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Transverse Spin Asymmetries in the $p^{\uparrow}p \to p\pi^0 X$ Process at STAR

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A significant sample of $p^{\uparrow}p \to p\pi^0 X$ events has been observed at STAR in $\sqrt{s} = 200$ GeV transversely polarized pp collisions, where an isolated π^0 is detected in the forward pseudorapidity range $2.65 < \eta < 3.9$ along with the forward-going proton p, which scatters with a near-beam forward pseudorapidity into Roman Pot detectors. The sum of the π^0 and the scattered proton energies is consistent with the incident proton energy of 100 GeV, indicating that no further particles are produced in this direction. It is postulated that the forward incident proton may have fluctuated into a $p+\pi^0$ system, with an angular momentum correlated with the initial proton spin. The backward-going proton interacts with the $p+\pi^0$ system, which then separates such that the π^0 has a transverse momentum of $\sim$2 GeV/c and the proton has a transverse momentum of $\sim$0.2 GeV/c, while the backward proton shatters into the remaining particles X. Correlations between the π^0 and scattered proton will be presented, along with single-spin asymmetries which depend on the azimuthal angles of both the pion and the proton. This is the first time that spin asymmetries have been explored for this process, and a model to explain their azimuthal dependence is needed.

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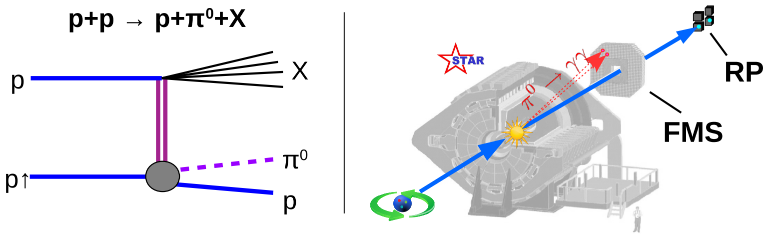

Figure 1: Left: schematic of $p^{\uparrow}p \to p\pi^0 X$. Right: schematic of detectors, the Forward Meson Spectrometer (FMS) for the $\pi^0 \to \gamma\gamma$ (red dashed arrows) and the Roman Pots (RP) for the proton (blue solid arrow).

1. Motivation

The transverse single-spin asymmetry, A_N, is an observable that probes the spin structure of the proton. It is defined via

$$A(\phi) = \frac{d\sigma^{\uparrow}(\phi) - d\sigma^{\downarrow}(\phi)}{d\sigma^{\uparrow}(\phi) + d\sigma^{\downarrow}(\phi)} = A_N \cos\phi, \tag{1.1}$$

where $d\sigma^{\uparrow(\downarrow)}(\phi)$ is a differential cross section, *e.g.*, for π^0 production, with azimuthal angle ϕ, from a spin-up(down) proton $p^{\uparrow(\downarrow)}$ scattering off an unpolarized proton. The spin asymmetry $A(\phi)$ is modulated by $\cos\phi$, and the amplitude is denoted by A_N. If $\phi = 0$ represents leftward π^0 production, then a positive A_N indicates spin-up(down) proton scattering favors producing π^0s to the left(right).

A_N for forward π^0s rises with Feynman-x and is independent of center-of-mass energy $\sqrt{s}$ [1, 2]; moreover, A_N is systematically larger for isolated π^0s than for those not as isolated [3, 4]. Several models have been proposed to explain the origin of this large A_N [5–8], and although the most promising of these involves a novel twist-3 fragmentation process [8], the origin of the π^0-isolation dependence remains unclear.

A possible channel for isolated π^0 production is the $p^{\uparrow}p \to p\pi^0 X$ process, as shown schematically in the left panel of figure 1. The forward polarized proton $p^{\uparrow}$ scatters off the backward proton p; the forward proton is deflected slightly with the production of a forward π^0, while the backward proton fragments into remnants denoted by X. By energy conservation, the sum of the deflected proton and forward π^0 energies is equal to or less than the incident proton energy, while the observed π^0 and proton transverse momentum sum should balance that of X.

Further study is needed to understand the $p^{\uparrow}p \to p\pi^0 X$ underlying mechanism, and especially its spin dependence. One possible model assumes the $p^{\uparrow}$ fluctuates into a $p+\pi^0$ state, with the π^0 in the proton periphery; if the π^0 scatters off another proton such that the $p+\pi^0$ state separates, then the π^0 could scatter with a moderate p_T, while the proton recoils at near-beam rapidity. It is thought that the proton angular momentum in the peripheral region is likely dominantly from orbital angular momentum, rather than from parton spin [9]; assuming the orbital angular momentum of the peripheral π^0 correlates to the proton spin, measurements of spin asymmetries in the $p^{\uparrow}p \to p\pi^0 X$ process could be sensitive to proton peripheral angular momentum.

2. Event Selection and Kinematics

The $p^{\uparrow}p \to p\pi^0 X$ process has recently been observed at STAR in transversely-polarized proton-proton scattering at $\sqrt{s} = 200$ GeV during the 2015 RHIC run. The π^0 is measured with the Forward Meson Spectrometer (FMS), a lead-glass electromagnetic calorimeter subtending the forward region $2.65 < \eta < 3.9$ [10], and the deflected proton with the Roman Pots (RP), hodoscopic silicon-strip trackers downstream of the FMS, at near-beam rapidity [11, 12]. The right panel of figure 1 shows the detectors, with overlaying $\pi^0 \to \gamma\gamma$ and proton trajectories.

The π^0s were selected from each event's highest-energy photon pair, with a transverse momentum p_T above the trigger threshold and energy $E_1 + E_2 > 12$ GeV. The invariant mass was constrained to the π^0 mass region and the photons' energy imbalance to $|E_1 - E_2| / (E_1 + E_2) < 0.8$. The proton was required to be detected in at least 7 of the 8 available silicon tracking planes, within geometric acceptance cuts, along with a veto on activity in the RPs in the backwards beam direction.

The selected events included a large contribution from accidental coincidences, for example, two collisions occurring in a single proton bunch crossing, where one collision sent a π^0 to the FMS while the second one was elastic, sending a proton to the RPs. For many of these accidental coincidences, the sum of the π^0 and proton energies, $E_{sum} := E_\pi + E_p$, is greater than the 100 GeV incident proton energy, which would violate energy conservation had the proton and π^0 originated from the same collision. The Beam Beam Counters (BBC), scintillators in both the forward and backward directions subtending $2.1 < |\eta| < 5$, were used with cuts set to reduce the level of accidental coincidences while minimizing the loss of $p^{\uparrow}p \to p\pi^0 X$ candidates. Moreover, evidence of hits in the backward BBC as well as in the central-rapidity Time Of Flight (TOF) detector was seen for all $p^{\uparrow}p \to p\pi^0 X$ events, indicating breakup of the backward-going proton.

The left panel of figure 2 shows a distribution of E_{sum}, and the right panel shows E_p plotted on the vertical axis versus E_π on the horizontal. The peak at $E_{sum} = 100$ GeV represents the $p^{\uparrow}p \to p\pi^0 X$ signal region, since the incident proton has an energy of 100 GeV and, by energy conservation, nothing else scattered in the forward direction; it corresponds to the region between the dashed lines in the right panel. The width of the 100 GeV E_{sum} peak is dominantly from the FMS energy resolution and an event selection of $90 < E_{sum} < 105$ GeV was used for asymmetry analysis event selection.

Since the RPs were designed to see elastic and diffractive-like events, the E_p distribution has a large peak at $E_p = 100$ GeV, which manifests as a band that spans the full E_π range. These events along with any others with E_{sum} above the $p^{\uparrow}p \to p\pi^0 X$ signal region are accidental coincidences, and their E_{sum} distribution likely extends to low E_{sum} as the dominant source of background under the $p^{\uparrow}p \to p\pi^0 X$ peak. The aforementioned BBC cut was tuned to minimize the accidental coincidence background distribution and maximize the $p^{\uparrow}p \to p\pi^0 X$ signal purity.

The resulting events have the following kinematics: the π^0 and proton transverse momenta respectively span $1 < p_{T,\pi} < 4$ GeV/c and $0.1 < p_{T,p} < 0.45$ GeV/c, while their energies span $12 < E_\pi < 35$ GeV and $68 < E_p < 90$ GeV. For about 2/3 of the events, the π^0 and proton are observed back-to-back, with azimuthal angles ϕ_π and ϕ_p such that $\Delta\phi := \phi_\pi - \phi_p \sim \pi$. While the FMS spans the full 2π azimuth, the RP silicon tracking planes are positioned above and below the beam, and $\phi_p \sim 0$ and $\phi_p \sim \pm\pi$, respectively left and right, are outside the RP acceptance.

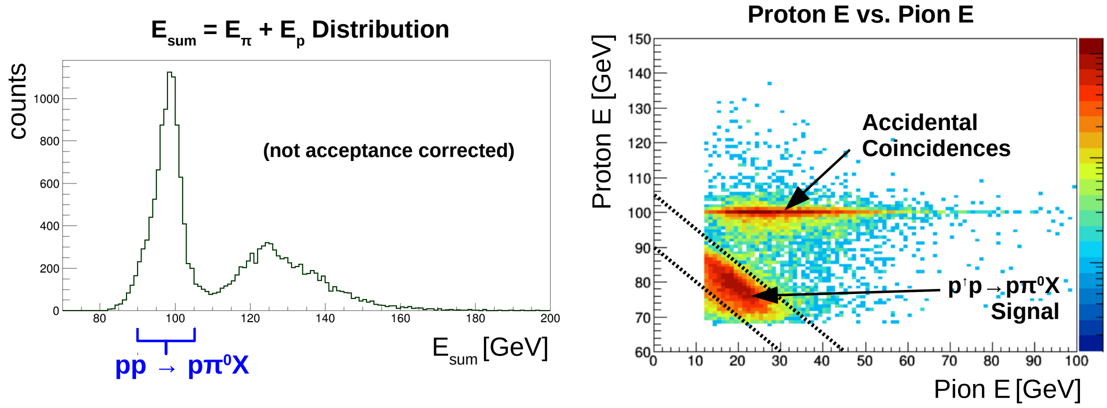

Figure 2: Left: distribution of summed π^0 and proton energies, E_{sum}, shown with the $p^{\uparrow}p \to p\pi^0 X$ selection region. Right: proton energy on the vertical axis plotted against π^0 energy; the region between the dashed lines is the $p^{\uparrow}p \to p\pi^0 X$ selection region.

There is a further limit on ϕ_p, since the RPs are positioned downstream of a RHIC dipole magnet that bends the outgoing beam to the left. This magnet is tuned to bend beam-energy protons appropriately, so any scattered proton with $E_p \sim 100$ GeV is likely to pass within the horizontal extent of the RPs. The $p^{\uparrow}p \to p\pi^0 X$ events, however, have protons with $E_p < 90$ GeV, which are bent more leftward than the 100 GeV protons. Therefore the azimuthal acceptance is biased toward rightward-scattered protons: $\pi/2 < |\phi_p| < \pi$ for 90% of the events. Despite this bias, it is still possible to analyze spin asymmetries which depend on both ϕ_π and ϕ_p; an upgraded RP system is required to characterize $p^{\uparrow}p \to p\pi^0 X$ events with full proton azimuthal acceptance.

3. Asymmetries

Spin asymmetries of the $p^{\uparrow}p \to p\pi^0 X$ process can be modulated by two possible azimuthal angles: ϕ_π and ϕ_p. In general, asymmetries and cross sections can depend on the incident $p^{\uparrow}$ momentum vector $\vec{Z}$, the observed π^0 and proton momentum vectors, respectively $\vec{\Pi}$ and $\vec{P}$, and the $p^{\uparrow}$ spin pseudovector $\vec{S}$ with spin projection $s = \pm\hbar/2$. Physically allowed terms must be Lorentz invariant and parity conserving, *i.e.* scalar, which can be formed by geometric products of momenta and spin. Asymmetry contributions must also depend on spin s and be invariant under rotations. For inclusive π^0 production, the scalar $\left(\vec{Z} \times \vec{\Pi}\right) \cdot \vec{S} \propto s\cos\phi_\pi$ represents the π^0 transverse single-spin asymmetry A_N of equation 1.1.

In $p^{\uparrow}p \to p\pi^0 X$, the additional proton momentum allows for the construction of scalars which depend on both ϕ_p and ϕ_π. Letting $\vec{L}_\pi := \vec{Z} \times \vec{\Pi}$ and $\vec{L}_p := \vec{Z} \times \vec{P}$, a possible scalar that satisfies the aforementioned requirements and depends on both ϕ_p and ϕ_π is

$$\left(\vec{L}_\pi \cdot \vec{L}_p\right)\left(\vec{L}_p \cdot \vec{S}\right) \propto s\cos\phi_p \cos\Delta\phi, \qquad (3.1)$$

which represents the transverse single-spin asymmetry of the π^0 within the scattering plane of the observed proton. Letting $A_{p\pi}$ denote the amplitude of this modulation, $|A_{p\pi}|$ is large when the

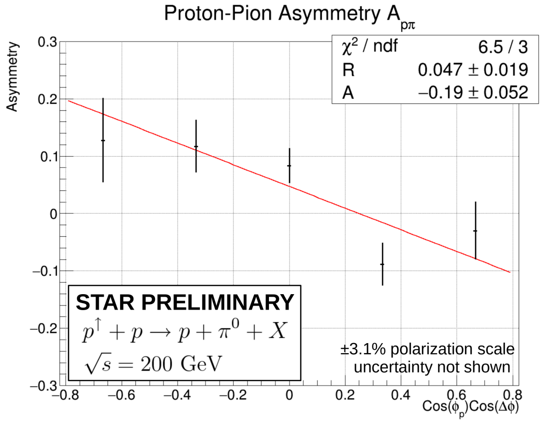

Figure 3: Transverse single-spin asymmetry in bins of $\cos\phi_p\cos\Delta\phi$. A linear fit is included, with constant term R and slope A, and the resulting fit values in the upper right corner.

proton scatters left or right ($\phi_p \sim 0$ or π) and when the π^0 is close to the proton scattering plane ($\Delta\phi \sim 0$ or π). Other possible scalars were tested, but their measured asymmetries were consistent with zero.

Let $N^{\uparrow(\downarrow)}(\phi_\pi, \phi_p)$ denote the yield from a spin-up(down) proton which scatters to a π^0 and proton with respective azimuthal angles ϕ_π and ϕ_p. With P denoting the beam polarization, the single-spin asymmetry was measured following equation 1.1 as

$$A(\phi_\pi, \phi_p) = \frac{1}{P}\frac{N^{\uparrow}(\phi_\pi, \phi_p) - N^{\downarrow}(\phi_\pi, \phi_p)}{N^{\uparrow}(\phi_\pi, \phi_p) + N^{\downarrow}(\phi_\pi, \phi_p)}. \tag{3.2}$$

Figure 3 shows $A(\phi_\pi, \phi_p)$ in bins of $\cos\phi_p\cos\Delta\phi$, including a linear fit with a slope that corresponds to the amplitude of the $\cos\phi_p\cos\Delta\phi$ modulation, $A_{p\pi}$, which evaluates to $-19\% \pm 5.2\%$. The fit's constant term R is included to account for possible nonzero relative luminosity which would systematically shift all data points upward or downward across all $\cos\phi_p\cos\Delta\phi$ bins. The vertical error bars represent statistical uncertainty, and the horizontal error bars are the combined propagated π^0 and proton position uncertainties. The average beam polarization was 56.5% and its uncertainty propagates to a 3.1% systematic uncertainty on the asymmetry scale.

A complementary view of this asymmetry is shown in figure 4, where the $\cos\phi_\pi$ modulation (π^0 A_N) is shown for π^0s which scatter near the proton scattering plane (left panel), where $\Delta\phi$ is within $\pi/6$ radians of 0 or $\pm\pi$, compared to the case where π^0s scatter away from the proton scatter plane (right panel), where $|\Delta\phi \pm \pi/2| < \pi/6$. When the π^0 scatters near the proton scatter plane, it shows an asymmetry of $-20\% \pm 5.7\%$, whereas when the π^0 scatters out-of-plane, the asymmetry is nearly consistent with zero, at $4.5\% \pm 3.8\%$.

Projections of $A_{p\pi}\cos\phi_p\cos\Delta\phi$ onto ϕ_π, ϕ_p, and $\Delta\phi$ were used to assess the impact of the limited ϕ_p acceptance; these are projections of a 2-dimensional asymmetry to 1-dimensional asymmetries and can be cross-checked with the corresponding 1-dimensional asymmetries in the data. Assuming the nominal value of $A_{p\pi} = -0.19$, projections of $A_{p\pi}\cos\phi_p\cos\Delta\phi$ onto 1-dimensional asymmetries modulated by ϕ_π, ϕ_p, or $\Delta\phi$ agree with data only when the ϕ_p acceptance limitations are applied. While the 1-dimensional asymmetries are dependent on the ϕ_p acceptance limitations, the 2-dimensional $A_{p\pi}$ asymmetry is not and seems to most closely match the data. Several

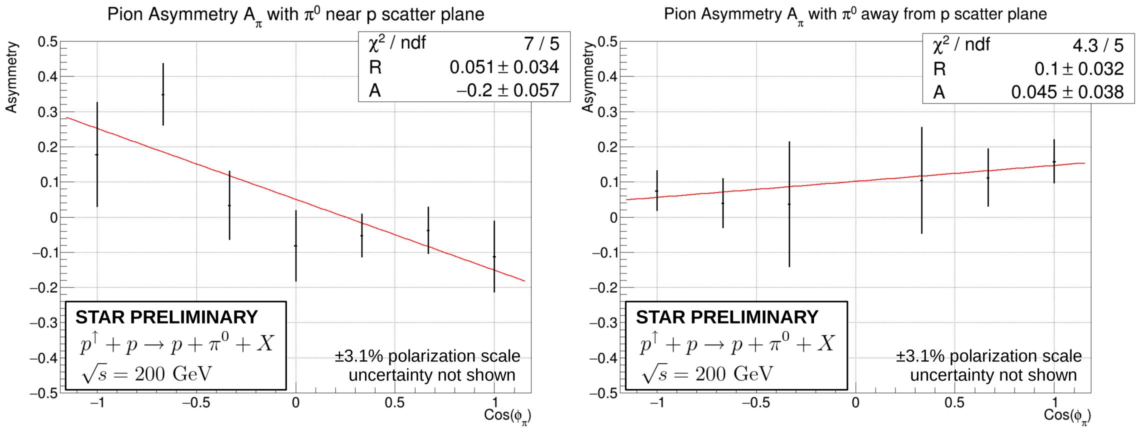

Figure 4: Transverse single-spin asymmetry in bins of $\cos\phi_\pi$ for π^0s near the proton scattering plane (left) or away (right). A linear fit is included in each.

other possibilities were tested, such as the assumption that the asymmetry is just a π^0 single-spin asymmetry, however their projections do not agree with the data.

4. Summary

The $p^{\uparrow}p \to p\pi^0 X$ process has been observed at STAR, and a $-19\% \pm 5.2\%$ asymmetry of the π^0 in the scattering plane of the proton is observed, via the modulation in equation 3.1. This effect may serve as a probe to the orbital angular momentum of fluctuated π^0s in the proton periphery. As far as we know, the spin-dependence of this process has otherwise not yet been explored experimentally and a model is needed to understand it. Moreover, this process should be studied in more detail experimentally, with better azimuthal and kinematic coverage.

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