Event-by-event correlations between $\Lambda/\bar{\Lambda}$ handedness and CME observable in Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV from STAR

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STAR

Physics and Astronomy

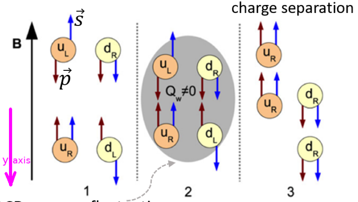
PURDUE UNIVERSITY

Motivation

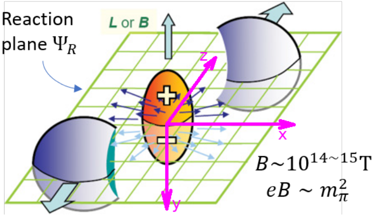
QCD vacuum fluctuation
$Q_w < 0$ (for example)
↓
chirality anomaly in local domain $\Delta N(q) = N_L(q) - N_R(q) < 0$
↓
$\Delta N(s) < 0$
$\Delta N(\bar{s}) < 0$
↓
$\Delta N(\Lambda) < 0$
$\Delta N(\bar{\Lambda}) < 0$
↓
positively correlated

chirality anomaly in local domain →
$\Delta N(u) < 0$
$\Delta N(d) < 0$
↓
charge separation
CME
$a_1^{\pm} = \langle \sin(\phi_{\pm} - \Psi_{\text{RP}}) \rangle$
$a_1^{+} < 0,\ a_1^{-} > 0$
$\Delta \tilde{a}_1 = a_1^{+} - a_1^{-} < 0$
→ positively correlated

spectator protons
↓
magnetic field $\vec{B}$
→ charge separation CME



QCD vacuum fluctuation
Topological charge $Q_w \propto \int \vec{E}_c \cdot \vec{B}_c$



For each event, $\Delta N(\Lambda) + \Delta N(\bar{\Lambda})$ and $\Delta \tilde{a}_1$ are expected to be correlated (L. E. Finch and S. J. Murray, Phys.Rev.C.96.044911).

General selections and particle identifications

Run18 Au+Au $\sqrt{s_{NN}} = 27$ GeV

- $|V_z| \leq 70$ cm
- $\sqrt{V_x^2 + V_y^2} \leq 2.0$ cm
- $|V_z - V_z^{\text{VPD}}| < 3.0$ cm
- 0.2 GeV$/c \leq p_T \leq 2.0$ GeV$/c$
- $15 \leq$ nHitsFit < 50
- $0.52 \leq$ nHitsFit/nHitsMax ≤ 1.05
- 390M events

pion identification

- using TOF+TPC
- $-0.013p + 0.017 < m^2 < 0.04$
- $|n\sigma_\pi| < 3$
- $|\eta| < 1$

proton identification

- using TOF+TPC
- $0.5 < m^2 < 1.5$
- $|n\sigma_p| < 3$
- $|\eta| < 1$

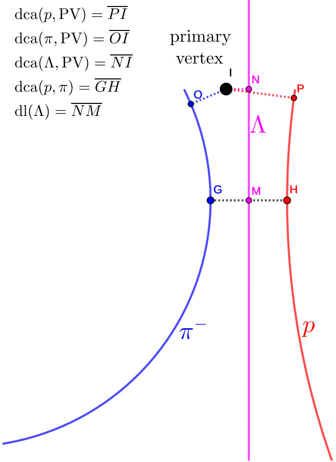


Figure 1: Topology of a Λ decay.

Topological cuts

- dca$(p, \text{PV}) > 0.1$ cm
- dca$(\pi, \text{PV}) > 0.7$ cm
- dca$(\Lambda, \text{PV}) < 1.3$ cm
- dca$(p, \pi) < 1.0$ cm
- dl$(\Lambda) > 2.0$ cm
- $(\vec{r}_\Lambda - \vec{r}_{\text{PV}}) \cdot \vec{p}_\Lambda > 0$

*dca: distance of closest approach
*dl: decay length
*PV: primary vertex

$\Lambda/\bar{\Lambda}$ mass spectra

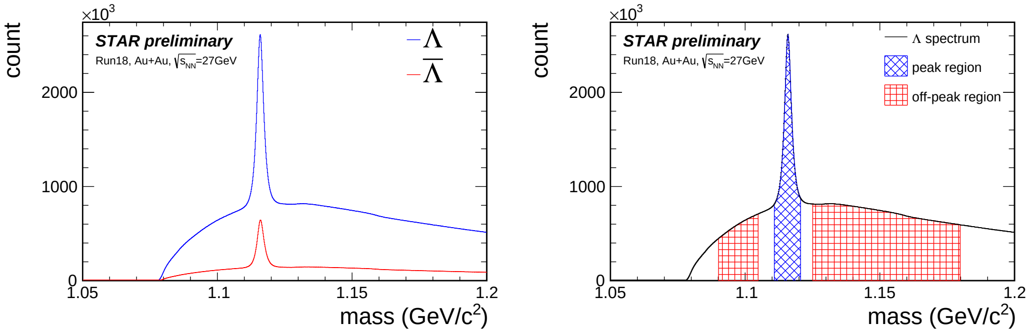


Figure 2: $\Lambda/\bar{\Lambda}$ mass spectra. The peak region ($1.110683 \sim 1.120683$ GeV$/c^2$) and the off-peak background region ($1.090 \sim 1.105$ GeV$/c^2$ and $1.125 \sim 1.180$ GeV$/c^2$) are shaded.

B/S ratio (in peak region) for purity correction

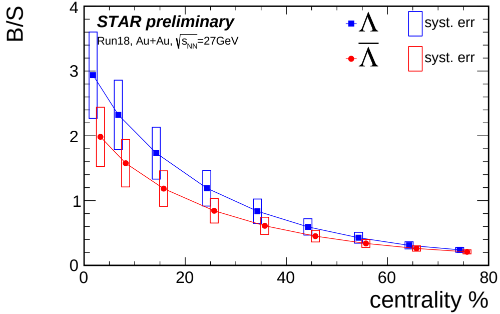


Figure 3: Background over Signal ratio depending on centrality in the $\Lambda/\bar{\Lambda}$ mass peak region ($1.110683 \sim 1.120683$ GeV$/c^2$).

The peak region contains a mixture of signal and background. We can fit the mass spectra in $1.110683 \sim 1.120683$ GeV$/c^2$ and get the number of signal particle (S) and background particle (B) in each centrality bin.

Event Plane Detector (EPD, coverage $2.1 < |\eta_{\text{EPD}}| < 5.1$) resolutions

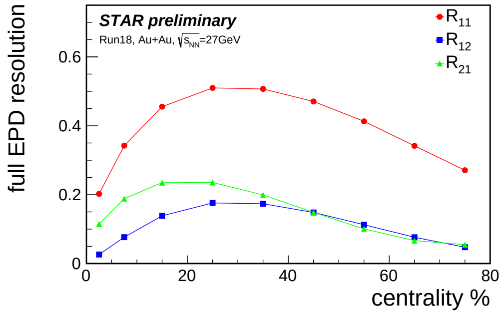


Figure 4: Full EPD resolution. Reweighting and shifting are used to flatten the event planes.

The reaction plane is approximated by Ψ_1 from EPD. Theoretically with respect to reaction plane (Ψ_{RP}), the resolution R_{nk} is defined as

$$R_{nk} \equiv \langle \cos(kn(\Psi_n - \Psi_{\text{RP}})) \rangle. \qquad (1)$$

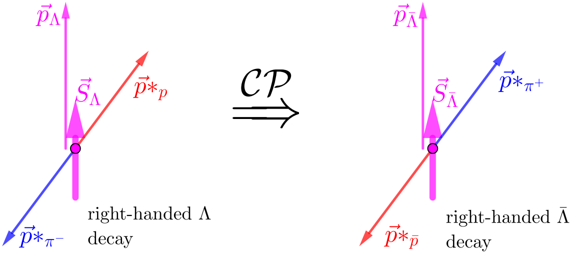
In analysis, for $k = 1$, subevent R_{n1}^{sub} can be estimated by

$$R_{n1}^{\text{sub}} = \sqrt{\langle \cos(n(\Psi_n^E - \Psi_n^W)) \rangle} \qquad (2)$$

The full resolution R_{n1} and also R_{nk} $(k \neq 1)$ are then obtained using Bessel functions (A. M. Poskanzer and S. A. Voloshin, Phys.Rev.C.58.1671).

For a decay $\Lambda \to p + \pi^-$, the spin direction of Λ ($\bar{\Lambda}$) can be approximated by its decay daughter proton's momentum $\vec{p}_p^*$ ($-\vec{p}_{\bar{p}}^*$) in the rest frame of that Λ. On the other hand, the momentum of Λ $\vec{p}_\Lambda$ can be reconstructed by its decay daughters. Then, the helicity sign of Λ ($\bar{\Lambda}$) can be determined by $\vec{p}_p^* \cdot \vec{p}_\Lambda$ ($\vec{p}_{\bar{p}}^* \cdot \vec{p}_{\bar{\Lambda}}$).

$$\begin{cases} \vec{p}_p^* \cdot \vec{p}_\Lambda < 0 & \Rightarrow \quad \text{“left-handed” } \Lambda \\ \vec{p}_p^* \cdot \vec{p}_\Lambda > 0 & \Rightarrow \quad \text{“right-handed” } \Lambda \end{cases} \qquad \begin{cases} \vec{p}_{\bar{p}}^* \cdot \vec{p}_{\bar{\Lambda}} < 0 & \Rightarrow \quad \text{“right-handed” } \bar{\Lambda} \\ \vec{p}_{\bar{p}}^* \cdot \vec{p}_{\bar{\Lambda}} > 0 & \Rightarrow \quad \text{“left-handed” } \bar{\Lambda} \end{cases} \tag{3}$$



To make connection from the observed to the true Λ ($\bar{\Lambda}$) handedness, detector effects and decay angular distribution need to be considered. In this exploratory study we will only consider the observed difference between the number of left and right handed Λ ($\bar{\Lambda}$), which is referred to as ΔN^{obs}.

Observed $\Delta N^{\text{obs}} = N_L^{\text{obs}} - N_R^{\text{obs}}$

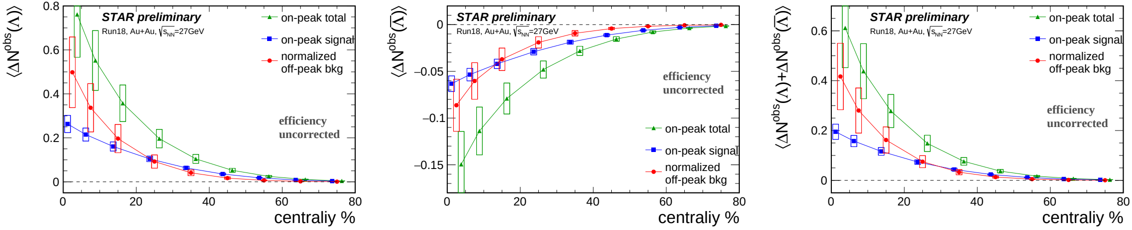
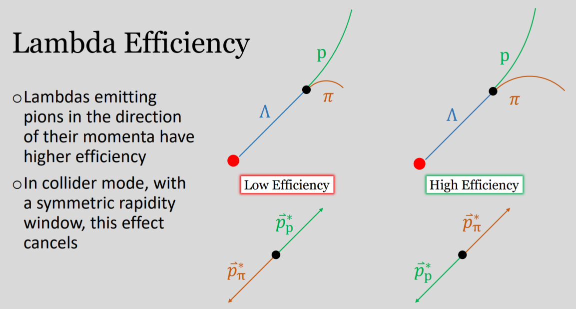


Figure 5: ΔN^{obs} event average of each centrality bin (efficiency uncorrected).

- The "on-peak total" (green, $\Delta N^{\text{on-peak}}$) is calculated from all Λ $(\bar{\Lambda})$ candidates in the peak region.
- The "normalized off-peak bkg" (red, $\Delta N_B^{\text{on-peak}}$) is $\Delta N_B^{\text{on-peak}} = \frac{N_B^{\text{on-peak}}}{N^{\text{off-peak}}} \Delta N^{\text{off-peak}}$, because we assume that the on-peak background can be approximated by the off-peak background.
- The "on-peak signal" (blue, $\Delta N_S^{\text{on-peak}}$) is the difference $\Delta N_S^{\text{on-peak}} = \Delta N^{\text{on-peak}} - \Delta N_B^{\text{on-peak}}$
- The topological cuts affect backgrounds, but not much on signal, so systematic uncertainties are correlated and largely cancelled for signal.

Lambda efficiency

- Handedness results in very different daughter pion p_T.
- STAR TPC detector efficiency has a strong p_T dependence at low p_T.
- Thus, very different detection efficiencies for left- and right-handed Λ ($\bar{\Lambda}$).
- The detector effect causing $\Delta N^{\text{obs}} \neq 0$ should not affect the physics correlations between ΔN^{obs} and Δa_1.



Cartoon: Joseph Adams, Quark Matter 2019

Δa_1 of primordial particles

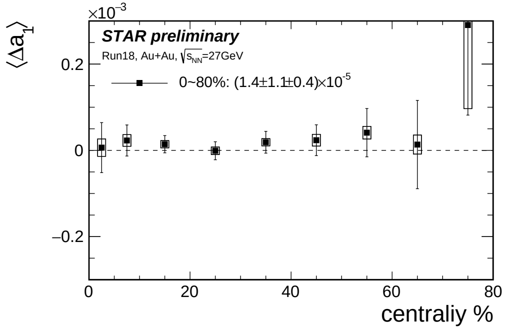


Figure 6: The Δa_1 dependence on centrality. Decay daughters from on-peak $\Lambda/\bar{\Lambda}$ are removed.

$$\frac{1}{N_\pm}\frac{dN_\pm}{d\phi} = \frac{1}{2\pi}(1 + 2a_1^\pm \sin(\phi - \Psi_{\text{RP}}) + 2v_2 \cos(2(\phi - \Psi_{\text{RP}})) + \ldots) \quad (4)$$

In each event, $a_1^\pm$ and Δa_1 could be extracted as follows

$$a_1^\pm = \langle \sin(\phi_\pm - \Psi_{\text{RP}}) \rangle = \langle \sin(\phi_\pm - \Psi_1) \rangle / R_{11} \quad (5)$$

$$\Delta a_1 = \frac{N_+}{N_+ + N_-} a_1^+ - \frac{N_-}{N_+ + N_-} a_1^- \quad (6)$$

$\langle \Delta a_1 \rangle$ should be zero because of random Q_w fluctuations.

Δa_1 vs. ΔN^{obs}

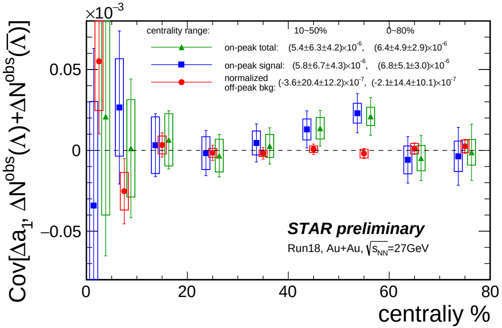


Figure 7: The covariance between Δa_1 and $\Delta N^{\text{obs}}(\Lambda) + \Delta N^{\text{obs}}(\bar{\Lambda})$.

- The covariance is defined as

$$\text{Cov}(X, Y) = \langle XY \rangle - \langle X \rangle \langle Y \rangle \qquad (7)$$

- $\langle \cdot \rangle$ means the event average.
- The background is consistent with zero as expected.
- The signal is consistent with zero within the current uncertainties.

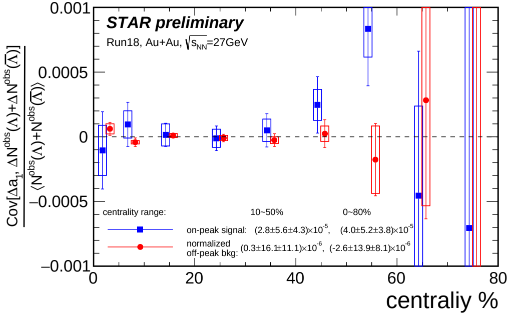


Figure 8: The covariance between Δa_1 and $\left(\Delta N^{\text{obs}}(\Lambda) + \Delta N^{\text{obs}}(\bar{\Lambda})\right) / \left(N^{\text{obs}}(\Lambda) + N^{\text{obs}}(\bar{\Lambda})\right)$.

- The "on-peak signal" is divided by $\langle N_S^{\text{on-peak}} \rangle$.
- The "normalized off-peak bkg" is divided by $\langle N_B^{\text{on-peak}} \rangle$.
- The background is consistent with zero as expected.
- The signal is consistent with zero within the current uncertainties.

Conclusion

- A novel event-by-event correlation method to search for the CME. (L. E. Finch and S. J. Murray, Phys.Rev.C.96.044911).
- We report an exploratory measurement of event-by-event correlation between ΔN^{obs} and Δa_1, by the STAR experiment in Au+Au collisions at 27 GeV.
- With the current statistics, the signal is consistent with zero.