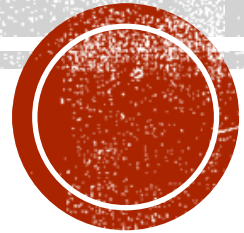
Supported in part by:

# Measurement of $\Lambda$ hyperon polarization and spin-spin correlations in p+p collisions by the STAR experiment



Jan Vanek, for the STAR Collaboration

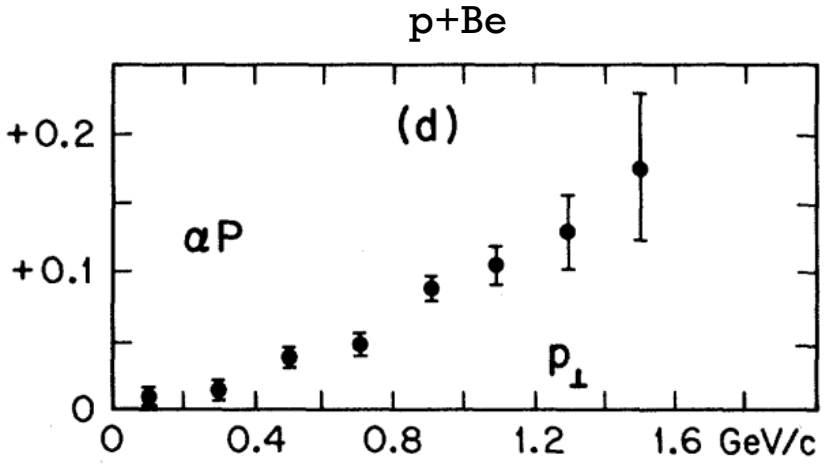
Brookhaven National Laboratory

AGS/RHIC Annual Users' Meeting

06/11/2024

# $\Lambda$ POLARIZATION PUZZLE

- In the 70's, it was discovered that $\Lambda^0$ 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, $\Lambda^0$ 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

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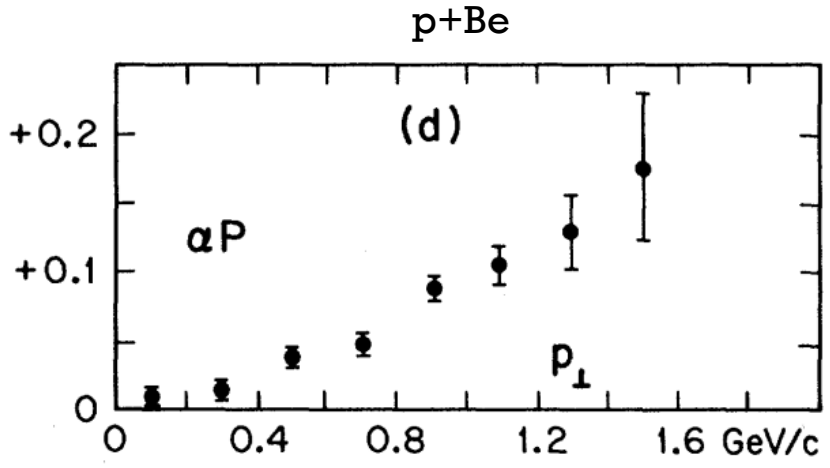



*Phys. Rev. Lett. 36, 1113-1116 (1976)*

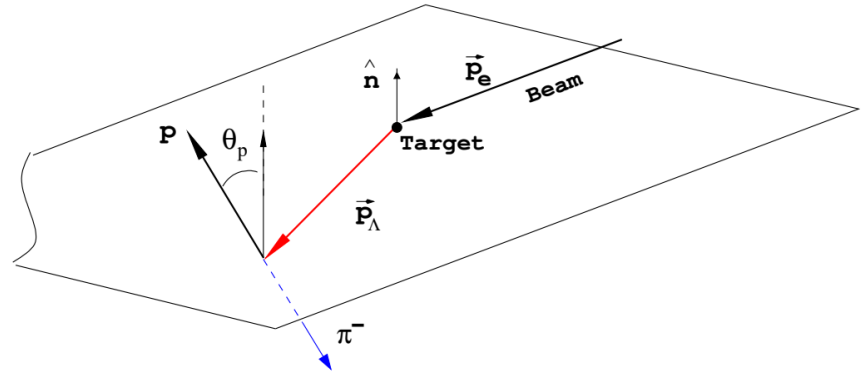
**What is the origin of the $\Lambda^0$ polarization?**

- Does polarization of $\Lambda^0$ depend on spin of the target/projectile?
- Is there a contribution of an **initial-state** effect?
- Will parton spin correlation and entanglement manifest in $\Lambda^0$ polarization? [*W. Gong, et al.: Phys. Rev. D 106 (2022) 3, L031501*]

# $\Lambda$ POLARIZATION MEASUREMENT

- Single $\Lambda^0$ polarization is measured via $\Lambda^0 \to p\pi^+$ decay channel with $BR = (64.1 \pm 0.5)\%$. In the $\Lambda^0$ rest frame, protons are emitted preferentially in the direction of $\Lambda^0$ spin

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




HERMES: Phys.Rev.D76:092008,2007

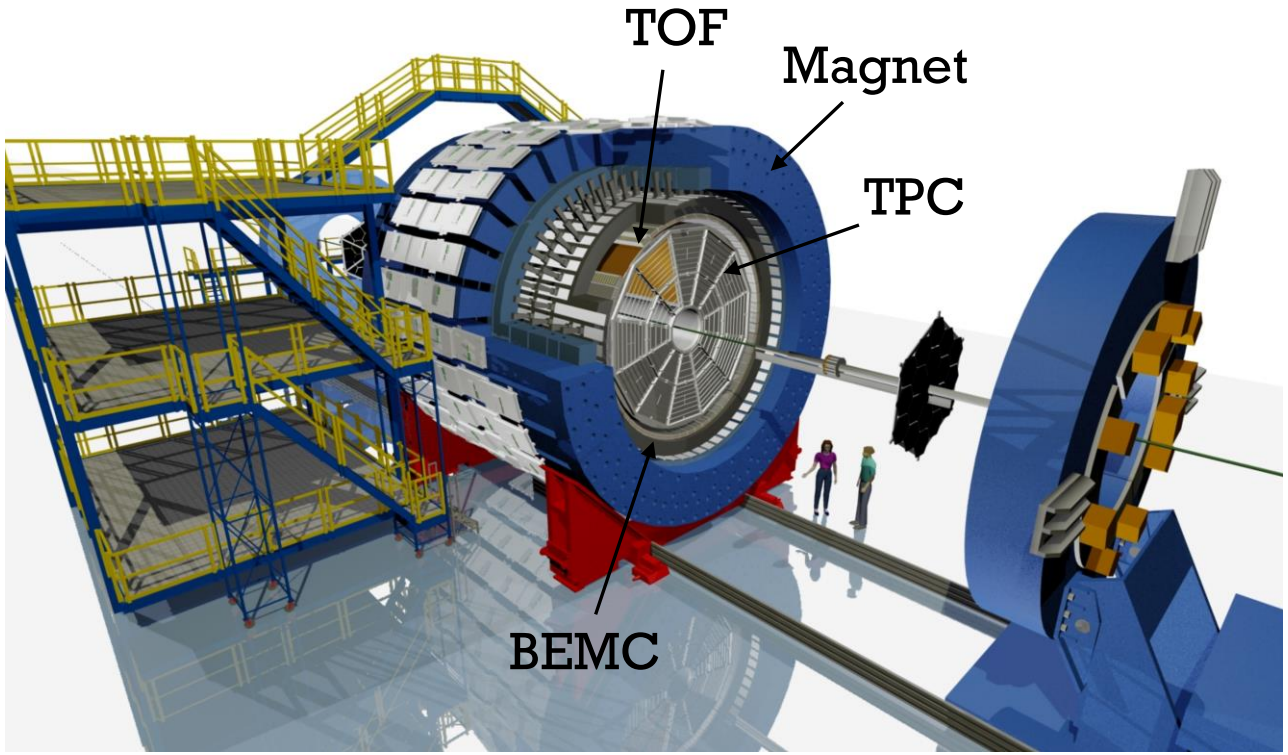
- The distribution of protons in $\Lambda^0$ rest frame is then given by:

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

  - $P_\Lambda$ is the $\Lambda^0$ 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 ($\theta^*$, or $\theta_p$) is measured between $\hat{n}$ and momentum of proton ($p$) in $\Lambda$'s rest frame**

# SOLENOIDAL TRACKER AT RHIC (STAR)

- 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 based on energy loss in TPC gas
  - Full azimuthal coverage for $|\eta| < 1$
- Time-of-Flight detector (TOF)
  - Particle identification
  - Full azimuthal coverage for $|\eta| < 0.9$
- Barrel Electromagnetic Calorimeter (BEMC)
  - Reconstruction of jets, photons, $\pi^0$, …
  - Full azimuthal coverage for $|\eta| < 1$

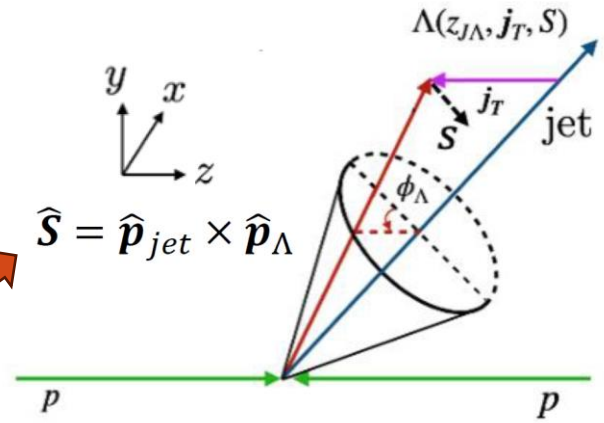


# Λ POLARIZATION IN JETS

- Measurement of transverse polarization of $\Lambda^0$ and $\overline{\Lambda}^0$ hyperons in jets gives access to polarizing fragmentation functions (pFFs)

- Test of universality of the pFFs with results from SIDIS and $e^+ + e^-$

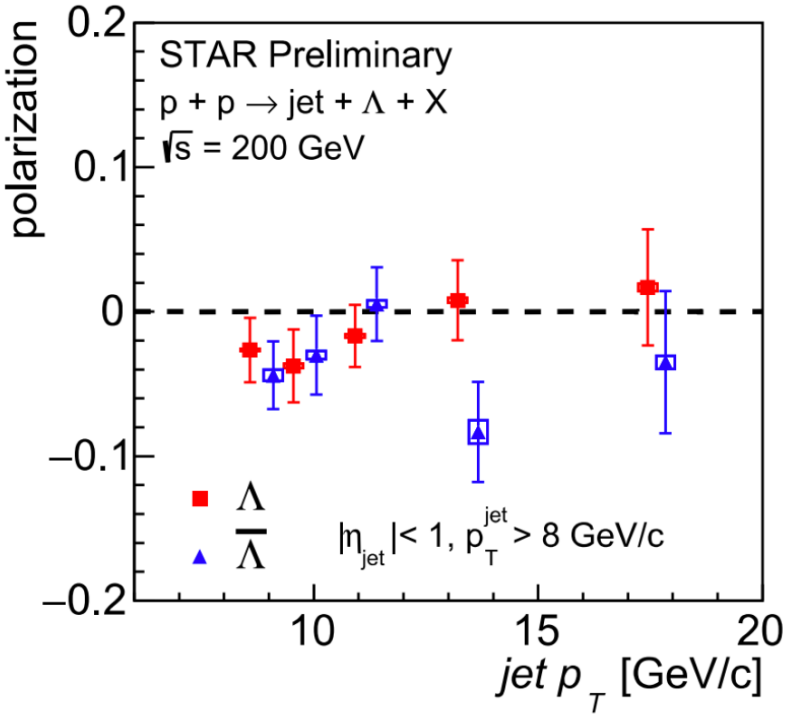
- Polarization measured with respect to the jet axis
  - Angle $\theta^*$ measured between $\hat{S}$ and momentum of proton in $\Lambda$'s rest frame




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

# $\Lambda$ POLARIZATION IN JETS – RESULTS

- Transverse polarization of $\Lambda^0$ and $\overline{\Lambda}^0$ hyperons in jets
- No significant $p_T$ dependence
  - Hint non-zero polarization for $\overline{\Lambda}^0$ at $2\sigma$ level
- New data for pFFs



# SPIN TRANSFER MEASUREMENT WITH $\Lambda$

- Measurements with longitudinally polarized $p^+ + p$ collisions

- Longitudinal spin transfer $D_{LL}$ of $\Lambda$ and $\overline{\Lambda}$ hyperons
  - Sensitive to helicity distributions of $s$ and $\bar{s}$ quarks via **polarized fragmentation functions**
  - Polarization $P_\Lambda$ measured with respect to hyperon momentum in laboratory frame (CMS frame of $p + p$)

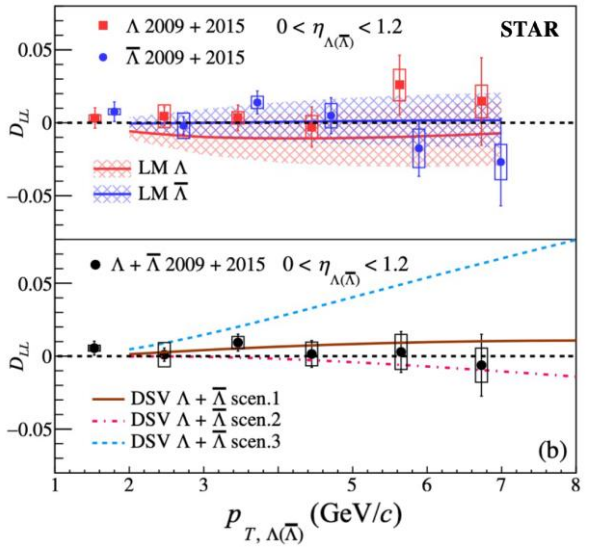
$$D_{LL} = \frac{\sigma_{p^+p\to\Lambda^+X} - \sigma_{p^+p\to\Lambda^-X}}{\sigma_{p^+p\to\Lambda^+X} + \sigma_{p^+p\to\Lambda^-X}}$$

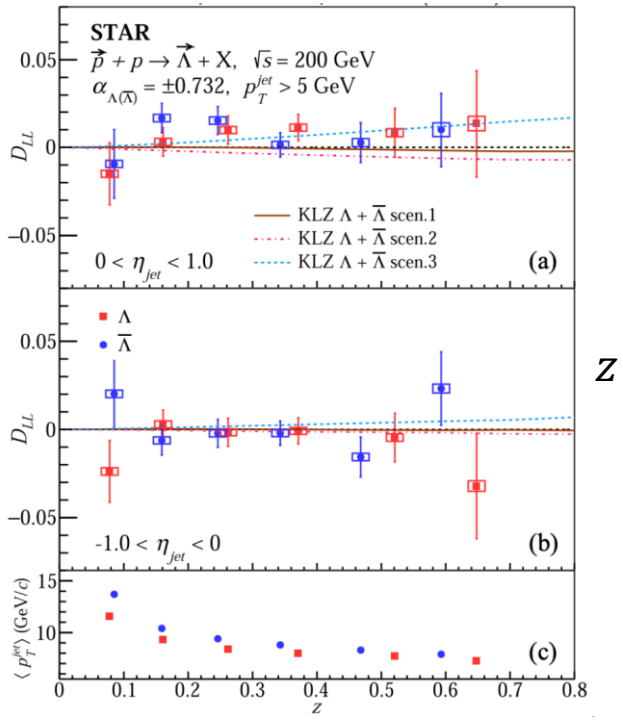
# LONGITUDINAL SPIN TRANSFER

- Longitudinal spin transfer $D_{LL}$ of $\Lambda^0$ and $\overline{\Lambda}^0$ hyperons measured in $\vec{p}+p$ collisions at $\sqrt{s}=200$ GeV

- Consistent results between $\Lambda^0$ and $\overline{\Lambda}^0$ hyperons
- Data compared to certain polarized FFs scenarios:
  - 1: $\Lambda^0$ polarization given by $s$ quark
  - 2: $u$ and $d$ quarks contribute to the $\Lambda^0$ polarization, but with opposite sign as the $s$ quark
  - 3: All $u$, $d$, and $s$ quarks contribute to the $\Lambda^0$ polarization, but with the same sign
- Data strongly disfavor scenario 3

- The $z$ dependence directly probes polarized fragmentation function




$$z = \frac{\vec{p}_\Lambda \cdot \vec{p}_{\text{jet}}}{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{jet}}}$$

Models:
D. de Florian et al, PRL 81, 530 (1998)
Z.B. Kang et al, PLB 809, 135756 (2020)

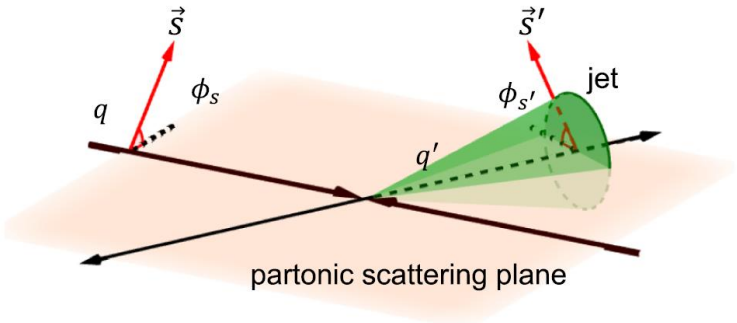
STAR, PRD 109, 12004 (2024)

# SPIN TRANSFER MEASUREMENT WITH $\Lambda$

- Measurements with transversely polarized $p^{\uparrow} + p$ collisions

- Transverse spin transfer $D_{TT}$ of $\Lambda$ and $\overline{\Lambda}$ hyperons
  - Sensitive to transversity distributions of $s$ and $\bar{s}$ quarks via **transversely polarized fragmentation functions**
  - Polarization $P_{\Lambda}$ measured with respect to the jet axis used as a substitute for the direction of the outgoing fragmenting quark

$$D_{TT} = \frac{\sigma_{p^{\uparrow}p \to \Lambda^{\uparrow}X} - \sigma_{p^{\uparrow}p \to \Lambda^{\downarrow}X}}{\sigma_{p^{\uparrow}p \to \Lambda^{\uparrow}X} + \sigma_{p^{\uparrow}p \to \Lambda^{\downarrow}X}}$$



# TRANSVERSE SPIN TRANSFER

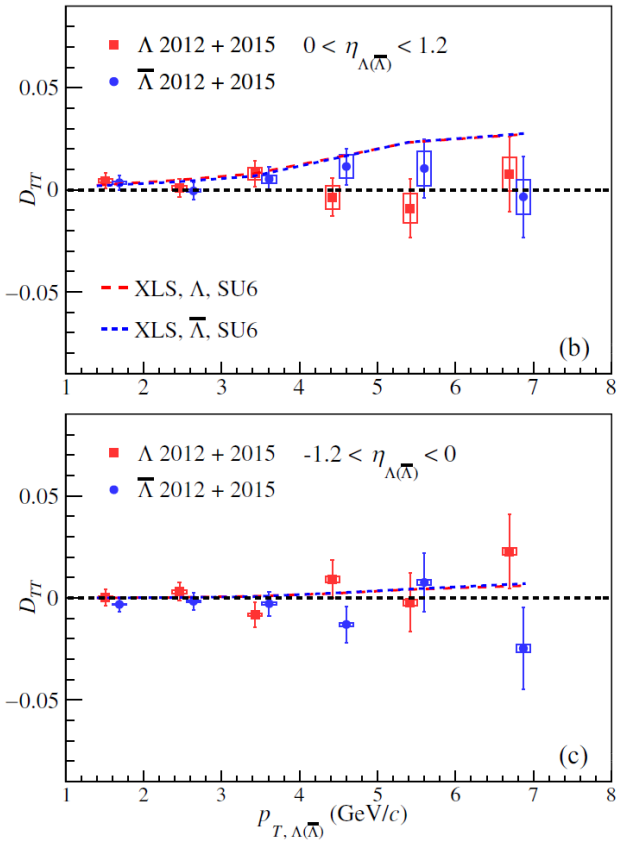
- Transverse spin transfer $D_{TT}$ of $\Lambda^0$ and $\overline{\Lambda}^0$ hyperons measured in $p^{\uparrow} + p$ collisions at $\sqrt{s} = 200$ GeV

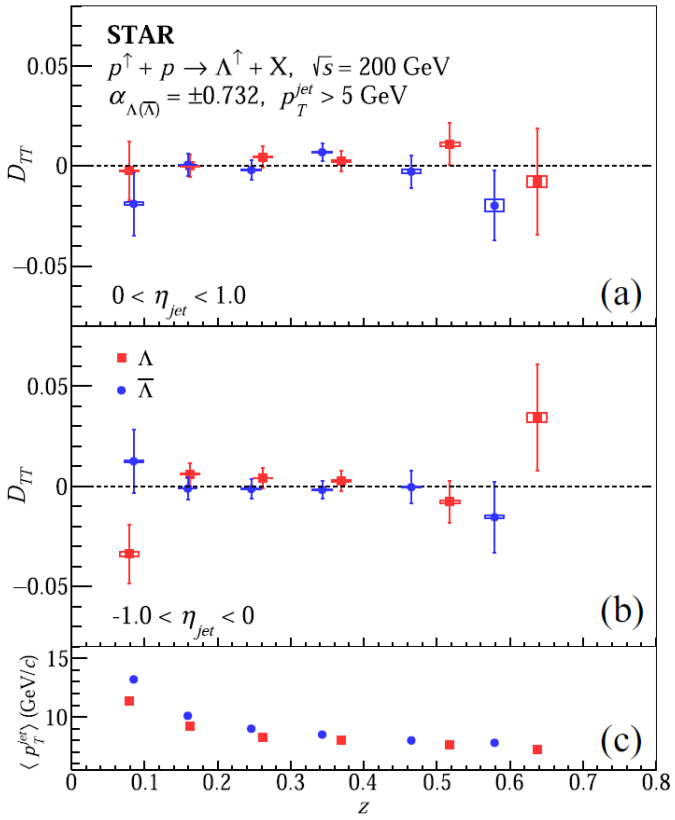
- Consistent results between $\Lambda^0$ and $\overline{\Lambda}^0$ hyperons

- Data consistently below prediction by models at high $p_T$
  - Phys. Rev. D 70, 034015 (2004)
  - Phys. Rev. D 73, 077503 (2006)

- The $z$ dependence directly probes transversely polarized fragmentation function

STAR, PRD 109, 12004 (2024)

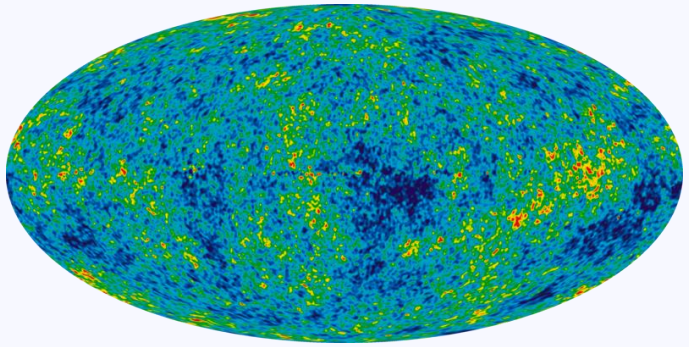



$$z = \frac{\vec{p}_{\Lambda} \cdot \vec{p}_{\text{jet}}}{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{jet}}}$$

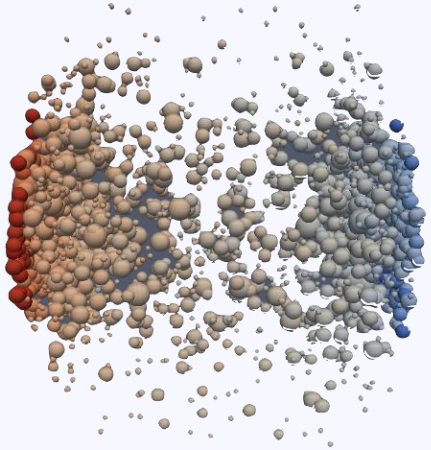
# MOTIVATION FOR Λ SPIN-SPIN CORRELATIONS

**CMB radiation**



Temperature correlations

**Heavy-ion collisions**

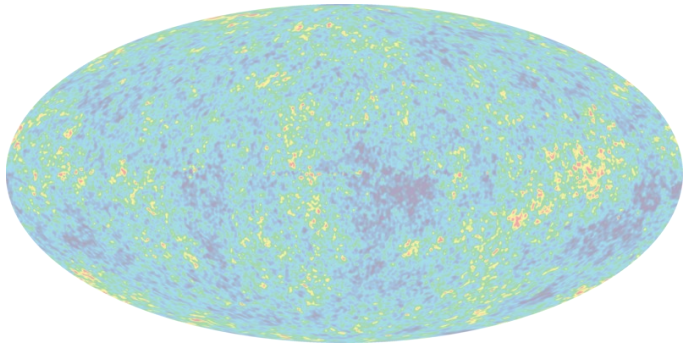


Momentum correlations

`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

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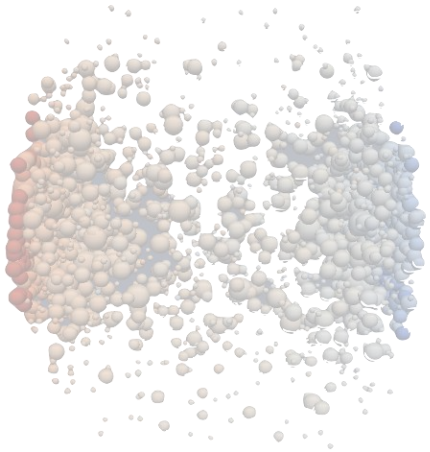
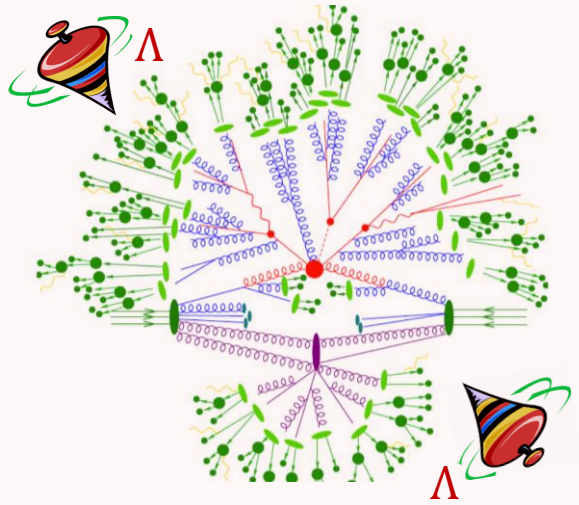


Momentum correlations

**Proton-Proton collisions**




Spin correlation

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

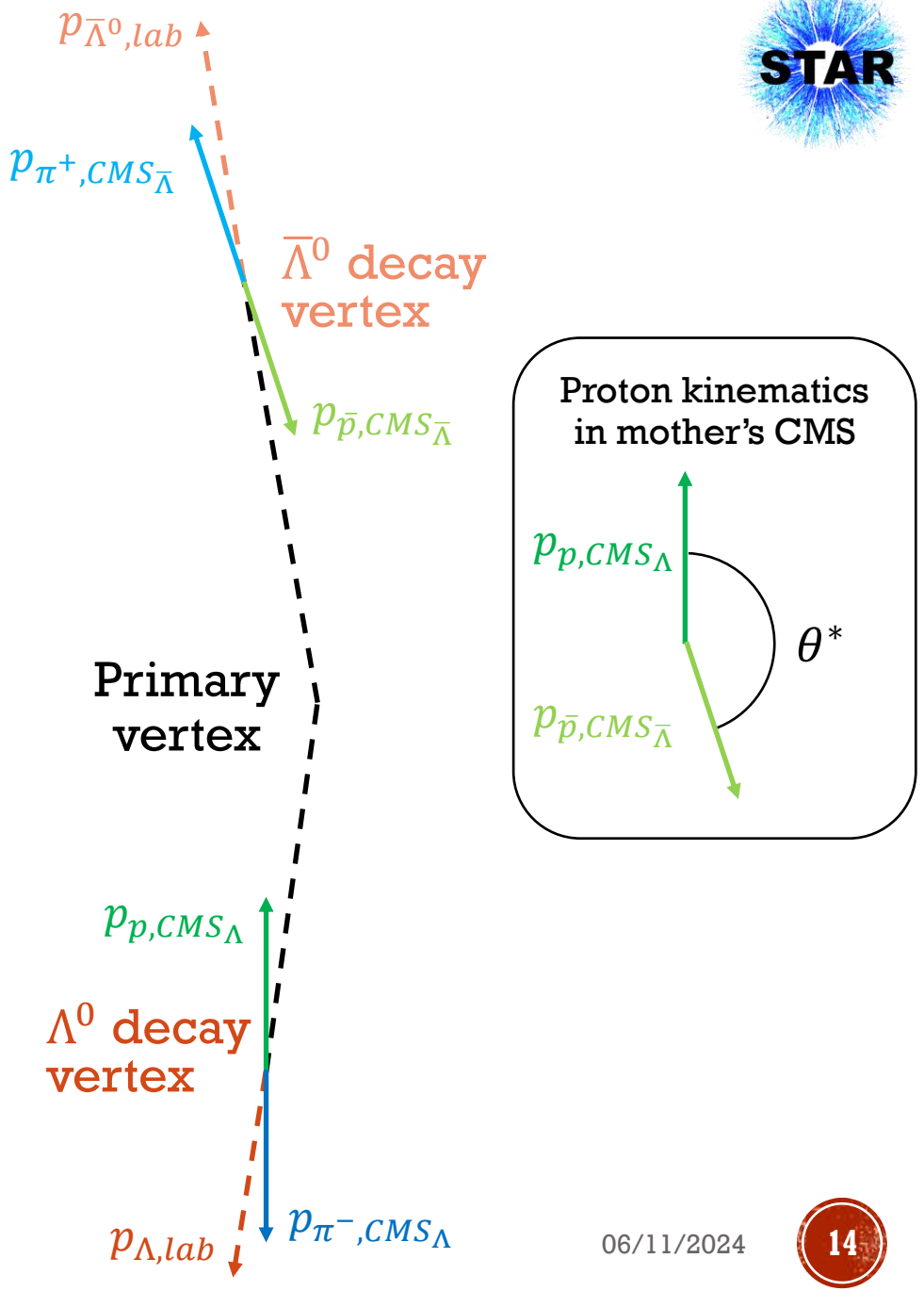
`Anisotropies` measured by two-point correlation function. Pure final-state effects cannot contribute to the correlation **as it violates causality**.

# $\Lambda$ SPIN-SPIN CORRELATIONS

- Find a $\Lambda^0$ 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 $\Lambda^0$ ($\overline{\Lambda}$) to rest frame of its mother
  - Proton momenta in mother rest frame: $p_{p,CMS_\Lambda}$, $p_{\bar{p},CMS_{\overline{\Lambda}}}$
- Measure angle $\theta^*$ between the two boosted protons
  - The distribution of pair angle is given by:

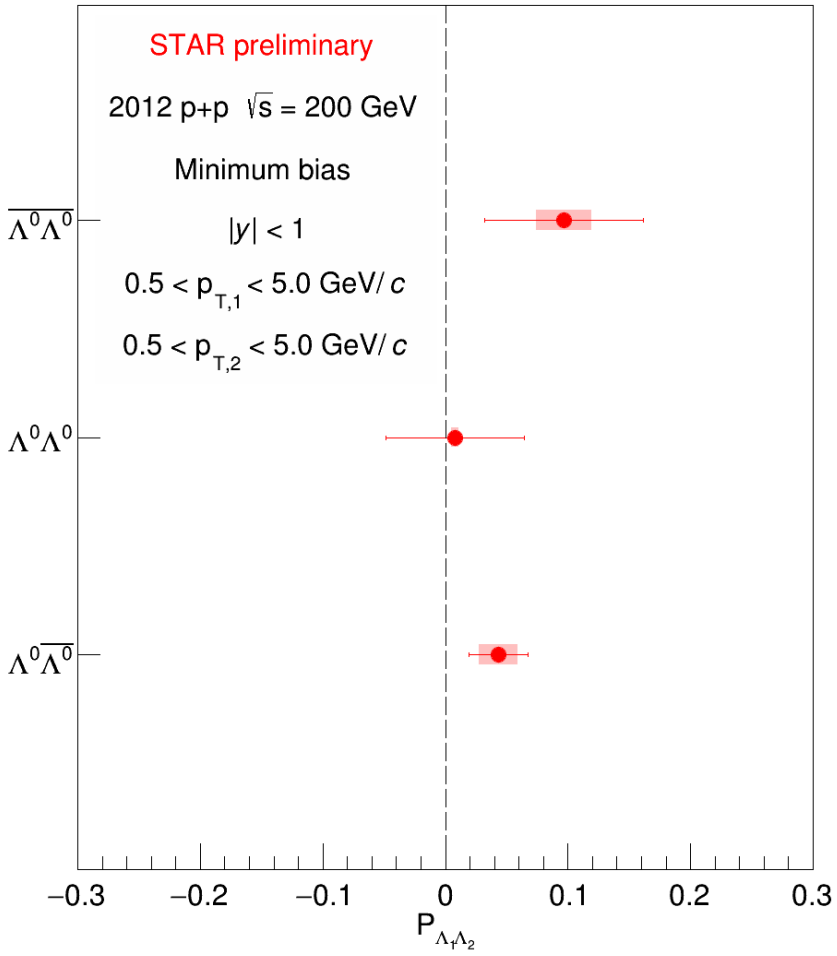
$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} \sim 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)$$

  - $\alpha_1$ and $\alpha_2$ are $\alpha_+$ or $\alpha_-$, depending on $\Lambda^0$ hyperon pair
- A non-zero $P_{\Lambda_1\Lambda_2}$ would indicate spin correlation between the two $\Lambda^0$ ($\overline{\Lambda}^0$) hyperons



# $\Lambda$ SPIN-SPIN CORRELATIONS – RESULTS

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



# SUMMARY

- First experimental measurement of transverse polarization of $\Lambda^0$ in jets in $p+p$ collisions
  - $\Lambda^0$ polarization found consistent with 0
  - $\overline{\Lambda}^0$ shows hint of $2\sigma$ polarization

- Improved measurement of $D_{LL}$ and $D_{TT}$ of $\Lambda^0$ and $\overline{\Lambda}^0$ in polarized $p+p$ collisions
  - First measurement as a function of $z$ in $p+p$ collisions
  - $D_{LL}$: Disfavors one extreme scenario about polarized FFs
  - $D_{TT}$: Data below model prediction at high $p_T$

- First experimental search for $\Lambda^0$ hyperon spin-spin correlations in $p+p$ collisions
  - 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

# THANK YOU FOR ATTENTION