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

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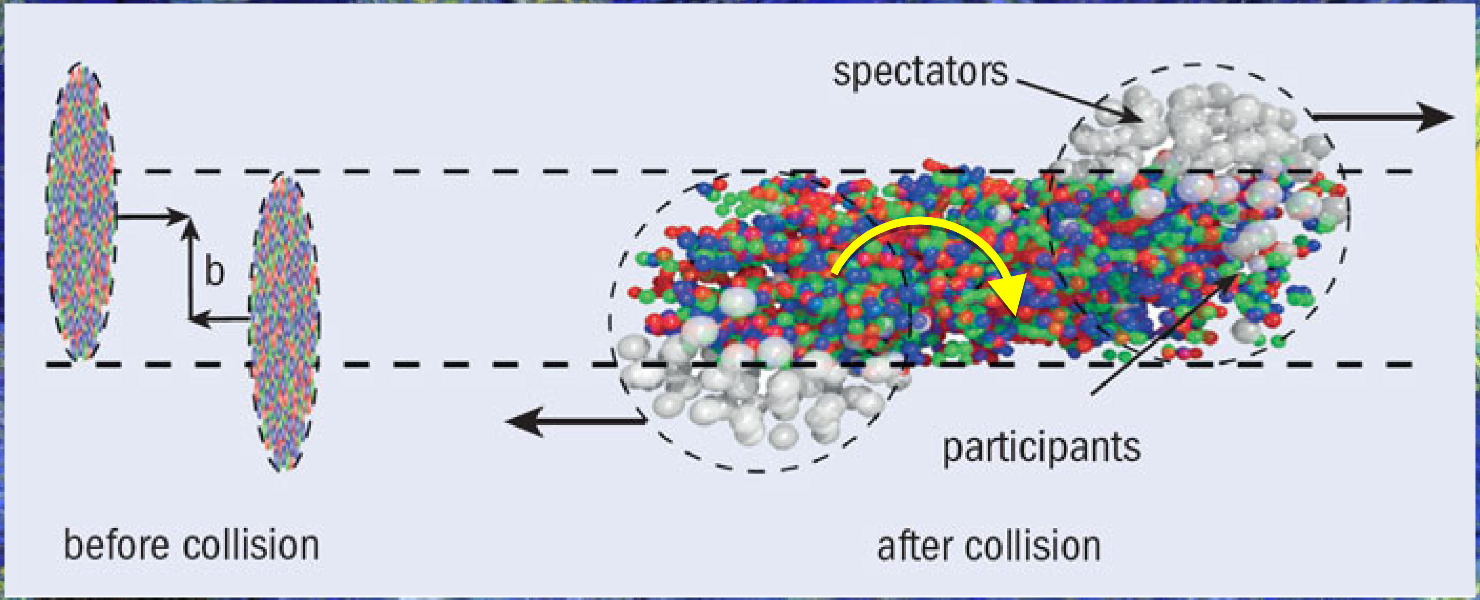
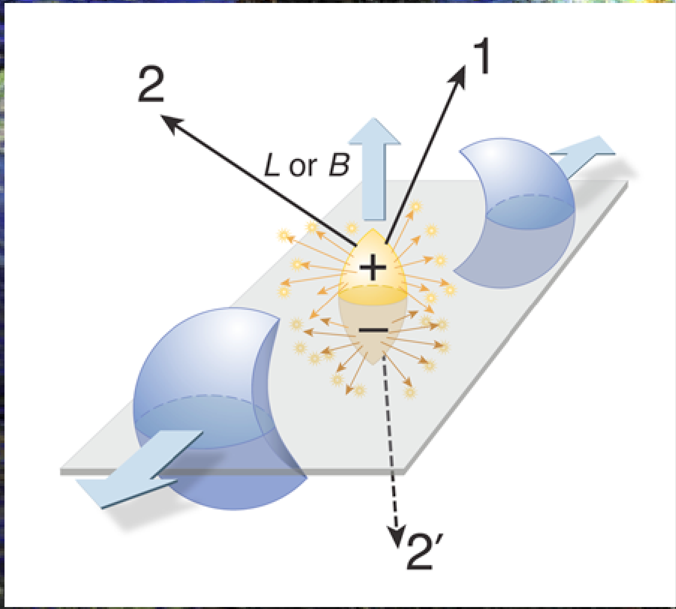
For the STAR collaboration

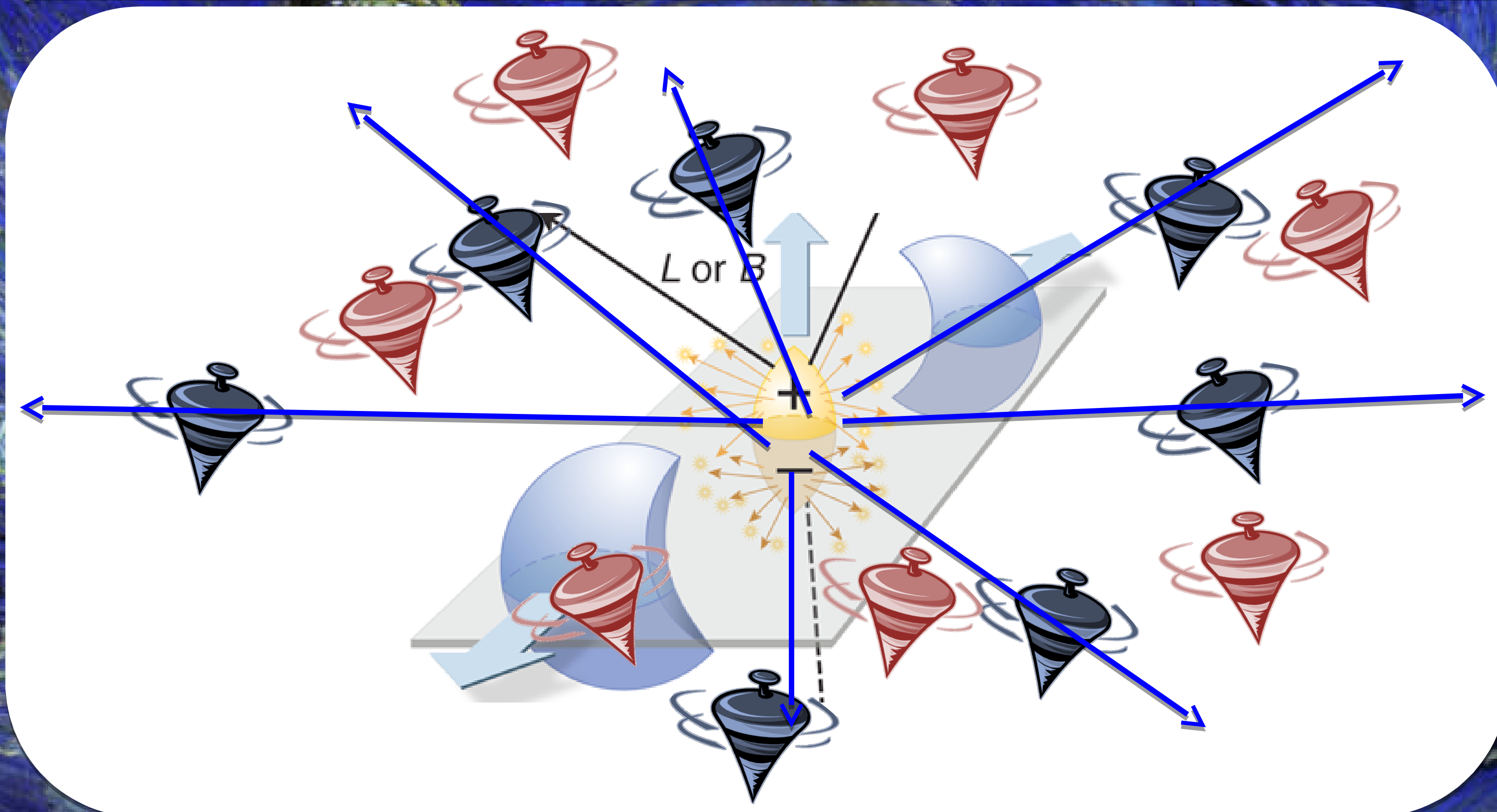
08/09/17





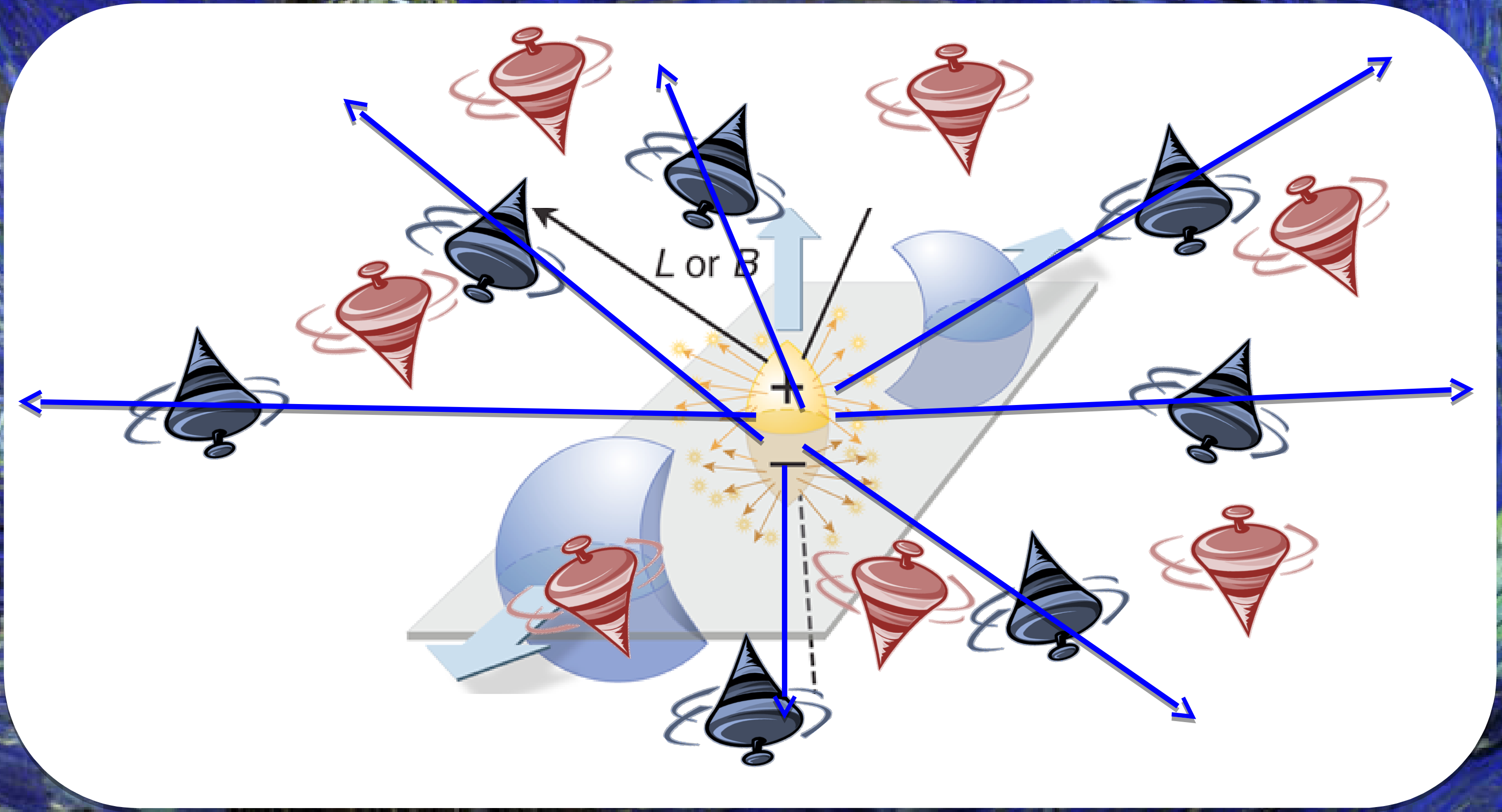
- $|L| \sim 10^3\ \hbar$ in non-central collisions
- How much is transferred to particles at mid-rapidity?
- Does angular momentum get distributed thermally?
- Does it generate a “spinning QGP?”
  - consequences?
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} \equiv \frac{1}{2} \vec{\nabla} \times \vec{v}$
- 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

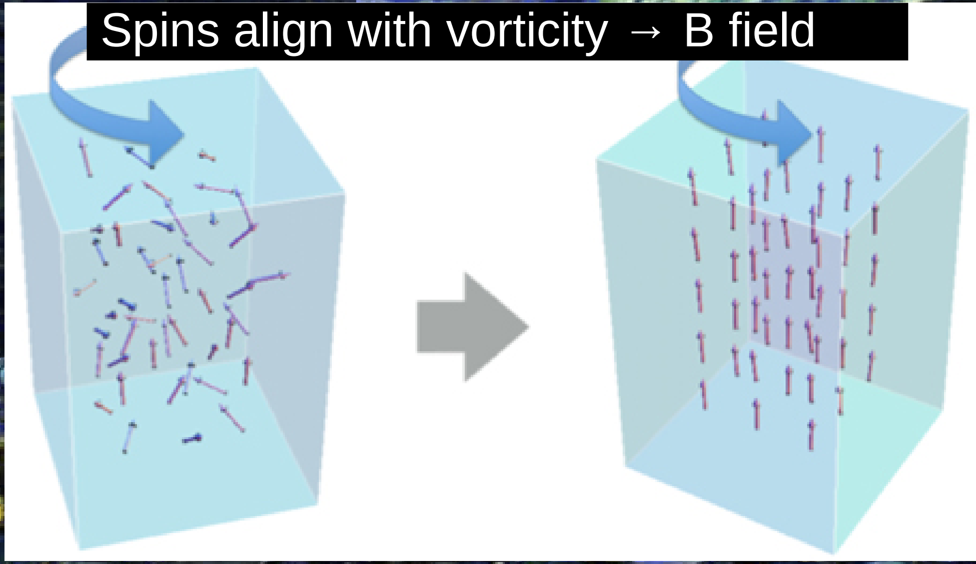
- Vortical or QCD spin-orbit: Lambda and Anti-Lambda spins aligned with L
- (electro)magnetic coupling: Lambdas *anti*-aligned, and Anti-Lambdas aligned

Barnett effect

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

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

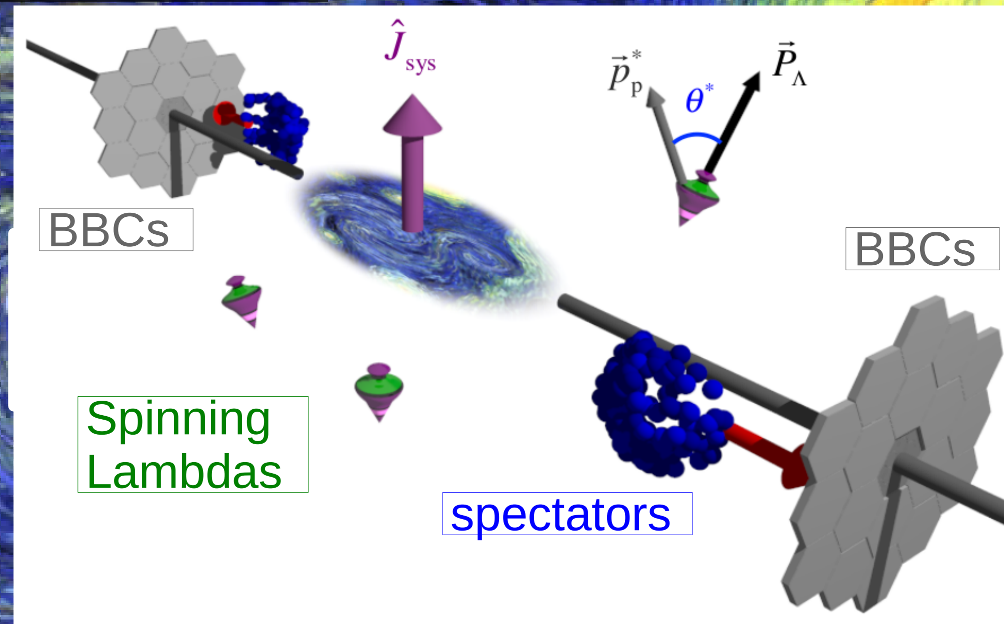
- γ = gyromagnetic ratio,
  χ = magnetic susceptibility

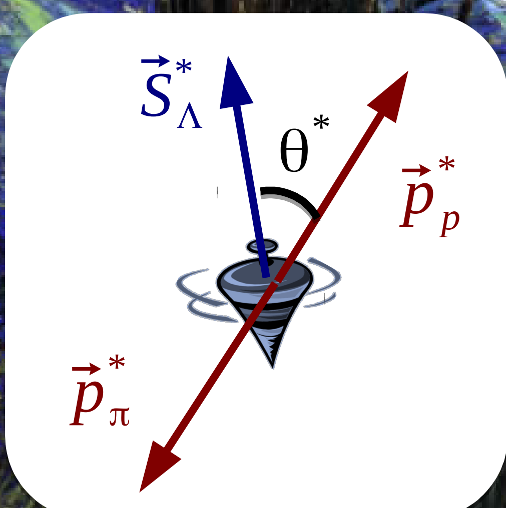


S.J. Barnett, Science 42, 163, 459 (1915); S.J. Barnett, Phys. Rev. 6, 239–270 (1915)

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:

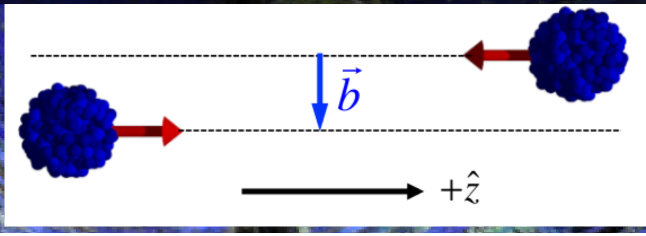
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha \vec{P} \cdot \hat{p}_p^*\right) = \frac{1}{4\pi}\left(1 + \alpha P \cos\theta^*\right)$$

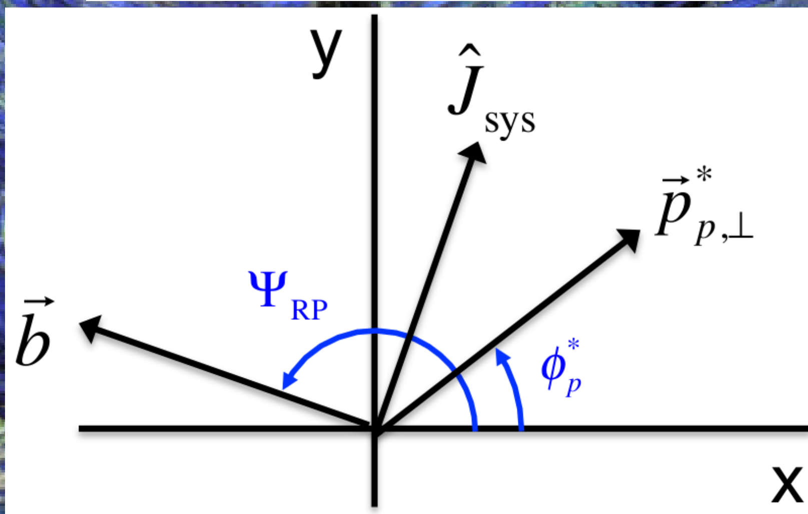
$\alpha = 0.642 \pm 0.013$ [measured]

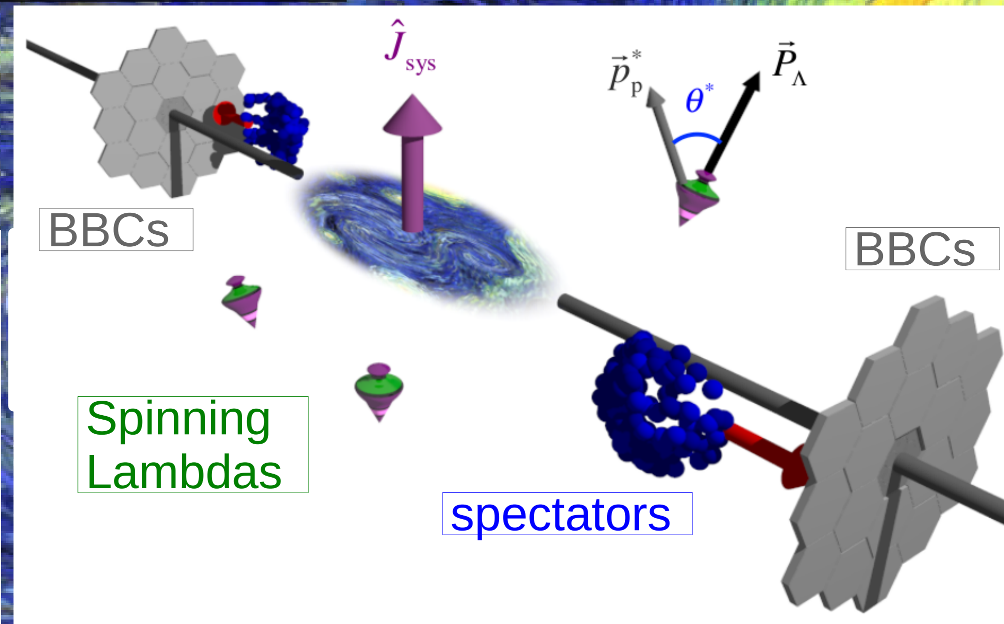
$\hat{p}_p^*$ is the daughter proton momentum direction *in the Λ frame* (note that this is opposite for $\overline{\Lambda}$)

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

How to quantify the effect (II)







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

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

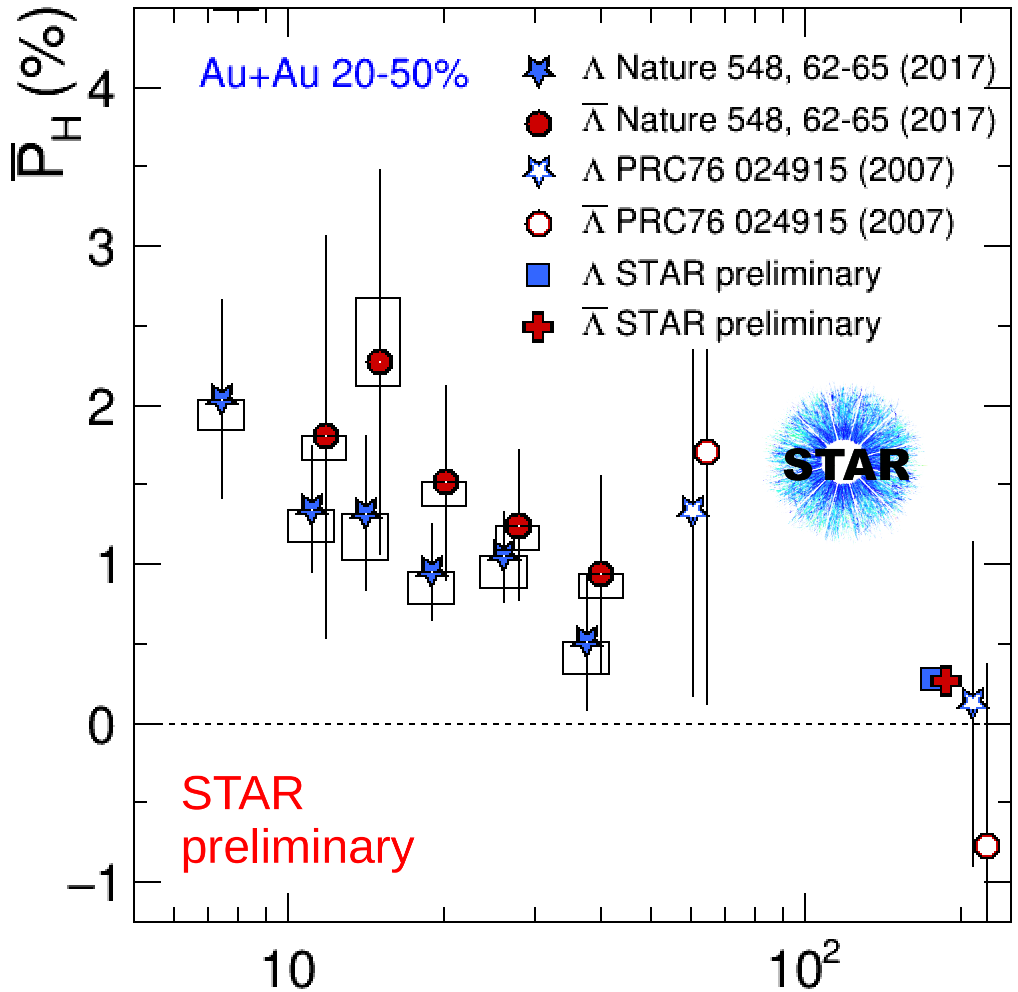
$P_{AVE} = \frac{8}{\pi\alpha} \frac{\langle \sin(\varphi_{\hat{b}} - \varphi^*_p)\rangle}{R^{(1)}_{EP}}$ ** where the average is performed over events and Λs

$R^{(1)}_{EP}$ 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



STAR, Nature **548**, 62–65 (2017)

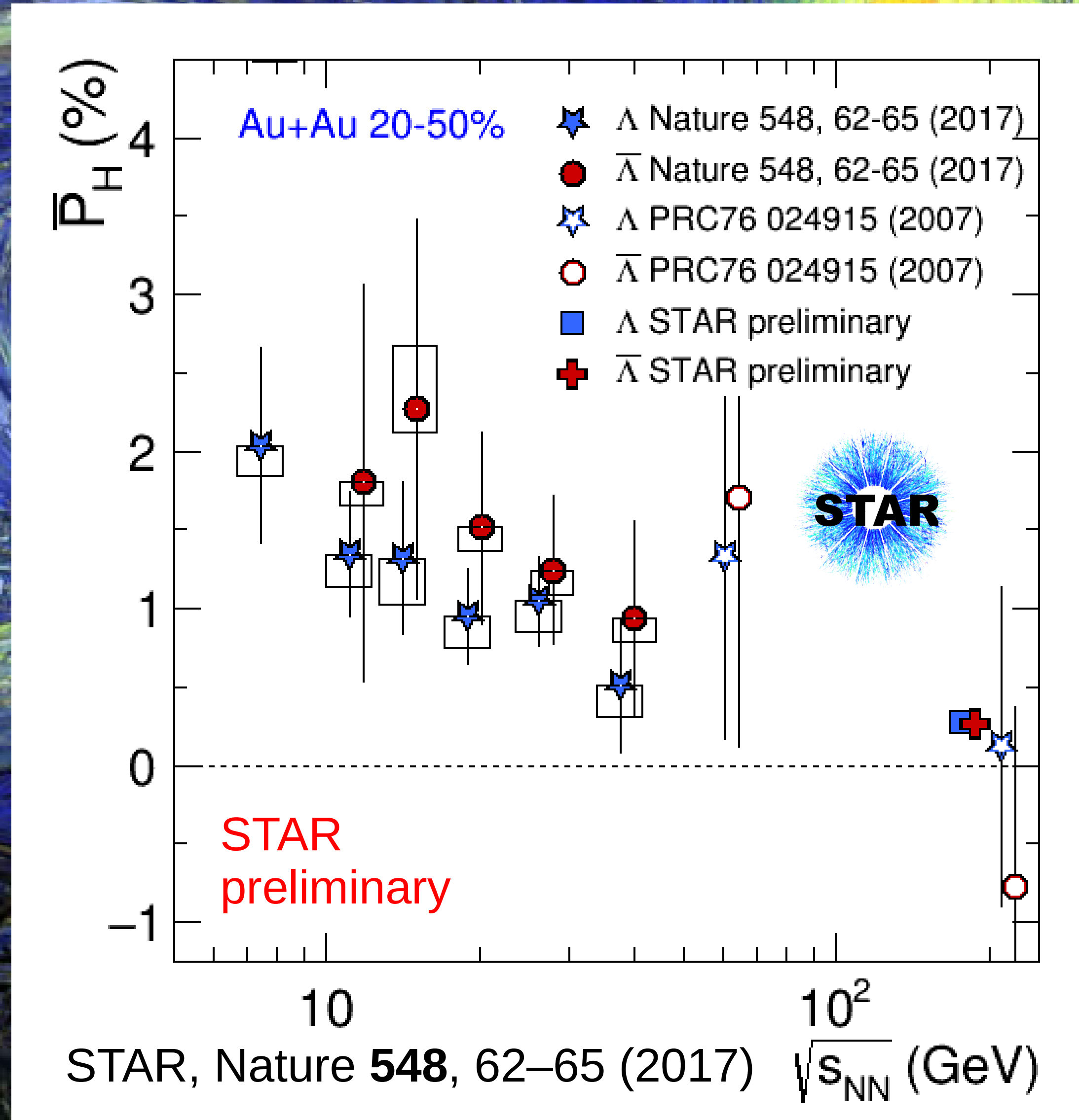
Global polarization measure

- Measured Lambda and Anti-
- previous STAR null result (2007)

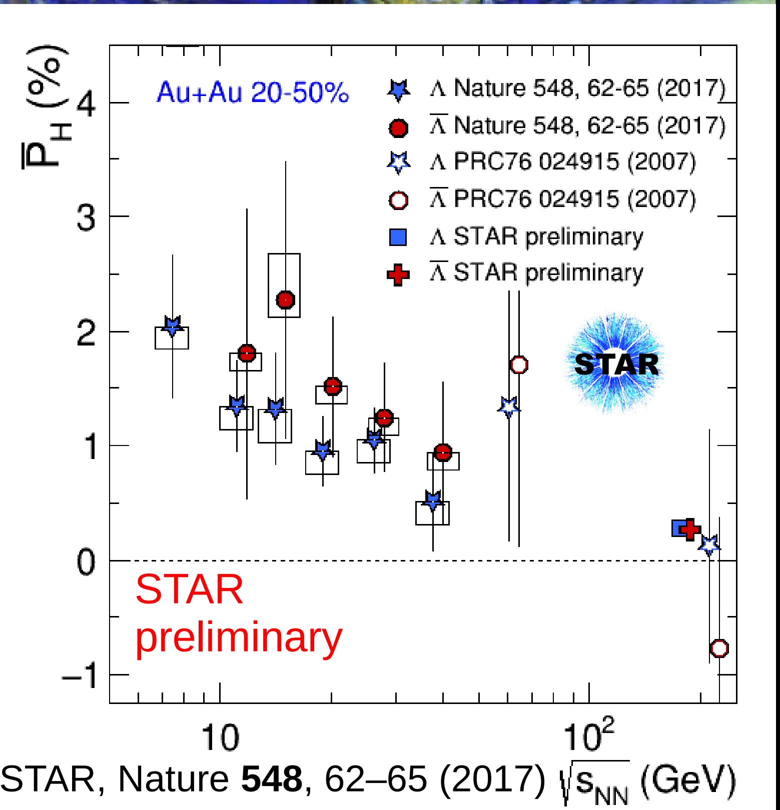
We can study more fundamental properties of the system

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

- $\overline{P}_H(\bar{\Lambda})>\overline{P}_H(\Lambda)$ would imply magnetic coupling



Vortical and Magnetic Contributions



STAR, Nature **548**, 62–65 (2017)

- 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 feed-down from Σ^0, $\Xi^{0/-}$, $\Sigma^{*\,\pm/0}$ … which themselves will be polarized...

Accounting for polarized feeddown

PRIMARY + FEED-DOWN POLARIZATION

VORTICAL COMPONENT

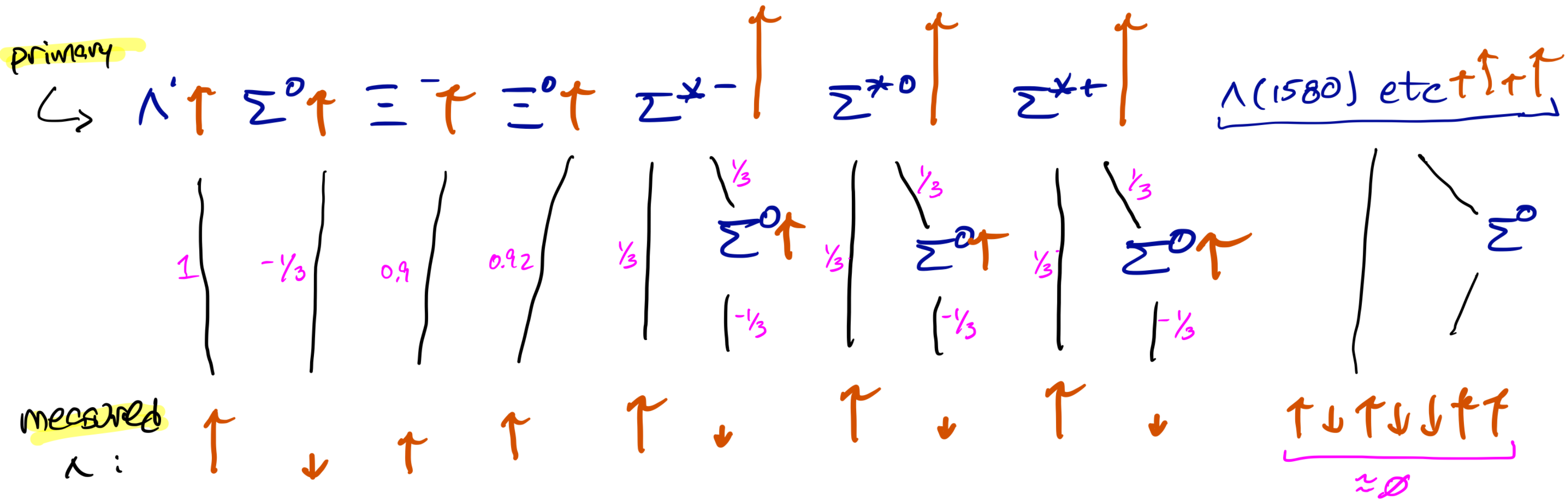
primary

↳ Λ ↑ Σ^0 ↑ Ξ^- ↑ Ξ^0 ↑ Σ^{*-} ↑ Σ^{*0} ↑ Σ^{*+} ↑ $\Lambda(1580)$ etc ↑↑↑↑

Accounting for polarized feeddown

PRIMARY & FEED-DOWN POLARIZATION

VORTICAL COMPONENT



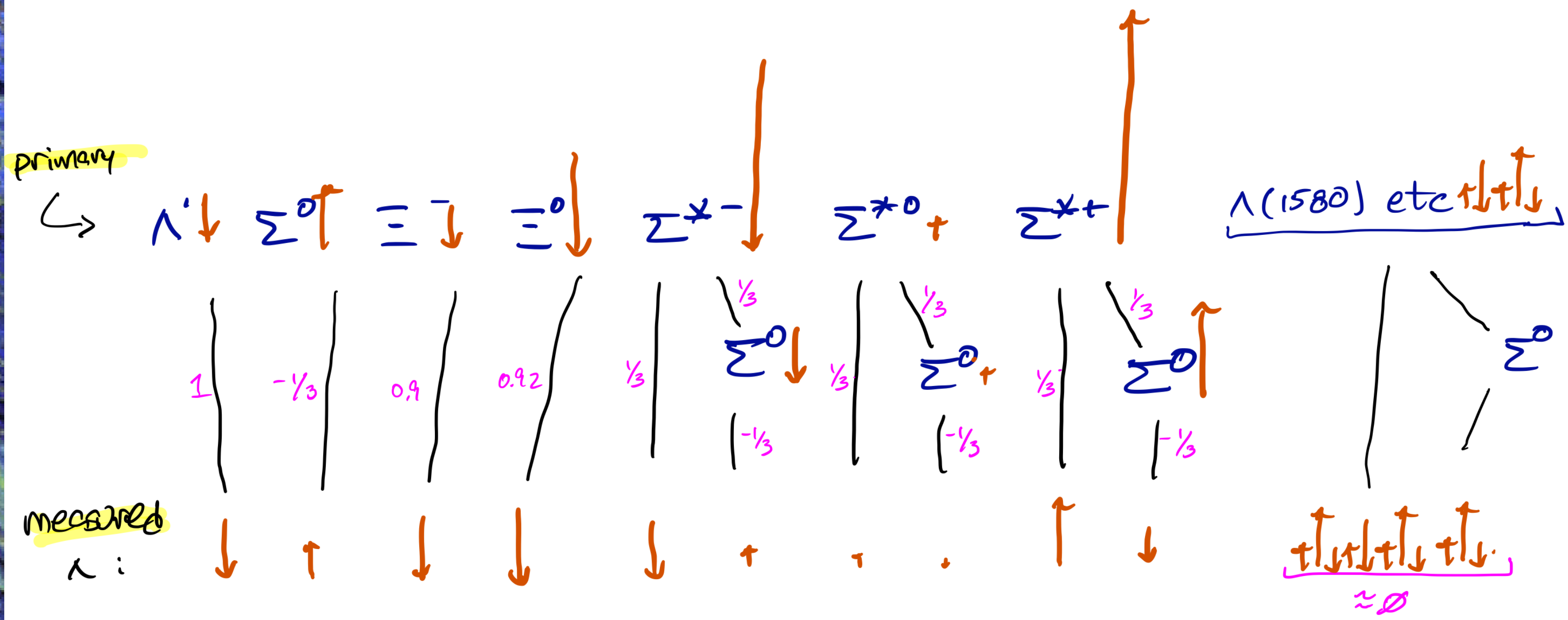
	J^π	μ		J^π	μ
Λ	$1/2^+$	-0.613	Σ^{*-}	$3/2^+$	-2.41
Σ^0	$1/2^+$	$+0.79$	Σ^{*0}	$3/2^+$	$+0.30$
Ξ^-	$1/2^+$	-0.651	Σ^{*+}	$3/2^+$	$+3.02$
Ξ^0	$1/2^+$	-1.25			

Becattini, Karpenko, Lisa, Upsal, Voloshin Phys. Rev. C **95**, 054902 (2017)

Accounting for polarized feeddown

PRIMARY + FEED-DOWN POLARIZATION

MAGNETIC COMPONENT



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Becattini, Karpenko, Lisa, Upsal, Voloshin Phys. Rev. C **95**, 054902 (2017)

Accounting for polarized feed-down

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

- $f_{\Lambda R} =$ fraction of Λs that originate from parent $R \rightarrow \Lambda$
- $C_{\Lambda R} =$ 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

From a statistical hadronization model with STAR measurements as parameter inputs (THERMUS)

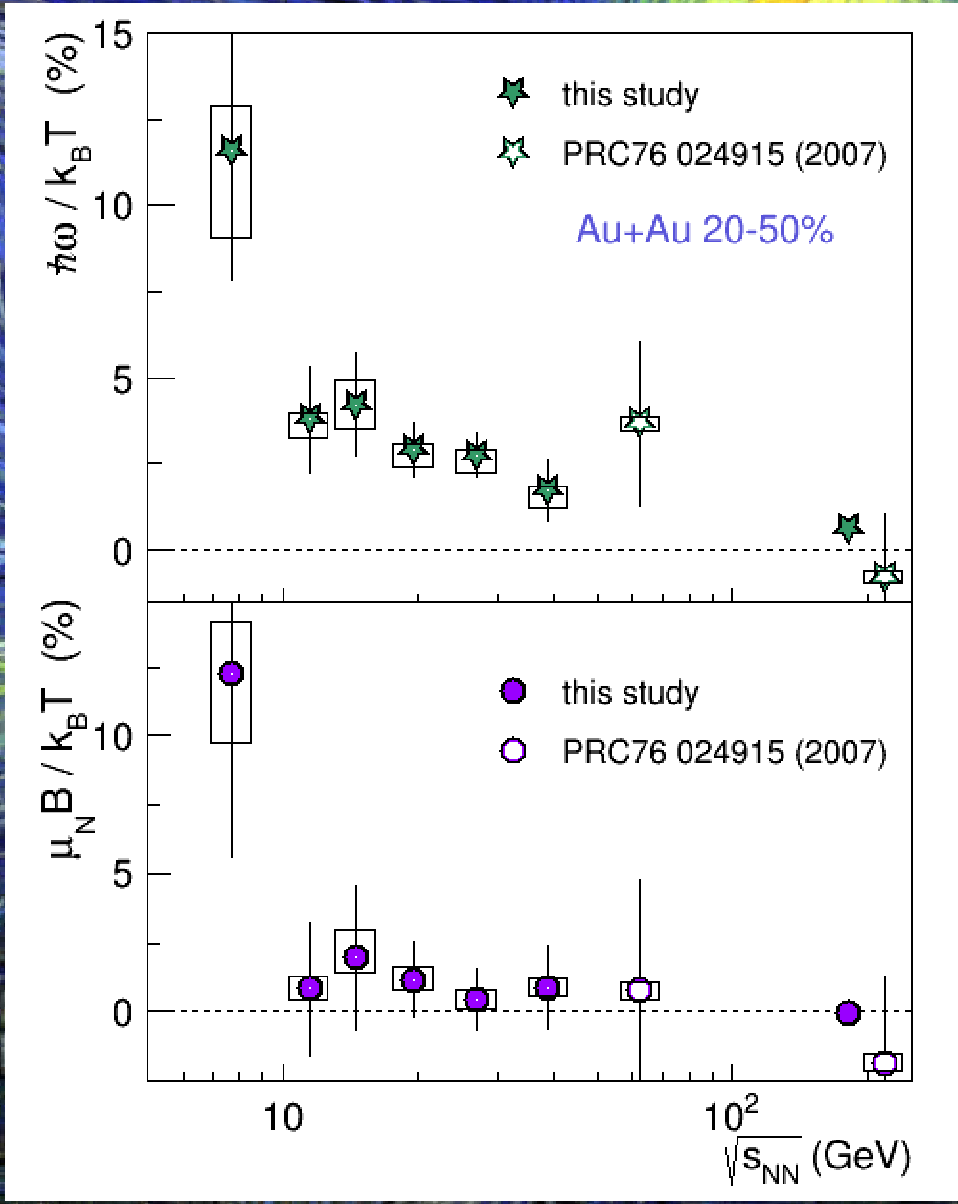
Decay	C
parity-conserving: $1/2^+ \rightarrow 1/2^+ \; 0^-$	$-1/3$
parity-conserving: $1/2^- \rightarrow 1/2^+ \; 0^-$	1
parity-conserving: $3/2^+ \rightarrow 1/2^+ \; 0^-$	$1/3$
parity-conserving: $3/2^- \rightarrow 1/2^+ \; 0^-$	$-1/5$
$\Xi^0 \rightarrow \Lambda + \pi^0$	$+0.900$
$\Xi^- \rightarrow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

** $\hbar = k_B = 1$

Becattini, Karpenko, Lisa, Upsal, Voloshin Phys. Rev. C **95**, 054902 (2017)

Extracted Physical Parameters

- Significant vorticity signal
  - Hints at falling with energy, despite increasing J_{sys}
  - 6σ average for 7.7-39 GeV
  - $P_{\Lambda_{primary}} = \frac{\omega}{2T} \sim 5\,\%$
- Magnetic field
  - $\mu_N \equiv \frac{e\hbar}{2m_p}$, where m_p is the proton mass
  - positive value, 2σ average for 7.7-39 GeV



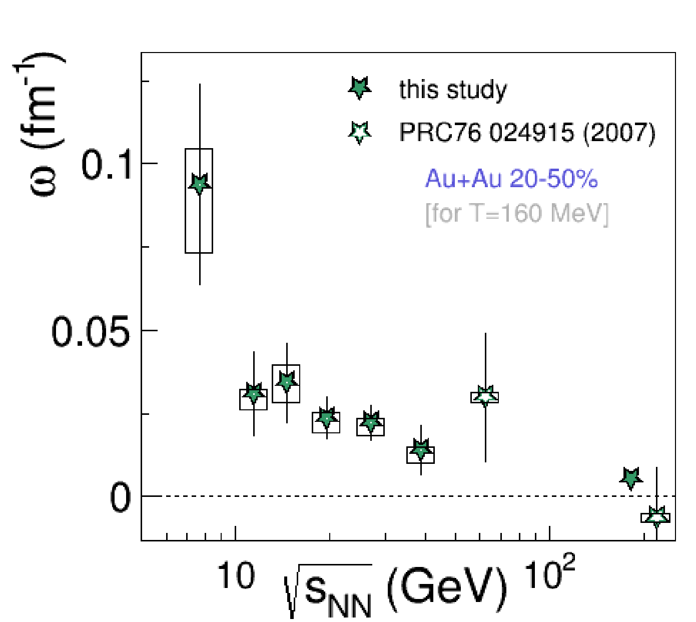
Vorticity ~ theory expectation

- Thermal vorticity:

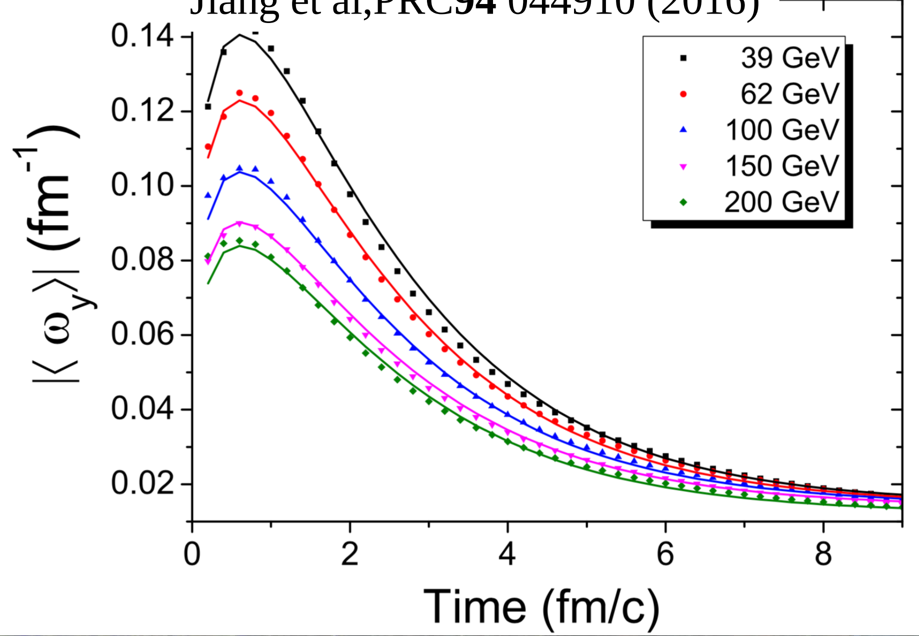
$$\frac{\omega}{T} \approx 2-10\,\%$$

$$\omega \approx 0.02-0.09\, fm^{-1} \quad (T_{assumed} = 160\,\text{MeV})$$

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



Jiang et al,PRC**94** 044910 (2016)



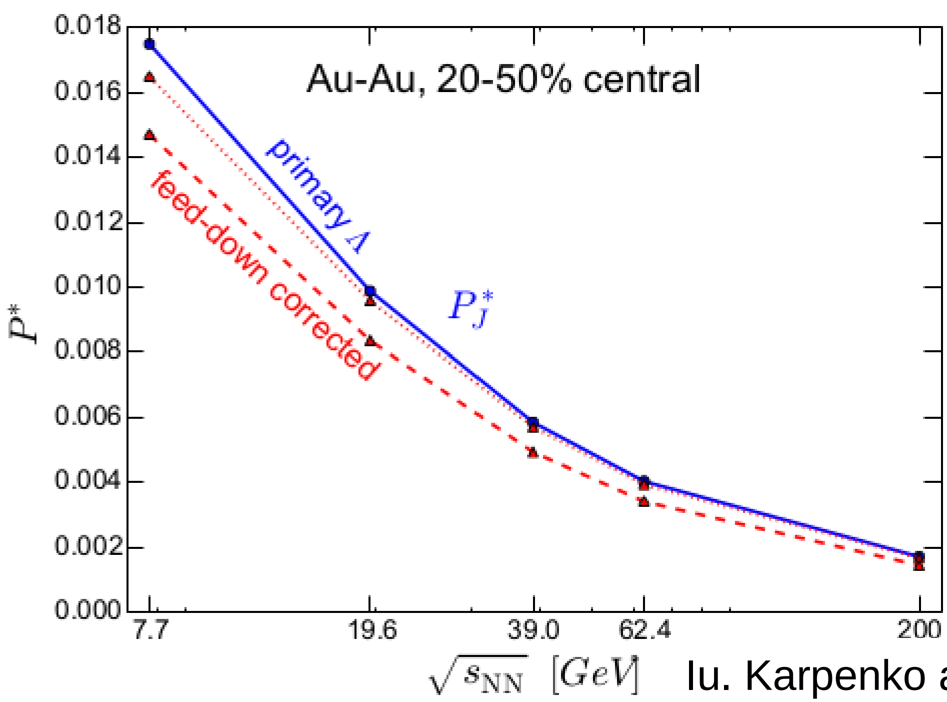
Csernai et al, PRC**90** 021904(R) (2014)

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.

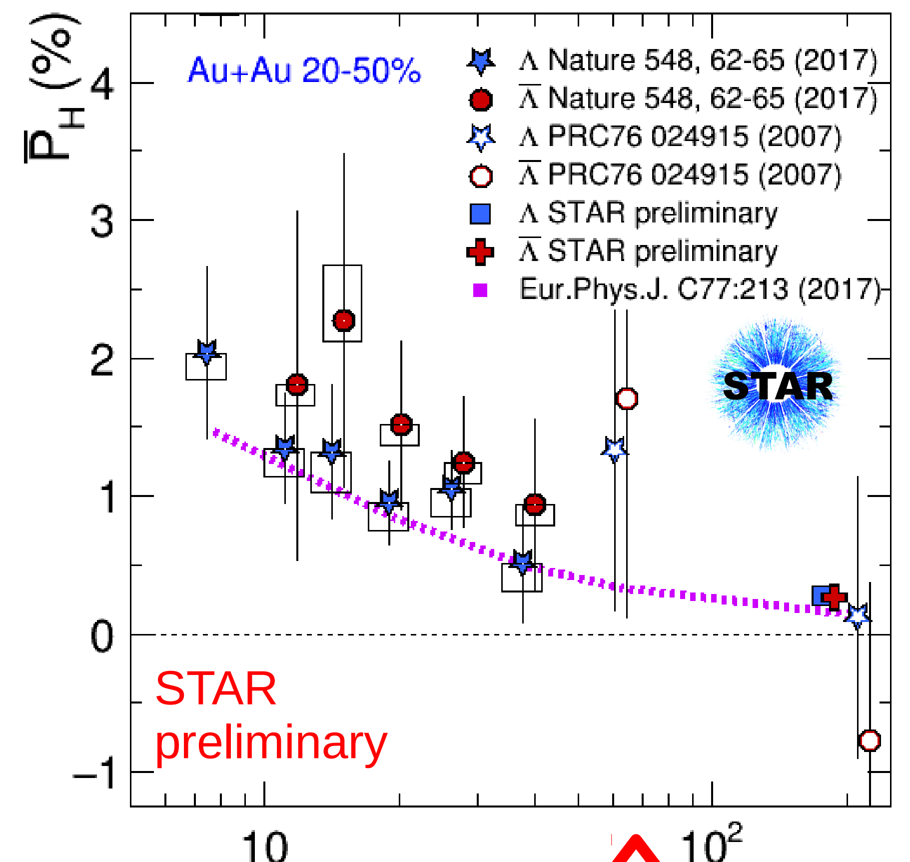
t (fm/c)	Vorticity (classical) (c/fm)	Thermal vorticity (relativistic) (1)
0.17	0.1345	0.0847
1.02	0.1238	0.0975
1.86	0.1079	0.0846
2.71	0.0924	0.0886
3.56	0.0773	0.0739

Polarization ~ theory expectation

- 3+1D viscous hydrodynamics
  - Not very sensitive to shear viscosity
  - Very sensitive to initial conditions
- Expectation: falling with √s



Iu. Karpenko and F. Becattini Eur. Phys. J. C (2017) 77: 213



STAR, Nature **548**, 62–65 (2017)

Compare “feed-down corrected” curve in dashed magenta line

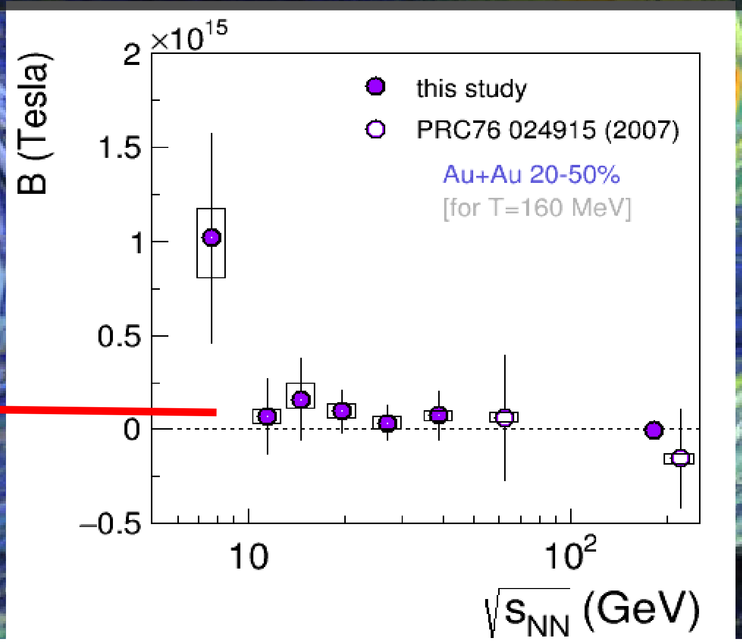
B-Field ~ theory expectation

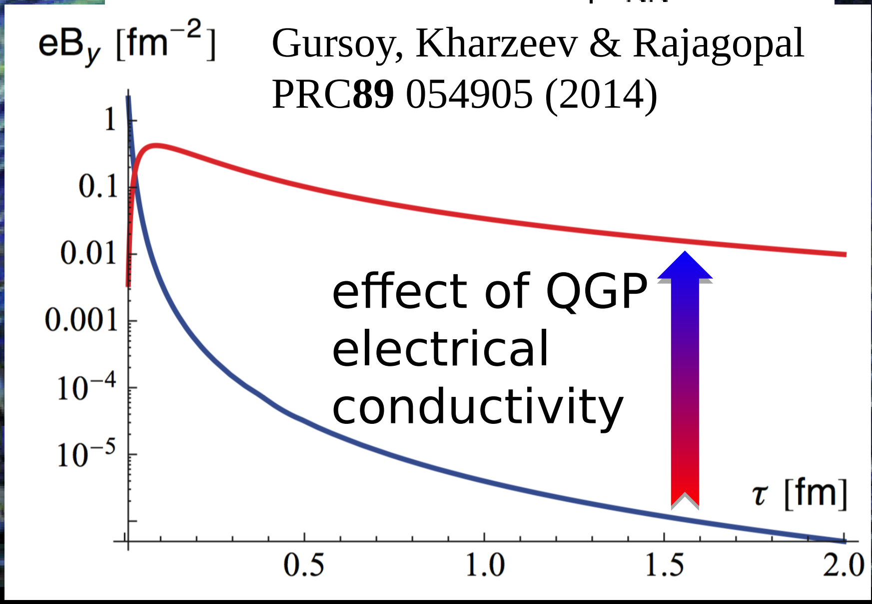
Magnetic field:

- Expected sign

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

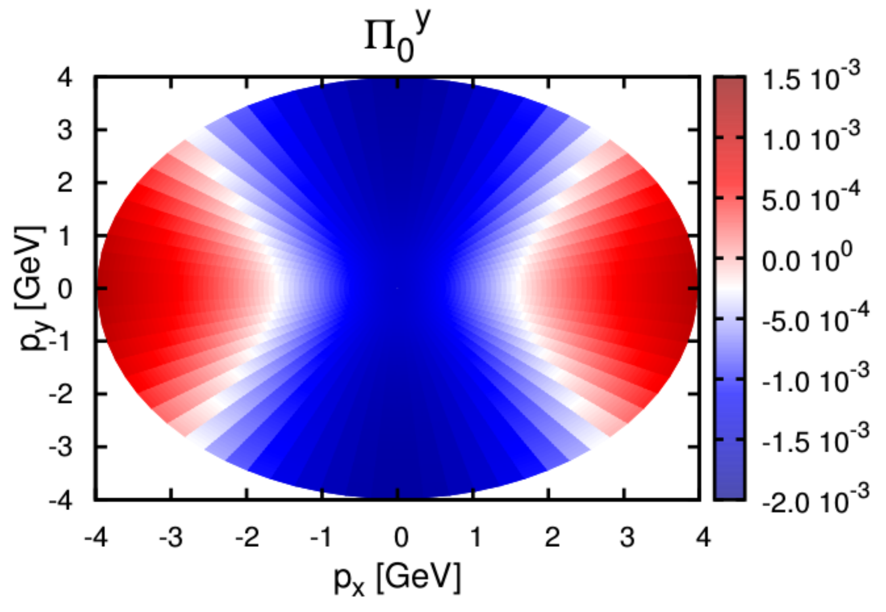
- Magnitude at high end of theory expectation (expectations vary by orders of magnitude)
- But… consistent with zero
  - –A definitive statement requires improved statistics/EP determination





Azimuthal dependence

- Naively collision starts with strongest vorticity gradient in plane
- A model predicts the opposite dependence
- The dependence of P_H on $\varphi_\Lambda - \Psi_1$ tests spin local thermal equilibrium and model initial conditions



Becattini, F., Inghirami, G., Rolando, V. et al. Eur. Phys. J. C (2015) 75: 406

*Note that Π_0^y depicts the vorticity projected on the direction opposite to that of the system angular momentum

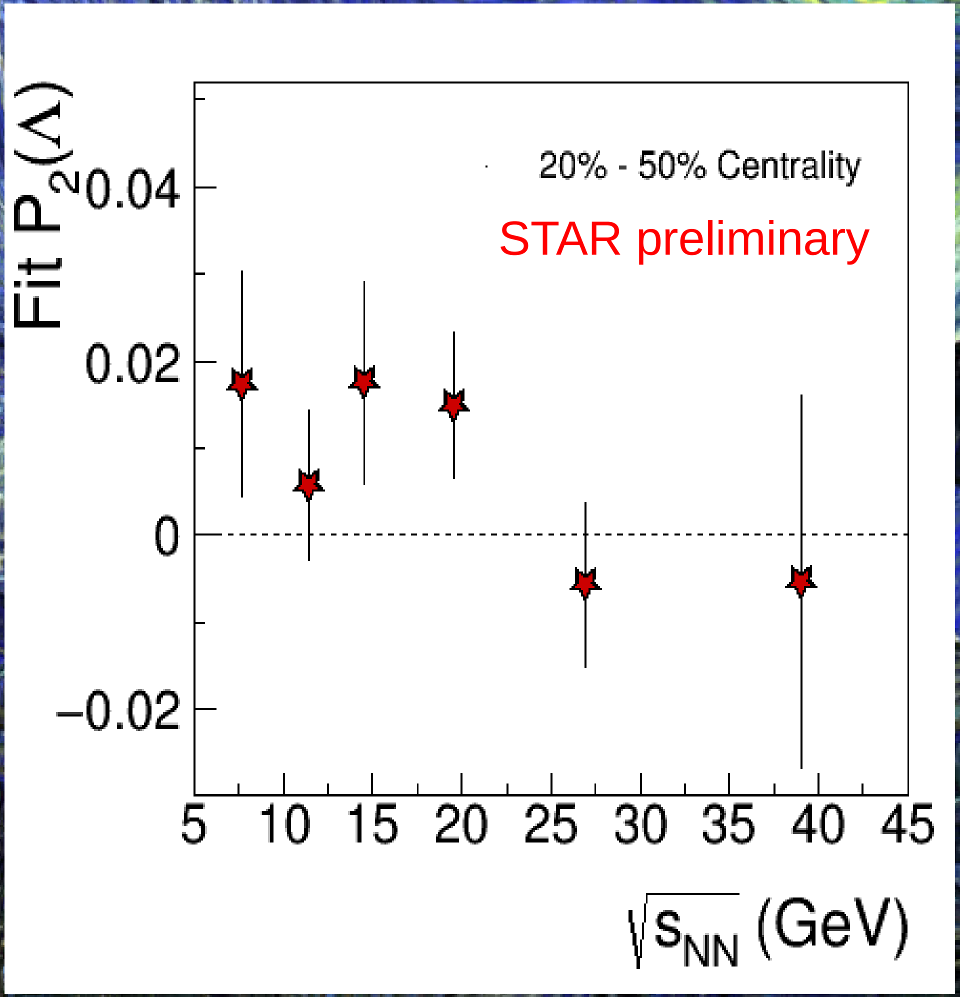
Azimuthal dependence (BES)

- Measure Lambda azimuthal dependence by fitting (like v_2) a second-order azimuthal dependent polarization P_2

- To properly perform resolution correction minimize χ^2 where x is $\varphi_\Lambda - \Psi_1$ (second order)

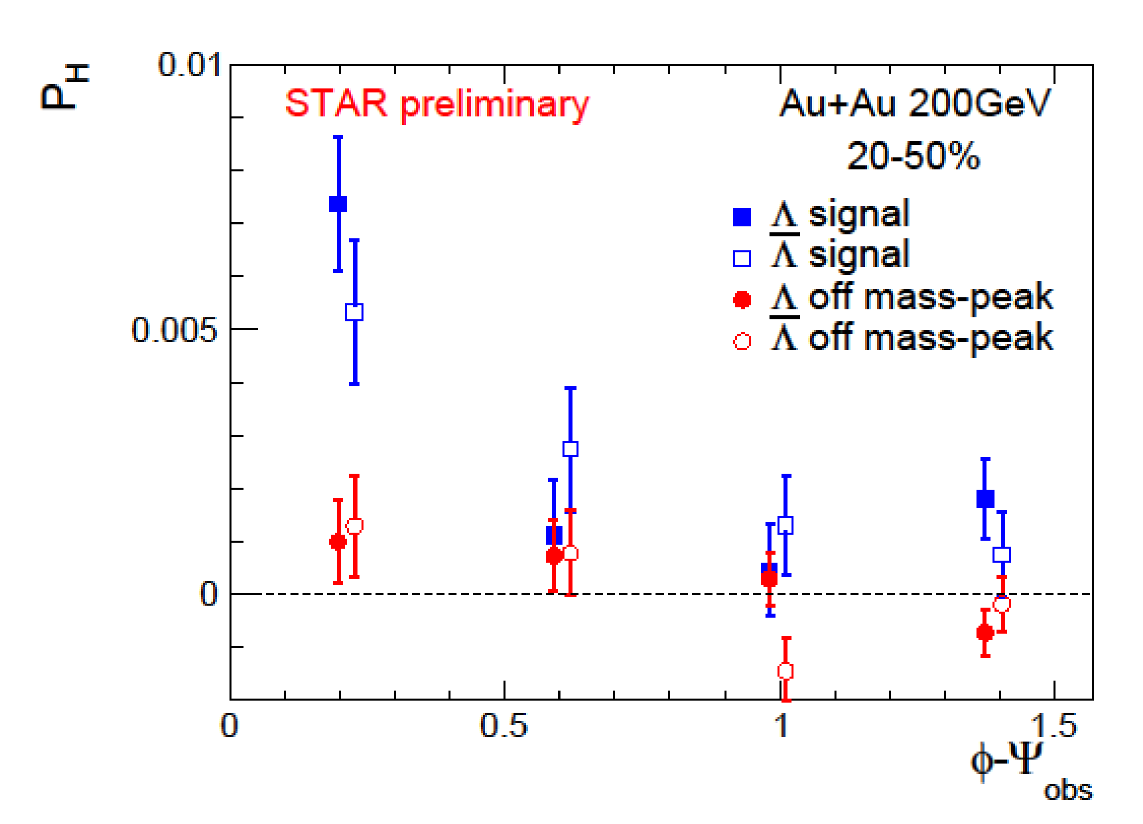
- Uncertainties for Anti-Lambda results larger than plot range

$$\chi^2 = \sum_{\text{Centrality, } i} \sum_{\varphi \text{ bins, } j} \frac{\left(P_H + R_i P_2 \cos(2x_j) - P_{i,j}\right)^2}{\sigma_{i,j}^2}$$



Azimuthal dependence (200GeV)

- Top energy results are more significant, allow for simple subtraction
- Difference in polarization between bin [0°, 22.5°] and bin [67.5°, 90°] for combined Lambdas and Anti-Lambdas is 4.7σ
  - Consistent with larger in-plane vorticity
- No resolution correction yet performed for smearing in $\varphi_\Lambda - \Psi_1$



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 in heavy-ion collisions
    - 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

- Interpretation in magnetic-vortical model:
  - clear vortical component of right sign
  - magnetic component of right sign, magnitude *hinted at* in BES, but consistent with zero at each $\sqrt{s_{NN}}$

- Azimuthal dependence may offer more insight into modeling
  - hint of BES signal, but clearer 200 GeV signal
  - results for Lambda and Anti-Lambda are consistent for 200GeV


END

Azimuthal dependence (BES)

- Measure Lambda azimuthal dependence by fitting (like v_2) a second-order azimuthal dependent polarization P_2
- To properly perform resolution correction minimize χ^2 where x is $\varphi_\Lambda - \Psi_1$ (second order)
- Errors for Anti-Lambda results are too large to display

$$\chi^2 = \sum_{\text{Centrality},\ i} \ \sum_{\varphi\ \text{bins},\ j} \frac{\left(P_H + R_i P_2 \cos(2 x_j) - P_{i,j}\right)^2}{\sigma_{i,j}^2}$$