Differential measurements of Lambda polarization in Au+Au collisions and a search for the magnetic field by STAR

Joseph Adams, on behalf of the STAR collaboration

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THE OHIO STATE UNIVERSITY

BROOKHAVEN NATIONAL LABORATORY

Global hadron polarization P_H: a *new* agreement with the hydro paradigm

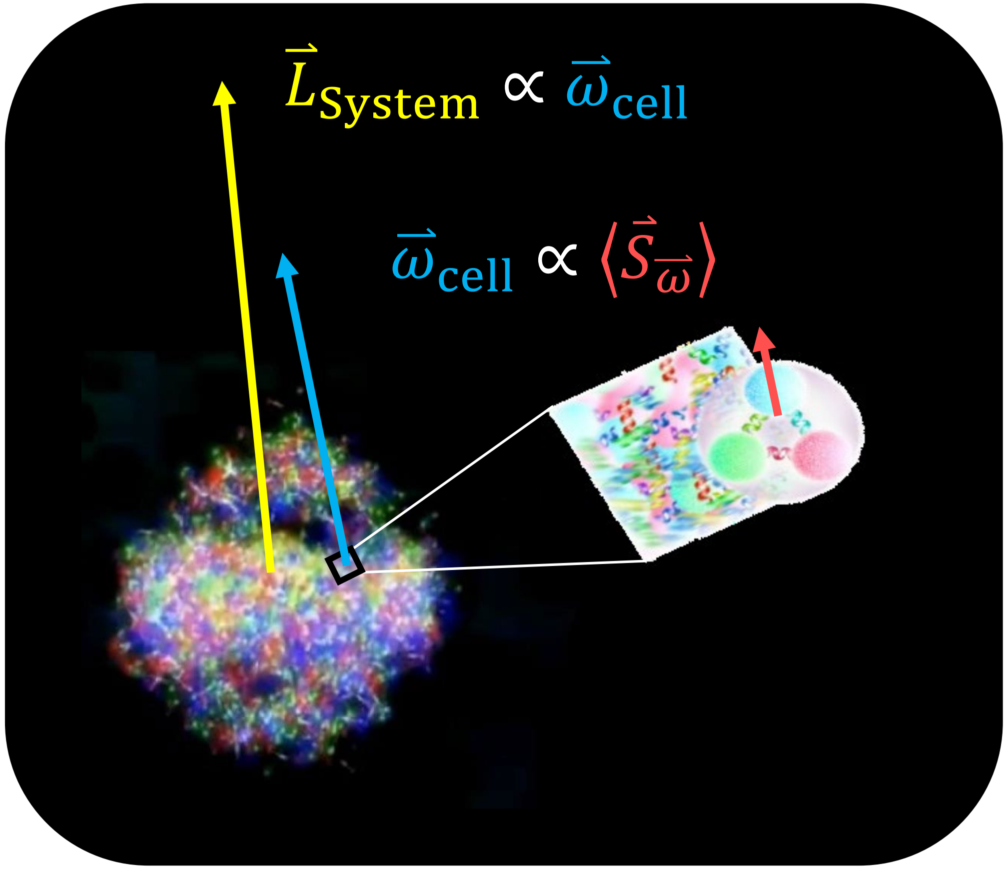
Equilibrium Hydro

System angular momentum

$\langle\vec{\omega}_{\mathrm{QGP}}\rangle \| \vec{L}_{\mathrm{QGP}}$

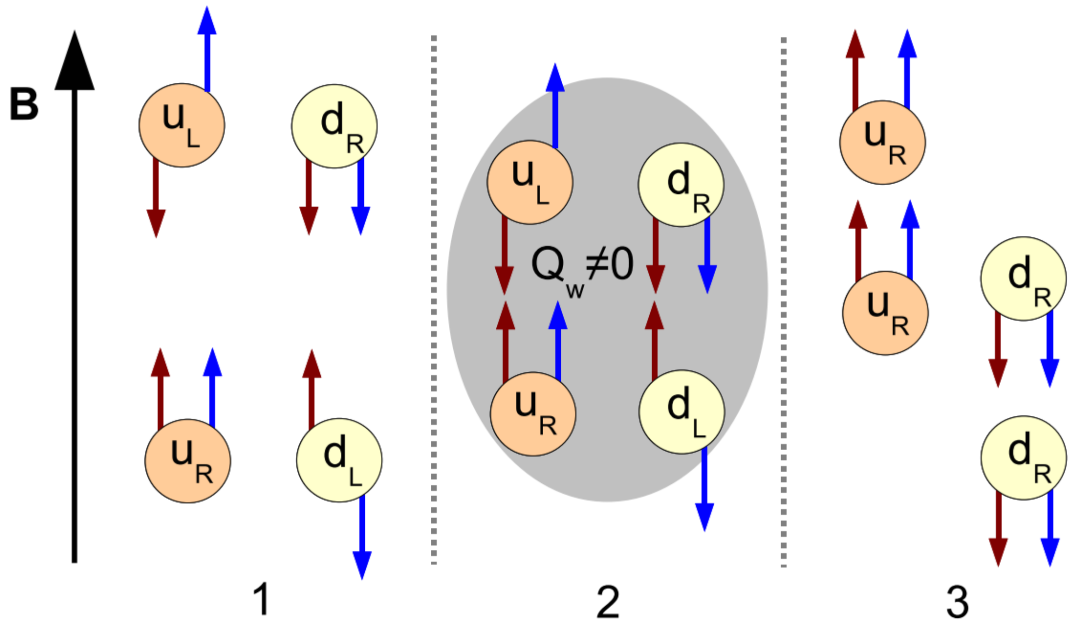
Local angular momentum conservation

$\langle\vec{S}_{\vec{\omega};\,\mathrm{hadrons}}\rangle \| \vec{L}_{\mathrm{QGP}}$



Motivations

- Large $|\vec{B}|$ *essential* for measuring $\mathcal{CP}$-violation observables like CME [1]



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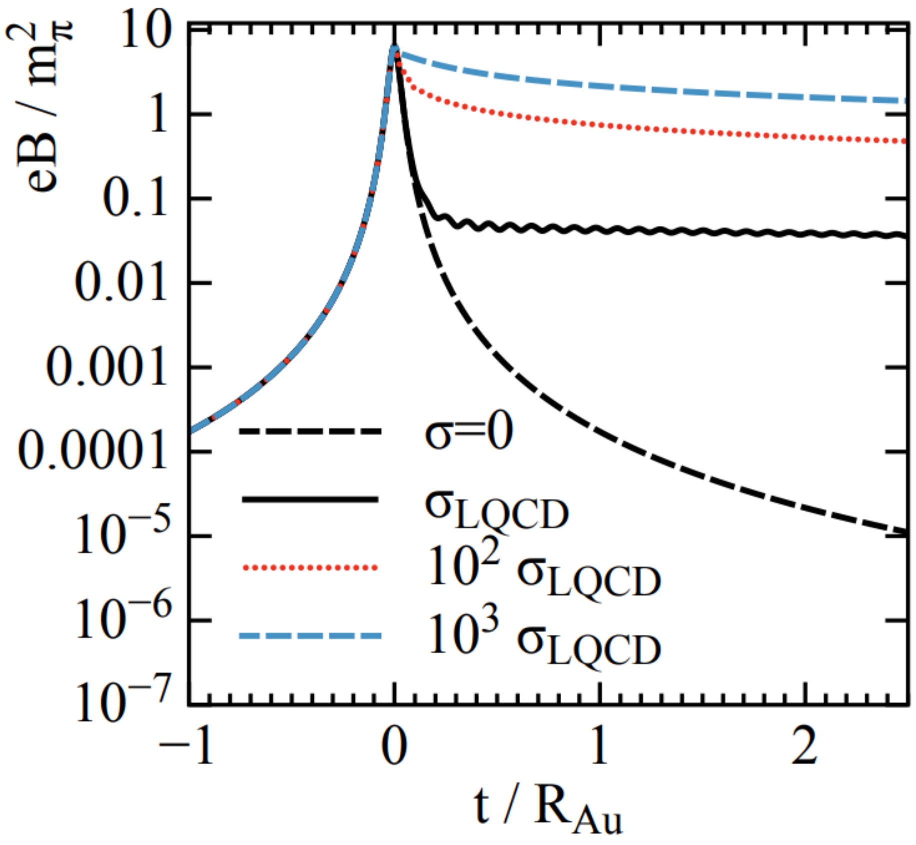

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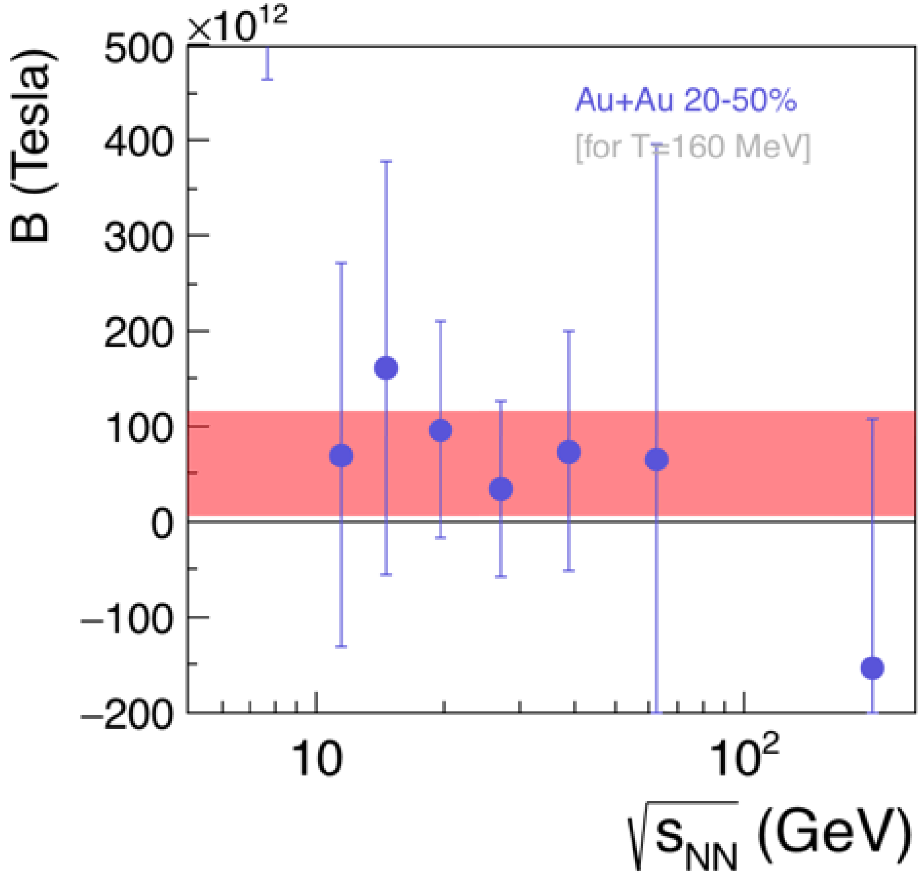
  - but $|\vec{B}| > 0$ for BES-I energies is enticing



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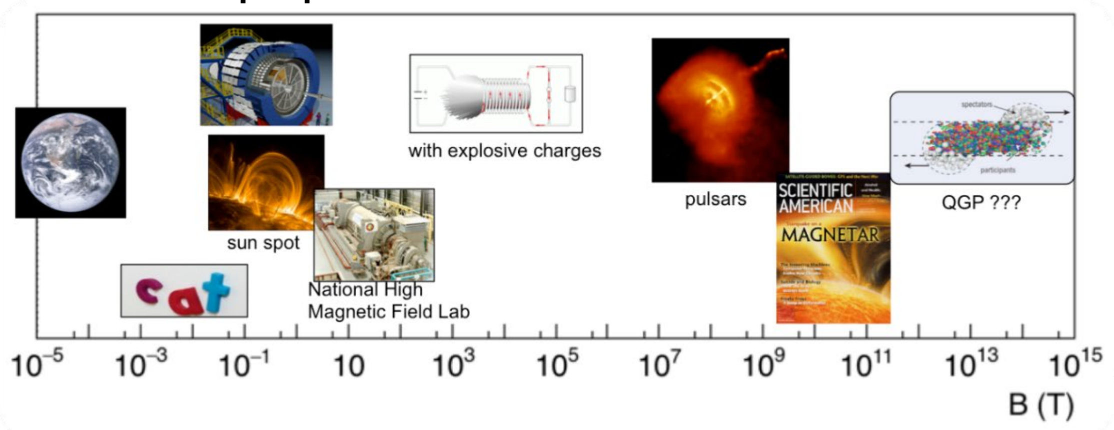

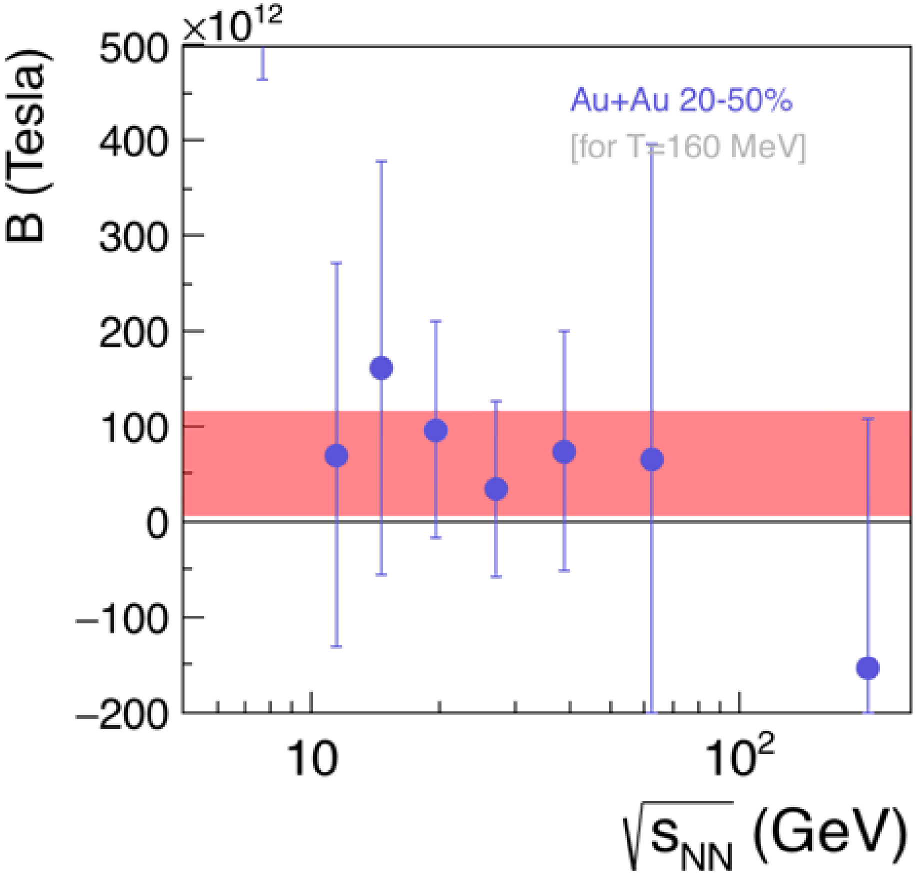

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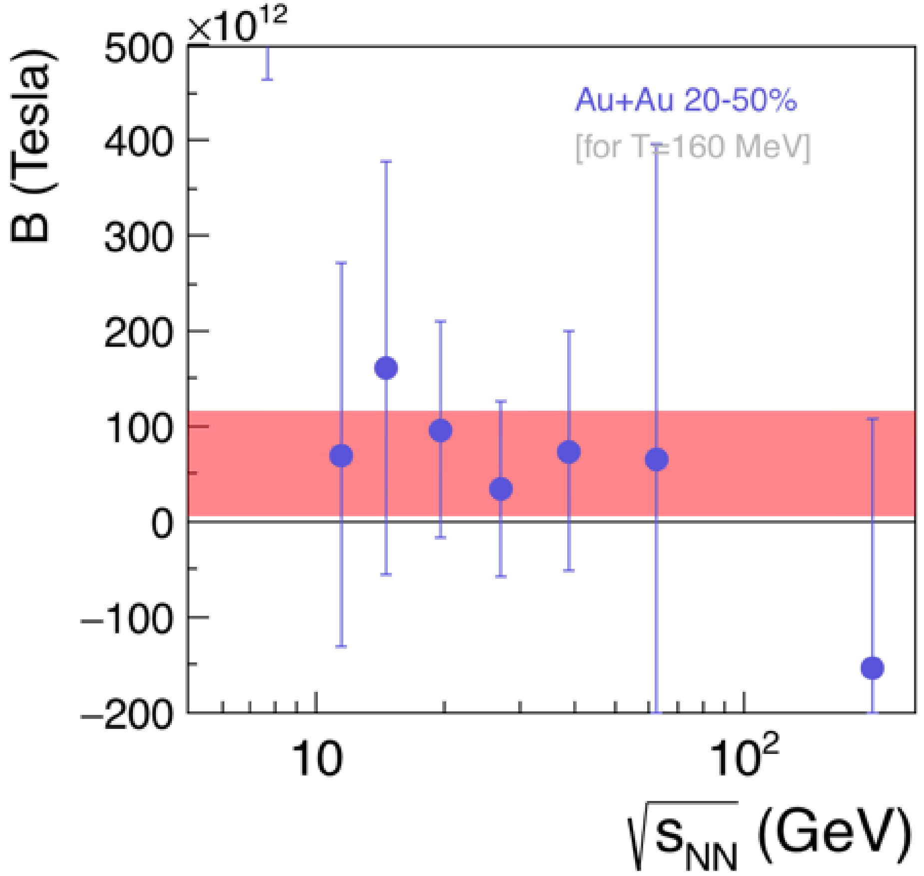
    - A high-statistics data set at 27 GeV



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- Differential measurements of P_H test model predictions
  - STAR recently published a high-statistics P_H study at 200 GeV
  - We compare differential measurements using 27 and 54 GeV

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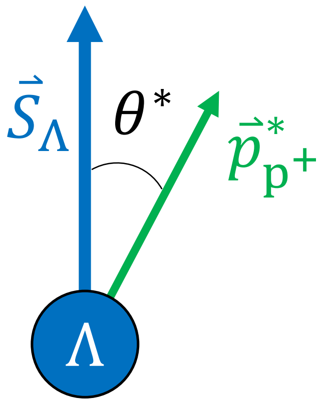
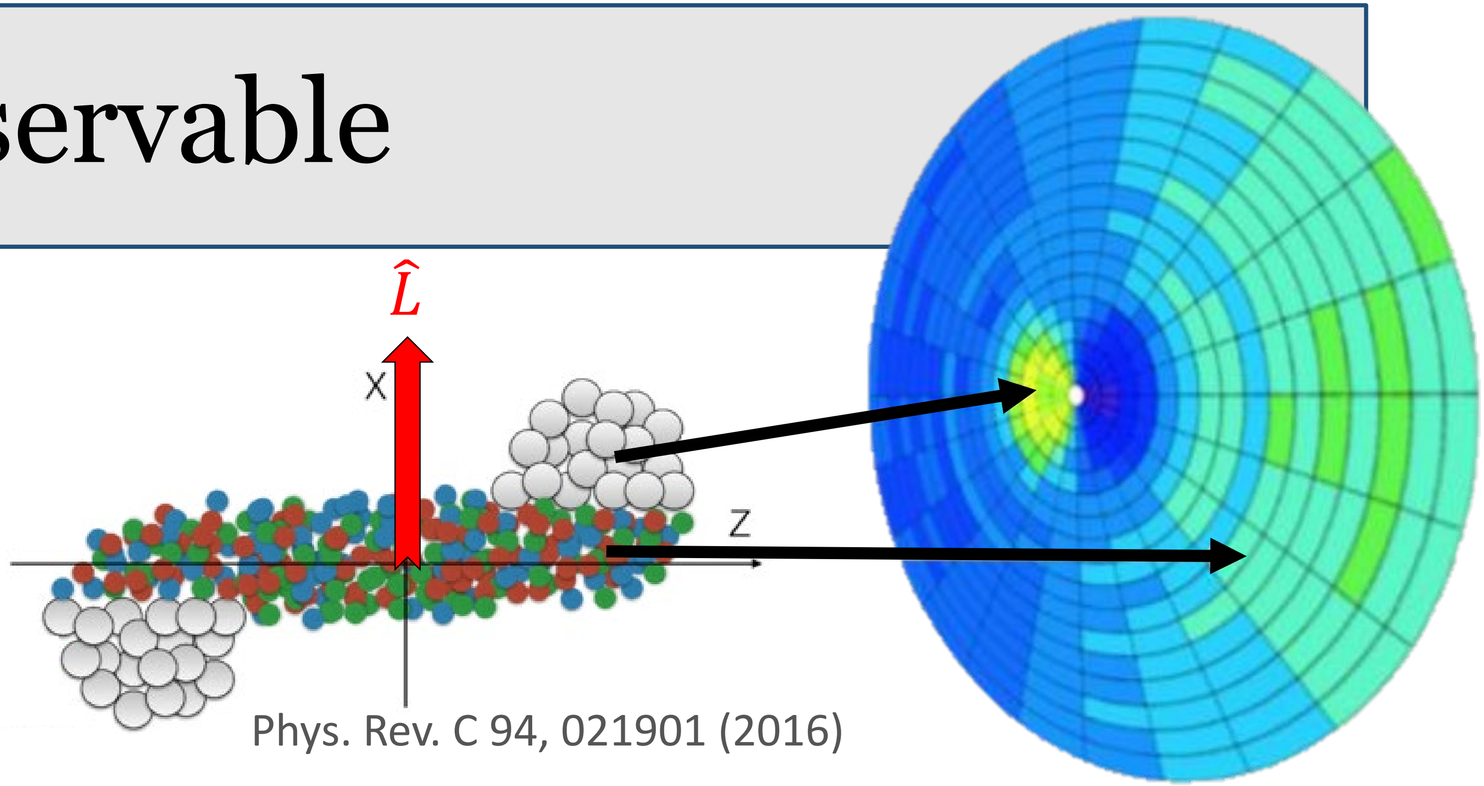
Polarization observable

“*” indicates Lambda’s frame





Phys. Rev. C 94, 021901 (2016)

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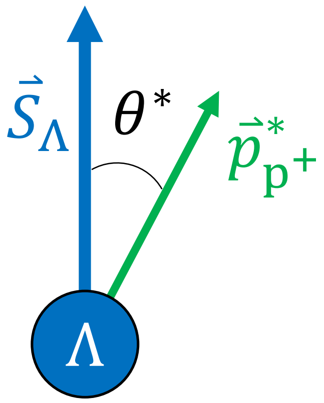

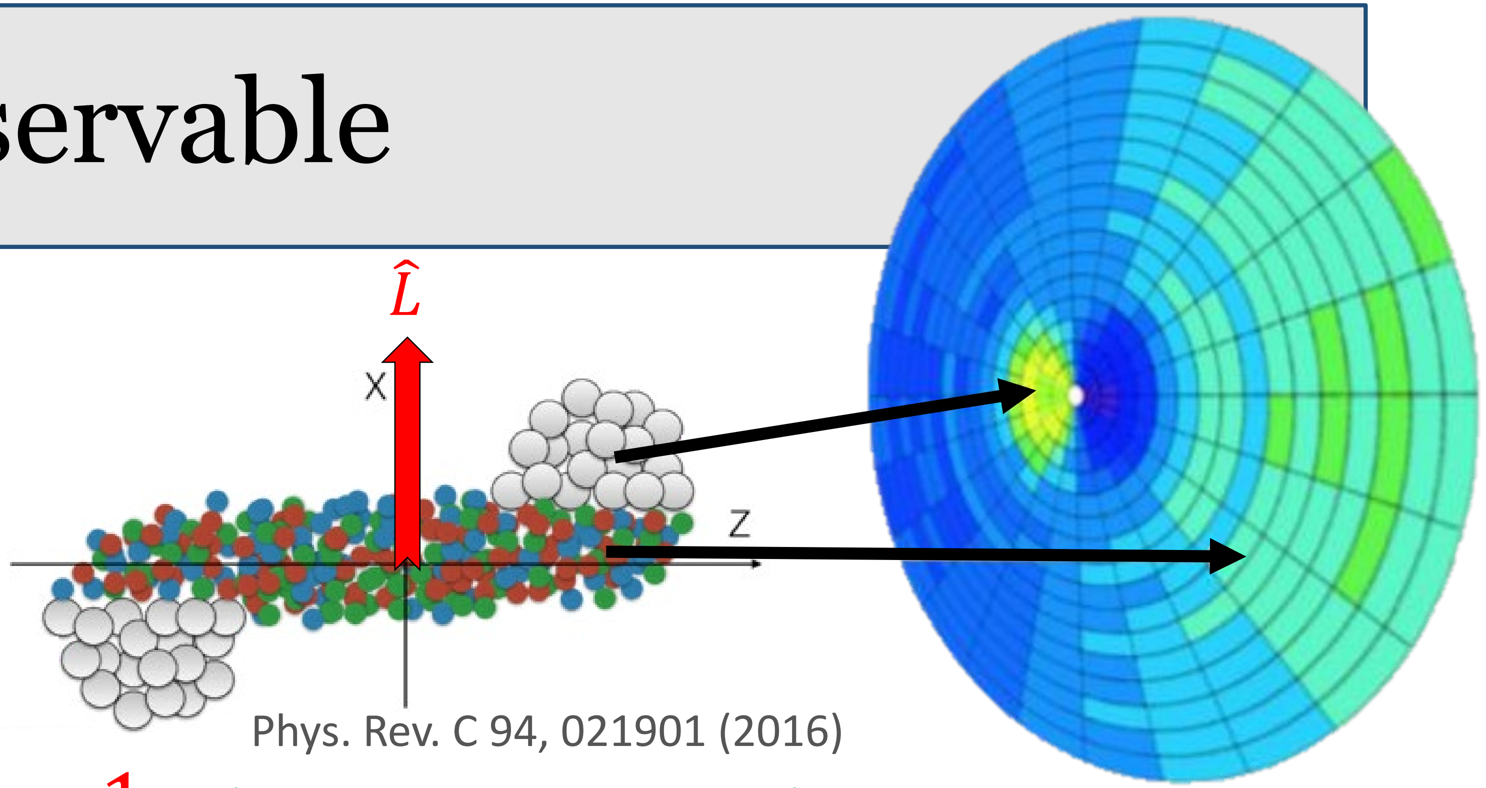

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$$\mathrm{P}_{\Lambda/\bar{\Lambda}} = \frac{1}{\Pi}\frac{8}{\pi\alpha_{\Lambda/\bar{\Lambda}}}\frac{1}{R_{\mathrm{EP}}^{(1)}}\left\langle \sin\left(\Psi_1 - \varphi^*_{\mathrm{p}^+}\right)\right\rangle$$

Lambdas don't emit daughters exactly along spin

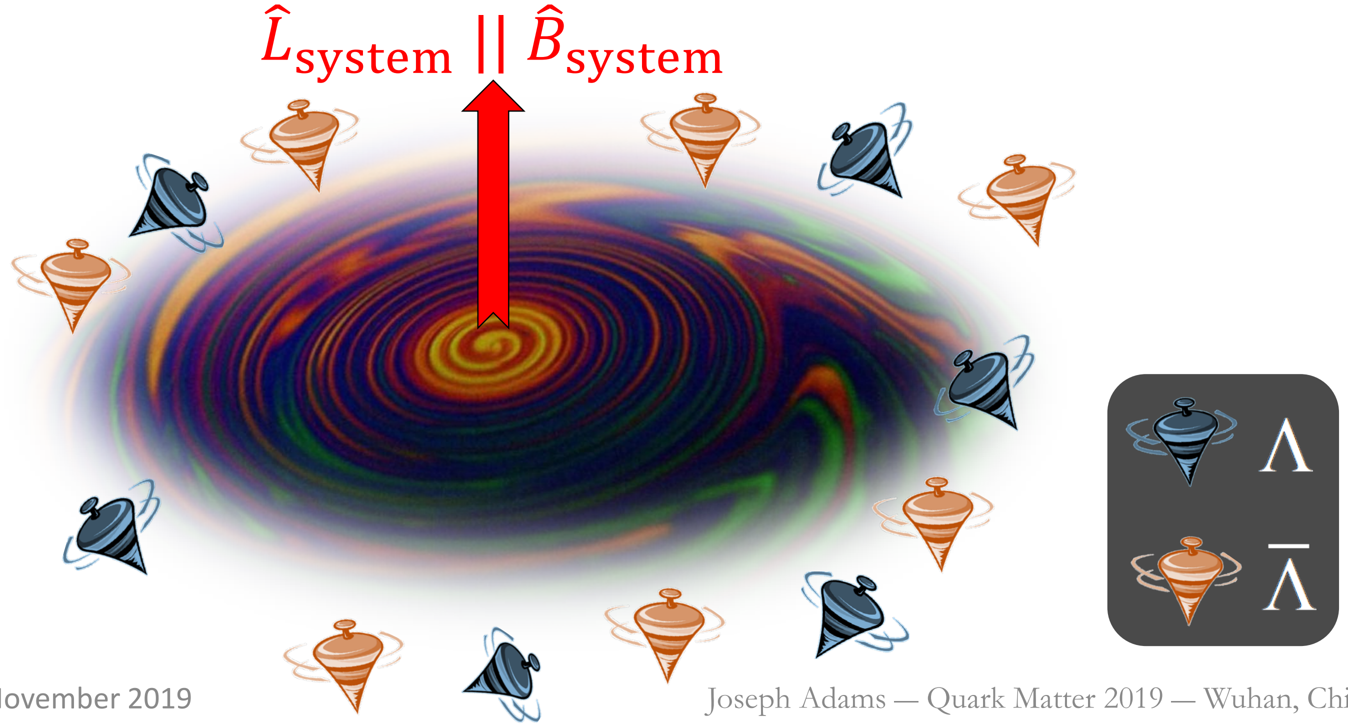
Correlates angular momentum of QGP with Lambda's spin

Not all reconstructed p-π pairs are actually Lambdas

The measured Ψ_1 differs from Ψ_{RP}

Magnetic field observable

- Vorticity gives positive contribution to P_Λ *and* $P_{\bar{\Lambda}}$
- $|\vec{B}|$ enhances $P_{\bar{\Lambda}}$ and suppresses P_Λ ($\vec{\mu}_{B,\Lambda} = -\vec{\mu}_{B,\bar{\Lambda}}$)



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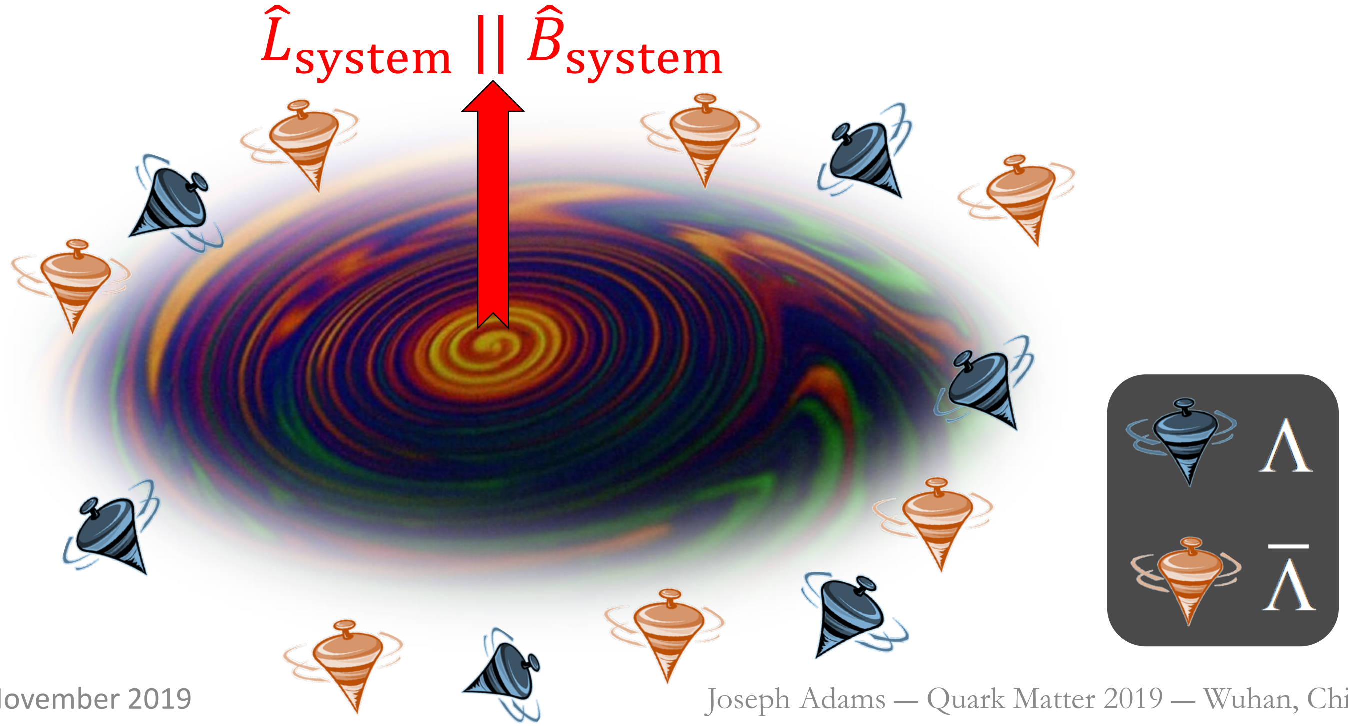
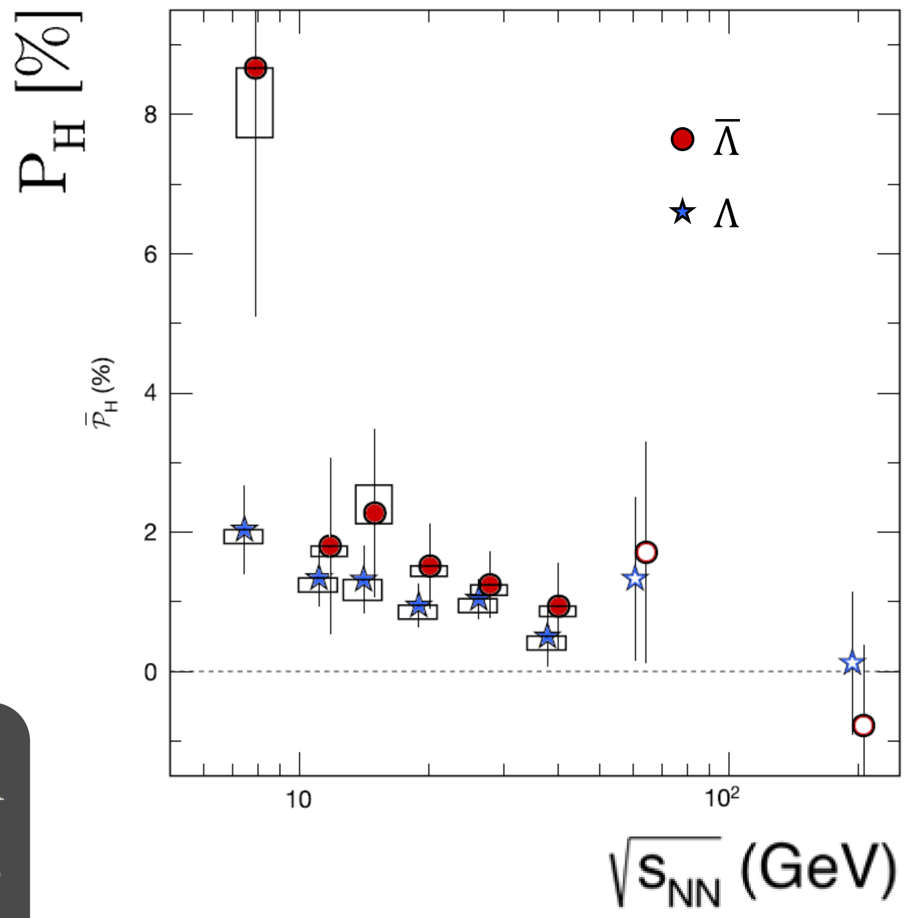
- We measure $|\vec{B}|$ via splitting between P_Λ and $P_{\bar{\Lambda}}$





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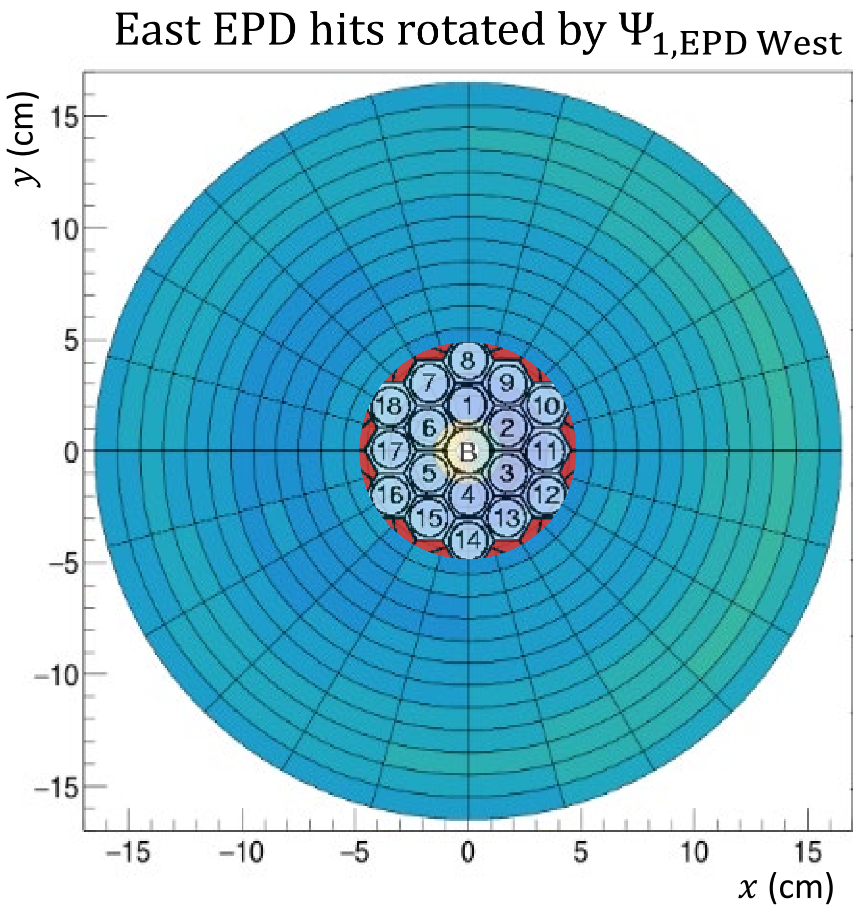
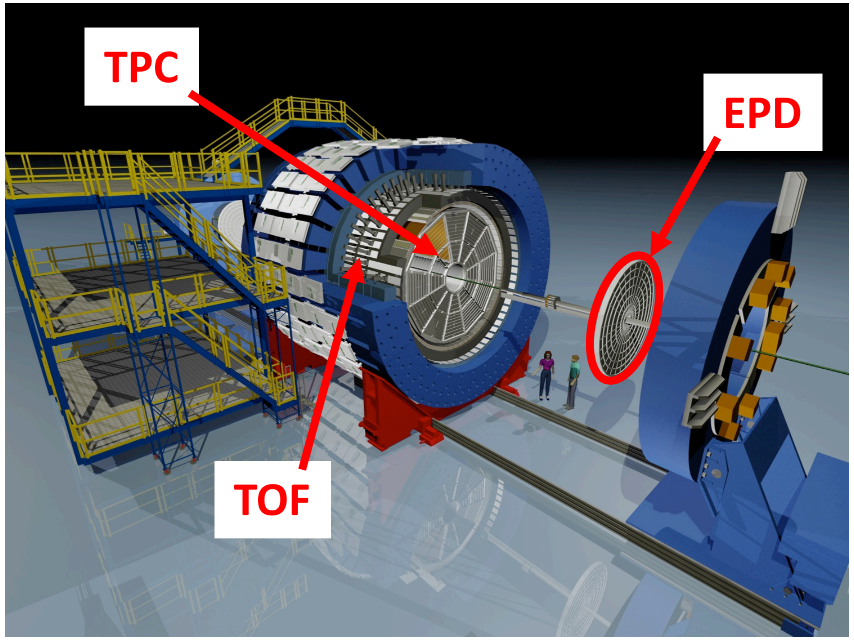
Event-plane determination

- The EPD has far more coverage than the BBC





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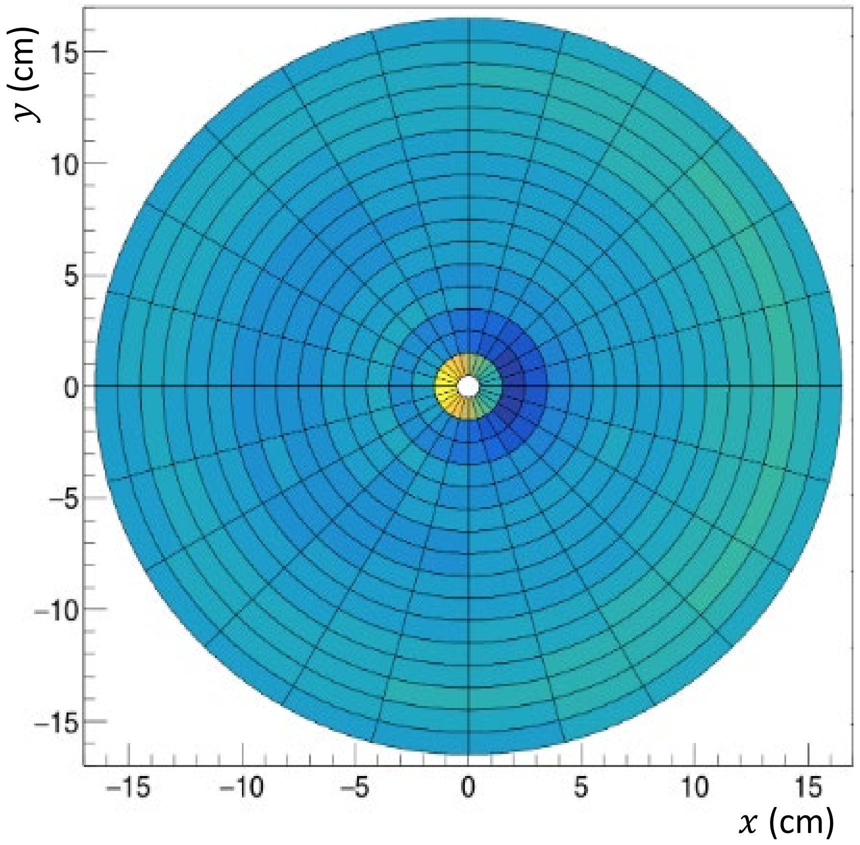
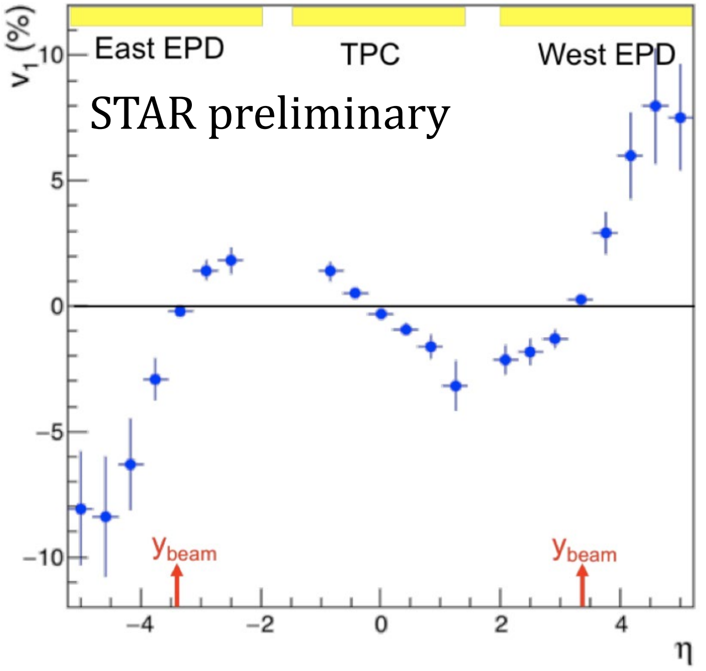
- MUST account for flow!
  - Otherwise, near-zero resolution

East EPD hits rotated by $\Psi_{1,\mathrm{EPD\ West}}$





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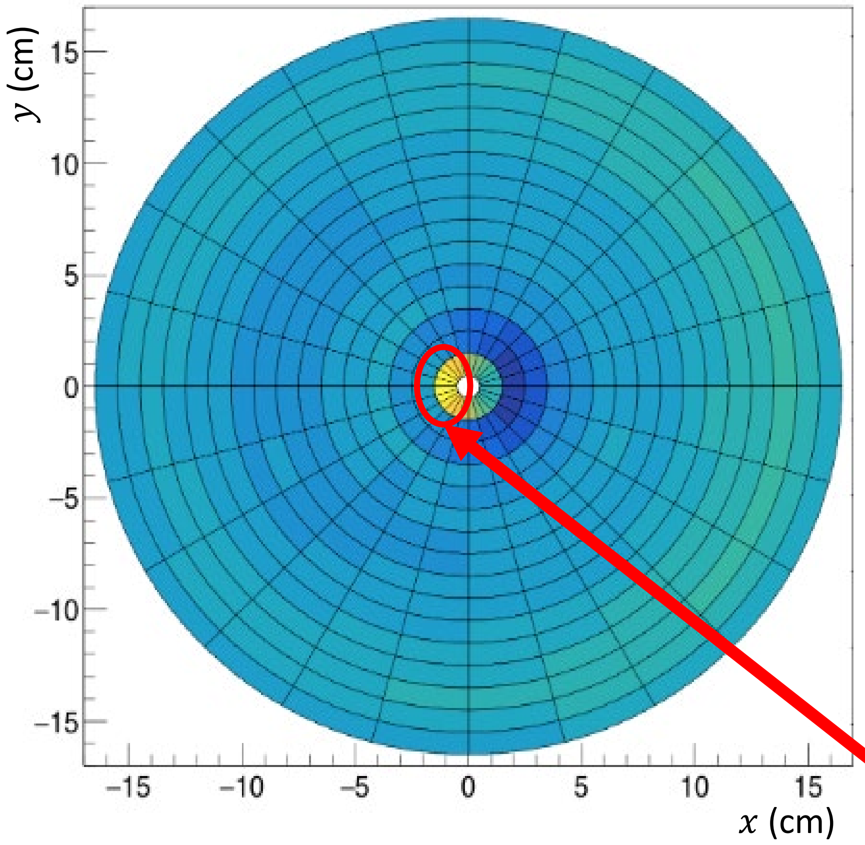

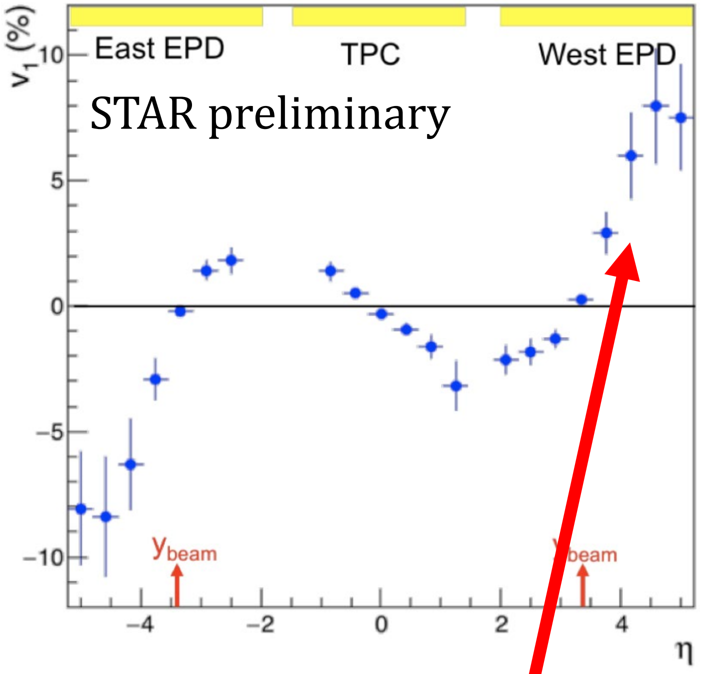

Positive flow obvious over few tiles

Event-plane determination

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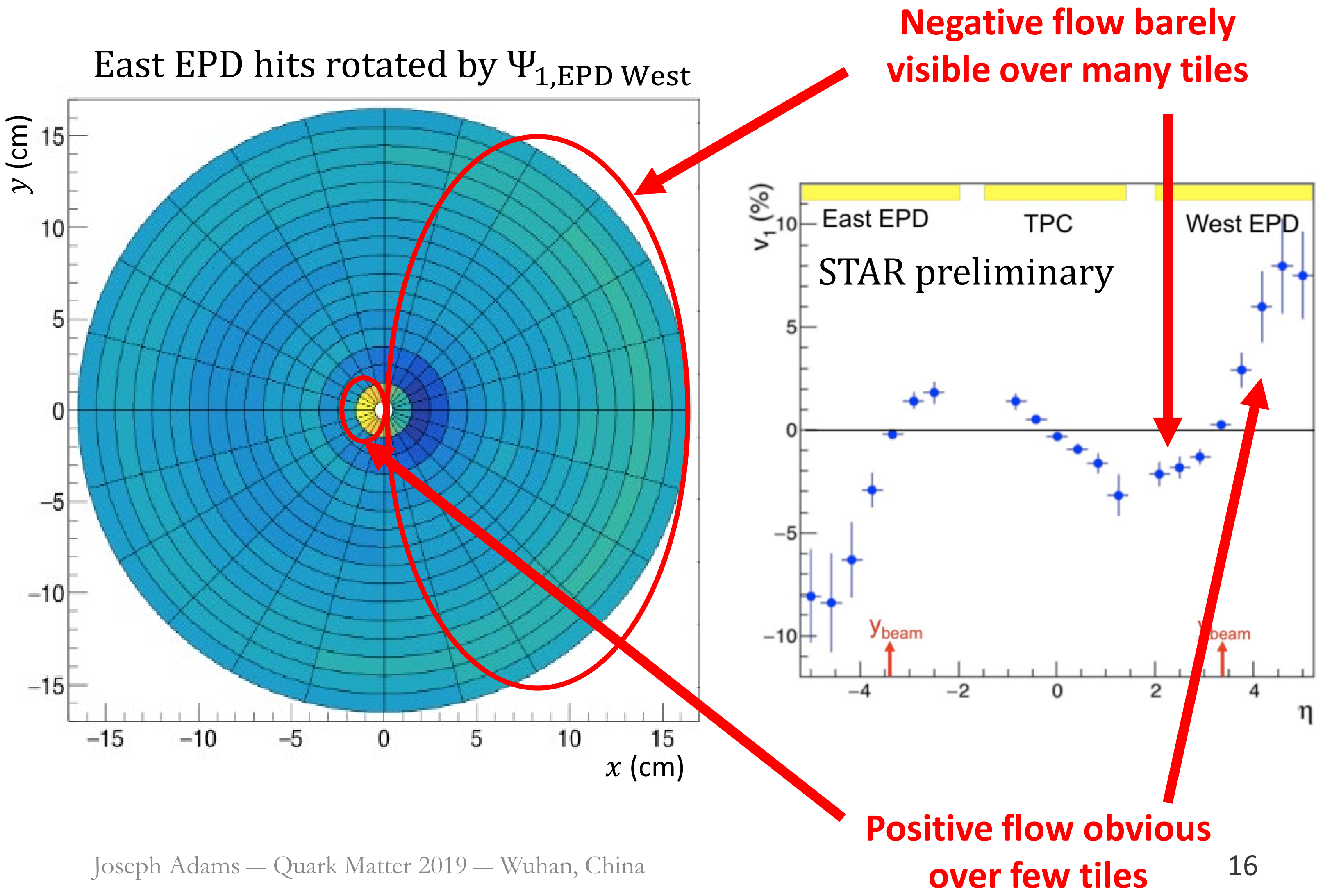
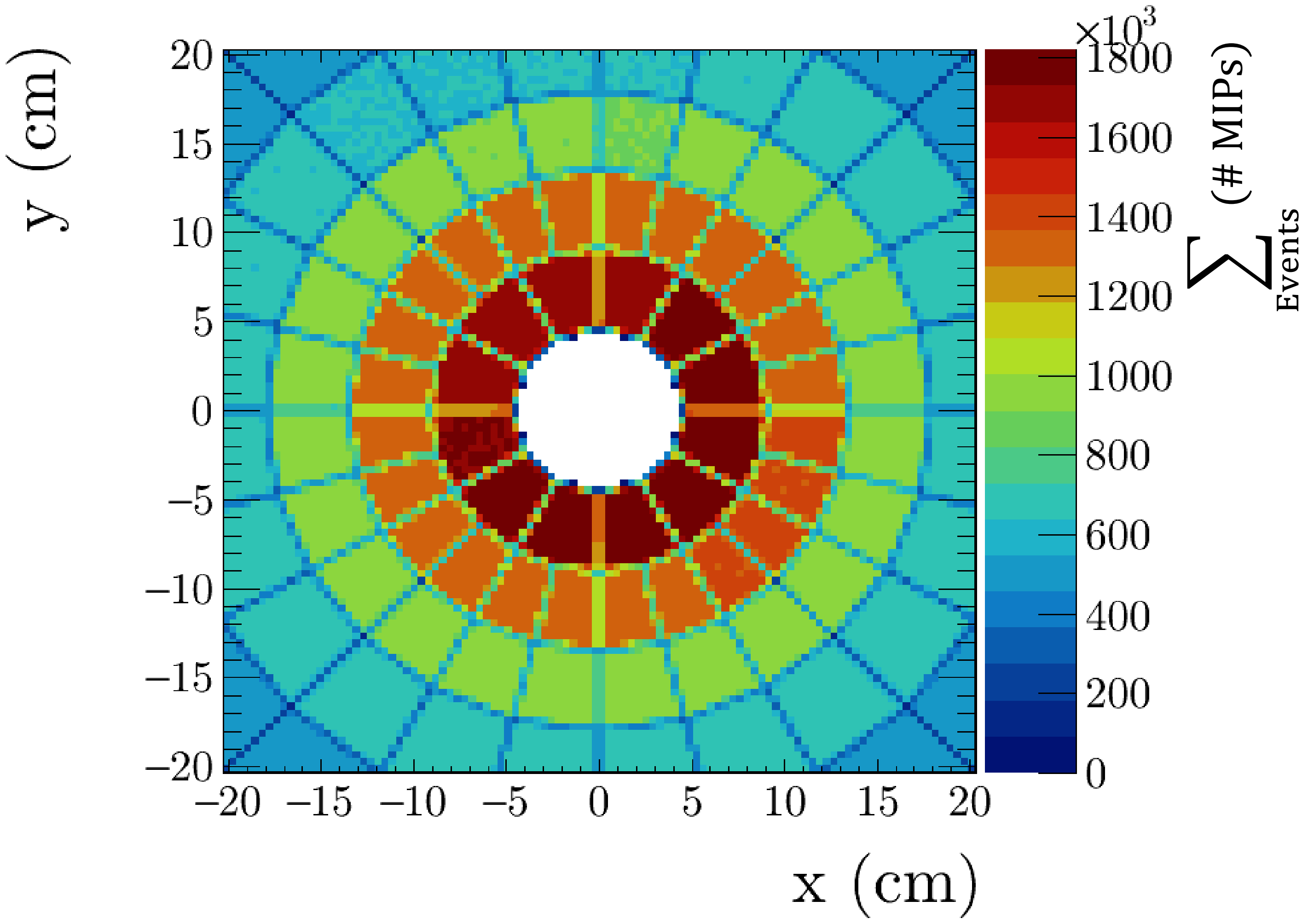


Event-plane determination

- Distribution of measured hits not symmetric in φ
  - Weight hits to enforce symmetry ("gain match")



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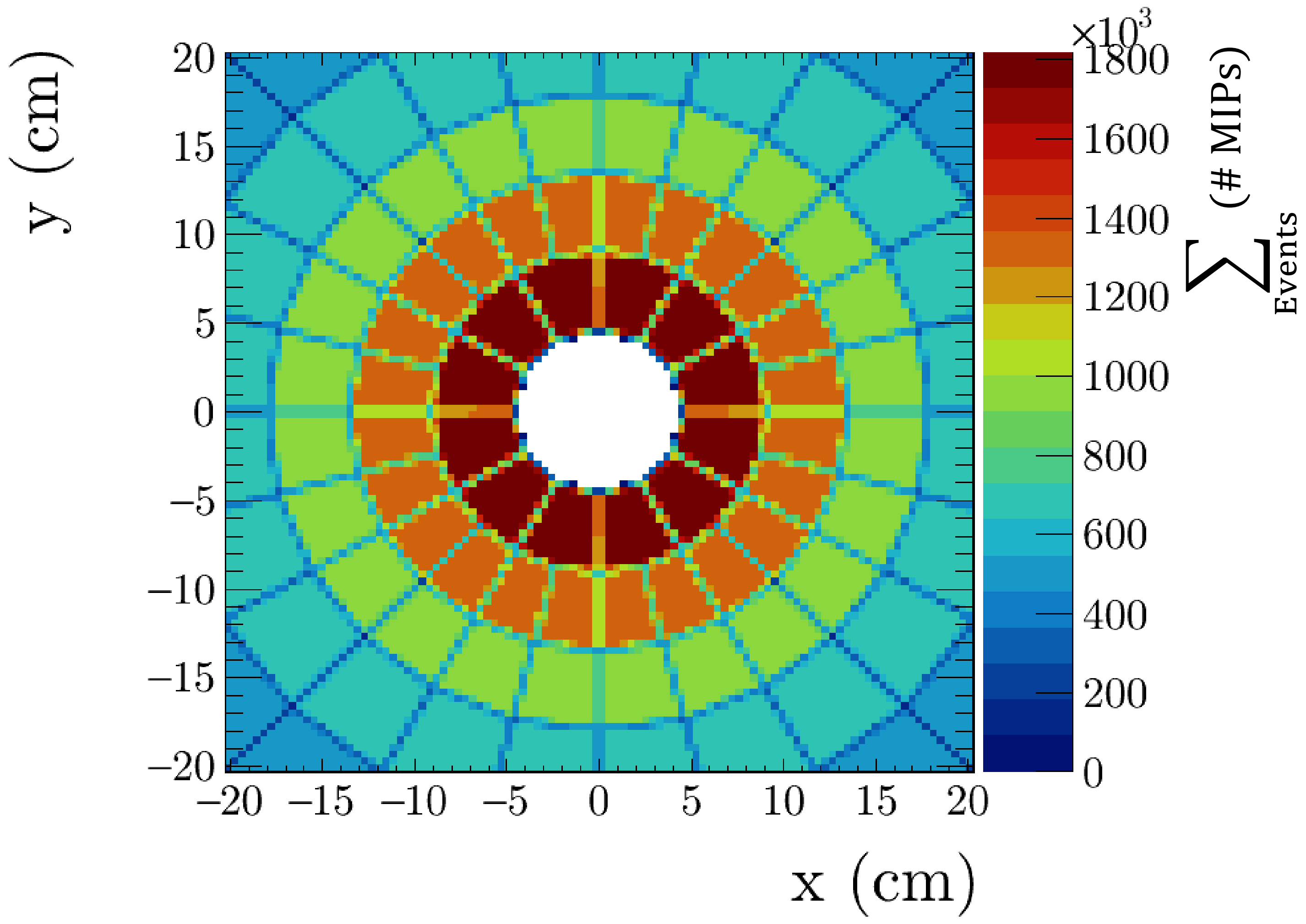


Event-plane determination

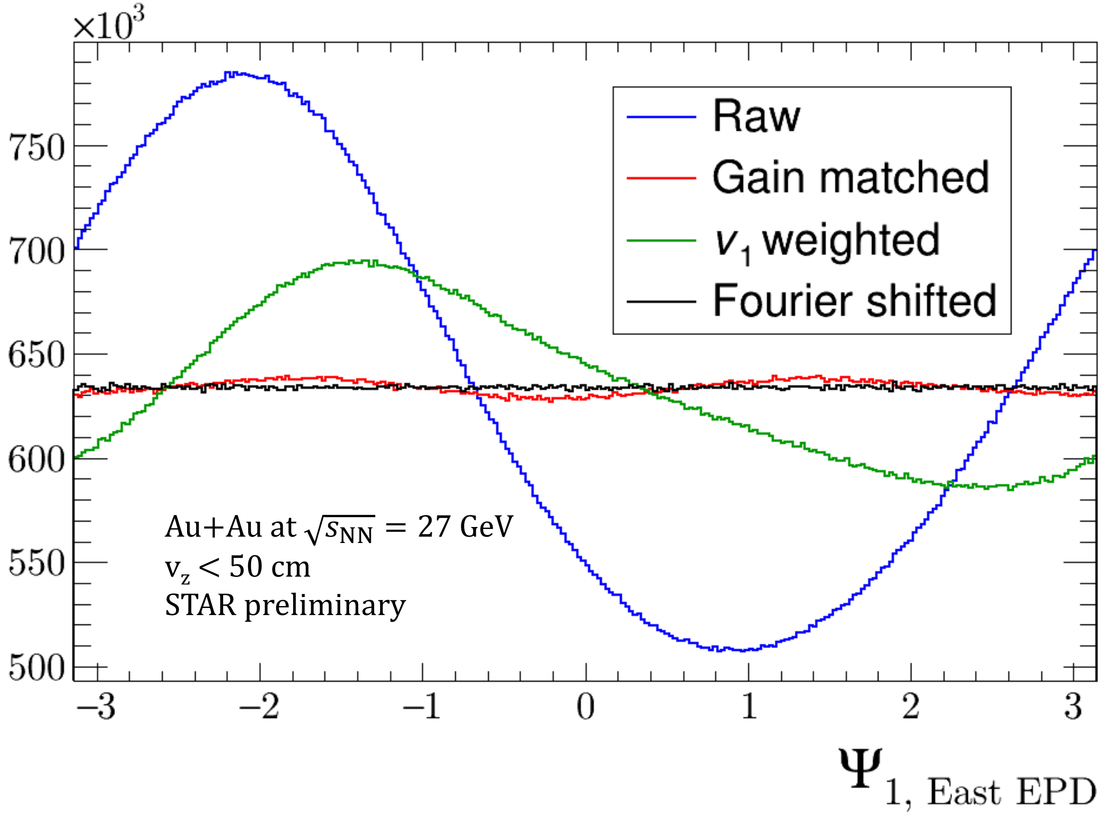
- Distribution of measured hits not symmetric in φ
  - Weight hits to enforce symmetry ("gain match")
- Ψ_1 determined by azimuthal distribution of weighted hits

$$Q_{1,x} = \sum_{i=1}^{\#\text{ hits}} w_i \left.\langle v_1 \rangle\right|_{\eta_i} \cos(\varphi_i)$$

$$Q_{1,y} = \sum_{i=1}^{\#\text{ hits}} w_i \left.\langle v_1 \rangle\right|_{\eta_i} \sin(\varphi_i)$$

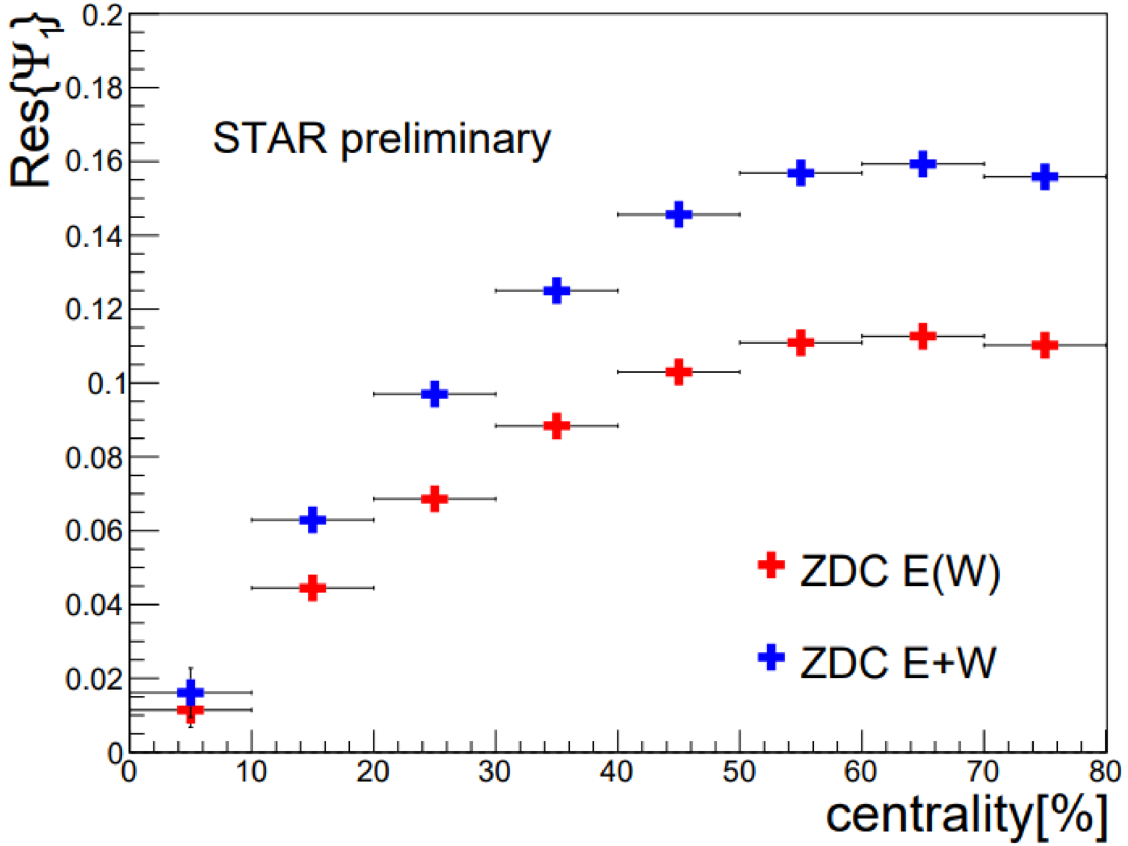
$$\Psi_1 = \text{atan2}(Q_{1,y}, Q_{1,x})$$

$$w_i = \frac{\frac{\langle\#\text{MIPs in tile}\rangle}{\#\text{ tiles in ring}}}{\langle\#\text{MIPs in tile}\rangle}$$



Event-plane resolution

- Event-plane resolution describes how well $\hat{L}_{\text{system}}$ is measured
  - $R_{\text{EP}}^{(1)} \approx \sqrt{2\langle\cos(\Psi_{\text{sub evt. 1}} - \Psi_{\text{sub evt. 2}})\rangle}$
- At 54.4 GeV, Zero Degree Calorimeter (ZDC) is used
  - Peak $R_{\text{EP}}^{(1)}$ is ~0.16
  - Beam-Beam Counter (BBC) was used as cross check; see poster by Kosuke Okubo (#746)



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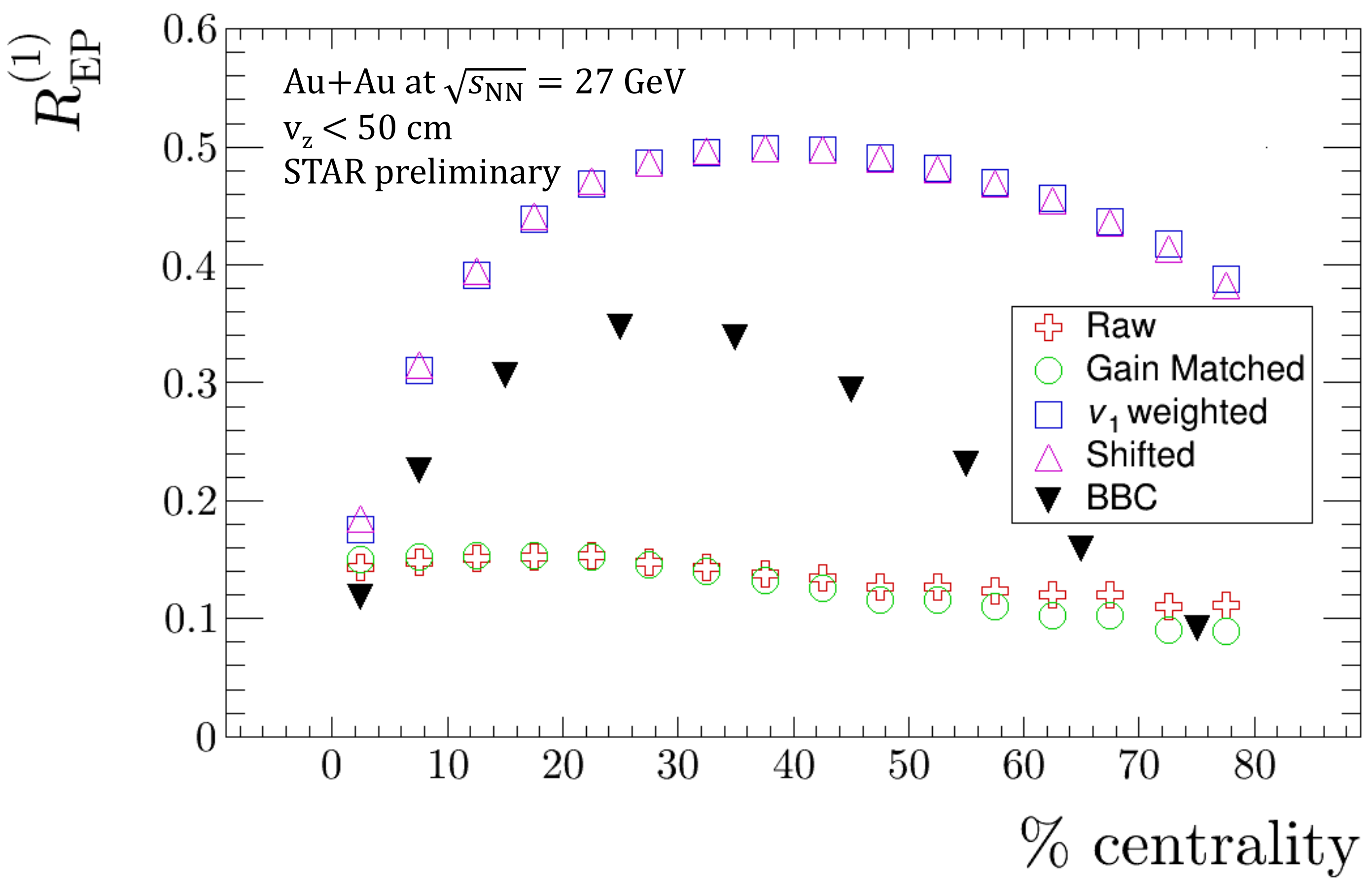
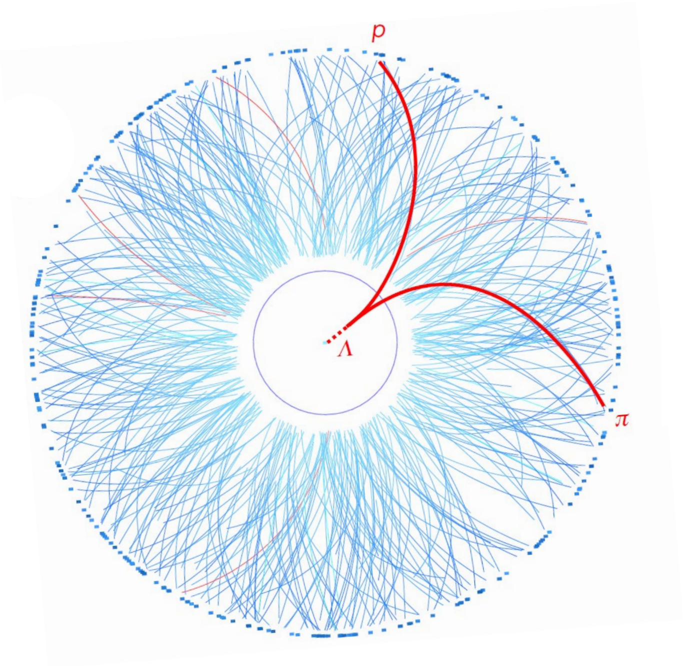
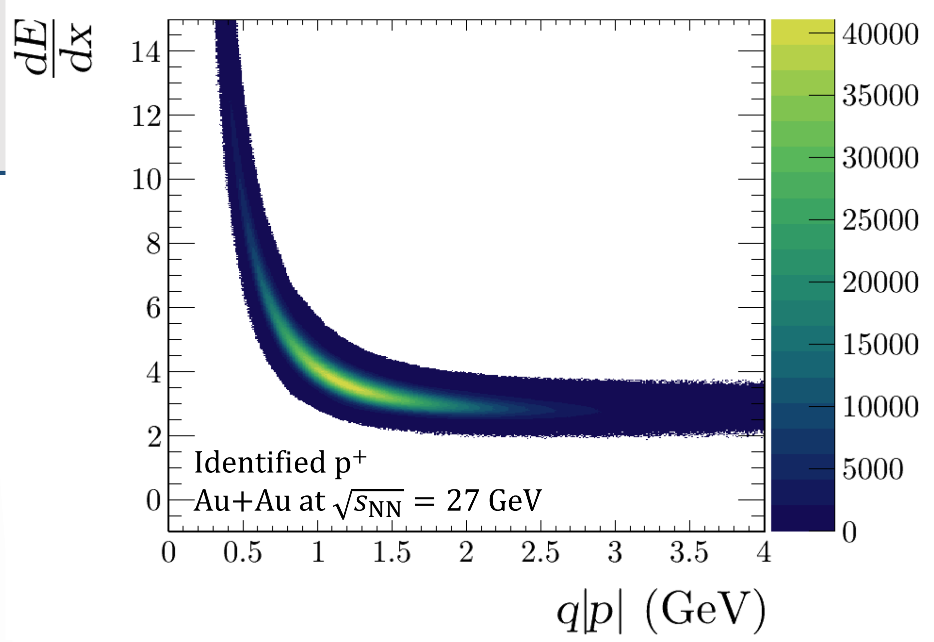
- At 27 GeV, newly installed Event Plane Detector (EPD) is used
  - Peak $R_{\text{EP}}^{(1)}$ is ~0.5
  - Significant increase over BBC previously used

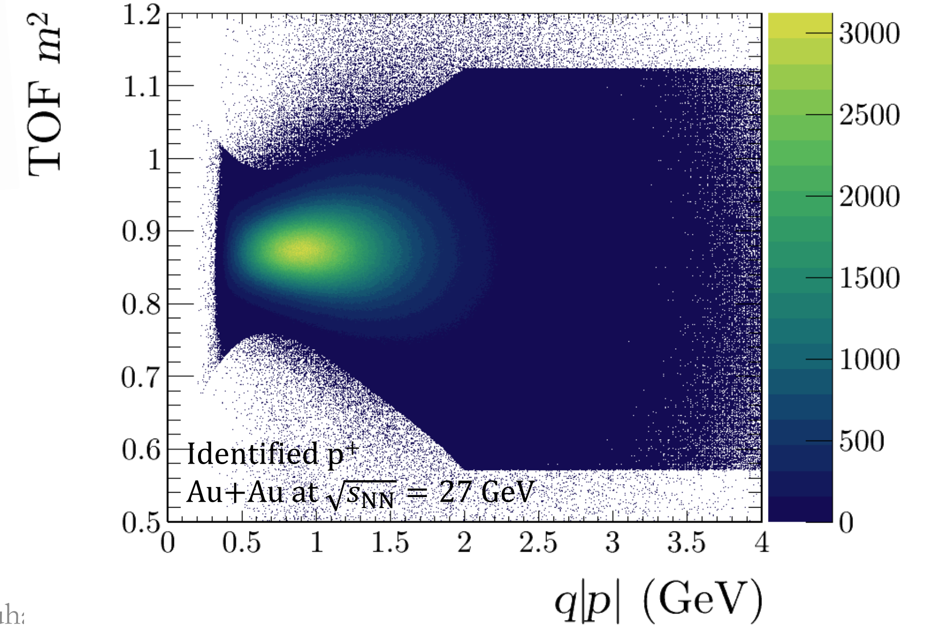


Finding Lambdas

- Protons and pions ID with TPC and TOF

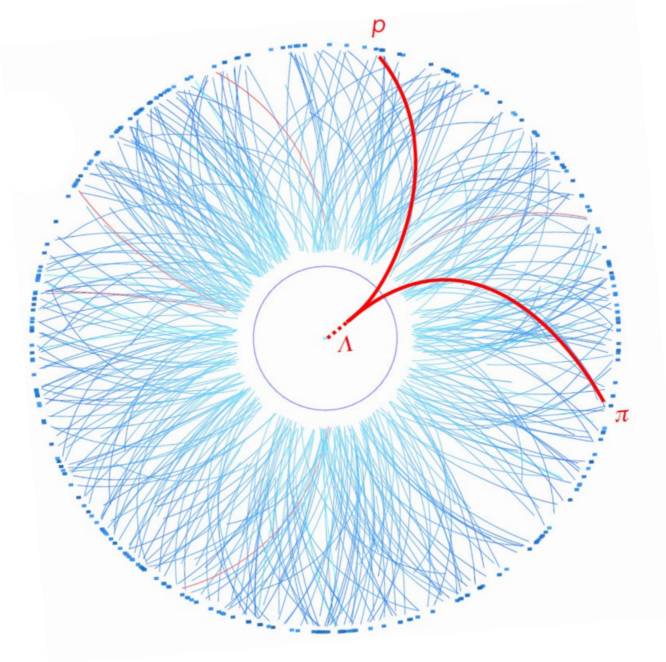


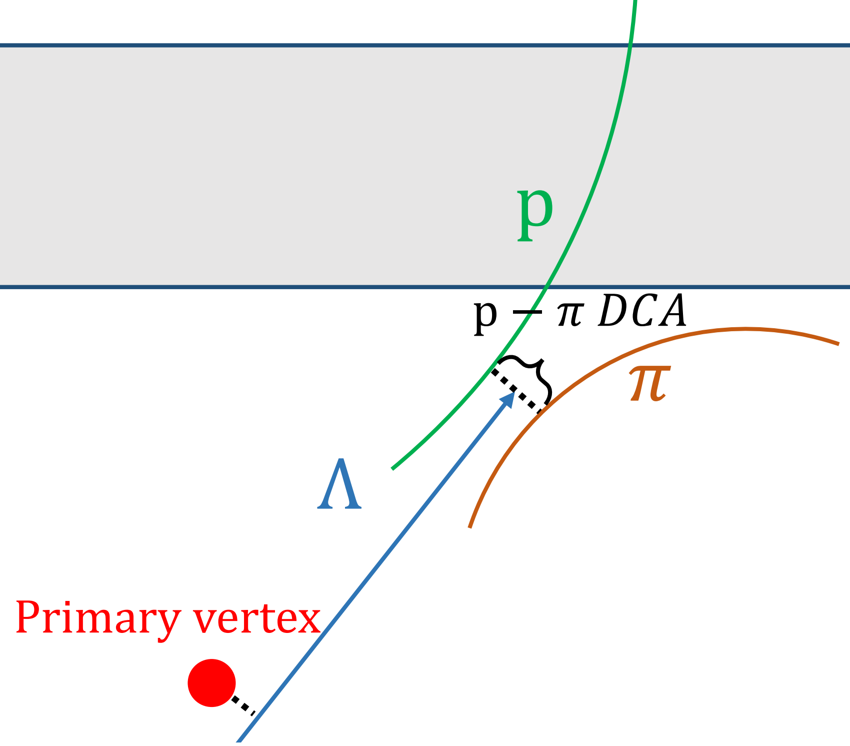


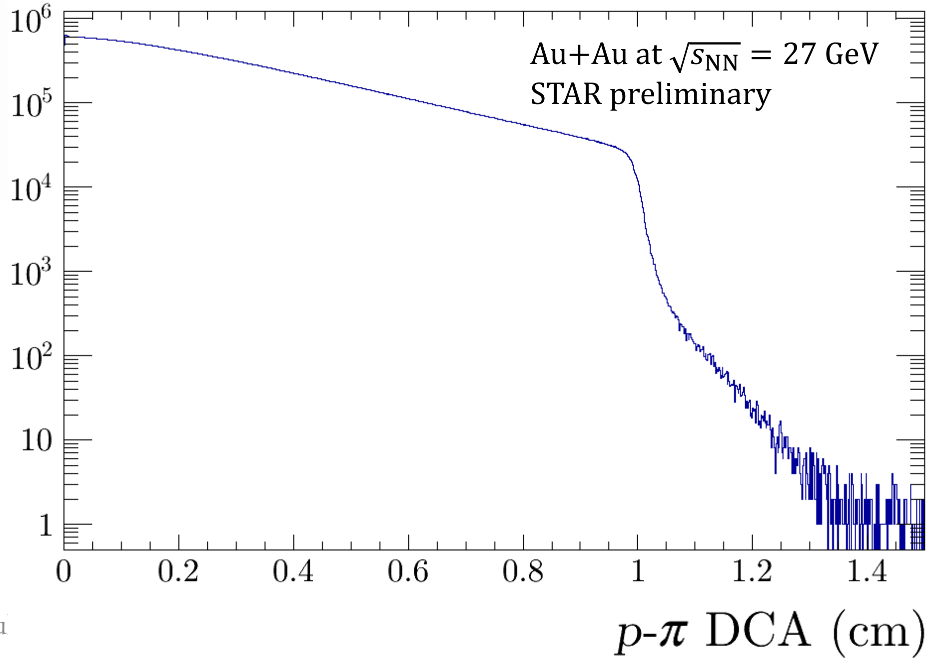


Finding Lambdas

- Protons and pions ID with TPC and TOF
- Topological cuts on p-π pairs identify Lambdas

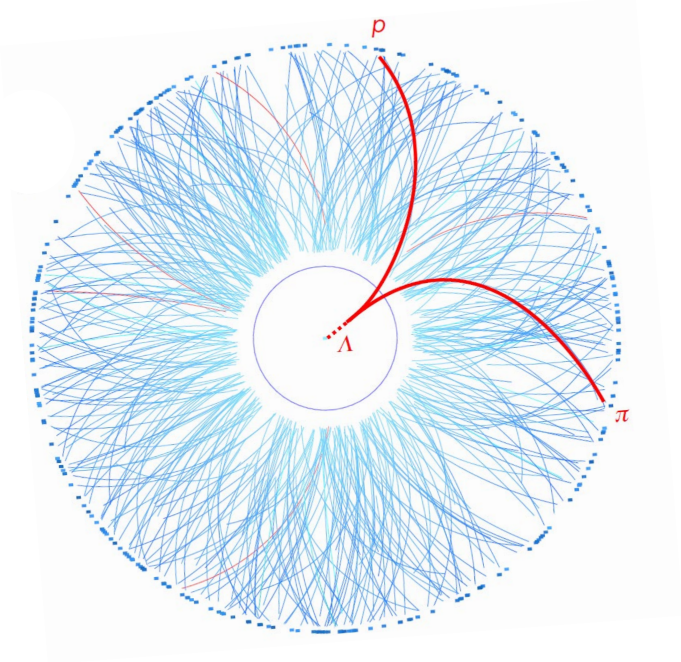


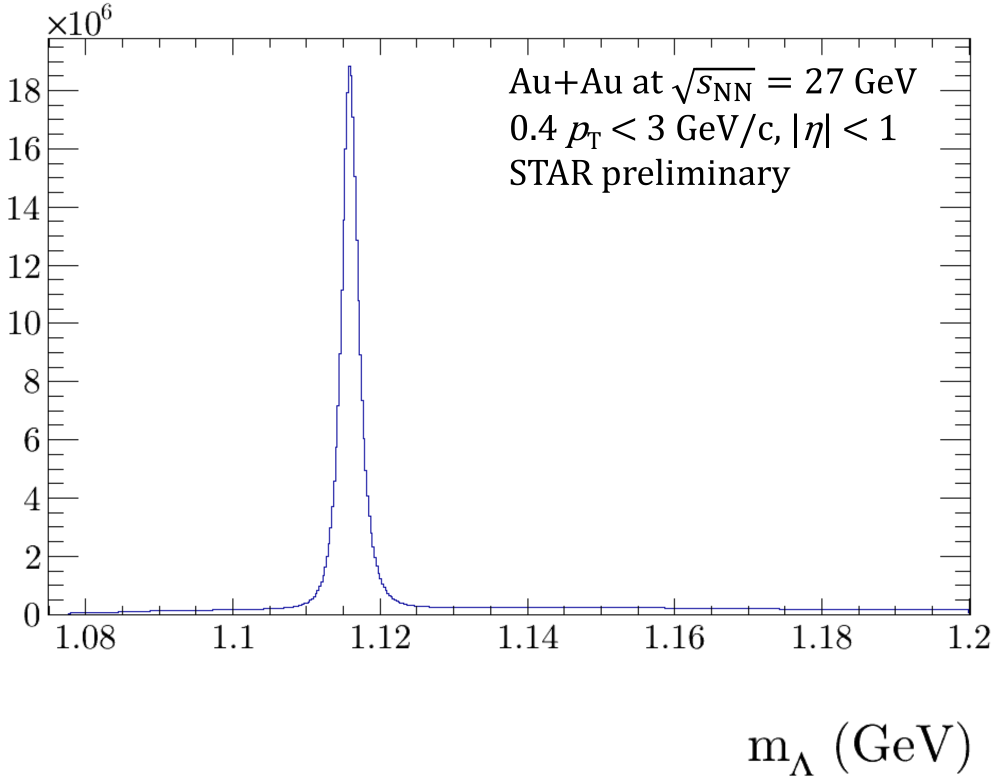




Finding Lambdas

- Protons and pions ID with TPC and TOF
- Topological cuts on p-π pairs identify Lambdas
- Some reconstructed Lambdas are "false"

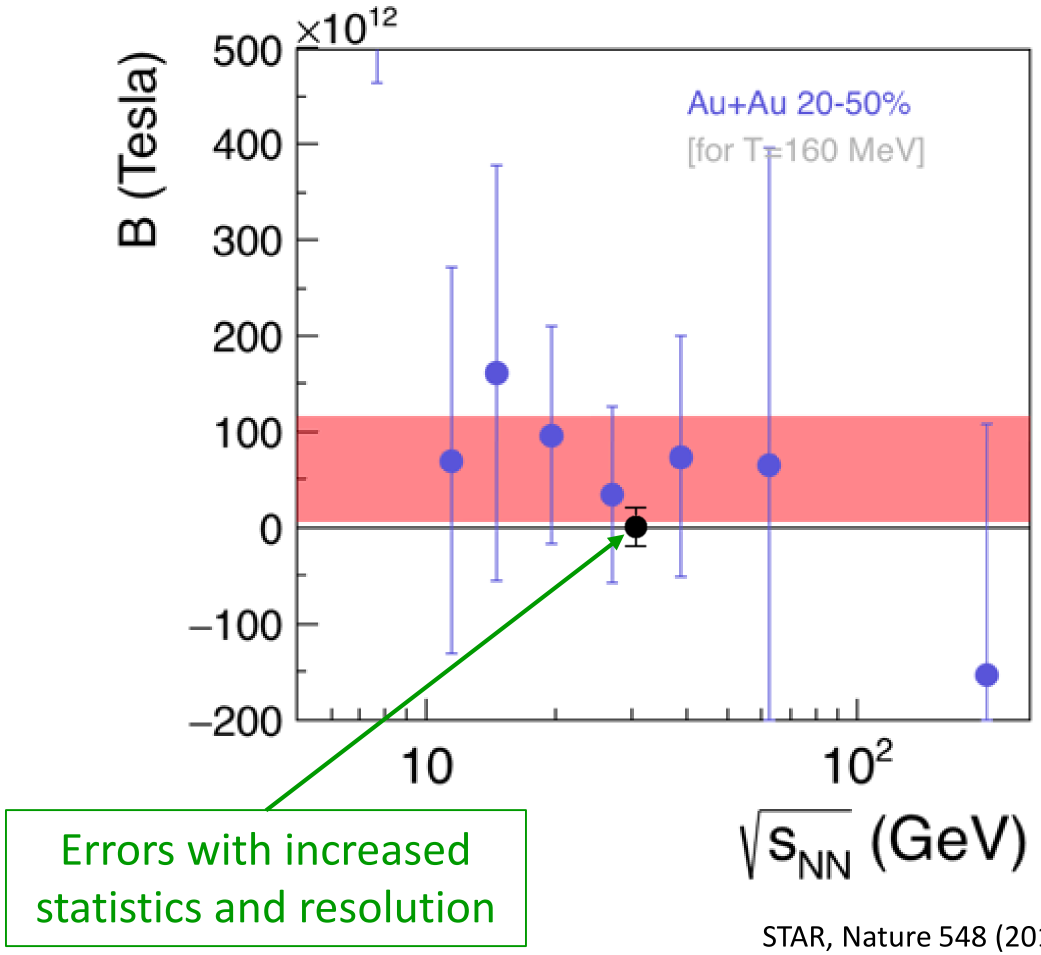




$$\frac{Signal}{Signal + Background} \approx \begin{cases} 27\text{ GeV:} \begin{cases} 91\%, \Lambda \\ 89\%, \bar{\Lambda} \end{cases} \\ 54\text{ GeV:} \begin{cases} 86\%, \Lambda \\ 80\%, \bar{\Lambda} \end{cases} \end{cases}$$

The search for $|\vec{B}|$ at 27 GeV

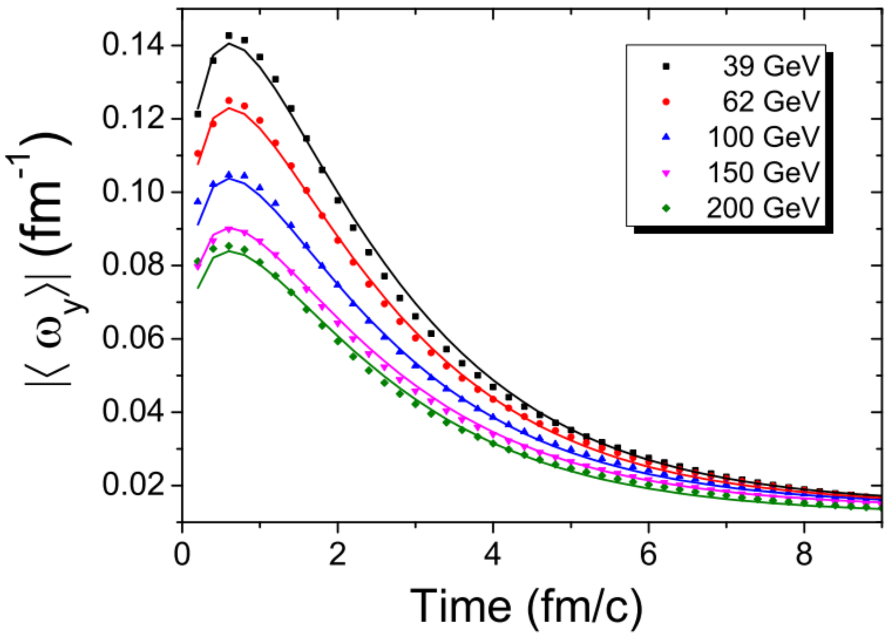
- A high-statistics Au+Au run at 27 GeV with good $R_{\mathrm{EP}}^{(1)}$ allows for a high-precision $|\vec{B}|$ measurement
  - This analysis is ongoing
    - We are not yet able to make a claim of the magnetic field
  - With event yield and $R_{\mathrm{EP}}^{(1)}$ achieved, will reduce errors significantly compared to previous study
    - $\delta \mathrm{P_H} \propto \frac{1}{\sqrt{\#\Lambda}} \frac{1}{R_{\mathrm{EP}}^{(1)}}$

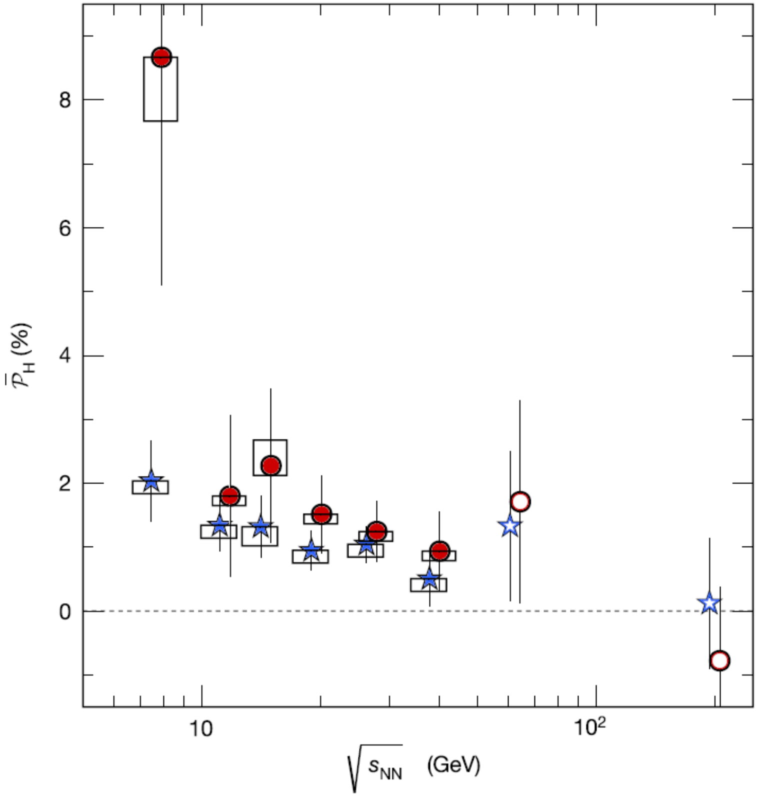


STAR, Nature 548 (2017) 62548

$\sqrt{s_{NN}}$ dependence of P_H

- AMPT shows decrease in P_H with increasing $\sqrt{s_{NN}}$ (1)
- Previous studies across broad range of $\sqrt{s_{NN}}$ suggest this trend (2)



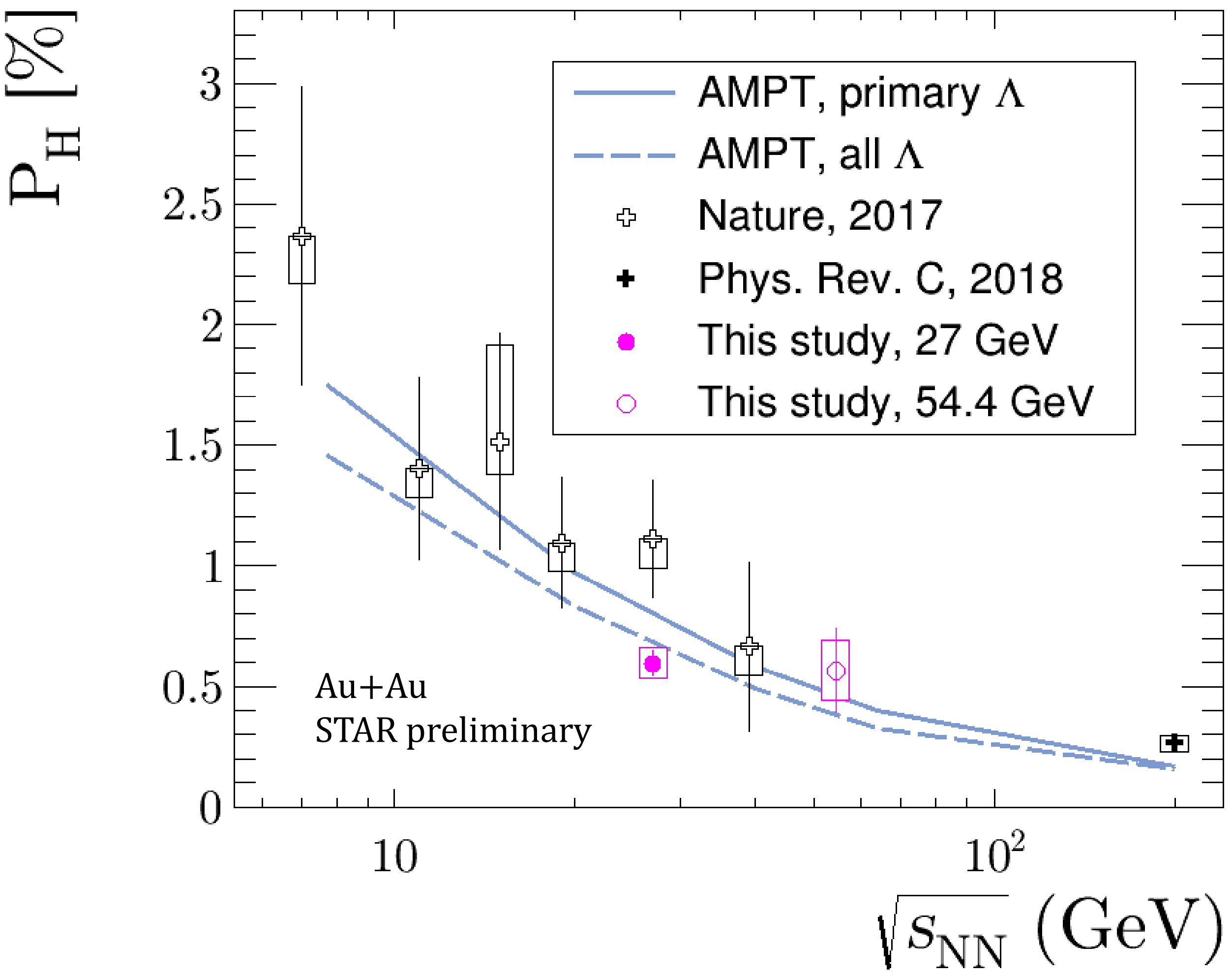


[1] Y. Jiang, et. al., Phys. Rev., vol. C94, no. 4, p. 044910, 2016

[2] STAR, Nature 548 (2017) 62548

$\sqrt{s_{NN}}$ dependence of P_H

- AMPT shows decrease in P_H with increasing $\sqrt{s_{NN}}$ [1]
- Previous studies across broad range of $\sqrt{s_{NN}}$ suggest this trend [2]
- These studies agree with this trend
- Recent high-statistics run at 19 GeV, 14.5, and 3 GeV will be useful



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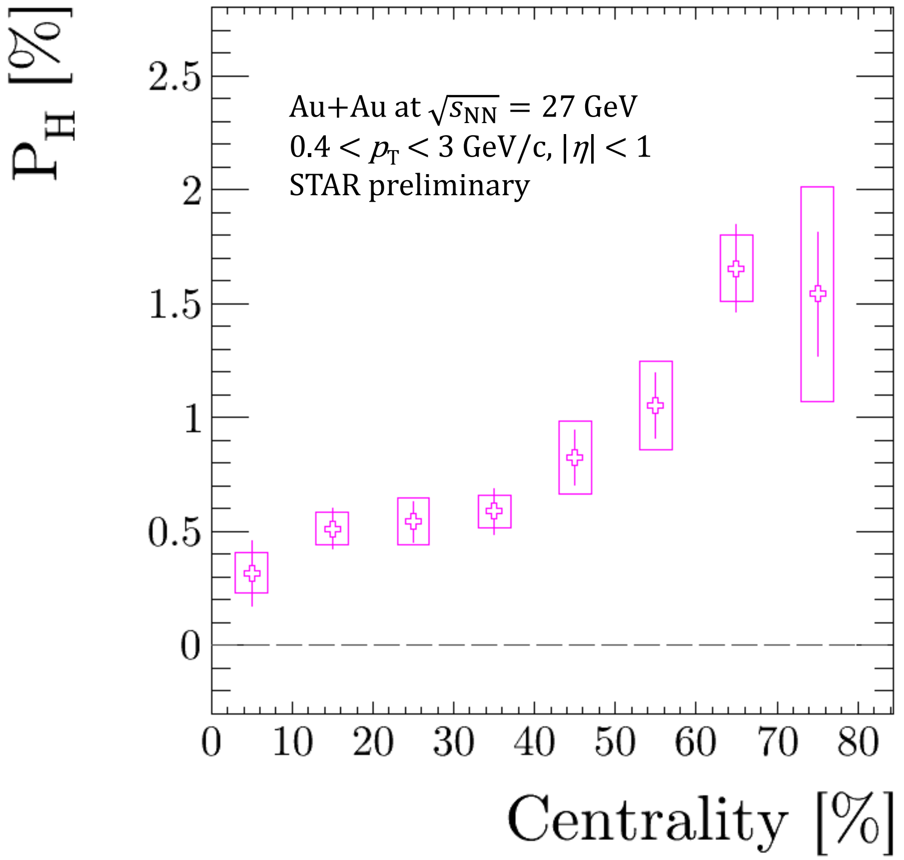
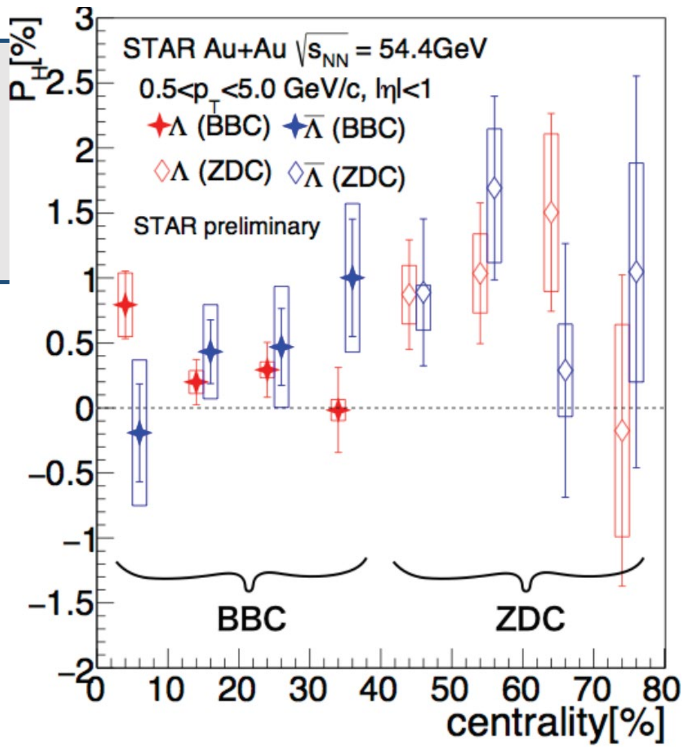
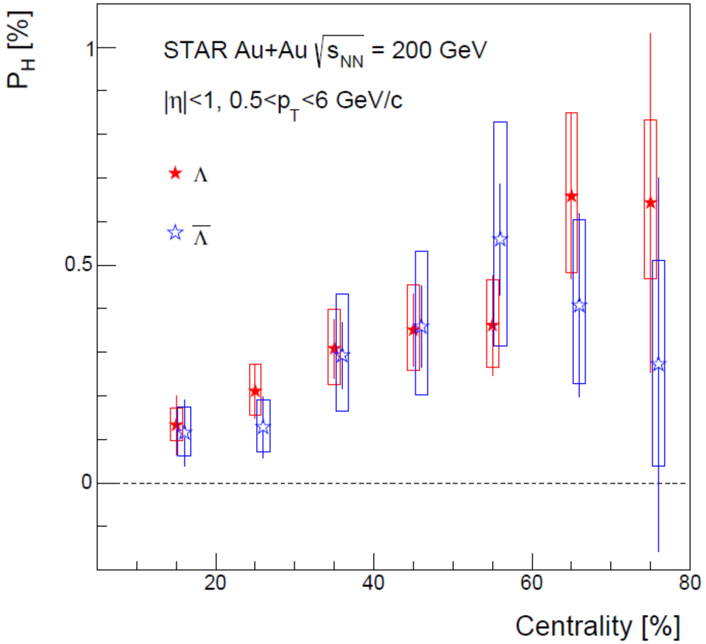
Centrality dependence of P_H

- We observe P_H increasing with centrality
  - 54 GeV study uses BBC and ZDC based on $R_{EP}^{(1)}(centrality)$
- This trend previously suggested by study at 200 GeV [1]

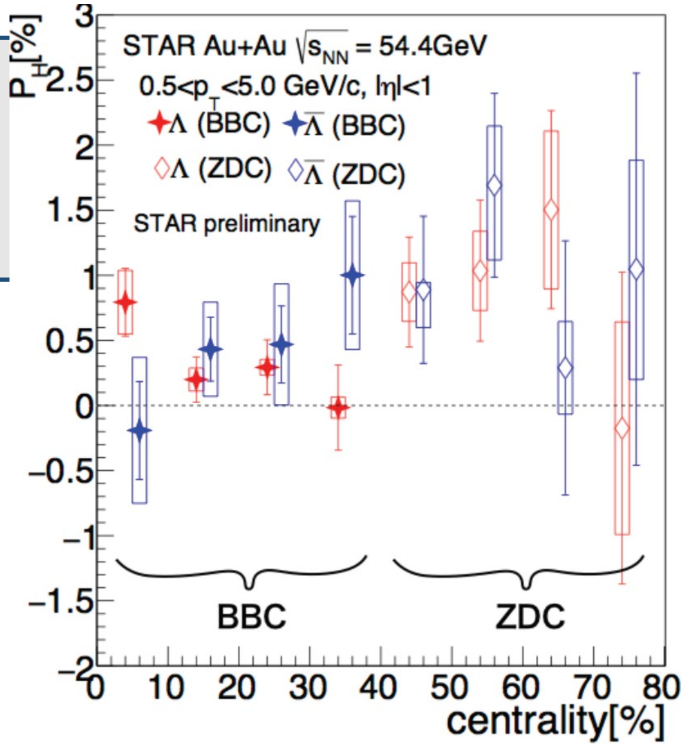


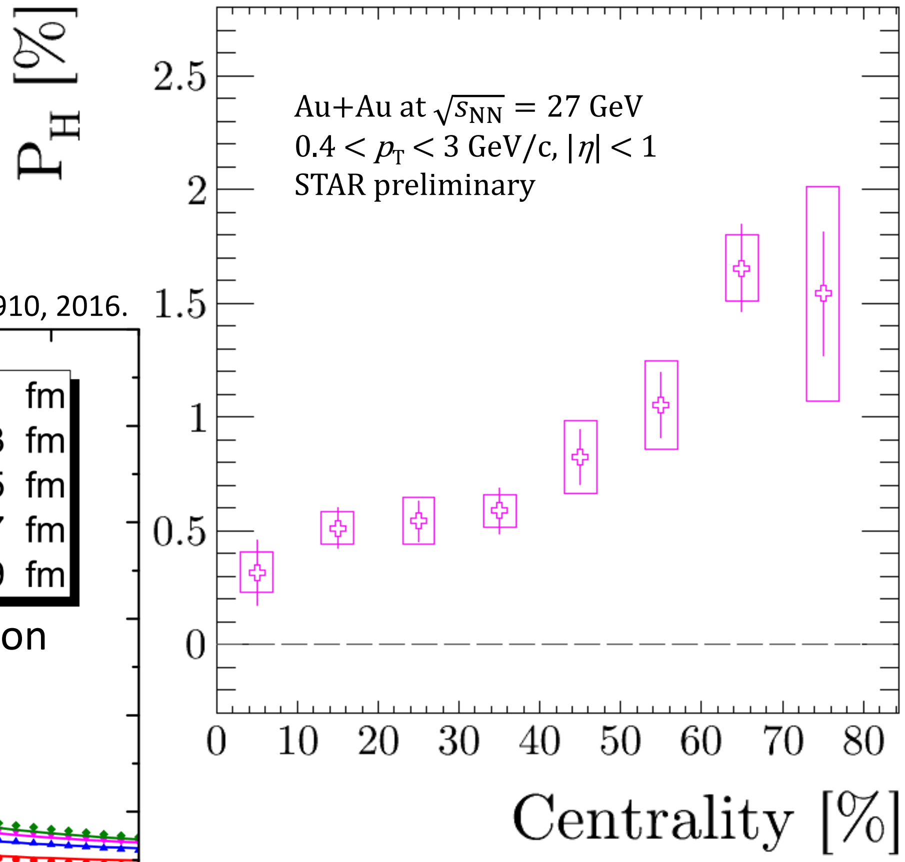


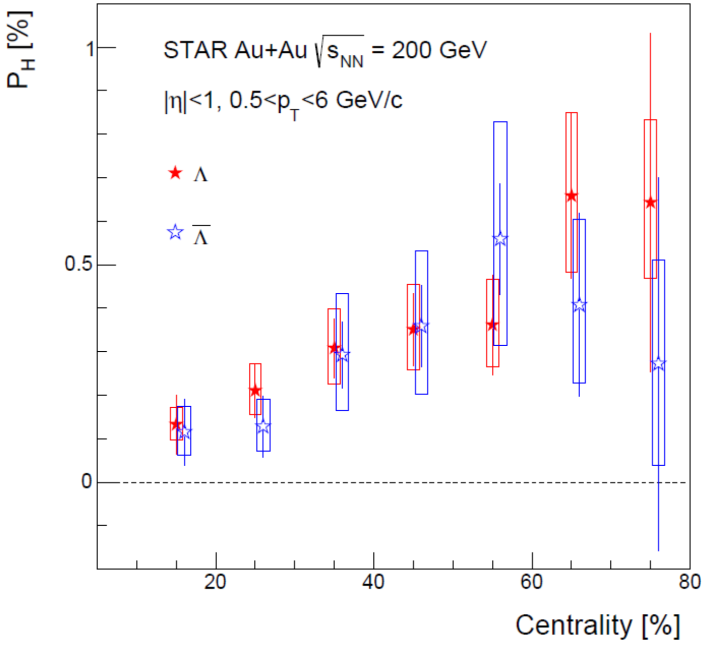


Centrality dependence of P_H

- Our observation confirms AMPT predictions [1]







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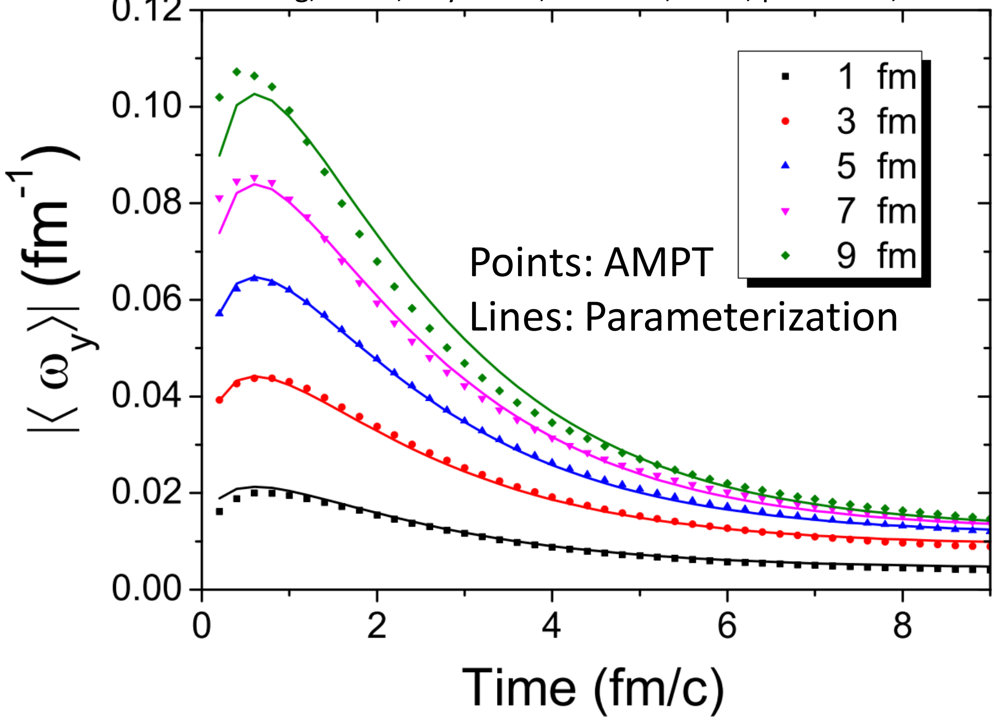
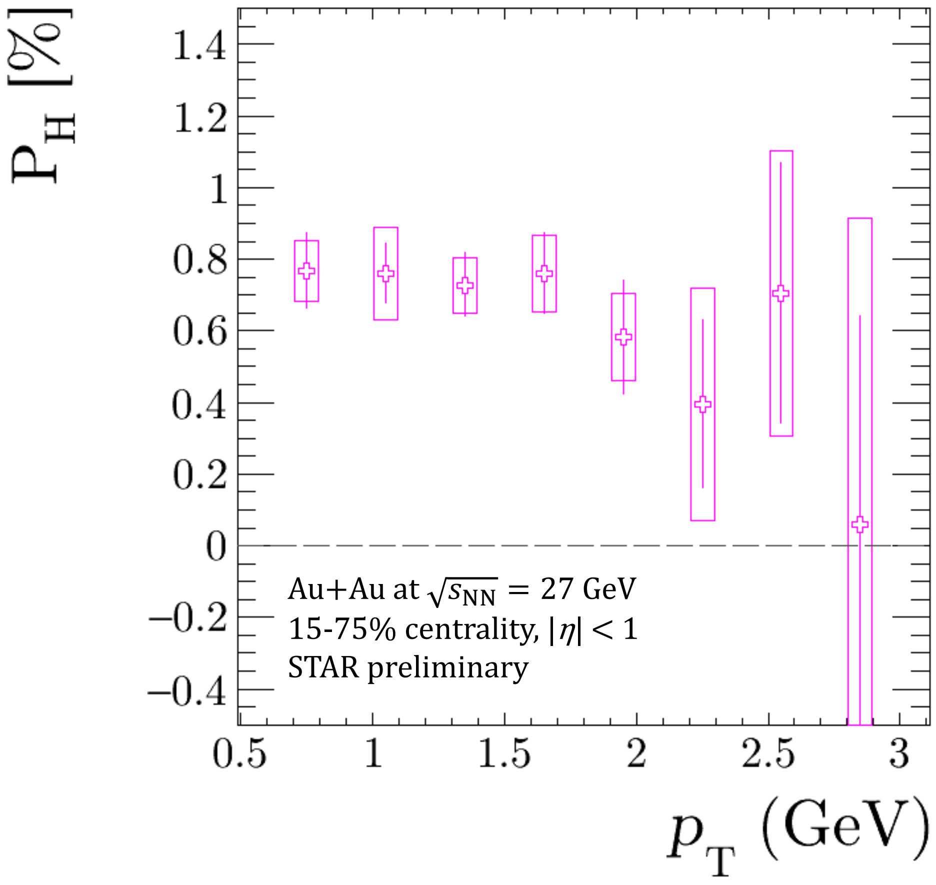
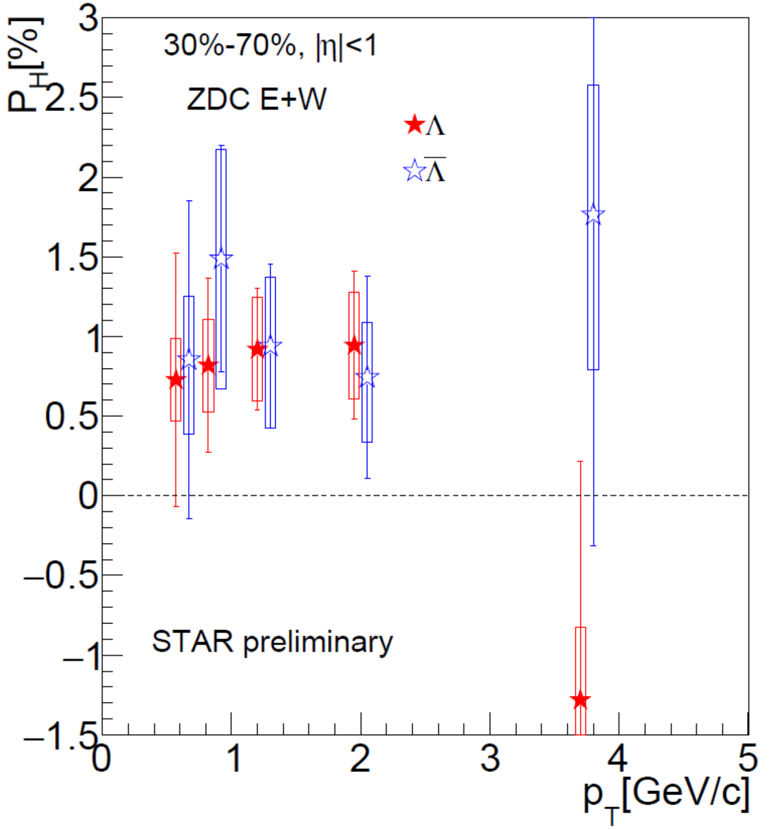


p_T dependence of P_H

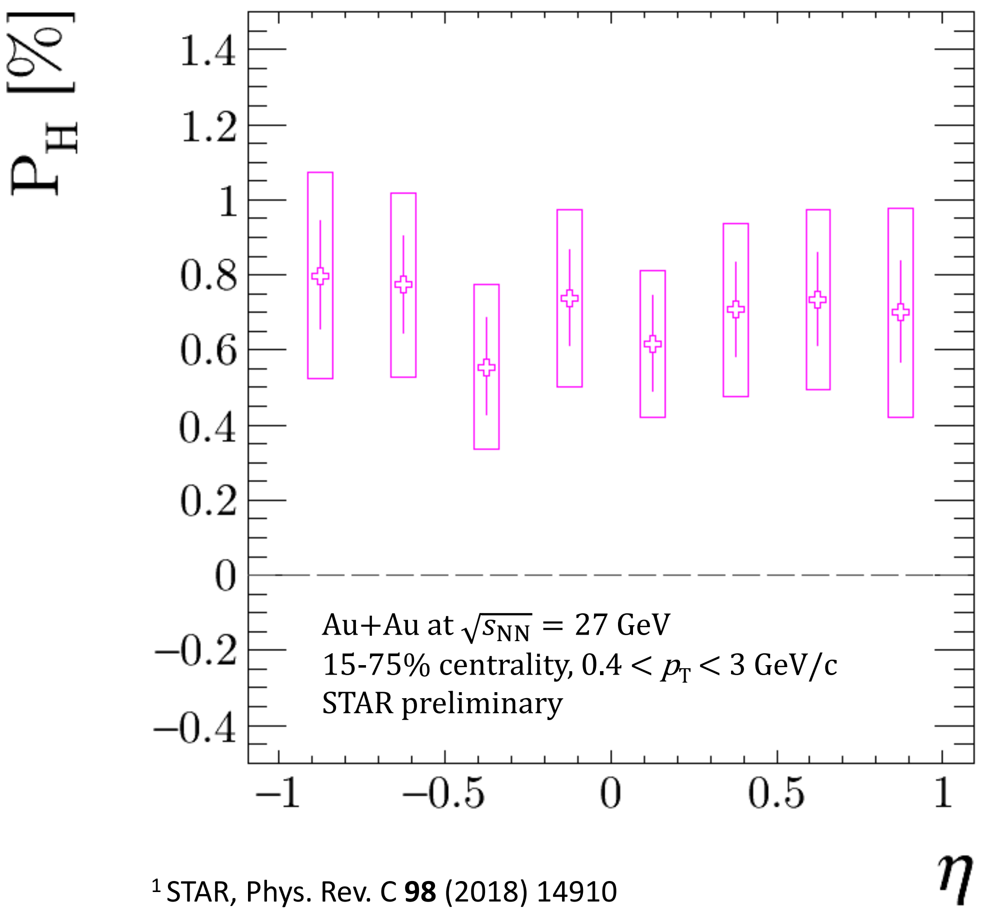
- We see no dependence on p_T at 27 or 54.4 GeV
  - Enough statistics to say P_H flat in range $0.5 < p_T < 1.75$ GeV
  - If P_H drops at low p_T due to scattering or high p_T due to jet fragmentation, it must be outside this p_T range

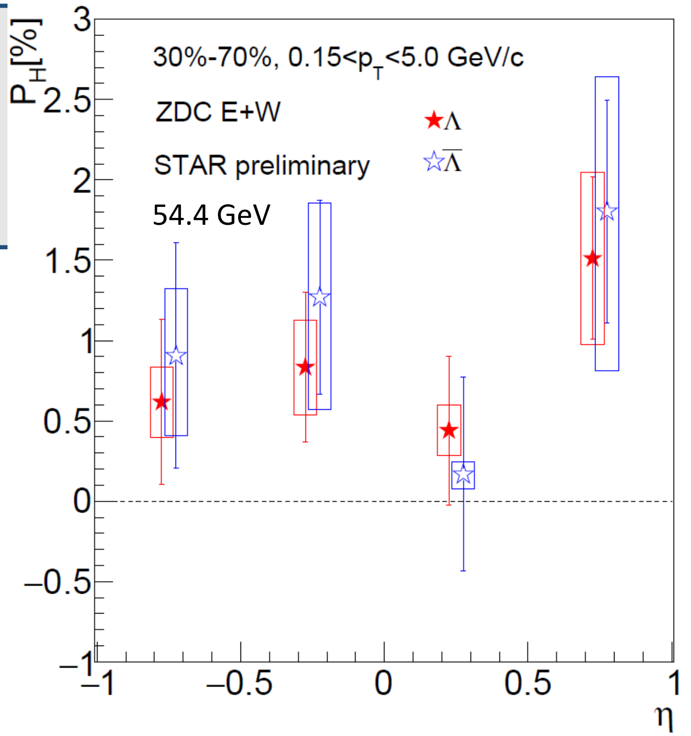


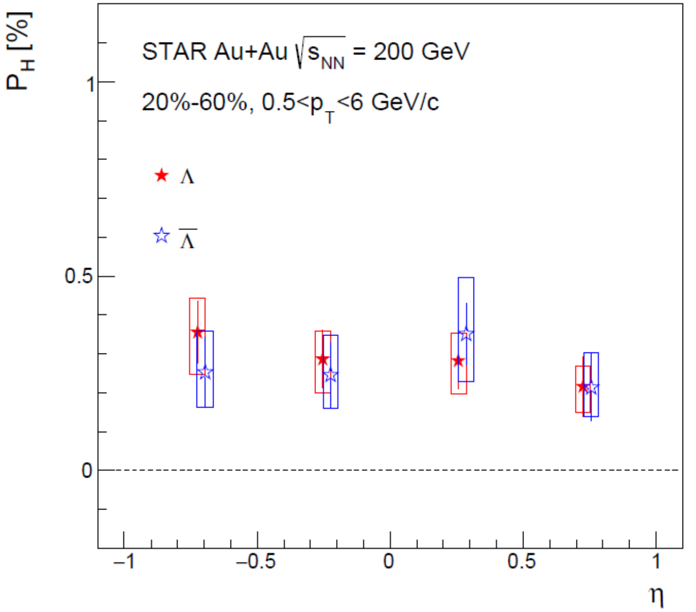


η dependence of P_H

- We see no dependence on η with our statistics and acceptance
  - Consistent with study at 200 GeV [1]





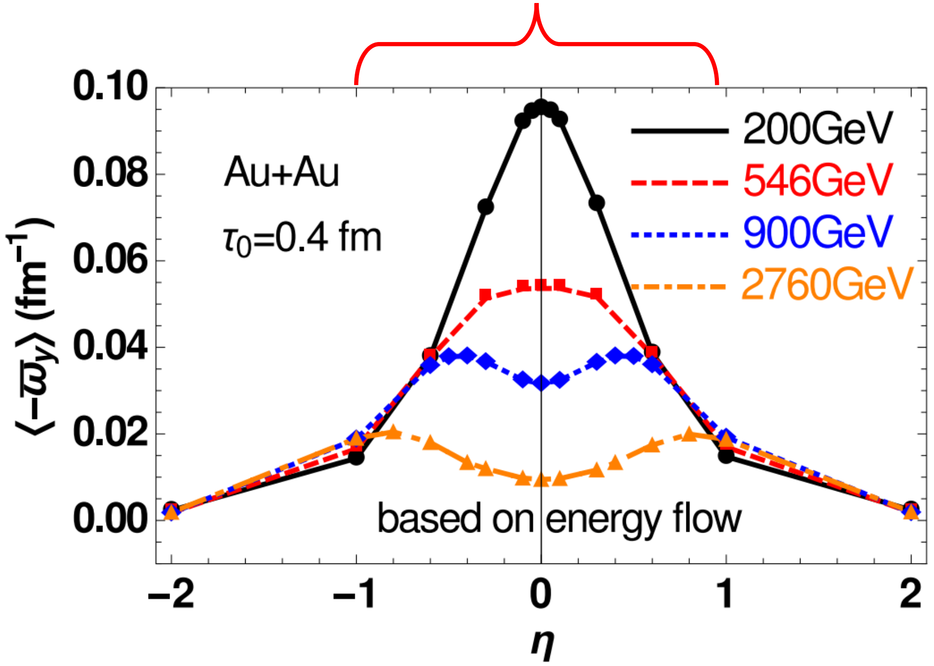


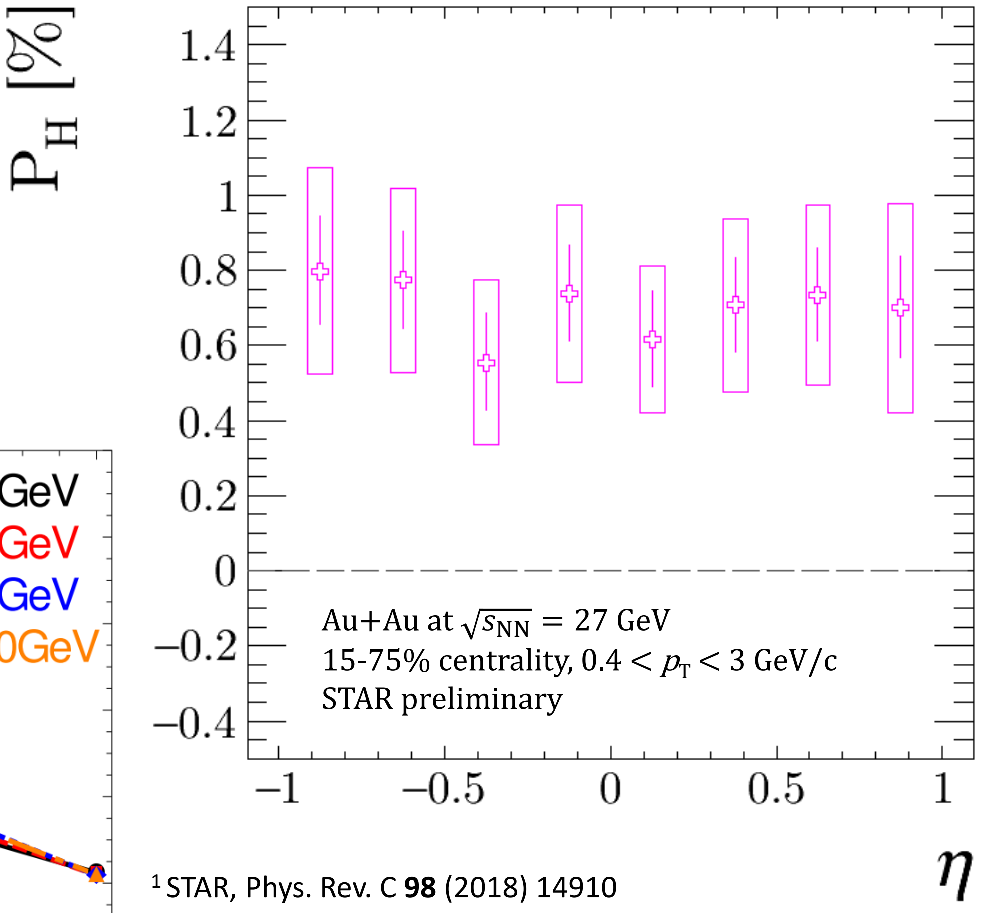
[1] STAR, Phys. Rev. C **98** (2018) 14910

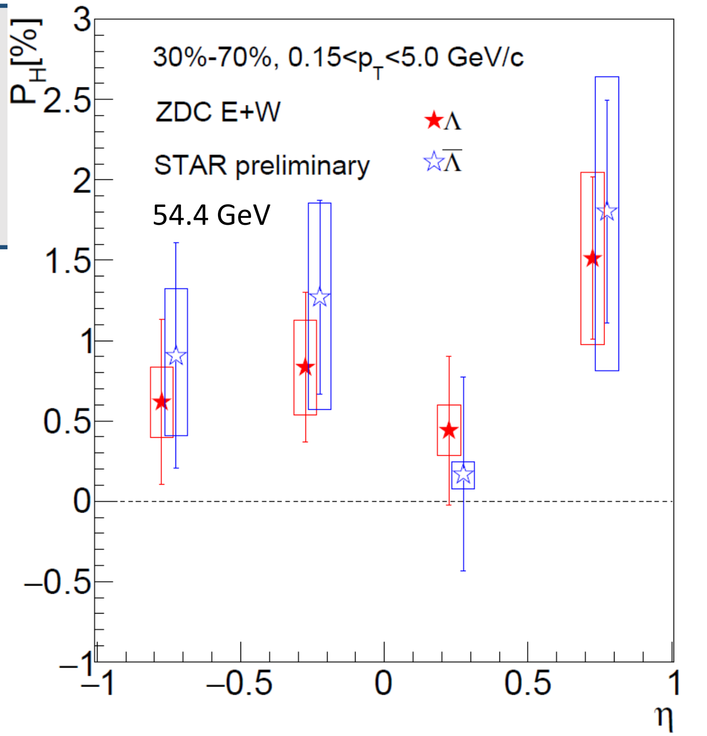
η dependence of P_H

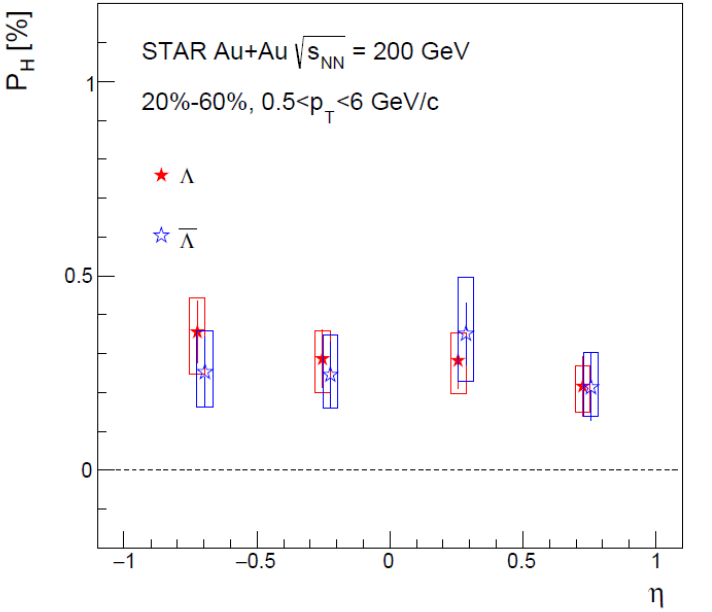
- Simulations show strong η dependence of $\bar{P}_H$ (2)
  - Not observed within $|\eta| < 1$
  - Forward upgrade can study this with better η acceptance

STAR η range







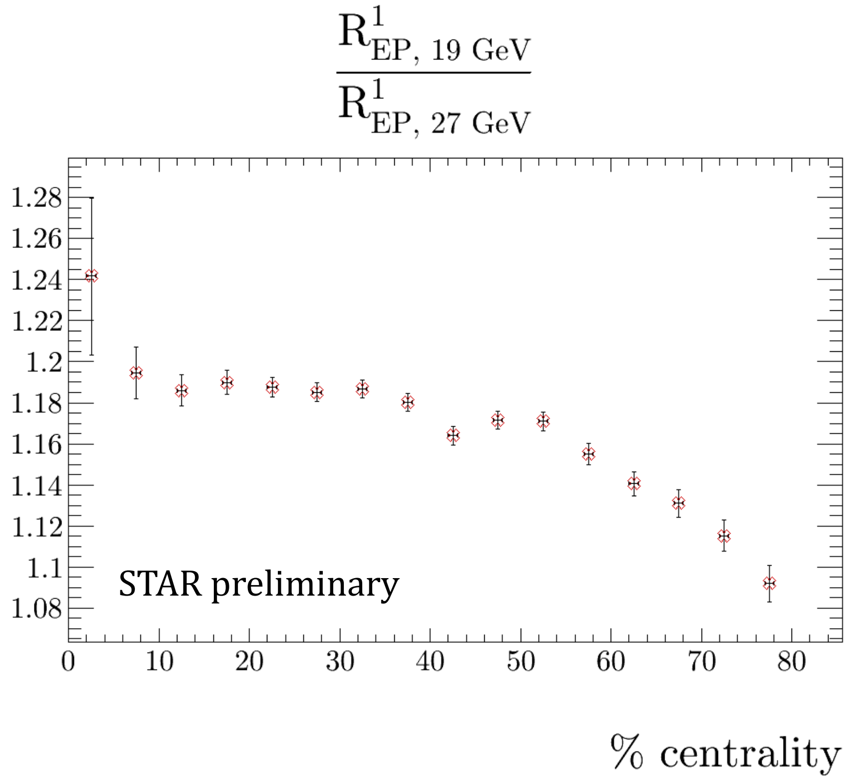


[1] STAR, Phys. Rev. C **98** (2018) 14910

[2] Deng,W-T and Huang, X-G., Phys. Rev. C **93**, 064907 (2016)

Summary and Outlook

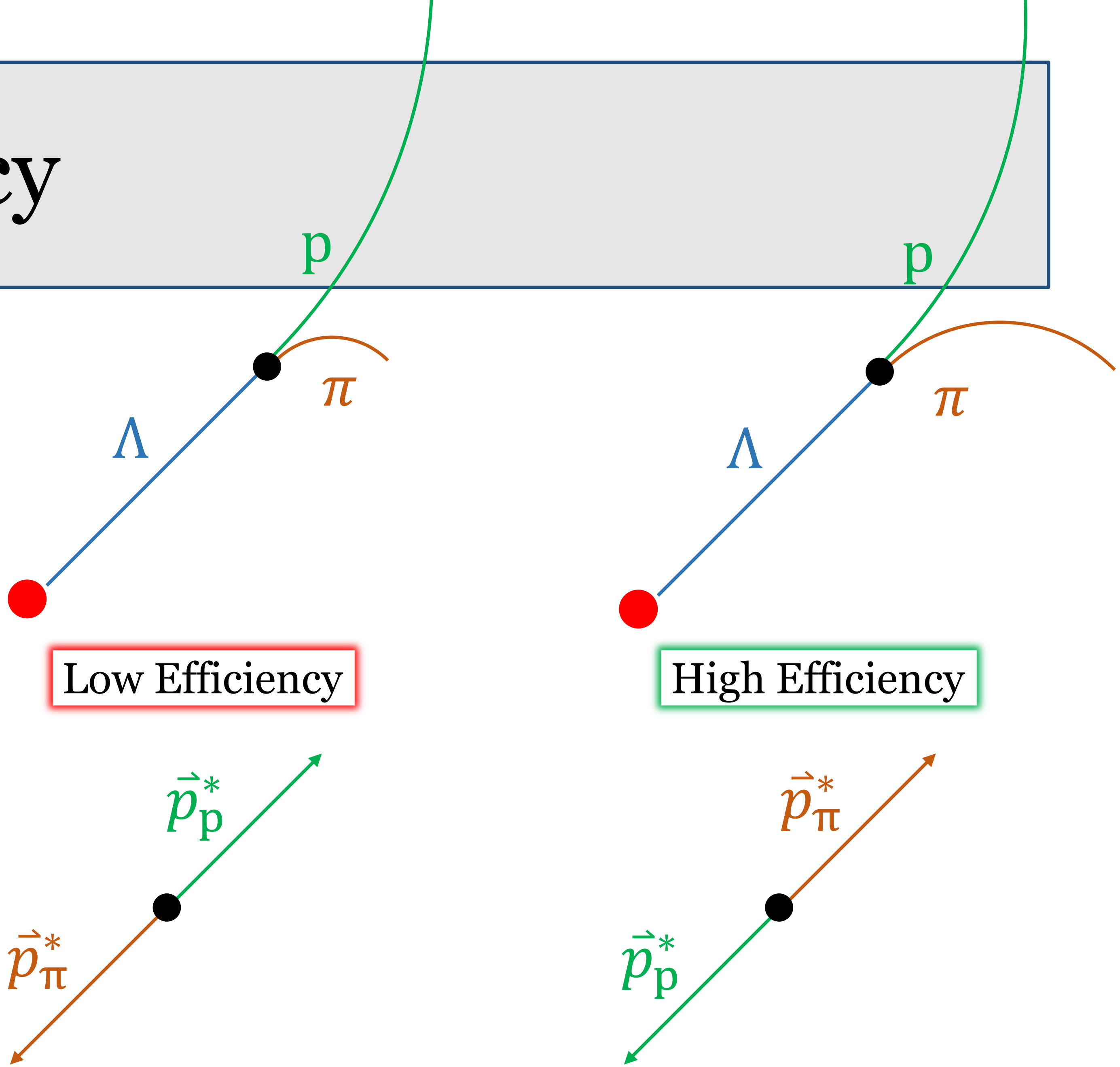
- Various differential measurements of $\mathrm{P_H}$ were studied at 27 GeV and 54.4 GeV
  - There is an increase in $\mathrm{P_H}$ for more central events
  - $\mathrm{P_H}$ is flat in the range $0.5 < p_T < 1.75$
  - There is no observable η dependence within $|\eta| < 1$
- This high-statistics data set at 27 GeV will be able to measure the magnetic field with much smaller error bars than before
- The search will continue at 19.6 and 14.5 GeV
  - High-statistics data sets
  - Uniform Lambda acceptance in the TPC
  - Larger event-plane resolution with the EPD



BACKUP

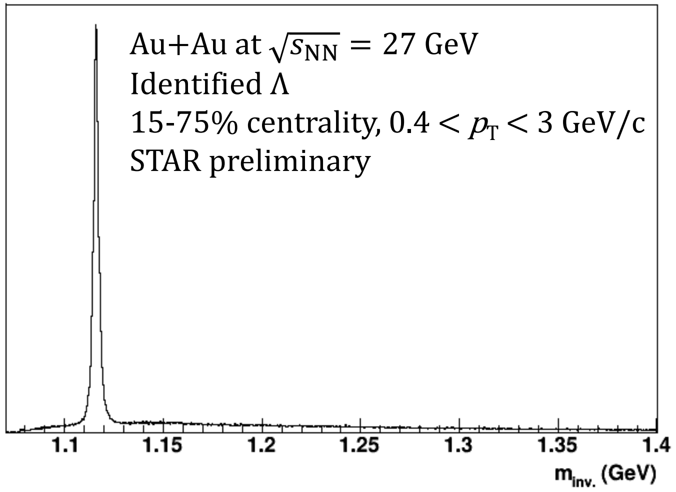
Lambda Efficiency

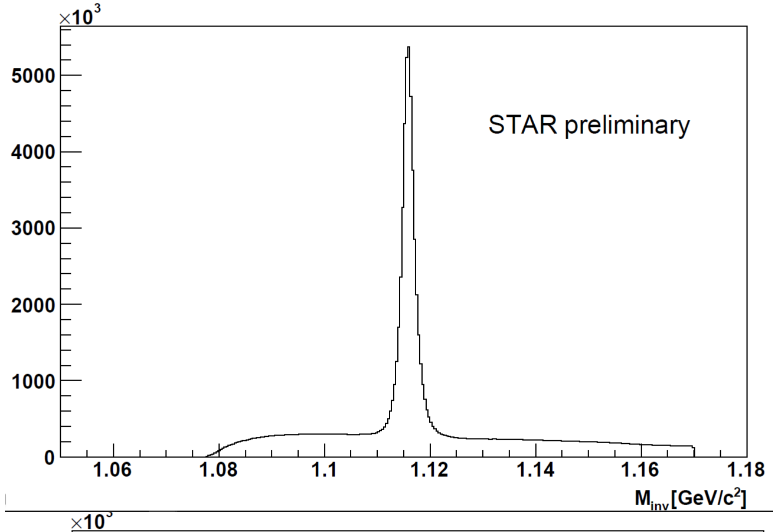
- Lambdas emitting pions in the direction of their momenta have higher efficiency

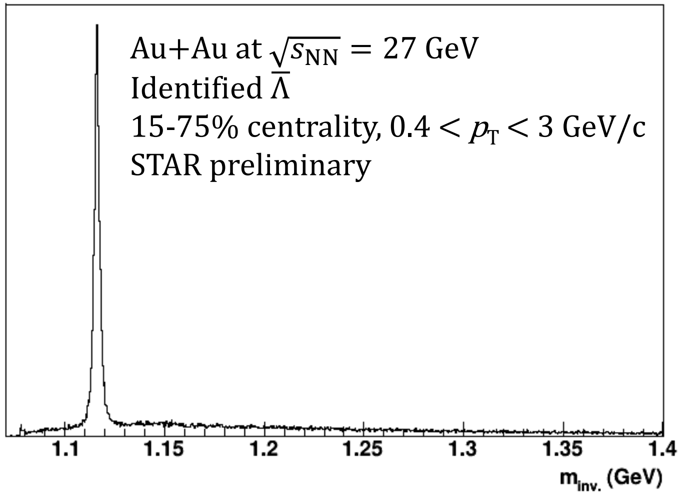


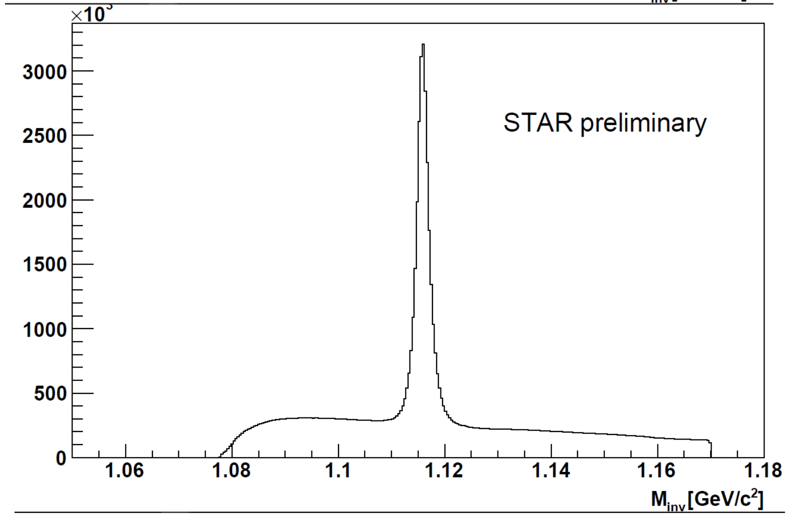
Finding Lambdas

- The "significance" of the Lambda mass distribution describes the ability of the Lambda-finding algorithm to pick out Lambdas
    - $\frac{1}{\sqrt{N_{\text{Events}}}} \frac{N_{\Lambda}}{\sqrt{N_{\Lambda} + N_{\Lambda\ \text{background}}}} = 0.615$
    - $\frac{1}{\sqrt{N_{\text{Events}}}} \frac{N_{\bar{\Lambda}}}{\sqrt{N_{\bar{\Lambda}} + N_{\bar{\Lambda}\ \text{background}}}} = 0.320$
    - $\frac{N_{\Lambda}}{N_{\Lambda} + N_{\Lambda\ \text{background}}} = 0.914$
    - $\frac{N_{\bar{\Lambda}}}{N_{\bar{\Lambda}} + N_{\bar{\Lambda}\ \text{background}}} = 0.893$









Finding Lambdas

✔Proton and Pion identification

(for proton)

- $|n\sigma| < 3$
- $0.5 < m^2 < 1.5\ GeV^2/c^4$

(for pion)

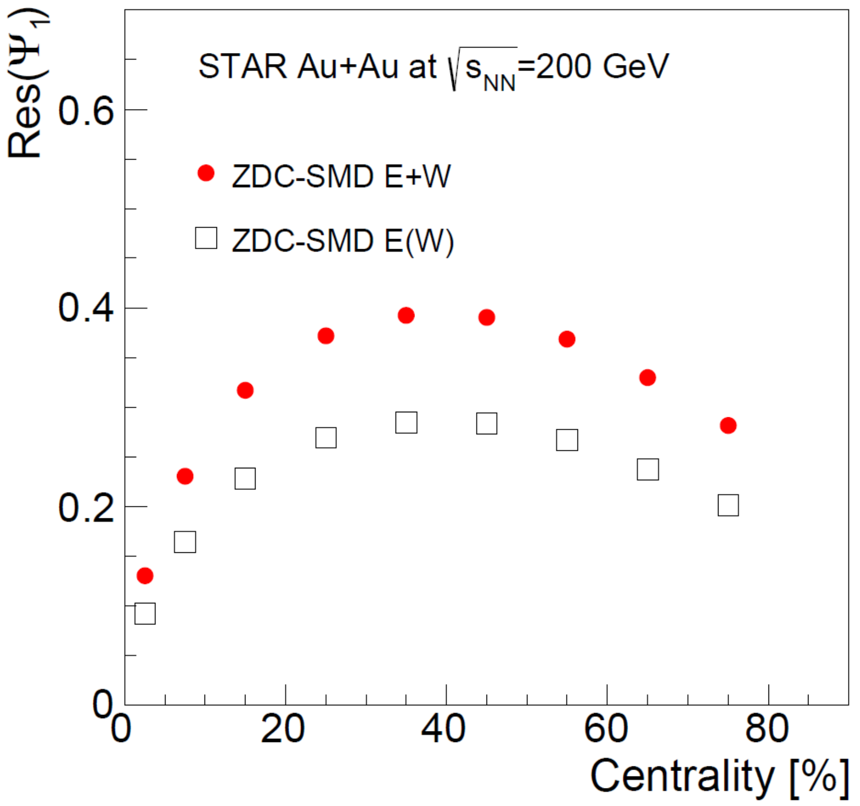
- $|n\sigma| < 3$
- $-0.029 + 0.017p < m^2 < 0.04\ GeV^2/c^4$

✔**Topological cut**

Centrality	p-DCA	π-DCA	p-π DCA	Λ-DCA	Decay length
0%-10%	>0.4 cm	>1.5 cm	< 0.9 cm	< 0.8 cm	>4.0 cm
10%-20%	>0.4 cm	>1.5 cm	< 0.9 cm	< 0.8 cm	>4.0 cm
20%-30%	>0.3 cm	>1.3 cm	< 1.0 cm	< 0.9 cm	>3.5 cm
30%-40%	>0.2 cm	>1.2 cm	<1.0 cm	< 0.9 cm	>3.5 cm
40%-50%	>0.2 cm	>1.0 cm	< 1.0 cm	< 1.0 cm	>3.0 cm
50%-60%	>0.2 cm	>0.8 cm	< 1.1 cm	< 1.0 cm	>3.0 cm
60%-70%	>0.1 cm	>0.8 cm	< 1.1 cm	< 1.1 cm	>2.5 cm
70%-80%	>0.1 cm	>0.7 cm	< 1.2 cm	< 1.2 cm	>2.5 cm

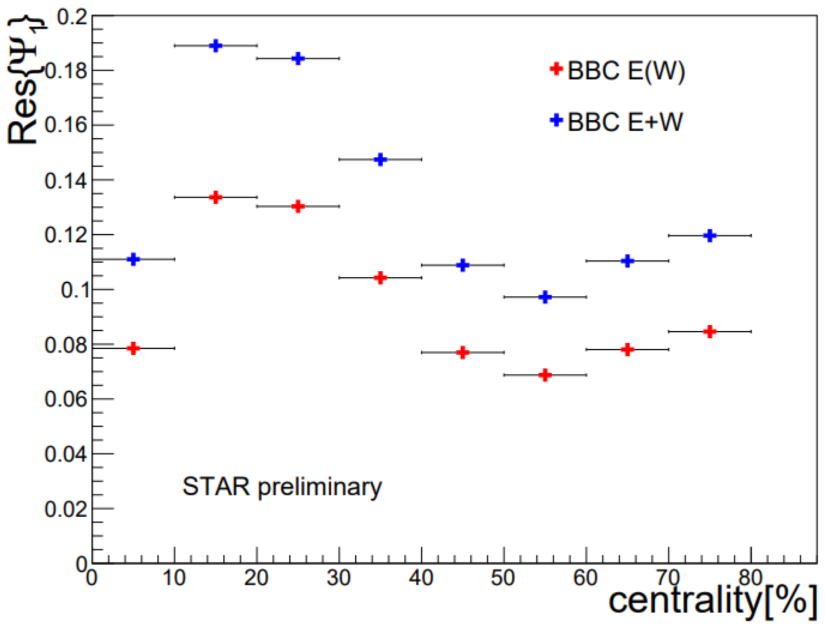
Event-plane resolution

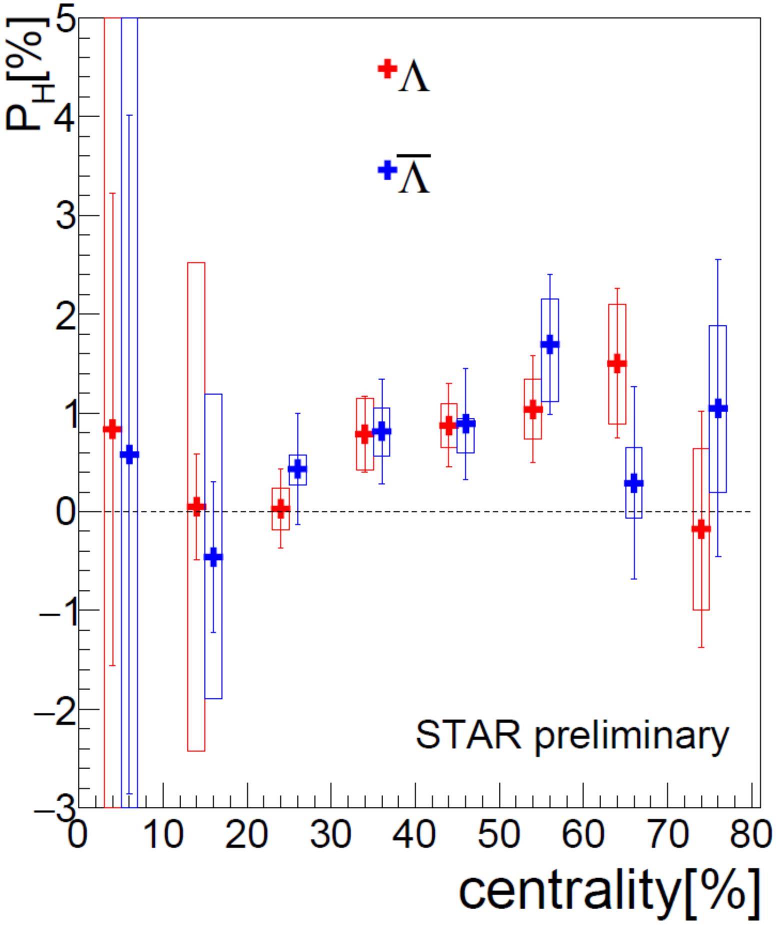
- STAR's recent study at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV had peak resolutions around 0.4



STAR, Phys. Rev. C **98** (2018) 14910 arXiv:190

BBC


Res{Ψ1}
BBC E(W)
BBC E+W
STAR preliminary
centrality[%]


P_H[%]
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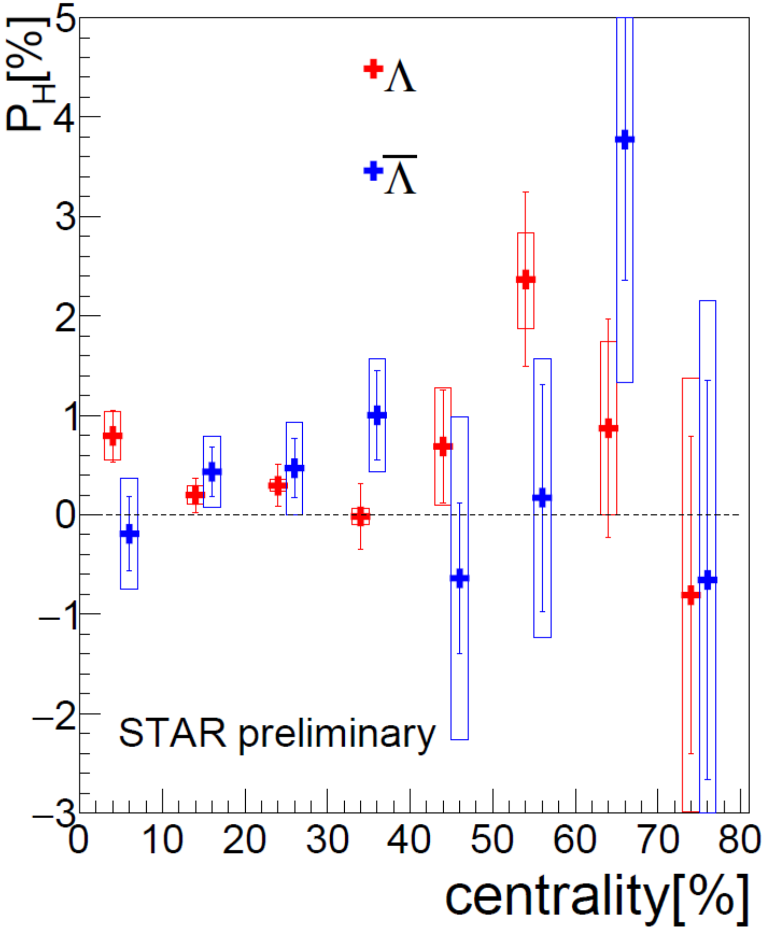
centrality[%]


P_H[%]
Λ
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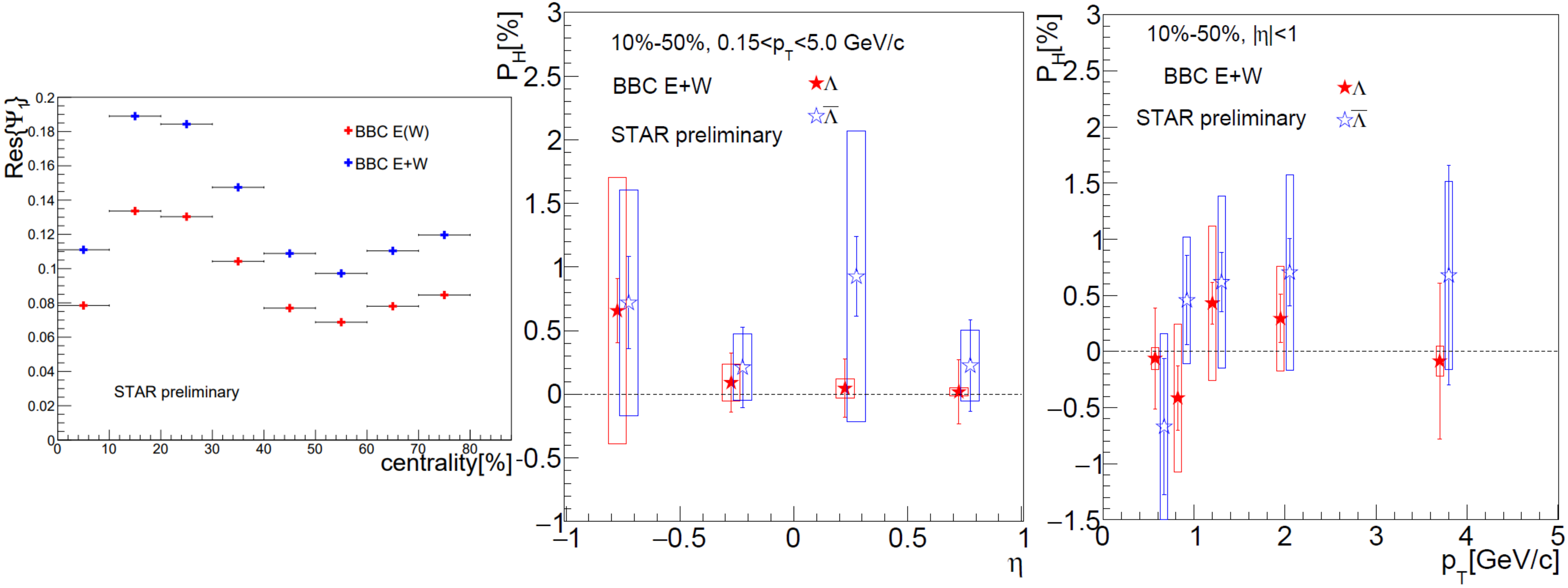
STAR preliminary
centrality[%]

BBC



Res{Ψ1}
BBC E(W)
BBC E+W
STAR preliminary
centrality[%]
P_H[%]
10%-50%, 0.15<p_T<5.0 GeV/c
BBC E+W
STAR preliminary
Λ
Λ̄
η
10%-50%, |η|<1
p_T[GeV/c]

Magnetic field

Vortical coupling: $P \propto \omega$

$\vec{P}_{\Lambda} \parallel +\hat{J}_{sys}$ $\vec{P}_{\bar{\Lambda}} \parallel +\hat{J}_{sys}$

Magnetic coupling: $P \propto \vec{\mu} \cdot \vec{B}$

$\vec{P}_{\Lambda} \parallel -\hat{J}_{sys}$ $\vec{P}_{\bar{\Lambda}} \parallel +\hat{J}_{sys}$

$$\begin{pmatrix} \varpi_c \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right) S_R(S_R+1) & \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)(S_R+1)\mu_R \\ \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda}\overline{R}}C_{\overline{\Lambda}\overline{R}} - \frac{1}{3}f_{\overline{\Sigma}^0\overline{R}}C_{\overline{\Sigma}^0\overline{R}}\right) S_{\overline{R}}(S_{\overline{R}}+1) & \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda}\overline{R}}C_{\overline{\Lambda}\overline{R}} - \frac{1}{3}f_{\overline{\Sigma}^0\overline{R}}C_{\overline{\Sigma}^0\overline{R}}\right)(S_{\overline{R}}+1)\mu_{\overline{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_{\Lambda}^{\text{meas}} \\ P_{\overline{\Lambda}}^{\text{meas}} \end{pmatrix}$$