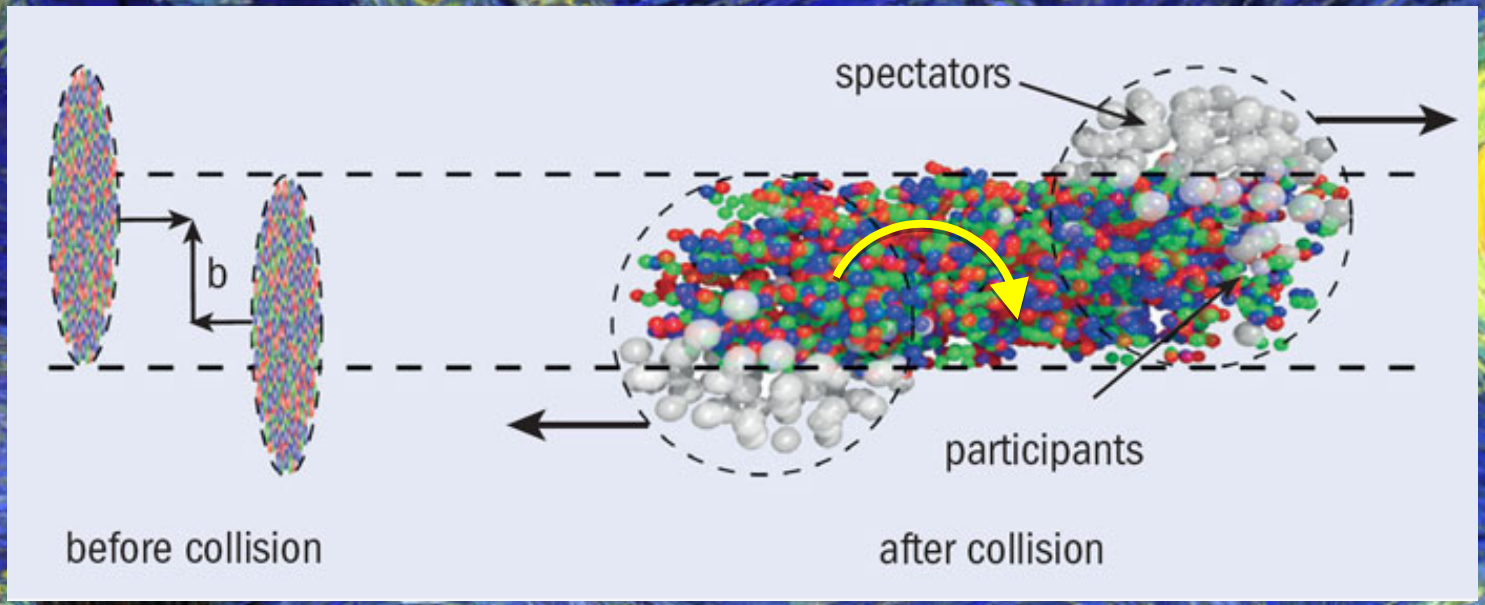
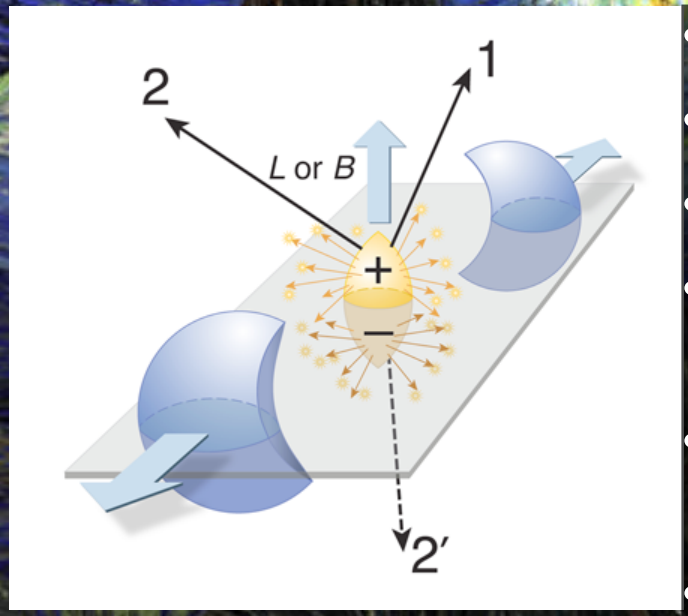
Global polarization opportunities for a RHIC isobar run

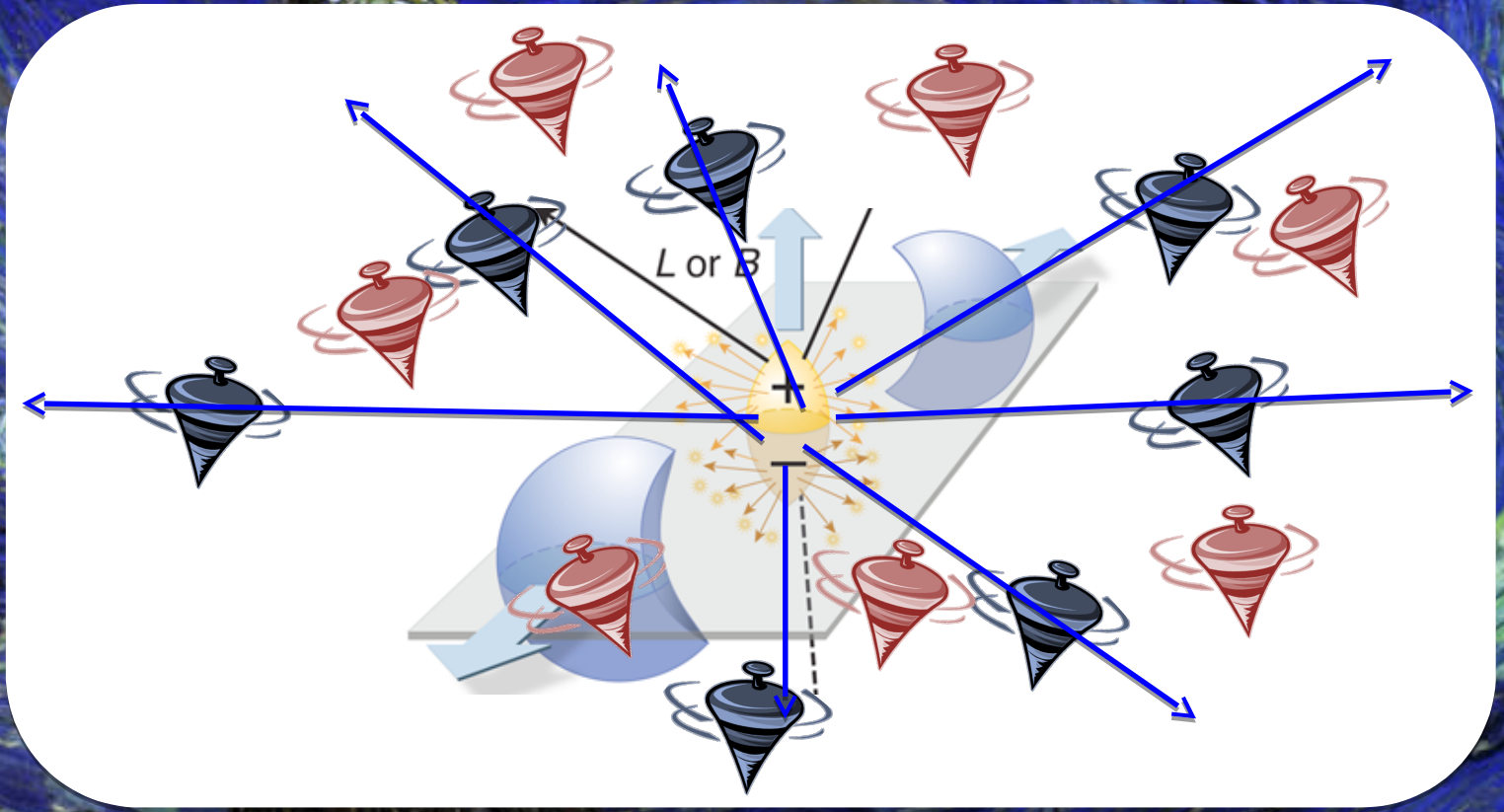
Isaac Upsal (OSU)
For the STAR collaboration
06/17





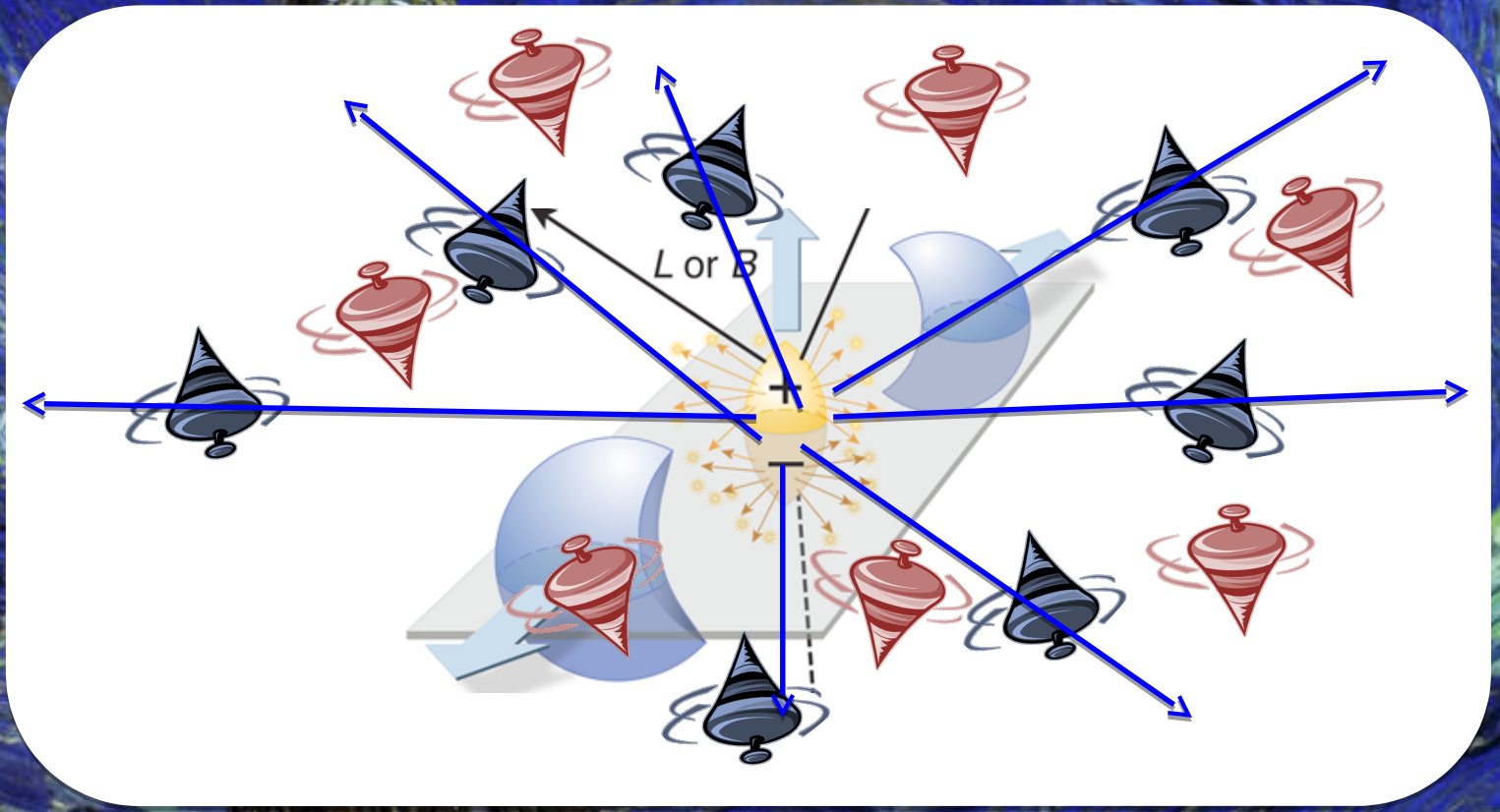
- $|L| \sim 10^3\ \hbar$ in non-central collisions
- How much is transferred to particles at mid-rapidity?
- Does angular momentum get distributed thermally?
- Does it generate a "spinning QGP?"
  - consequences?
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} \equiv \frac{1}{2}\vec{\nabla}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

Vorticity → Global Polarization



- <u>Vortical or QCD spin-orbit</u>: Lambda and Anti-Lambda spins aligned with L

Magnetic field → Global Polarization

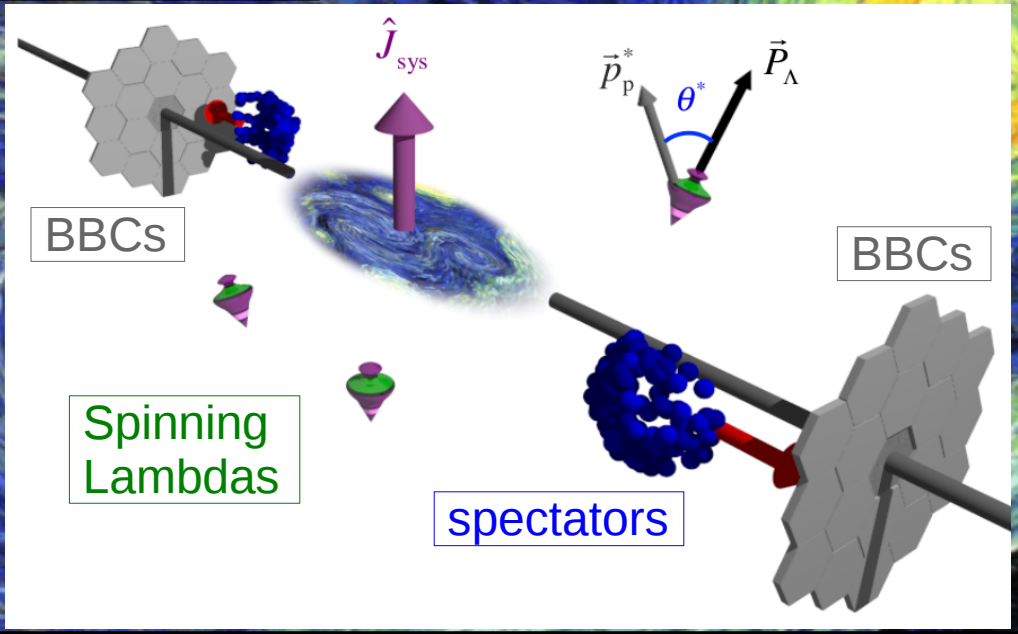


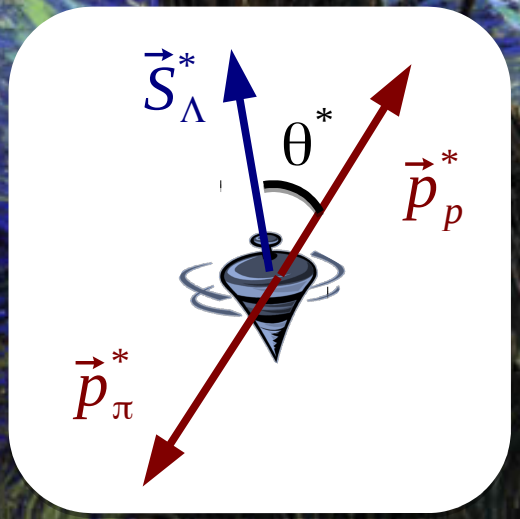
Both may contribute

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

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:

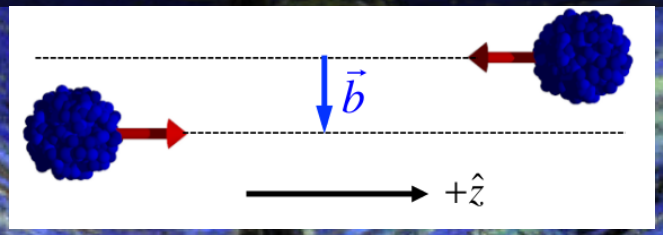
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\,\vec{P}\cdot\hat{p}^*_p\right) = \frac{1}{4\pi}\left(1+\alpha\,P\cos\theta^*\right)$$

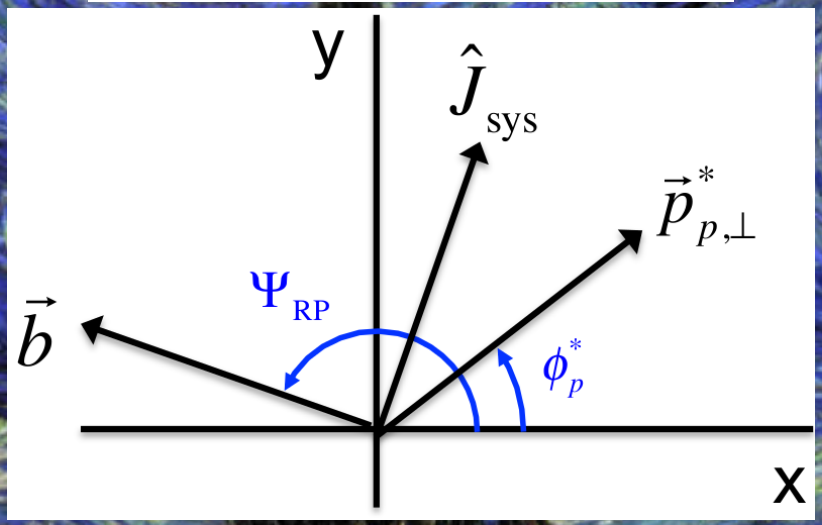
$\alpha = 0.642 \pm 0.013$ [measured]

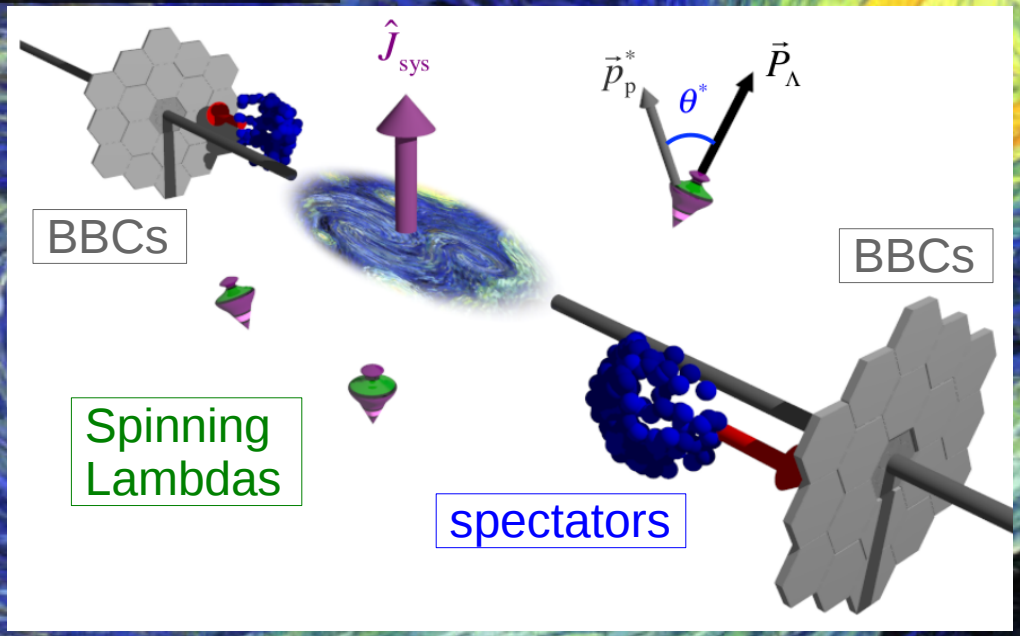
$\hat{p}^*_p$ is the daughter proton momentum direction *in the Λ frame* (note that this is opposite for $\overline{\Lambda}$)

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

How to quantify the effect (II)







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

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

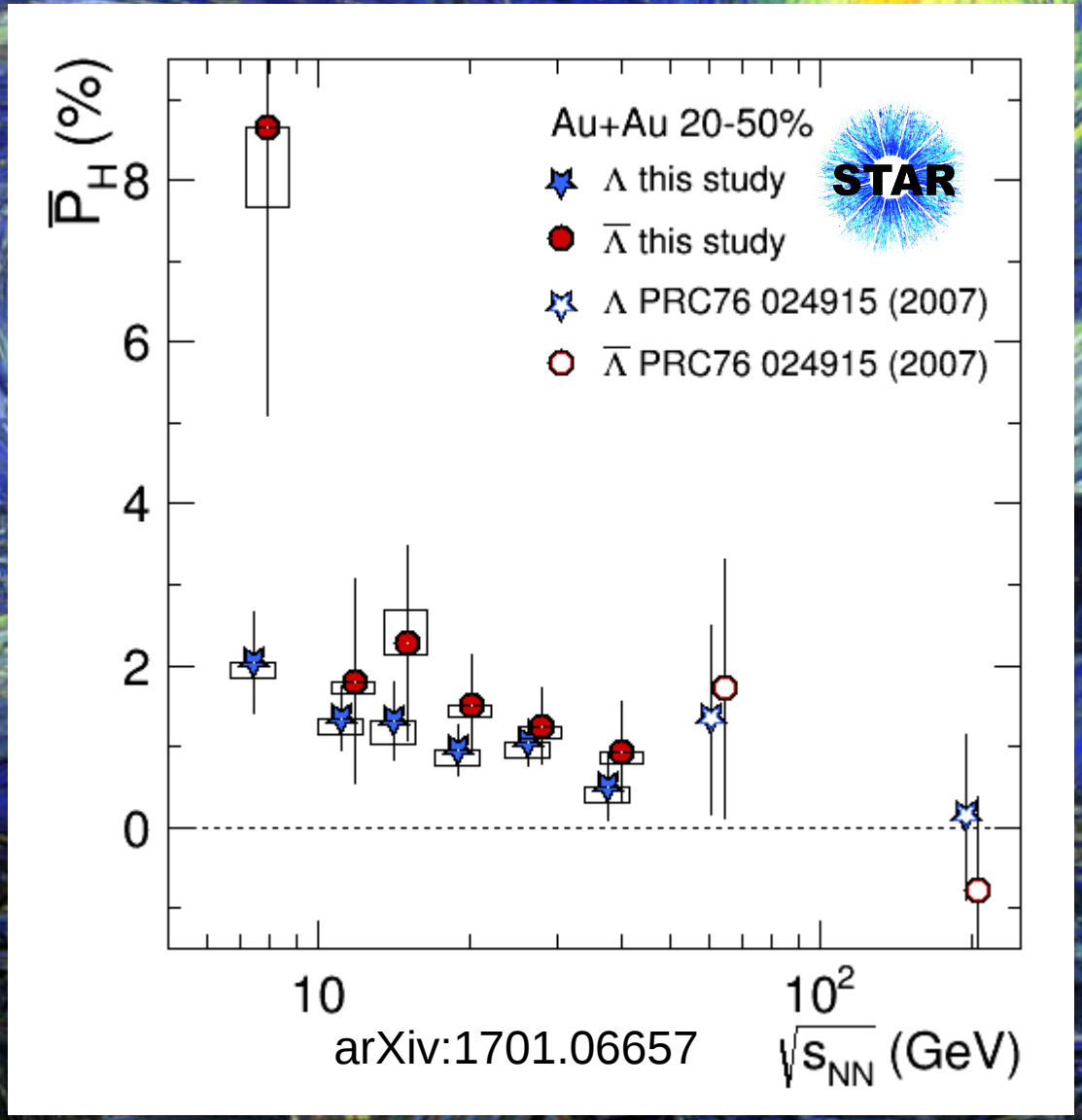
$P_{AVE} = \frac{8}{\pi\alpha} \frac{\langle \sin(\varphi_{\hat{b}} - \varphi^*_p)\rangle}{R^{(1)}_{EP}}$ ** where the average is performed over events and Λs

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

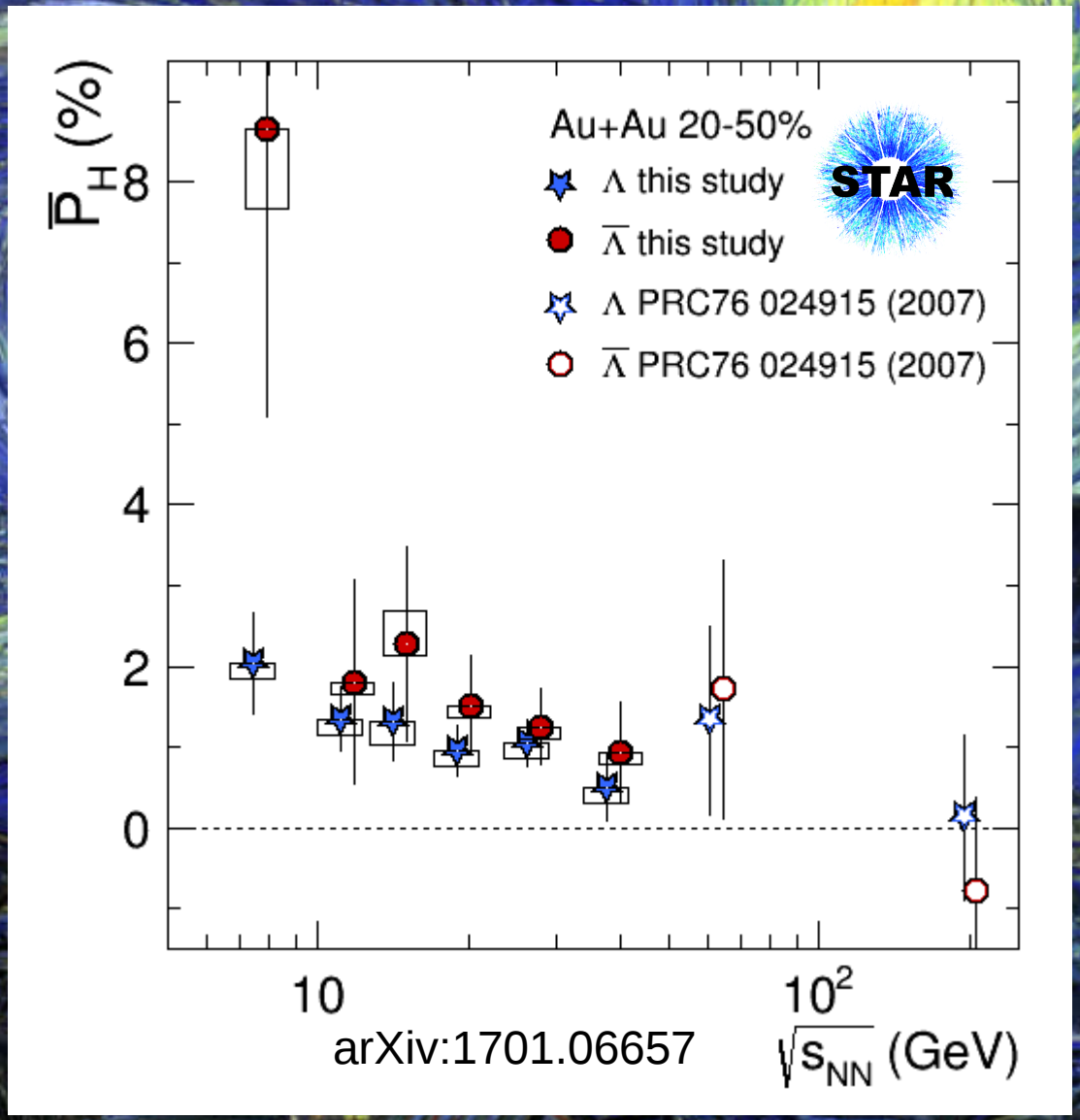


Global polarization measure

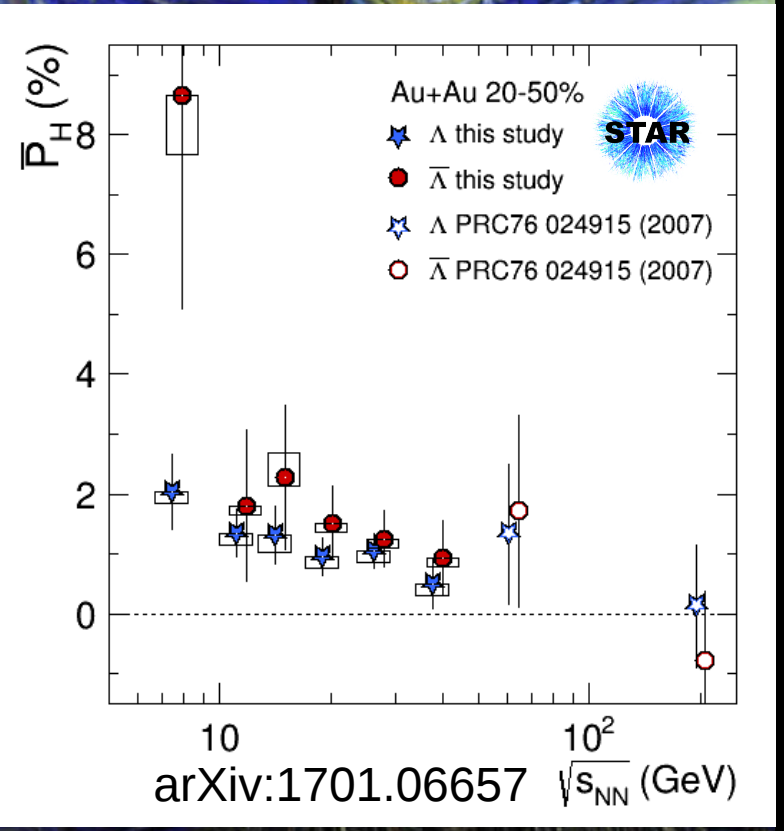
- Measured Lambda and Anti-
- previous STAR null result (2007)

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



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

PRIMARY + FEED-DOWN POLARIZATION

VORTICAL COMPONENT

primary

$\hookrightarrow \Lambda' \uparrow \quad \Sigma^0 \uparrow \quad \Xi^- \uparrow \quad \Xi^0 \uparrow \quad \Sigma^{*-} \uparrow \quad \Sigma^{*0} \uparrow \quad \Sigma^{*+} \uparrow \quad \underline{\Lambda(1580) \text{ etc} \uparrow \uparrow \uparrow}$

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

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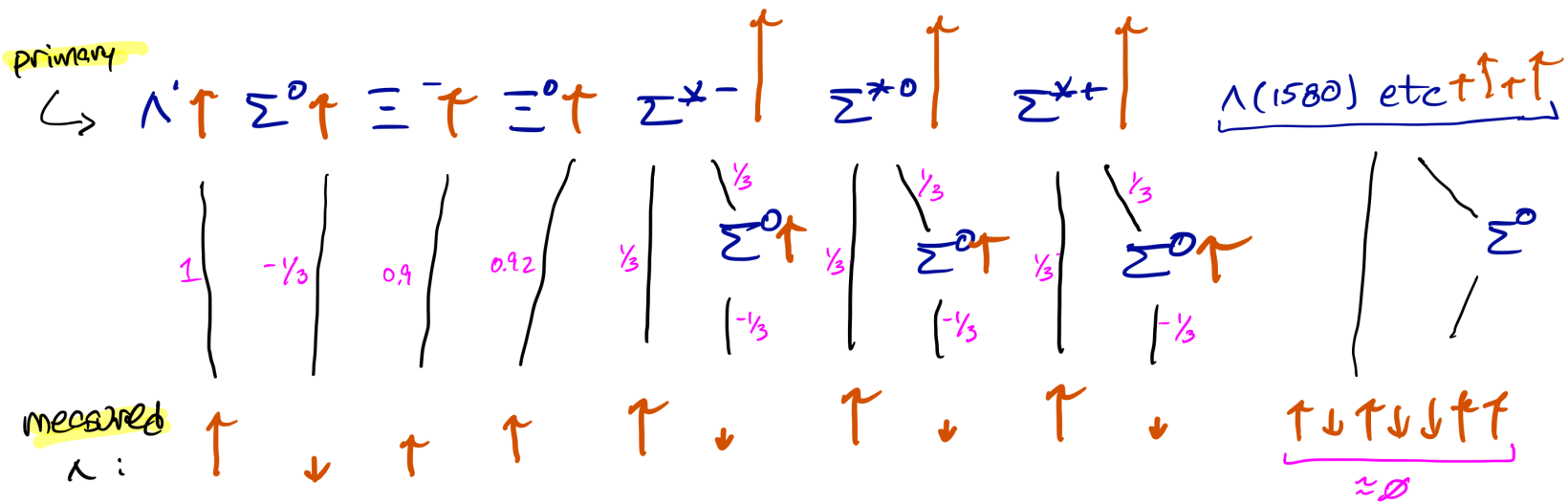

	J^{π}	μ		J^{π}	μ
Λ	$1/2^+$	-0.613	Σ^{*-}	$3/2^+$	-2.41
Σ^0	$1/2^+$	$+0.79$	Σ^{*0}	$3/2^+$	$+0.30$
Ξ^-	$1/2^+$	-0.651	Σ^{*+}	$3/2^+$	$+3.02$
Ξ^0	$1/2^+$	-1.25			

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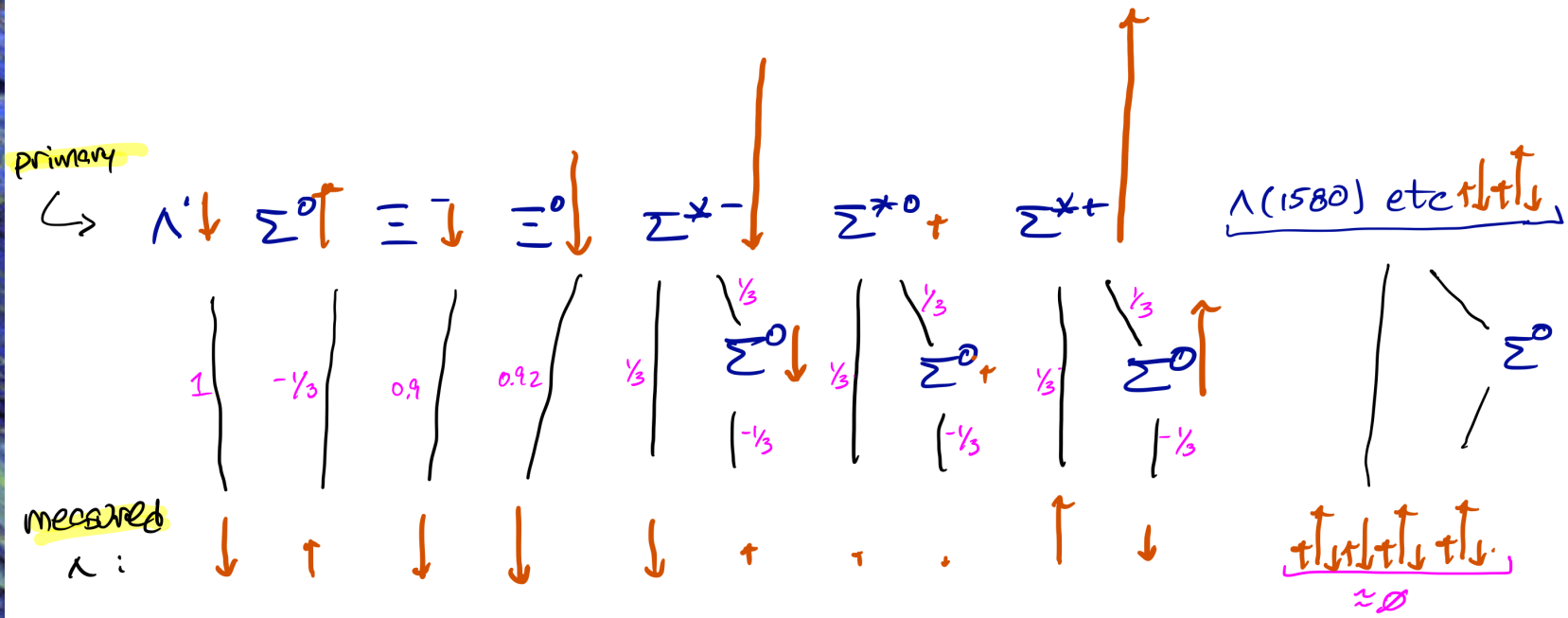
MAGNETIC COMPONENT



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

Accounting for polarized feeddown

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

- $f_{\Lambda R}$ = fraction of Λ s that originate from parent $R \rightarrow \Lambda$ → 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: $1/2^+ \rightarrow 1/2^+ \; 0^-$	$-1/3$
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

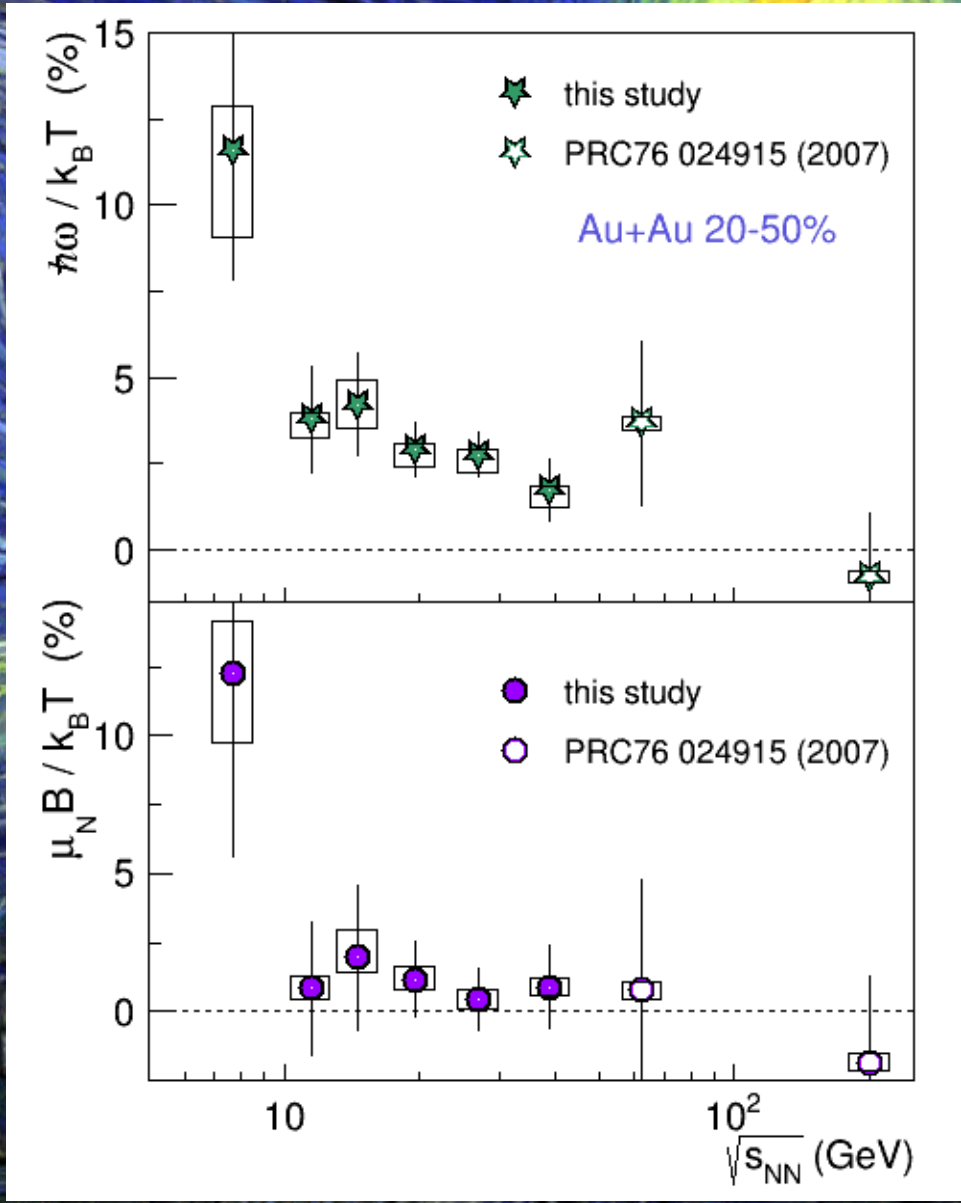
TABLE I. Polarization transfer factors C (see eq. (31)) for

** $\hbar = k_B = 1$

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, 1.5σ average for 7.7-39GeV



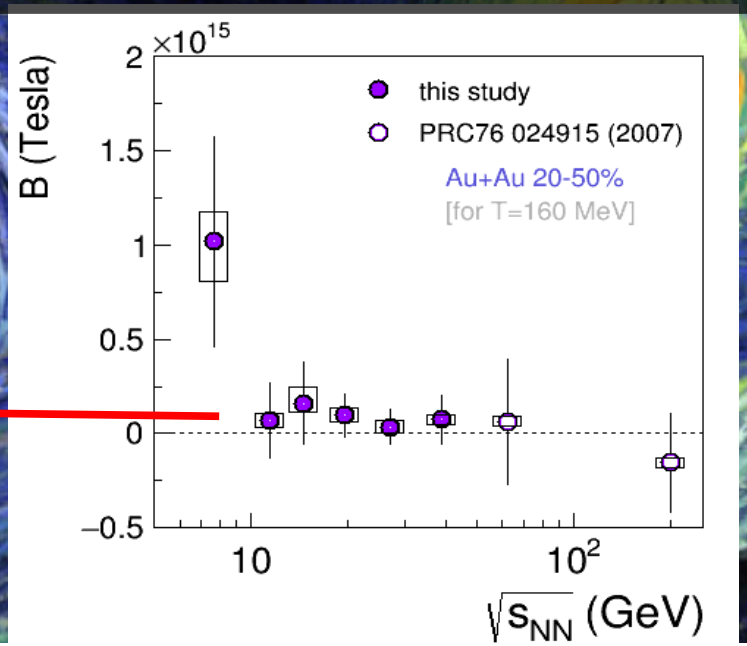
B-Field ~ theory expectation

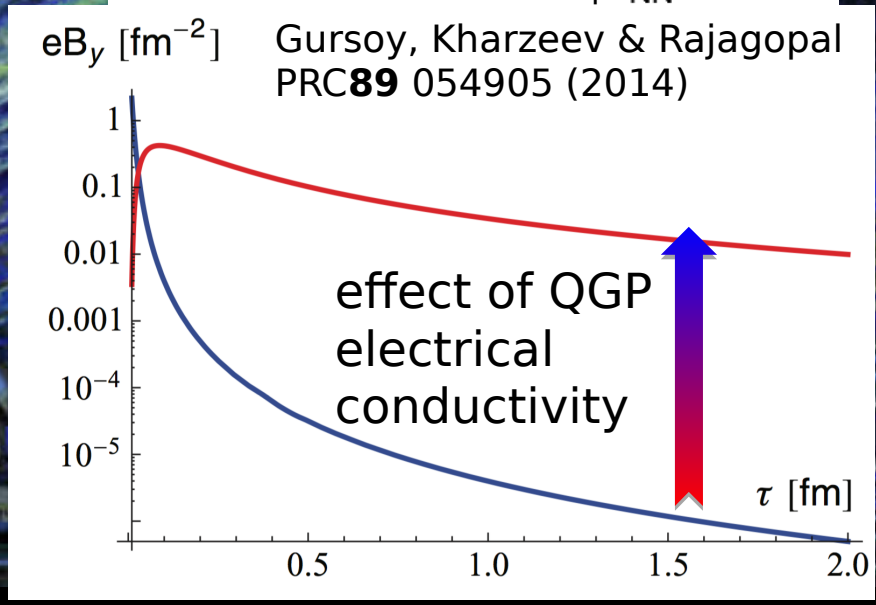
Magnetic field:

- 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





B-Field search

- The formalism makes sense, but is it correct?

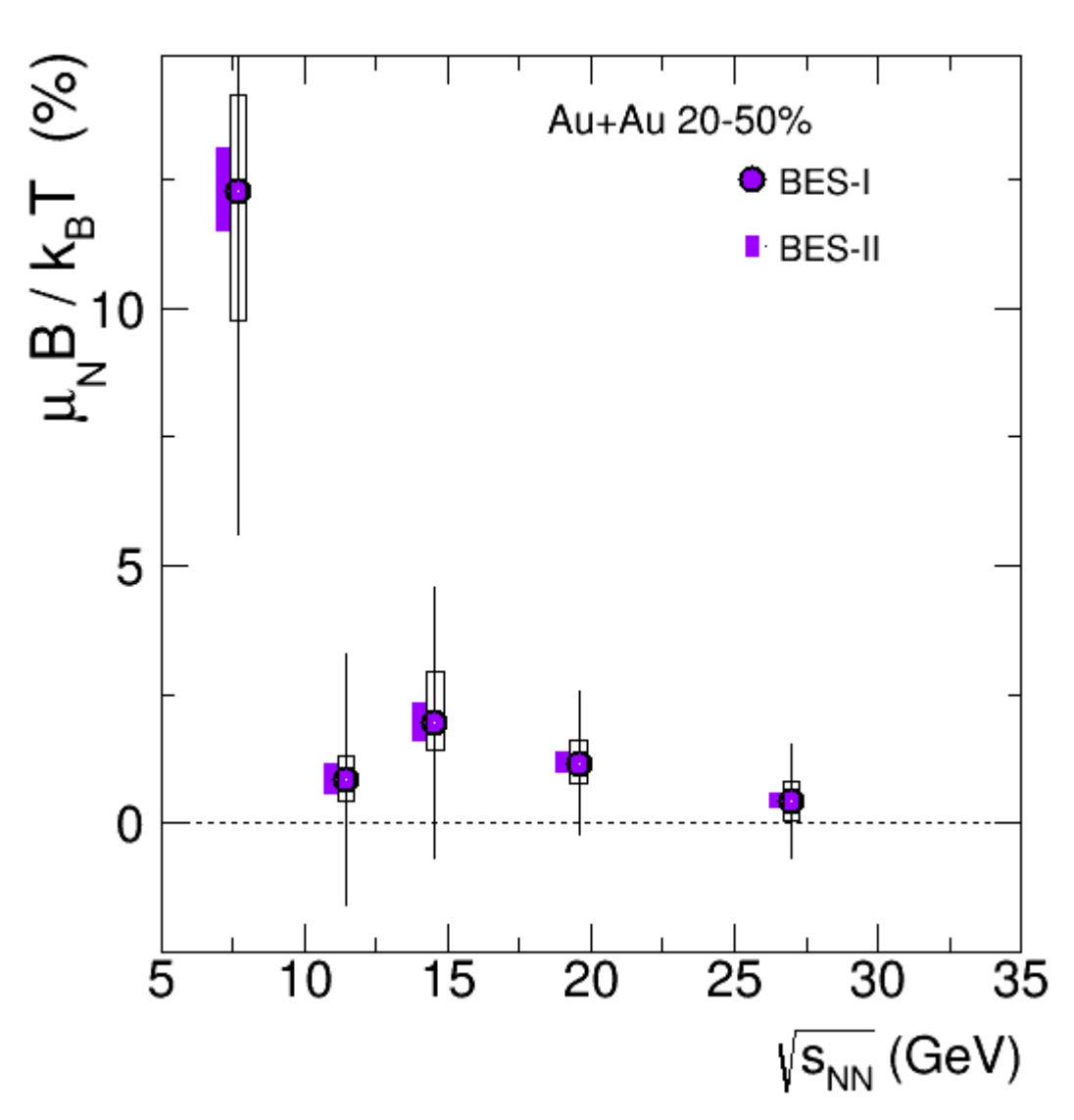
- Step 1: Determine that there is a difference in the Polarization of the Lambda and AntiLambda
  - BES II AuAu increased statistics and resolution

- Step 2: Determine if this difference can *best* be attributed to magnetic field
  - Isobar (^{96}Ru and ^{96}Zr) beam scan
  - Does the Lambda and AntiLambda polarization gap differ for the isobars?

effect of QGP
electrical
conductivity

BES-II Projections – “Is there a difference”

- Using statistics from Chi Yang's QM 2017 talk for BES II and 1B events for 27GeV in 2018
- Assuming present centerpoints 9.6 sigma result



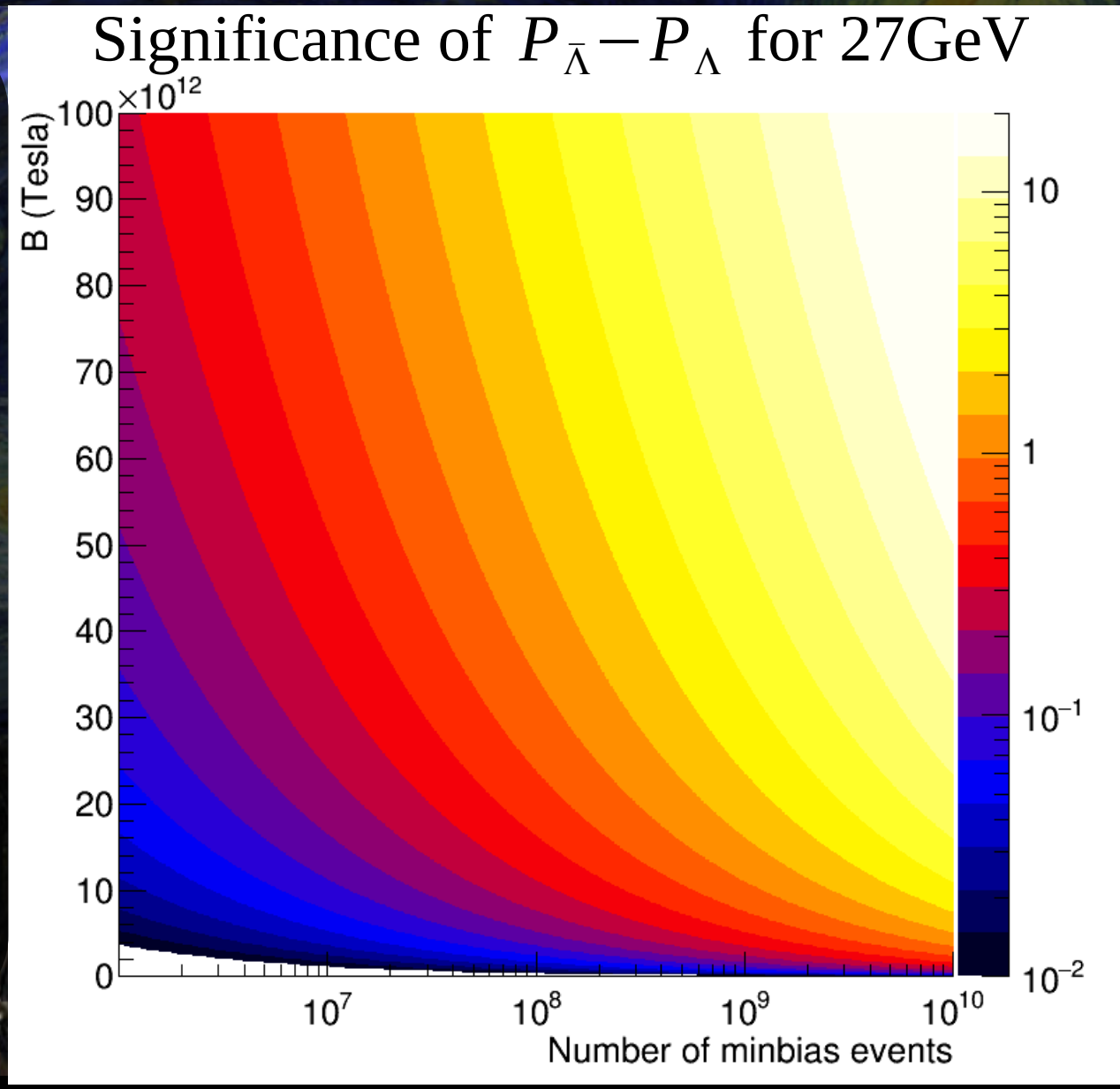
B-Field measurement in 27GeV

- 27GeV (2018) projected significance of the gap

$$P_{\bar{\Lambda}} - P_{\Lambda}$$

- Extrapolated from BES 27GeV error with the assumption

$$R_{EPD} = 2 R_{BBC}$$



B-Field with real data

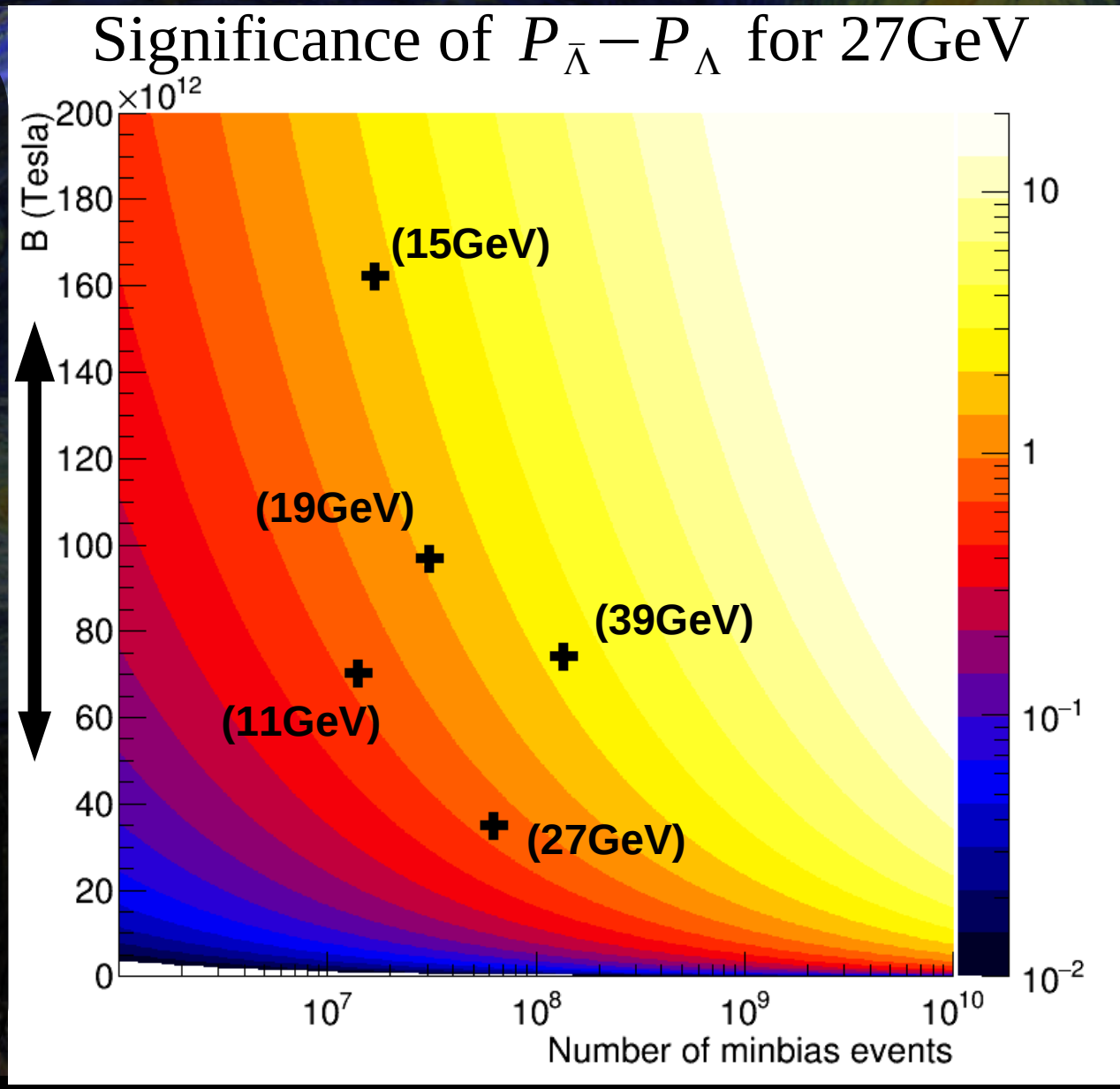
- 27GeV (2018) projected significance of the gap

$$P_{\bar{\Lambda}} - P_{\Lambda}$$

- Extrapolated from BES 27GeV error with the assumption

$$R_{EPD} = 2 R_{BBC}$$

- Real data added (expand vertical scale)
- (7GeV is too big)



B-Field measurement for 96 nucleons

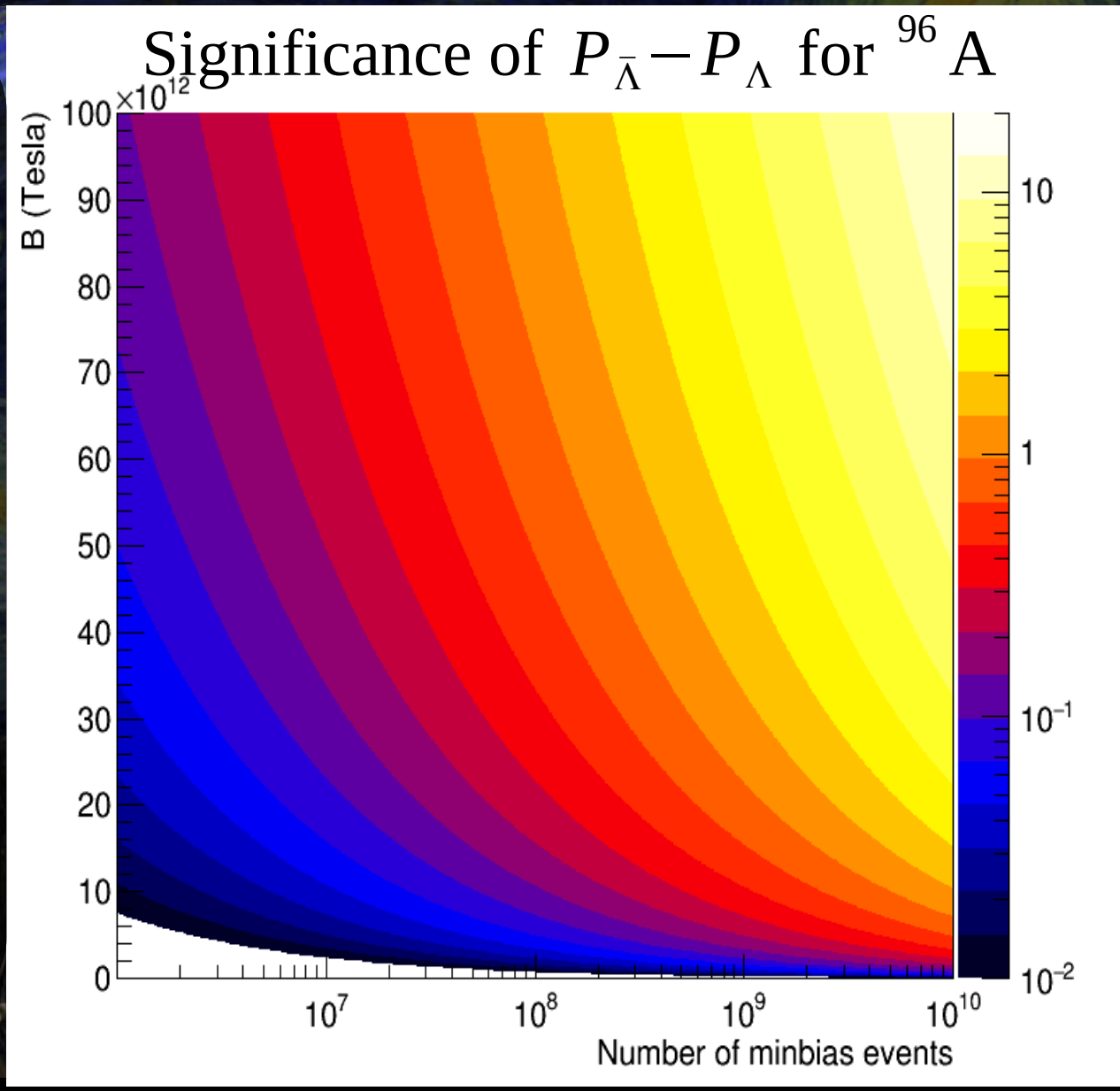
- Isobar projected significance of the gap

$$P_{\bar{\Lambda}} - P_{\Lambda}$$

- Extrapolated from BES 27GeV error with the assumption

$$R_{EPD} = 2\, R_{BBC}$$

- Smaller systems → lower statistics



Isobar system's B-Field difference

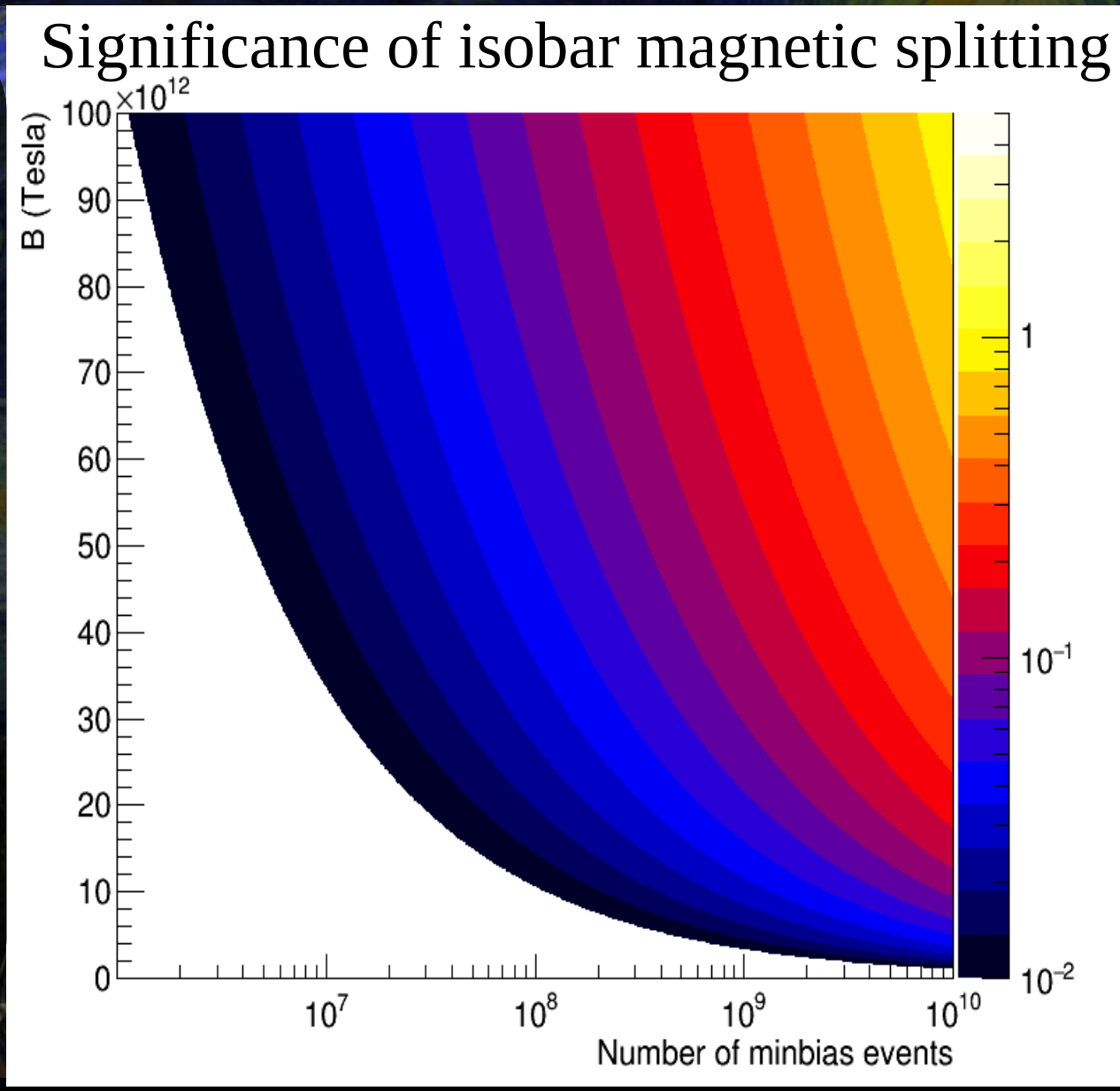
- Isobar projected significance of the gap

$$[P_{\bar{\Lambda}} - P_{\Lambda}]_{Ru} - [P_{\bar{\Lambda}} - P_{\Lambda}]_{Zr}$$

- Extrapolated from BES 27GeV error with the assumption

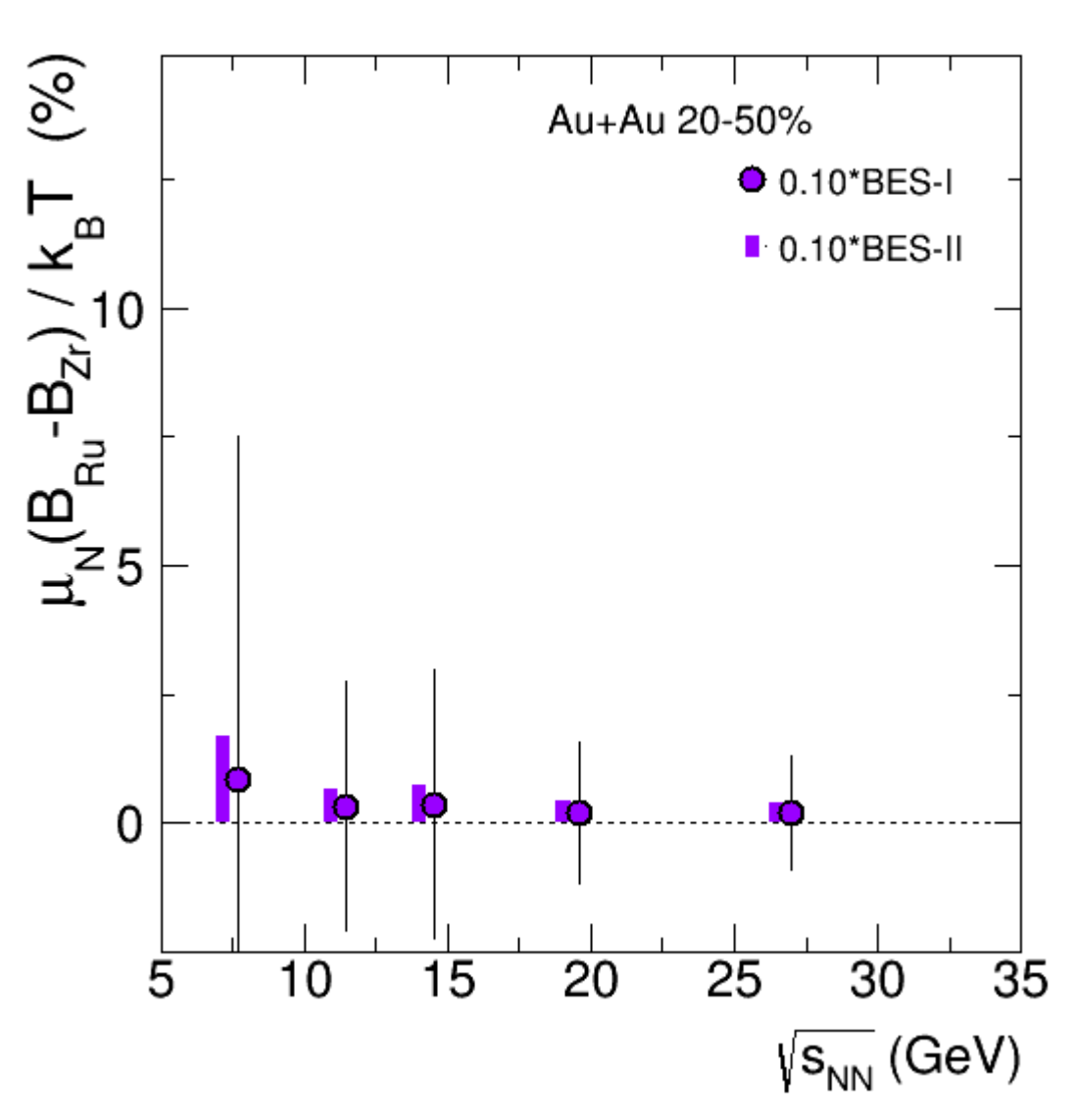
$$R_{EPD} = 2 R_{BBC}$$

- Input difference is ~10%



Isobar Projections – “Can we see 10%”

- Using given BES-I and BES-II statistics, what do we get for a 10% difference between the isobars?
- Such a small small signal is not statistically significant



Summary

- Particle/antiparticle polarization gap difference for Isobars at the level of expected B-field
  - → strong evidence for B-field measurement

- As compared to Au, Ru and Zr have
  - Lower statistics
  - Lower B fields

- Likely the difference in the gap for Ru and Zr is <u>too small to measure</u>

END