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Measurement of Λ hyperon spin-spin correlation in p+p collisions at RHIC

Jan Vanek, for the STAR Collaboration

Brookhaven National Laboratory

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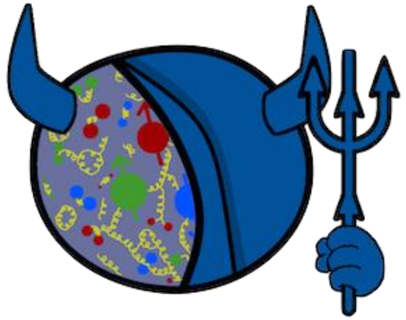
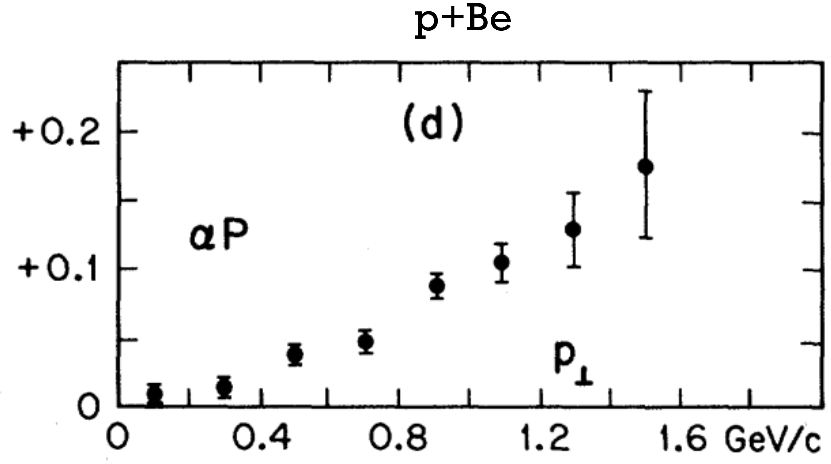


Λ POLARIZATION PUZZLE

- In the 70's, it was discovered that Λ^0 hyperons are polarized in collisions of unpolarized p+Be collisions [*G.Bunce, et al.: Phys. Rev. Lett. 36, 1113-1116 (1976)*]
- Over nearly 50 years, Λ^0 polarization has been seen in p+p, p+A, e+p, **e^+e^- collisions** up to collision energies about 40 GeV
- These indicate the **importance of final-state effects**, e.g., fragmentation and hadronization



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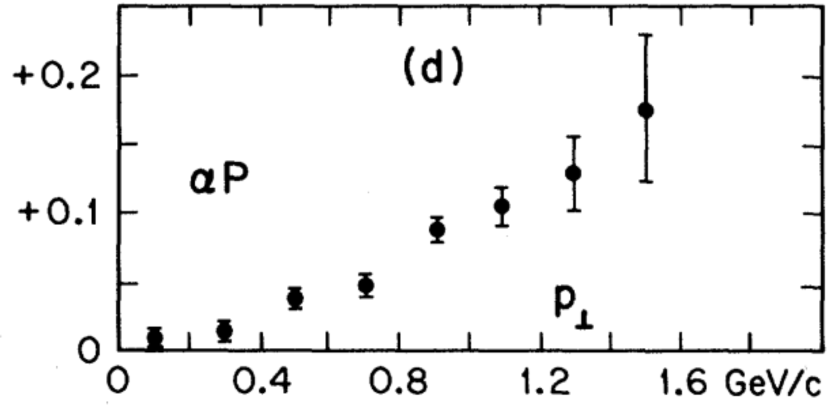
p+Be



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What is the origin of the Λ^0 polarization?

- Does polarization of Λ^0 depend on spin of the target/projectile?
  - Following talk in this session by Q. Xu
- Is there a contribution of an **initial-state** effect?
- Will parton spin correlation and entanglement manifest in Λ^0 polarization? [*W. Gong, et al.: Phys. Rev. D 106 (2022) 3, L031501*]

Λ POLARIZATION MEASUREMENT

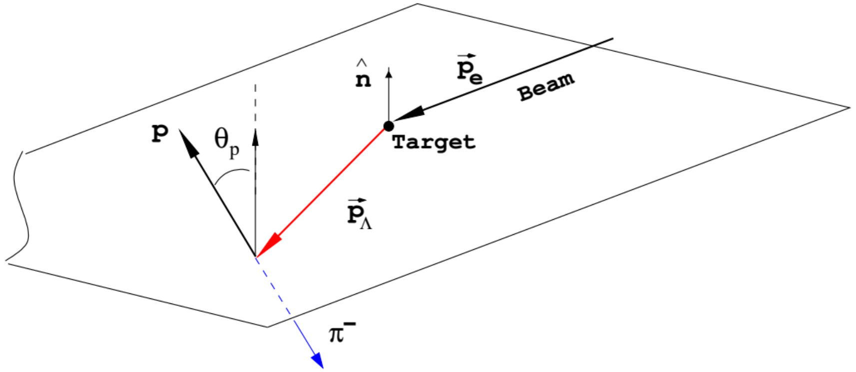
- Single Λ^0 polarization is measured via $\Lambda^0 \rightarrow p\pi^+$ decay channel. In the Λ^0 rest frame, protons are emitted preferentially in the direction of Λ^0 spin

- The distribution of protons in Λ^0 rest frame is then given by:

$$\frac{\mathbf{d}\boldsymbol{N}}{\mathbf{d}\cos(\boldsymbol{\theta}^{*})} = \mathbf{1} + \boldsymbol{\alpha} \boldsymbol{P}_{\boldsymbol{\Lambda}} \cos(\boldsymbol{\theta}^{*})$$

  - P_Λ is the Λ^0 polarization
  - $\Lambda^0: \alpha_+ = 0.732 \pm 0.014,\ \overline{\Lambda^0}: \alpha_- = -0.758 \pm 0.012$
  - $\hat{n}$ is normal vector to the production plane
  - **Angle (θ^*, or θ_p) is measured between $\hat{n}$ and momentum of proton (p) in Λ's rest frame**

$$\hat{n} = \vec{p}_{beam} \times \vec{p}_{\Lambda}$$

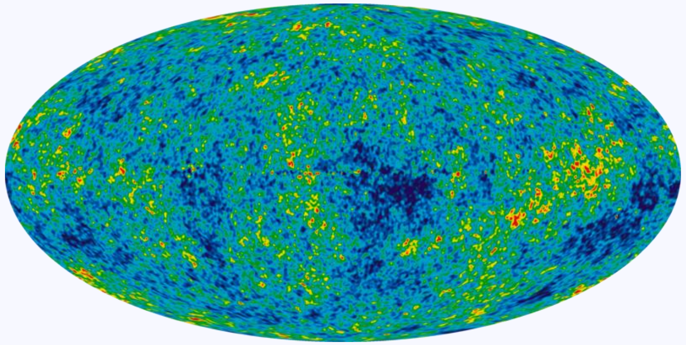


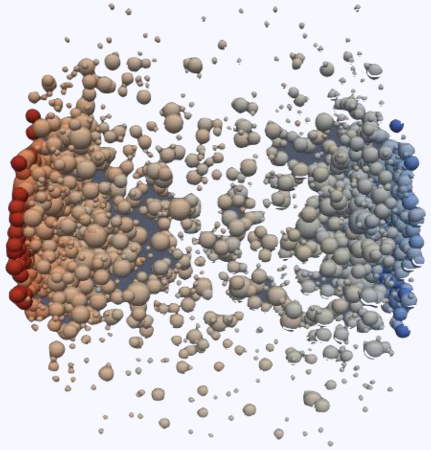
HERMES: Phys.Rev.D76:092008,2007

MOTIVATION FOR Λ SPIN-SPIN CORRELATIONS

CMB radiation

Heavy-ion collisions





Temperature correlations

Momentum correlations

\`Anisotropies\` measured by two-point correlation function. Pure final-state effects cannot contribute to the correlation **as it violates causality.**

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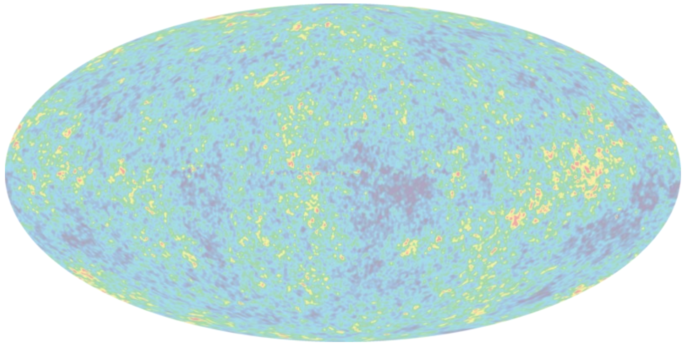

Temperature correlations

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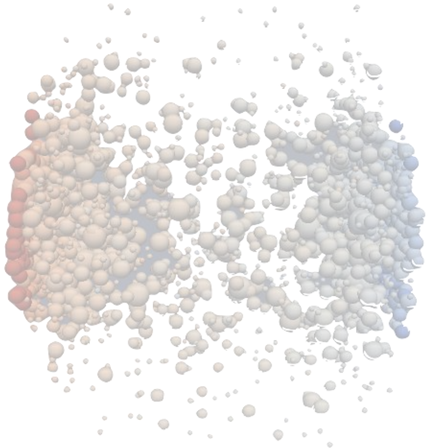
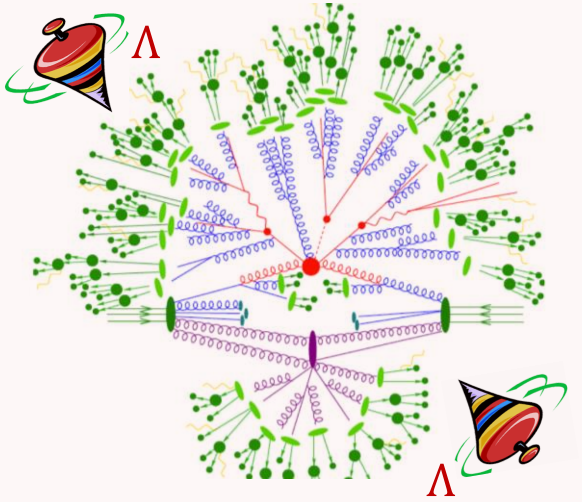


Momentum correlations

`Anisotropies` measured by two-point correlation function. Pure final-state effects cannot contribute to the correlation **as it violates causality**.

Proton-Proton collisions



Spin correlation

A (more) direct probe to the initial-state parton spin effects

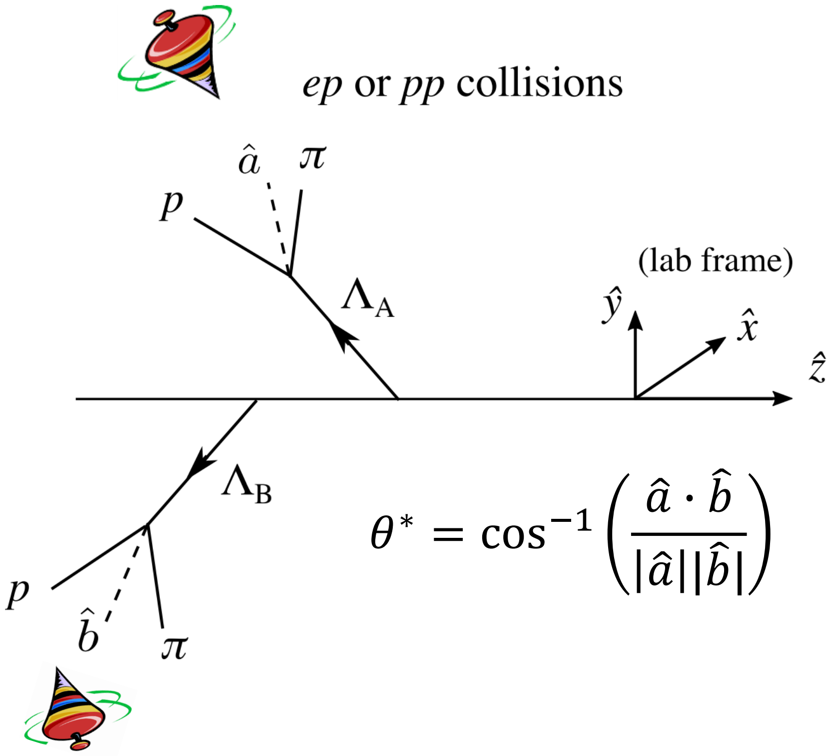
EXPERIMENTAL METHOD

- Find $\Lambda^0\overline{\Lambda^0}$, $\Lambda^0\Lambda^0$, or $\overline{\Lambda^0\Lambda^0}$ pair(s) in one event
  - Decay channel $\Lambda^0 \to p\pi^+$ and charge conjugate
- Boost (anti-)proton from decay of the corresponding Λ^0 ($\overline{\Lambda}$) to **rest frame of its mother**
  - Proton momenta in mother rest frame: $\hat{a}$, $\hat{b}$
- Measure angle θ^* between the two **boosted protons**
- The distribution of pair angle is given by:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} \sim 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)$$

  - α_1 and α_2 are α_+ or α_-, depending on Λ^0 hyperon pair

- **A non-zero $P_{\Lambda_1\Lambda_2}$ would indicate spin correlation between the two Λ^0 hyperons**

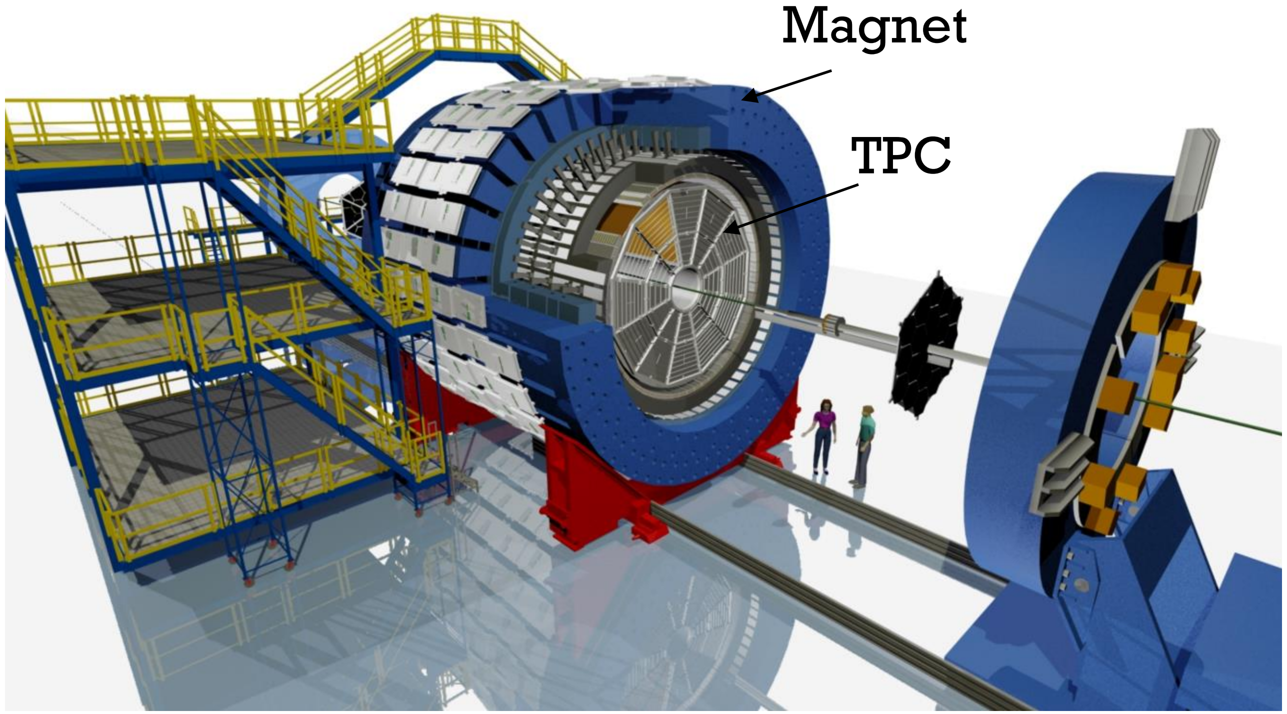


$$\theta^* = \cos^{-1}\left(\frac{\hat{a}\cdot\hat{b}}{|\hat{a}||\hat{b}|}\right)$$

W. Gong, *et al.*: Phys. Rev. D 106 (2022) 3, L031501

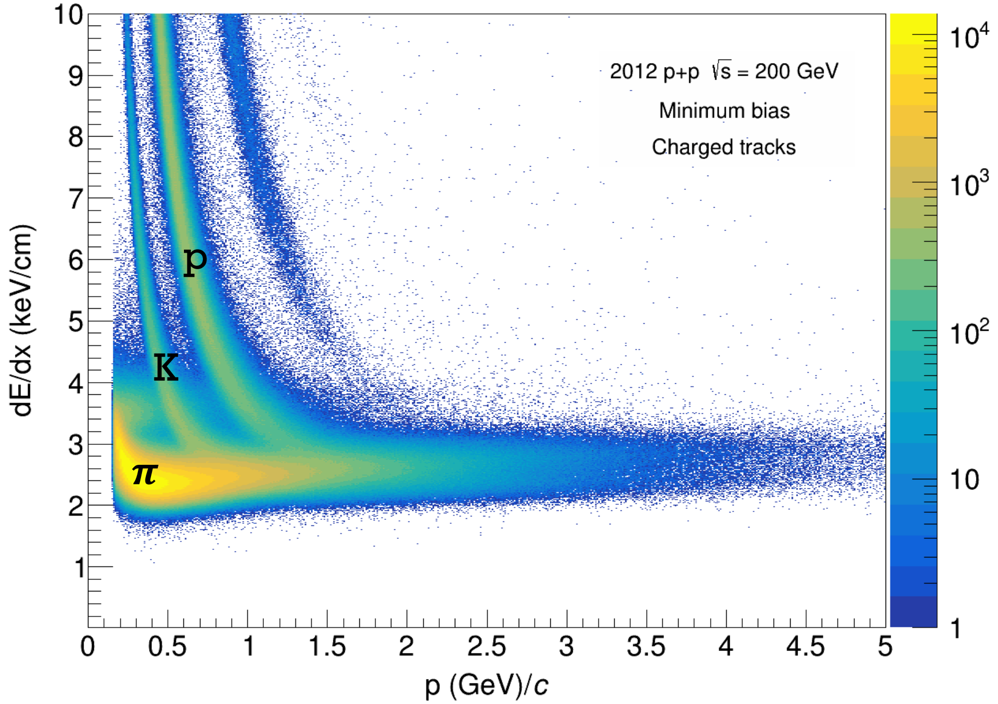
SOLENOIDAL TRACKER AT RHIC (STAR)

- Key subsystems for this analysis:
  - Solenoidal magnet
    - 0.5 T magnetic field **with low p_T coverage**
  - Time Projection Chamber (TPC)
    - Measurement of particle transverse momentum (p_T)
    - Particle identification (PID) based on energy loss in TPC gas
    - **Full azimuthal coverage for $|\eta| < 1$**



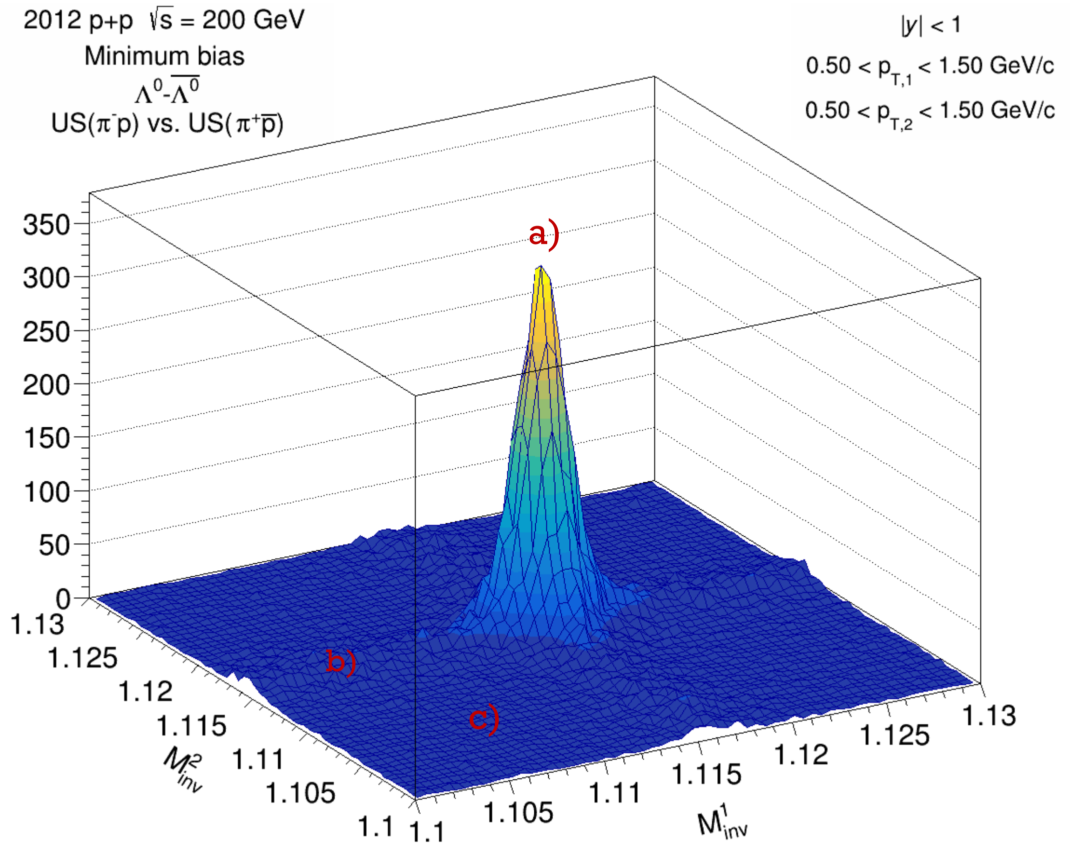
EVENT AND TRACK SELECTION, PID

- Data-set:
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 400M minimum bias events
- Track selection to ensure good track quality within geometrical acceptance
- Particle identification to obtain pure proton and pion sample
- Decay topology to suppress combinatorial background from tracks originating from close to primary vertex



Λ SIGNAL EXTRACTION

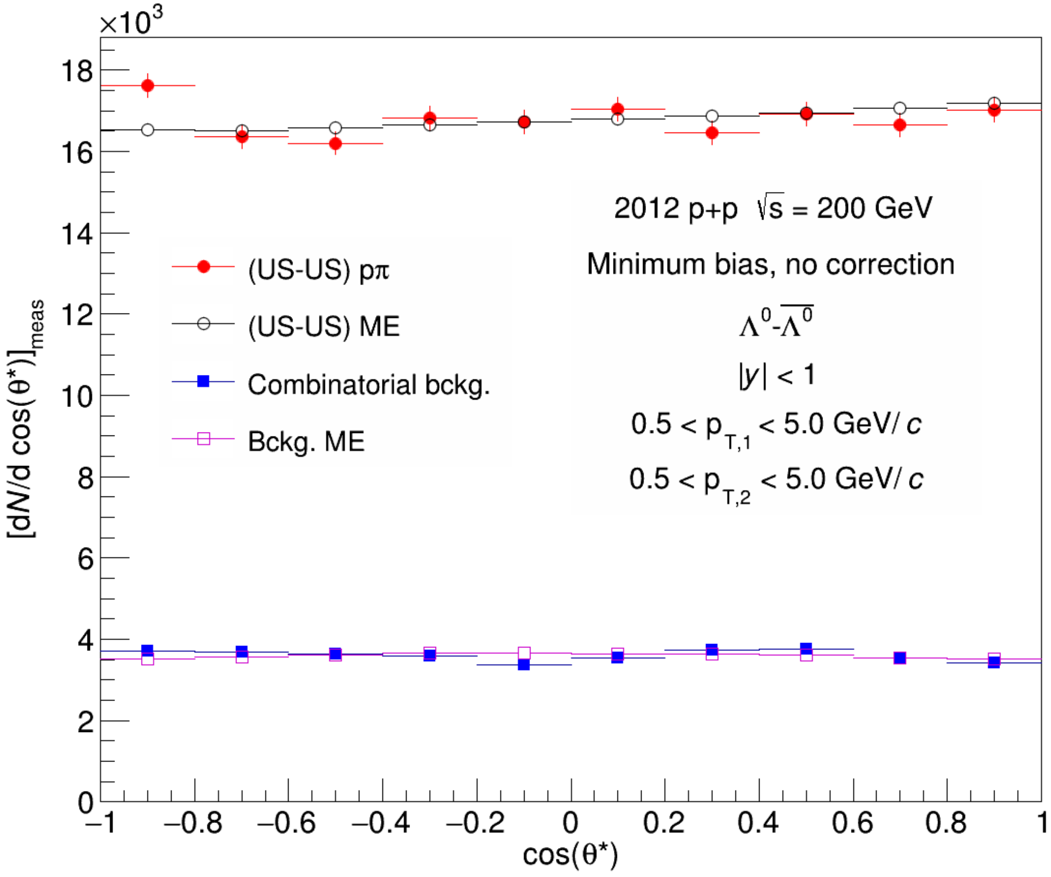
- Signal extraction determined from 2D M_{inv} distributions of unlike-sign (US) πp pairs
- Three components:
  a) Peak: πp from Λ decay paired with another πp from Λ decay
  b) Ridges: πp from Λ decay paired with combinatorial background
  c) Continuum: combinatorial background paired with combinatorial background



- Contributions (b) and (c) are subtracted from (a) and fitted with 2D Gaussian function
  - Signal region is defined as mean $\pm 3\sigma$

CORRECTIONS, BACKGROUND SUBTRACTION

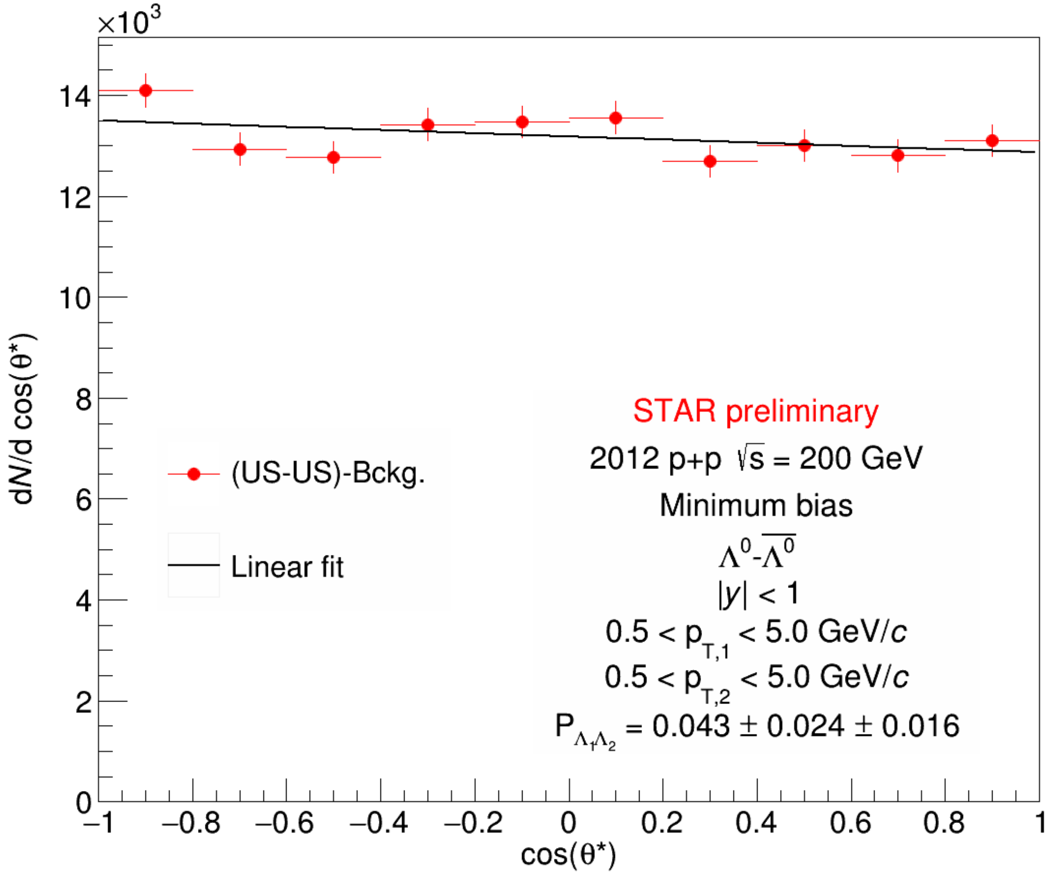
- Measured $\left[\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)}\right]_{meas}$ distributions of $\Lambda^0\overline{\Lambda^0}$, $\Lambda^0\Lambda^0$, and $\overline{\Lambda^0\Lambda^0}$ pairs before acceptance correction
  - (US-US) distribution (red) has a shape which originates from acceptance and resolution of the STAR detector
- Acceptance correction done using mixed (ME) event $\Lambda^0\overline{\Lambda^0}$, $\Lambda^0\Lambda^0$, and $\overline{\Lambda^0\Lambda^0}$ pairs
  - Separate for (US-US) and background
- Background distribution is subsequently subtracted from the (US-US) distribution



Λ SPIN-SPIN CORRELATION EXTRACTION

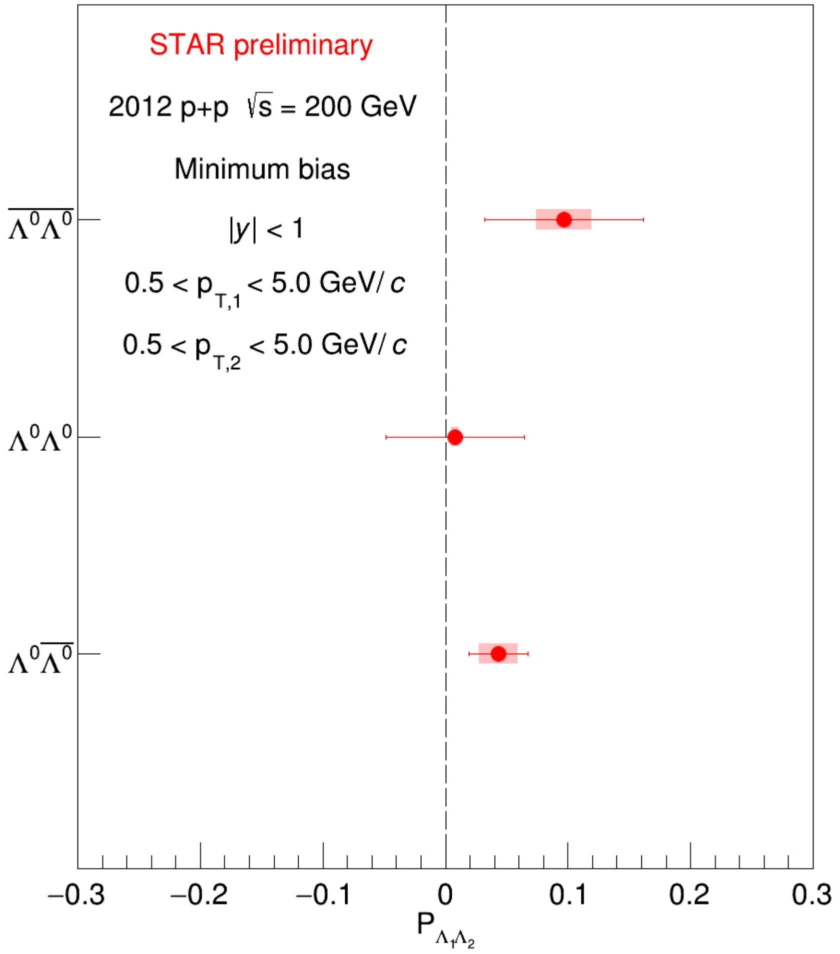
- $\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)}$ distributions from data after acceptance correction and background subtraction
- Linear fit is used to extract $P_{\Lambda_1\Lambda_2}$ according to formula from slide 7
- Observed a hint of 2σ signal for $\Lambda^0\overline{\Lambda^0}$, but statistics is limited

$$P_{\Lambda_1\Lambda_2} = 0.043 \pm 0.024_{stat} \pm 0.016_{sys}$$



Λ SPIN-SPIN CORRELATIONS

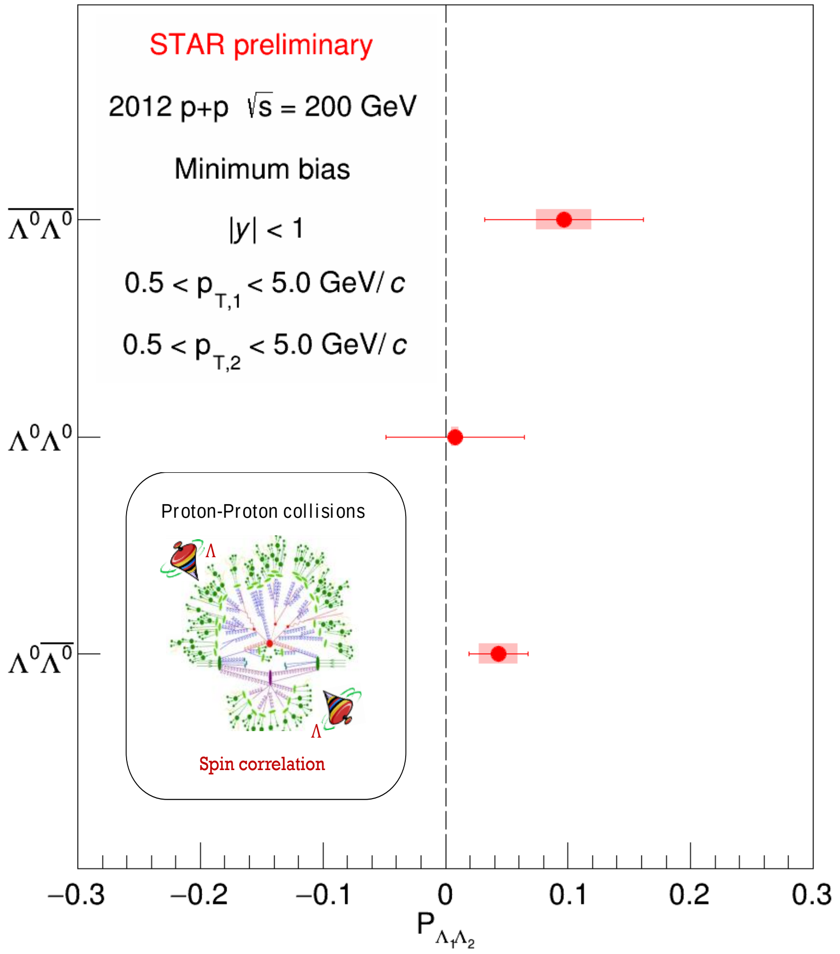
- $P_{\Lambda_1\Lambda_2}$ are consistent with zero within uncertainties for all three combinations of Λ^0 pairs
  - No spin-spin correlations measured in p+p collisions at $\sqrt{s} = 200$ GeV
  - This measurement provides upper limit on Λ^0 hyperon spin-spin correlations in p+p collisions at $\sqrt{s} = 200$ GeV
- Data suggest no significant/large spin-spin correlation of initial state s (anti-)quark pair
- First experimental search for Λ^0 hyperon spin-spin correlations - **We encourage theory colleagues to calculate this from different physics frameworks**



SUMMARY AND OUTLOOK

- We conduct the first experimental search for Λ^0 hyperon spin-spin correlations
  - It is found consistent with zero within uncertainty, although uncertainty is large
  - This new approach provides additional insights to the initial-state parton spin effects
  - There is another new proposal in this conference, given by Z. Tu at [Tues, joint GPD/future]

- **Next steps:**
  - More data from p+p collisions at $\sqrt{s} = 200$ GeV from year 2015 and later 2024 to improve statistical precision
  - Analysis of 2017 p+p collisions at $\sqrt{s} = 510$ GeV to study collision energy dependence of Λ^0 spin-spin correlations with possible addition of data from 2022
  - Study p_T dependence of the spin-spin correlations
  - Investigate the correlation for Λ^0 pairs with different rapidity gaps



THANK YOU FOR ATTENTION

BACKUP

EVENT AND TRACK SELECTION, PID

- Data-set:
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 400M minimum bias events
- Events with primary vertex close to center of STAR detector selected
- Track selection to ensure good track quality within geometrical acceptance
- Particle identification to obtain pure proton and pion sample
- Decay topology to suppress combinatorial background from tracks originating from close to primary vertex

Event selection	$\lvert V_z \rvert < 30$ cm
Track selection	$p_T > 150$ MeV/c
	$\lvert \eta \rvert < 1$
	nHitsFit > 20
	nHitsFit/nHitsMax > 0.52
Particle identification	$\lvert n\sigma_\pi \rvert < 3$
	$\lvert n\sigma_p \rvert < 2$
Decay topology Λ^0	$DCA_{\pi\text{-}PV} > 0.3$ cm
	$DCA_{p\text{-}PV} > 0.1$ cm
	$DCA_{pair} < 1$ cm
	2 cm < L_{dec} < 25 cm
	$\cos(\theta) > 0.996$

SYSTEMATIC ERRORS OVERVIEW

- Summary table of systematic uncertainties
  - σ_{ME} - Residual effect from ME correction
  - σ_{bckg} - Background subtraction systematic uncertainty
  - σ_{α} - Uncertainty of polarization from weak decay parameter α_{+} and α_{-}
  - σ_{cuts} - Variation of selection criteria
- $\sigma_{sys} = \sqrt{\sigma_{ME}^2 + \sigma_{bckg}^2 + \sigma_{\alpha}^2 + \sigma_{cuts}^2}$

	σ_{ME} [%]	σ_{bckg} [%]	σ_{α} [%]	σ_{cuts} [%]
$\Lambda\bar{\Lambda}$	36.6	< 1	2.5	< 1
$\Lambda\Lambda$	37.3	< 1	2.7	< 1
$\bar{\Lambda}\bar{\Lambda}$	23.1	< 1	2.2	< 1