\epsilon_1^{*\nu}(q)],\\ W_{\Delta\Delta} =& \epsilon_1^\mu(q) W_{\mu\nu}(P,S)\epsilon_{-1}^{*\nu}(q), \end{aligned}$$

Angular Distributions Explained (Cont.)

Angular parameters are linear combinations of virtual photon structure functions:

$$\lambda = \frac{W_T - W_L}{W_T + W_L} \qquad \mu = \frac{W_\Delta}{W_T + W_L} \qquad \nu = \frac{W_{\Delta\Delta}}{W_T + W_L}$$

in the familiar equation:

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

If two-to-two process involves fermions at the initial and final state:

$$W_L = 2W_{\Delta\Delta} \implies 1 - \lambda = 2\nu$$

with $\lambda = 1$ & $\nu = 0$

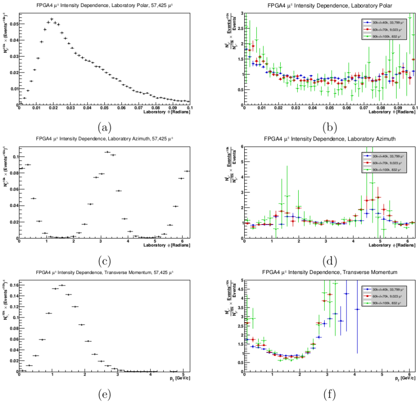
Trigger Efficiency

Left: $\mathcal{I} < 10k$, Right: $\frac{\mathcal{I}_{bin}}{\mathcal{I} < 10k}$

Pseudo-Efficiency evaluated by comparing relative rates of different samples. First evaluated by examining FPGA4 relative intensity dependence:

$$\frac{N(Muon(\mathcal{I}_{bin}), Y)}{N(Muon(\mathcal{I} < 10k), Y)} = 1$$

where Y is a single muon observable.



(a) (b) (c) (d) (e) (f)

Relative intensity dependence in FPGA4 is negligible.

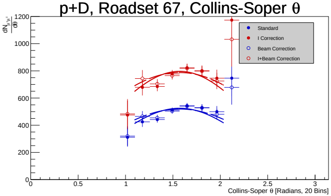
Extractions

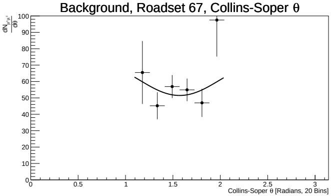
One-dimensional polar and azimuthal extractions with four different configurations:

- Standard - No corrections, Kenichi's beam shift: $p_y \rightarrow p_y + 0.004p_z$, cuts shifted by 1.7 cm.
- I Corrected - Dimuon observable QIE intensity correction, bins of 10k ppp, Kenichi's beam shift, cuts shifted by 1.7 cm.
- Beam Shift - Standard cuts, acceptance corrected beam shift, *no intensity* corrections, cuts without 1.7 cm shift
- I+Beam Corrected - Dimuon observable QIE intensity correction, bins of 10k ppp, acceptance corrected beam shift, cuts without 1.7 cm shift.

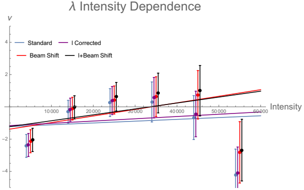
Polar Extractions

Polar Moment Extractions





Intensity Dependence



Extraction Values

$\sin\theta\,[\kappa] + [\nu\kappa]\cos^2\theta$ Extractions				
Sample Class	$\chi^2/n.d.f$	λ	$[\kappa]$	$[\lambda\kappa]$
Standard	$10.846/4 \approx 2.712$	-0.555 ± 0.440	525.0 ± 14.0	-291.0 ± 231.0
I	$7.562/4 \approx 1.890$	-0.401 ± 0.450	797.0 ± 21.3	-320.0 ± 358.0
Beam	$7.342/4 \approx 1.835$	-0.235 ± 0.440	520.0 ± 13.6	-122.0 ± 229.0
I+Beam	$5.576/4 \approx 1.394$	-0.069 ± 0.450	788.0 ± 20.8	-54.2 ± 354.0
Background	$6.500/4 \approx 1.625$	1.580 ± 2.030	41.0 ± 4.10	65.0 ± 83.1

Yields: $\lambda^{Sa.} = -0.069 \pm 0.450$ & $\lambda^{Bg.} = 1.580 \pm 2.030$

Background Subtraction and Statistical Uncertainty

Assuming $r = 0.393 \pm 0.036$, calculated from the statistical uncertainty in the mass fit.

Polar Moment

- $\lambda^{Sa.} = -0.069 \pm 0.450$
- $\lambda^{Bg.} = 1.580 \pm 2.030$

Yields $\lambda^{DY} = -1.13 \pm 1.19$

Azimuthal Moment

- $\nu^{Sa.} = 0.204 \pm 0.029$
- $\nu^{Bg.} = 0.286 \pm .103$

Yields $\nu^{DY} = 0.151 \pm 0.088$

Systematic Uncertainties

Considered systematic uncertainties are from extraction method, intensity dependence, beam shift, and background contamination estimation. $\sigma_r^{syst.} = .30$ from comparison to Jason's and Kenichi's fits.

Polar Systematic

- $\sigma_{\lambda^{Sa./Bg.}}^{syst.(ext.)} = 0.445$, from linear interpolation of simulation at $\nu = .151$
- $\sigma_{\lambda^{Sa./Bg.}}^{syst.(int.)} = 3.68$, from intensity variations
- $\sigma_{\lambda^{Sa./Bg.}}^{syst.(shift.)} = 0.326$, from shifted/unshifted differences

Yields $\sigma_{\lambda^{Sa./Bg.}}^{syst.} = 3.72 \implies \sigma_{\lambda^{DY}}^{syst.} = 6.52$

Azimuthal Moment

- $\sigma_{\nu^{Sa./Bg.}}^{syst.(ext.)} = 0.01$, from interpolation to $\nu = .151$
- $\sigma_{\nu^{Sa./Bg.}}^{syst.(int.)} = 0.133$ from intensity variations
- $\sigma_{\nu^{Sa./Bg.}}^{syst.(shift)} = 0.001$ from beam shift

Yields $\sigma_{\nu^{Sa./Bg.}}^{syst.} = .133 \implies \sigma_{\nu^{DY}}^{syst.} = 0.346$

Final Polar Moment Extraction

Final Polar Moment $\lambda = -1.13 \pm 1.19(stat.) \pm 6.52(syst.)$

- With statistical uncertainty, Deuterium polar extraction is consistent with 0, likely a result of background contamination.
- Systematic range is > 3 times larger than physical range of variable, biggest source of uncertainty is intensity dependence (~ 1.8 times physical range of variable)