山东大学
SHANDONG UNIVERSITY

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Update of Spin Hall Effect study with Heavy-Ion collisions

Qiang Hu, Subhash Singha, Hao Qiu (IMP)

Zhenyu Chen, Xingrui gou, Qinghua Xu (SDU)

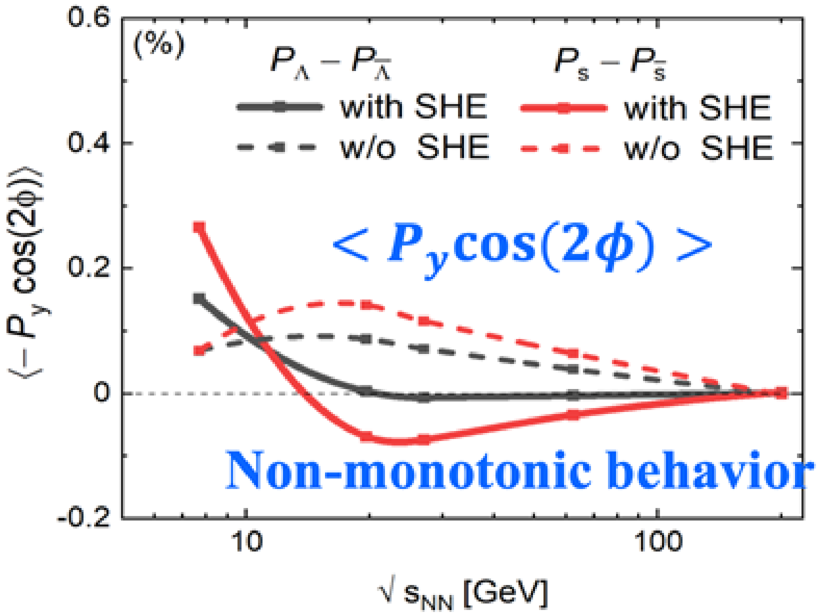
STAR FCV Meeting, May 11, 2022

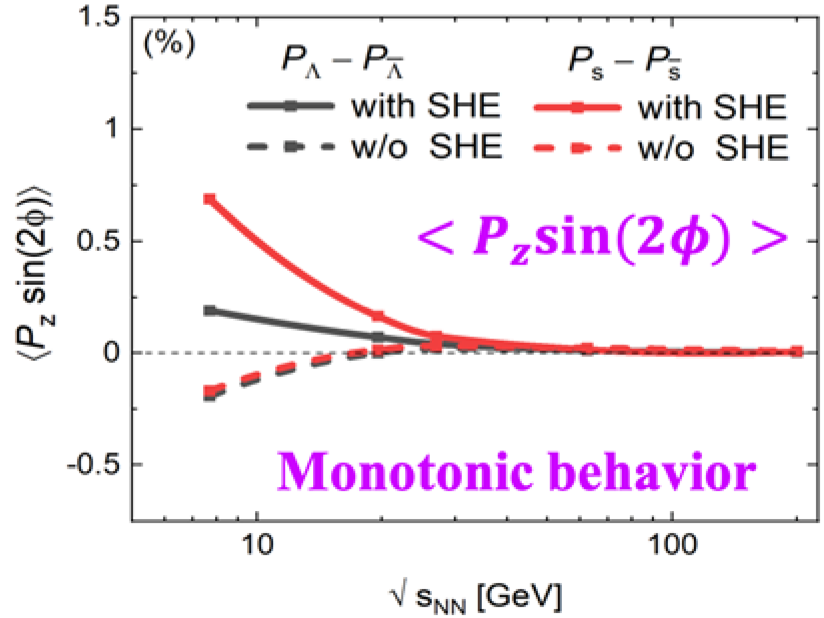
Outline

- **Motivation**
- **Data analysis for Au+Au @ 27 GeV**
  - **Global polarization for Λ**
  - **Local polarization for Λ**
- **Data analysis for Au+Au @ 19.6 GeV**
  - **Global polarization for Λ**
  - **Local polarization for Λ**
- **Summary**

Part I: Motivation

Baryonic Spin Hall Effect





- B. Fu, L. G. Pang, H. Song, Yi Yin, On-line seminar series III on "RHIC Beam Energy Scan: Theory and Experiment", Nov 23,2021
- arXiv:2201.12970v1 [hep-ph] 31 Jan 2022

Proposed signature for SHE:

$< P_y \cos(2\phi) >$ → Non-monotonic energy dependence

$< P_z \sin(2\phi) >$ → Monotonic energy dependence

No investigation of proposed SHE in heavy ion collisions!

Part II

Data analysis for Au+Au @ 27 GeV

Part II: Data analysis (27 GeV)

Dataset and analysis details

Au+Au @ 27 GeV, BES-II
production=P19ib

Event Cuts
— Vertex: $|Vz| < 70$ cm
$|Vr| < 2$ cm

— Trigger ID (610011 || 610011 || 610021 610031 || 610041|| 610051) [minbias]

— Pile-up rejection
— Centrality from "StRefMultCorr"

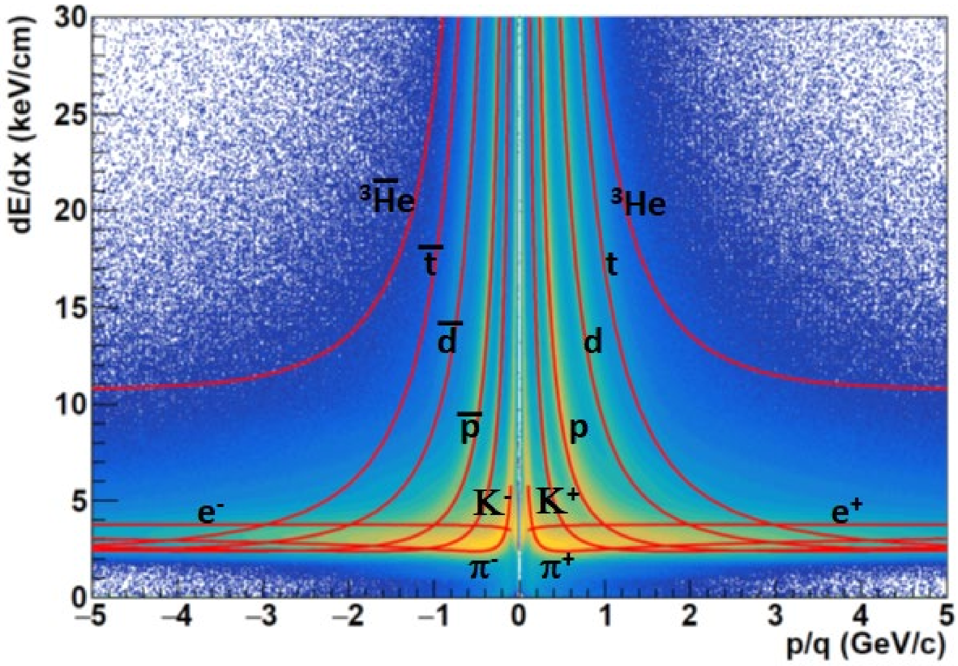
Single track Cuts
— 0.15 GeV/c < p_t < 5 GeV/c
— No. of TPC hits > 15
— Nhits-TPC/Possible Hits >= 0.52
— $|\eta| < 1.0$

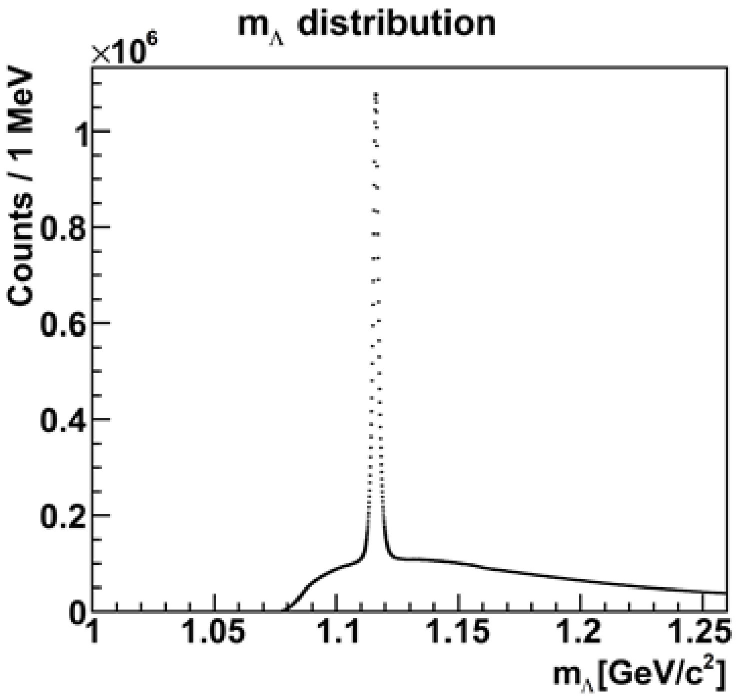
Pion/Proton PID Cuts
— if ToF available
$(1/\beta - 1/\beta_\pi) < 0.03$
$(1/\beta - 1/\beta_p) < 0.04$

— else use TPC
$|N\sigma| < 3$ for both π and p

No. of events for analysis: ~ 378 M → ~ 524 M

Part II: Analysis details (27 GeV)





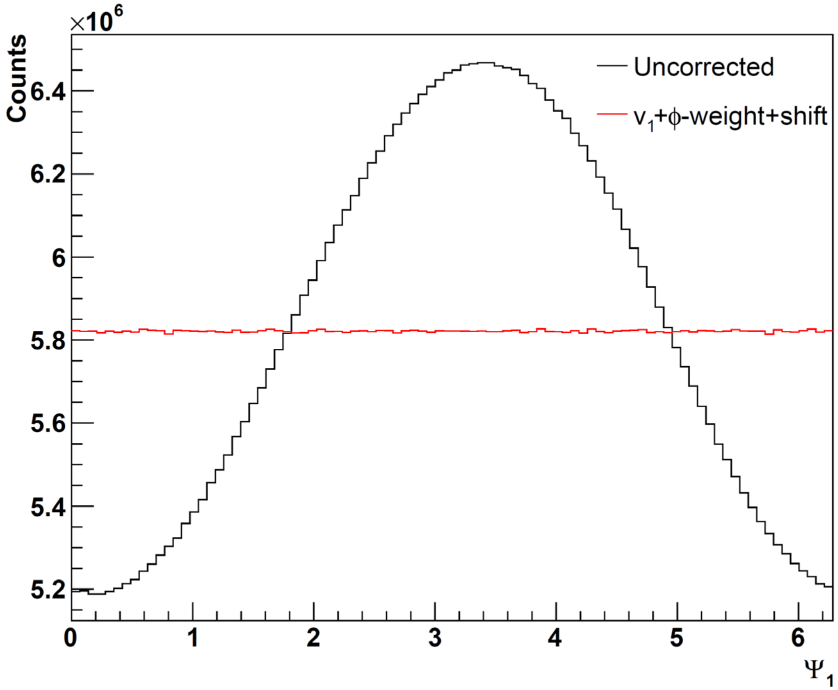
$\Lambda \rightarrow p+\pi^-$

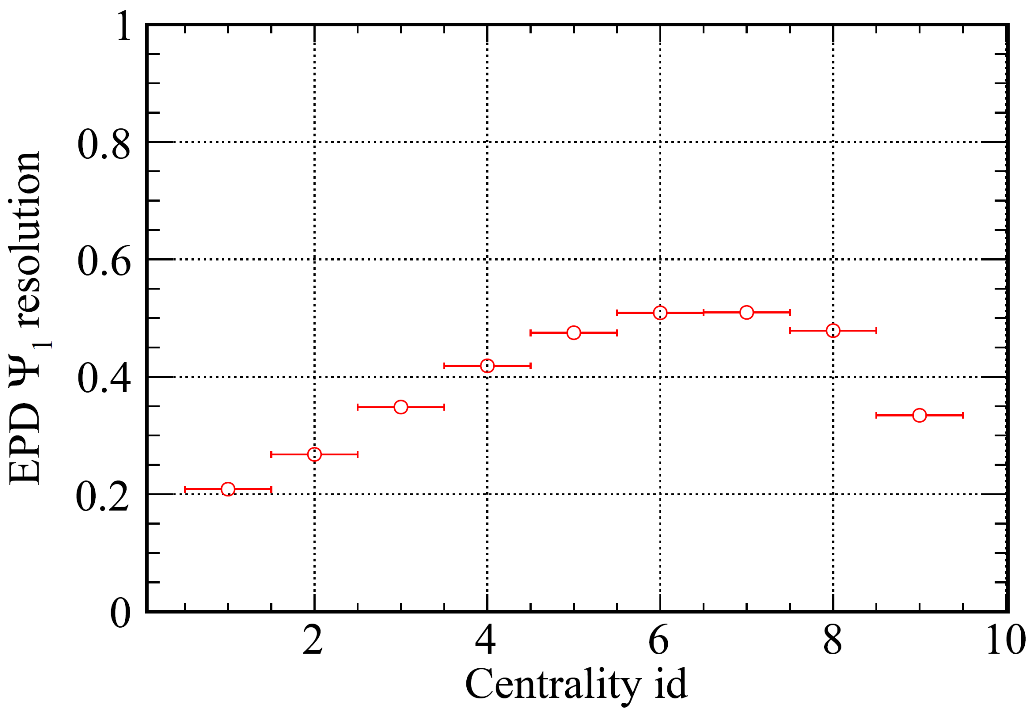
$\bar{\Lambda} \rightarrow \bar{p}+\pi^+$

Using STAR Helix method
- — **Decay length > 3.0 cm**
- — **DCA to prim vertex < 0.8**
- — **DCA between π/p < 0.8**
- — **DCA to p > 0.3**
- — **DCA to π > 1.6**
- — **p & π: p_t>0.15 GeV/c;**
- — **Λ(anti-Λ): p_t>0.5 GeV/c**
- — **$|y_{p\text{-}\pi\ pair}| < 1.0$**

Part II: Analysis details (27 GeV)

Event plane reconstruction (EPD)



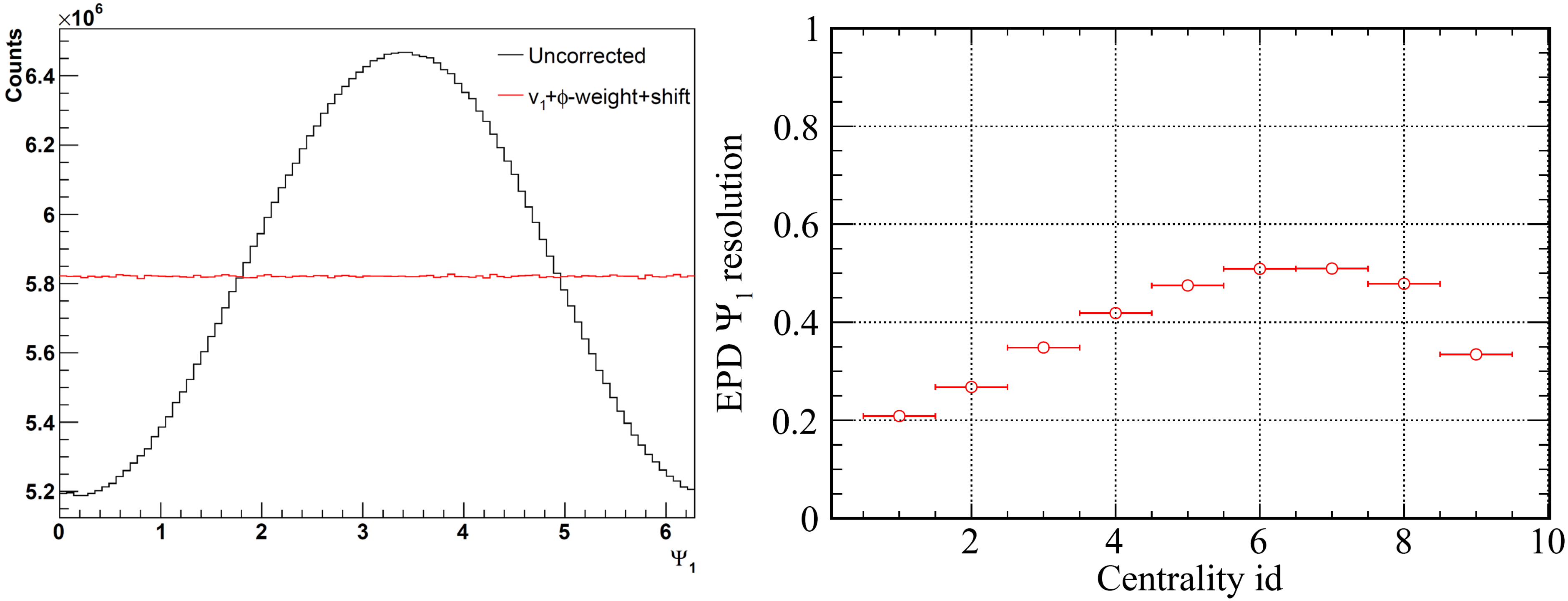


EPD Event Plane Cuts
— Using standard cuts implemented in "StEpdEpFinder" (by Mike Lisa)

Apply phi weights, v1 weights and shift calibrations

Part II: Analysis details (27 GeV)

Event plane reconstruction (EPD)



EPD Event Plane Cuts

— Using standard cuts implemented in "StEpdEpFinder" (by Mike Lisa)

Apply phi weights, v1 weights and shift calibrations

Part II: Analysis details (27 GeV)

Event plane reconstruction (TPC)

TPC Event Plane Cuts

— $|p_t|$ > (0.15 GeV/c && < 2.0 GeV/c)

— |DCA| < 3.0 cm

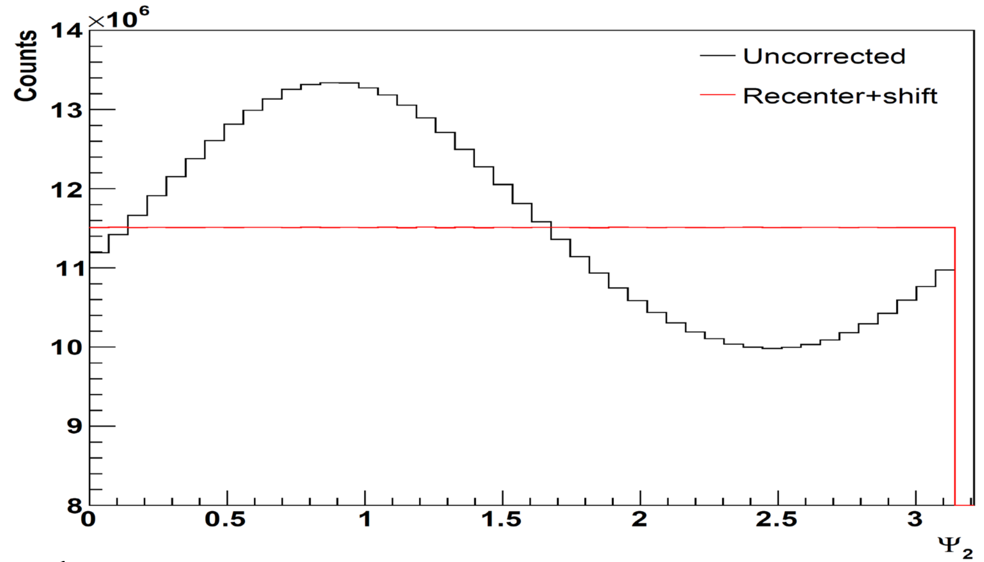
— No. of TPC hits > 15

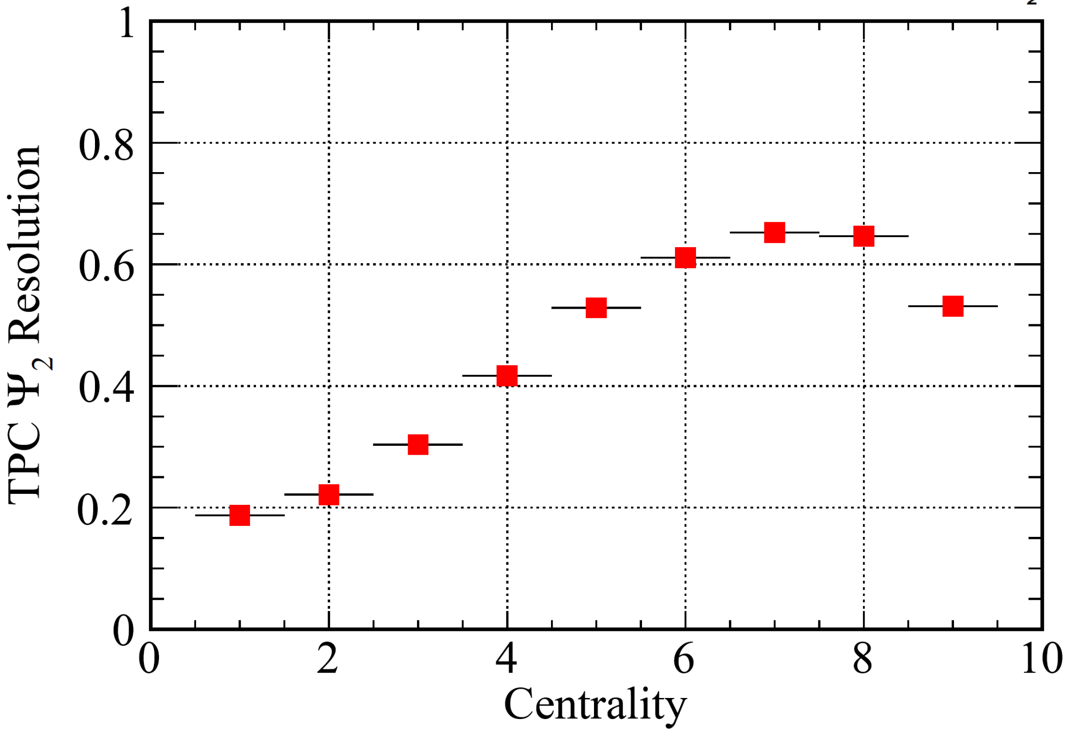
— Nhits-TPC/Possible Hits > 0.52

— $|\eta| < 1.0$

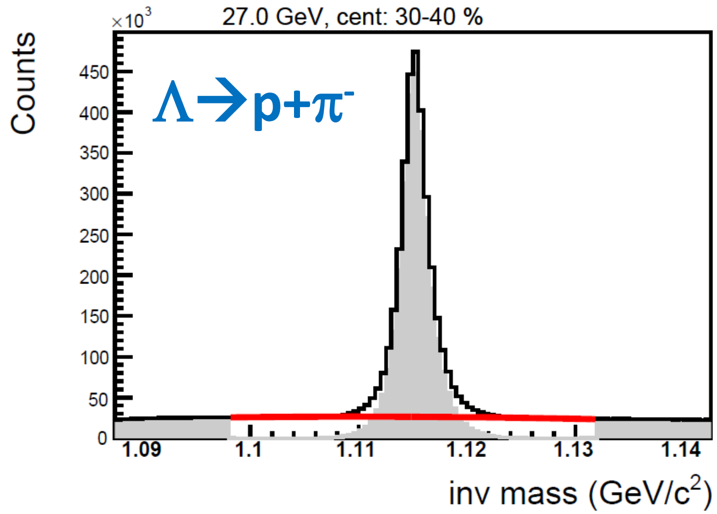
Combined two sub-events with η-gap ~ 0.1

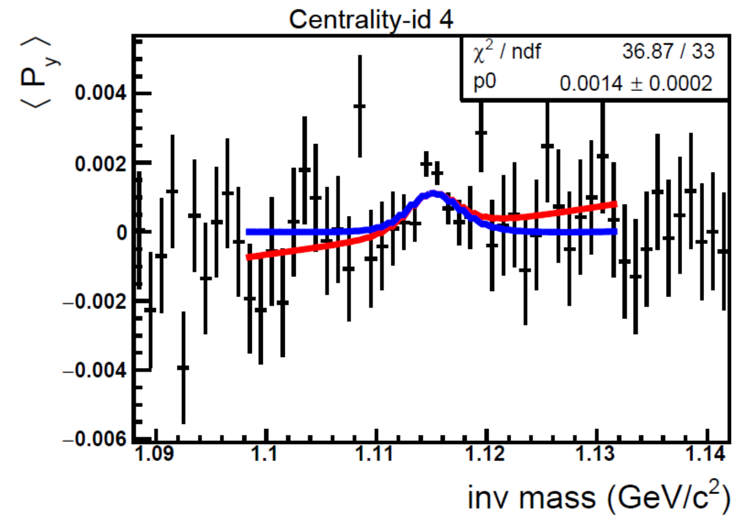
Apply run-by-run and centrality wise re-centering and shift calibrations

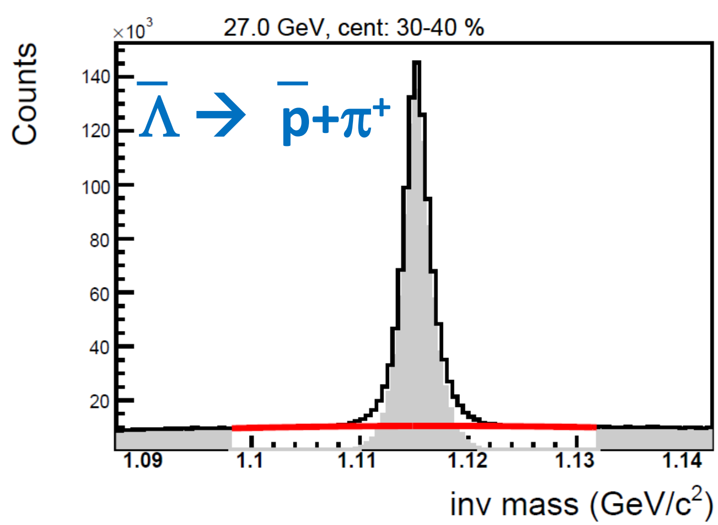


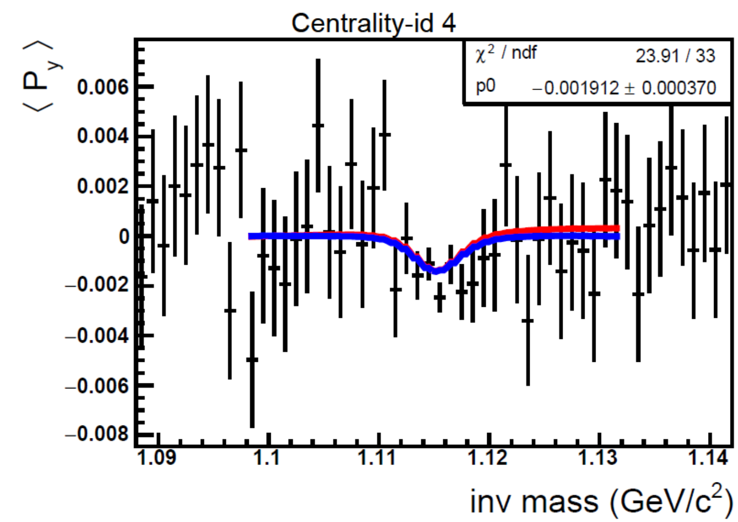


Part II: Global polarization (27 GeV)







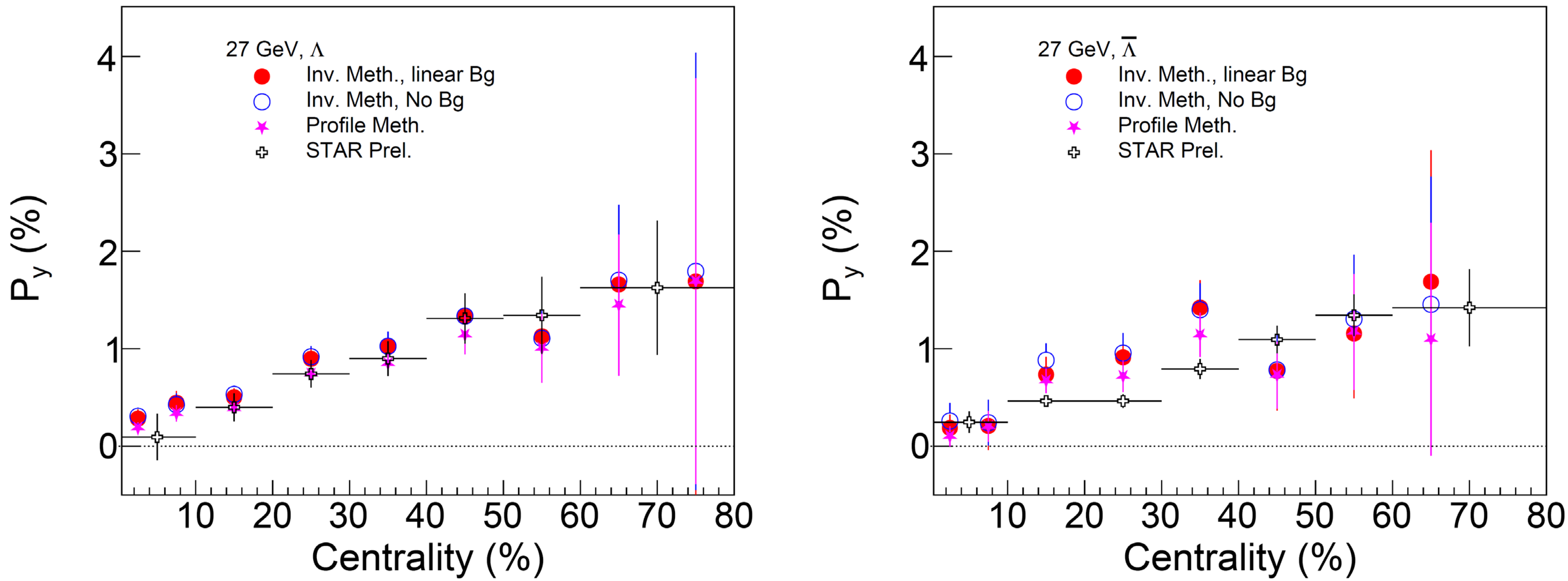


$$\langle\sin(\Delta\phi)\rangle^{\rm obs} = (1 - f^{Bg}(M_{\rm inv}))\langle\sin(\Delta\phi)\rangle^{\rm Sg} + f^{\rm Bg}(M_{\rm inv})\langle\sin(\Delta\phi)\rangle^{\rm Bg}$$

$\Delta\phi=\psi_1-\phi^*_p$

Blue: w/o bkg; Red: with bkg ($\alpha+\beta M_{inv.}$)

Part II: Global polarization (27 GeV)

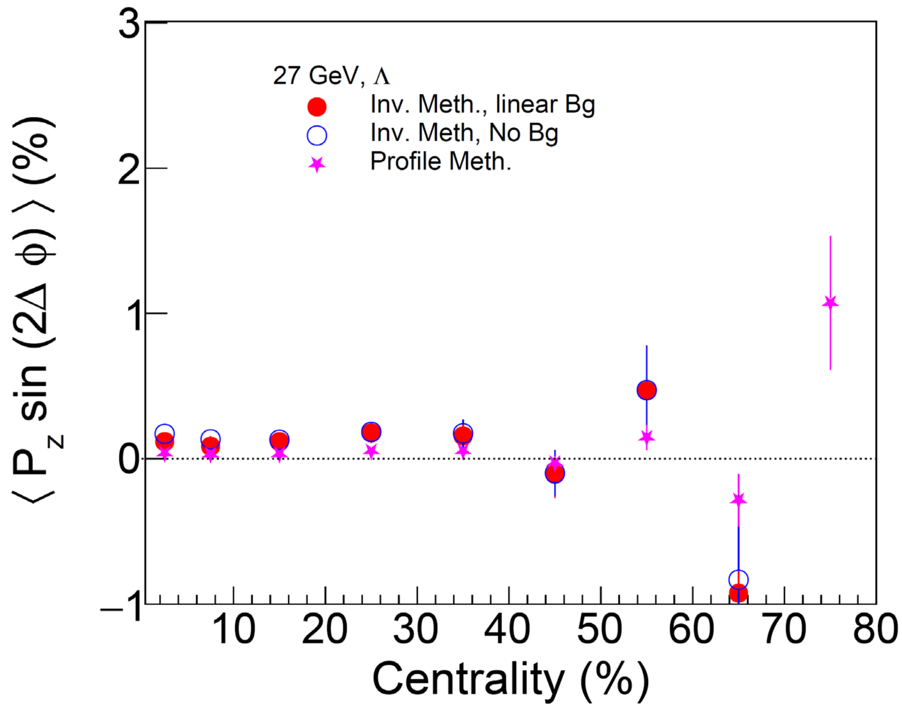


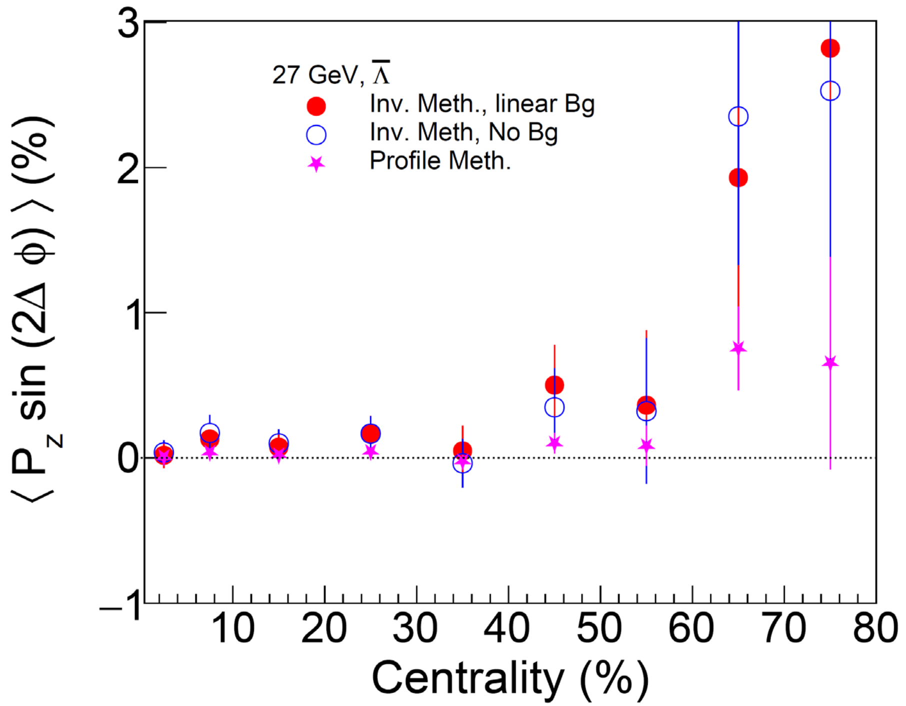
Joey Adams, STAR Collaboration Meeting-FCV PWG, May 2022

0.5 GeV/c<p_t<5.0 GeV/c; |η|<1.0; α(Λ)=0.732

P_y for lambda and anti-lambda increase with centrality, the trend mostly consistent with the previous STAR measurements

Part II: Local polarization (27 GeV)





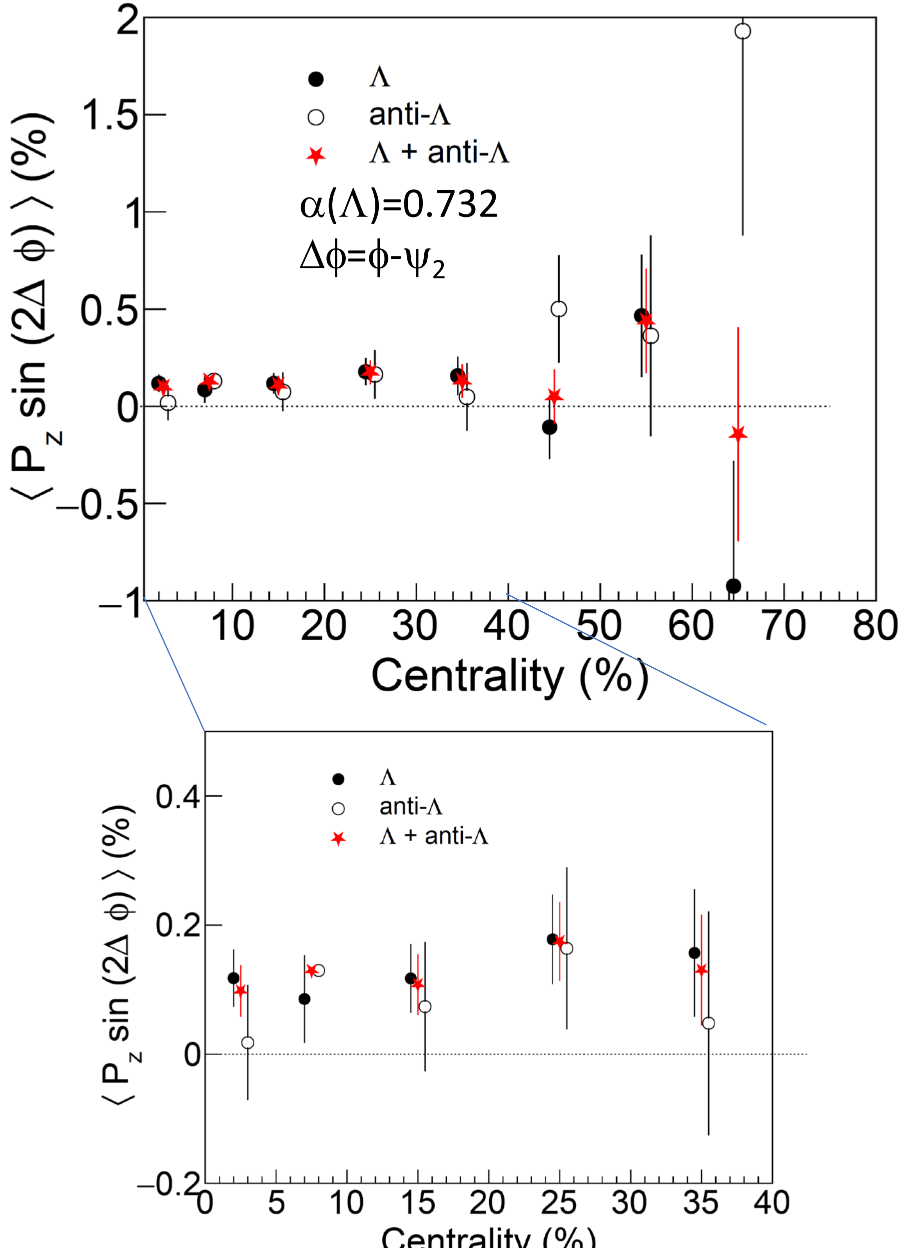
$$P_z = \frac{< cos\theta_p^* >}{\alpha_H < (cos\theta_p^*)^2 >}$$

0.5 GeV/c<p_t<5.0 GeV/c; |η|<1.0

$\alpha(\Lambda)=0.732$; $\Delta\phi=\phi_\Lambda-\psi_2$

For profile method, bkg is included, it will be corrected later.

Part II: Local polarization (27 GeV)



$p_t \in (0.5,5.0)$ **GeV/c**

$|\eta|<1.0$

Part III

Data analysis for Au+Au @ 19.6 GeV

Part III: Data analysis (19.6 GeV)

Dataset and analysis details

Au+Au @ 19.6 GeV, BES-II
production=P21ic

Event Cuts
— Vertex: $|Vz| < 70$ cm
$|Vr| < 2$ cm

— Trigger ID (640002 || 640012 || 640022 || 640032) [minbias-hltgood]

— Pile-up rejection
— Centrality from "StRefMultCorr"

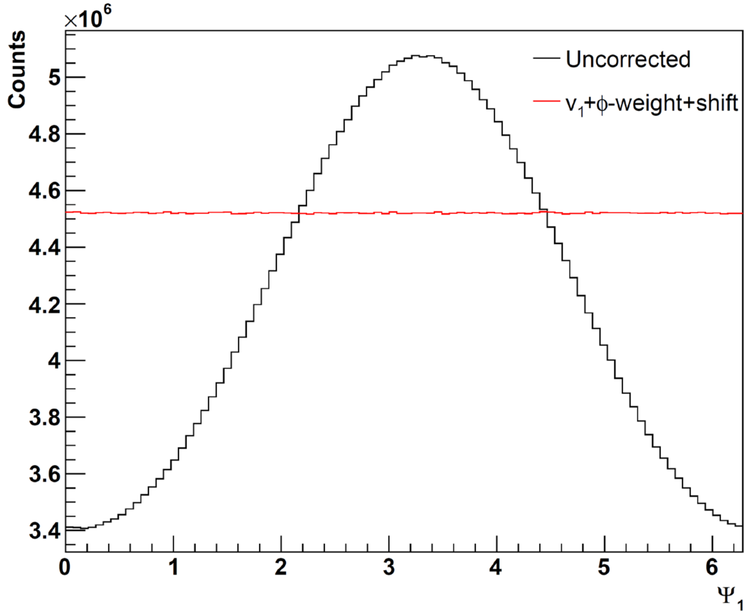
Single track Cuts
— 0.15 GeV/c < p_t < 5 GeV/c
— No. of TPC hits > 15
— Nhits-TPC/Possible Hits >= 0.52
— $|\eta| < 1.5$

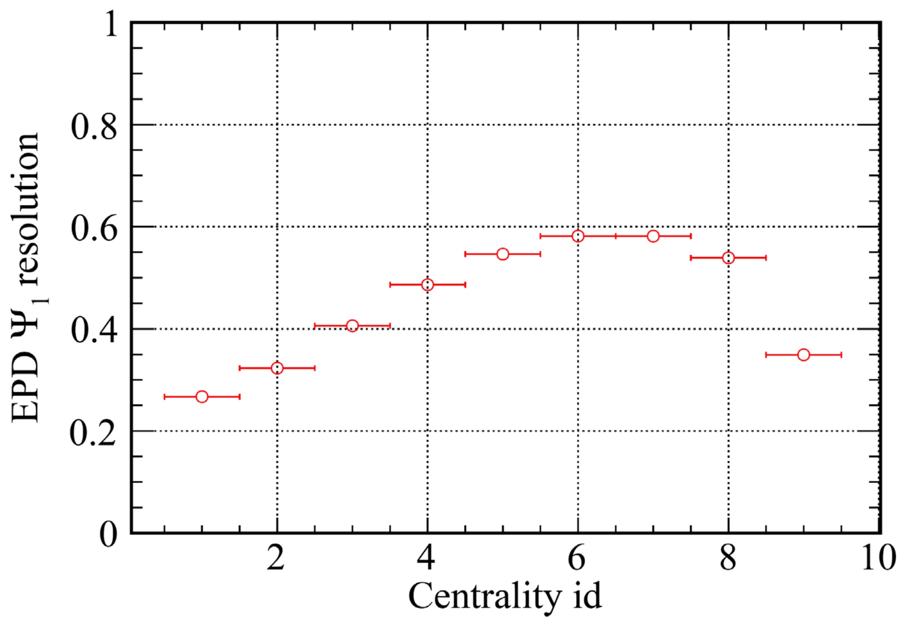
Pion/Proton PID Cuts
— if ToF available
$(1/\beta - 1/\beta_\pi) < 0.03$
$(1/\beta - 1/\beta_p) < 0.04$

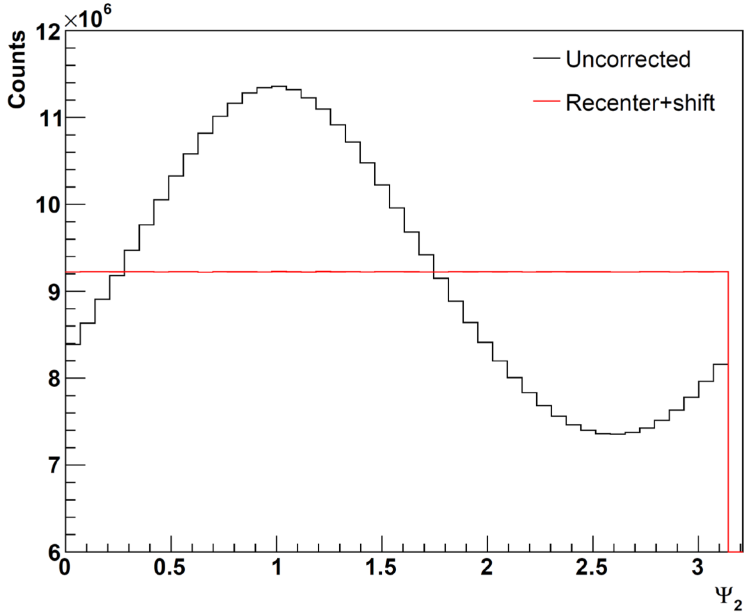
— else use TPC
$|N\sigma| < 3$ for both π and p

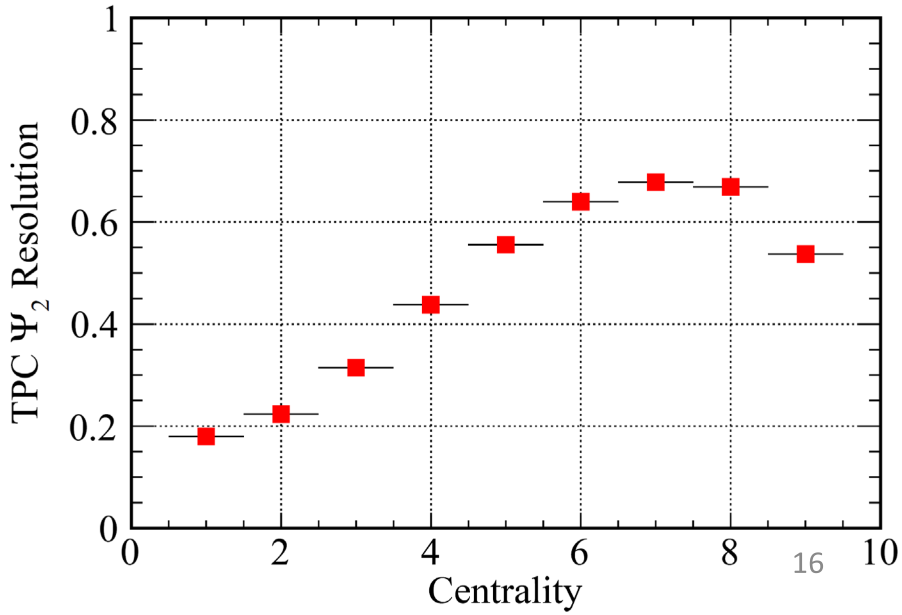
No. of events for analysis: ~ 418 M

Part III: Global polarization (19.6 GeV)

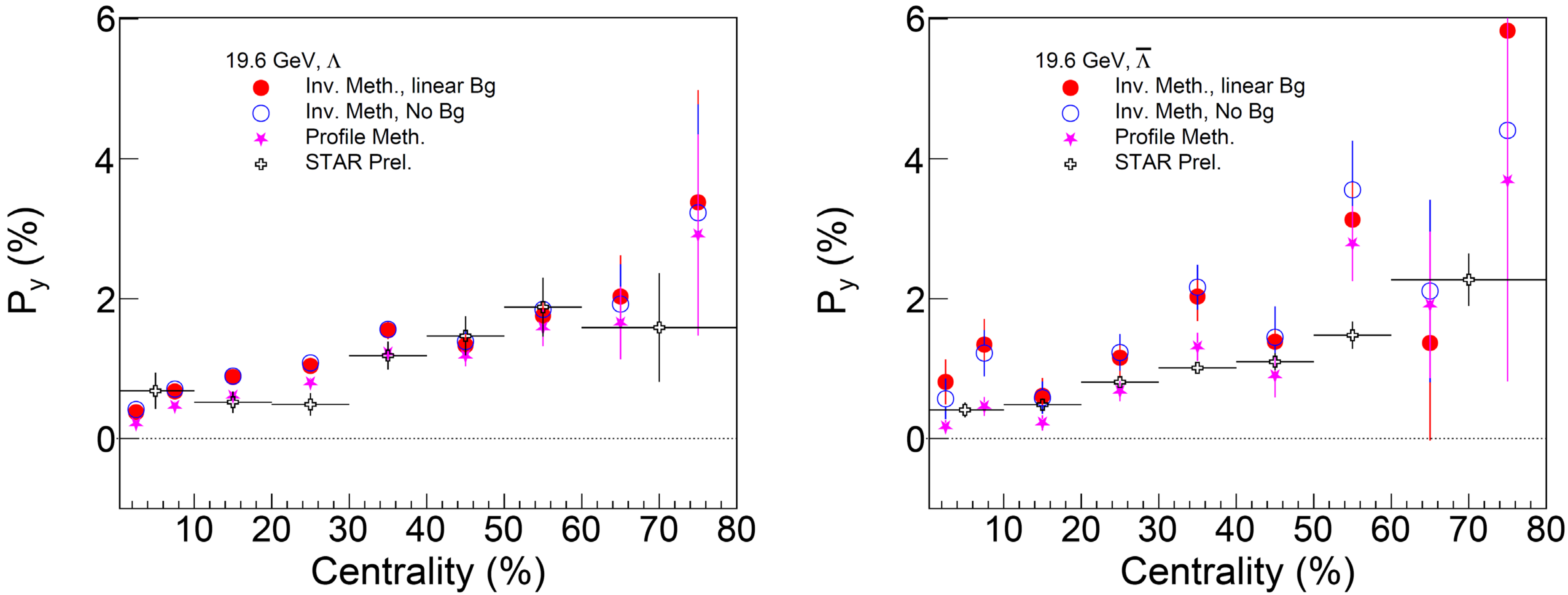








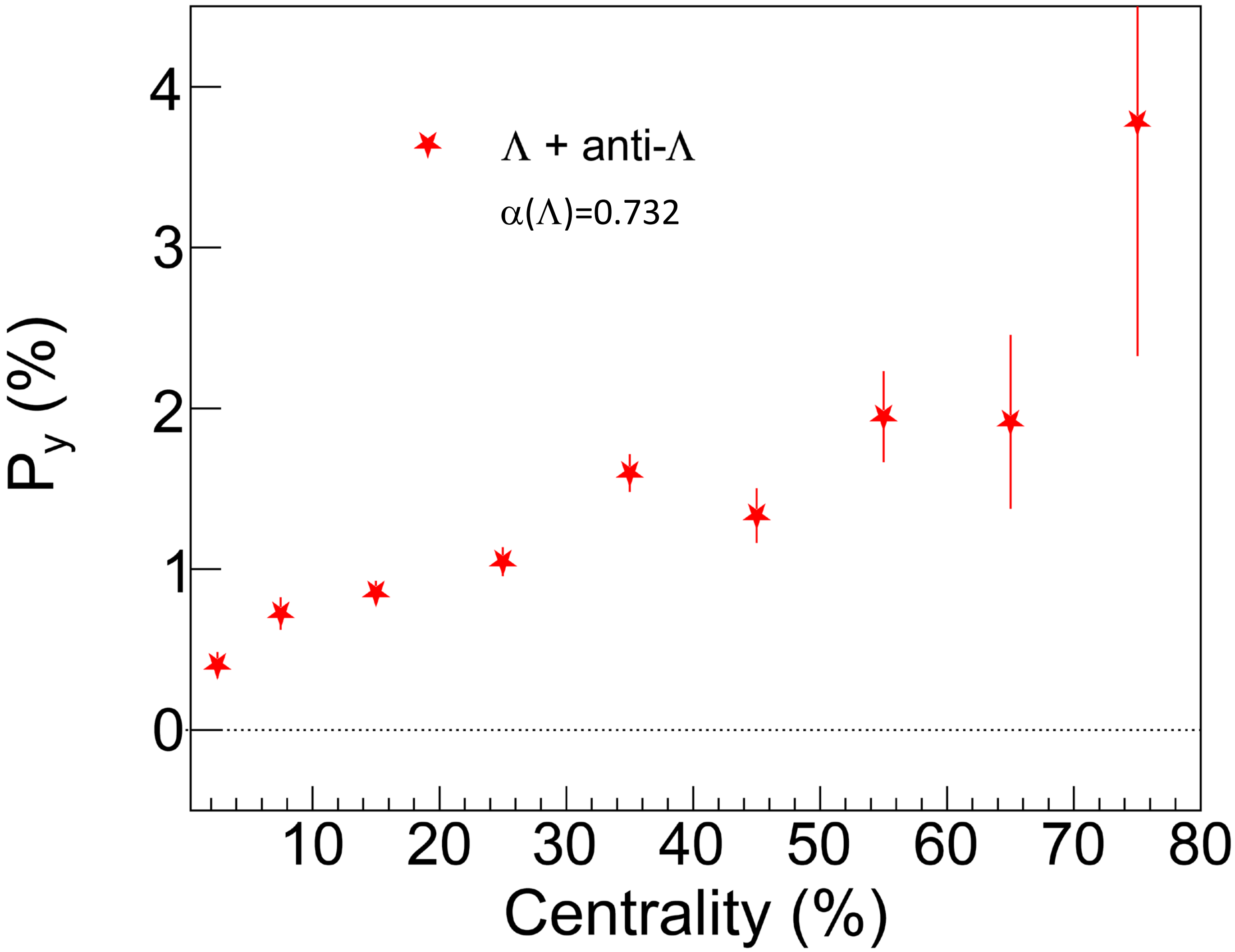
Part III: Global polarization (19.6 GeV)



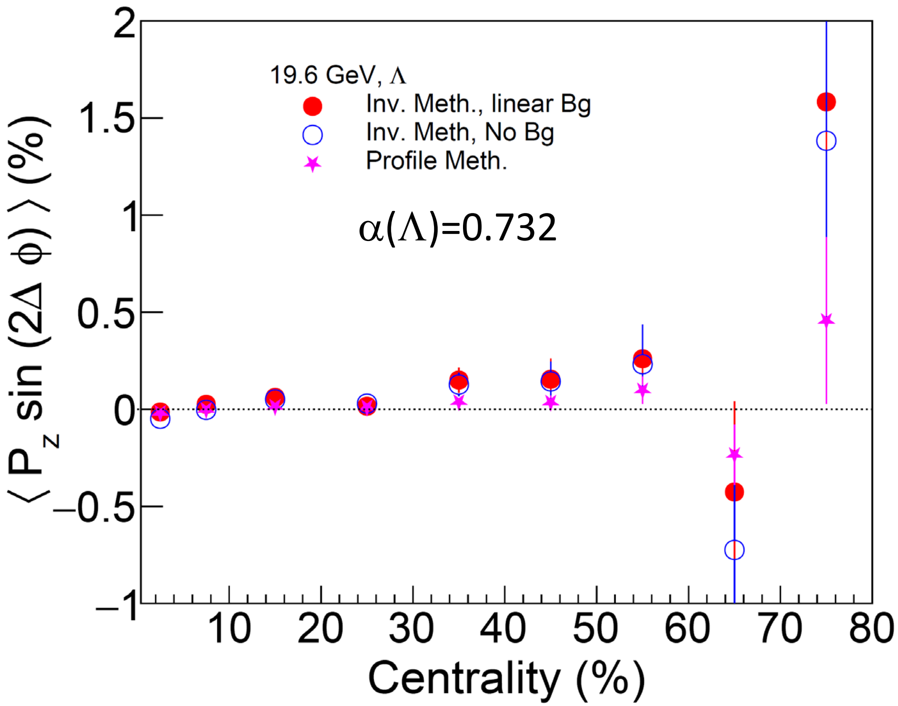
Joey Adams, STAR Collaboration Meeting-FCV PWG, May 2022

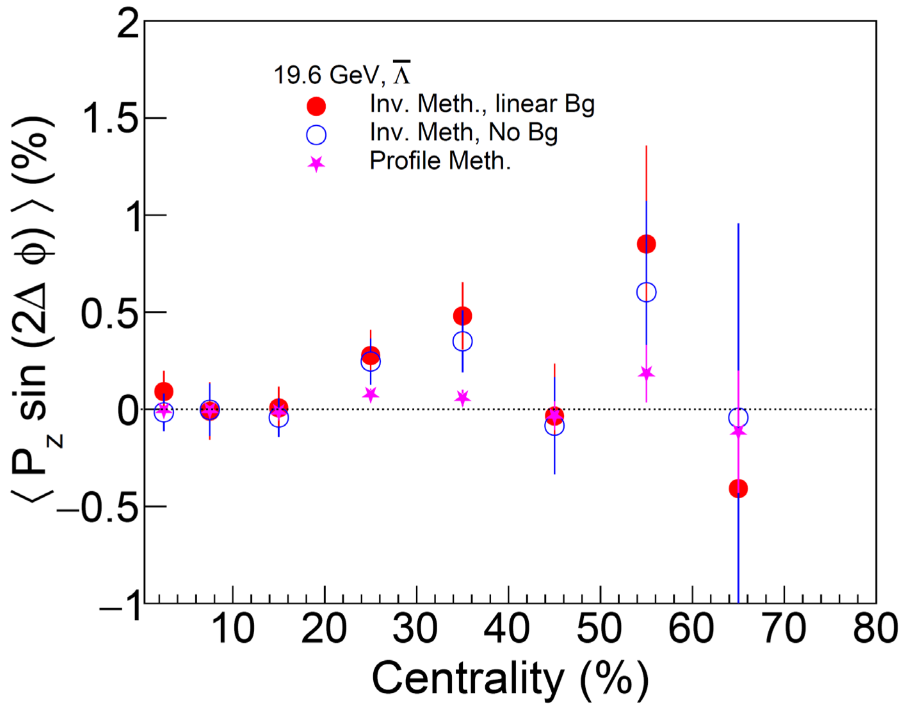
For profile method, bkg is included, it will be corrected later.

Part III: Global polarization (19.6 GeV)



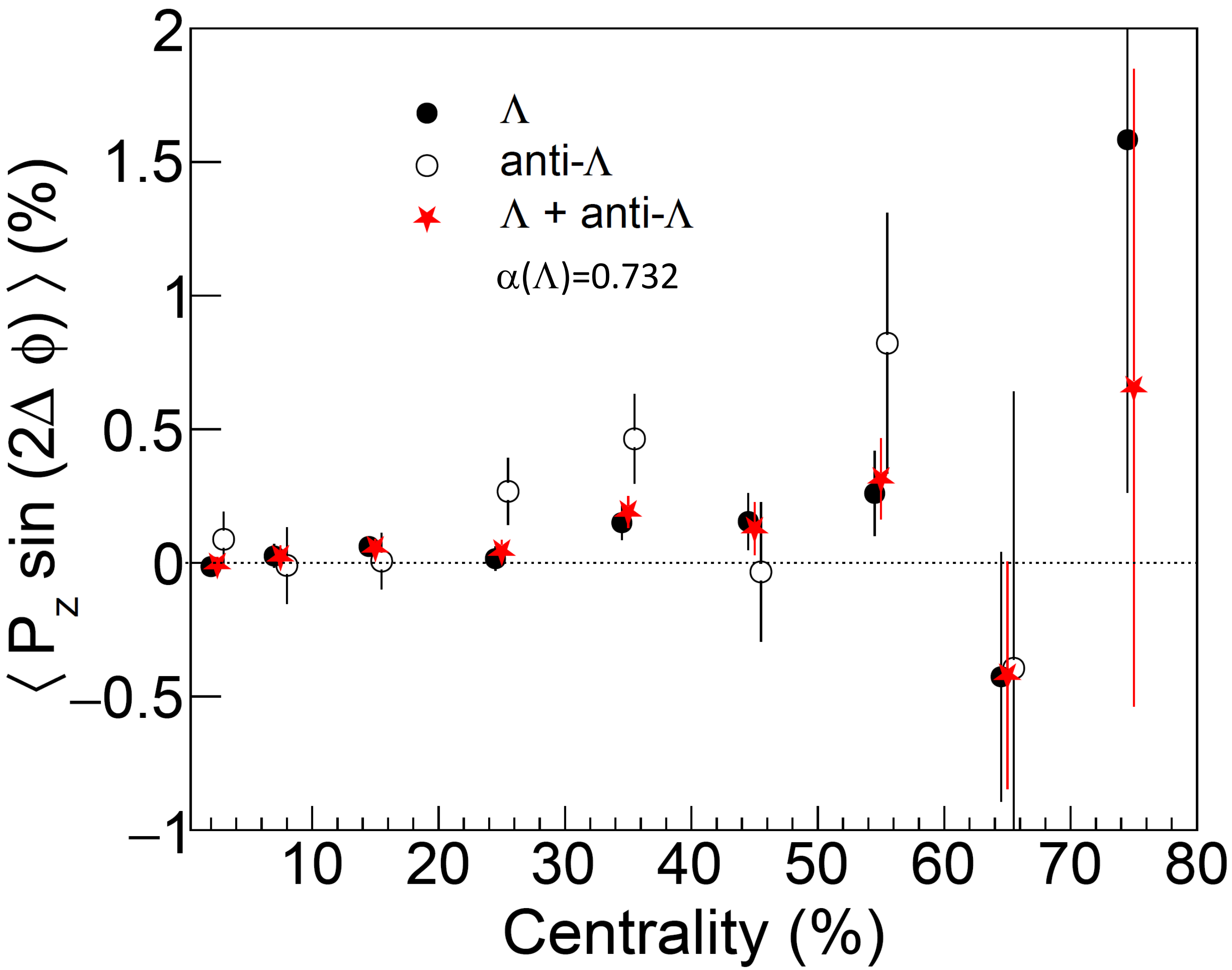
Part III: Local polarization (19.6 GeV)





For profile method, bkg is included, it will be corrected later.

Part III: Local polarization (19.6 GeV)



Summary

- **Centrality dependent global and local polarization of Λ are studied without efficiency correction for Au+Au @ 27 and 19.6 GeV**
- **The trend of Λ's global polarization is consistent with the STAR preliminary one for Au+Au@27 GeV and 19.6 GeV**

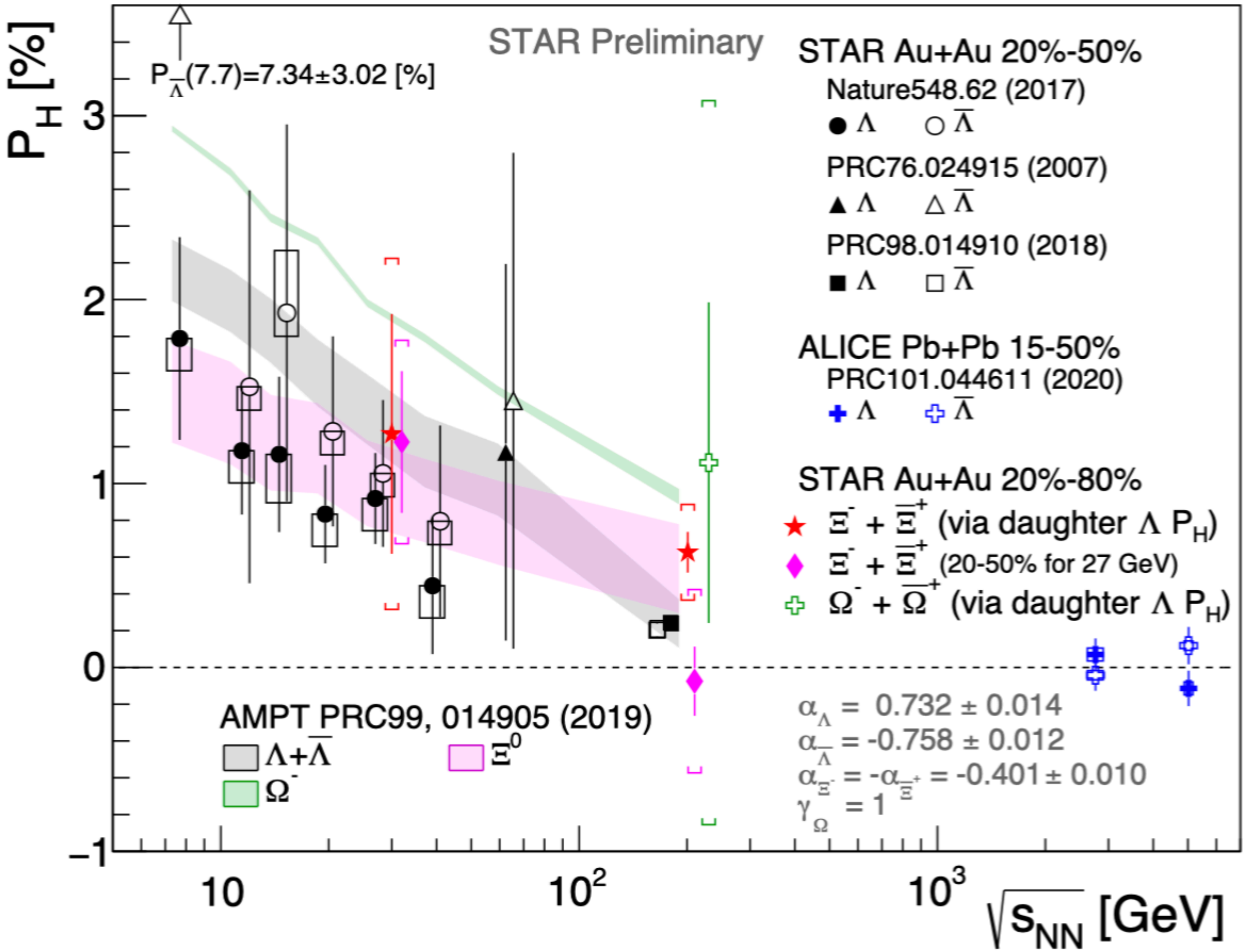
Next steps

- **Extraction of <P_x*sin(2ϕ)> and <P_y*cos(2ϕ)>**
- **Systematic error estimation for local polarization**
- **Continue to analysis the BES-II Au+Au collisions data at lower energies (14.6 GeV and 7.7 GeV et al.) to search SHE signal**

Thank you for your attention!

Part I: Motivation

Global spin polarization of hyperons



$$\bar{P}_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{1}{R_{EP}^{(1)}}\langle \sin(\psi_1 - \phi_p^*)\rangle$$

α_Λ: Λ's decay parameter

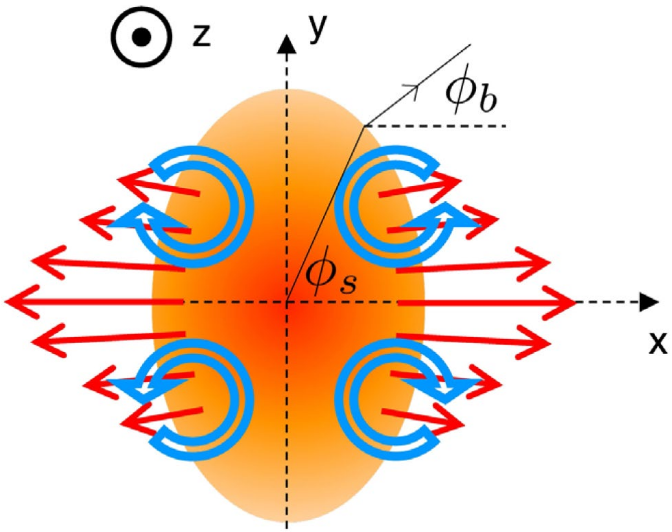
ϕ_p^*: the azimuthal angle of the daughter proton in Λ rest frame

$P_{\Lambda,\,\Xi,\,\Omega}$ ~ Positive and non-zero across BES energies

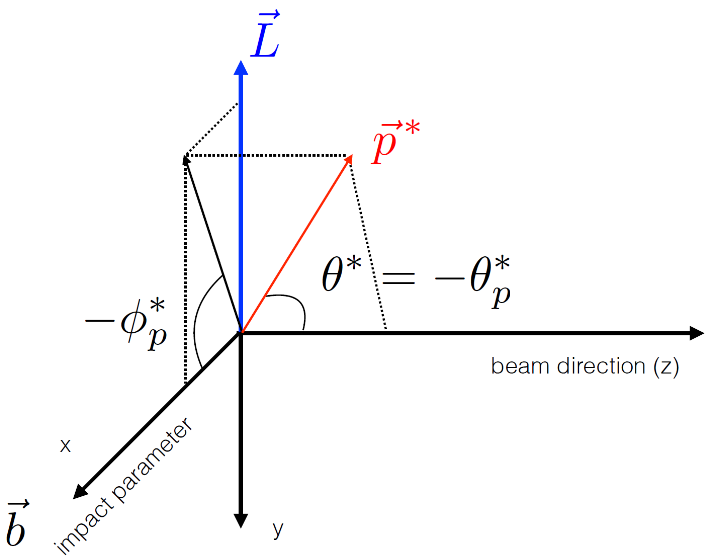
→ Global nature of hyperon polarization in HIC

Part I: Motivation

Local spin polarization of hyperons



- Elliptic flow (stronger flow in-plane than out-of-plane) is expected to generate a longitudinal component of polarization (P_z)



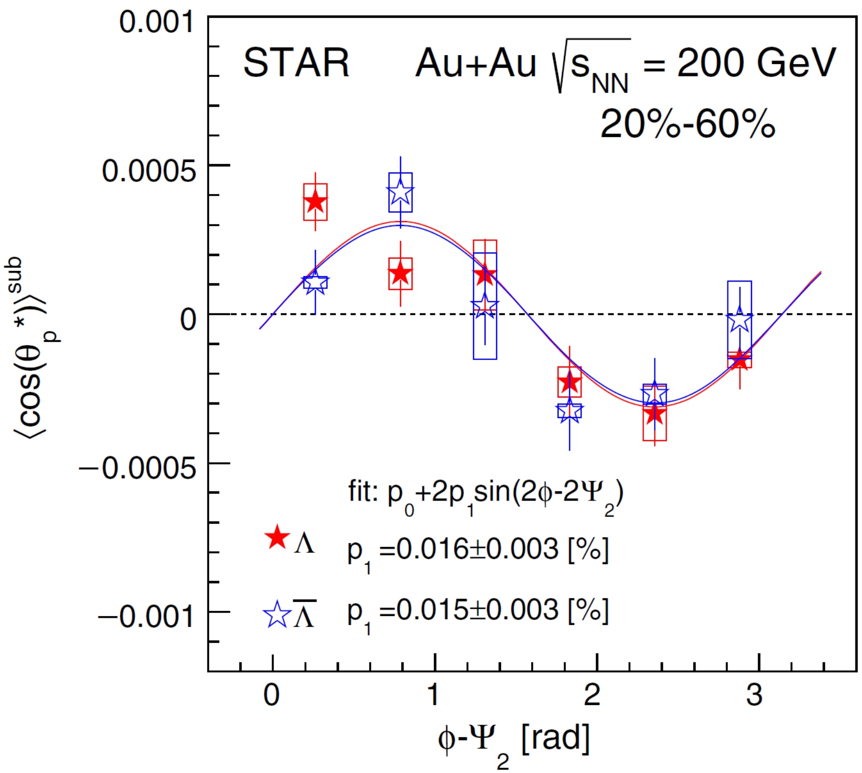
$$P_z = \frac{< cos\theta_p^* >}{\alpha_H < (cos\theta_p^*)^2 >}$$

θ*: angle between daughter proton momentum vector in Λ rest frame and polarization direction

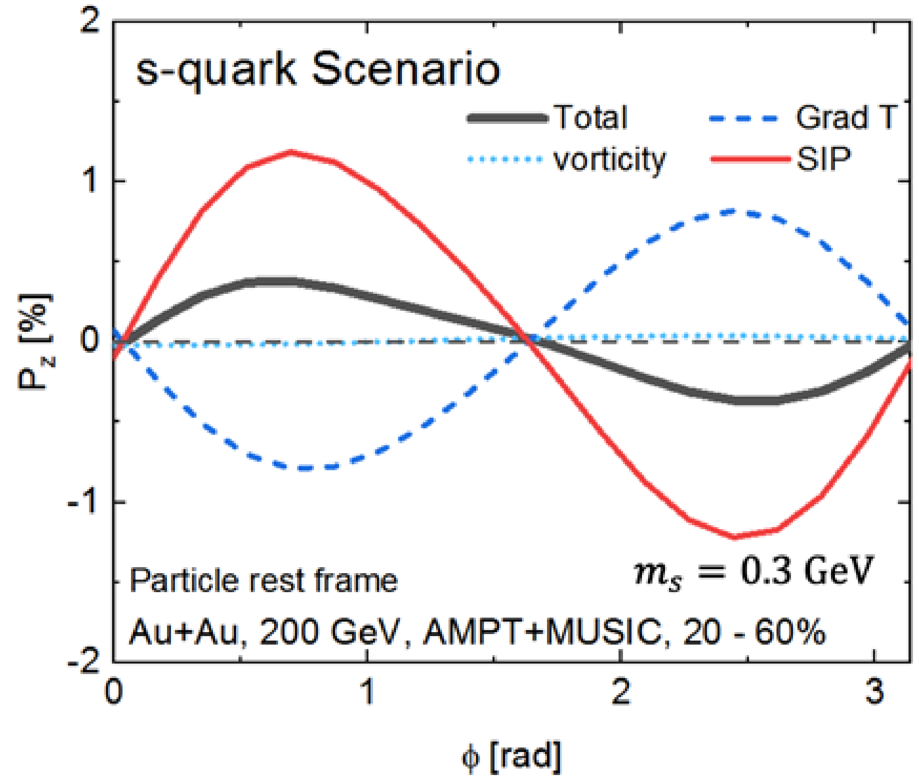
PRL 123,132301 (2019)

Part I: Motivation

Local spin polarization of hyperons



PRL 123,132301 (2019)



Total: Vorticity + Grad T + SIP

B. Fu, S. Liu et al. PRL 127,142301 (2021)

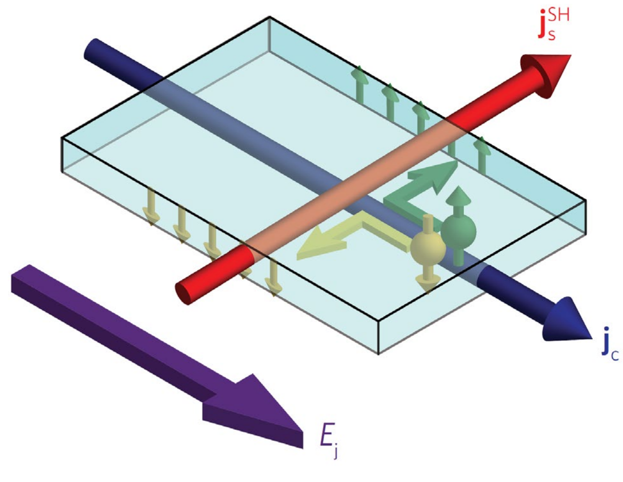
- **Observation of (P_z) in Au+Au 200 GeV**
- **Many models fail to capture trend with proper sign**
- **New developments, Shear Induced Polarization (SIP) can capture the trend**

Part I: Motivation

Baryonic Spin Hall Effect

Spin Hall Effect in Condensed matter: $s \propto \pm \boldsymbol{p} \times \boldsymbol{E}$

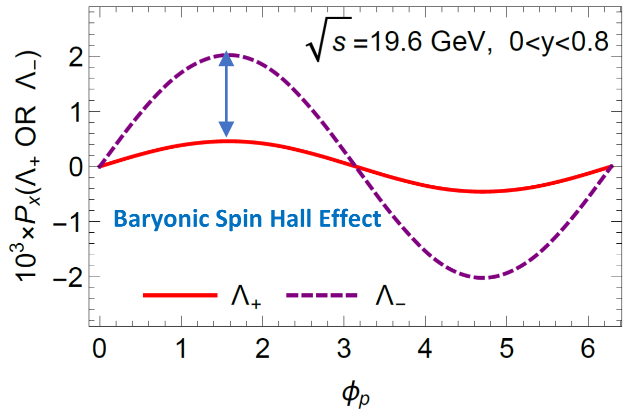
Electric field (E) —"Spin-orbit" interaction→ **Splitting in spin in opposite directions**



Spin Hall effect, (1972) 2004

Spin Hall Effect in hot QCD matter: $s \propto \pm \boldsymbol{p} \times \nabla \mu_B$

Baryon density gradient ($\nabla \mu_B$) —"Spin-orbit" interaction→ **Splitting in spin between Λ and anti-Λ local spin polarization**



S. Liu & Y. Yin, Phys. Rev. D 104 (2021) 054043 (IMP,CAS)

Backup

Spin Hall Effects in Heavy Ion Collisions

Can we observe and explore SHE in heavy ion collisions ?

SHE for hot **QCD** matter $\vec{P}_{\pm} \propto \pm \hat{p} \times \nabla \mu_B$

- -Induced by baryon density gradient ⟶ RHIC –BES & forward rapidity
- -Sign dependence on baryon charge ⟶ Net Lambda Polarization
- -Momentum dependence ⟶ Local polarization

(For global polarization, see arXiv:2106.08125)

Expand /decompose $\mathcal{A}^\mu$ to 1st order gradient of the fields:

$$\mathcal{A}^\mu(x,p) = \beta f_0(x,p)(1-f_0(x,p))\varepsilon^{\mu\nu\alpha\rho} \times \Big(\underbrace{\frac{1}{2}p_\nu \partial_\alpha^\perp u_\rho}_{\text{vorticity}} + \underbrace{\frac{1}{\beta}u_\nu p_\alpha \partial_\rho \beta}_{\text{T-gradient}} - \underbrace{\frac{p_\perp^2}{\varepsilon_0}u_\nu Q_\alpha^\lambda \sigma_{\rho\lambda}}_{\text{SIP}} - \underbrace{\frac{q_B}{\varepsilon_0 \beta}u_\nu p_\alpha \partial_\rho(\beta\mu_B)}_{\text{SHE}} \Big),$$

-Λ, + $\bar{\Lambda}$
-s, + $\bar{s}$

Spin Cooper-Fryer:

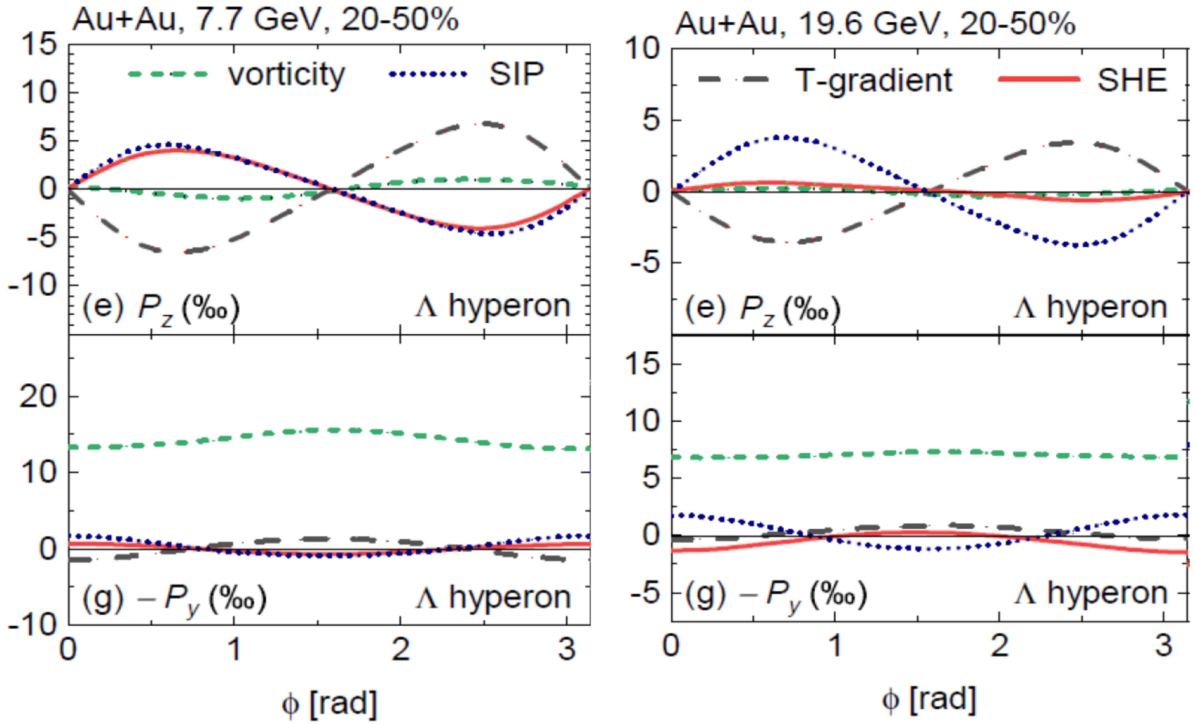
$$P^\mu(\boldsymbol{p}) = \frac{\int d\Sigma^\alpha p_\alpha \mathcal{A}^\mu(x,\boldsymbol{p};m)}{2m\int d\Sigma^\alpha p_\alpha f_0(x,p)},$$

S. Y. F.Liu and Y. Yin, JHEP07, 188 (2021); *Phys.Rev.D* 104 5, 054043(2021); 29
B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

B. Fu, L. G. Pang, H. Song, Yi Yin, On-line seminar series III on "RHIC Beam Energy Scan: Theory and Experiment", Nov 23,2021

Backup

Competition between different effects

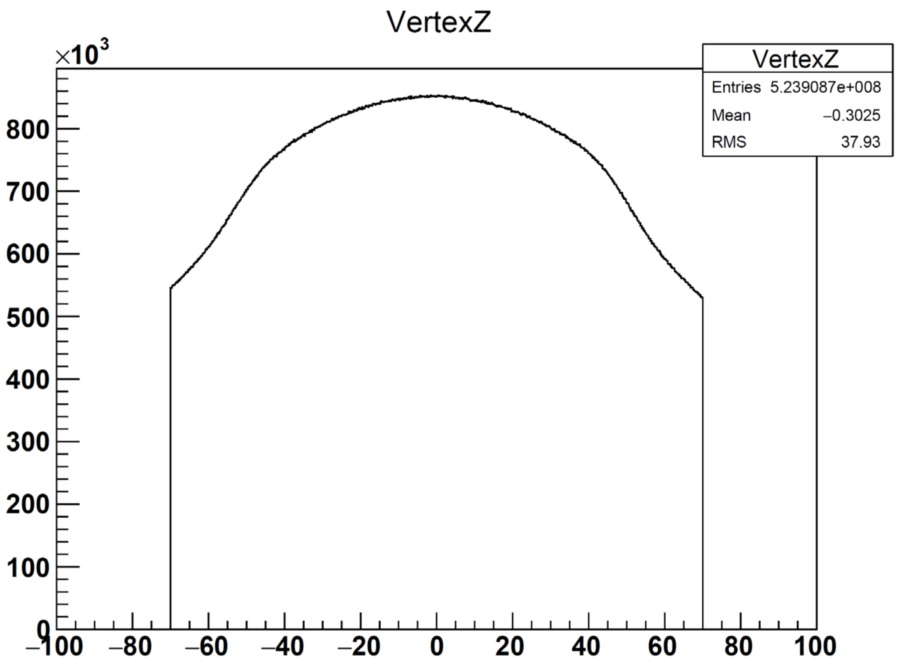


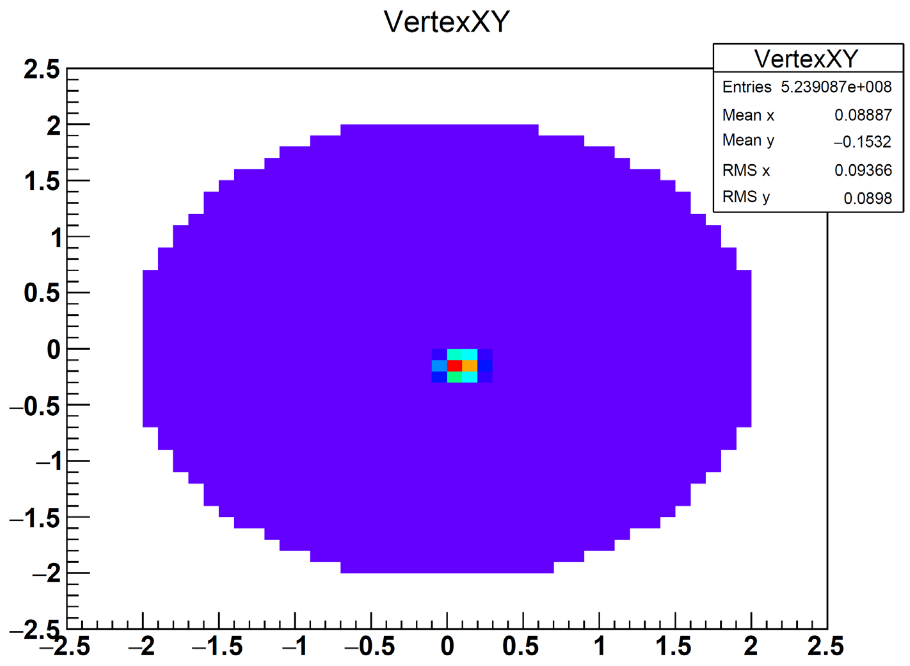
-SHE(μ_B gradient effects): comparable to T-gradient and Shear (SIP) effects

depends on collision energy

31

B. Fu, L. G. Pang, H. Song, Yi Yin, On-line seminar series III on "RHIC Beam Energy Scan: Theory and Experiment", Nov 23,2021

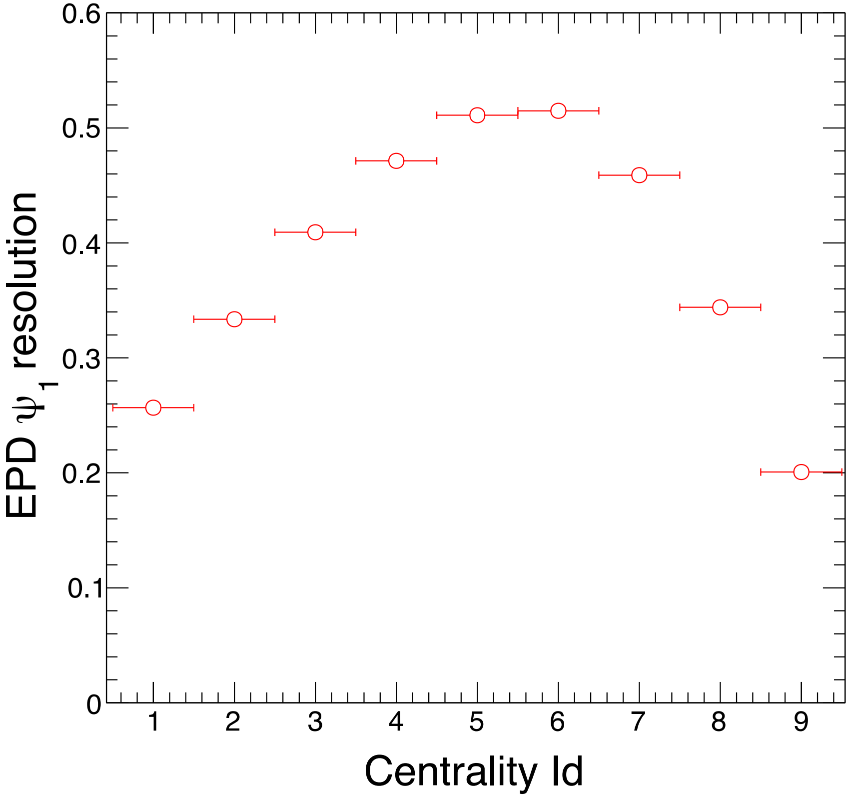




update vertex distribution

Part II: Analysis details

Event plane reconstruction (EPD)



EPD Event Plane Cuts

— Using standard cuts implemented in "StEpdEpFinder" (by Mike Lisa)

Apply phi weights, v1 weights and shift calibrations

2021.12.15

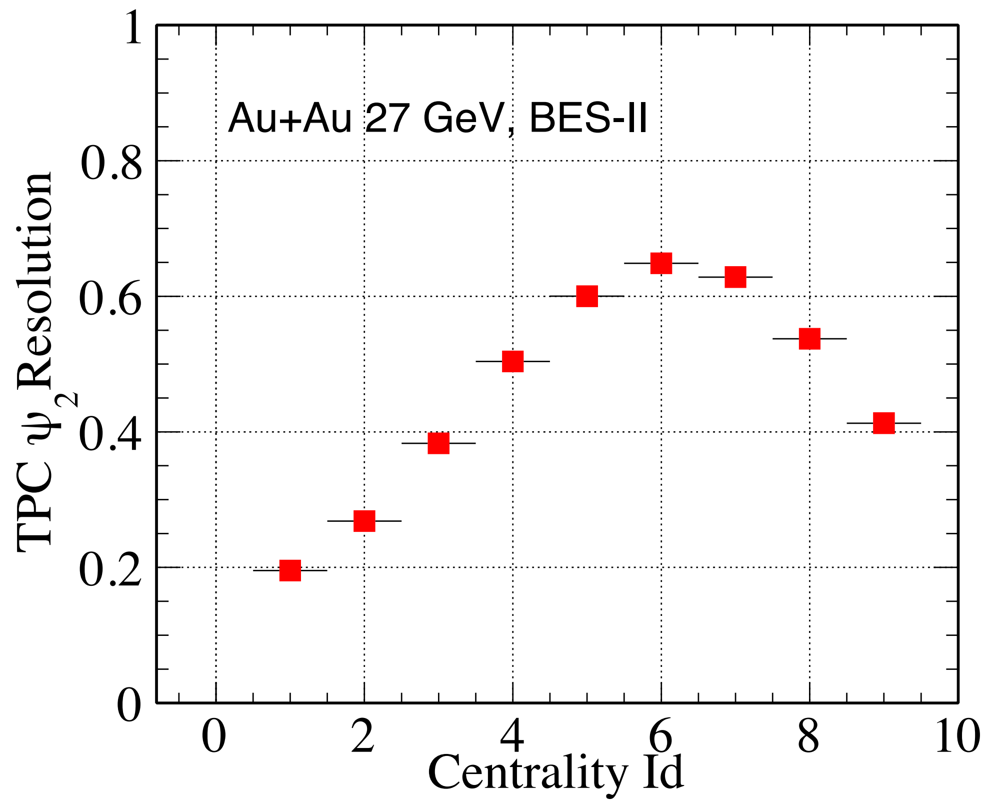
Part II: Analysis details

Event plane reconstruction (TPC)

TPC Event Plane Cuts
— $|p_t|$ > (0.15 GeV/c && < 2.0 GeV/c)
— |DCA| < 3.0 cm
— No. of TPC hits > 15
— Nhits-TPC/Possible Hits > 0.52
— $|\eta|$ < 1.0

Combined two sub-events with η-gap ~ 0.1

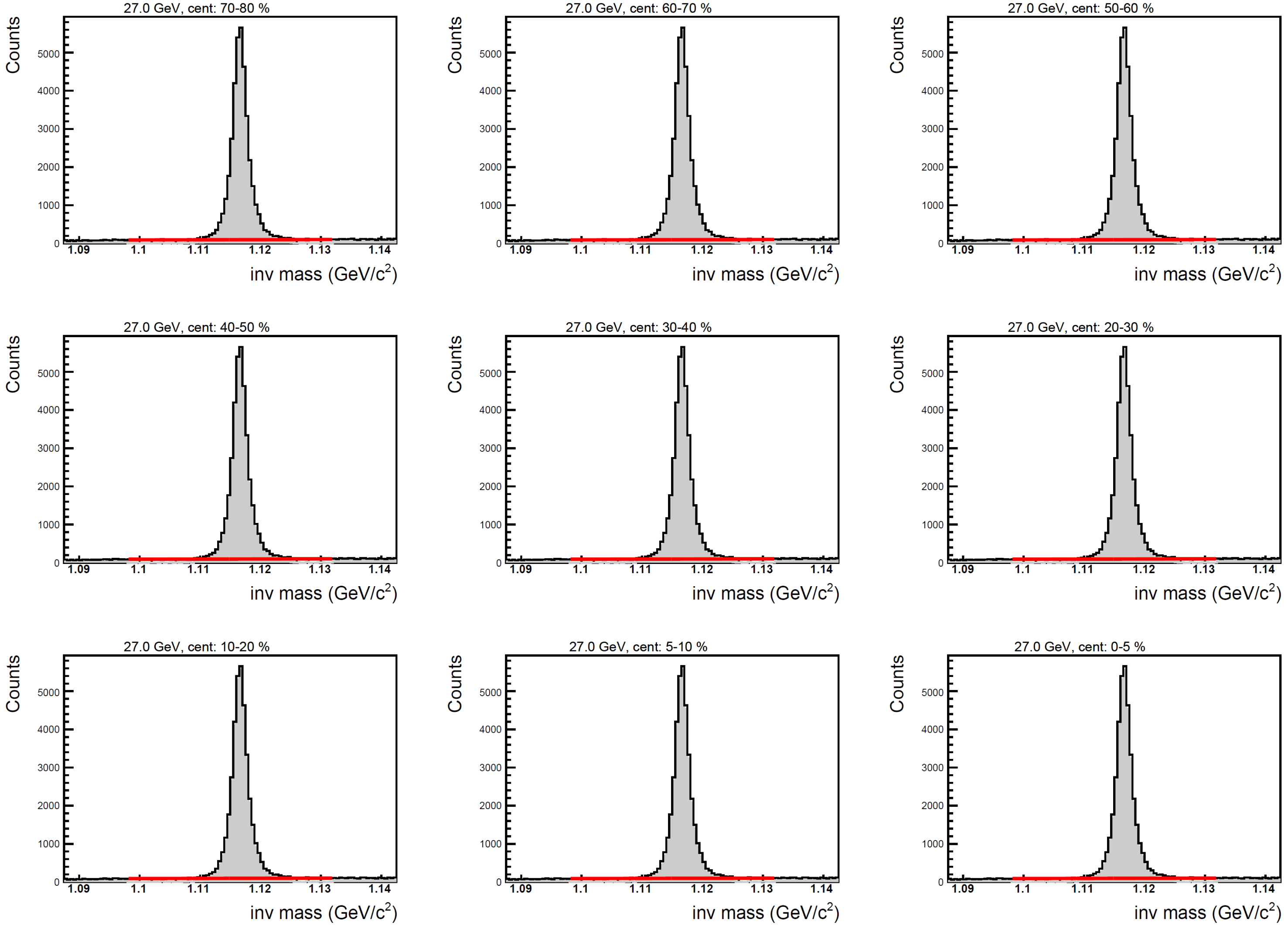
Apply run-by-run and centrality wise re-centering and shift calibrations



2021.12.15

Part II: Global polarization (27 GeV)

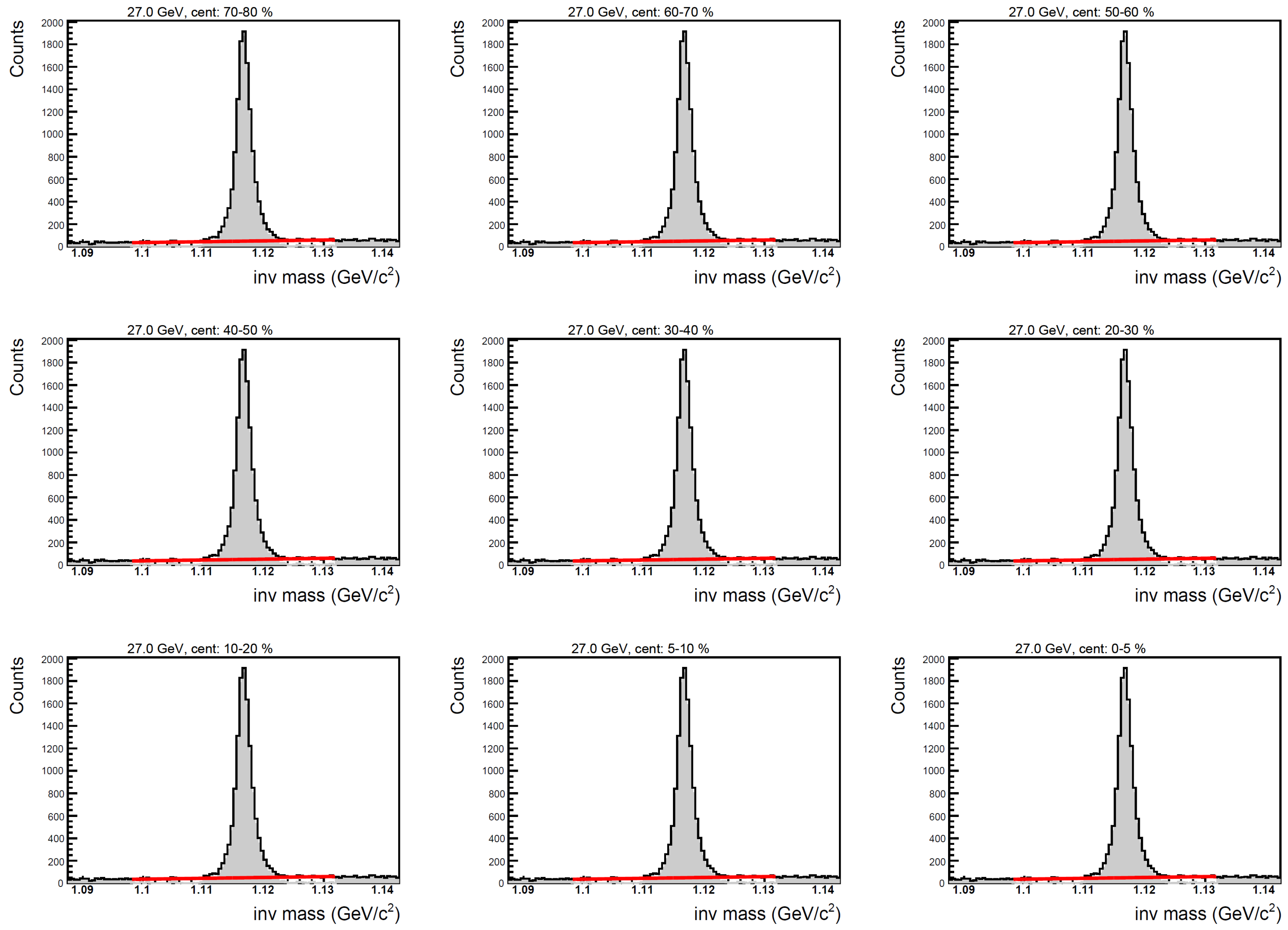
$\Lambda \rightarrow p+\pi^-$



Different panels are Λ invariant mass spectra for different centrality

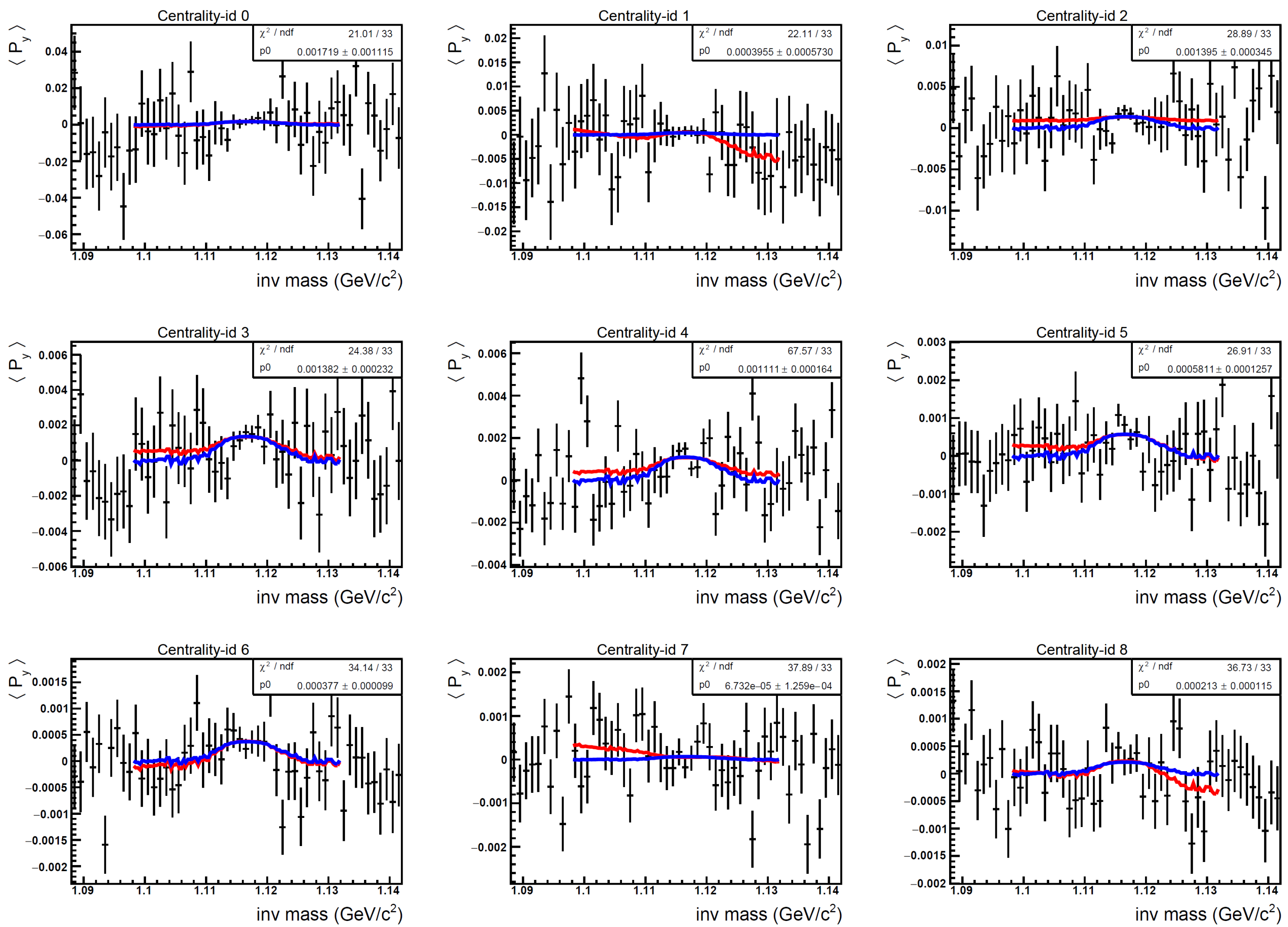
Part III: Global polarization (27 GeV)

$\bar{\Lambda} \rightarrow \bar{p}+\pi^+$



Different panes are anti-Λ invariant mass spectra for different centrality

Part III: Global polarization (27 GeV)



Λ

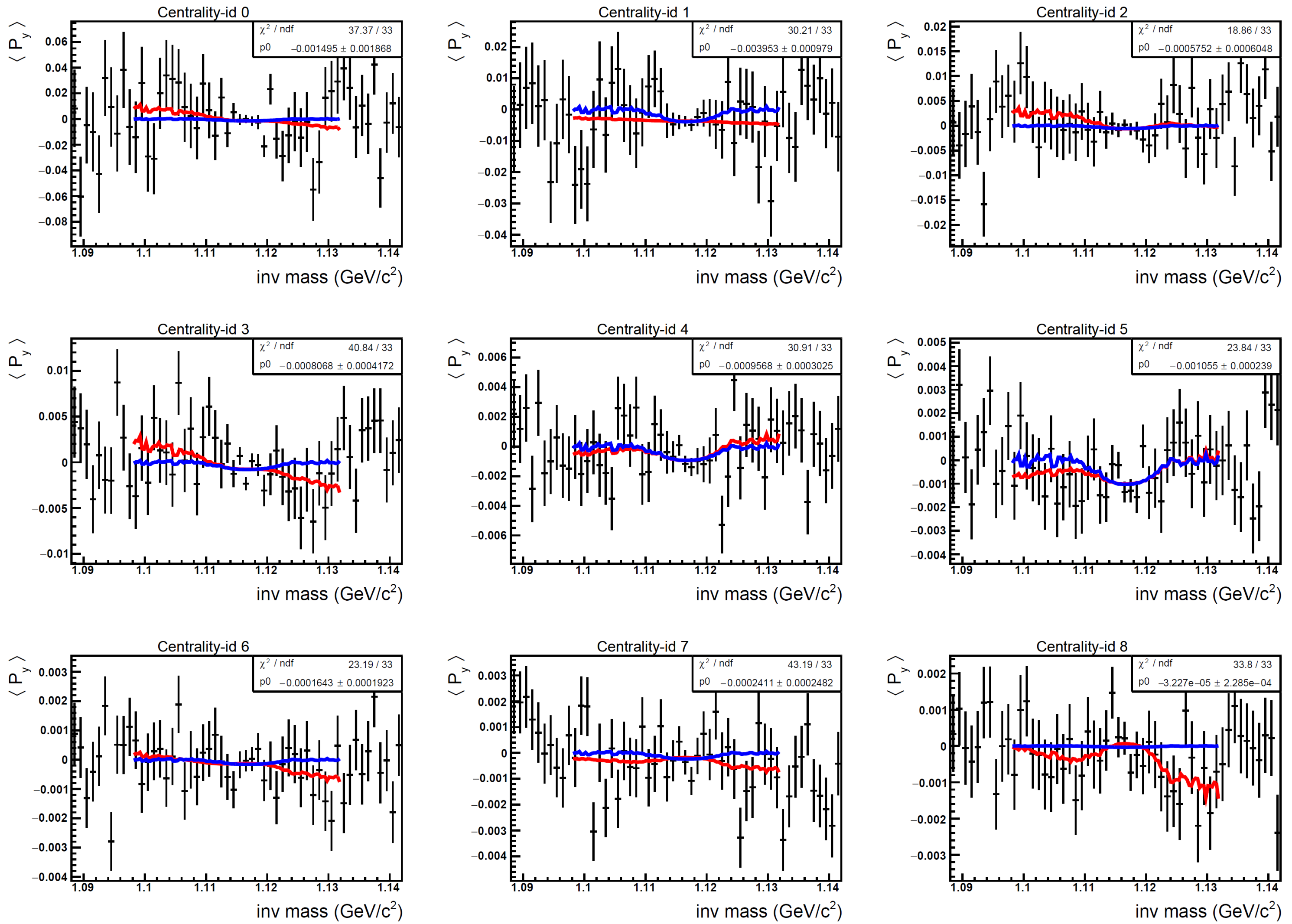
$$\langle\sin(\Delta\phi)\rangle^{\mathrm{obs}} = (1 - f^{Bg}(M_{\mathrm{inv}}))\langle\sin(\Delta\phi)\rangle^{\mathrm{Sg}} + f^{\mathrm{Bg}}(M_{\mathrm{inv}})\langle\sin(\Delta\phi)\rangle^{\mathrm{Bg}}$$

$\Delta\phi=\psi_1-\phi^*_p$

Blue: w/o bkg; Red: with bkg ($\alpha+\beta M_{inv.}$)

Part II: Global polarization (27 GeV)

anti-Λ

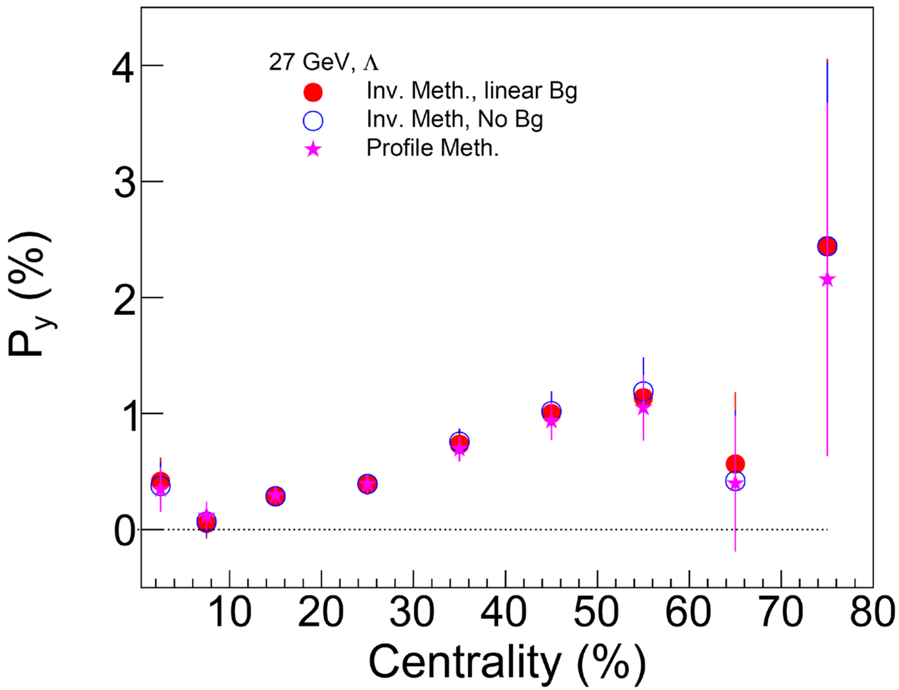


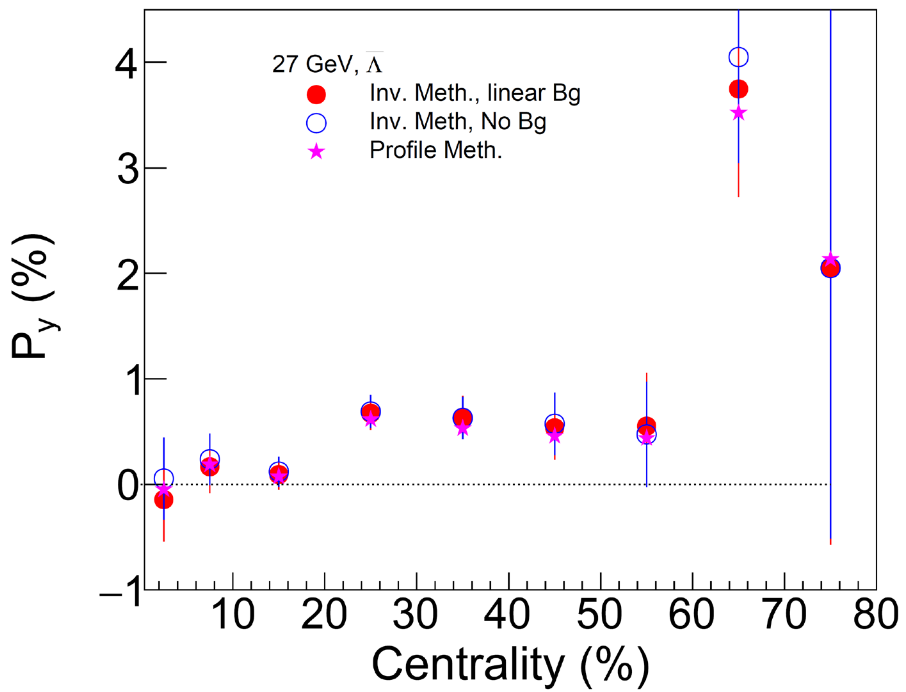
$$\langle\sin(\Delta\phi)\rangle^{\rm obs} = (1 - f^{Bg}(M_{\rm inv}))\langle\sin(\Delta\phi)\rangle^{\rm Sg} + f^{\rm Bg}(M_{\rm inv})\langle\sin(\Delta\phi)\rangle^{\rm Bg}$$

$\Delta\phi=\psi_1-\phi^*_p$

Blue: w/o bkg; Red: with bkg ($\alpha+\beta M_{inv.}$)

Part III: Global polarization



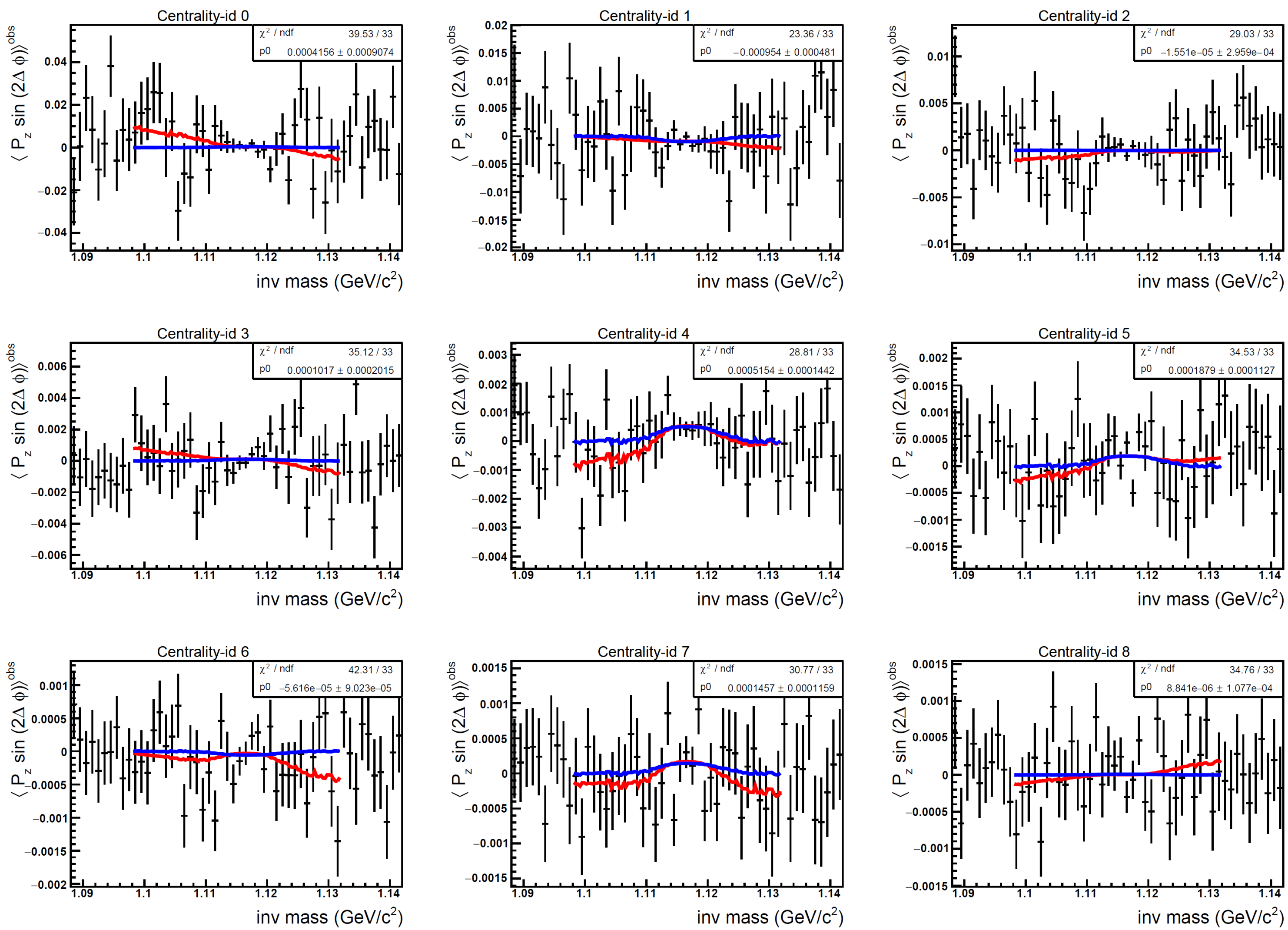


0.5 GeV/c<p_t<5.0 GeV/c; |η|<1.0

α(Λ)=0.732; α(anti-Λ)=-0.758

Part IV: Local polarization

Λ

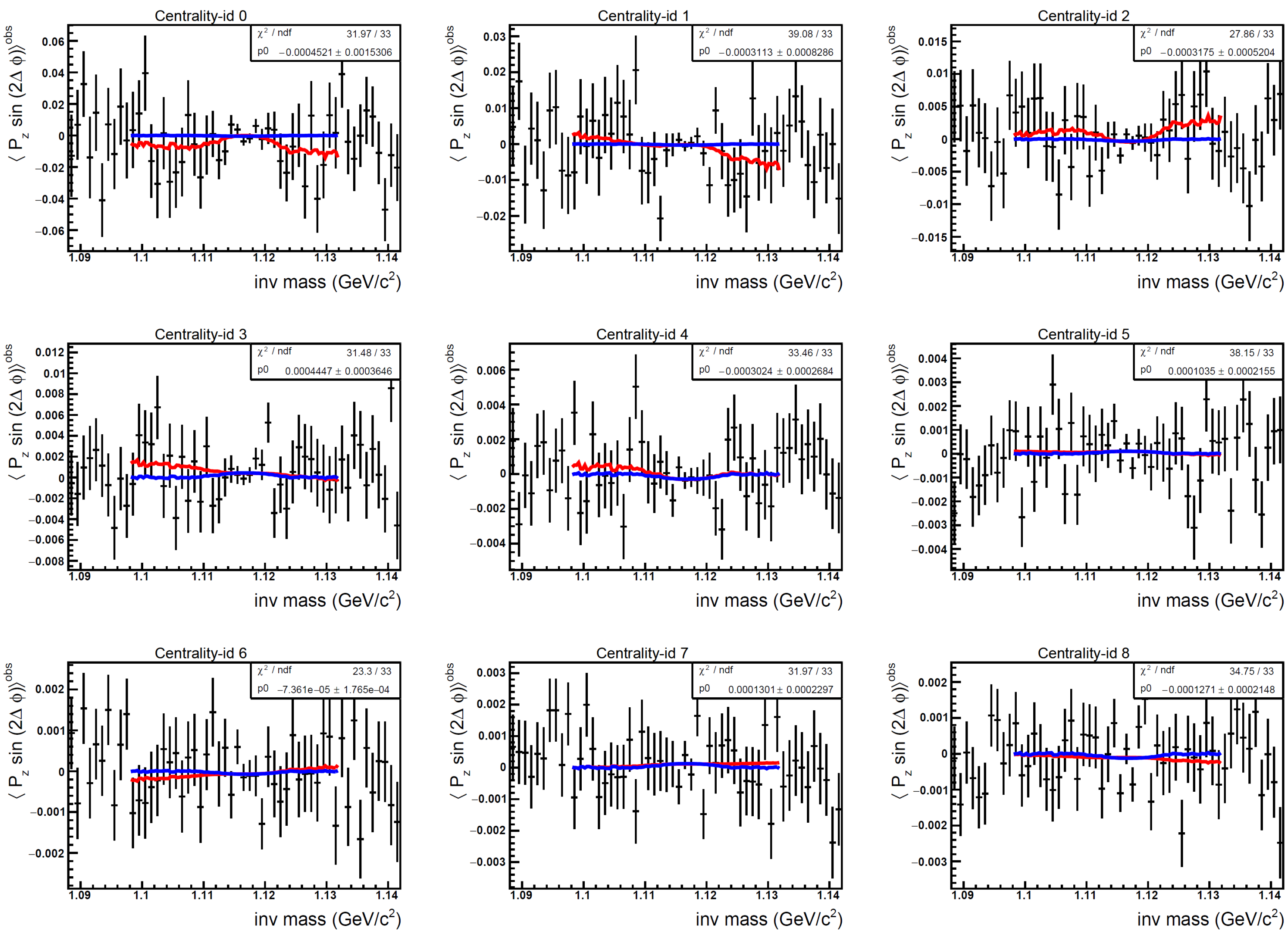


$$\langle\cos(\theta^*)\sin(2\phi-2\Psi_2)\rangle^{\rm obs} = (1-f^{Bg}(M_{\rm inv}))\langle\cos(\theta^*)\sin(2\phi-2\Psi_2)\rangle^{\rm Sg} + f^{\rm Bg}(M_{\rm inv})\langle\cos(\theta^*)\sin(2\phi-2\Psi_2)\rangle^{\rm Bg}$$

Blue: w/o bkg; Red: with bkg ($\alpha+\beta M_{inv.}$)

Part IV: Local polarization

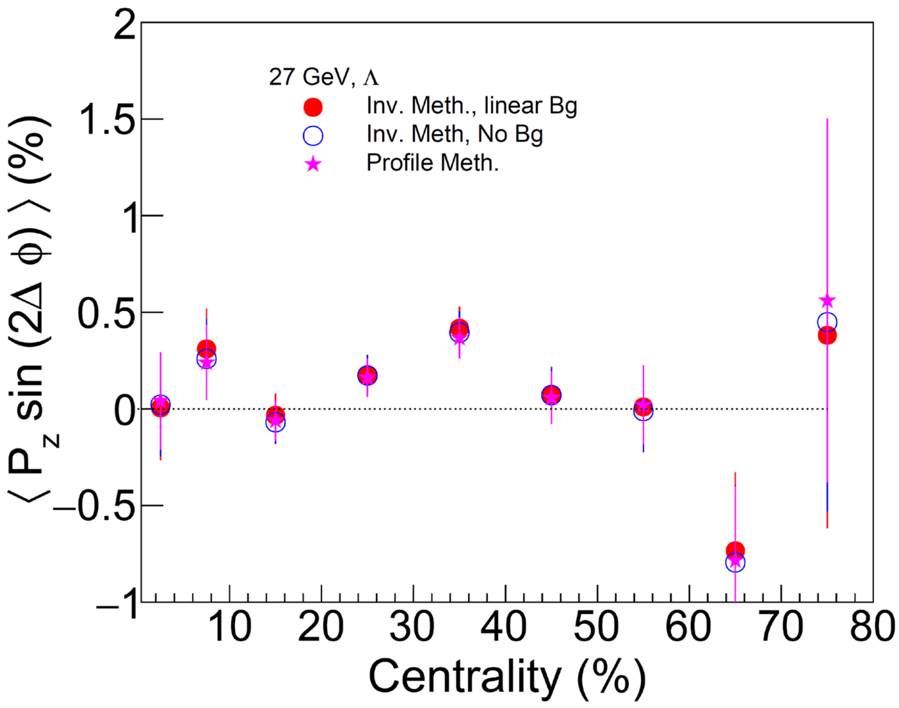
anti-Λ

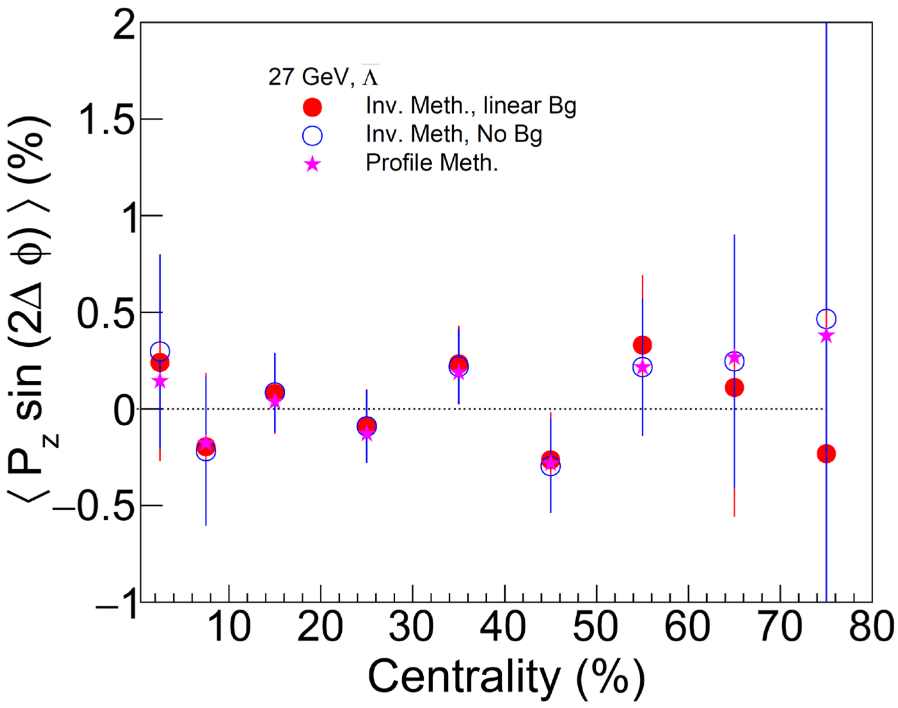


$$\begin{aligned}\langle\cos(\theta^*)\sin(2\phi-2\Psi_2)\rangle^{\rm obs} &= (1-f^{Bg}(M_{\rm inv}))\langle\cos(\theta^*)\sin(2\phi-2\Psi_2)\rangle^{\rm Sg}\\ &+ f^{\rm Bg}(M_{\rm inv})\langle\cos(\theta^*)\sin(2\phi-2\Psi_2)\rangle^{\rm Bg}\end{aligned}$$

Blue: w/o bkg; Red: with bkg ($\alpha+\beta M_{inv.}$)

Part IV: Local polarization



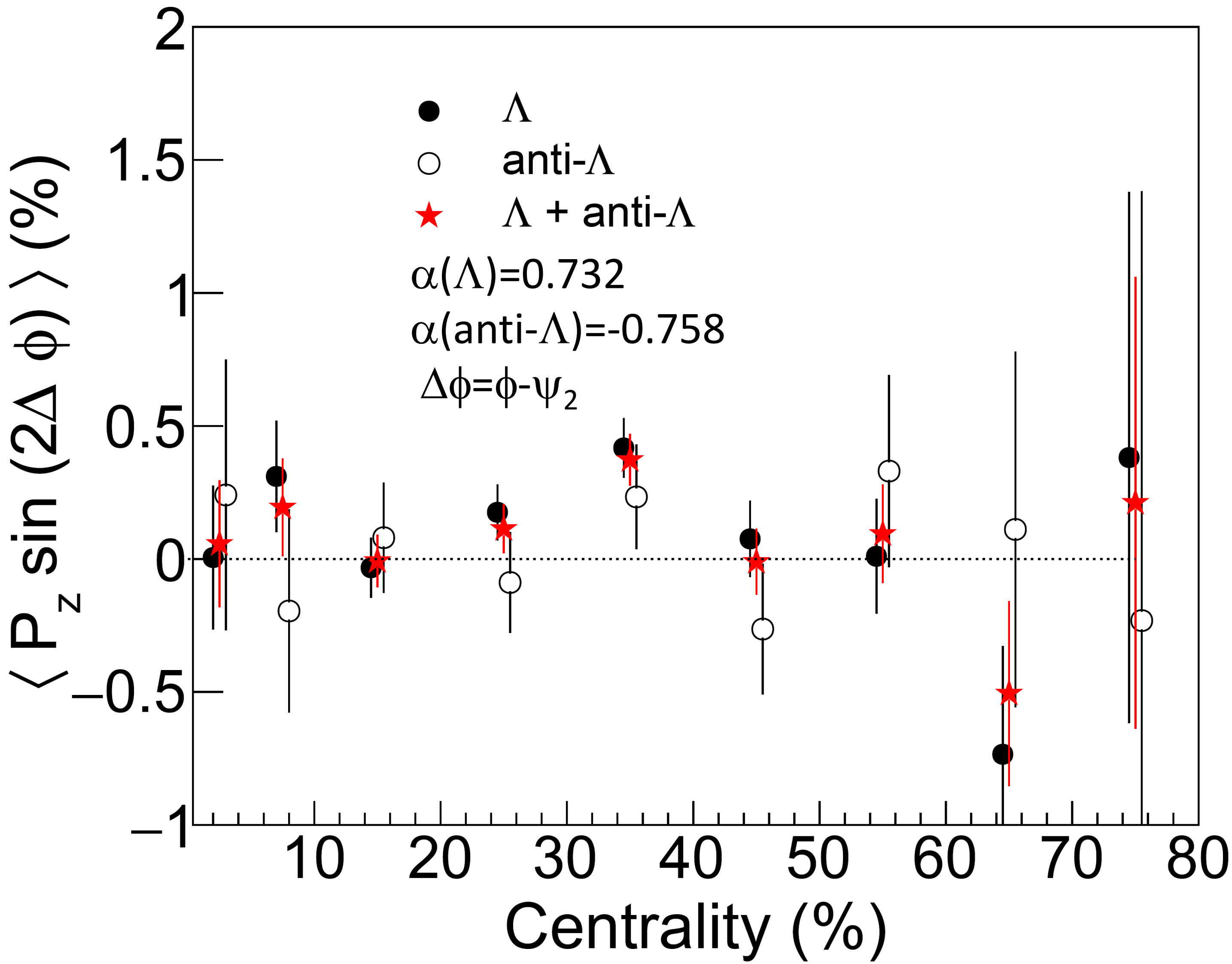


0.5 GeV/c<p_t<5.0 GeV/c; |η|<1.0

$\alpha(\Lambda)$=0.732; α(anti-Λ)=-0.758; $\Delta\phi=\phi-\psi_2$

Hints for non-zero P_z in midcentral collisions

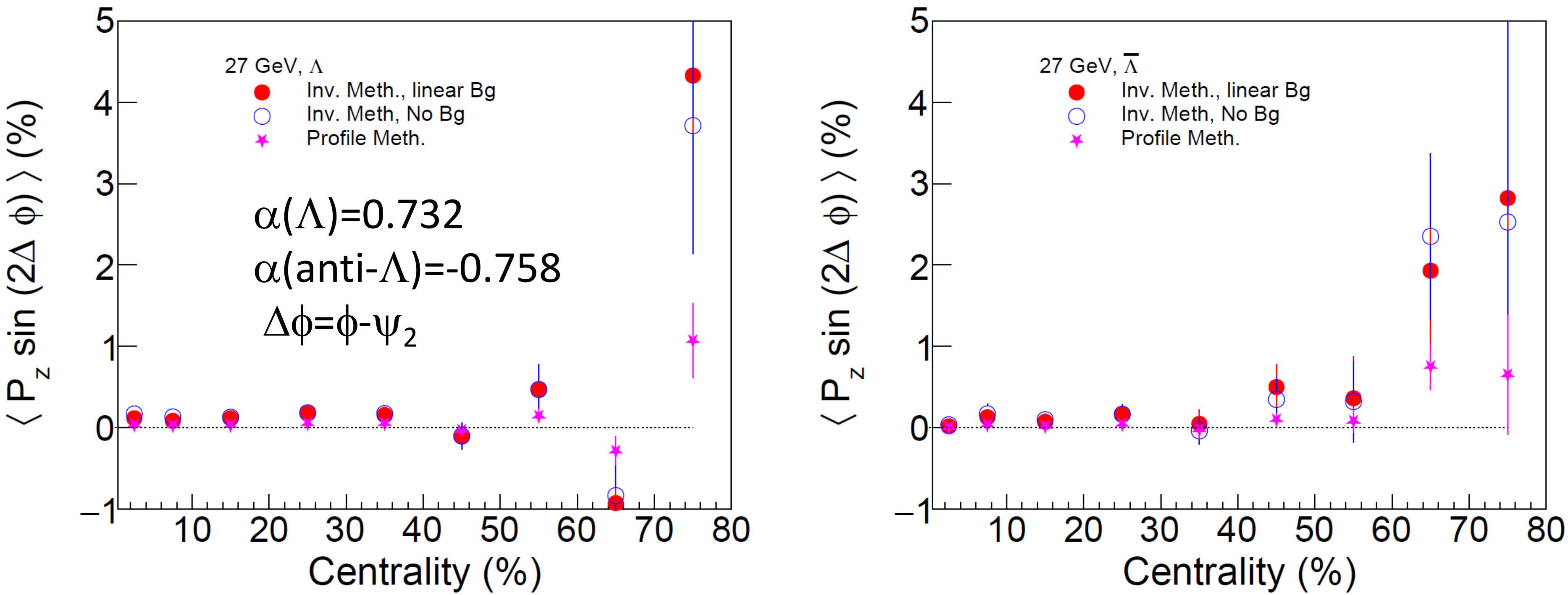
Part IV: Local polarization



0.5 GeV/c$<p_t<5.0$ GeV/c; $|\eta|<1.0$

Hints for non-zero P_z in midcentral collisions

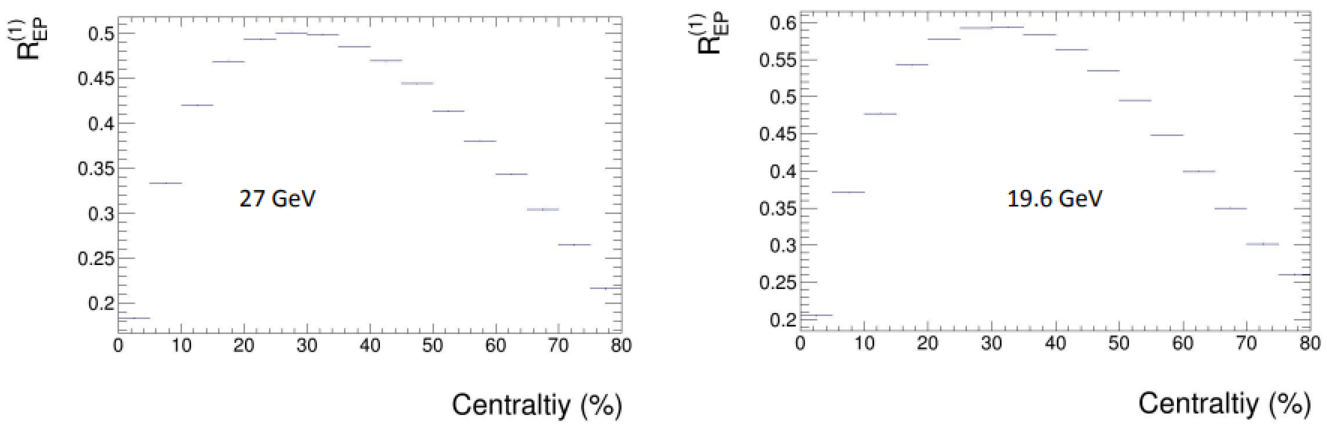
Part IV: Local polarization



Update on 2022.05.09

0.5 GeV/c<p_t<5.0 GeV/c; |η|<1.0

Hints for non-zero P_z in midcentral collisions



Joey Adams, STAR Collaboration Meeting-FCV PWG, May 2022