Supported in part by

Global polarization of Λ hyperons in RHIC Beam Energy Scan II from STAR

Kosuke Okubo for the STAR collaboration
University of Tsukuba
JPS meeting
15 , Mar, 2022

Introduction

✦In non-central collisions…

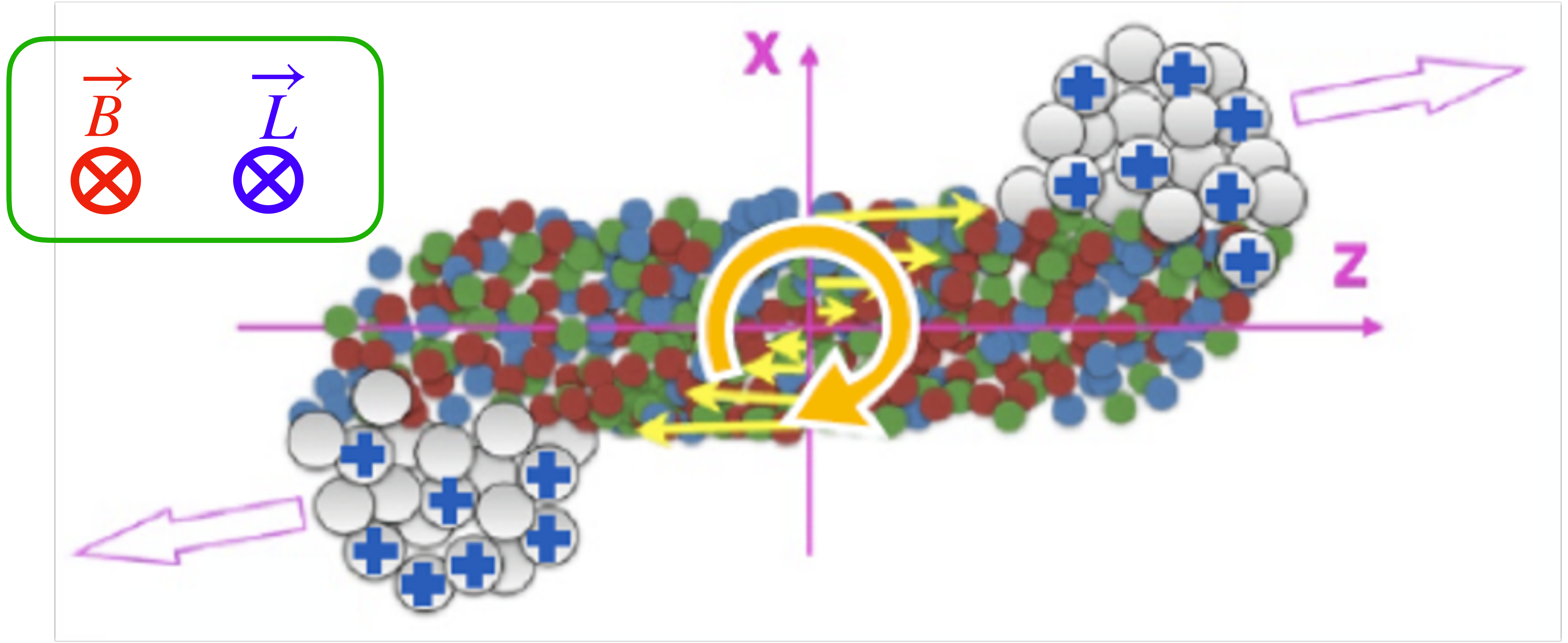
- The created matter should exhibit strong vorticity.

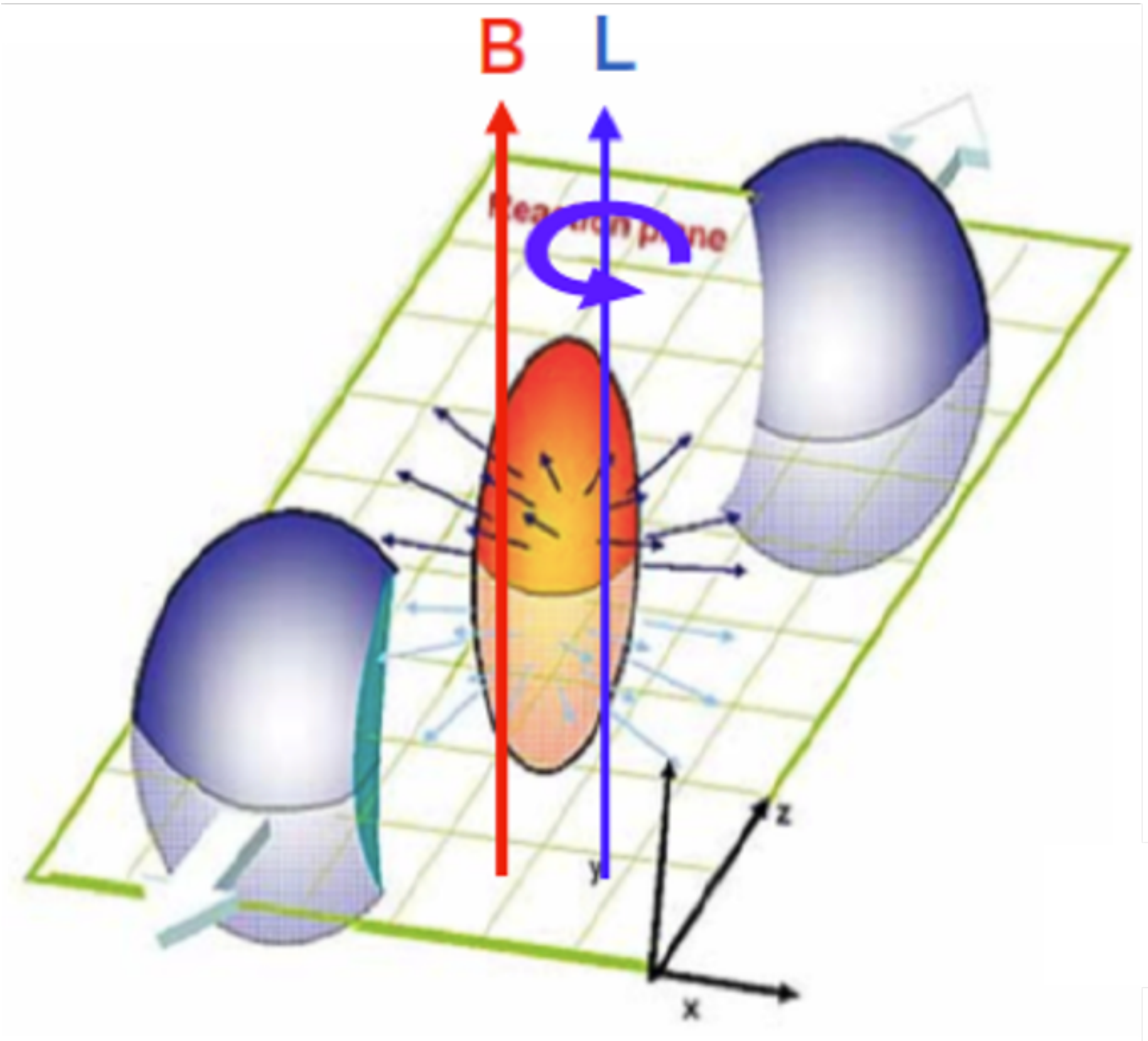
  -Z.-T.Liang and X.-N. Wang, PRL94, 102301

- The strong magnetic field would appear in the initial state.

  -D. Kharzeev, L. McLerran, and H. Warring, Nucl.Phys.A803, 227 (2008)

  -McLerran and Skokov, Nucl. Phys. A929, 184 (2014)

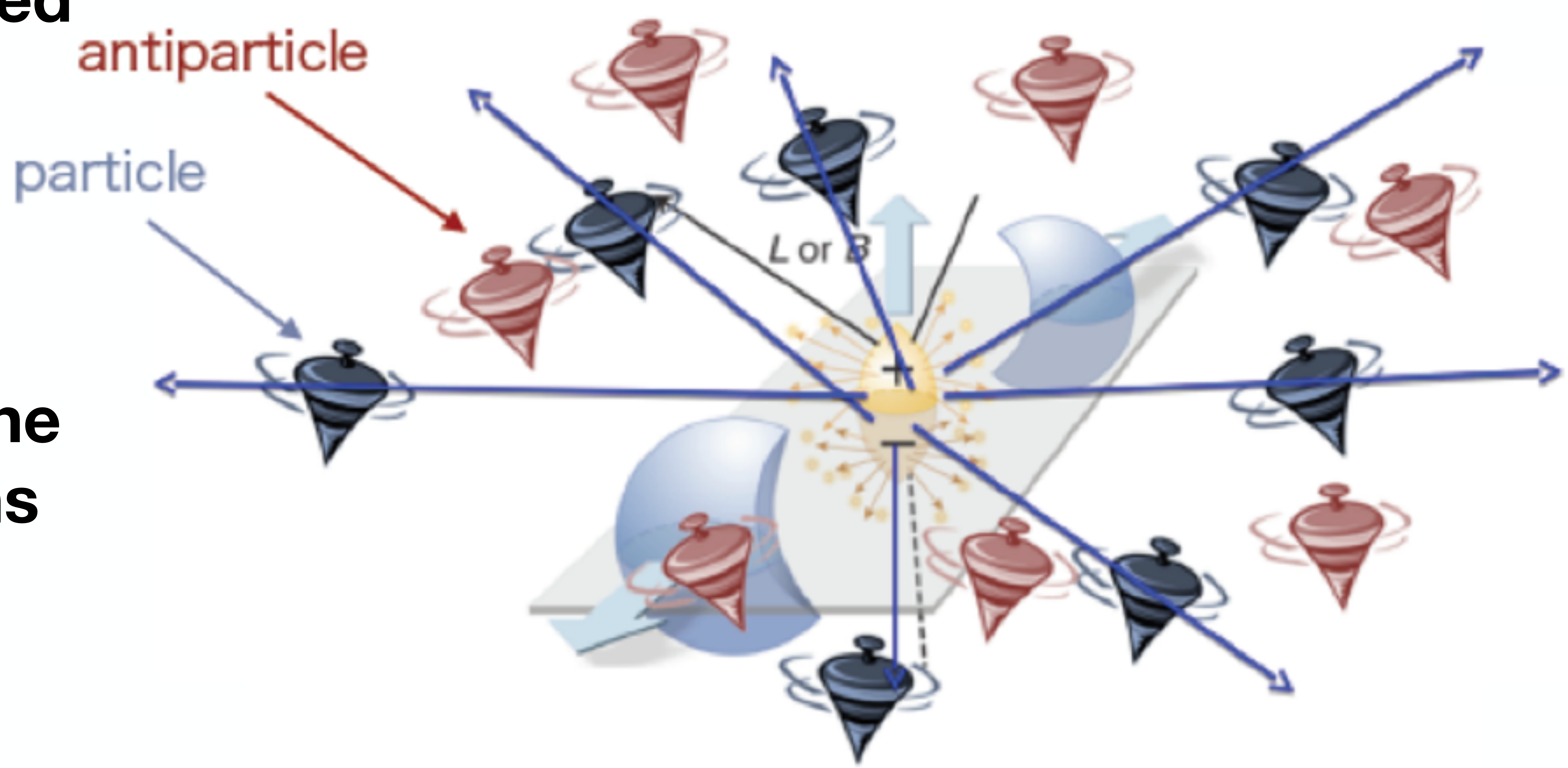




Global polarization

- Large orbital angular momentum transfers to the spin degrees of freedom:
  - **Particles and anti-particles' spins are aligned with the angular momentum.**
- Spin alignment by magnetic field:
  - **Particles and anti-particles get aligned in the opposite direction due to the opposite signs of their magnetic moments.**

✓ **Both are considered to contribute to the global polarization.**



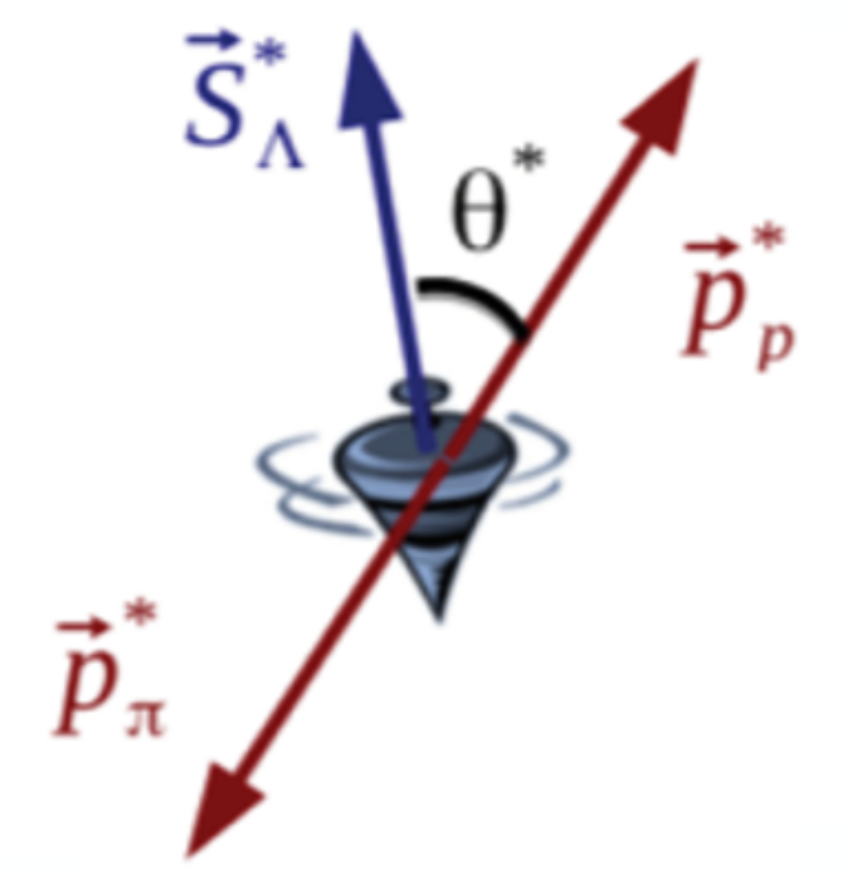
How to measure the global polarization?

✦Parity-violating decay of hyperon

- **Daughter proton preferentially decays along the Λ's spin (opposite for anti-Λ).**

$$\Lambda \rightarrow p + \pi^{-}$$ (BR:63.9%, cτ~7.9cm)

- **Polarization can be measured via the distribution of the azimuthal angle of the daughter proton (in the hyperon rest frame).**



✦Projection onto the transverse plane

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{Res(\Psi_1)}$$

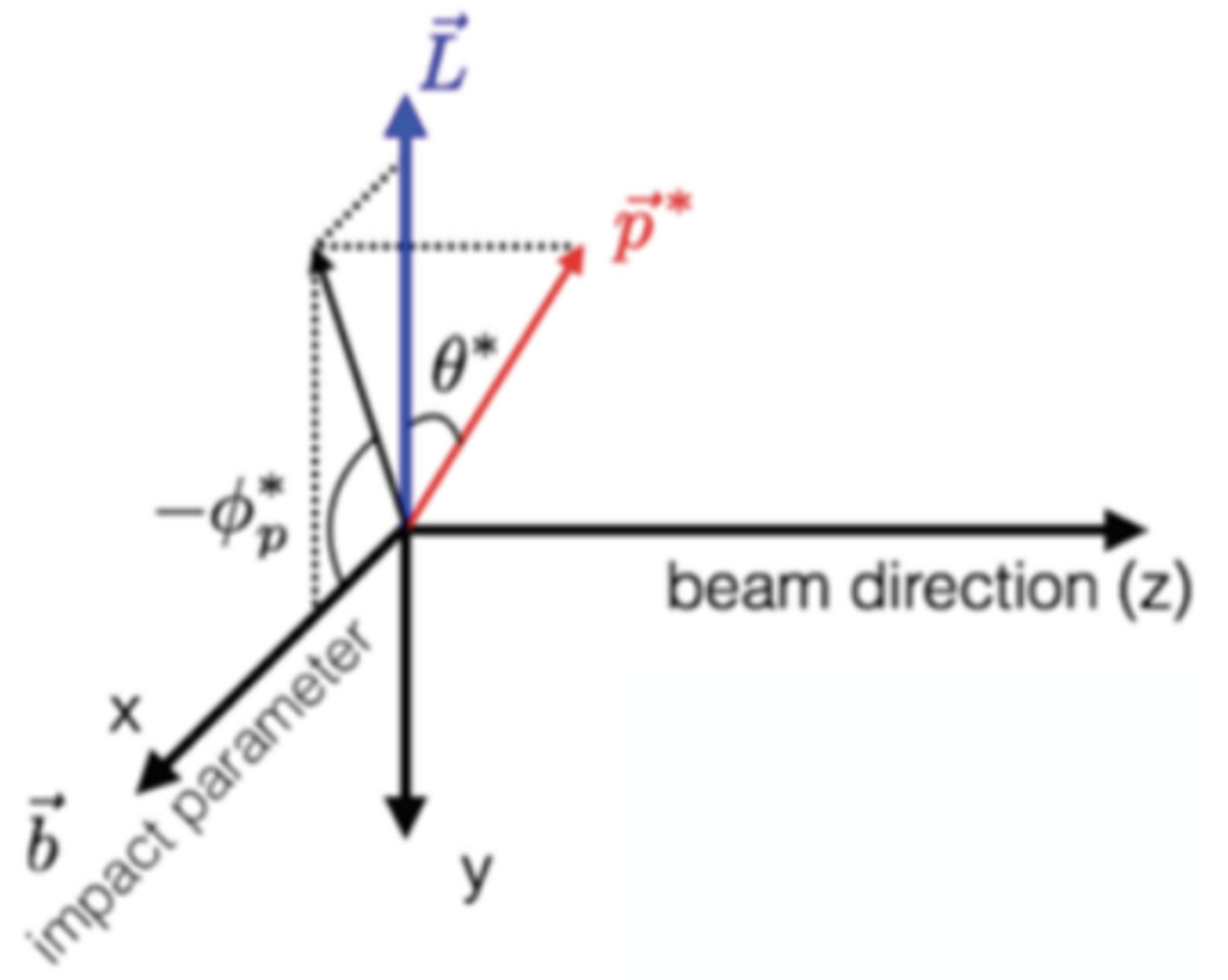
- STAR, PRC76, 024915(2007)

α_H : decay parameter ($\alpha_\Lambda = 0.732 \pm 0.014$)

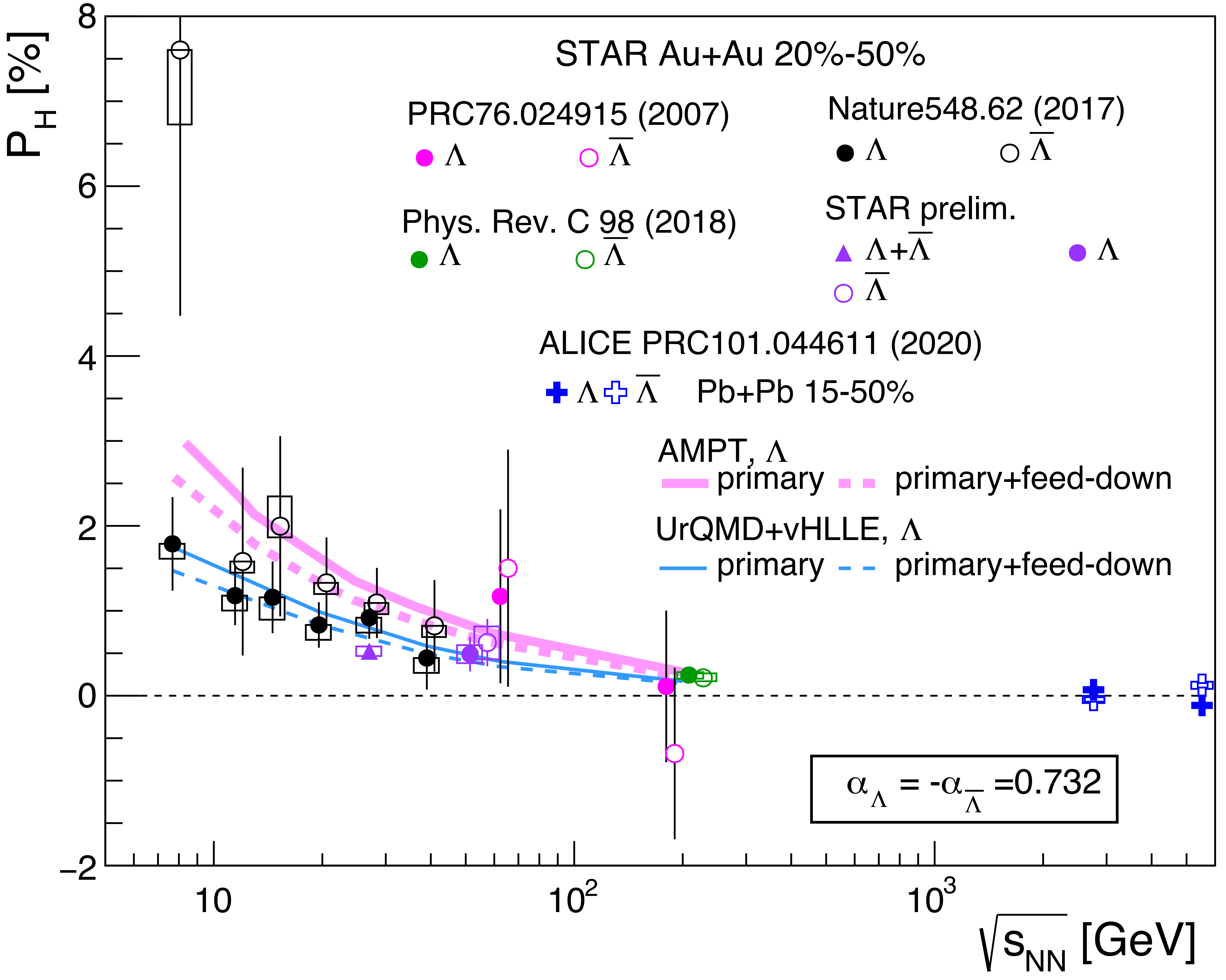
P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys.2020, 083C01 (2020).

Ψ_1 : 1^{st}-order event plane

ϕ_p^* : azimuthal angle of the daughter proton in the Λ's rest frame

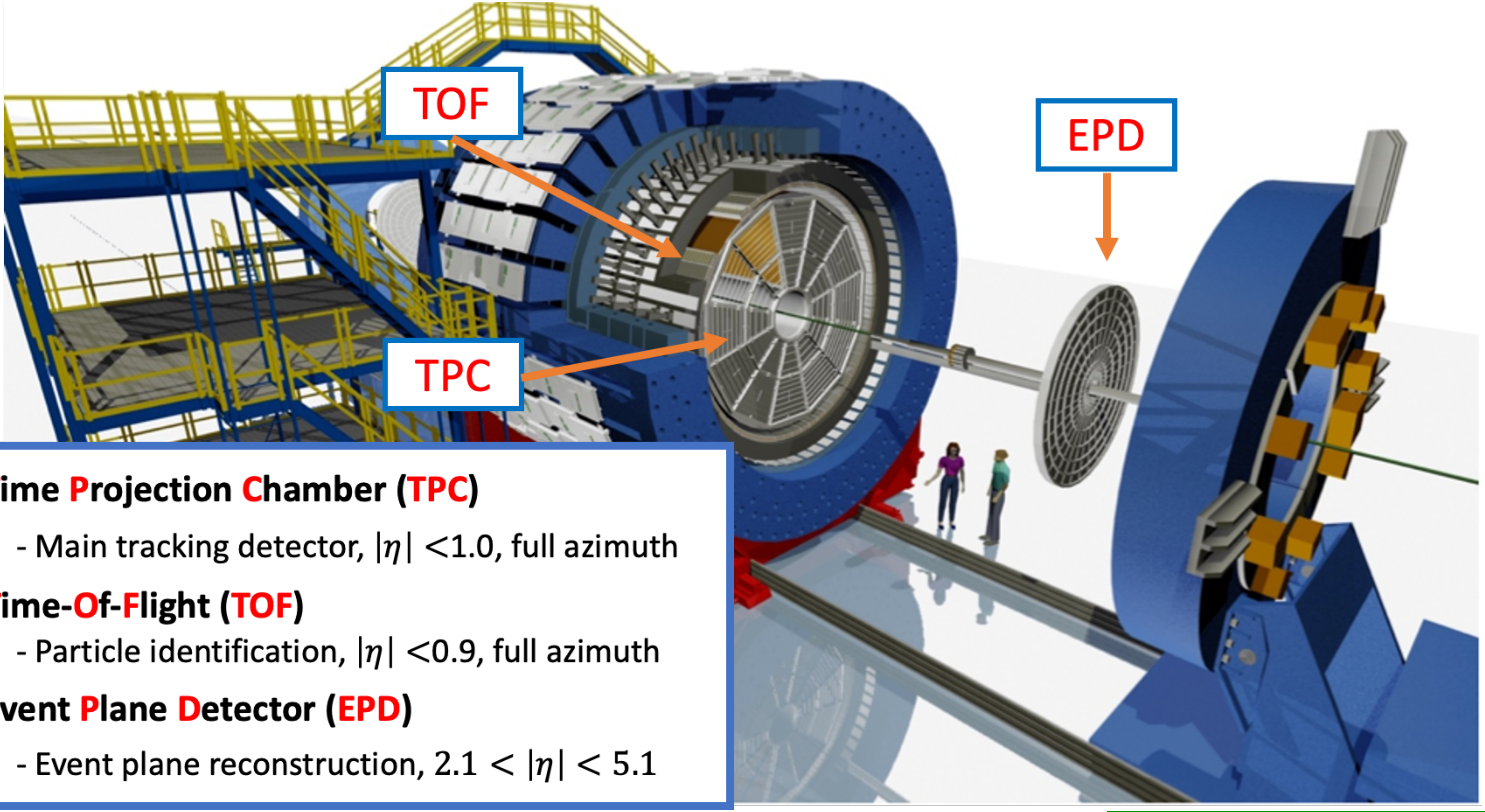


Motivation



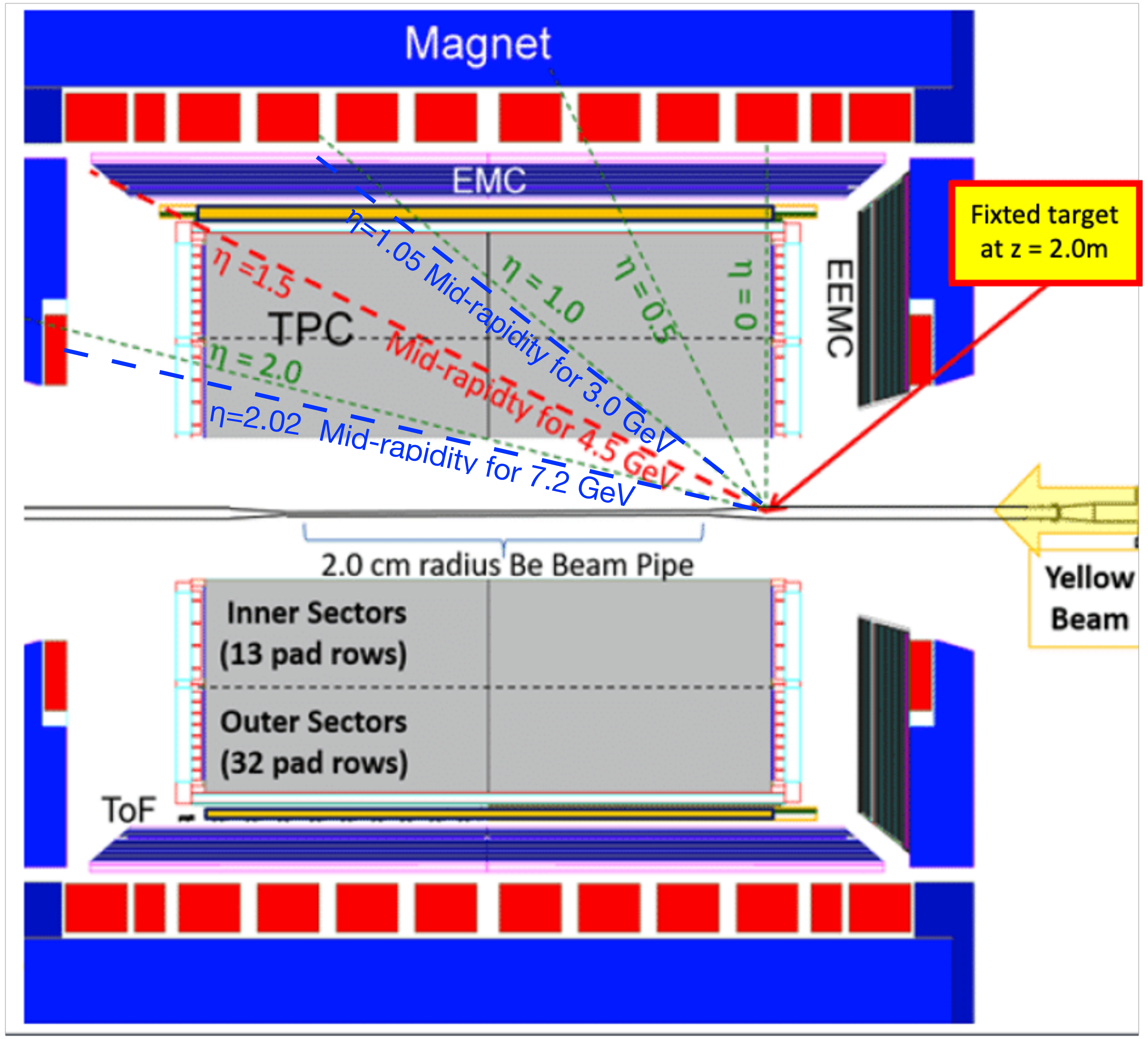
- **Λ global polarization has been measured from $\sqrt{s_{NN}}$ = 7.7 GeV to 5.02 TeV.**
  - ✓Polarization increases toward lower collision energy.
  - ✓No significant difference between Λ and anti-Λ.
  - ✓Consistent with AMPT and hydrodynamics models (UrQMD provides the initial condition of vHELLE in this case) within uncertainties.
- **New analysis of global polarization at $\sqrt{s_{NN}}$ = 3.0, 7.2 GeV with fixed-target experiment.**
  - ✓These allow to explore the behavior in the low energy.

The STAR detector



- **Time Projection Chamber (TPC)**
  - Main tracking detector, $|\eta| < 1.0$, full azimuth
- **Time-Of-Flight (TOF)**
  - Particle identification, $|\eta| < 0.9$, full azimuth
- **Event Plane Detector (EPD)**
  - Event plane reconstruction, $2.1 < |\eta| < 5.1$

STAR fixed-target program

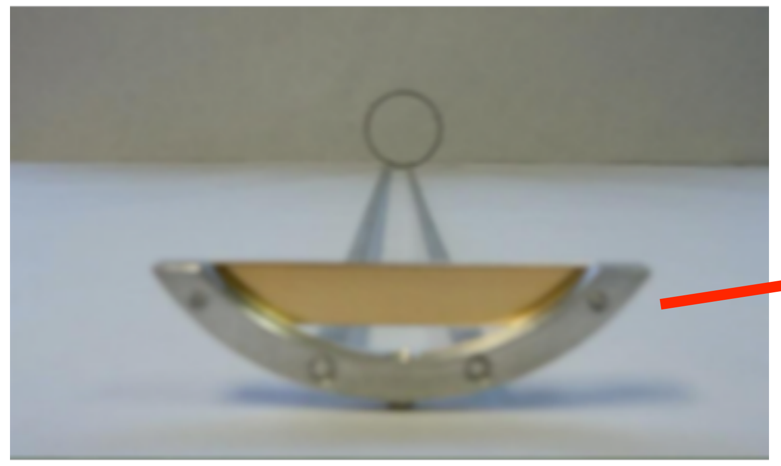


✓The gold target was installed inside the beam pipe at z = 2.0 m.

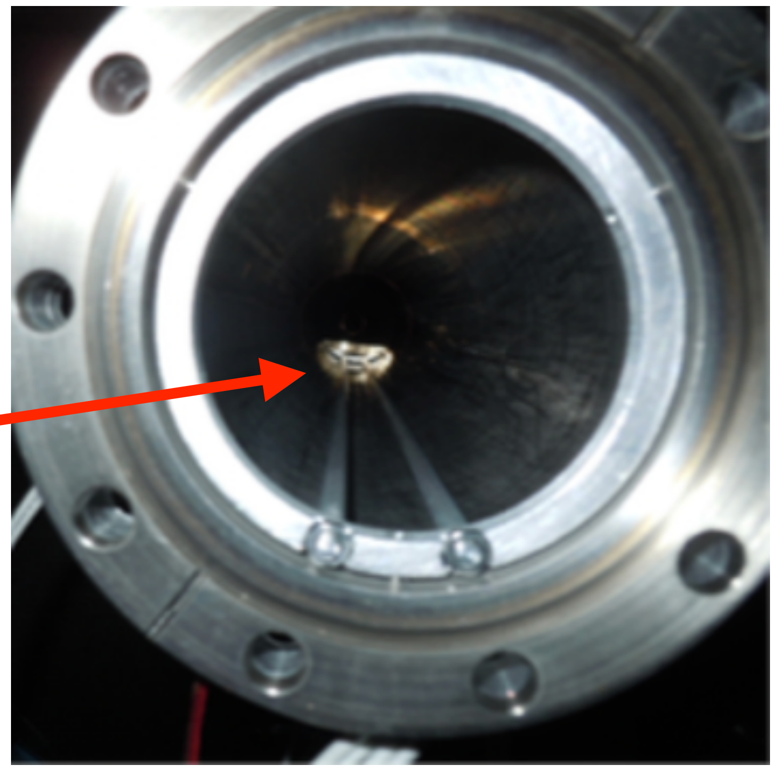
✓Target is 0.25 mm thick and ~1% interaction probability.

	$\sqrt{s_{NN}}$ = 3.0 GeV	$\sqrt{s_{NN}}$ = 7.2 GeV
Beam rapidity	1.05	2.02
Number of events	253M	209 M

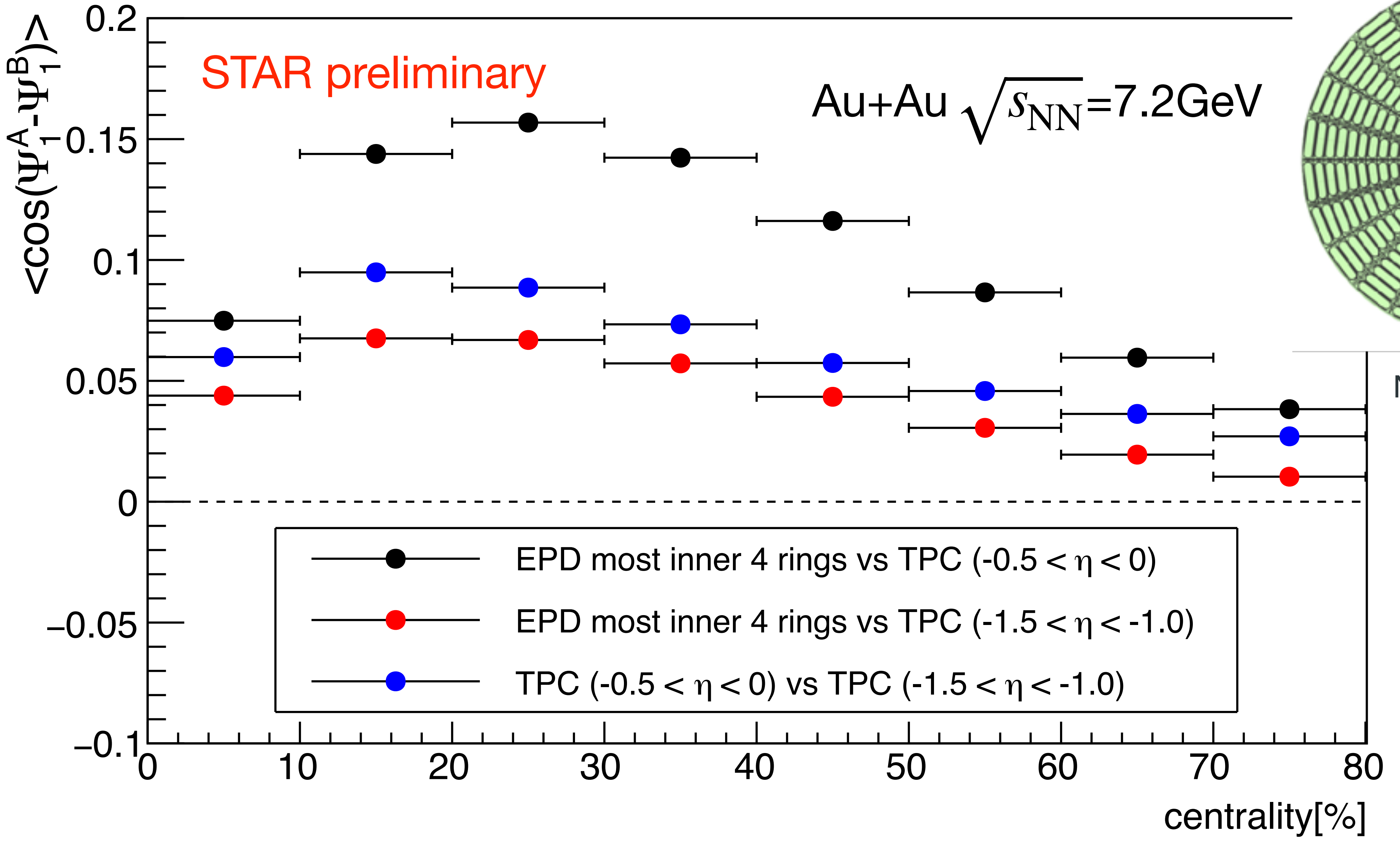
Fixed-target

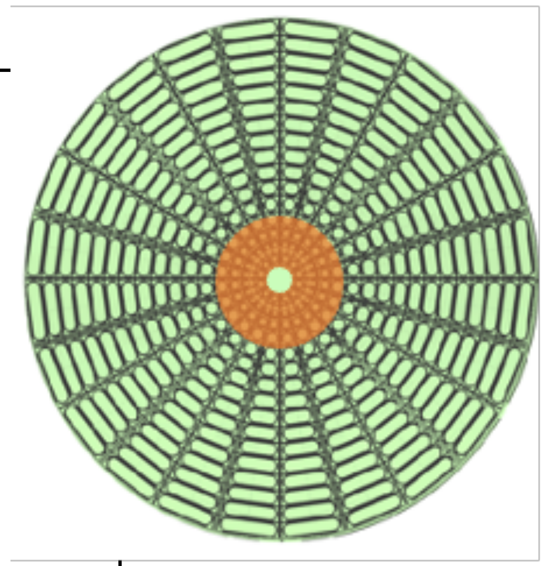


Beam pipe



Event Plane resolution





NIM A968 (2020) 163970

arxiv:1912.05243

✓First-order event plane

$$\Psi_1 = \tan^{-1}\left(\frac{\sum w_i \sin(\phi_i)}{\sum w_i \cos(\phi_i)}\right)$$

First,

$$w_i^{\mathrm{TPC}} = \eta - y^{\mathrm{mid}} \quad w_i^{\mathrm{EPD}} = \mathrm{nMip}$$

Second,

$$w_i = \langle \cos(\phi^A - \Psi_1) \rangle$$ A : pion or proton

✓Event plane resolution was calculated by 3-subevent method.

$$\langle \cos([\Psi_1^A - \Psi_1^B]) \rangle = \langle \cos([\Psi_1^A - \Psi_1^{\mathrm{true}}] \rangle \langle \cos([\Psi_1^{\mathrm{true}} - \Psi_1^B]) \rangle$$

$$= \sigma_n^A \sigma_n^B$$

$$Res(\Psi_1^A) = \sqrt{\frac{\langle \cos([\Psi_1^A - \Psi_1^B]) \rangle \langle \cos([\Psi_1^A - \Psi_1^C]) \rangle}{\langle \cos([\Psi_1^B - \Psi_1^C]) \rangle}}$$

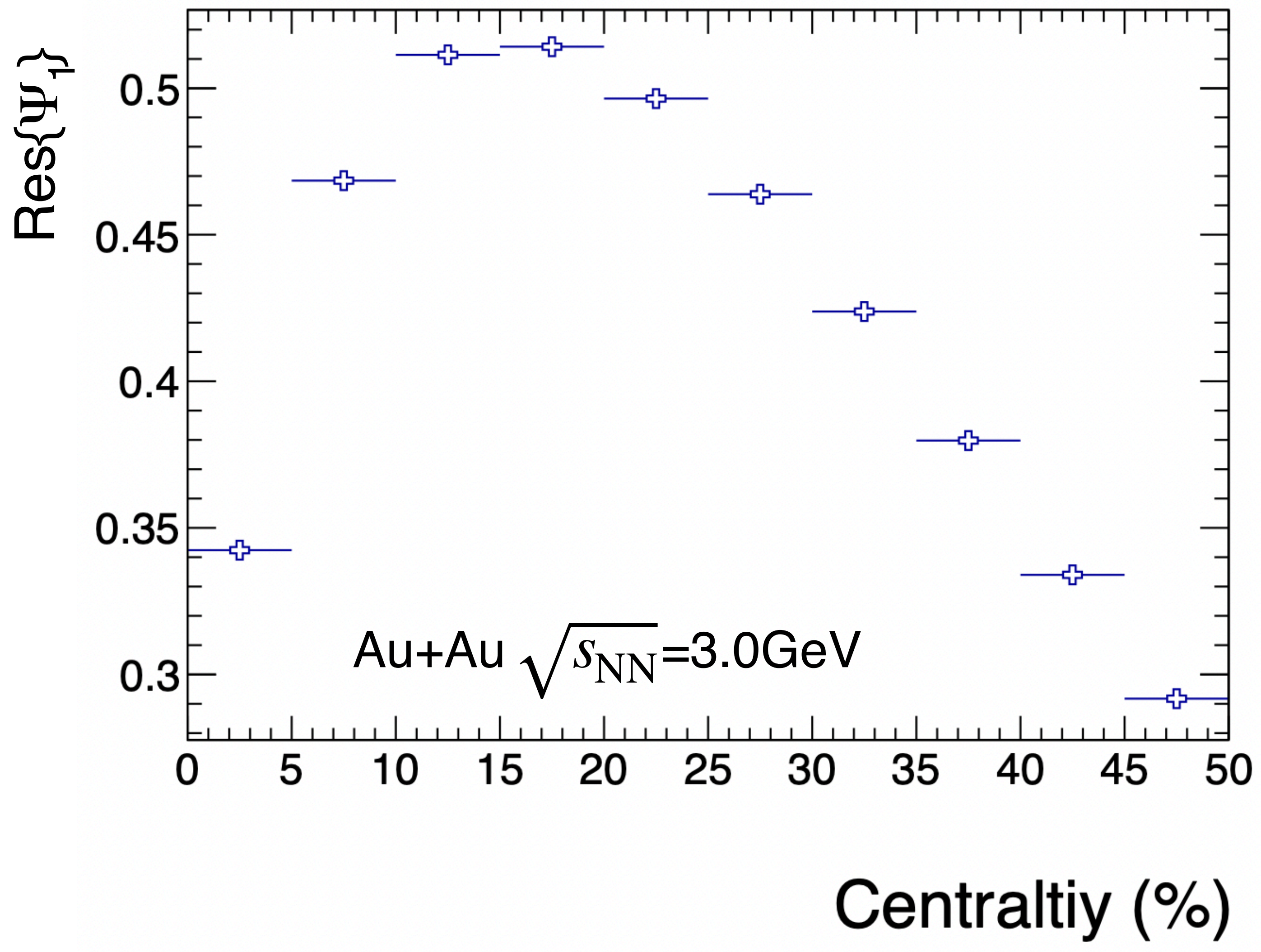
A : EPD most inner 4 rings

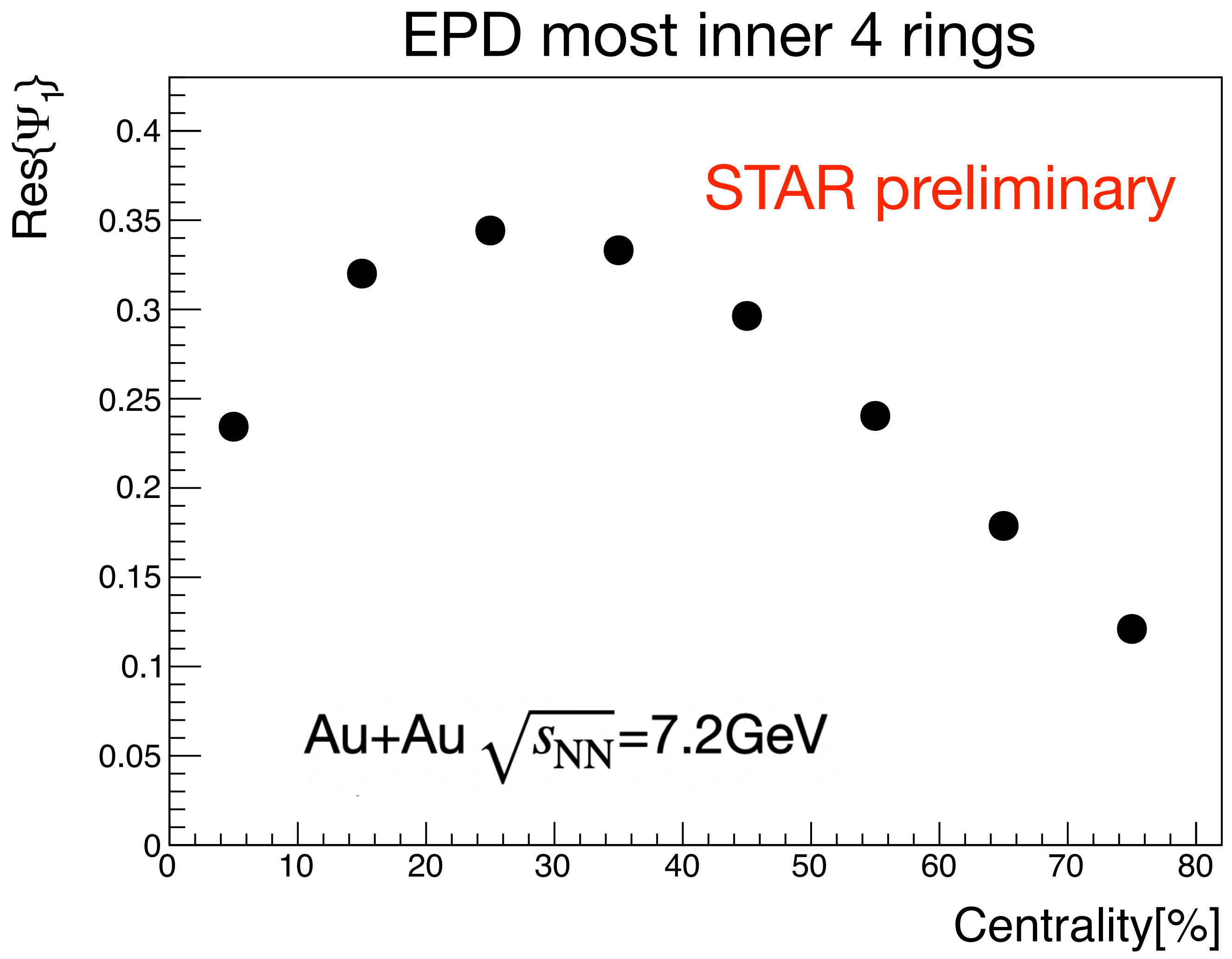
B : TPC $(-0.5 < \eta < 0)$

C : TPC $(-1.5 < \eta < -1.0)$

A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998).

M. S. Abdallah et al. (STAR Collaboration) Phys. Rev. C 104, L061901





Λ reconstruction

- **Charged particles can be identified via specific ionization energy loss in the TPC and mass estimated from TOF.**

❖Proton

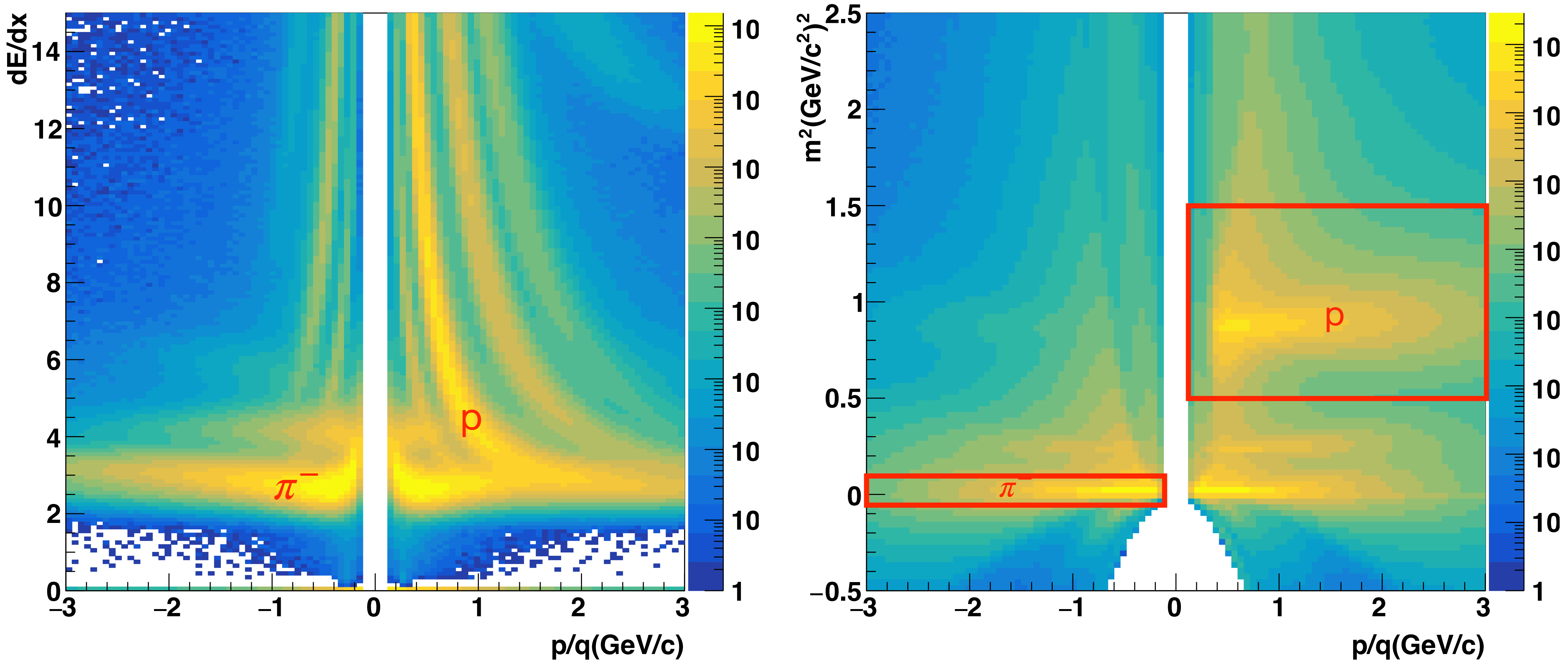
✓ $|n\sigma| < 3$

✓ $0.5 < m^2 < 1.5$ (GeV/c^2)^2

❖Pion

✓ $|n\sigma| < 3$

✓ $-0.06 < m^2 < 0.1$ (GeV/c^2)^2



❖Topological cuts

✓p-DCA > 0.4 cm

✓π-DCA > 1.6 cm

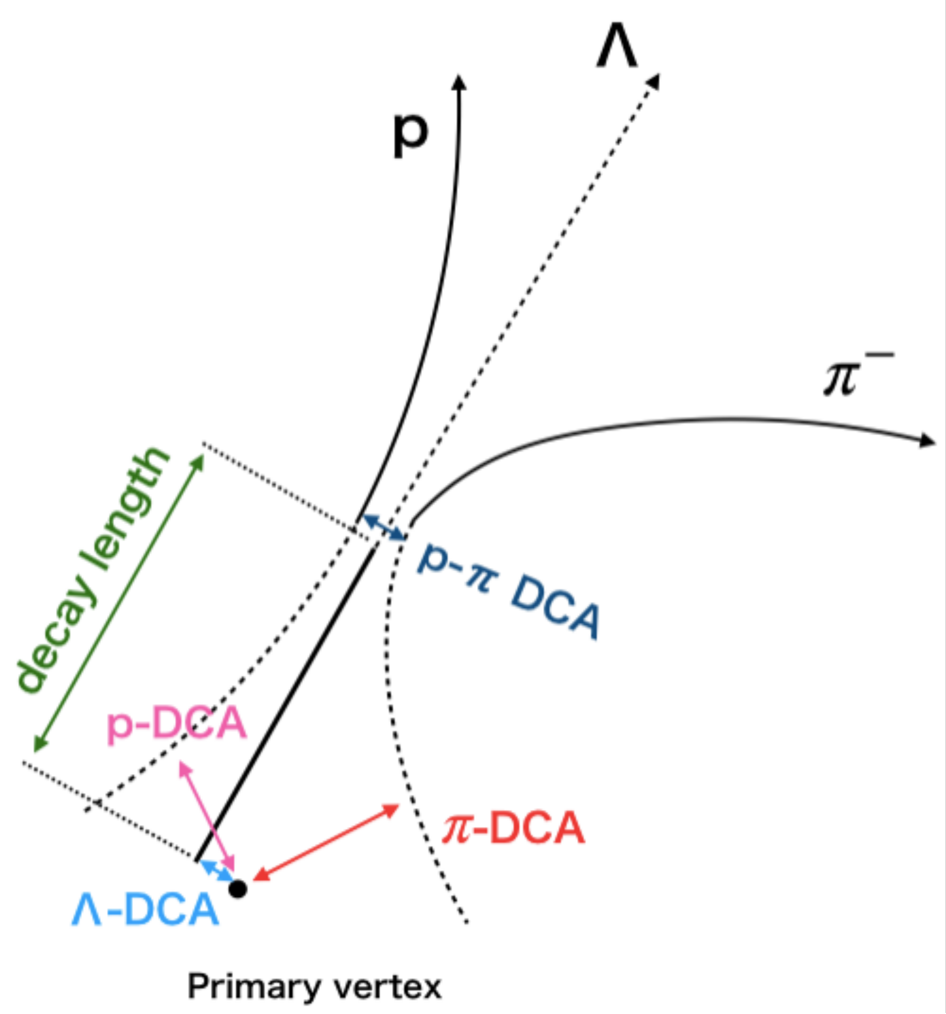
✓p-π DCA < 1.1 cm

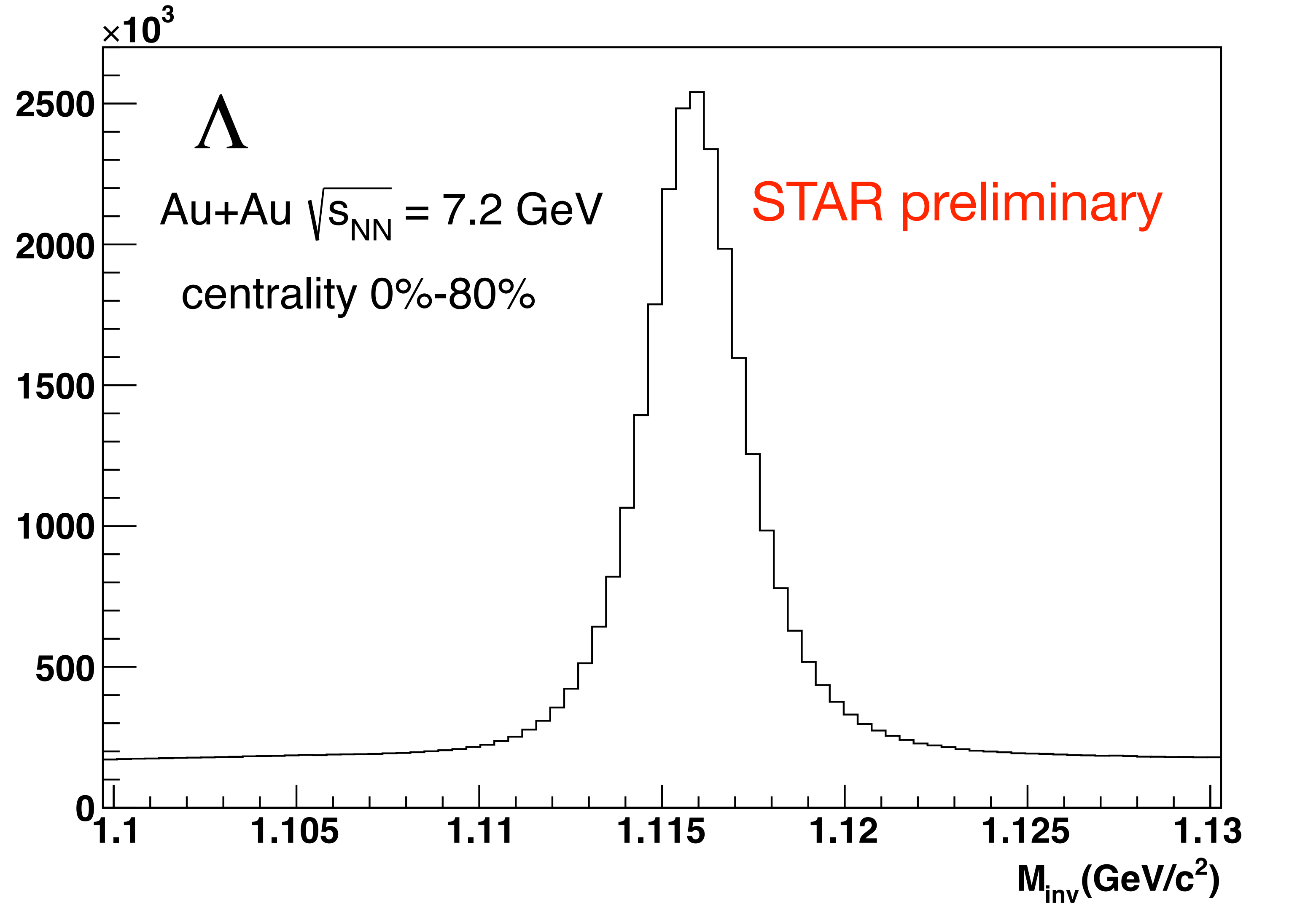
✓Λ-DCA < 0.8 cm

✓Decay length > 5.0 cm

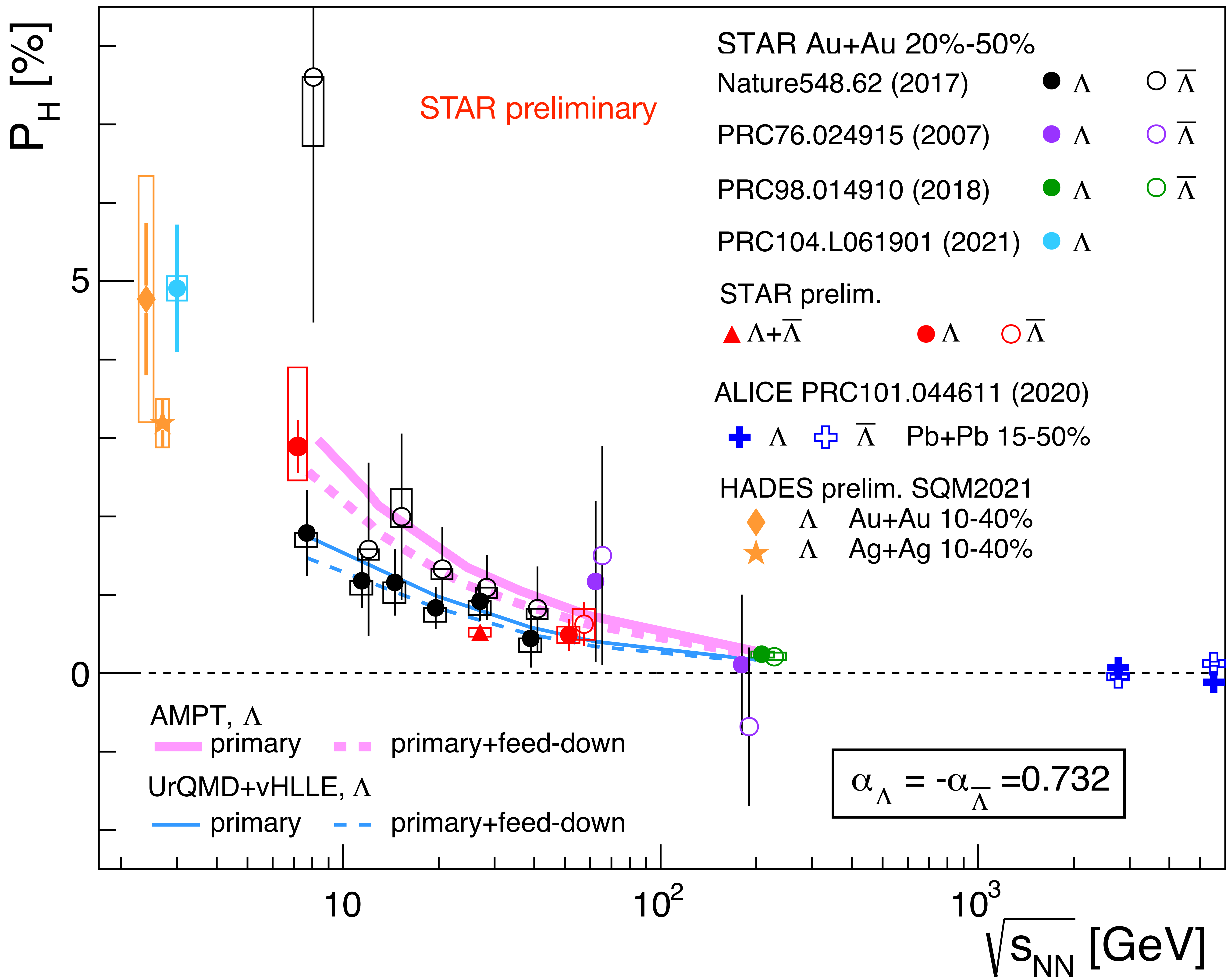
(Centrality 30-40%)

These values of topological cuts are slightly tuned depending on centrality.





Collision energy dependence of P_H



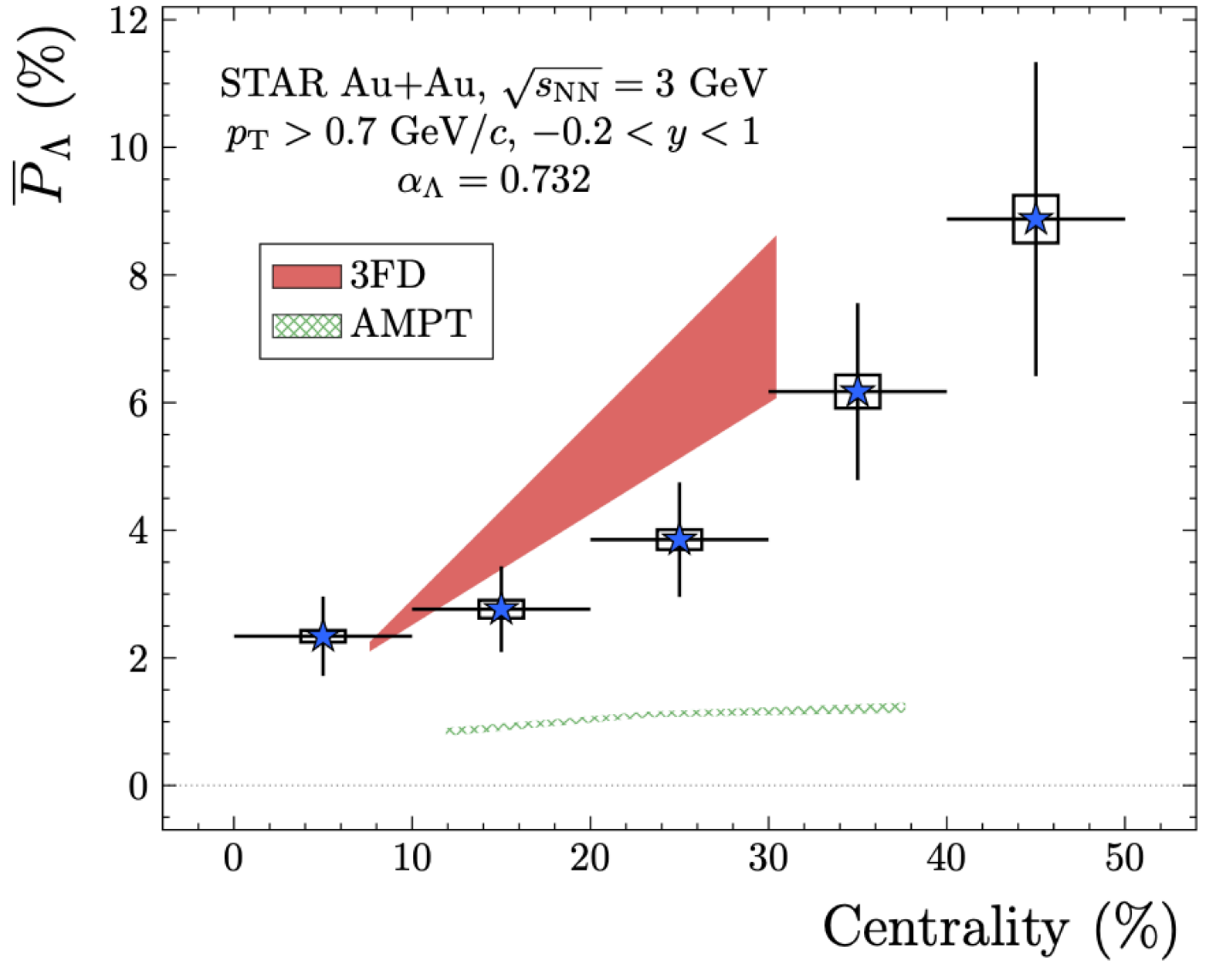
✓**First measurements in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.0, 7.2 GeV.**

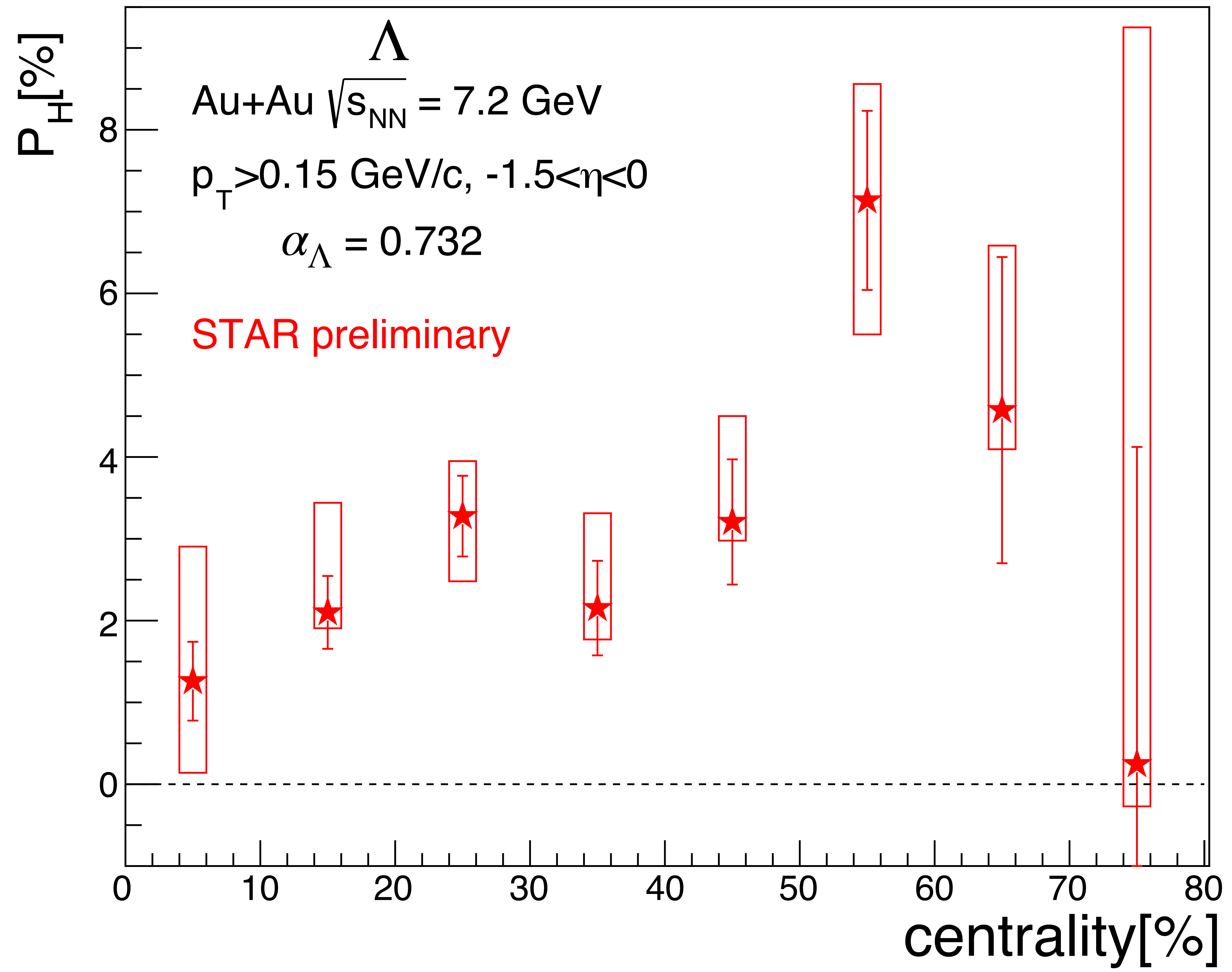
✓New HADES results in Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV and Au+Au $\sqrt{s_{NN}}$ = 2.4 GeV.

✓**The increasing trend with the decrease of collisions energy persists down to $\sqrt{s_{NN}}$ = 2.4 GeV.**

Centrality dependence of P_H

M. S. Abdallah et al. (STAR Collaboration) Phys. Rev. C 104, L061901

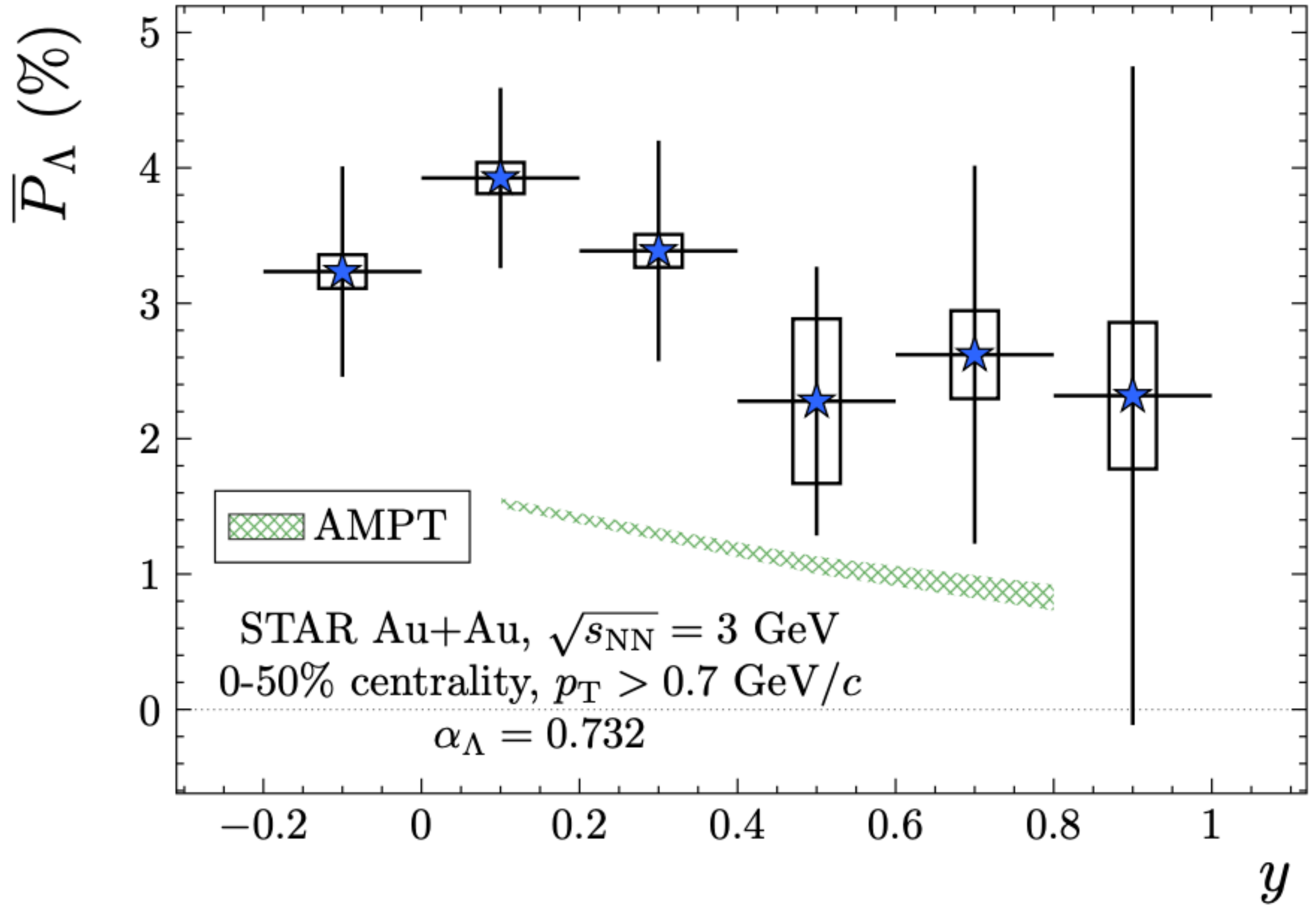




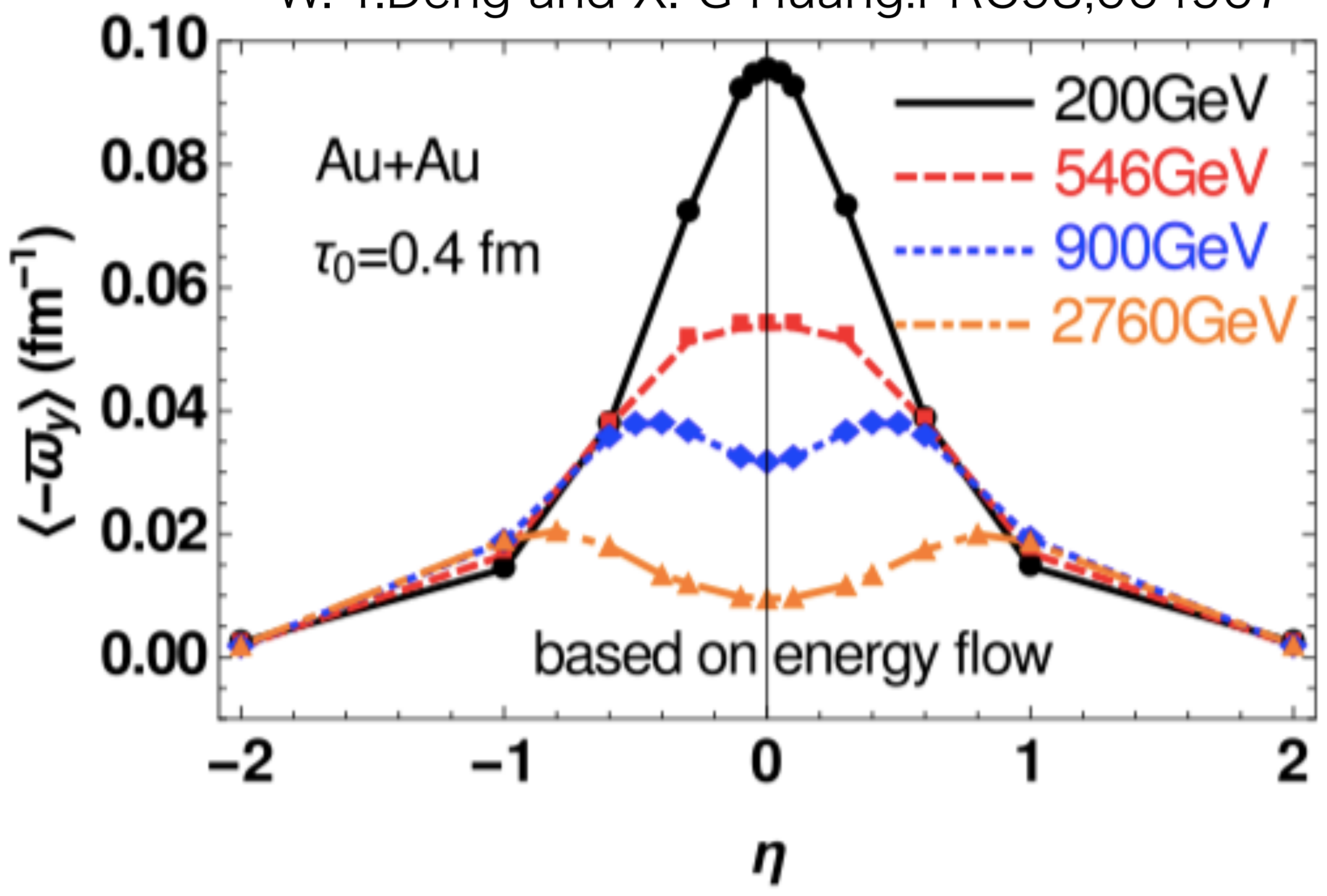
✓**Polarization increases in more peripheral collisions at both energies!**

Rapidity dependence of P_H

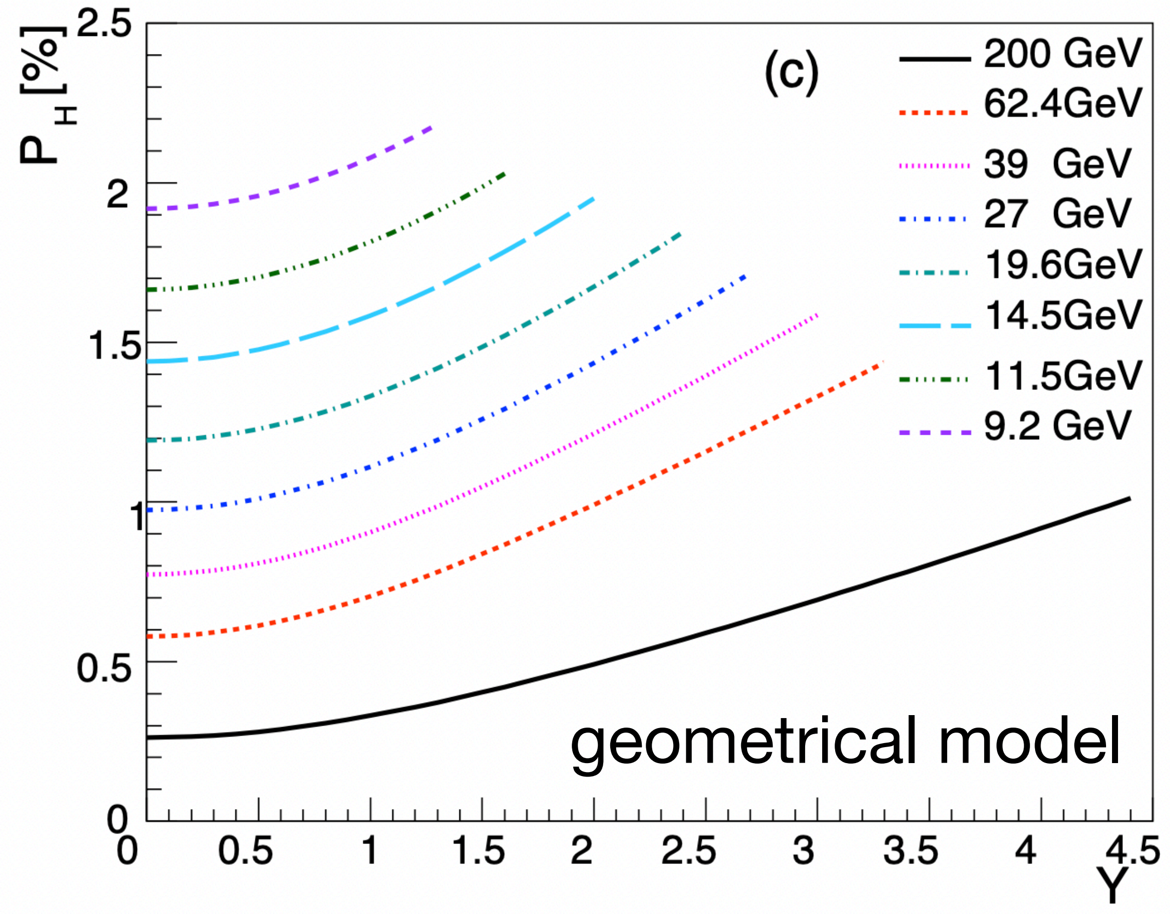
M. S. Abdallah et al. (STAR Collaboration) Phys. Rev. C 104, L061901

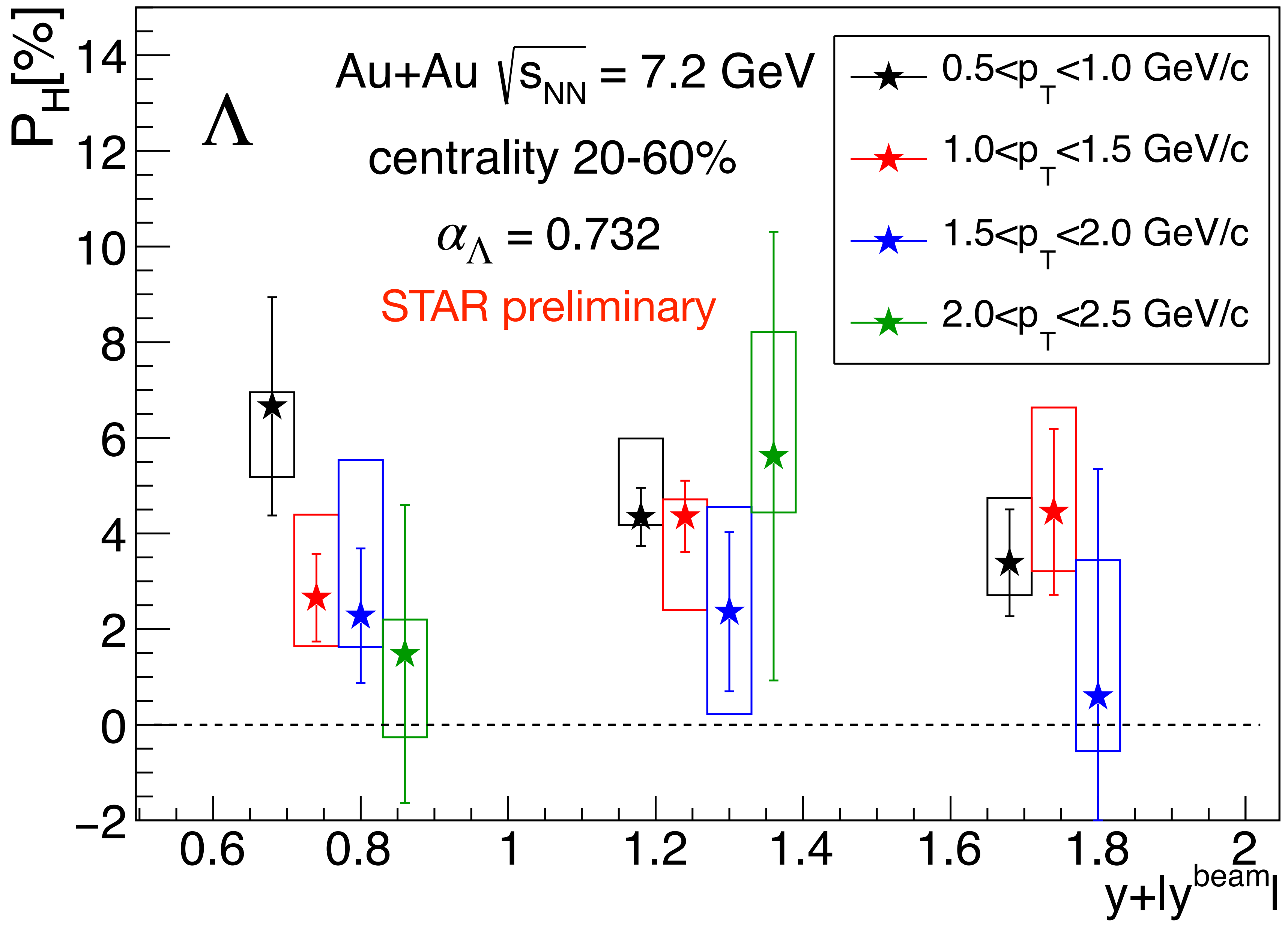


W.-T.Deng and X.-G Huang:PRC93,064907



Z.T.Liang et al., Chin.Phys.C 45 (2021) 1, 014102





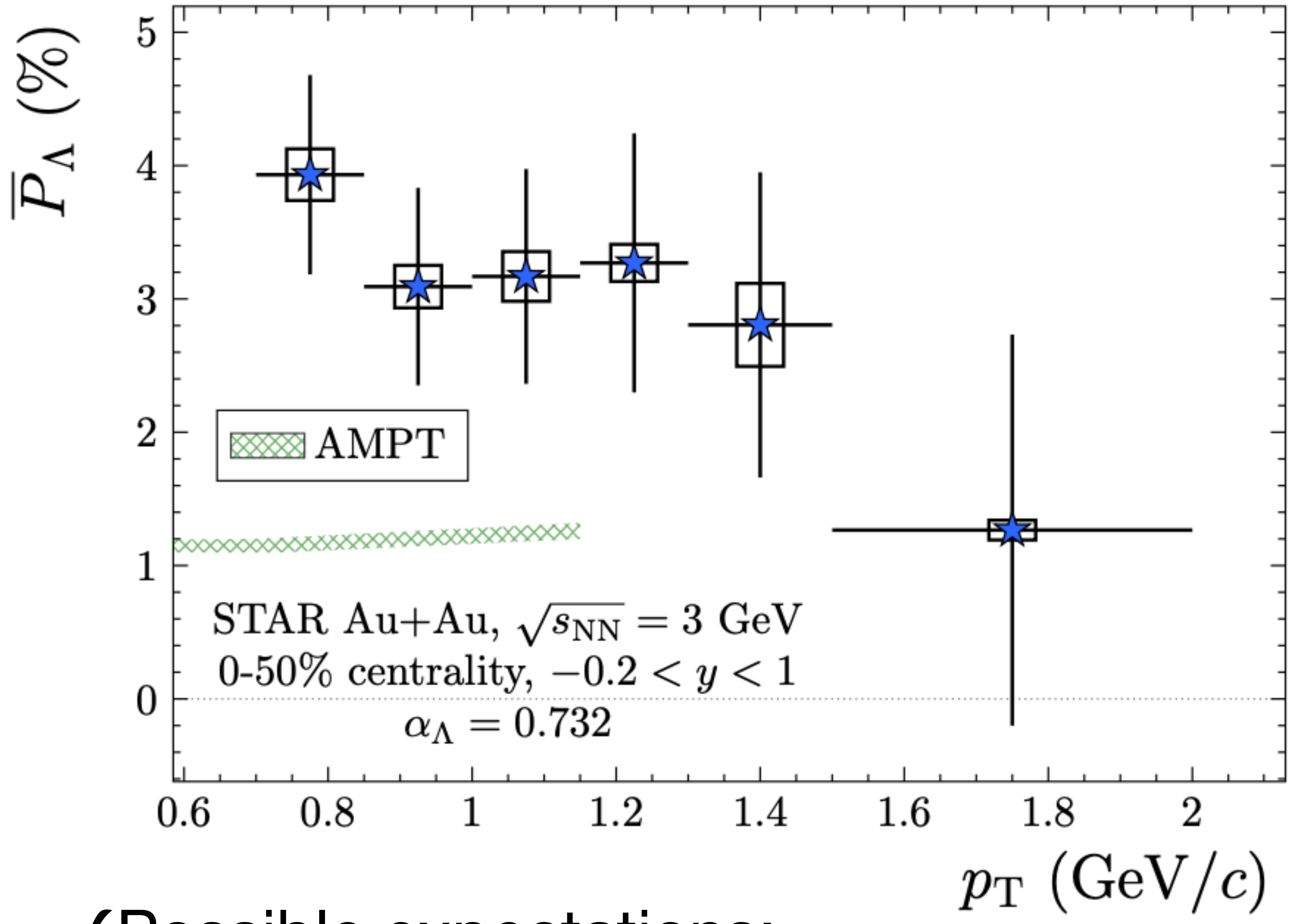
✓Polarization is expected to depend on rapidity but the prediction is different among models.

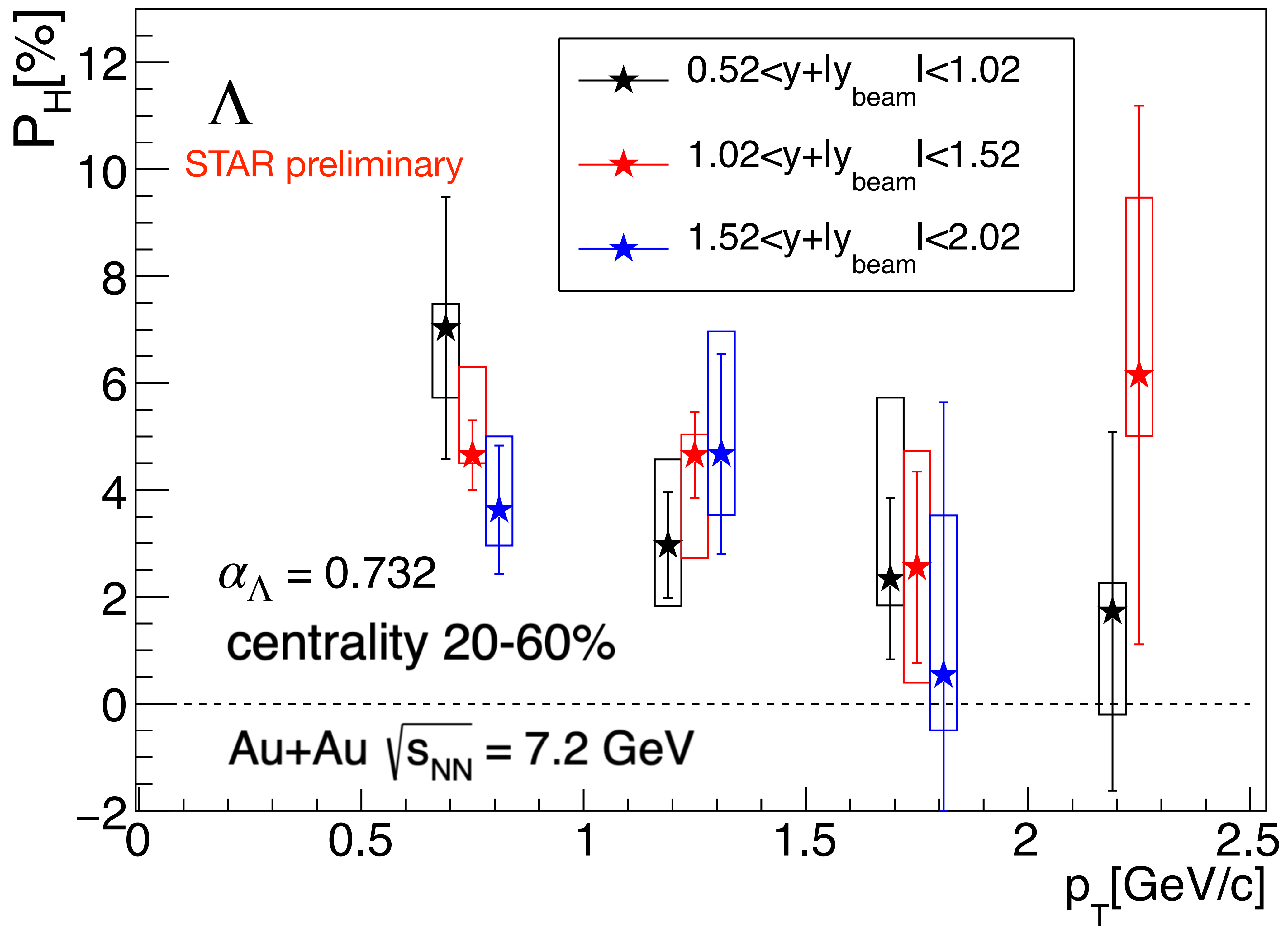
✓The result does not show significant rapidity dependence within our acceptance.

✓Polarization in large rapidity region can be explored in the future with iTPC and forward upgrade (2023+2025).

Transverse momentum dependence of P_H

M. S. Abdallah et al. (STAR Collaboration) Phys. Rev. C 104, L061901





✓Possible expectations:

- decrease at low p_T due to the smearing effect caused by scattering at the later stage of the collisions.
- decrease at high p_T due to jet fragmentation.

J. Adams et al. (STAR), PRC98, 14910 (2018)

✓**No significant p_T dependence seen in data.**

Summary

Summary

✦**We presented measurements of Λ global polarization in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.0, 7.2 GeV from STAR in fixed target mode.**

- Positive polarization is observed.
- Λ polarization increases at lower collision energies.
- Increasing trend towards peripheral collisions as expected.
- No significant dependence on p_T and rapidity is observed.

Outlook

- Measurement of anti-Λ polarization at 7.2 GeV.

✓We completed the data taking of BES II + FXT.

- $\sqrt{s_{NN}}$ = 3.0 GeV : 337M(now) → about 2B.
- $\sqrt{s_{NN}}$ = 7.2 GeV : 267M(now) → 267M + about 400M.

Collider mode data at BES II

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Number Events Requested (Recorded)	Date Collected
13.5	27	156	(560 M)	Run-18
9.8	19.6	206	400 M (582 M)	Run-19
7.3	14.6	262	300 M (324 M)	Run-19
5.75	11.5	316	230 M (235 M)	Run-20
4.59	9.2	373	160 M (162 M)	Run-20+20b
3.85	7.7	420	100 M (100 M)	Run-21

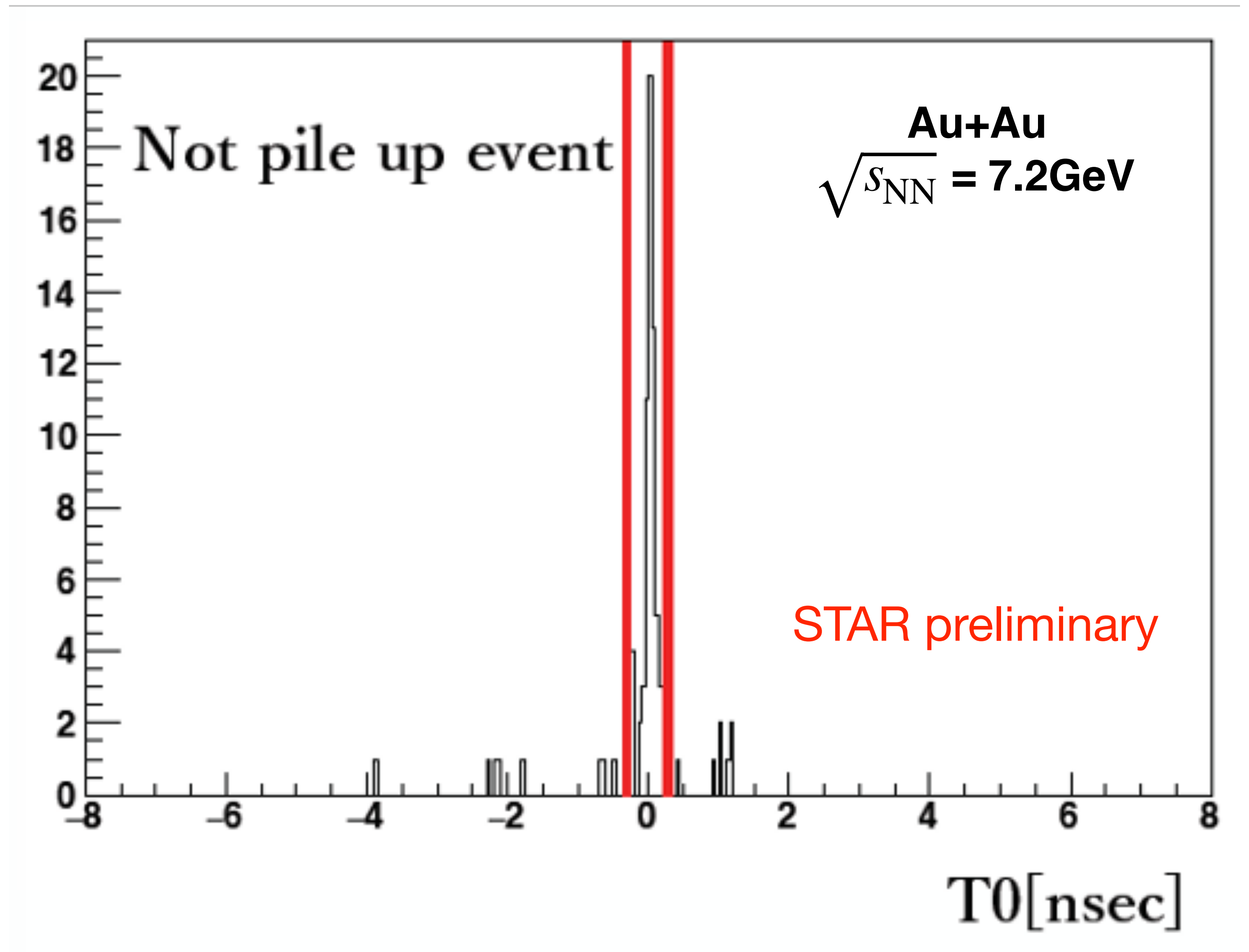
Fixed-target mode data at BES II

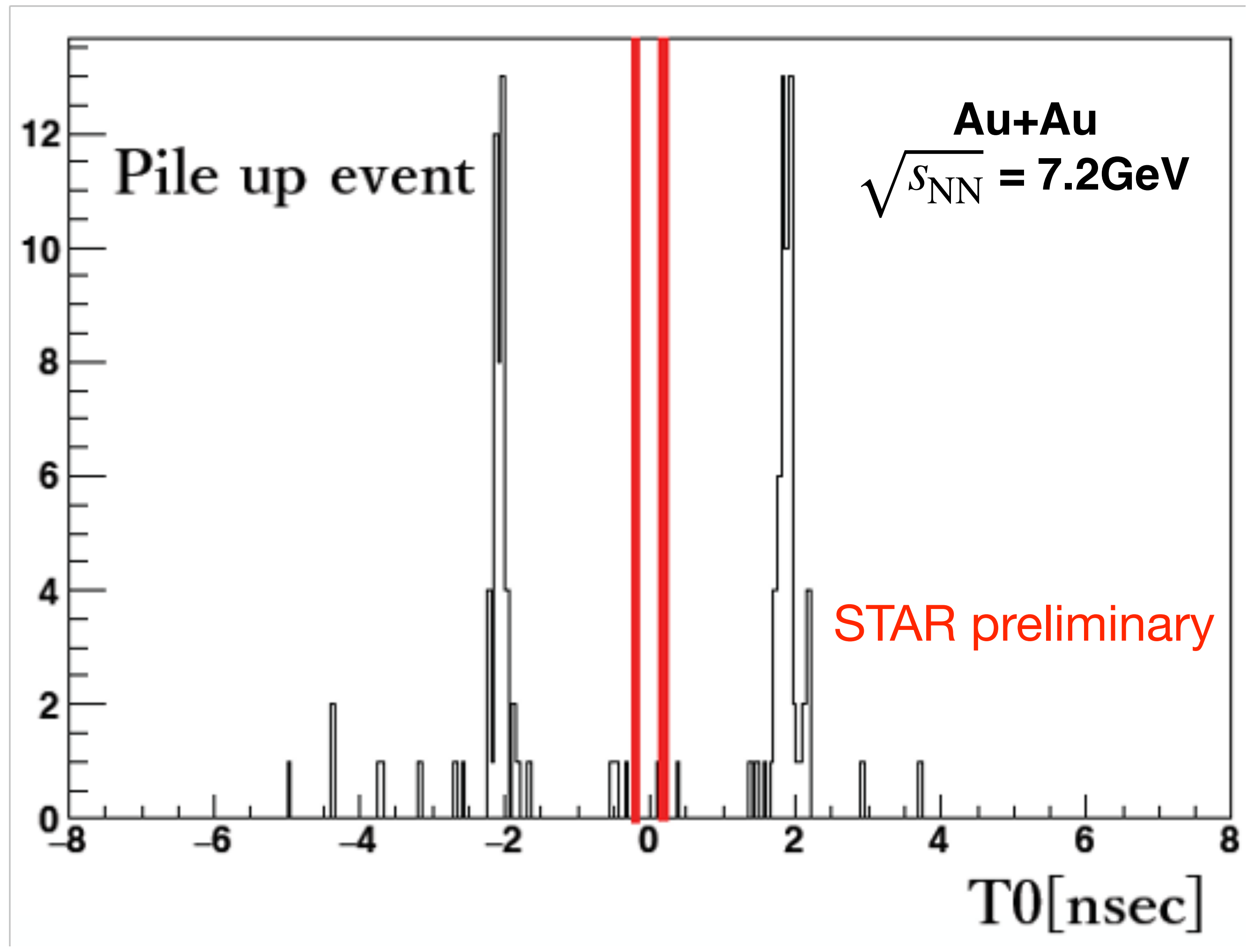
Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18

Back up

Pile up rejection

✓Pile up events are removed using start timing (T0) estimated using TOF and TPC.



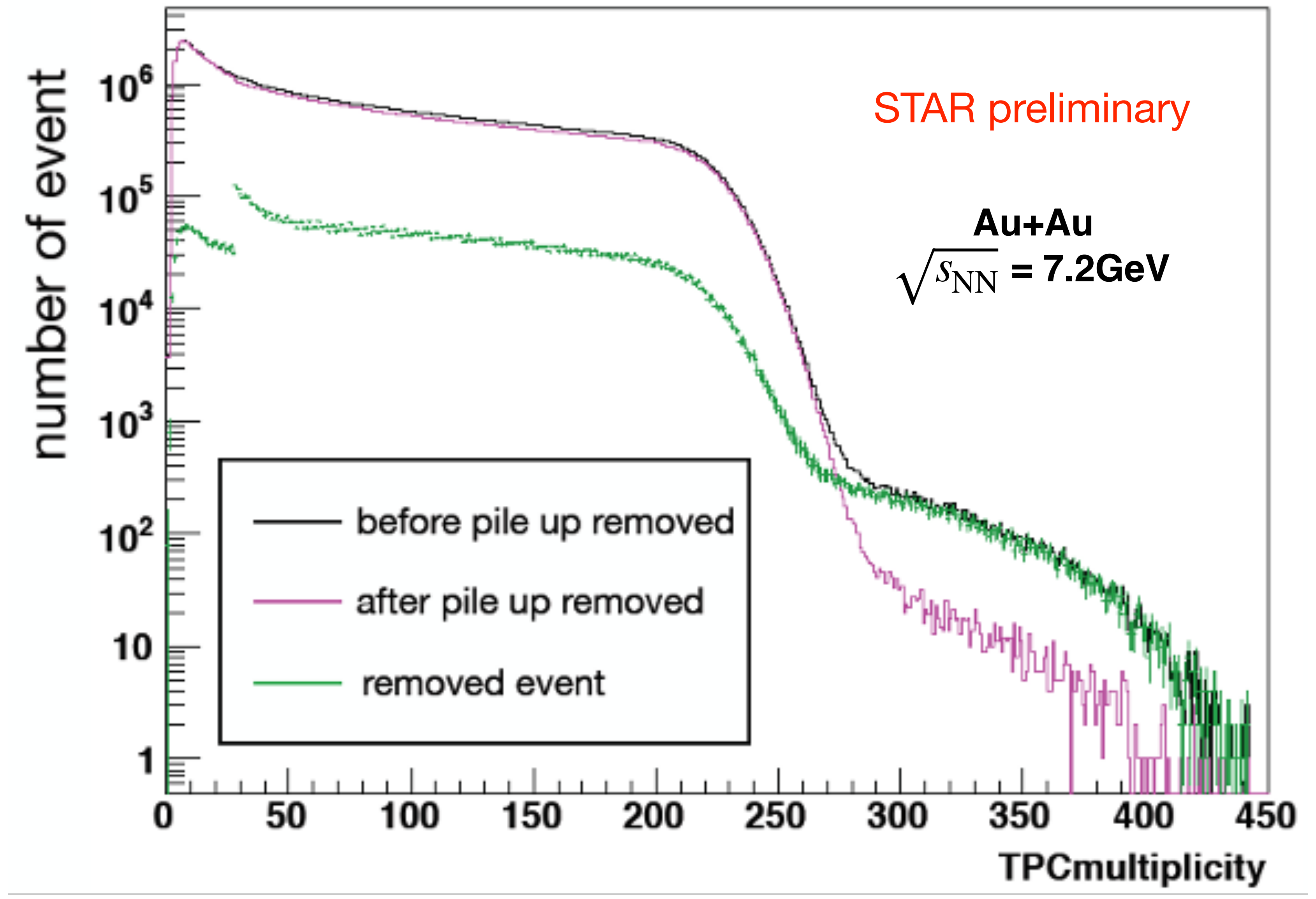


T0 = the average of Time of Flight
- Time of Flight of each particle

Step1 : Count number of pion and proton with T0 from -0.3 to 0.3 [nsec].

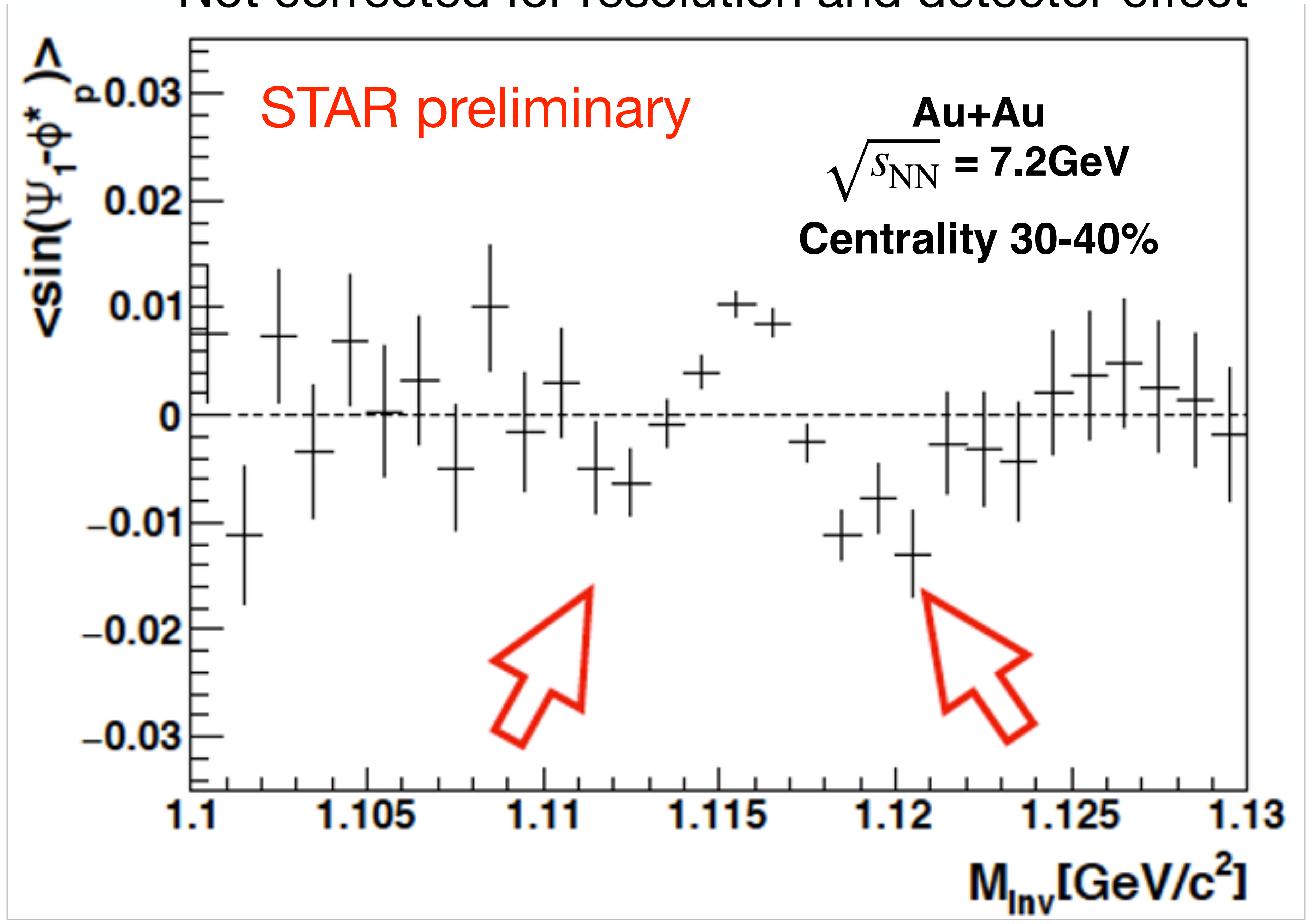
Step2 : The event where the number of pion and proton is far from average are removed as pile up events in each multiplicity bin.

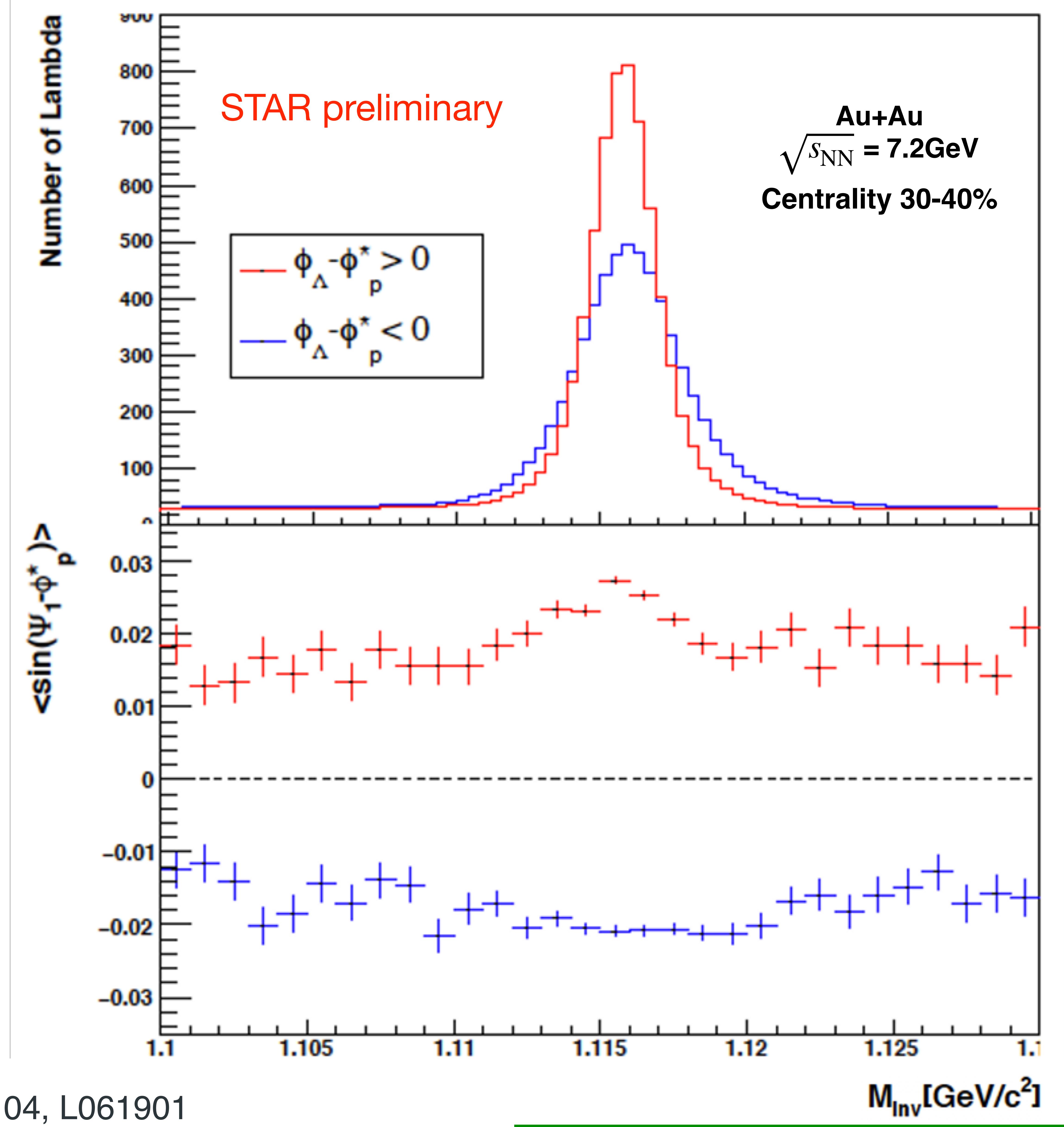
‣ **About 90% of the pile up events would be removed using our technique.**



Extraction of the polarization signal

Not corrected for resolution and detector effect





✓Observed polarization is more sharply peaked near Λ mass and it dips on the sides mass peak.

The width of the invariant mass depends on the daughter's azimuthal emission angle relative to the Λ.

Discussed in more detail ; M. S. Abdallah et al. (STAR Collaboration) Phys. Rev. C 104, L061901

Extract the polarization signal

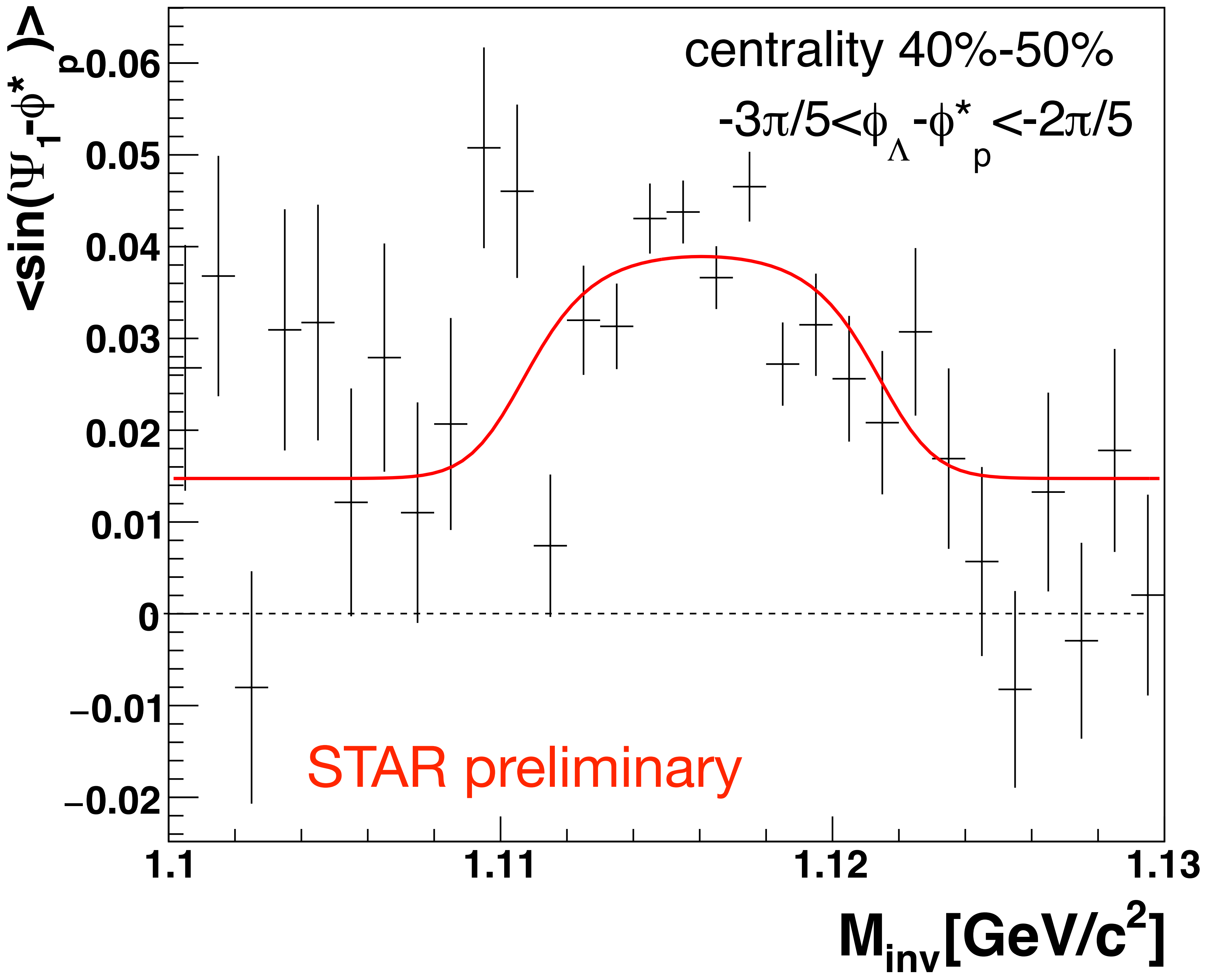
✓Calculate polarization each $\phi_\Lambda - \phi_p^*$ bin.

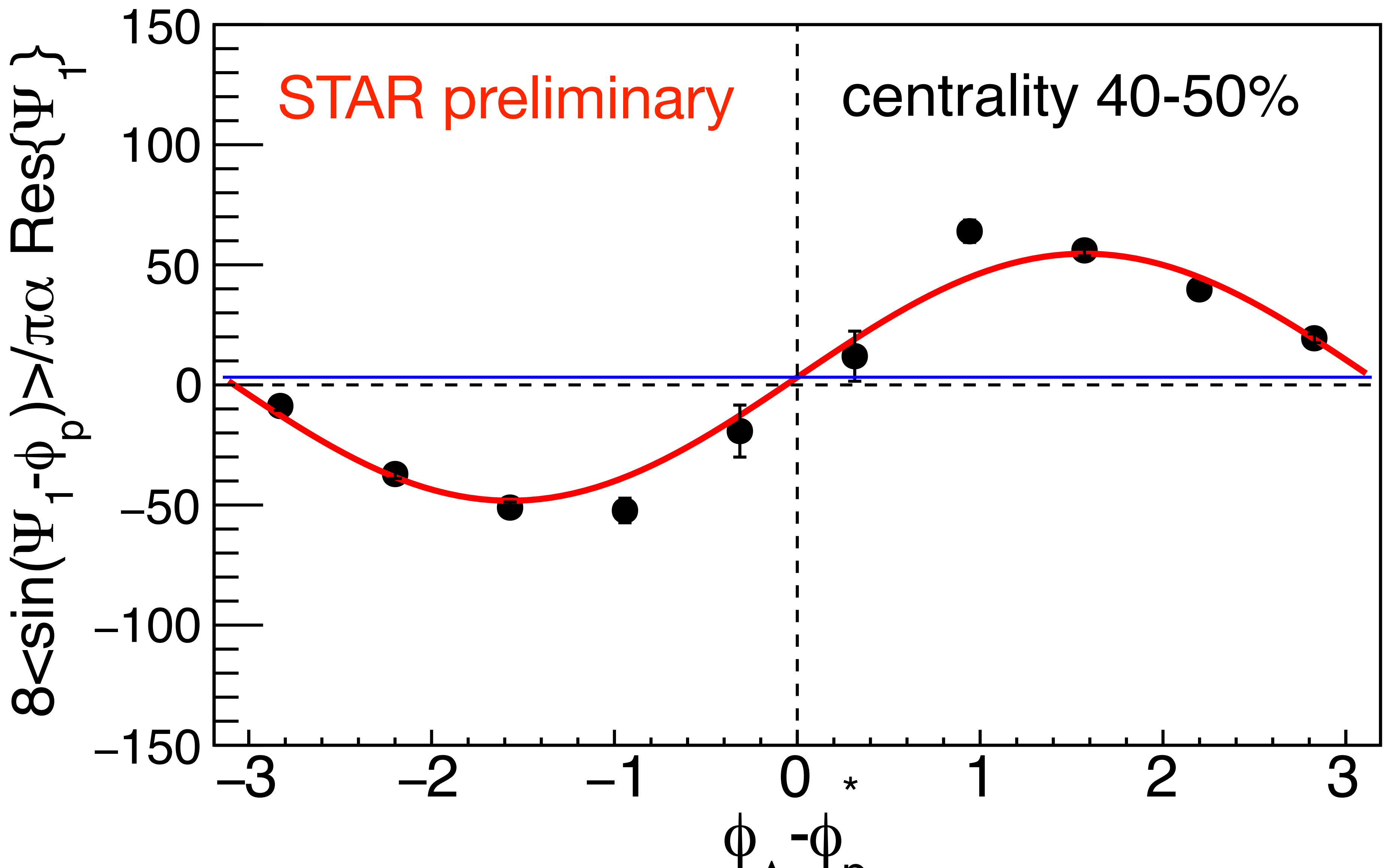
- Invariant mass method
  - The data was fitted with the following formula.

$$\langle\sin(\Delta\phi)\rangle^{\mathrm{obs}} = (1 - f^{\mathrm{Bg}}(M_{inv}))\langle\sin(\Delta\phi)\rangle^{\mathrm{Sg}} + f^{\mathrm{Bg}}(M_{inv})\langle\sin(\Delta\phi)\rangle^{\mathrm{Bg}}$$

$$\Delta\phi = \Psi_1 - \phi_p^*$$

$$f^{Bg}(M_{inv}) = f(M_{inv}^{Bg})/f(M_{inv}^{obs})$$





✓Observed polarization is described as follows.

$$\frac{8}{\pi\alpha_H}\frac{1}{R^1{}_{EP}}\left\langle\sin\left(\Psi_1 - \phi^*{}_p\right)\right\rangle^{Sg} = P_\Lambda{}^{true} + cv_1\sin\left(\phi_\Lambda - \phi^*{}_p\right)$$

Systematic uncertainty at 7.2 GeV

✓Different topological cut(~1.6%)

- Ten different cuts are applied.

• p-DCA±0.1cm
• π-DCA±0.1cm
• p-π DCA±0.1cm
• Λ-DCA±0.1cm
• Decay length±0.5cm

✓Method comparison for extracting polarization signal (~17.0%)

- Invariant mass method
- Event plane method

✓Background assumption for polarization in the invariant mass method(~0.4%)

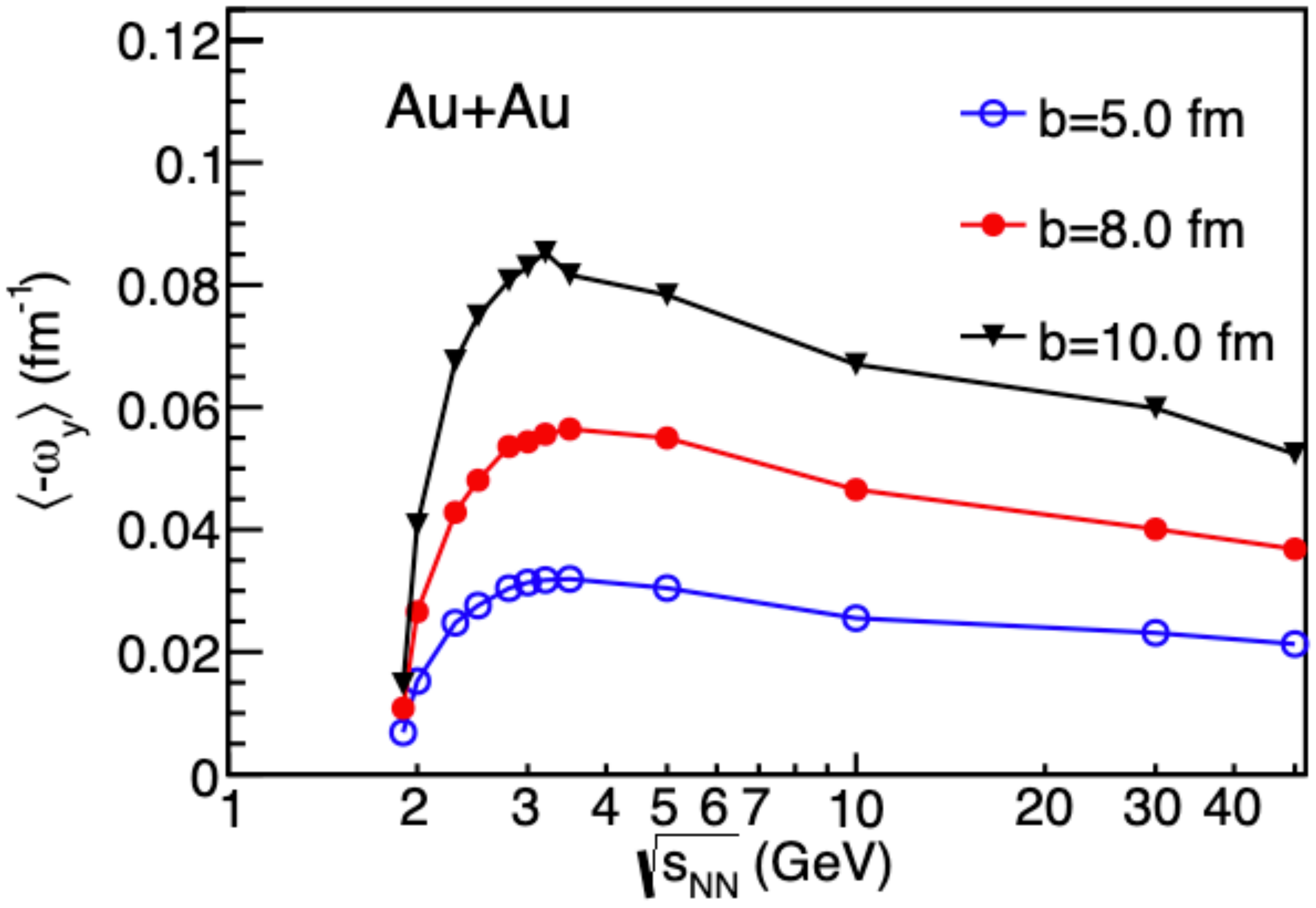
✓Uncertainty from decay parameter α_H(~3.2%)

✓Cumulant correction(~3.8%)

✓Efficiency correction(~8.2%)

Vorticity at low energy

X.-G. Deng et al., PRC101.064908 (2020)



✓UrQMD model predicts that kinetic/thermal vorticity is the largest around 3 GeV.