Global polarization of Lambda hyperons in Au+Au Collisions at RHIC BES

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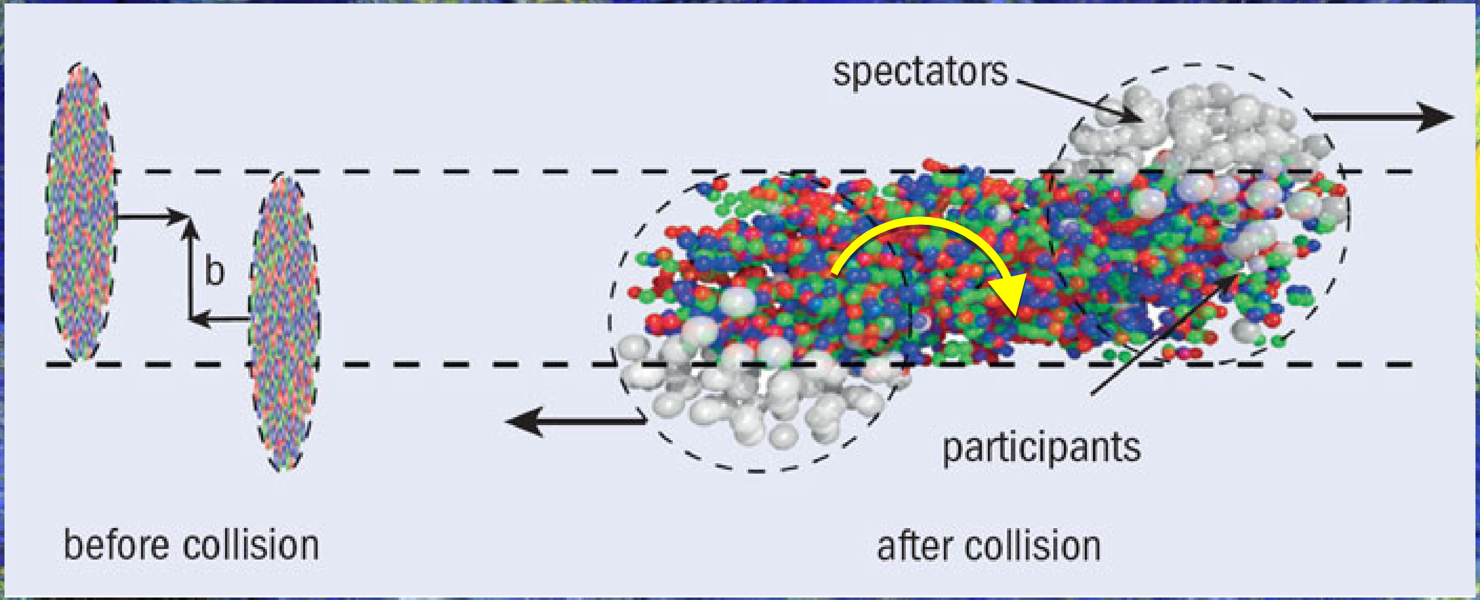
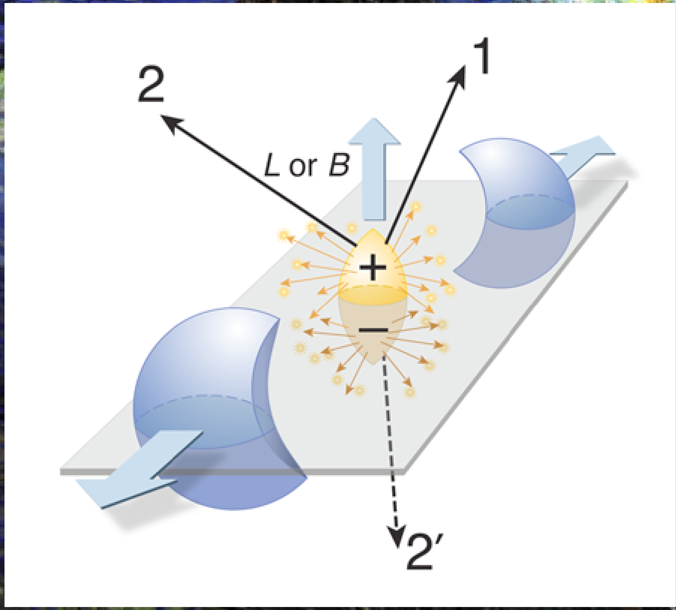
For the STAR collaboration

02/07/17

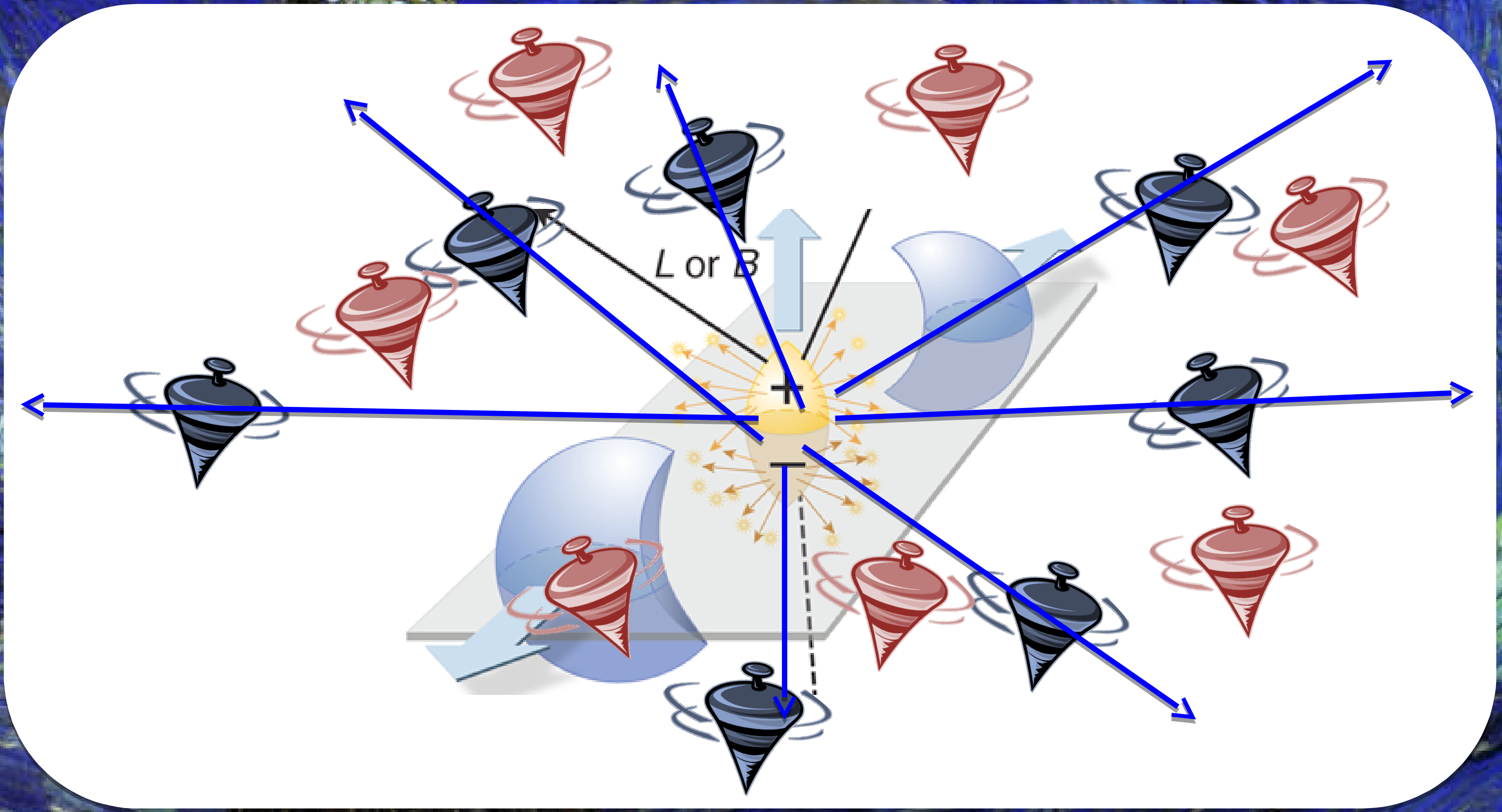
Quark Matter 2017





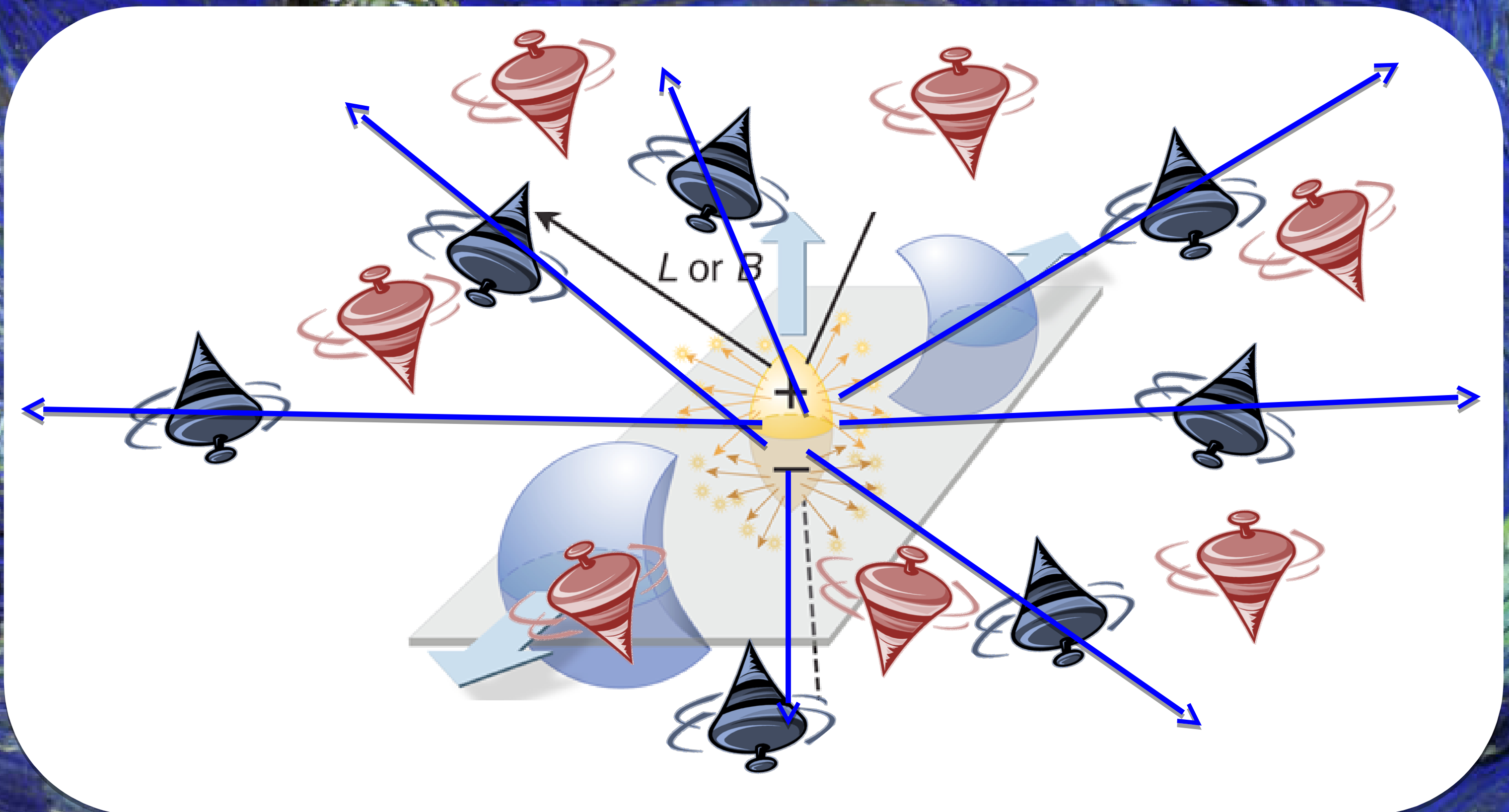
- |L| ~ 10³ ħ in non-central collisions
- How much is transferred to particles at mid-rapidity?
- Does angular momentum get distributed thermally?
- Does it generate a “spinning QGP?”
  - consequences?
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} \equiv \frac{1}{2}\vec{\nabla} \times \vec{v}$
- How would it manifest itself in data?

Vorticity → Global Polarization



- Vortical or QCD spin-orbit: Lambda and Anti-Lambda spins aligned with L

Magnetic field → Global Polarization



Both may contribute

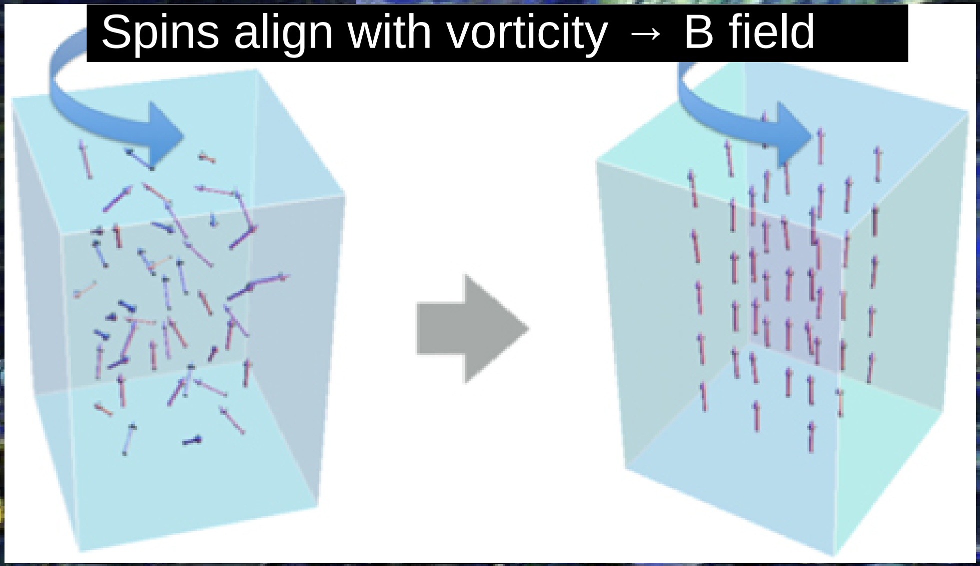
- Vortical or QCD spin-orbit: Lambda and Anti-Lambda spins aligned with L
- (electro)magnetic coupling: Lambdas *anti*-aligned, and Anti-Lambdas aligned

Barnett effect

- Nice correspondence in **Barnett effect**
- **BE**: uncharged object rotating with angular velocity ω magnetizes

$$M = \chi \omega / \gamma$$

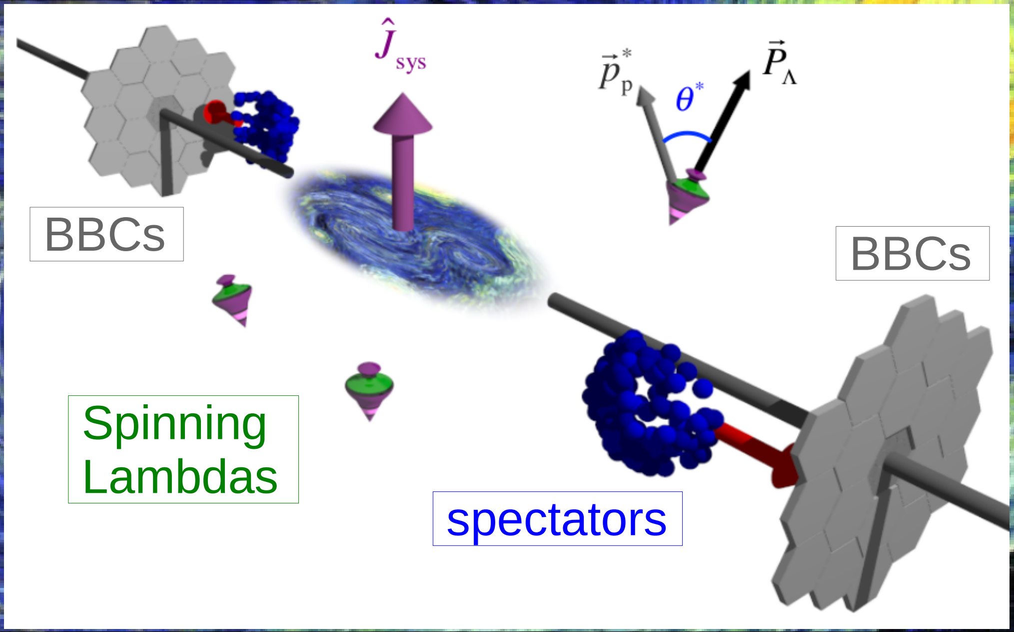
- γ = gyromagnetic ratio, χ = magnetic susceptibility

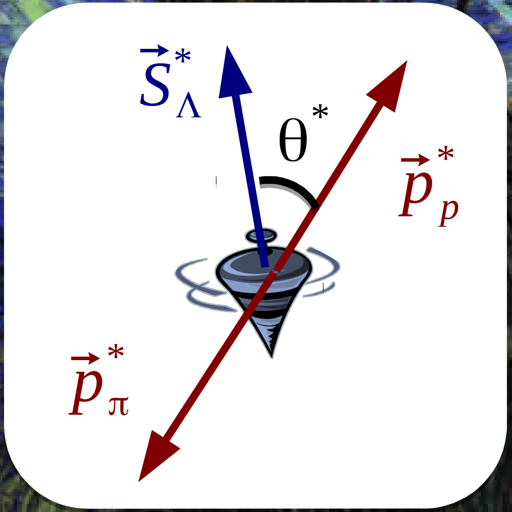


Barnett Science 42, 163, 459 (1915); Barnett Phys. Rev. 6, 239–270 (1915)

How to quantify the effect (I)

- Lambdas are "self-analyzing"
  - Reveal polarization by preferentially emitting daughter proton in spin direction





Λs with Polarization $\vec{P}$ follow the distribution:

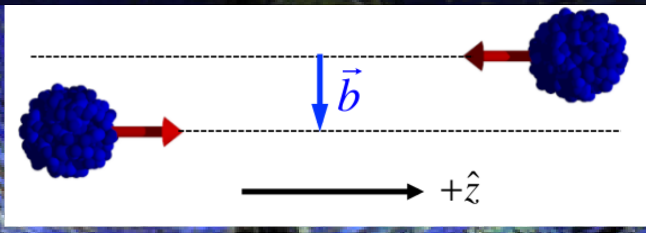
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\,\vec{P}\cdot\hat{p}_p^{\,*}\right) = \frac{1}{4\pi}\left(1+\alpha\,P\cos\theta^*\right)$$

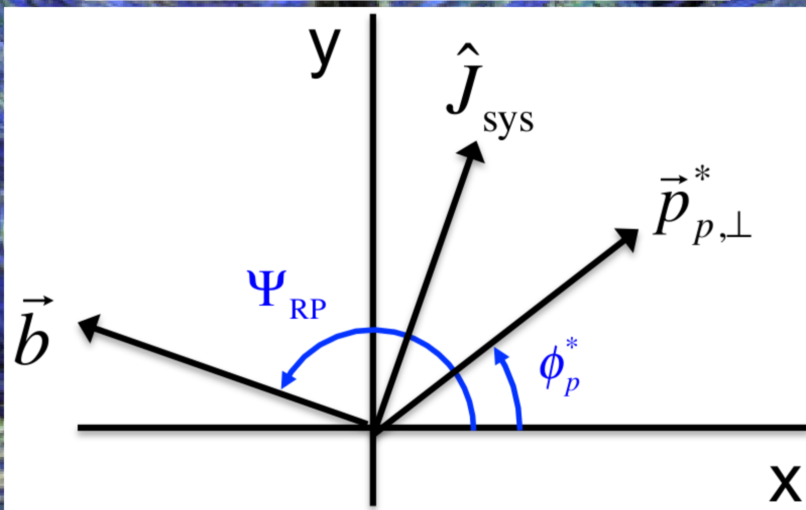
$\alpha = 0.642 \pm 0.013$ [measured]

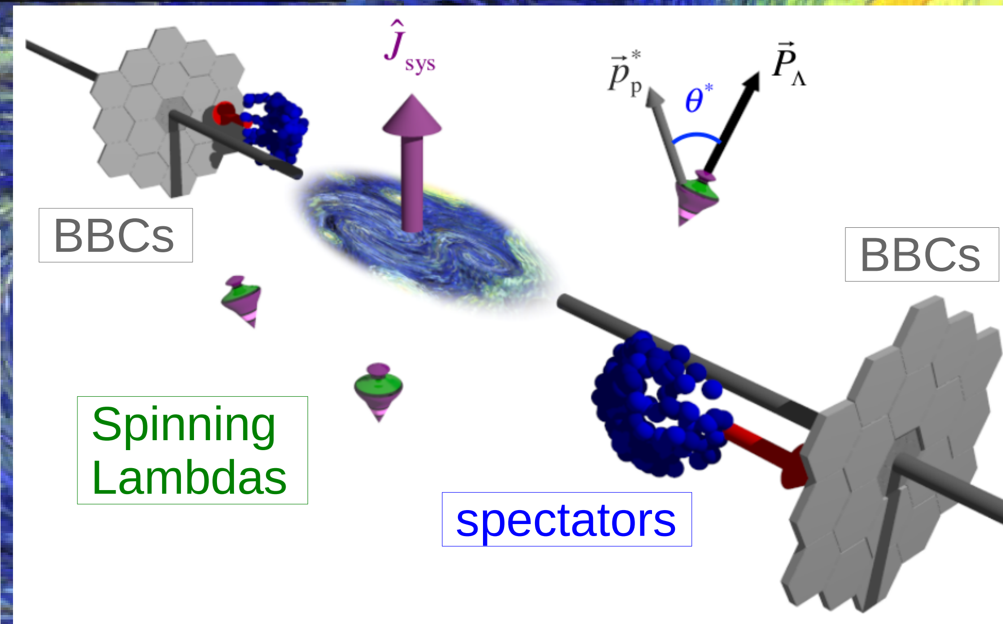
$\hat{p}_p^{\,*}$ is the daughter proton momentum direction *in the Λ frame* (note that this is opposite for $\overline{\Lambda}$)

$$0<|\vec{P}|<1: \quad \vec{P} = \frac{3}{\alpha}\,\overline{\hat{p}_p^{\,*}}$$

How to quantify the effect (II)







Symmetry: $|\eta|<1,\ 0<\varphi<2\pi \rightarrow \parallel \hat{L}$

Statistics-limited experiment: we report acceptance-integrated polarization, $P_{ave} \equiv \int d\vec{\beta}_\Lambda \frac{dN}{d\vec{\beta}_\Lambda} \vec{P}(\vec{\beta}_\Lambda) \cdot \hat{L}$

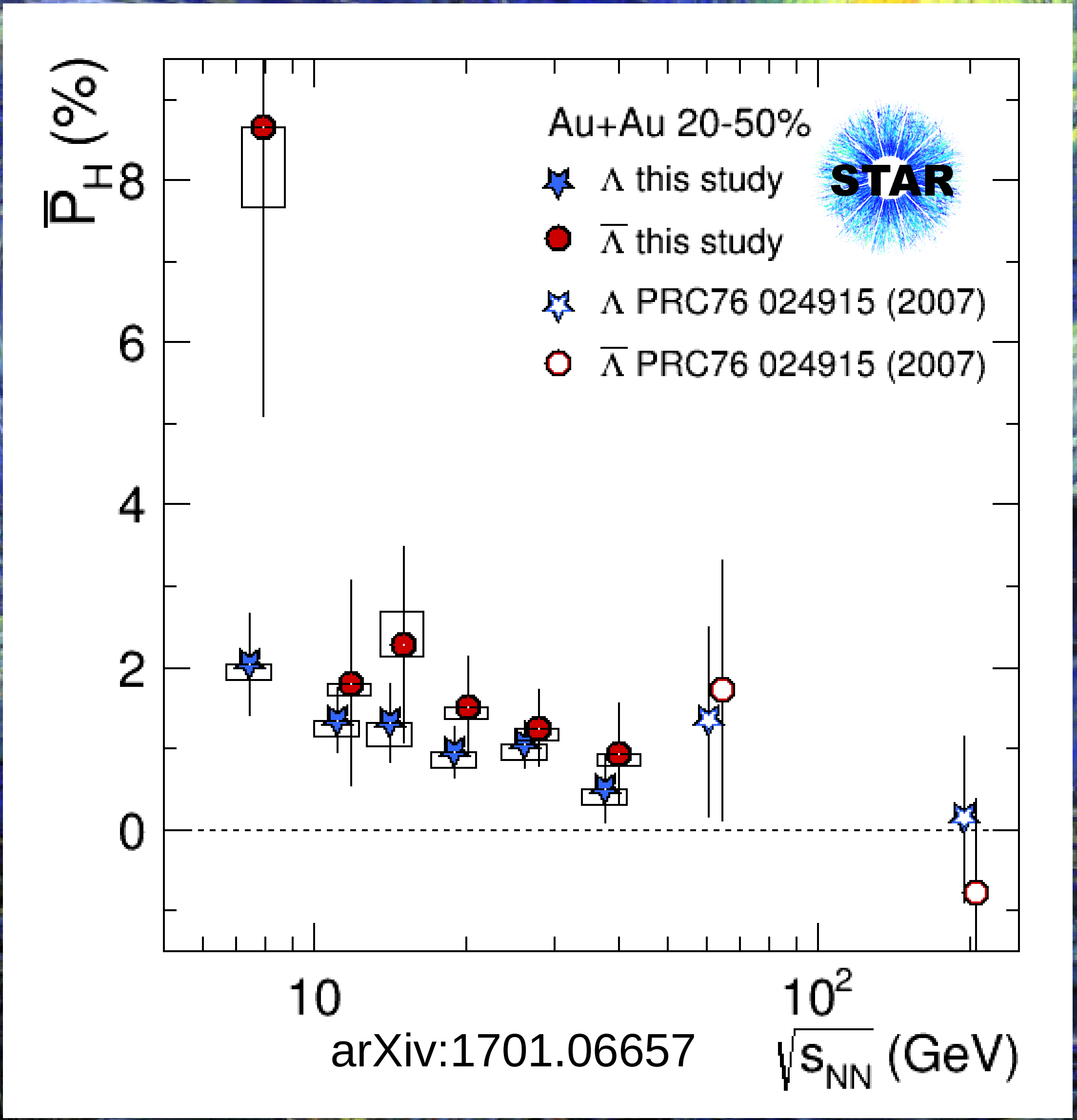
$P_{AVE} = \frac{8}{\pi\alpha} \frac{\langle \sin(\varphi_{\hat{b}} - \varphi^*_p) \rangle}{R^{(1)}_{EP}}$ ** where the average is performed over events and Λs

$R^{(1)}_{EP}$ is the first-order event plane resolution and $\varphi_{\hat{b}}$ is the impact parameter angle

** if $v_1 \cdot y > 0$ in BBCs $\varphi_{\hat{b}} = \Psi_{EP}$, if $v_1 \cdot y < 0$ in BBCs $\varphi_{\hat{b}} = \Psi_{EP} + \pi$

Global polarization measure

- Measured Lambda and Anti-Lambda polarization
- Includes results from previous STAR null result (2007)
- $\overline{P}_H(\Lambda)$ and $\overline{P}_H(\bar{\Lambda})>0$ implies positive vorticity
- $\overline{P}_H(\bar{\Lambda})>\overline{P}_H(\Lambda)$ would imply magnetic coupling



Global polarization measure

- Measured Lambda and Anti-

We can study more fundamental properties of the system

- previous STAR null result (2007)

- $\overline{P}_H(\Lambda)$ and $\overline{P}_H(\bar{\Lambda})>0$ implies positive vorticity

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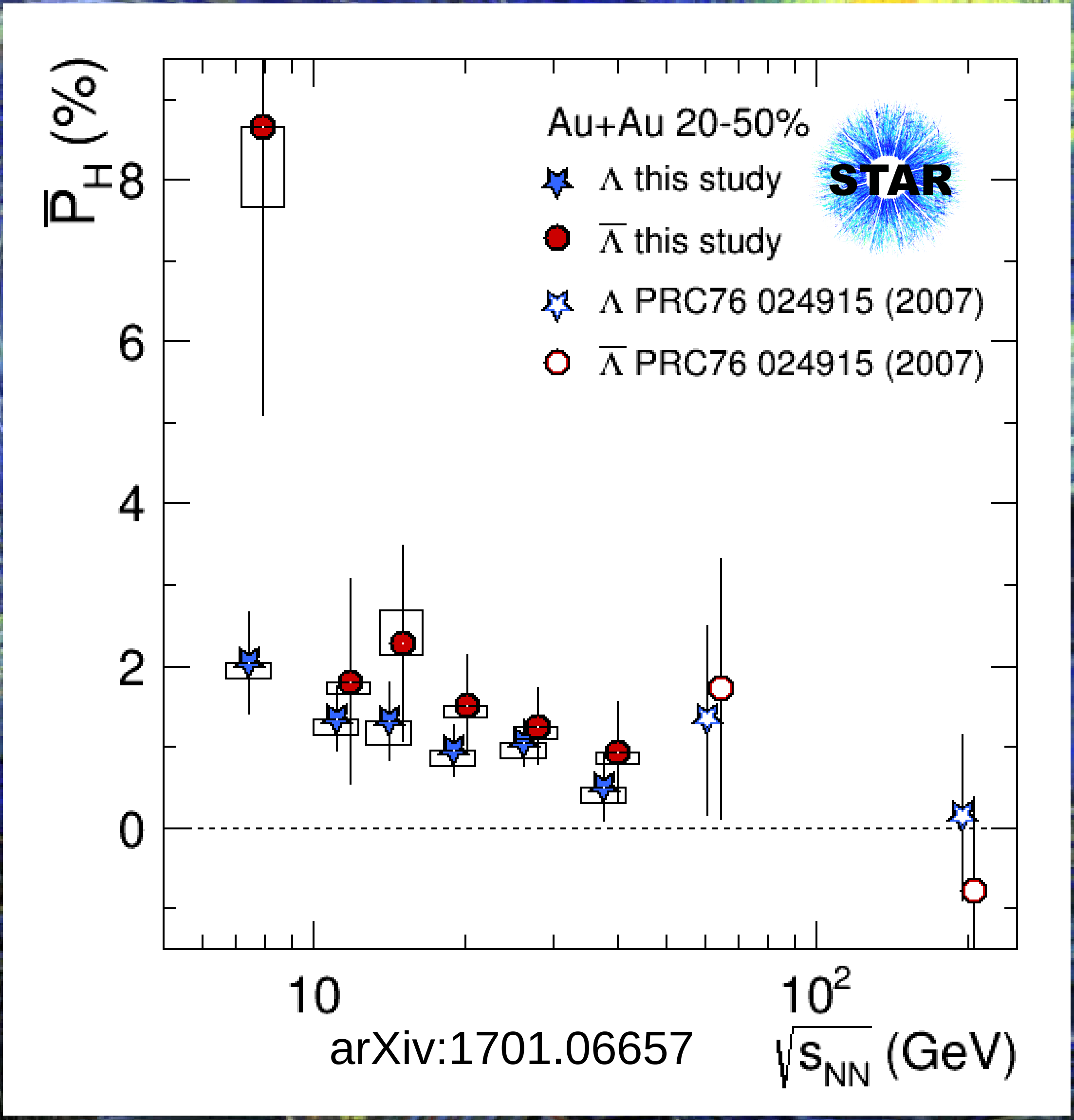
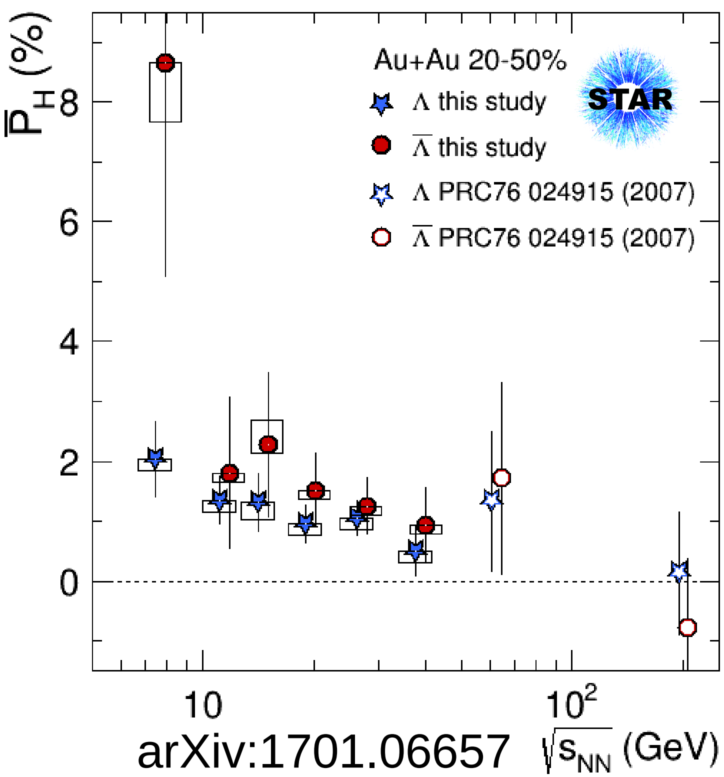


Vortical and Magnetic Contributions



arXiv:1701.06657

- Magneto-hydro equilibrium interpretation

$$P \sim \exp\left(-E/T + \mu_B B/T + \vec{\omega}\cdot\vec{S}/T + \vec{\mu}\cdot\vec{B}/T\right)^{**}$$

- for small polarization:

$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \qquad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

- vorticity from addition:

$$\frac{\omega}{T} = P_{\bar{\Lambda}} + P_\Lambda$$

- B from the difference:

$$\frac{B}{T} = \frac{1}{2\mu_\Lambda}\left(P_{\bar{\Lambda}} - P_\Lambda\right)$$

** $\hbar = k_B = 1$

But even with topological cuts, significant feeddown from Σ^0, $\Xi^{0/-}$, $\Sigma^{*\pm/0}$...

... which themselves will be polarized...

Becattini, Karpenko, Lisa, Upsal, Voloshin arxiv:1610.02506

Accounting for polarized feeddown

$$\begin{pmatrix}\frac{\omega}{T}\\[4pt] \frac{B}{T}\end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R}\right) S_R(S_R+1) & \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R}\right)(S_R+1)\mu_R \\ \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda}\overline{R}}C_{\overline{\Lambda}\overline{R}} - \frac{1}{3} f_{\overline{\Sigma^0}\overline{R}} C_{\overline{\Sigma^0}\overline{R}}\right) S_{\overline{R}}(S_{\overline{R}}+1) & \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda}\overline{R}}C_{\overline{\Lambda}\overline{R}} - \frac{1}{3} f_{\overline{\Sigma^0}\overline{R}} C_{\overline{\Sigma^0}\overline{R}}\right)(S_{\overline{R}}+1)\mu_{\overline{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_{\Lambda}^{\text{meas}} \\[4pt] P_{\overline{\Lambda}}^{\text{meas}}\end{pmatrix} \quad {}^{**}$$

- $f_{\Lambda R}$ = fraction of Λs that originate from parent $R \to \Lambda$ → From THERMUS
- $C_{\Lambda R}$ = coefficient of spin transfer from parent R to daughter Λ
- S_R = parent particle spin
- μ_R is the magnetic moment of particle R
- overlines denote antiparticles

Decay	C
parity-conserving: $1/2^+ \to 1/2^+ \; 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+ \; 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+ \; 0^-$	$1/3$
parity-conserving: $3/2^- \to 1/2^+ \; 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$	-1/3

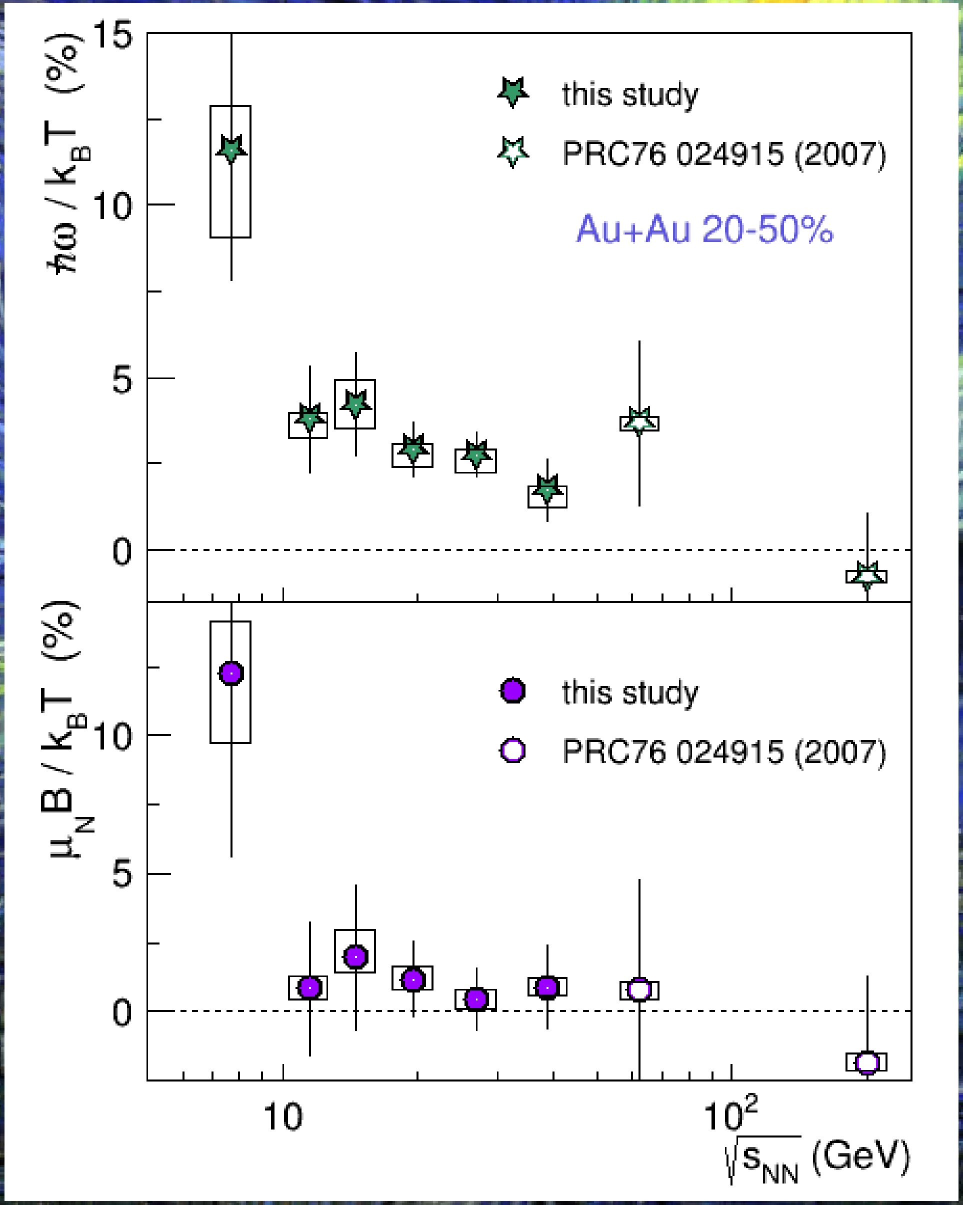
TABLE I. Polarization transfer factors C (see eq. (31)) for

** $\hbar = k_B = 1$

Becattini, Karpenko, Lisa, Upsal, Voloshin arxiv:1610.02506

Extracted Physical Parameters

- Significant vorticity signal
  - Hints at falling with energy, despite increasing $J_{collision}$
  - 6σ average for 7.7-39GeV
  - $P_{\Lambda_{primary}} = \frac{\omega}{2T} \sim 5\%$
- Magnetic field
  - μ_N = nuclear magneton
  - positive value, 2σ average for 7.7-39GeV



Vorticity ~ theory expectation

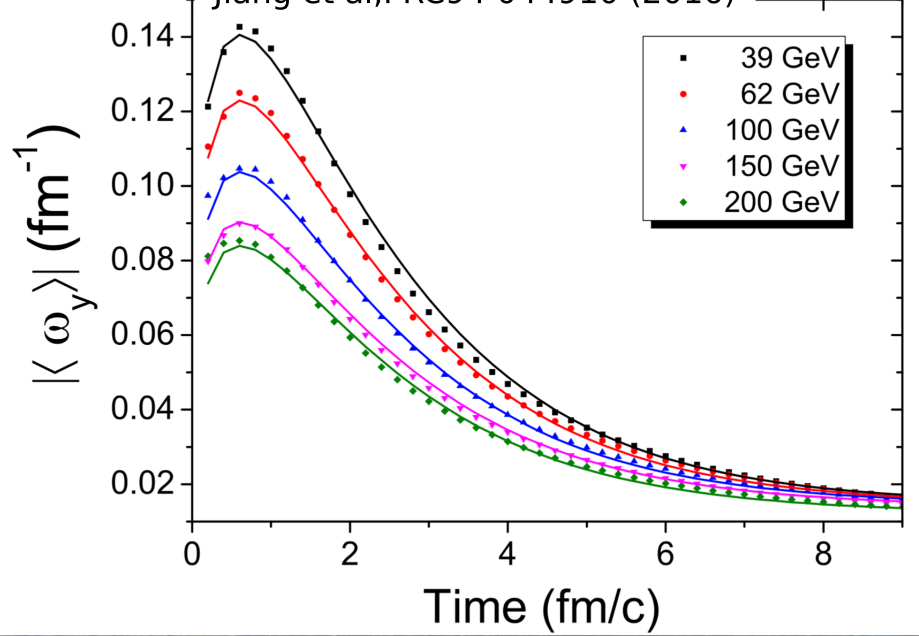
- Thermal vorticity:

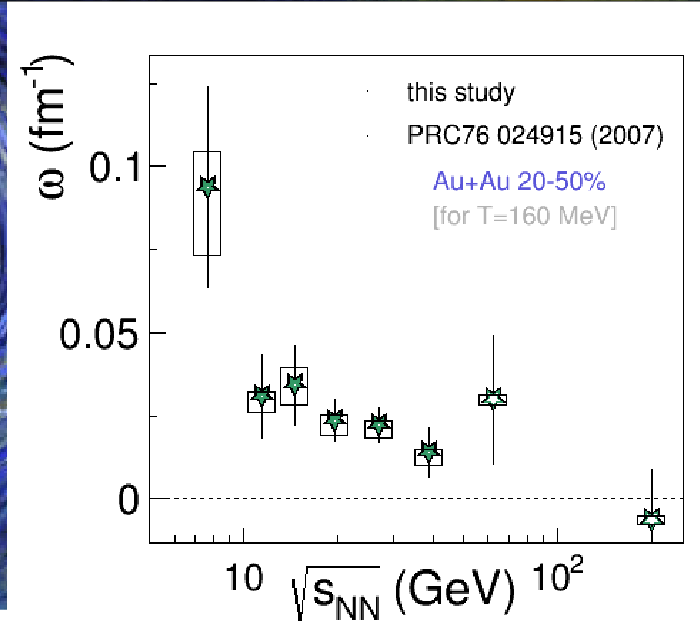
$$\frac{\omega}{T} \approx 2-10\,\%$$

$$\omega \approx 0.02-0.09\, fm^{-1} \qquad (\mathrm{T}_{\mathrm{assumed}} = 160\,\mathrm{MeV})$$

- Magnitude, √s-dep. in range of transport & 3D viscous hydro calculations with rotation

Jiang et al,PRC94 044910 (2016)





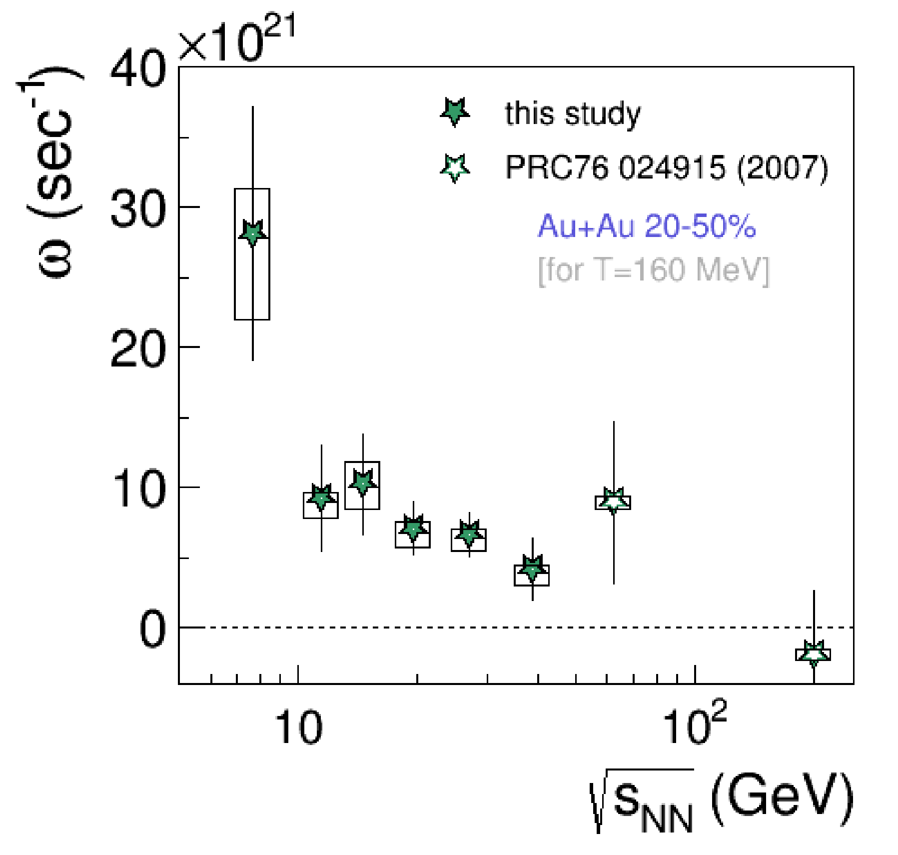
Csernai et al, PRC**90** 021904(R) (2014)

TABLE I. Time dependence of average vorticity projected to the reaction plane for heavy-ion reactions at the NICA energy of $\sqrt{s_{NN}} = 4.65 + 4.65$ GeV.

t (fm/c)	Vorticity (classical) (c/fm)	Thermal vorticity (relativistic) (1)
0.17	0.1345	0.0847
1.02	0.1238	0.0975
1.86	0.1079	0.0846
2.71	0.0924	0.0886
3.56	0.0773	0.0739

Vorticity comparison

- Solar subsurface flow: $\omega \sim 10^{-6}\ s^{-1}$
- Ocean flows: $\omega \sim 10^{-5}\ s^{-1}$
- Terrestrial atmosphere: $\omega \sim 10^{-4}\ s^{-1}$
- "Collar" of Jupiter's Great Red Spot : $\omega \sim 10^{-4}\ s^{-1}$
- Core of supercell tornado : $\omega \sim 10^{-1}\ s^{-1}$



- Max vorticity in bulk superfluid He-II: $\omega \sim 150\ s^{-1}$
  - R. Donnelly, Ann. Rev. Fluid Mech. 25, 325 (1993)
- Max vorticity in nanodroplets of superfluid He-II: $10^{6}\ s^{-1}$
  - Shomroni et al, Science 345 (2014) 903

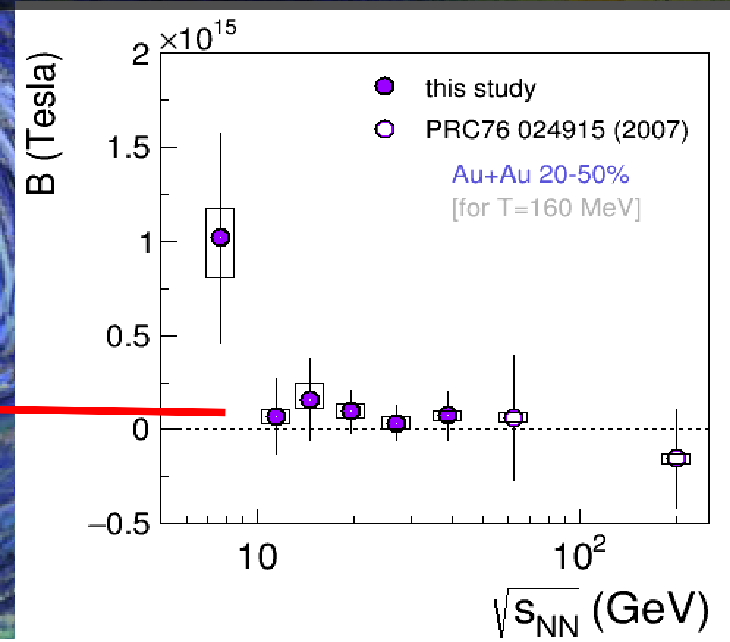
RHIC produces the least viscous fluid.
RHIC produces the most vortical fluid!

B-Field ~ theory expectation

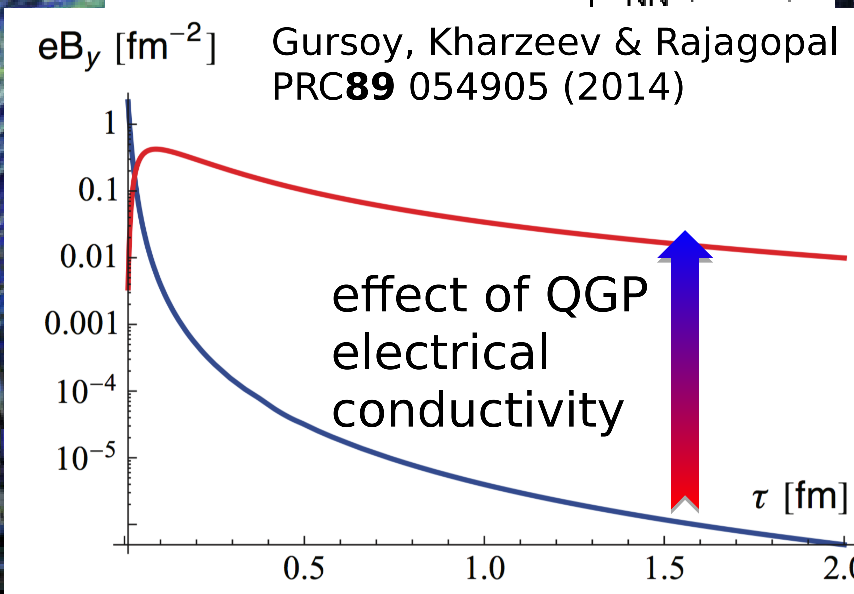
Magnetic field:

- Expected sign

$$B \sim 10^{14}\ \text{Tesla}$$
$$eB \sim 1\, m_\pi^2 \sim 0.5\, fm^{-2}$$



- Magnitude at high end of theory expectation (expectations vary by orders of magnitude)
- But... consistent with zero
  - –A definitive statement requires more statistics/better EP determination



Summary I

- Non-central heavy ion collisions create QGP with high vorticity
  - *generated* by early shear viscosity (closely related to initial conditions), *persists* through low viscosity
  - fundamental feature of *any* fluid, unmeasured until now
    - an incomplete characterization of QGP
    - relevance for other hydro-based conclusions?
- Huge and rapidly-changing B-field in non-central collisions
  - not directly measured
  - theoretical predictions vary by orders of magnitude
  - sensitive to electrical conductivity, early dynamics
- Both of these extreme conditions must be established & understood to put recent claims of chiral effects on firm ground

Summary II

- Global hyperon polarization: unique probe of vorticity & B-field
  - non-exotic, non-chiral
  - quantitative input to calibrate chiral phenomena
- STAR has made the first observation of global Λ polarization
  - statistics- & resolution-limited: 1-5σ effect for any given $\sqrt{s_{NN}}$
    - ~6σ effect on average
- Interpretation in magnetic-vortical model:
  - clear vortical component of right sign, magnitude for $\sqrt{s_{NN}} < 30$ GeV
  - magnetic component of right sign, magnitude *hinted at*, but consistent with zero at each $\sqrt{s_{NN}}$
- BES-II: Statistics & upgrades [Chi Yang 02/07 18:10] will allow characterization & model discrimination


END