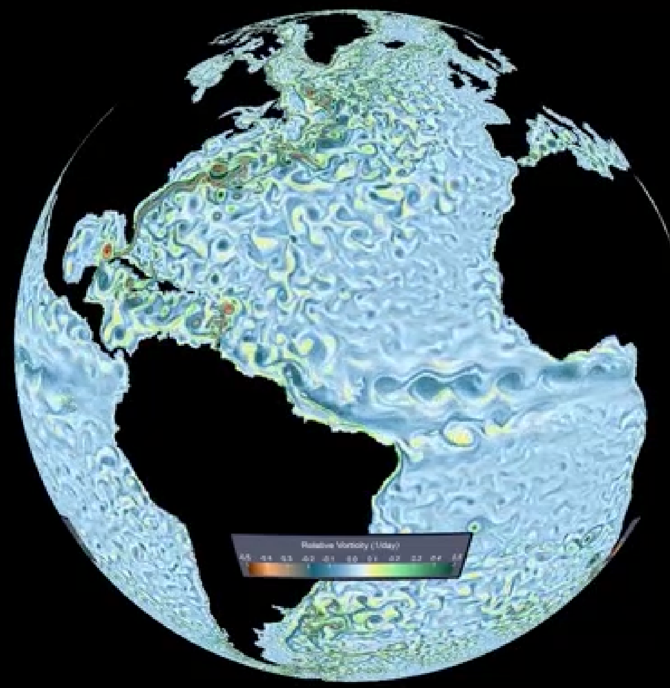
Global polarization of Lambda hyperons in Au+Au Collisions at RHIC BES

Isaac Upsal, OSU

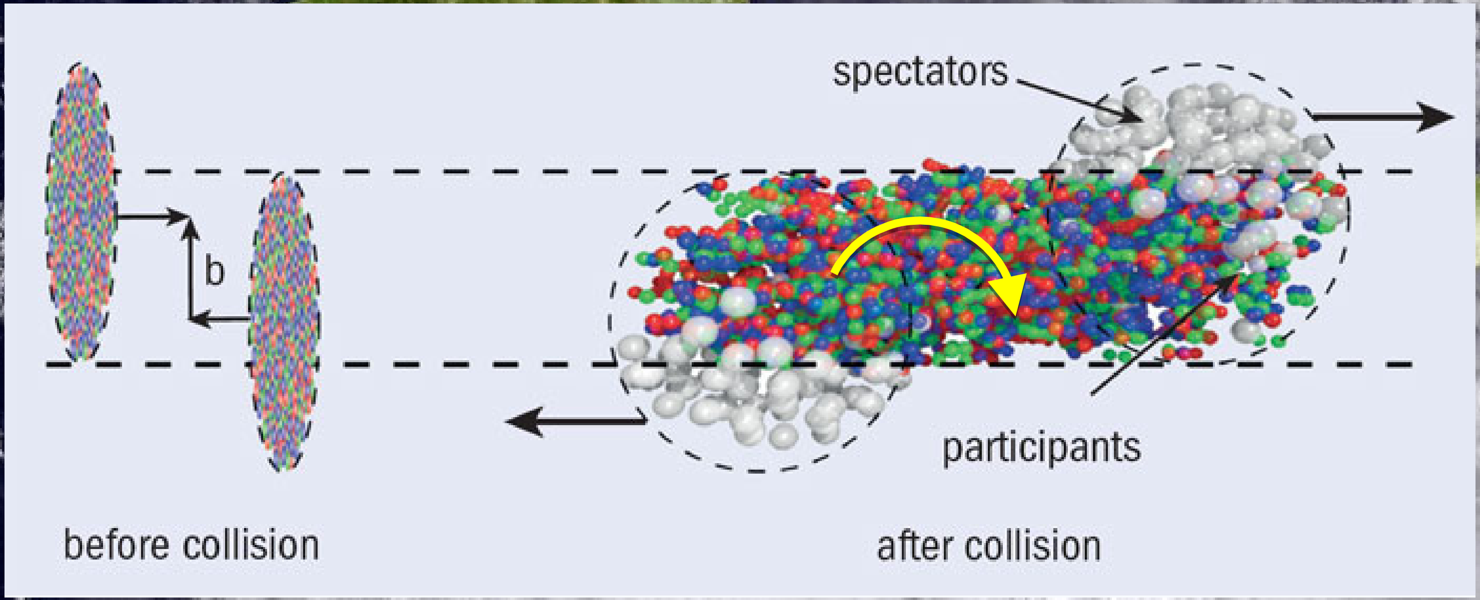
INT Workshop

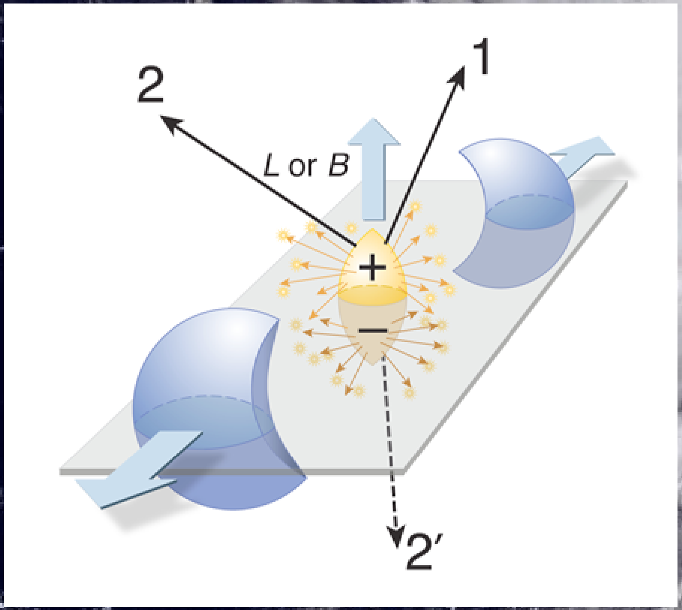
10.5.16

Global



Hyperon Polarization





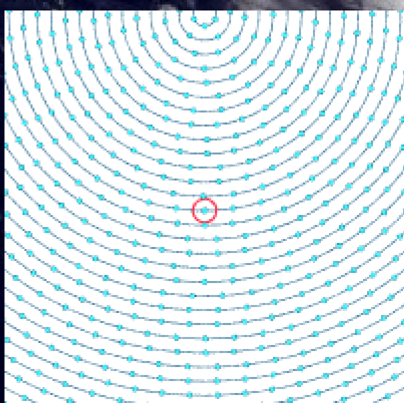
- $|L| \sim 10^5\ \hbar$ in non-central collisions
- How much is transferred to mid-rapidity?
- Does angular momentum get distributed thermally?
- Does it generate a “spinning QGP?”
  - consequences?
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} = \vec{\nabla} \times \vec{v}$
- How would it manifest itself in data?

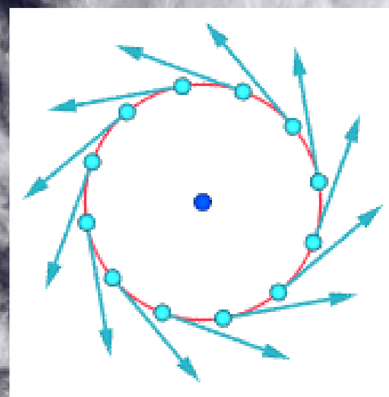
Rotational & Irrotational Vortices

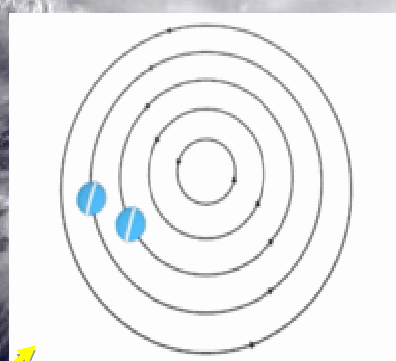
Simplest vorticity: $\vec{\omega} = \vec{\nabla} \times \vec{v}$

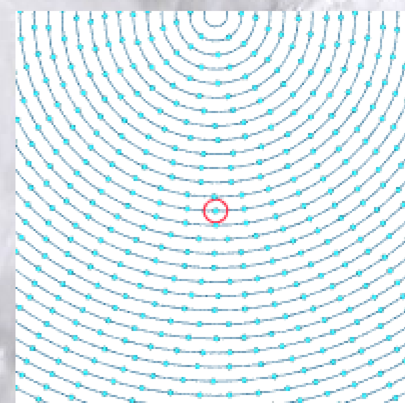
Rigid-body-like vortex
$v \propto r$

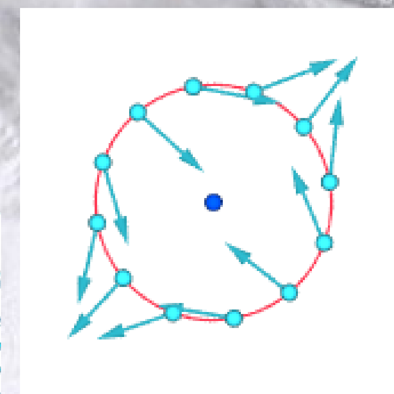
Irrotational vortex
$v \propto 1/r$

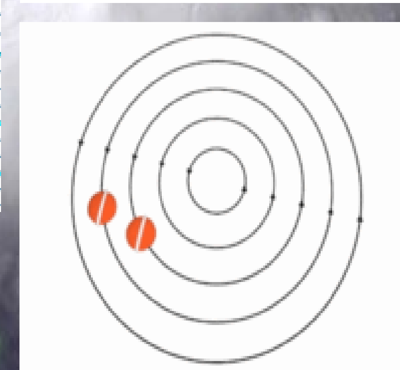






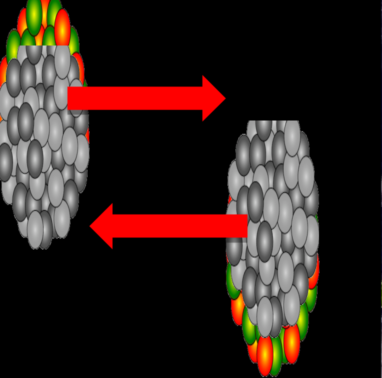


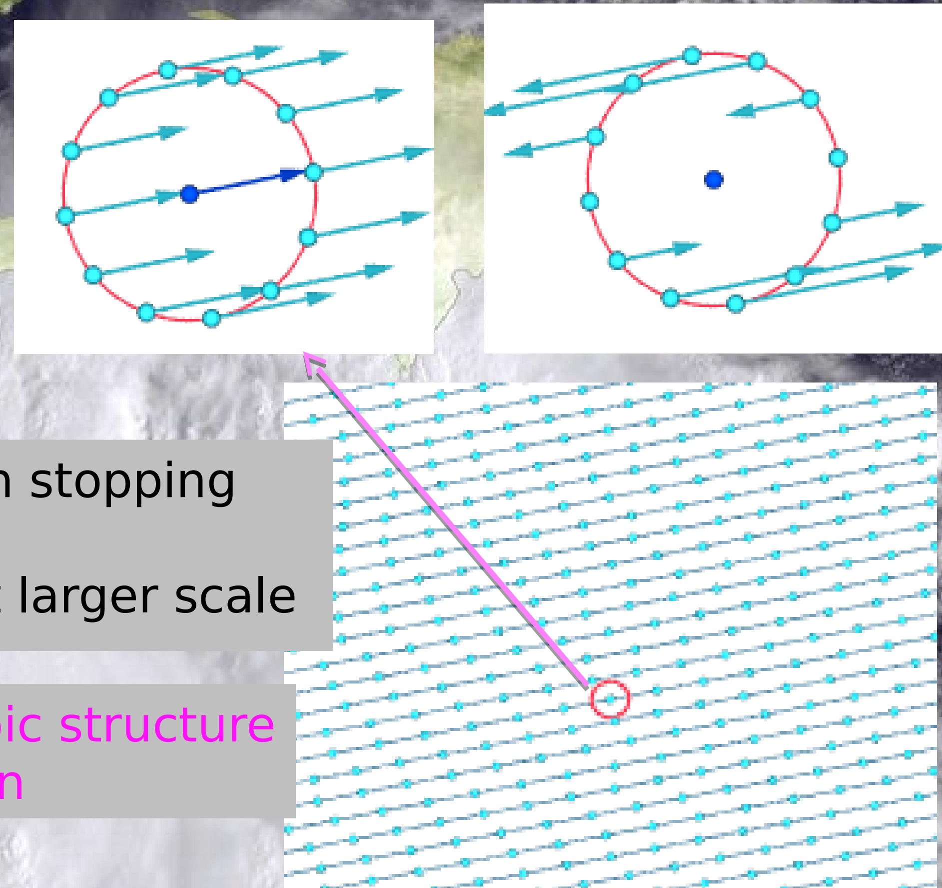




Like the moon, always the same side toward Earth

Notice the rotation, or lack thereof, in the fluid elements





Localized vortex generation via baryon stopping

Viscosity dissipates vorticity to fluid at larger scale

Vorticity – fundamental sub-femtoscopic structure of the “perfect fluid” and its generation

Calculations behind the “perfect fluid” story neglect angular momentum & vorticity altogether.
Problem?

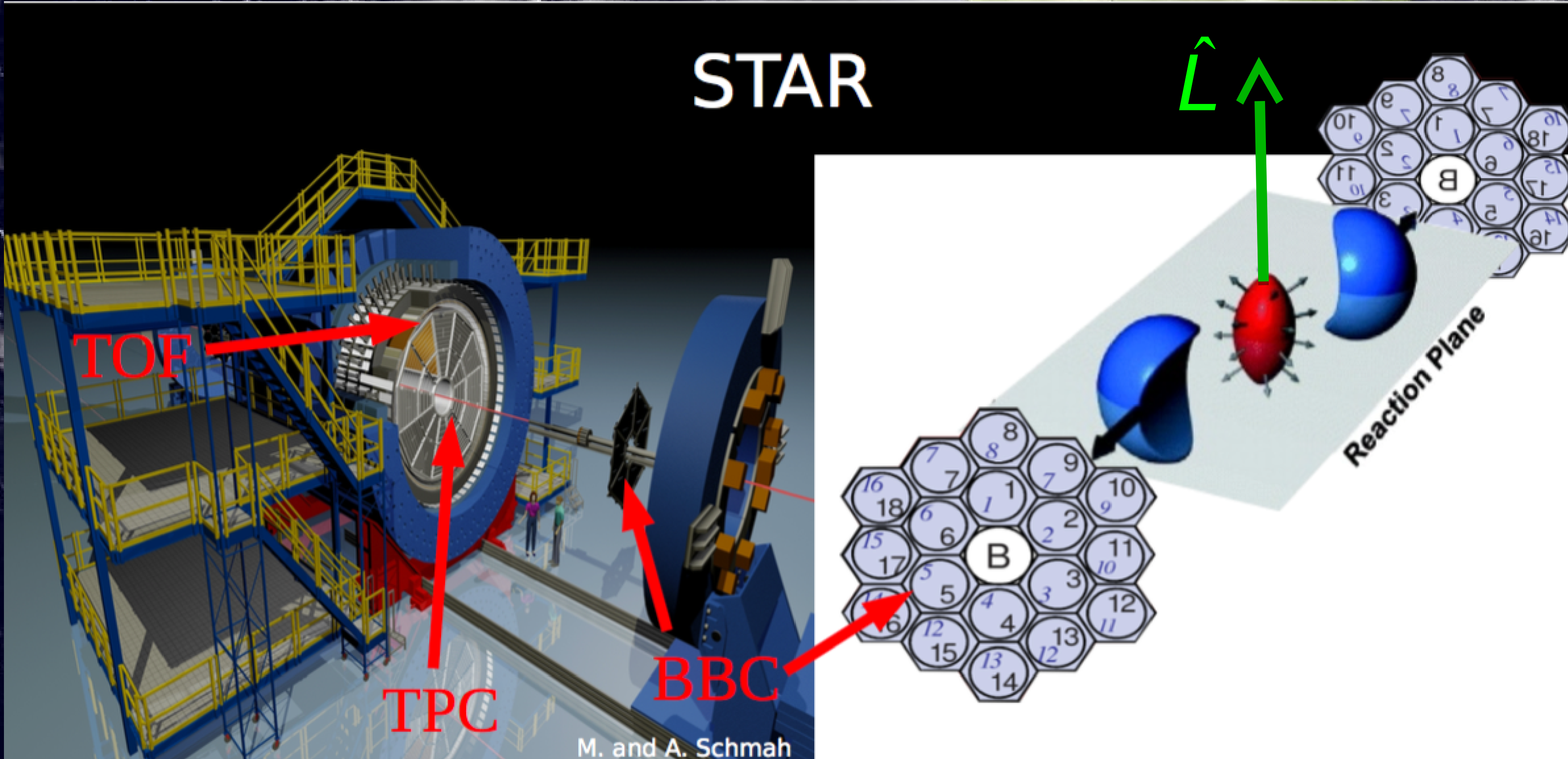
Connection to experiment

- Fluid vorticity may generate **global polarization (alignment of spin with collision system angular momentum) of emitted particles**
  - Betz, Gyulassy, Torrieri PRC76 044901 (2007)
  - Becattini et al., PRC88 034905 (2013)
  - Becattini et al., JPhys 509 012055-5 (2014) (SQM2013)
  - Csernai et al., JPhys 012054-5 (2014) (SQM2013)
  - Grossi JPhys 527 012015-5 (2014) (XIV Conf. Th. Physics)
  - Becattini et al. Eur. Phys. J. C (2015) 75: 406

- Similar conclusions based on QCD spin-orbit coupling (non-hydro picture)
  - Voloshin arxiv:nucl-th/0410089
  - Liang and Wang, PRL94 102301 (2005); PRL96 039901(E) (2006)
  - Liang and Wang, PLB629 20 (2005)

- Collective vorticity in microscopic transport (AMPT) Jiang, Lin, and Liao, arxiv:1602.06580

Analysis approach



- Study Au+Au collision in the BES:

7.7, 11.5, 14.5, 19.6, 27, 39 GeV

- Tracking is performed by the TPC
- PID is done using the TPC + TOF

- BBC detects participants to determine first order event plane

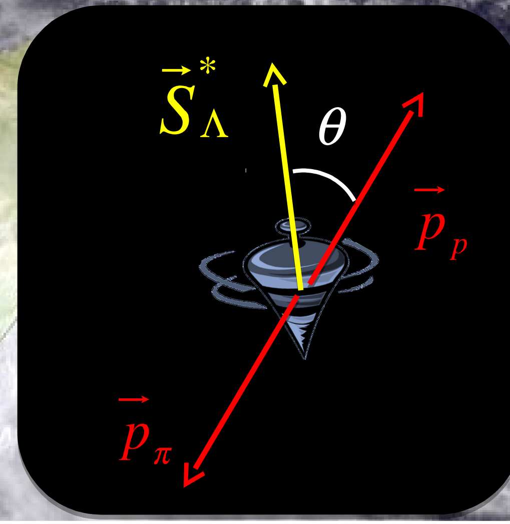
→ estimate of direction of angular momentum $\hat{L}$

Analysis approach

Lambdas are "self-analyzing"

- Reveal polarization by preferentially emitting daughter proton in spin direction
- For AntiLambdas spin is opposite anti-proton direction

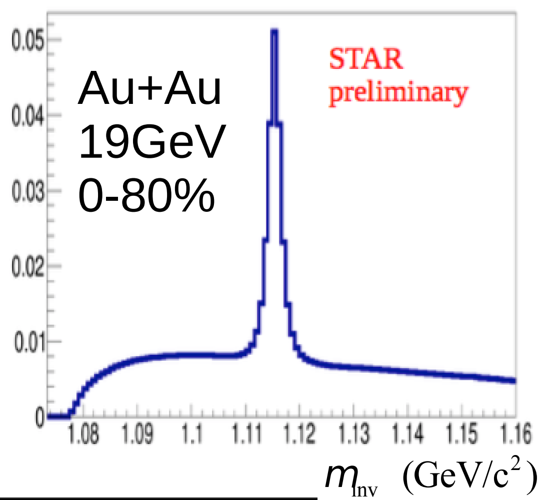
E. Cummins, Weak Interactions (McGraw-Hill, 1973)



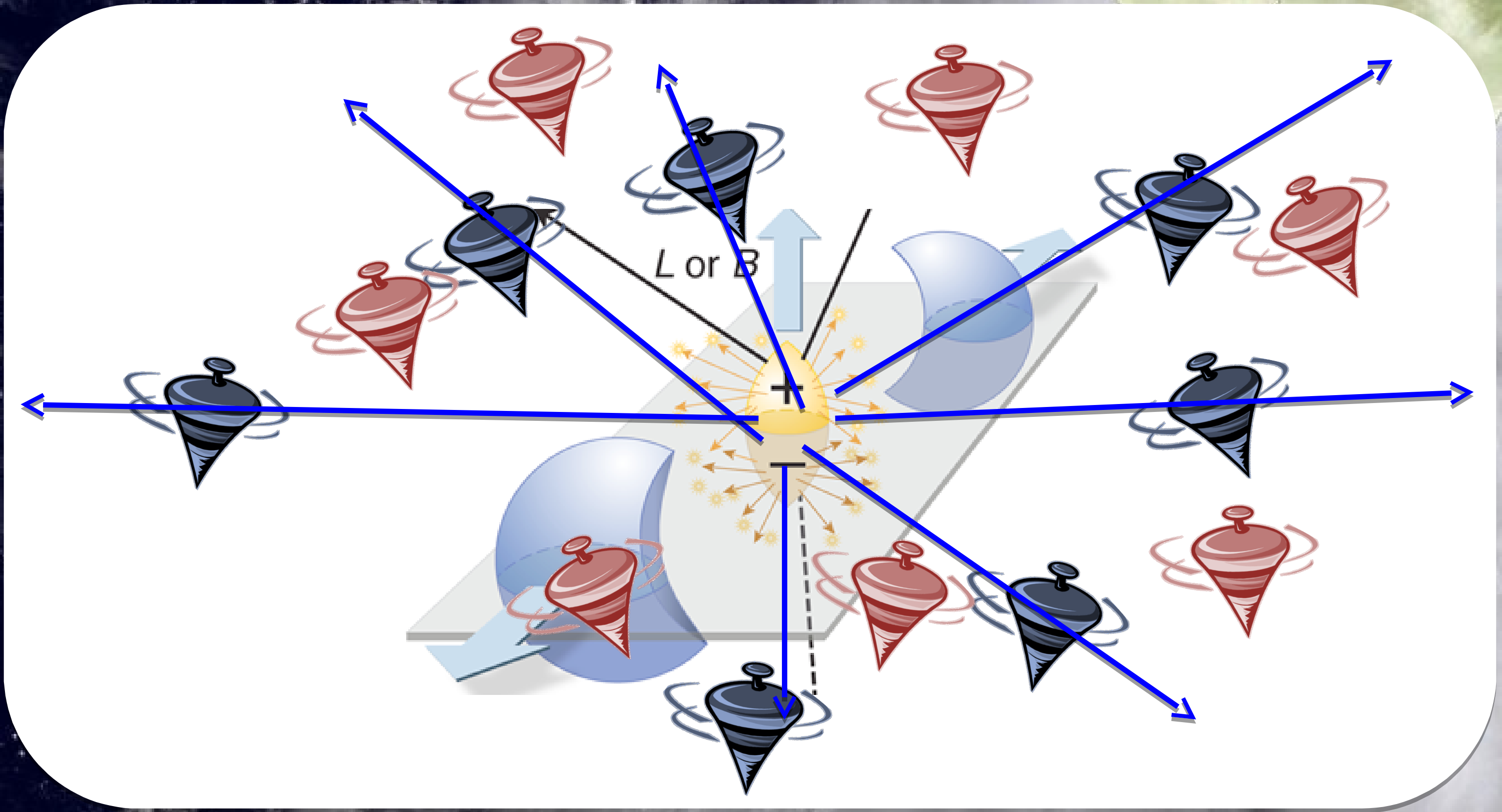
- Basic track cuts
  - If proton has ToF: $0.5\,(GeV/c^2)^2 < m^2_{ToF} < 1.5\,(GeV/c^2)^2$ and TPC $|n_\sigma| < 3$
  - If pion has ToF: $(0.017 - 0.013\,\frac{p}{GeV/c})(GeV/c^2)^2 < m^2_{ToF} < 0.04\,(GeV/c^2)^2$ and TPC $|n_\sigma| < 3$
- Lambda topological cuts:
  - daughter DCA < 1cm, $1.108\,GeV/c^2 < m_{inv} < 1.122\,GeV/c^2$

Topological cuts optimized to maximize yield significance

lengths in cm	Both have ToF	Proton has ToF	Pion has ToF	Neither has ToF
Proton DCA	0.1	0.15	0.5	0.6
Pion DCA	0.7	0.8	1.5	1.7
Lambda DCA	1.3	1.2	0.75	0.75
Lambda Decay Length	2	2.5	3.5	4



Contributors to Global Polarization



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

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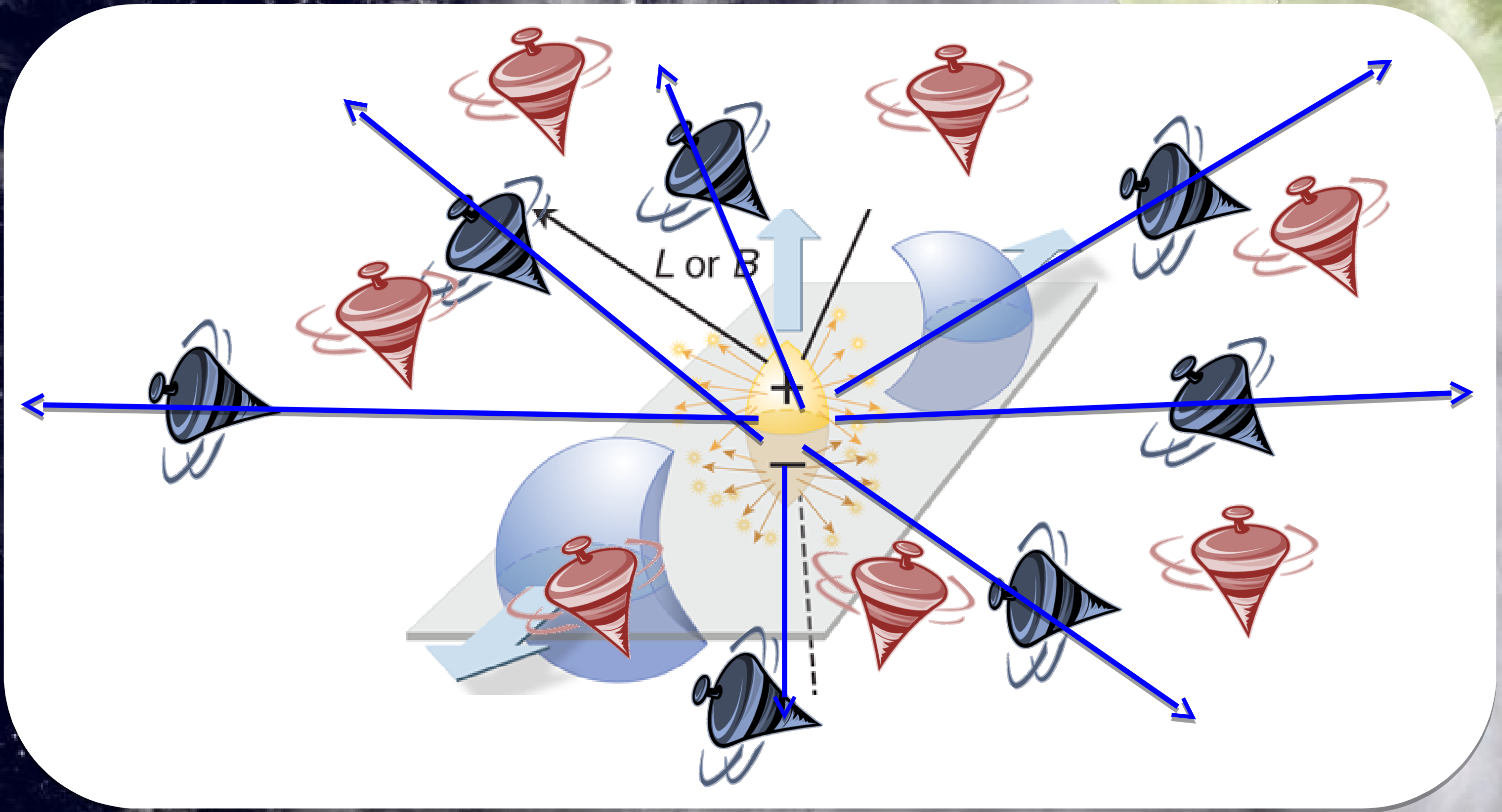


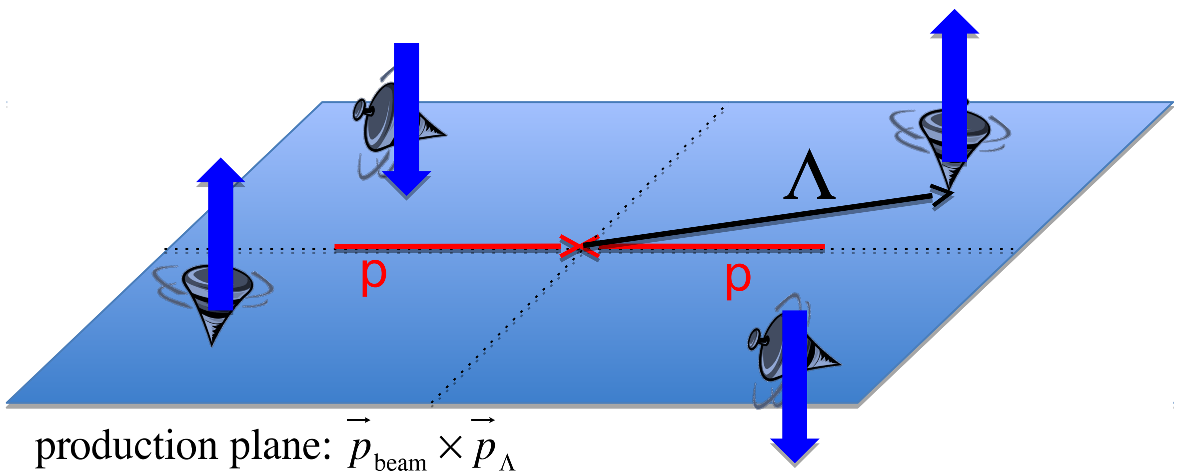
- Vortical or QCD spin-orbit: Lambda and AntiLambda spins aligned with L
- (electro)magnetic coupling: Lambdas *anti*-aligned, and AntiLambdas aligned

Both may contribute

Contributors to Global Polarization

Known effect in p+p collisions [e.g. Bunce et al, PRL 36 1113 (1976)]

- Lambda polarization at *forward* rapidity relative to *production plane*



Both may contribute

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

Not global

- Polarization w/ *production* plane: No integrated effect at midrapidity for Lambda
  - also, would polarize perpendicular to L for out-of-plane particles – tested (big errors)

How to quantify the effect?

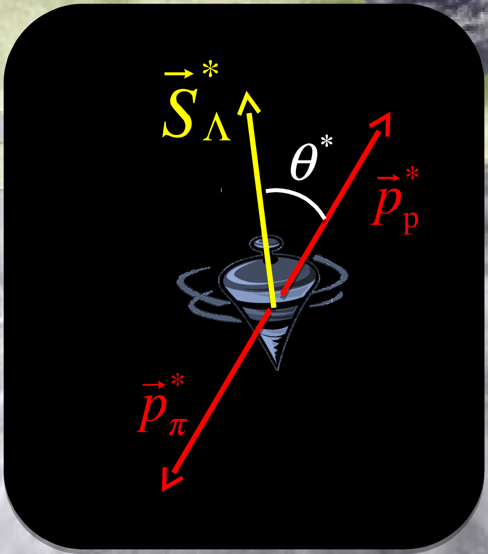
For an ensemble of Λs with polarization $\vec{P}$:

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

$\alpha = 0.642$ [measured]

$\hat{p}_p^*$ is daughter proton momentum direction *in Λ frame*
*note this is opposite for $\bar{\Lambda}$

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



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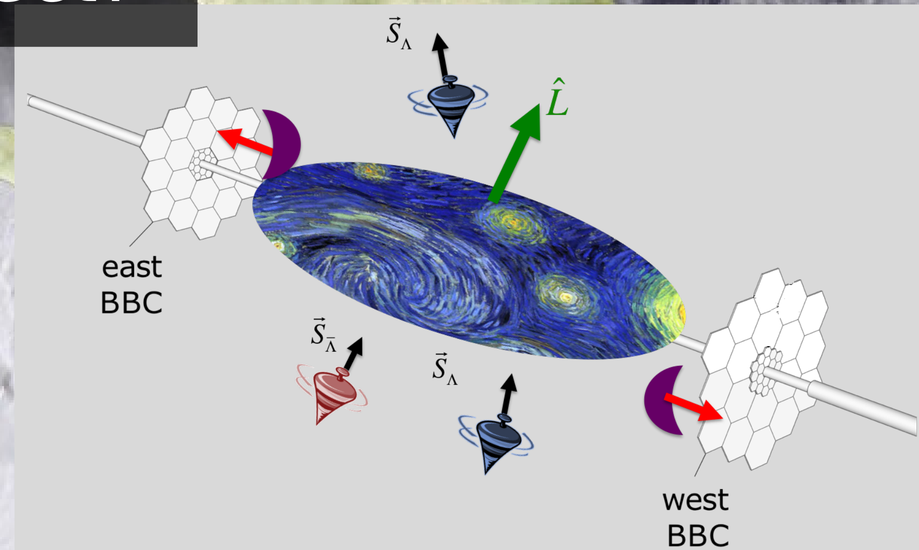

Dynamic heavy ion collision may produce several "ensembles" $\rightarrow$ $\vec{P}$ may depend on $\vec{\beta}_\Lambda$

Models [Beccatini, Csernai, Liang, Wang, others] predict various dependence on p_T, ϕ

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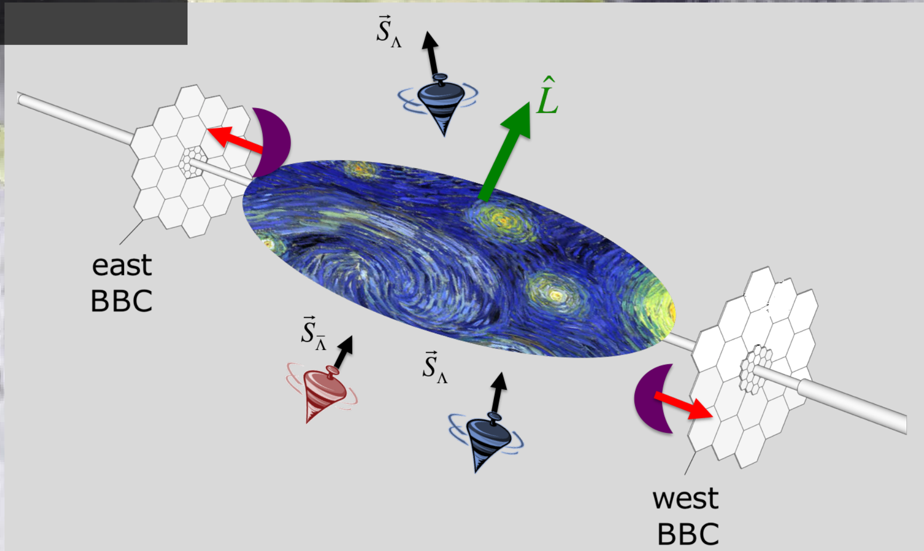

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Symmetry: $|y| < 1,\ 0 < \phi < 2\pi \rightarrow \vec{P}_{\mathrm{ave}} \parallel \hat{L}$

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

$P_{AVE} = \frac{8}{\pi\alpha}\frac{\langle\sin(\Psi_{EP}^{(1)} - \varphi_p^*)\rangle}{R_{EP}^{(1)}}$ where the average is performed over events and Λs

$\Psi_{\mathrm{EP}}^{(1)}$ is the first-order event plane (found with BBCs)

$R_{\mathrm{EP}}^{(1)}$ is the first-order event plane resolution (same as v_1 analysis)

STAR, PR**C76** 024915 (2007)

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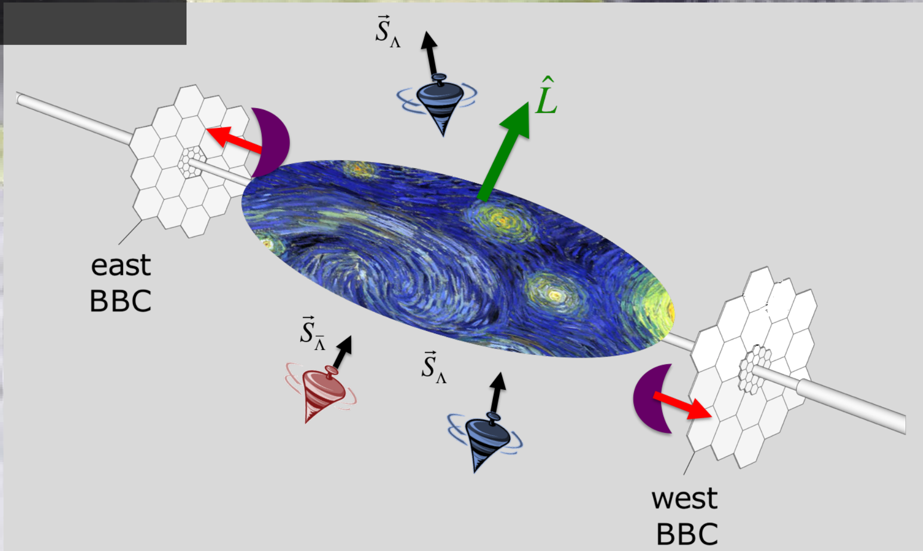


Dy

Syn

Stat

P_{AVE}

$\Psi^{(1)}_{EP}$

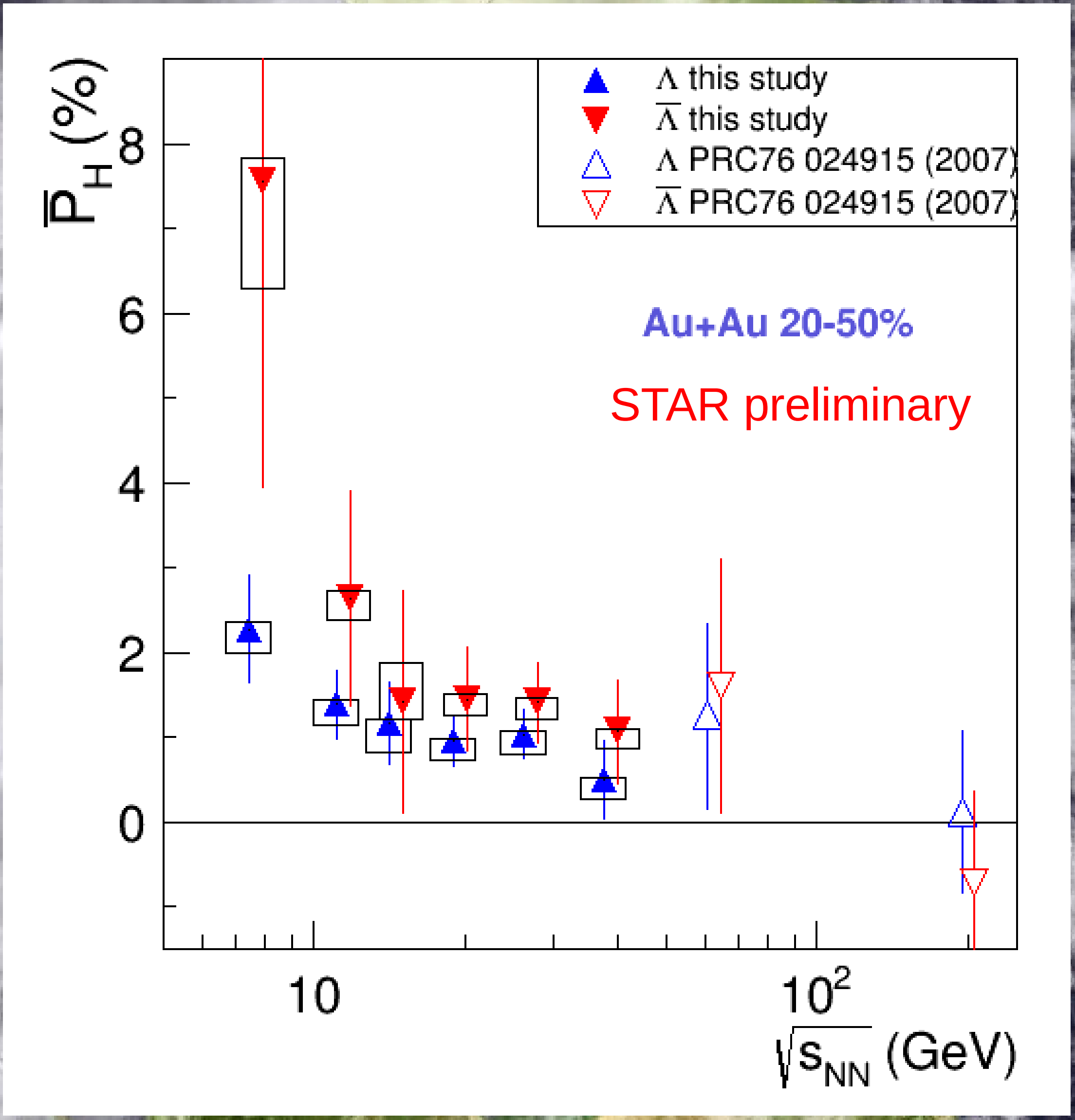
$R^{(1)}_{EP}$

$$P_{AVE} = \frac{8}{\pi\alpha}\frac{\left\langle \sin\left(\Psi^{(1)}_{EP} - \varphi^*_p\right)\right\rangle}{R^{(1)}_{EP}}$$

STAR, PRC76 024915 (2007)

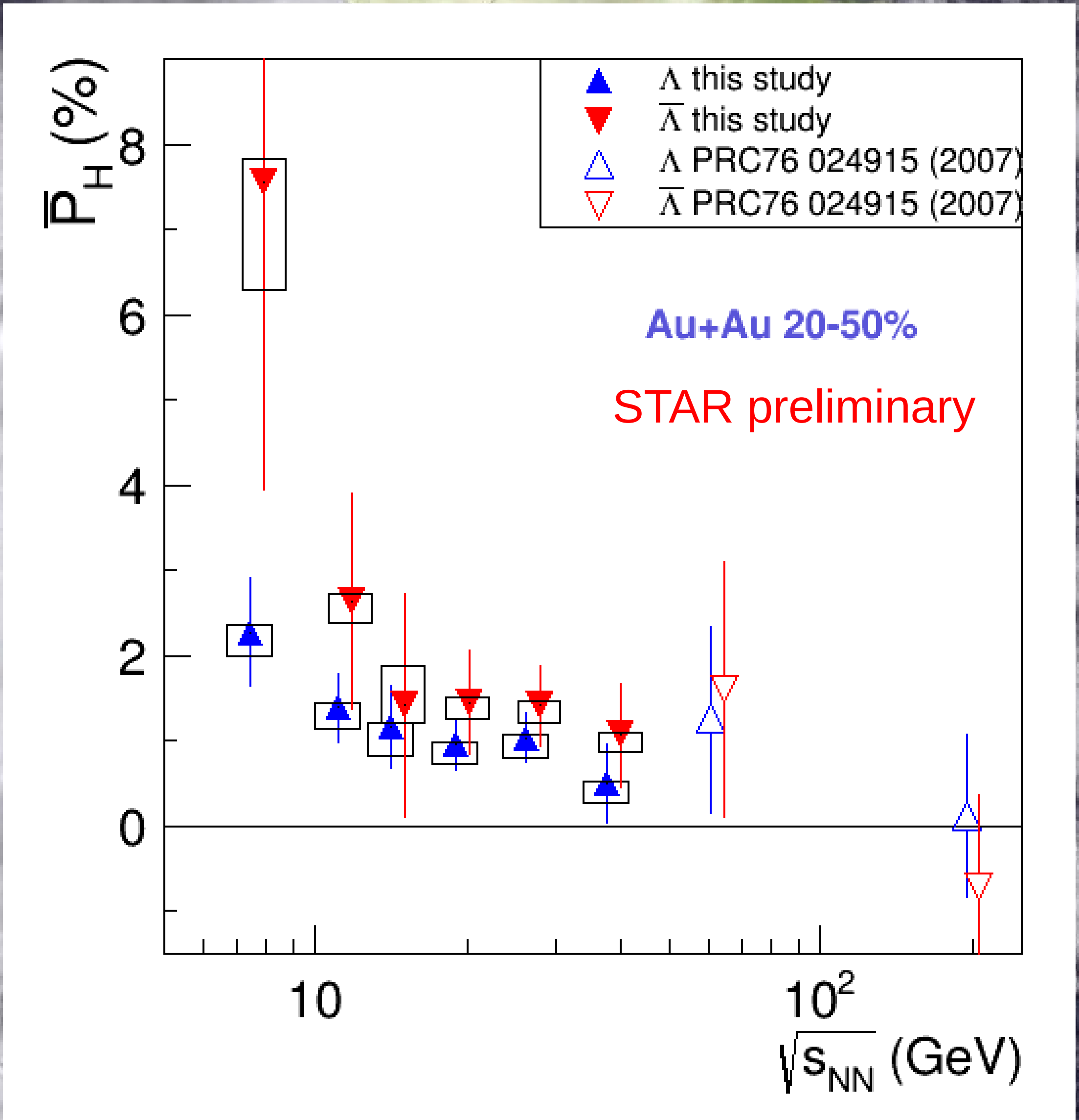
Global polarization measure

- Measured Lambda and AntiLambda polarization
- Positive signal!
- Includes results from previous STAR null result (2007)



What does it *mean*?

- Spin aligned with $\hat{L}$
- AntiLambda higher → magnetic coupling?
- What about feed-down?
  - Primary Lambdas can tell us something about the *system*
  - Only ~25% of Lambdas are primary!



Effects of feed-down, e.g.

- ~60% Lambdas come from Σ^0, Ξ^0, Ξ^-, Σ^{*-}, Σ^{*0}, Σ^{*+}
- What if the Λ comes from a Σ^0?

$$\Sigma^0 \rightarrow \Lambda + \gamma \qquad \langle \vec{S}_{\Lambda \text{ daughter}} \rangle = -\frac{1}{3} \langle \vec{S}_{\Sigma^0 \text{ mother}} \rangle$$

  - Σ^0 suppresses measured signal

- What if the Λ comes from a Σ^{*+} (1385)?

$$\Sigma^{*+} \rightarrow \Lambda + \pi^+ \qquad |\vec{S}_{\Sigma^{*+}}| = 3/2 \qquad \mu_{B,\, \Sigma^{*+}} \approx -5 \mu_{B,\, \Lambda}$$

  - Spin 3/2 → large coupling
  - Strong magnetic coupling

Spin feed down

- Most (grand)parents, X, decay either to a Λ directly or to a Σ^0 which decays into a Λ

$$\vec{S}_{\Lambda}^{*,\mathrm{meas}} = \sum_X \left[f_{\Lambda X} C_{\Lambda X} - \frac{1}{3} f_{\Sigma^0 X} C_{\Sigma^0 X} \right] \vec{S}_X^{*}$$

$X \rightarrow \Lambda$

$f_{\Lambda X}$: Fraction Λ directly from X

$C_{\Lambda X}$: Fraction of X spin transferred to daughter Λ

$X \rightarrow \Sigma^0 \rightarrow \Lambda$

$f_{\Sigma^0 X}$: Fraction of Λ from Σ^0 which come directly from X

$C_{\Sigma^0 X}$: Fraction of X spin transferred to daughter Σ^0

*Becattini, Karpenko, Lisa, Upsal, Voloshin (in preparation)

Thermal assumption

- At approx. constant temperature, T, the thermal vorticity is well described by

$$\varpi = \omega / T$$

- In a <u>thermal assumption</u> all primary baryons, X, couple to the same vorticity via their spin projection

- In a thermal fluid of temperature T the average spin of a particle is

$$\langle \vec{S} \rangle = \hat{\omega} \frac{\sum_{m=-S}^{m=S} m \exp[m\omega/T]}{\sum_{m=-S}^{m=S} \exp[m\omega/T]}$$

- Where $\hat{\omega}$ is the direction of vorticity and m is the spin projection

Magnetic field contribution

- Additionally there is the possibility of magnetic coupling

- If the magnetic field is parallel to the vorticity, one can get magnetic field contributions by substituting

$$\omega \rightarrow \omega + \mu B/S$$

μ is magnetic moment of particle

- It is not entirely clear what magnetic field this might be

  - Low pt Lambdas are emitted late, some sort of late time integral

  - Magnetic field duration depends on QGP conductivity

Polarization decomposition

- For small vortical and magnetic coupling the polarization for a given primary particle is

$$P = \frac{\langle \vec{S} \rangle}{S} \simeq \frac{(S+1)}{3} \left(\frac{\omega}{T} + \frac{\mu B}{S} \right)$$

- Vortical coupling is even WRT particle number
  - (average Lambda and AntiLambda)
- Magnetic coupling is odd ($\mu_{\text{anti particle}} = -\mu_{\text{particle}}$)
  - (subtract AntiLambda from Lambda /2)

Relate measured polarization to B and ω

$$\begin{pmatrix} P_{\Lambda}^{\mathrm{meas}} \\ P_{\overline{\Lambda}}^{\mathrm{meas}} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} \omega/T \\ B/T \end{pmatrix}$$

$$A_{11} = \frac{2}{3} \sum_X \left(f_{\Lambda X} C_{\Lambda X} - \frac{1}{3} f_{\Sigma^0 X} C_{\Sigma^0 X} \right) S_X \left(S_X + 1 \right)$$

$$A_{12} = \frac{2}{3} \sum_X \left(f_{\Lambda X} C_{\Lambda X} - \frac{1}{3} f_{\Sigma^0 X} C_{\Sigma^0 X} \right) \left(S_X + 1 \right) \mu_X$$

$$A_{21} = \frac{2}{3} \sum_{\overline{X}} \left(f_{\Lambda X} C_{\overline{\Lambda}\overline{X}} - \frac{1}{3} f_{\overline{\Sigma}^0 \overline{X}} C_{\Sigma^0 X} \right) S_X \left(S_X + 1 \right)$$

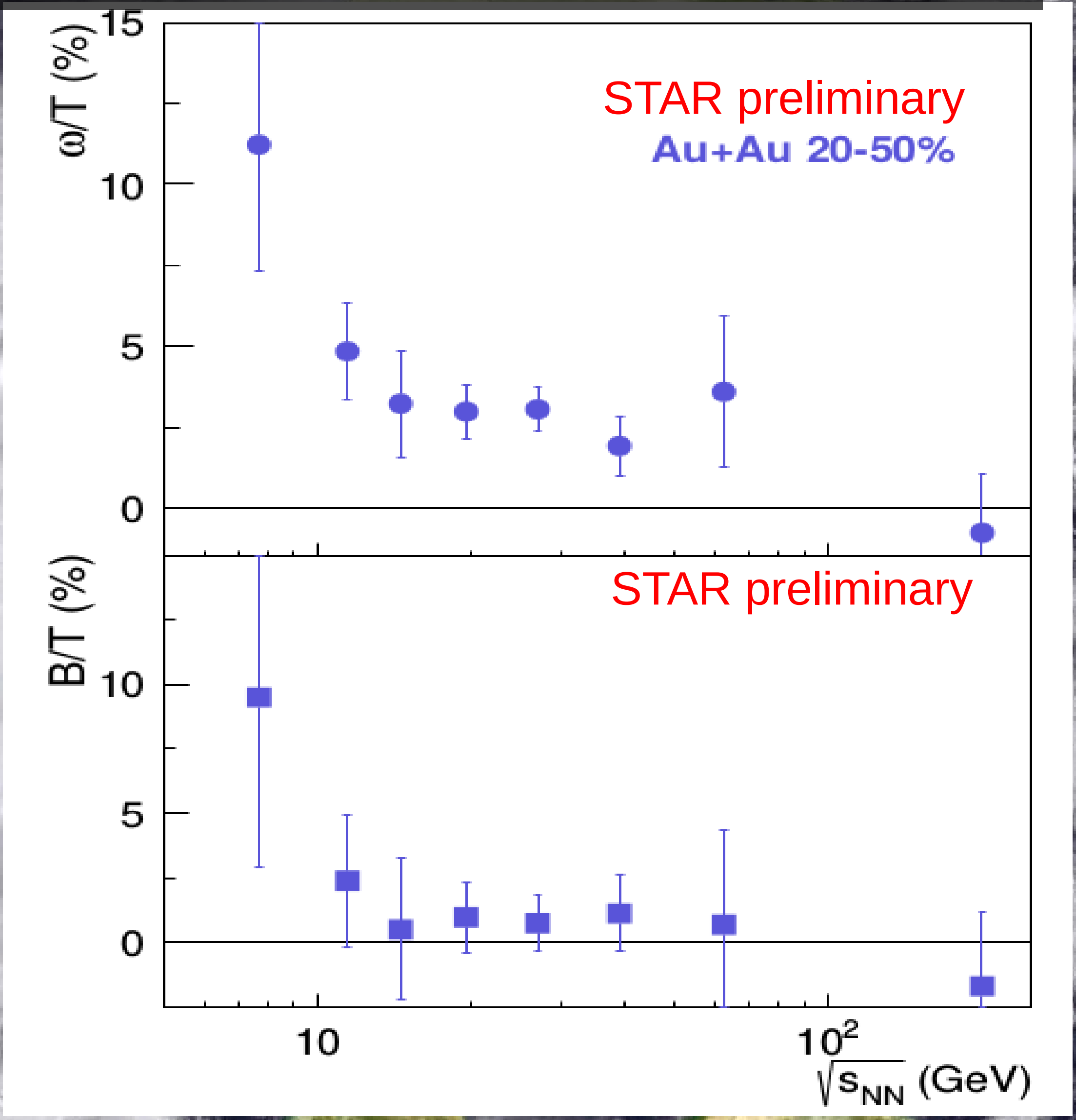
$$A_{22} = -\frac{2}{3} \sum_{\overline{X}} \left(f_{\Lambda X} C_{\overline{\Lambda}\overline{X}} - \frac{1}{3} f_{\overline{\Sigma}^0 \overline{X}} C_{\Sigma^0 X} \right) \left(S_X + 1 \right) \mu_X$$

Vorticity and magnetic field

- Fig. depicts vorticity and magnetic field
- Magnetic field is ~ polarization in percentage

$$P_B \approx 1\,\%\,,\, B \approx m_\pi^2 \approx 10^{14}\, T$$

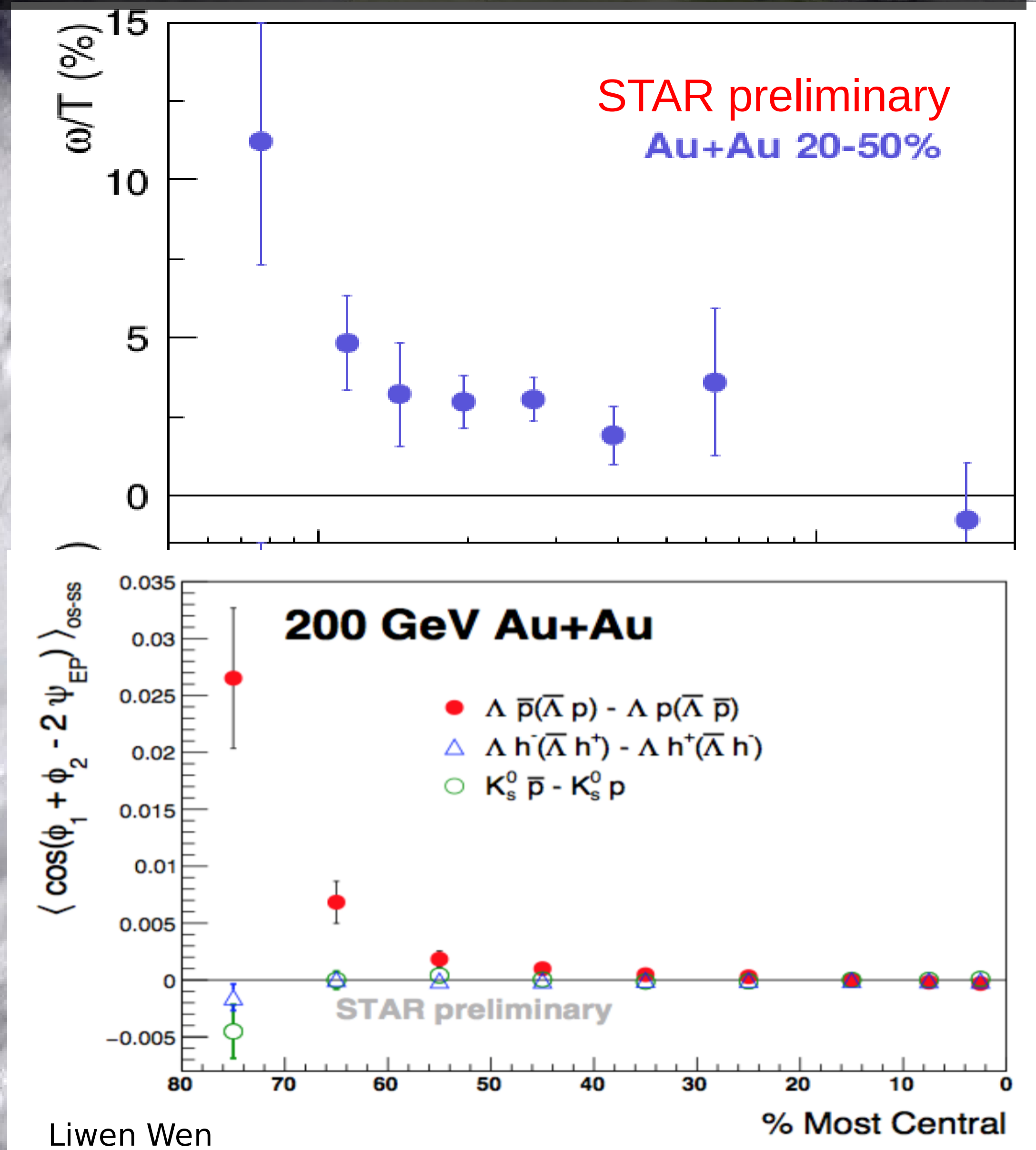
- Yields from THERMUS
- Negative magnetic component means magnetic coupling



Broader context: CVE

- Polarization not inherently chiral
- Large uncertainty term, μ_5, in the delta correlator (related to Chern–Simons)
- For neutral baryons (Lambdas) correlator predicts separation of B# along vorticity, ω

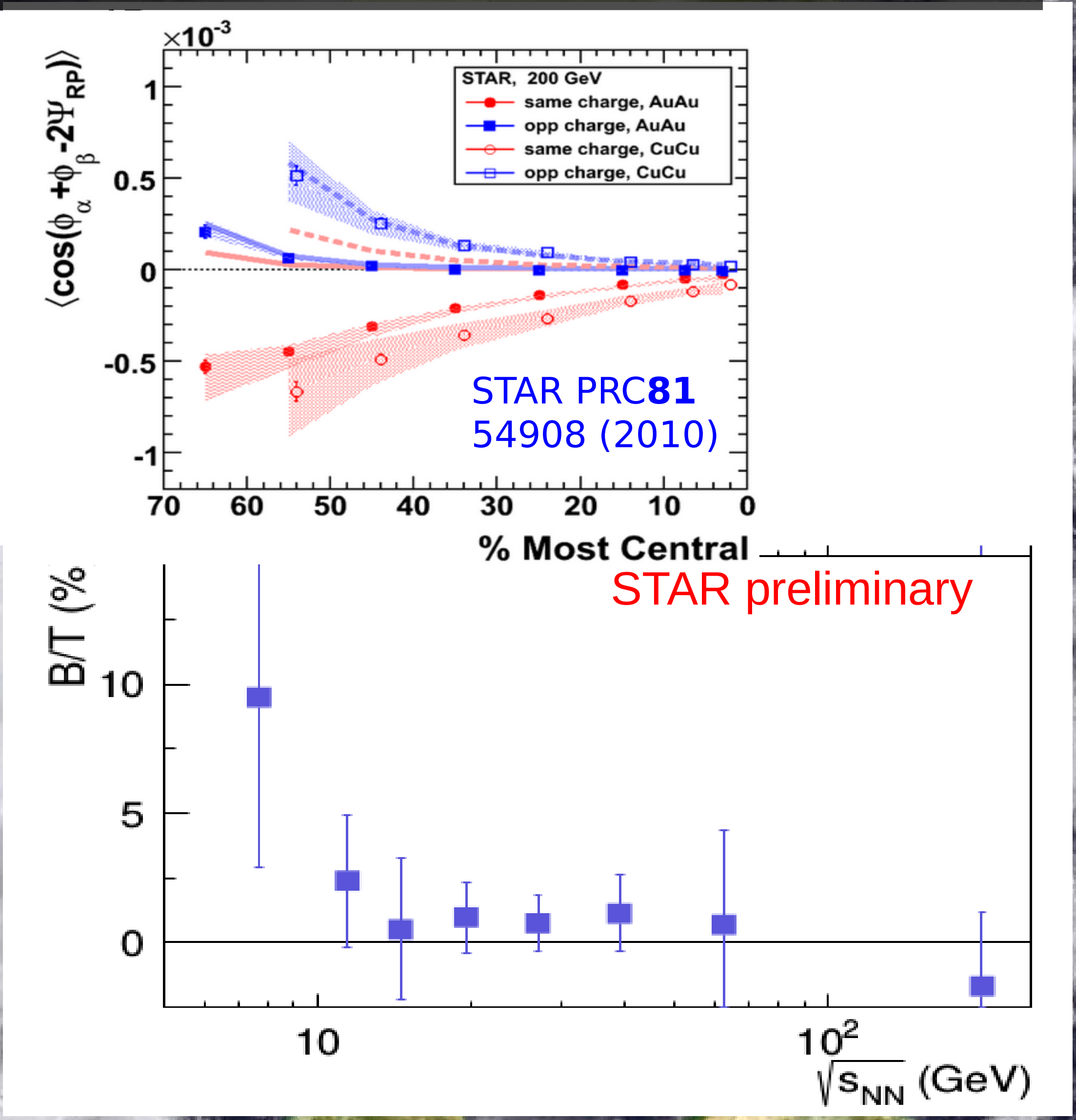
$$J_E = \frac{N_c \mu_5}{3\pi^2} \mu_B \, \omega$$



Broader context: CME

- Large theoretical uncertainly on B (orders of magnitude + $\sqrt{s_{NN}}$)
- Large uncertainty term, μ_5, in the delta correlator (related to Chern–Simons)
- For charged particles CME predicts separation of +/- along B

$$J_E = \frac{N_c \mu_5}{3\pi^2} B$$



Summary I

- Large angular momentum in non-central heavy-ion collisions may be partially transferred to the hot fireball at midrapidity
  - thermalization: if angular momentum is distributed thermally, spin states will be preferentially occupied
  - In a hydro scenario, achieved through vorticity generated by shear viscosity – sensitive to initial conditions
  - At a microscopic level, may be due to QCD spin-orbit coupling
- Global hyperon polarization probes this (largely unexplored) physics

Summary II

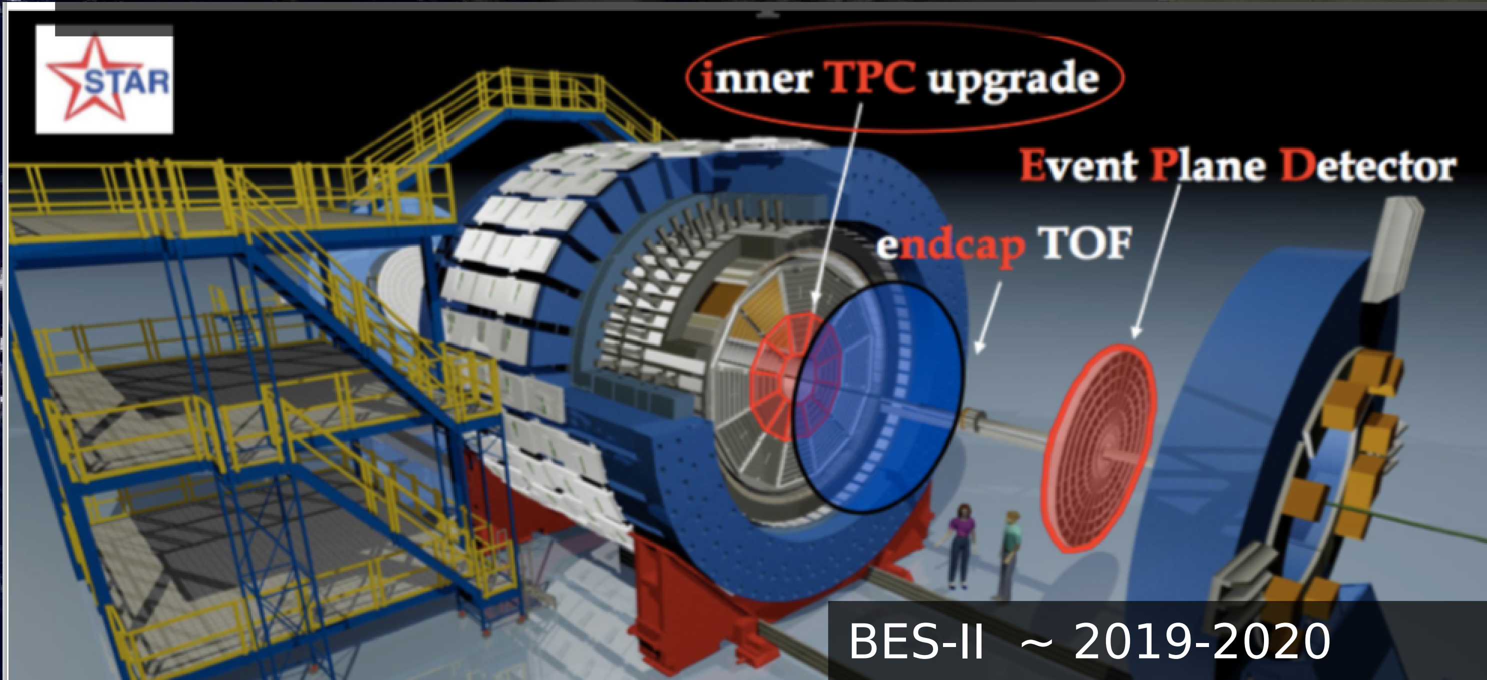
- STAR has seen the first positive signal of global hyperon polarization
  - 2.5σ to 3.5σ signal for Λ's at each energy below 39 GeV
  - previous STAR "null result" appears to fall in line with systematics!
  - falls with energy – driving physics?
  - Higher statistics & resolution in BES-II will allow important differential studies
    - centrality, p_T, phi, rapidity

- Hint of larger signal for antibaryons – additional magnetic effect?
  - B field is poorly constrained
  - Non-trivial energy dependence
  - Has connections to conductivity of QGP

- Both magnetic and vortical may constrain chiral phenomena


END

BES-II: 2019-2020



$\sqrt{S_{NN}}$ (GeV)	5.0	7.7	9.1	11.5	13.0	14.5	19.6
μ_B (MeV)	550	420	370	315	290	250	205
BES I (MEvts)	---	4.3	---	11.7	---	24	36
Rate(MEvts/ day)		0.25		1.7		2.4	4.5
BES I $\mathcal{L}$ ($1\times10^{25}/cm^2sec$)		0.13		1.5		2.1	4.0
BES II (MEvts)		100	160	230	250	300	400
eCooling (Factor)	2	3	4	6	8	11	15
Beam Time (weeks)		**14**	**9.5**	**5.0**	**3.0**	**2.5**	**3.0**

BES-II ~ 2019-2020

- Collider (e-cooling) & detector upgrades
- Finer-grained measurements
  - what drives energy dependence of P?
- Increase statistics by order of magnitude
  - stat. errorbars reduced by ~3
- Improve avg 1st-order RP resolution by 2x
  - stat. errorbars reduced by another ~2

Feed-down numbers

index i	particle	spin J	C_V	C_M	$\mu\,(\mu_N)$	F
0	Λ'	$\frac{1}{2}$	1	1	-0.613 [2]	+1 (trivially)
1	Σ^0	$\frac{1}{2}$	1	1	+0.79 (quark model [2])	$-\frac{1}{3}$ [3, 4]
2	Ξ^-	$\frac{1}{2}$	1	1	-0.651 [2]	+0.927 (c.f. Appendix A)
3	Ξ^0	$\frac{1}{2}$	1	1	-1.25 [2]	+0.900 (c.f. Appendix A)
4	Σ^{*-}	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{5}{9}$	-2.41 [5]	$+\frac{1}{3}$ (c.f. ****)
5	Σ^{*0}	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{5}{9}$	+0.30 [5]	$+\frac{1}{3}$ (c.f. ****)
6	Σ^{*+}	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{5}{9}$	+3.02 [5]	$+\frac{1}{3}$ (c.f. ****)

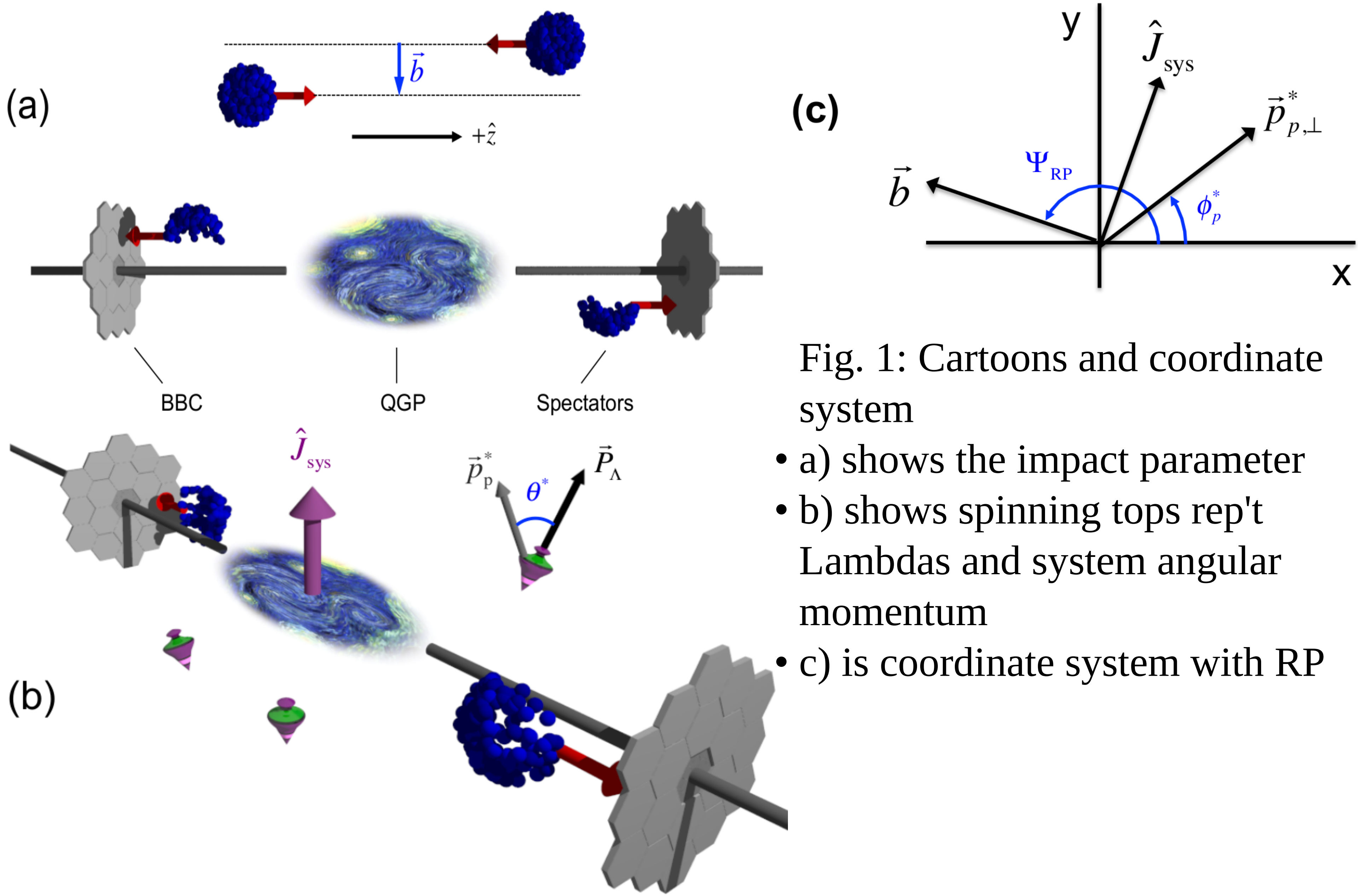
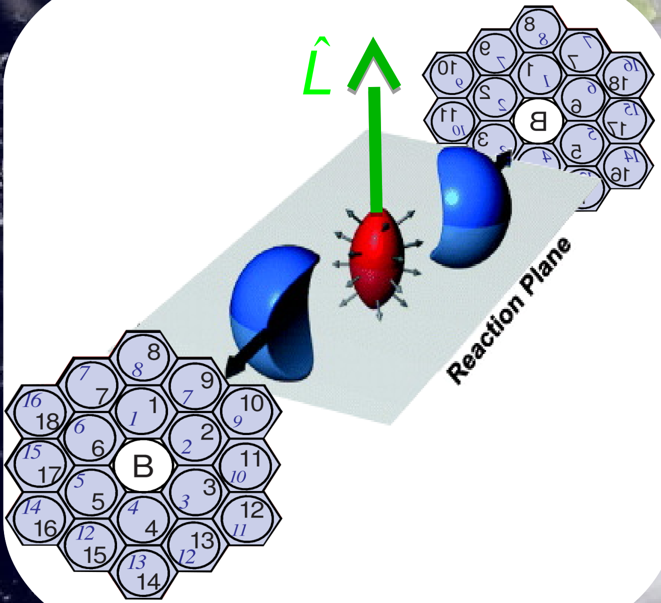


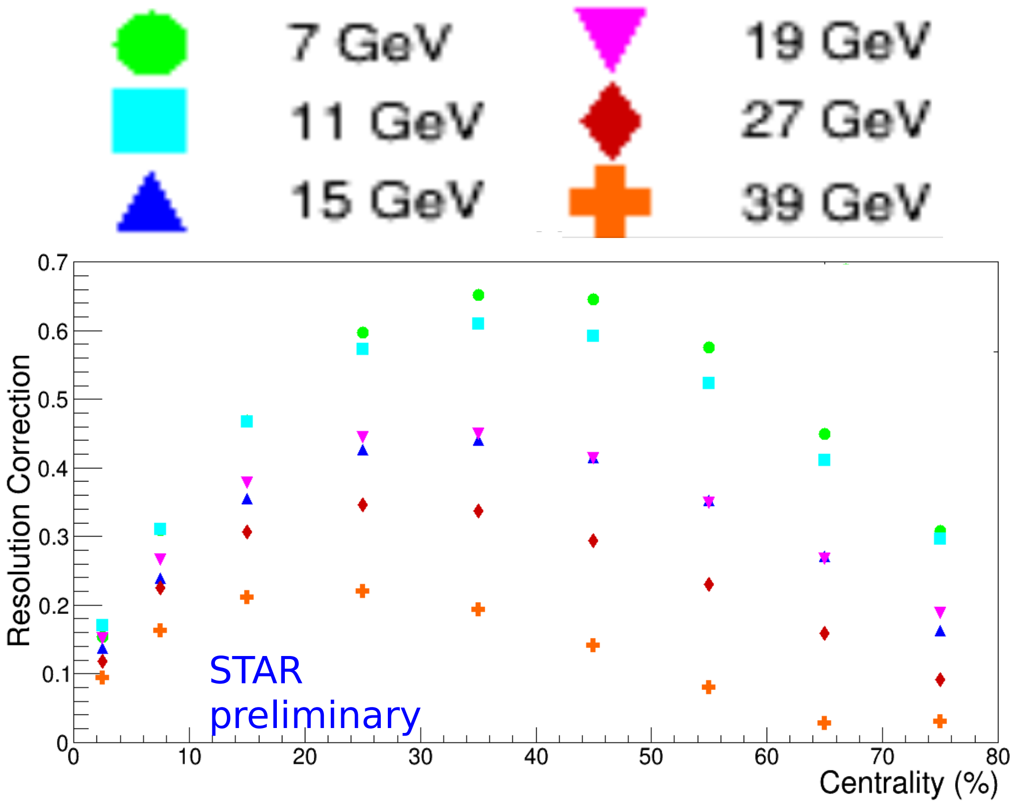
Fig. 1: Cartoons and coordinate system

- a) shows the impact parameter
- b) shows spinning tops rep't Lambdas and system angular momentum
- c) is coordinate system with RP

Correcting for reaction-plane resolution

$$R_{\mathrm{EP}}^{(1)} = \langle \cos \Delta\psi \rangle = \langle \cos(\Psi_{\mathrm{RP}} - \Psi_{EP}^{(1)}) \rangle$$



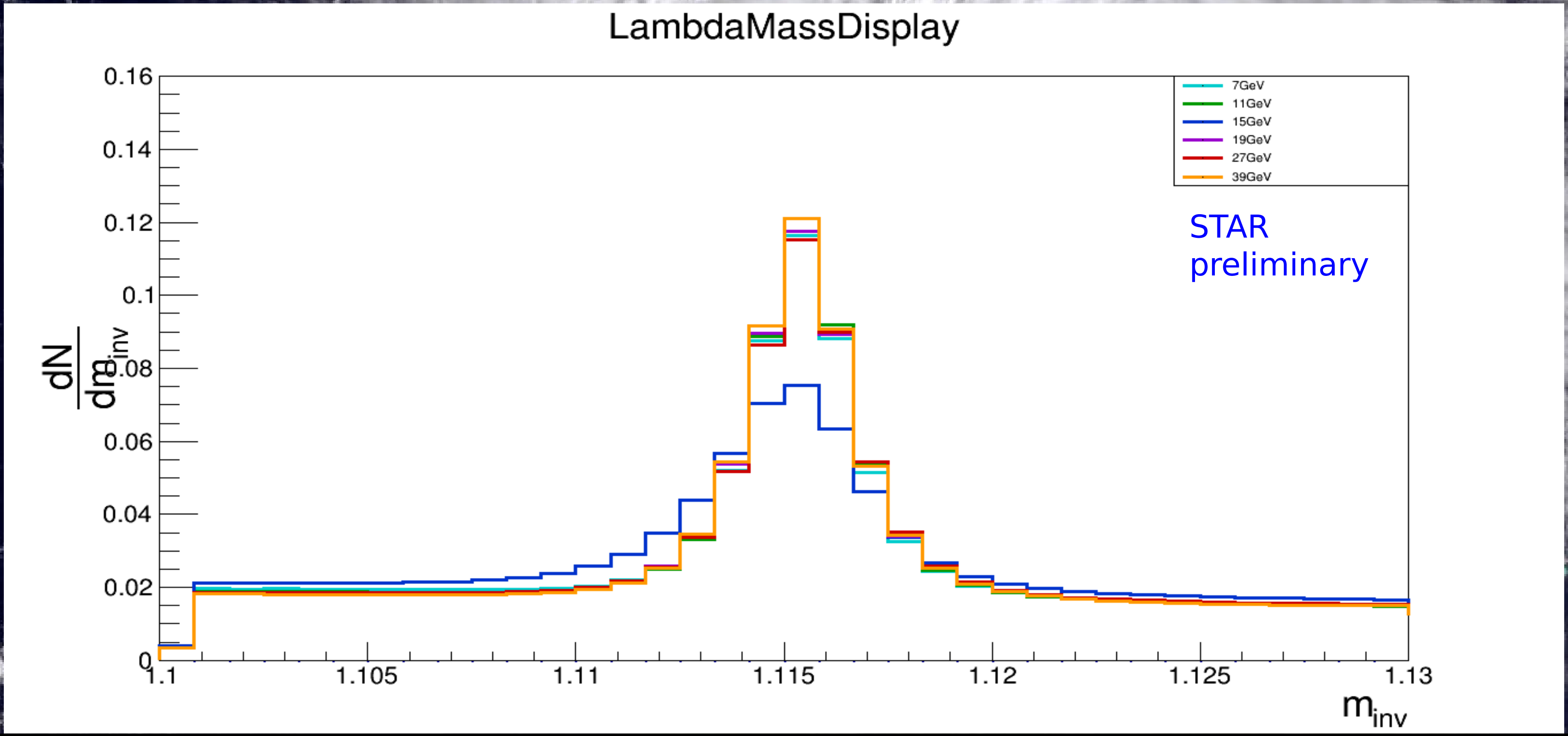


$$P_{AVE} = \frac{8}{\pi\alpha} \frac{\langle \sin(\Psi_{EP}^{(1)} - \varphi_p^*) \rangle}{R_{EP}^{(1)}}$$

Purity Correction

Combinatoric background to the Lambda distribution

- Should give a null result
- Simply scale data by (S+B)/B



Topologically-dependent efficiency

Spin-orientation-dependent efficiency (!)

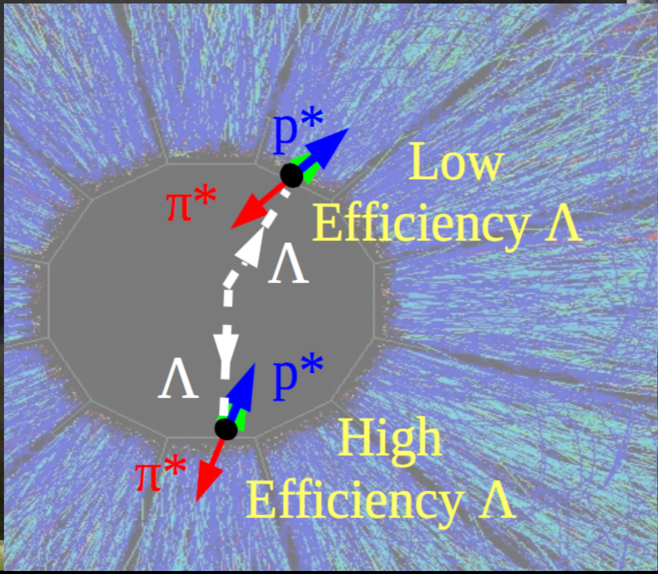
Daughter proton & pion have equal-magnitude momentum in Lambda frame, but not in STAR frame

$$\left.\frac{R_\pi}{R_p} = \frac{\left|\vec{p}_{T,\pi}\right|}{\left|\vec{p}_{T,p}\right|} \sim \frac{m_\pi}{m_p} \sim \frac{1}{7}\right\} \quad \rightarrow \quad \pi \text{ tracking drives } \Lambda \text{ efficiency}$$

pion emitted backward in Lambda c.m., → tight curl, large DCA (distance to collision vertex)

→ much-reduced efficiency

→ higher efficiency to find negative-helicity Lambdas



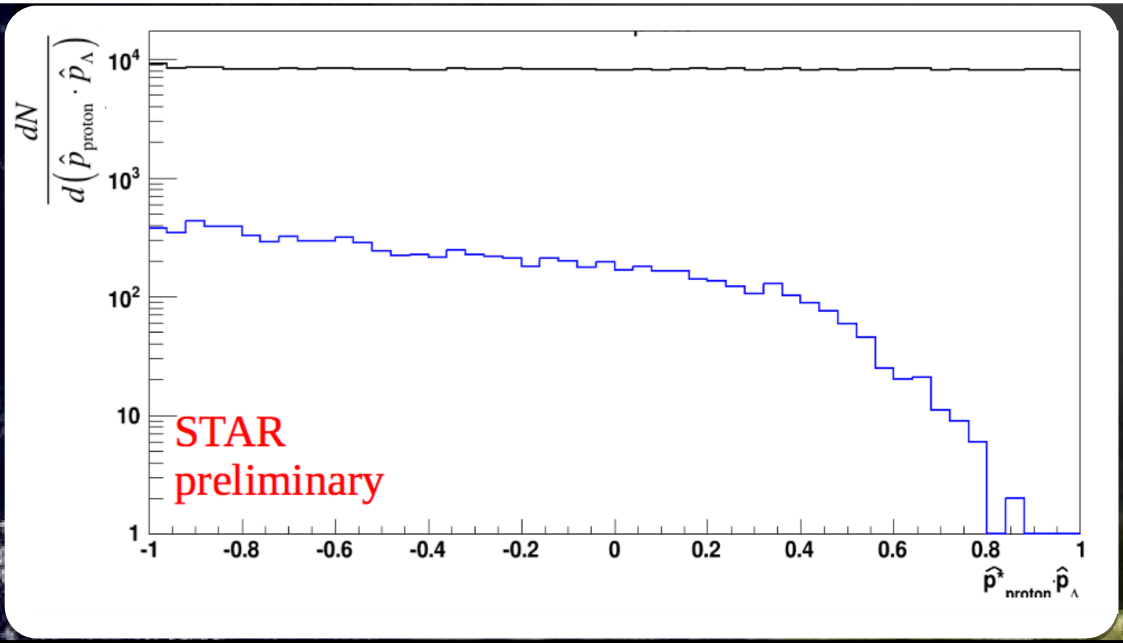
Topologically-dependent efficiency

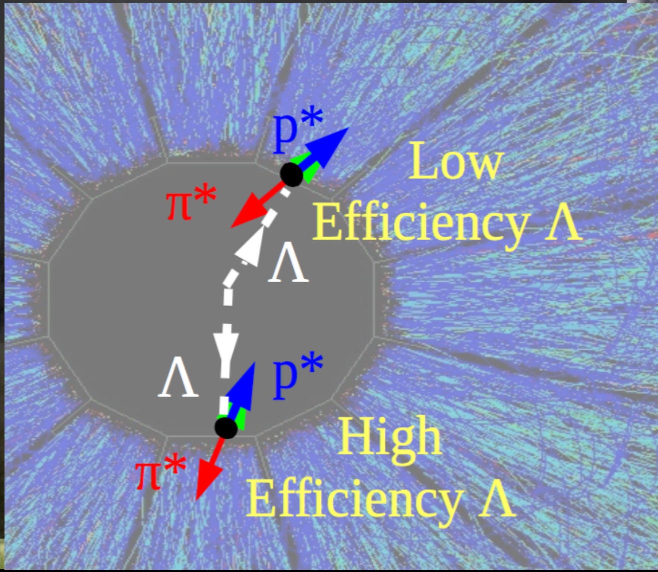
Spin-orientation-dependent efficiency (!)

- Same effect seen in embedding/GEANT simulations
- p_T-dependent
- not correlated with RP
- explicitly cancels when summing regions separated by 180 degrees

effect does not affect P_{ave}

HIJING events through simulated STAR detector & tracking





Effect of (Anti)Sigma feed-down

$$\underbrace{\Sigma^0}_{\frac{1}{2}^+} \rightarrow \underbrace{\Lambda}_{\frac{1}{2}^+} + \underbrace{\gamma}_{1^-}$$

(p-wave decay)

- A significant fraction (~30%) of our Lambdas are actually feed-down from Sigma0
- The daughter Lambda tends to have spin direction opposite that of the parent Sigma

Scenario 1: spin of all primary particles $\left(\Lambda,\Sigma^0,\bar{\Lambda},\bar{\Sigma}^0\right)$ aligned with $\vec{J}_{\text{system}}$, due to vorticity (or whatever):

$\Rightarrow$ primary Λ $\left(\text{and } \bar{\Lambda}\right)$ aligned with $\vec{J}_{\text{system}}$, but secondary Λ $\left(\text{and } \bar{\Lambda}\right)$ aligned against $\vec{J}_{\text{system}}$

Thus, for vorticity-induced polarization, **feed-down tends to damp the signal**. STAR's 2004 paper estimated < 30% damping effect

Scenario 2: polarization through coupling of particle magnetic moment to B-field of the system

$$\vec{\mu}_{\Lambda} = \left(-0.613\mu_N\right)\vec{S}_{\Lambda} \;\Rightarrow\; \vec{S}_{\Lambda[\text{primary}]} \text{ will be antialigned with } \vec{J}_{\text{system}} \quad \left(\vec{S}_{\Lambda[\text{primary}]} \parallel -\vec{J}_{\text{system}}\right)$$

$$\vec{\mu}_{\Sigma^0} = \left(+0.79\mu_N\right)\vec{S}_{\Sigma^0} \;\Rightarrow\; \vec{S}_{\Sigma^0} \text{ will be aligned with } \vec{J}_{\text{system}} \quad \left(\vec{S}_{\Sigma^0} \parallel +\vec{J}_{\text{system}}\right)$$

$$\Rightarrow \text{daughter } \Lambda\text{'s will be antialigned with } \vec{J}_{\text{system}} \quad \left(\vec{S}_{\Lambda[\text{secondary}]} \parallel -\vec{J}_{\text{system}}\right)$$

Similar argument for the antiparticles, where both the primary and secondary $\bar{\Lambda}$ align with $\vec{J}_{\text{system}}$

Thus, for magnetic-coupling-induced polarization, **feed-down goes in the same direction as the signal from primary Lambdas.**

Effect of (Anti)Sigma feed-down

$$\underbrace{\Sigma^0}_{\frac{1}{2}^+} \rightarrow \underbrace{\Lambda}_{\frac{1}{2}^+} + \underbrace{\gamma}_{1^-}$$

(p-wave decay)

- A significant fraction (~30%) of our Lambdas are actually feed-down from Sigma0
- The daughter Lambda tends to have spin direction opposite that of the parent Sigma

under assumption that Σ^0 polarizes as Λ does:

$$P_{\text{primary }\Lambda} = \frac{1 + N_{\Sigma^0} / N_{\text{prim }\Lambda}}{1 - \frac{1}{3} N_{\Sigma^0} / N_{\text{prim }\Lambda}} P_{\text{measured }\Lambda} \equiv \mathrm{K}_{\Sigma^0 \rightarrow \Lambda} P_{\text{measured }\Lambda}$$

model	N[Sigma0]/N[Lambda]	K[Sigma0->Lambda]
"isospin effect" (COSY-11) (*)	1/3	1.5
THERMUS with, w/o resonances (*)	0.36-0.67	1.5-2.2
"Coalescence" (*)	0.2-1.0 (1.0?)	1.3-3
Chemical equilibrium with T=150 MeV	**0.59**	**2**
STAR estimate from p-Lambda paper	0.73	2.3
(*) G. Van Buren (STAR) nucl-ex/0412034		

Used here

Conservative range: 1.5-2.5

Previous STAR result

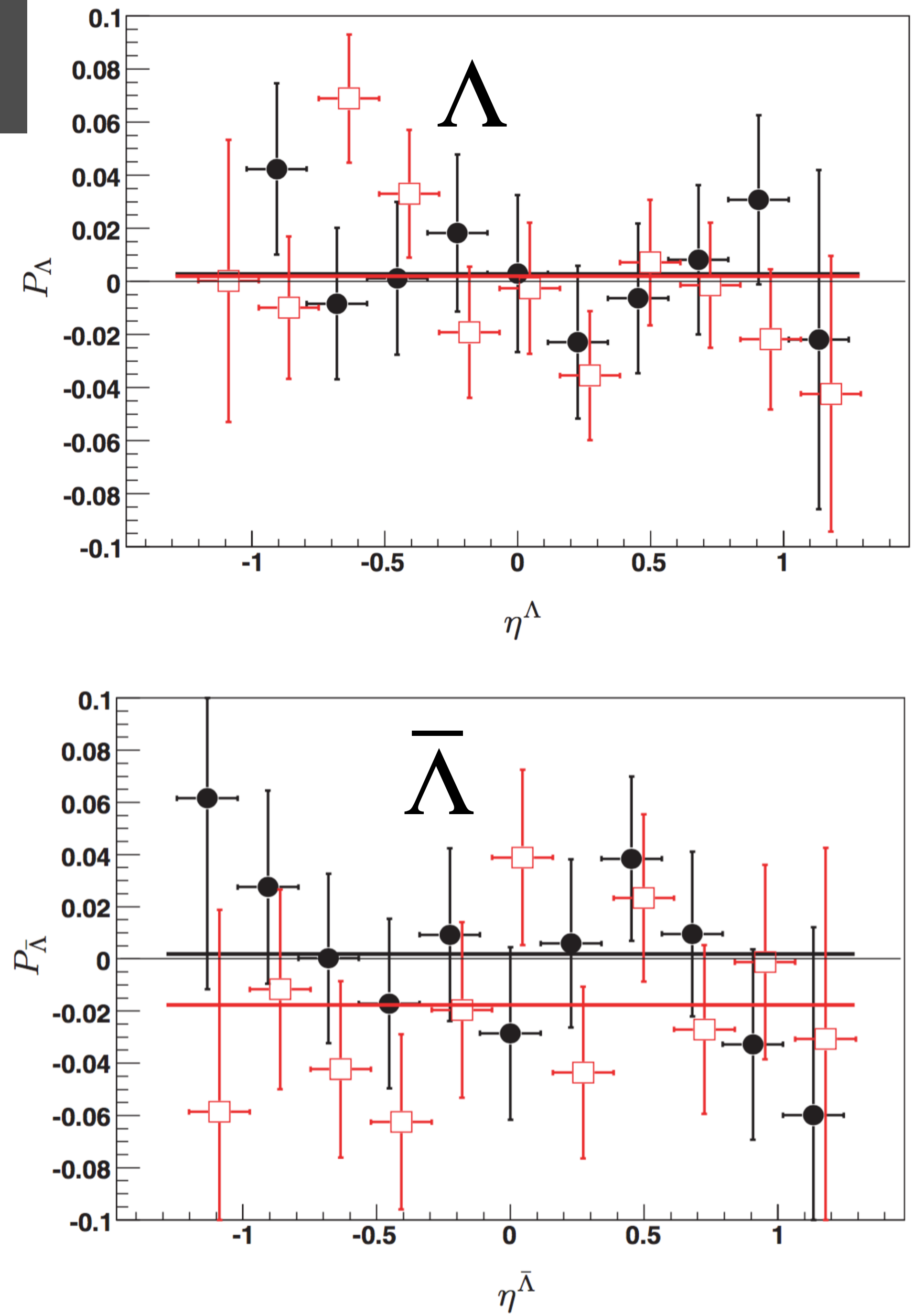
Phys RevC **76**, 024915 (2007)
concluded null signal

$$\left\langle \vec{S}^{*}_{\Lambda} \cdot \hat{L} \right\rangle = -\frac{1}{2}\,"P_{\Lambda}"$$

oops

● 200 GeV
□ 62.4 GeV

A 1.7-sigma signal seen for Anti-Lambdas at 62.4 GeV?



Mass Purity Correction

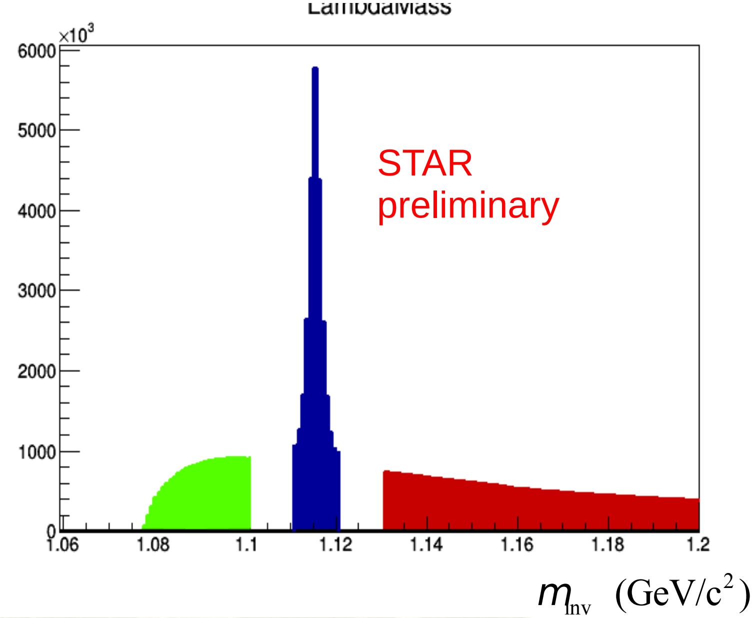
- Effect: overall scale up
- Correction based on the fact that not all “Lambdas” in the mass peak are real

$$\langle \hat{S}^{*} \cdot \hat{L} \rangle_{\text{On Peak}} = \frac{S \langle \sin(\Psi_1 - \varphi_p^{*}) \rangle_{\Lambda} - B \langle \sin(\Psi_1 - \varphi_p^{*}) \rangle_{\text{Off Peak}}}{S+B}$$

$$\langle \hat{S}^{*} \cdot \hat{L} \rangle_{\Lambda} = \frac{S+B}{S} \langle \sin(\Psi_1 - \varphi_p^{*}) \rangle_{\text{On Peak}} - \frac{B}{S} \langle \sin(\Psi_1 - \varphi_p^{*}) \rangle_{\text{Off Peak}}$$

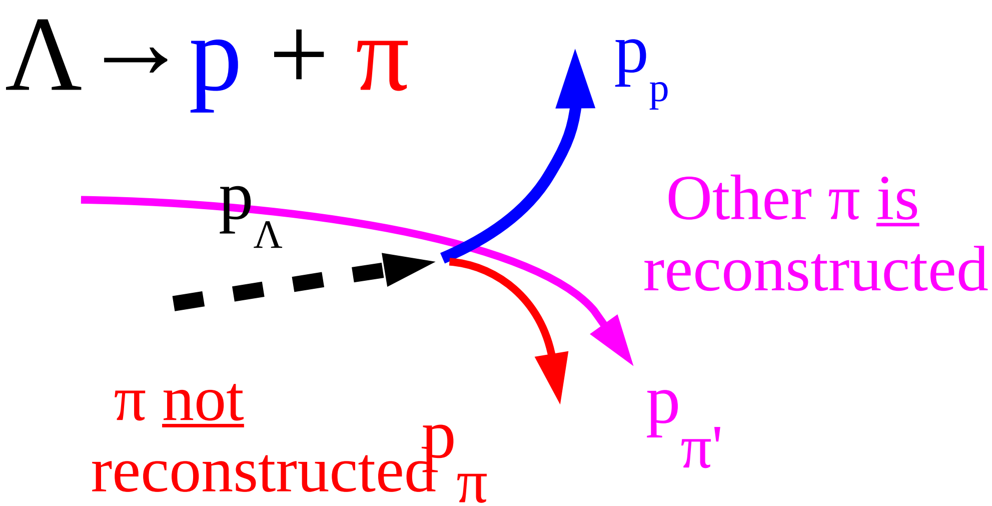
- We measure the signal on peak, but we want to know the underlying signal for the Lambdas

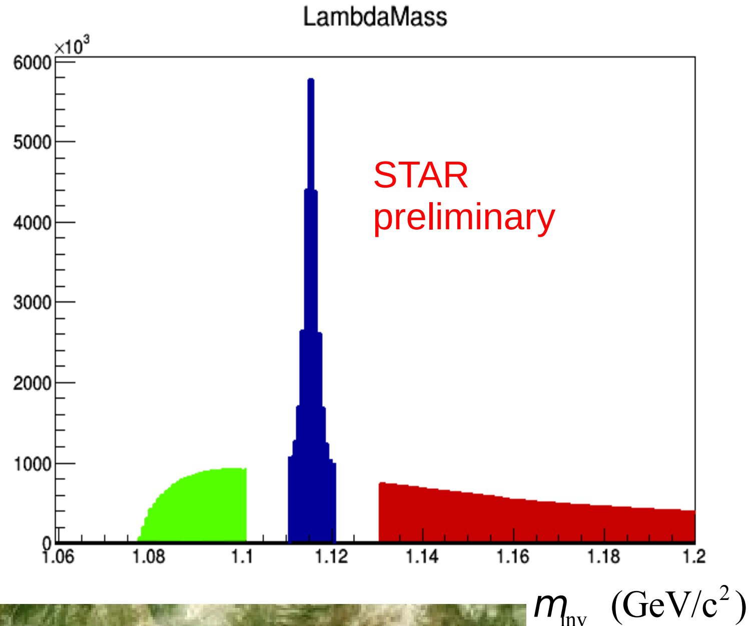
- Much like flow we can subtract off any signal we see off peak



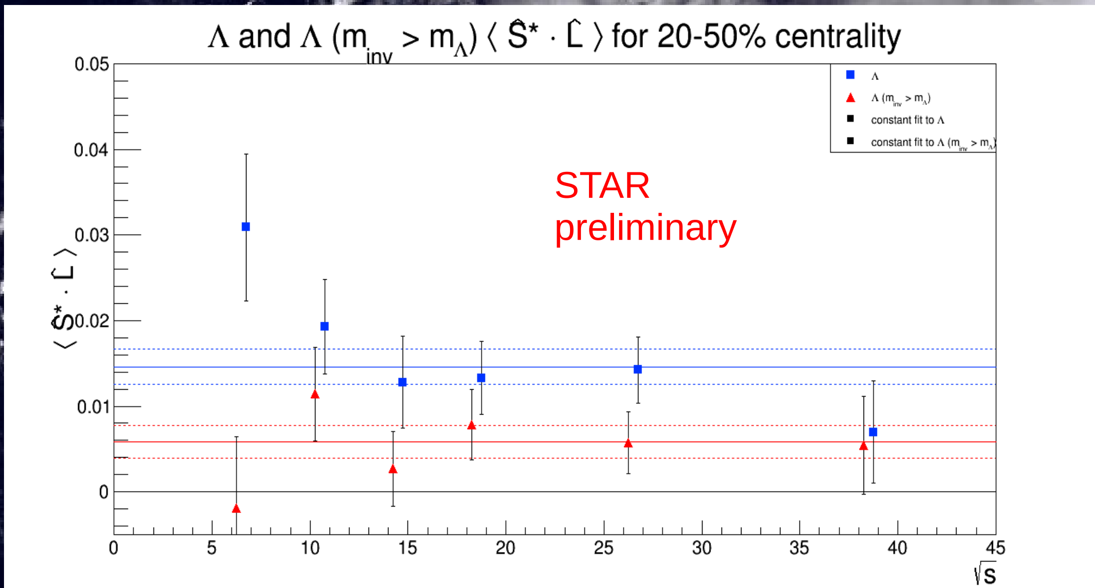
Where does $\langle \sin(\Psi_1 - \varphi_p^*) \rangle_{\text{Off Peak}} \neq 0$ come from?

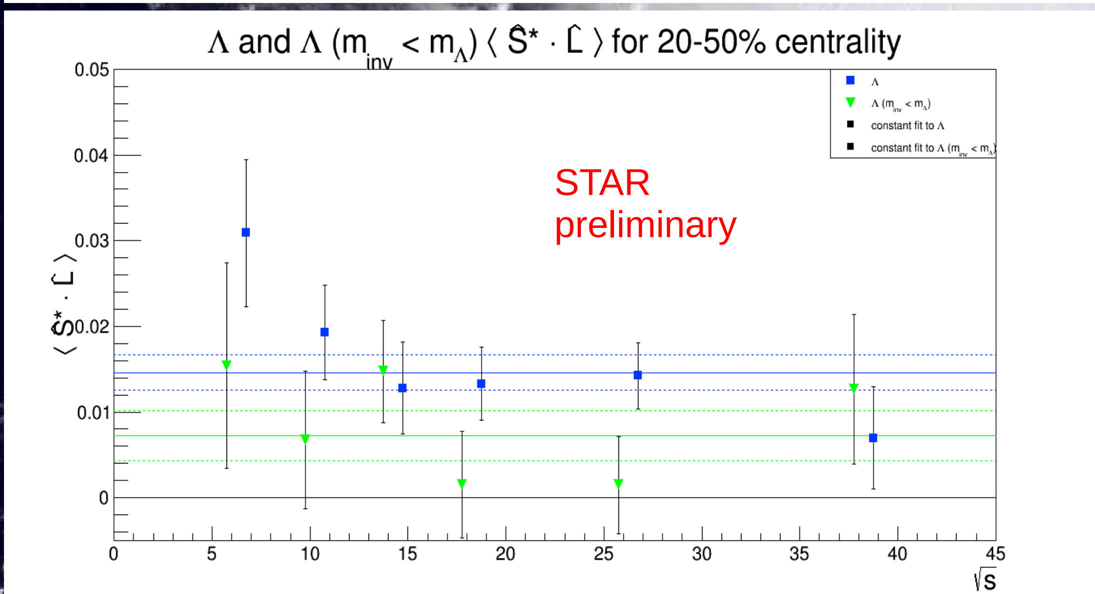
- Formalism works but does it make sense?
- Primary protons and pions should have no signal
- Few non-Lambda sources for non-primary protons
- Perhaps off mass signals come from orphan protons





Mass Purity Correction: Lambda





- Linear fit to on peak: Signal/Error = 7.00
- Linear fit to high mass: Signal/Error = 3.03
- Linear fit to low mass: Signal/Error = 2.52