Supported in part by:

Measurement of Λ hyperon pair spin correlation in p+p collisions by the STAR experiment

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DIS 2023, Michigan State University

03/29/2023

Λ POLARIZATION PUZZLE

- In the 70's, it was discovered that Λ hyperons are polarized in collisions of unpolarized p+Be collisions, which raised many questions G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)
- Over nearly 50 years, Λ polarization has been seen in p+p, p+A, e+p, e^+e^- collisions up to collision energies about 40 GeV

ATLAS: Phys. Rev. D 91, 032004 (2015)
BELLE: Phys.Rev.Lett. 122, 042001 (2019)

- **What is the origin of the Λ polarization?**
  - Does polarization of Λ depend on spin of the target/projectile?
  - Is the observed Λ polarization an initial state effect or a final state effect?
  - Is there Λ hyperon spin correlation present in high energy collisions? Parton spin correlation and entanglement? W. Gong, *et al.*: Phys.Rev.D 106 (2022) 3, L031501

TRADITIONAL EXPERIMENTAL METHOD

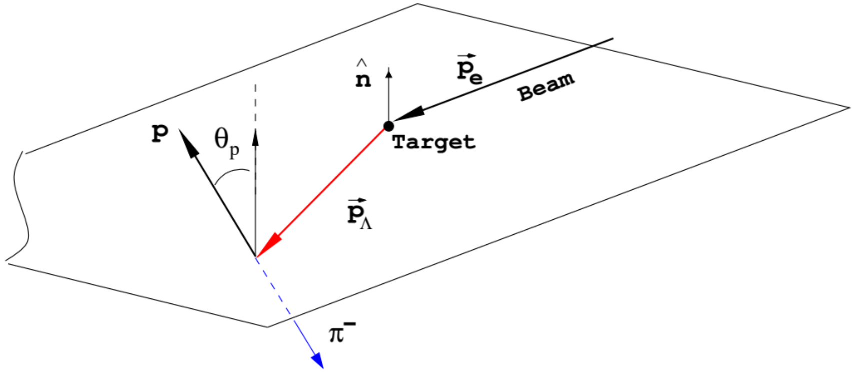
- Single Λ polarization is measured via $\Lambda^0 \to p\pi^+$ decay channel
  - In Λ rest frame, protons are emitted preferentially in direction of Λ spin

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

- The distribution of protons in Λ's 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 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 ($\vec{p}_{\Lambda}$) in Λ's rest frame

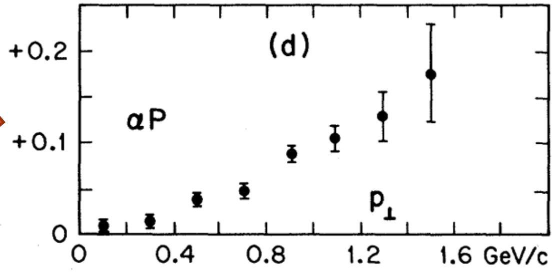


HERMES: Phys.Rev.D76:092008,2007

OVERVIEW OF Λ POLARIZATION MEASUREMENTS

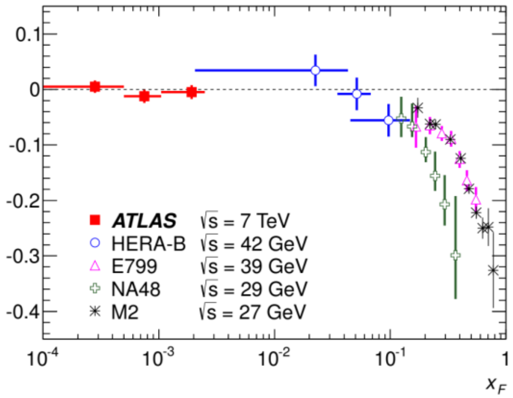
- Λ polarization observed even in collisions of unpolarized particles
- The polarization depends on collision energy, Λ momentum and $x_F = p_z^\Lambda / p_{beam}$
- Polarization observed in various collision systems, even e^+e^- collisions
- No spin transfer in high energy collisions of longitudinally polarized protons

p+Be



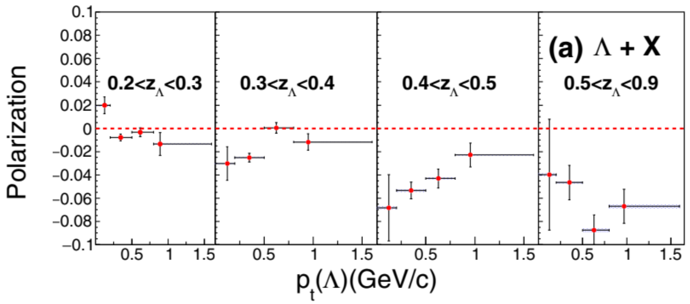
G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)

p+p and e+p



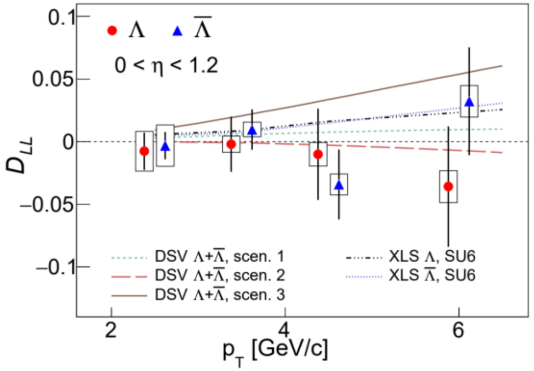
ATLAS: Phys. Rev. D 91, 032004 (2015)

e^+e^-



BELLE: Phys.Rev.Lett. 122, 042001 (2019)

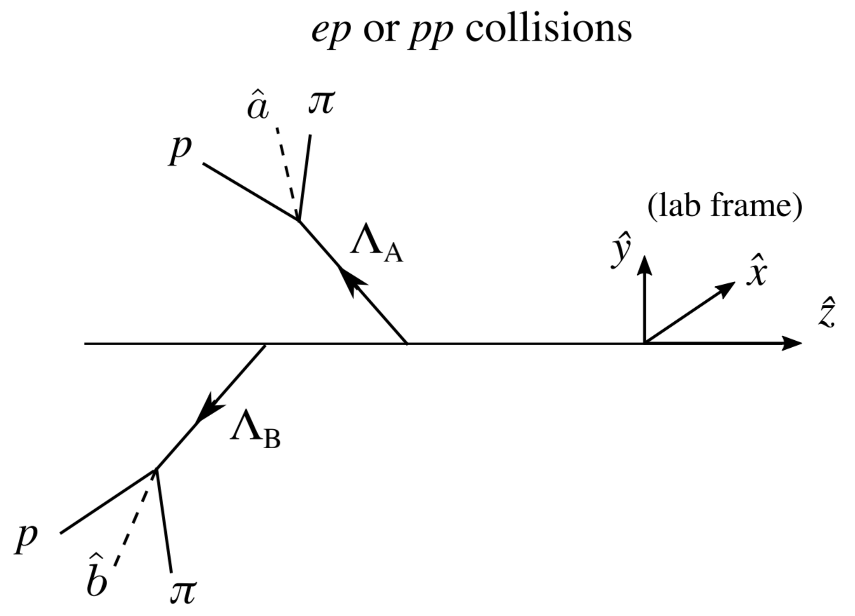
Polarized p+p



STAR: Phys. Rev. D 98, 112009 (2018)

MOTIVATION FOR Λ PAIR SPIN CORRELATIONS

- Single Λ polarization observed in collisions at low energies, but not at higher energies (e.g. RHIC) when measured with respect to production plane
- New, alternative approach is to measure spin correlations of $\Lambda\bar{\Lambda}$, ΛΛ, and $\bar{\Lambda}\bar{\Lambda}$ pairs
  - New choice of reference direction for polarization measurement – spin direction of a different Λ ($\bar{\Lambda}$) in the same event
- **Where could correlation of spins of $\Lambda\bar{\Lambda}$, ΛΛ, or $\bar{\Lambda}\bar{\Lambda}$ pairs come from in high energy collisions?**
  - Initial parton spin correlations may result in final-state hadron spin correlation?
  - Can final-state effect, e.g., hadronization, generate spin correlation?
  - A Bell-type inequality test using Λ hyperon pair spin correlations in high energy collisions?



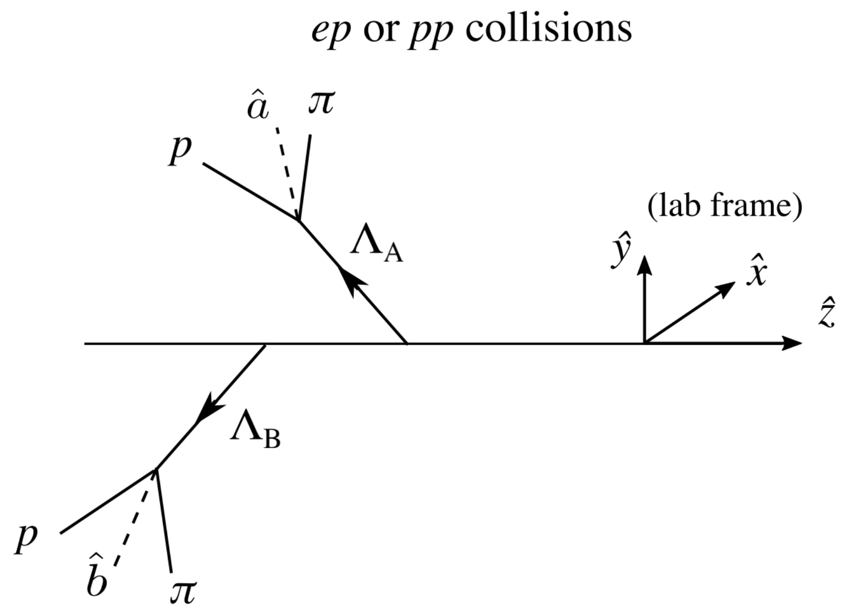
W. Gong, *et al.*: Phys.Rev.D 106 (2022) 3, L031501

NEW EXPERIMENTAL METHOD

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

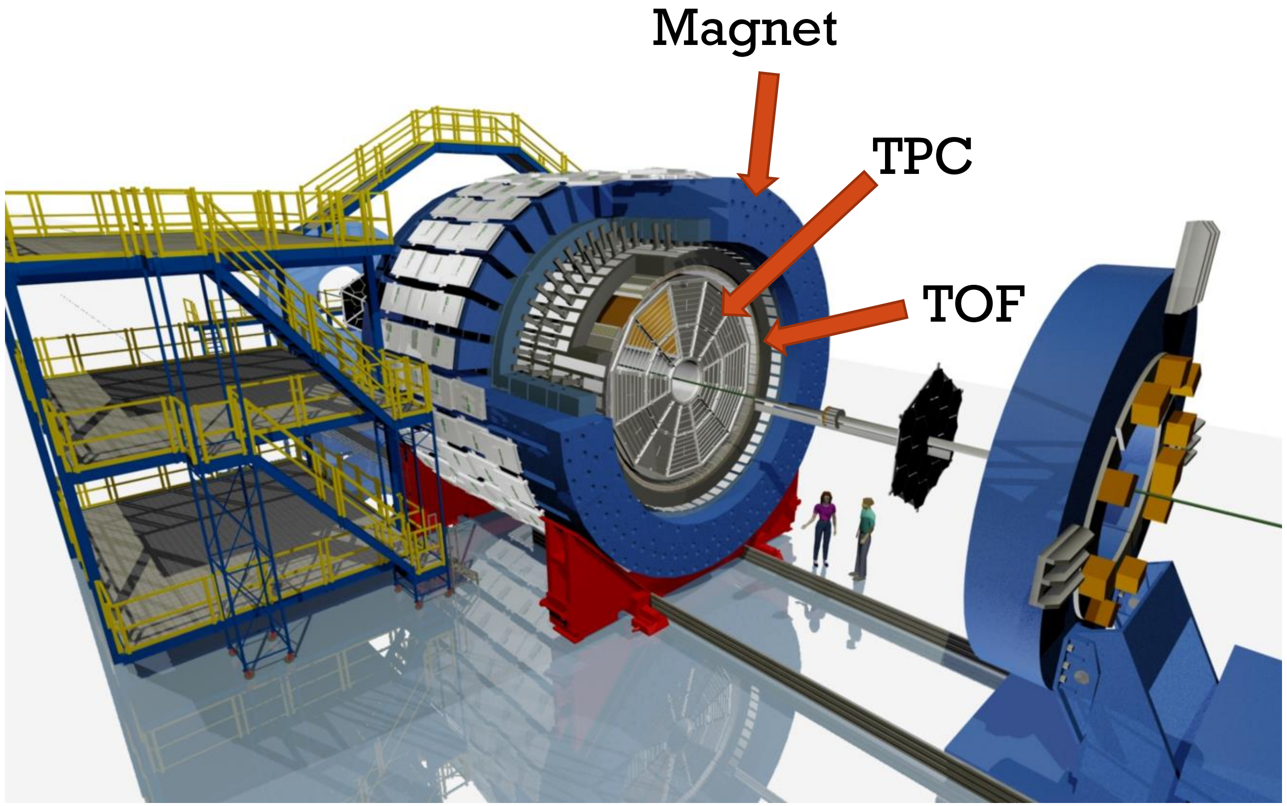
$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} = 1 + \alpha_1\alpha_2 P_{\Lambda\Lambda}\cos(\theta^*)$$

- **A non-zero $P_{\Lambda\Lambda}$ would indicate spin correlation between the pair**
- Possible thanks to high statistics p+p data-sets at STAR



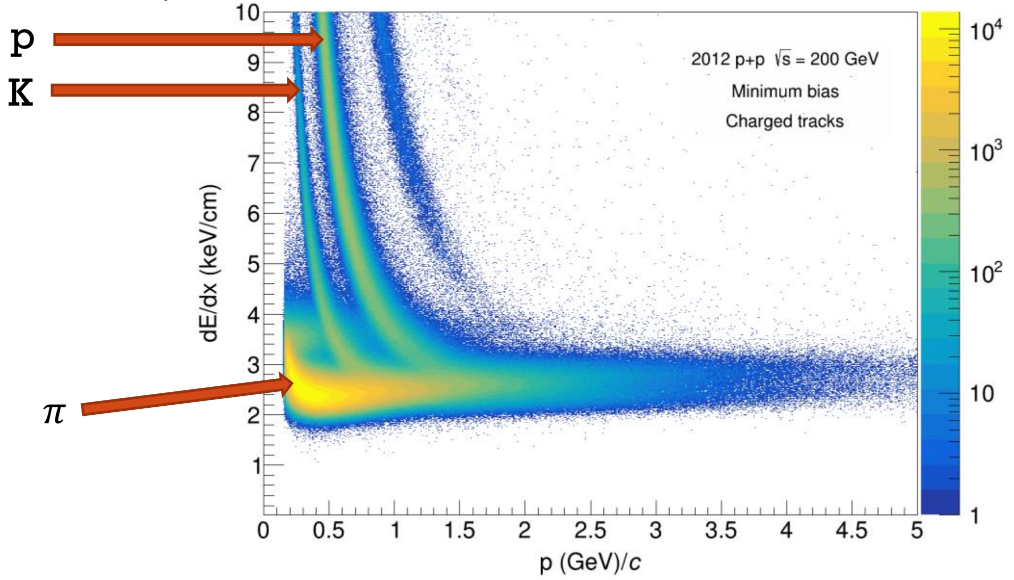
STAR DETECTOR

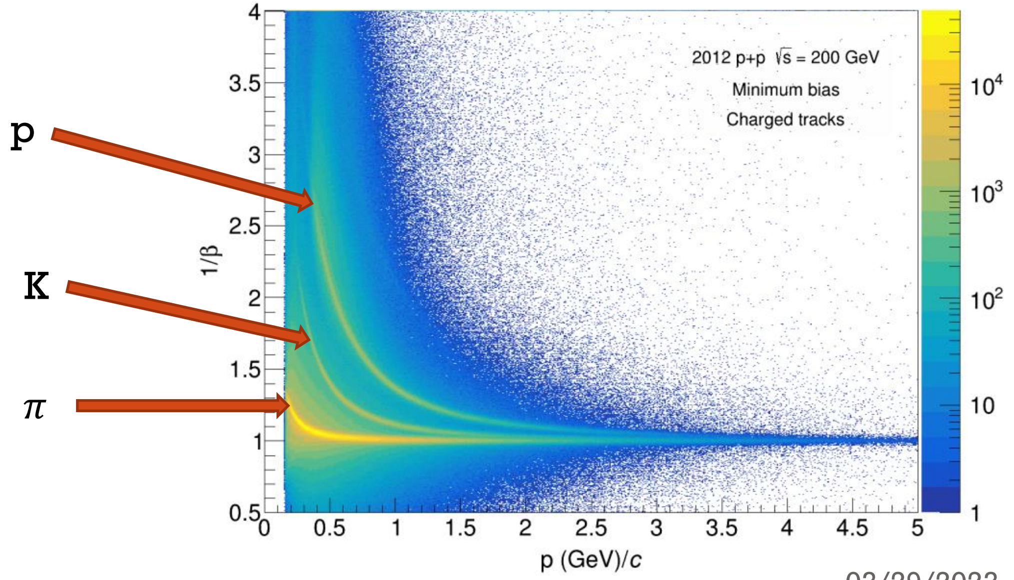
- **S**olenoidal **T**racker **A**t **RHIC**
- Only running experiment at RHIC (2017-2022)
  - This year being joined by sPHENIX experiment
- Key subsystems for this analysis:
  - Solenoidal magnet
    - 0.5 T magnetic field
  - Time Projection Chamber (TPC)
    - Measurement of particle transverse momentum (p_T)
    - Particle identification (PID) based on energy loss in TPC gas
  - Time Of Flight detector (TOF)
    - Additional PID information
    - Suppression of background from pileup events



EVENT AND TRACK SELECTION, PID

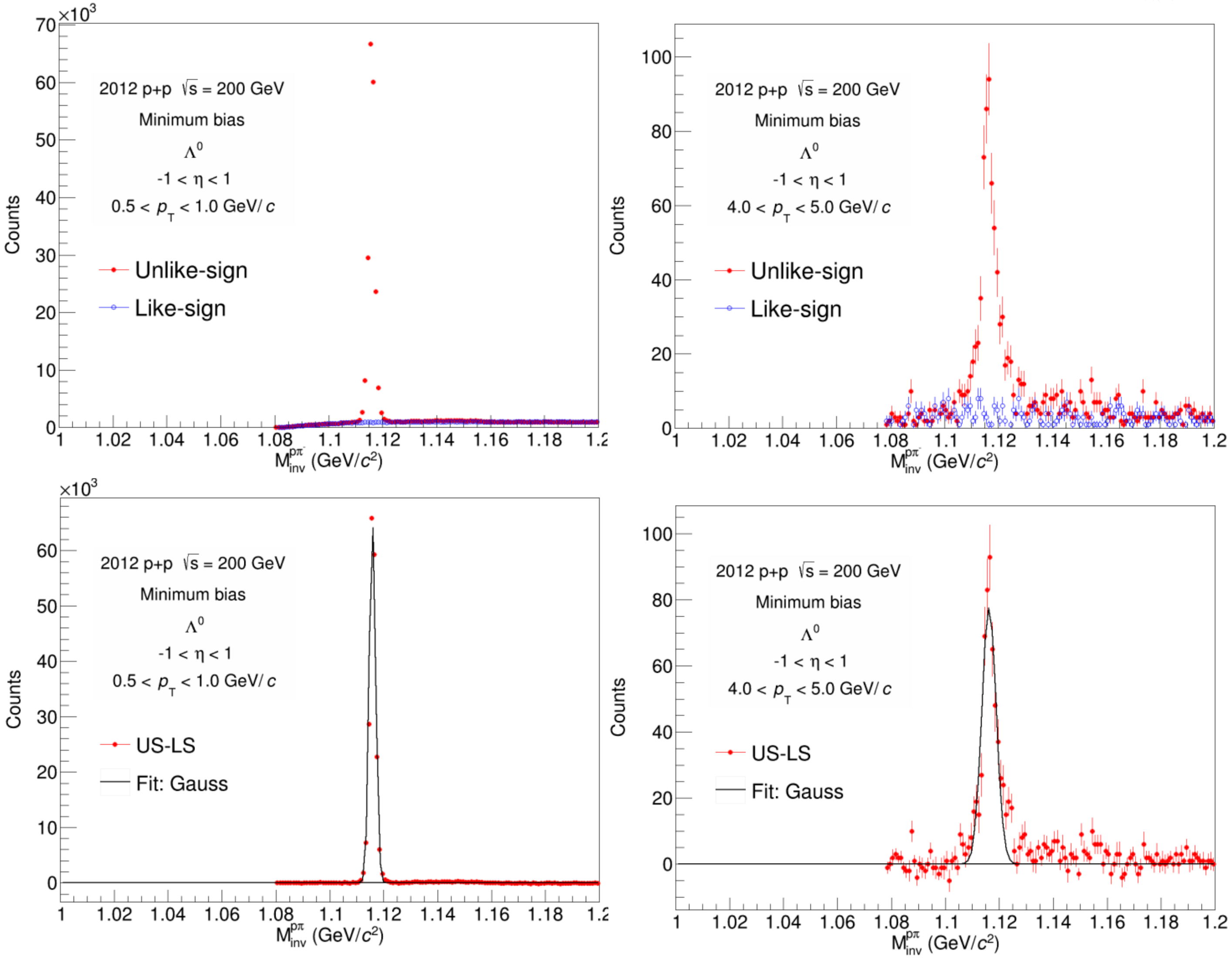
- Data-set:
  - p+p collisions at $\sqrt{s} = 200$ GeV (2012)
    - Ca. 400M minimum bias events
- Events with primary vertex close to center of STAR detector selected
- Track selection to ensure good track quality within geometrical acceptance
- Particle identification to obtain pure proton and pion sample
  - *TOF PID used only for Λ signal region determination, but not directly for the correlation study
- Decay topology to suppress combinatorial background from tracks originating from close to primary vertex





Λ RECONSTRUCTION

- First step of the analysis is determination of signal region from invariant mass (M_{inv}) spectra of $p\pi$ pairs
- Invariant mass spectra of $p\pi$ pair filled for unlike-sign (US) and like-sign (LS) charge combinations
  - LS provides good estimation of the combinatorial background
- The US-LS spectrum is fitted with Gaussian function
- The signal region is Gauss mean (from fit) $\pm 3\sigma$
- Done for Λ^0 and $\overline{\Lambda^0}$ separately in multiple p_{T} bins



Λ PAIRS IN DATA

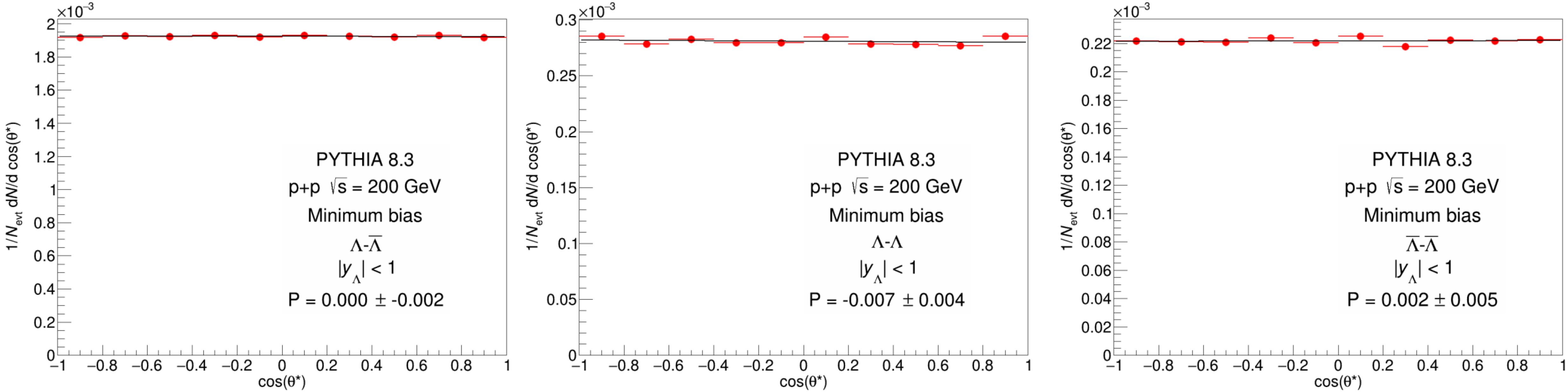
- Total raw counts (N_{sig}) of $\Lambda\bar{\Lambda}$, $\Lambda\Lambda$, and $\bar{\Lambda}\bar{\Lambda}$ pairs in 2012 200 GeV p+p data sample with combinatorial background levels (N_{bkg})
  - Λ and $\bar{\Lambda}$ candidates selected from M_{inv} window identified in previous step, but without TOF
    - TOF would reduce statistics significantly due to finite matching efficiency
    - Combinatorial background levels for Λ pairs are low even without TOF in the 2012 200 GeV p+p data
  - Five different combinations of p_T of Λ ($\bar{\Lambda}$) in the pair

- **Good statistics for all three pair combinations to perform the spin correlation measurement**

p_T (GeV/c)	$\Lambda\bar{\Lambda}$		$\Lambda\Lambda$		$\bar{\Lambda}\bar{\Lambda}$	
	N_{sig}	N_{bkg}	N_{sig}	N_{bkg}	N_{sig}	N_{bkg}
Λ_1: 0.5 – 5.0 Λ_2: 0.5 – 5.0	32057	667	9630	363	6563	187
Λ_1: 0.5 – 1.5 Λ_2: 0.5 – 1.5	14062	184	4099	94	2573	48
Λ_1: 0.5 – 1.5 Λ_2: 1.5 – 5.0	6913	172	1990	82	1439	41
Λ_1: 1.5 – 5.0 Λ_2: 0.5 – 1.5	6883	124	2322	101	1621	43
Λ_1: 1.5 – 5.0 Λ_2: 1.5 – 5.0	4199	187	1219	86	930	55

Λ PAIRS IN PYTHIA

- $dN/d\cos(\theta^*)$ from PYTHIA 8.3 for $\Lambda\bar{\Lambda}$ (left), $\Lambda\Lambda$ (middle), and $\bar{\Lambda}\bar{\Lambda}$ (right) pairs
  - 1B minimum bias PYTHIA events at $\sqrt{s} = 200$ GeV
  - Only additional requirement is on Λ ($\bar{\Lambda}$) rapidity: $|y| < 1$
- **$P_{\Lambda\Lambda}$ = 0 in PYTHIA – no Λ-hyperon pair spin correlations**
- If non-zero $P_{\Lambda\Lambda}$ is observed in data, it would indicate possible spin correlations of Λ hyperons



SUMMARY

- We propose a new method for studying the origin of Λ hyperon polarization using Λ hyperon pair spin correlations
  - This new approach could provide additional insights on the topic

- Expect good statistical precision when using the 2012 dataset of 200 GeV p+p collisions to perform the proposed spin correlation measurement

- PYTHIA does not predict any Λ hyperon pair spin correlation signal
  - Any observed non-zero $P_{\Lambda\Lambda}$ in data would indicate Λ hyperon pair spin correlations

OUTLOOK

STAR

- Near future
  - Determine detector efficiency and acceptance correction for $\mathrm{d}N/\mathrm{d}\cos\theta^*$ using 2012 datset
  - Include 2017 data for p+p collisions at $\sqrt{s} = 510$ GeV (2017)
    - Ca. 500M minimum bias events

- Longer term possibilities
  - Use data with STAR forward upgrade to study the Λ hyperon pair spin correlations at large η range (small x_F)
  - Λ hyperon pair spin correlations in other collision systems at STAR (p+Au, d+Au, Au+Au)

- General outlook
  - Perform spin correlation measurement on data from other experiments, e.g. where single Λ polarization has been observed

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
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Event selection	$\|V_z\| < 30$ cm
Track selection	$p_T > 150$ MeV/c $\|\eta\| < 1$ nHitsFit > 20 nHitsFit/nHitsMax > 0.52
Particle identification	$\|n\sigma_\pi\| < 3$ $\|n\sigma_p\| < 2$ $\|1/\beta - 1/\beta_\pi\| < 0.03$*
Decay topology Λ^0	$DCA_{\pi\text{-}PV} > 0.3$ cm $DCA_{p\text{-}PV} > 0.1$ cm $DCA_{pair} < 1$ cm $2 \text{ cm} < L_{dec} < 25$ cm $\cos(\theta) > 0.996$