$\Lambda(\bar{\Lambda})$ Hyperons Polarization in Au+Au collisions at RHIC

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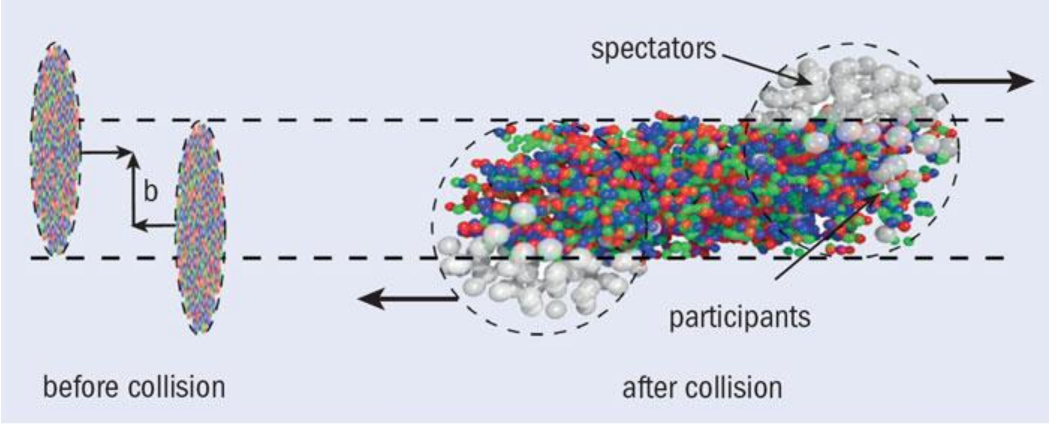
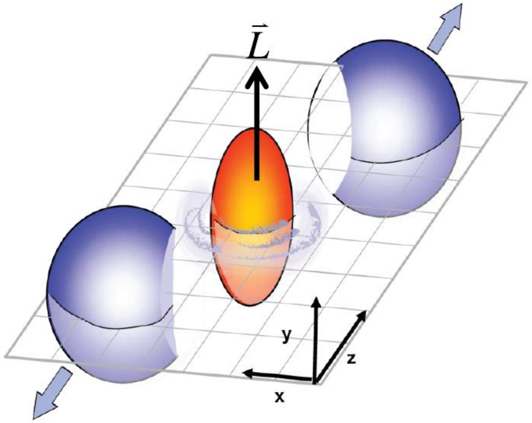
Introduction





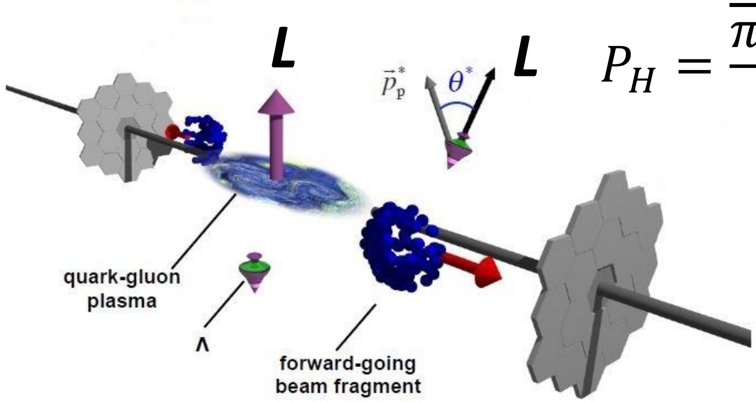
- Initial angular momentum $|\boldsymbol{L}| \sim 10^3 \hbar$ in non-central heavy-ion collisions.
- Baryon stopping may transfer this angular momentum, in part, to the fireball.
- Due to the vorticity and spin-orbit coupling, spin of Λ may align with $\boldsymbol{L}$.
- Polarization is a sensitive probe to vortical structure of QGP and fluid properties.

Λ polarization observable

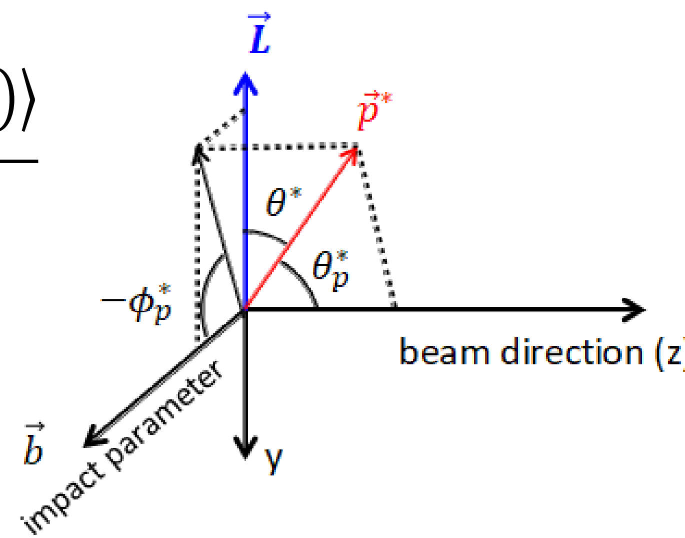
The global polarization of Λ hyperons can be determined from the angular distribution of Λ decay products relative to the system orbital momentum ***L***

$$\frac{dN}{d(\cos\theta^*)} = \frac{1}{2}\left(1 + \alpha_H \left|\vec{P}_H\right| \cos\theta^*\right)$$

Project to the transverse plane

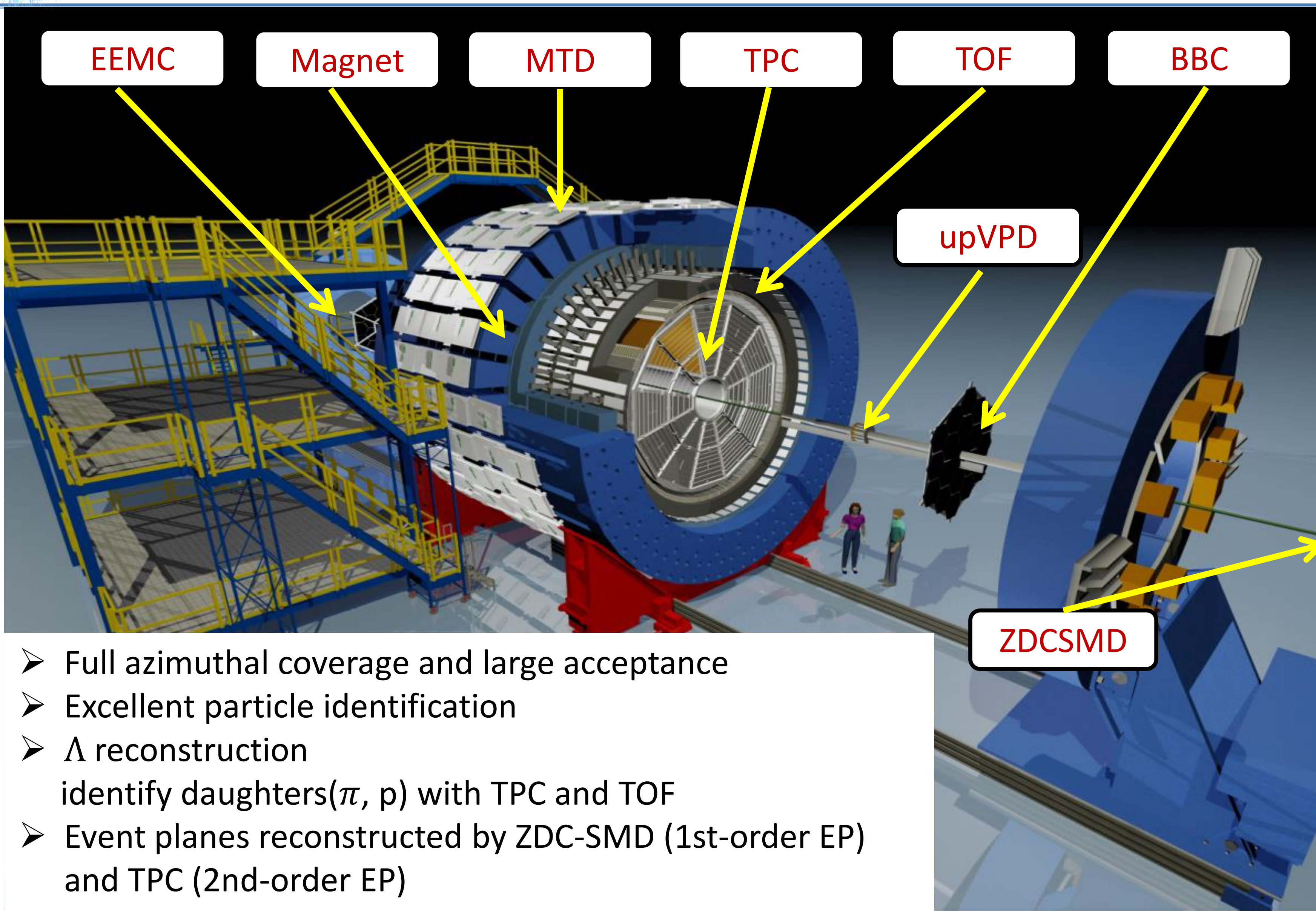


$$P_H = \frac{\frac{8}{\pi\alpha_H}\left\langle \sin\left(\Psi - \phi_p^*\right)\right\rangle}{\mathrm{Res}^{\Psi}}$$



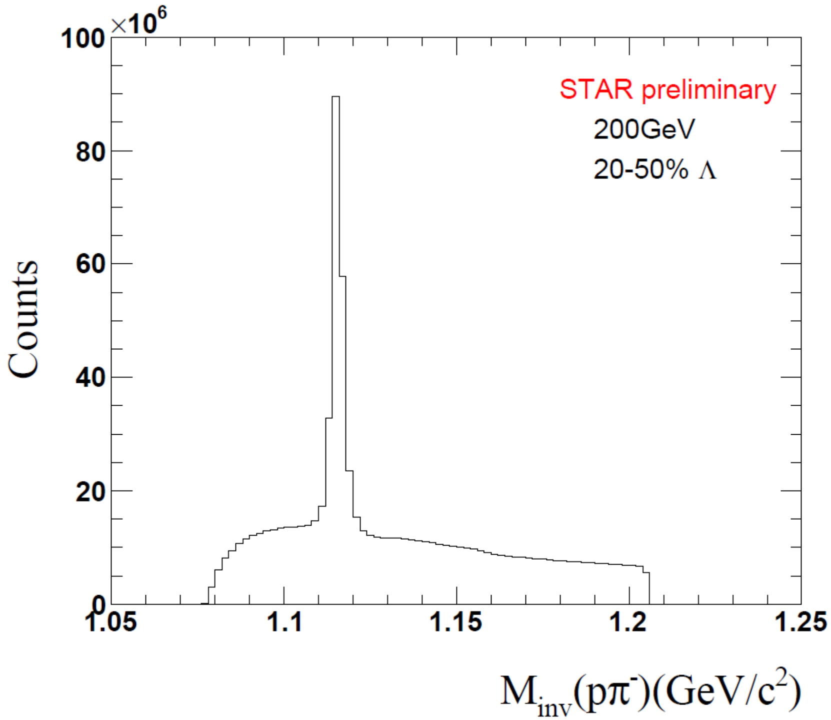
- Daughter proton preferentially points into the direction of Λ spin.
- θ^* is the angle between the system orbital momentum ***L*** and the momentum of the daughter proton in the Λ rest frame.
- ϕ_p^* is the ϕ of daughter proton in Λ rest frame.
- Ψ is the 1st-order event plane reconstructed by ZDC-SMD in this analysis.
- α_H is the Λ decay parameter ($\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$).

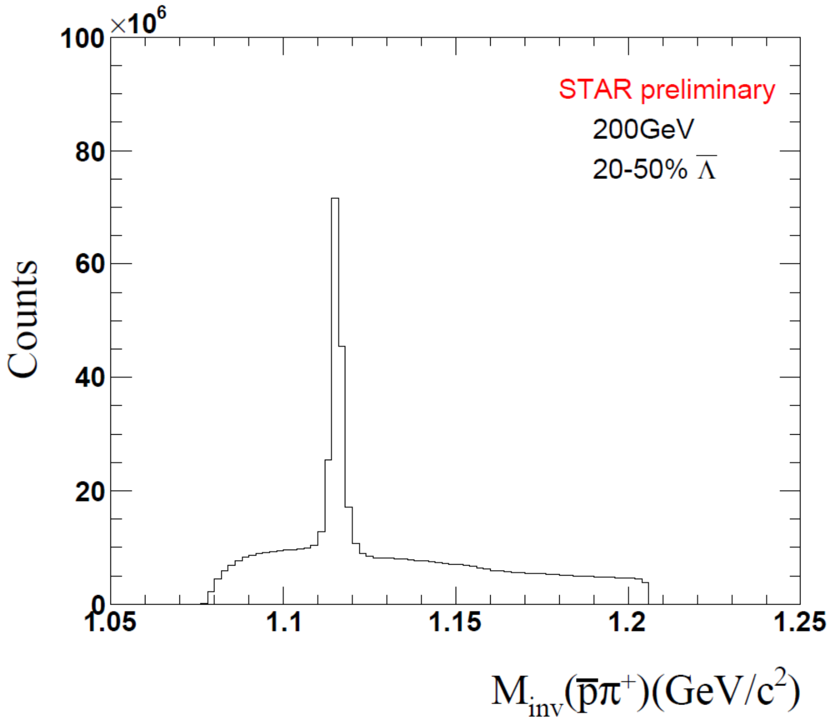
The STAR Detector



- Full azimuthal coverage and large acceptance
- Excellent particle identification
- Λ reconstruction
  identify daughters(π, p) with TPC and TOF
- Event planes reconstructed by ZDC-SMD (1st-order EP) and TPC (2nd-order EP)

Λ reconstruction

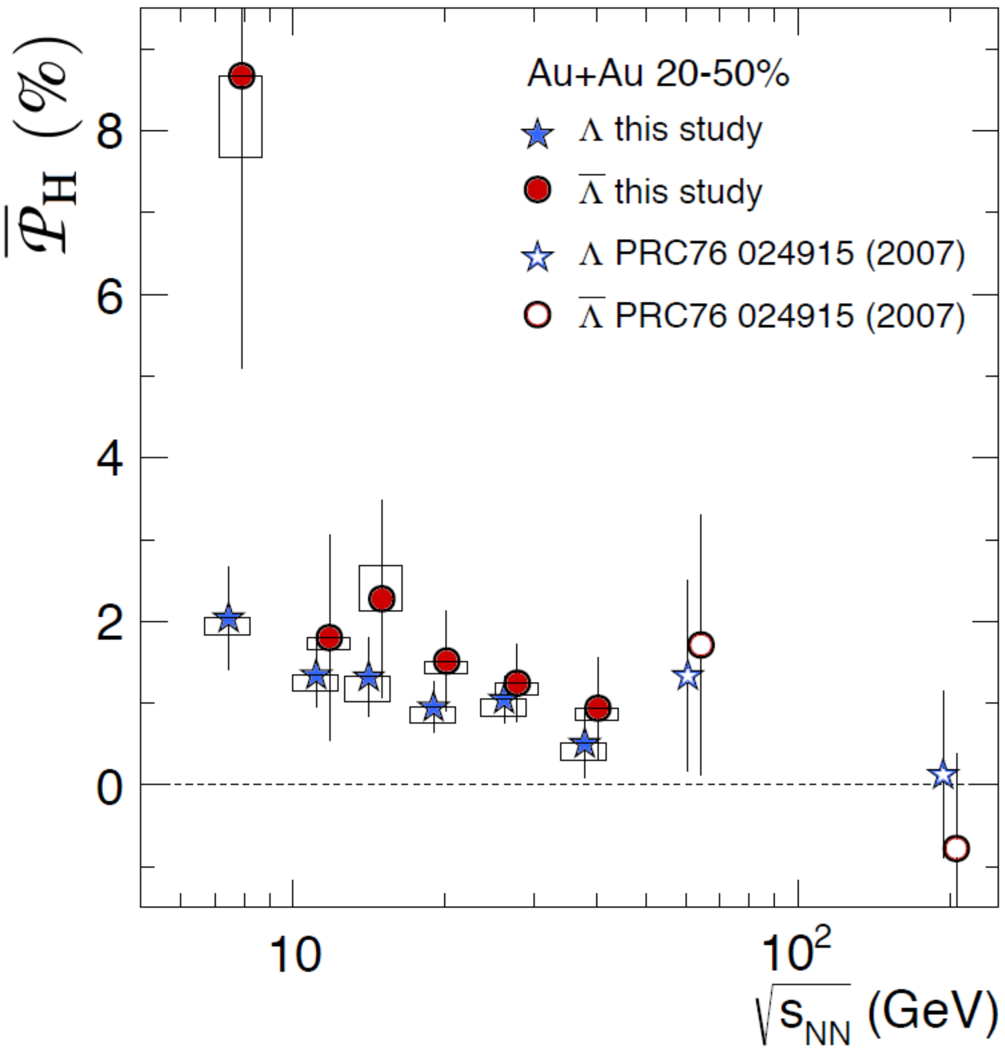


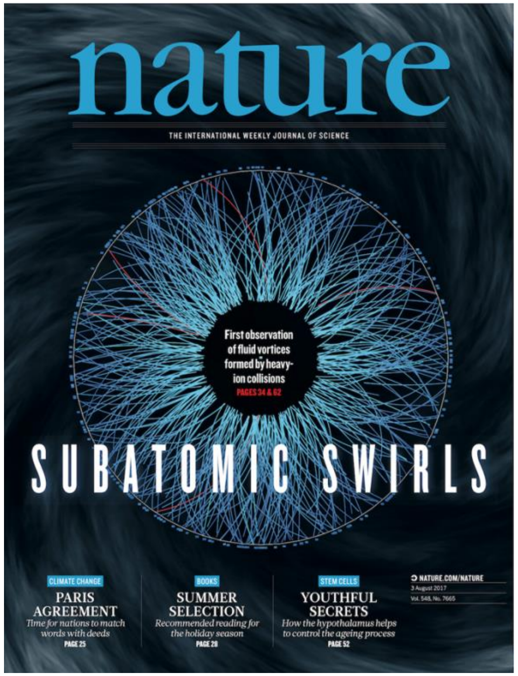


- Calculate the invariant mass of (p,π^-) and $(\bar{p},\pi^+)$ pairs.
- Decay topological cuts to reduce combinatorial background.

First observation of Λ global polarization

STAR Nature 548, 62 (2017)

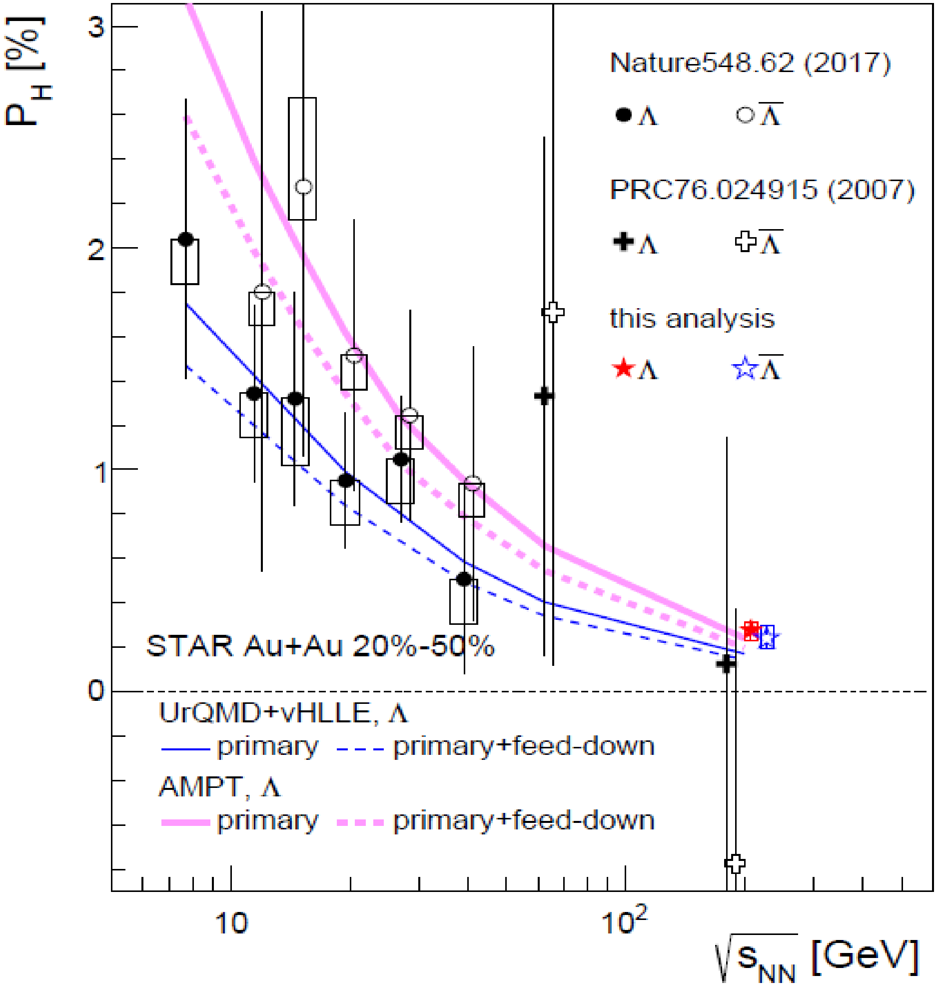




- Finite global polarization is observed at low energies.
- Most vortical fluid produced at RHIC.
- P_H for $\overline{\Lambda}$ is systematically larger than P_H for Λ.
  - Implying a contribution from B-filed.

Global polarization at 200 GeV

STAR PRC 98, 014910 (2018)



- Finite signal is observed at $\sqrt{s_{NN}}$ = 200 GeV.

$$P_H(\Lambda) = 0.277 \pm 0.044(stat.) \pm^{0.039}_{0.049} (sys.)\%$$

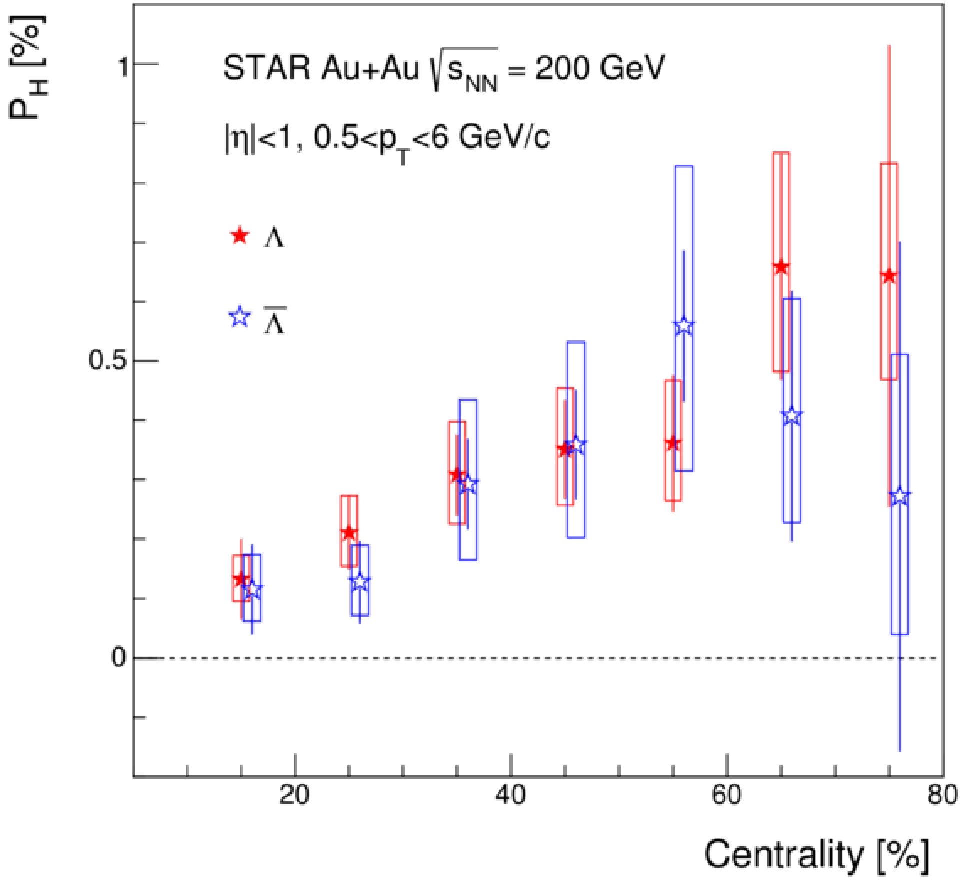
$$P_H(\bar{\Lambda}) = 0.240 \pm 0.045(stat.) \pm^{0.062}_{0.045} (sys.)\%$$

- No significant difference between Λ and $\bar{\Lambda}$ at $\sqrt{s_{NN}}$ = 200 GeV.

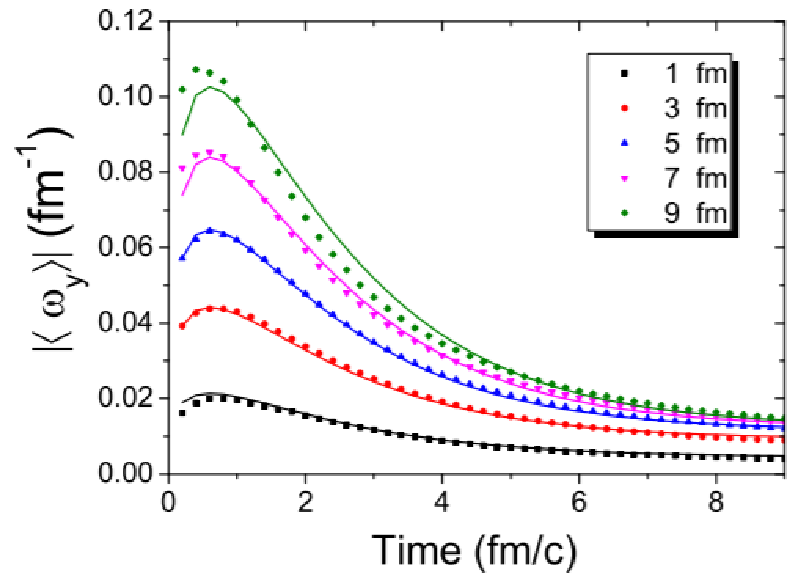
- Following the trend of BES data and close to model predictions in all energies.
  - **UrQMD+VHLLE:** L. Karpenko and F. Becattini, EPJC (2017) 77:213
  - **AMPT:** H. Li et al., PRC 96,054908(2017)

Centrality dependence

STAR PRC 98, 014910 (2018)



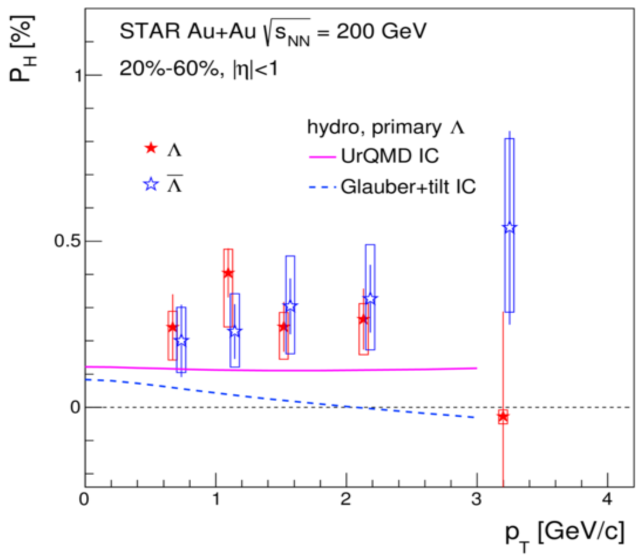
AMPT model,
Y. Jiang et al., PRC 94, 044910 (2016)

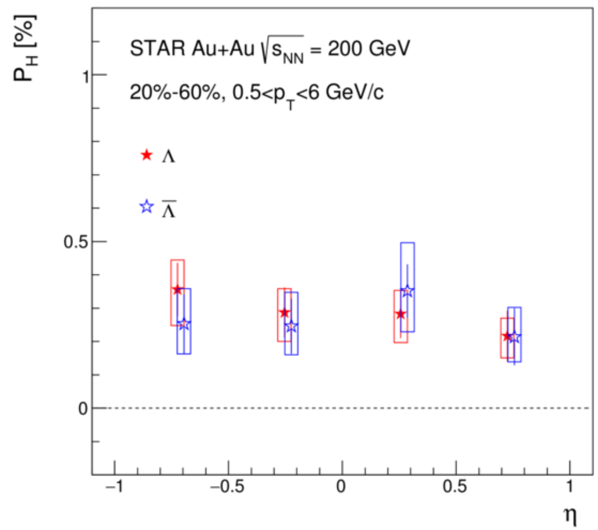


- Polarization increase from central to peripheral collisions. Qualitatively consistent with the AMPT calculation.
- Not clear if there is a saturation or decrease in very peripheral collisions.

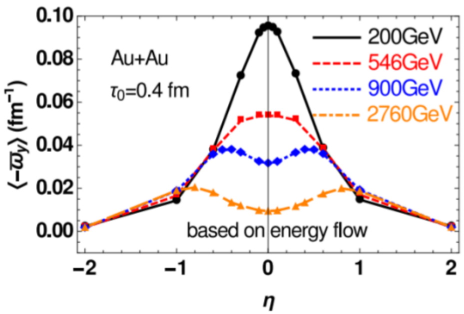
p_T and η dependence

STAR PRC 98, 014910 (2018)

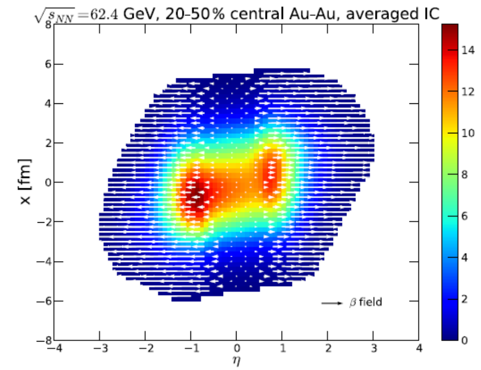




W. T. Deng and X. G. Huang
PRC **93**, 064907 (2016)

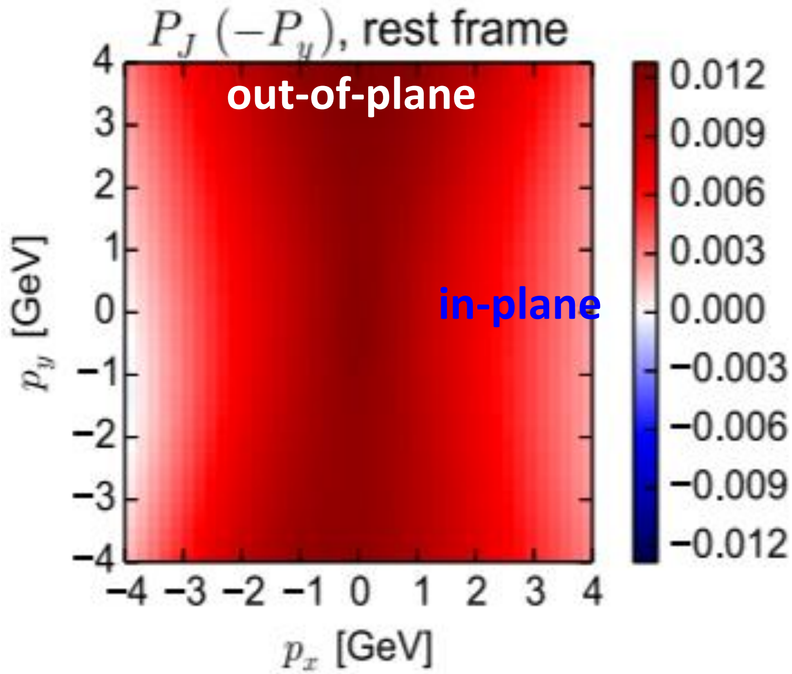


L. Karpenko and F. Becattini
EPJC (2017) 77:213

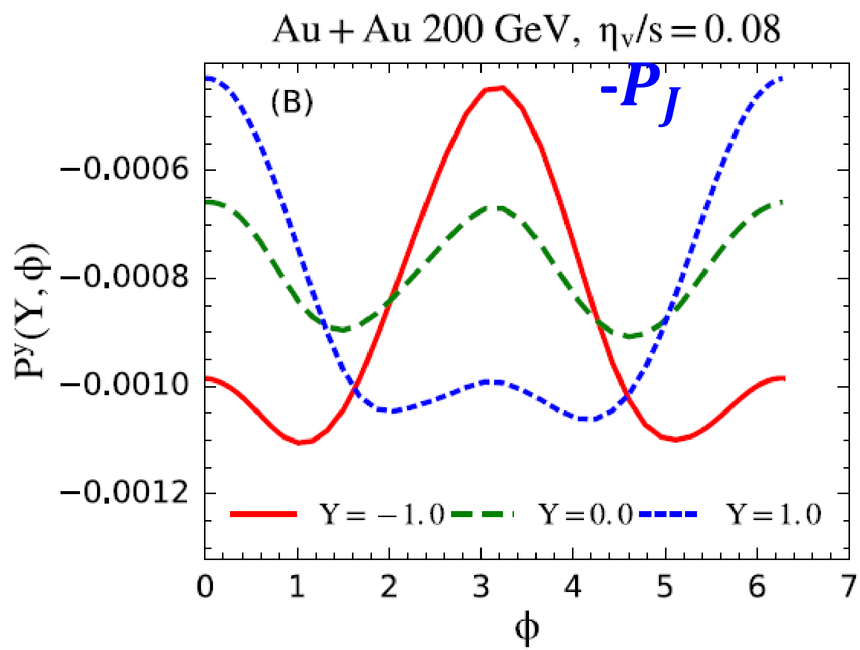


- No significant p_T dependence as expected from the initial angular momentum of the system.
- No significant η dependence.
  - A smaller shear flow structure at midrapidity than at forward (backward) rapidity due to baryon transparency at higher energies.

Azimuthal angle dependence (Hydro calculation)



F. Becattini et al,
PRC93, 069901(E)(2016)
PRC88, 034905 (2013)
L. Karpenko and F. Becattini,
EPJC(2017) 77:213

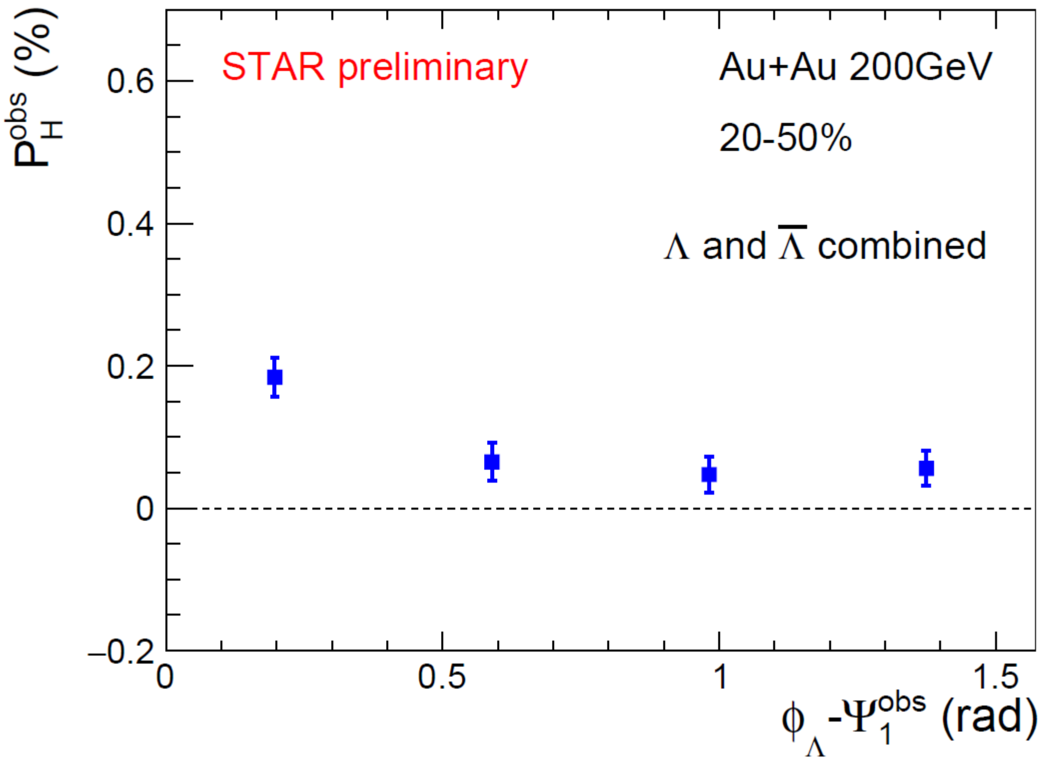


Hui Li et al,
NPA 967 (2017) 772–775

$$\Pi_0 = \Pi - \frac{\vec{p}}{E(E+m)} \Pi \cdot \vec{p}$$

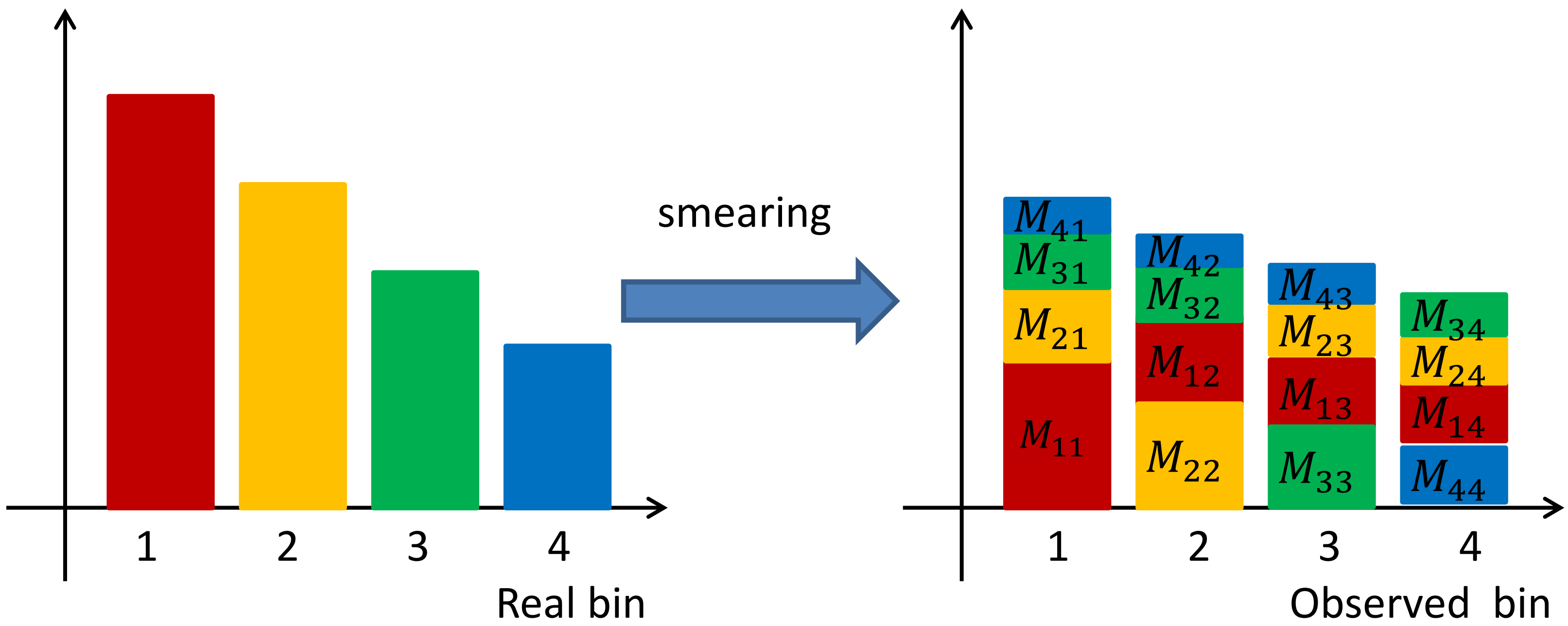
- Hydrodynamic calculations predict a larger polarization in out-of-plane than in in-plane.

Azimuthal angle dependence (raw signal)



- Lager polarization in the in-plane than it in out-of-plane without resolution correction.
- The measured event plane is different from reaction plane, both $(\Psi - \phi_p^*)$ and $(\phi_\Lambda - \Psi)$ are affected.
- The smearing of reaction plane not only reduces the observed overall polarization, but also makes the observed azimuthal dependence smaller.

Resolution Correction (trace how it happens)

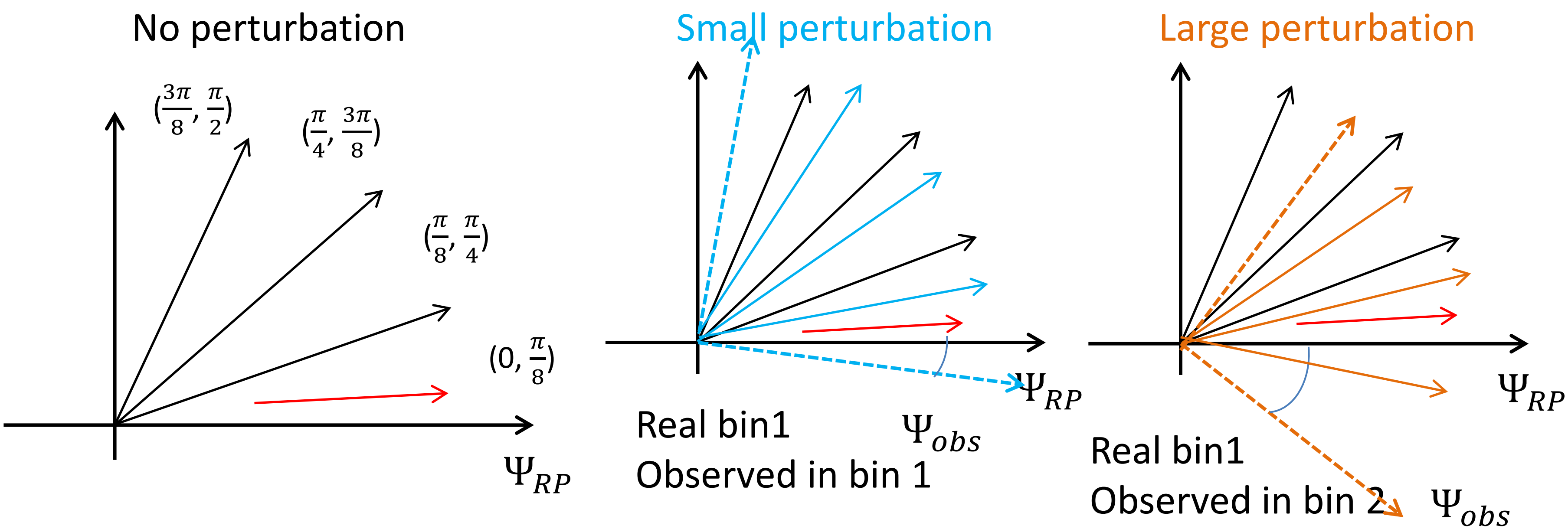


Define M_{ij} as the particle yield from bin i before smearing and observed in bin j after smearing.

$$M_{ij} = \sum_k m_{ij}^k$$

Where m_{ij}^k is the same but for k^{th} event.

Resolution Correction (trace how it happens)



- For particles that stay in the vicinity bins after smearing, their events experience less EP perturbation than those that end further from the original bin. Thus, the EP resolution correction should be applied differently for different bins.
- Define particle level resolution, r_{ij}, which takes care of particles that are from bin i before smearing and observed in bin j,

$$\mathrm{r_{ij}} = \frac{\sum_k\left(m_{ij}^k * w_{ij} * \cos\left(\Psi_{\mathrm{obs}}^k - \Psi_{RP}\right)\right)}{M_{ij}} = \frac{\sum_k\left(m_{ij}^k * w_{ij} * \cos(\Delta\Psi)\right)}{M_{ij}},$$

where $w_{ij} = \frac{\langle \sum_j m_{ij} \rangle}{\sum_j m_{ij}^k}$, and $\langle \cdots \rangle$ denotes the average over events.

Resolution Correction (method)

A correction method was applied:

$$P_H^{\text{obs}} = A \times P_H^{real} \qquad\qquad P_H^{real} = A^{-1} \times P_H^{obs}$$

The matrix A can be define as

$$\begin{bmatrix} P_{H,1}^{\text{obs}} \\ P_{H,2}^{obs} \\ \vdots \\ P_{H,n}^{obs} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{21} & \cdots & a_{1n} \\ a_{12} & a_{22} & & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{1n} & a_{2n} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} P_{H,1}^{real} \\ P_{H,2}^{real} \\ \vdots \\ P_{H,n}^{real} \end{bmatrix}$$

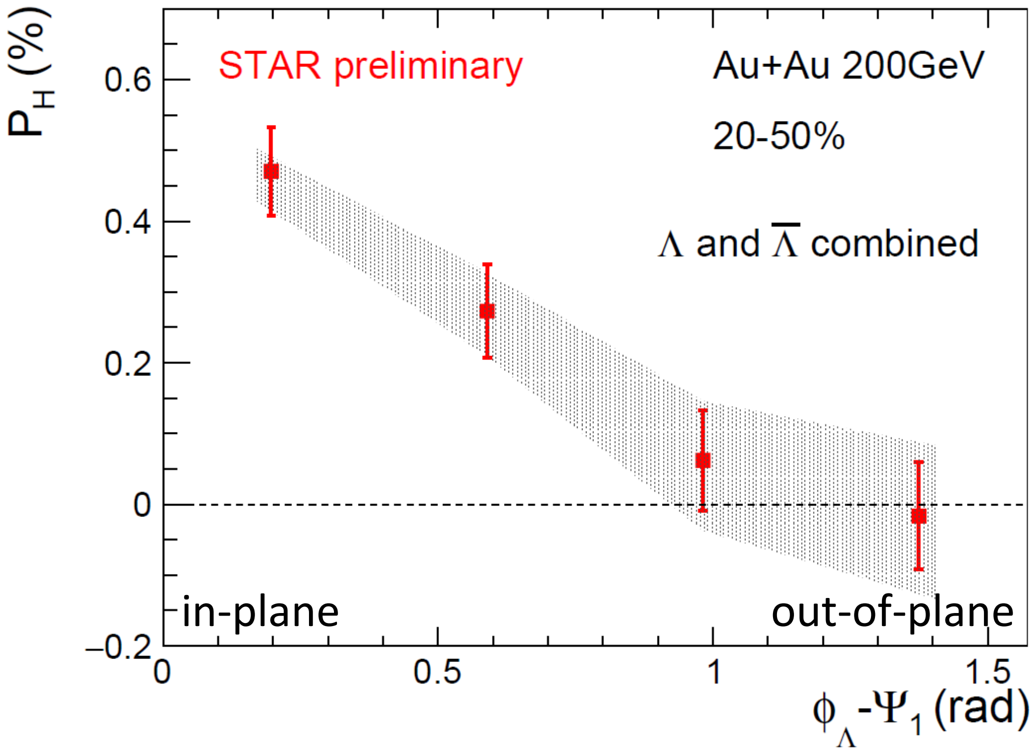
Matrix elements defined as

$$a_{ij} = \frac{M_{ij}}{\sum_i M_{ij}} * r_{ij}$$

Here M_{ij} is particle yield, r_{ij} is particle level resolution.

A.H. Tang, B. Tu and C.S. Zhou, arxiv:1803:05777

Azimuthal angle dependence

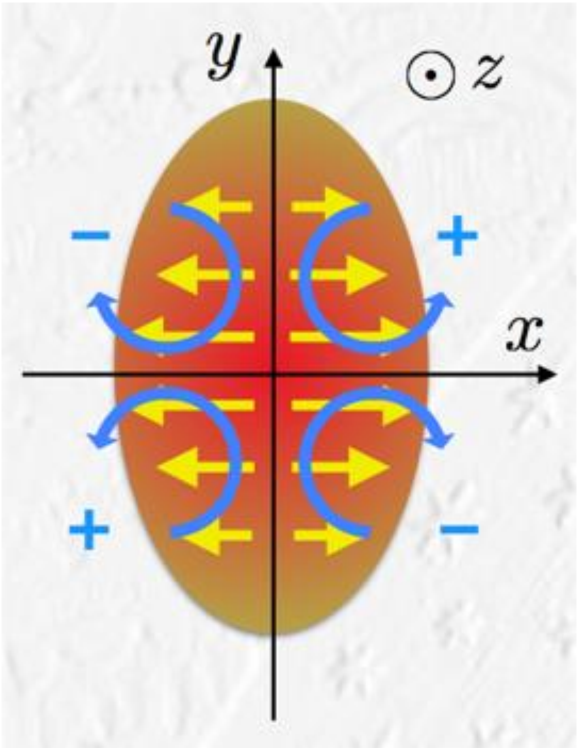


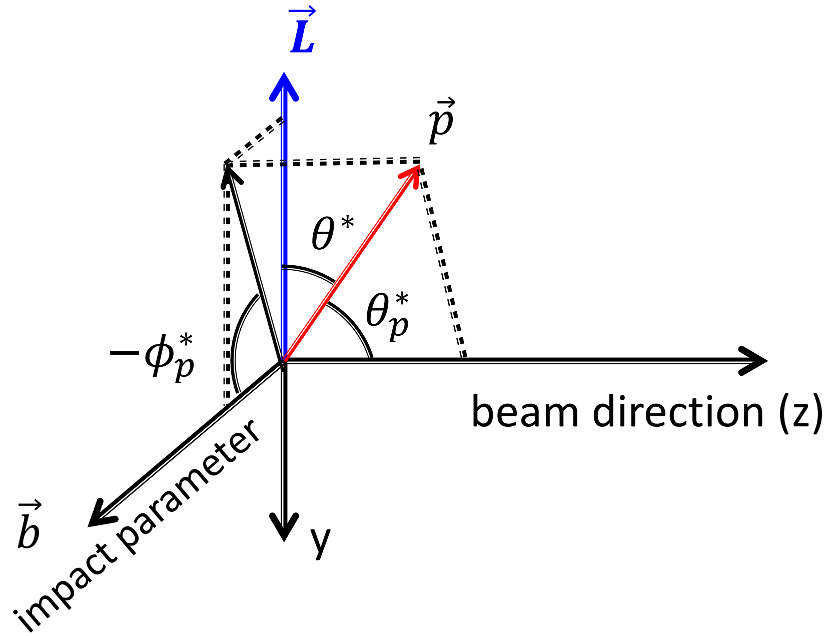
Note: Resolution correction is applied.
Here, Ψ is ZDC-SMD 1st-order event plane
The band is the systematical errors

- An azimuthal angle dependence is observed. Larger polarization in in-plane than in out-of-plane.
- Opposite trend to the hydrodynamic calculation.
  - F. Becattini et al,
    PRC93, 069901(E)(2016)
    PRC88, 034905 (2013)
    L. Karpenko and F. Becattini,
    EPJC (2017) 77:213
  - Hui Li et al,
    NPA 967 (2017) 772–775
- Consistent with below simple picture. Vorticity, maximum in the reaction plane, may not propagate efficiently from in to out of reaction plane due to the low viscosity of the system. This may lead to a larger in-plane than out-of-plane polarization for both Λ and $\bar{\Lambda}$.

Polarization along beam direction

S. Voloshin, EPJ Web Conf. **171**, 07002 (2018)





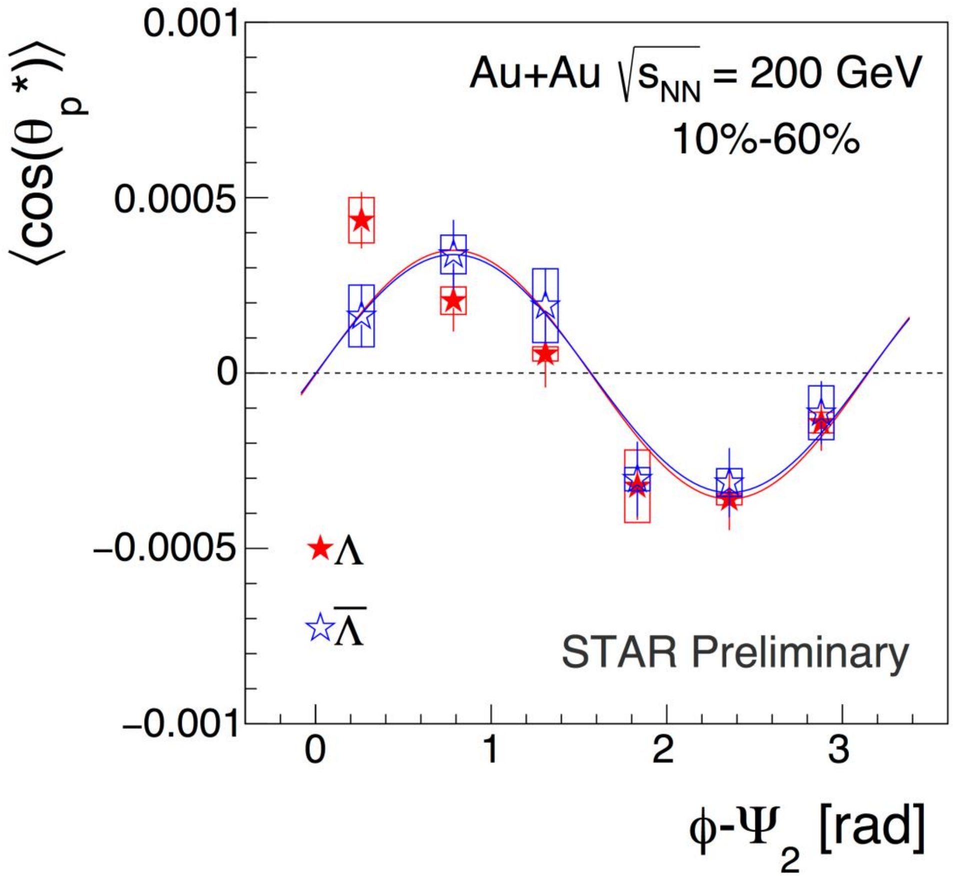
$$\frac{dN}{d(\cos\theta_p^*)} = \frac{1}{2}\left(1 + \alpha_H |\vec{P}_Z| \cos\theta_p^*\right)$$

Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis!

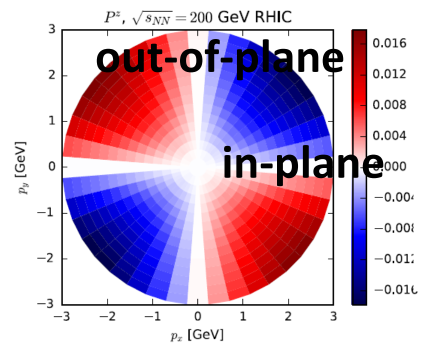
$$|\vec{P}_Z| = \frac{3\langle\cos\theta_P^*\rangle}{\alpha_H}$$

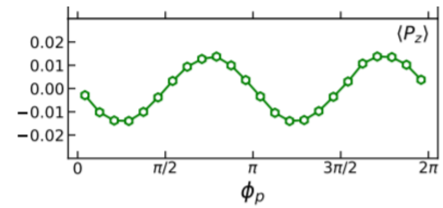
(with the perfect detector)

Polarization along beam direction



Note: Effect of Ψ_2 resolution is not corrected here.
Here Ψ_2 is TPC 2nd order event plane.





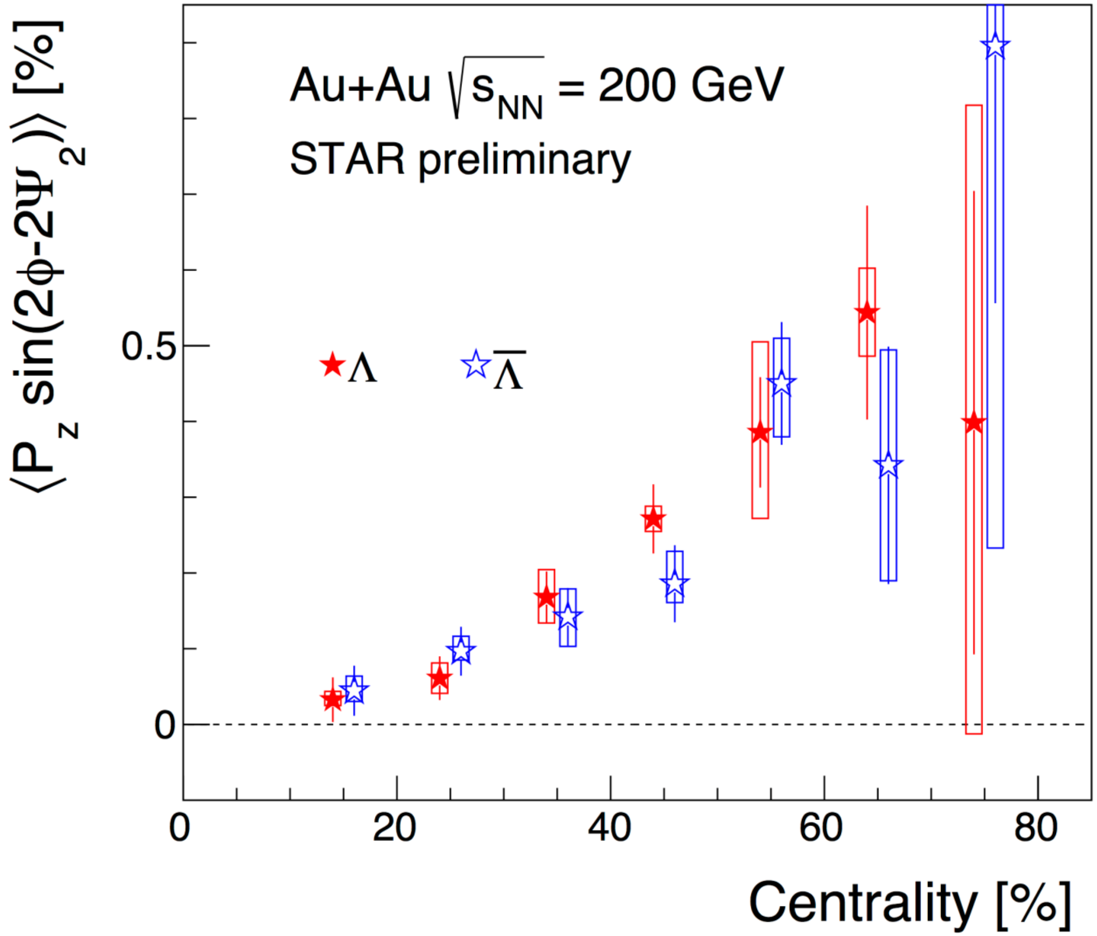
- Sine structure as expected from the elliptic flow.
- Different trend to the theoretical calculations
  - **Hydro model**: F. Becattini and L. Karpenko , PRL. 120.012302(2018)
  - **AMPT model** : X. Xia, H. Li, Z. Tang, Q. Wang, PRC 98, 024905
- Based on Blast-Wave model, the sign of $< \cos\theta_P^* >$ may depend on the relation between the magnitudes of spatial and flow anisotropy

$$\omega_z = \frac{1}{2}(\nabla \times \boldsymbol{v})_z \approx \left(\frac{\rho_{t,nmax}}{R}\right)\sin(n\phi_s)[b_n - a_n]$$

a_n is spatial , b_n is flow

S. Voloshin, EPJ Web Conf. **171**, 07002 (2018)

Centrality dependence of P_z modulation



- Significant centrality dependence as in the elliptic flow.

Summary

- First observation of Λ global polarization in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 – 39 GeV:
  - Most vortical fluid produced at RHIC.
  - The difference between Λ and $\overline{\Lambda}$ implies a contribution from B-field.

- Finite Λ polarization observed in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV:
  - Larger polarization in peripheral collisions.
  - No significant p_T and η dependence.
  - Larger polarization in in-plane than out-of-plane.

- Polarization along beam direction:
  - Quadrupole structure of polarization along beam direction is observed, as expected from elliptic flow.
  - Strong centrality dependence similar to that of elliptic flow.

Backup

Resolution Correction (determine the matrix)

For a given $\Delta\Psi$, we can trace the contribution from the original bin i to bin j after smearing by integrating the relative particle yield:

$$\frac{1}{2\pi}\int_{x1}^{x2} 1 + 2v_2\cos(2(\phi-\Psi))d\phi = \left(\frac{1}{2\pi}(\phi - v_2\sin(2(\phi-\Psi))\right)\Big|_{x1}^{x2}$$

$$\Psi_{obs} = \Psi_{RP} + \Delta\Psi$$

This process can be repeated over many $\Delta\Psi$ for which the probability distribution function is given by:

$$f(\Delta\Psi) = \frac{1}{2\pi}[e^{-\frac{\chi^2}{2}} + \sqrt{\frac{\pi}{2}}\chi\cos(\Delta\Psi)\,e^{-\frac{\chi^2\sin^2(\Delta\Psi)}{2}}\left(1+\mathrm{erf}(\chi\cos\frac{(\Delta\Psi)}{\sqrt{2}})\right)]$$

S. Voloshin and Y. Zhang *Z. Phys. C 70 (1996)665*

Thus, $a_{ij} = \frac{M_{ij}}{\sum_i M_{ij}} * r_{ij}$ can be determined