Chapter 1

Transverse Momentum Dependent Analysis

This chapter goes over the results for two additional transverse momentum dependent analyses from the 2015 Drell-Yan data set. The first analysis is for a traditional asymmetry method used at COMPASS, the double ratio method. The double ratio method is an analysis technique to determine spin-dependent phenomena without acceptance effects. The second results are from q_T-weighted transverse momentum dependent asymmetries. The theoretical introduction and motivation for measuring q_T-weighted asymmetries is provided in Sec **??**. The author of this thesis was a cross checker for the q_T-weighted asymmetry results which is a required step for any results to become public. For the full details of the q_T-weighted analysis see reference [1].

The same data taking conditions, Sec **??**, and stability tests, Sec **??**, used for determining the left-right asymmetry, Ch **??**, are also used for both of these analyses. In particular, the data is from the same nine taking periods were the transversely polarized NH_3 target polarization is flip between each sub-period of data taking. Therefore only the differences in event selection and analysis techniques will be provided in this chapter.

1.1 Double Ratio Analysis

why we use 8 bins

$$\frac{a_1^{\uparrow}(\Phi)a_2^{\uparrow}(\Phi)}{a_1^{\downarrow}(\Phi)a_2^{\downarrow}(\Phi)} = 1 \tag{1.1}$$

$$\Phi = \phi_S, \Phi = 2\phi - \phi_S, \Phi = 2\phi + \phi_S \tag{1.2}$$

1.2 q_T-Weighted Asymmetries

The q_T weighting asymmetries analysis is used to determine three asymmetry amplitudes related to TMD functions. This analysis determined the three amplitudes: $A_T^{\sin\phi_S q_T/M_N}$, $A_T^{\sin(2\phi+\phi_S)q_T^3/(2M_\pi M_N^2)}$ and $A_T^{\sin(2\phi-\phi_S)q_T/M_\pi}$.

These three amplitudes are related to the Sivers, Preztelosity and transversity TMDs respectively.

1.2.1 Event Selection

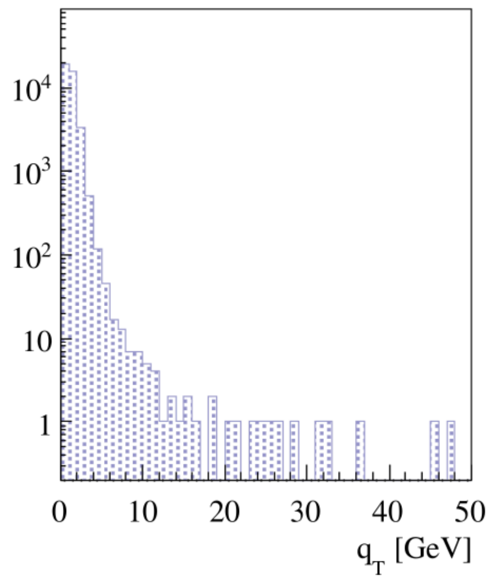
The results for this analysis were released prior to the slot1 reconstruction production and therefore this analysis uses the t3 reconstruction. For q_T-weighted asymmetries the results depend on the full range of the q_T distribution. In the analysis of the left-right asymmetry however, a cut was placed on high and low q_T values to ensure quality azimuthal angular resolution and quality reconstructed events. This cut cannot be applied for q_T-weighted analysis because it will effect the weighting used to determine the asymmetry. The next section goes into the details and the remedy for a q_T related cut. All of the other cuts from Sec **??** are the same except for this q_T cut. Table 1.2 provides the final cut order and the remaining statistics after each cut.

High q_T

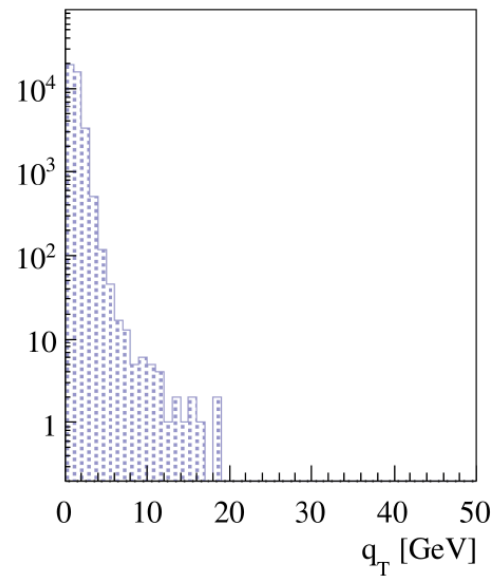
For the both the left-right asymmetry analysis and the double ratio analysis the event selection includes a cut limiting $q_T < 5\ GeV/c$ to ensure quality of the reconstructed events. Higher q_T events are often unphysical results from bad reconstruction or combinatorial background events. The q_T distribution without any q_T cuts is shown in Fig. 1.1a and as can be seen the q_T distribution reaches very high values some of which violates conservation of momentum. A first remedy to the high q_T values then is to add a cut which demands momentum conservation. Therefore the momentum sum of the detected muons is required to be physical, $\ell^+ + \ell^- < 190$ GeV/c. Fig. 1.1b shows how this cut effects the q_T distribution. As can be seen, q_T still reach values much higher than the 5 GeV/c cut from the other TMD analyses. The remaining high q_T events still have the potential to be poorly reconstructed events or combinatorial background and for this reason an additional cut was put on the individual muons transverse momentum so that $\ell_T^{\pm} < 7$ GeV/c.

1.2.2 Binning

The asymmetry is determined in bins of physical kinematic variables and an overall integrated value. The binning kinematical variables are x_N, x_π, x_F and $M_{\mu\mu}$ which are the same as the left-right asymmetry and double ratio kinematical variables without the q_T binning. No q_T binning is used because full integrated of the q_T variable needs to be taken into account to form the weighted asymmetry. The binning boundaries for the physical kinematics are the same as that of the left-right asymmetry and are provided in Tab **??**.



(a) q_T distribution without cuts on q_T. All other cuts expect the q_T cut from table ?? are applied. This image is from [1]



(b) q_T distribution after the momentum conservation cut is added, $\ell^+ + \ell^- < 190$ GeV/c. All other cuts expect the q_T cut from table ?? are applied. This image is from [1]

Cuts	Events	% Remaining
$\mu^+\mu^-$ from best primary vertex, 4.3< $M_{\mu\mu}$ < 8.5 GeV/c^2	1,159,349	100.00
Triggers: (2LAS or LASxOT) and not LASxMiddle	868,291	74.89
Z_{first} < 300 cm, Z_{last} > 1500 cm	784,379	67.66
Δt defined	776,643	66.99
$\|\Delta t\|$< 5 ns	337,081	32.18
χ^2_{track}/ndf < 10	370,054	31.92
$\ell^+ + \ell^- < 190$ GeV/c	219,304	18.92
$\ell_T^\pm < 7$ GeV/c	219,014	18.89
Trigger Validation	168,939	14.57
Good Spills	137,812	11.89
0< x_π x_N <1, -1< x_F <1	137,802	11.89
Z Vertex within NH_3	42,646	3.68
Vertex Radius < 1.9cm	39,088	3.37

Figure 1.2: Event selection statistics for q_T-weighed asymmetry analysis from all periods combined

1.2.3 Asymmetry Method

The weighted asymmetry amplitudes $A_T^{\sin(\phi_S)q_T/M_N}$, $A_T^{\sin(2\phi+\phi_S)q_T^3/(2M_\pi M_N^2)}$ and $A_T^{\sin(2\phi-\phi_S)q_T/M_\pi}$ are all determined using a modified double ratio. As with the double ratio method from Sec 1.1, the modified double ratio does not depend on the spectrometer acceptance. The modified double ratio is defined as

$$R^W_{DM}(\Phi) = \frac{N_1^{\uparrow W} N_2^{\uparrow W} - N_1^{\downarrow W} N_2^{\downarrow W}}{\sqrt{(N_1^{\uparrow W} N_2^{\uparrow W} + N_1^{\downarrow W} N_2^{\downarrow W})(N_1^{\uparrow} N_2^{\uparrow} + N_1^{\downarrow} N_2^{\downarrow})}}, \tag{1.3}$$

where similar notation is used from the previous analyses with $\uparrow$ ($\downarrow$) giving the transverse polarization direction, 1(2) is the upstream(downstream) cell, N^W representing the weighted counts, W being the weight used and N being the unweighted counts. The angles Φ, in the modified double ratio, are the same used for the double ratio, Eq. 1.2, and give access to asymmetry amplitudes related to the same corresponding TMD functions. Under the same reasonable acceptance ratio assumption, Eq. 1.1, from the double ratio method the acceptance cancels out in the double ratio method. The modified double ratio then reduces to

$$R^W_{DM}(\Phi) \approx 2\tilde{D}_{\sin\Phi} \langle S_T \rangle A_T^{\sin(\Phi) W} \sin\Phi, \tag{1.4}$$

where $\tilde{D}_{\sin\Phi}$ is an integrated depolarization factor defined as

$$\tilde{D}_{\sin\phi_S} = 1, \qquad \tilde{D}_{\sin(2\phi\pm\phi_S)} = \frac{\int a(\theta)\sin^2\theta d\cos\theta}{\int a(\theta)(1+\cos^2\theta)d\cos\theta} = \frac{1-\langle\cos^2\theta\rangle}{1+\langle\cos^2\theta\rangle}. \tag{1.5}$$

The statistical error for the modified double ratio is

$$\sigma^2 R^W_{DM} = \frac{\sum_{c,p} \sigma^2_{N_c^p W} 4(N_1^{\uparrow} N_2^{\uparrow}) N_1^{\downarrow} N_2^{\downarrow})^2}{\sum_{c,p} \sigma^2_{N_c^p} (N_1^{\uparrow} N_2^{\uparrow} + N_1^{\downarrow} N_2^{\downarrow})^4} \sum_{c,p} \frac{1}{N_c^p}, \tag{1.6}$$

where $\sigma^2_{N_c^p W} = \sum (W_c^p)^2$ is the sum of event weights, c is cell 1 or cell 2 and p is polarization $\uparrow$ or $\downarrow$.

The weighted asymmetry amplitude are determined by forming the modified double ratio in eight bins in the appropriate Φ angle and fitting this distribution. If an infinite number of bins where used, the modified double ratio distribution would be the function form of Eq. 1.4. To account for the fact that ratio is determined in a finite number of Φ bins, the average value of Eq. 1.4 over the bin width is used as the fit distribution. This means the functional fit is

$$\langle R^W_{DM} \rangle = \frac{1}{\Delta\Phi} \int_{\Phi_i - \frac{\Delta\Phi}{2}}^{\Phi_i + \frac{\Delta\Phi}{2}} R^W_{DM} d\Phi = \frac{2}{\Delta\Phi} \sin(\frac{\Delta\Phi}{2}) R^W_{DM}(\Phi_i), \tag{1.7}$$

where $\Delta\Phi = \frac{2\pi}{8}$ for eight bins in Φ.

1.2.4 Results

As with the other analyses in this thesis, the asymmetry amplitudes are determine for each period and the final asymmetry is determined as a period weighted average as in Eq. **??**. For the same reason as the previous analyses and explained in Sec **??**, the polarization and depolarization factors from each period are used to correct the asymmetry amplitude determined in each period. The final results are shown in Fig. 1.3 along with the results from the release values. As can be seen the results agree with those results obtained for the release which was a requirement before the result could be release to the public.

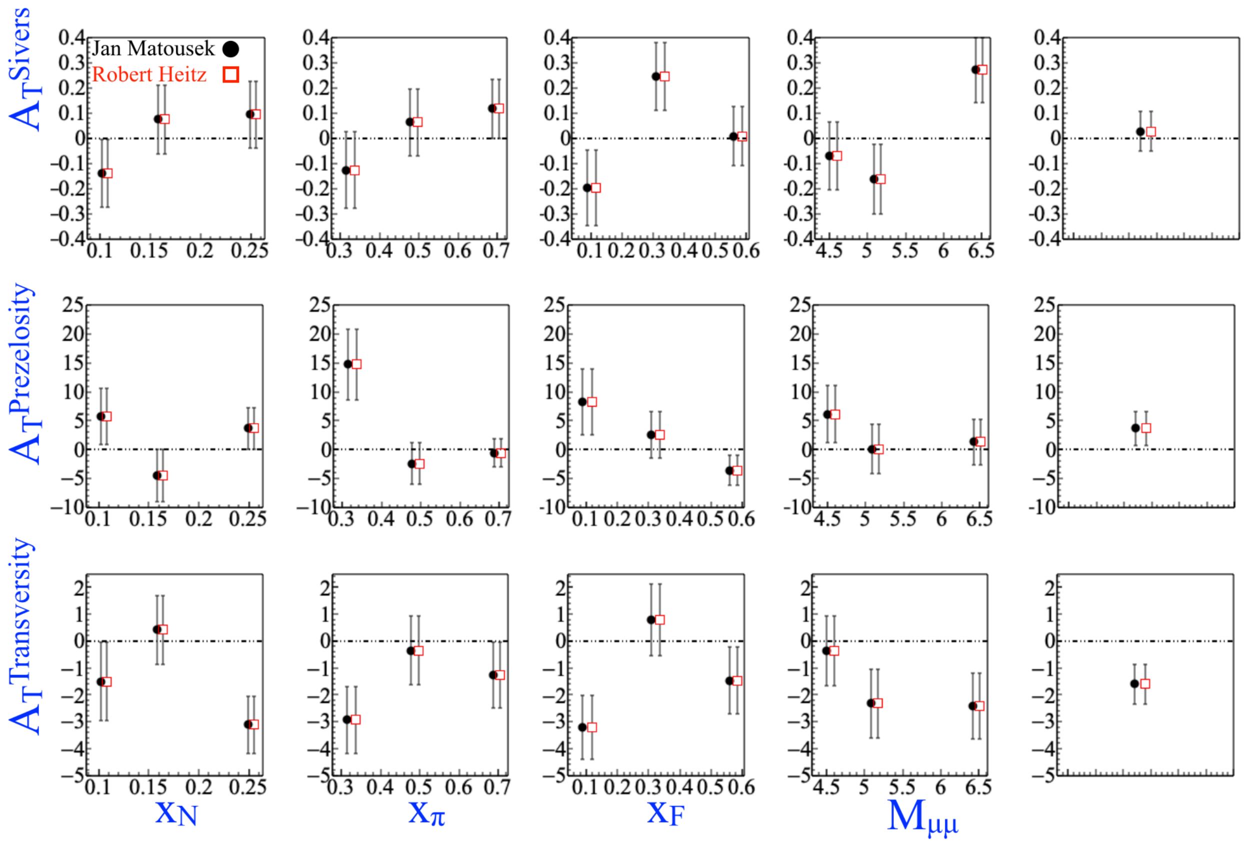


Figure 1.3: The comparison of weighted asymmetry amplitude results from the released values from Jan Matousek (black) and the cross checker Robert Heitz (red). From the top row down the asymmetry amplitudes are $A_T^{\sin(\phi_S)q_T/M_N}$, $A_T^{\sin(2\phi+\phi_S)q_T^3/(2M_\pi M_N^2)}$ and $A_T^{\sin(2\phi-\phi_S)q_T/M_\pi}$ respectively.

References

[1] Jan Matousek. *Nucleon spin structure studies in Drell-Yan process at COMPASS*. PhD thesis, University of Trieste, April 2018.