Supported in part by:

Measurement of Λ hyperon spin-spin correlations in p+p collisions by the STAR experiment

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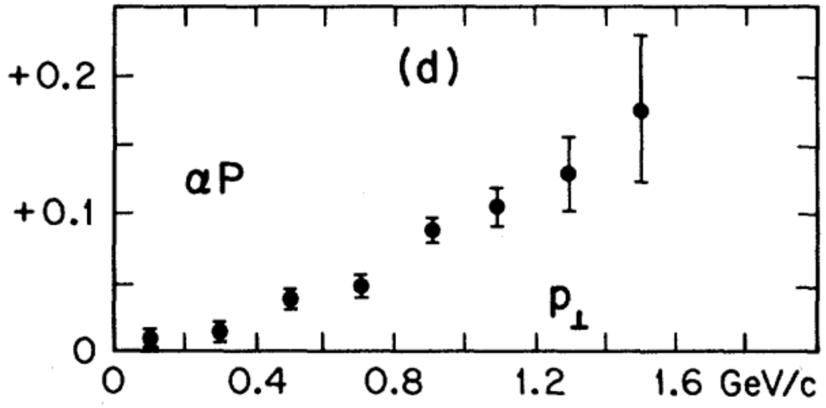
Λ POLARIZATION PUZZLE

- 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

p+Be



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STAR

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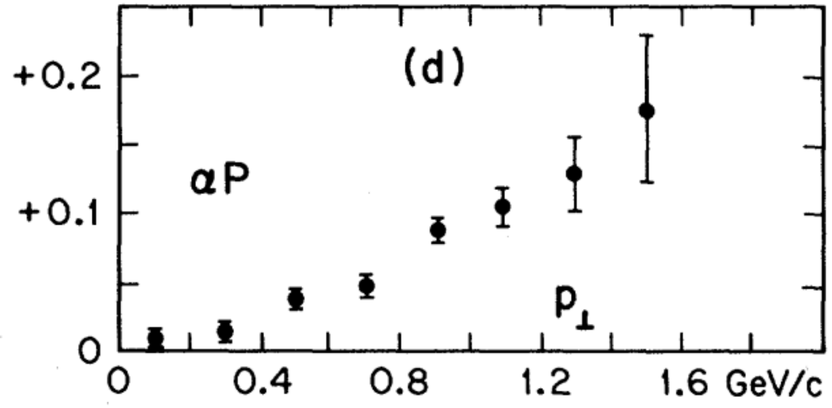

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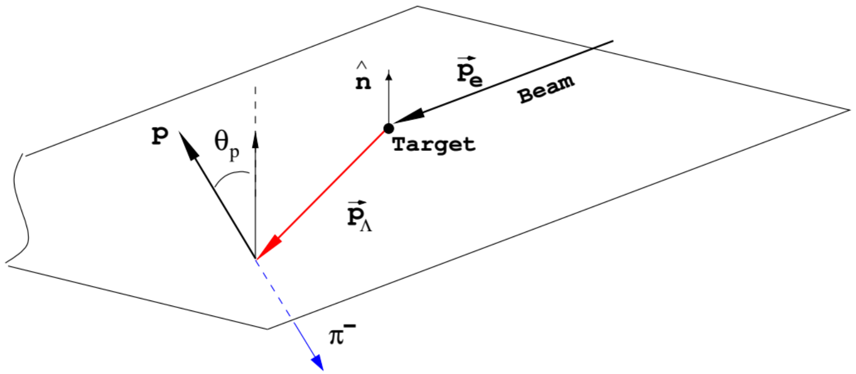
What is the origin of the Λ^0 polarization?

- Does polarization of Λ^0 depend on spin of the target/projectile?
- 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 with $BR = (64.1 \pm 0.5)\%$. In the Λ^0 rest frame, protons are emitted preferentially in the direction of Λ^0 spin

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



HERMES: Phys.Rev.D76:092008,2007

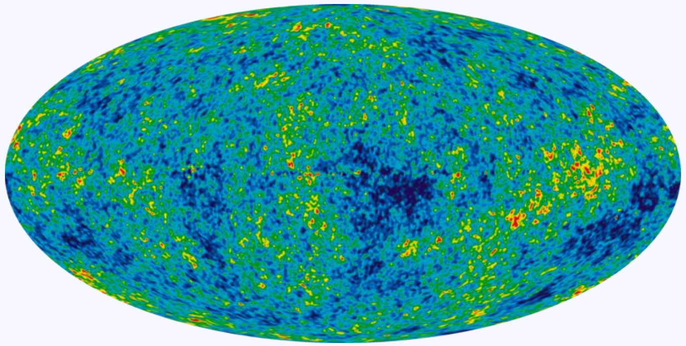
- The distribution of protons in Λ^0 rest frame is then given by:

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

  - P_Λ is the Λ^0 polarization
  - Λ^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**

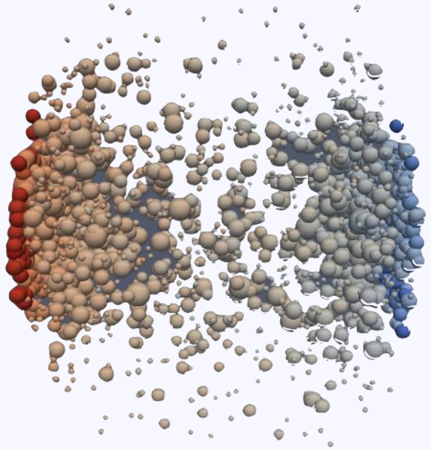
MOTIVATION FOR Λ SPIN-SPIN CORRELATIONS

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.**

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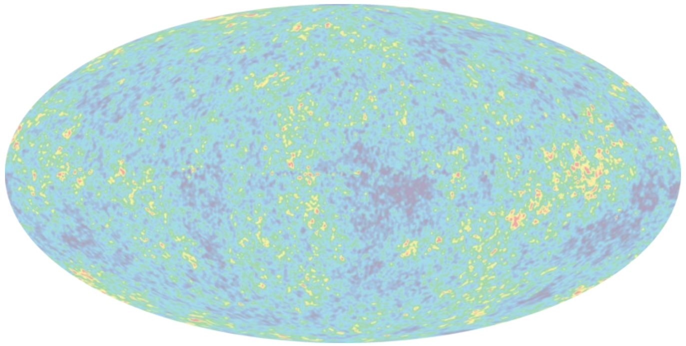

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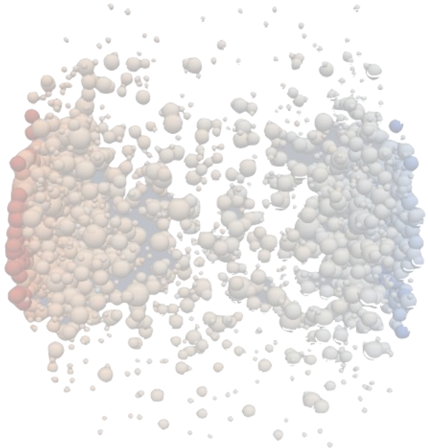
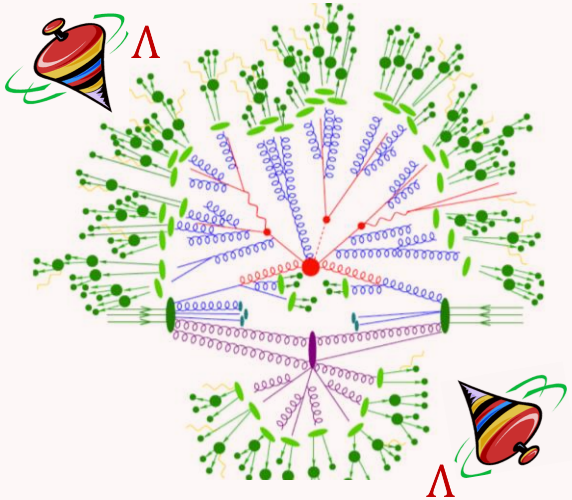


Momentum correlations

Proton-Proton collisions



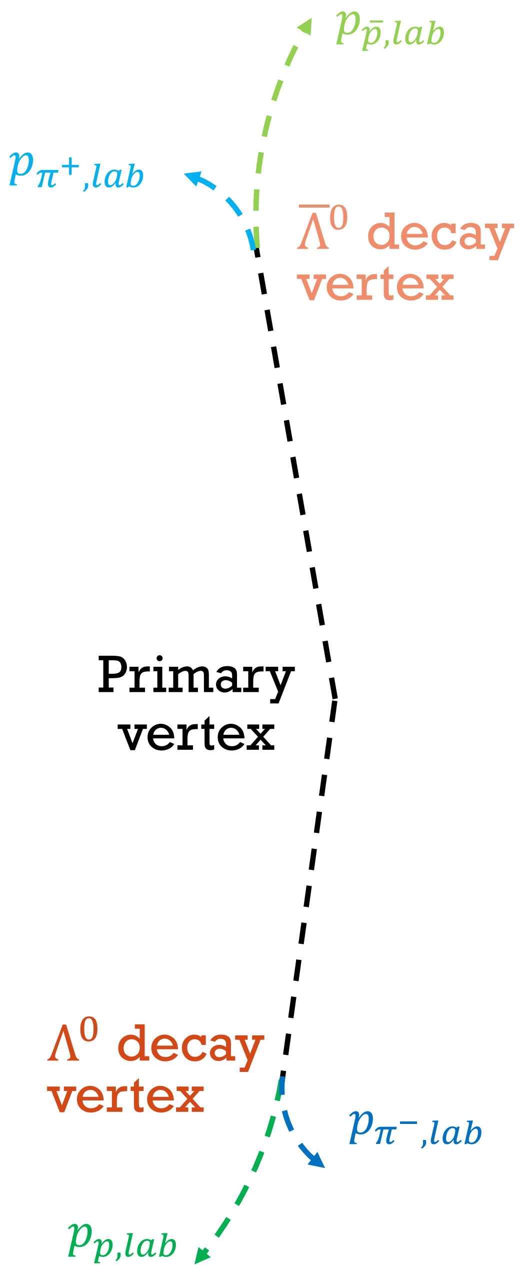
Spin correlation

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

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

EXPERIMENTAL METHOD

- Find a Λ^0 hyperon pair (any combination) in one event
  - Decay channel $\Lambda^0 \to p\pi^+$ and charge conjugate



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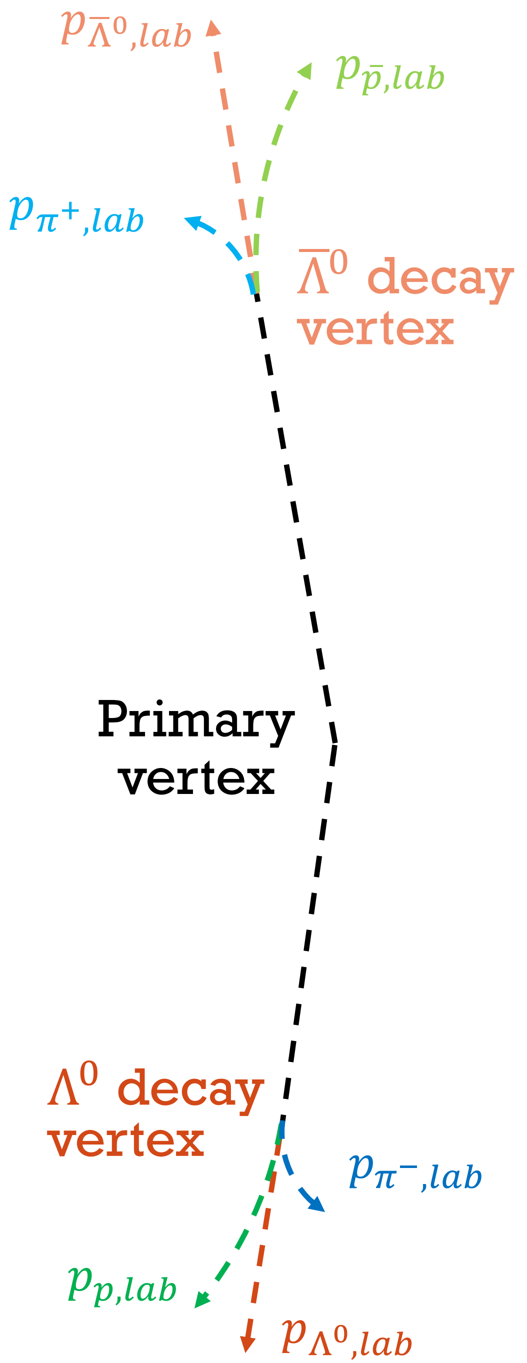
  - $p_{\Lambda^0,lab} = p_{p,lab} + p_{\pi^-,lab}$



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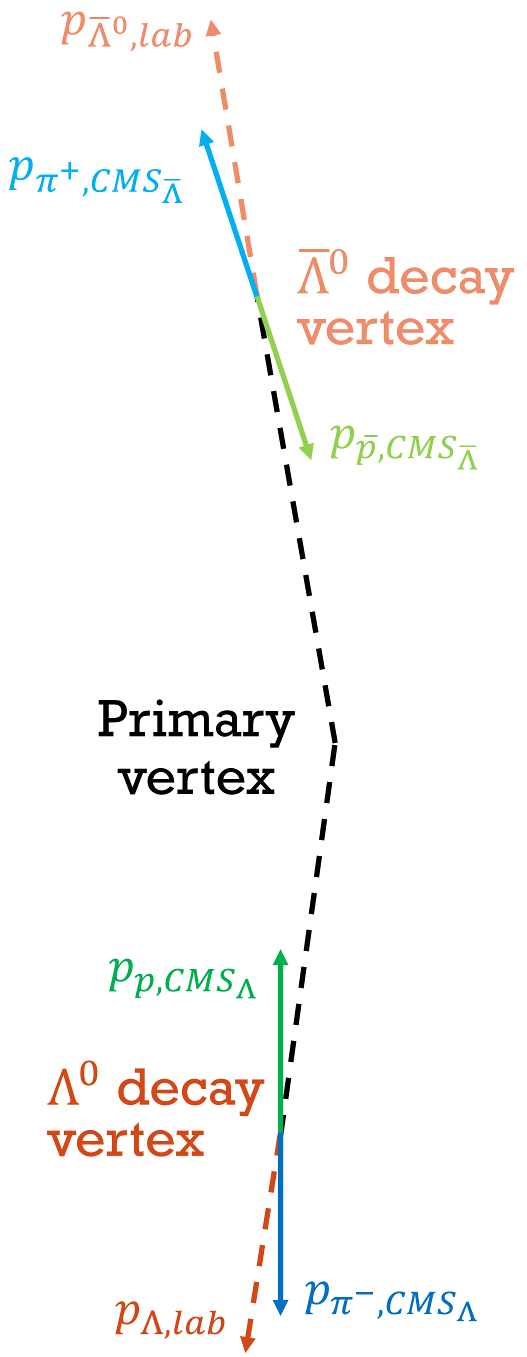
- Boost (anti-)proton from decay of the corresponding Λ^0 ($\overline{\Lambda}^0$) to **rest frame of its mother**
  - Proton momenta in mother rest frame: p_{p,CMS_Λ}, $p_{\bar{p},CMS_{\bar{\Lambda}}}$



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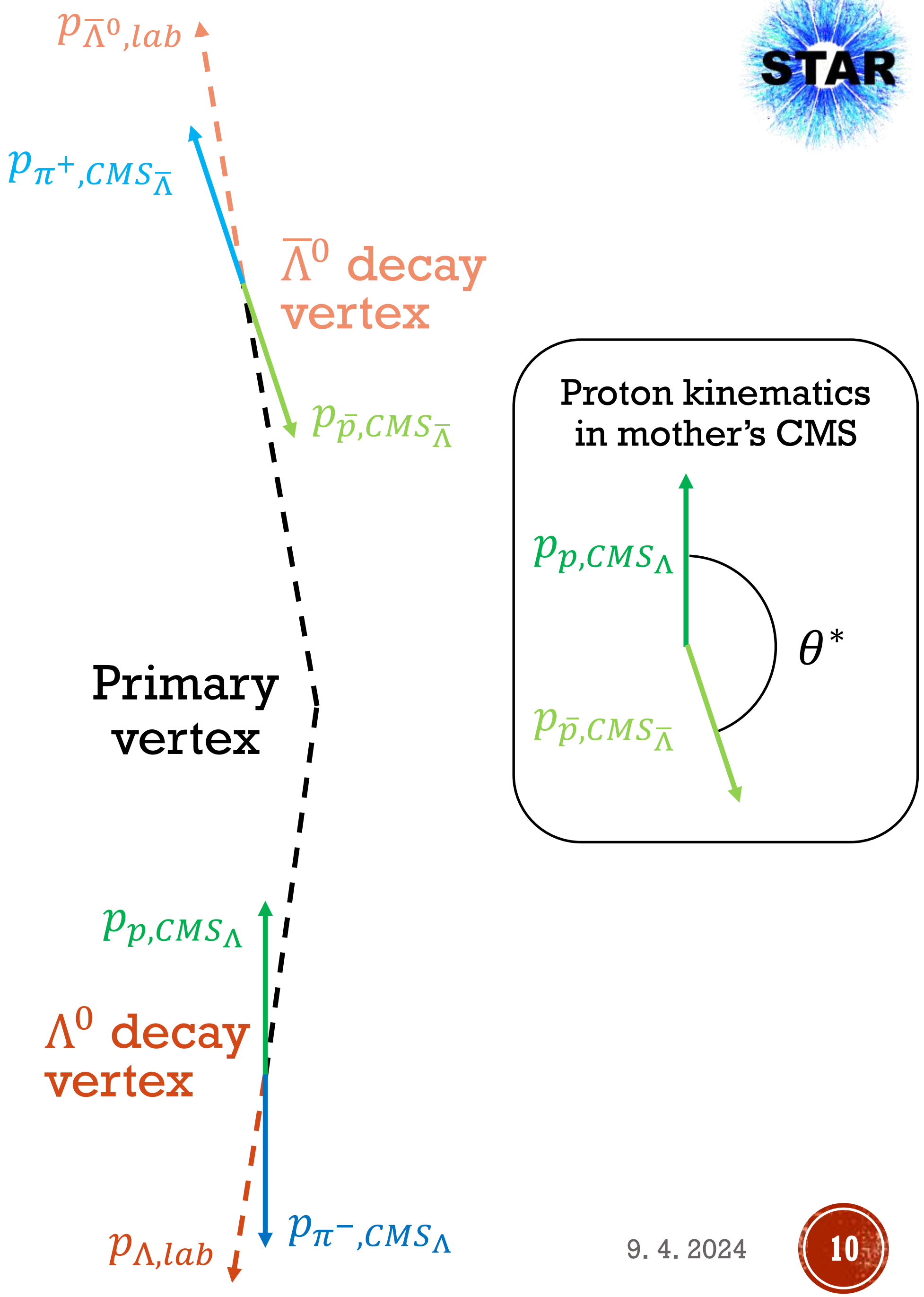
- Boost (anti-)proton from decay of the corresponding Λ^0 ($\overline{\Lambda}$) to **rest frame of its mother**
  - Proton momenta in mother rest frame: $p_{p,CMS_\Lambda}, p_{\bar{p},CMS_{\overline{\Lambda}}}$
- Measure angle θ^* between the two **boosted protons**
  - The distribution of pair angle 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 ($\overline{\Lambda}^0$) hyperons**



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- This experimental method is sensitive to selection criteria and detector acceptance
- Major source is lower cut on p_T of π
  - Preferential selection of Λ decays, where π is emitted along Λ momentum
- This is called the **acceptance effect** and is corrected for in this analysis

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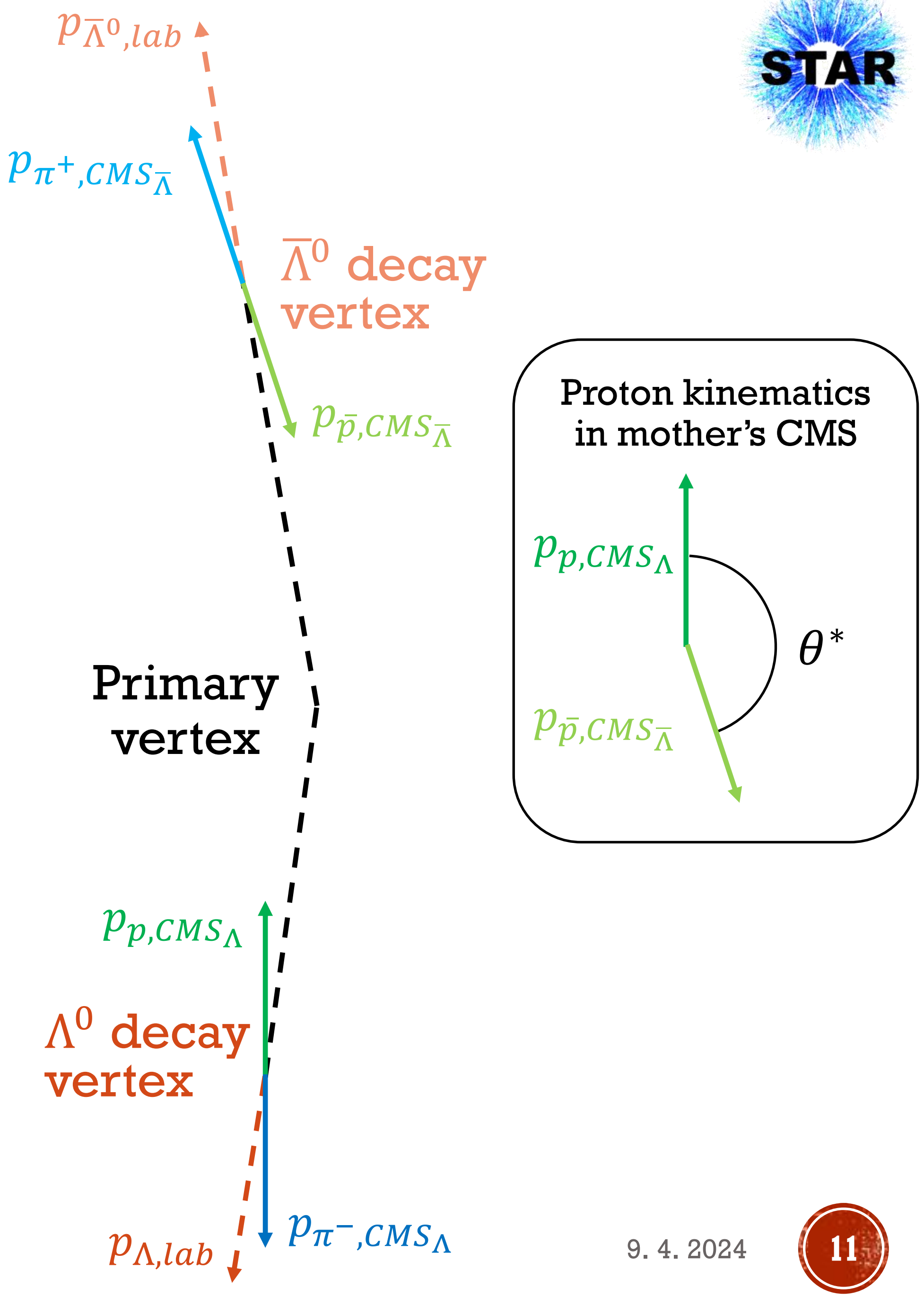
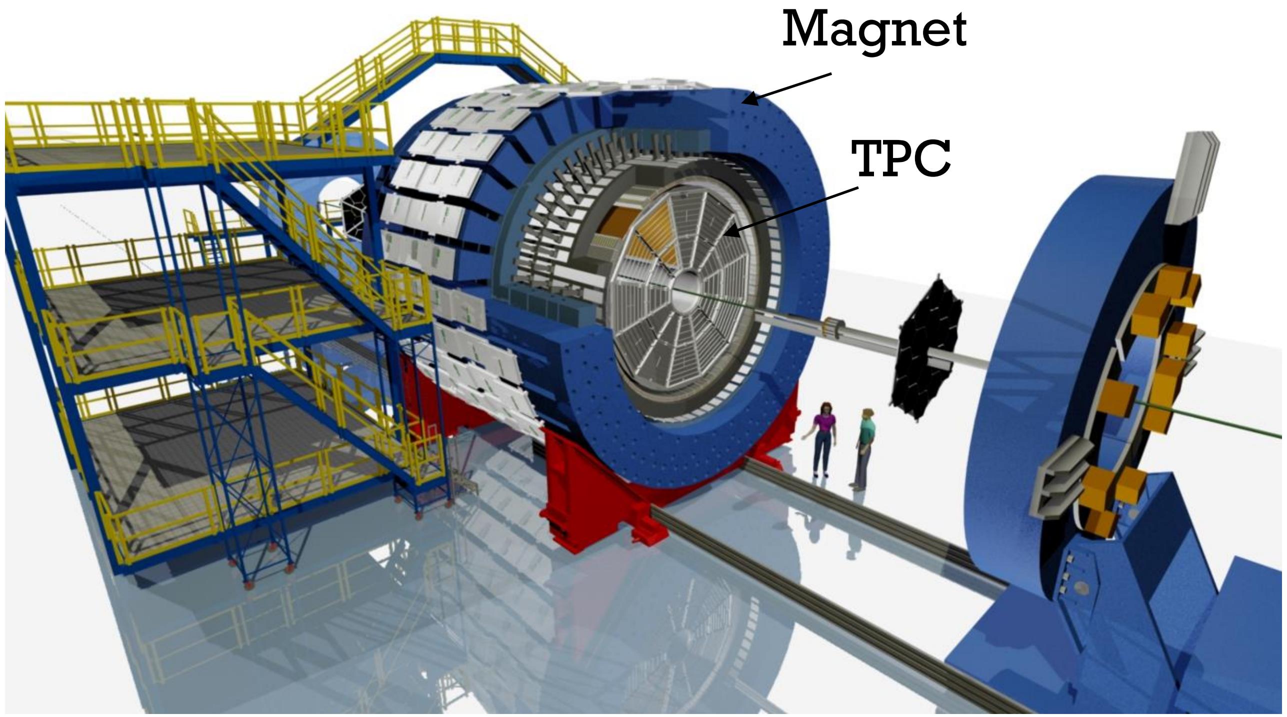


SOLENOIDAL TRACKER AT RHIC (STAR)

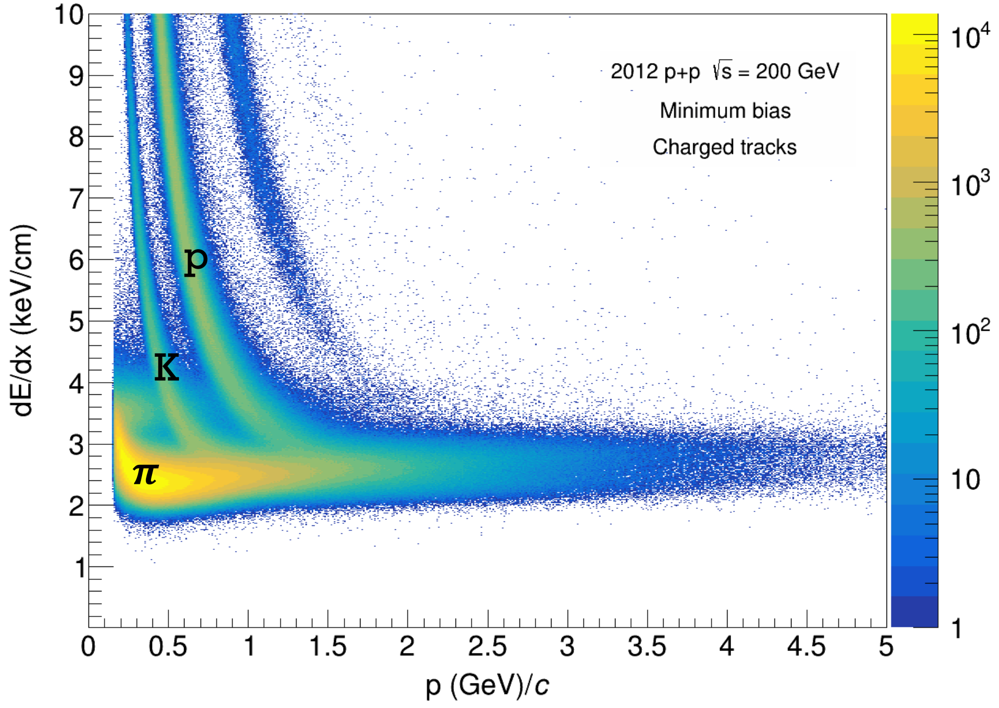
- Key subsystems for this analysis:
  - Solenoidal magnet
    - 0.5 T magnetic field **with low p_T coverage**
  - Time Projection Chamber (TPC)
    - Measurement of charged particle transverse momentum (p_T)
    - Particle identification (PID) based on energy loss in TPC gas
    - **Full azimuthal coverage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



EVENT AND TRACK SELECTION, PID

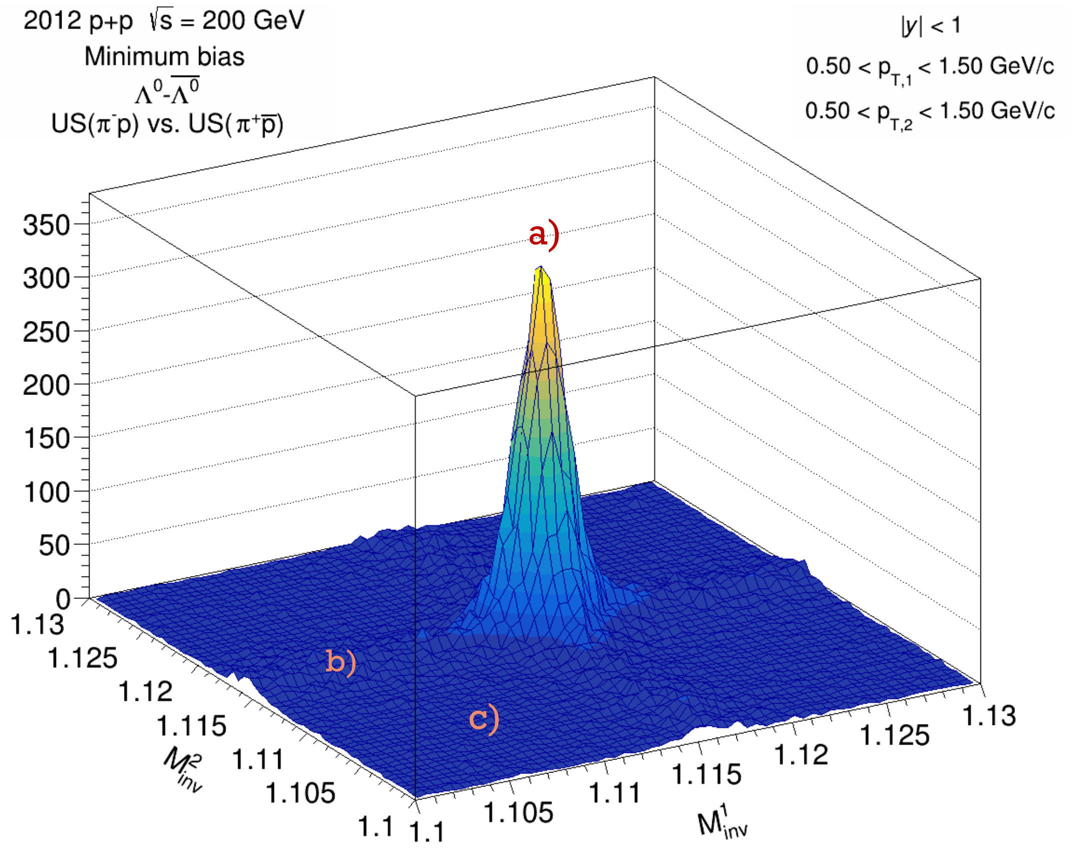
- Data-set:
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 400M minimum bias events
- Track selection to ensure good track quality within geometrical acceptance
- Particle identification to obtain pure proton and pion sample
- Decay topology to suppress combinatorial background from tracks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

Ionization energy loss in TPC



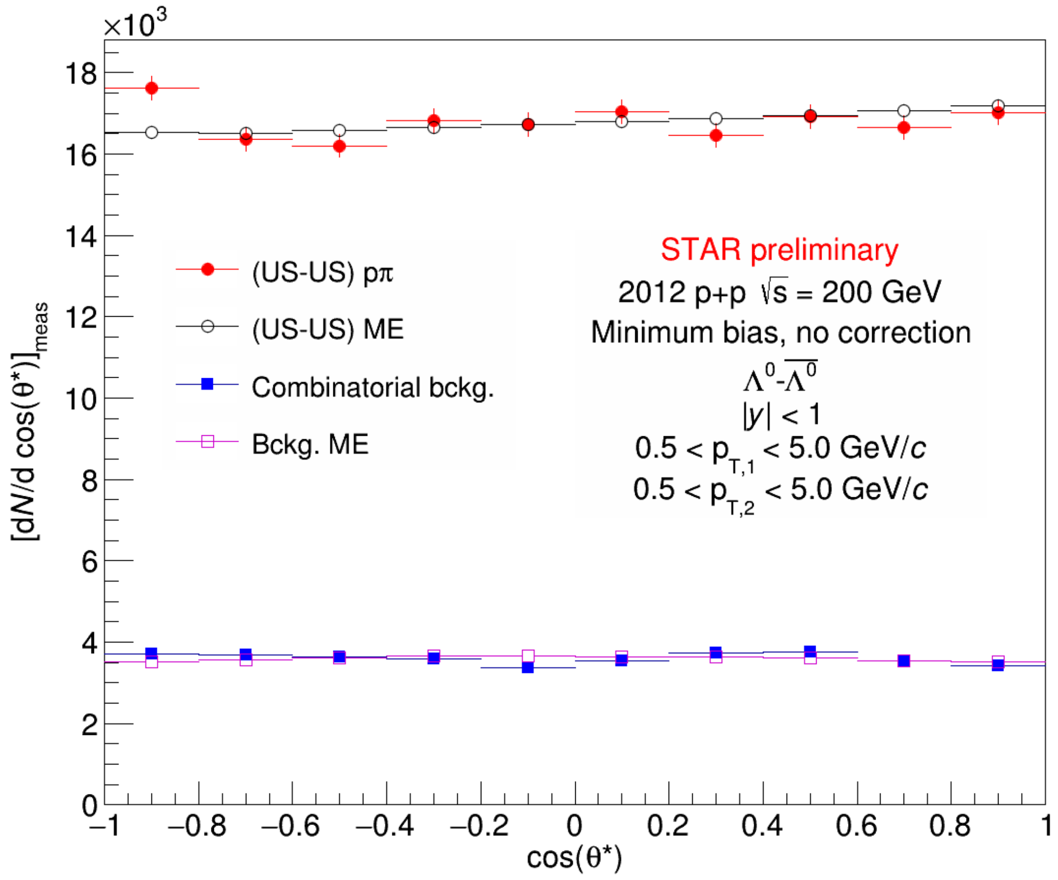
Λ Signal Extraction

- Signal extraction determined from 2D M_{inv} distributions of unlike-sign (US) πp pairs
- Three components:
  a) <u>Peak</u>: πp from Λ^0 ($\overline{\Lambda}^0$) decay paired with another πp from Λ^0 ($\overline{\Lambda}^0$) decay
  b) <u>Ridges</u>: πp fromΛ^0 ($\overline{\Lambda}^0$) decay paired with combinatorial background
  c) <u>Continuum</u>: 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

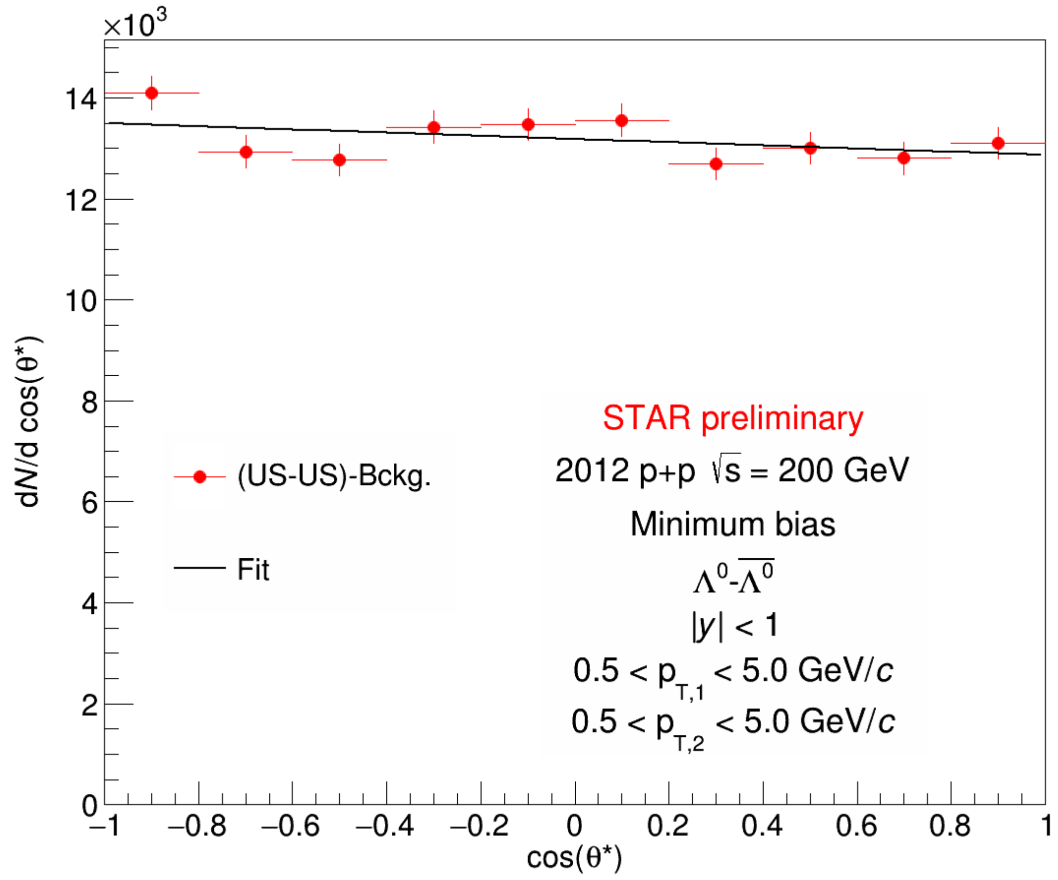
- Measured $[\mathrm{d}N/\mathrm{d}\cos(\theta^*)]_{meas}$ distribution for $\Lambda^0\overline{\Lambda}^0$ pairs before acceptance correction
  - (US-US) distribution (red) has a shape which originates from acceptance and resolution of the STAR detector
- Acceptance correction done using mixed (ME)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



Λ SPIN-SPIN CORRELATION EXTRACTION

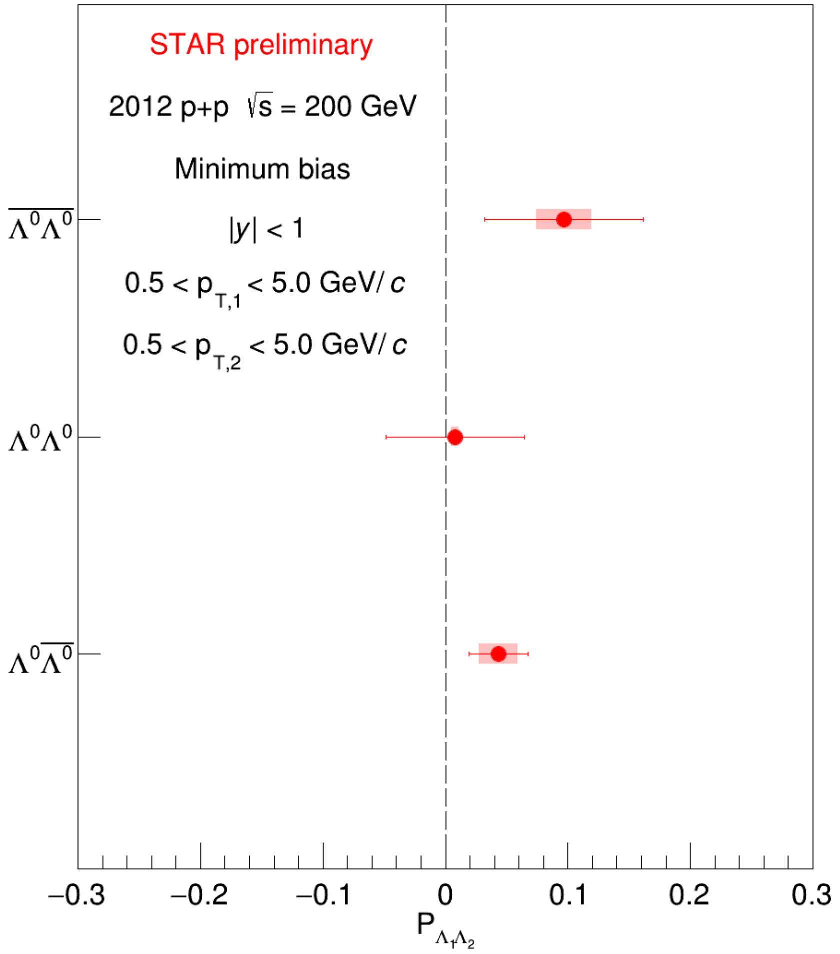
- $\mathrm{d}N/\mathrm{d}\cos(\theta^*)$ distributions from data after acceptance correction and background subtraction

- Corrected distribution is fitted with
$$\mathrm{d}N/\mathrm{d}\cos(\theta^*) = A[1 + B\cos(\theta^*)]$$
  - A and B are parameters of the fit
  - A is normalization, $B = \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}$



Λ SPIN-SPIN CORRELATIONS

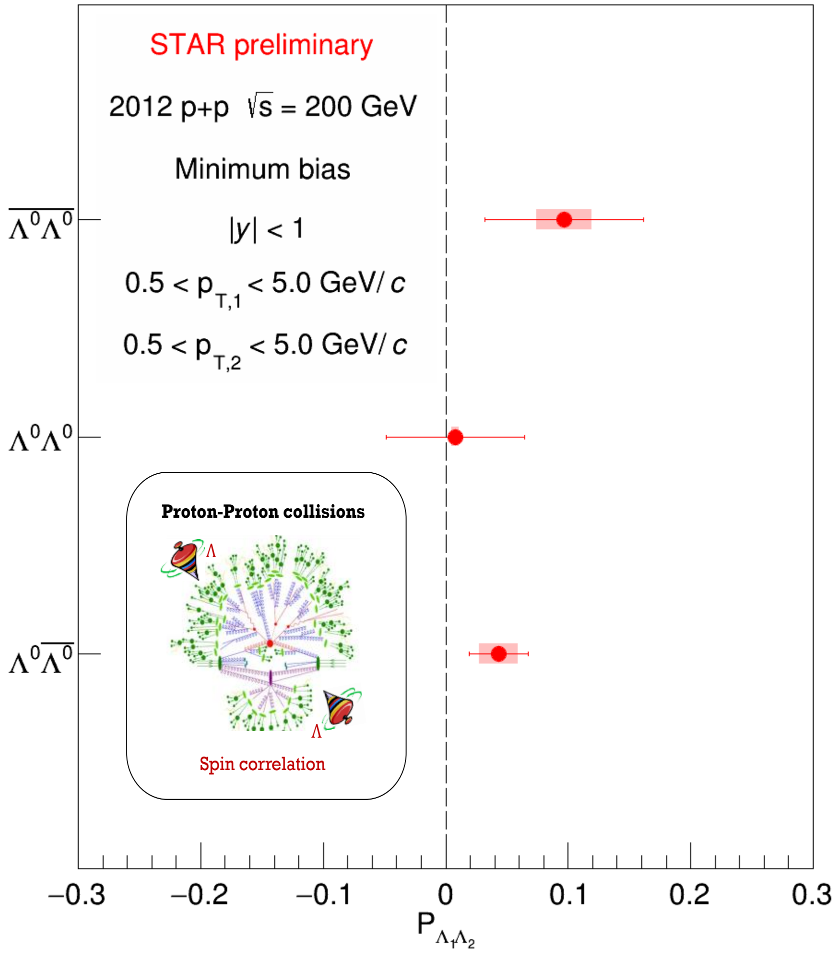
- $P_{\Lambda_1\Lambda_2}$ are consistent with zero within uncertainties
- Hint of polarization signal for $\Lambda^0\overline{\Lambda}^0$ pairs at 2σ statistical significance
- Data suggest no significant spin-spin correlation of initial state s (anti-)quark pair
  - This measurement provides upper limit on Λ^0 hyperon spin-spin correlations in p+p collisions at $\sqrt{s} = 200$ GeV
- 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

- **Outlook:**
  - Investigate the correlation for Λ^0 pairs with different rapidity and azimuthal angle gaps
  - Study p_{T} dependence of the spin-spin correlations
  - Study the correlations with large rapidity gap utilizing the STAR forward upgrade using p+p collisions at $\sqrt{s} = 200$ GeV to be collected in 2024
  - Publication of the 2012 data coming soon!
    - First steps of publication process starting now



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	$DCA_{\pi\text{-PV}} > 0.3$ 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