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STAR

# Measurement of longitudinal spin transfer of the $\Lambda(\bar{\Lambda})$ hyperon in polarized p+p collisions at $\sqrt{s} = 200\ \mathrm{GeV}$ at RHIC-STAR


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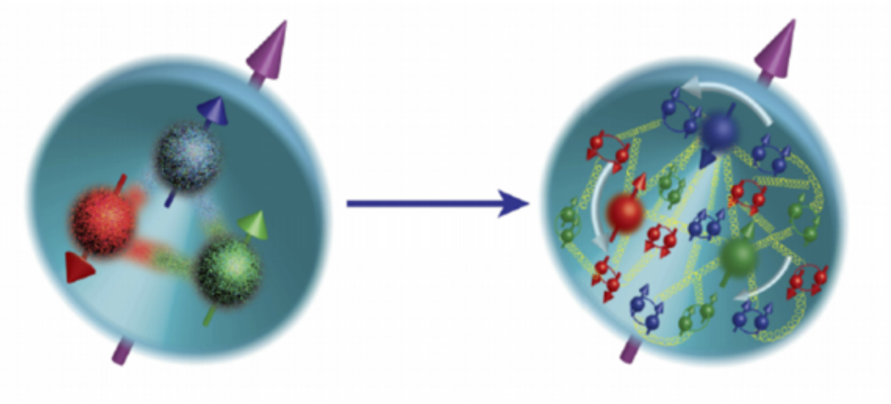
# Outline

- Motivation
- Introduction to RHIC and STAR
- $\Lambda$ and $\bar{\Lambda}$ reconstruction
- Longitudinal spin transfer $D_{LL}$ vs hyperon $p_T$
- Longitudinal spin transfer $D_{LL}$ vs hyperon fragmentation $z$
- Summary

# Motivation



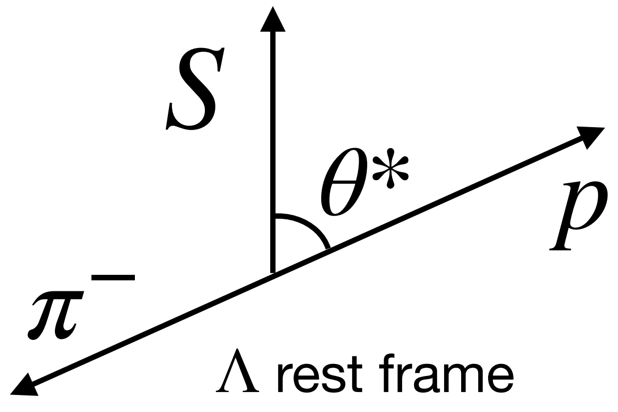
- ✦ **Nucleon spin structure ( from DIS and p-p )**
  - Spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$.
  - Valence quark helicity distributions are well known.
  - **Poor knowledge on sea quarks**, especially for **strange quark**.

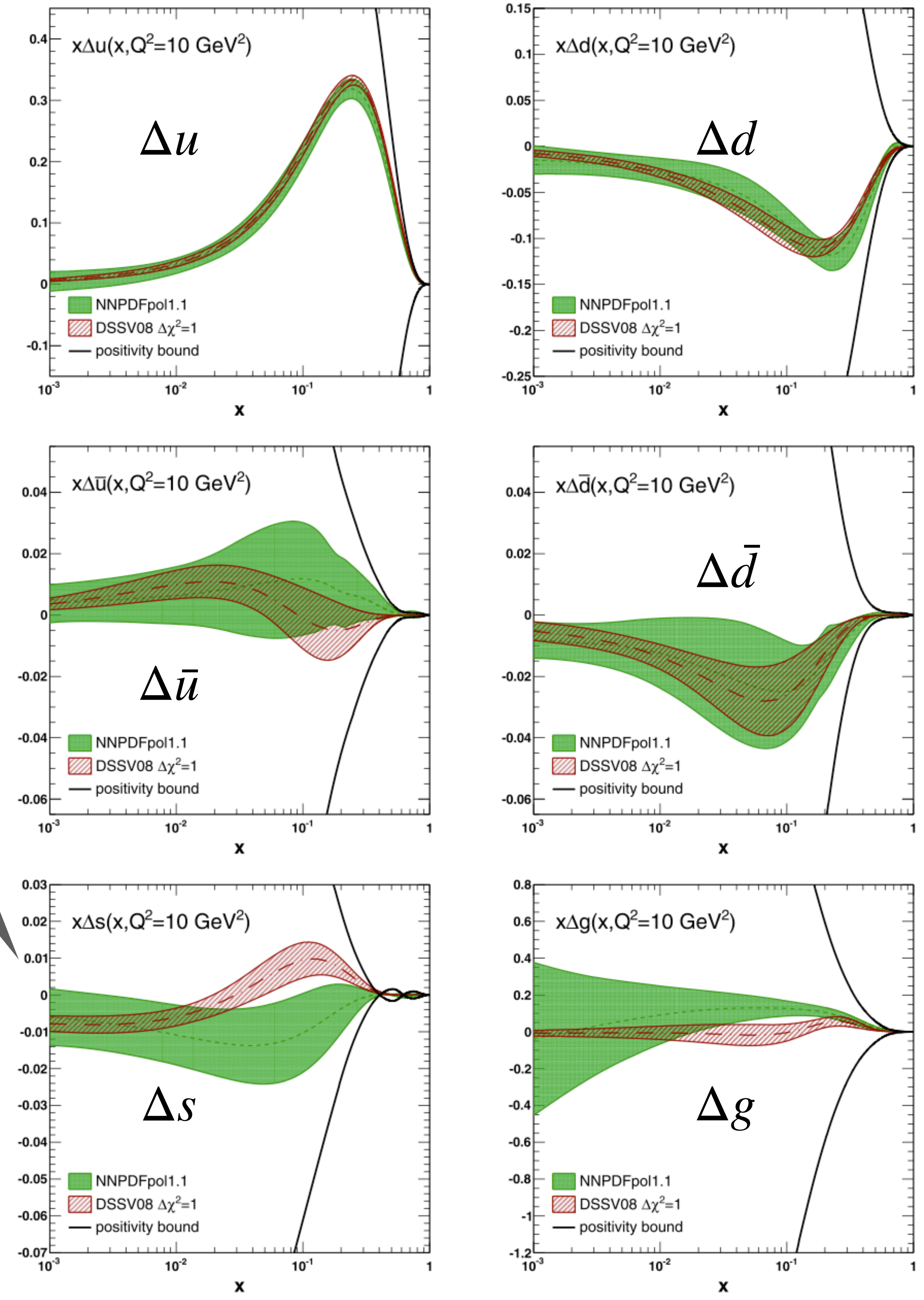
- ✦ **Why choose $\Lambda$ ?**
  - The spin of $\Lambda$ is expected to be carried mostly by its constituent strange quark.
  - The weak decay of $\Lambda$ provides a way to measure its polarization.

$$dN \sim (1 + \alpha P_\Lambda cos\theta^*) dcos\theta^*$$

$\alpha$ : weak decay parameter of $\Lambda$

$P_\Lambda$: the polarization of $\Lambda$




NNPDFpol1.1, Nucl. Phys. B887,276 (2014)

# Longitudinal spin transfer $D_{LL}$

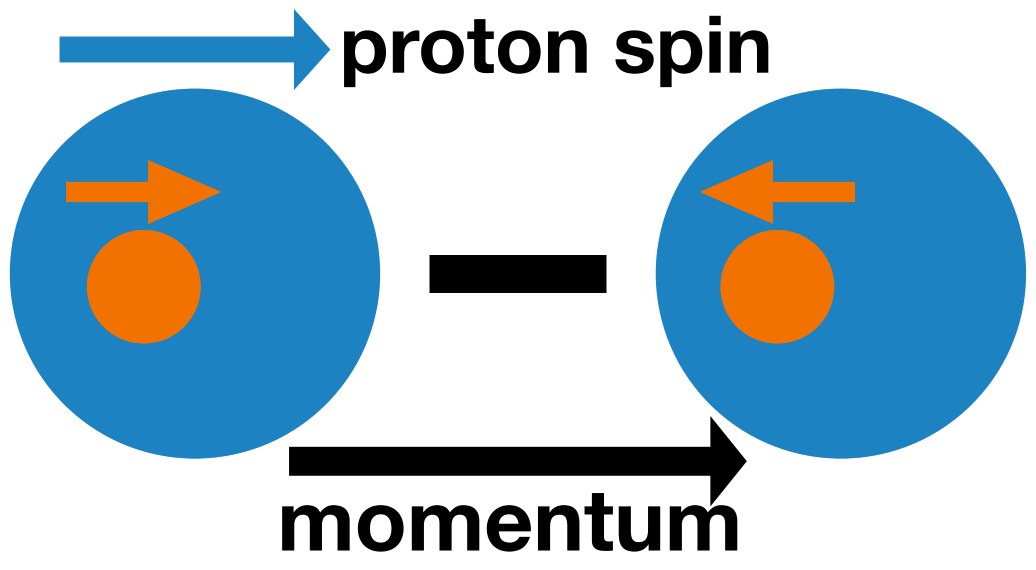
✦ **Definition of $D_{LL}$ in p+p collisions**

$$D^{\Lambda}_{LL} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma(ab \to cd) \Delta D^{\Lambda}(z)$$

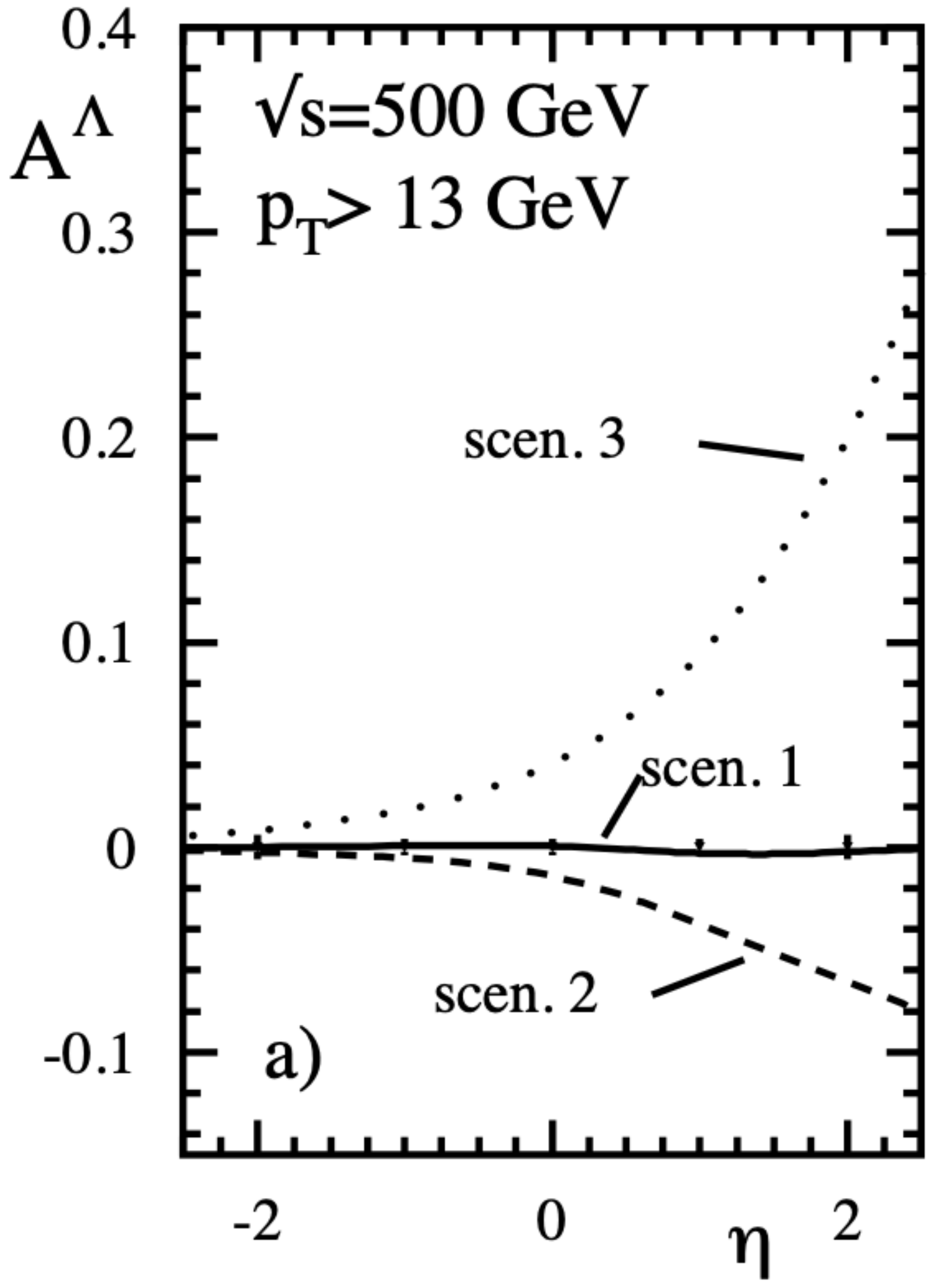
**helicity distribution** **pQCD calculable** **polarized FF**

$$\Delta f_a(x_a) = f_a^+(x_a) - f_a^-(x_a)$$

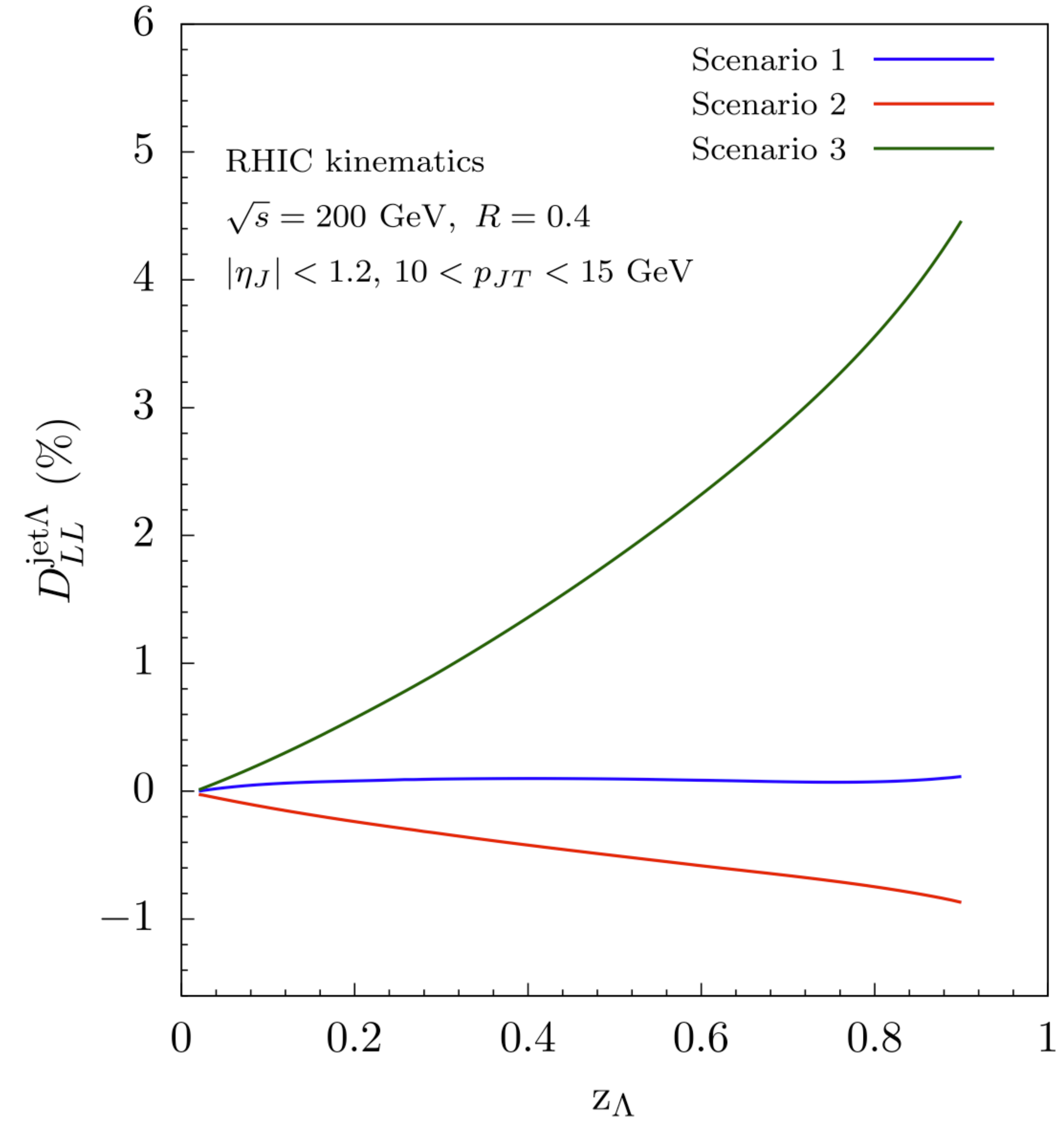



✦ $\Lambda$ $D_{LL}$ can shed light on both **polarized fragmentation functions (FF)** and the **helicity distributions** of $s(\bar{s})$.

**Prediction of $D_{LL}$ at RHIC**




D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. **81**, 4 (1998).

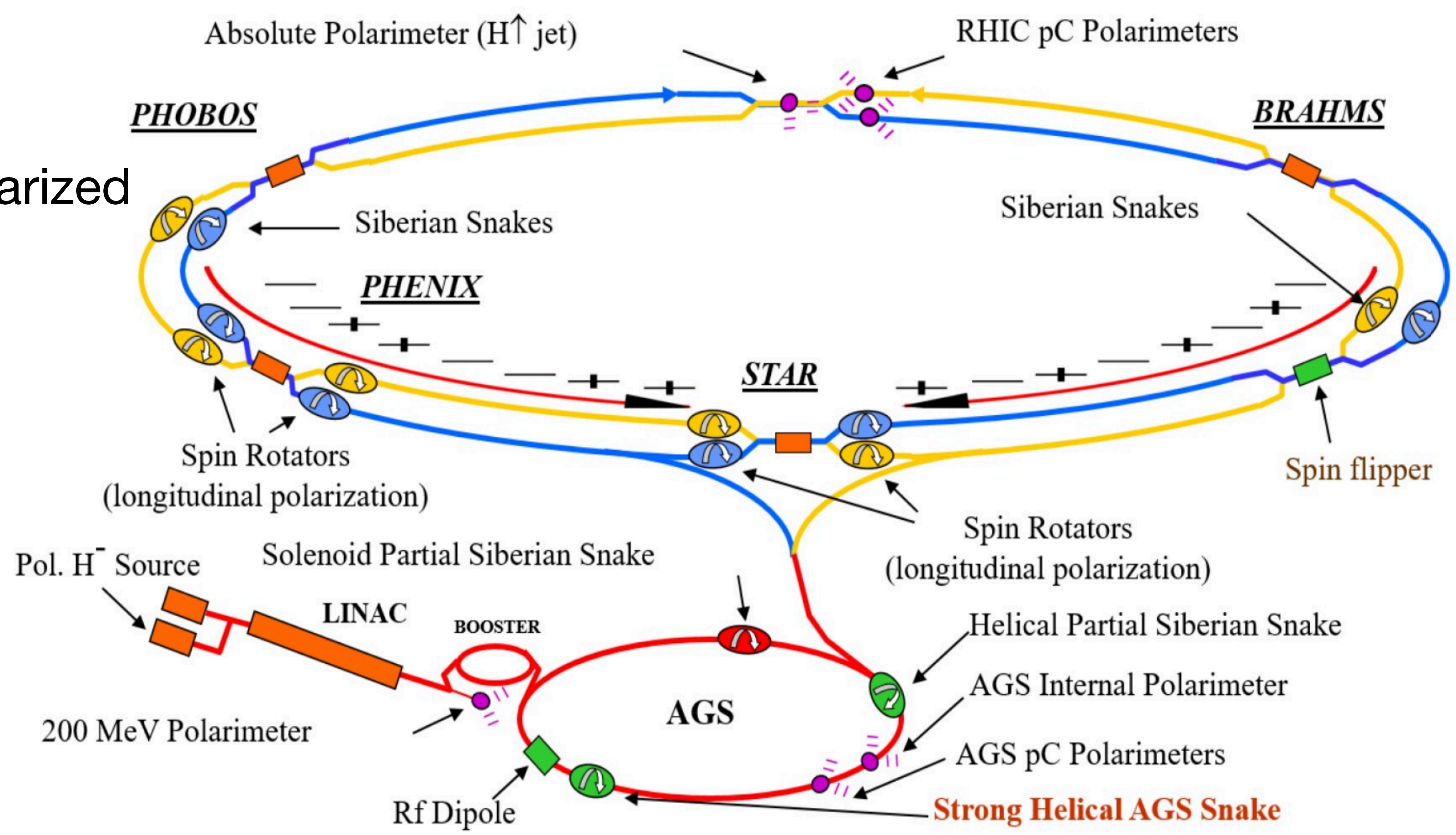



Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B **809**, 135756 (2020).

**scenario 1:** only s quark can produce polarized $\Lambda$ in the fragmentation process.
**scenario 2:** u and d quarks have the same contribution to polarized $\Lambda$ but with an opposite sign from s quark.
**scenario 3:** u, d and s quarks have the same contribution to the polarized $\Lambda$

# Relativistic Heavy Ion Collider

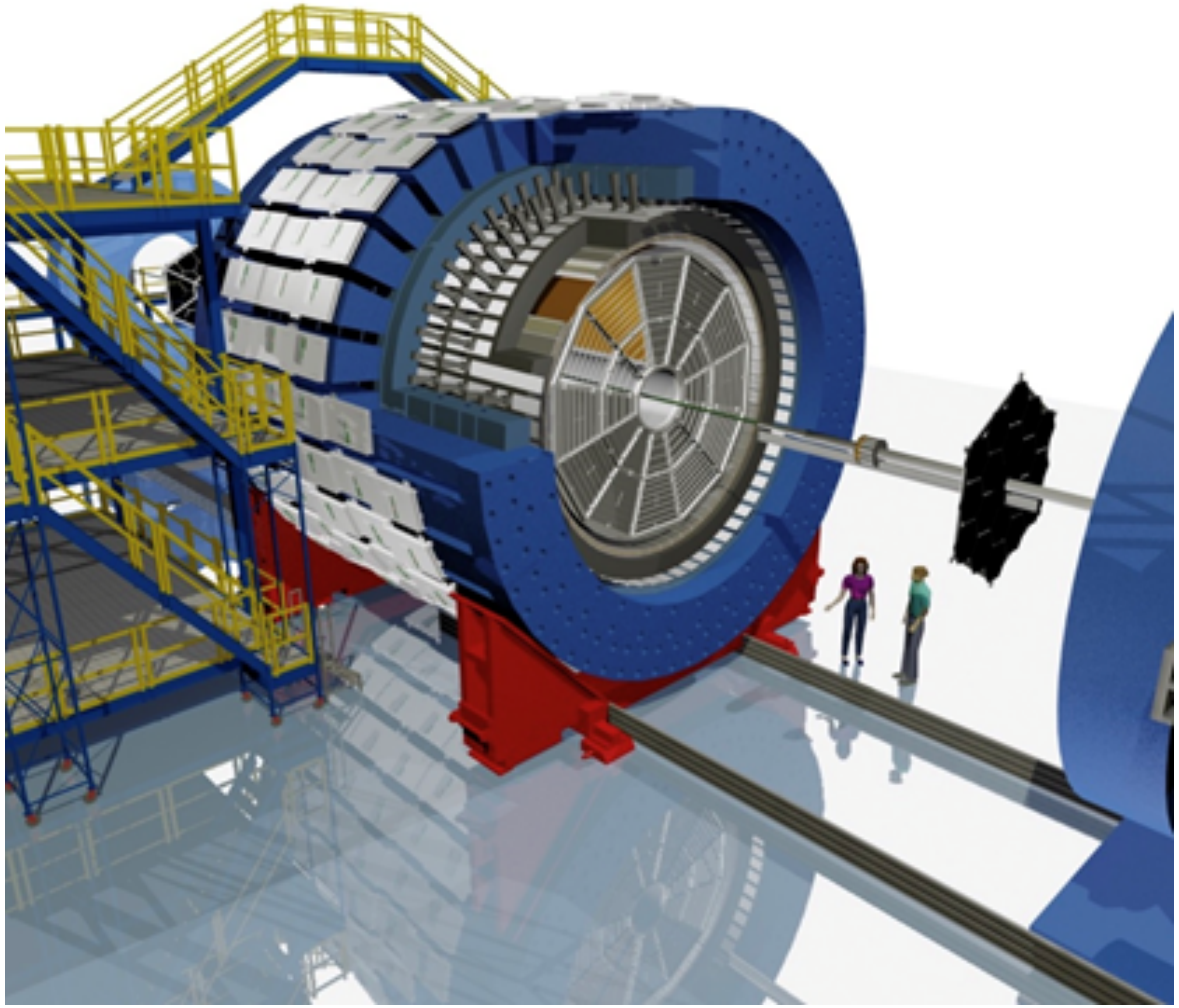
- First and only polarized p+p collider in the world
- Collides both transversely and longitudinally polarized proton beams at $\sqrt{s} = 200$ and 500/510 GeV.
- Ideal for studying nucleon spin structure




## Dataset

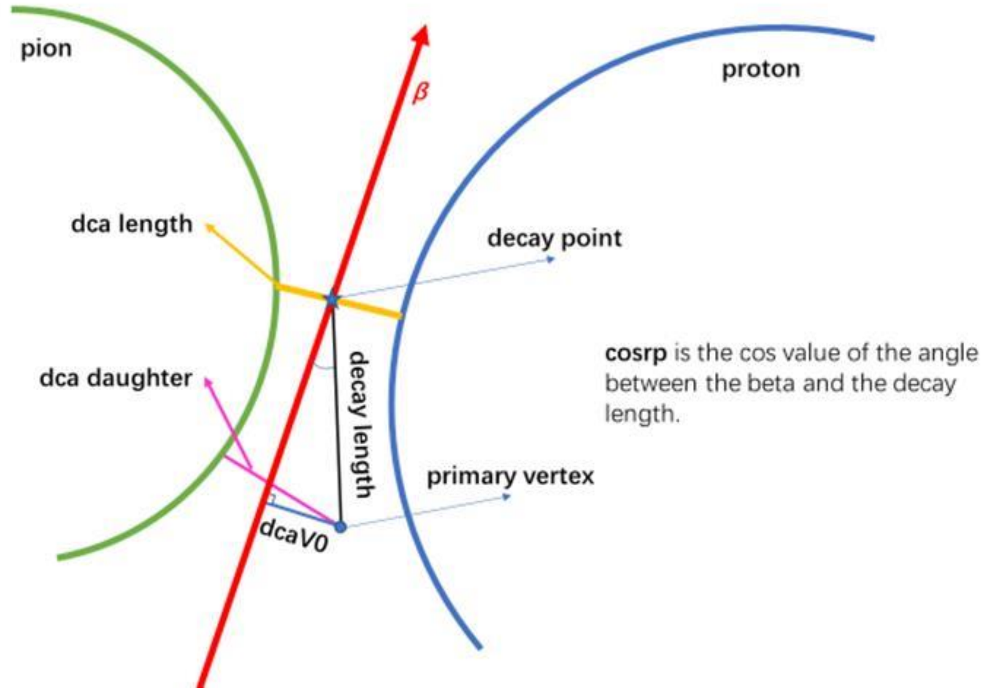
| Year | $\sqrt{s}\ (GeV)$ | $L_{int}\ (pb^{-1})$ | $P_{beam}$ |
|---|---|---|---|
| **2009** | 200 | 19 | 57% / 57% |
| **2015** | 200 | 52 | 52% / 56% |

# The Solenoidal Tracker At RHIC



- **Time Projection Chamber ( TPC )**
  - $|\eta| < 1.3$ and $0 \leq \phi \leq 2\pi$.
  - Tracking and particle identification.
- **Electromagnetic Calorimeter ( EMC )**
  - Barrel EMC ( BEMC ): $|\eta| < 1.0$ and $0 \leq \phi \leq 2\pi$.
  - Endcap EMC ( EEMC ): $1.086 < \eta < 2.0$ and $0 \leq \phi \leq 2\pi$.
  - Photon, $\pi^0$, jet …
  - Serve as the trigger detectors.
- **Time of Flight detector ( TOF )**
  - $|\eta| < 1.0$ and $0 \leq \phi \leq 2\pi$.
  - Particle identification
- **Vertex Position Detector ( VPD )**
  - $4.24 < |\eta| < 5.1$
  - Determine the primary vertex position
  - Monitor the relative luminosity

# $\Lambda(\bar{\Lambda})$ hyperons selection

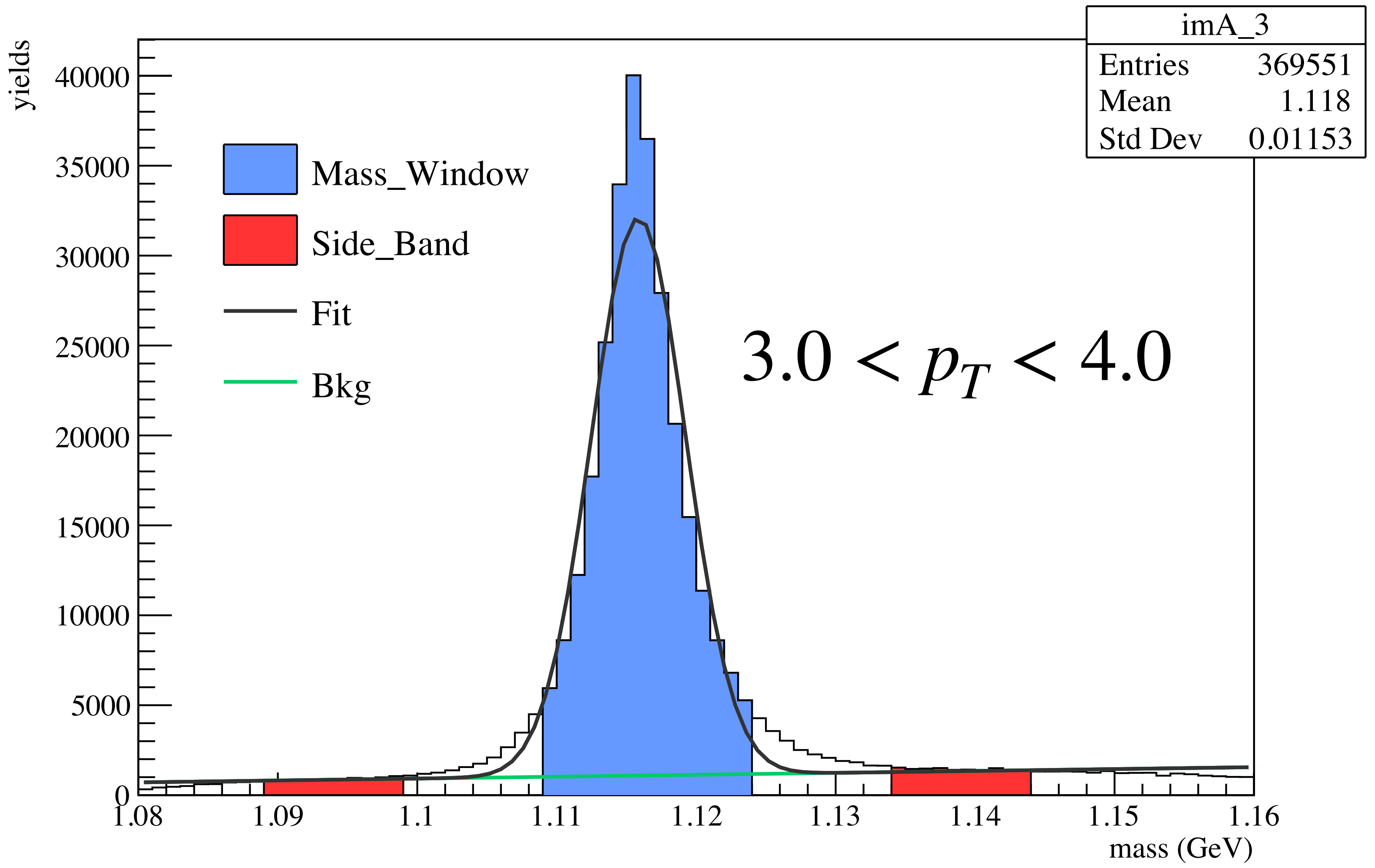



- **Select hard scattering events**

  Select the hard scattering events using a **jet trigger** based on the energy deposits in the EMC

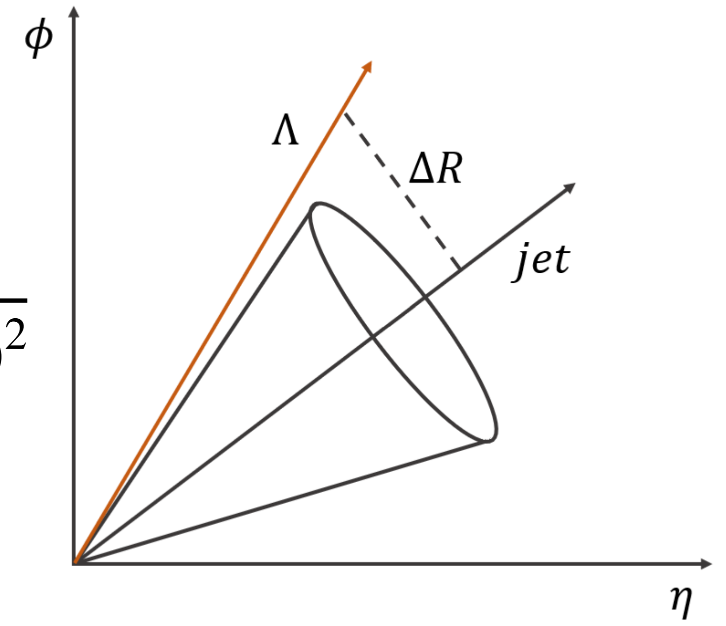
- **$\Lambda(\bar{\Lambda})$ reconstruction** **reconstruction channel** $\Lambda \to p + \pi^-$ $\bar{\Lambda} \to \bar{p} + \pi^+$
  - Apply a set of topological cuts to reduce the background.
  - Side-band method is used to estimate the residual background.

Invariant mass of $\bar{\Lambda}$




- Require hyperons to be associated with a jet with $\Delta R < 0.6$.
  - Jets are reconstructed with anti-$k_T$ algorithm ($R = 0.6$) using TPC tracks and EMC energy deposits.
  - Jet $p_T > 5$ GeV and $-0.7 < \eta_{jet} < 0.9$

$$\Delta R = \sqrt{(\eta_{jet} - \eta_\Lambda)^2 + (\phi_{jet} - \phi_\Lambda)^2}$$



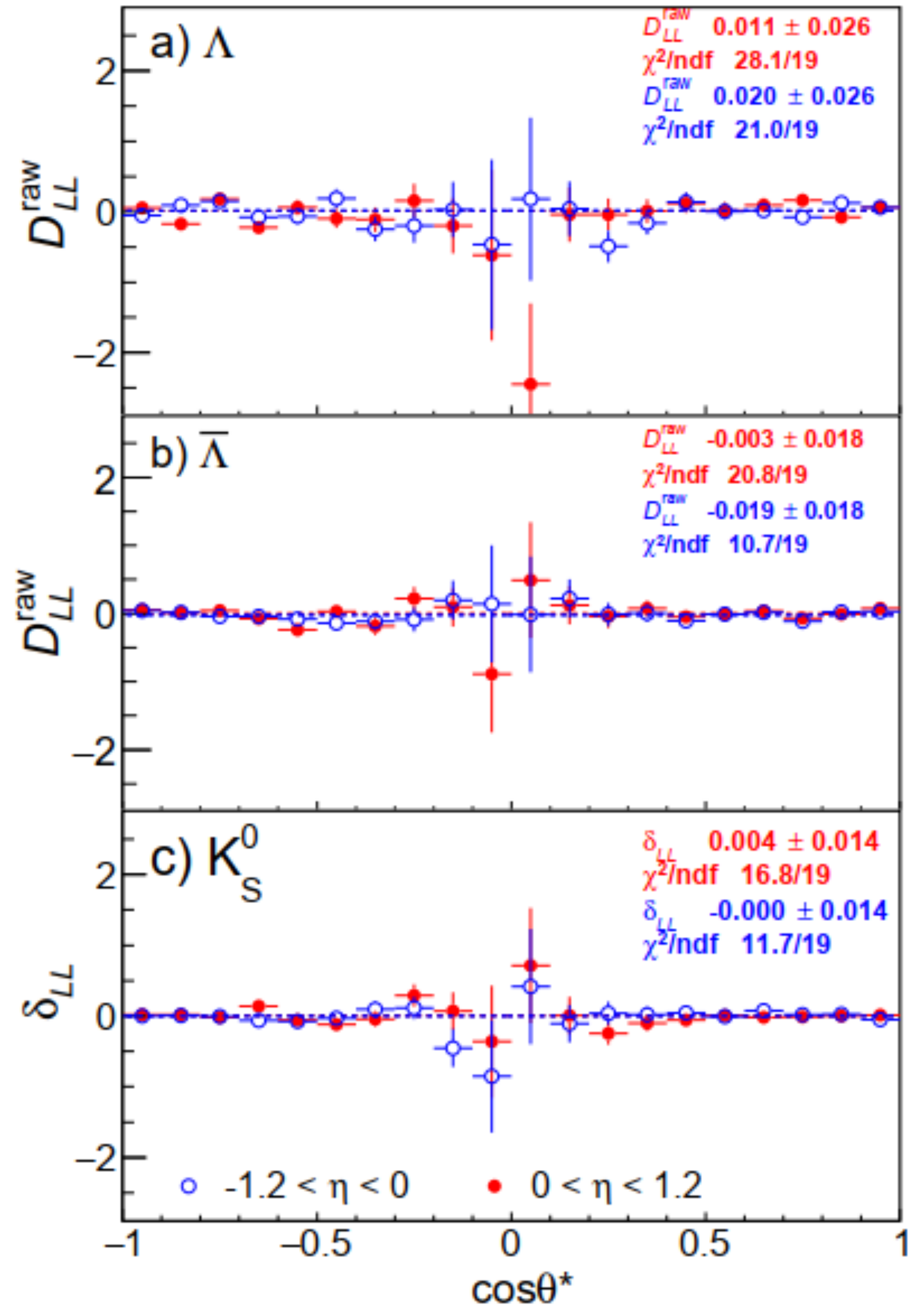

**background subtraction**

$$D_{LL} = \frac{D_{LL}^{raw} - rD_{LL}^{bkg}}{1 - r}$$

$r$ : background fraction

# Measurements of $D_{LL}$

STAR, *Phys. Rev. D* **98**, 032011 (2018).




- ✦ $D_{LL}$ **is measured with the asymmetry of** $\Lambda(\bar{\Lambda})$ **yields in a small** $cos\theta^*$ **interval**

$$D_{LL} = \frac{1}{\alpha P_{beam} < cos\theta^* >} \frac{N^+ - R_L N^-}{N^+ + R_L N^-}$$

→ Acceptance canceled

first used in STAR, *Phys. Rev. D* 80, 111102 (2009).

- $N^{+(-)}$: the $\Lambda$ yields with positive and negative beam helicity.
- $R_L$: relative luminosity measured by the VPD.
- $\alpha = 0.732$: decay parameter of $\Lambda$ hyperon.
- $P_{beam}$: the beam polarization.

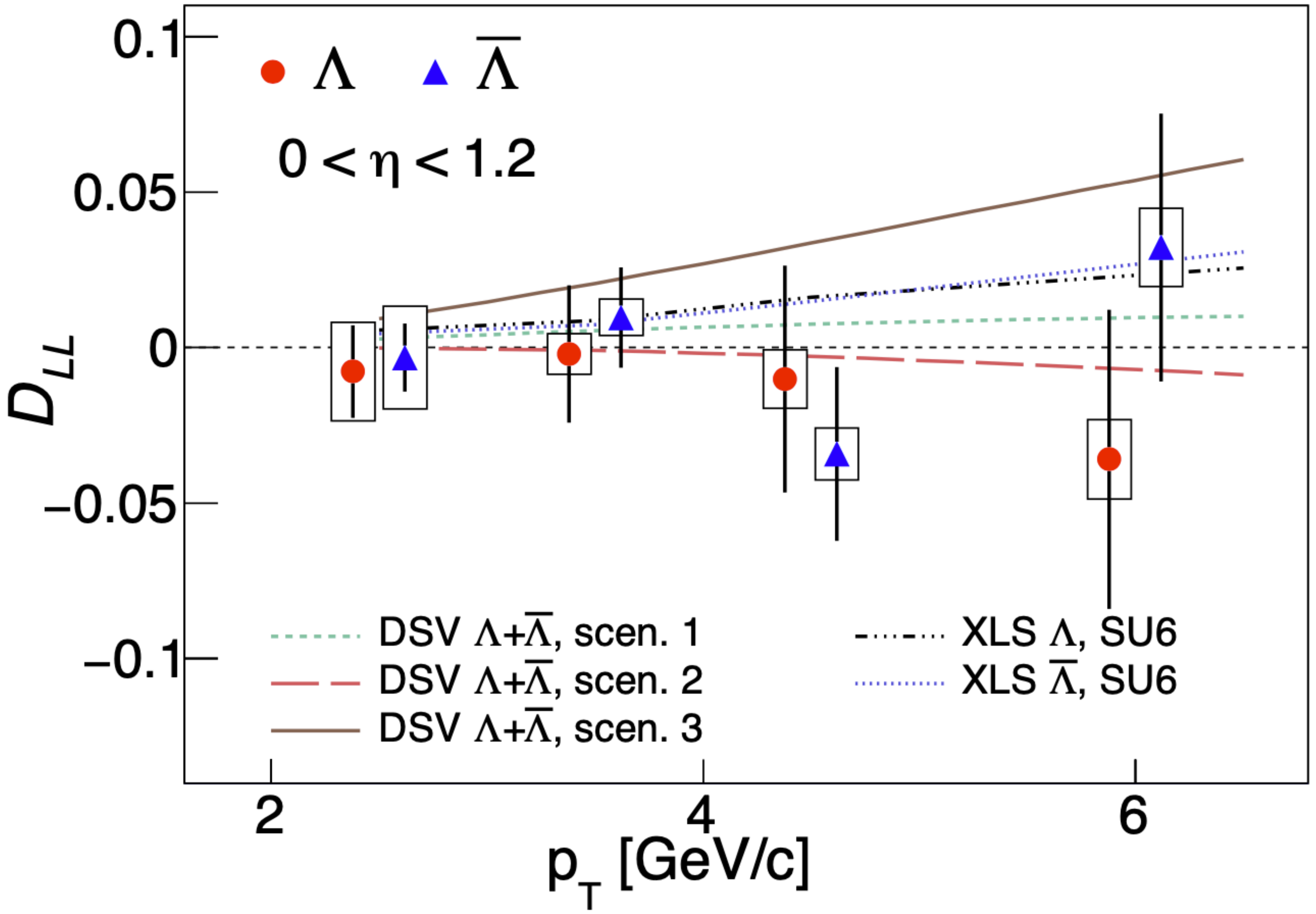
- ✦ $\delta_{LL}$ **of** $K_S^0$ **as a null check.**
  - Same method as $D_{LL}$
  - Using an artificial decay parameter $\alpha = 1$

→ **consistent with zero as expected**

# Previous $D_{LL}$ results

- $D_{LL}$ vs $p_T$ results with STAR 2009 data

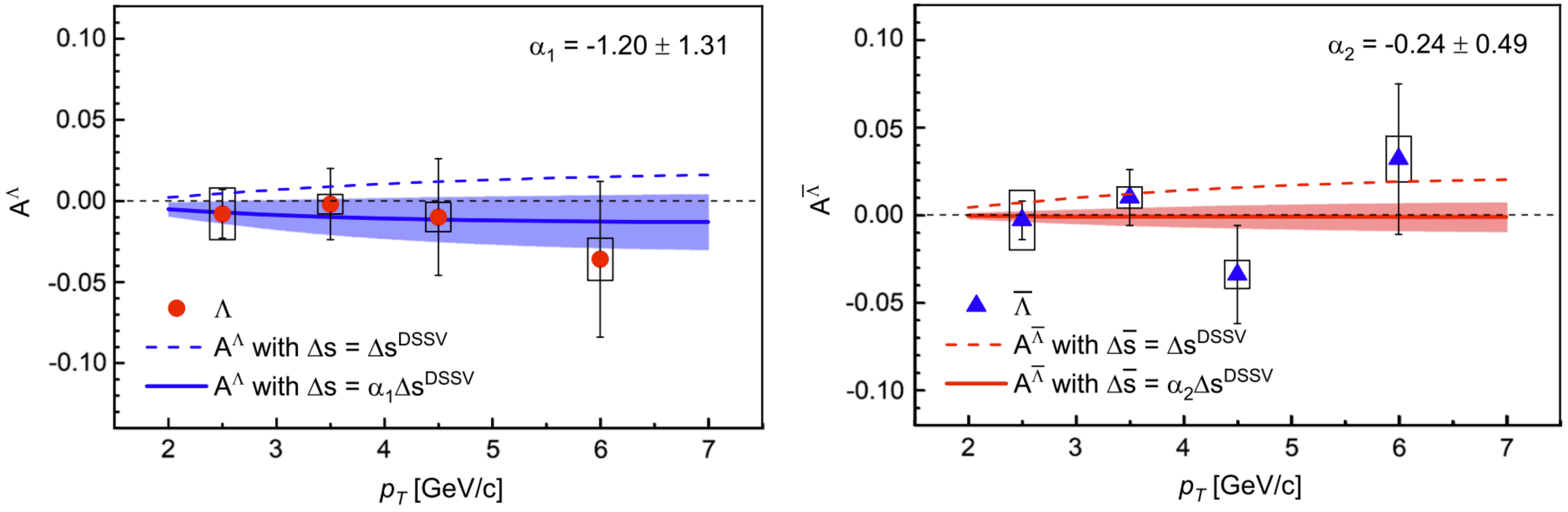
STAR, *Phys. Rev. D* **98**, 112009 (2018).




- Statistically limited
- In agreement with models

- Theoretical models, when fit to data, provide constraints to strange quark and anti-quark polarization

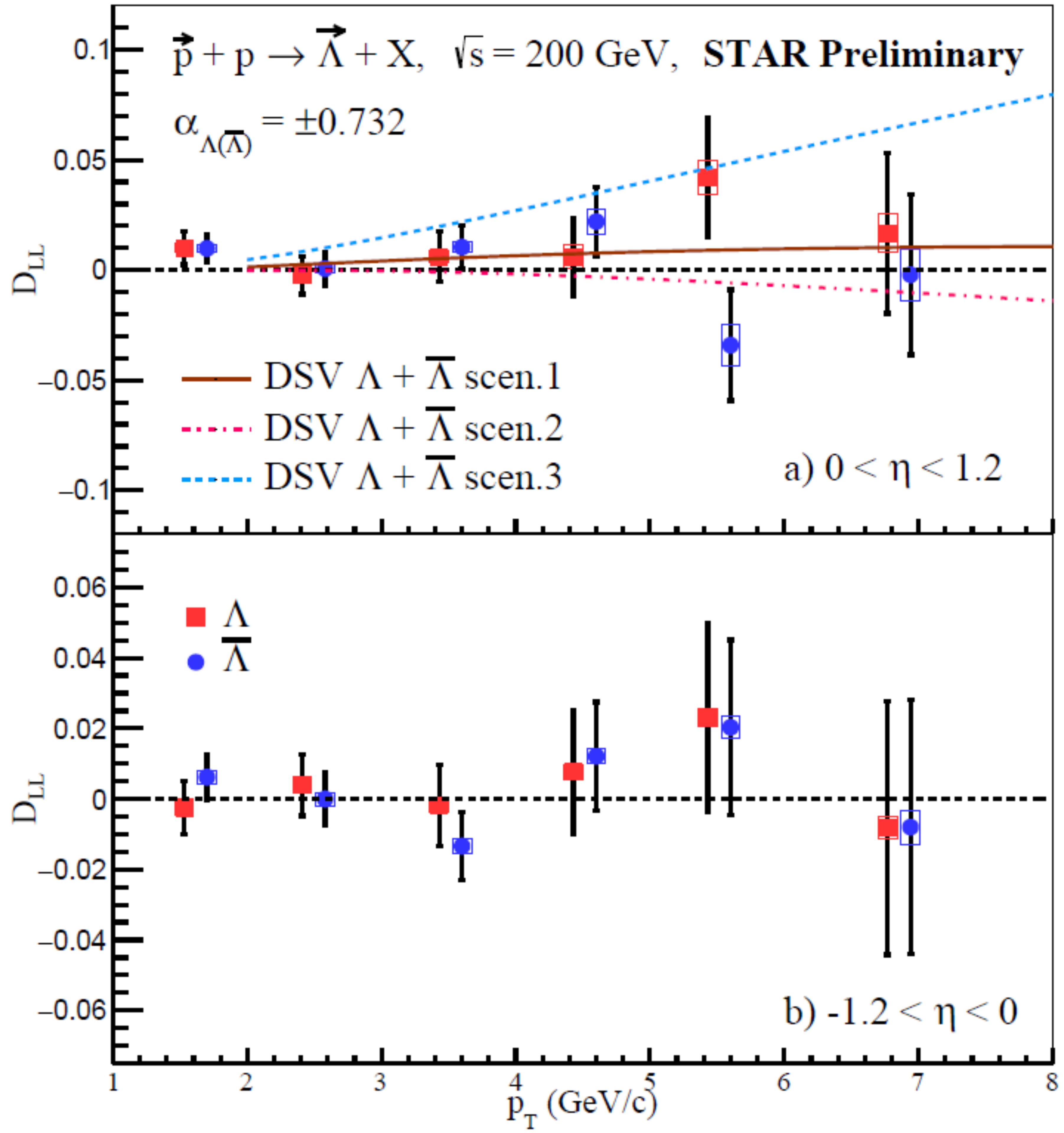
X.N. Liu, B.Q. Ma. *Eur. Phys. J. C* 10 (2019).




**(a)** Longitudinal spin transfer to $\Lambda$. **(b)** Longitudinal spin transfer to $\overline{\Lambda}$.

# New $D_{LL}$ vs $p_T$ results

- $D_{LL}$ vs $p_T$ results with STAR 2015 data




$D_{LL}$ as a function of hyperon $p_T$, with small offset applied for better visibility

- The hyperon $p_T$ range is extended up to 7 $GeV/c$.
- Results show consistency between $\Lambda$ and $\bar{\Lambda}$.
- Data are in agreement with various models within uncertainties.
- Most precise measurements to date with twice the statistics of the 2009 dataset.

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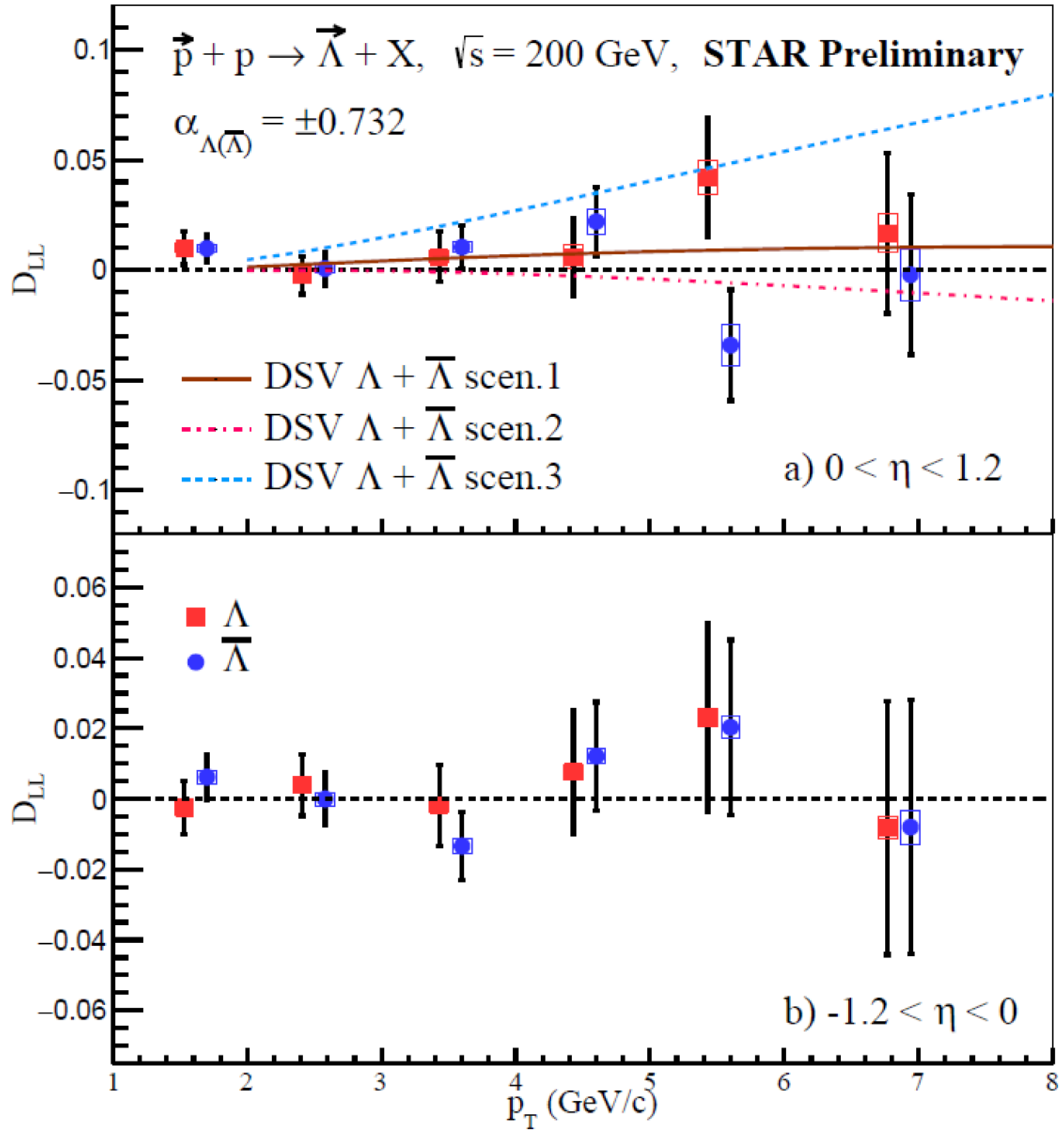


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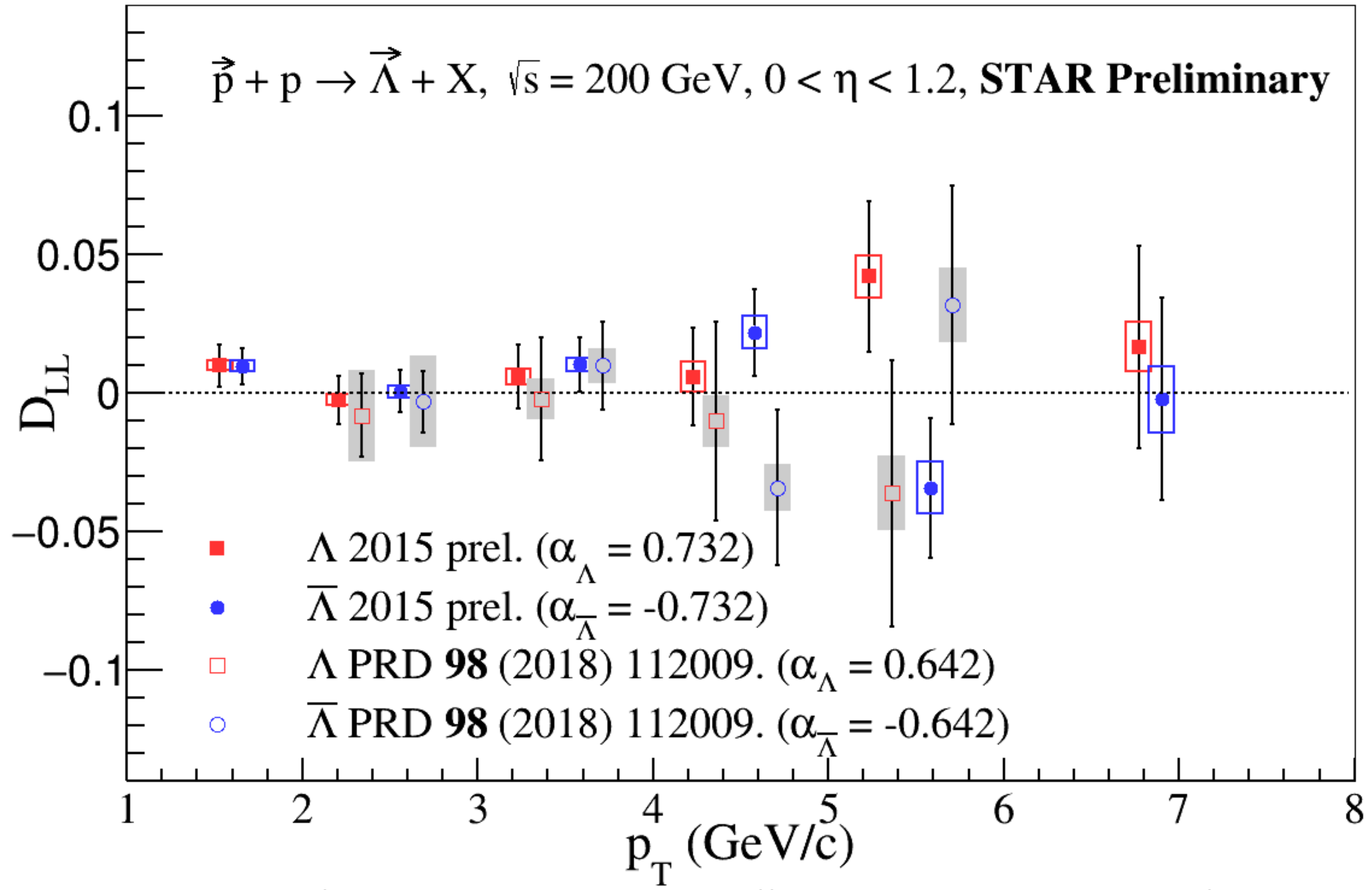
comparison between STAR 2009 and 2015 data




The results of 2009 data have been offset slightly to larger $p_T$ for clarity.

# Measurement of $D_{LL}$ vs $z$

**Definition of $z$**

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

$z$: longitudinal momentum fraction of the jet carried by $\Lambda(\bar{\Lambda})$ hyperon

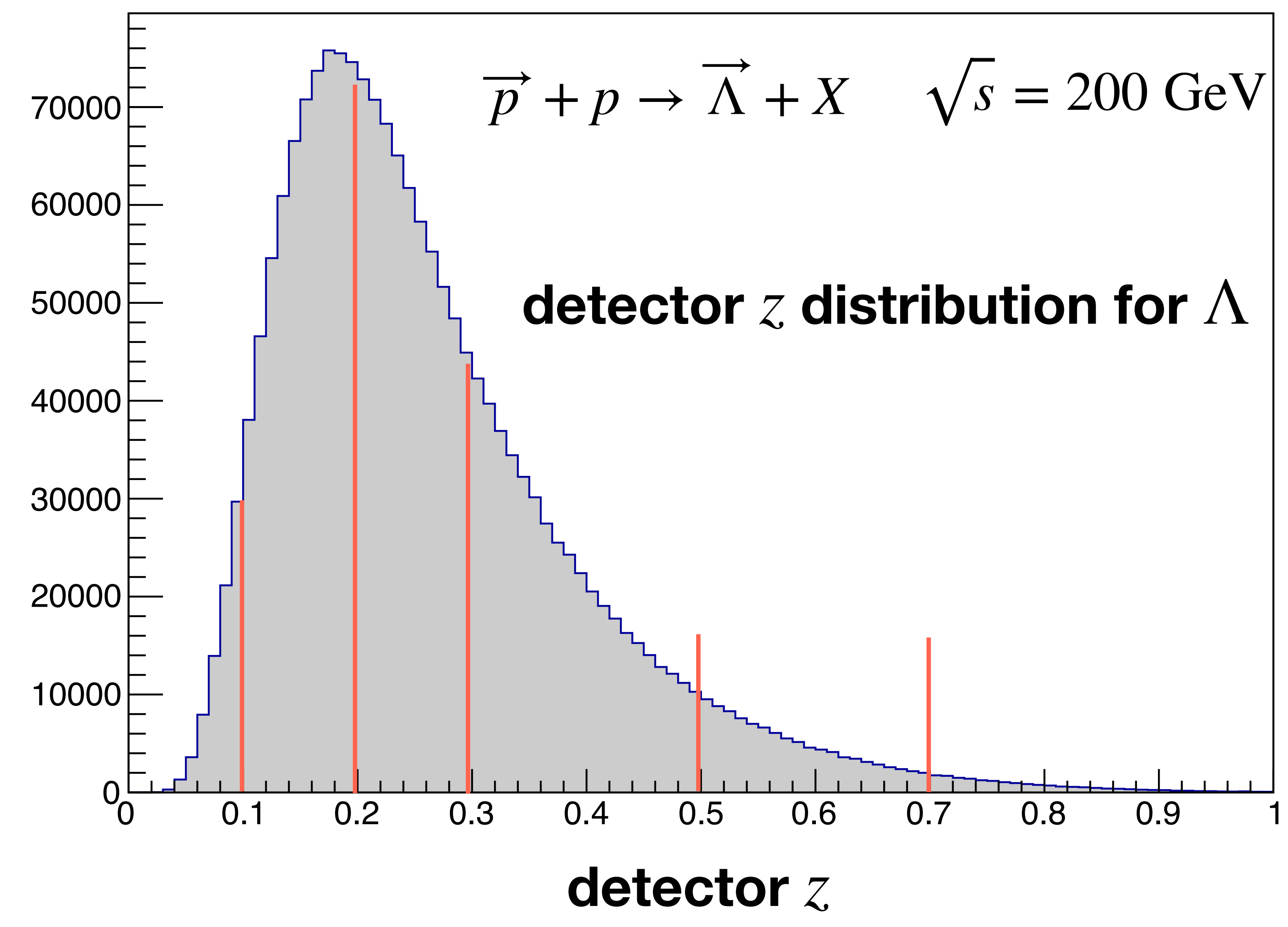
✦ **$D_{LL}$ vs $z$ can provide direct information for polarized fragmentation functions**

✦ **Correct the detector $z$ to particle $z$**

1. **In STAR, jets are reconstructed using TPC tracks and EMC energy deposits.** → detector jet
2. **Theoretical studies use all the particles for the jet.** → particle jet
3. **Need to correct the "detector z" (based on detector jet) to "particle z" (based on particle jet) in our measurement.**

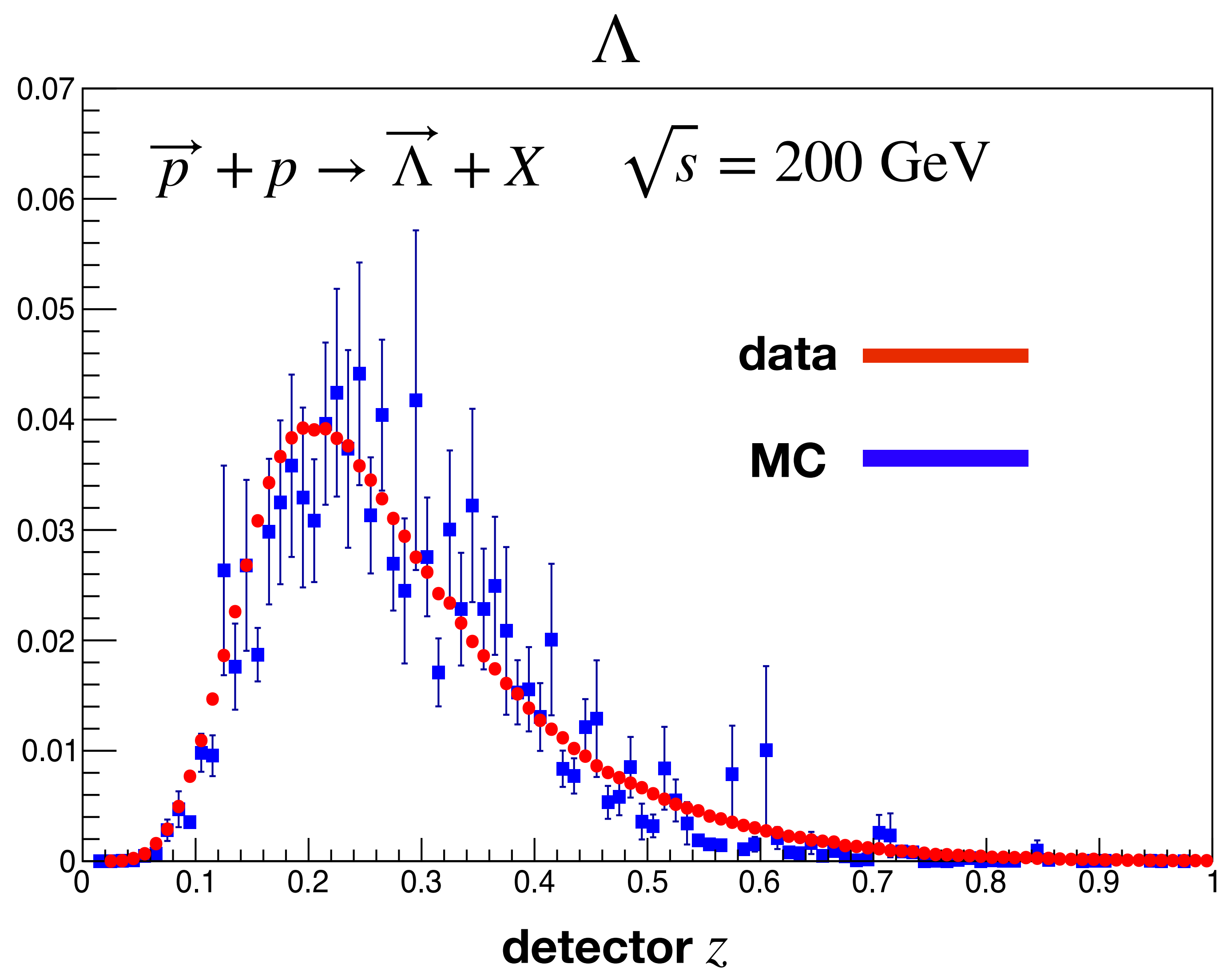
# Measurement of $D_{LL}$ vs $z$

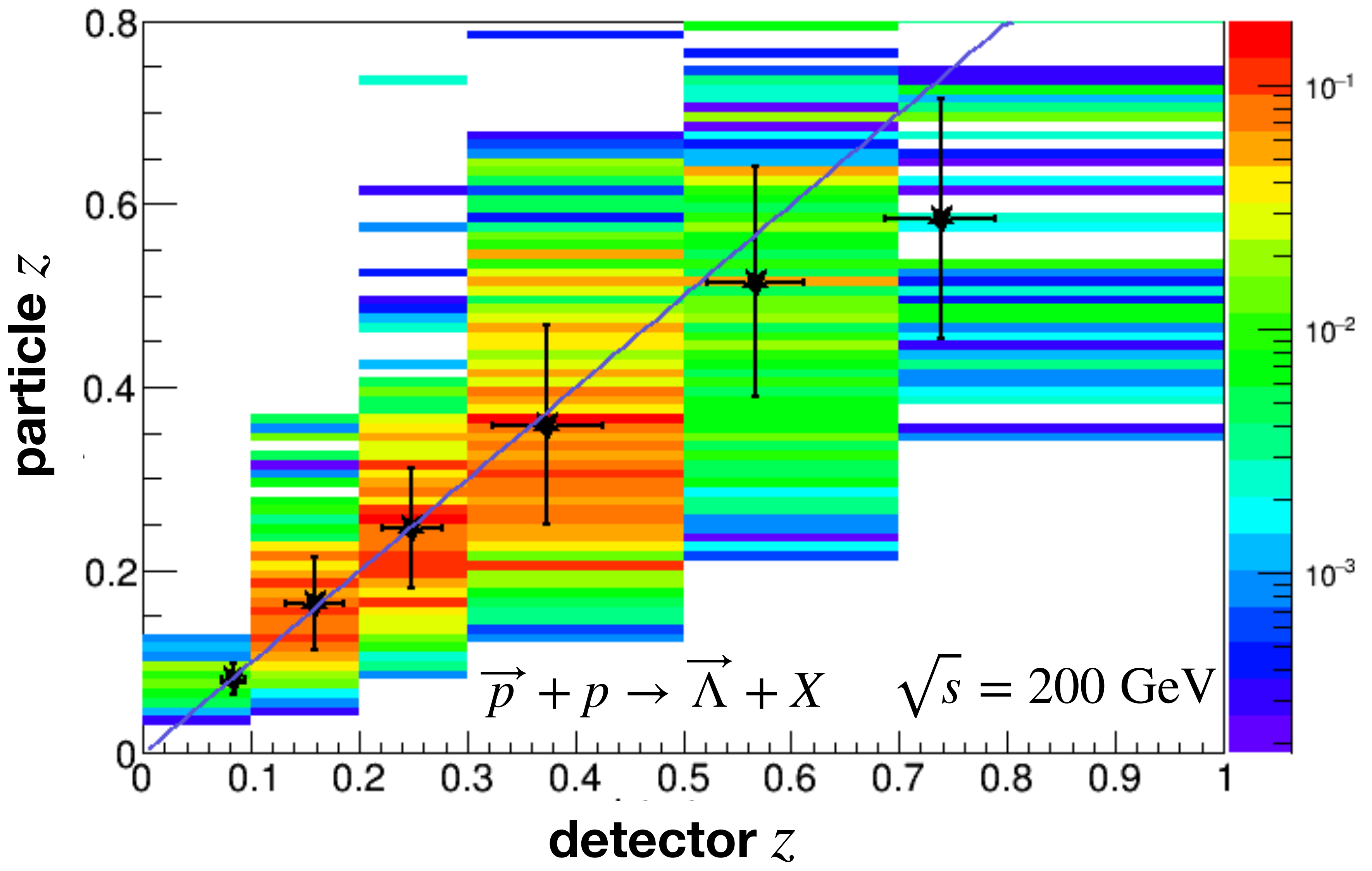
1. **Obtain the detector $z$ and calculate the $D_{LL}$ in each detector $z$ bin**




2. **Correct the average of detector $z$ to particle $z$**
    - **Monte Carlo sample**: pythia6 + geant3
    - Correlate detector jet with particle jet
    - Get the mean value of particle $z$ in each detector $z$ bin

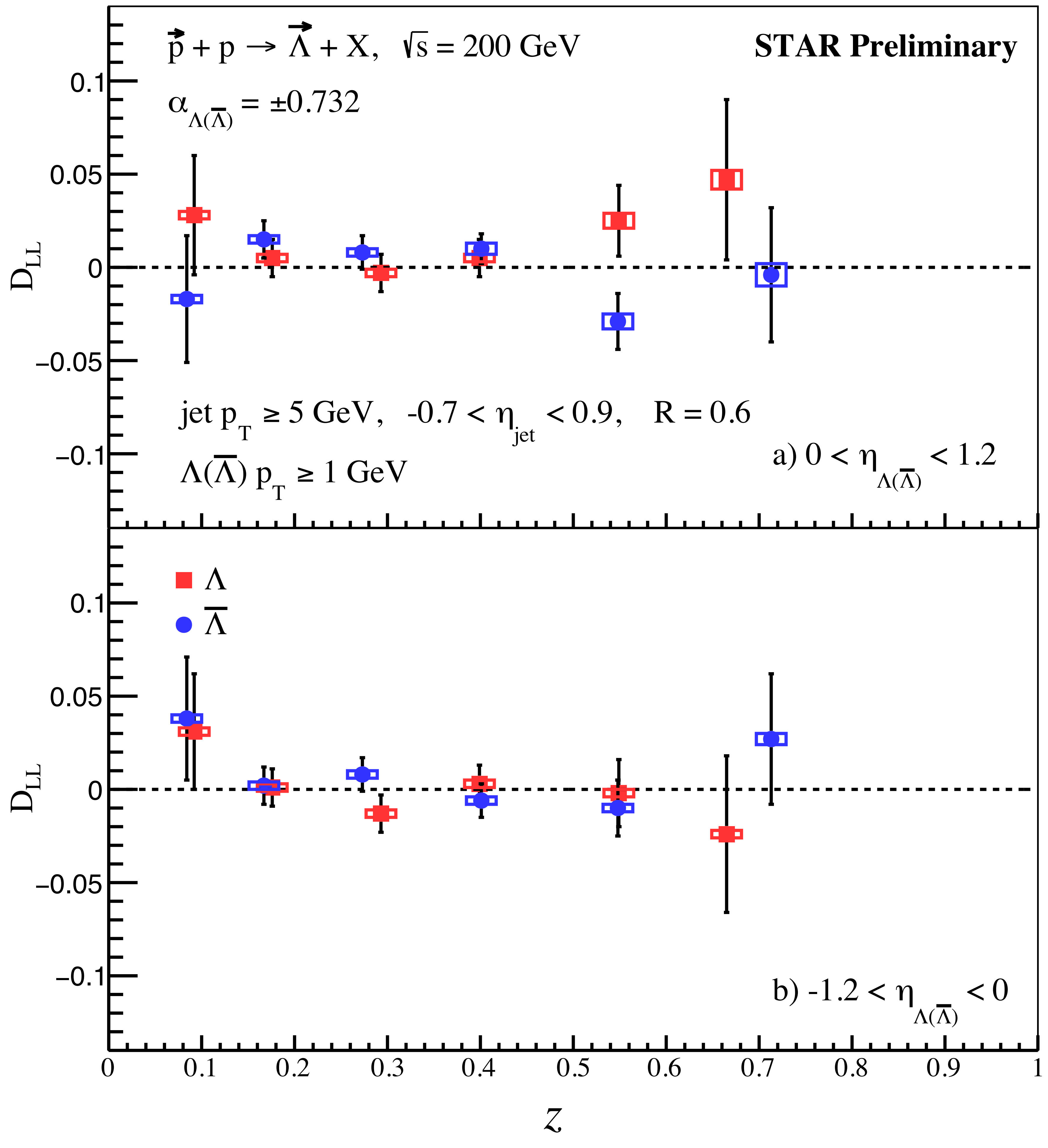
**data and MC comparison for detector $z$**



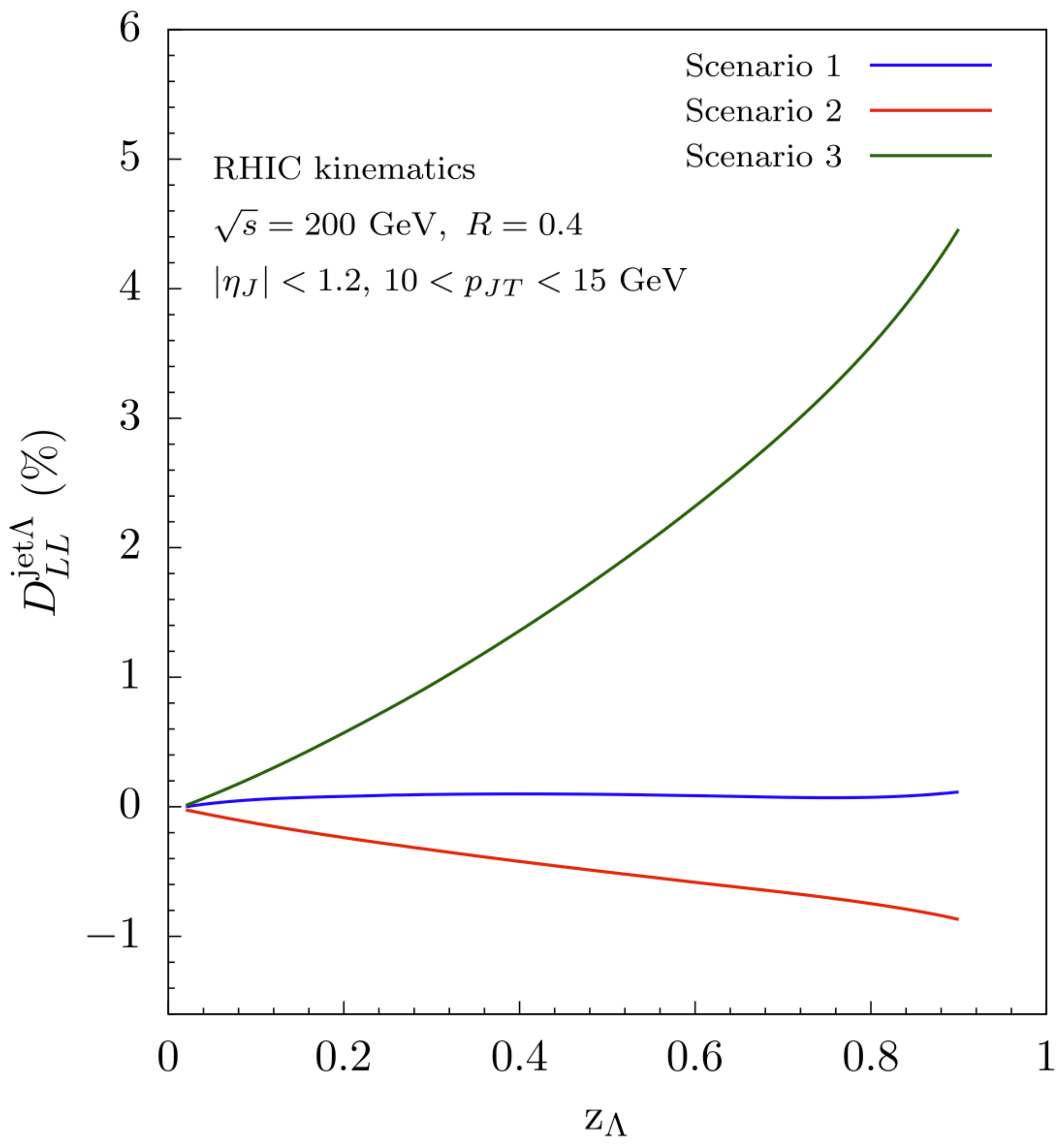



# $D_{LL}$ vs $z$ results

- $D_{LL}$ vs $z$ results with STAR 2015 data




- First measurements of $D_{LL}$ vs $z$ in polarized p+p collisions
- $D_{LL}$ results directly probe the polarized fragmentation functions.




Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B **809**, 135756 (2020).

# Summary

- The measurements of $D_{LL}$ in polarized p+p collisions can provide insights into polarized fragmentation functions and also the helicity distributions for strange quarks.
- Longitudinally polarized p+p data taken in 2015 at 200 $\mathrm{GeV}$ at STAR provide about two times the statistics as compared to previous $D_{LL}$ measurements.
- The new $D_{LL}$ vs $p_T$ results for $\Lambda(\bar{\Lambda})$ are consistent with previous measurements and also consistent with zero.
- The first measurement of $D_{LL}$ vs $z$ in p+p collision is reported, which can constrain the polarized fragmentation functions.

# Back up

# systematic uncertainties

- Decay parameter $\alpha$: 1.9% relative uncertainties
- Beam polarization: 3.0% relative uncertainties
- Relative luminosity: 0.00186 for all $p_T$ and z bins (dominated at low $p_T$ and z bins )
- Background fraction: small contribution
- The trigger bias: dominated at high $p_T$ and z bins