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

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Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science

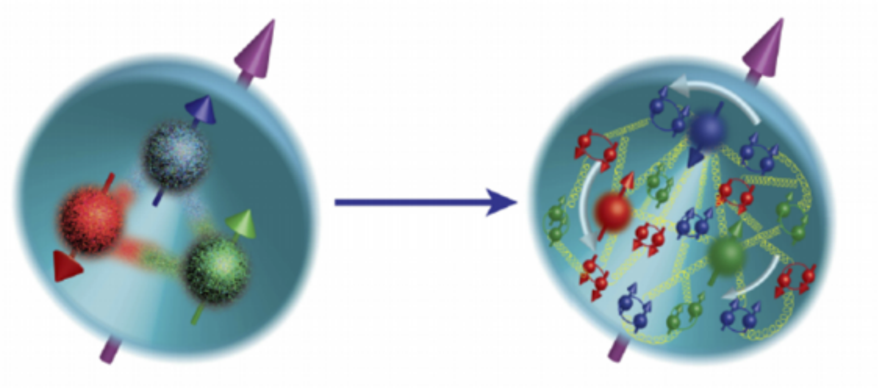
山东大学 SHANDONG UNIVERSITY

NSFC National Natural Science Foundation of China

Outline

- Motivation.
- Λ and $\bar{\Lambda}$ reconstruction.
- Longitudinal spin transfer D_{LL} vs hyperon p_T and fragmentation z.
- Summary.

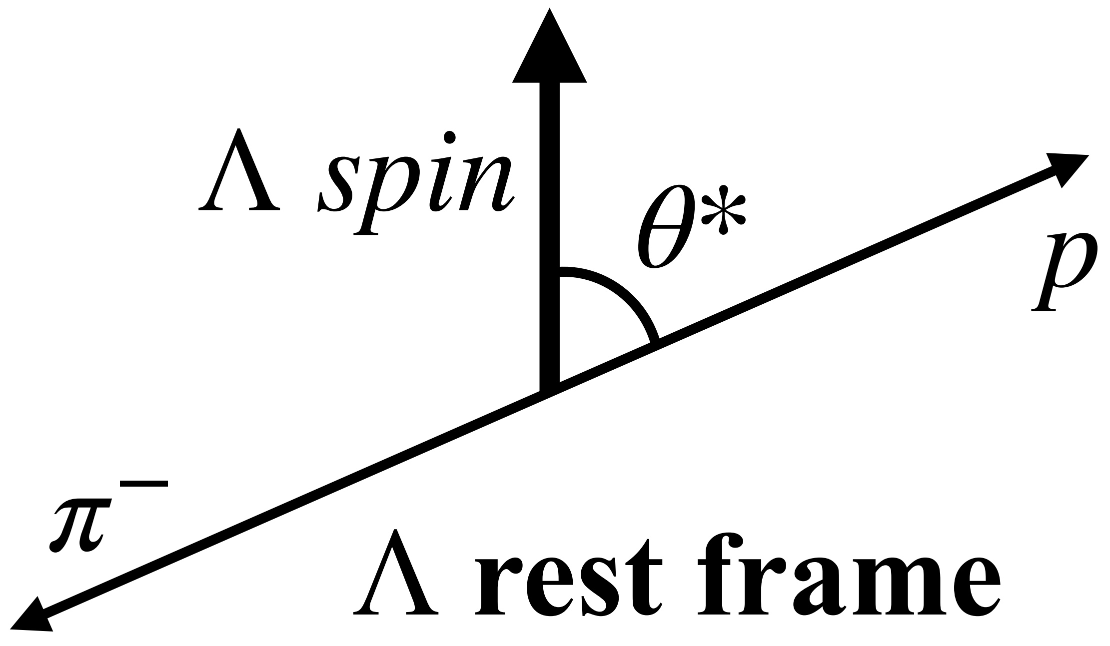
Motivation

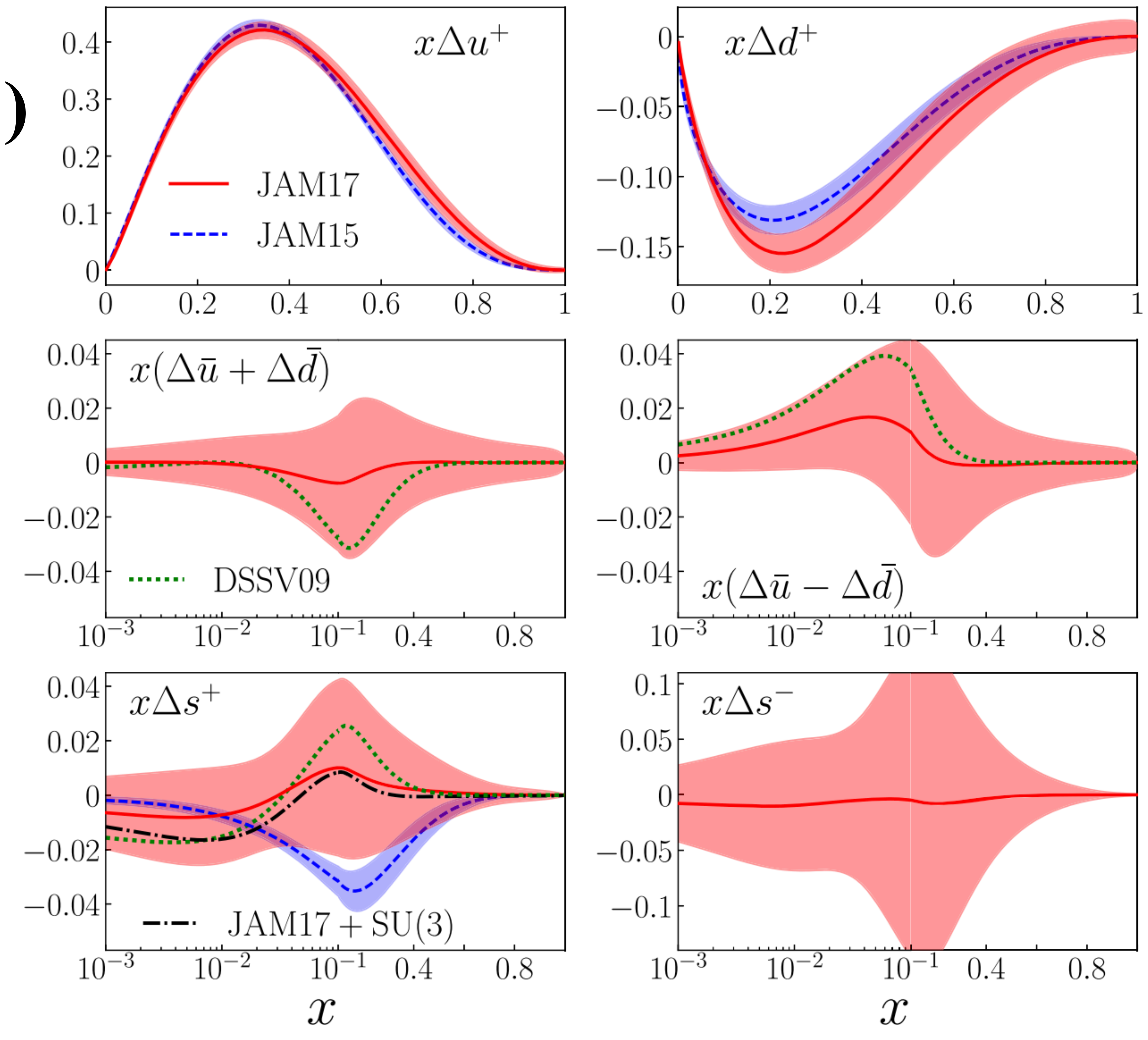


- **Nucleon spin structure (from DIS and p+p)**
  - Spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}.$
  - Valence quark helicity distributions are well known.
  - Poor knowledge on strange quark.
- **Why choose Λ ?**
  - s quark is expected to carry a large fraction of Λ spin.
  - The weak decay of Λ enables experimental measurability of its polarization.

$dN \sim (1 + \alpha P_{\Lambda}\cos\theta^{*})d\cos\theta^{*}$

α : weak decay parameter of Λ
P_{Λ}: the polarization of Λ





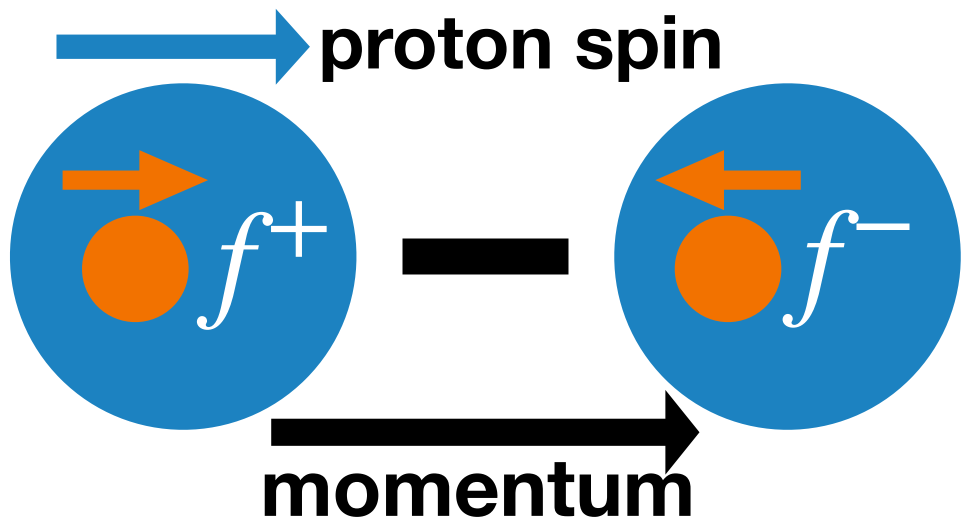
J. J. Ethier, N. Sato, and W. Melnitchouk, Phys. Rev. Lett. **119**, 132001 (2017).

Longitudinal spin transfer D_{LL} in p+p collisions

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

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

$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \underbrace{\Delta f_a(x_a)}_{\text{helicity distribution}} f_b(x_b) \underbrace{\Delta\sigma(ab \to cd)}_{\text{pQCD calculable}} \underbrace{\Delta D^{\Lambda}(z)}_{\text{polarized FF}}$$

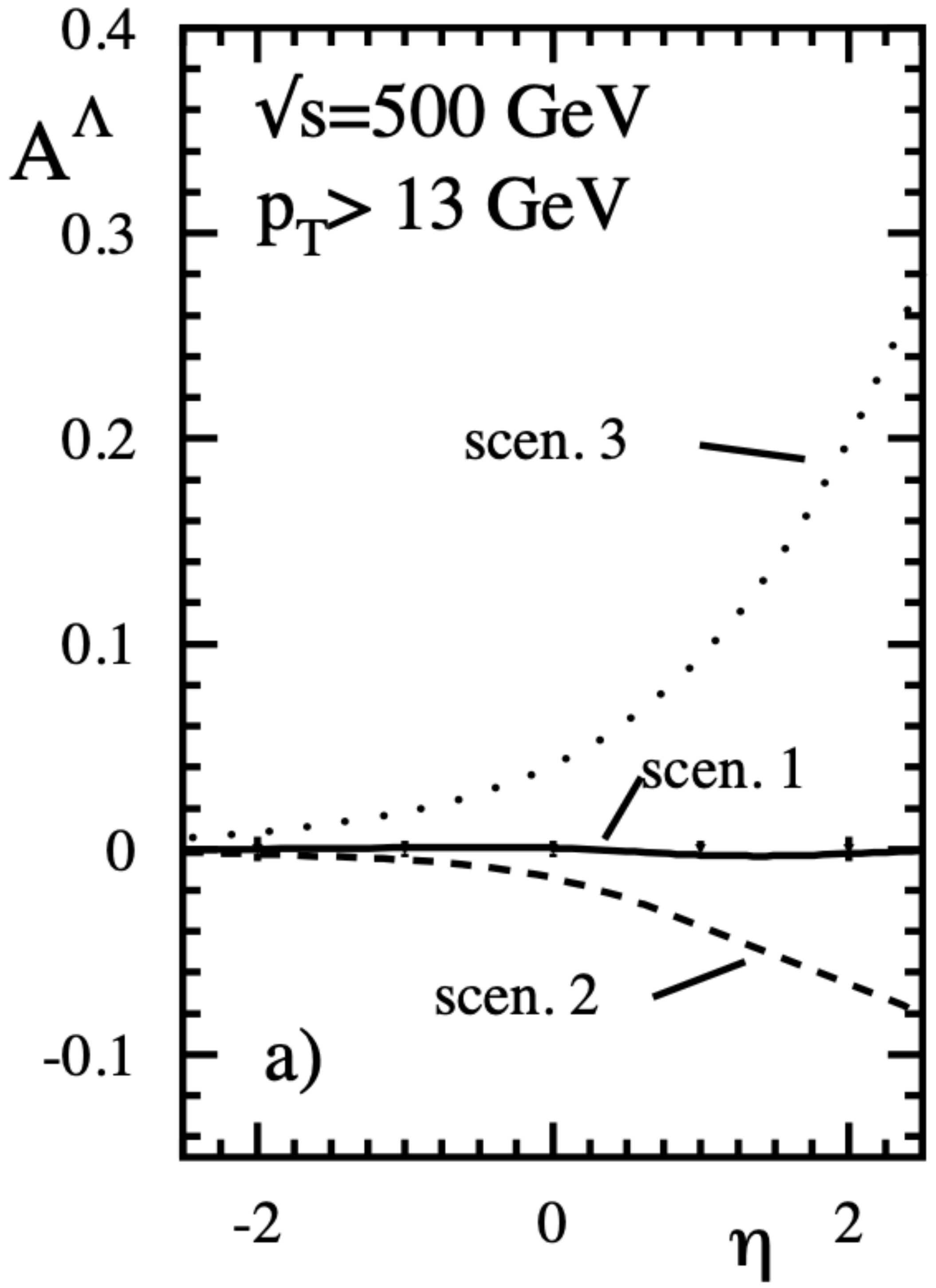


$$\Delta f(x) = f^+(x) - f^-(x)$$

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

Prediction of D_{LL} at RHIC energy

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



scenario 1: only s quark can contribute to Λ polarization.

scenario 2: u and d quarks have the same contribution to polarized Λ but with an opposite sign from s quark.

scenario 3: u, d and s quarks have the same contribution to the polarized Λ.

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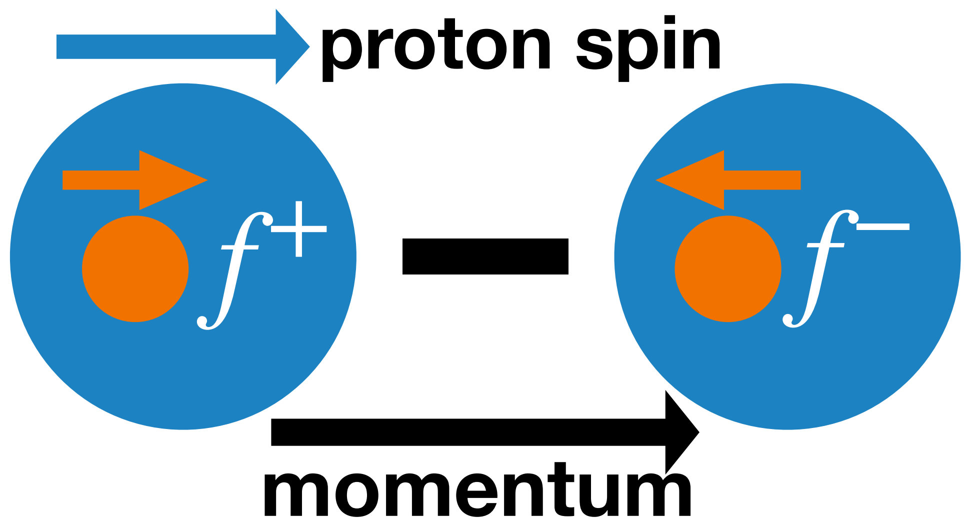

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✦ D_{LL} vs z can provide direct probe to the polarized fragmentation function

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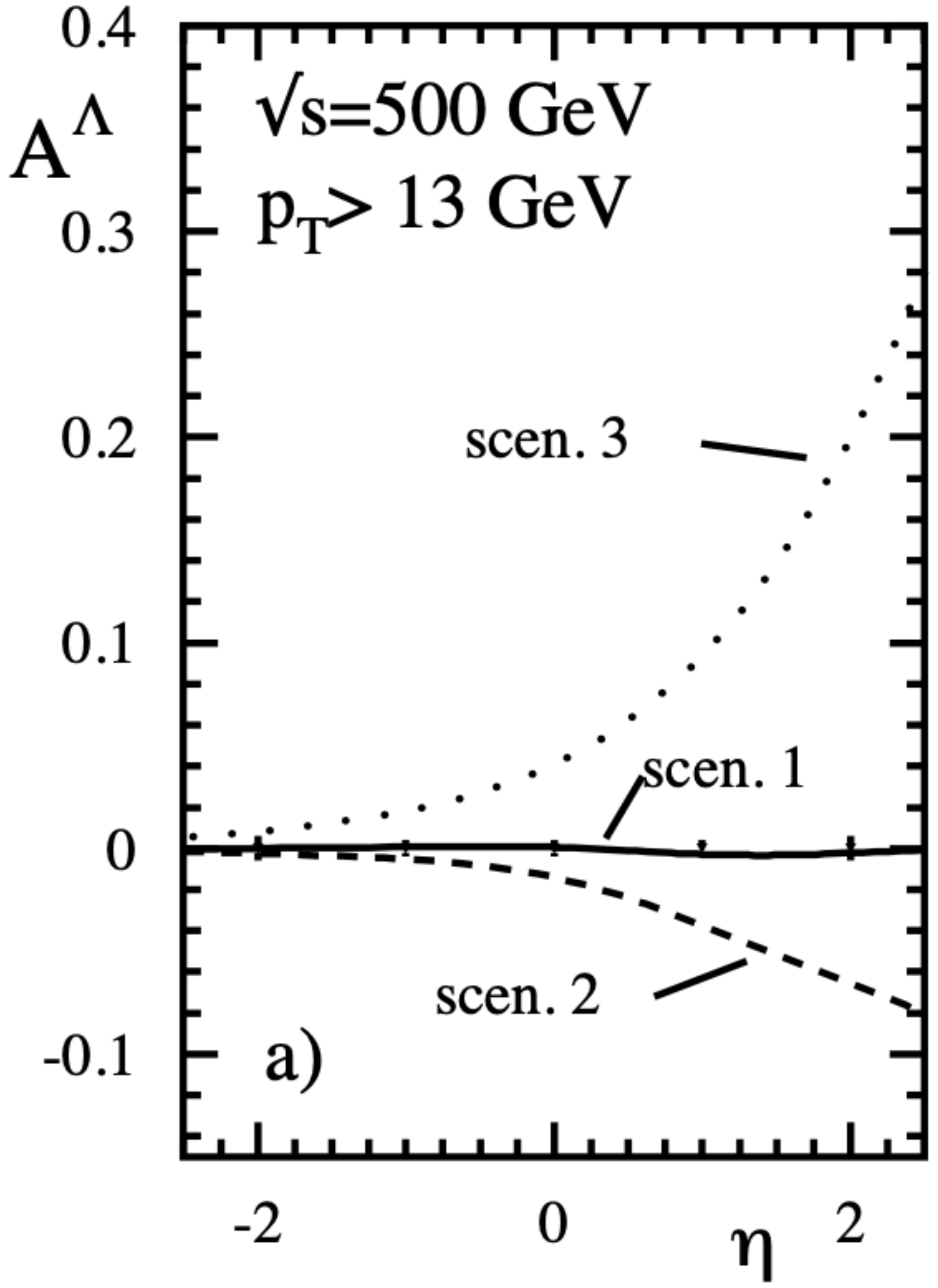
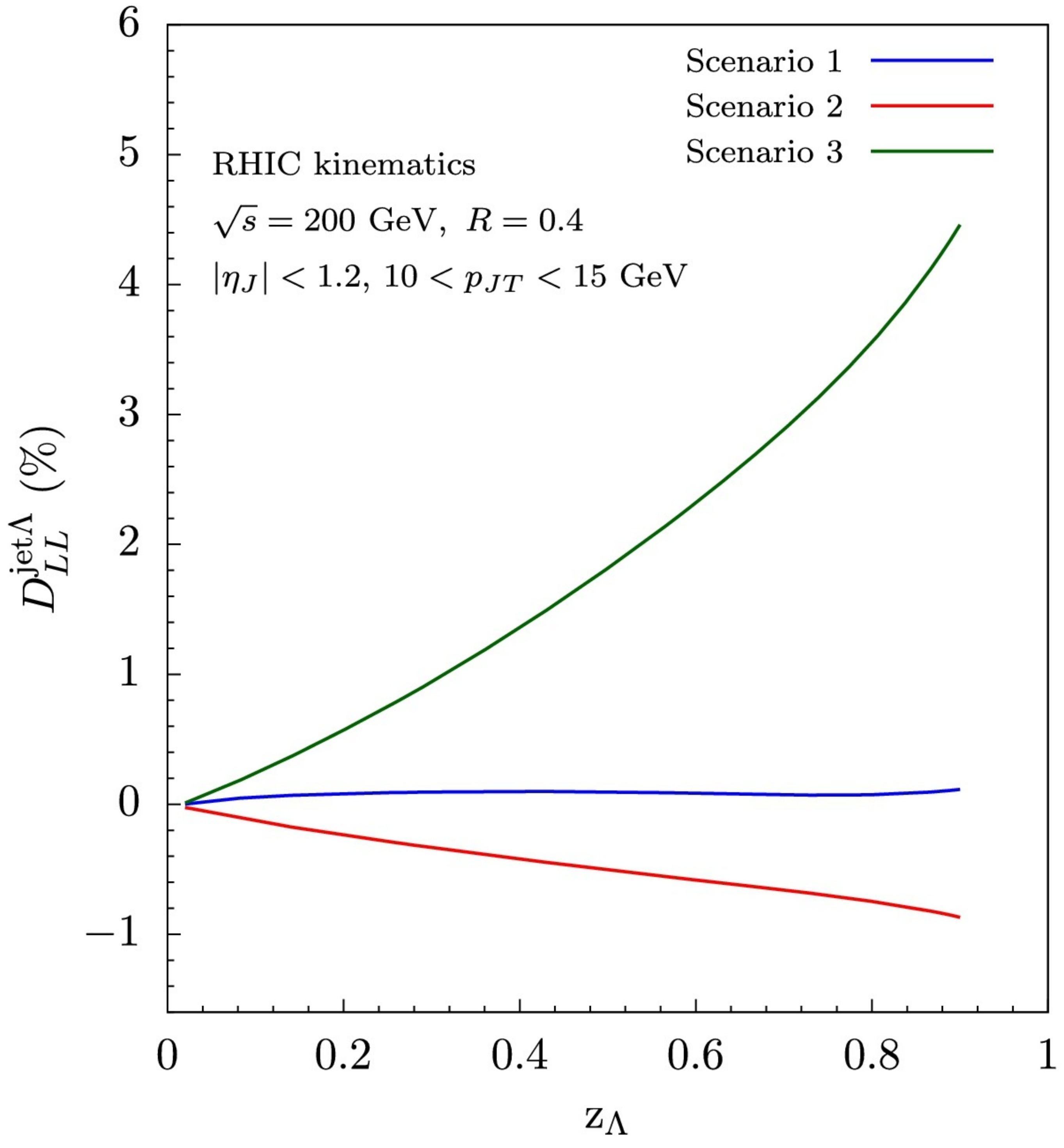


Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B **809**, 135756 (2020).



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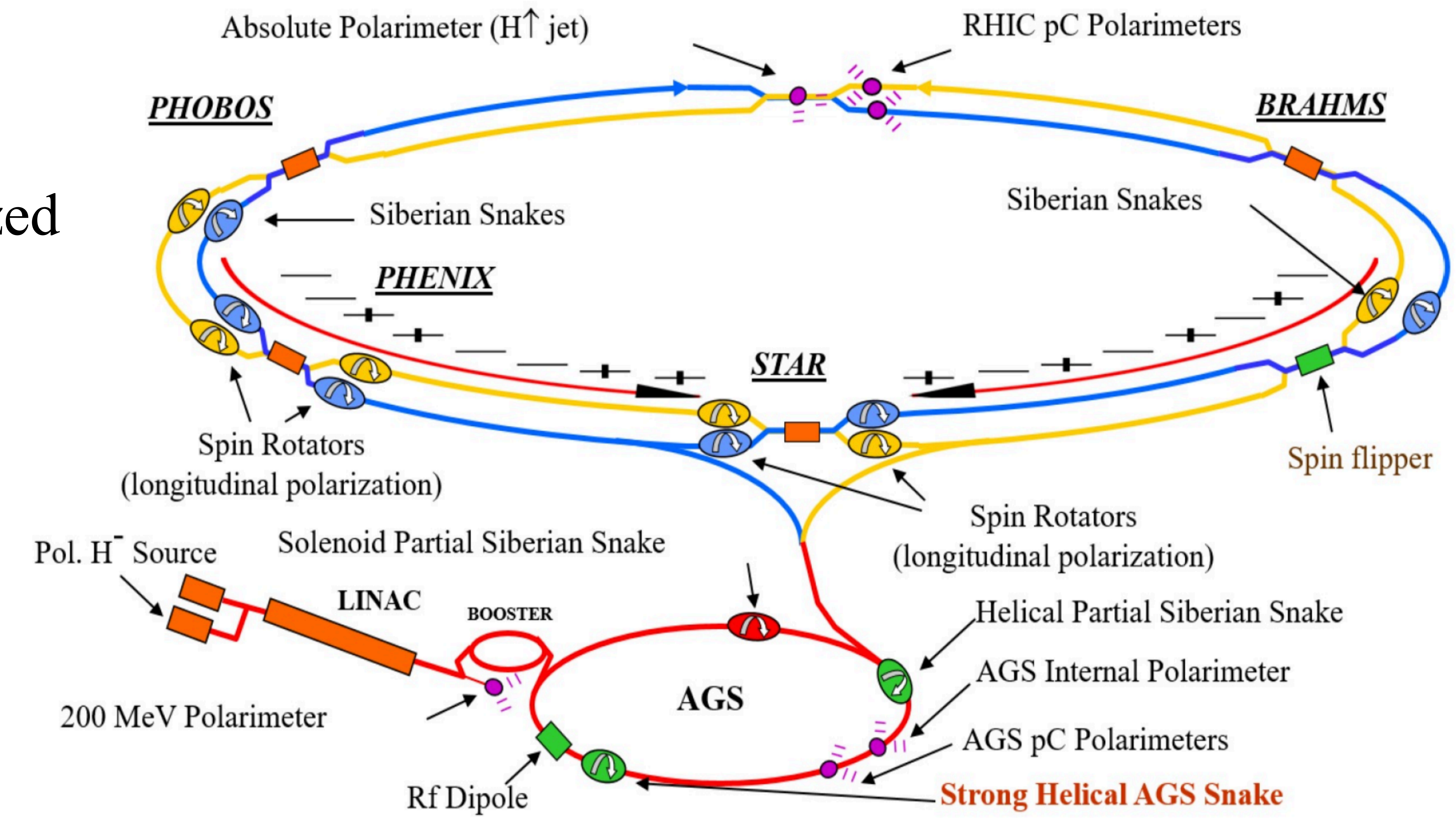
Relativistic Heavy Ion Collider

- 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.

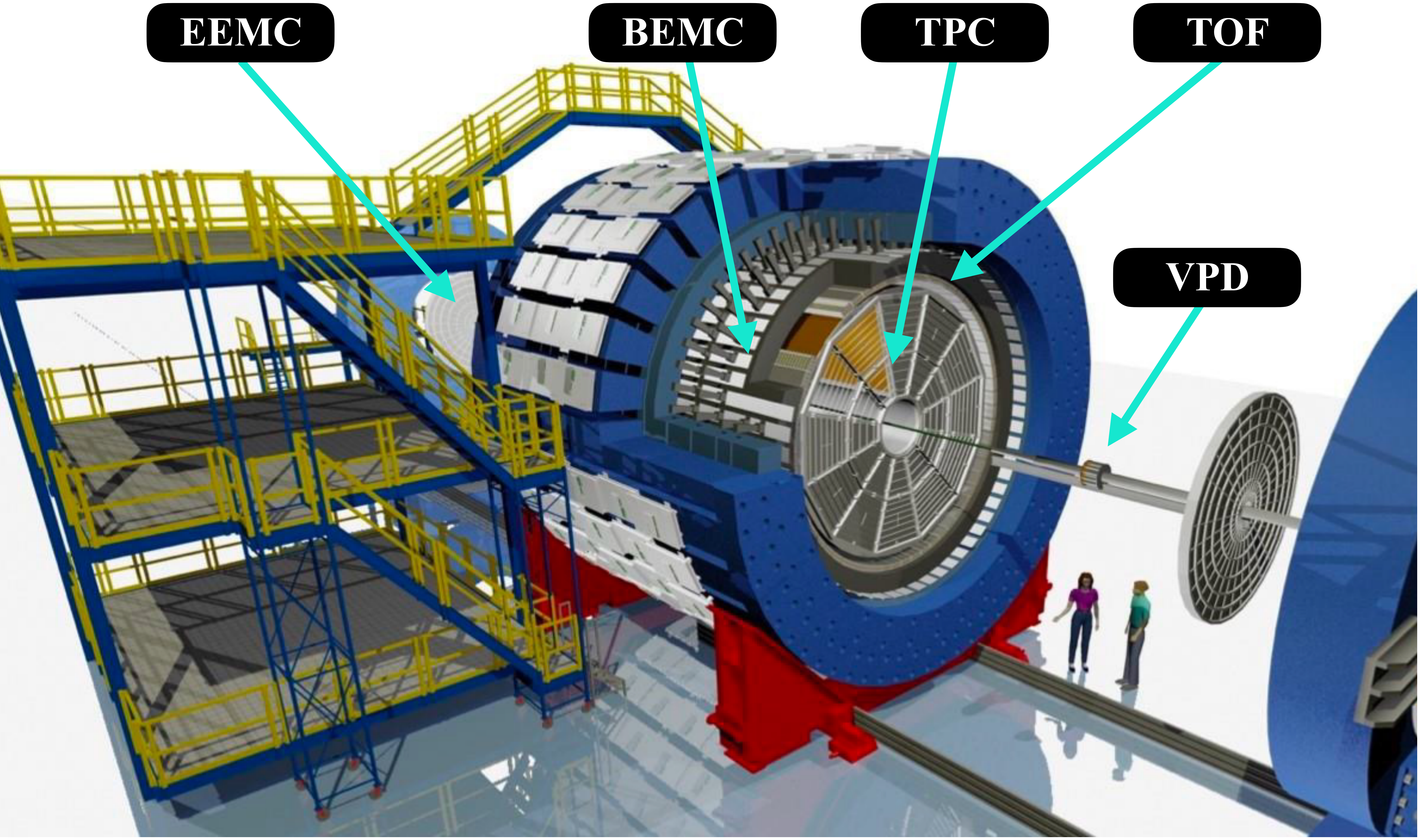


Dataset with longitudinally polarized p+p collision

Year	$\sqrt{s}$ (GeV)	$L_{int}\ (pb^{-1})$	P_{beam}
2009	200	19	57% / 57%
2015	200	52	52% / 56%
2012	510	82	50% / 53%
2013	510	300	51% / 52%

} used in this analysis

The Solenoidal Tracker At RHIC



✦ Time Projection Chamber (TPC)

- $|\eta| < 1.3$ and $0 \leq \phi \leq 2\pi$.
- **Tracking** and **particle identification**.

✦ Time of Flight detector (TOF)

- $|\eta| < 1.0$ and $0 \leq \phi \leq 2\pi$.
- 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, π^0, jet …
- Serve as the trigger detectors.

✦ Vertex Position Detector (VPD)

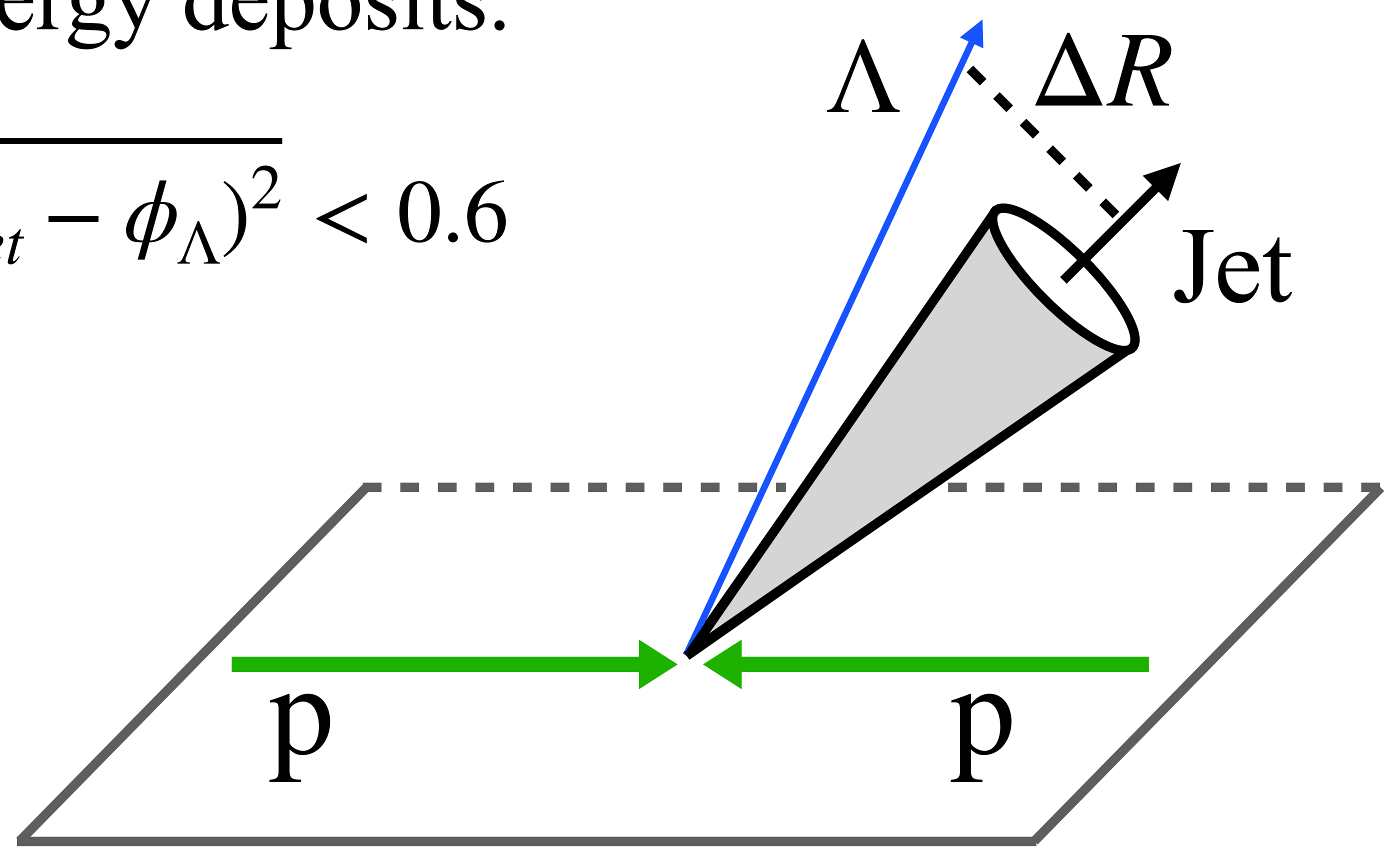
- $4.24 < |\eta| < 5.1$.
- Determine the primary vertex position.
- Monitor the relative luminosity.

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

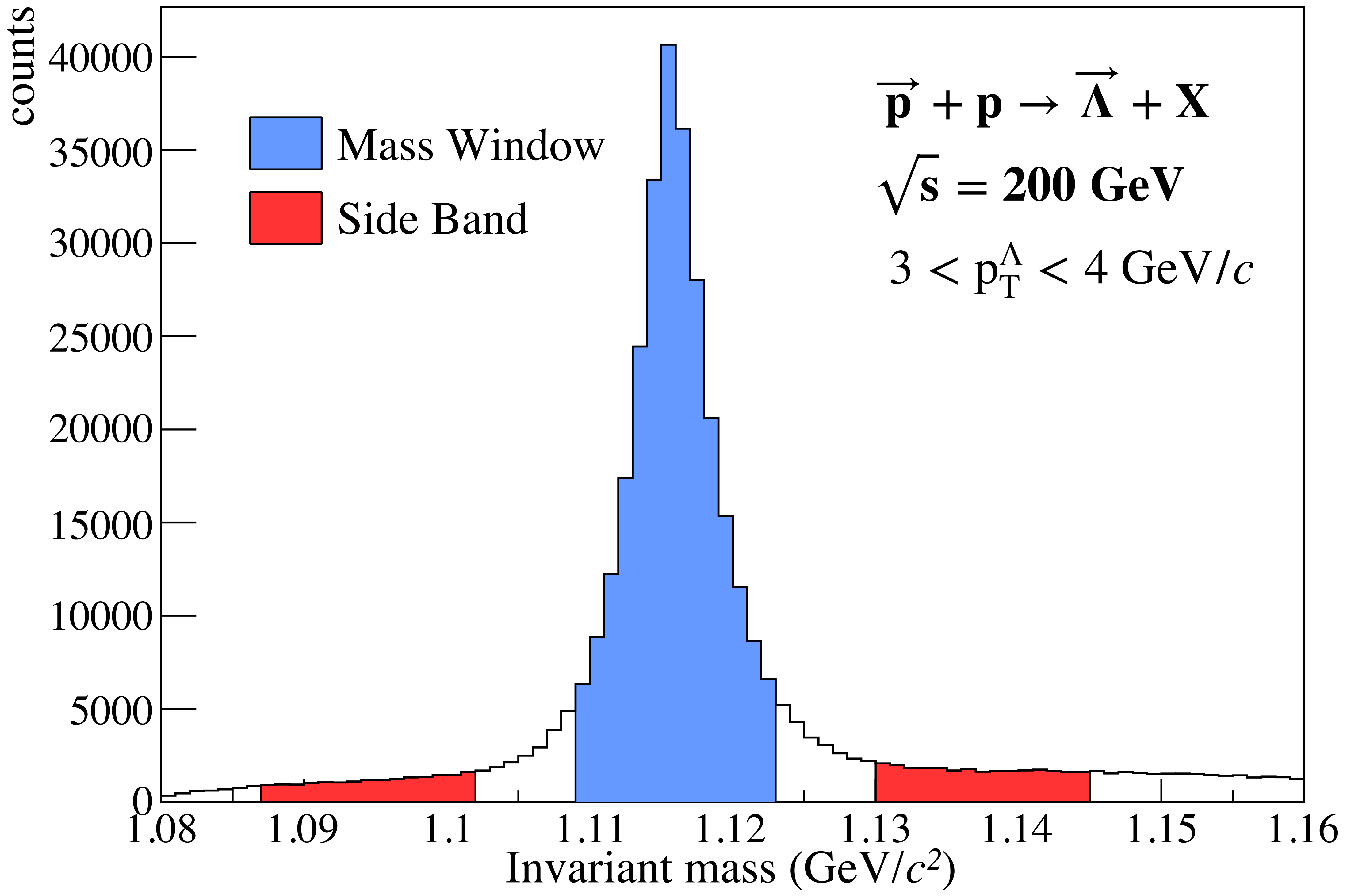
- Select hard scattering events using a jet trigger based on the energy deposits in the EMC

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

- **Require hyperons to be associated with a jet**
  - Jets are reconstructed with anti-k_T algorithm ($R = 0.6$) using TPC tracks and EMC energy deposits.
  - $\Delta R = \sqrt{(\eta_{jet} - \eta_\Lambda)^2 + (\phi_{jet} - \phi_\Lambda)^2} < 0.6$



Invariant mass of Λ



background correction → $D_{LL} = \dfrac{D_{LL}^{raw} - rD_{LL}^{bkg}}{1 - r}$

r : background fraction under mass window

Measurements of D_{LL}

✦ **D_{LL} is measured with the asymmetry of $\Lambda(\bar{\Lambda})$ yields as a function of $\cos\theta^*$**

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

Acceptance canceled

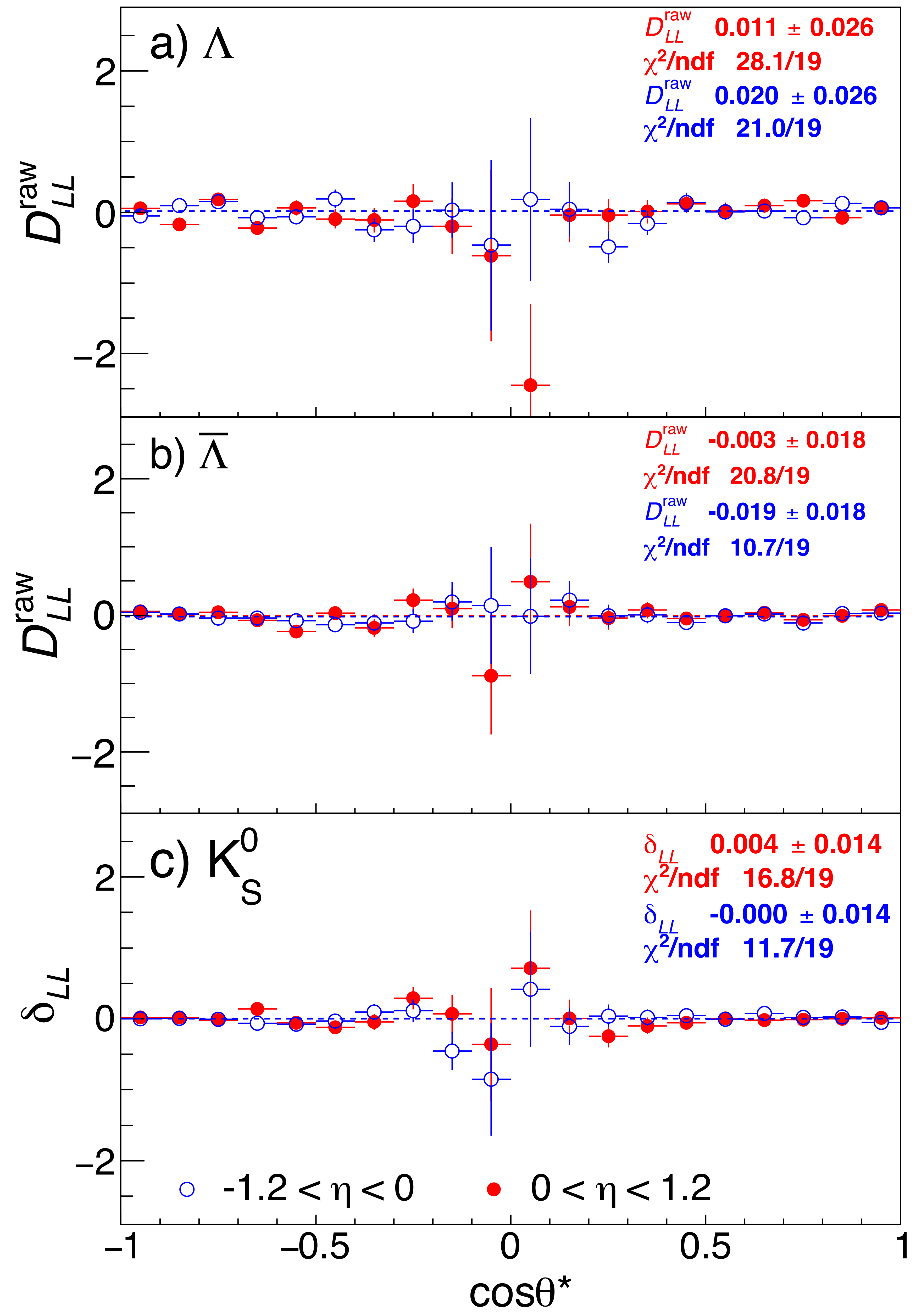
firstly used in STAR, *Phys. Rev. D* 80, 111102 (2009).

- $N^{+(-)}$: the Λ yields with positive (negative) beam helicity.
- R_L: relative luminosity measured by the VPD.
- α: decay parameter of Λ.
- P_{beam}: the beam polarization.

✦ **δ_{LL} of K_S^0 as a null check**

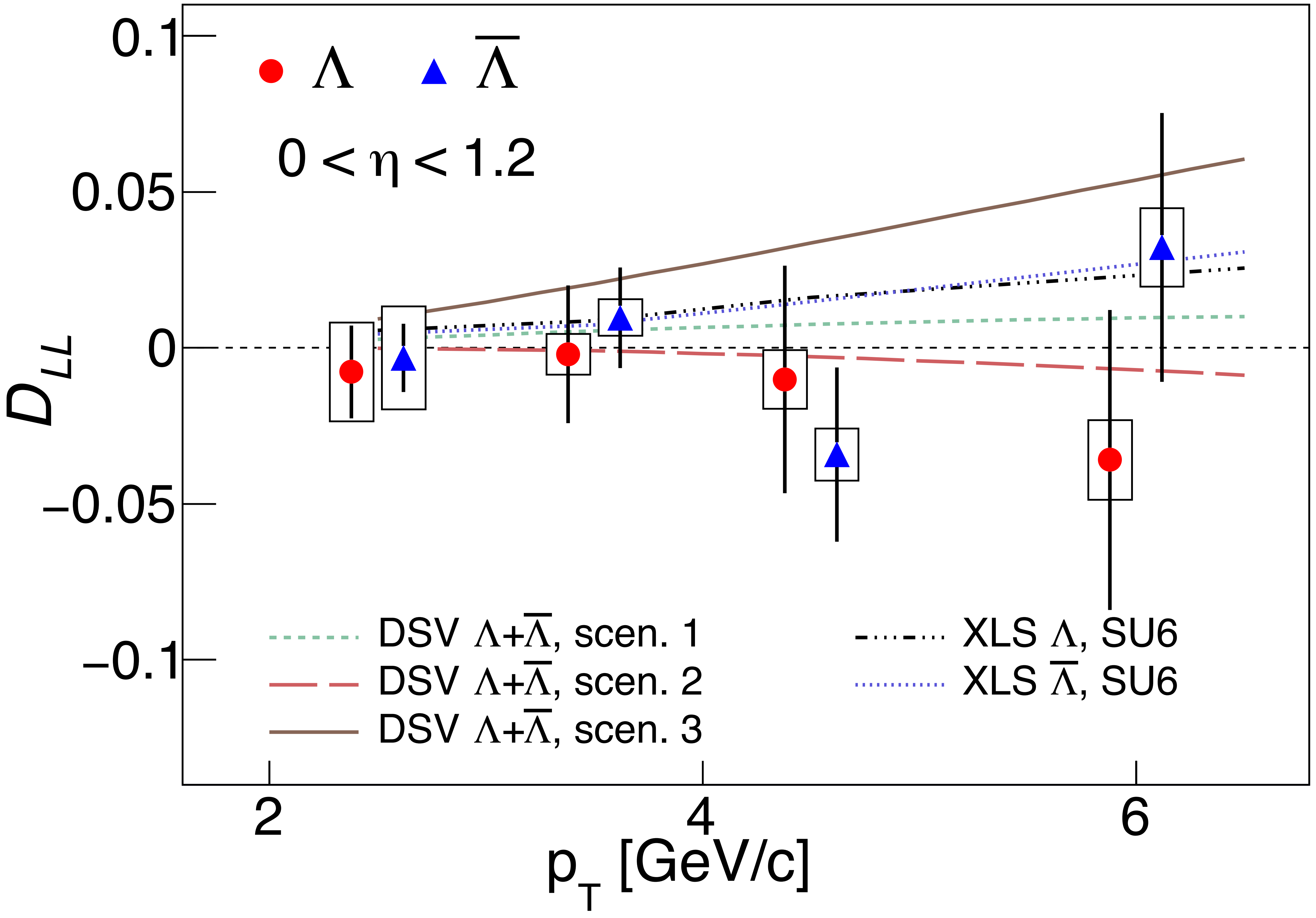
- Same method as D_{LL}.
- Using an artificial decay parameter $\alpha = 1$.
- Consistent with 0 as expected.

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



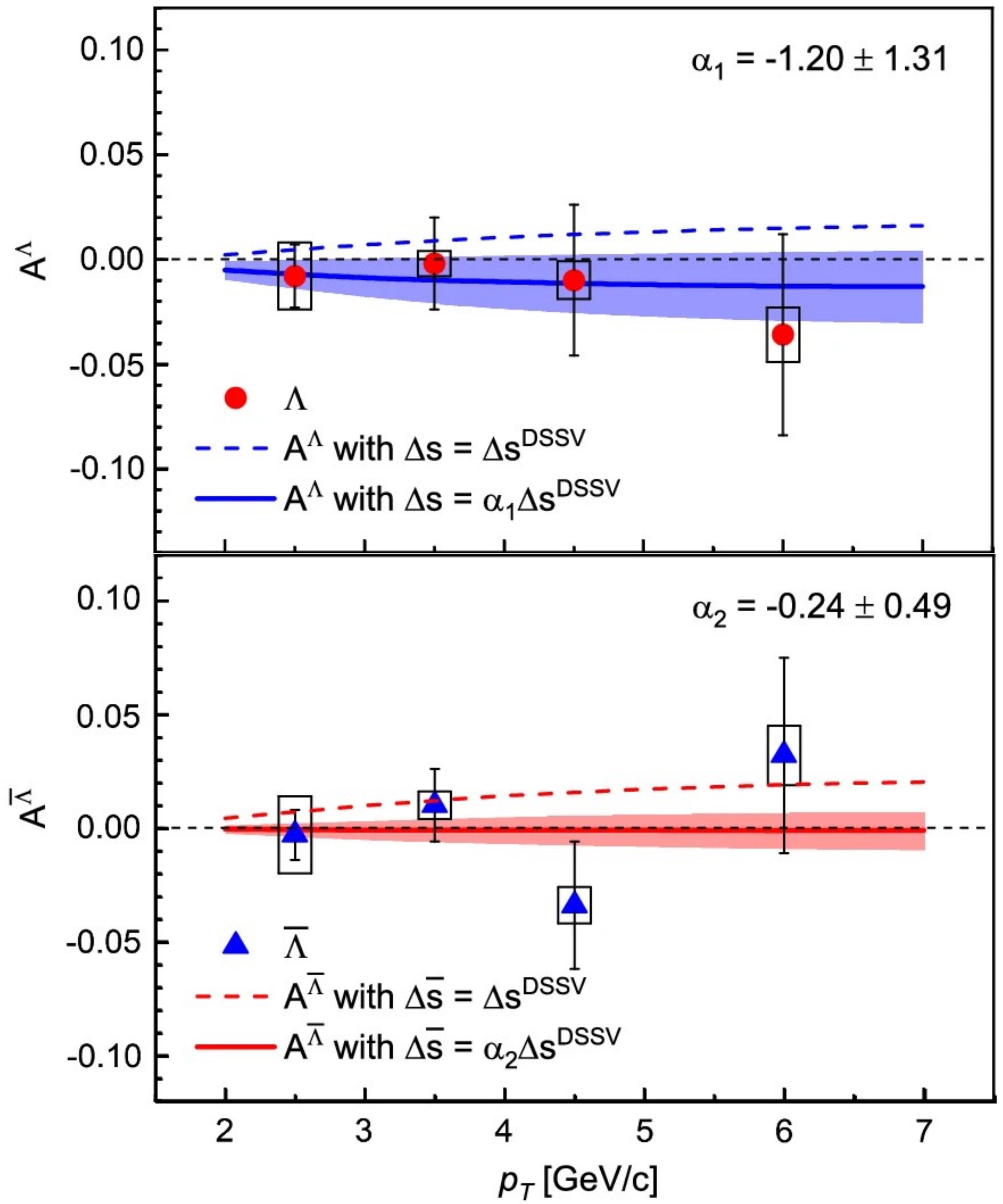
Previous D_{LL} vs p_T results with STAR 2009 data

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



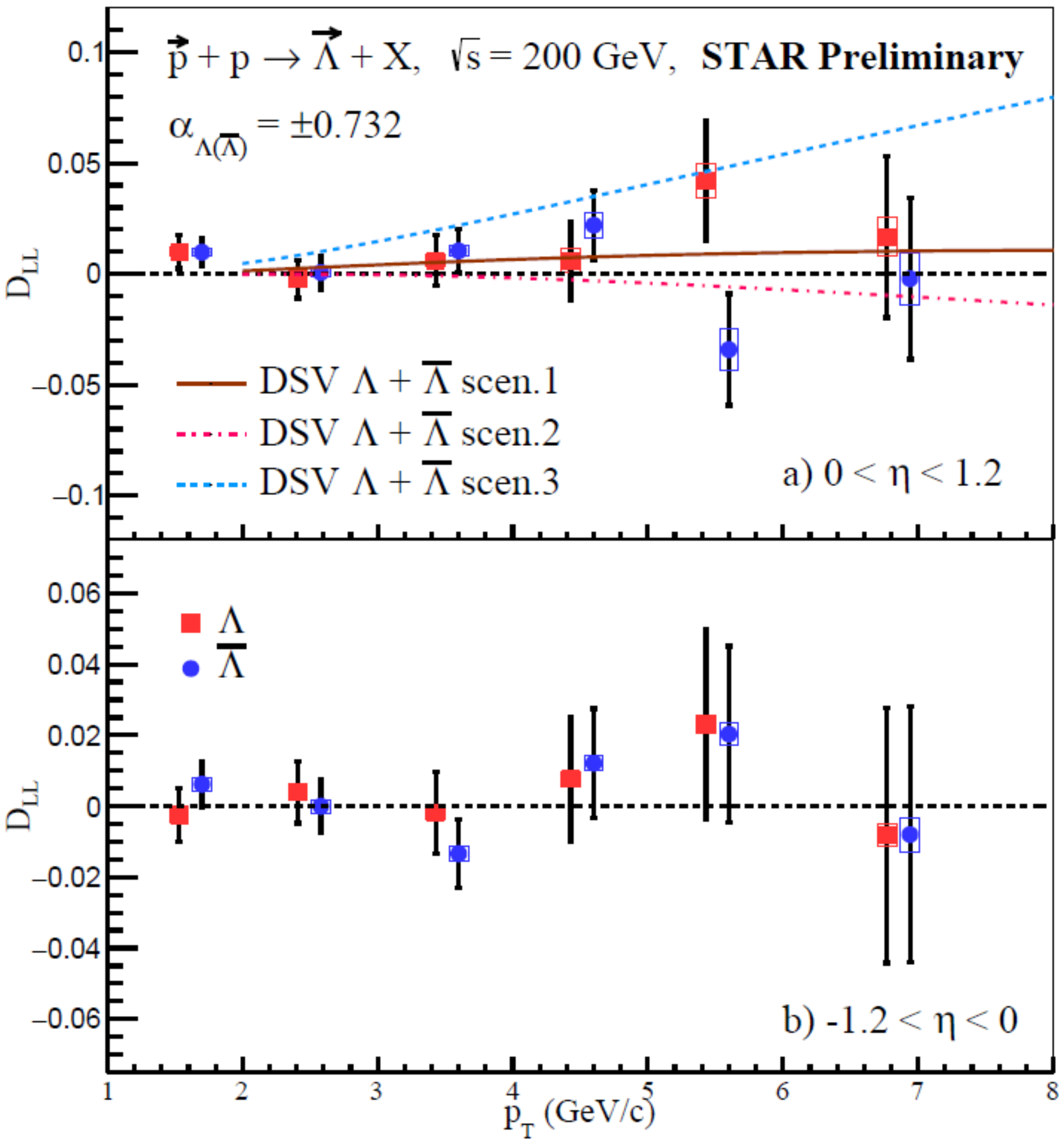
- Statistically limited.
- In agreement with models.

✦ 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).

New 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 Λ and $\bar{\Lambda}$.
- ✦ Data are in agreement with various scenarios within uncertainties.
- ✦ Most precise measurements to date.

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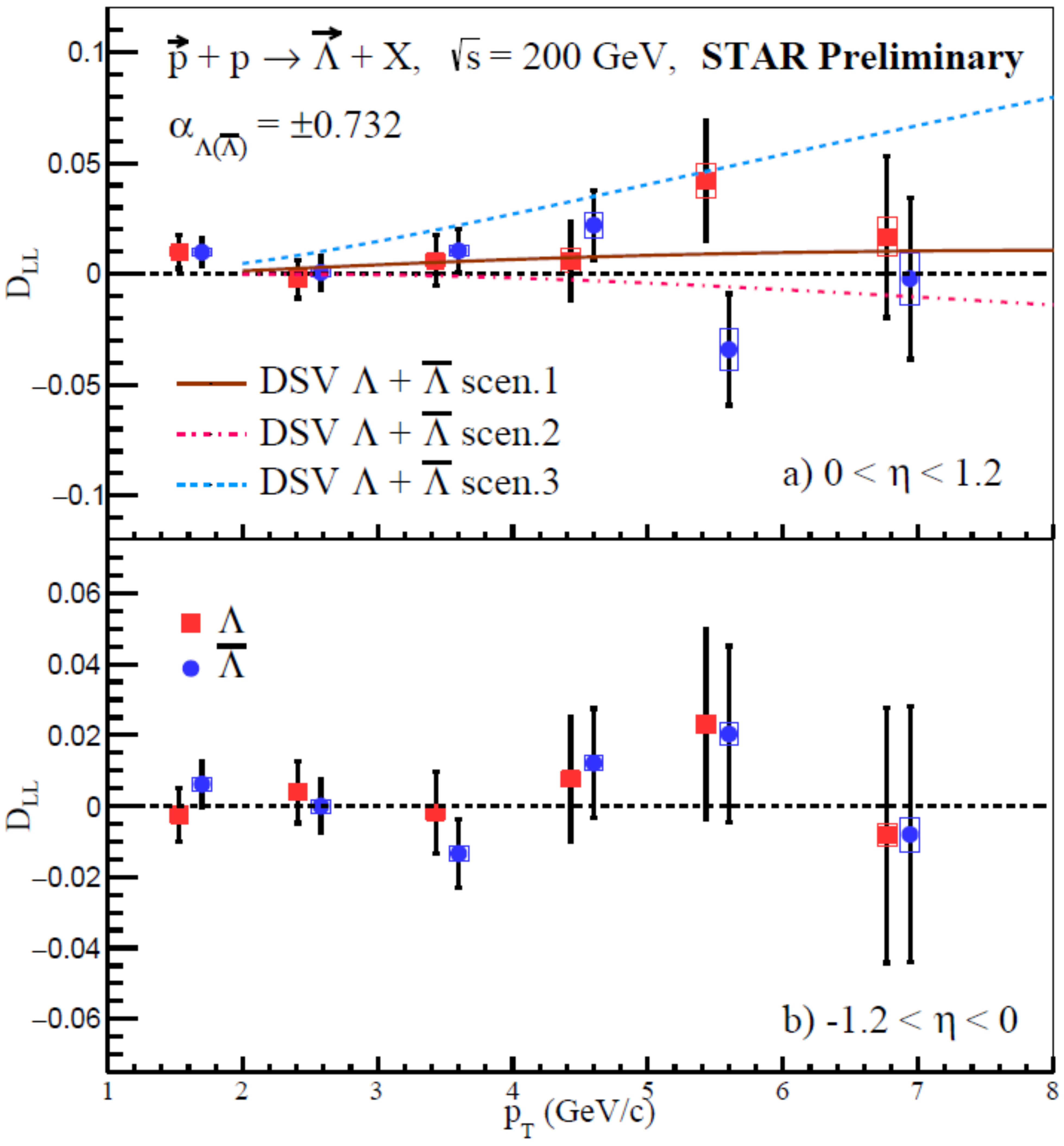

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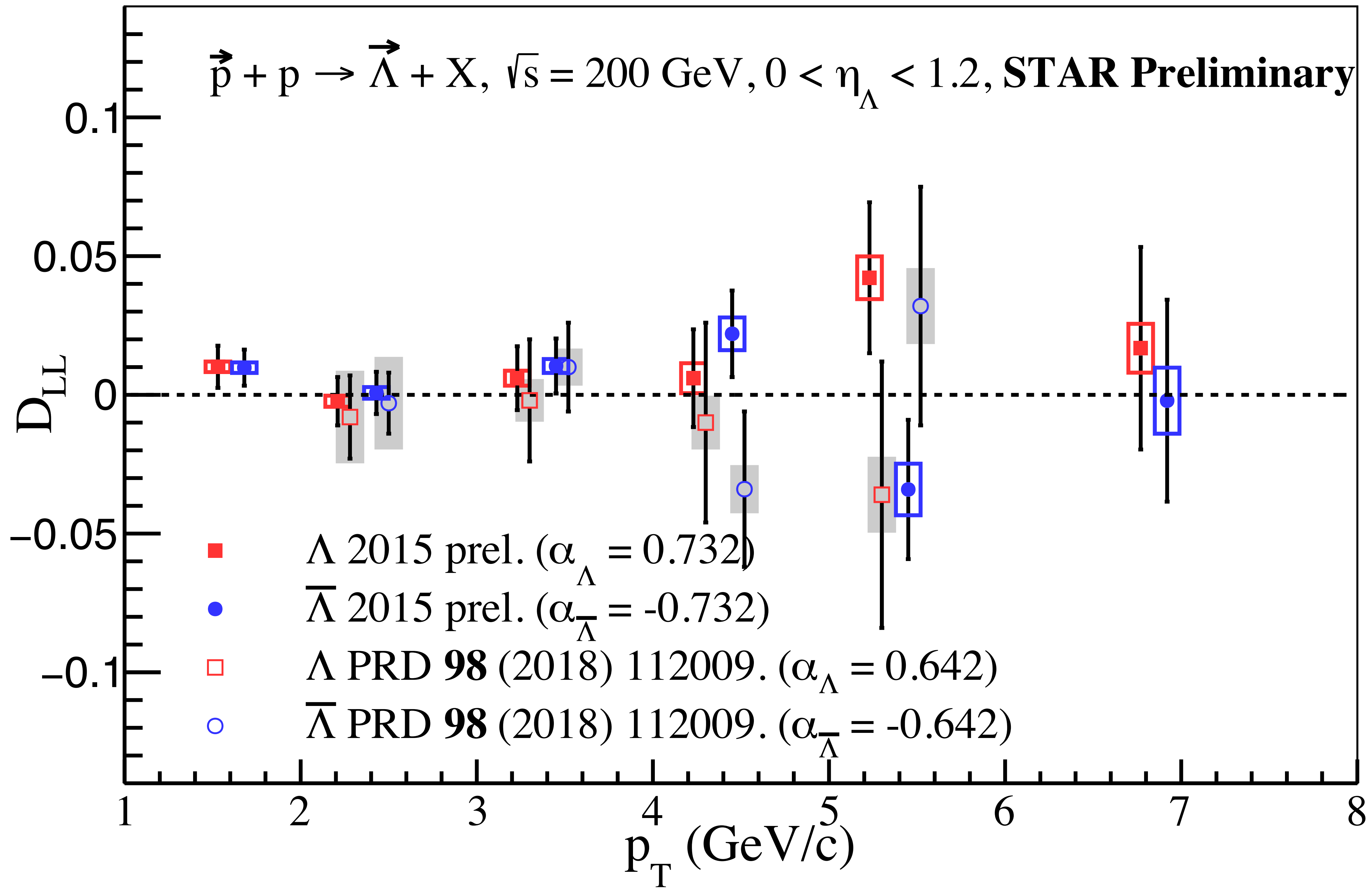
2015 vs 2009



Measurement of D_{LL} vs z

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

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

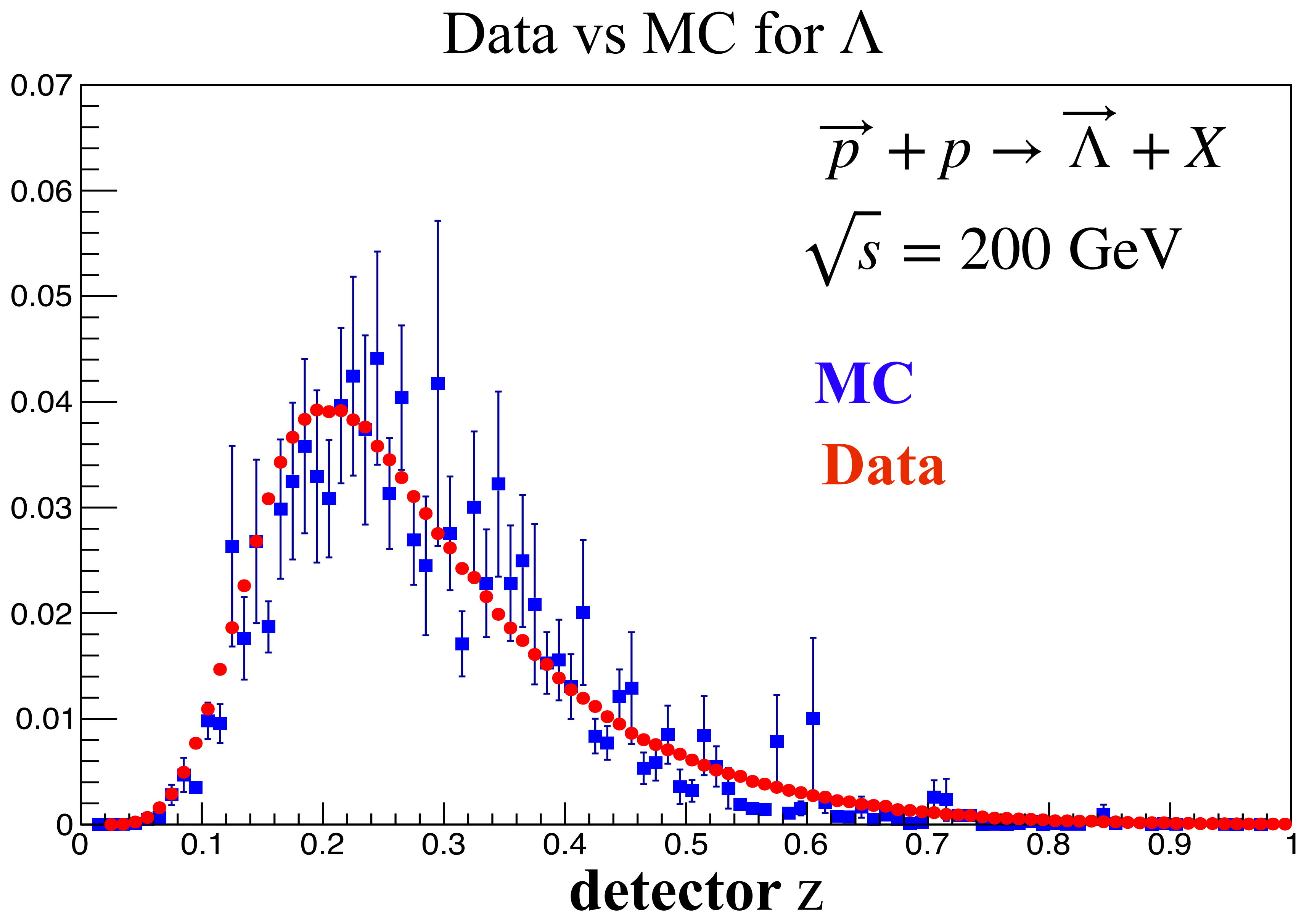
✦ **Correct the detector z to particle z**

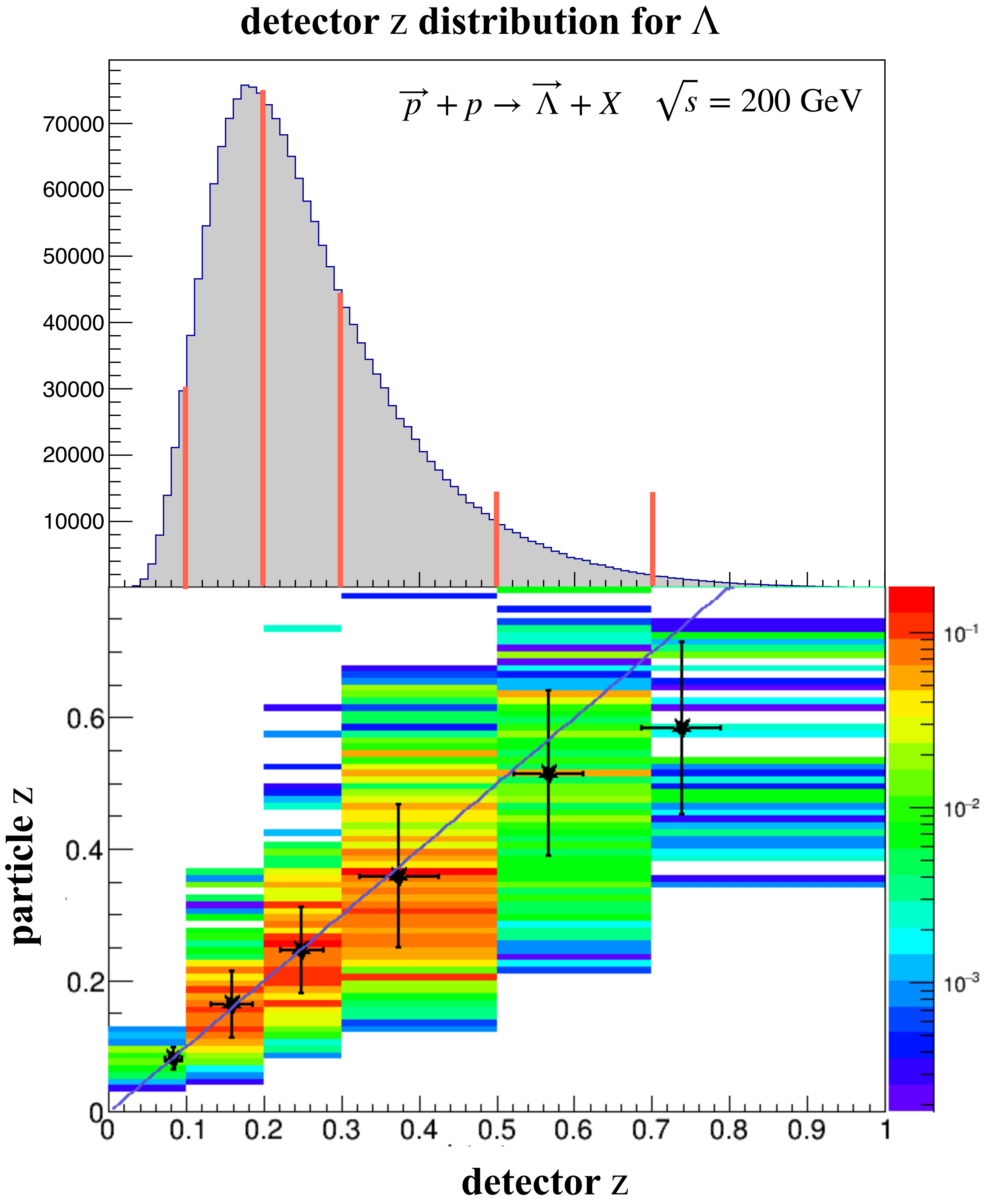
- In STAR, jets are reconstructed using TPC tracks and EMC energy deposits. → **detector jet**
- Theoretical studies use all the particles for the jet. → **particle jet**
- Need to correct the "detector z" (based on detector jet) to "particle z" (based on particle jet) in our measurement.

Correction of z

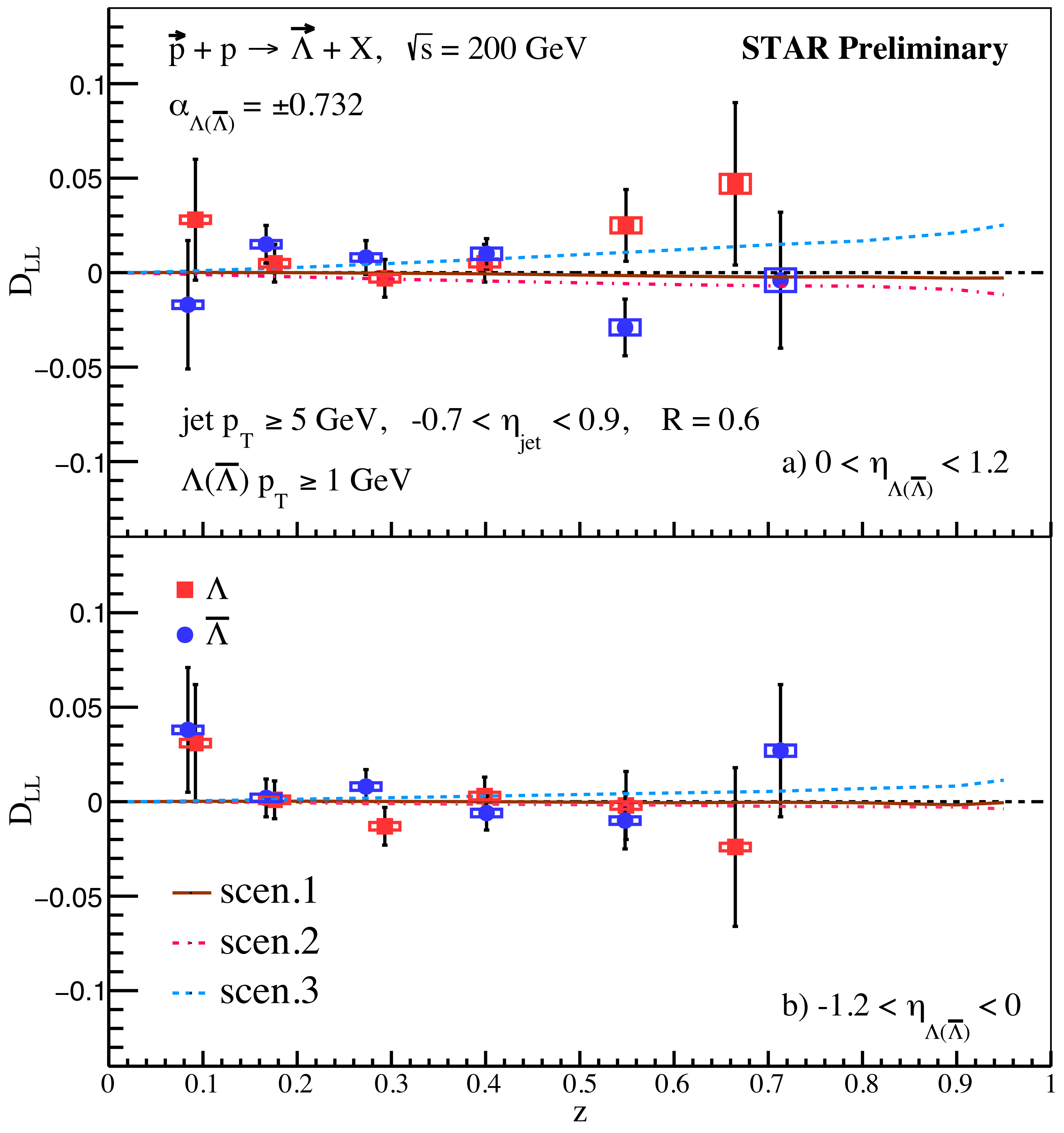
1. Obtain the detector z and calculate the D_{LL} in each detector z bin

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.





D_{LL} vs z results with STAR 2015 data



Theory curves: Z.-B. Kang, K. Lee, and F. Zhao, Phys. Lett. B **809**, 135756 (2020).

- First measurements of D_{LL} vs z in polarized p+p collisions.
- D_{LL} results directly probe the polarized fragmentation functions.
- The uncertainties are larger than the model variations of polarized fragmentation functions.

Summary

- The measurements of D_{LL} in polarized p+p collisions can provide insights into polarized FFs and the helicity distributions for strange quarks.

- Longitudinally polarized p+p data taken in 2015 at 200 GeV at STAR provide about two times the statistics as compared to previous D_{LL} measurements using 2009 data.

- The new D_{LL} vs p_T results for $\Lambda(\bar{\Lambda})$ are consistent with previous measurements and also consistent with model calculations.

- The first measurement of D_{LL} vs z in p+p collision is reported, which can provide constraints to the polarized fragmentation functions.

- Larger data samples of p+p collisions at 510 GeV taken in 2012 and 2013 will improve the precision of D_{LL} measurement significantly.

Back up

systematic uncertainties

- Decay parameter α: 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