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Angular Distributions of Drell-Yan Dimuons at Fermilab E906/SeaQuest

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The Lam-Tung relation, a pertubative QCD, "Callan-Gross-like" correlation of the azimuthal and polar angles of leptonic products relative to the initial hadronic plane in multiple frames, defines a standard component of any analysis using Drell-Yan as a nucleon probe. In at least three experiments involving Drell-Yan between various species of pions and nuclei at CERN and Fermilab, the existence of what appears to be (at leading-order) a double-spin flip in a single photon process manifests itself as a cosine modulation in dilepton azimuthal distributions. This modulation suggests significant non-perturbative effects, including the Boer-Mulders distribution, a nonzero correlation between the motion and spin of transversely polarized (anti)quarks within their encompassing unpolarized nucleon. Fermilab Experiment 866/NuSea saw a Lam-Tung violation in proton-induced Drell-Yan characterized by a smaller cosine dilepton azimuthal modulation relative to previous experiments conducted with pions and heavier nuclear targets with lower energy beams from the SPS at CERN. SeaQuest is investigating the difference with greater precision and at a higher target x range than any previous Drell-Yan experiment. Current progress in analysis of the angular distributions of dimuons at SeaQuest is shown.

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1. Introduction

At least three experiments have used unpolarized Drell-Yan interactions to observe a convolution of correlations between transversely polarized quark motion and the longitudinal motion of their respective unpolarized nucleons (analogous to "spin-orbit coupling" in the hydrogen atom), known as the Boer-Mulders Transverse Momentum Dependent distribution (TMD)[1]:

$$\frac{d\sigma}{d\phi} \propto f_1^q(x,\mathbf{k}_T^2)f_1^{\bar{q}}(x,\mathbf{k}_T^2)+ \\ h_\perp^q(x,\mathbf{k}_T^2)h_\perp^{\bar{q}}(x,\mathbf{k}_T^2)\cos(2\phi). \tag{1.1}$$

The first, a 1988 CERN experiment at North Area 10 (NA10) observed the angular distributions of products from the interaction of pion beams at 140, 194, and 286 GeV wth deuterium and tungsten targets[2]. From a study of the kinematics of an s-channel QED process mediated by a vector boson it can be shown:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\bigg(1+\lambda\cos^2(\theta)+ \\ \mu\sin(2\theta)\cos(\phi)+\frac{\nu}{2}\sin^2(\theta)\cos(2\phi)\bigg). \tag{1.2}$$

where θ and ϕ are the zenith and azimuthal angles of the produced leptons in the Collins-Soper frame and λ, μ, and ν are linear combinations of the transverse, longitudinal, single-spin flip, and double-spin flip structure functions of the mediating polarized virtual photon[3, 4]. With consideration of the spin-$\frac{1}{2}$ nature of the partons, a "Callan-Gross-like" relationship between the virtual photon polarization and the structure function describing double-spin flips and known as the Lam-Tung relation appears: $1-\lambda = 2\nu$[5]. Surprisingly, a significant nonzero $\cos(2\phi)$ modulation (hereafter referred to as the ν-modulation or ν-parameter) in the data forces a violation of the relation.

Completed in 1989, Fermi National Accelerator Laboratory (Fermilab) Experiment 615 (E615), again observed a nonzero ν-parameter in unpolarized Drell-Yan from pion interactions with a stationary tungsten target, with a beam energy of 252 GeV[6]. The most recent experiment, Fermilab Experiment 866 (E866/NuSea) of 1995, observed unpolarized Drell-Yan from nucleon-nucleon interactions, with proton beams at 800 GeV on stationary liquid hydrogen and deuterium targets. It is speculated that the valence anti-quark provided by the pions in NA10 and E615 resulted in an enhanced ν-parameter relative to E866/NuSea but it is unclear whether additional non-perturbative QCD effects also contribute to the greater magnitude of the parameter[7, 8]. A summary of the results of these experiments is shown in Figure 1.

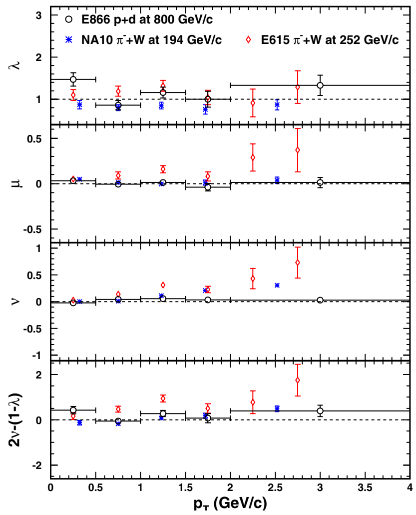

Figure 1: Angular distribution moments of Experiments NA10, E615, and E866. The pion induced Drell-Yan experiments show very clear violation of the Lam-Tung relation with E615 even showing a nonzero μ-parameter. E866 results are consistent with the Lam-Tung relation.

Fermilab Experiment 906/SeaQuest (E906/SeaQuest) will complement E866/

NuSea by extending measurements of observed target anti-quark momentum fractions to those unobtainable during the operation of the Tevatron. Using beam from the Fermilab Main Injector, a high intensity proton accelerator at 120 GeV, on stationary liquid hydrogen targets of hydrogen and deuterium it is expected that SeaQuest will also produce at least an order of magnitude more target Drell-Yan events overall, yielding dramatically increased sensitivity in the medium and high-momentum fraction regions.

2. The SeaQuest Spectrometer

The SeaQuest spectrometer is twenty-five meters long and consists of a cycling stationary target table with two different liquid hydrogen species as well as three nuclear targets; a large iron core focusing magnet, which also acts as a beam dump and muon filter; a smaller air core analysis magnet; and four measurement planes arranged perpendicular to the beam axis. The measurement planes are made of three major types of measurement subsystems. One of the three subsystems, the Photomultiplier Tube and Scintillator Hodoscope combination, are represented at various sizes and spatial resolutions on all four SeaQuest measurement planes and are responsible for high resolution temporal measurement with a response time on the order of tens of nanoseconds. The Drifts Chambers (DCs) are present on the first three measurement planes and have spatial resolution around 200-300 micrometers. Finally, the fourth station Proportional Tubes (PTs) (and the meter thick solid iron wall directly preceding it), are responsible for the identification of Muons, and are analogous in operation to the DCs but with fractional millimeter resolution. A model of the spectrometer is shown in Figure 2 while its effect in the Collins-Soper frame is shown in Figure 3.

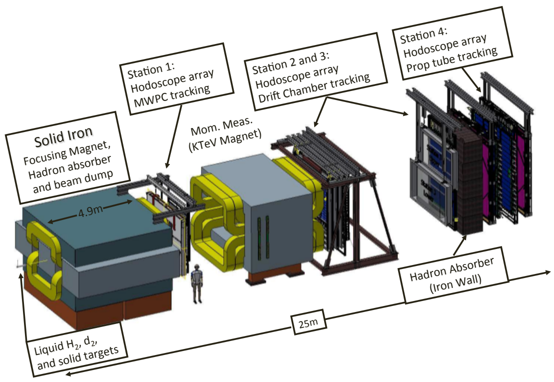

Figure 2: The SeaQuest Spectrometer. In this picture beam enters from the left of the detector and either interacts in the target or solid iron beam dump.

3. Angular Distributions Analysis

The ultimate goal of this analysis is to extract the various angular distribution parameters: λ, μ, and ν with a fourth scaling parameter, κ, added for completeness and fitting purposes, from the angular distribution of target Drell-Yan dimuons in the Collins-Soper frame. The Collins-Soper frame is more sensitive to asymmetries in initial quark motion because any excess transverse momentum present in the virtual photon or dimuon pair is evenly distributed between the quark-antiquark pair. Current progress of the analysis consists of simulated extractions of the ν-parameter through the SeaQuest spectrometer and trigger but have not been completed at the muon reconstruction level.

3.1 Geometric Acceptance Corrections

An *ab initio* geometric analysis begins with the intersection of a spherical conic centered on a beam axis and a plane perpendicular to that beam axis. The dome can be thought of as a surface through which some arbitrary unit of flux representing any decay or productive interaction process passes. It can be reasoned that

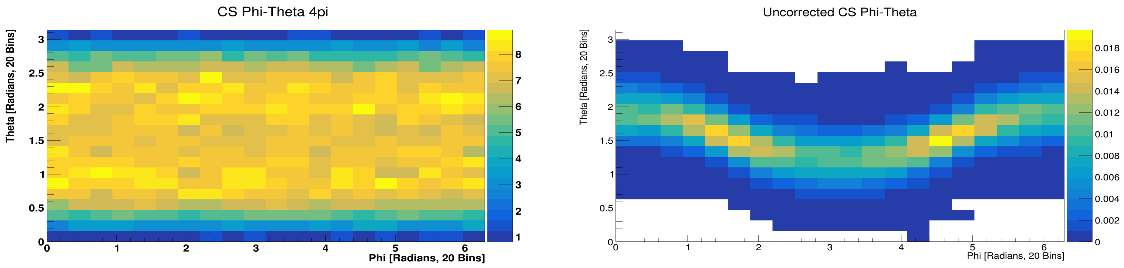

Figure 3: The Spectrometer Acceptance. The acceptance of the detector introduces a mixing in the Collins-Soper frame which stipulates extraction of angular moments in 2 dimensions.

even if the process in question does not have an isotropic distribution over the surface of an ellipsoid (like for instance, a fixed target Drell-Yan process), its specific deformation in spherical coordinates can be implemented as a coordinate transformation and projected onto the dome. The plane represents the spatial limit of the detector.

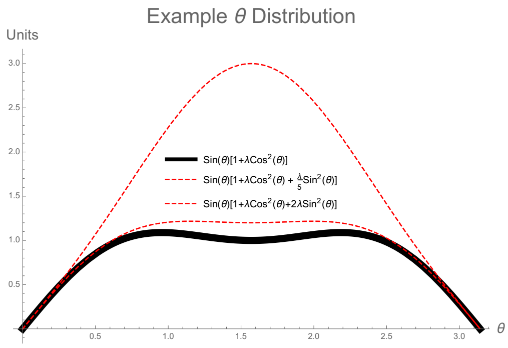

Figure 4: Collins-Soper θ theoretical Drell-Yan distribution with possible spectrometer additions. The black curve is the distribution predicted with a +1 virtual photon polarization.

If we assume that the initial frame of interaction is the laboratory frame it should be noted in distributions of ϕ where transverse quark momentum is assumed to be zero, the center-of-mass frame and Collins-Soper frame are identical, indicating that when laboratory θ is small (as it is for a fixed target experiment in the forward direction) ϕ is mostly independent of boosts along the beam axis. With this insight we can proceed with an analysis of ϕ in any frame and apply it to all relevant frames of this analysis. However, it should be noted that Collins-Soper ϕ is not fixed with respect to the lab frame but it is assumed (but not shown) that because we use an isotropic function any idiosyncrasies caused by the geometry should be directly translated from the lab through the center-of-mass frame and into the Collins-Soper frame with minor differences.

Both the ellipsoid and plane have simple forms in a three dimensional Cartesian coordinate system:

$$ax^2+by^2+cz^2=d^2 \tag{3.1}$$

$$ex+fy+gz=h, \tag{3.2}$$

which can be augmented such that the generalized plane becomes perpendicular to the beam axis (i.e. $e\to 0$, $f\to 0$). Converting to spherical coordinates and plugging the equation for a plane into the ellipsoid equation yields a general equation for the intersection of the plane and ellipsoid:

$$\rho\sin^2(\theta)\left[a\cos^2(\phi)+b\sin^2(\phi)\right]+\left(\frac{ch^2}{g^2}-d^2\right)=0. \tag{3.3}$$

From here, the effect of the spectrometer geometry on Collins-Soper θ can be read off as a $\sin^2(\theta)$ modulation.

For calculation of spectrometer effects in Collins-Soper ϕ, a distance from the source of the flux to the plane, r, must be established and the physical limits of the plane must be simulated. Given the Jacobian for the transformation from Cartesian coordinates it can be shown:

$$r = \rho\cos(\theta) \implies \theta(\rho) = \cos^{-1}\left(\frac{r}{\rho}\right). \tag{3.4}$$

For the implementation of detector boundaries in the perpendicular plane, a relation between Collins-Soper θ and ϕ is used:

$$\Theta(\phi) = \tan^{-1}\Bigg((|a\cos(\phi) + b\sin(\phi)| + |a\cos(\phi) - b\sin(\phi)|)^{\frac{1}{2}}(r)^{-\frac{1}{2}}\Bigg). \tag{3.5}$$

where a and b are the same constants from the original ellipsoid and plane equations. Rearranging equation 3.4 and substituting it along with equation 3.5 for a free θ parameter in equation 3.3 gives the general ϕ equation:

$$(|a\cos(\phi) + b\sin(\phi)| + |a\cos(\phi) - b\sin(\phi)|)\,[a\cos^2(\phi) + b\sin^2(\phi)] + (\frac{ch^2}{g^2} - d^2) = 0. \tag{3.6}$$

The constants a and b can be varied to capture the effects of specific plane lengths or various other changes in the overall acceptance in ϕ.

The final piece of this analysis concerns simulation of the effects of the SeaQuest focusing magnet in the lab frame. Referring again to the Jacobian of the spherical coordinate system with reference to the Cartesian coordinate system (ie $x = \rho\sin(\theta)\cos(\phi)$ and $y = \rho\sin(\theta)\sin(\phi)$) the general effect of the magnet can be simulated by adjusting the values of a and b relative to each other. Setting $a < b$ represents a shrinking of the acceptance in the x-direction and the appearance of a function very similar to $\sin(\phi)^2$.

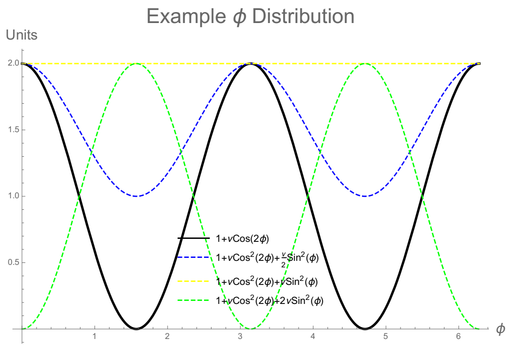

Figure 5: Collins-Soper ϕ theoretical Drell-Yan distribution with the addition of spectrometer effects, including the effect of the focusing magnet.

3.2 Trigger Acceptance Corrections

The experimental trigger is based on the quick response time of the hodoscopes and consists of cascading chains of various Field Programmable Gate Arrays (FPGAs) for dimuon events and Nuclear Instrumentation Modules (NIMs) for diagnostic, random, and "minimum-bias" like event selection. In order to limit the background dominated event rate to below the 3×10^4 event limit decided by the read out time of the DCs and PTs, a Level 1 trigger consisting of combinations of hodoscope elements from each station, individually known as a "Trigger Road" has been implemented, with a Level 2 trigger consisting of a pair of these roads from the top and bottom halves of the detector.

To test both levels of the trigger for efficacy in detecting possible angular modulations, custom Monte Carlo was generated with varying magnitudes of the ν-modulation and extracted. Trigger corrections in Collins-Soper θ and ϕ as well as extraction results in Collins-Soper ϕ are shown in Figure 6. Three of the five extractions are within 1σ of the artificially generated value while the remaining two with the largest magnitudes are within 2σ of the generated value.

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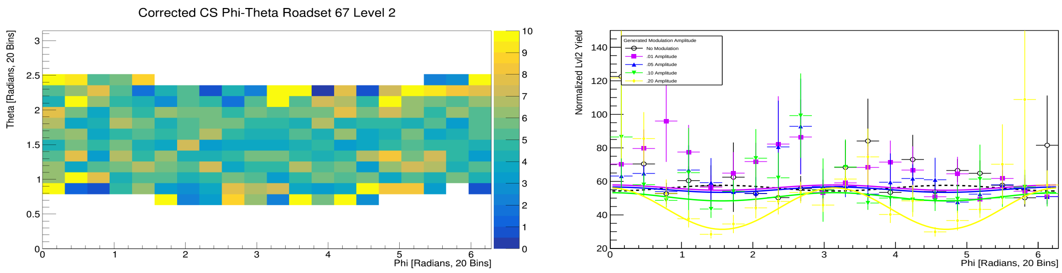

Lvl2 $[\alpha] + [\beta]\cos(2\phi)$ Extractions				
Generated ν	$\chi^2/n.d.f$	Extracted $\nu = [\beta]/[\alpha]$	$[\alpha]$	$[\beta]$
None	16.201/18 $\approx$ 0.90003	-0.0303 $\pm$ 0.0508	55.9 $\pm$ 1.66	-1.7 $\pm$ 2.84
.01	25.7/18 $\approx$ 1.4278	0.028 $\pm$ 0.0374	56.3 $\pm$ 1.69	1.58 $\pm$ 2.1
.05	10.485/18 $\approx$ 0.5825	0.0291 $\pm$ 0.039	55.1 $\pm$ 1.67	1.6 $\pm$ 2.15
.10	13.079/18 $\approx$ 0.72663	0.0482 $\pm$ 0.051	50.8 $\pm$ 1.69	2.45 $\pm$ 2.59
.20	27.694/18 $\approx$ 1.5386	0.283 $\pm$ 0.0414	43.8 $\pm$ 1.46	12.4 $\pm$ 1.76

Figure 6: Trigger acceptance corrections and extractions. The graph on the left is the Drell-Yan distribution in Collins-Soper θ and ϕ with corrections applied. The graph on the right shows the generated distributions after acceptance corrections in ϕ. The details of each extraction are color coded to the extraction in the graph above.

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