Measurement of the Angular Distribution of Drell-Yan Production in p+Fe Interactions at 120 GeV Beam Energy

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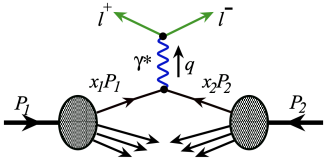
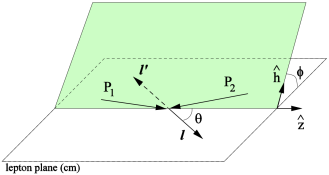
Angular distribution of Drell–Yan

Drell Yan Process



(a) Drell and Yan Process[1][2]



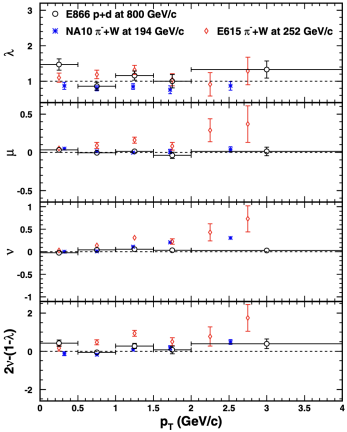
(b) Collins-Soper Frame[3]

- $q + \bar{q} \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$
- In the right plot, the polar and azimuthal angles, θ and ϕ, have measured in the Collins-Soper reference frame. The Collins-Soper reference frame is "a particular rest frame of the muon pair".
- Two successive boosts are required to get the Collins-Soper Frame. First boost is along the laboratory z azis to eliminate the z component of the dimuon momentum $\vec{q}$, and the second one is along $\vec{q_T}$.

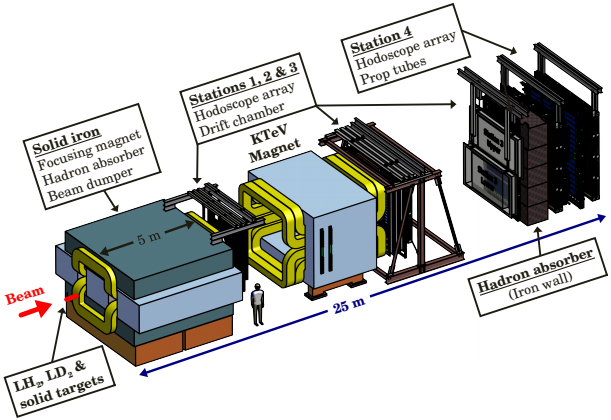
Accessing Angular Coefficients in Unpolarized DY

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\ cos^2\theta + \ \mu\ sin2\theta\ cos\phi + \frac{\nu}{2} sin^2\theta\ cos2\phi \qquad (1)$$

- In the lower p_T region, the proton-induced Drell-Yan experiment[4] shows the $\lambda = 1$ within the statistical uncertainty, which also obeys $(1 - \lambda = 2\nu)$; and it's known as Lam-Tung relation. However, we see a clear violation in the pion-induced Drell-Yan experiment.
- $cos2\phi$ term is sensitive to correlations between quark transverse spin and quark transverse momentum. It describes the polarization of quarks inside an unpolarized proton (A.K.A Boer-Mulders function $h_1^{\perp}$)). [5].



SeaQuest Spectrometer



- 120 GeV proton beam provided in a 4 sec spill by Fermilab Main Injector.
- The experiment used many solid and liquid targets, but this presentation will focus on data from the beam dump.

Dimuon Mass Spectra from the Beam Dump

Forming Combinatorial Background

- The combinatorial background was created by combining all of the opposing sign tracks from two different events. We ensured that the occupancy of the drift chamber was similar in both events.
- SIGNAL = DATA - BACKGROUND.
- The green vertical line shows a lower mass cut that isolates DY events from all other decay channels (J/ψ,$\psi^{'}$ etc.).
- The following slides will focus on using Monte Carlo data to correct the spectrometer acceptance.

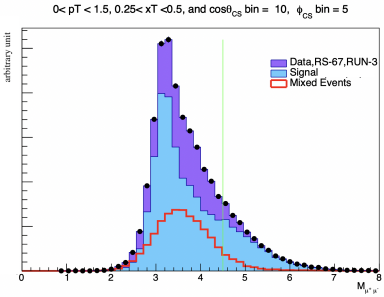


Figure: The figure shows typical dimuon mass spectra. We have used 12 and 20 bins for the polar and azimuthal angles, respectively.

Unfolding the Angular Distributions

Building Response Matrix

The process of extracting true events in the reconstructed bin is called "unfolding".
The first step of unfolding is building a response matrix which is defined as:
S_{ij} = Prob(Observed in bin j|true in bin i)

$$n(R_j^{MC}) = \sum_i S_{ij}\, n(T_i^{MC}) \tag{2}$$

- Number of Events in the reconstructed bin j
- Folding or Response Matrix
- Number of Events in the True bin i
- We can build the response matrix from Monte Carlo events. For the acceptance correction, we include the reconstruction inefficiency in the response matrix.

Unfolding the Reconstructed Test Data Using Bayesian Iterative Method

$$P(T_i^{MC}|R_j^{MC}) = \frac{P(R_j^{MC}|T_i^{MC})\,P(T_i^{MC})}{P(R_j^{MC})} \tag{3}$$

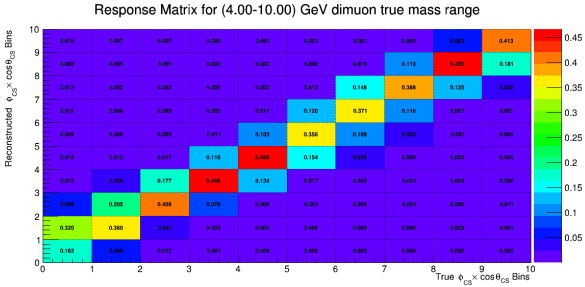
- Unfolding Matrix
- Response Matrix
- Prior probability
- $P(R_j^{MC}) = \sum_i P(R_j^{MC}|T_i^{MC})P(T_i^{MC})$

$$n(T_i^{data}) = \frac{1}{\epsilon_i}\sum_j P(T_i^{MC}|R_j^{MC})n(R_j^{data}) \tag{4}$$

- Unfolded Distributions with corrected acceptance [6],[7]
- The software package RooUnfold[8] has been used for the unfolding.

Bin Migration for 2D distributions of $cos\theta_{CS}$ and ϕ_{CS} (S_{ji} without Acceptance Correction)

- The $cos\theta_{CS}$ range -0.5 to 0.5. ϕ_{CS} bin $N_i = 12$, and $\cos\theta_{CS}$ bin N_j =10.
- Therefore the total response matrix elements would be $(recoN_i^{\phi_{CS}} \times recoN_j^{cos\theta_{CS}})$ vs. $(trueN_i^{\phi_{CS}} \times trueN_j^{cos\theta_{CS}})$ =120 $\times$ 120; and we have not shown all bin to bin probabilities.
- The color in the 2D bins represent the bin-to-bin migration probabilities without acceptance correction.



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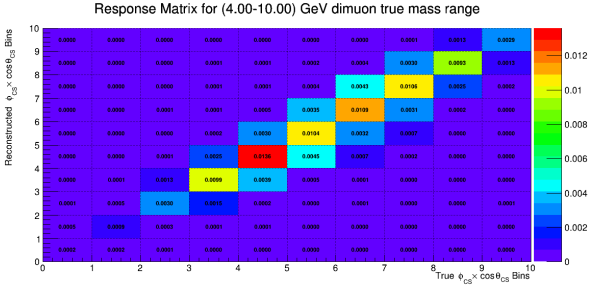
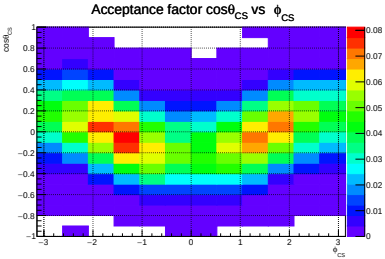
- The color in the 2D bins represent response matrix with considering the acceptance correction.



Bin-by-bin Acceptance Correction

$$\epsilon_i = \frac{N_i^{MC,rec\wedge gen}}{N_i^{MC,gen}} \tag{5}$$

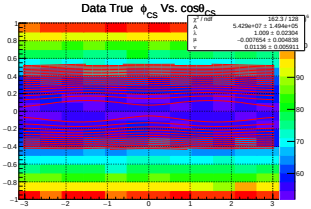
- Acceptance Factor in i bin of $(\phi_{CS}, cos\theta_{CS})$.
- Number of Monte Carlo events that reconstructed in the bin i.
- Number of Monte Carlo events that Generated in true bin i.



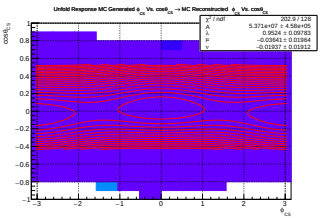
If we divide the total data by the acceptance factor, we will get the acceptance corrected angular distribution.

Unfolding the Test Data: Unfolding ($\lambda = 1$)

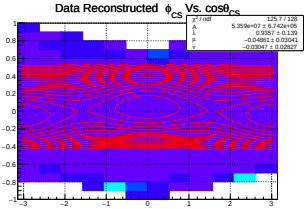
- The test data used to construct the response matrix remains unchanged, and we unfolded the reconstructed test data with the expected value of $\lambda = 1, \mu = 0$, and $\nu = 0$.
- The unfolding regularization has not been optimized yet, which we are working on.



(a) Test True $cos\theta_{CS}$ vs ϕ_{CS} with 2D fit



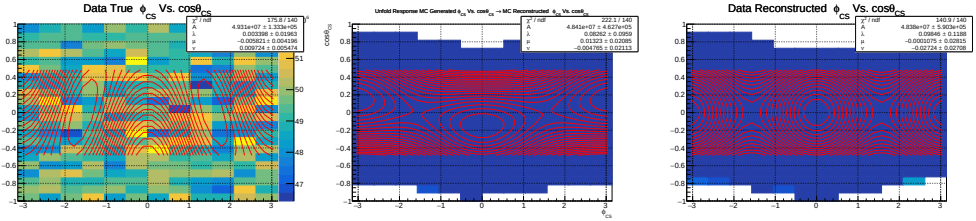
(b) Unfolded test Reco data with 3 iterations.



(c) Acc factor Corrected test Reco data.

Unfolding the Test Data with Embedded Signal ($\lambda = 0$)

- $\lambda_w = \frac{1+0\times cos^2\theta_{CS}}{1+cos^2\theta_{CS}}$; total weight = generator weight $\times$ λ_w.
- The test data used to construct the response matrix remains unchanged, and we unfolded the reconstructed test data with the expected value of $\lambda = 0, \mu = 0$, and $\nu = 0$.
- The unfolding regularization has not been optimized yet, which we are working on.



(a) Test True $cos\theta_{CS}$ vs ϕ_{CS} with 2D fit

(b) Unfolded test Reco data with 3 iterations.

(c) Acc factor Corrected test Reco data.

Conclusions

Conclusions

- Since the beam dump target is thick, we have a better statistical significance in extracting the angular coefficients than the other solid or liquid targets that were used in the experiment.
- The angular coefficients of the proton-induced Drell-Yan experiment at SeaQuest will test the validity of the Lam-Tung relation in the different kinematic regions, especially, in the low dimuon p_T regions.
- A non-zero ν value will indicate a non-zero Boer-Mulders function for the proton-induced Drell-Yan process.
- Currently, we are working on the unfolding-regularization and sanity check with the bin-by-bin acceptance correction; therefore, we can use the combinatorial-subtracted and acceptance-corrected Drell-Yan signal to extract the angular coefficients.

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