**Spin physics with STAR at RHIC**

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Our group continues to play major roles in STAR investigations of both longitudinal and transverse spin phenomena in polarized *pp* collisions at RHIC. During the past year, we have been working to finalize several of the analyses that were discussed in last year's *Progress in Research*.

A major goal of the RHIC spin program is to determine the gluon polarization in the proton over a wide range of momentum fraction $x$. The longitudinal double-spin asymmetry, $A_{LL}$, for inclusive jet production is an ideal tool in this effort because the cross section is large and dominated by quark-gluon and gluon-gluon scattering processes, both of which have large partonic asymmetries. Our paper describing the final $A_{LL}$ results for inclusive jets at $\sqrt{s}$ = 200 GeV, based on data that STAR recorded during 2009, was published in *Physical Review Letters* this past year [1]. It was chosen to be an Editors' Suggestion article. The implication of the results, that the gluons in the proton with $x > 0.05$ have their spins preferentially aligned with the proton spin, was called "a significant breakthrough" in the 2015 NSAC Long-Range Plan.

As reported last year, we presented preliminary results at the SPIN 2014 conference in Beijing on $A_{LL}$ for inclusive jets at a higher beam energy, $\sqrt{s}$ = 510 GeV, based on data that STAR recorded during 2012. The higher beam energy extends the sensitivity to gluon polarization to lower $x$ gluons. Since then, we have been working to on the steps necessary to complete the final analysis.

The larger phase space for soft particle production at 510 GeV relative to 200 GeV produces a substantial increase in the underlying event (UE) activity. This can distort the jet finding, especially for low-$p_T$ jets. An additional concern is that the UE activity might itself have a spin asymmetry that could distort measurements of the jet $A_{LL}$. For the preliminary result, we required $p_T > 7.1$ GeV to minimize these systematic effects. We want to lower the $p_T$ cut-off for the final result further to enhance our sensitivity to low-$x$ gluon polarization. We also want to obtain a direct experimental estimate of the UE $A_{LL}$ to set a limit on its contribution to our measured jet asymmetries. A PYTHIA study showed that we could substantially reduce our sensitivity to UE contributions by implementing an "off-angle cone" subtraction procedure, similar to that used for *pp* collisions by ALICE [2]. Thus, we developed the tools necessary to match each reconstructed jet with the charged-particle tracks and calorimeter towers present in two cones at the same pseudorapidity as the jet, but offset azimuthally from the jet by $\Delta\varphi = \pi/2$. The STAR TPC and BEMC are symmetric under such a rotation, which makes this procedure particularly attractive. Furthermore, the procedure also provides an approximate subtraction of pile-up backgrounds, which are much larger in 510 GeV *pp* collisions than in 200 GeV collisions. We are now using the new tools both to subtract the UE and pile-up contributions and to measure the UE $A_{LL}$ for the first time. The tools that we developed will also be utilized to subtract combinatorial background for jet analyses in *p*+A collisions.

Preliminary measurements of pion azimuthal distributions in jets utilizing 500 GeV data that STAR recorded during 2011 indicated that the Perugia-0 tune that we've used for PYTHIA in previous

200 GeV analyses has shortcomings when applied to 500 GeV collisions. Therefore, our group, in collaboration with colleagues from University of Kentucky, undertook a study to find PYTHIA parameters that would simultaneously describe jet data at 200 and 500 GeV. We found that the Perugia-2012 tune provides a good description of the jets, but produces too much UE activity. Reducing the PARP(90) parameter from 0.24 (default for Perugia-2012) to 0.213 provides the best compromise between good jet and UE descriptions. The STAR Spin PWG has now adopted this combination for all on-going jet analyses.

We have now completed the reanalysis of the 2012 inclusive jet data with the off-axis cone subtraction implemented, and are about to start the production of the Monte Carlo embedding simulations required to calculate corrections for jet energy scale distortions and trigger and reconstruction bias. We will complete the final 2012 inclusive jet $A_{LL}$ analysis within the coming year.

In last year's *Progress in Research*, we described the first measurements of the "Collins effect" in transversely polarized *pp* collisions. The Collins effect involves the convolution of the quark transversity distributions in the proton with the Collins fragmentation function. The net result is to produce an azimuthally asymmetric distribution of charged pions within jets. During the past year, first calculations [3] of the Collins effect have been performed for STAR kinematics, as shown in Fig. 1. These

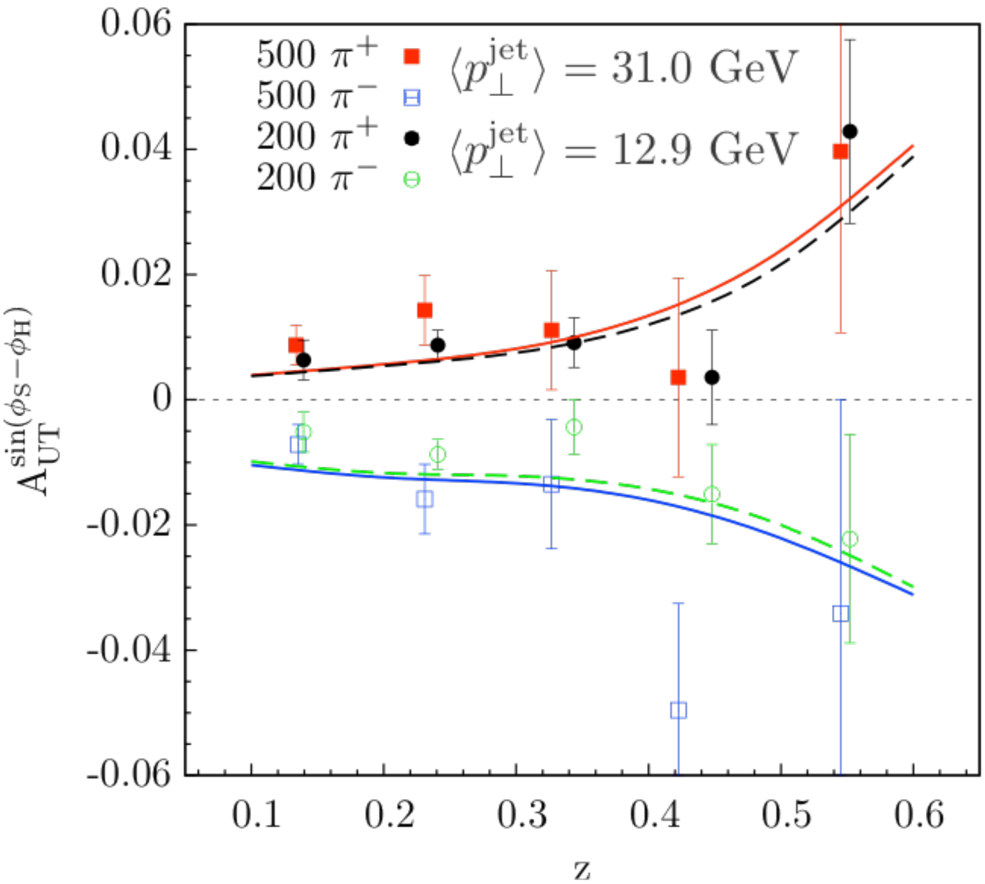


**FIG. 1.** A comparison of our preliminary measurement of the Collins effect in 200 and 500 GeV *pp* collisions with recent calculations from [3].

calculations are based on global analyses of the Collins fragmentation function from $e^+e^-$ collisions and transversity extracted from semi-inclusive deep-inelastic scattering (SIDIS). The good agreement between the preliminary STAR results and the Collins effect calculations provide the first ever test of the predicted universality of the Collins effect for SIDIS and *pp* collisions. It's also important to recognize that the calculations do not include any TMD evolution effects for the Collins fragmentation function. $Q^2 \sim 1000$ GeV$^2$ for the 500 GeV STAR data, approximately two orders of magnitude larger than for the SIDIS data at the comparable $x$ value. This might indicate that TMD evolution effects are small, or perhaps they tend to cancel between the polarized numerator and the unpolarized denominator for asymmetry measurements like this.

For the preliminary analysis, we estimated the kaon, proton, and electron contaminations with simple 4-Gaussian fits to the measured TPC *dE/dx* distributions. We used the same procedure while preparing a first draft paper describing these results, together with collaborators from Lamar University, University of Kentucky, and Valparaiso University. The paper also described measurements of asymmetries in lower-$p_T$ jets. During the God-Parent Committee review of our draft, concerns were raised about similar particle identification procedures for a different STAR spin analysis. Although the concerns had not been directed toward analysis, we quickly realized that they could also apply to the lower-$p_T$ pions that we use to investigate gluon linear polarization. During the past year, we have developed far more sophisticated procedures for particle identification. The net result for the high-$p_T$ jets, relevant for the Collins effect measurement, is a substantial reduction in the systematic uncertainties at the expense of a small loss of statistics. We expect the same will be true for the lower-$p_T$ jets that provide information about gluon linear polarization, but that analysis is not quite complete yet. We are now writing a letter describing the Collins effect results, while working in parallel to complete the lower-$p_T$ jet analysis.

[1] L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. Lett. **115**, 092002 (2015).
[2] B. Abelev *et al*. (ALICE Collaboration), Phys. Rev. D **91**, 112012 (2015).
[3] Z. Kang *et al*., (to be submitted).