Measurements of hyperon polarization in heavy-ion collisions at $\sqrt{s_{\mathrm{NN}}} = 3 - 200$ GeV with the STAR detector

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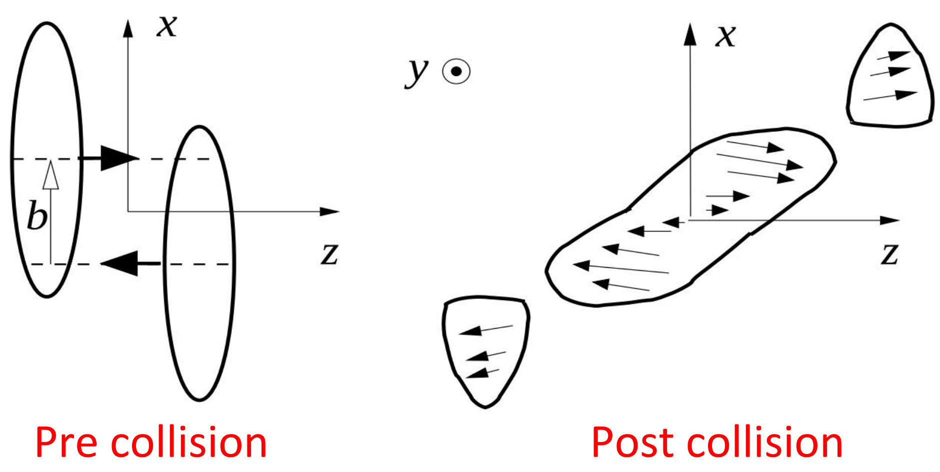
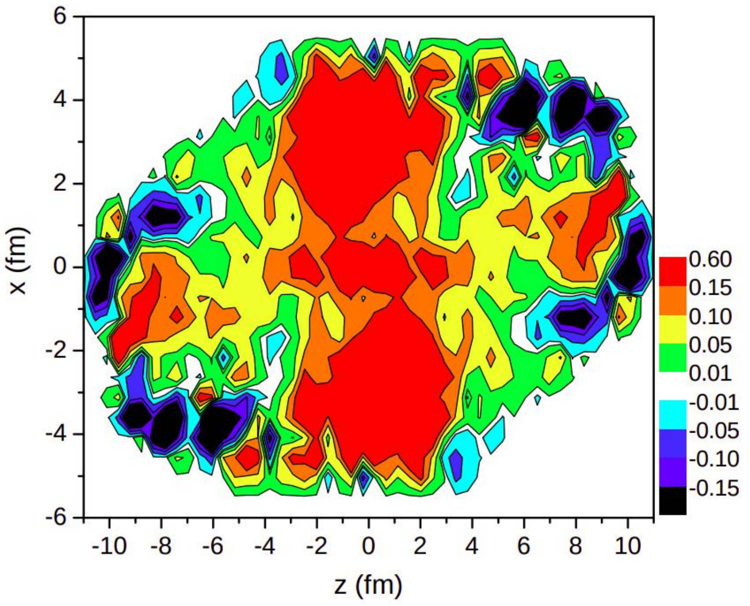
Global hadron polarization

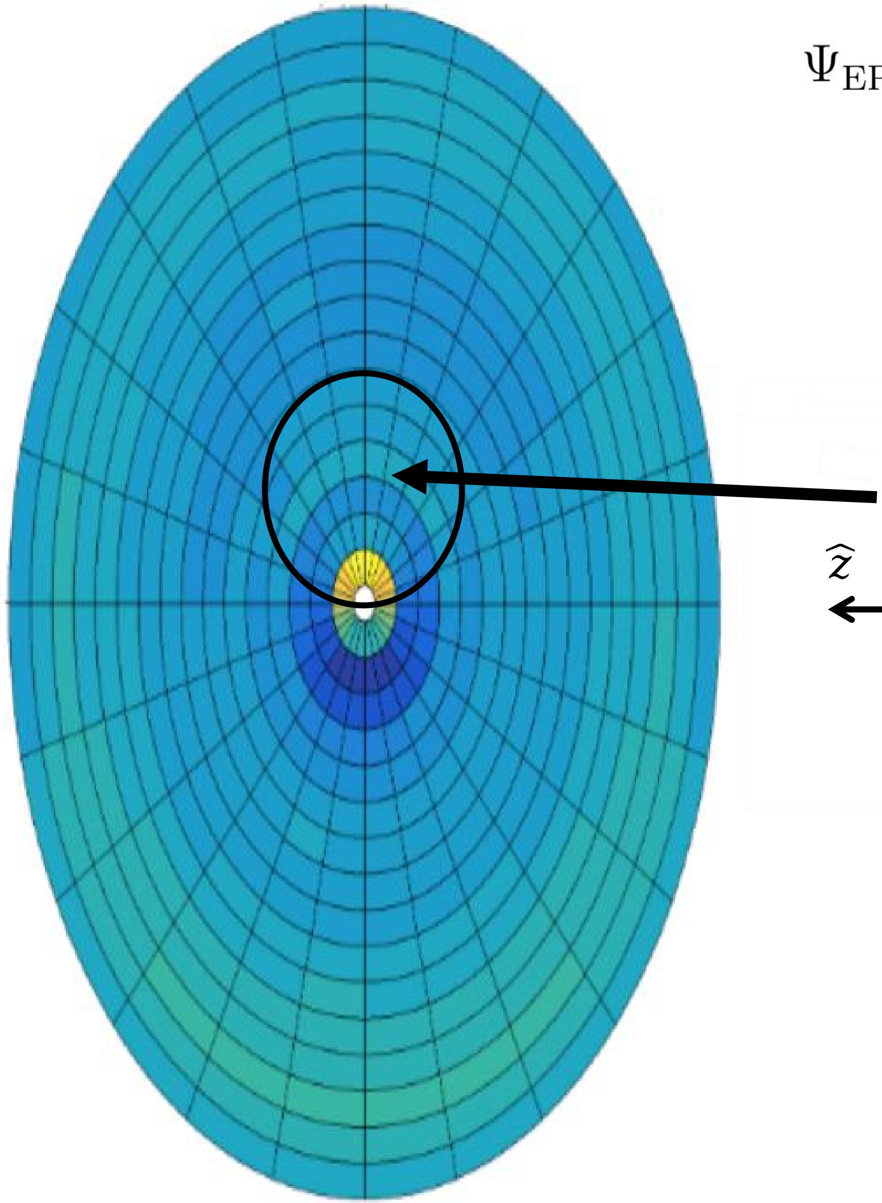
- Non-central nuclear collisions carry large angular momentum, $\vec{J} = \vec{r} \times \vec{p}$
- Hadron spin alignment, $\overline{\mathrm{P}}_{\mathrm{H}}$, with $\vec{J}$ via parton scattering (spin-orbit coupling)
- In hydro, fluid cells are considered and thermal vorticity is calculated
  - $\varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right), \quad \beta = \frac{u(x)}{T}$
- ω is transferred to hadron spin under the assumption of local thermodynamic equilibrium
  - Cooper-Frye formula



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

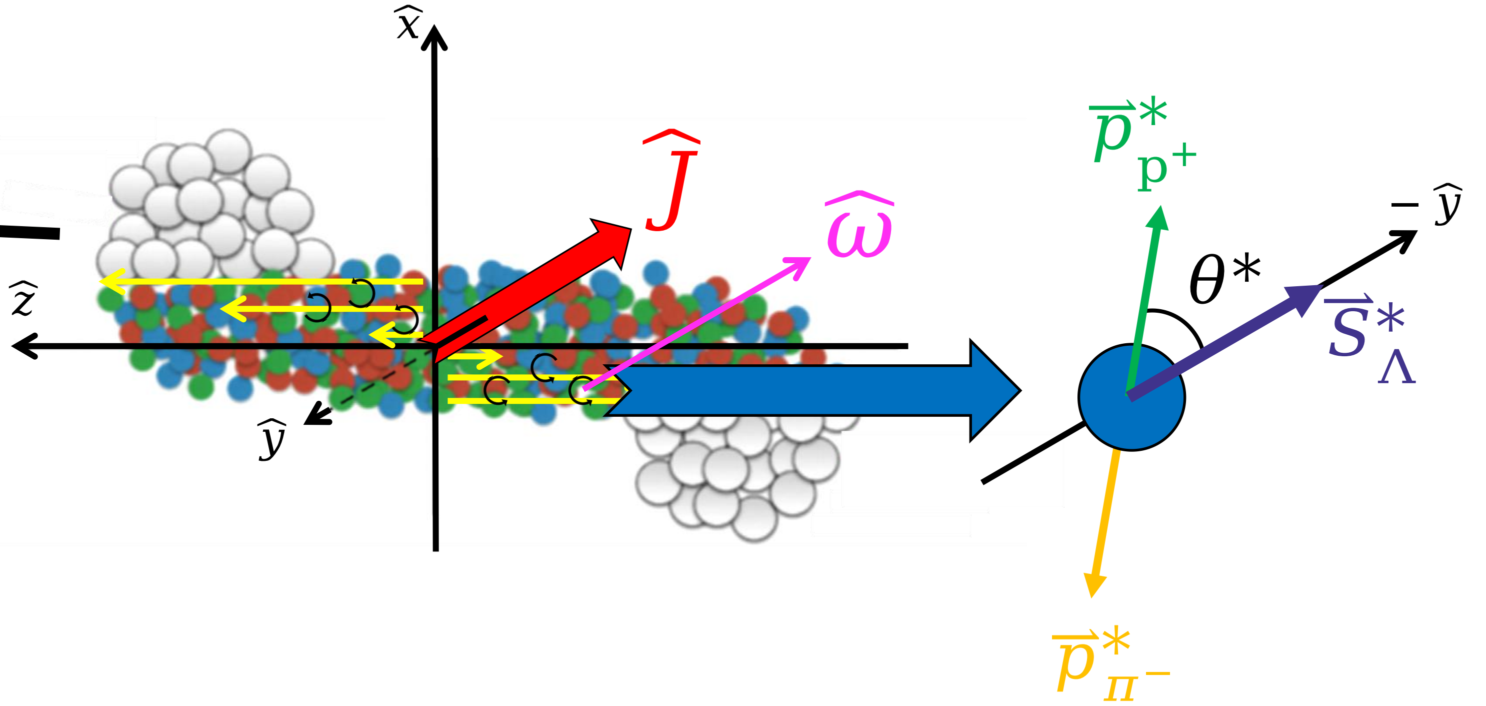


Becattini F, Csernai L, Wang DJ. Phys. Rev. C 88 034905 (2013), Erratum: Phys. Rev.C 93 6 069901(2016)



$$\Psi_{\mathrm{EP},1} = \mathrm{atan2}\left(\sum_i w_i \sin\phi_i, \sum_i w_i \cos\phi_i\right)$$

“First-order event-plane angle”



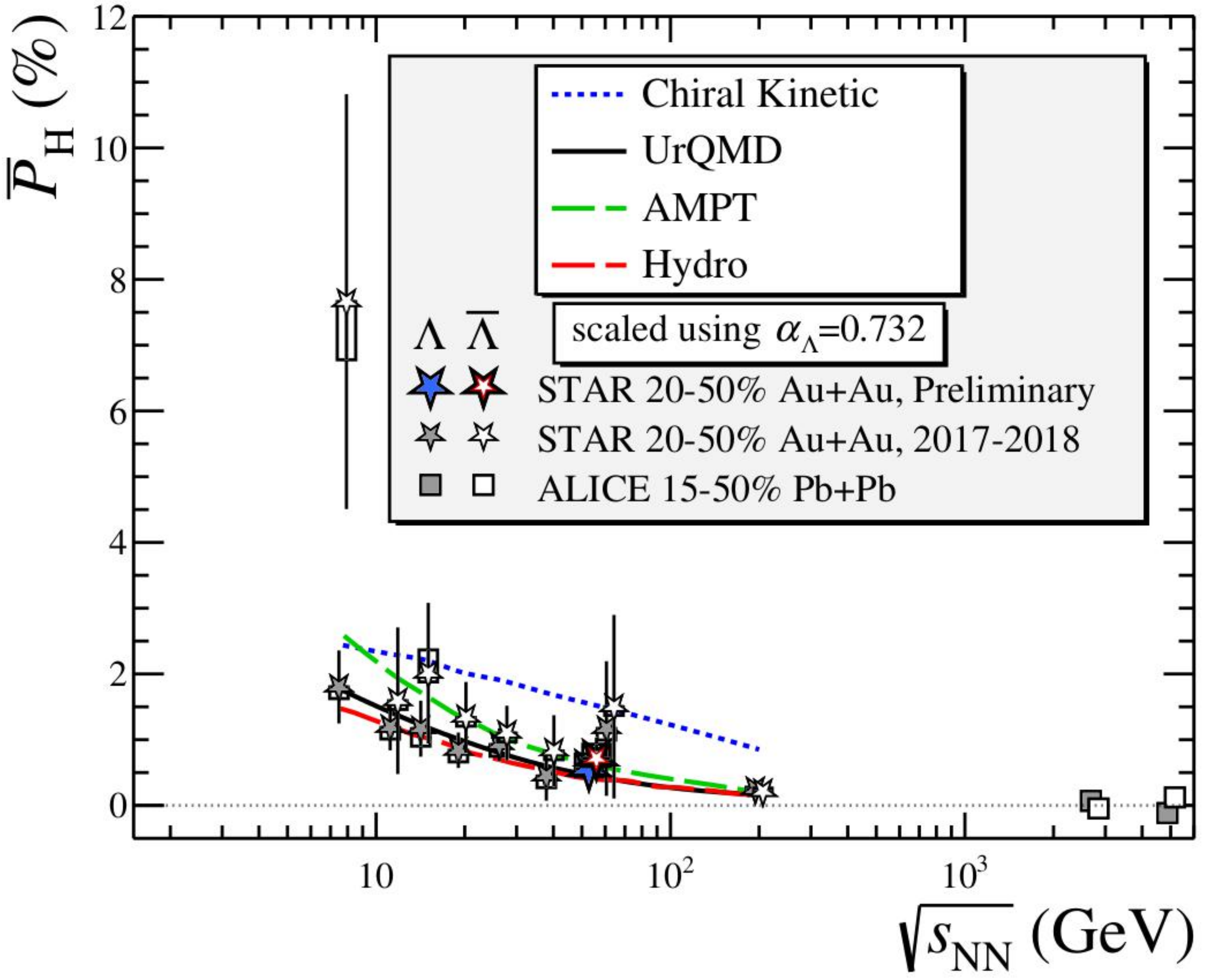
* indicates Λ rest frame

$$\sin\left(\Psi_1 - \varphi_p^*\right)$$

Correlation of interest

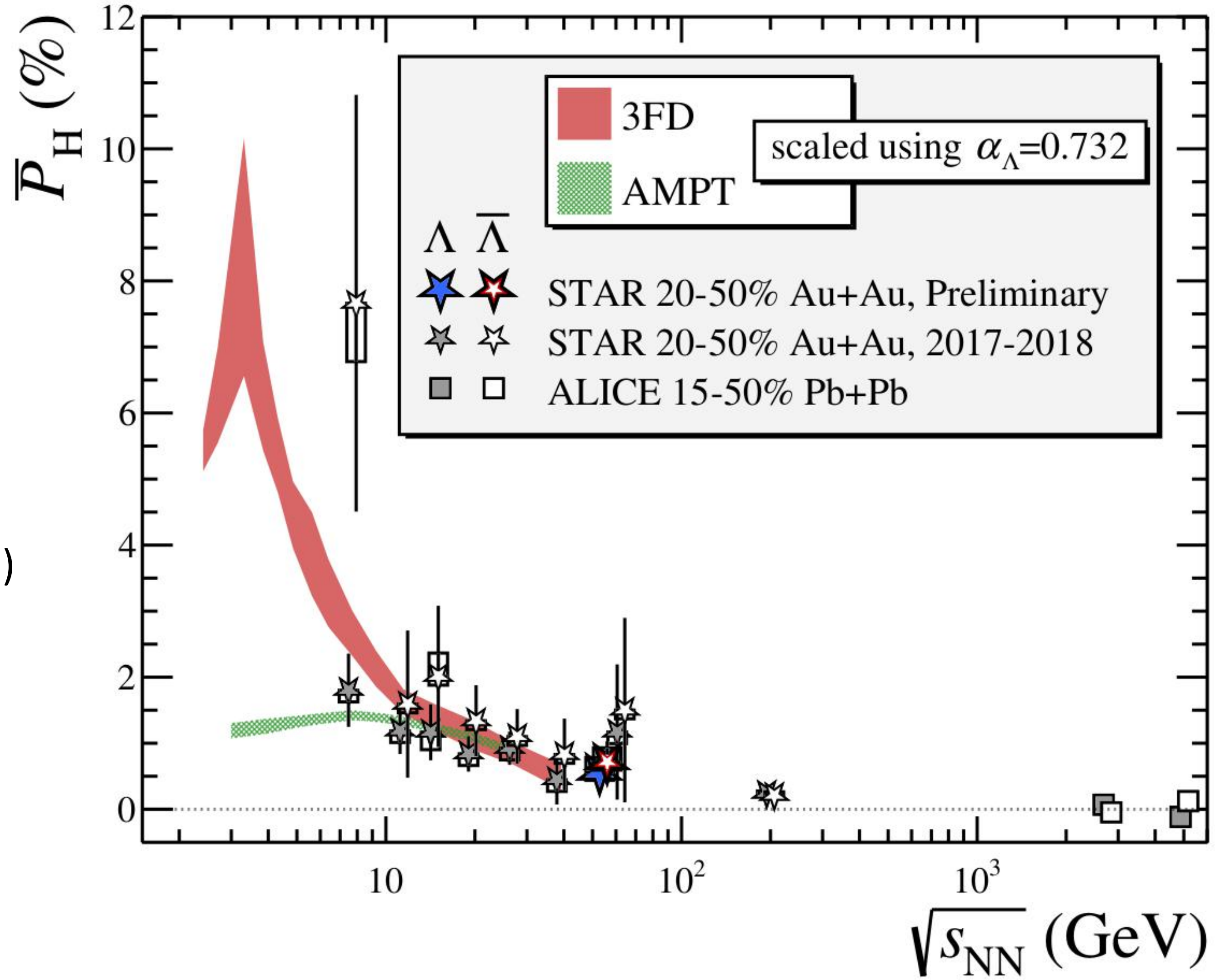
Initial measurements

- Measurements by STAR and ALICE showed significant $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$, decreasing with $\sqrt{s_{\mathrm{NN}}}$
- The trend is reproduced by numerous model *pre*dictions
  - Viscous hydro: I. Karpenko, F. Becattini, Eur. Phys. J. C77:213 (2017)
  - Partonic transport: H. Li, *et. al.* Phys. Rev. C96:054908 (2017)
  - Hadronic transport: O. Vitiuk, *et. al.* Phys. Lett. B 803 135298 (2020)
  - Chiral-kinetic transport: Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)
  - *New confirmation of equilibrium hydrodynamics!*
  - Previously limited to $\sqrt{s_{\mathrm{NN}}}$ > 7.7 GeV



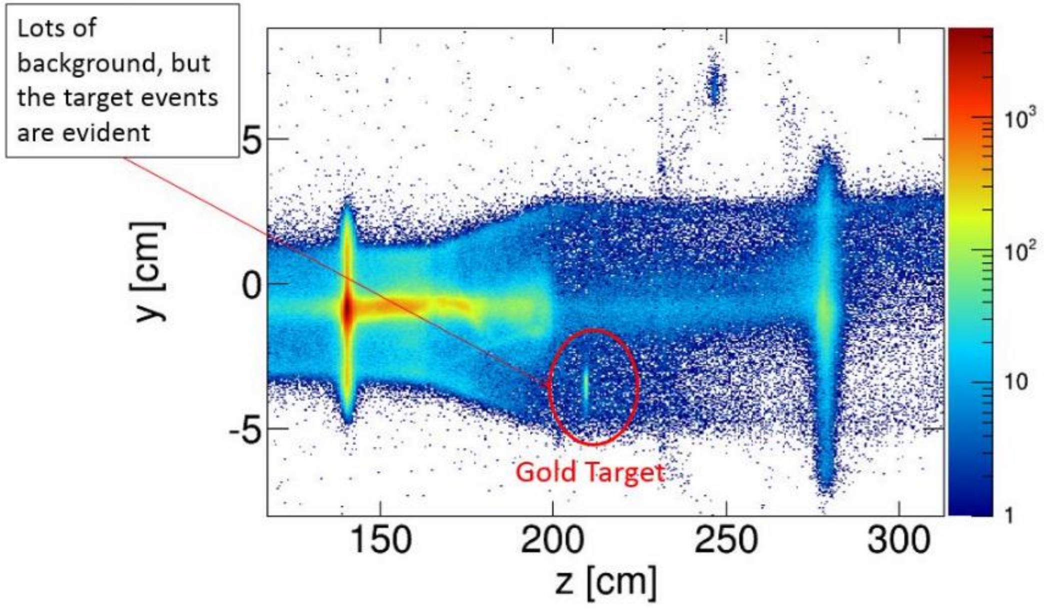
Recent model studies

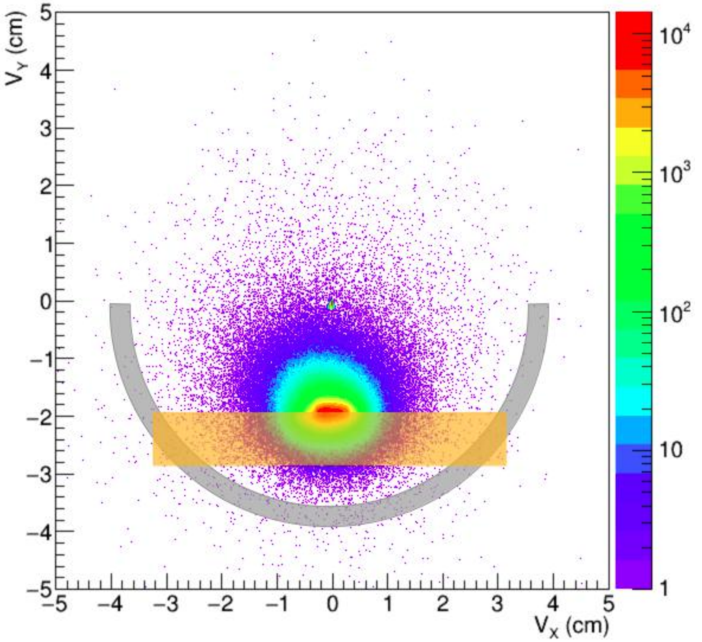
- Recent low-energy model studies don't agree on the energy of $\overline{\mathrm{P}}_{\mathrm{H,\ max}}$ or its magnitude below $\sqrt{s_{\mathrm{NN}}} \approx 10$ GeV
  - UrQMD: Y. Guo, *et. al.* Phys. Rev. C 104 4 L041902 (2021) arXiv:2105.13481
  - AMPT: X.G. Deng, *et. al.*, Phys. Rev. C 101, 064908 (2020), arXiv:2001.01371
  - 3-Fluid: Y.B. Ivanov, Phys. Rev. C 103, L031903 (2021) arXiv:2012.07597
- $\overline{\mathrm{P}}_{\mathrm{H}}$ measurements at low $\sqrt{s_{\mathrm{NN}}}$ will provide constraints on the set of assumptions valid at low collision energy

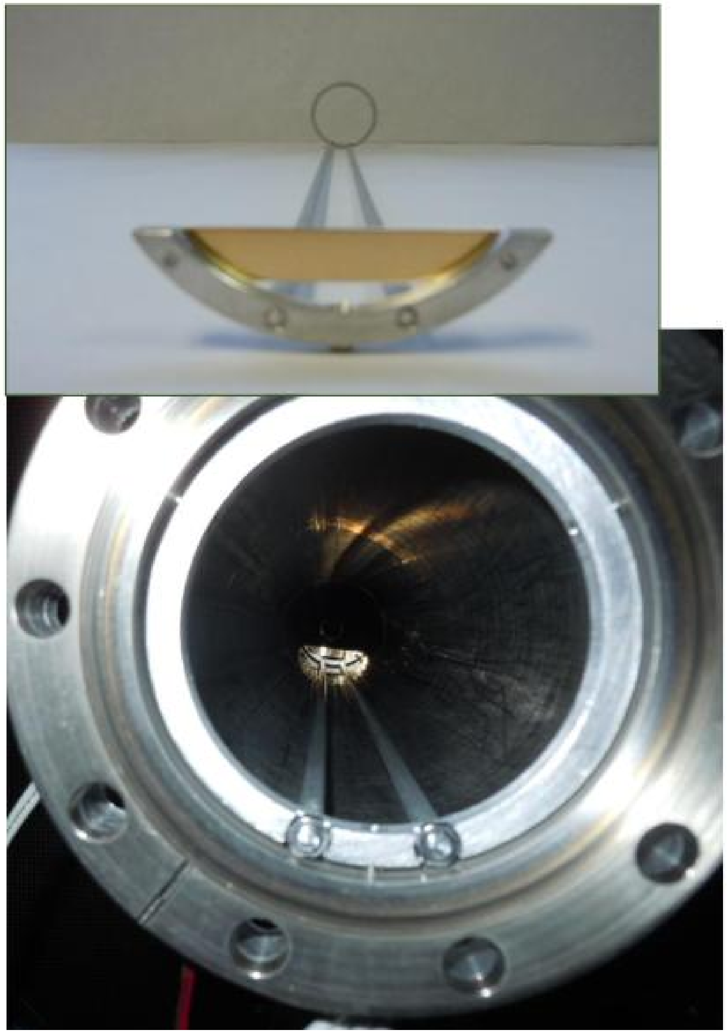


Fixed-target collisions in STAR

- A gold target was installed within the beam pipe allowing fixed-target collisions at energies extending below 7.7 GeV
- High-statistics data sets at $\sqrt{s_{\mathrm{NN}}} = 3,\ 7.2$ GeV

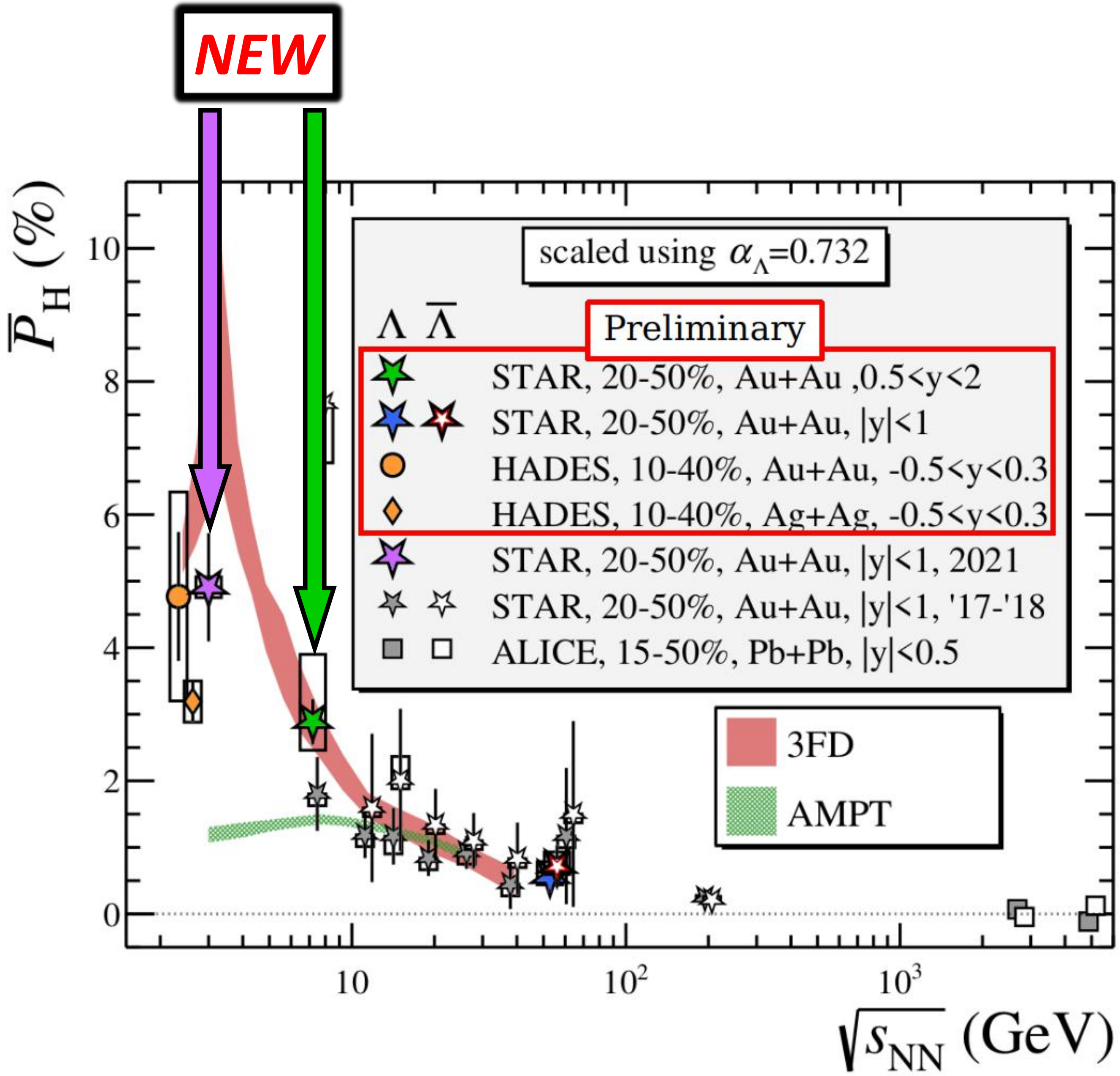






Fixed-target results

- At $\sqrt{s_{\mathrm{NN}}} = 7.2$ GeV we measure $\overline{\mathrm{P}}_{\mathrm{H}}$ consistent with 3FD
  - Rapidity range is not consistent
- At $\sqrt{s_{\mathrm{NN}}} = 3$ GeV we see the trend of increasing $\overline{\mathrm{P}}_{\mathrm{H}}$ persist
  - The hadron gas supports enormous ω at low $\sqrt{s_{\mathrm{NN}}}$
  - The magnitude is consistent with 3-Fluid Dynamics (3FD)
    - System evolves hydrodynamically
- More model studies needed

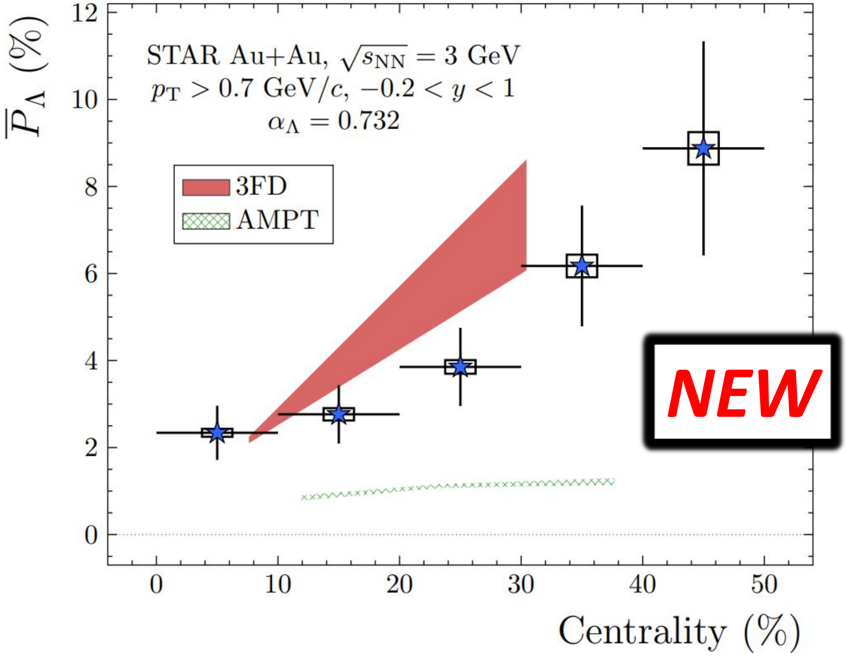


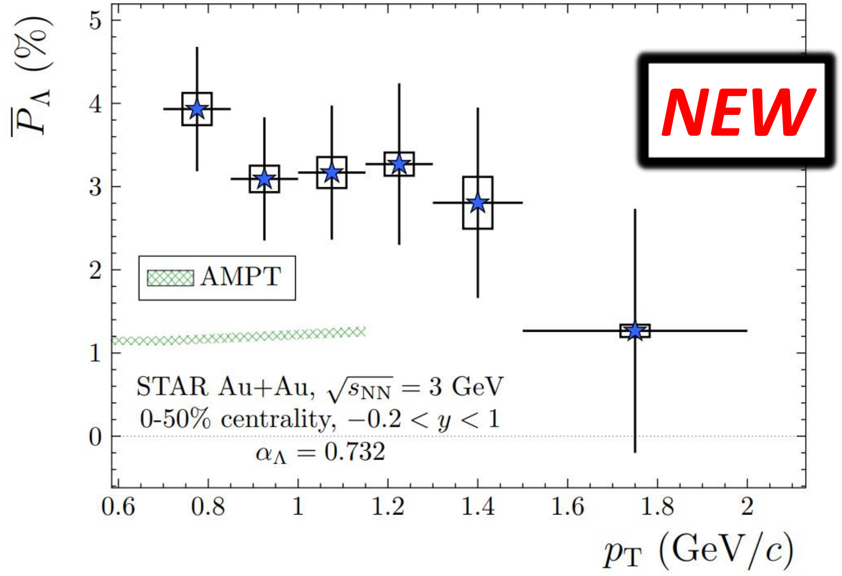
p_T and centrality dependence

- $\overline{\mathrm{P}}_{\mathrm{H}}$ increases with centrality
  - Consistent with angular-momentum-driven phenomenon
- No observed dependence on p_T
- Both measurements qualitatively agree with previous studies

3 GeV

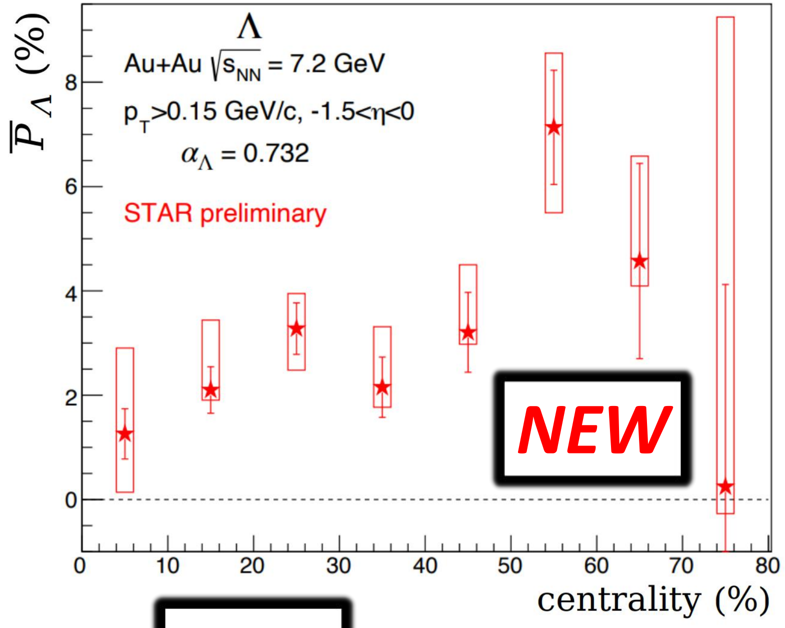
STAR, Phys. Rev. C, 104(6):L061901, 2021

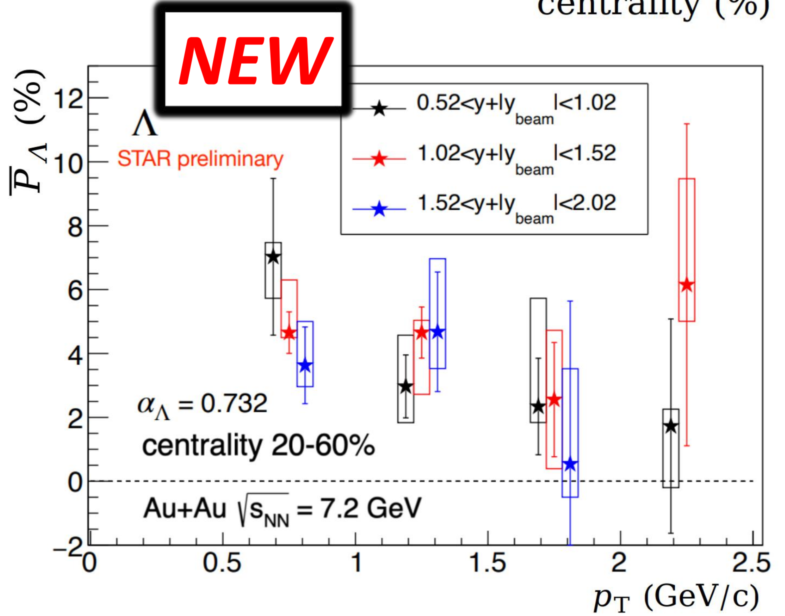




7.2 GeV

Kosuke Okubo, Poster Session 2 T02

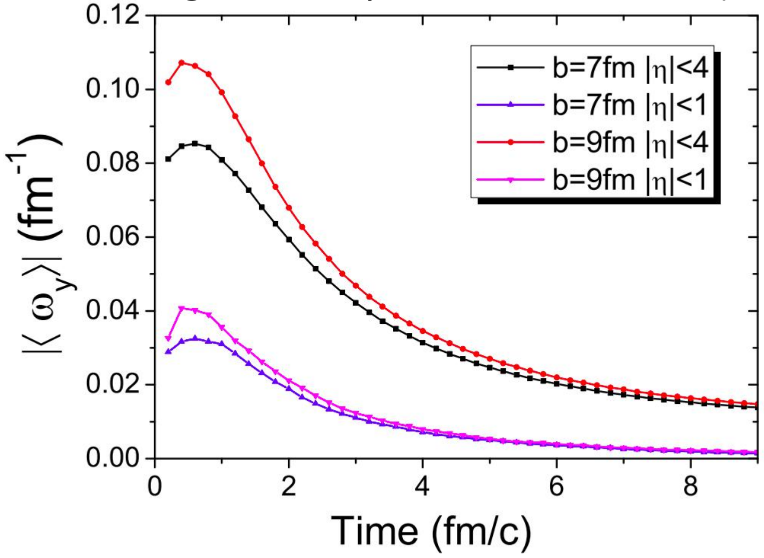




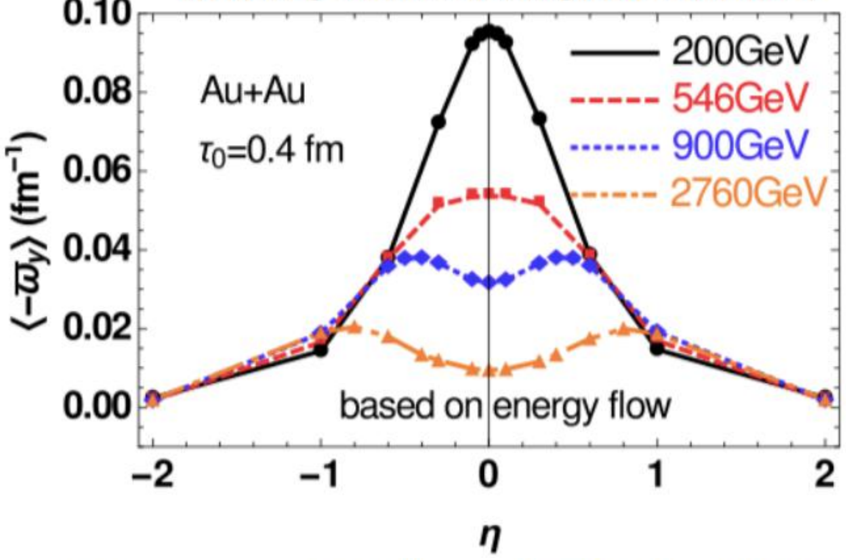
y dependence

- Numerous models predict strong dependence on y
- Previous studies found no dependence, but did not have access to forward rapidity
- These low-energy data sets give us the unique opportunity to study $\overline{\mathrm{P}}_{\mathrm{H}}$ to the limits of Λ production in y

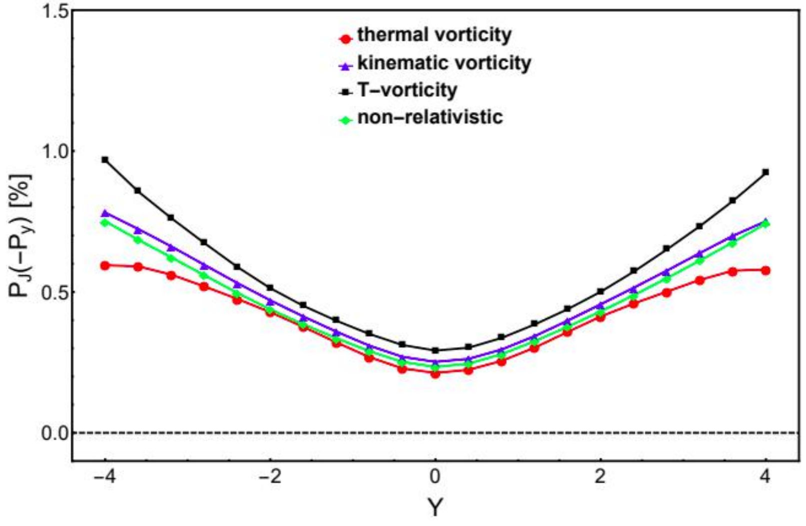
Y. Jiang, *et al.*, Phys. Rev. C 94, 044910 (2016)



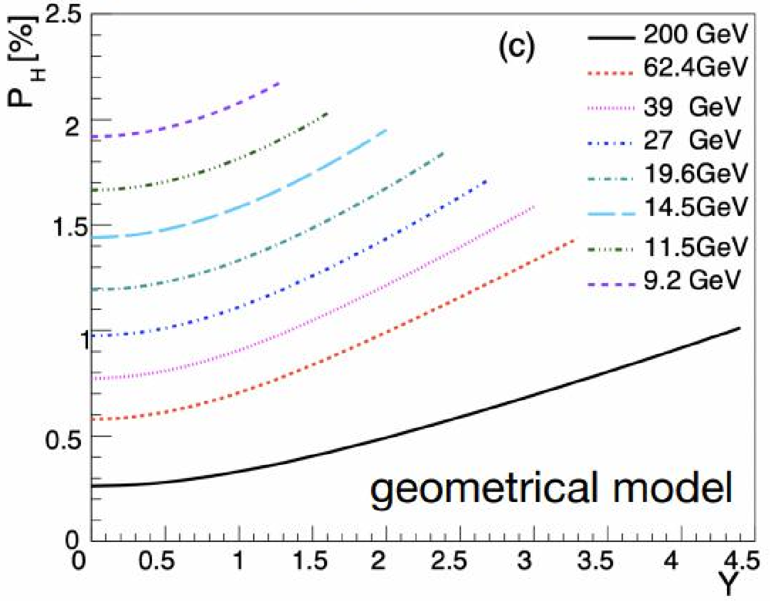
W.-T.Deng and X.-G Huang:PRC93,064907



H.-Z. Wu, *et al.* , PR Research. 1, 033058 (2019)



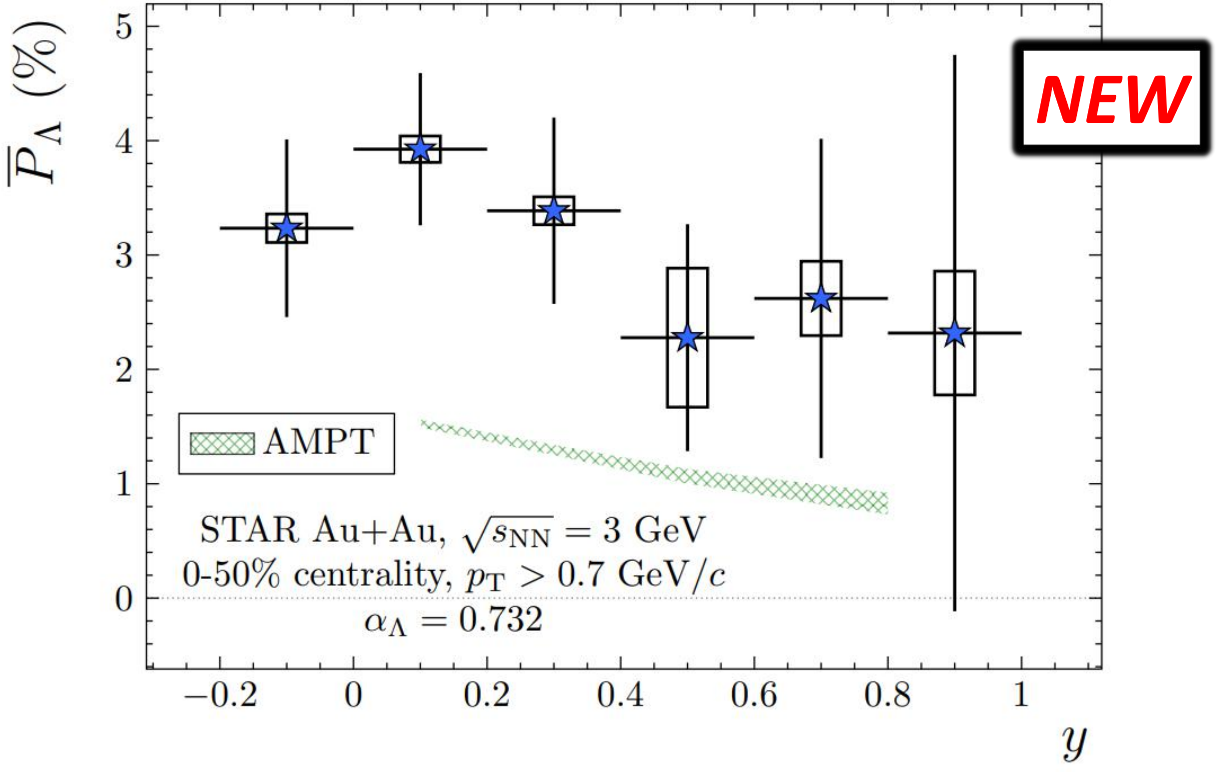
Z.T.Liang et al., Chin.Phys.C 45 (2021) 1, 014102



y dependence

- Within uncertainties no such dependence is observed
  - Uncertainties grow at forward rapidity and a dependence can't be ruled out
  - Future STAR measurements will help provide insight

STAR, Phys. Rev. C, 104(6):L061901, 2021



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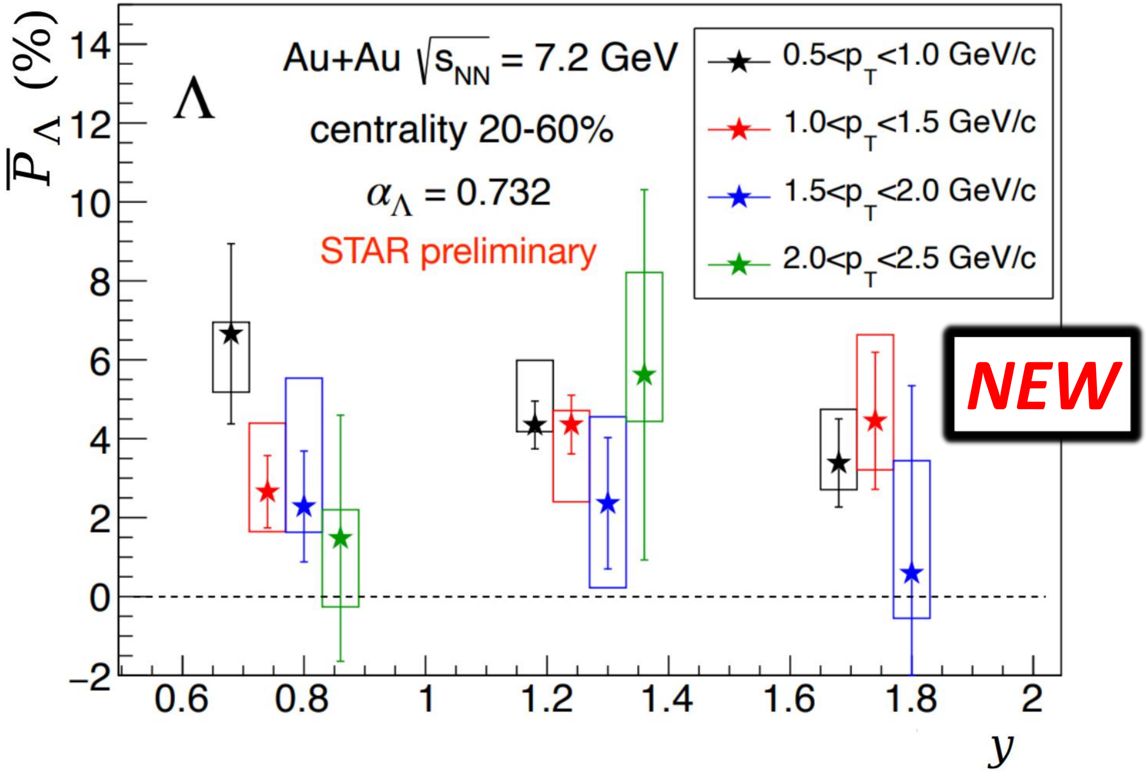
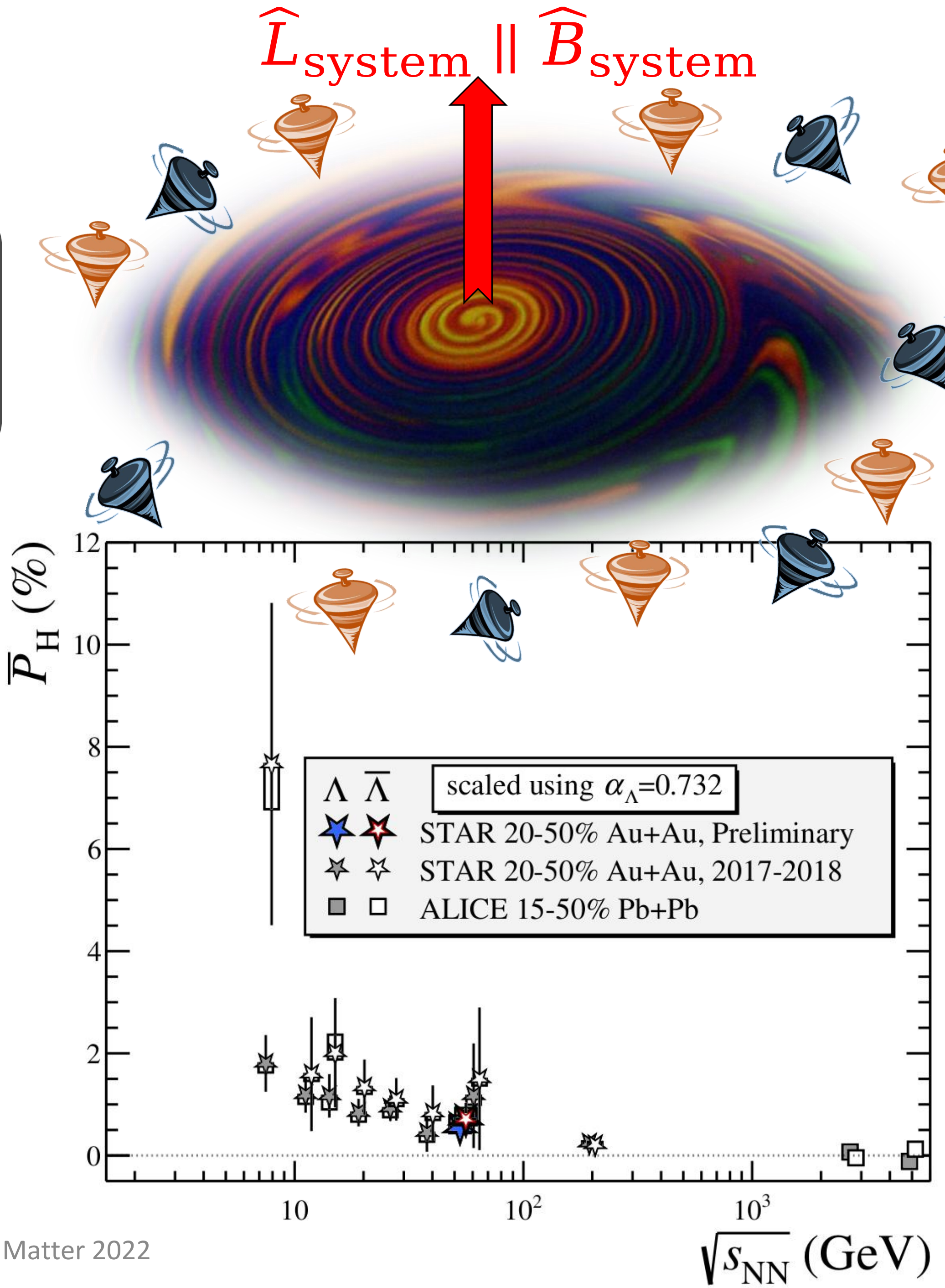


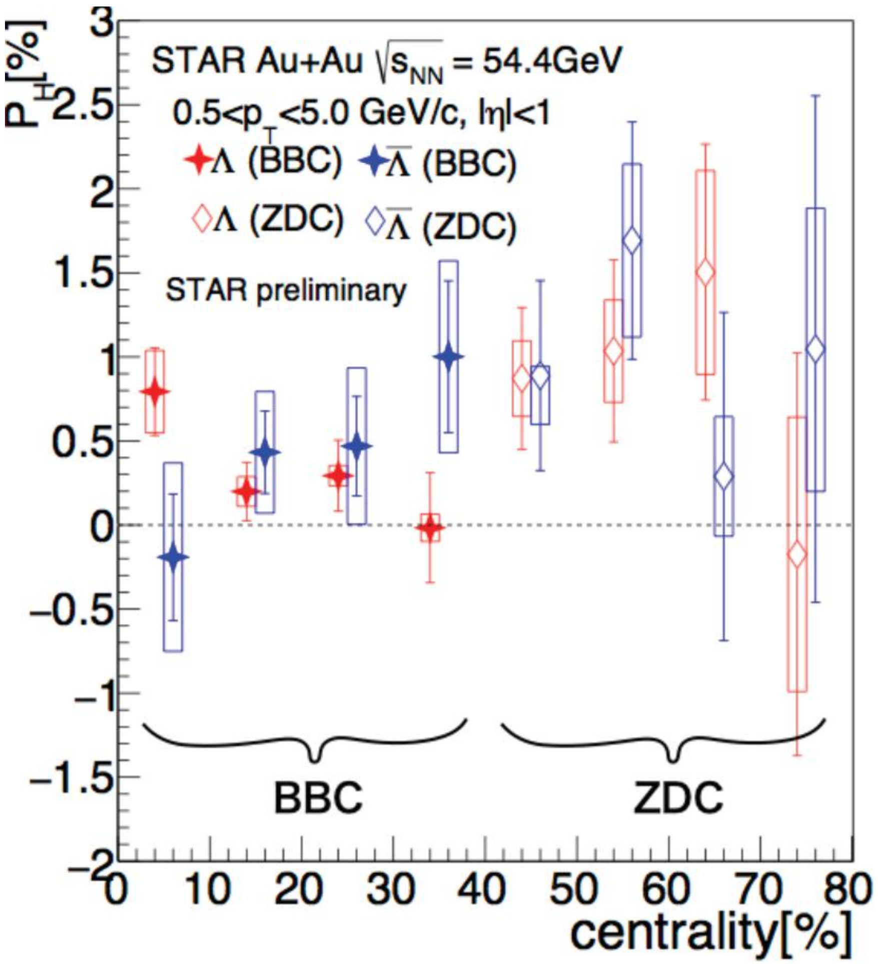
Magnetic-field observable

- Vorticity gives positive contribution to P_{Λ} *and* $\mathrm{P}_{\overline{\Lambda}}$
- $|\vec{B}|$ enhances $\mathrm{P}_{\overline{\Lambda}}$ and suppresses P_{Λ}
  - $(\vec{\mu}_{B,\,\Lambda} = -\,\vec{\mu}_{B,\,\overline{\Lambda}})$
- We measure $|\vec{B}|$ via splitting between P_{Λ} and $\mathrm{P}_{\overline{\Lambda}}$
  - Late-stage magnetic field sustained by the QGP
- Suggested splitting in BES
  - ~2 sigma effect



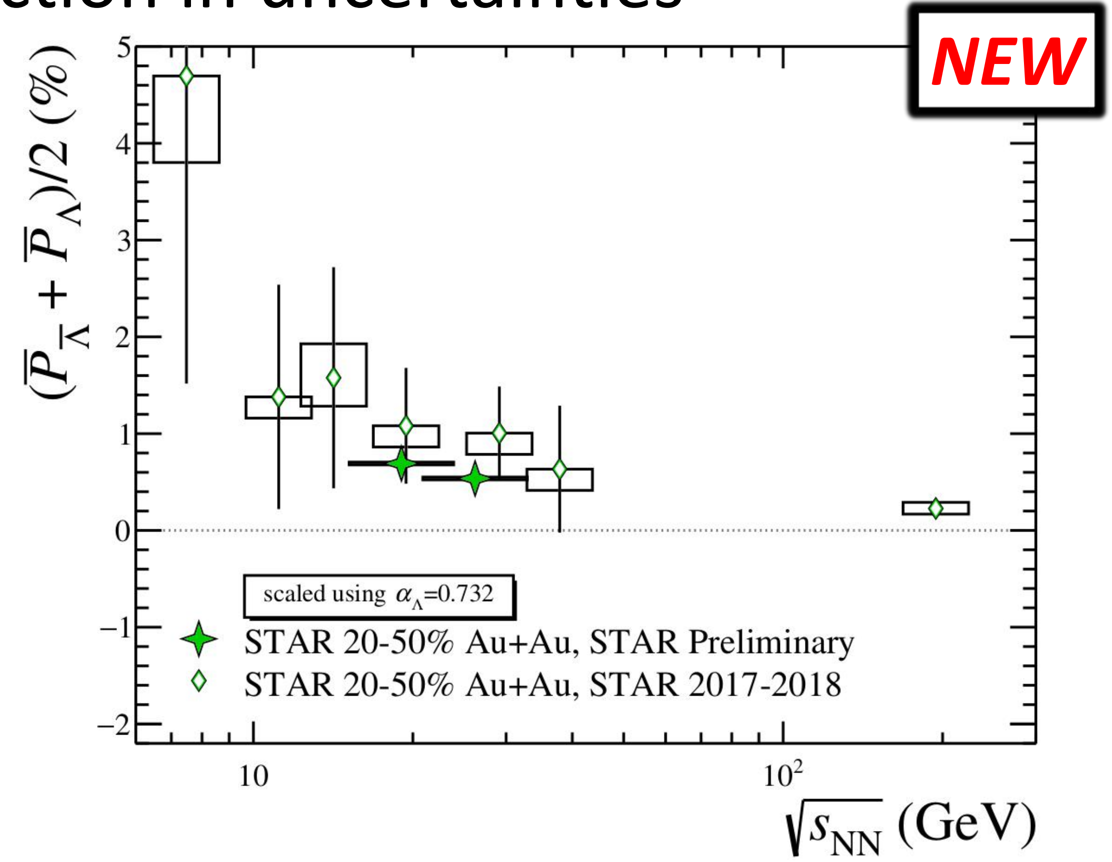
Magnetic-field observable: previous measurements

- Studies at $\sqrt{s_{\mathrm{NN}}} = 54.4,\ 200$ GeV show no splitting
- High-statistics data sets taken by STAR at $\sqrt{s_{\mathrm{NN}}} = 19.6,\ 27$ GeV will allow for a statistically significant study of any such splitting suggested in previous measurements



Magnetic-field observable: new data sets

- The average polarizations and differential measurements are consistent with previous observations
- A factor of 10 reduction in uncertainties



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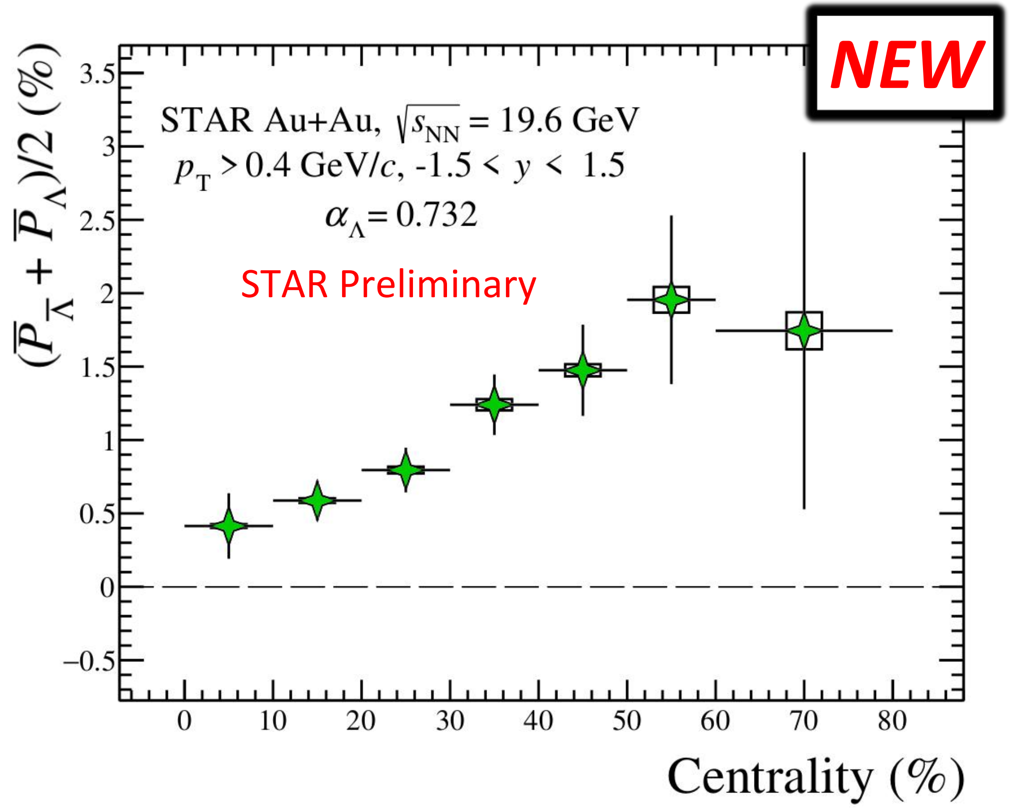

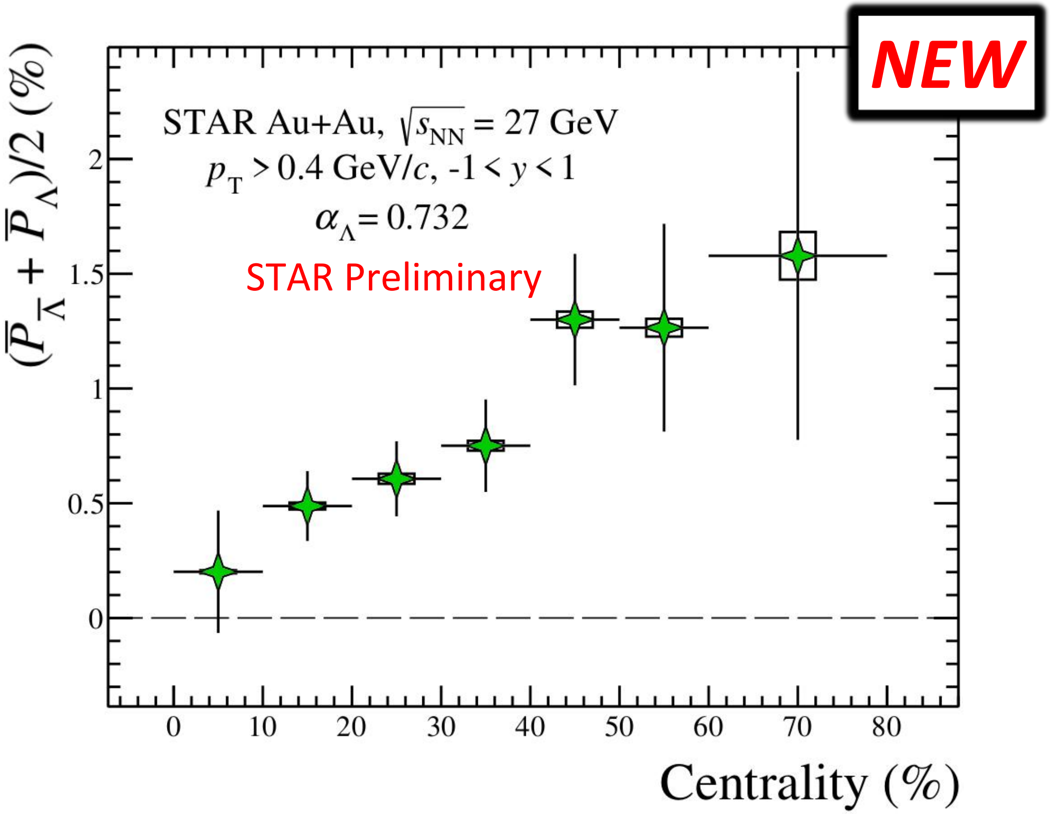

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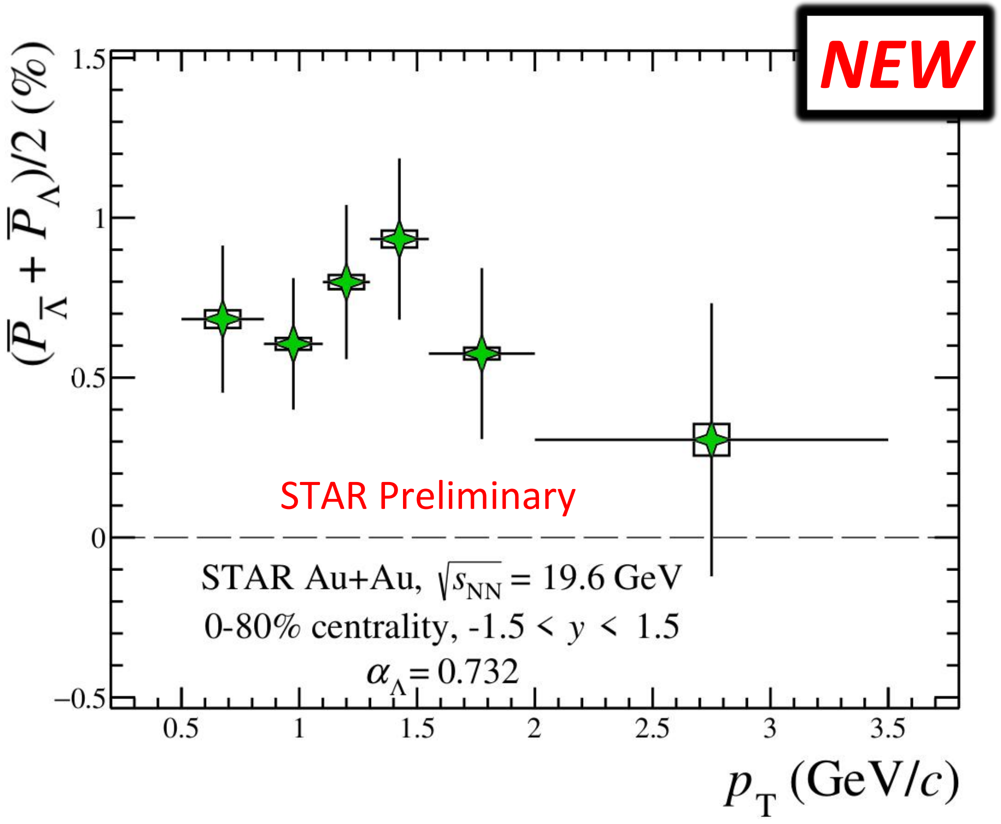

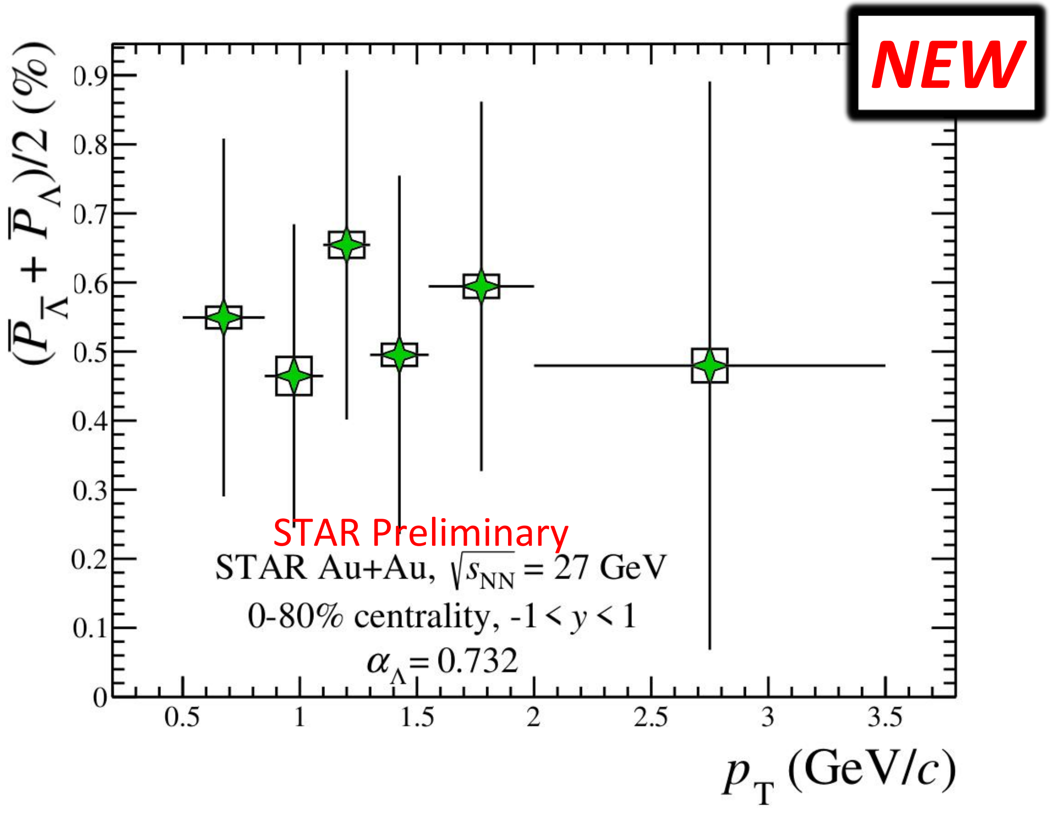

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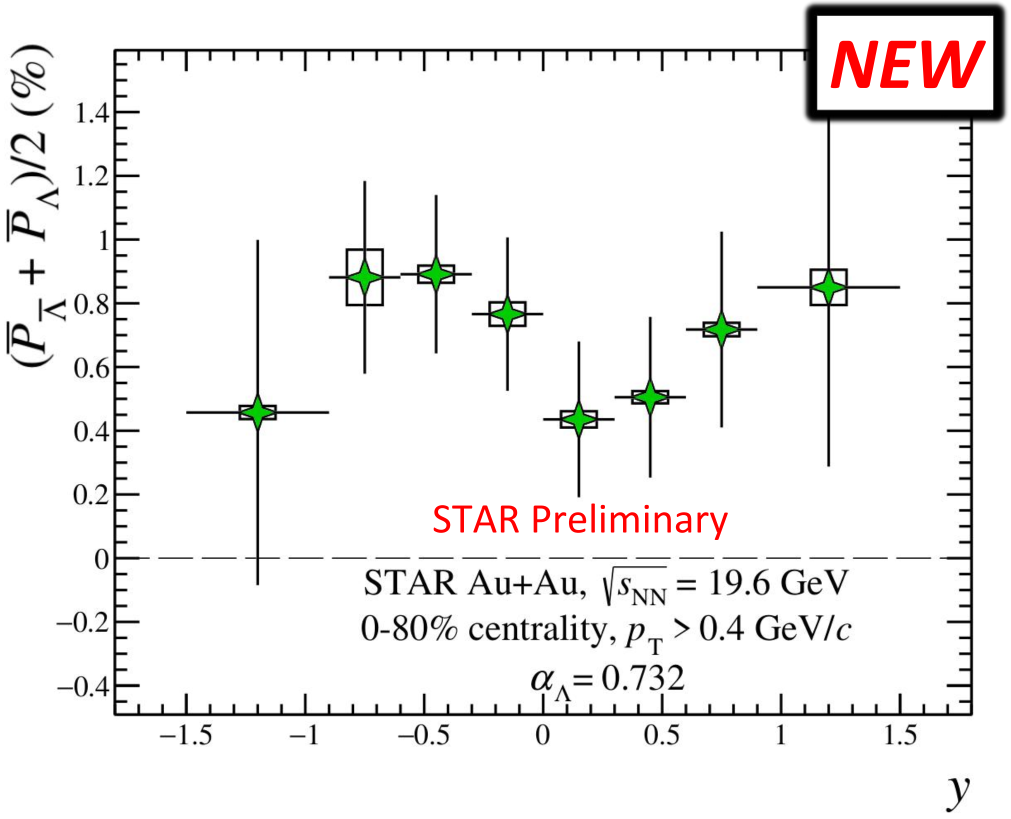
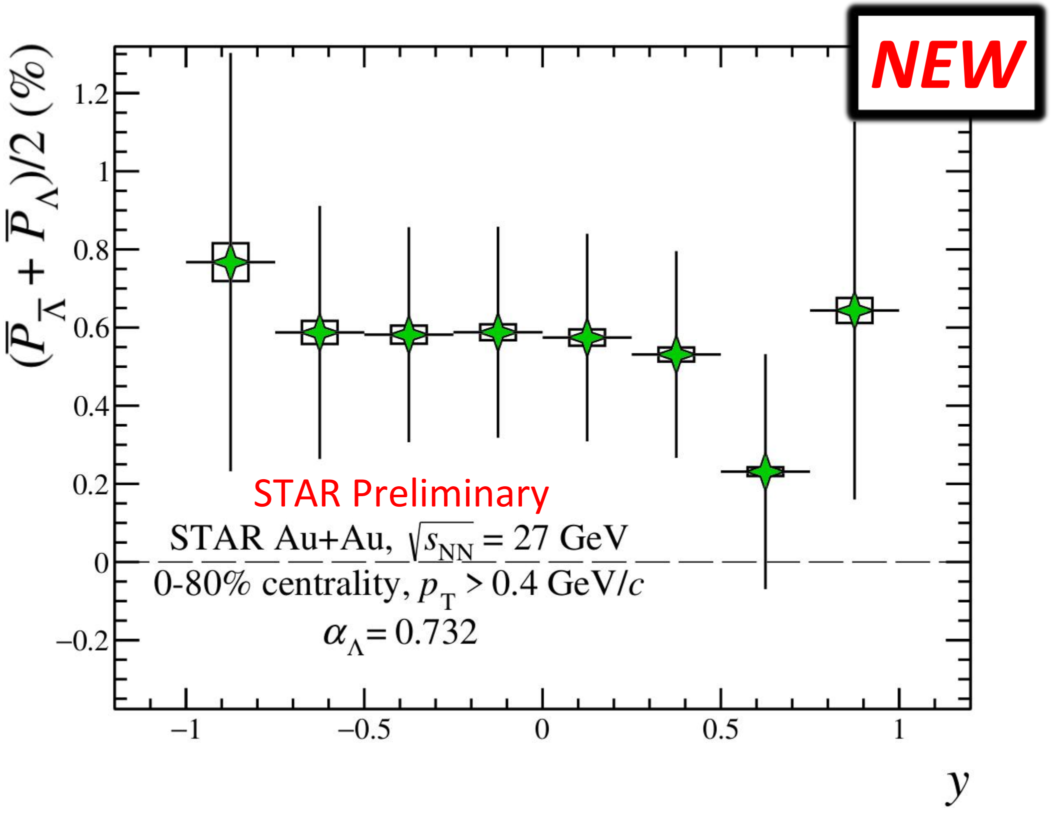
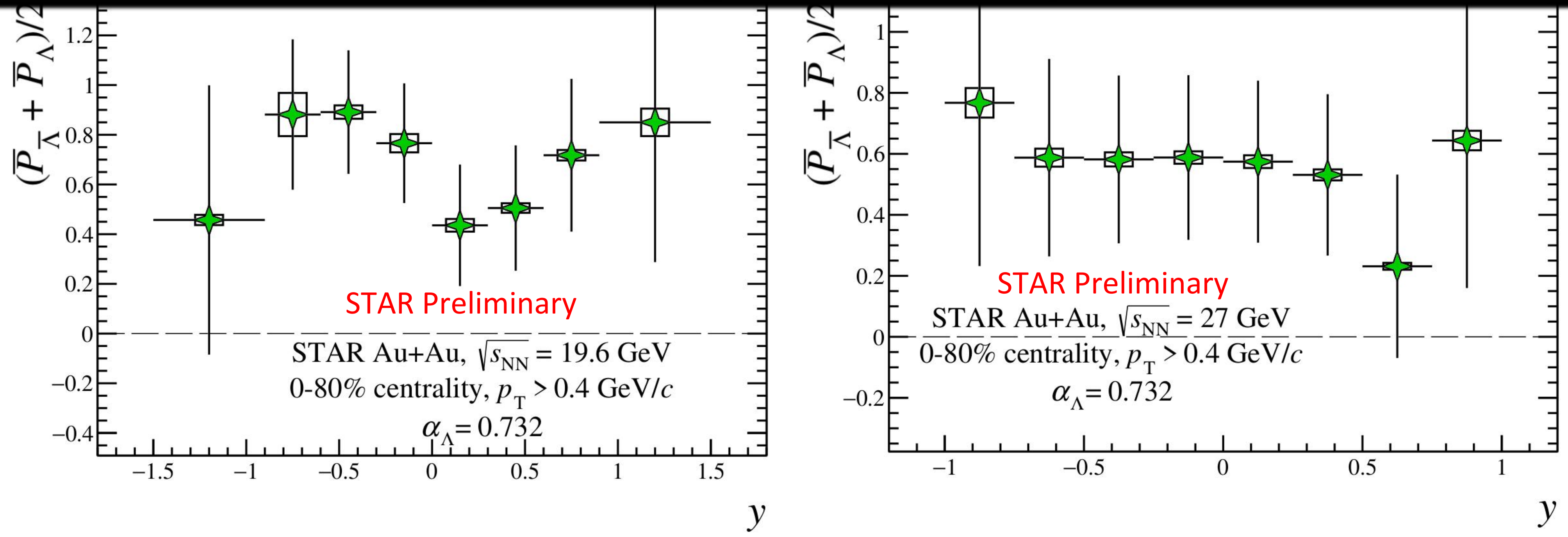




Magnetic-field observable: new data sets

- The average polarizations and differential measurements are consistent with previous observations
- A factor of 10 reduction in uncertainties

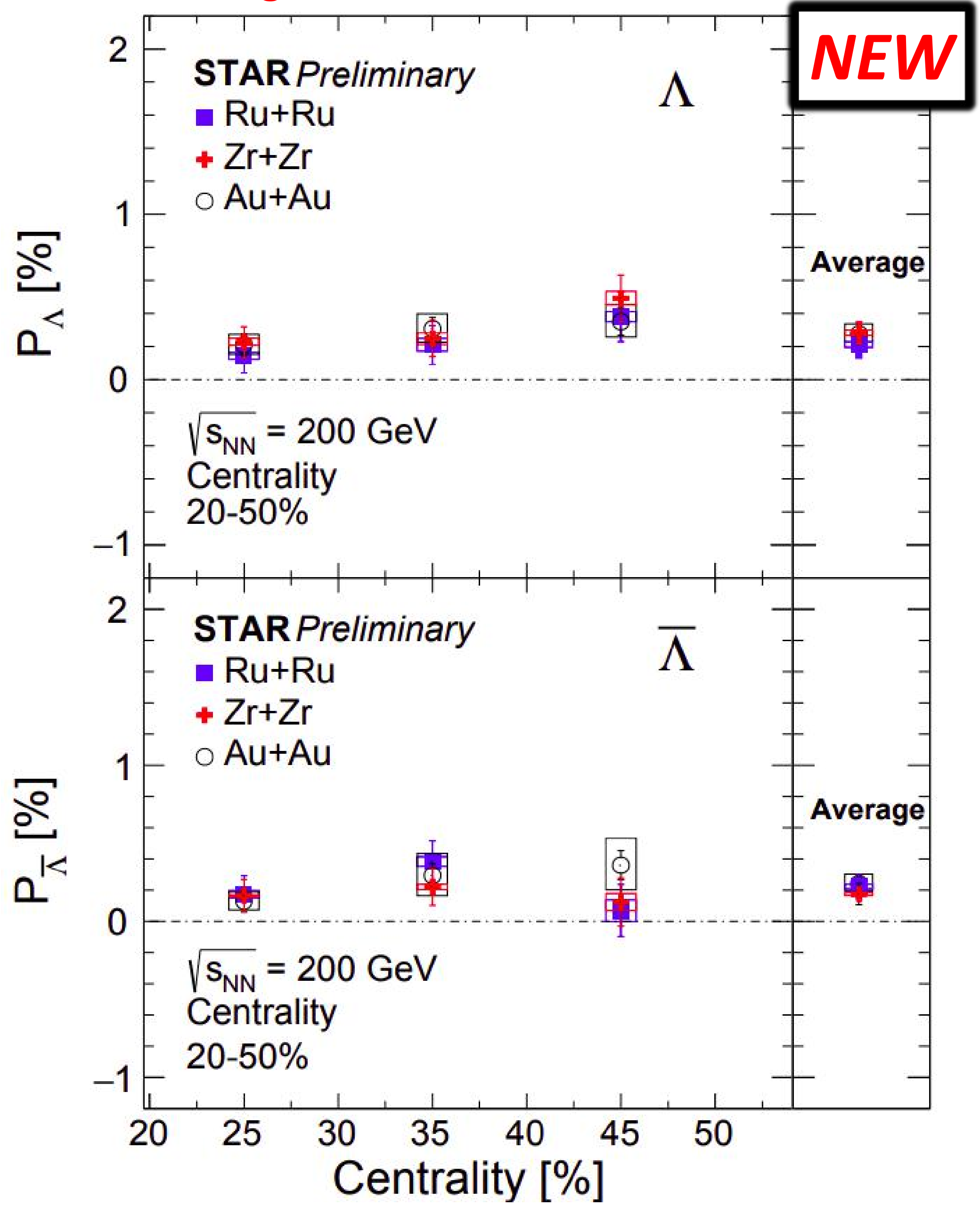
Results on splitting will be published soon!



Magnetic-field observable

- Evidence for a magnetic field may also be found in a difference between $\overline{P}_{\Lambda}$ and $\overline{P}_{\overline{\Lambda}}$ in Ru+Ru and Zr+Zr isobar data
  - Same system size
- STAR collected high-statistics data sets using these species at 200 GeV
- No significant difference is observed

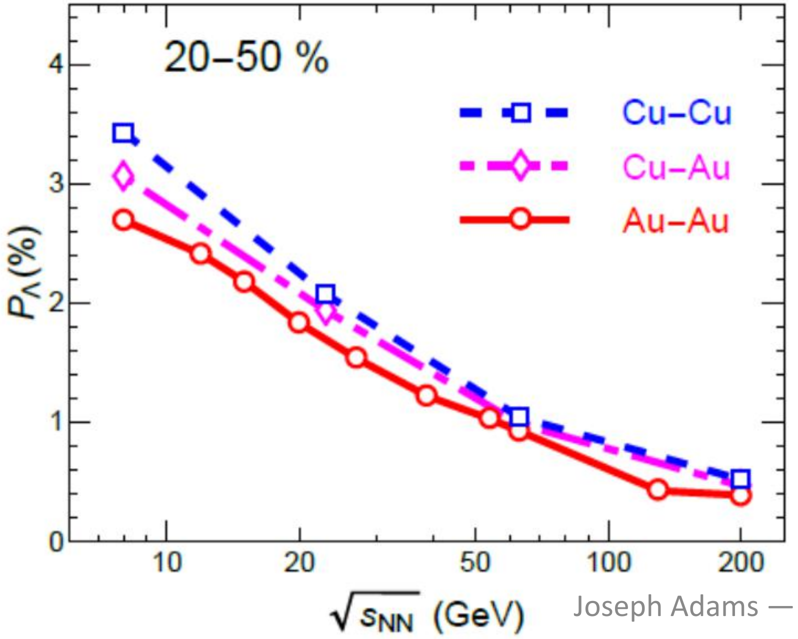
Xingrui Guo, Poster Session 2 T02



System-size dependence of $\overline{\mathrm{P}}_{\mathrm{H}}$

- Isobar data also allows us to study system size dependence
  - Model calculations suggest a decrease in $\overline{\mathrm{P}}_{\mathrm{H}}$ as system size becomes larger
- Integrated result shows no enhancement over previous measurement in Au+Au

S. Shi, K. Li, PLB 788 409413 (2019)



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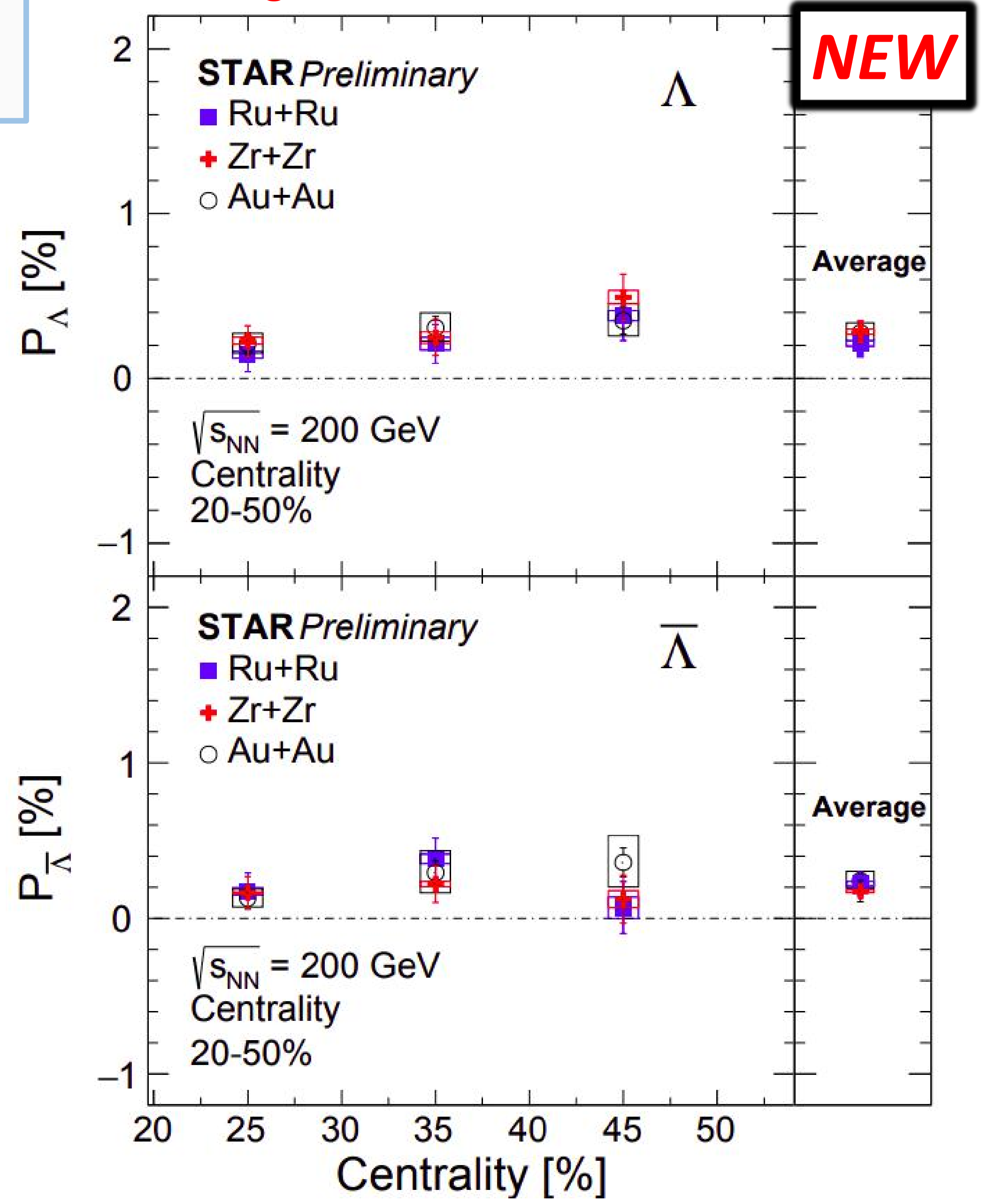
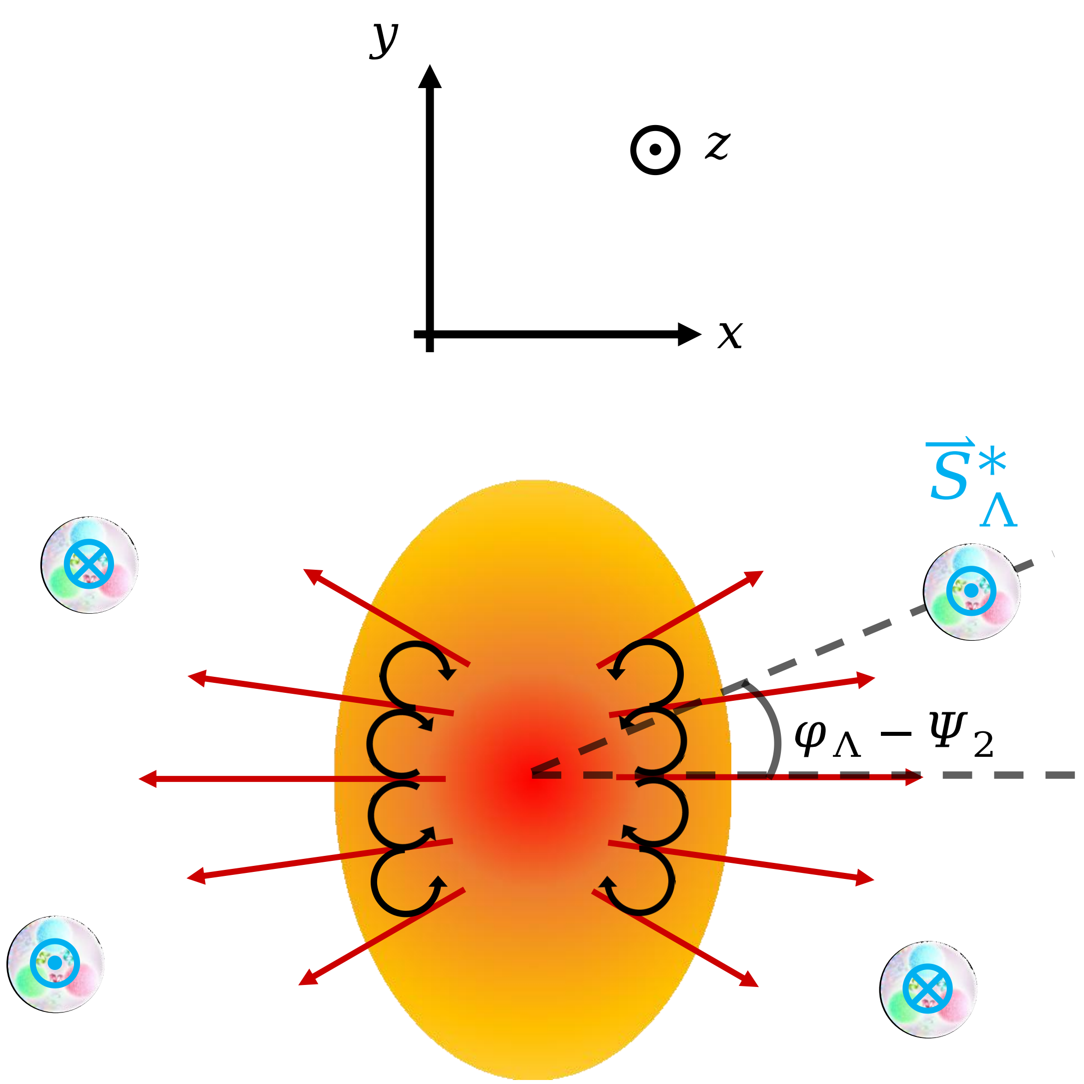


Longitudinal polarization

- We can expect $\overline{\mathrm{P}}_{\Lambda/\overline{\Lambda}}$ along $\hat{z}$, $\overline{\mathrm{P}}_z$, coming from flow-driven shear in the $\hat{x} - \hat{y}$ plane
  - Measure with $\langle \cos(\theta_p^*) \rangle$ as a function of $\varphi_{\Lambda/\overline{\Lambda}} - \Psi_2$
- Naïvely expect $\langle \cos(\theta_\mathrm{p}^*) \rangle \propto \sin(\varphi_{\Lambda/\overline{\Lambda}} - \Psi_2)$



Longitudinal polarization: previous measurement

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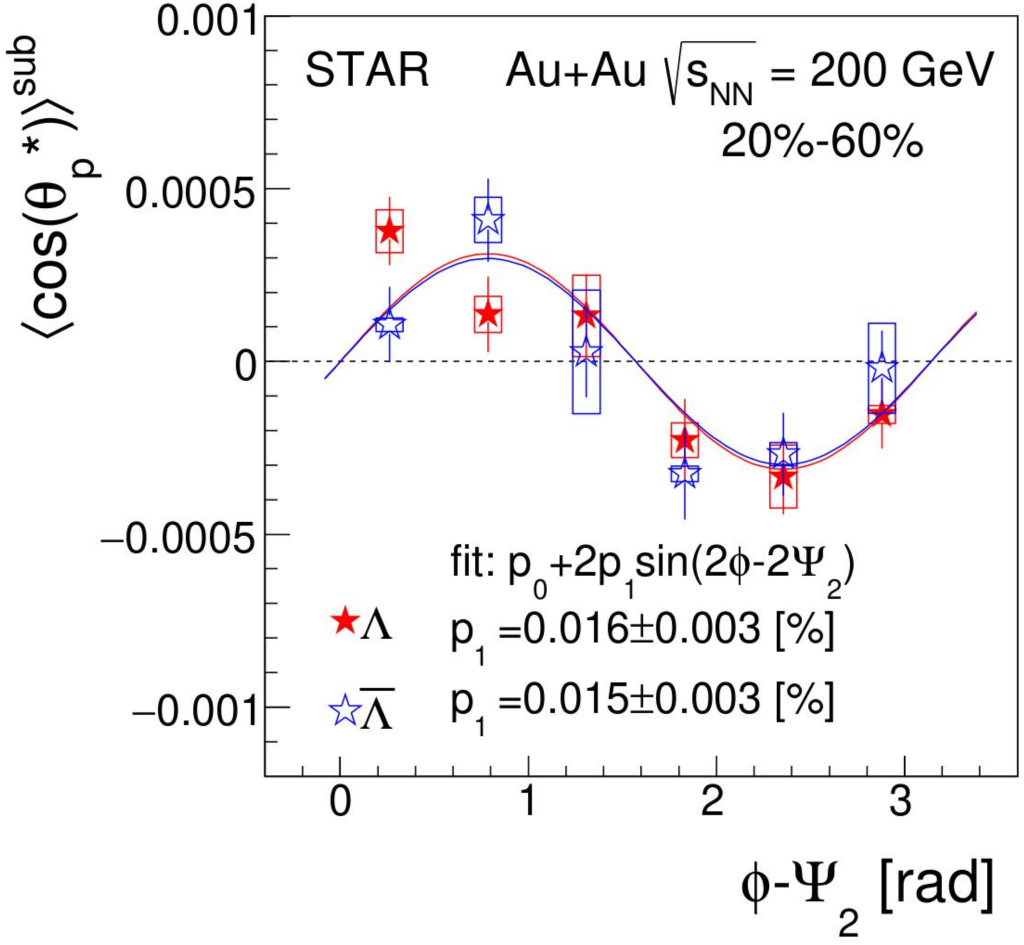
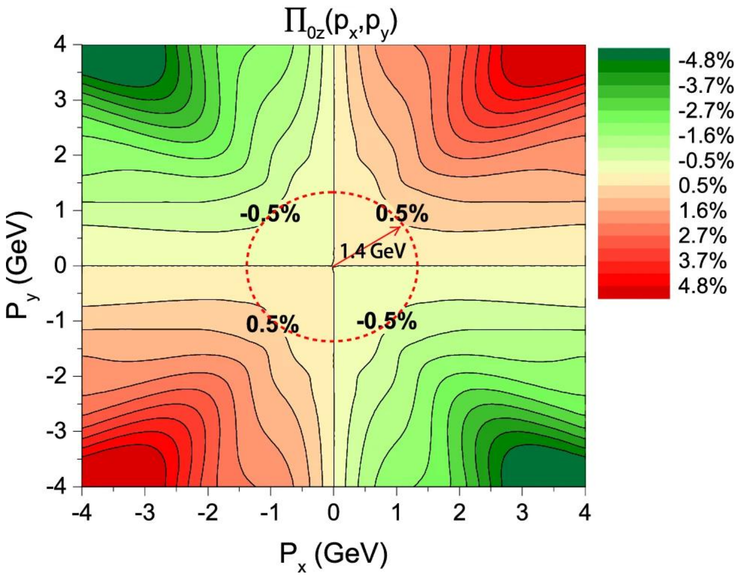
  - Measure with $\langle \cos(\theta_p^*) \rangle$ as a function of $\varphi_{\Lambda/\overline{\Lambda}} - \Psi_2$
- Naïvely expect $\langle \cos(\theta_{\mathrm{p}}^*) \rangle \propto \sin(\varphi_{\Lambda/\overline{\Lambda}} - \Psi_2)$
- Non-zero, sinusoidal $\overline{\mathrm{P}}_z$ measured by STAR in 2019

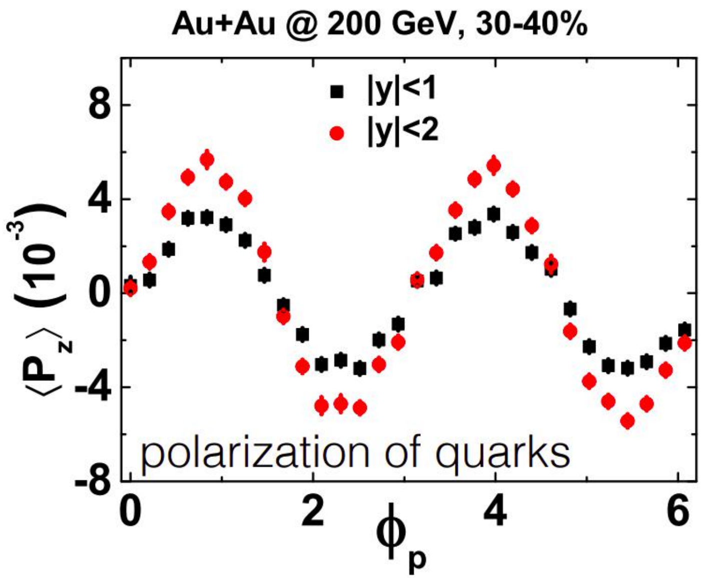
STAR, PRL 123 13201 (2019)



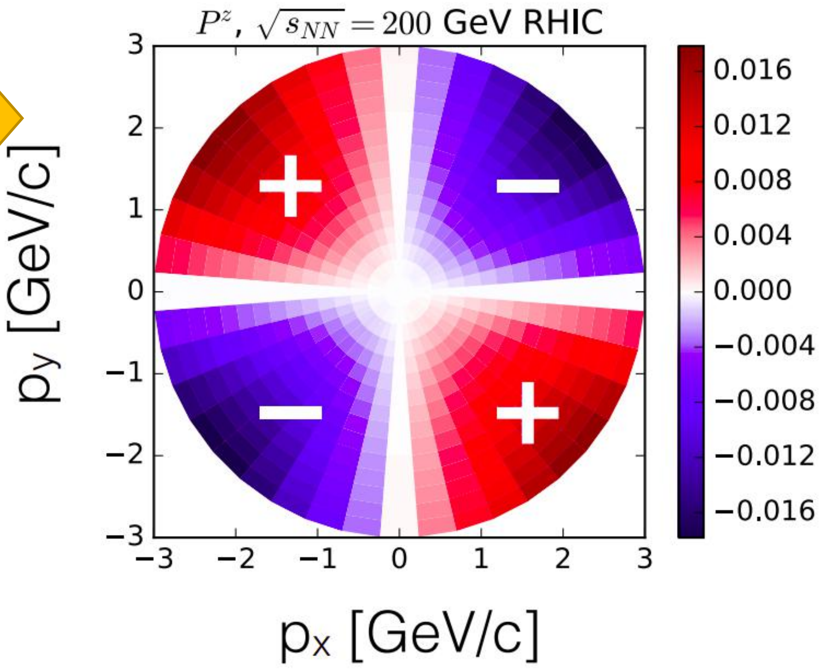
P_z: sign problem

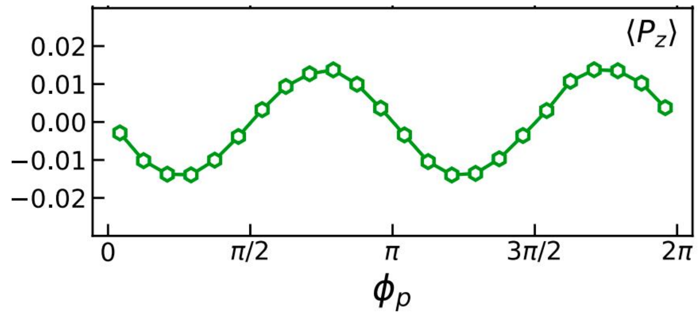
- Some model studies predicted this behavior with the correct sign
  - (3+1)D PICR hydro.: Y. Xie, *et. al.*, EPJ C 80, 39 (2020)
  - Chiral kinetic: Y. Sun, *et. al.*, PRC 99, 011903(R) (2019)





- Others predicted the incorrect sign
  - UrQMD+hydro: F. Becattini, *et. al.*, PRL.120.012302 (2018)
  - AMPT: X. Xia, *et. al.*, PRC98.024905 (2018)

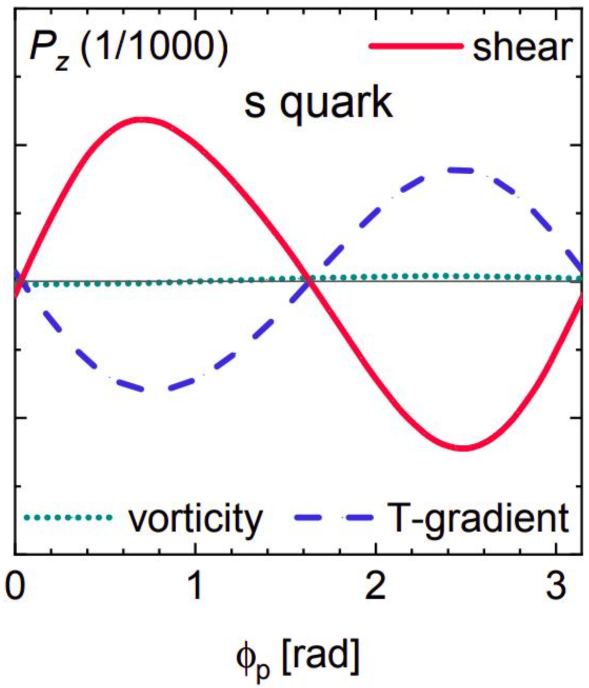




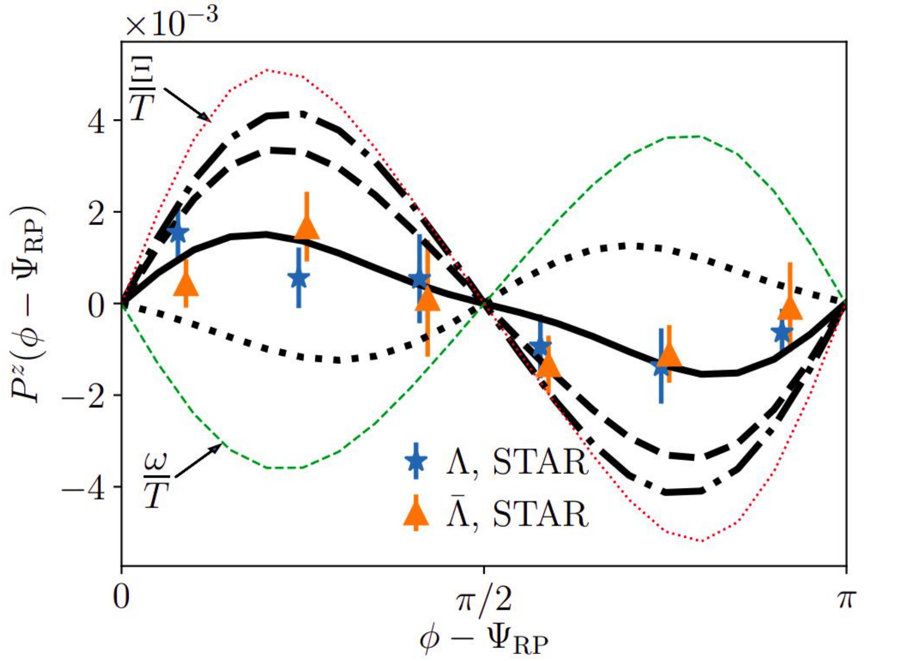
P_z: sign problem

- Recent considerations of a shear term may resolve these discrepancies
  - $\xi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu\right)$
- See also: Tuesday slides from T02

B. Fu, et al. PRL 127 (2021) 14, 142301



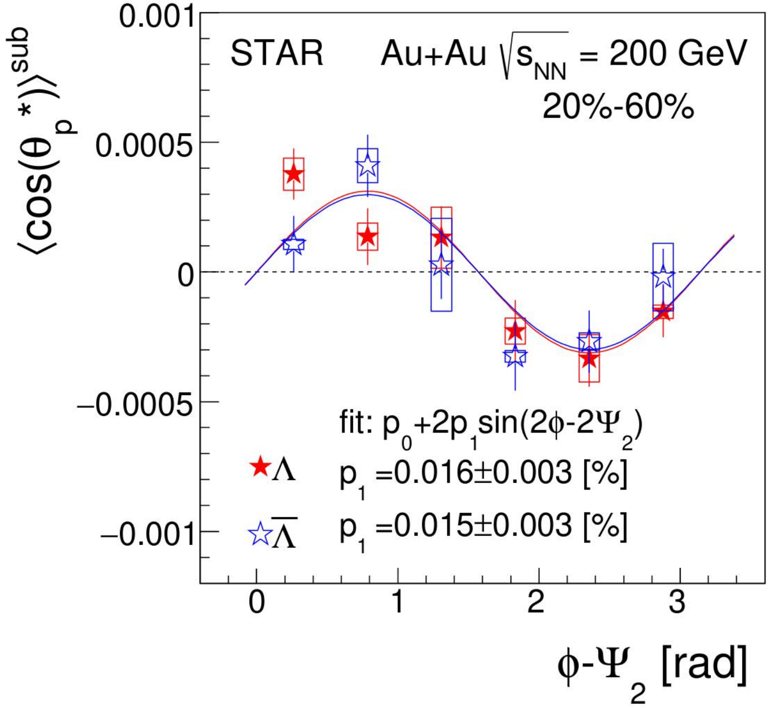
F. Becattini et al., PRL 127, 272302 (2021)



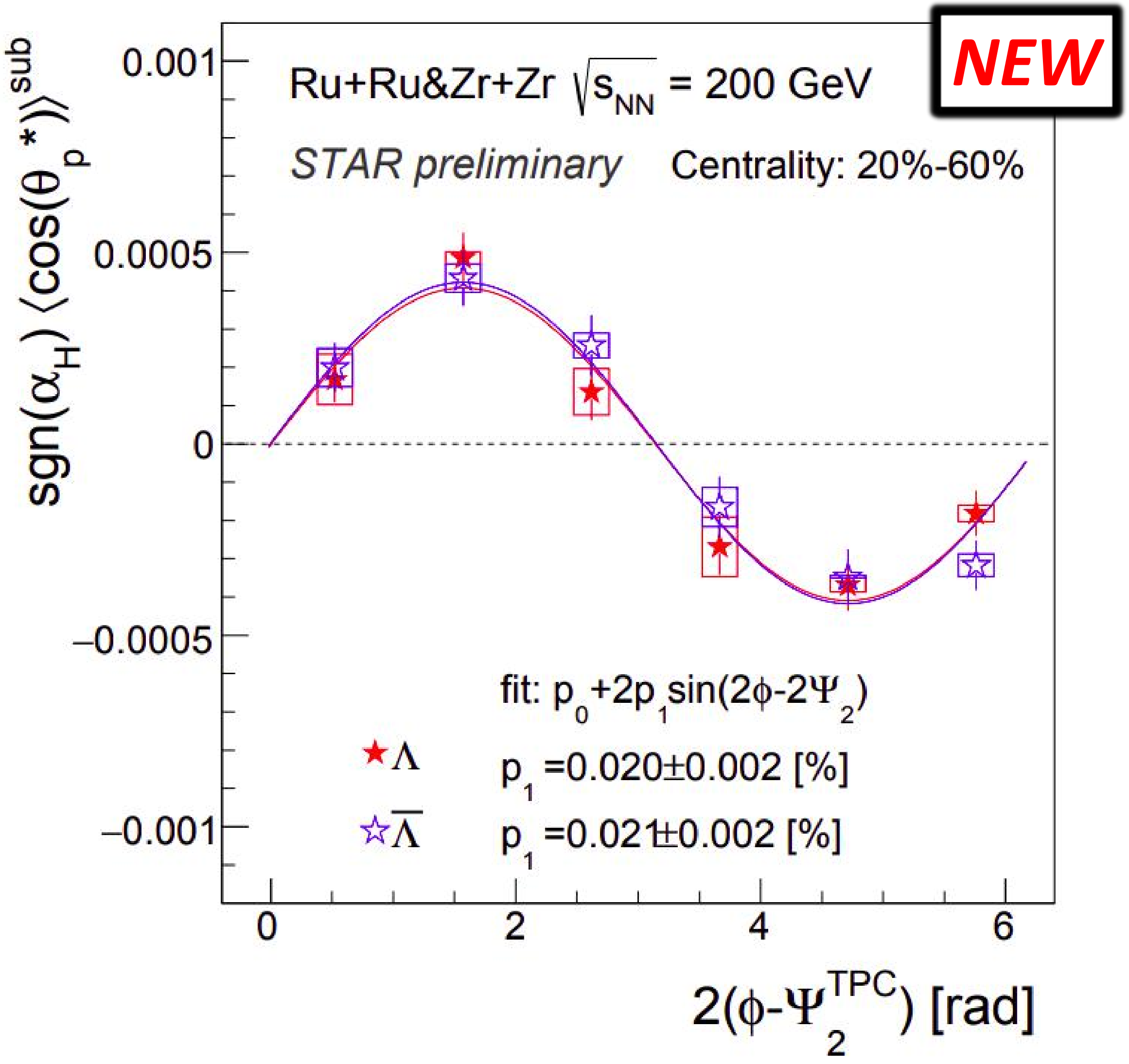
P_z in isobar data set

- Measurements in isobar collisions are qualitatively consistent with those in Au+Au collisions
  - Uncertainties significantly reduced

STAR, PRL 123 13201 (2019)

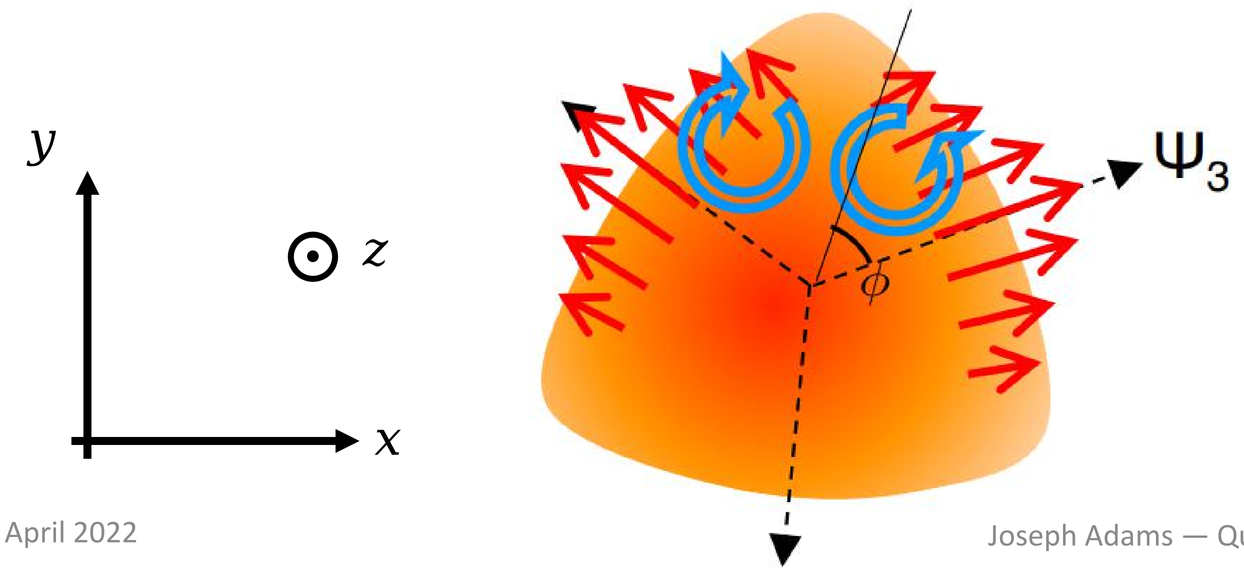


Takafumi Niida, Poster Session 1 T02

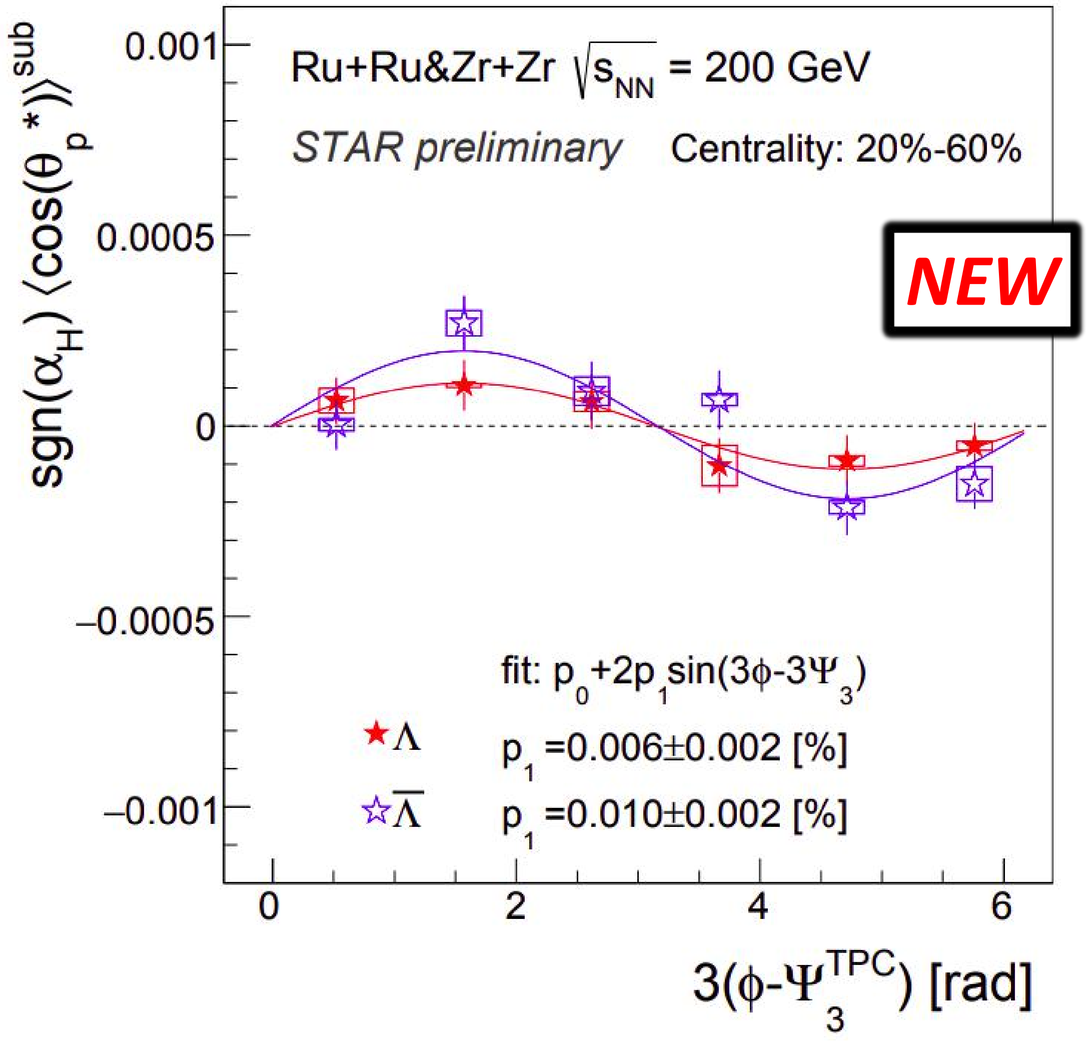


3rd order P_z: a new observable

- Through the same mechanisms, triangular flow should lead to a polarization with respect to Ψ_3
  - S.A. Voloshin, EPJ Web Conf. 171, 07002 arXiv:1710.08934 (2018)
- Same qualitative behavior is observed
- Model studies will provide insight



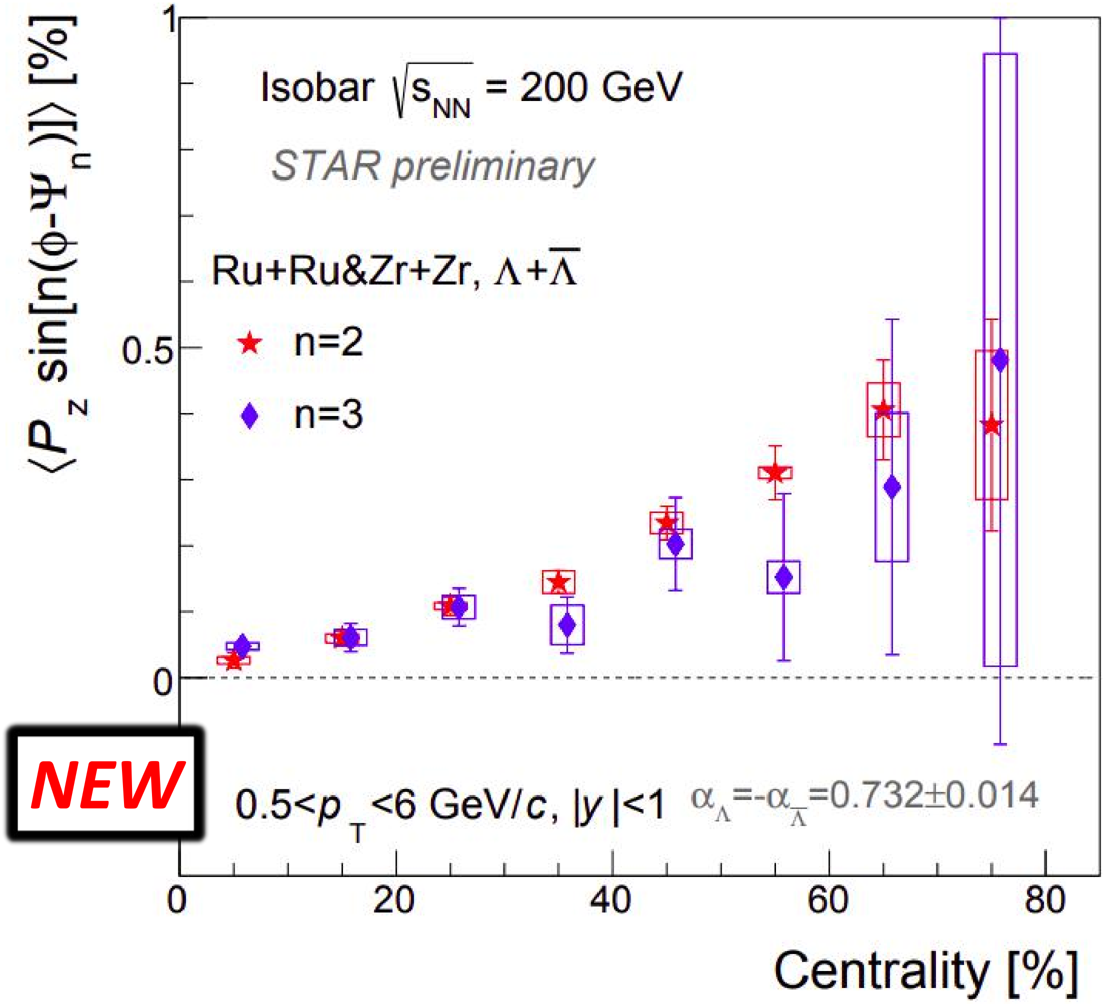
Takafumi Niida, Poster Session 1 T02



3rd order P_z: a new observable

- Through the same mechanisms, triangular flow should lead to a polarization with respect to Ψ_3
- Second and third-order local polarization, $P_{z,\, n=2,3}$ increase with centrality and have comparable magnitude
  - Above 30% centrality $P_{z,\, n=3}$ is systematically smaller than $P_{z,\, n=2}$

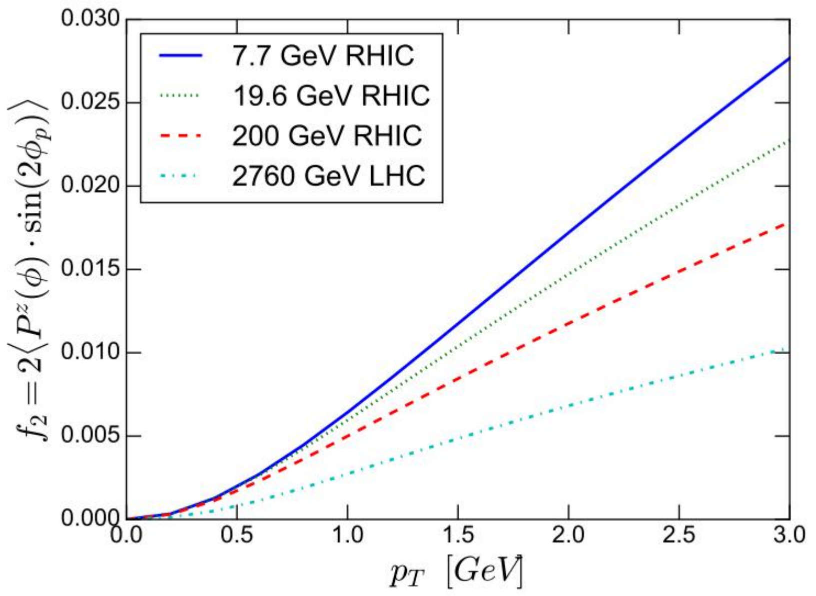
Takafumi Niida, Poster Session 1 T02



P_z: $\sqrt{s_{\mathrm{NN}}}$ & size dependence

- Compared to global polarization, longitudinal polarization is predicted to have a weak collision-energy dependence
- Comparison with ALICE results shows consistent P_z with Au+Au at 200 GeV
  - No observed dependence on $\sqrt{s_{\mathrm{NN}}}$
- Comparison between isobar and Au+Au data in STAR shows a drop in P_z with system size for central collisions

F. Becattini, I. Karpenko, Phys.Rev.Lett. 120 (2018) 1, 012302



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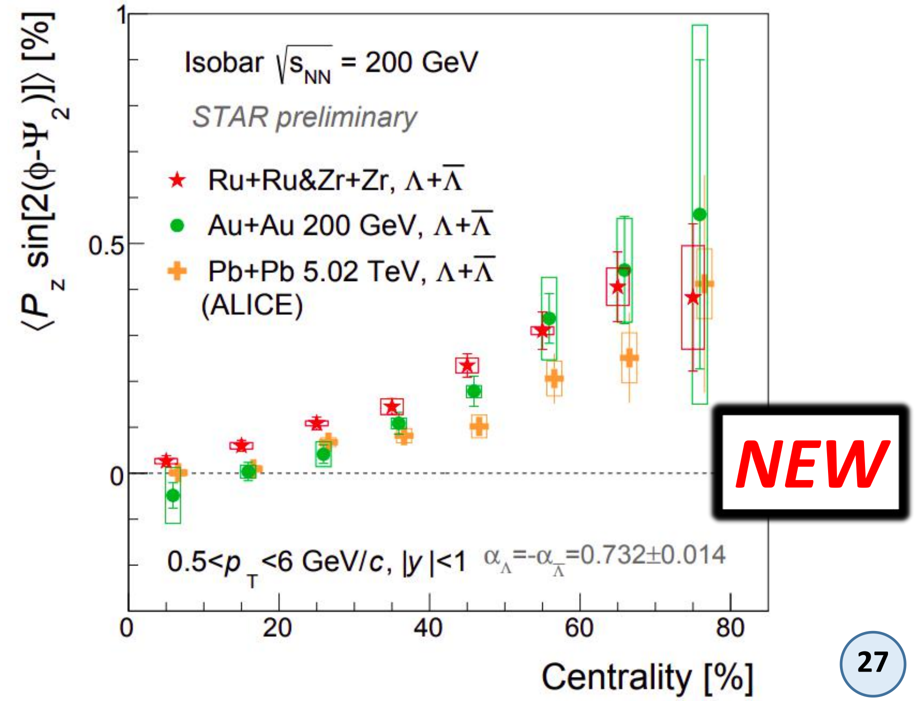
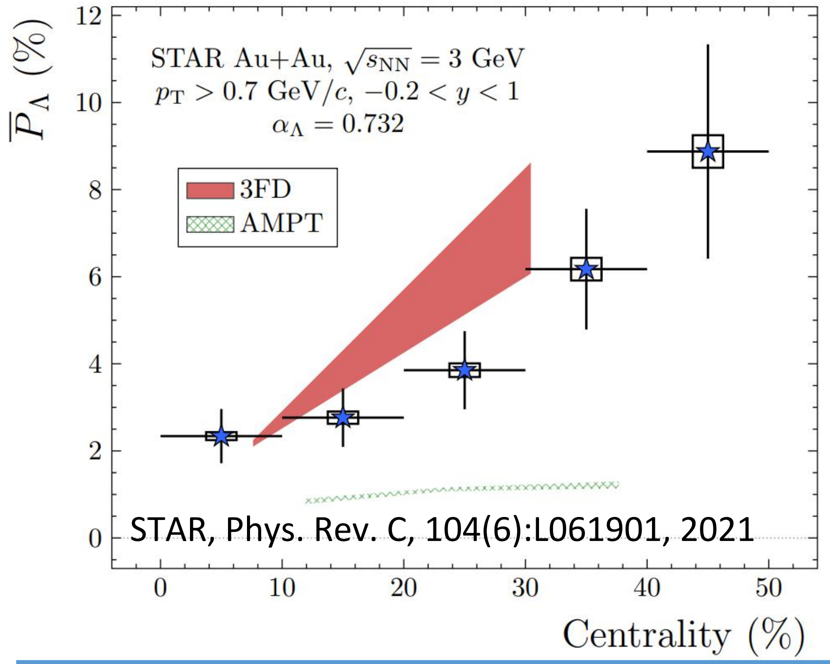
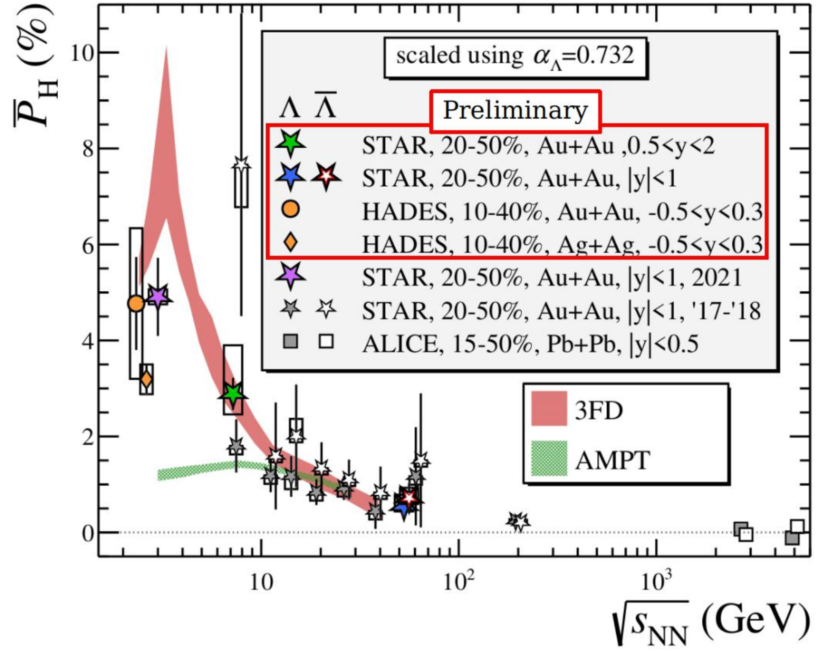


y and $\sqrt{s_{\mathrm{NN}}}$ dependence

- $|\vec{J}|$ increases with $\sqrt{s_{\mathrm{NN}}}$, so we might expect the rapidity-integrated $\overline{\mathrm{P}}_{\mathrm{H}}$ to also increase with $\sqrt{s_{\mathrm{NN}}}$
- Mid-rapidity region becomes more boost invariant (which doesn't support ω well) as $\sqrt{s_{\mathrm{NN}}}$ grows, so we expect mid-rapidity $\overline{\mathrm{P}}_{\mathrm{H}}$ to fall with $\sqrt{s_{\mathrm{NN}}}$
- This is essentially a rapidity-dependence argument, which we have yet to see!

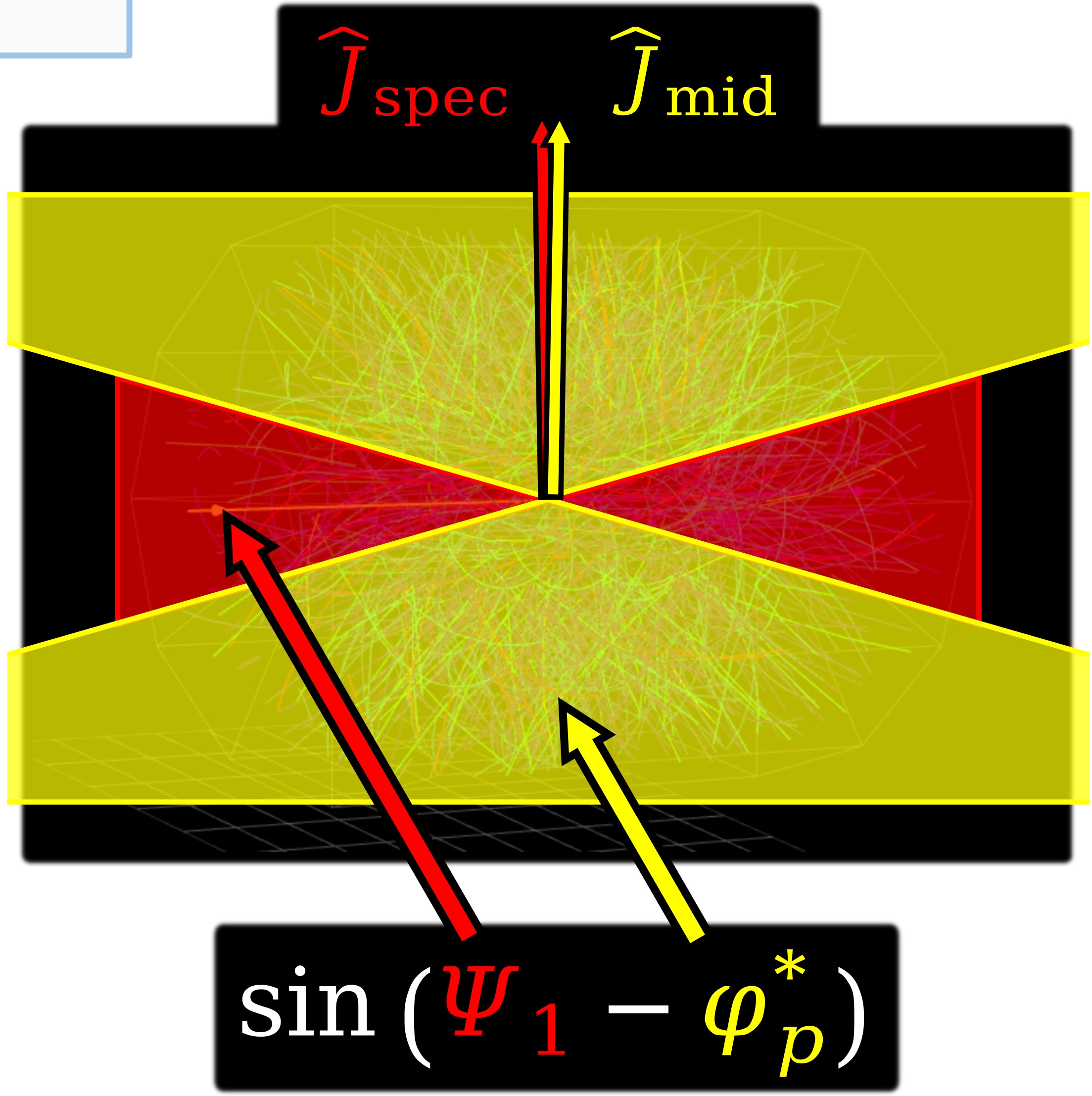


$|\vec{J}|\uparrow$



Collision-energy dependence

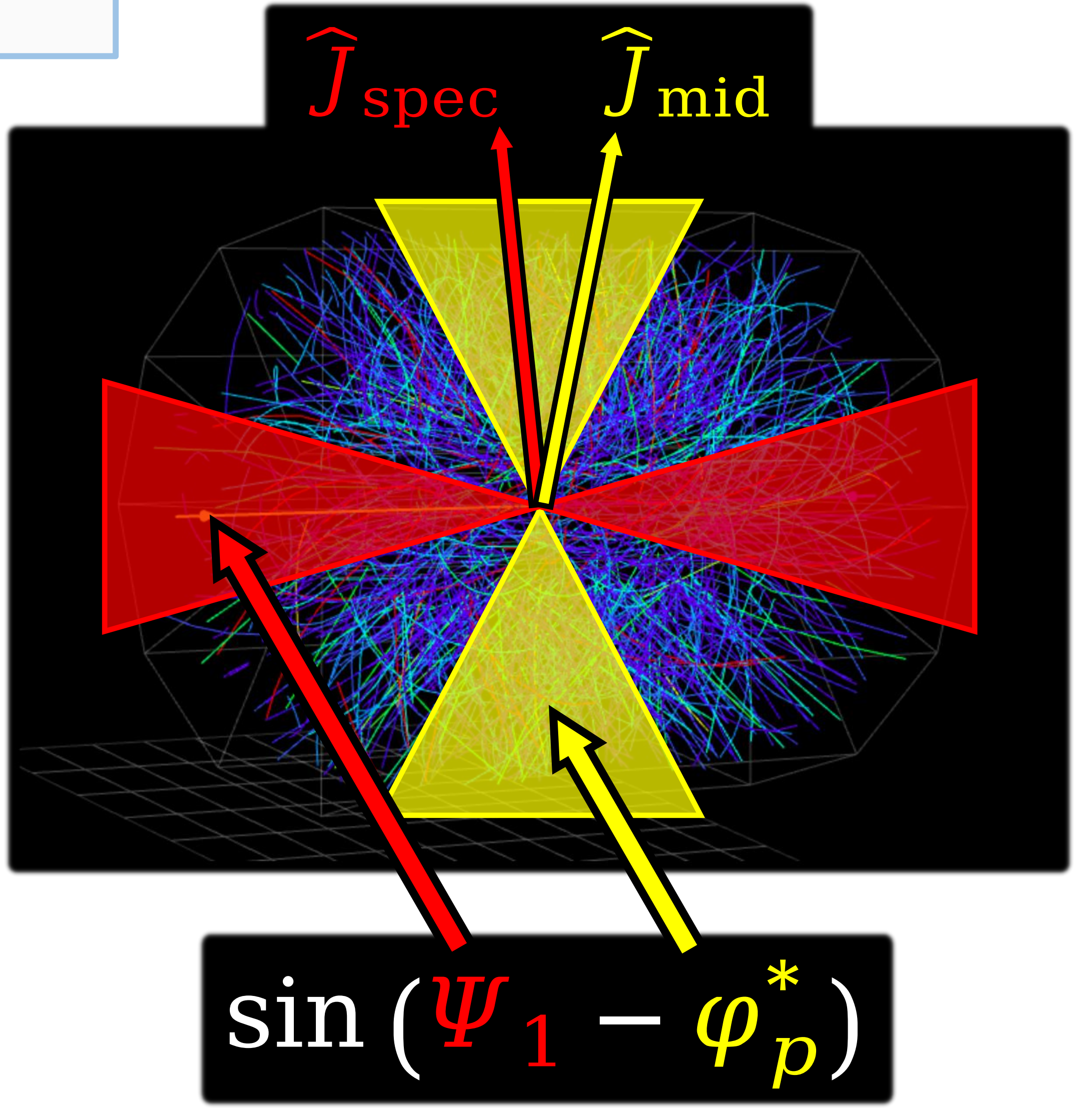
- Theory and experiment have assumed alignment between system $\widehat{J}$ and mid-rapidity $\widehat{J}$
  - Experiment approximates $\widehat{J}_{\text{syst}}$ with $\widehat{J}_{\text{spec}}$
  - This *would* be a good approximation if spectator and mid-rapidity regions touch



Correlation of interest

Collision-energy dependence

- Theory and experiment have assumed alignment between system $\widehat{J}$ and mid-rapidity $\widehat{J}$
  - Experiment approximates $\widehat{J}_{\mathrm{syst}}$ with $\widehat{J}_{\mathrm{spec}}$
  - This *would* be a good approximation if spectator and mid-rapidity regions touch
- With a gap, these angular momenta are decorrelated

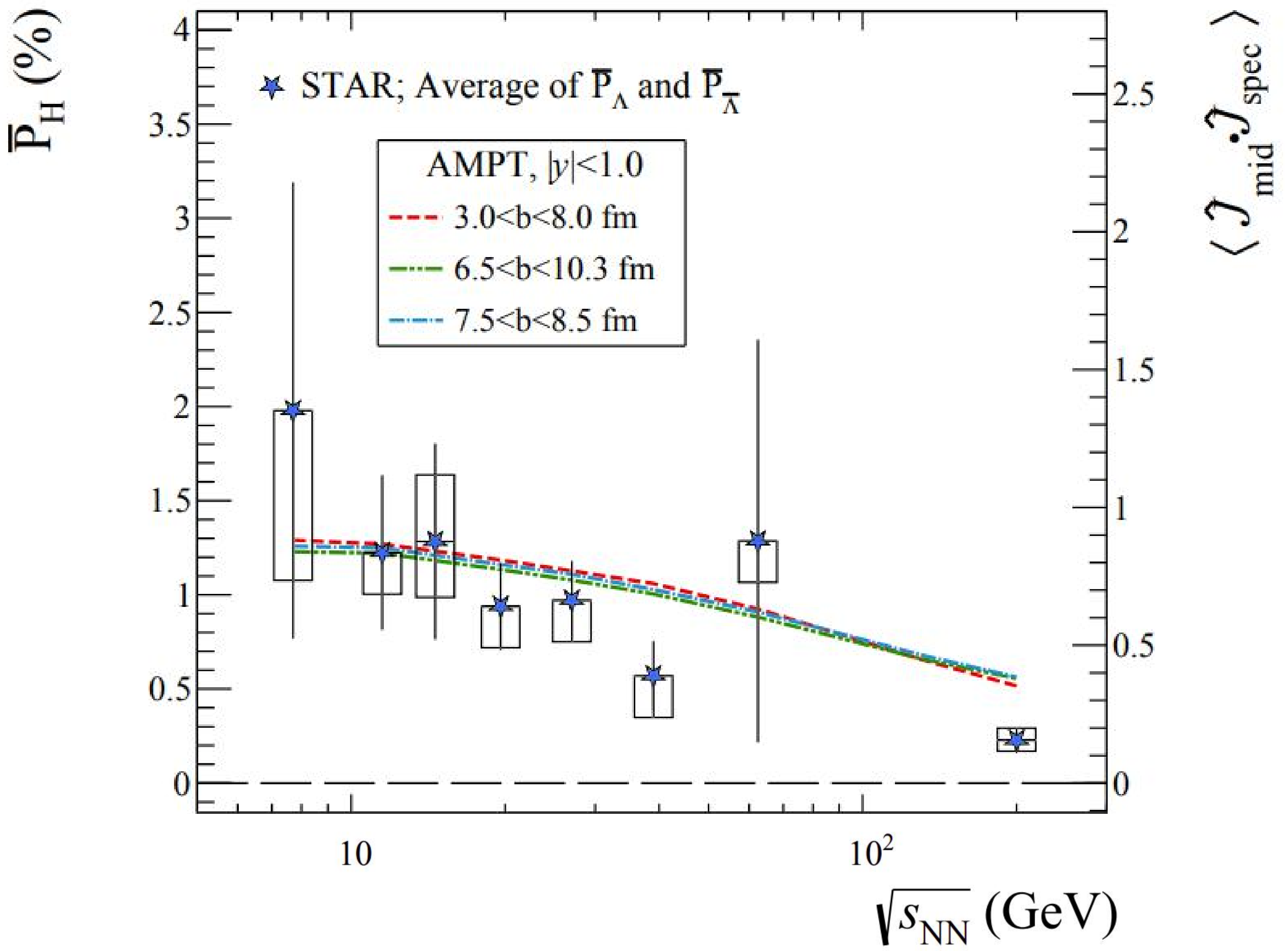


Correlation of interest

Collision-energy dependence

- This decorrelation becomes more significant with larger $\sqrt{s_{NN}}$
- This decorrelation effect leads to a drop in $\overline{\mathrm{P}}_{\mathrm{H}}$ with $\sqrt{s_{NN}}$
- Appropriate corrections are needed both in experiment and theory

J.R. Adams, M.A. Lisa. arXiv:2109.14726



Summary

- Low-energy measurements are possible in STAR using fixed-target collisions
  - Theory predictions disagree in the low-energy range
  - We observe large polarization at 3 and 7.2 GeV, in agreement with hydro
- High-statistics data sets at 19.6 and 27 GeV offer a factor of 10 improvement on uncertainties for the measurement on the late-stage magnetic field
  - $|\overrightarrow{B}|$ not observed with isobar and other high-statistics data sets
- System-size dependence of global polarization is not observed
- Longitudinal polarization in isobar data shows dependence on system size
- First measurement of third-order longitudinal polarization

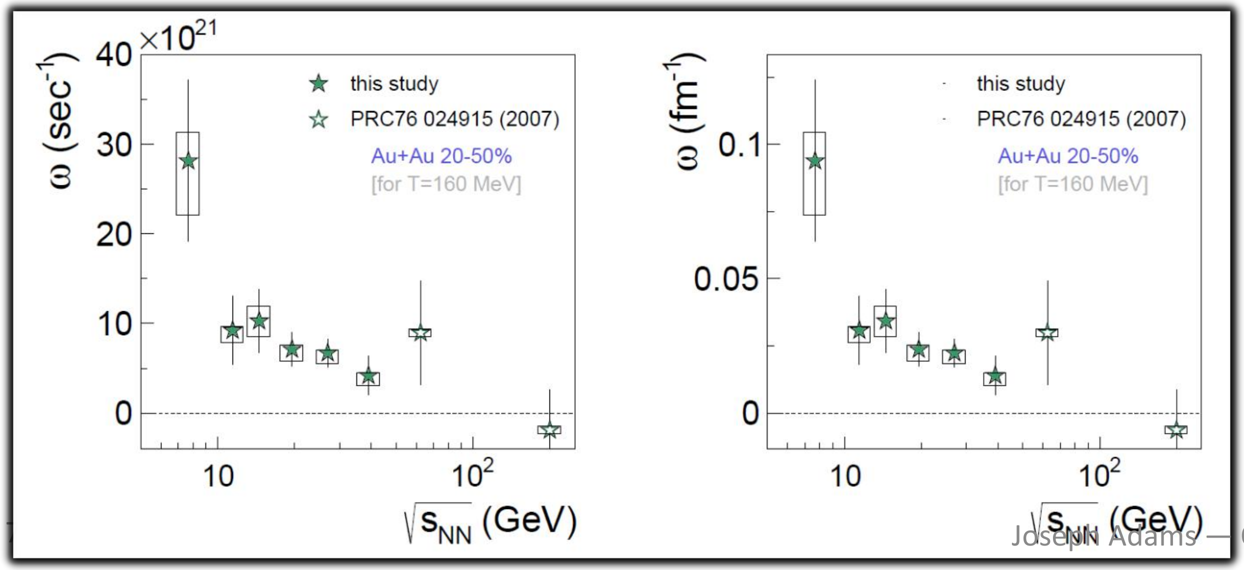
BACKUP

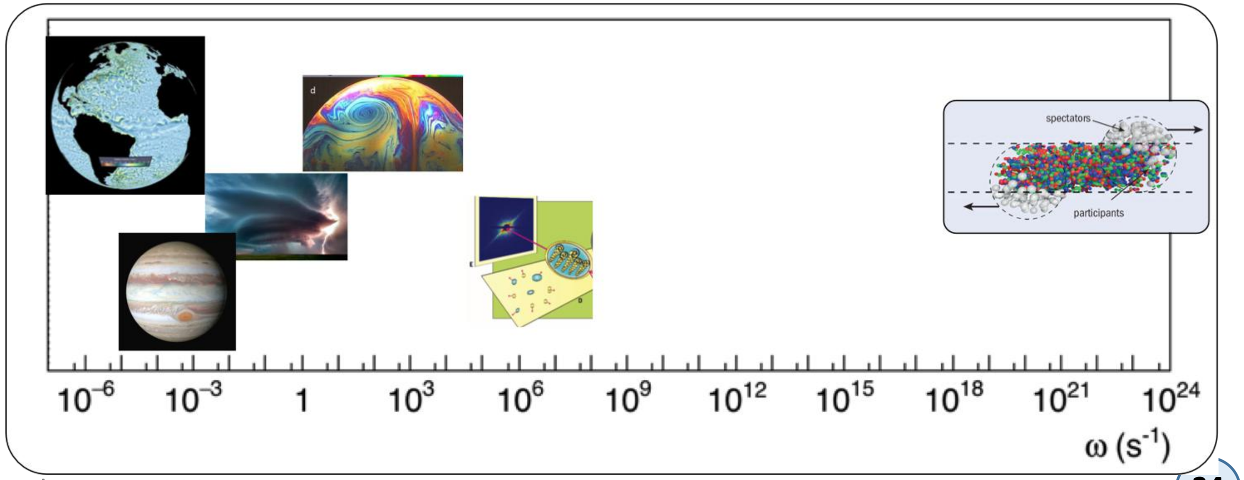
Relation to vorticity

- Feedown of Lambdas from parent particles needs acounting for
- A confirmation of the fluid-like nature of the QGP

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

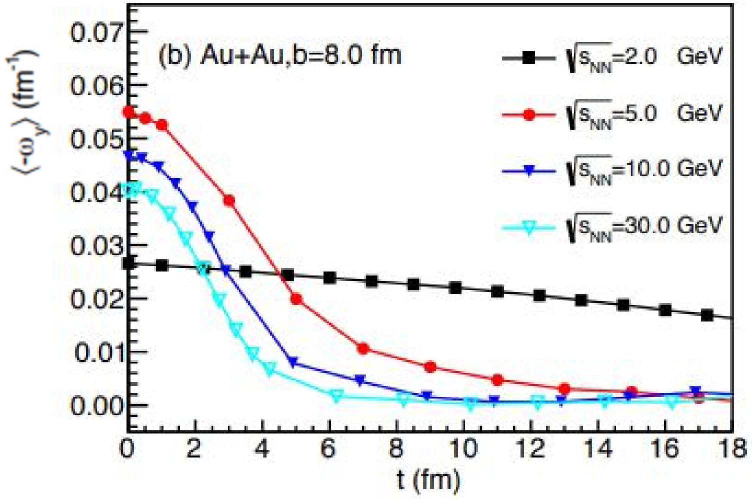
F. Becattini,1 I. Karpenko, M.A. Lisa, I. Upsal, and S.A. Voloshin, Phys. Rev. C **95**, 054902 (2017)



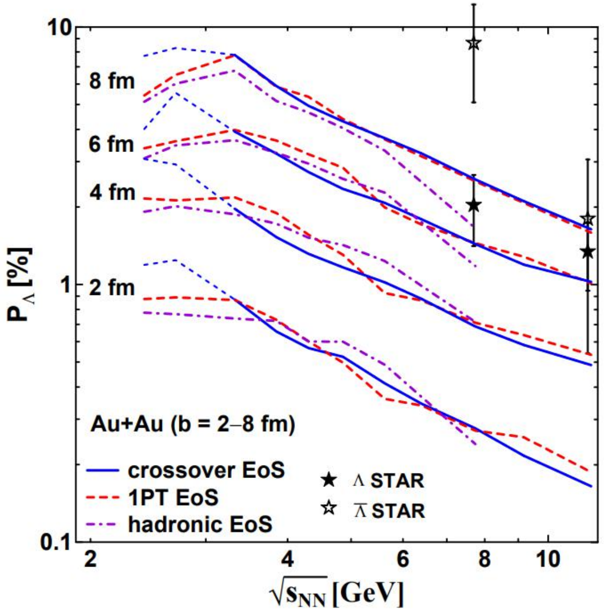


Model predictions

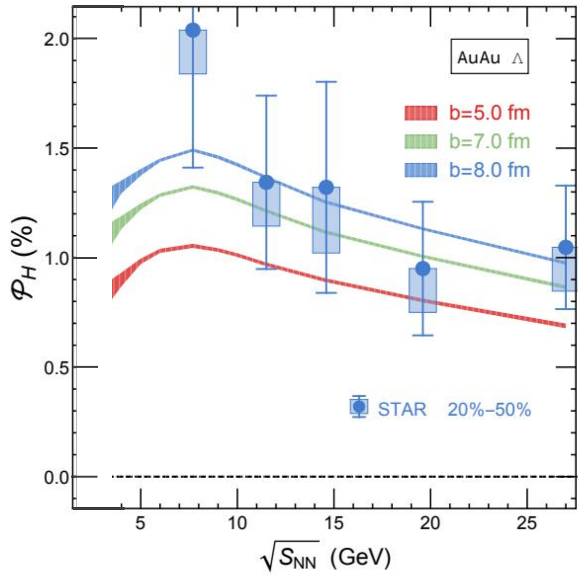
Y. Guo, et al. Phys. Rev. C 104 4 L041902 (2021) arXiv:2105.13481



- Various model predictions show increasing $\overline{\mathrm{P}}_{\mathrm{H}}$ as $\sqrt{s_{\mathrm{NN}}}$ decreases
- This trend is clearly carried out in experimental observations… but what happens below $\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV?
  - UrQMD shows large late-stage vorticity at $\sqrt{s_{\mathrm{NN}}} = 2$ GeV
  - 3FD shows peak polarization at $\sqrt{s_{\mathrm{NN}}} = 3 - 4$ GeV
  - AMPT shows peak polarization around $\sqrt{s_{\mathrm{NN}}} = 7$ GeV



X.G. Deng, X.G. Huang, Y.G. Ma, and S. Zhang, Phys. Rev. C 101, 064908 (2020), arXiv:2001.01371



Y.B. Ivanov, Phys. Rev. C 103, L031903 (2021) arXiv:2012.07597