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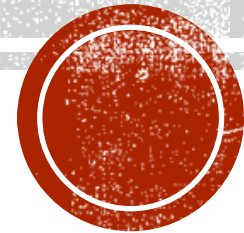
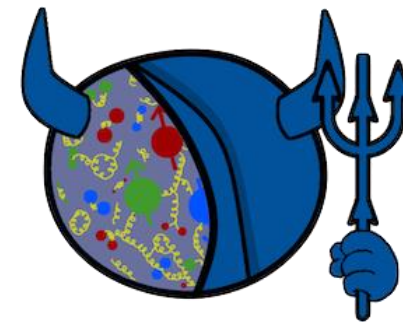
Measurement of Λ hyperon spin-spin correlation in $p+p$ collisions at RHIC

Jan Vanek, for the STAR Collaboration

Brookhaven National Laboratory

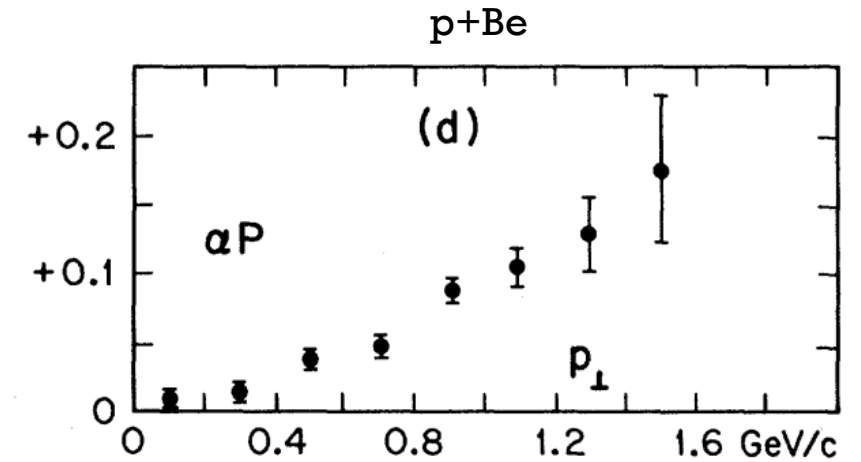
SPIN 2023, Duke University

09/26/2023



Λ POLARIZATION PUZZLE

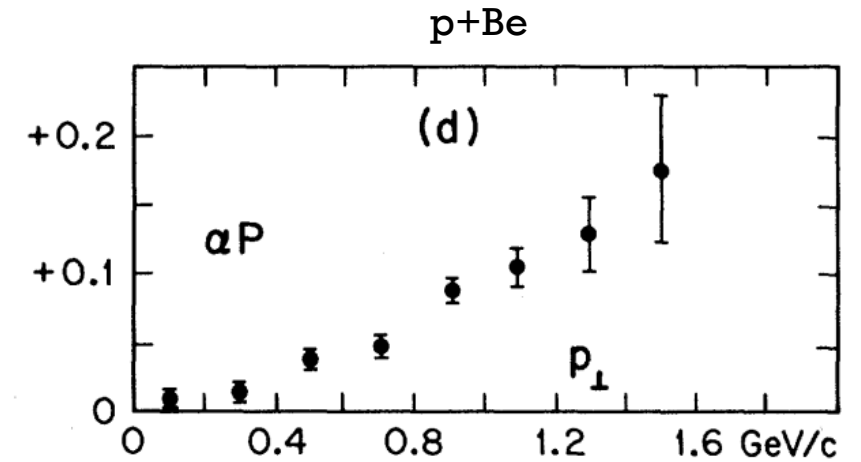
- In the 70's, it was discovered that Λ^0 hyperons are polarized in collisions of unpolarized p+Be collisions [*G.Bunce, et al.: Phys. Rev. Lett. 36, 1113-1116 (1976)*]
- Over nearly 50 years, Λ^0 polarization has been seen in p+p, p+A, e+p, **e⁺e⁻ collisions** up to collision energies about 40 GeV
-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



Phys. Rev. Lett. 36, 1113-1116 (1976)

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Phys. Rev. Lett. 36, 1113-1116 (1976)

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

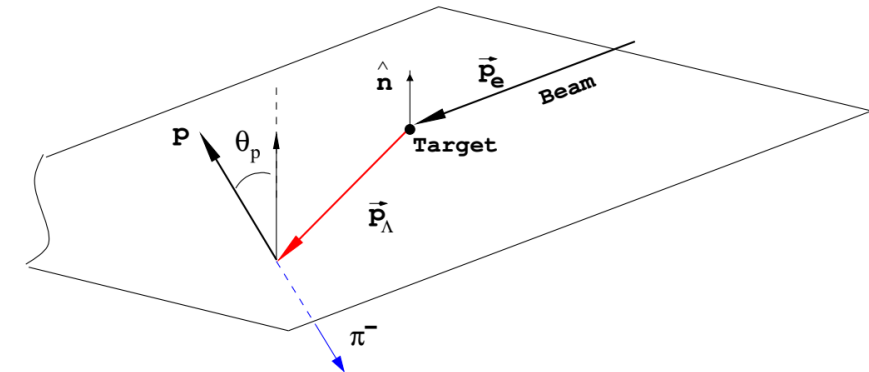
- Single Λ^0 polarization is measured via $\Lambda^0 \rightarrow p\pi^+$ decay channel. In the Λ^0 rest frame, protons are emitted preferentially in the direction of Λ^0 spin

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

$$\frac{dN}{d\cos(\theta^*)} = 1 + \alpha P_\Lambda \cos(\theta^*)$$

- P_Λ is the Λ^0 polarization
- $\Lambda^0: \alpha_+ = 0.732 \pm 0.014, \bar{\Lambda}^0: \alpha_- = -0.758 \pm 0.012$
- \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**

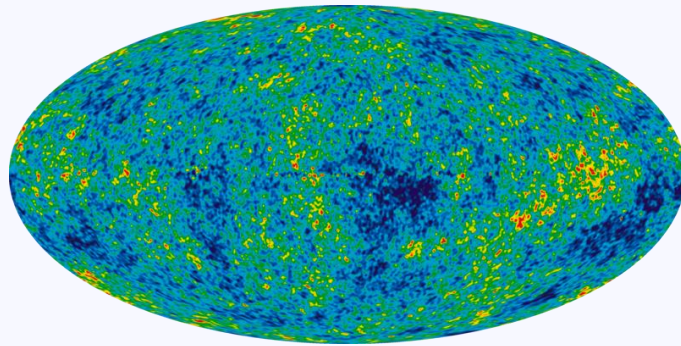
$$\hat{n} = \vec{p}_{beam} \times \vec{p}_\Lambda$$



HERMES: Phys.Rev.D76:092008,2007

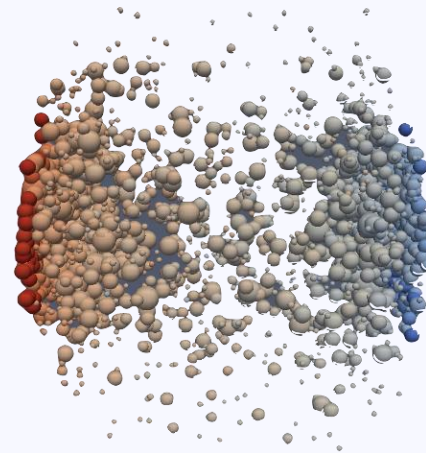
MOTIVATION FOR Λ SPIN-SPIN CORRELATIONS

CMB radiation



Temperature correlations

Heavy-ion collisions

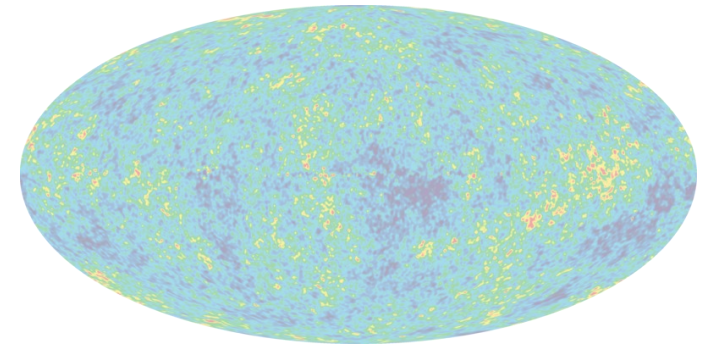


Momentum correlations

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

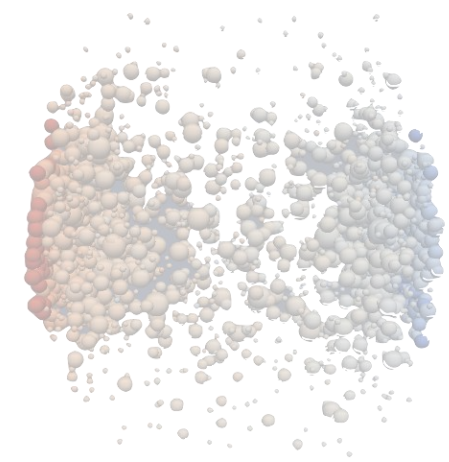
MOTIVATION FOR Λ SPIN-SPIN CORRELATIONS

CMB radiation



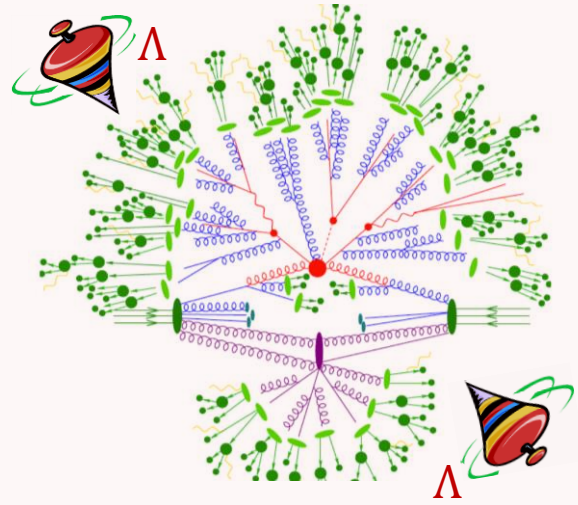
Temperature correlations

Heavy-ion collisions



Momentum correlations

Proton-Proton collisions



Spin correlation

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

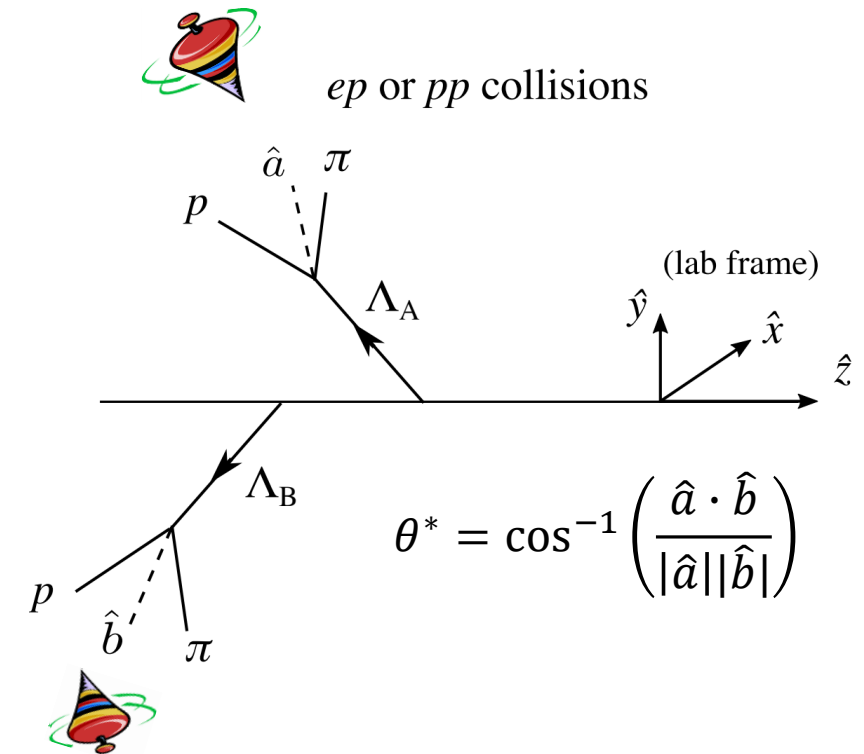
`Anisotropies` measured by two-point correlation function. Pure final-state effects cannot contribute to the correlation as it **violates causality**.

EXPERIMENTAL METHOD

- Find $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, or $\bar{\Lambda}^0\Lambda^0$ pair(s) in one event
 - Decay channel $\Lambda^0 \rightarrow p\pi^+$ and charge conjugate
- Boost (anti-)proton from decay of the corresponding Λ^0 ($\bar{\Lambda}$) 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:

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

- 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**

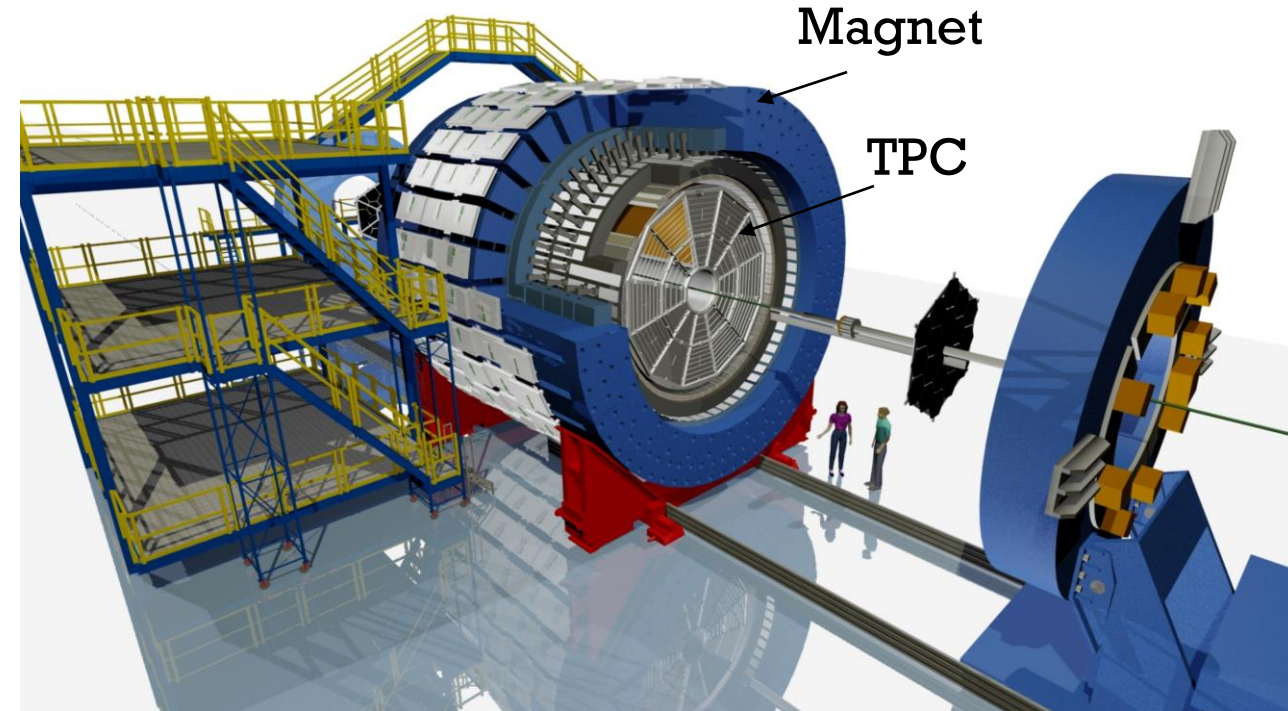


W. Gong, *et al.*: Phys. Rev. D 106 (2022) 3, L031501

SOLENOIDAL TRACKER AT RHIC (STAR)



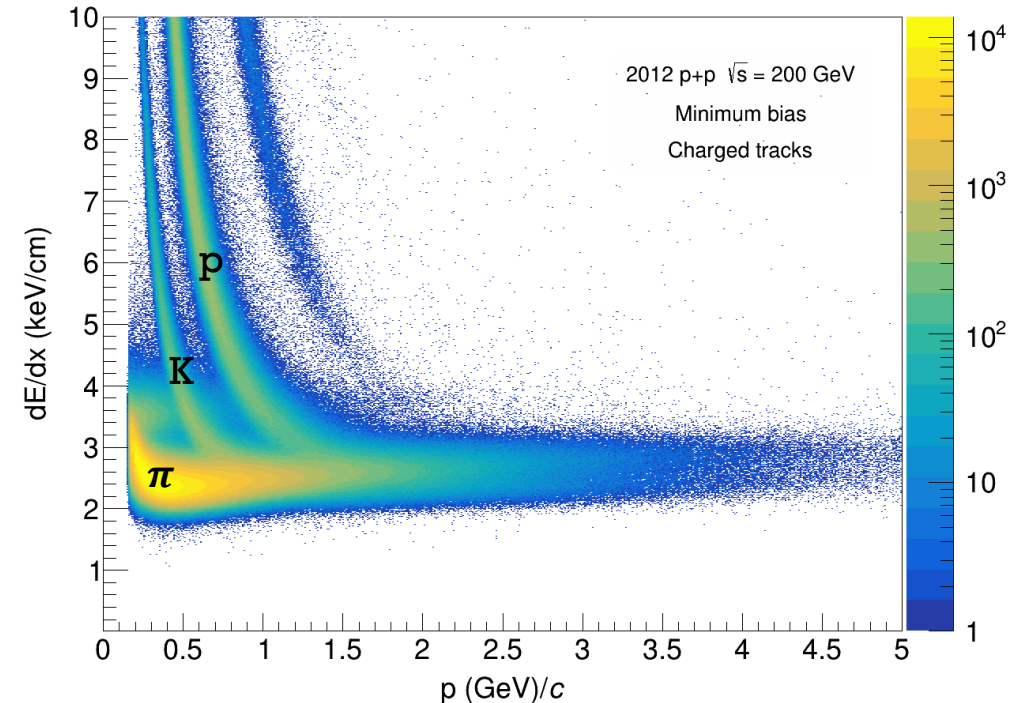
- Key subsystems for this analysis:
 - Solenoidal magnet
 - 0.5 T magnetic field **with low p_T coverage**
 - Time Projection Chamber (TPC)
 - Measurement of particle transverse momentum (p_T)
 - Particle identification (PID) based on energy loss in TPC gas
 - **Full azimuthal coverage for $|\eta| <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



EVENT AND TRACK SELECTION, PID



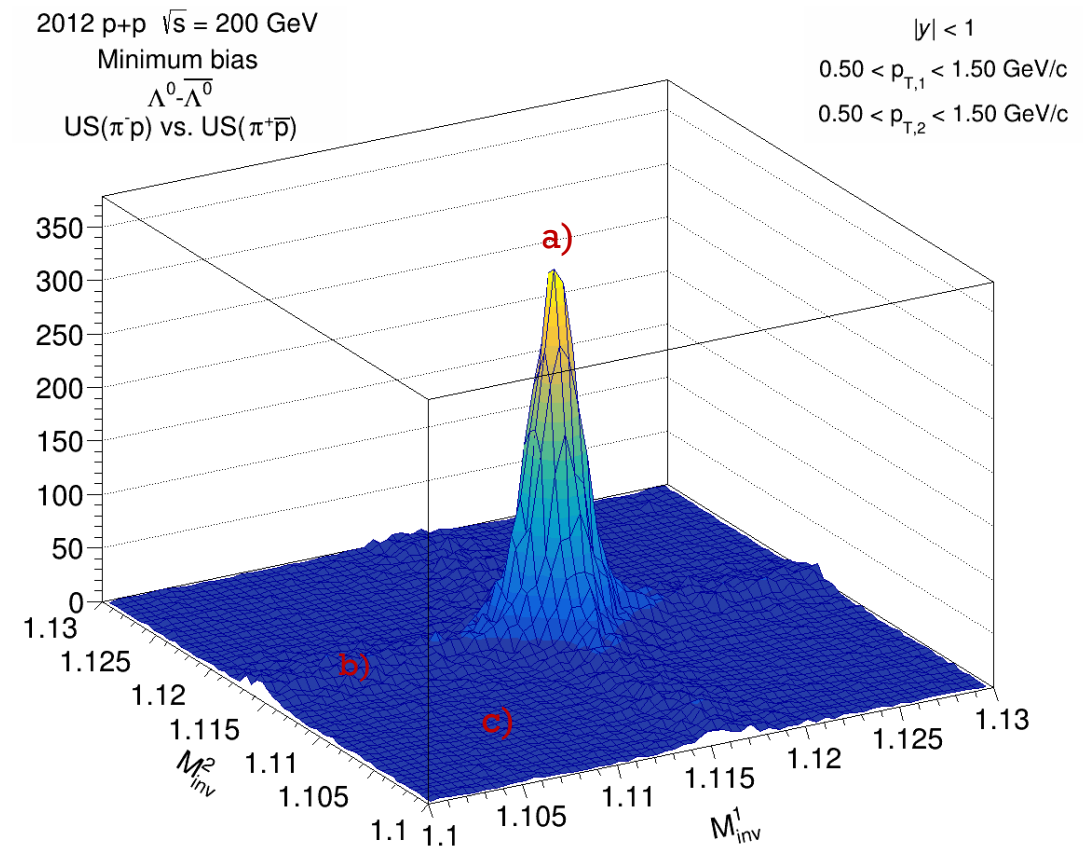
- Data-set:
 - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
 - Ca. 400M minimum bias events
- Track selection to ensure good track quality within geometrical acceptance
- Particle identification to obtain pure proton and pion sample
- Decay topology to suppress combinatorial background from tracks originating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



Λ SIGNAL EXTRACTION



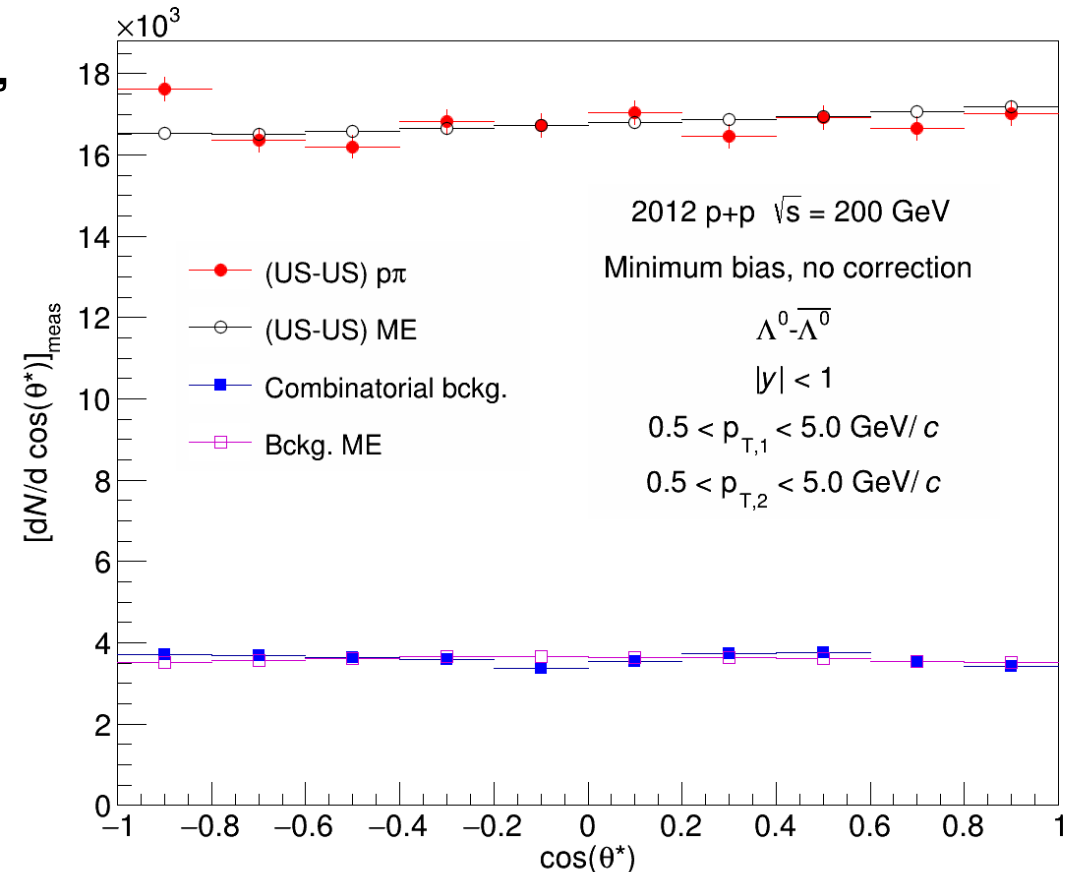
- Signal extraction determined from 2D M_{inv} distributions of unlike-sign (US) πp pairs
- Three components:
 - a) Peak: πp from Λ decay paired with another πp from Λ decay
 - b) Ridges: πp from Λ decay paired with combinatorial background
 - c) Continuum: combinatorial background paired with combinatorial 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 $\left[\frac{dN}{d \cos(\theta^*)}\right]_{meas}$ 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

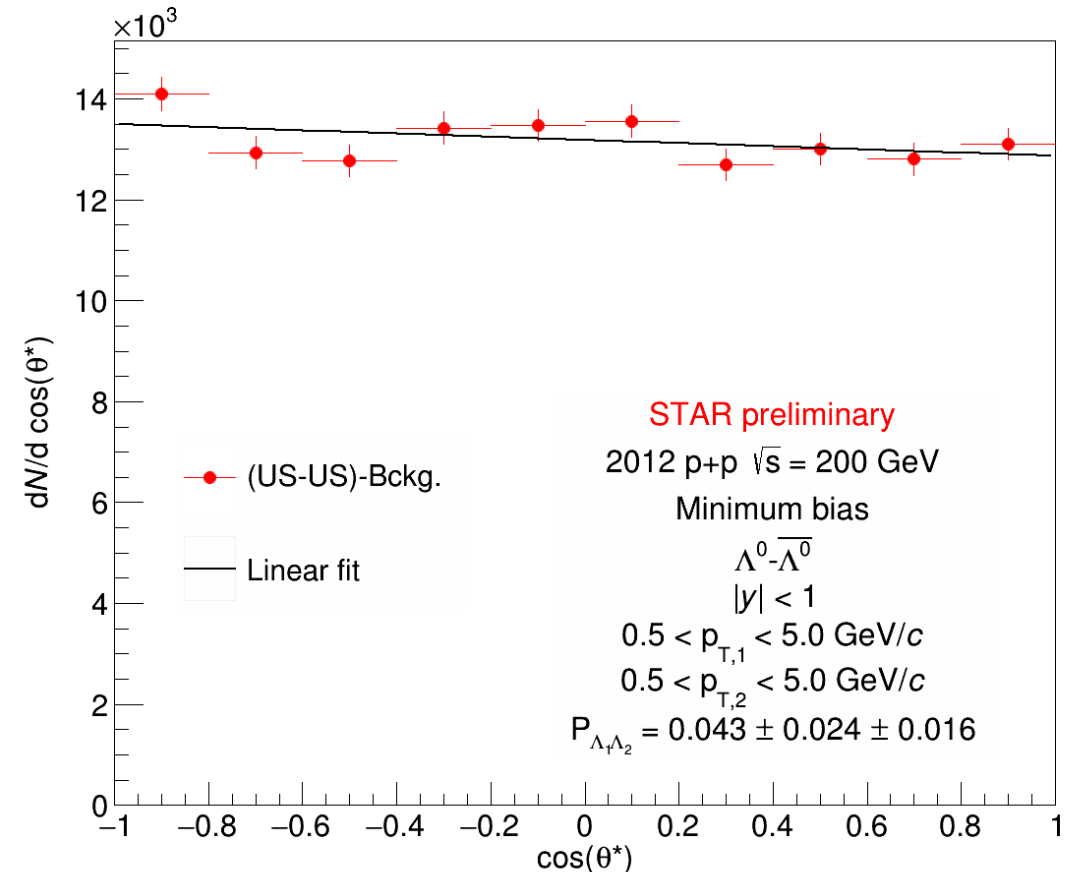


- $\frac{dN}{d \cos(\theta^*)}$ distributions from data after acceptance correction and background subtraction

- Linear fit is used to extract $P_{\Lambda_1\Lambda_2}$ according to formula from slide 7

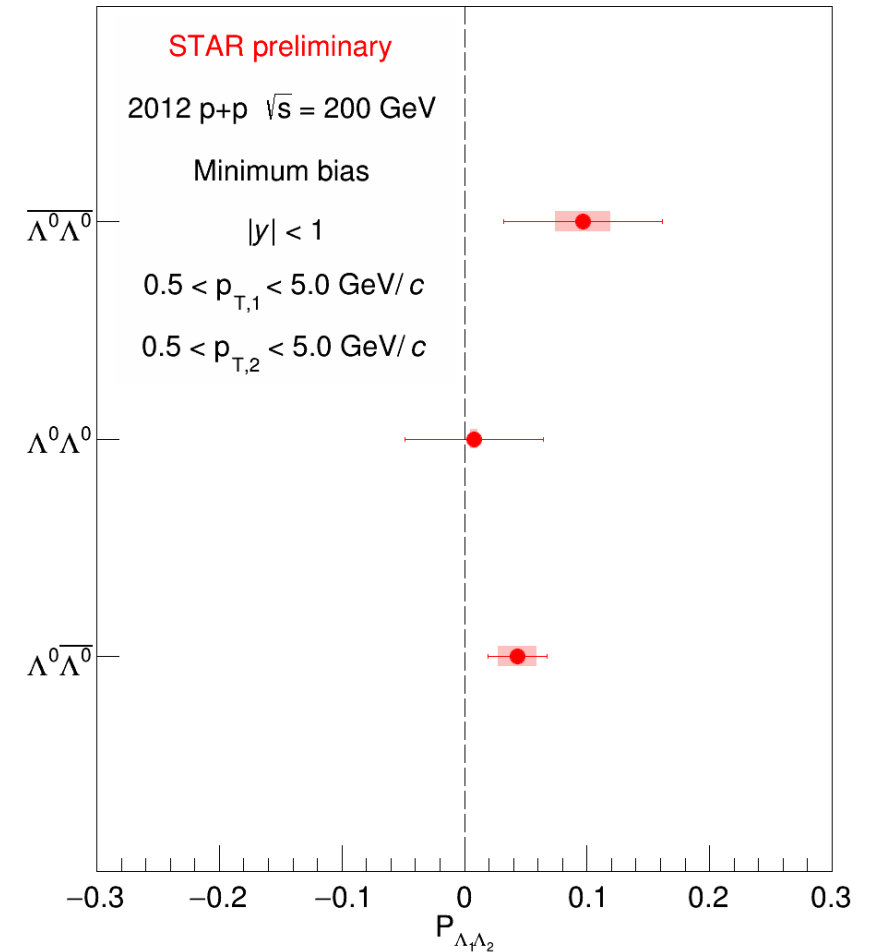
- Observed a hint of 2σ signal for $\Lambda^0\overline{\Lambda^0}$, but statistics is limited

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



Λ SPIN-SPIN CORRELATIONS

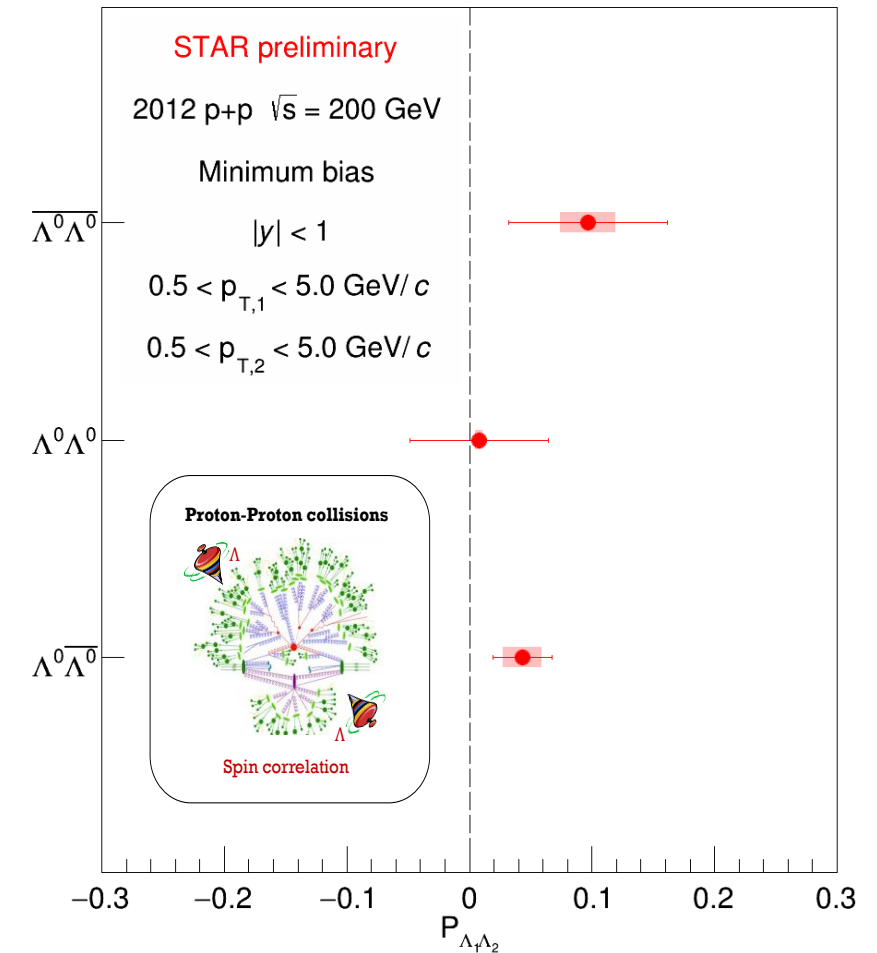
- $P_{\Lambda_1\Lambda_2}$ are consistent with zero within uncertainties for all three combinations of Λ^0 pairs
 - No spin-spin correlations measured in p+p collisions at $\sqrt{s} = 200$ GeV
 - This measurement provides upper limit on Λ^0 hyperon spin-spin correlations in p+p collisions at $\sqrt{s} = 200$ 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	$ V_z < 30$ cm
Track selection	$p_T > 150$ MeV/c
	$ \eta < 1$
	nHitsFit > 20
	nHitsFit/nHitsMax > 0.52
Particle identification	$ n\sigma_\pi < 3$
	$ n\sigma_p < 2$
Decay topology Λ^0	$DCA_{\pi-PV} > 0.3$ cm
	$DCA_{p-PV} > 0.1$ cm
	$DCA_{\text{pair}} < 1$ cm
	$2 \text{ cm} < L_{\text{dec}} < 25$ 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