Supported in part by:

Evidence of $\Lambda\bar{\Lambda}$ spin correlation in p+p collisions at STAR

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NON-PERTURBATIVE QCD: QUARK CONFINEMENT

- Quarks and gluons are **confined** within hadrons due to the nature of the strong interaction, a standing QCD challenge

- **Challenges:**
  - Difficult to calculate because the number of gluons increases at large distances in strong interaction

- **Questions:**
  - How do hadrons acquire their properties?
    - Parton properties vs. hadron properties (mass, spin…)
  - How does transition from partons to hadrons occur?
    - Hadronization

Uncovering how confinement shapes hadron properties is one of the key questions in nuclear and particle physics.

EMERGENT HADRON PROPERTIES

- **Mass**
  - Hadron masses far exceed those of their constituent partons
    - Chiral symmetry breaking
    - Dynamical mass generation from **QCD vacuum**

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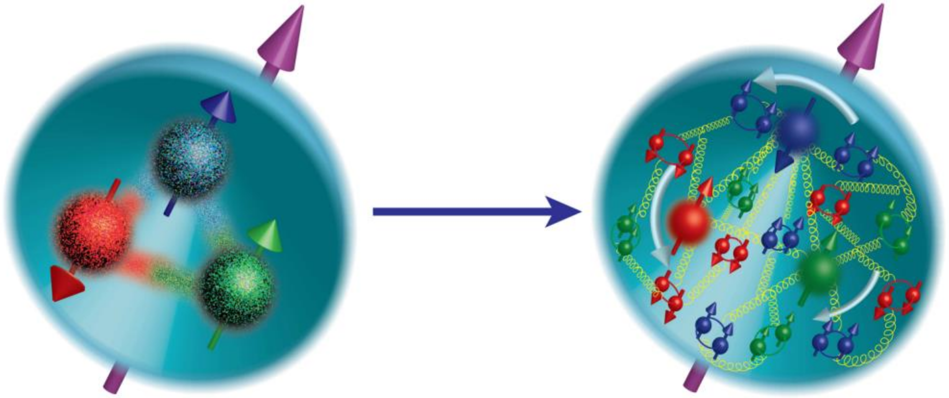
    - Chiral symmetry breaking
    - Dynamical mass generation from **QCD vacuum**

- **Spin**
  - Proton spin crisis
    - Valence quarks account for only ~30% of proton's spin
  - Λ^0 hyperon polarization puzzle
    - Polarized Λ^0 observed in collisions of unpolarized particles



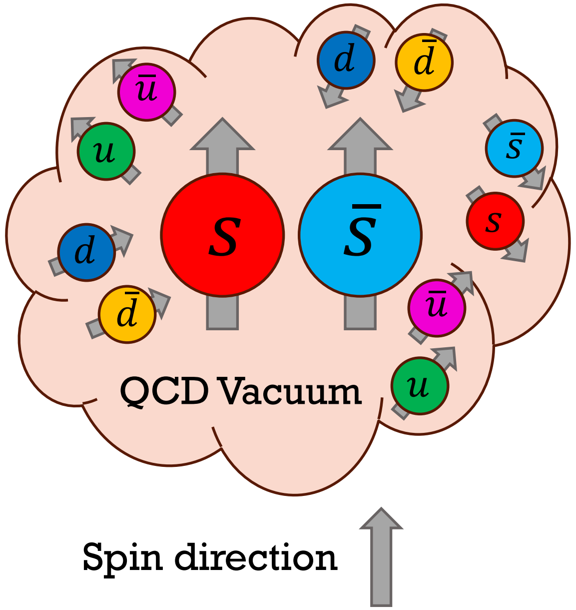
- Our goal is to experimentally reveal the origin of these emergent hadron properties

VACUUM: MAXIMALLY ENTANGLED QUARK PAIRS

- Quark condensate has up $(u, \bar{u})$, down $(d, \bar{d})$, and strange $(s, \bar{s})$ quarks
- **Quark pairs from the vacuum** are expected to emerge as **maximally entangled spin-triplet states** with aligned spins
  - The only way to preserve the vacuum's quantum numbers $J^{PC} = 0^{++}$

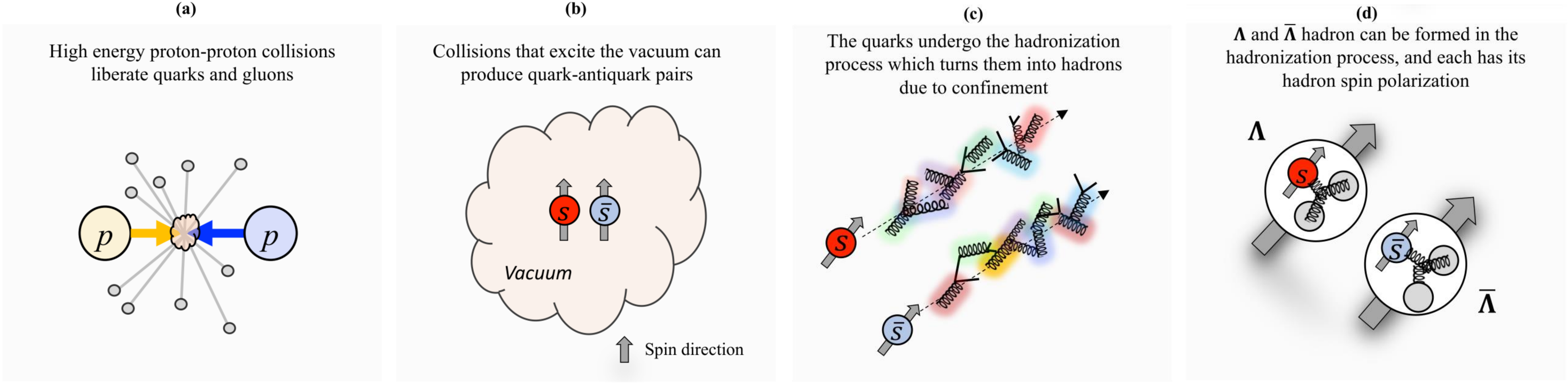
J. R. Ellis, D. Kharzeev, and A. Kotzinian, Z. Phys. C 69, 467 (1996)

- We aim to experimentally track the evolution of these entangled $s\bar{s}$ quark pairs into the hadronic level



NEW EXPERIMENTAL APPROACH

- Λ^0 **hyperon pair spin-spin correlations in *p+p* collisions:**



- We use the spin-spin correlation of $\Lambda^0\overline{\Lambda}^0$ hyperon pairs measured in *p+p* collisions to study the hadronization of the entangled $s\bar{s}$ quark pairs from the QCD vacuum

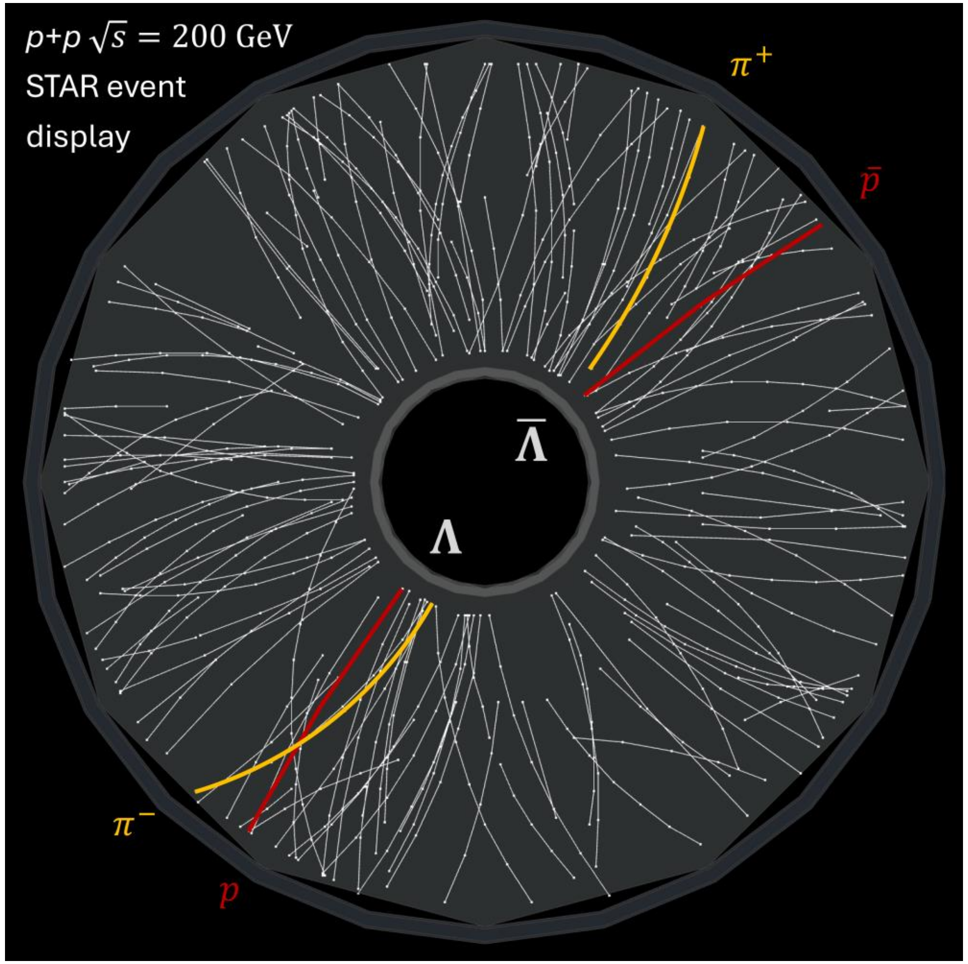
EXPERIMENTAL METHOD

- Find a Λ^0 hyperon pair (any combination) 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**
- Measure angle θ^* between the two **boosted protons**
  - The distribution of pair angle is given by:

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} = \frac{1}{2}\left[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)\right]$$

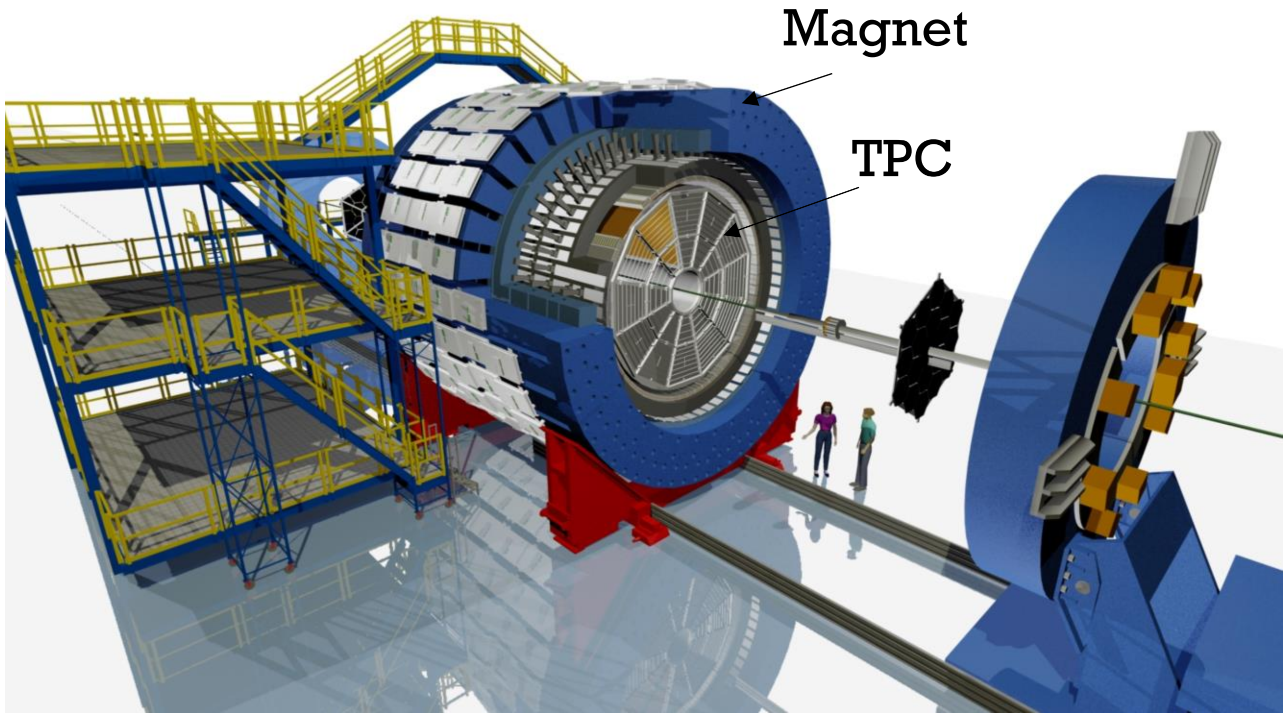
  - α_1 and α_2 are weak decay parameters of Λ^0 or $\overline{\Lambda}^0$ (α_- or α_+)

- **A non-zero $P_{\Lambda_1\Lambda_2}$ would indicate spin correlation between the two Λ^0 ($\overline{\Lambda}^0$) hyperons**
  - No global single Λ^0 hyperon polarization expected at STAR at mid-rapidity



SOLENOIDAL TRACKER AT RHIC (STAR)

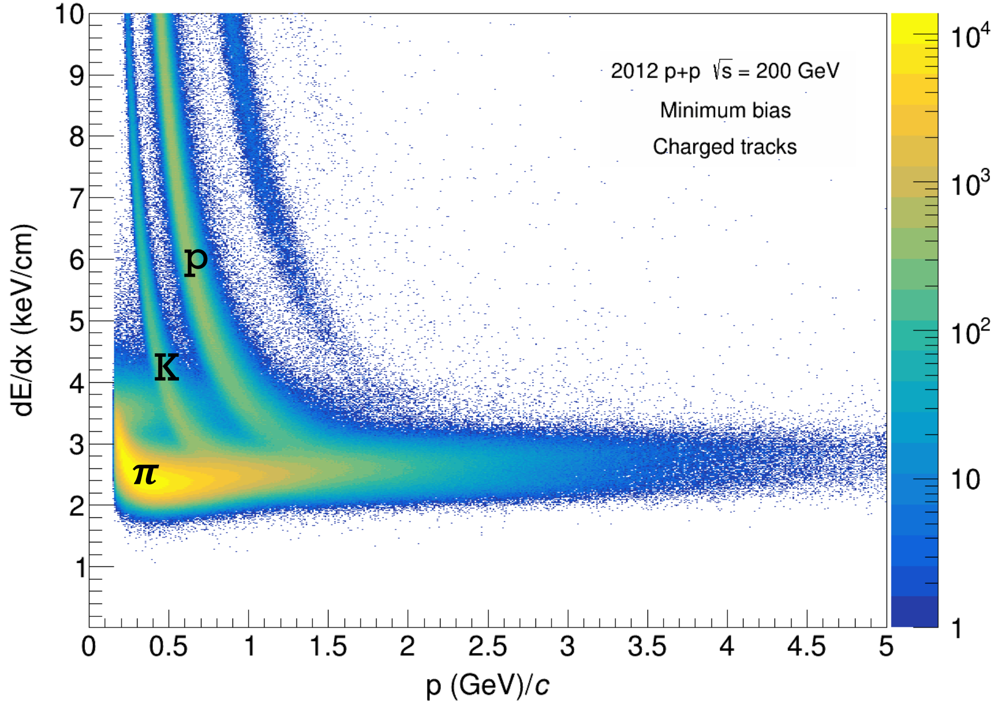
- Key subsystems for this analysis:
  - Solenoidal magnet
    - 0.5 T magnetic field **allowing low p_T coverage**
  - Time Projection Chamber (TPC)
    - Measurement of charged particle transverse momentum (p_T)
    - Particle identification (PID) based on energy loss in TPC gas
    - **Full azimuthal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



EVENT AND TRACK SELECTION, PID

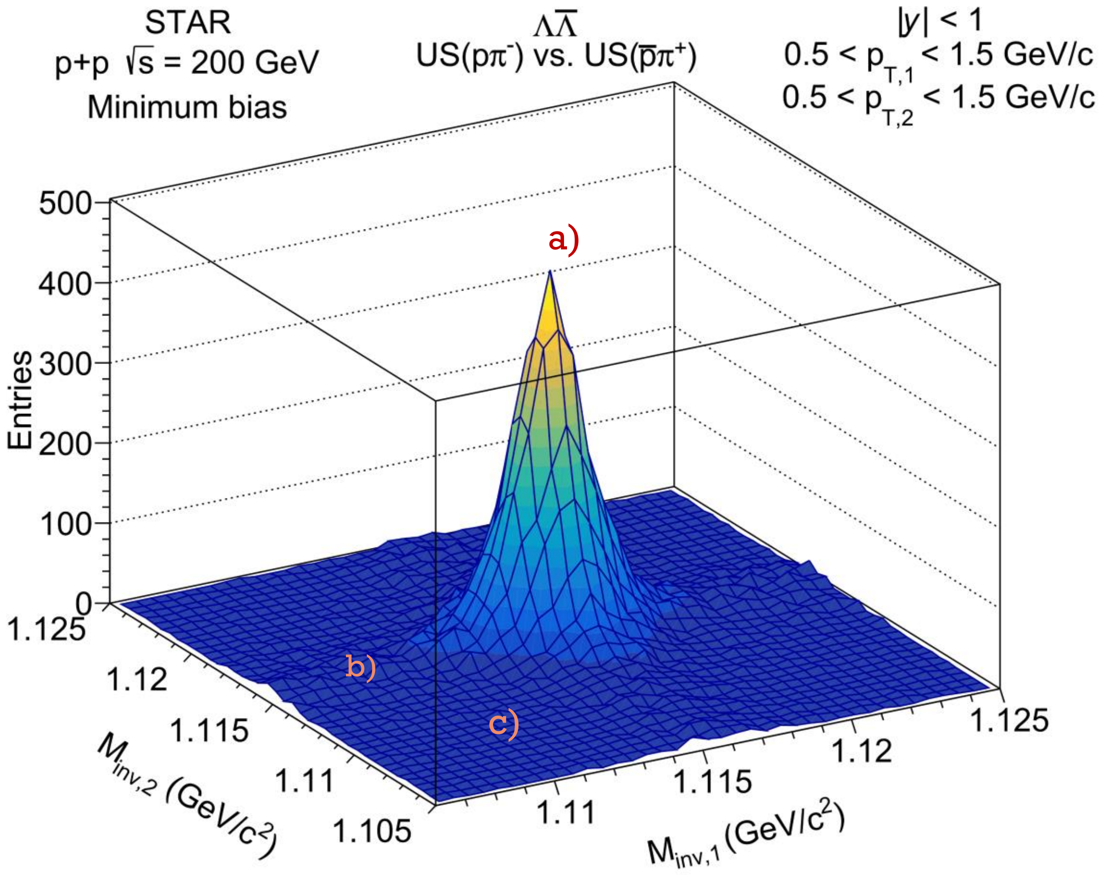
- Data-set:
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 600M minimum bias events
- Track selection to ensure good track quality within geometrical acceptance
- Particle identification (PID) to obtain pure proton and pion sample
- Decay topology to suppress combinatorial background from tracks originating from close to primary vertex

Ionization energy loss in TPC



Λ^0 SIGNAL EXTRACTION

- Signal extraction determined from 2D M_{inv} distributions of unlike-sign (US) πp pairs
- Three components:
  a) Peak: πp from Λ^0 ($\bar{\Lambda}^0$) decay paired with another πp from Λ^0 ($\bar{\Lambda}^0$) decay
  b) Ridges: πp from Λ^0 ($\bar{\Lambda}^0$) 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 $\pm 2\sigma$



ACCEPTANCE EFFECT CORRECTION

- Measured $\mathrm{d}N/\mathrm{d}\cos(\theta^*)$ distributions have significant slope originating from acceptance effect
  - Predominantly from lower p_T cut on daughter π

- Correction done using mixed-event (ME) hyperon pairs
  - ME definition example:

Same-event $\Lambda\bar{\Lambda}$

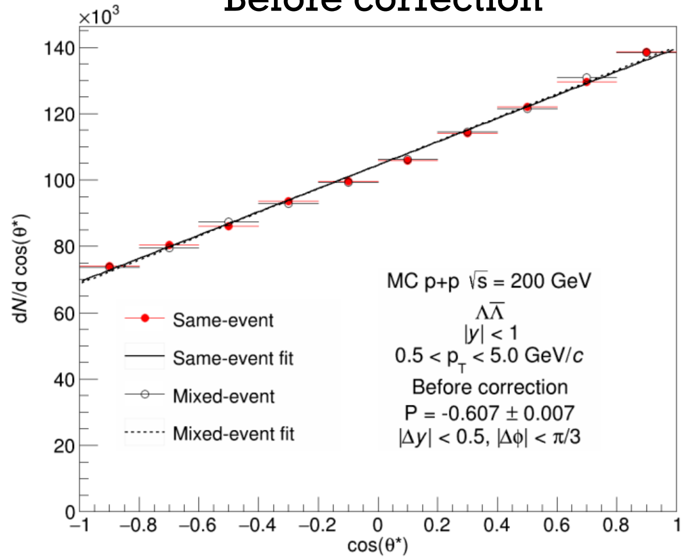
Single $\bar{\Lambda}$ from different event

Mixed-event $\Lambda\bar{\Lambda}$

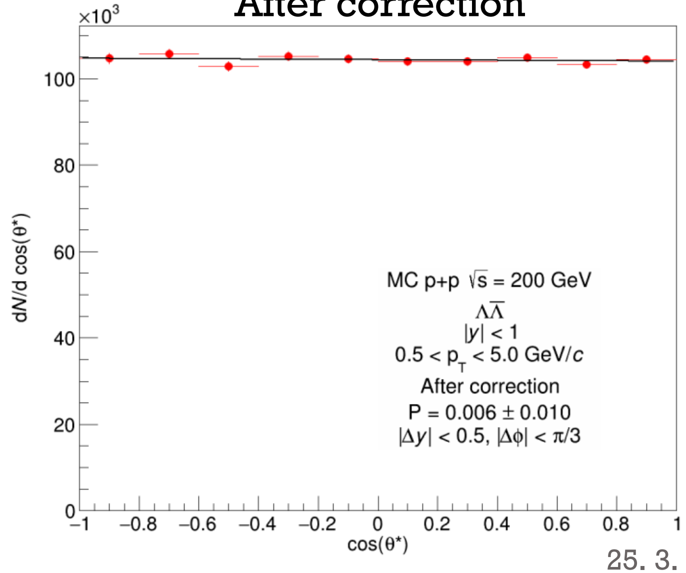
$$|p_{T,SE} - p_{T,single}| < 0.1\ \mathrm{GeV}/c$$
$$|y_{SE} - y_{single}| < 0.1$$
$$|\phi_{SE} - \phi_{single}| < 0.1$$

  - Verified using standalone PYTHIA simulation (shown on the right), as well as full simulation with detector effects

Before correction



After correction



SPIN-SPIN CORRELATION EXTRACTION

- Spin-spin correlation is extracted by fitting $\mathrm{d}N/\mathrm{d}\cos(\theta^*)$ distributions after ME correction for signal+background (P_{S+B}) and background (P_B) using:

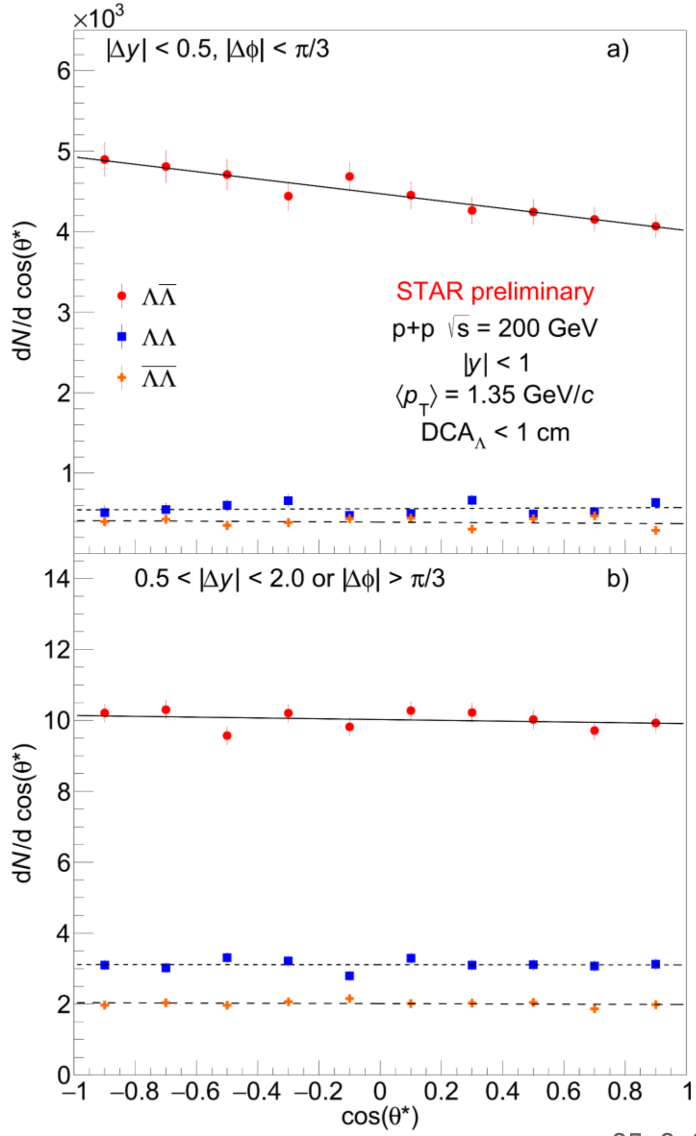
$$\mathrm{d}N/\mathrm{d}\cos(\theta^*) = A[1 + B\cos(\theta^*)]$$

  - A and B are parameters of the fit
  - A is normalization, $B = \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}$

- Signal (P_S) is calculated according to:

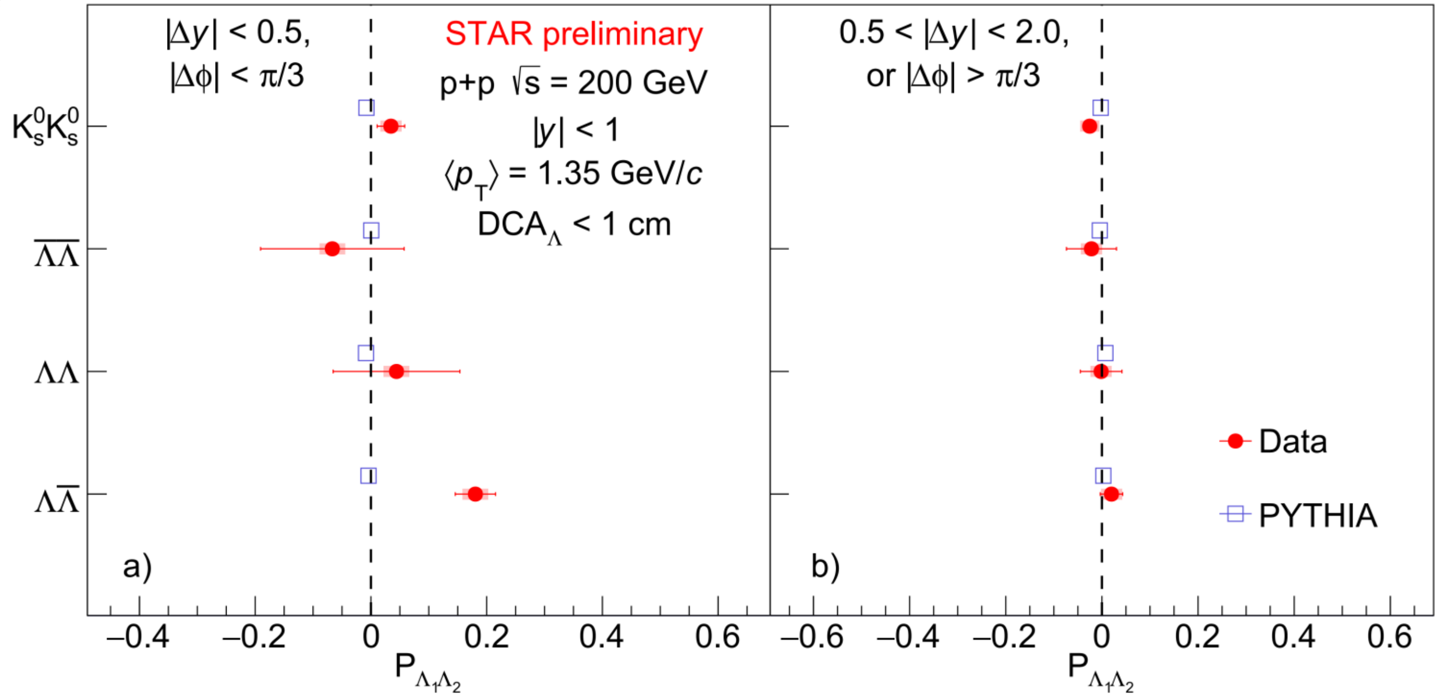
$$P_{S+B} = f_s P_S + (1 - f_s) P_B$$

- Signal extracted for two relative pair kinematics:
  - **Short-range:** $|\Delta y| < 0.5$ and $|\Delta\phi| < \pi/3$
  - **Long-range:** $0.5 < |\Delta y| < 2.0$ or $\pi/3 < |\Delta\phi| < \pi$



Λ SPIN-SPIN CORRELATIONS

- Spin-spin correlation for short-range (a) and long-range (b) hyperon pairs
  - Compared to null measurement of K_s^0 and PYTHIA calculation
- Short-range $\Lambda\bar{\Lambda}$ pairs show non-zero spin-spin correlation
  - $P_{\Lambda_1\Lambda_2} = 0.181 \pm 0.035_{stat} \pm 0.022_{sys}$
    - Significance 4.4 standard deviation
- All other pairs are consistent with zero



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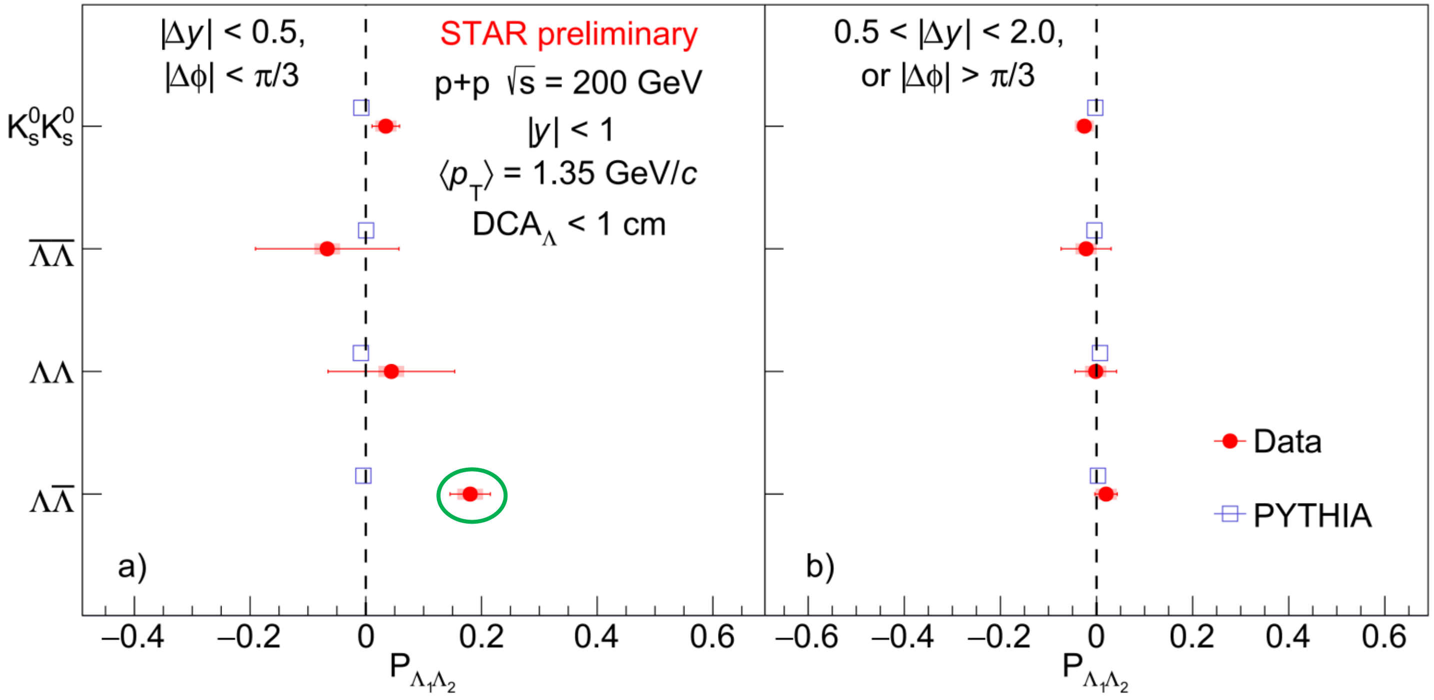


MAXIMUM EXPECTED SPIN-SPIN CORRELATION

- **Pure spin triplet $s\bar{s}$ pairs** from QCD vacuum: $P_{s\bar{s}} = 1/3$ N. A. Tornqvist, Phys. Lett. A542117, 1 (1986)
  - What happens when such pair hadronizes into $\Lambda^0\overline{\Lambda}^0$ pair?

- **Expected maximum for $\Lambda^0\overline{\Lambda}^0$ pairs** in our dataset based on models and feed-down from decay of heavier hyperons:
  - $P_{\Lambda_1\Lambda_2,\mathrm{SU(6)}} = 0.096 \pm 0.004$
  - $P_{\Lambda_1\Lambda_2,BJ} = 0.015 \pm 0.002$

- Model prediction has two components:
  - Single Λ^0 ($\overline{\Lambda}^0$) polarization depending on its mother particle from two models:
    - Non-relativistic SU(6) quark model and Burkardt-Jaffe (BJ) model
  - Feed-down mixture for $\Lambda^0\overline{\Lambda}^0$ pairs from PYYHIA 8 + Geant simulation

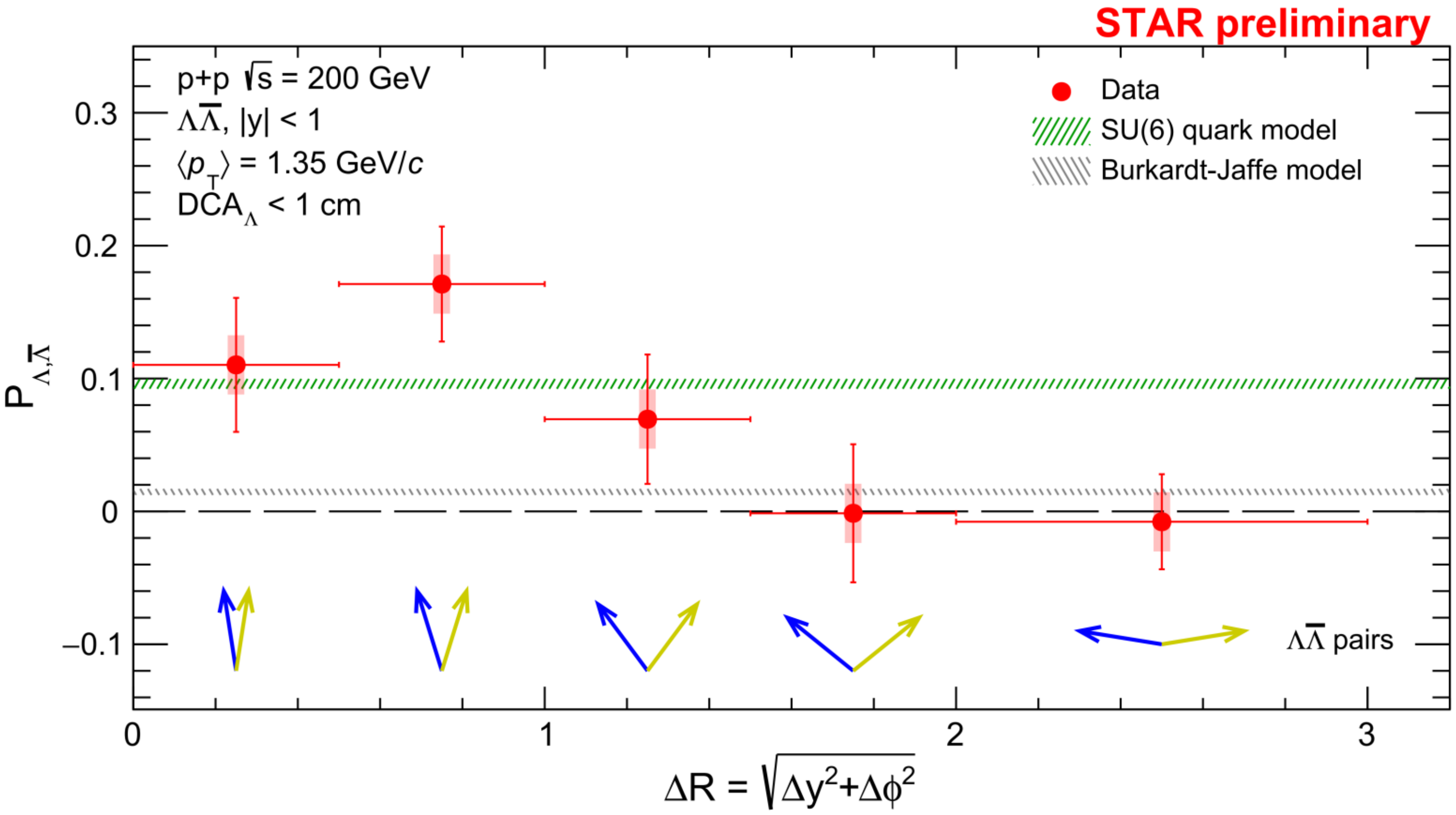
Single Λ^0 ($\overline{\Lambda}^0$) polarizations depending on its mother particle from SU(6) and BJ models

Λ's parent	SU(6)	BJ model
Primary	1	0.63
Σ^0	1/9	0.15
Ξ^0	0.6	−0.37
Ξ^-	0.6	−0.37
Σ^*	5/9	N/A

M. Burkardt and R. L. Jaffe, Phys. Rev. Lett. 70, 2537 (1993)

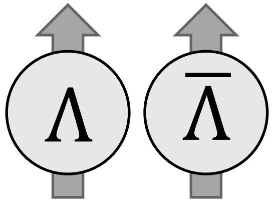
$\Lambda\bar{\Lambda}$ SPIN-SPIN CORRELATIONS

- Spin-spin correlation of $\Lambda\bar{\Lambda}$ pairs as a function of $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$
  - Compared to SU(6) and BJ models
- **Short range $\Lambda\bar{\Lambda}$ pairs appear to be in triplet state**
  - First direct probe of QCD vacuum?
- **Possible observation of quantum decoherence**
  - Spin-spin correlation seem to "turn off" with larger pair separation

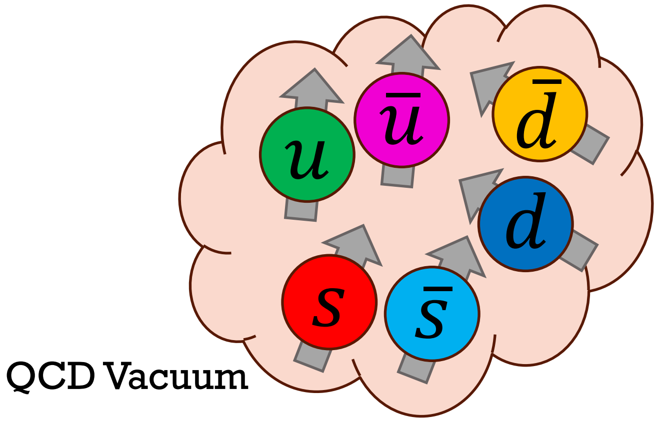


PHYSICS IMPLICATIONS

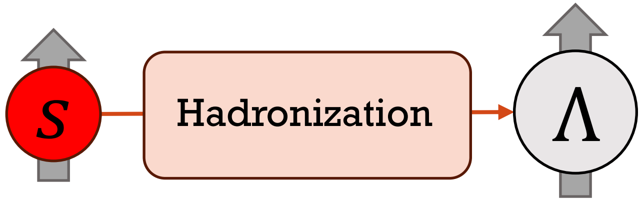
- We observed the **first evidence of a positive spin-spin correlation** of short-range $\Lambda\bar{\Lambda}$ pairs from p+p collisions at 200 GeV, recorded by the STAR experiment in 2012.



- **This may represent a new experimental approach to probing the quark condensate**
  - Our results align with short-range $\Lambda\bar{\Lambda}$ pairs being in a spin-triplet state, as expected for $\Lambda\bar{\Lambda}$ pairs from the QCD vacuum

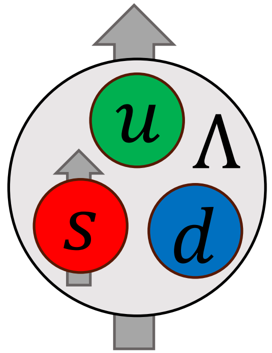


- The $s\bar{s}$ **pair's spin-spin correlation** appears to largely **survive hadronization**
  - First time, we seem to track the spin degree of freedom through QCD quark-to-hadron transition
  - A key insight into hadronization process of (s) quarks

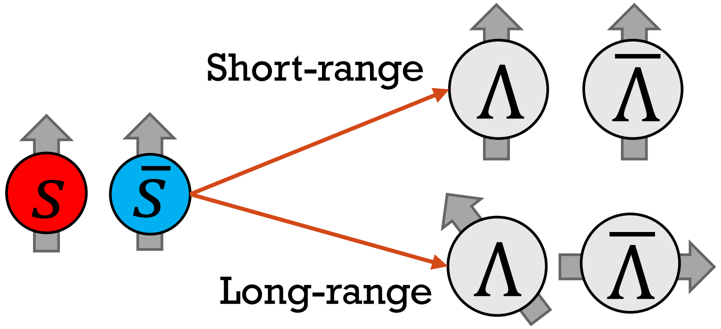


PHYSICS IMPLICATIONS CONT.

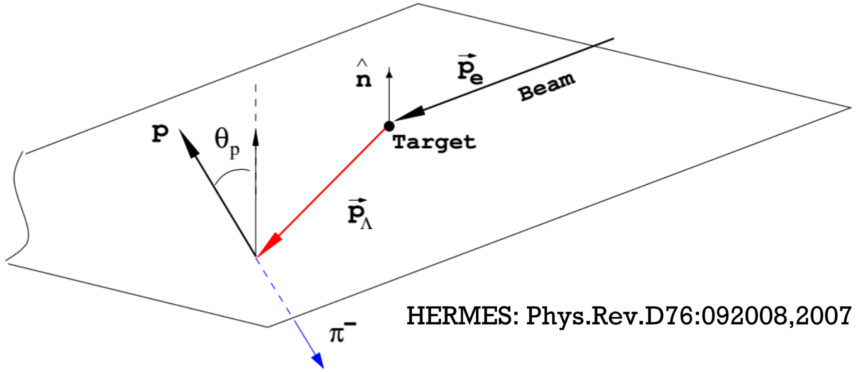
- **Result support a scenario** where ***s* quarks carry most of the hyperon's spin**
  - Results offer valuable insight into how partons contribute to the Λ hyperon's spin



- **Possible experimental approach to observe quantum decoherence**
  - Spin-spin correlation weakens with increasing pair separation
  - Can be extended to *p*+Au or Au+Au to study influence of cold nuclear matter effects and the QGP



- **Provides new insight into the Λ hyperon polarization puzzle and spin transfer**
  - New experimental constraints on both initial- and final-state models

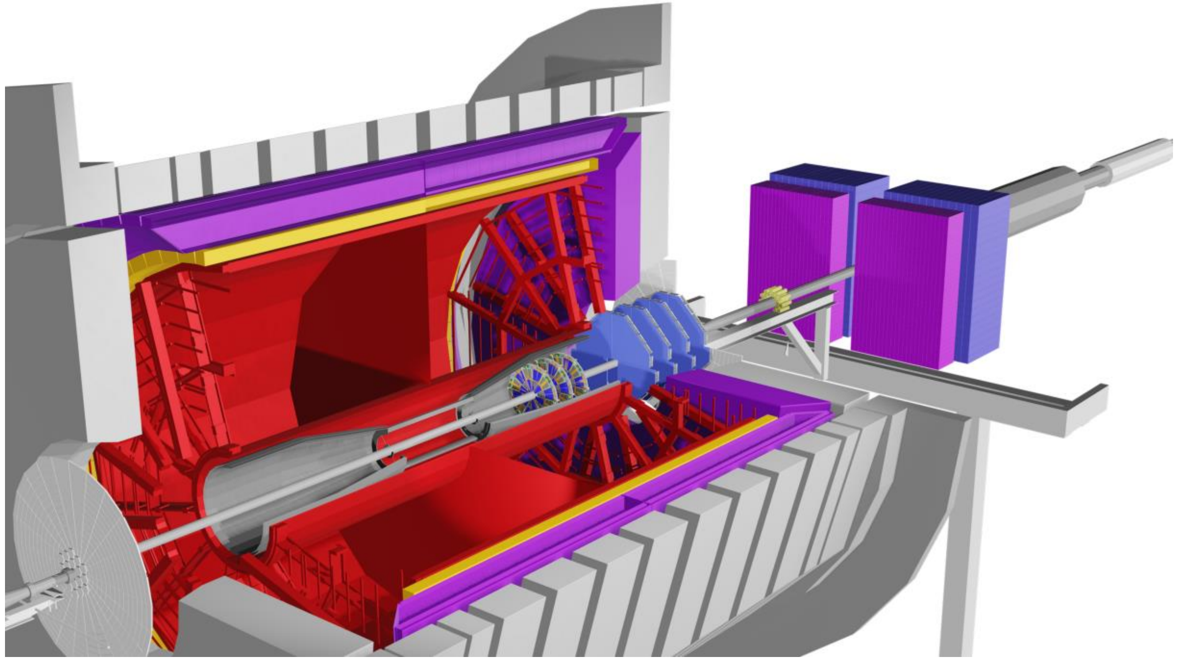


HERMES: Phys.Rev.D76:092008,2007

FUTURE PROSPECTS

- Extension of kinematic coverage beyond $|y| < 1$
  - Access to region with non-zero single Λ^0 hyperon polarization
  - **STAR forward upgrade**
- Hight p_T Λ^0 in jets – study of $g \rightarrow s\bar{s}$
  - Spin configuration of $s\bar{s}$ given by gluons
- Collision energy dependence
  - From RHIC to LHC
- Other collision systems
  - p+A – cold nuclear matter effects
  - A+A – Quark Gluon Plasma, chiral symmetry restoration

STAR forward upgrade
$2.5 < |\eta| < 4$
Forward Tracking and Calorimeter Systems
Taking data since 2022



THANK YOU FOR ATTENTION

BACKUP

EVENT AND TRACK SELECTION, PID

- Data-set:
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 600M 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	$\lvert V_z \rvert < 60$ 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
	$DCA_{\Lambda\text{-}PV} < 1.0$ cm
	$DCA_{pair} < 1.0$ cm
	$2\text{ cm} < L_{dec} < 25$ cm
	$\cos(\theta) > 0.996$

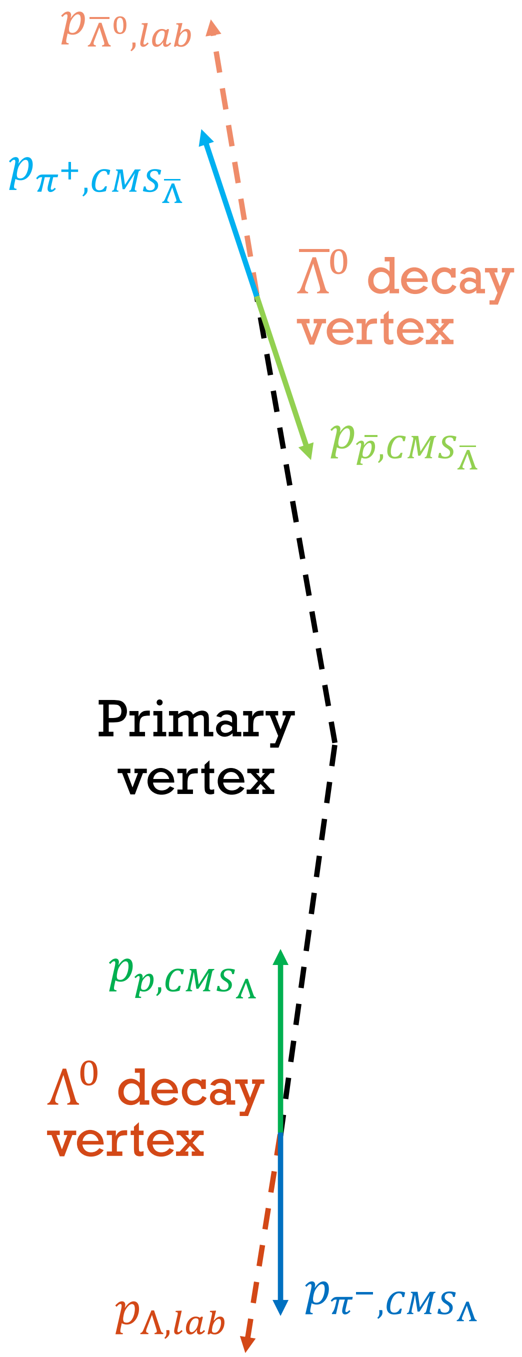
EXPERIMENTAL METHOD

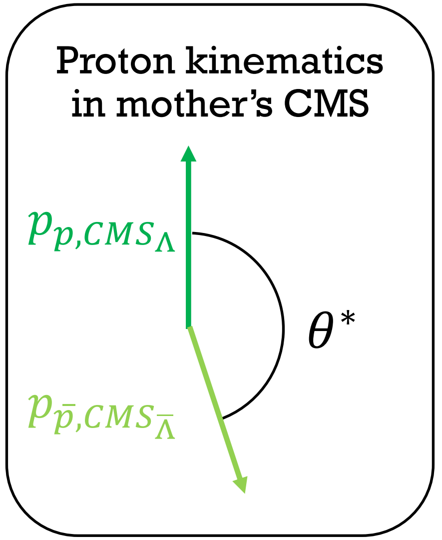
- Find a Λ^0 hyperon pair (any combination) in one event
  - Decay channel $\Lambda^0 \to p\pi^+$ and charge conjugate
  - $p_{\Lambda^0,lab} = p_{p,lab} + p_{\pi^-,lab}$
- Boost (anti-)proton from decay of the corresponding Λ^0 ($\overline{\Lambda}$) to **rest frame of its mother**
  - Proton momenta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

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} = \frac{1}{2}\left[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)\right]$$

  - 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**





EXPERIMENTAL METHOD

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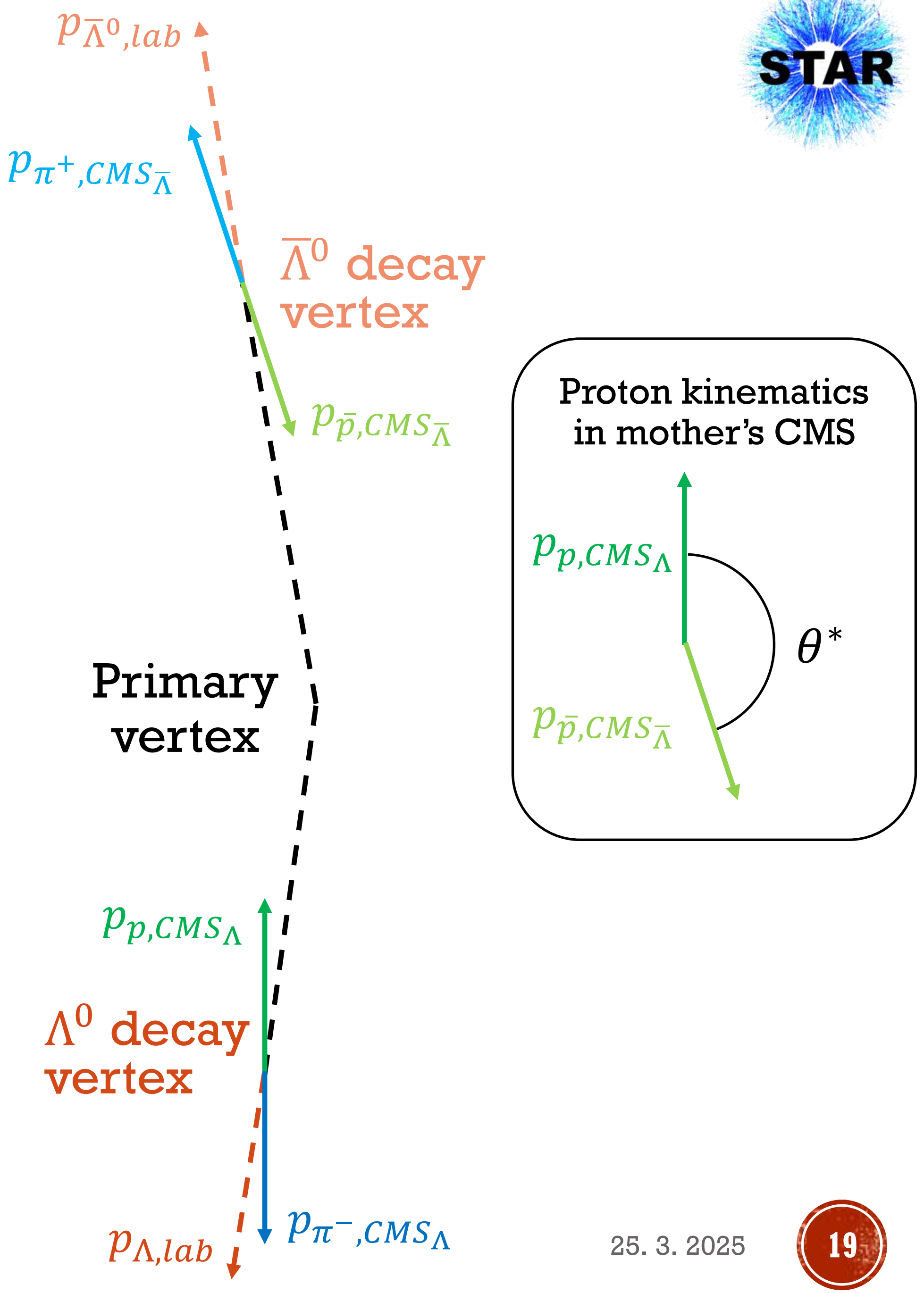
  - Decay channel $\Lambda^0 \rightarrow p\pi^+$ and charge conjugate
  - $p_{\Lambda^0,lab} = p_{p,lab} + p_{\pi^-,lab}$
- Boos ... ding Λ^0 ($\bar{\Lambda}$) ...
- Me ... ns
  - ... air

- 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 in this analysis

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



FEED-DOWN ESTIMATION

- Feed-down estimation for of $\Lambda^0\overline{\Lambda}^0$ in p+p collisions at $\sqrt{s} = 200$ GeV
  - PYTHIA 8 + Geant simulation