Recent Results on Hyperon Polarization & Vector Meson Spin Alignment at RHIC

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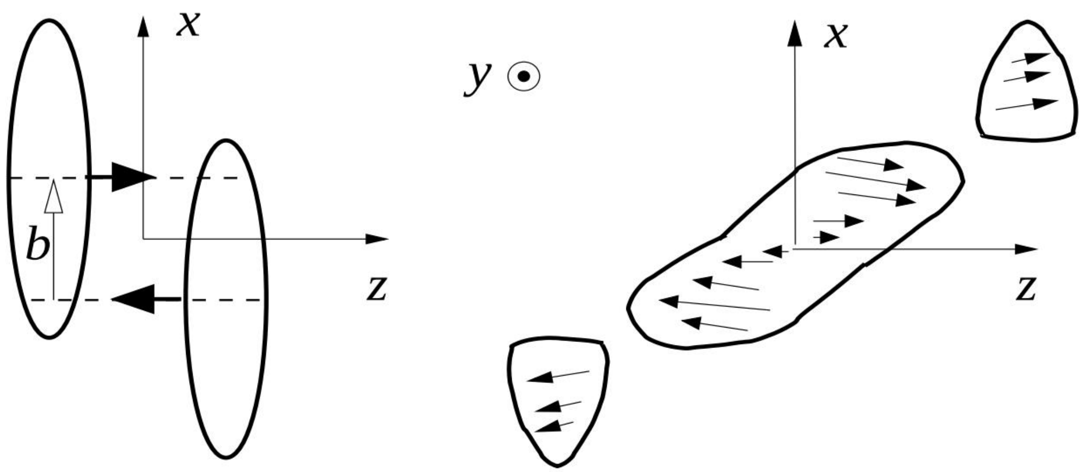
Produced-particle polarization

- Non-central nuclear collisions carry large angular momentum, $\vec{J} = \vec{r} \times \vec{p}$
- $\vec{J}$ is manifested in the gradient (along $\hat{x}$) of the longitudinal momentum, p_z
- Simply through spin-orbit coupling, there can be non-zero polarization of produced particles aligned with $\vec{J}$



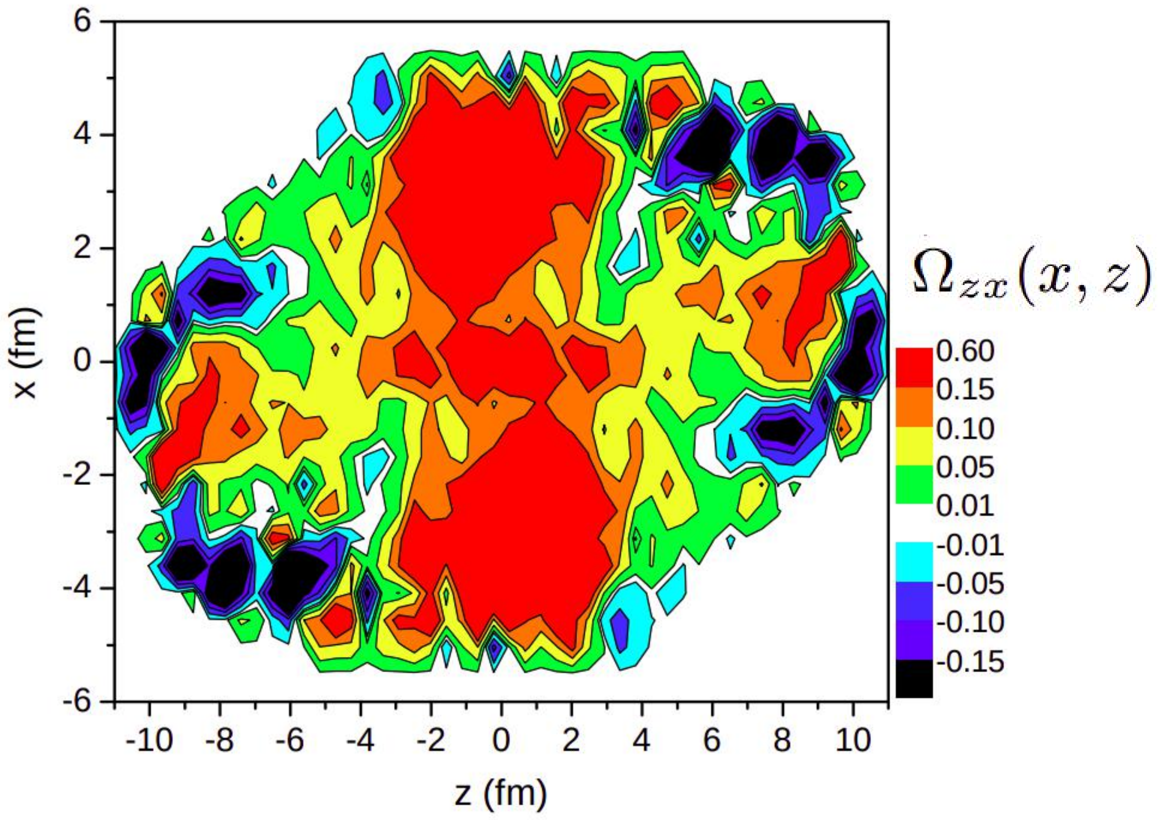
Pre collision

Post collision

Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005), Erratum:ibid. 96, 039901 (2006).

Produced-particle polarization

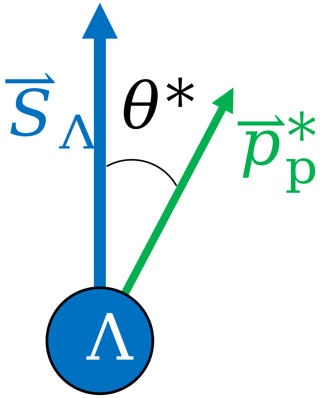
- Equilibrium hydrodynamics has proven as a successful description of the QGP
- Particle polarization should be able to be derived using this framework as well
- In this context, we think about thermal vorticity of QGP fluid cells that is transfered to hadron spin at freeze out

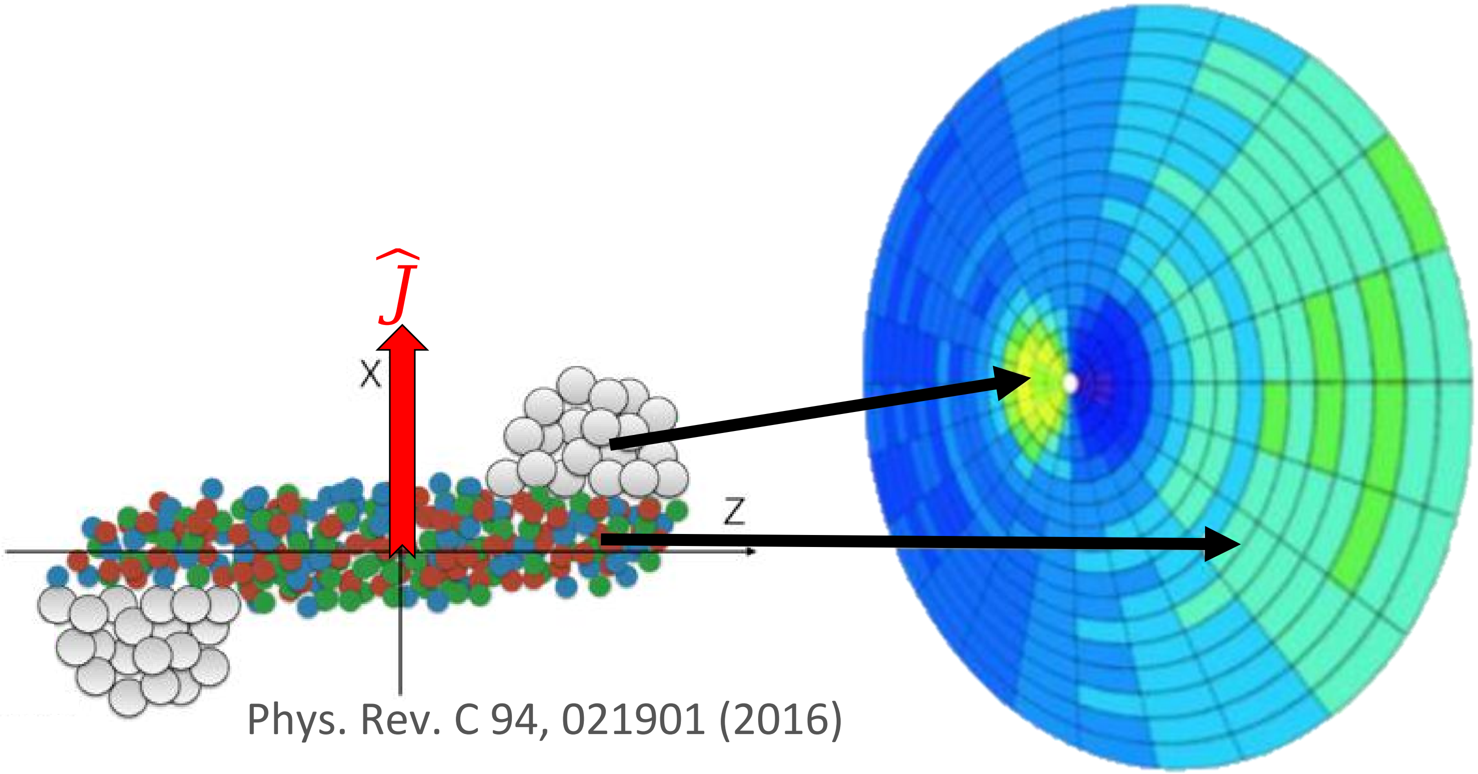


Becattini F, Csernai L, Wang DJ. Phys. Rev. C 88 034905 (2013), Erratum: Phys. Rev.C 93 6 069901(2016)

Measuring $\overline{\mathrm{P}}$

“*” indicates Lambda’s frame





Phys. Rev. C 94, 021901 (2016)

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

Lambdas don’t emit daughters exactly along spin

The measured Ψ_1 differs from Ψ_{RP}

Correlates angular momentum of QGP with Lambda’s spin

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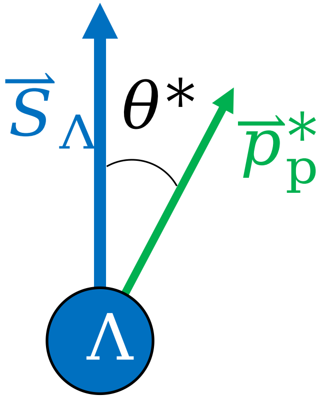

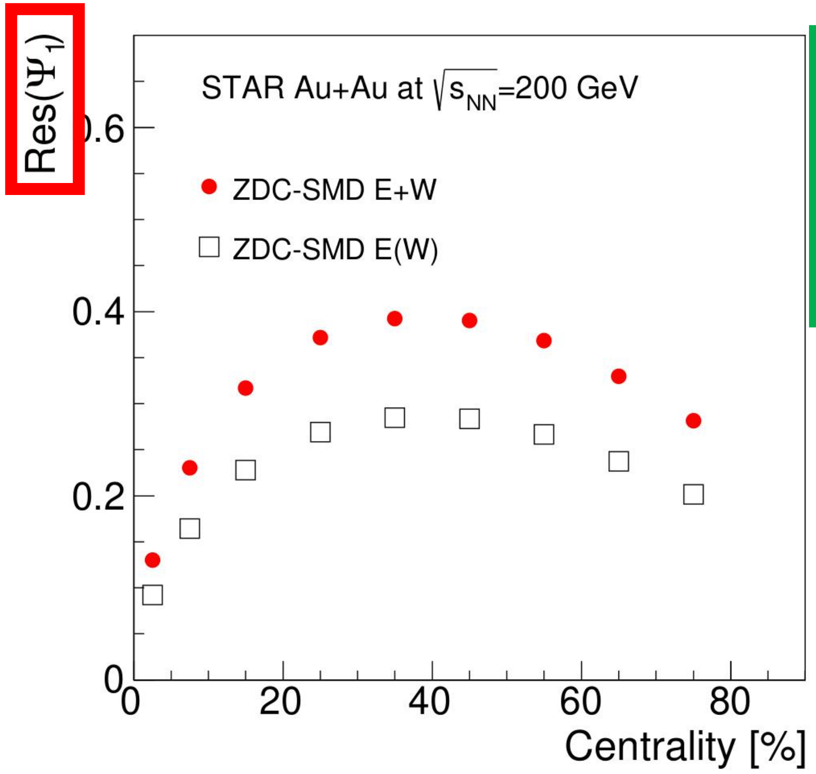

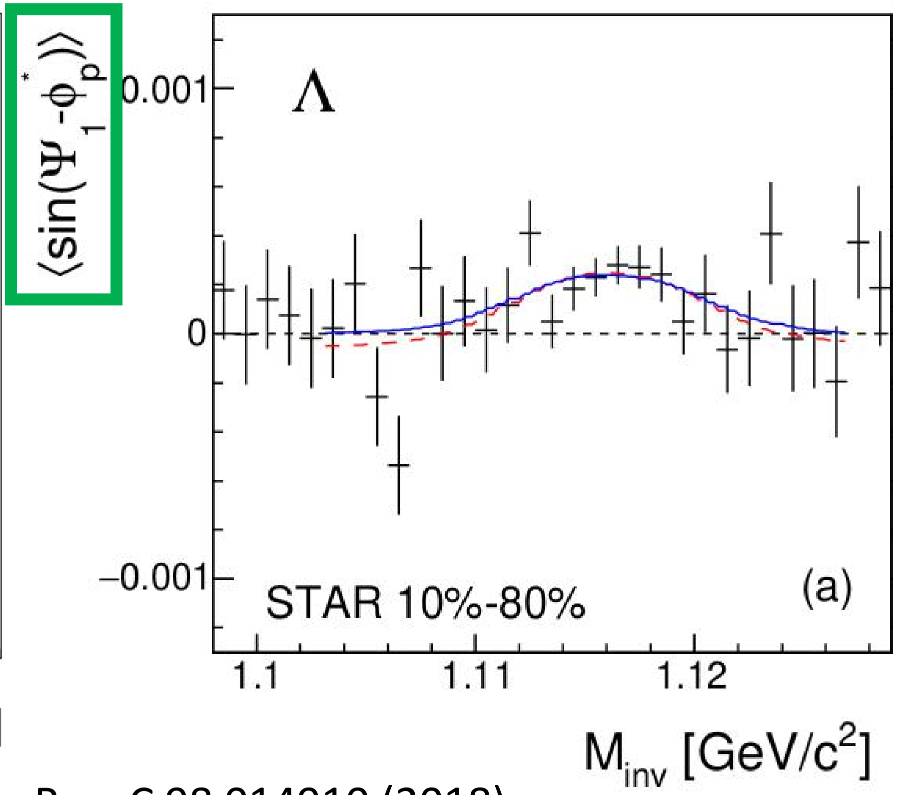

STAR, Phys. Rev. C 98 014910 (2018)

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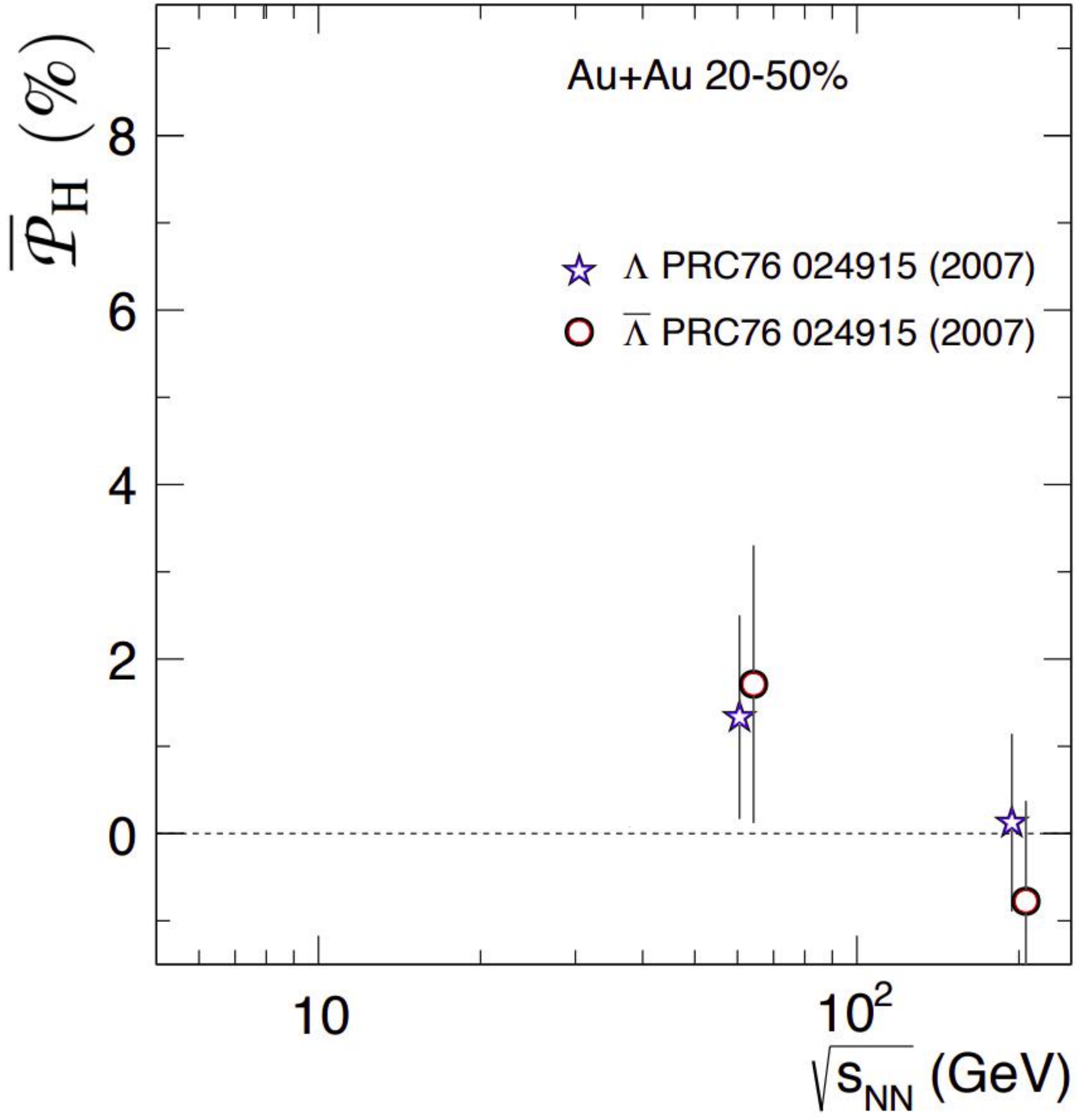
Initial measurements

- The STAR collaboration in 2007 measured $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ at $\sqrt{s_{NN}} = 62.4$ and 200 GeV consistent with zero with an upper limit of 2%



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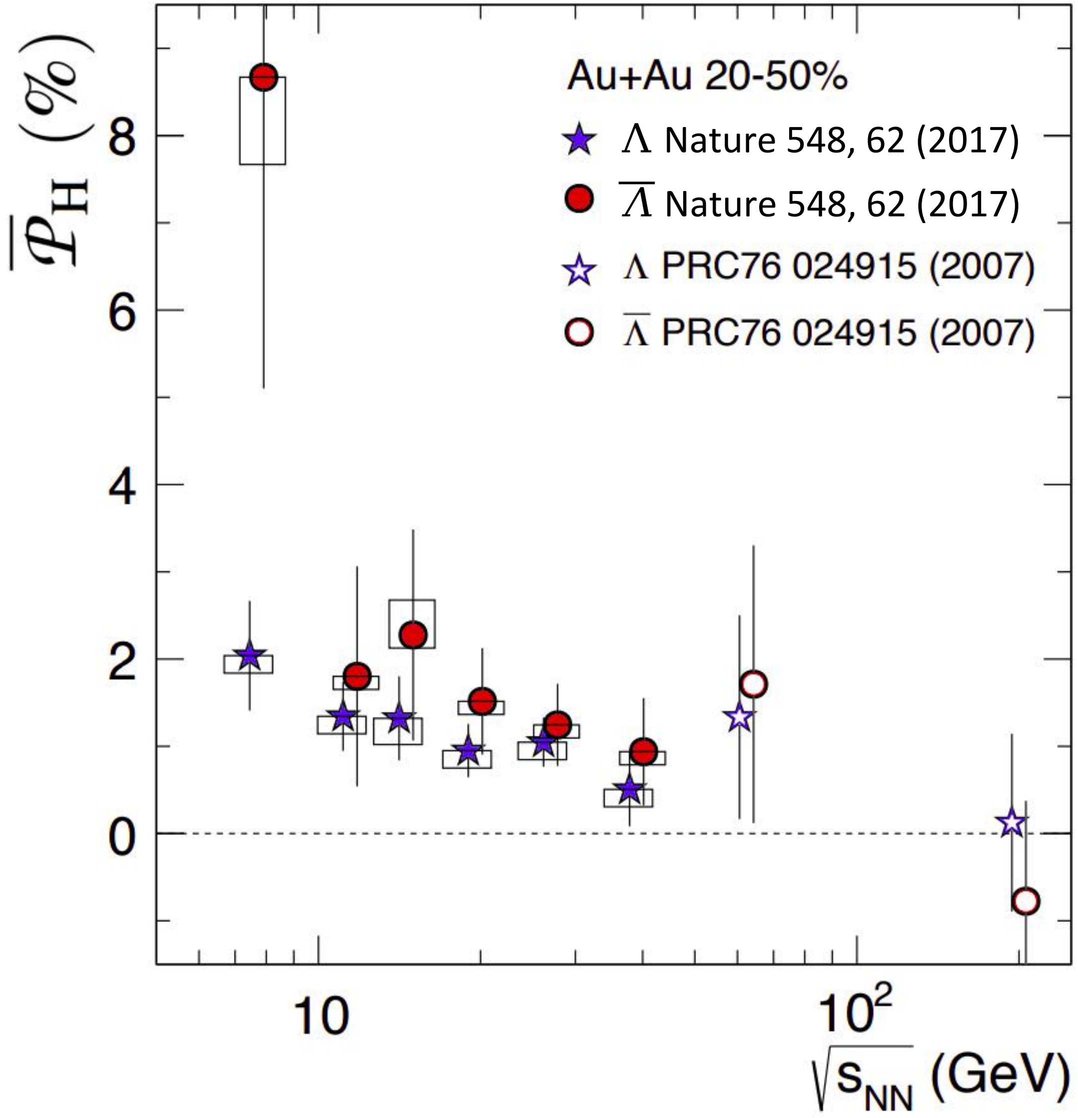
- Later measurements at lower energies showed significant $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ getting larger with decreasing $\sqrt{s_{NN}}$



Initial

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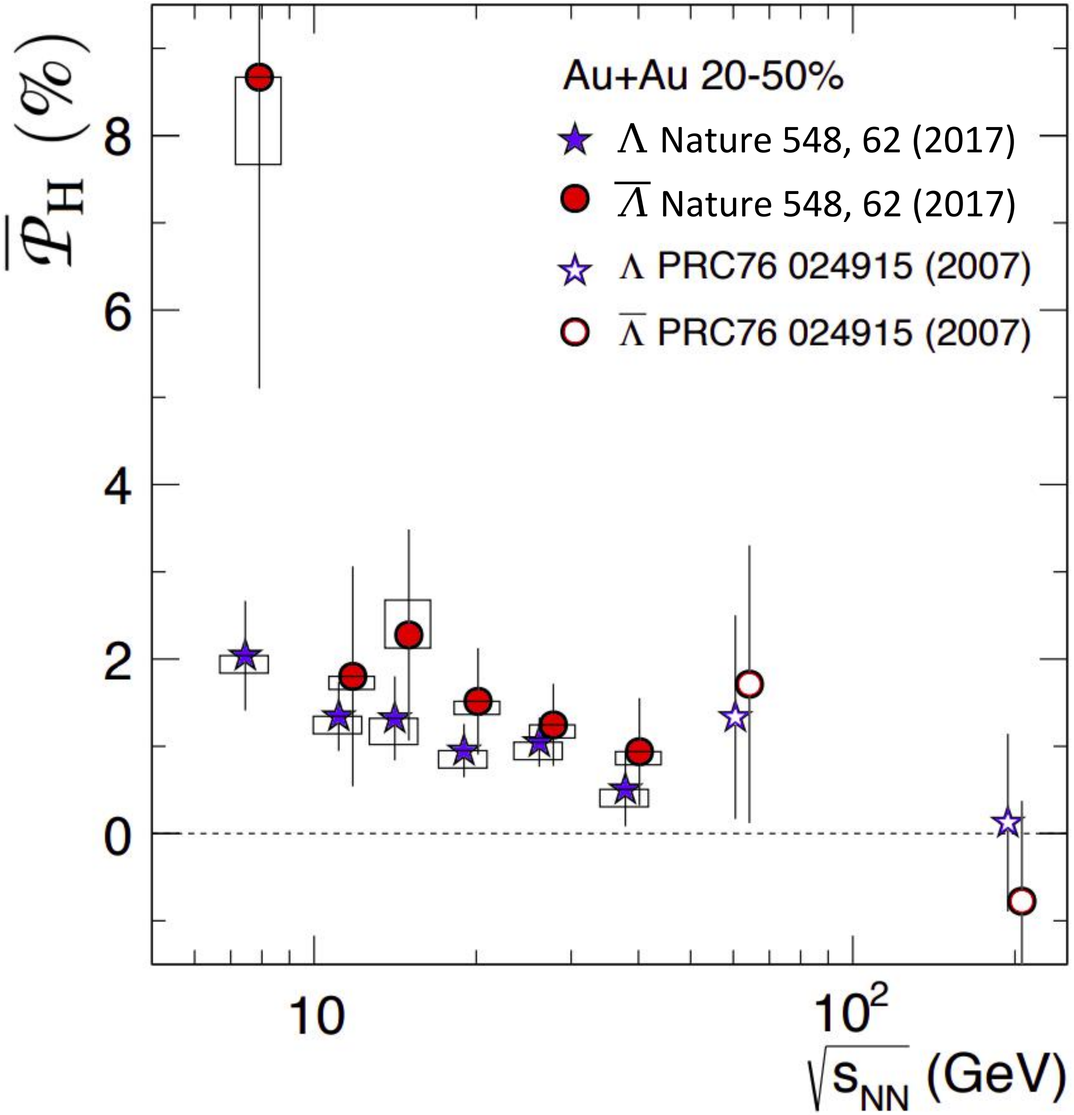
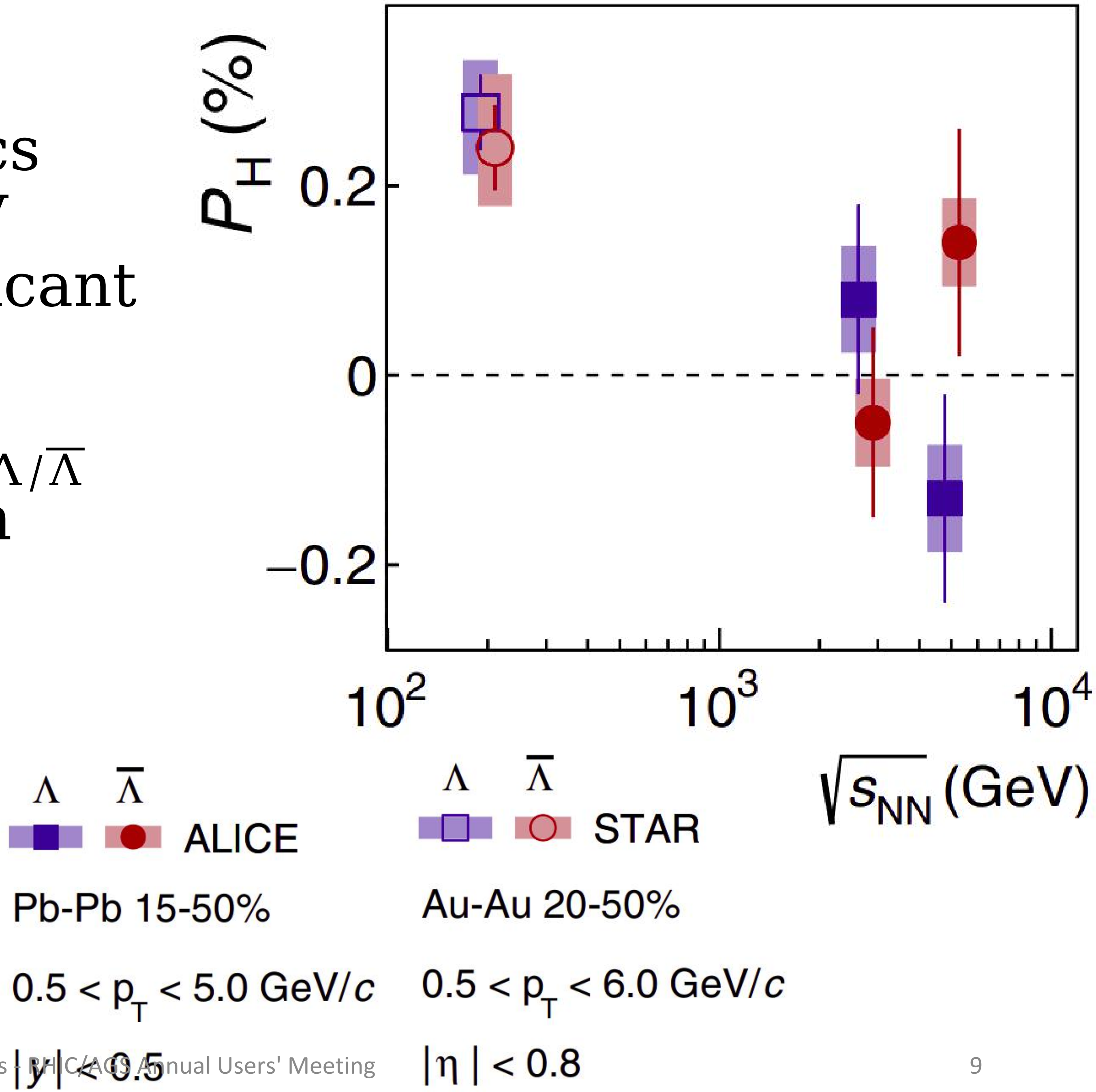


Later observation

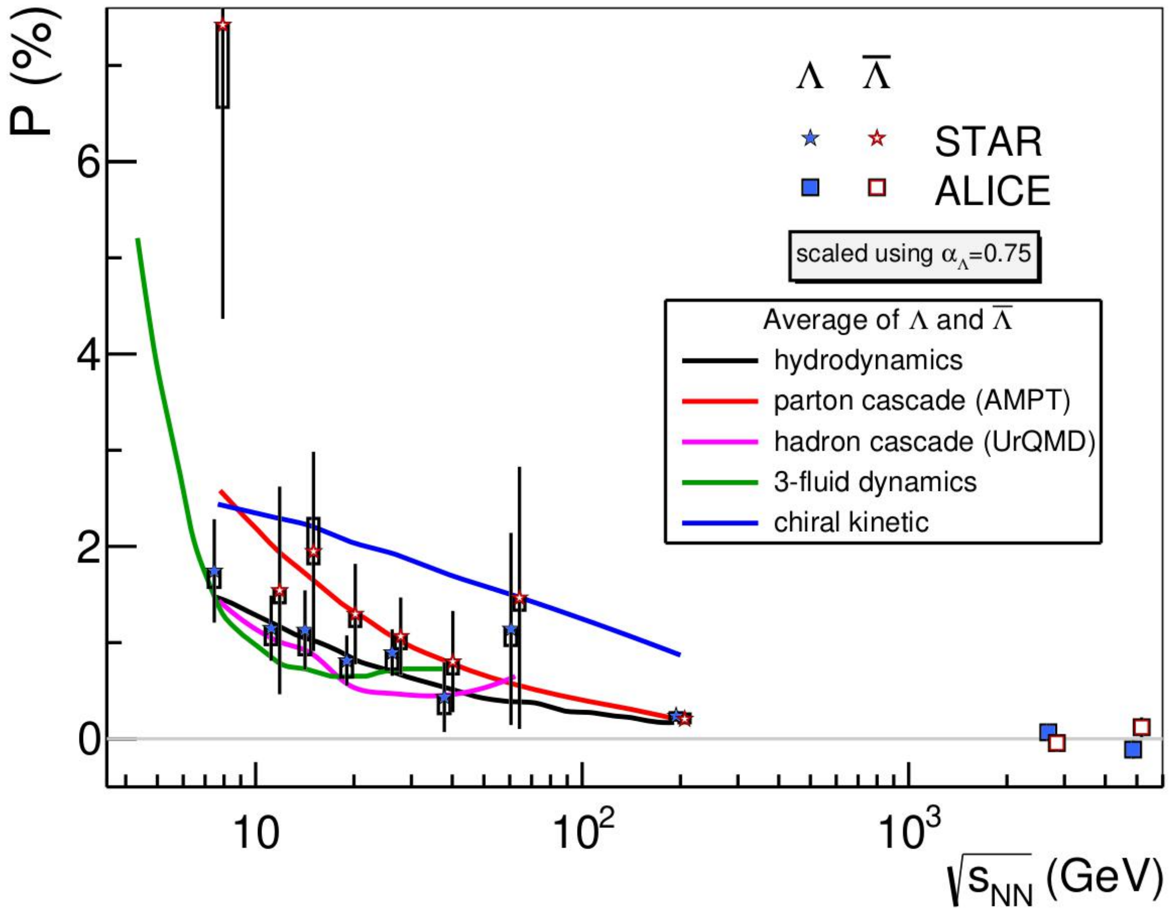
- A more recent, high-statistics data set at $\sqrt{s_{NN}} = 200$ GeV taken by STAR shows significant $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ of 0.25%
- ALICE recently measured $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ using Pb+Pb consistent with zero within uncertainties



STAR, Phys. Rev. C 98 014910 (2018)
ALICE, Phys. Rev. C 101 044611 (2020)

Energy-dependent model predictions

- Various model predictions show increasing $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ as $\sqrt{s_{NN}}$ decreases
  - Viscous hydrodynamics
    - Karpenko I, Becattini F. Eur. Phys. J. C77:213 (2017)
  - Partonic transport
    - Li H, Pang LG, Wang Q, Xia XL. Phys. Rev. C96:054908 (2017)
  - Hadronic transport
    - Vitiuk O, Bravina LV, Zabrodin EE arXiv:1910.06292 [hep-ph] (2019)
  - Chiral-kinetic transport
    - Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)

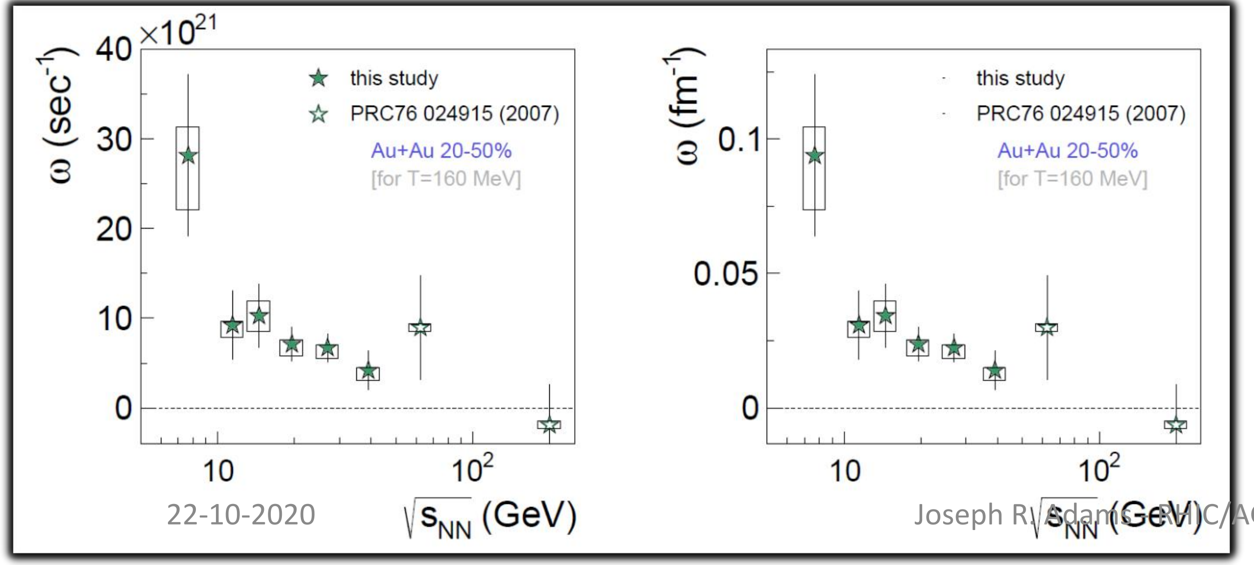


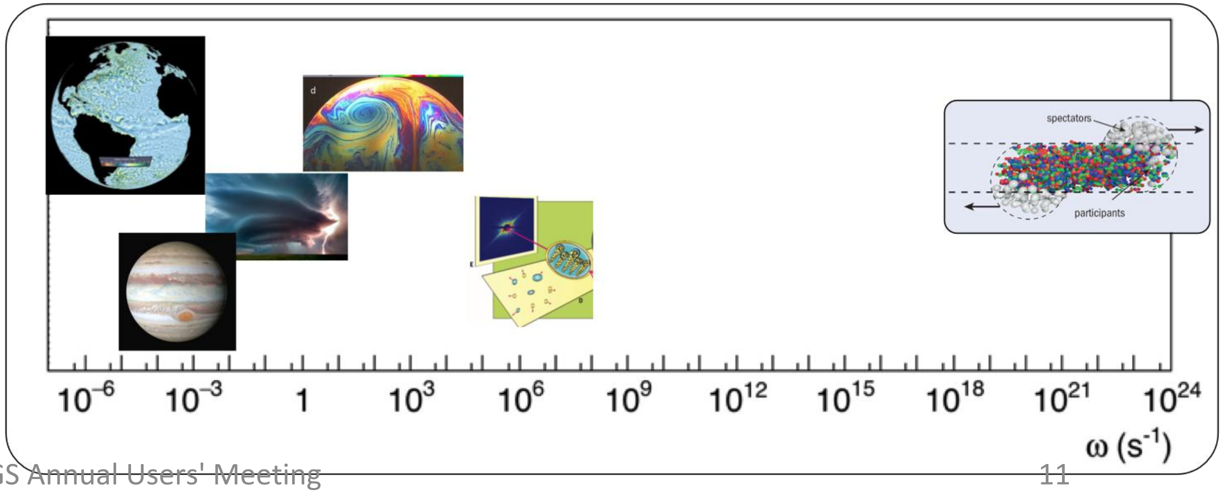
Relation to vorticity

- Using $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ to measure vorticity should be straightforward, but “feeddown” of Lambdas from parent particles complicates things

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

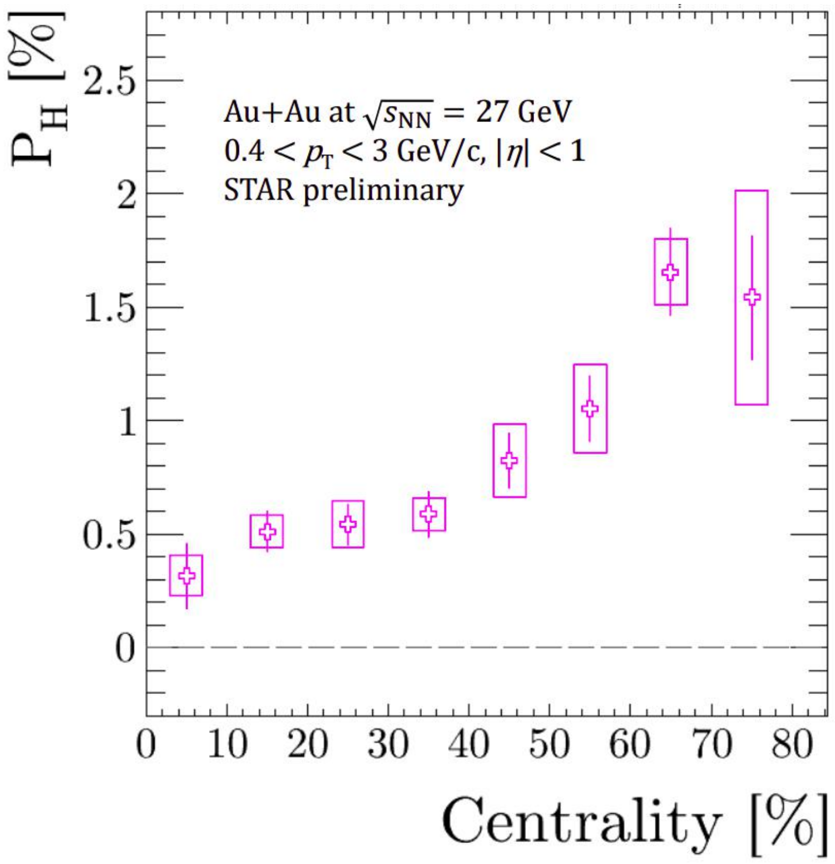
F. Becattini,1 I. Karpenko, M.A. Lisa, I. Upsal, and S.A. Voloshin, Phys. Rev. C **95**, 054902 (2017)



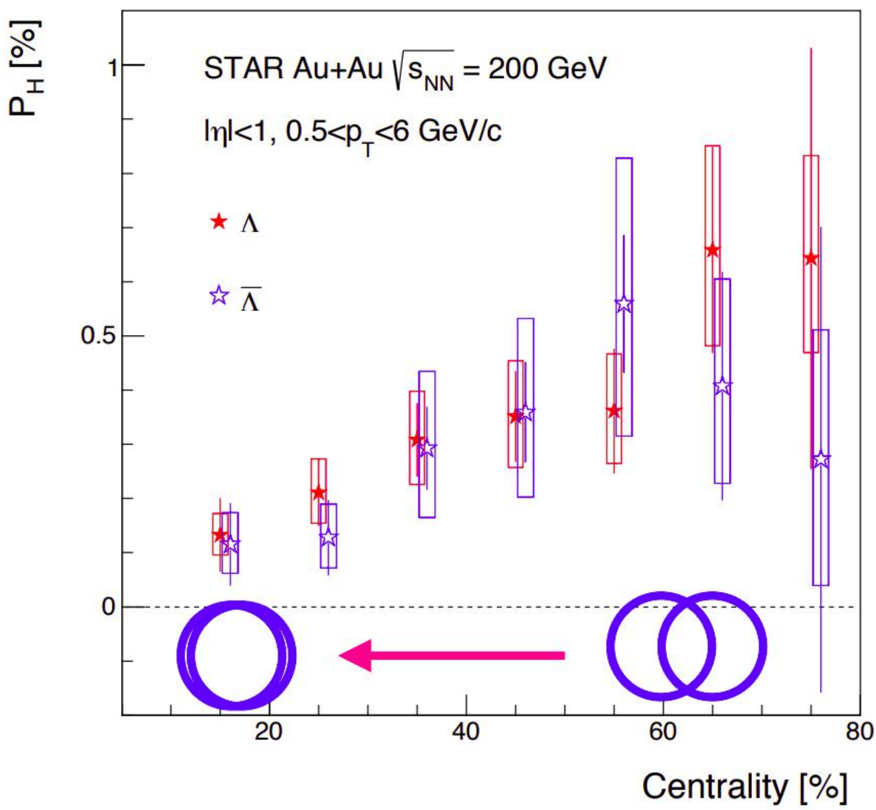


Centrality dependence

- High-statistics data sets at $\sqrt{s_{NN}} = 27$ and 200 GeV allow for the study of centrality dependence
- $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ becomes larger for more peripheral collisions; *as expected from a $\vec{J}$-driven effect!*



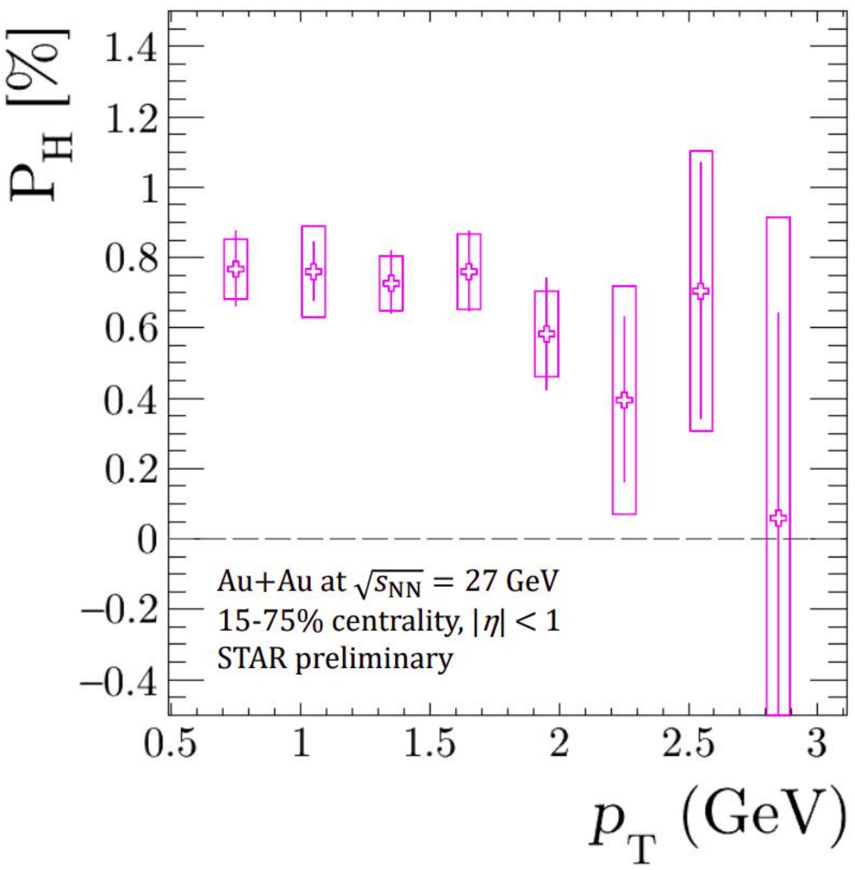
J. R. Adams (STAR), Quark Matter 2019 Proceedings (Phys. Rev. C)



Adam J, et al. Phys. Rev. C 98 14910 (2018)

p_T dependence

- These data sets also allow for study of p_T dependence
- Scattering at low p_T or jet fragmentation at high p_T may reduce $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$
- With given uncertainties, we see no such dependence



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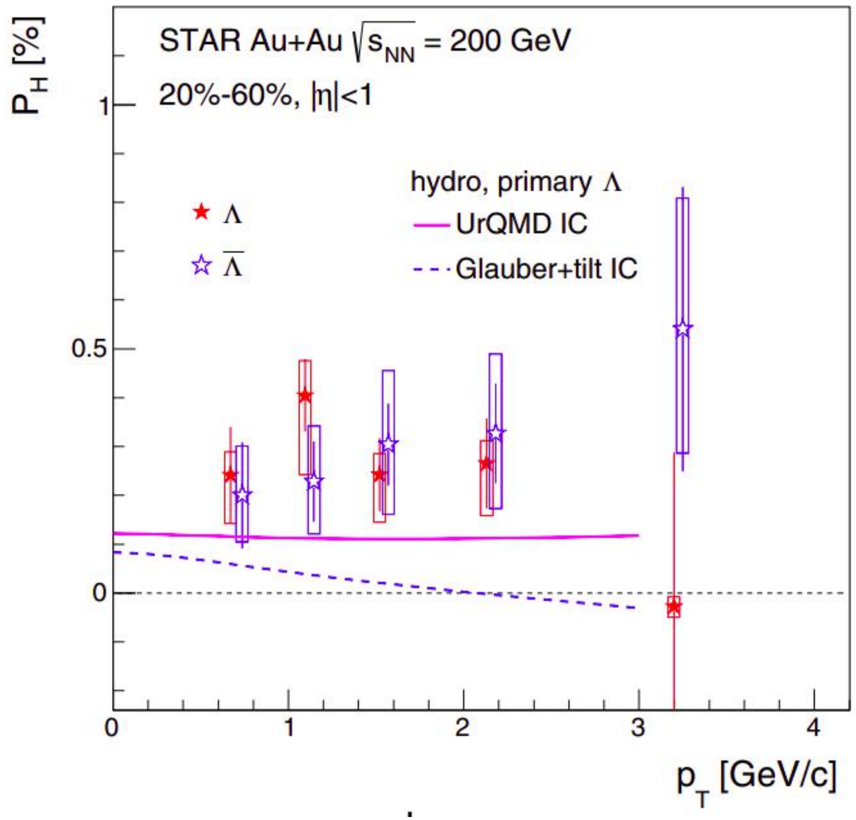
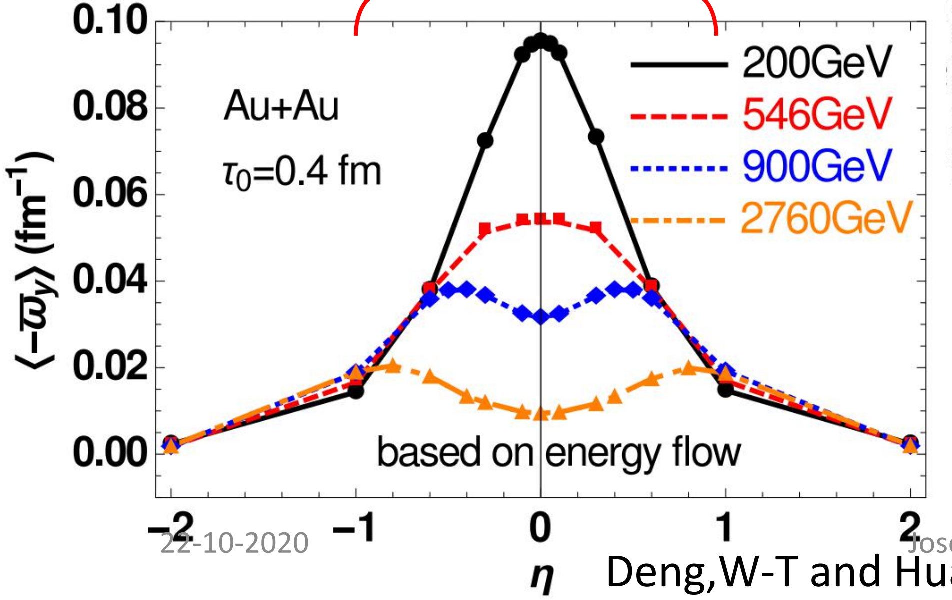


Adam J, et al. Phys. Rev. C 98 14910 (2018)

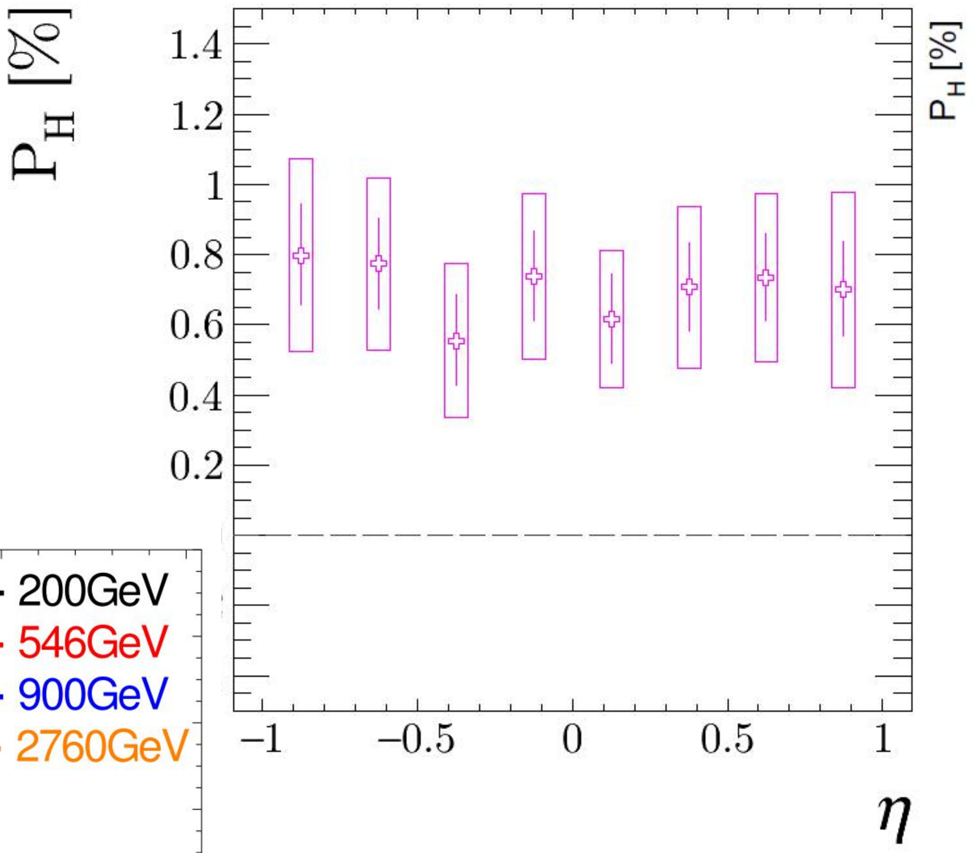
η dependence

- The $\sqrt{s_{NN}}$ dependence could be dominated by an underlying η dependence
- Not observed!

STAR η range



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



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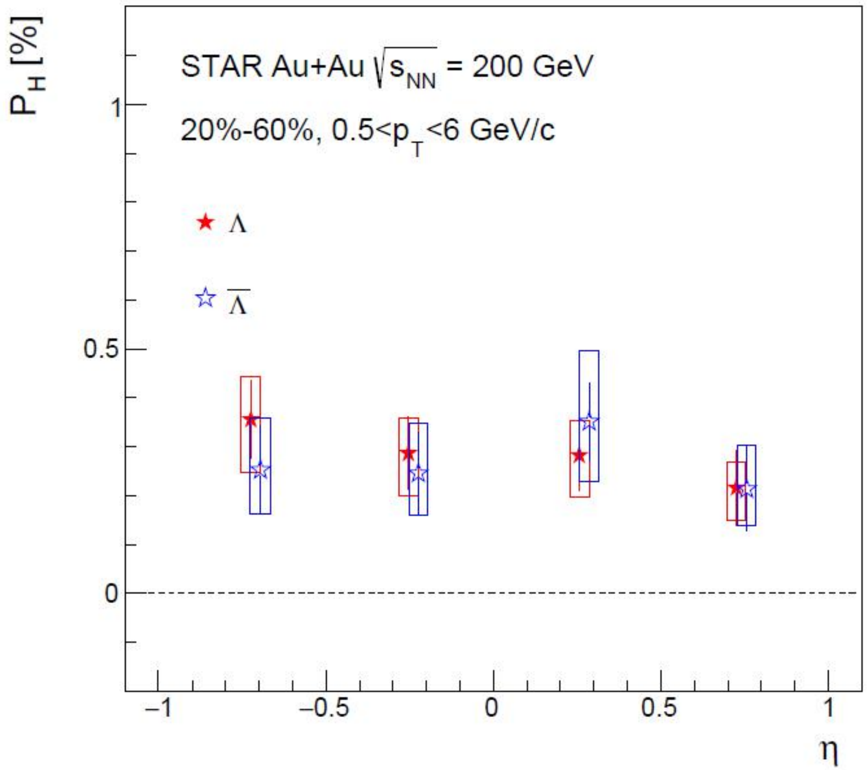
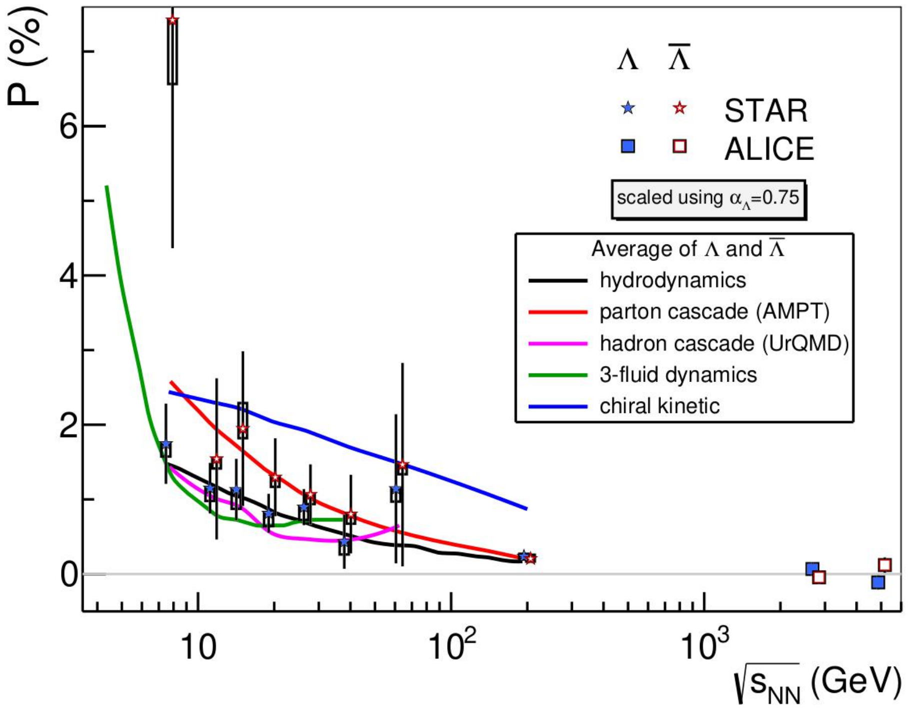
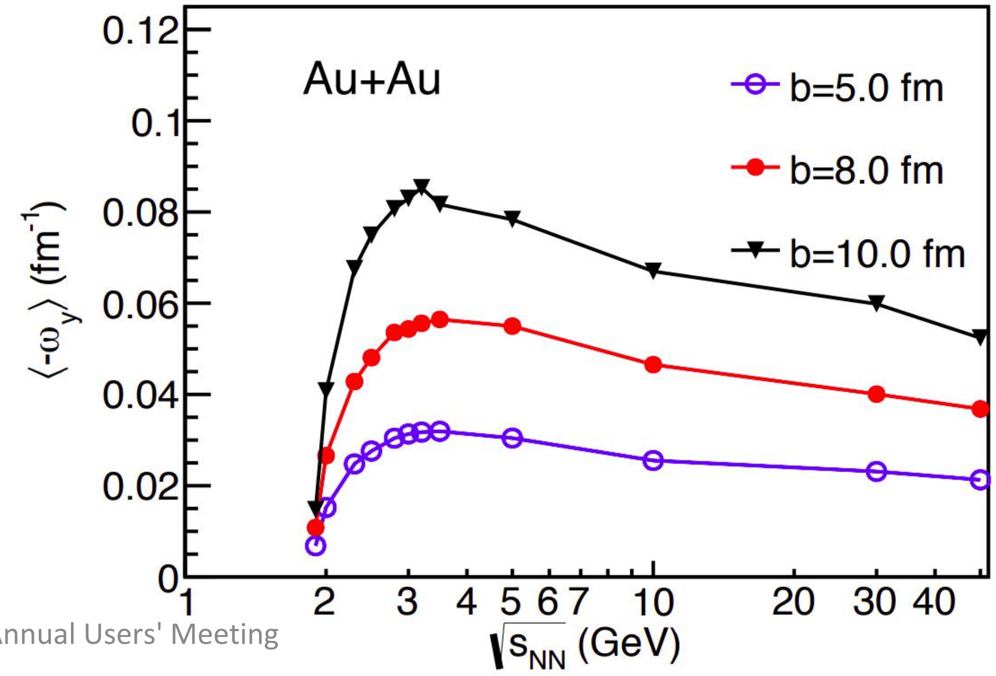


Adam J, et al. Phys. Rev. C 98 14910 (2018)

Low energy

- It is unlikely $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ ever starts to rise as $\sqrt{s_{NN}}$ increases
- What happens as $\sqrt{s_{NN}}$ goes to zero?
- Various models predict sharp rise below STAR BES energies before falling, but models are being "pushed to the limits"
  - Three-fluid dynamics
    - Y. Ivanov, V. Toneev, and A. Soldatov, Phys. Rev. C483100, 014908 (2019).
  - UrQMD
    - Deng XG, Huang XG, Ma YG, Zhang S arXiv:2001.01371 [nucl-th] (2020)





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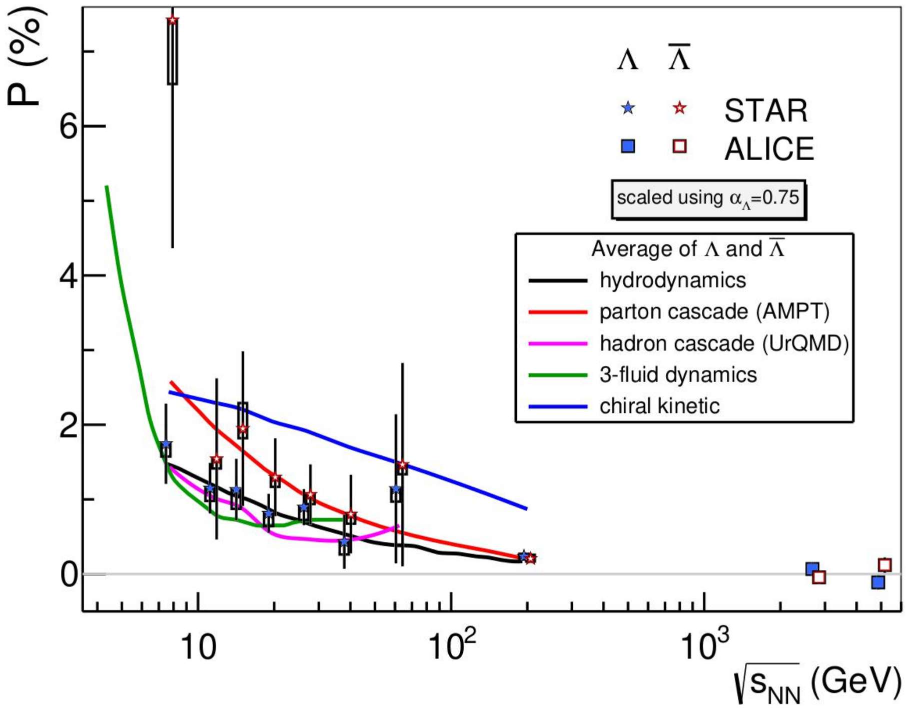
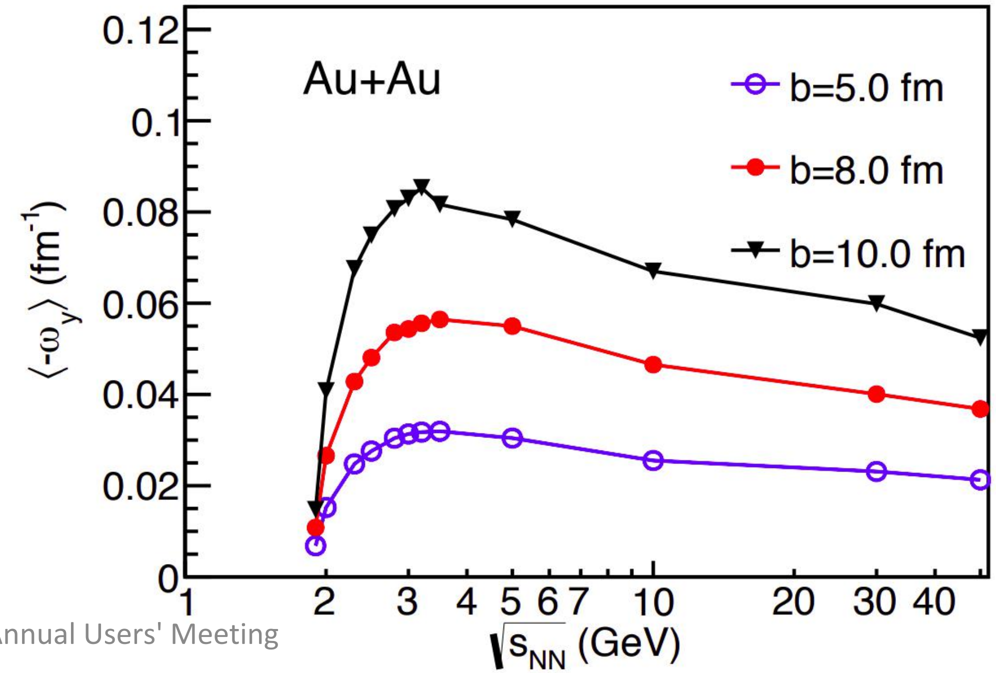
- What happens as $\sqrt{s_{NN}}$ goes to zero?
- The STAR Collaboration recently took a high-statistics data set at $\sqrt{s_{NN}} = 3$ GeV, which will shed light on $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ at sub-QGP energies
- η dependence at this energy will also answer questions
  - STAR will be able to accept even the most forward Λs





Low energy

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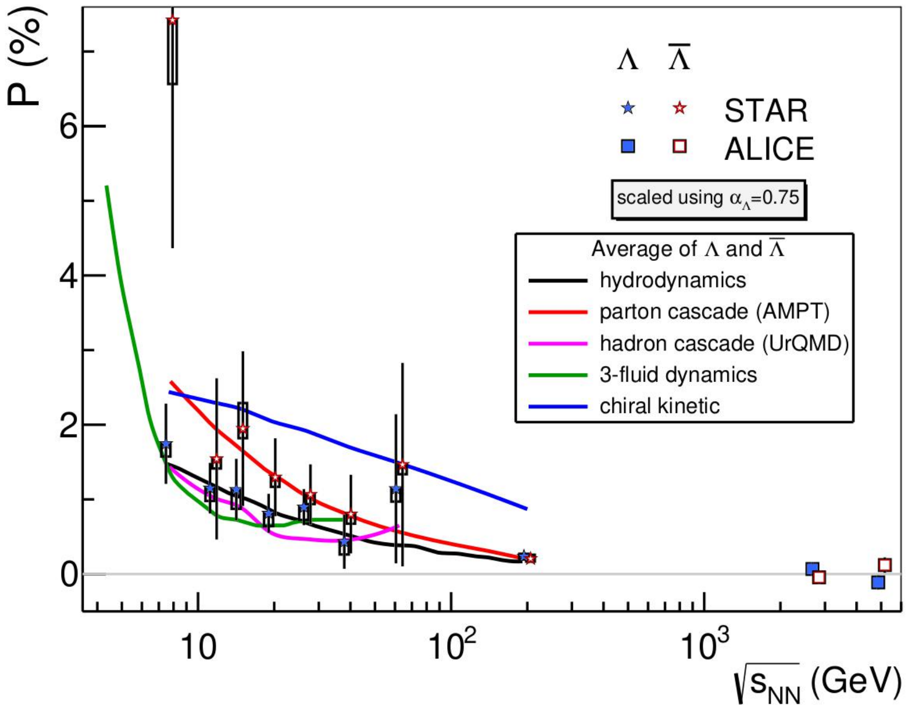
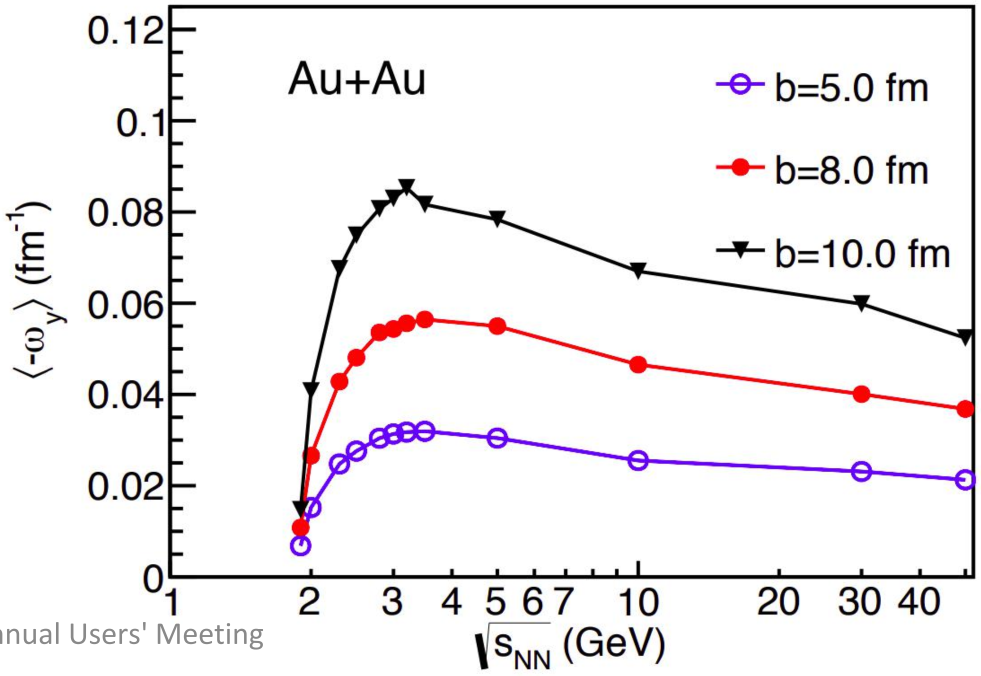
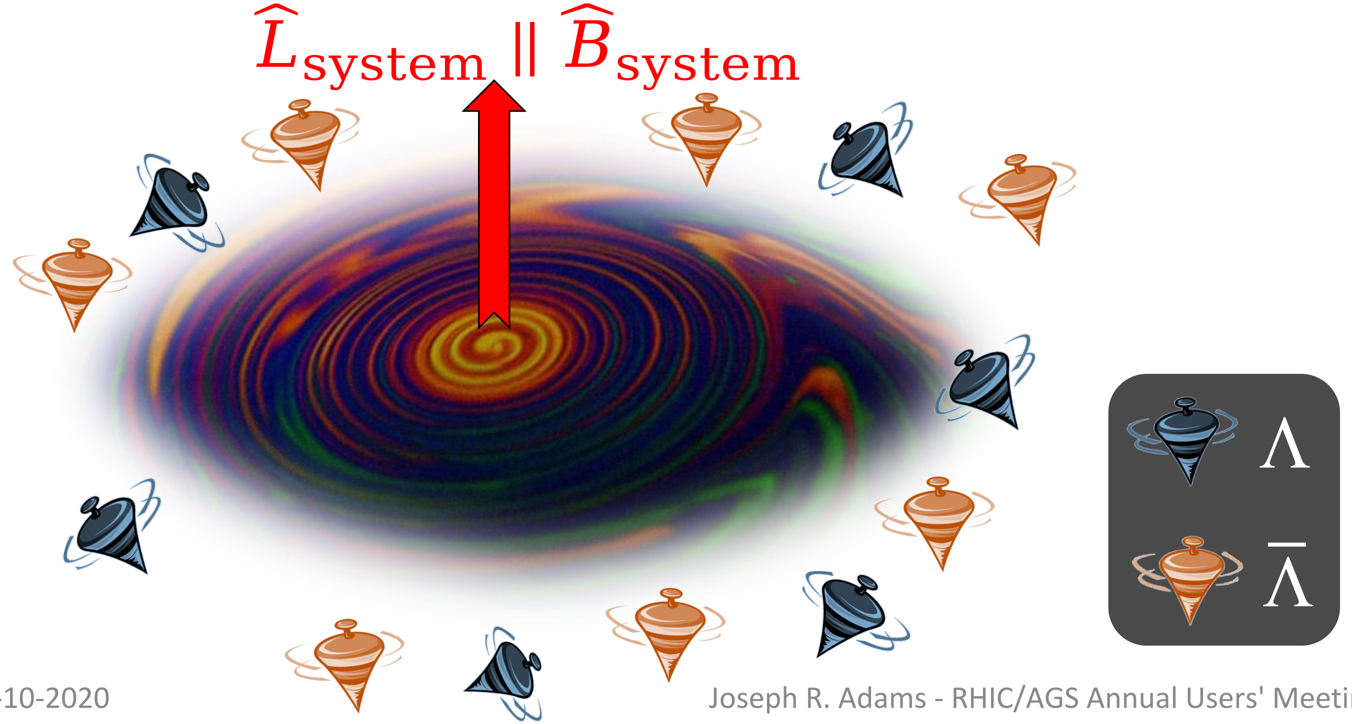
- What happens as $\sqrt{s_{NN}}$ goes to zero?
- If we find non-zero $\overline{\mathrm{P}}_{\Lambda}$ at $\sqrt{s_{NN}} = 3$ GeV…
  - Are we forming QGP droplets?
  - How viscous is the overlap region?
  - What is the spin equilibration timescale?





Global $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ as a tool

- Vorticity gives positive contribution to P_{Λ} *and* $\mathrm{P}_{\overline{\Lambda}}$
- $|\vec{B}|$ enhances $\mathrm{P}_{\overline{\Lambda}}$ and suppresses P_{Λ}
  - $\vec{\mu}_{B,\ \Lambda} = -\vec{\mu}_{B,\ \overline{\Lambda}}$



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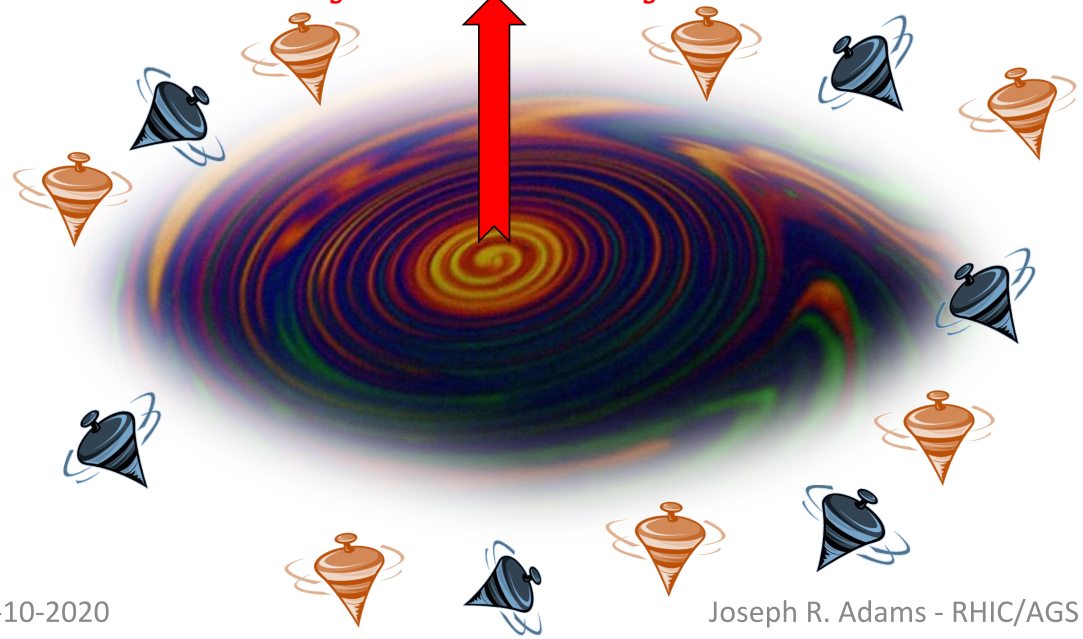
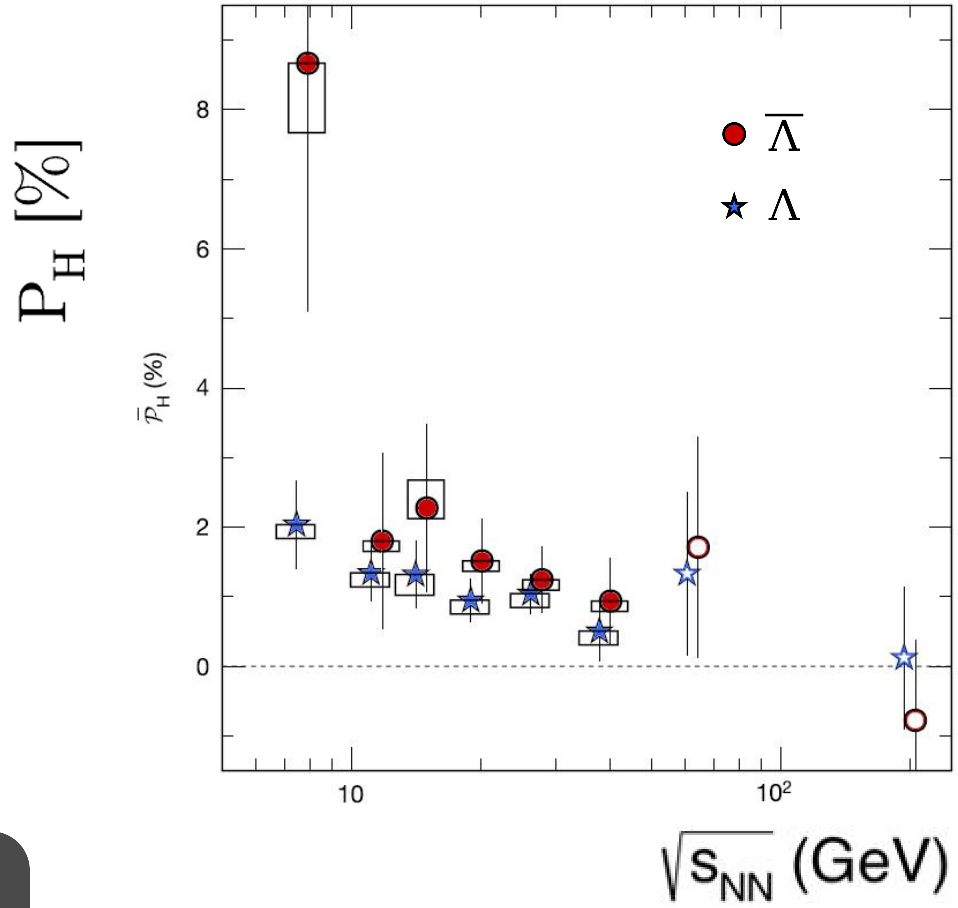
  - We measure $|\vec{B}|$ via $\mathrm{P}_{\Lambda}, \mathrm{P}_{\overline{\Lambda}}$ splitting

$\widehat{L}_{\mathrm{system}} \parallel \widehat{B}_{\mathrm{system}}$





STAR, Nature 548 (2017) 62548

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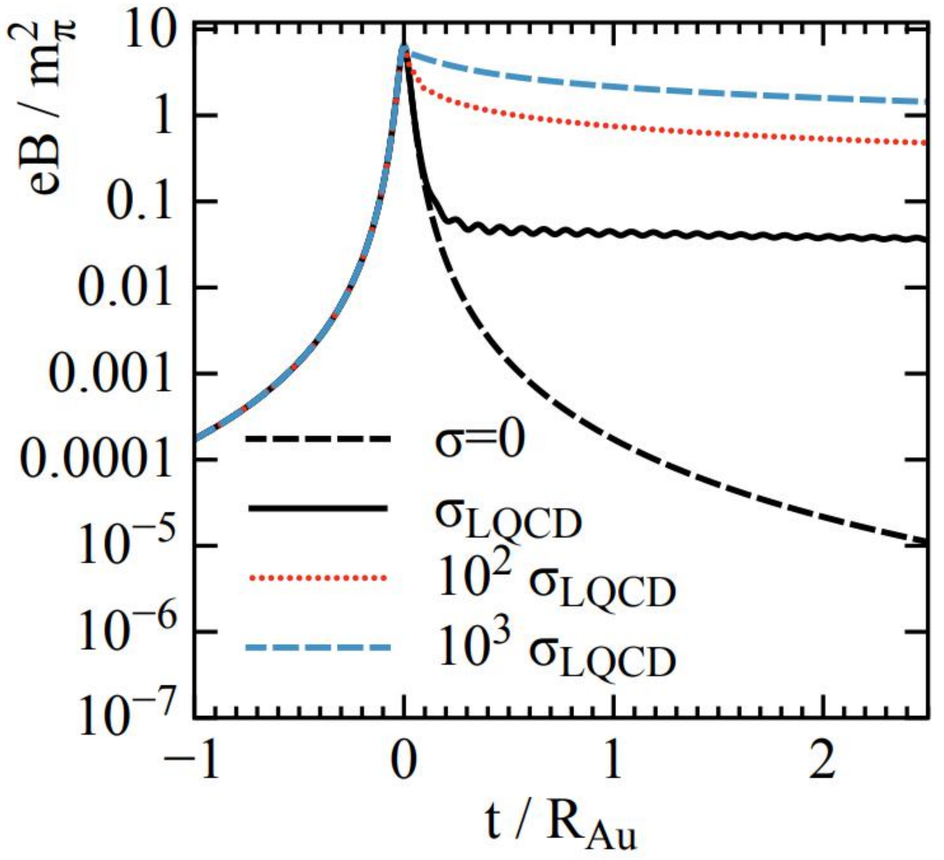

L. McLerran and V. Skokov, Nucl. Phys. A **929**, 184 (2014)

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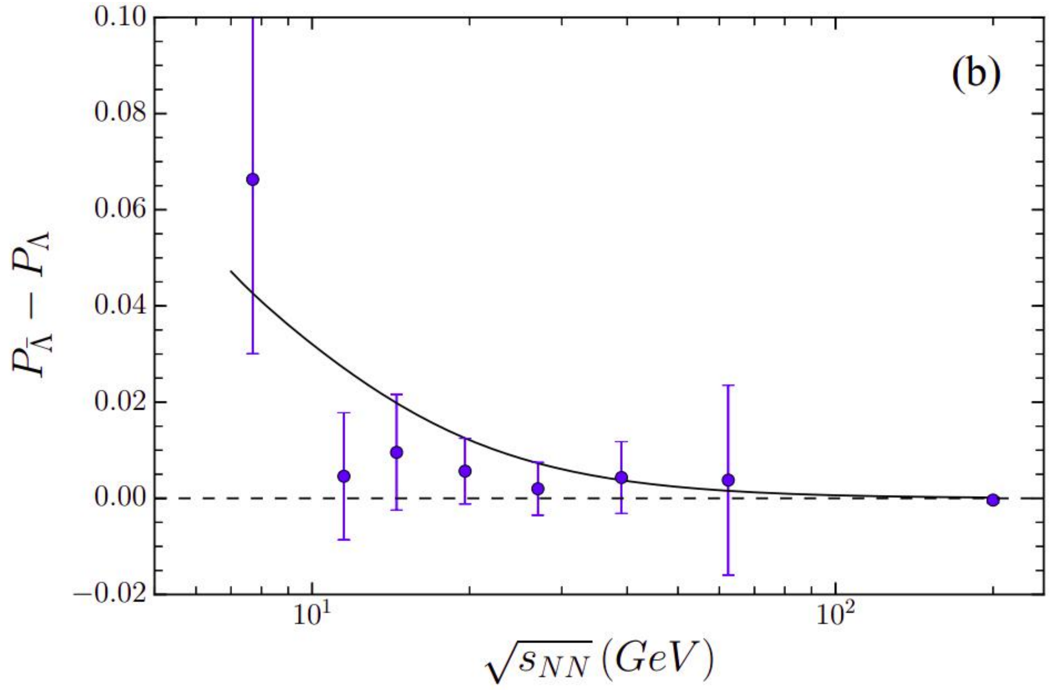
- We need to be careful with this interpretation! Such splitting can have other explanations
  - Spin-meson field interaction
    - L. Csernai, J. Kapusta, and T. Welle, PRC 99 021901(R) (2019)



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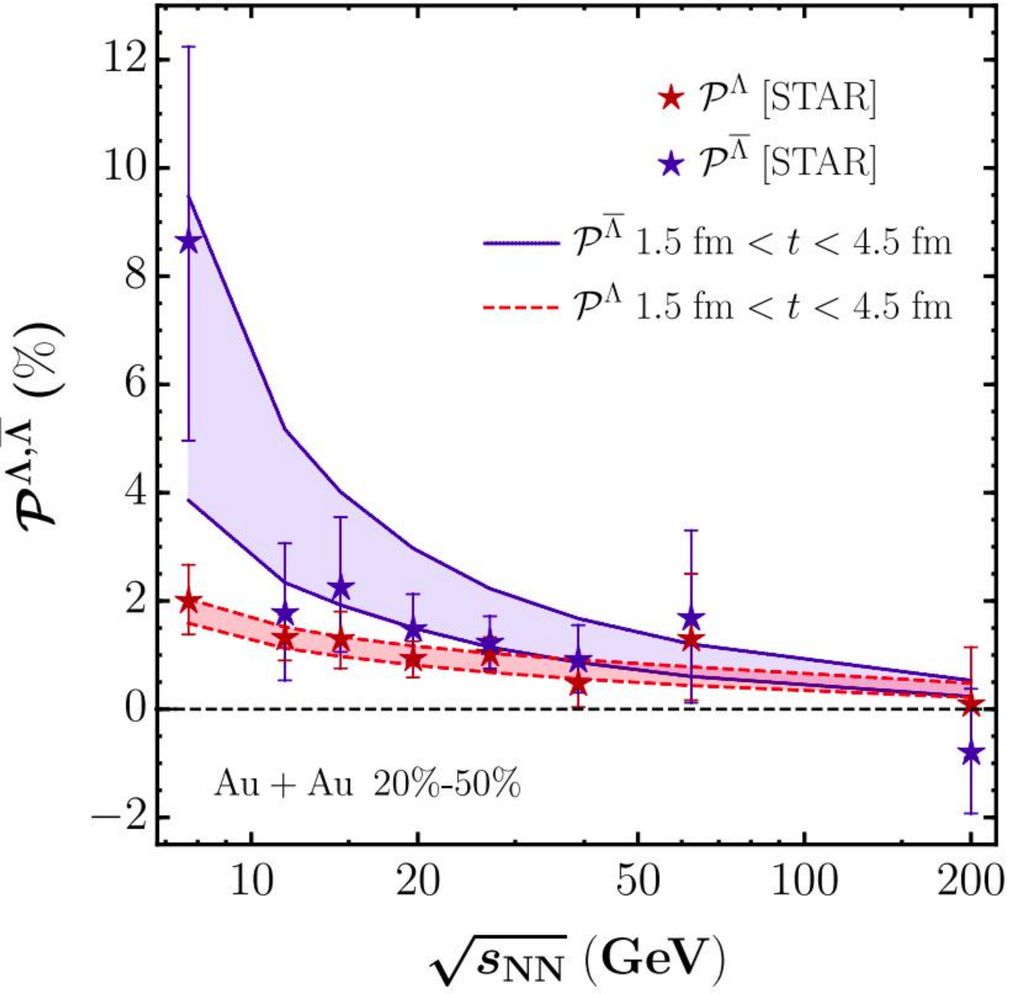
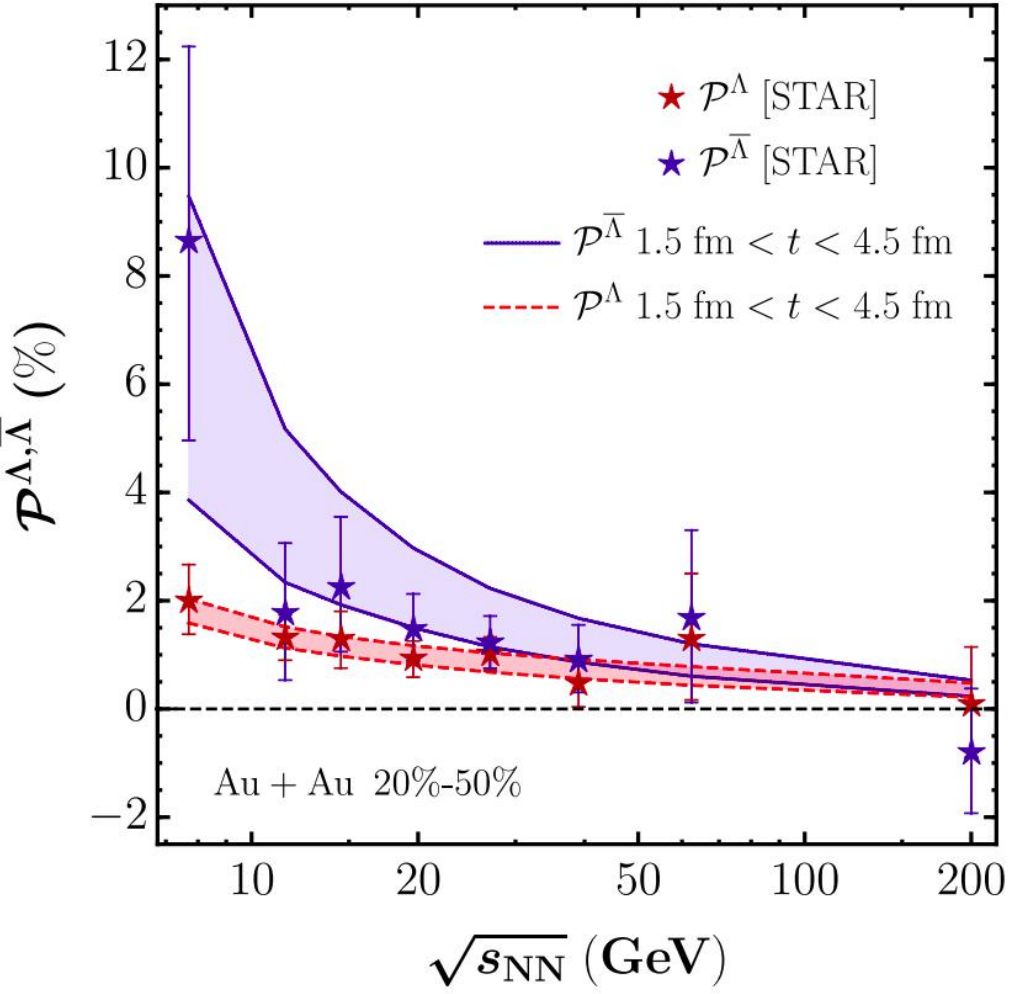
    - L. Csernai, J. Kapusta, and T. Welle, PRC 99 021901(R) (2019)
  - Core-corona
    - Ayala, A. *et al.* Phys. Lett. B 810, 10, 135818 (2020)



Global $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ as a tool

- $\overline{\mathrm{P}}$ is affected by:
  - $\langle \omega_{\mathrm{QGP}} \rangle$
  - $|\vec{B}|$
  - Production time
  - Production location
  - etc.
- To establish the global nature of $\overline{\mathrm{P}}$, it is necessary to study other particles
  - Parity-violating hyperons are the most straightforward way to do this

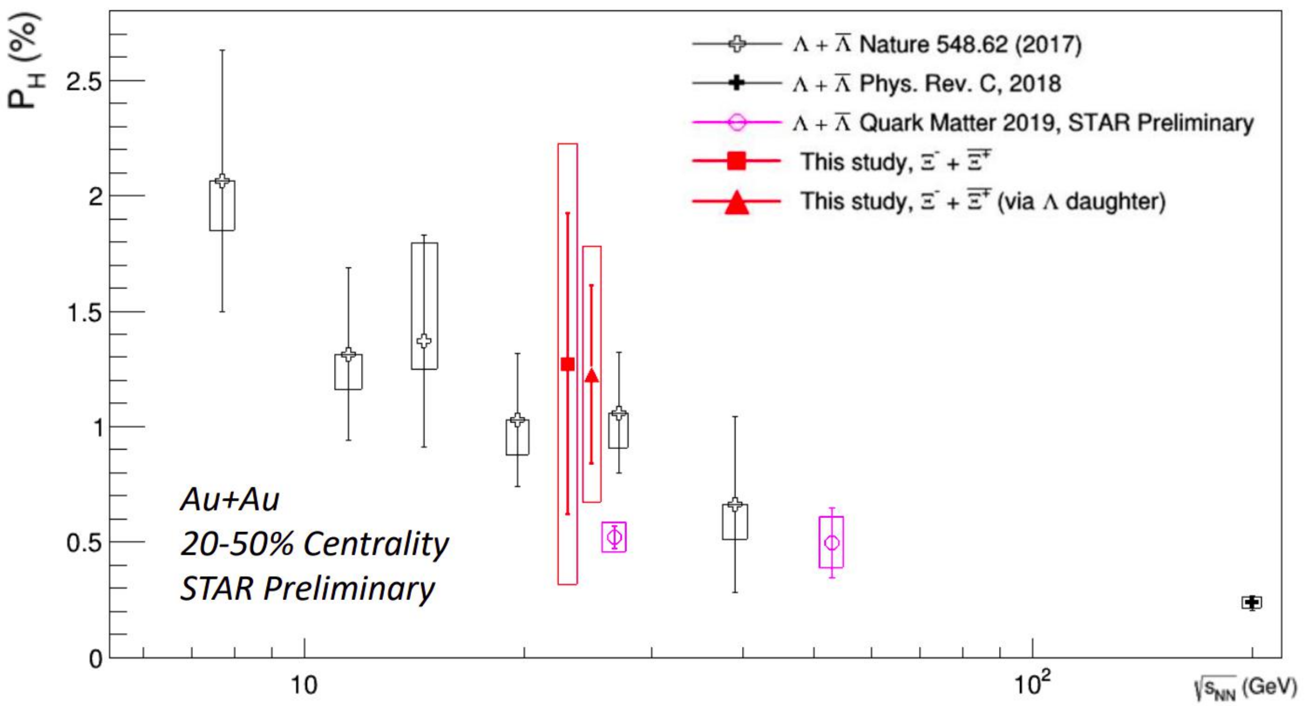


Global $\overline{\mathrm{P}}_{\Xi}$, $\overline{\mathrm{P}}_{\Omega}$

- As before (with Λs), we know how $\Xi \rightarrow \Lambda + \pi^-$ and $\Omega \rightarrow \Lambda + K$ decay with respect to their spin:

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \mathbf{P}_H \cdot \hat{\boldsymbol{p}}_B^*\right)$$

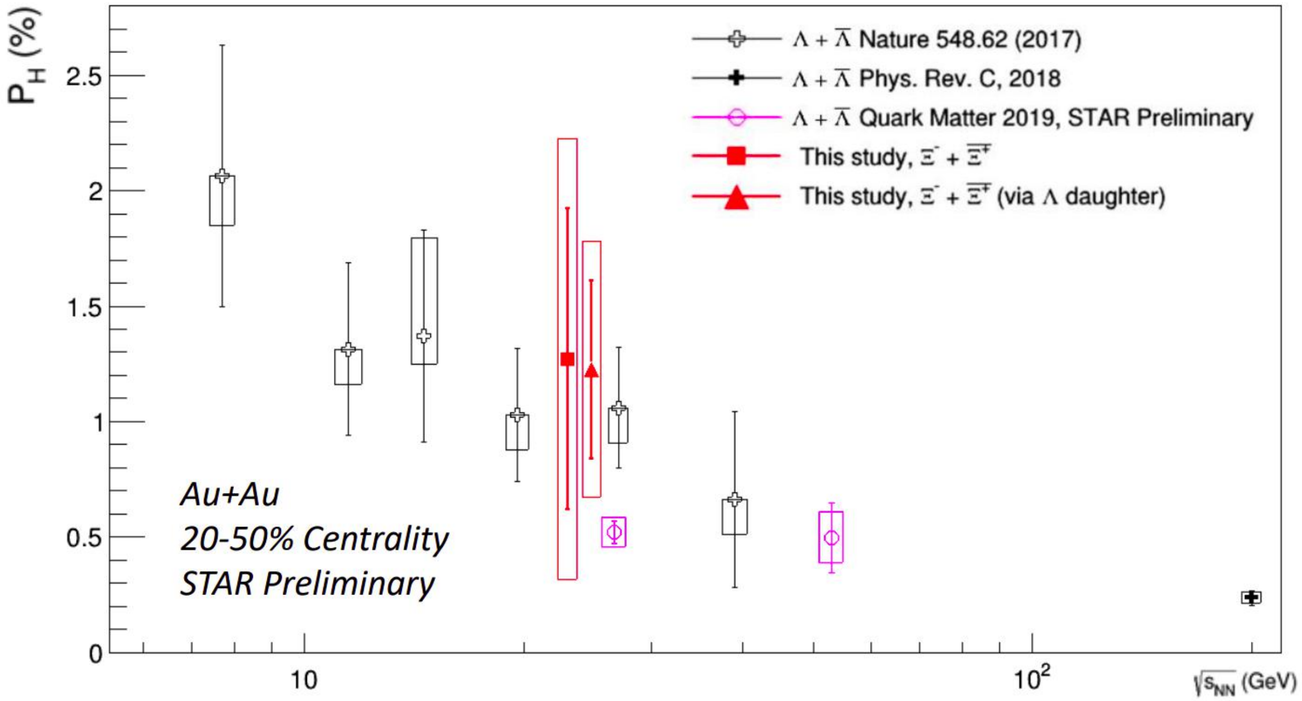
  - $\alpha_\Lambda = 0.750 \pm 0.009$
  - $\alpha_\Xi = -0.401 \pm 0.01$
  - $\alpha_\Omega = 0.0157 \pm 0.0021$
- α_Ω being small makes the measurement of $\overline{\mathrm{P}}_\Omega$ in this case difficult. Instead, $\overrightarrow{P}^*_\Lambda = C_{\Omega-\Lambda}\overrightarrow{P}^*_\Omega$ is used, with $C_{\Omega-\Lambda} = -0.6$



Egor Alpatov (STAR), iCPPA 2020

Global $\overline{\mathrm{P}}_{\Xi}$, $\overline{\mathrm{P}}_{\Omega}$

- Recent Measurements of $\overline{\mathrm{P}}_{\Xi}$ at $\sqrt{s_{NN}} = 27$ GeV by STAR agree with previous $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ measurements
- More statistics are obviously needed
- These polarizations are being actively studied at other energies by STAR
- Recent detector upgrades (esp. iTPC) will be very useful in this search



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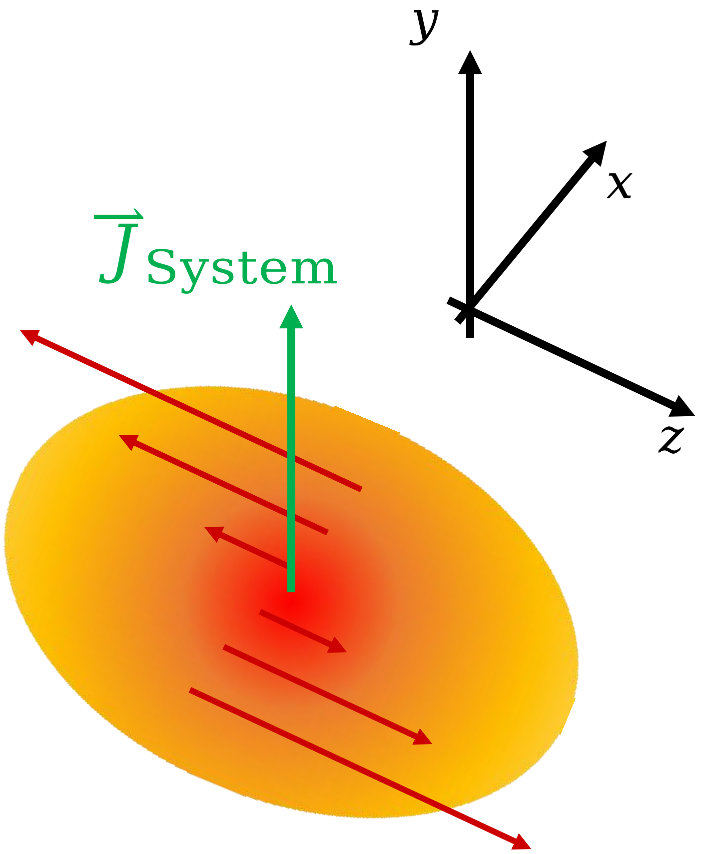
Further polarization studies

- Just as global $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ comes from collision-driven shear in the QGP in the $\widehat{x} - \widehat{z}$ plane…



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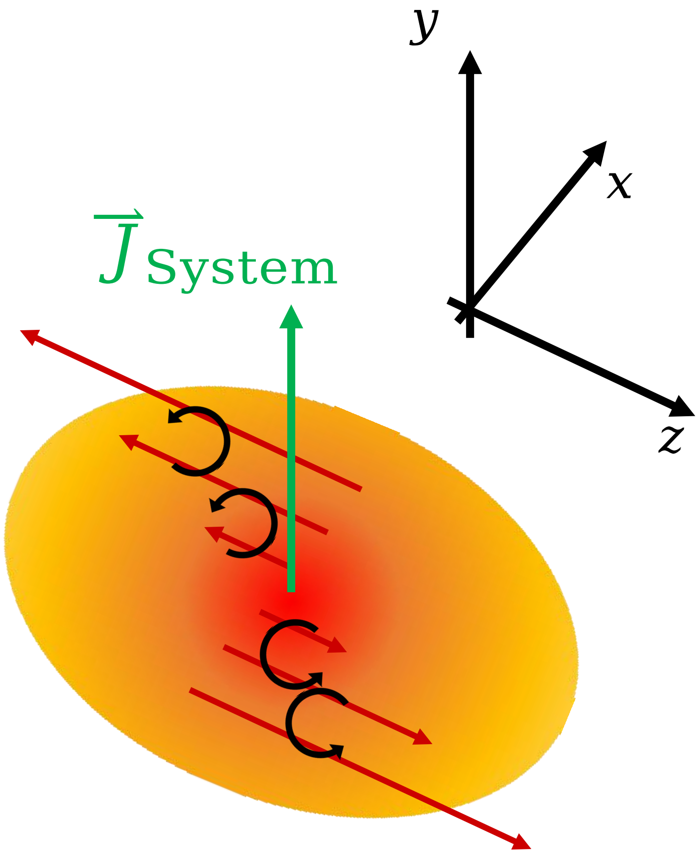

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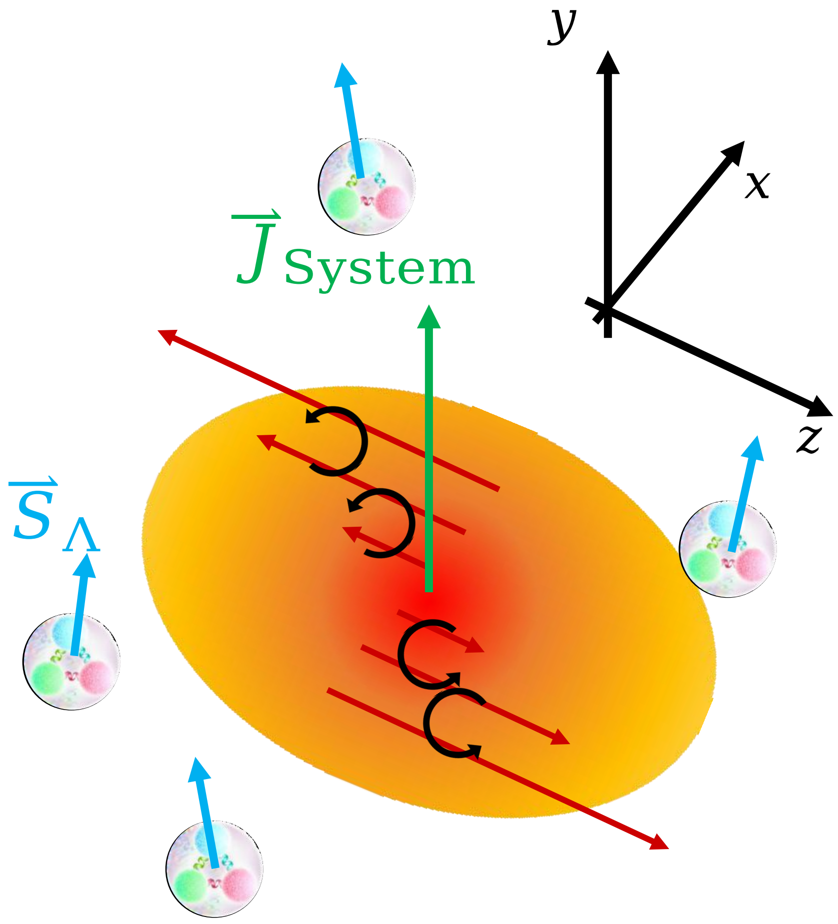
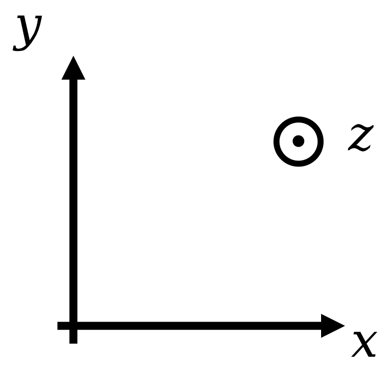
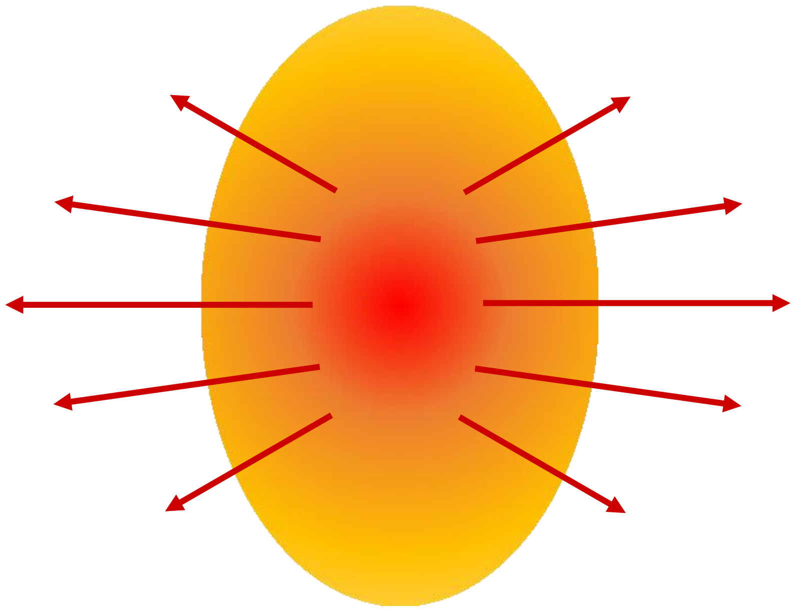


Further polarization studies

- Just as global $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ comes from collision-driven shear in the QGP in the $\hat{x}-\hat{z}$ plane, we can expect $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ along $\hat{z}$ coming from flow-driven shear in the $\hat{x}-\hat{y}$ plane





Further polarization studies

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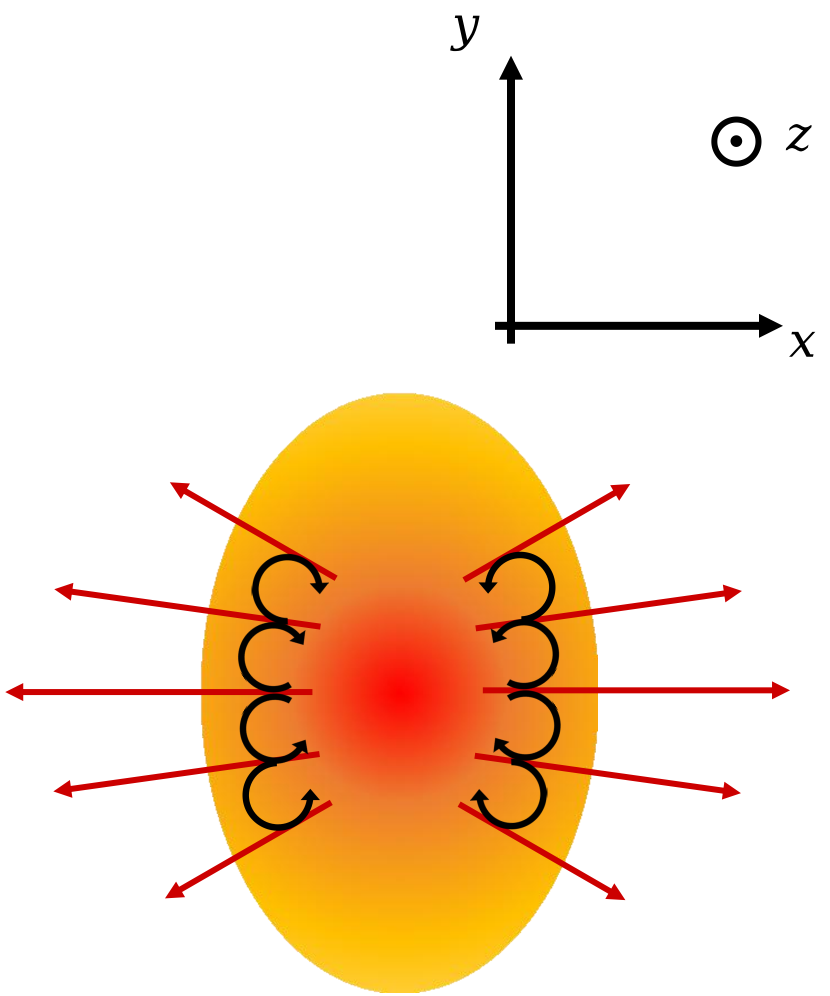

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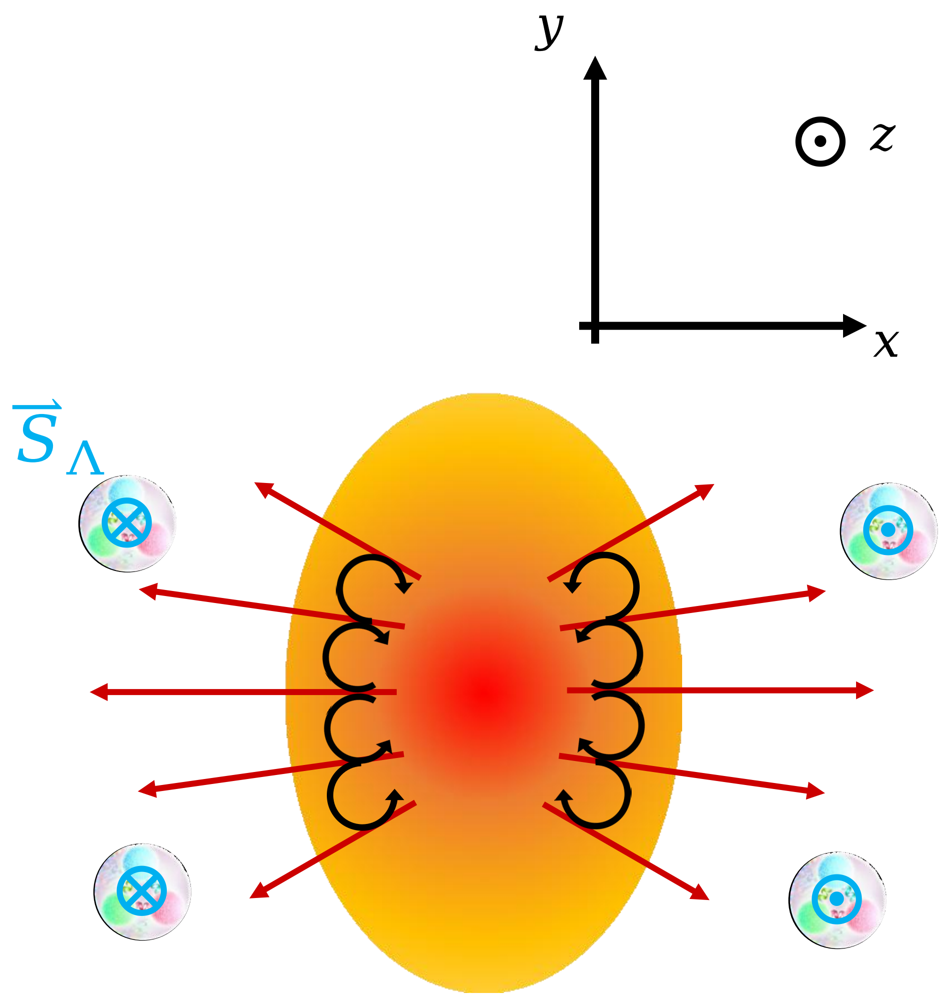

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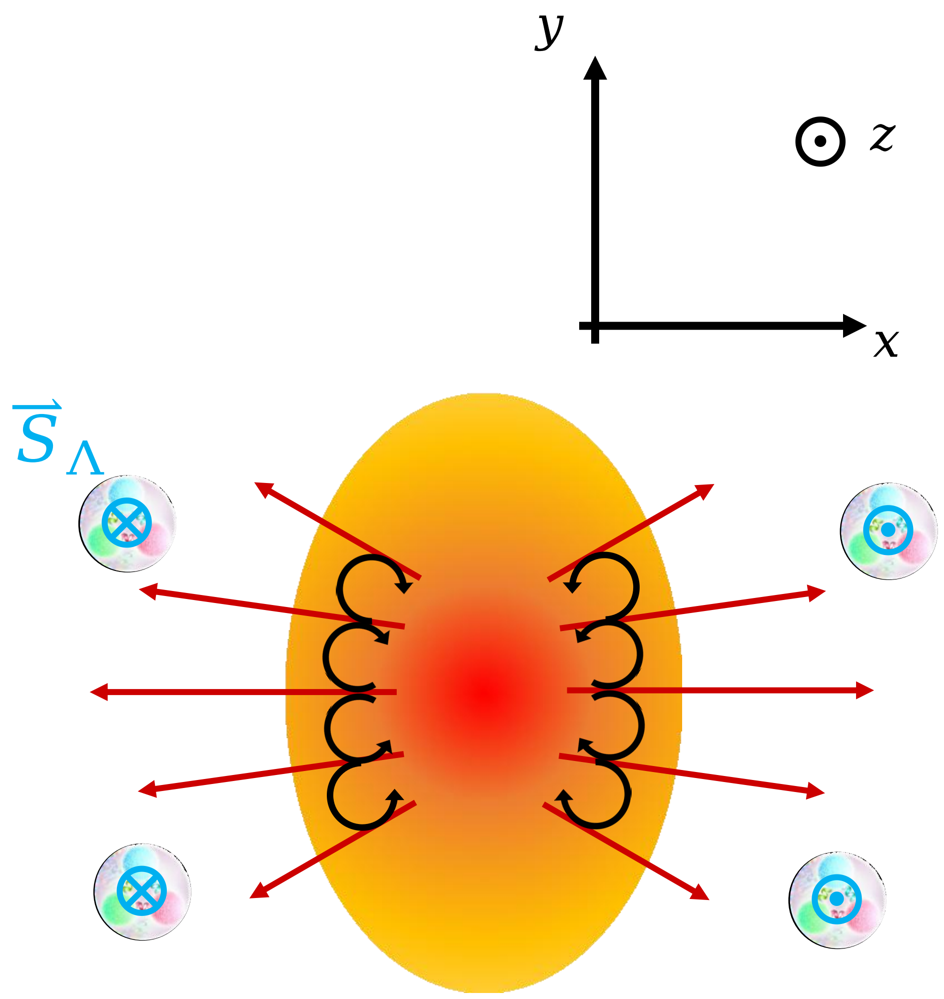

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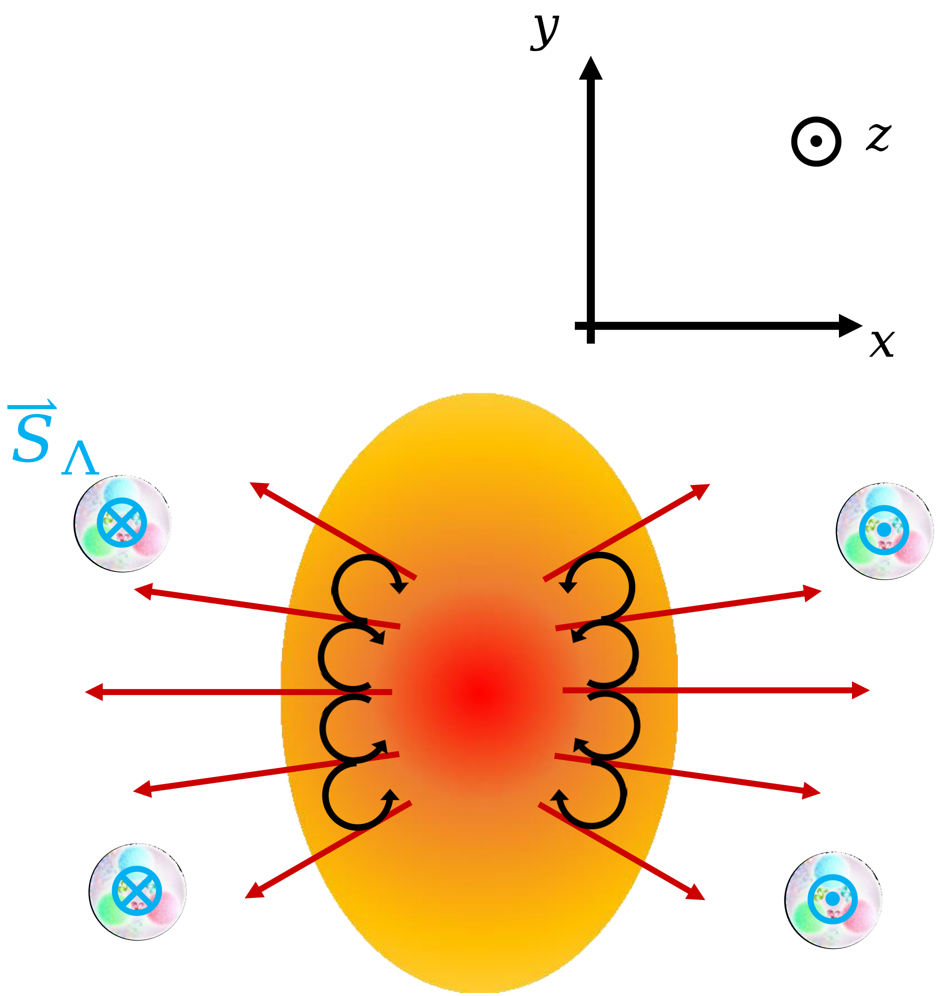

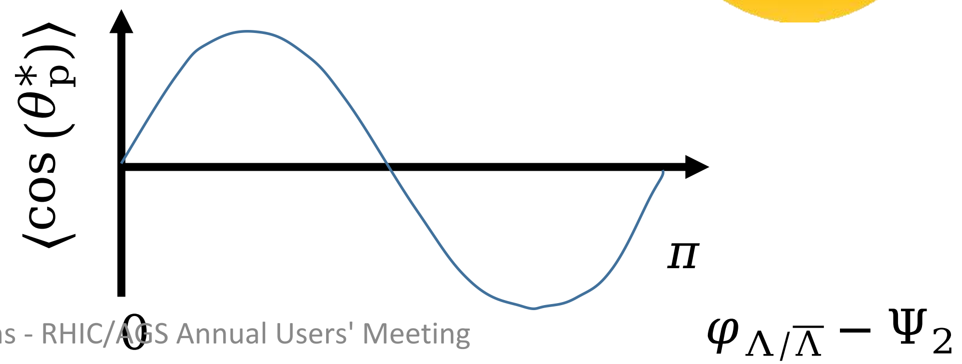

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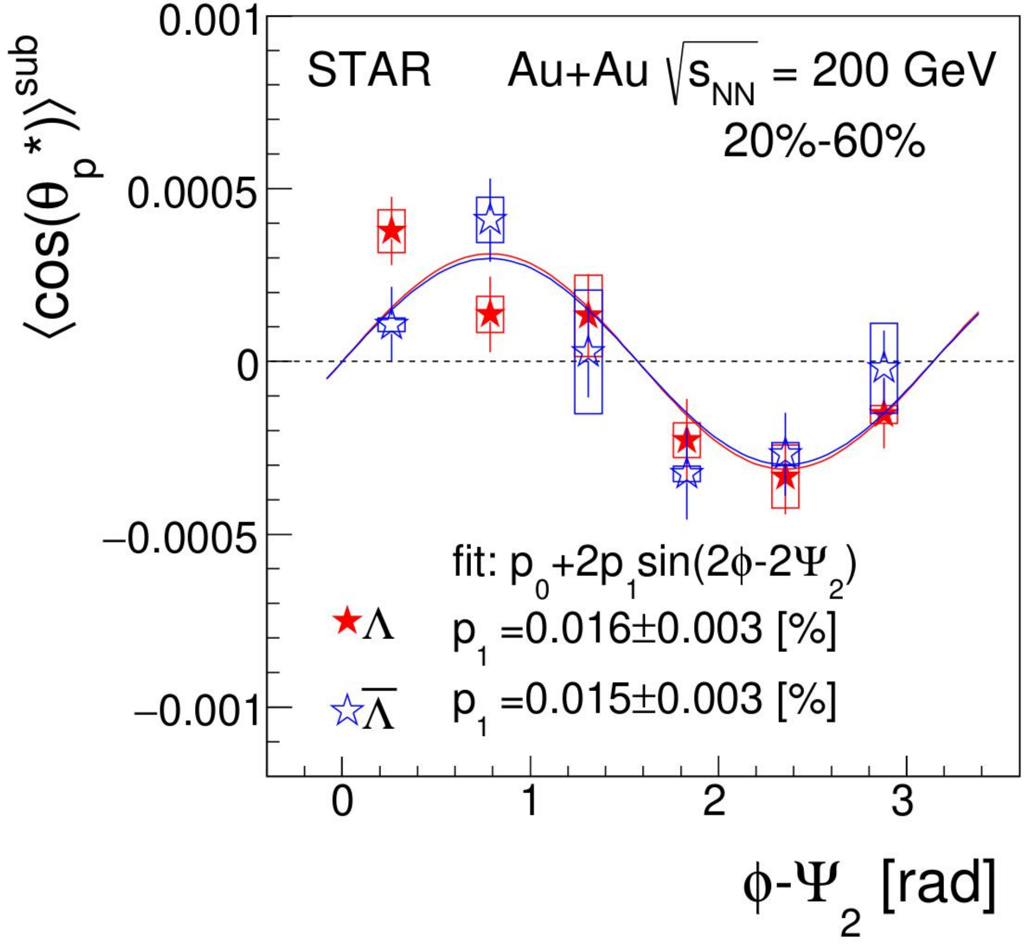
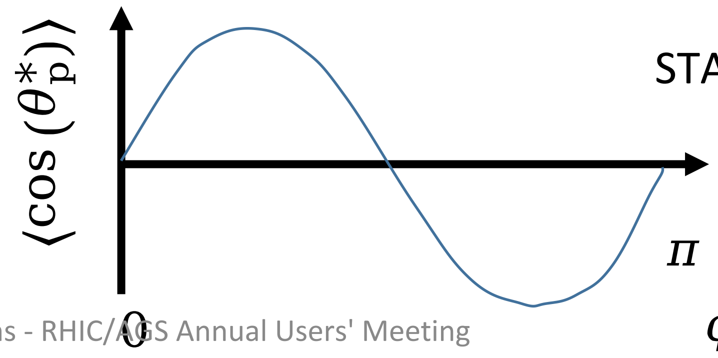
- Naïvely expect $\langle \cos(\theta_{\mathrm{p}}^{*}) \rangle \propto \sin(\varphi_{\Lambda/\overline{\Lambda}} - \Psi_2)$
  - This is what we measure!



STAR, PRL 123 13201 (2019)



Further polarization studies

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    - Y. Xie, D. Wang, and L. P. Csernai, EPJ C 80, 39 (2020)
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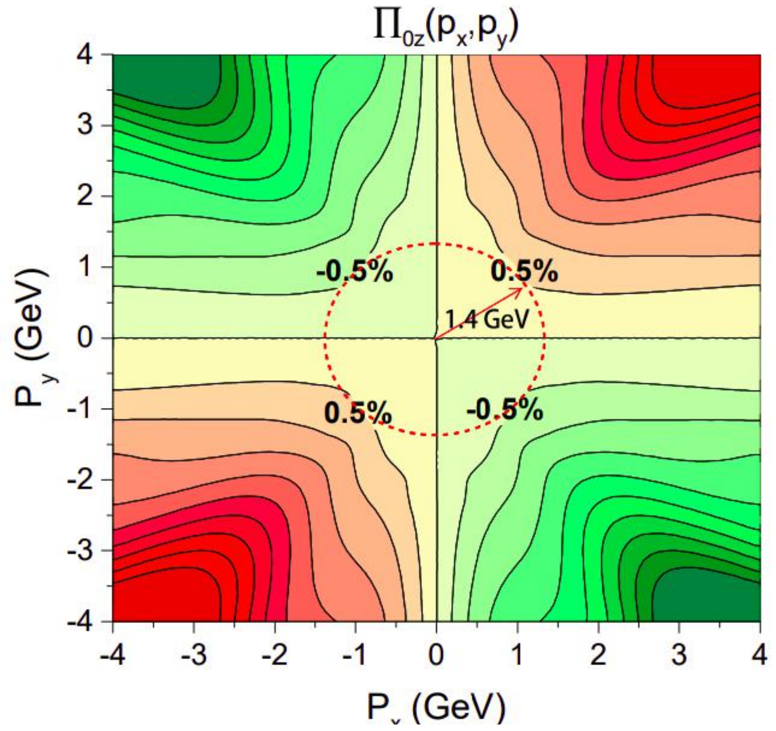
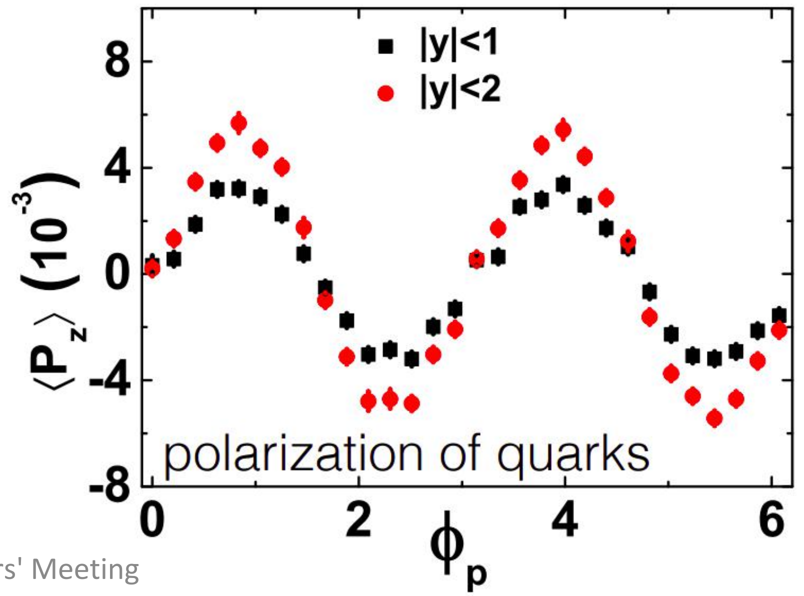


Au+Au @ 200 GeV, 30-40%



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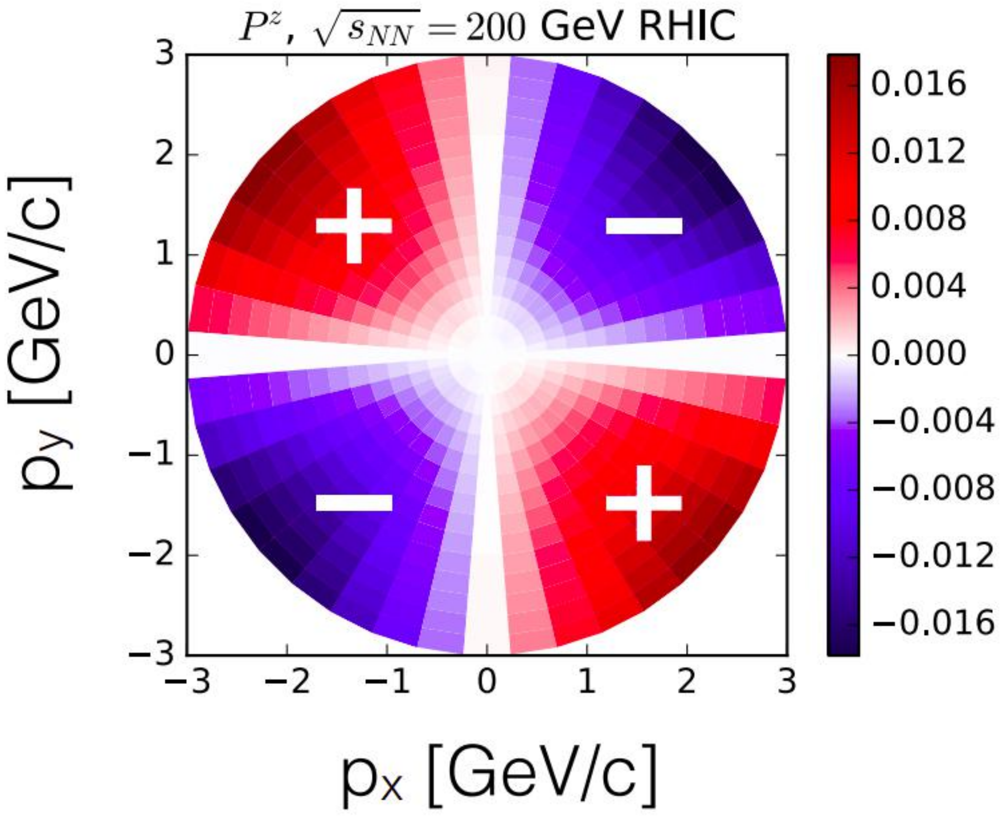
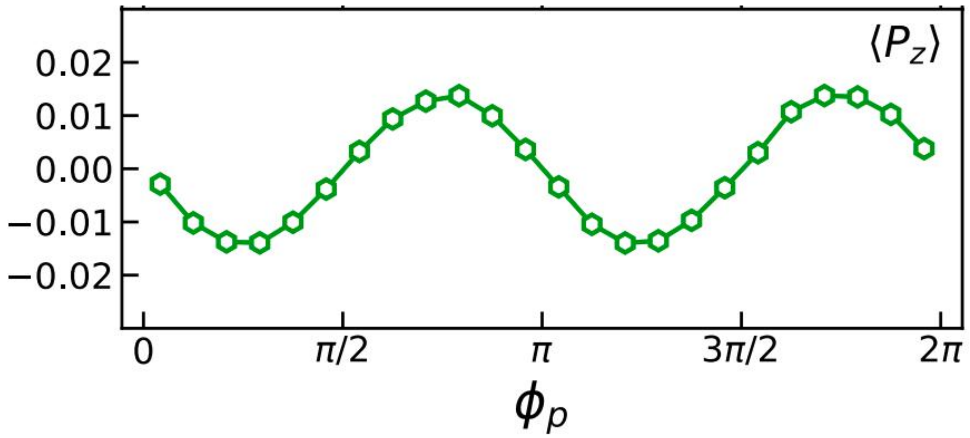
- it disagrees with others
  - UrQMD initial cond. + hydro
    - F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  - AMPT
    - X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)



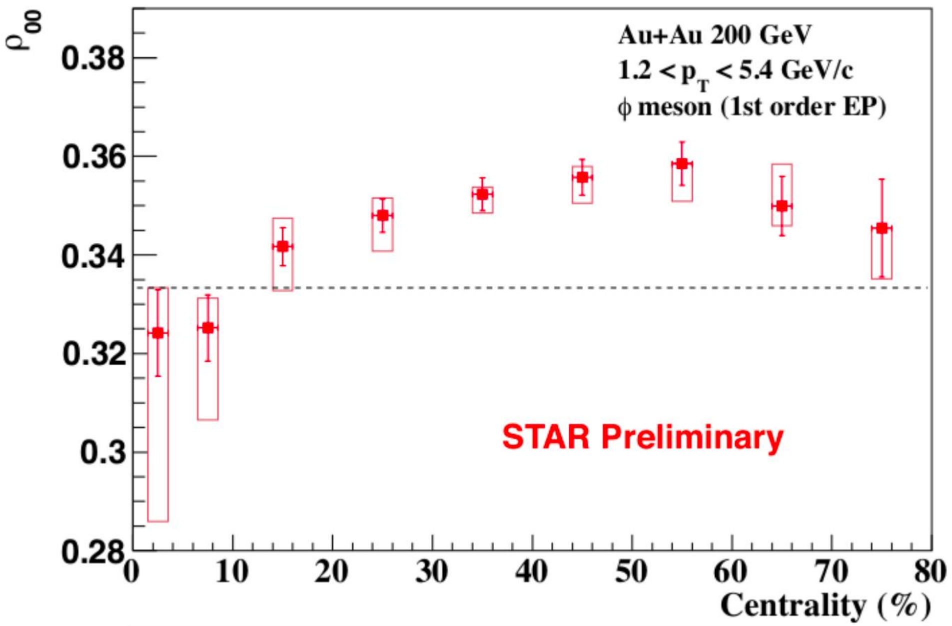


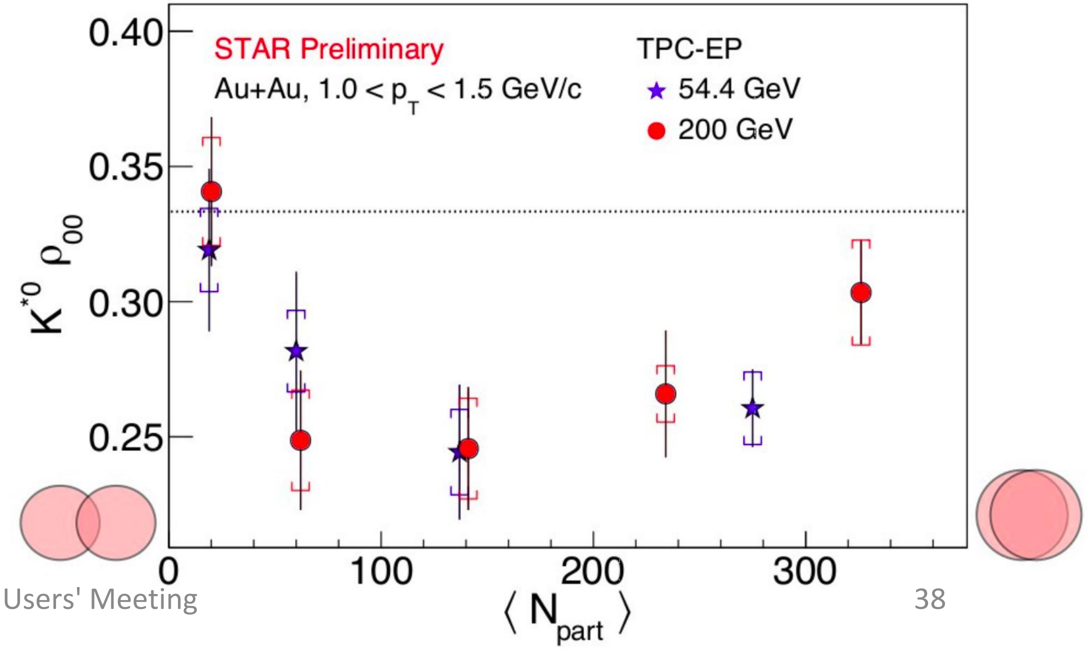
Global spin polarization of vector mesons

- Vector mesons produced by quark combination $q\overline{q} \to V$ have equal probabilities of occupying the three spin states, given no global polarization:
  - $|1\ 1\rangle = |\uparrow\uparrow\rangle$
  - $|1\ 0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$
  - $|1\ -1\rangle = |\downarrow\downarrow\rangle$
- The angular distribution of decay products can be written with the spin density matrix ρ_{NN}; the relevant observable is $\rho_{00} = \frac{1}{3} - \frac{8}{3}\langle\cos[2(\varphi_p^* - \Psi_{RP})]\rangle$
  - Deviation of ρ_{00} from indicates global polarization
  - $\rho_{00} < {}^1/_3 \leftrightarrow \overrightarrow{\omega}$

Global spin polarization of vector mesons

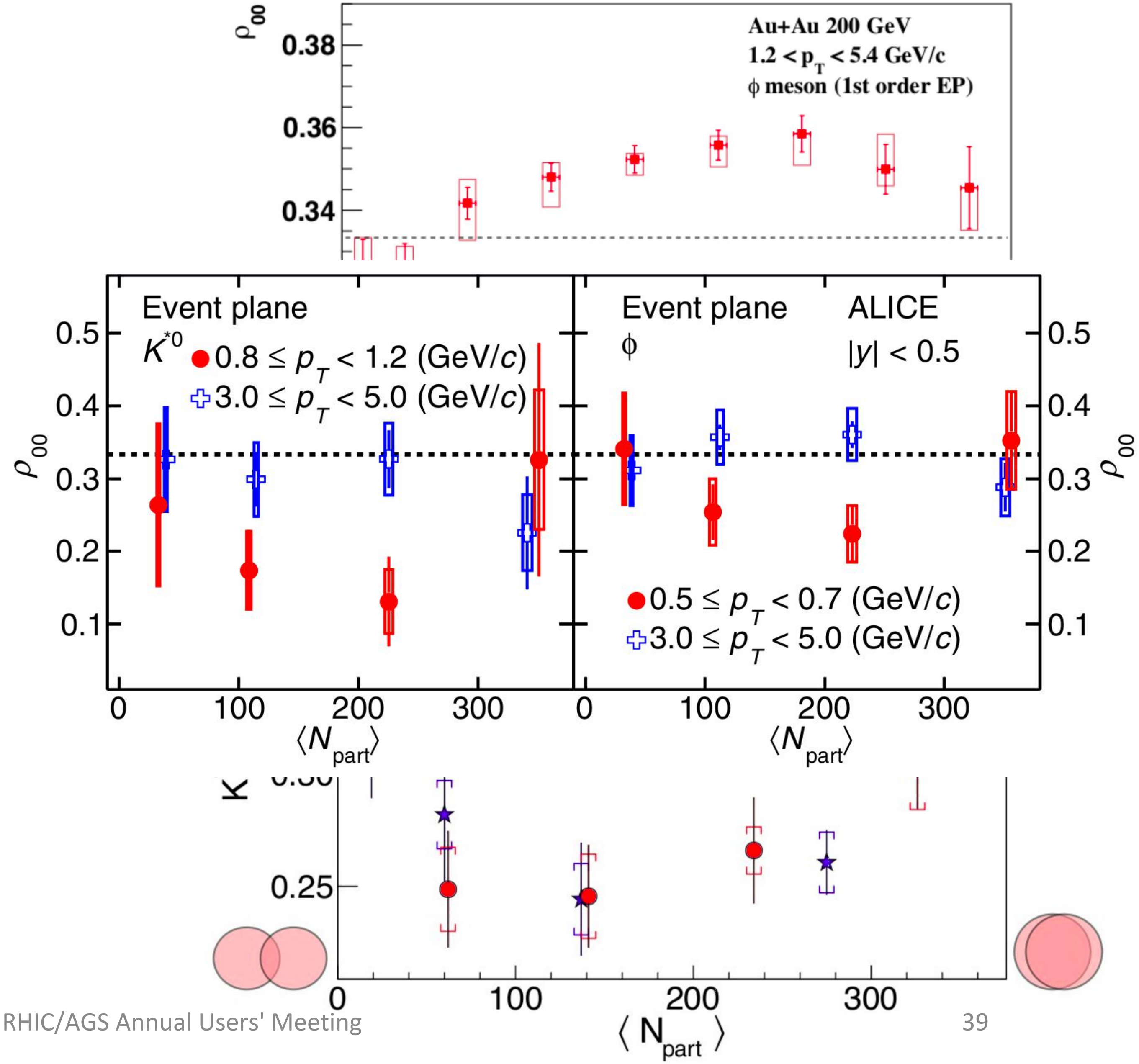
- STAR measurements of ρ_{00} at $\sqrt{s_{NN}} = 54.4,\ 200$ GeV for K^{*0}, φ mesons show deviation from ${}^{1}/_{3}$
  - Below ${}^{1}/_{3}$ for K^{*0} and above for φ





Global spin polarization of vector mesons

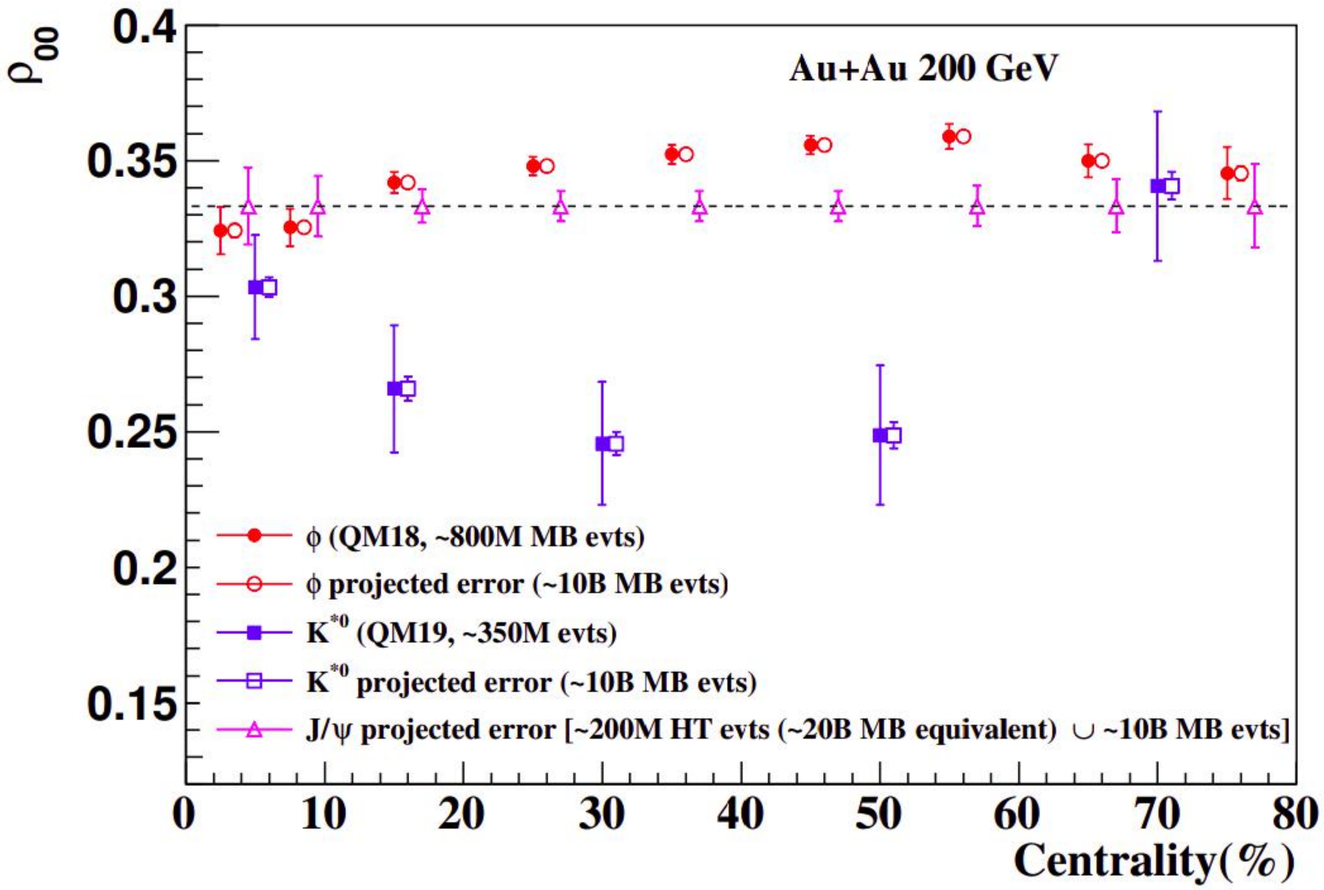
- STAR measurements of ρ_{00} at $\sqrt{s_{NN}} = 54.4$, 200 GeV for K^{*0}, φ mesons show deviation from $1/3$
  - Below $1/3$ for K^{*0} and above for φ
- ALICE measurements agree qualitatively for K^{*0}, but are below $1/3$ for φ
  - What is driving this? $\overrightarrow{\omega}$ domination at lower energy and fragmentation/$|\overrightarrow{B}|$ domination at higher energy?



Future measurements

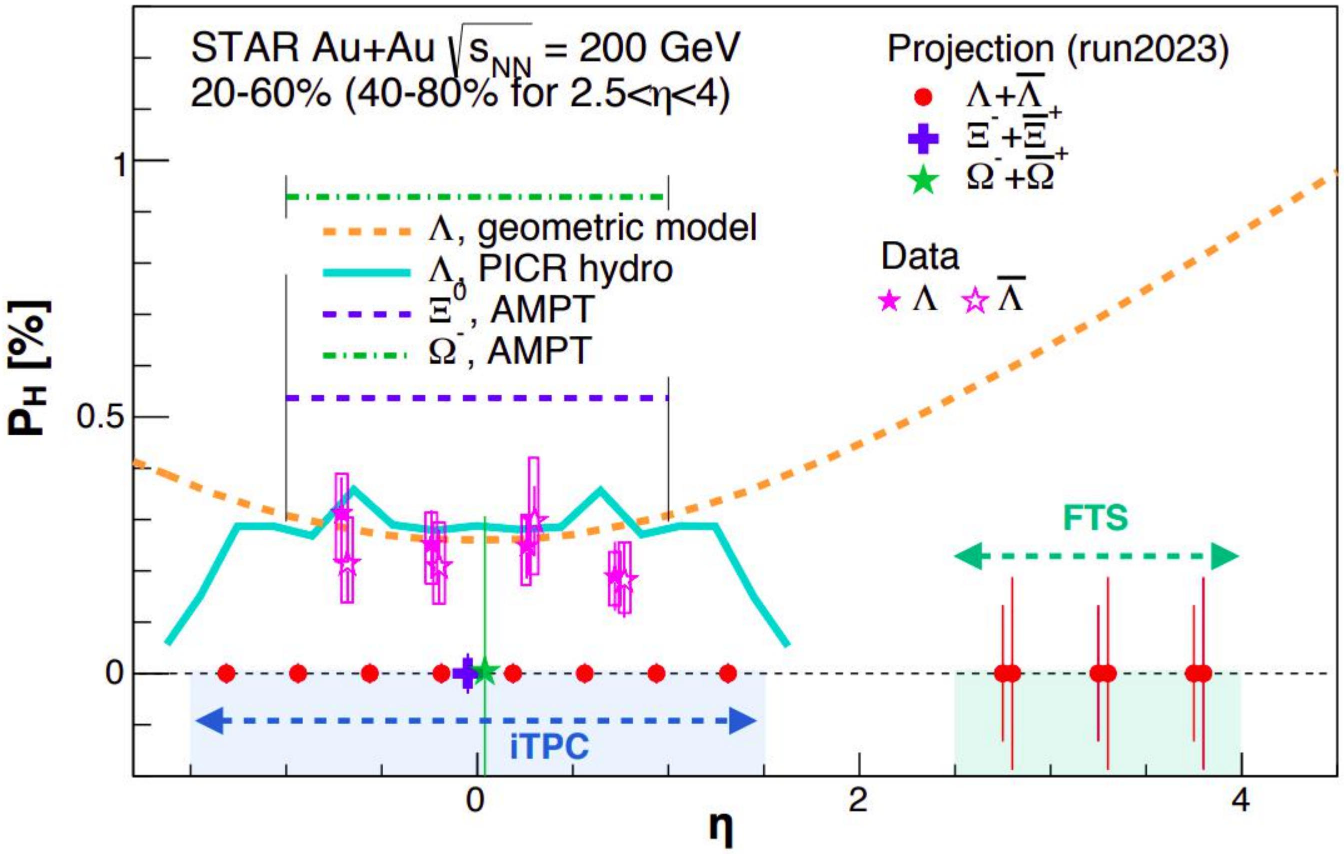
- Additionally, ρ_{00} falls below $^{1}/_{3}$ much further than expected based on $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$-driven vorticity measurements

- *Future high-statistics data sets complemented by detector upgrades hold important information!*



Future measurements

- To establish the global nature of $\overline{P}$, it is necessary to study how $\overline{P}$ depends on spatial/temporal particle formation
  - Study $\overline{P}_{\Lambda/\overline{\Lambda}}$ w.r.t. rapidity
  - Study $\overline{P}_{\Xi}$, $\overline{P}_{\Omega}$ alongside $\overline{P}_{\Lambda/\overline{\Lambda}}$
- *Future high-statistics data sets complemented by detector upgrades hold important information!*



Summary

- Significant $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ at RHIC energies
- Will soon measure $\overline{\mathrm{P}}_{\Lambda}$ at $\sqrt{s_{NN}} = 3$ GeV including y dependence *with most forward Λs being measured!*
- Possible $|\vec{B}|$ measurement via $\mathrm{P}_{\Lambda}, \mathrm{P}_{\overline{\Lambda}}$
- $\overline{\mathrm{P}}_{\Xi}$, $\overline{\mathrm{P}}_{\Omega}$ help establish global nature of $\overline{\mathrm{P}}$
- Important questions still remain!
    - Will we find non-zero $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ in collisions with insufficient energy to form QGP?
    - Is $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ migrating to forward rapidity at higher energies?
    - How do we reconcile measured longitudinal $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ with models that predict the opposite behavior?
    - Why the $\rho_{00,\,\varphi}$ discrepancy between STAR and ALICE?
    - Why the $\langle\omega_{\mathrm{QGP}}\rangle$ discrepancy between ρ_{00} and $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ derivations?
    - And more!!!
- High-statistics data sets by STAR along with numerous detector upgrades now in place will be cruicial to answering these!