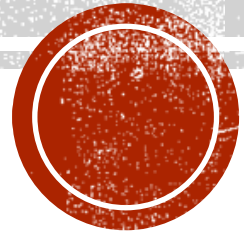
Λ hyperon pair spin-spin correlations at ePIC



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EICUG Early Career Workshop

07/24/2023

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

- **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

STANDARD EXPERIMENTAL METHOD

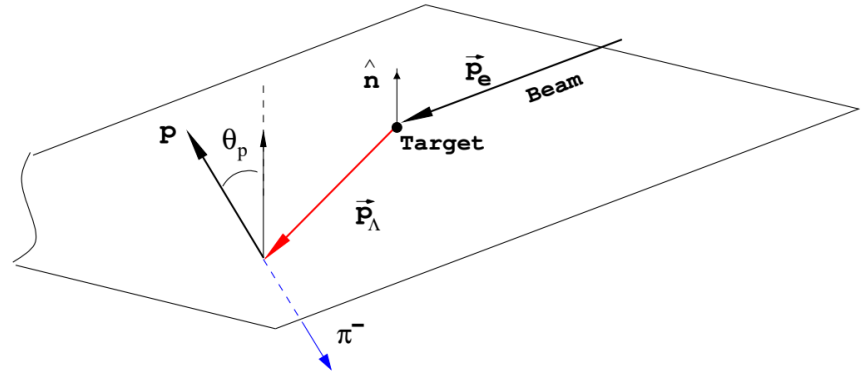
- Single Λ polarization is measured via $\Lambda^0 \rightarrow p\pi^+$ decay channel
  - In Λ rest frame, protons are emitted preferentially in direction of Λ spin

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

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

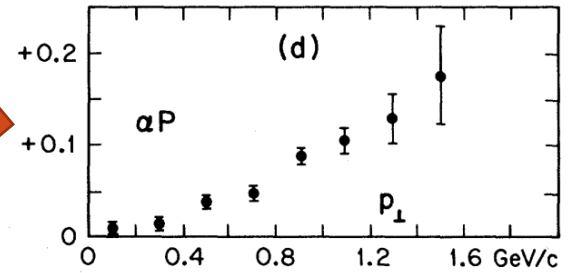


HERMES: Phys.Rev.D76:092008,2007

OVERVIEW OF Λ POLARIZATION MEASUREMENTS

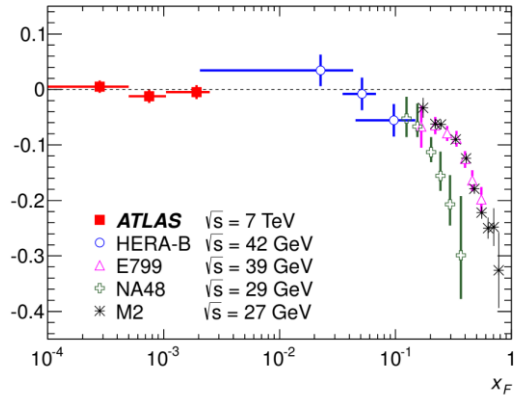
- Λ polarization observed even in collisions of unpolarized particles
- The polarization depends on Λ momentum and $x_F = p_z^{\Lambda}/p_{beam}$
- Polarization observed in various collision systems, even e^+e^- collisions
- No spin transfer in high energy collisions of longitudinally polarized protons

p+Be



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

p+p and e+p

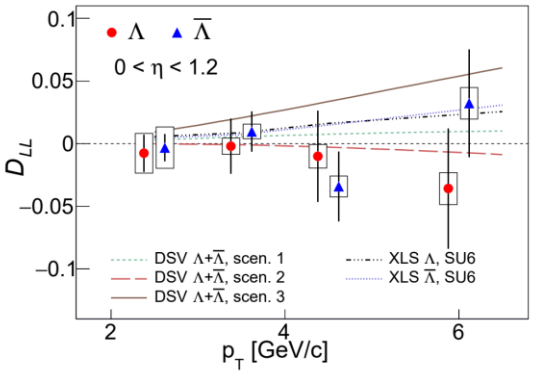


ATLAS: Phys. Rev. D 91, 032004 (2015)

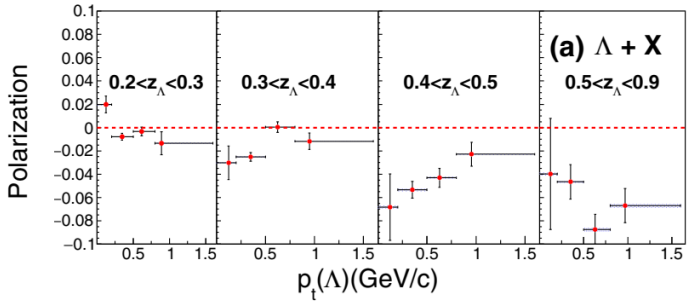
$$D_{LL} \overset{\text{def}}{=} \frac{\sigma_{p^+p\to\Lambda^+X} - \sigma_{p^+p\to\Lambda^-X}}{\sigma_{p^+p\to\Lambda^+X} + \sigma_{p^+p\to\Lambda^-X}}$$

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

Polarized p+p



e^+e^-



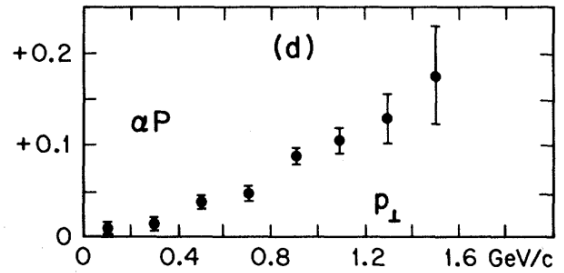
BELLE: Phys.Rev.Lett. 122, 042001 (2019)

OVERVIEW OF Λ POLARIZATION MEASUREMENTS

- **Current single Λ hyperon polarization results indicate the importance of the final state effects in Λ hyperon polarization**
  - No significant dependence on collision system or energy, polarization of the beams
  - Observed in e^+e^- collisions with no quarks or gluons in initial state

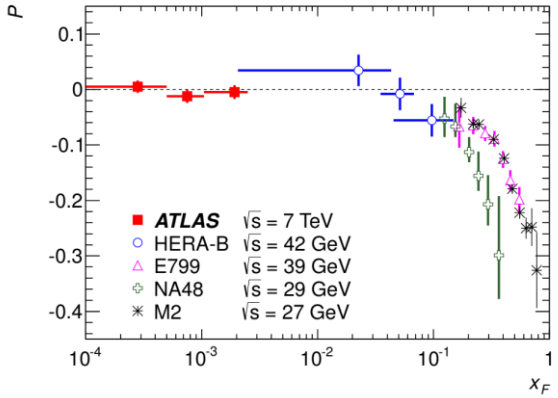
- Is there an initial state effect that cannot be accessed via single Λ hyperon polarization measurement?

p+Be



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

p+p and e+p



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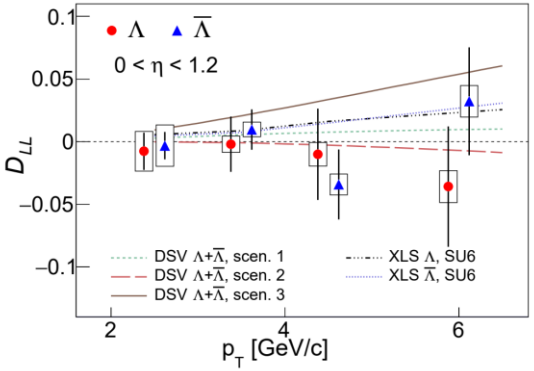
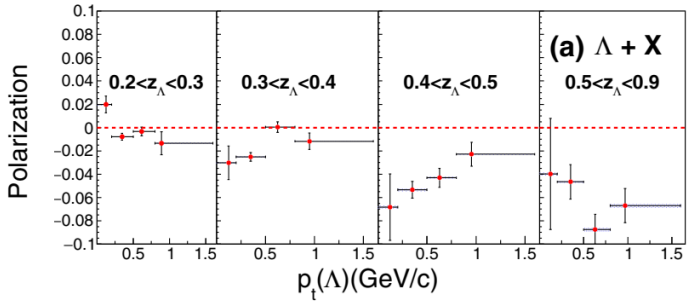
Polarized p+p

$$D_{LL} \overset{\text{def}}{=} \frac{\sigma_{p^+p\to\Lambda^+X} - \sigma_{p^+p\to\Lambda^-X}}{\sigma_{p^+p\to\Lambda^+X} + \sigma_{p^+p\to\Lambda^-X}}$$

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



e^+e^-



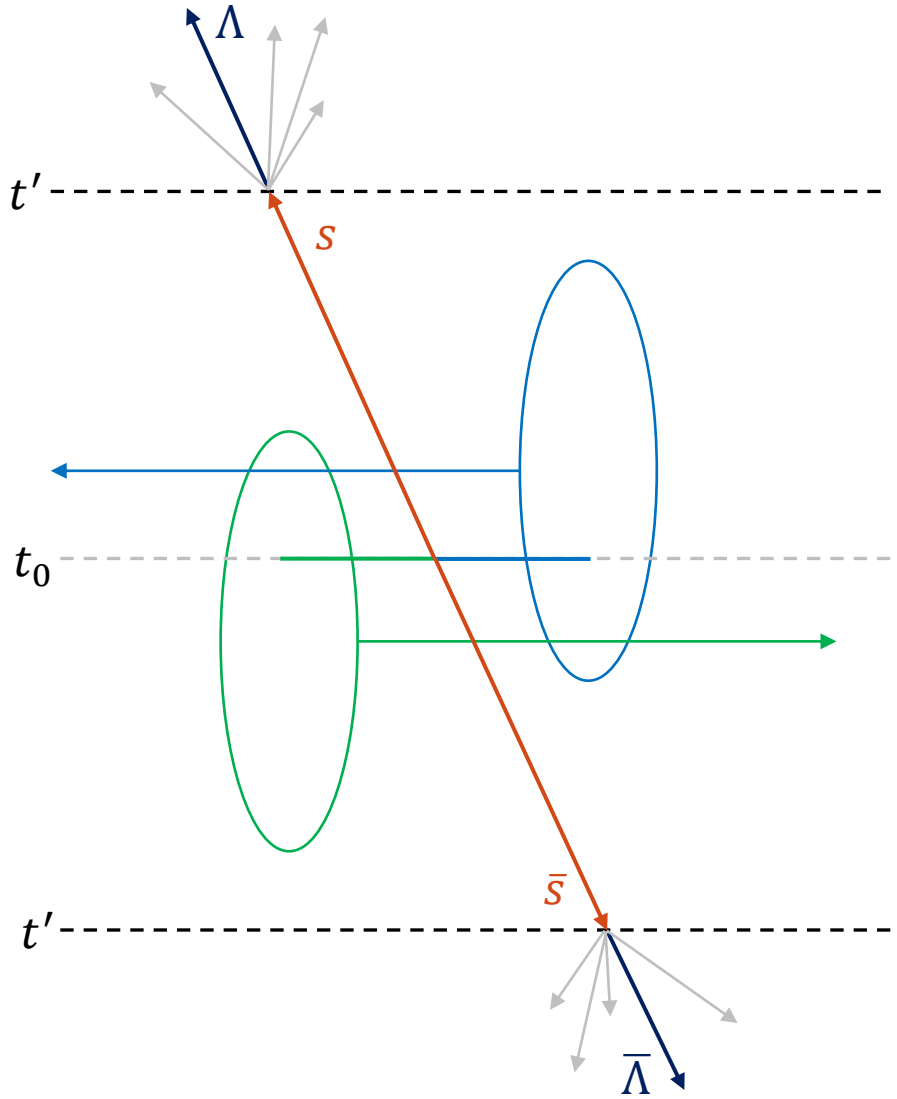
BELLE: Phys.Rev.Lett. 122, 042001 (2019)

MOTIVATION FOR Λ PAIR SPIN CORRELATIONS

- New, alternative approach is to measure spin correlations of $\Lambda\bar{\Lambda}$, $\Lambda\Lambda$, 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 $\Lambda\bar{\Lambda}$, $\Lambda\Lambda$, or $\bar{\Lambda}\bar{\Lambda}$ pairs come from in high energy collisions?
  - **Initial state** (IS, *t'*) parton spin correlations? **Final state** (FS, t_0) effects, as fragmentation or hadronization?
  - FS effects should not generate a spin-spin correlation
    - Polarization is generated at time *t'* at two independent places in space

- **Any non-zero signal for spin-spin correlation would indicate an IS contribution to the Λ hyperon polarization**
  - Would be a new observation as current single Λ polarization results indicate only importance of FS effects

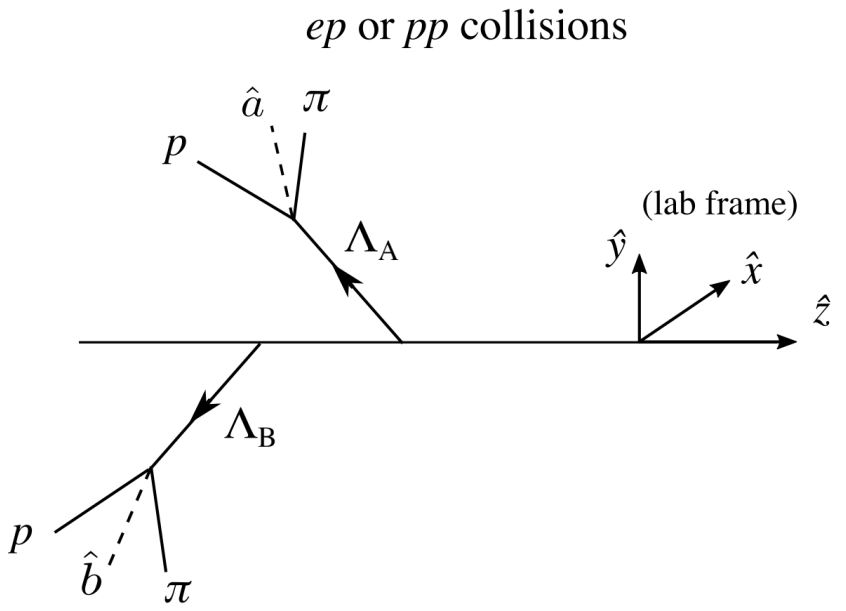


NEW EXPERIMENTAL METHOD

- 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:

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

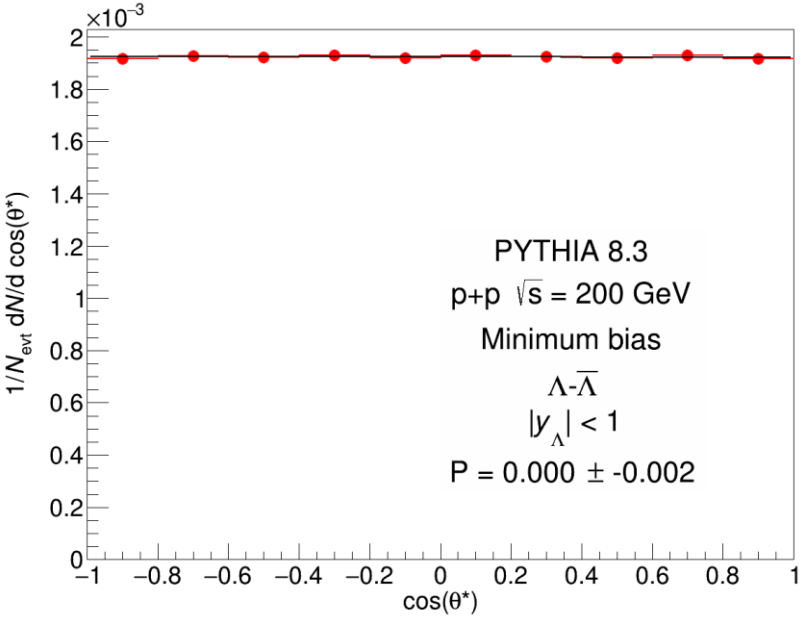
- **A non-zero $P_{\Lambda\Lambda}$ would indicate spin correlation between the pair**

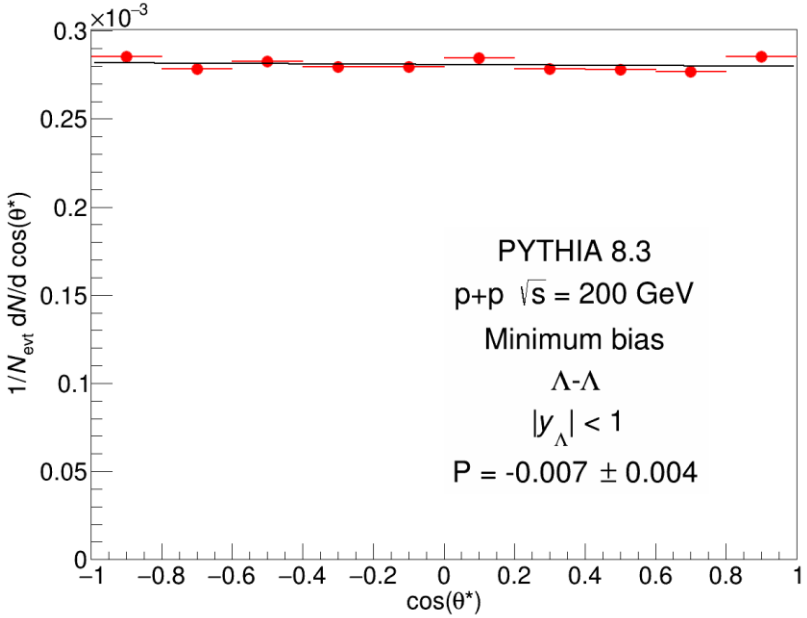


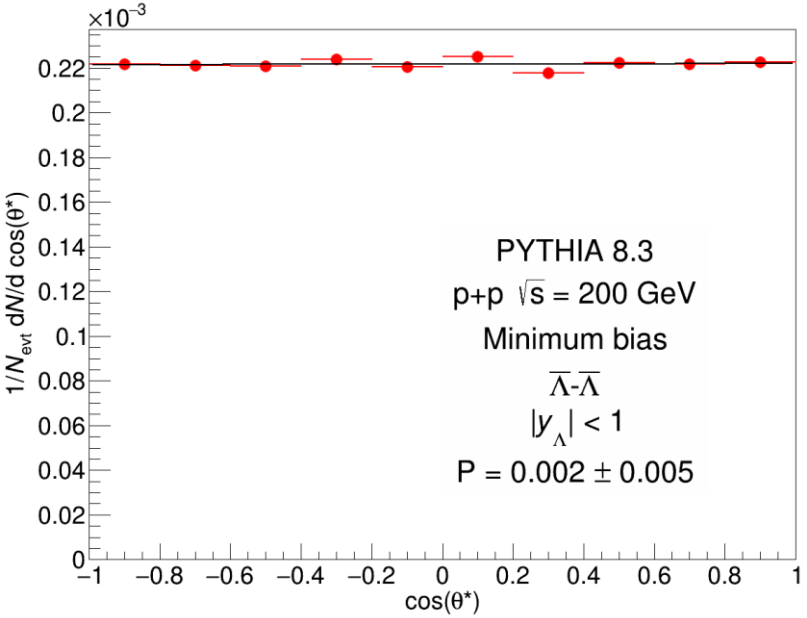
W. Gong, *et al.*: Phys.Rev.D 106 (2022) 3, L031501

Λ SPIN-SPIN IN p+p COLLISIONS FROM PYTHIA

- Λ hyperon spin-spin correlations in p+p collisions at $\sqrt{s} = 200$ GeV from PYTHIA 8.3
- Simulation used for evaluation of acceptance correction for analysis of Λ hyperon spin-spin correlations in p+p collisions at STAR
  - Can be used to estimate what will be needed at ePIC
- No expected signal for $P_{\Lambda\Lambda}$ from PYTHIA
  - $|y_\Lambda| < 1, 0.5 < p_T < 5$ GeV/c, no additional cuts

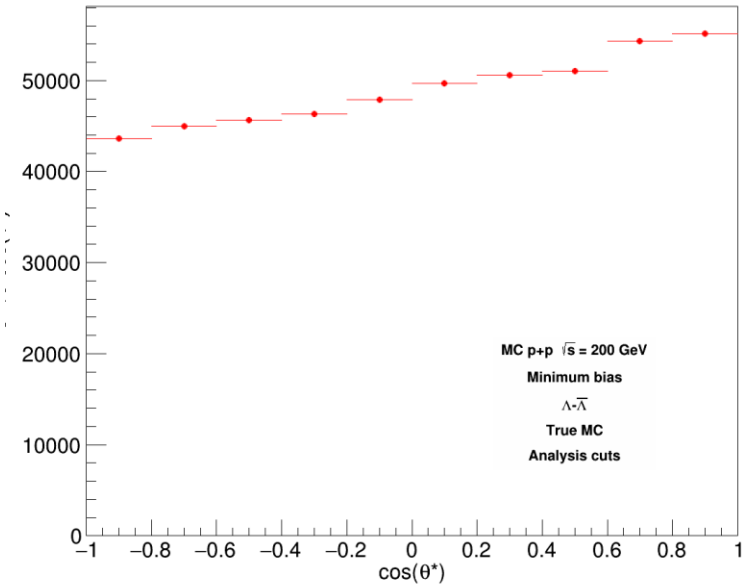


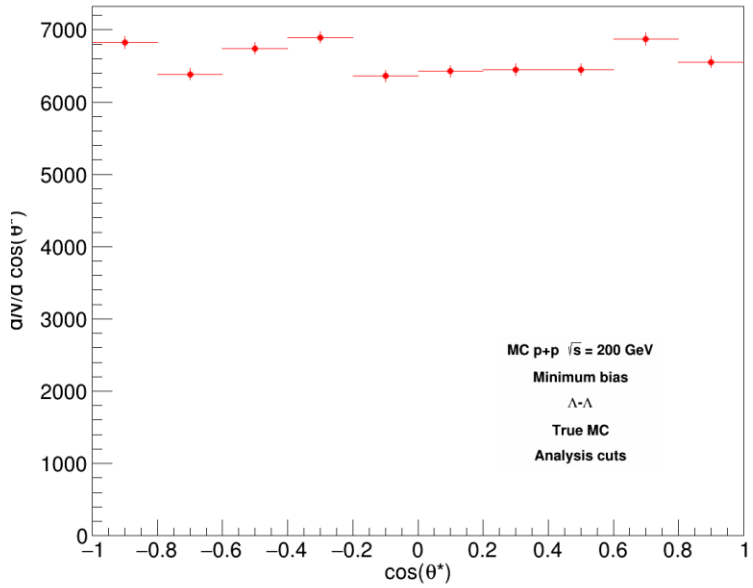


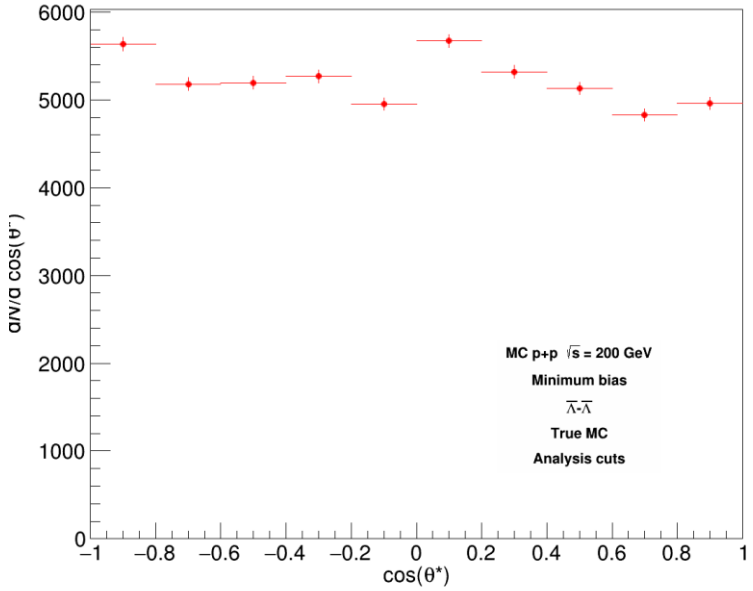


Λ SPIN-SPIN IN p+p COLLISIONS FROM PYTHIA

- Λ hyperon spin-spin correlations in p+p collisions at $\sqrt{s} = 200$ GeV from PYTHIA 8.3
- Single Λ ($\overline{\Lambda}$) selection
  - $|y_\Lambda| < 1, 0.5 < p_T < 5$ GeV/c, Decay length: $2 < L < 25$ cm
- Daughter selection (same for both)
  - $|\eta| < 1, p_T > 0.15$ GeV/c
- Significant acceptance effect for $\Lambda\overline{\Lambda}$ pairs





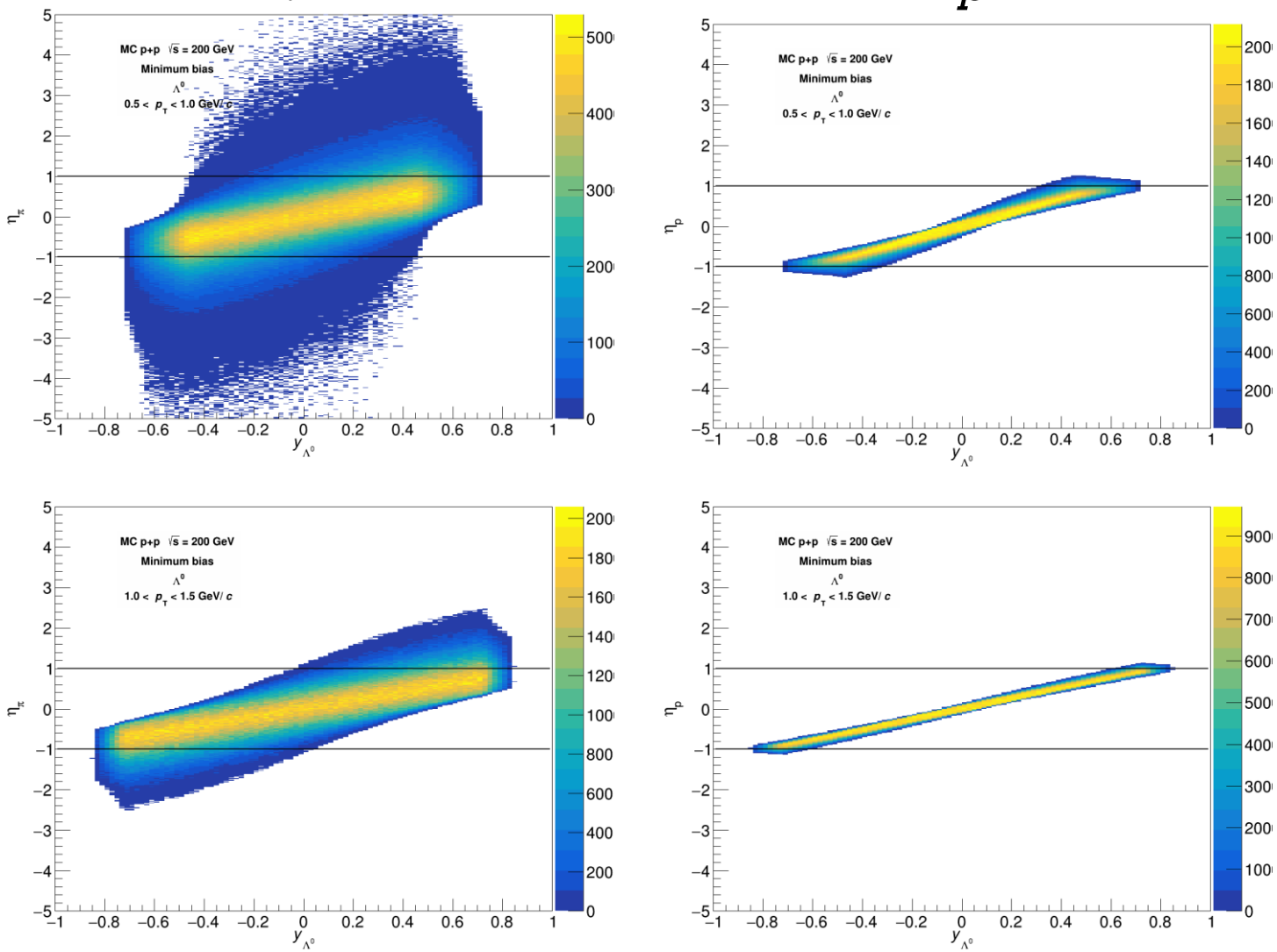


Λ DECAY DAUGHTER KINEMATICS

- Origin of the acceptance effect is mainly from soft decay pions falling outside $|\eta| < 1$ for low p_T Λ with $|y_\Lambda| < 1$
- Small effect for protons

- **Can utilize large η acceptance of ePIC detector**
  - Small acceptance effect
  - Access to large x_F
  - Possible to do long range spin-spin correlations
    - Long range η correlation ($2 < |\Delta\eta| < 7$) vs. only short range η correlation e.g. at STAR ($|\Delta\eta| < 2$)

π^- p



OUTLOOK

- Ongoing analysis of Λ hyperon spin-spin correlations in p+p collisions at $\sqrt{s} = 200$ and 510 GeV measured by the STAR experiment

- Goal is to perform the same analysis within the ePIC simulation framework

- Key steps:
  - Generate e+p sample using PYTHIA 8.3 and pass it through ePIC
  - Analyze produced MC sample using the same experimental method developed for the STAR analysis
  - Estimate e.g. reconstruction efficiency of $\Lambda\overline{\Lambda}$, $\Lambda\Lambda$, and $\overline{\Lambda}\overline{\Lambda}$ pairs and expected precision of $P_{\Lambda_1\Lambda_2}$

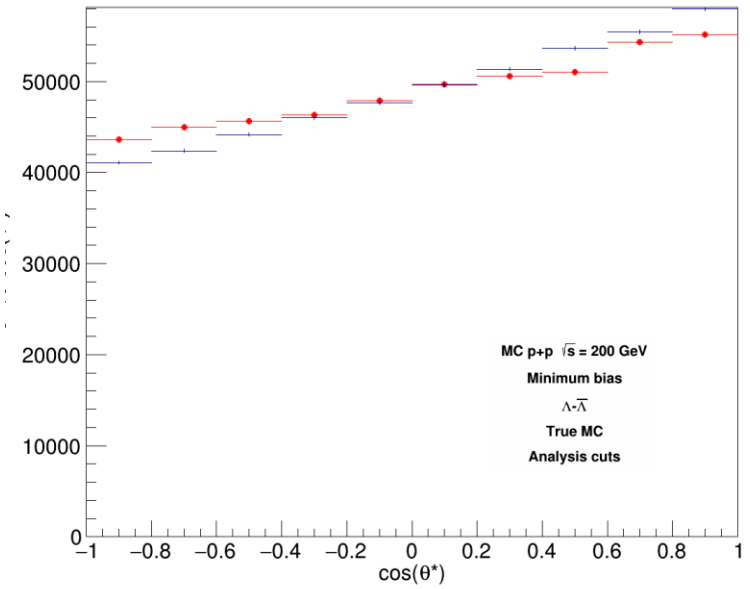
- Current status:
  - Have base for the PYTHIA simulation
  - Need to make some changes to produce output which can be used with ePIC simulation framework

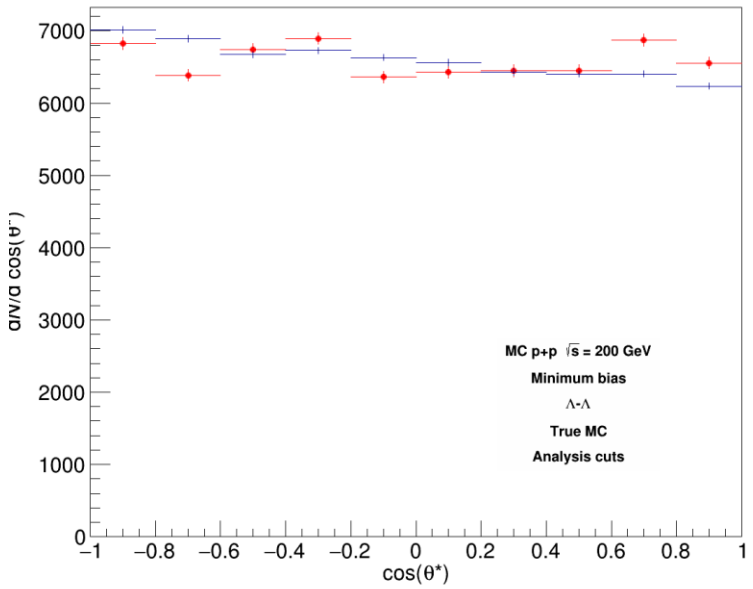
THANK YOU FOR ATTENTION

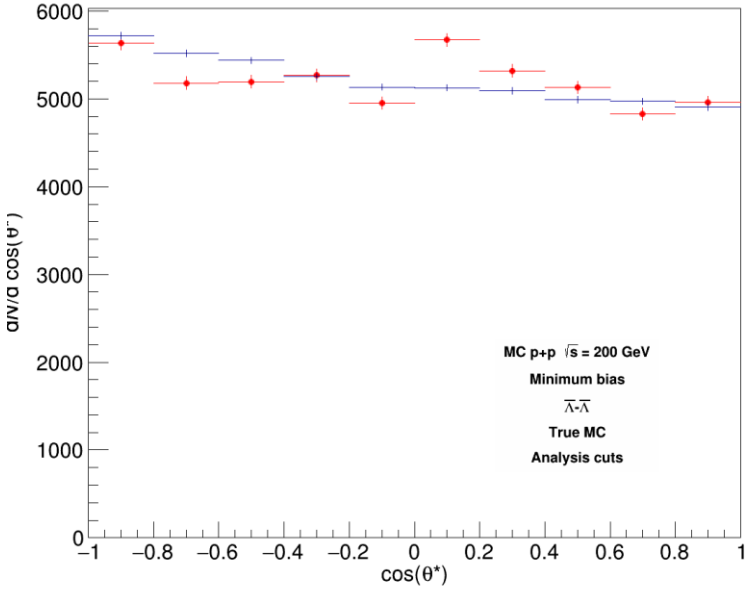
BACKUP

ACCEPTANCE EFFECT CORRECTION

- The acceptance effect can be corrected using mixed event (ME) $\Lambda\overline{\Lambda}$, $\Lambda\Lambda$, or $\overline{\Lambda}\overline{\Lambda}$ pairs
- ME has to be re-weighted to match kinematics of true MC pairs
  - Mainly issue for $\Lambda\overline{\Lambda}$ as those are highly correlated in η and ϕ due to IS kinematic correlation of $s\bar{s}$ pair
  - Here done using $\Delta\eta$ vs. $\Delta\phi$ vs. Δp_T distribution (Δ) of $\Lambda\overline{\Lambda}$, $\Lambda\Lambda$, and $\overline{\Lambda}\overline{\Lambda}$ pairs, $w = \Delta_{\mathrm{MC}}/\Delta_{\mathrm{ME}}$
  - Not perfect description of acceptance effect – have to improve weight calculation
- Red – distribution for true MC $\Lambda\overline{\Lambda}$, $\Lambda\Lambda$, and $\overline{\Lambda}\overline{\Lambda}$ pairs (from Slide 9), Blue – ME







ACCEPTANCE EFFECT CORRECTION

- The acceptance effect can be corrected using mixed event (ME) $\Lambda\overline{\Lambda}$, $\Lambda\Lambda$, or $\overline{\Lambda}\overline{\Lambda}$ pairs
- ME has to be re-weighted to match kinematics of true MC pairs
  - Mainly issue for $\Lambda\overline{\Lambda}$ as those are highly correlated in η and ϕ due to IS kinematic correlation of $s\bar{s}$ pair
  - Here done using $\Delta\eta$ vs. $\Delta\phi$ vs. Δp_T distribution (Δ) of $\Lambda\overline{\Lambda}$, $\Lambda\Lambda$, and $\overline{\Lambda}\overline{\Lambda}$ pairs, $w = \Delta_{\mathrm{MC}}/\Delta_{\mathrm{ME}}$
  - Not perfect description of acceptance effect – have to improve weight calculation
- Red – distribution for true MC $\Lambda\overline{\Lambda}$, $\Lambda\Lambda$, and $\overline{\Lambda}\overline{\Lambda}$ pairs **after ME correction**