Double Helicity Asymmetry in J/ψ Production in Polarized p+p Collisions at $\sqrt{s} =$ 510 GeV in Run13

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Abstract

This analysis is a follow up for Aaron Key's run 13 J/ψ A_{LL} analysis. The physics motivation, detail quality assurance and background fraction extraction have been extensively studied and described in Aaron Key's analysis note 1178. The goal for this analysis is finalized the asymmetry results and finish all the left over homework from spin working group and push the result to publication. This note will describe the details works from Haiwang's side. Please refer to Aaron's analysis note for historical reference.

This report is ordered as follows: in section 1, we will describe J/ψ quality cuts were used for this analysis. J/ψ invariant mass fitting and background fraction are shown in section 2. We will introduce spinAnalyzer framework in section 3. It developed by Jin huang and can be generically used in PHENIX spin analysis. This analysis was cross checked between traditional method and SpinAnalyzer framework. The traditional method was used for several J/ψ asymmetry measurement. In section 4, we will show the results for Inclusive dimuon asymmetry, background asymmetry and physics asymmetry. Systematic studies and bunch shuffling results are shown in section 5.

Contents

1 J/ψ quality cut

Analysis cuts are placed on a track by track basis. We used the J/ψ quality cuts described in Aaron's analysis

- BBC z-vertex: $-30 < z < 30$ cm.

  All following track cuts are applied to each individual μ track
- Rapidity: $1.2 \leq |\eta| \leq 2.2$.
- p_T range we choice is from 0 to 10 GeV.
- Number of MuTR hits > 12.
- $DG0 < 15$: The difference(unit in cm) between the MuTR track projection and the MuID road projection at MuID gap 0. The DG0 cut we are using is quiet loose.
- $DDG0 < 10$: Angle (in degrees) between the MuTR track at station 3 and the MuID road at gap 0.
- distance of closest approach ($DCA_r < 5$)
- require the last gap $lastGap > 2$;
- number of MuTr hits $ntrhits > 9$; (total MuTr hits is 16)

- number of MuID hits $nidhits > 5$; (total hits is 10)

  There are also some cuts applied for dimuon pairs listed below

- require these muon pair come from same events, same_event = 1;

- Event vertex χ^2, $Evt\_vtxchi2 < 5$

- $Evt\_vtxoor < 1$

  All above cuts are consistent with Aaron's analysis. Concerning about the multiple collision in high luminosity p + p collisions, In order to ensure the dimuon pair were produced in the same crossing as the triggered crossing, we applied extra RPC timing cuts for this study. We request each muon track has valid RPC timing in RPC1 or RPC3.

  $Tr0\_Rpc1St1Time$ or $Tr0\_Rpc1St1Time$ is valid;

  $Tr1\_Rpc1St1Time$ or $Tr1\_Rpc1St1Time$ is valid;

2 J/ψ invariant mass fit and background fraction

J/ψ yield, $N_{J/\psi}$ was extracted by fitting the invariant mass spectrum of oppositely charged muon pairs. J/ψ signal is fitted with crystal ball function and ψ' is fitted with a Gaussian function. We fixed the mean and width for the ψ' regarding to J/ψ resonances based on the simulation. The The Crystal Ball function is a gaussian which has been joined smoothly with a power law on one side such that it and the first and second derivative are continuous functions as defined in equation 11 in Aaron Key's analysis note section 4.1.

We also followed Aaron's method and used a technique known as Gaussian Process Regression (GPR) to fit the background. The details fitting procedure is described in analysis note 1178 section 4.2. In this fitting, the GPR method is trained on the data points in the green shadowed region.

J/ψ invariant mass fitting for different p_T and $|y|$ bins for south and north muon arms are showing in Fig. 1 and 2.

This background fraction is considered as one source of systematic uncertainty for the final physics asymmetry. As Aaron has done a very systematic study comparing different fitting method. We choose using systematic error for the background fraction for each arm/pT bin. And as we use slightly different J/ψ selection criteria. We keep using the mean value and statistic error listed in Fig. 1 and Fig. 2. And this is summarized in Table 1.

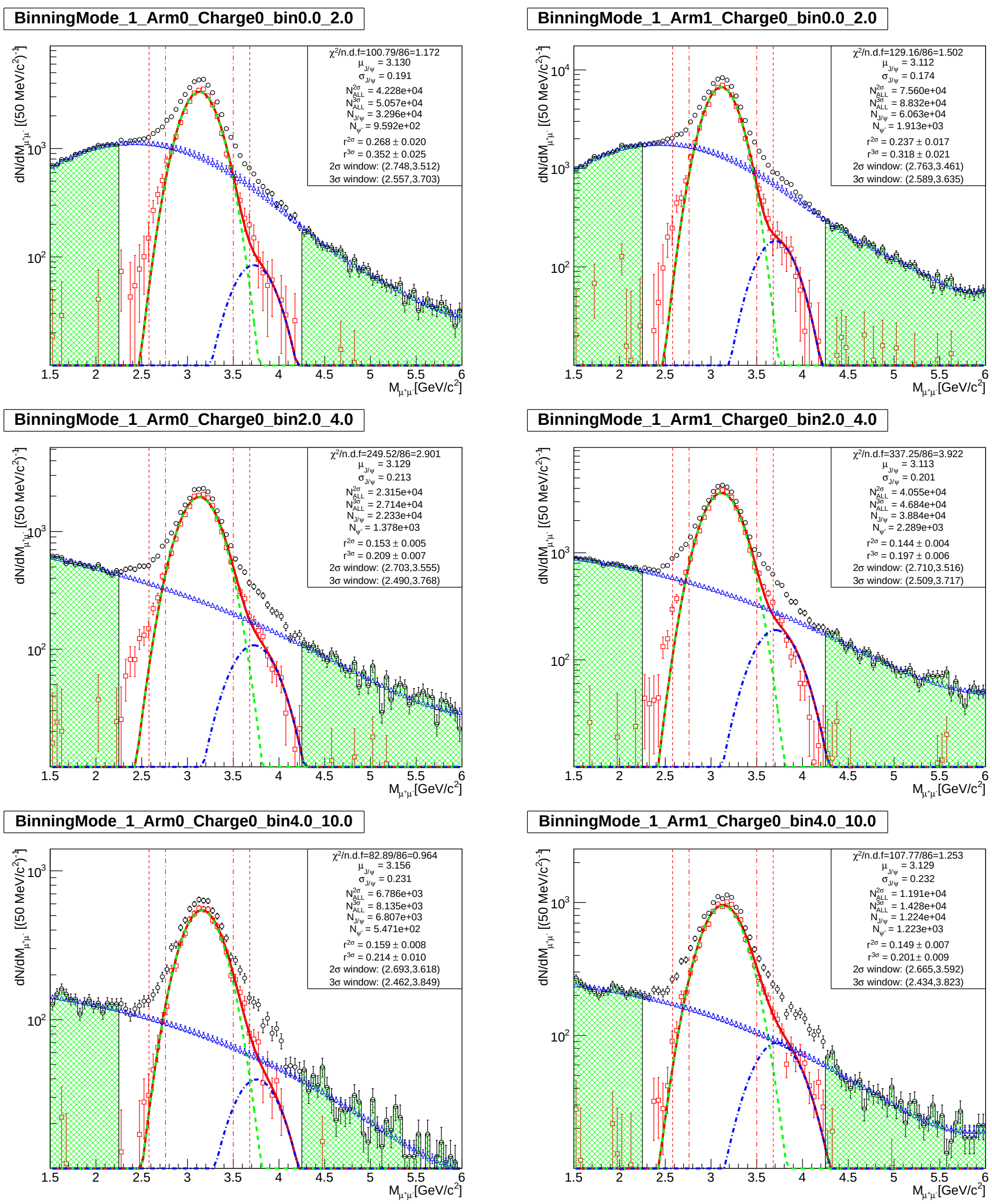

Figure 1: Di-muon invariant mass spectrum for three p_T bins (0-2, 2-4 and 4-10 GeV from top to bottom). The left column are is for north muon arm and right hand column is for south muon arm. The black circle is inclusive dimuon distribution. The red curve is for J/ψ signal. Dashed blue line is for ψ'. Blue cross is for background estimated by GPR.

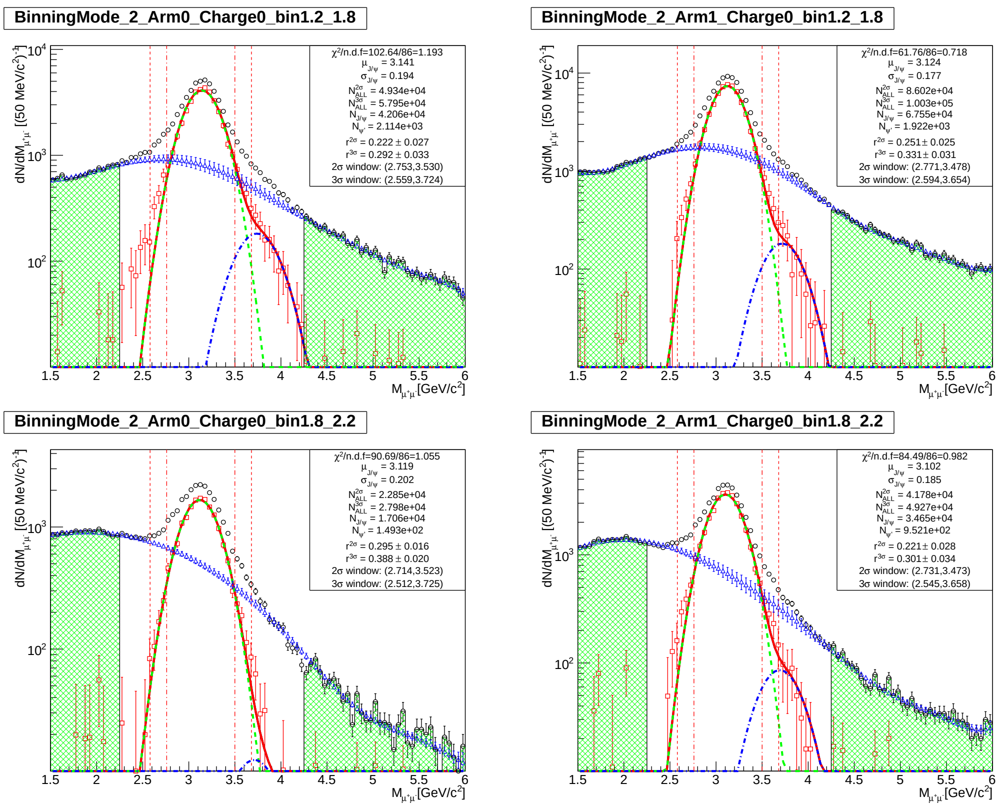

Figure 2: Di-muon invariant mass spectrum for three $|y|$ bins (1.2–1.8 and 1.8–2.2 from top to bottom). The left column are is for north muon arm and right hand column is for south muon arm. The black circle is inclusive dimuon distribution. The red curve is for J/ψ signal. Dashed blue line is for ψ'. Blue cross is for background estimated by GPR.

Table 1: Background fraction f_{Bkg} for each arm and each p_T or $|y|$ bin using the corresponding J/ψ 2σ mass window for that bin. The systematic uncertainty is 5 % (absolute value) for all the bins; see discussion in the text.

p_T (GeV/c) or $\lvert y\rvert$	$f_{\text{Bkg}} \pm \Delta f_{\text{Bkg}}\,(stat.)$ (%) North	$f_{\text{Bkg}} \pm \Delta f_{\text{Bkg}}\,(stat.)$ (%) South
$p_T \in$ 0–10	23 ± 1	22 ± 1
$p_T \in$ 0–2	27 ± 2	24 ± 2
$p_T \in$ 2–4	17 ± 1	16 ± 1
$p_T \in$ 4–10	18 ± 1	18 ± 1
$\lvert y\rvert \in$ 1.2–1.8	23 ± 3	26 ± 3
$\lvert y\rvert \in$ 1.8–2.2	32 ± 2	24 ± 3

3 Spin Analyzer framework

3.1 Overview

Spin Analyzer (or `SpinAnalyzer`) is a new tool to formalize the common part of the spin-asymmetry analysis under the PHENIX `Fun4All` framework. In a nut shell, `SpinAnalyzer` let user to input good event as if filling a histogram of count. Then `SpinAnalyzer` categorize the counts with respect to the spin patterns and convert the count and relative luminosity to asymmetry automatically in the background.

Its basic features are

- The analysis code is compiled and archived in CVS. The main directory is `offline/AnalysisTrain/SpinAnalyzer/`
- It takes input any `Fun4All` input format, including nDST (to run on taxi), filtered compact pico-DSTs or even PRDFs.
- It can run on taxi, on condor or interactively from a ROOT sessions
  - An example taxi macro can be found here: `offline/AnalysisTrain/pat/macro/Run_SpinAnalysis_Eval.C`
  - An example `Fun4All` macro for condor can be found here: `offline/AnalysisTrain/SpinAnalyzer/macros/Fun4FVTX_RecoDST_SpinAna.C`
- User code input selected good event and binning of kinematic bins. An example user code is at `offline/AnalysisTrain/SpinAnalyzer/saModuleSimpleDimuon.*`
- The spin information is directly loaded from the Spin Database through the standard USpin interface (`offline/packages/uspin/`). The newest database QA level is used at the time when `SpinAnalyzer` is run.
- The output from `SpinAnalyzer` is histograms of counts which is categorized with respect to spin combinations. And if chosen, it will also outputs histograms containing the single and double spin-asymmetry results.
- More features are discussed in SpinFest2014 tutorial `https://www.phenix.bnl.gov/phenix/WWW/p/draft/jinhuang/Meetings/2014.07.22%20SpinFest/SpinAnalyzer.pdf`

Users are welcomed to use `SpinAnalyzer` to carry out the asymmetry analysis or use it to cross check the results from their independent analysis code. The latter approach was adopted for this analysis, since this is the first analysis that `SpinAnalyzer` is used for preliminary results in PHENIX.

3.2 This Analysis

In this analysis the main analysis module is in CVS: `offline/analysis/Jpsi_A_LL`

We also used `SpinAnalyzer` to cross check the results. The user input module for `SpinAnalyzer` is located in CVS `offline/AnalysisTrain/SpinAnalyzer/saModuleDimuonJpsiHaiwang.*`

For the cross-check purpose, we pick up a typical indicator: $A_{LL}^{incl.}$. However this time point, there is a know difference in the code:

- For the `Jpsi_A_LL module`, different arm and p_T bins have different mass window derived from fitting. For `SpinAnalyzer` , right now we are using fixed mass window: $2.7GeV \sim 3.5GeV$

The result is shown in Figure 3. This result now shows there is no big bug in the `Jpsi_A_LL module`. Will update this result to make better cross-check.

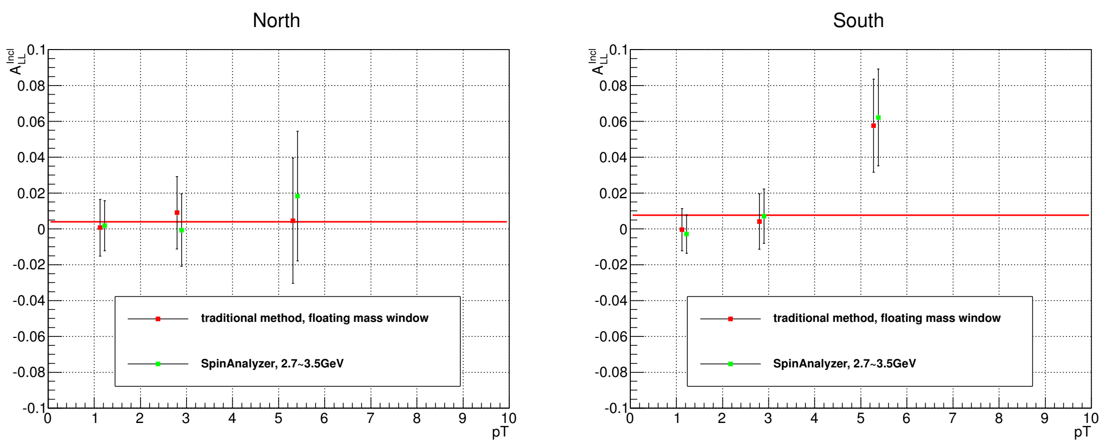

Figure 3: cross-check $A_{LL}^{incl.}$ using `SpinAnalyzer` , floating mass window for traditional method, fixed mass window for `SpinAnalyzer`

4 J/ψ double spin asymmetries

Equation 1, 2 shows how we extract the physics J/ψ double spin Asymmetry.

$$A_{LL}^{J/\psi} = \frac{A_{LL}^{incl} - r \cdot A_{LL}^{BG}}{1 - r}, \tag{1}$$

$$\Delta A_{LL}^{J/\psi} = \frac{\sqrt{(\Delta A_{LL}^{incl})^2 + r^2 \cdot (\Delta A_{LL}^{BG})^2}}{1 - r}. \tag{2}$$

where $r = N^{BG}/N^{incl} = (N^{incl} - N^{signal})/N^{incl}$ is the background fraction which comes from section 2. A_{LL}^{incl} is the inclusive dimuon asymmetry within 2 σ mass window cut. A_{LL}^{BG} is the background asymmetry which we estimate from the sideband dimuon.

4.1 run clustering

If calculate J/ψ asymmetry run-by-run, then due to the low counting of J/ψs in a run, the uncertainty would be non-Gaussian for a lot of runs. So traditionally, we calculate J/ψ asymmetry fill-by-fill. The advantage of fill-by-fill grouping is parameters such as polarization, spin pattern for each crossing etc. are the same for each fill. For this reason, in this section, most of distributions are given fill-by-fill. On the other hand, due to MuID efficiency is luminosity dependent, and the luminosity from the start of a fill to the end could change from $\sim 5MHz$ to $\sim 2MHz$. So Aaron proposed another run clustering method based on MuID efficiency. See [4] [6]. We tried both these 2 methods, and we feel that Aaron's clustering makes more sense. So for the final result, we use Aaron's clustering as the central value. And take the difference as one systematic uncertainty. Details are in section 5

4.2 Relative Luminosity

Since the statistic error is dominated in this analysis, The relative luminosity is calculated from BBC scalar directly from the database. Right now, There is no further corrections.

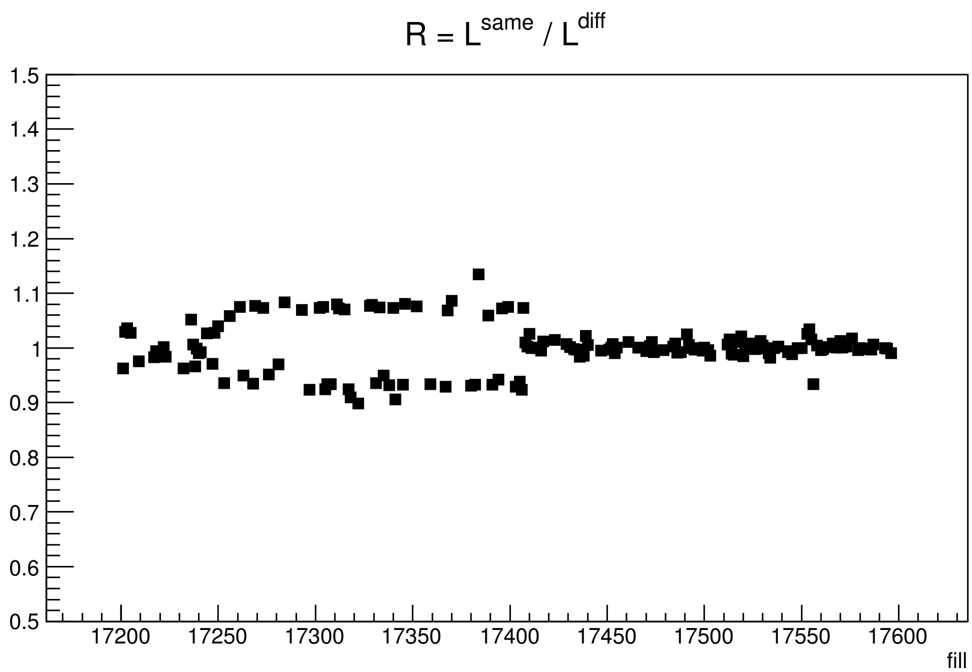

Figure 4: Relative Luminosity for run13.

4.3 Beam Polarization

The beam polarization also come from the spin database. The fill-by-fill beam polarization for blue and yellow beams are shown in Fig. 5. The luminosity weighted average polarizations are:

$$P_B = 0.55 \pm 0.02\,(\text{syst.}) \tag{3}$$
$$P_Y = 0.56 \pm 0.02\,(\text{syst.}). \tag{4}$$

The systematic uncertainty is given to be 0.02 same as used in ppg169.

4.4 Inclusive Asymmetries A_{LL}^{incl}

The inclusive dimuon asymmetry and background asymmetry are calculated group-by-group (fill-by-fill here) with

$$A_{LL}^{incl,BG} = \frac{\sigma^{++} + \sigma^{--} - \sigma^{+-} - \sigma^{-+}}{\sigma^{++} + \sigma^{--} + \sigma^{+-} + \sigma^{-+}} \tag{5}$$
$$= \frac{1}{P_B P_Y} \frac{\frac{N^{++}}{L^{++}} + \frac{N^{--}}{L^{--}} - \frac{N^{+-}}{L^{+-}} - \frac{N^{-+}}{L^{-+}}}{\frac{N^{++}}{L^{++}} + \frac{N^{--}}{L^{--}} + \frac{N^{+-}}{L^{+-}} + \frac{N^{-+}}{L^{-+}}} \tag{6}$$

Inclusive dimuon fill-by-fill asymmetry are shown in Figure 6

We fit the fill-by-fill asymmetry and get the fill averaged inclusive dimuon asymmetry vs p_T is shown in Figure 7

4.5 Background Asymmetries A_{LL}^{bkg}

The background asymmetry under the J/ψ peak cannot be measured directly. In this analysis, we use similar estimation method as described in [7].

We use the lower side-band ($1.5 \sim 2.5GeV$) unlike-sign dimuon to estimate the background asymmetry under J/ψ. As shown in Figure **??**, this region is out of J/ψ peak by 3σ and the low end does not reach the ρ, ω resonances at $\sim 1GeV$. Figure 8 shows the lower side band background fill-by-fill asymmetry.

We fitted the fill-by-fill asymmetry and got the fill averaged lower side-band background dimuon asymmetry vs p_T is shown in Figure 9

There is an assumption that the asymmetry from side-band is a good estimation of the background asymmetry under the peak. In other words, there is no invariant mass dependence of this asymmetry. To confirm this assumption, we divided the side band into 2 invariant mass bins: $1.5GeV \sim 2.0GeV$ and $2.0GeV \sim 2.5GeV$. The result is shown in Figure 10. Based on this result we would say no mass dependence of the background asymmetry is observed beyond the expected statistical fluctuation. Therefore, for this preliminary result, we would argue that the inv.mass dependence of asymmetry

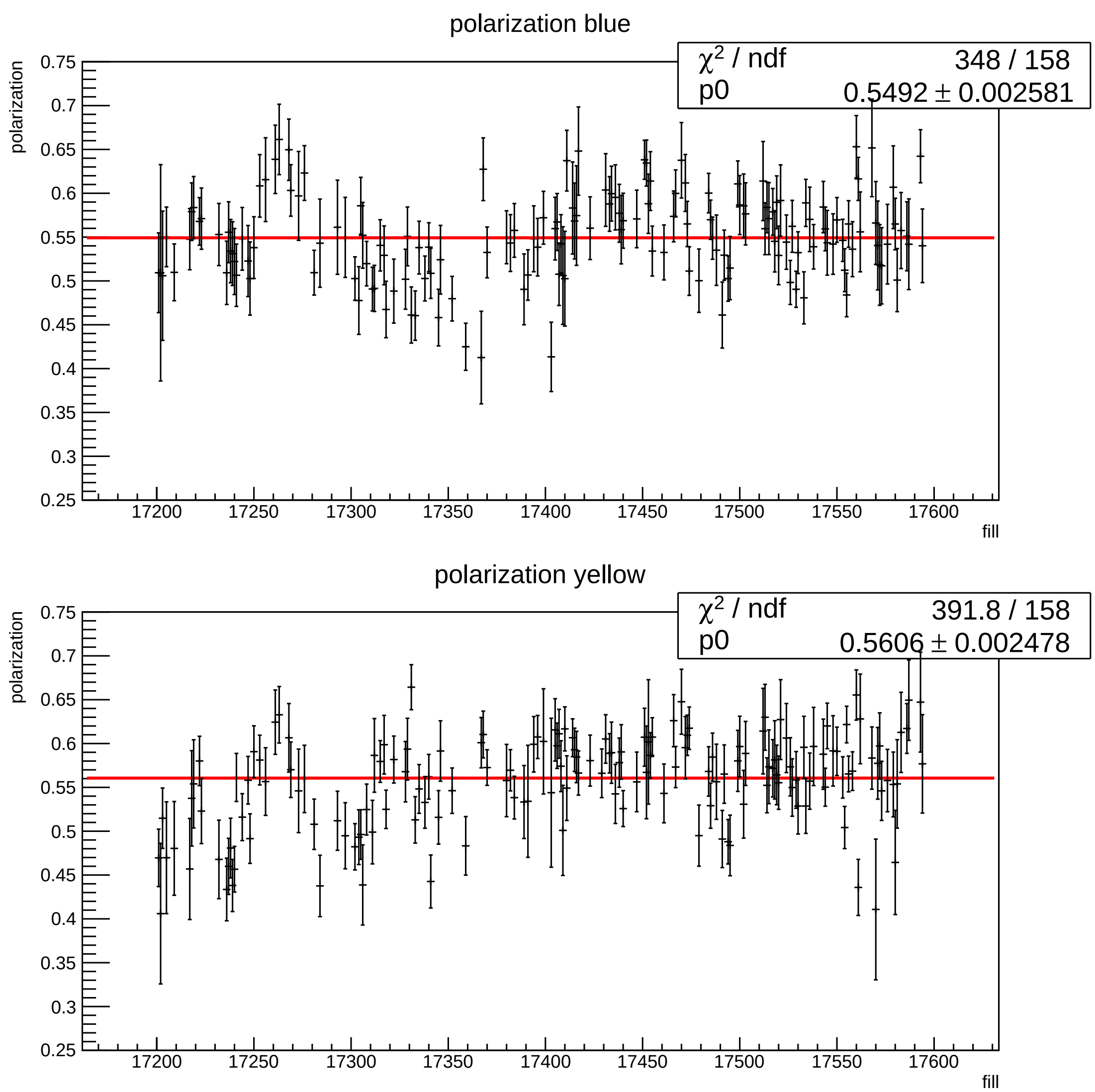

Figure 5: The blue and yellow beam fill-by-fill polarization.

is negligible comparing to the relative large statistical uncertainty ($\sim 2\% \sim 6\%$) we already assigned to the background asymmetry. Nevertheless, for future publication, we will further quantify its max size.

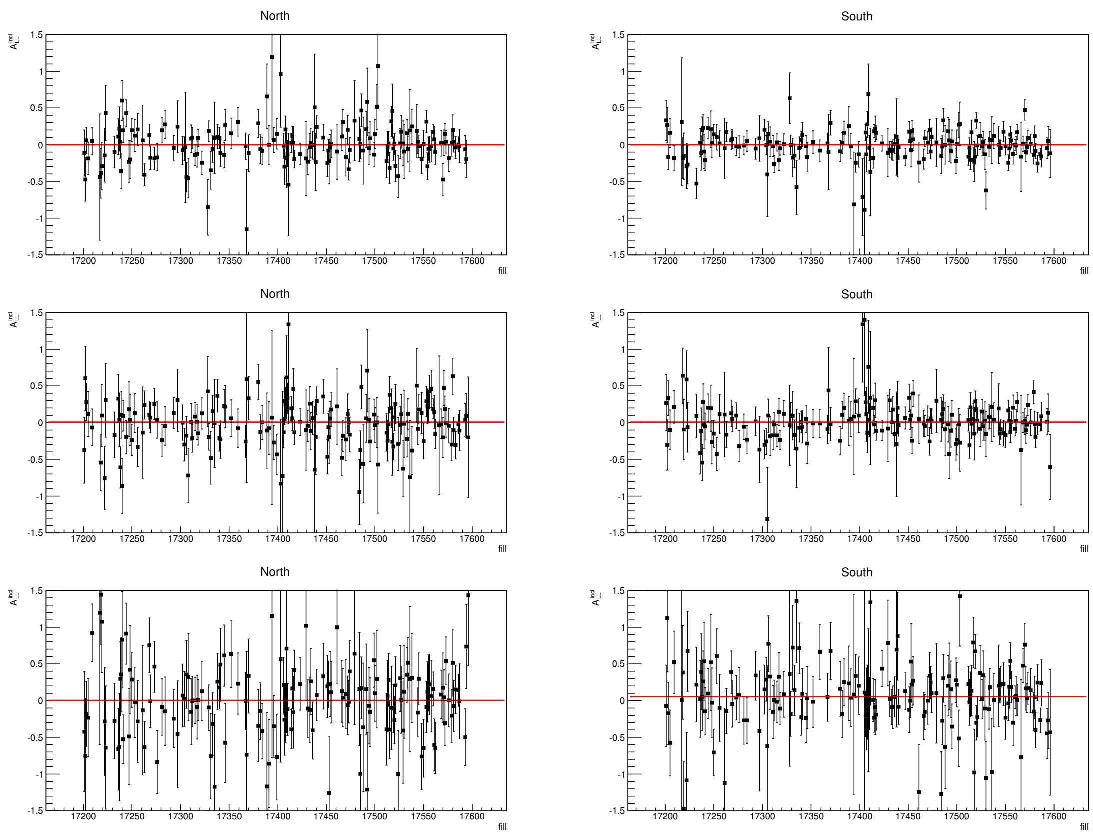

Figure 6: Inclusive J/ψ peak region dimuon fill-by-fill asymmetries for three p_T bins (0-2, 2-4 and 4-10 GeV from top to bottom). The left column are is for north muon arm and right hand column is for south muon arm.

4.6 Physics Asymmetries $A_{LL}^{J/\psi}$

We use formula 1 to extract the physics asymmetry. And use formula 2 to extract the statistical uncertainty. The statistical uncertainty from background fraction r is combined with systematic uncertainty of r and will propagate into the final systematic uncertainty. See 5.

Figure 11 shows the physics asymmetry vs p_T with statistical uncertainty derived from Figure 7, 9 and the formula 1, 2

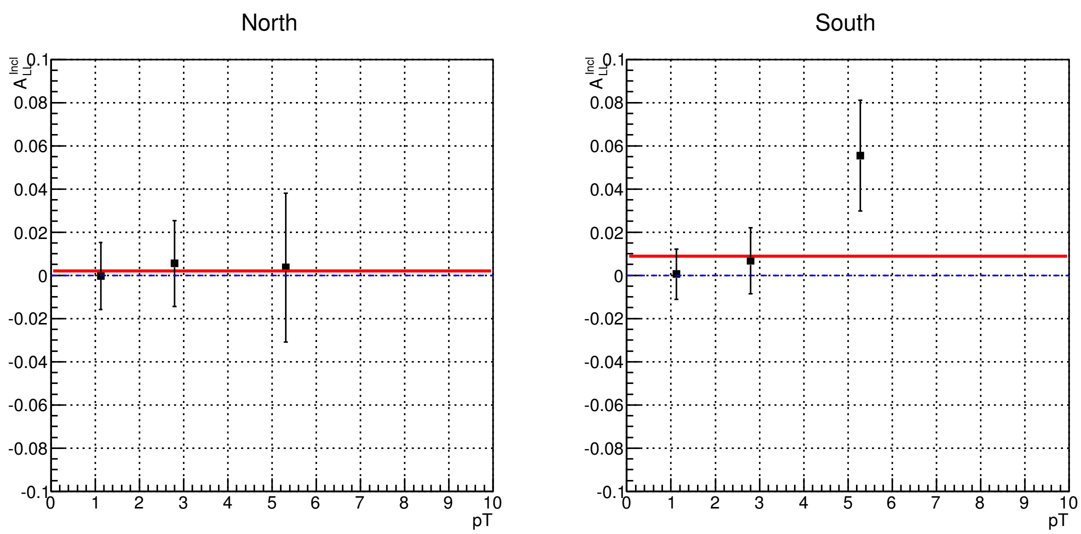

Figure 7: Inclusive dimuon vs p_T for north and south muon arm.

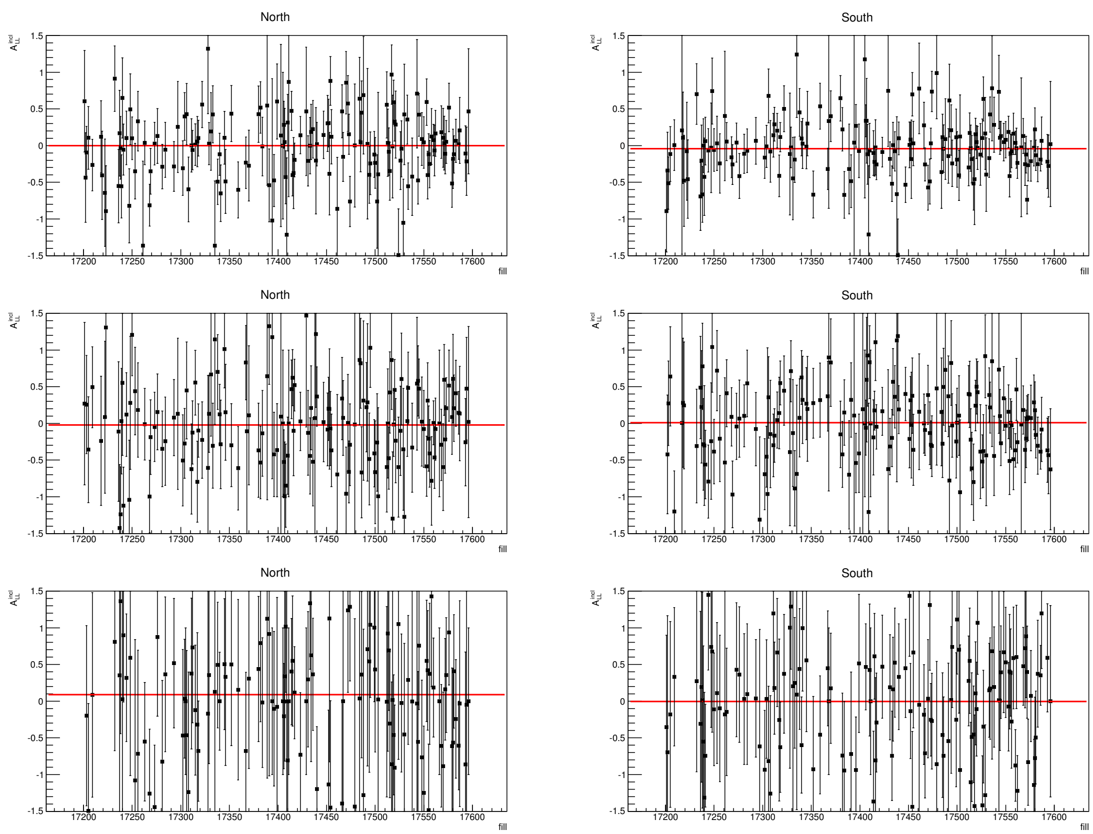

Figure 8: side-band dimuon fill-by-fill asymmetries for three p_T bins (0-2, 2-4 and 4-10 GeV from top to bottom). The left column are is for north muon arm and right hand column is for south muon arm.

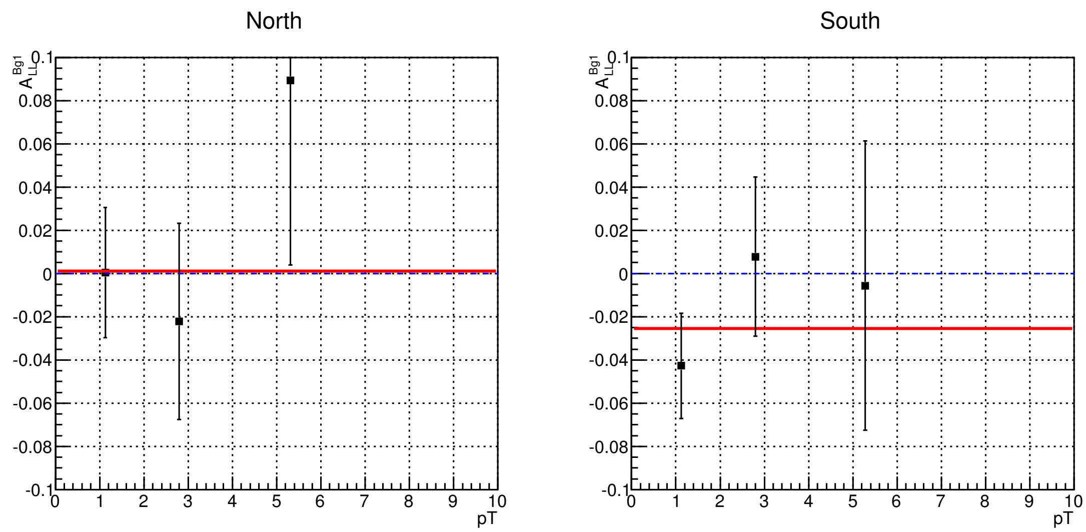

Figure 9: unlike-sign dimuon in lower side-band vs p_T for north and south muon arm.

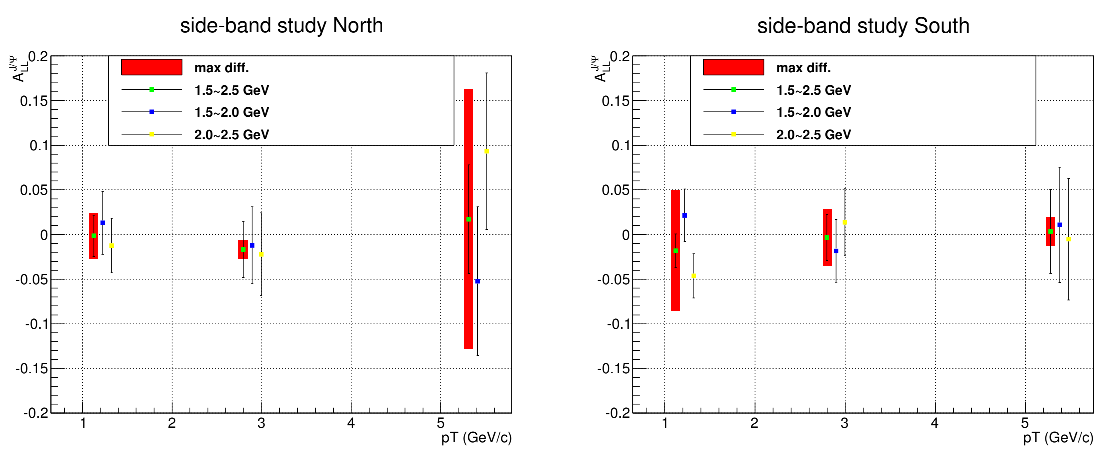

Figure 10: Invariant mass dependence of the background asymmetry

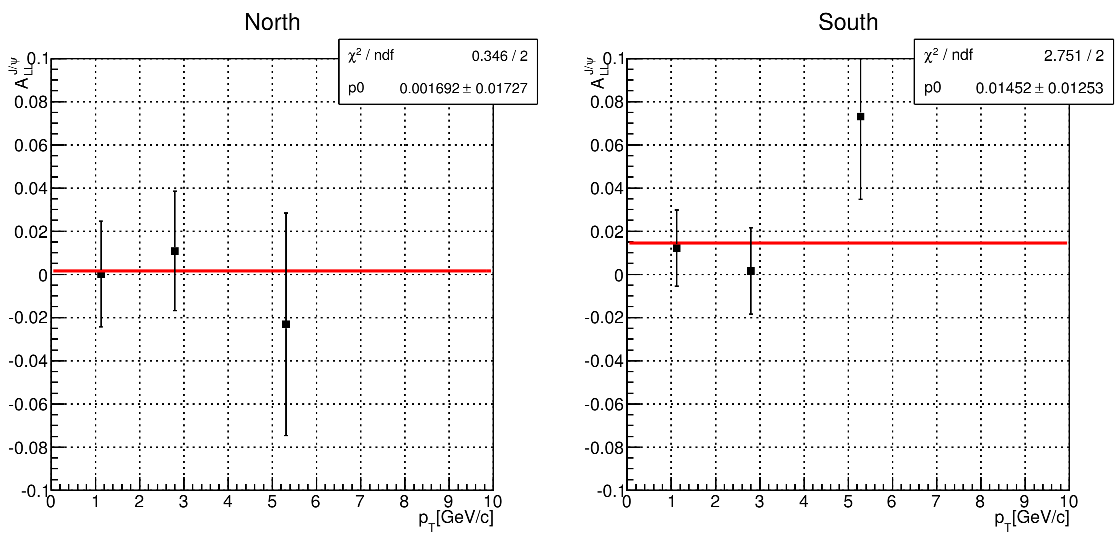

Figure 11: J/ψ A_{LL} vs p_T for north and south muon arm.

5 Systematic Uncertainty Study

In this section the results of a number of systematic studies are presented where the stability of the result is being probed.

5.1 bunch shuffling results for double spin asymmetry A_{LL}

Shuffling the assigned spin direction for each bunch is a method to check for bunch related false asymmetries. Those can occur if the acceptance or efficiency of the trigger or the detector depend on the bunch structure or the timing. By definition the average asymmetries with randomized spins are zero, but the distribution of asymmetries from many randomized samples would be wider than expected. Bunch shuffling is not sensitive to any physics related asymmetry, i.e., an asymmetry of the MiniBias trigger physics itself, background asymmetries or trigger biases. Of course, bunch shuffling is only sensitive to effects of a similar magnitude as the statistical error of the asymmetry.

The systematic bias has been checked with bunch shuffling. The procedure is:

1) randomly reassign the polarization direction for each bunch crossing,

2) recalculate the asymmetry,

3) repeat many times(in our case is 10000) to produce a shuffled asymmetry distribution centered around zero,

4) compare width of shuffled distribution to statistical error on the physics asymmetry.

Figure 12 shows dimuons double spin asymmetry from bunch shuffling. The mean value is consistent with zero and the normalized RMS is close to 1, which indicates that all other non correlated bunch-by-bunch and fill-by-fill systematic errors are much smaller than the statistical errors. This also means the statistical errors are properly assigned to double spin asymmetry values.

5.2 Systematic Errors

In the current analysis, the following several systematic uncertainties were considered in this J/ψ A_{LL} study.

5.2.1 fill-by-fill vs clustering

Traditionally we group runs fill-by-fill for the J/ψ asymmetry analysis. However, in Run13, From the beginning to the end of a fill, the BBC rate can drop from $\sim 5MHz$ to $\sim 2MHz$. And it is already shown that the MuID efficiency is highly luminosity correlated. So a better solution of run clustering may be group runs based on MuID efficiency. Details about this could be find in [6].

Another way of grouping the runs are simply put all the runs in one group.

Figure 13 shows the systematic uncertainty from using different run clustering method. We choose using Aaron's run clustering as the central value and use the maximum difference of these 3 methods as the systematic uncertainty.

5.2.2 uncertainty of S/B ratio from invariant mass fitting

Another source of the systematic uncertainty came from the background fraction determination. We use the statistical error from section 2. And as Aaron has already did a very nice fitting study. We use his systematic uncertainty for fitting listed in Table 7 of [6]. The stat. and sys. error of the background fraction r is summarize in Table 1. And the sys. err. propagated to the asymmetry from the fitting is shown in Figure 14.

5.3 Summary and Final result

The final J/ψ A_{LL} result with systematic errors mentioned above is shown in Figure 15 and summarized in Table 2. The systematic error from relative luminosity is assigned to 0.1% according to [6].

Table 2: Final asymmetry result for Run13

North

$p_T GeV/c$	$< p_T > GeV/c$	$A_{LL} \pm A_{LL}^{stat.} \pm A_{LL}^{sys.}$
0 - 2	1.13	$0.004 \pm 0.024 \pm 0.004$
2 - 4	2.79	$0.019 \pm 0.027 \pm 0.004$
4 - 10	5.31	$0.008 \pm 0.050 \pm 0.008$

South

$p_T GeV/c$	$< p_T > GeV/c$	$A_{LL} \pm A_{LL}^{stat.} \pm A_{LL}^{sys.}$
0 - 2	1.12	$0.008 \pm 0.018 \pm 0.001$
2 - 4	2.80	$0.009 \pm 0.020 \pm 0.005$
4 - 10	5.28	$0.083 \pm 0.037 \pm 0.010$

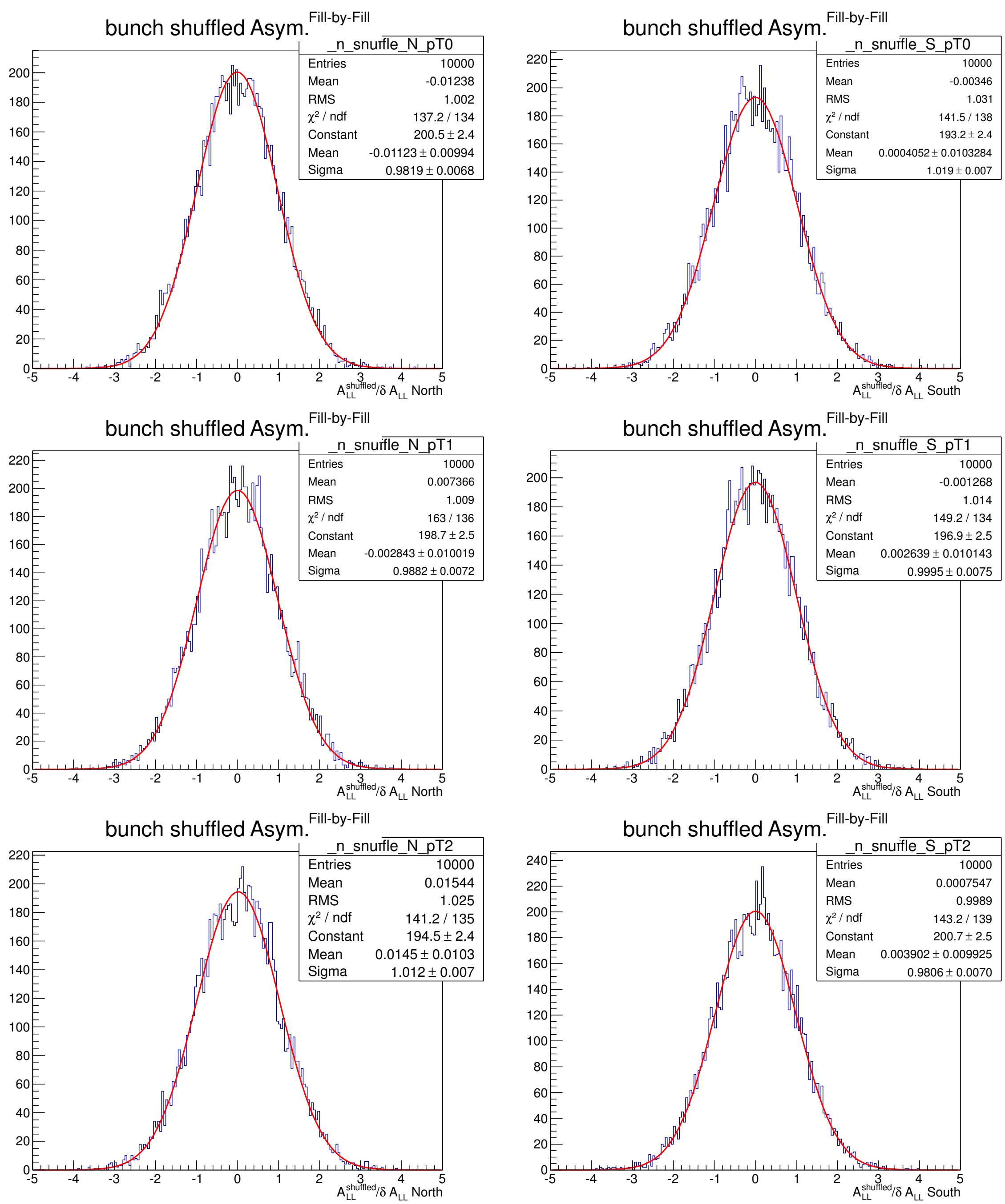

Figure 12: Bunch shuffled asymmetry for three p_T bins (0-2, 2-4 and 4-10 GeV from top to bottom). The left column are is for south muon arm and right hand column is for north muon arm.

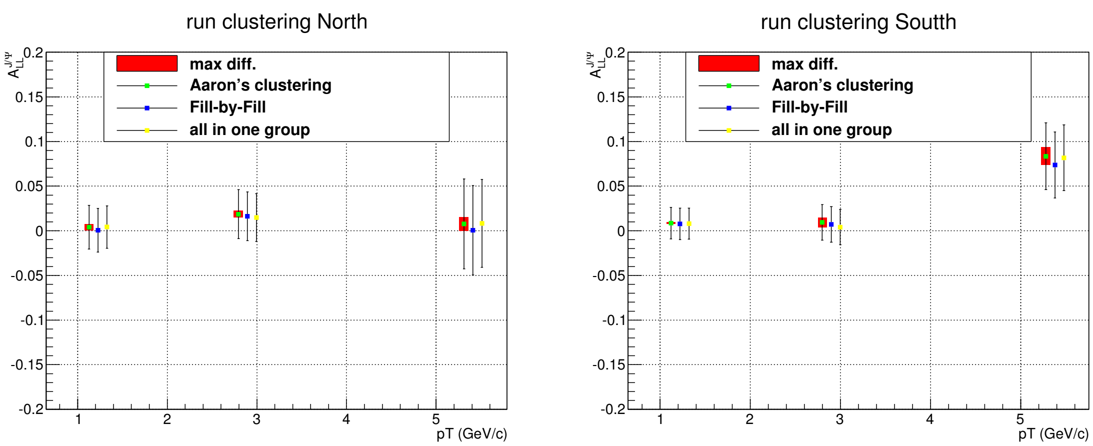

Figure 13: Sys. uncertainty from using different run clustering method

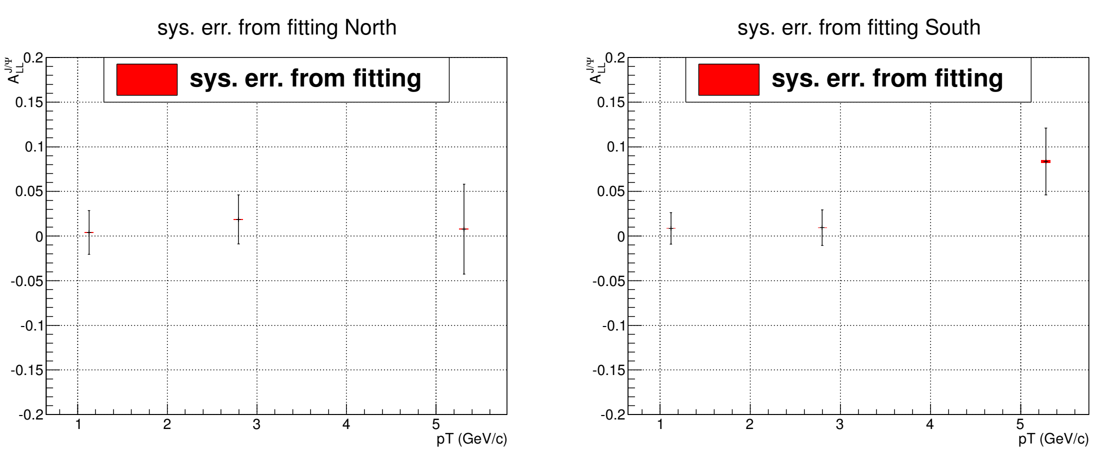

Figure 14: Sys. uncertainty from backgroud fraction extraction, using Aaron's sys. uncertainty for the fraction

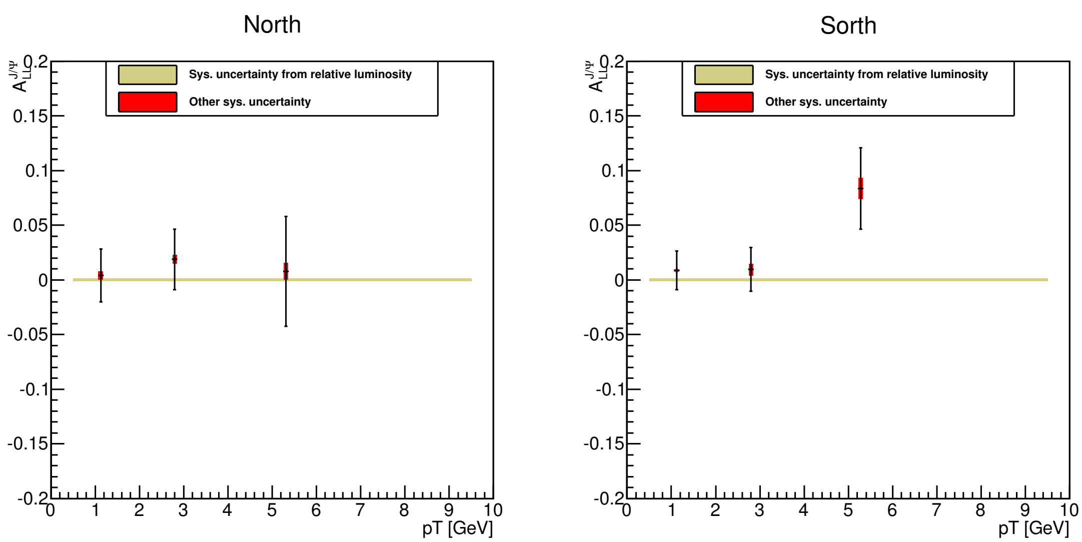

Figure 15: Final Run13 J/Ψ A_{LL} result with systematic uncertainty

6 Calculation $A_{LL}^{J/\psi}$ using Pythia 6 and NNPDFpol1.1

There were several NRQCD calculations of the $A_{LL}^{J/\psi}$ for RHIC energies $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV [10] with the old Gehrmann-Stirling and other polarized parton distribution functions [4]. Our knowledge of quark and gluon polarizations has been significantly improved over the last 10 years [2, 8]. In order to compare our results with the current understanding of the gluon polarization, we have estimated the $A_{LL}^{J/\psi}$ in our kinematics using the Pythia 6 [9] simulation with NNPDFpol1.1 [8] and NNPDF2.3 [1] as the polarized and unpolarized PDF respectively. To further simplify the asymmetry calculation, we have assumed $\hat{a}_{LL}^{gg\to J/\psi+X} = 1$, which is the leading order partonic asymmetry for open heavy quarks in the heavy mass limit at RHIC energies [5].

The procedures were:

- Simulate $p + p \to J/\psi + X$, $J/\psi \to \mu^+ + \mu^-$ events using Pythia 6.
- Filter the events using $1.2 < \eta_\mu < 2.2$.
- Then for each event, grab the p_T, y and the $x1$, $x2$. Then calculate $A_{LL}^{J/\psi}$ using:

  $$A_{LL} = \hat{a} \cdot \frac{\Delta g(x1)\Delta g(x2)}{g(x1)g(x2)} \quad (7)$$

  in which we assume $\hat{a}$ is 1. The $\Delta g(x)$s are obtained from NNPDFpol1.1 and the $g(x)$'s are obtained from NNPDF2.3. We used the LHAPDF library as the interface.
- A 2σ range was also estimated using the replica method [3].

The estimated asymmetry is shown in Fig. 16 together with the PHENIX data.

We averaged all simualtion events' $A_{LL}^{J/\psi}$ and got the $\pm$ 2 σ range for the asymmetry for our kinematics was approximately -0.008 to $+0.008$. The estimation is consistent with our data within the statistical uncertainties.

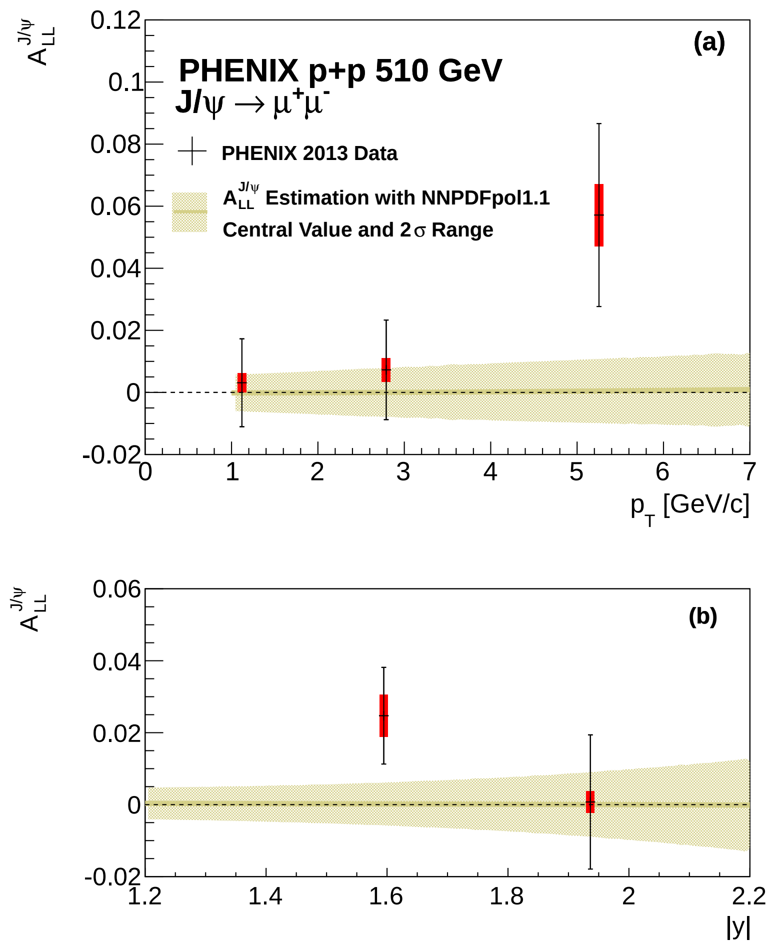

Figure 16: $A_{LL}^{J/\psi}$ as a function of p_T (top panel) and $|y|$ (bottom panel). The black error bars show the statistical uncertainty. The red boxes show only the Type A systematic uncertainties. There are additionally a 4×10^{-4} global systematic uncertainty from the relative luminosity determination and a 6.5 % global scaling systematic uncertainty from the polarization magnitude determination for all p_T or $|y|$ bins. The yellow curve with shaded band is our $A_{LL}^{J/\psi}$ estimation using PYTHIA 6 [9] simulation with NNPDF datasets under the assumption of $\hat{a}_{LL}^{gg\to J/\psi+X} = 1$. The solid yellow curve is the central value and the yellow shaded band is the $\pm$ 2 σ uncertainty range. See details in the text.

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