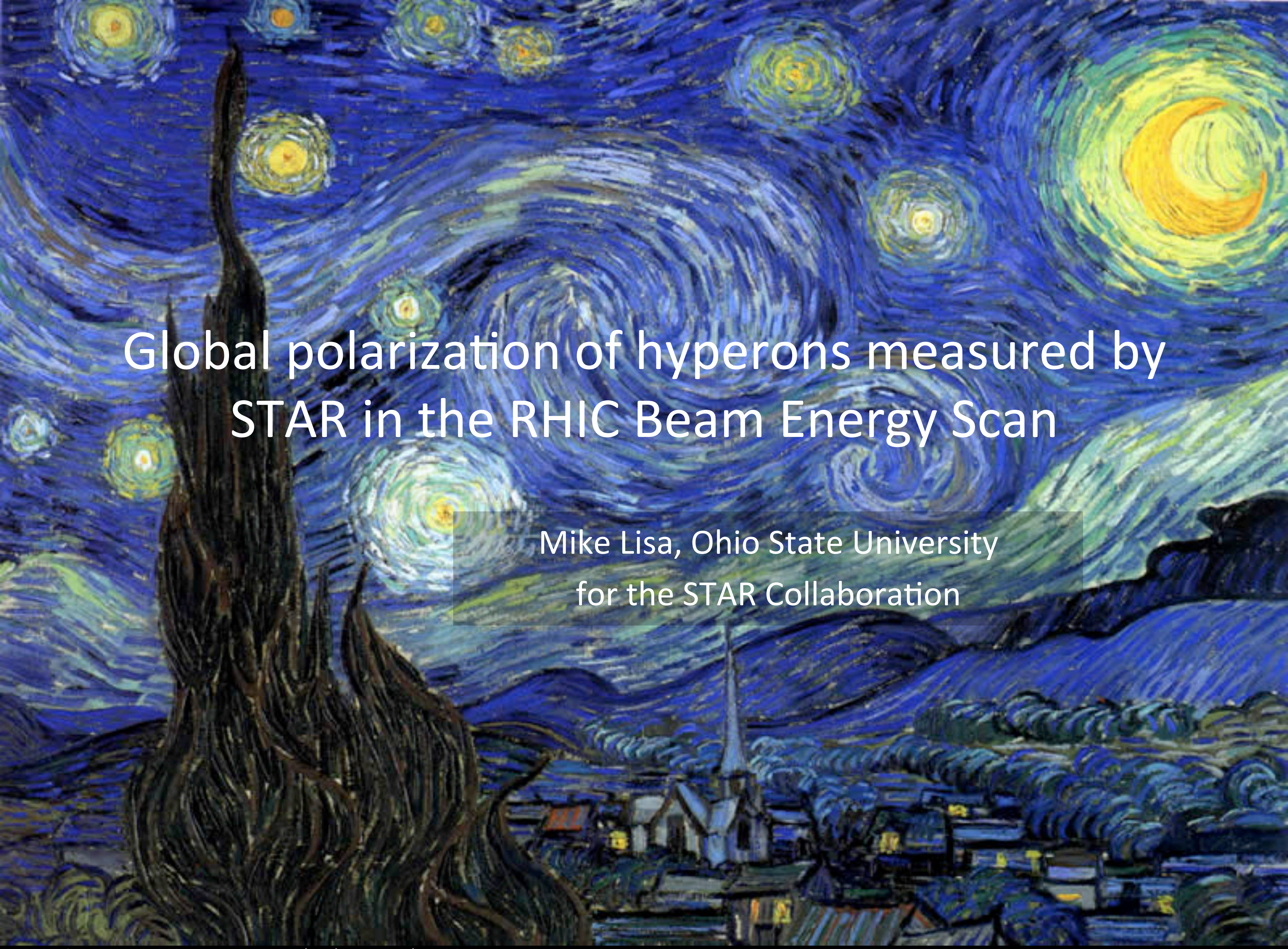


Global polarization of hyperons measured by STAR in the RHIC Beam Energy Scan

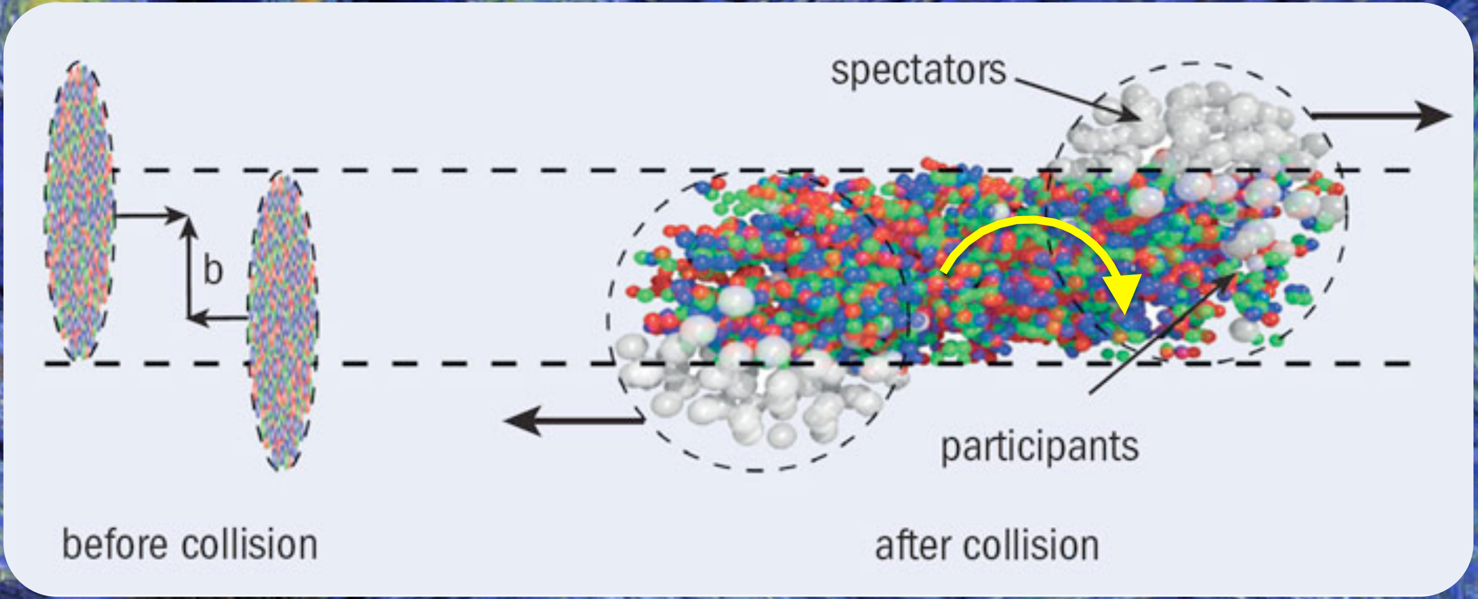
Mike Lisa, Ohio State University
for the STAR Collaboration

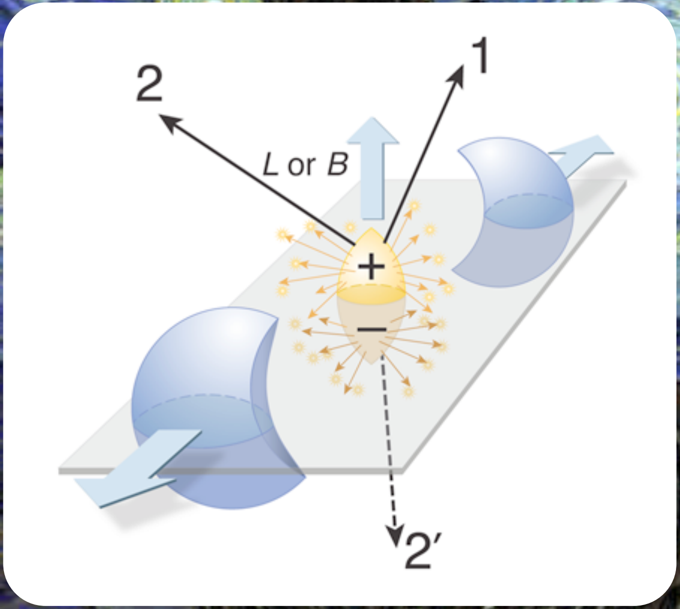
Outline

- Motivation
  - angular momentum and vorticity in heavy ion collisions
  - self-analyzing nature of Lambda decay

- Current analysis: STAR @ BES energies – preliminary results
    - Dealing with a strong artifact: decay-topology-dependent efficiency
    - positive signals for Lambdas and AntiLambdas
    - centrality dependence

- Summary & Outlook





- |L| ~ 10^6 ħ in non-central collisions
- 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?

Vorticity examples

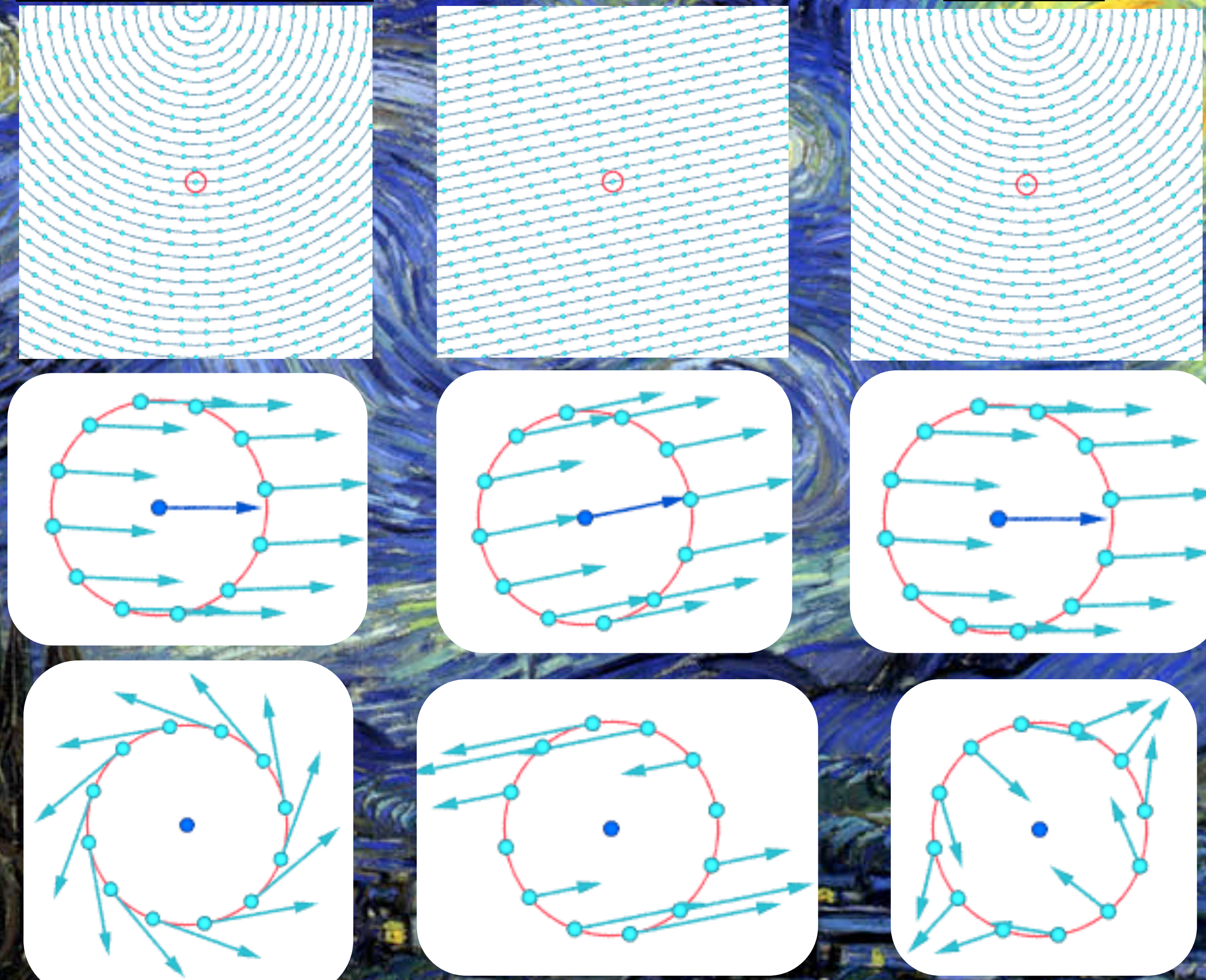
Figures by Jorge Stolfi posted on Wikipedia

	Rigid-body-like vortex	Parallel flow with shear	Irrotational vortex
	$v \propto r \quad \vec{v} = \alpha(-y\hat{x}, x\hat{y}, 0)$		$v \propto 1/r$

Flow field:

Absolute velocities around highlighted point

Relative velocities around highlighted point (i.e. in fluid rest frame)

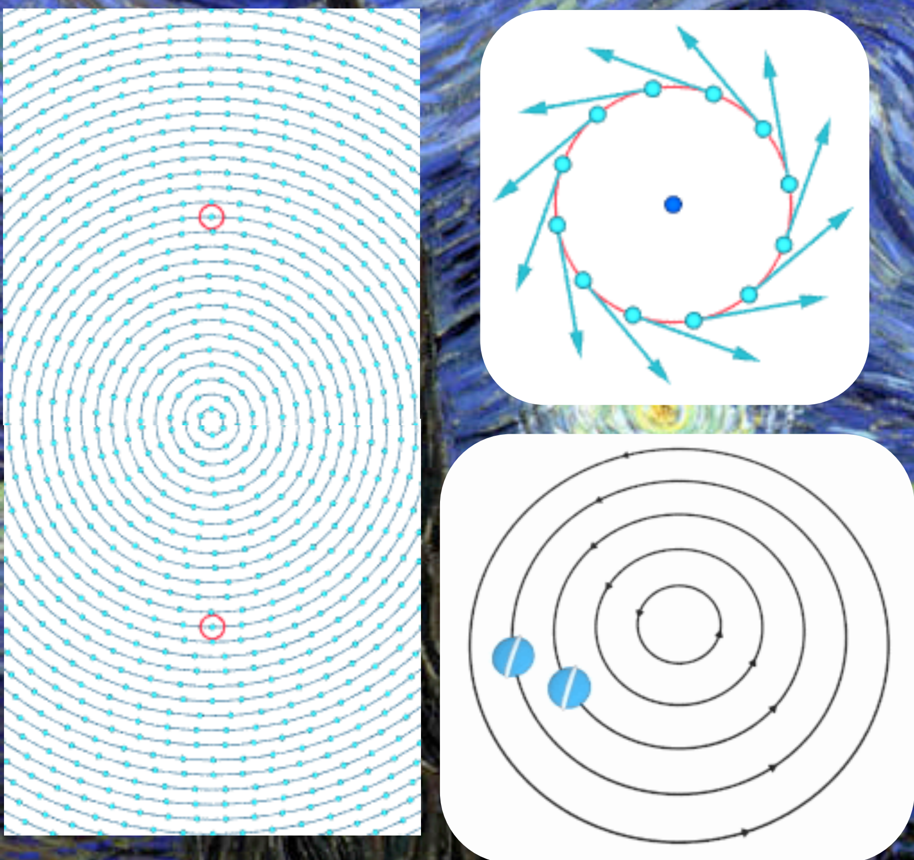


Vorticity:

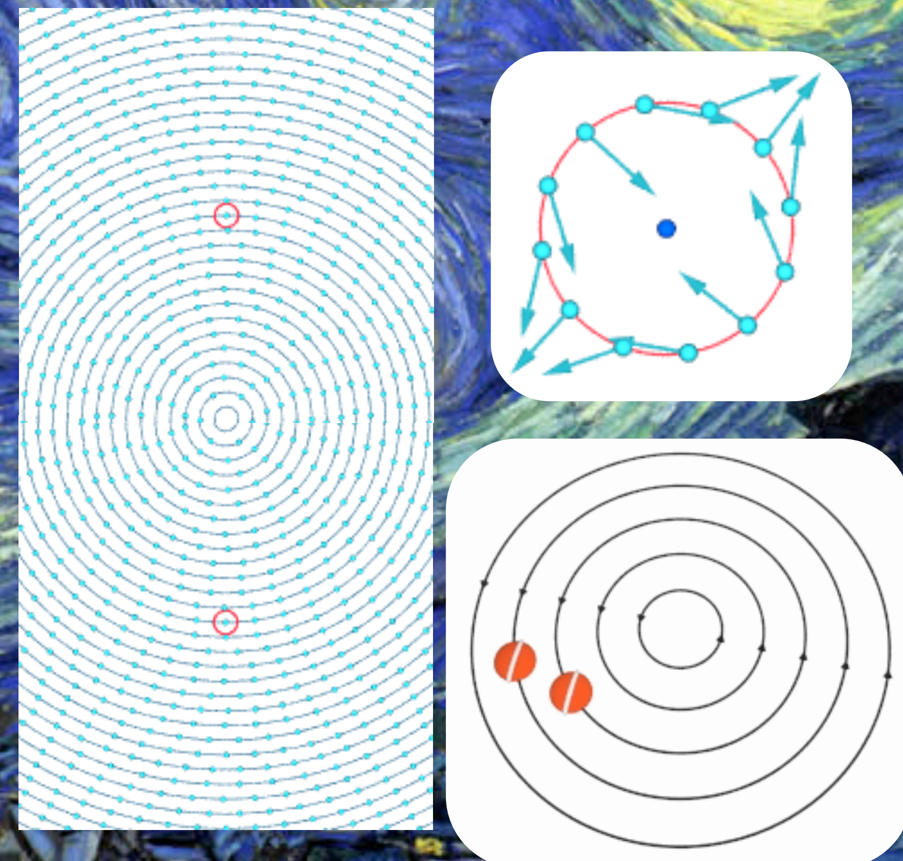
Rigid-body-like vortex	Parallel flow with shear	Irrotational vortex
$\vec{\omega} = \vec{\nabla} \times \vec{v} = \alpha$	$\vec{\omega} = \vec{\nabla} \times \vec{v} \neq 0$	$\vec{\omega} = \vec{\nabla} \times \vec{v} = 0$

Rotational & Irrotational Vortices

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



Irrotational vortex
$v \propto 1/r$



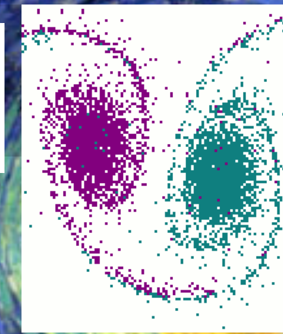
This one is like the moon, always facing the same side toward Earth

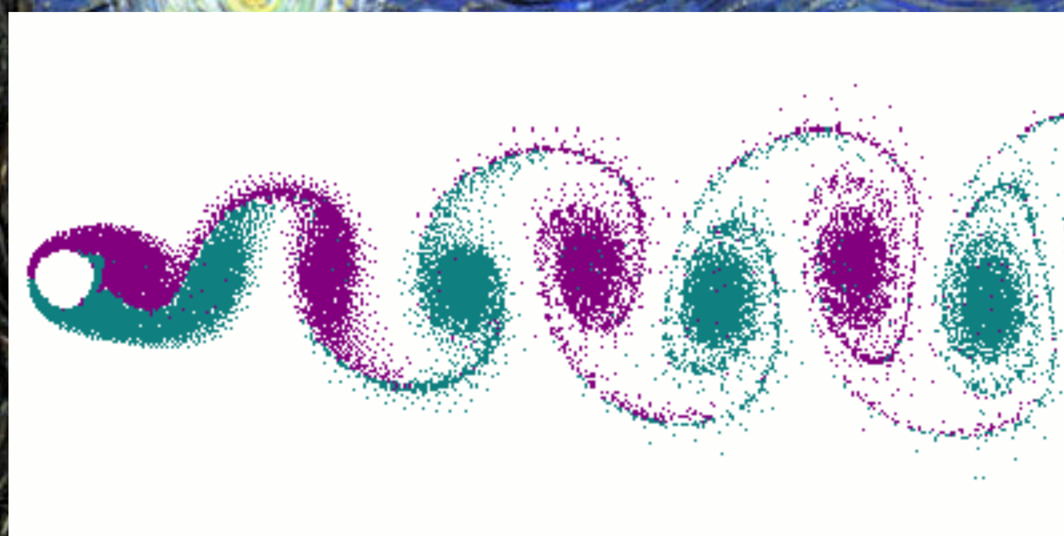
Notice the rotation, or lack thereof, in the fluid elements

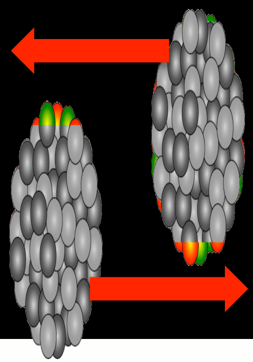
Vortex shedding

purple: $\vec{\omega}$ in

green: $\vec{\omega}$ out





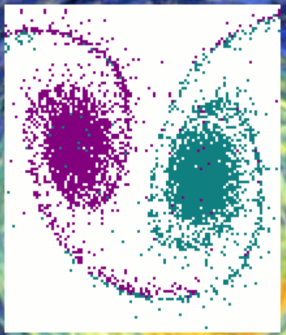


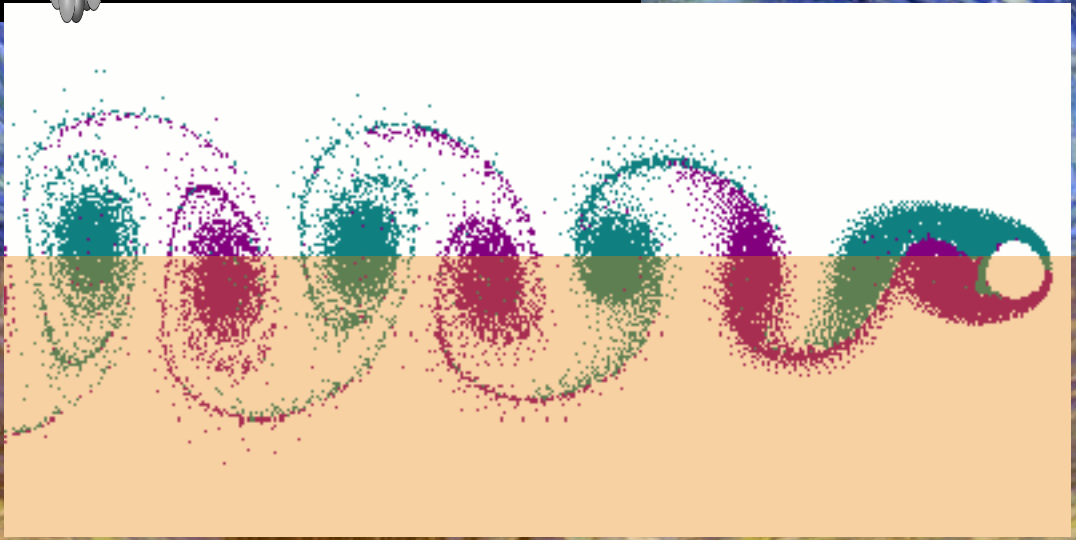
Asymmetry: preferential creation of inward vortices

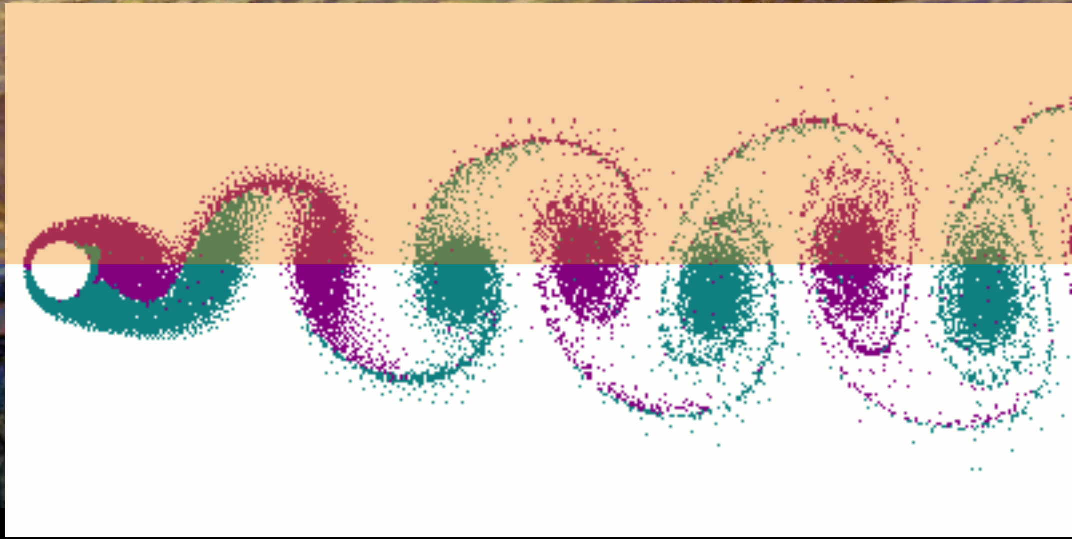
(in agreement with *total* angular momentum)

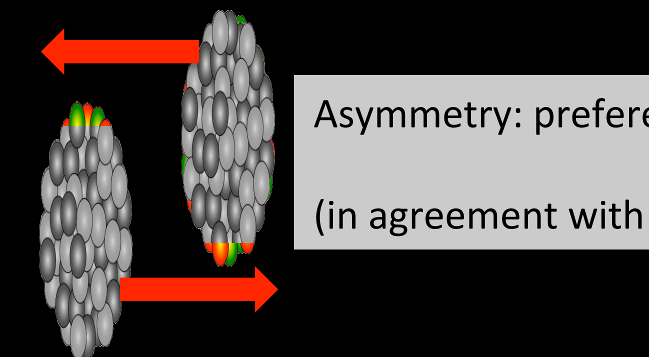
purple: $\vec{\omega}$ in

green: $\vec{\omega}$ out



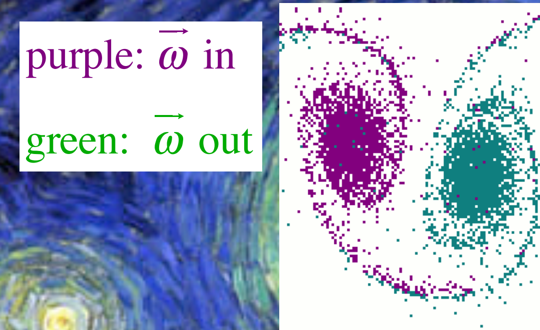




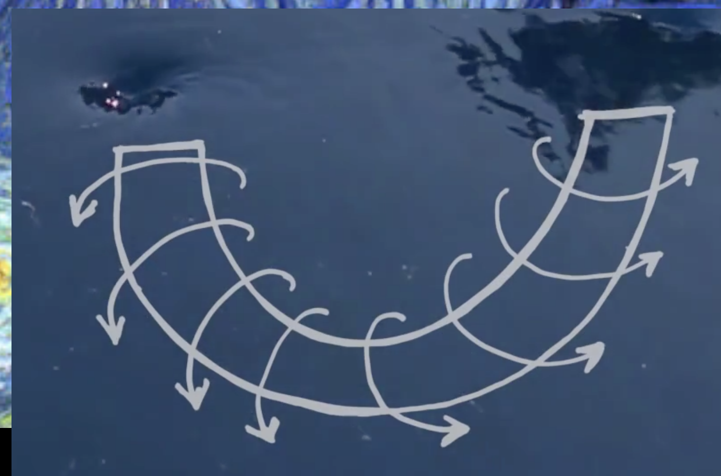


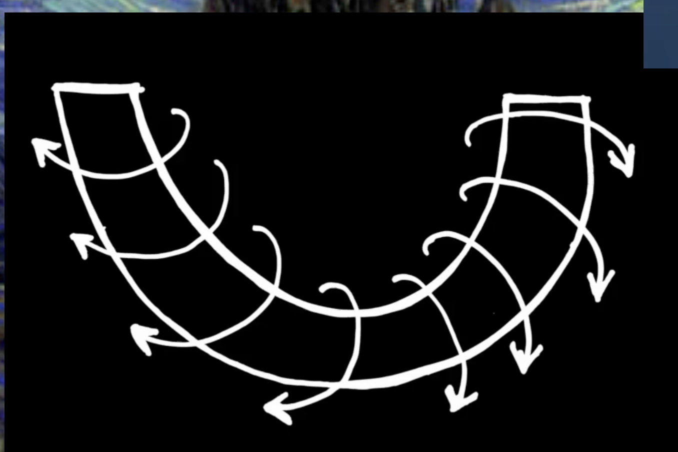
Asymmetry: preferential creation of inward vortices

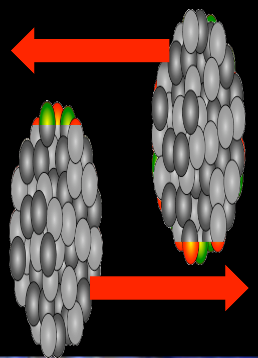
(in agreement with *total* angular momentum)



Remember your “homework” – vortices by Physics Girl https://www.youtube.com/watch?v=pnbJEg9r1o8

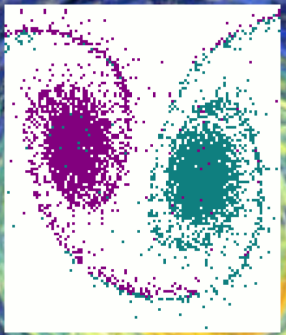






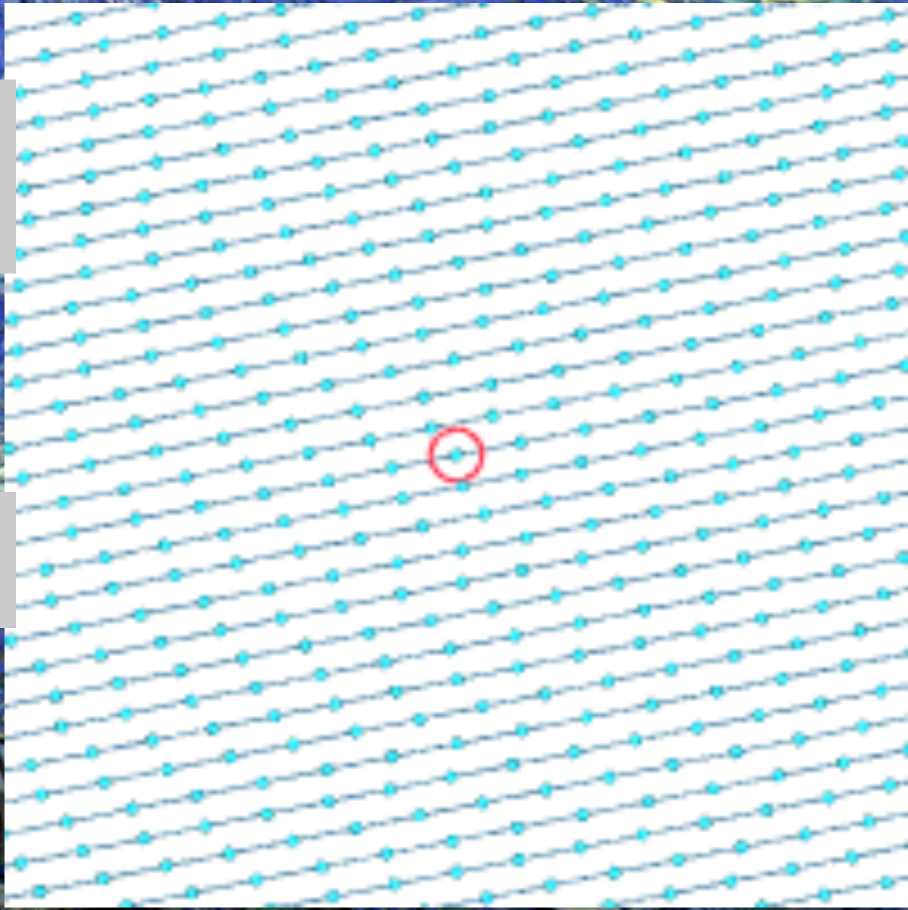
Asymmetry: preferential creation of inward vortices

(in agreement with *total* angular momentum)



Localized vortex generation via baryon stopping

Viscosity dissipates vorticity to fluid at larger scale



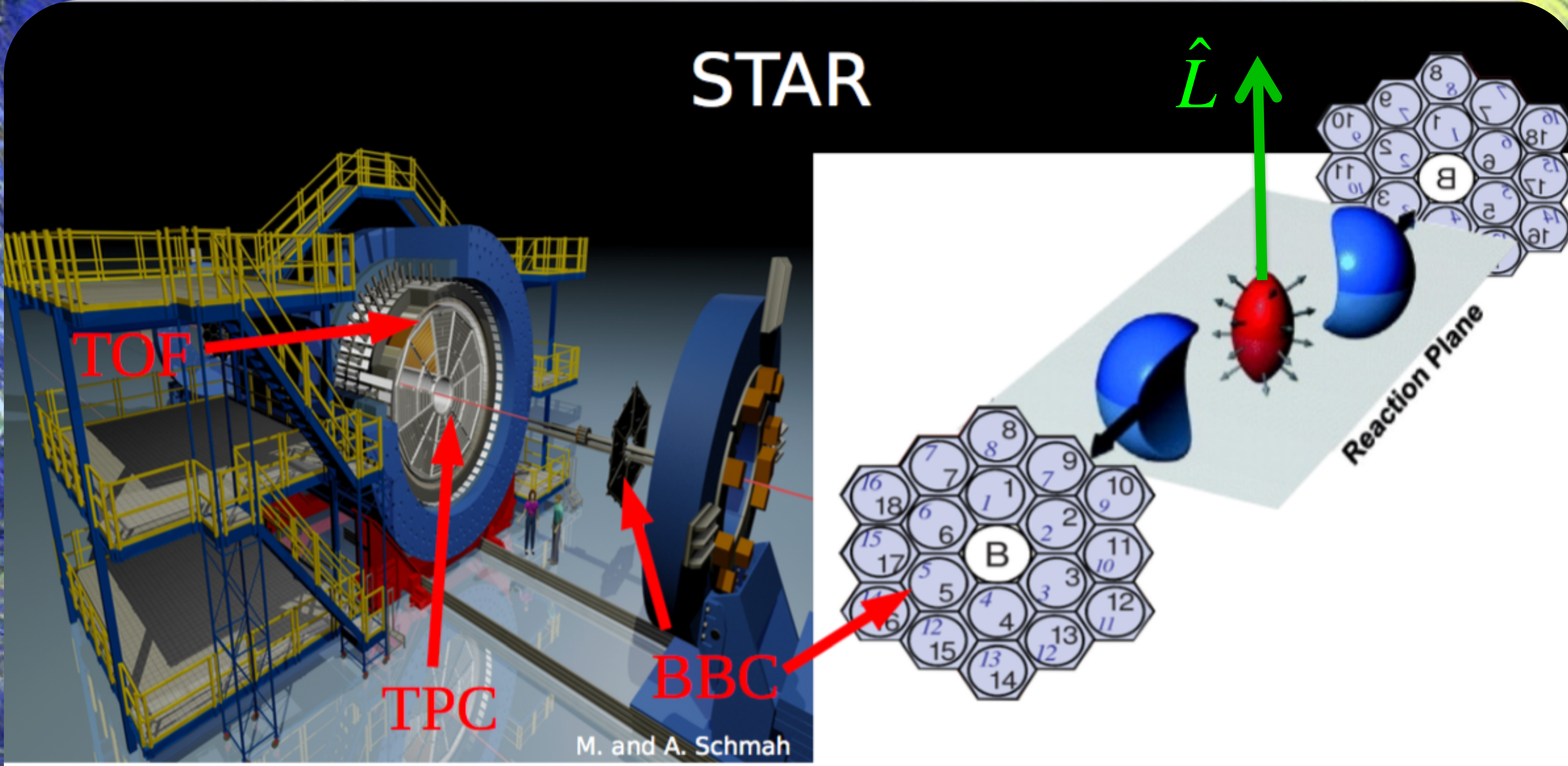
Vorticity – fundamental sub-femtoscopic structure of the “perfect fluid” and its generation

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. arxiv:1501.04468

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

Analysis approach



- Study Au+Au collision in the BES:
  - **7.7, 11.5, 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

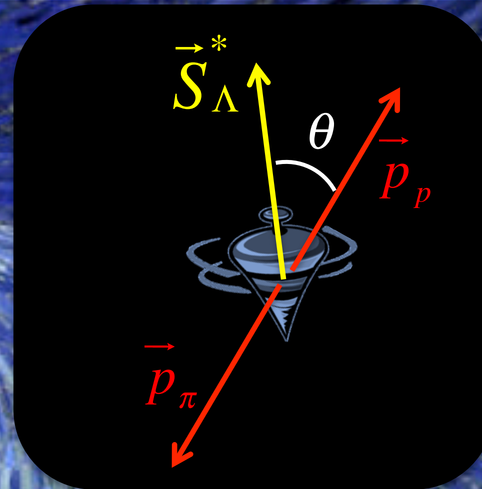
→ estimate of direction of angular momentum $\hat{L}$

Analysis approach

Lambdas are "self-analyzing"

- reveal polarization by preferentially emitting daughter proton in spin direction
- more on this in a few slides

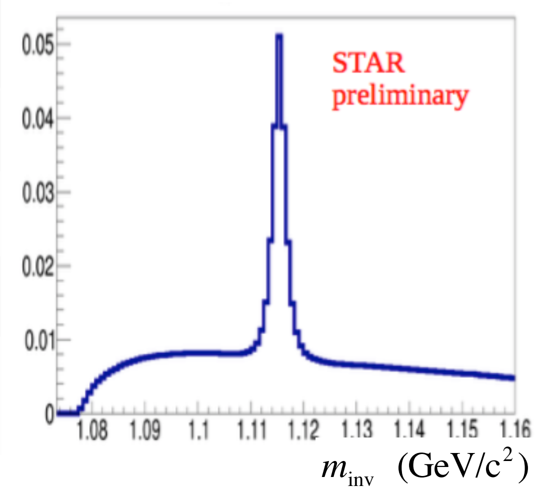
E. Cummins, Weak Interactions (McGraw-Hill, 1973)



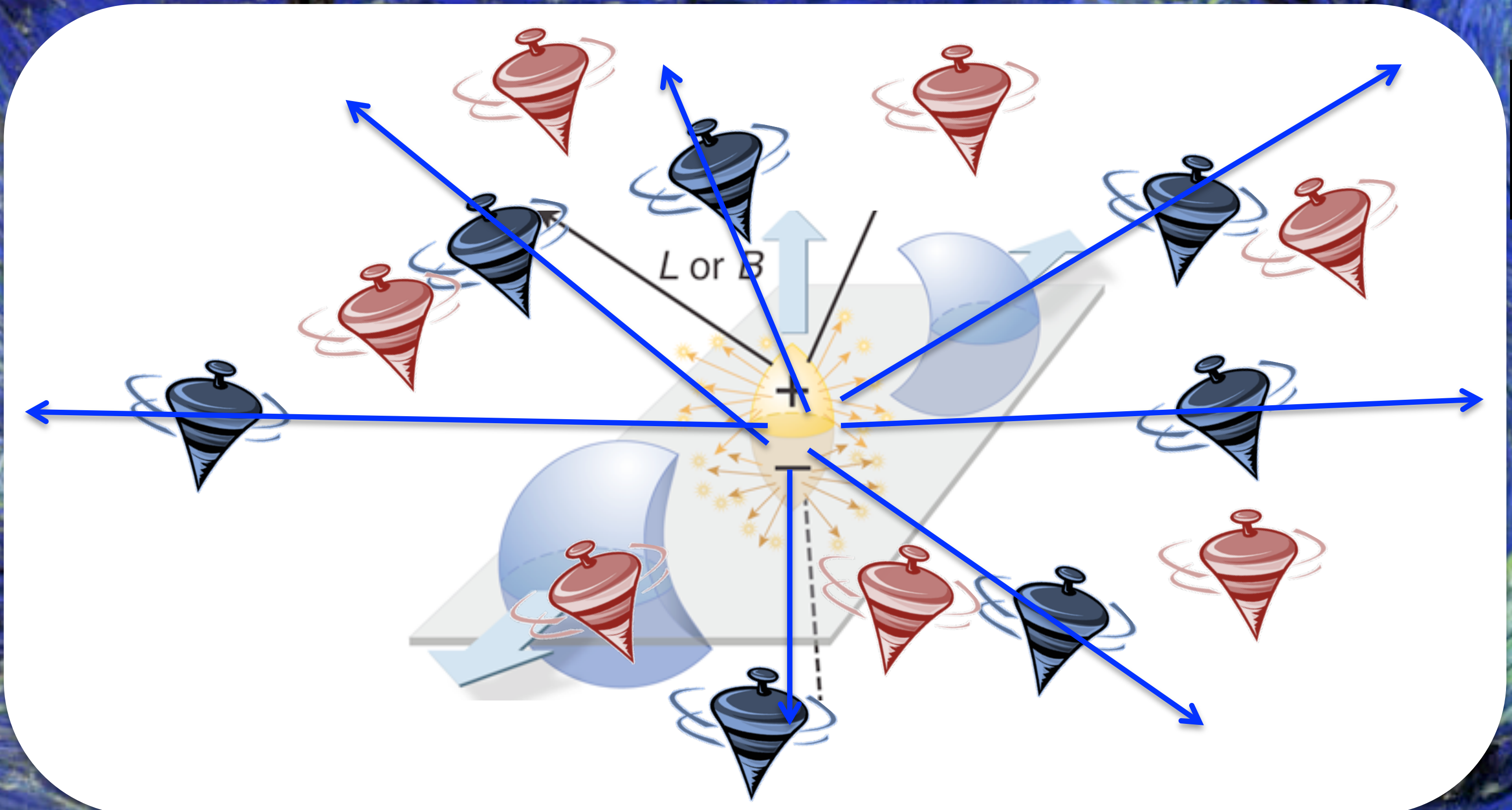
Topological cuts optimized to maximize yield significance

- Basic Track Cuts
  - If proton has ToF $0.5\ (\mathrm{GeV/c^2})^2 < m^2 < 1.5\ (\mathrm{GeV/c^2})^2 \quad (\mathrm{TPC}\ |n_\sigma| < 3)$
  - If pion has ToF $\left(0.017 - 0.013\cdot\frac{p}{GeV/c}\right)(\mathrm{GeV/c^2})^2 < m^2 < 04\ (\mathrm{GeV/c^2})^2 \quad (\mathrm{TPC}\ |n_\sigma| < 3)$
- Lambda Topological cuts
  - Daughter DCA < 1 cm, $1.108\ \mathrm{GeV/c^2} < m < 1.122\ \mathrm{GeV/c^2}$

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

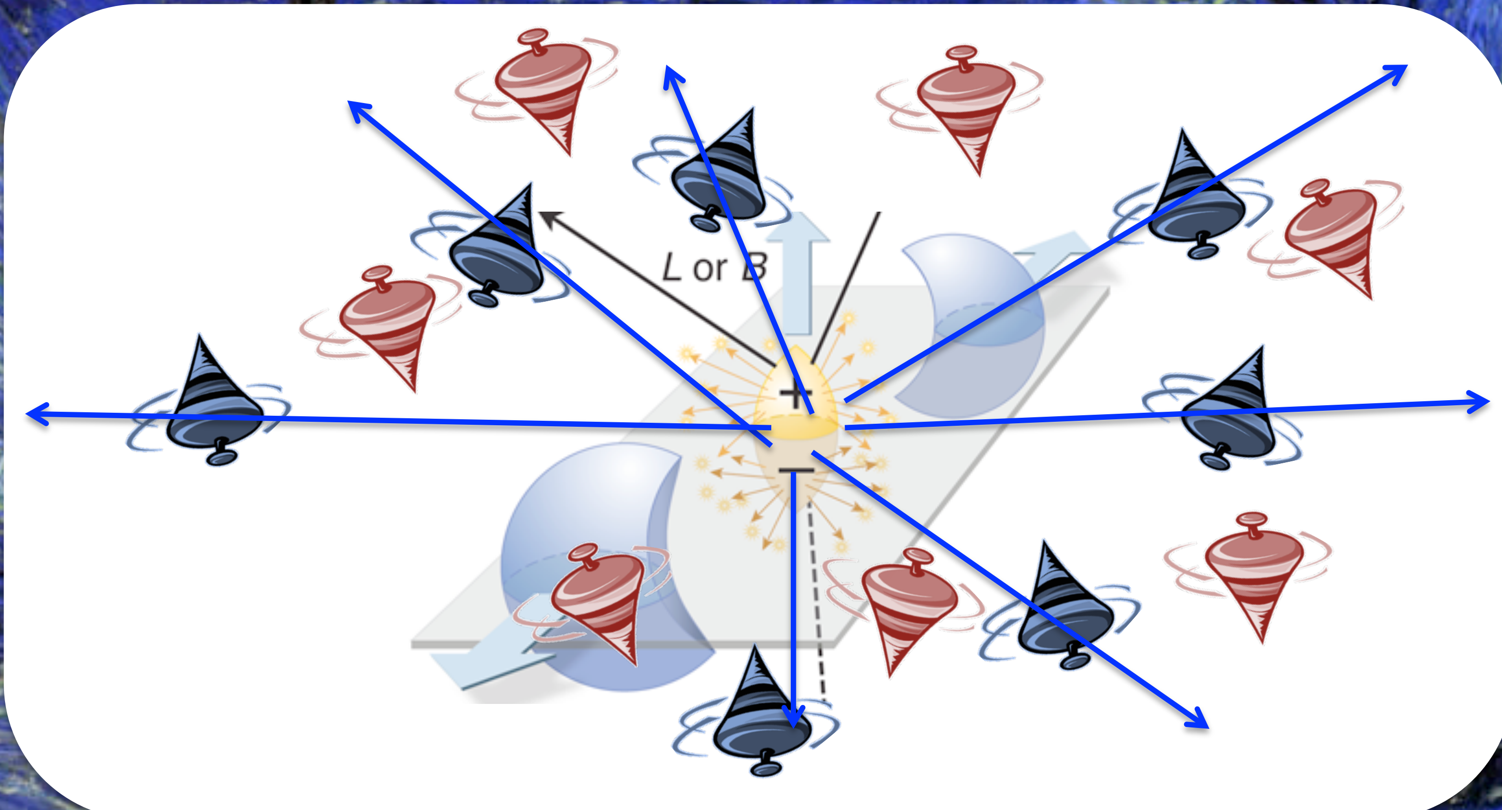


Relevant quantity

$\vec{S}_{\Lambda} \cdot \hat{L}$

- <u>Vortical or QCD spin-orbit</u>: Lambda and AntiLambda spins aligned with L
  - Sigma feed-down tends to dampen the effect

Contributors to Global Polarization



Relevant quantity

$\vec{S}_\Lambda \cdot \hat{L}$

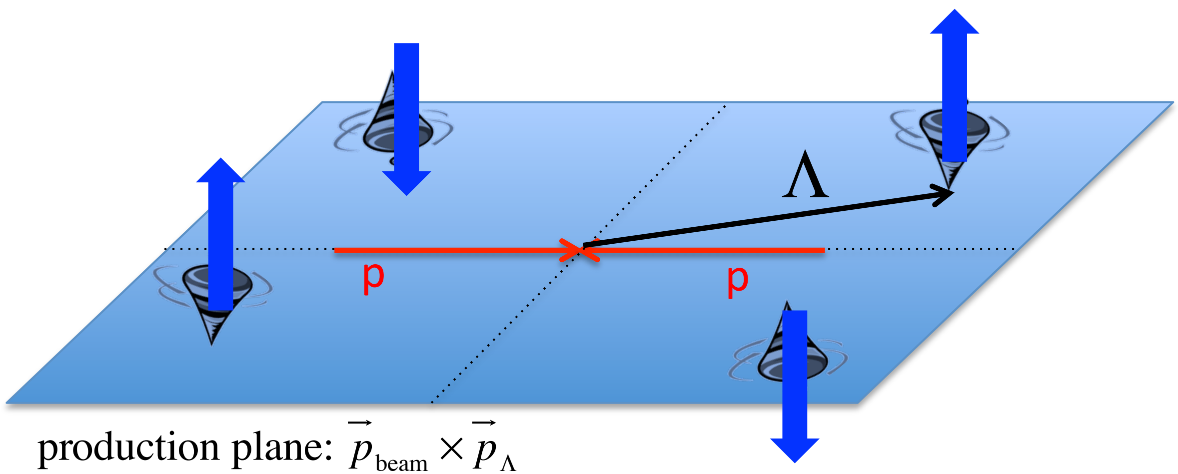
Both may contribute

- <u>Vortical or QCD spin-orbit</u>: Lambda and AntiLambda spins aligned with L
  - Sigma feed-down tends to dampen the effect
- <u>(electro)magnetic coupling</u>: Lamdas *anti*-aligned, and AntiLambdas aligned
  - Sigma feed-down goes in same direction as the effect on primaries

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*



production plane: $\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda}$

Relevant quantity

$\vec{S}_{\Lambda} \cdot \hat{L}$

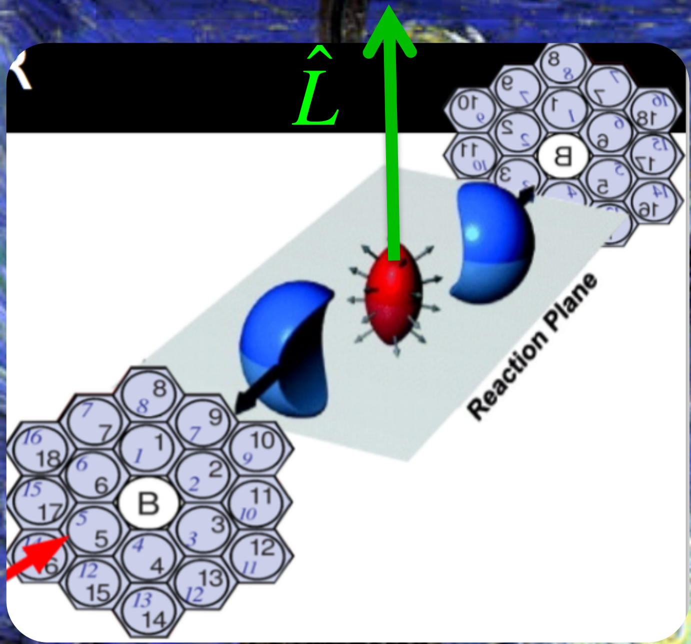
Both may contribute:

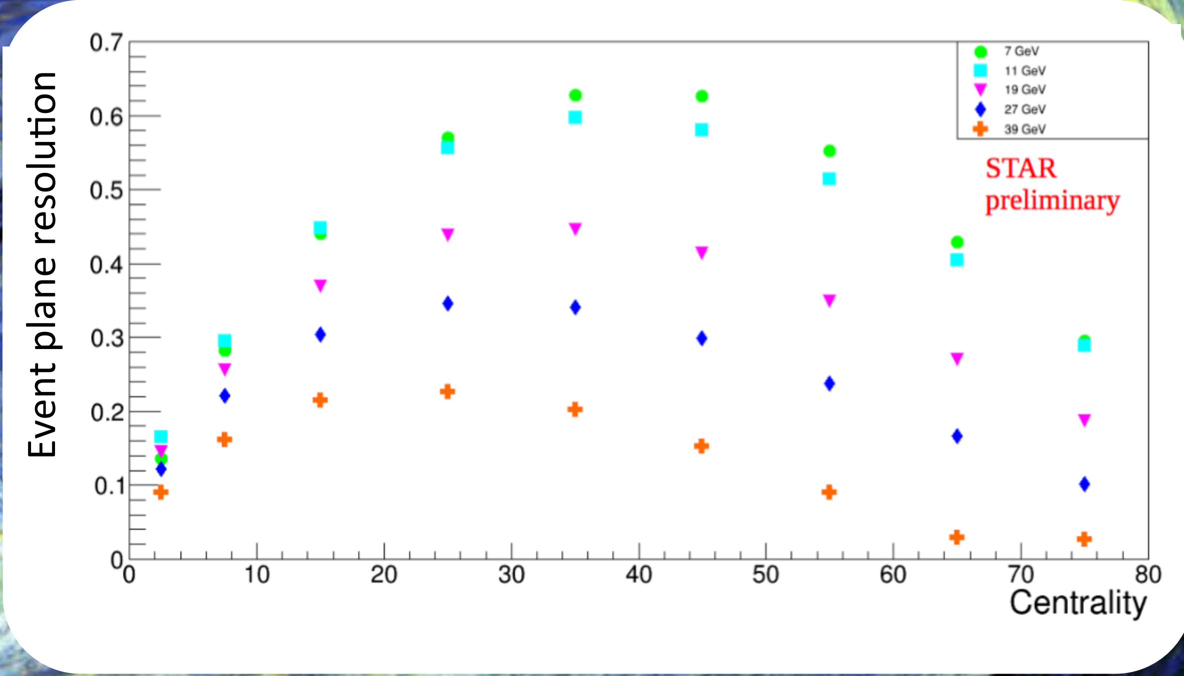
- Vortical or QCD spin-orbit: Lambda and AntiLambda spins aligned with L
  - Sigma feed-down tends to dampen the effect
- (electro)magnetic coupling: Lamdas *anti*-aligned, and AntiLambdas aligned
  - Sigma feed-down goes in same direction as the effect on primaries
- Polarization w/ *production* plane: No integrated effect at midrapidity for Lambda
  - no effect *at all* for AntiLambdas
  - also, would polarize perpendicular to L for out-of-plane particles – tested

Important analysis details

Relevant quantity

$\vec{S}_\Lambda \cdot \hat{L}$





Results shown today

- *not* corrected for reaction plane resolution (i.e. smearing of L)
  ➔ final result will be larger when correction is applied

Important analysis details

Relevant quantity

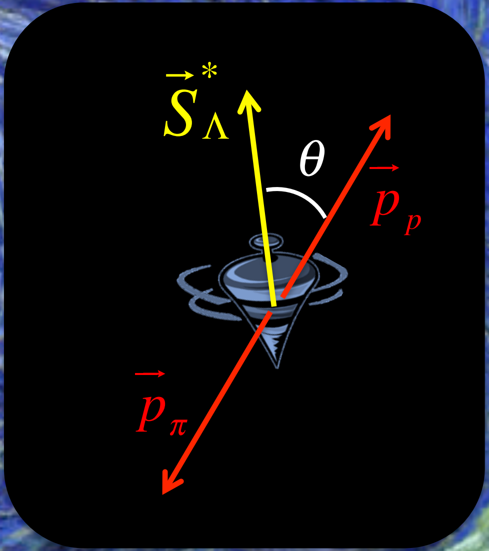
$\vec{S}_\Lambda \cdot \hat{L}$

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

$\alpha = 0.642$ [measured]

$\vec{S}^*_\Lambda$ is Λ spin *in Λ frame*

$\hat{p}^*_p$ is proton momentum direction *in Λ frame*



$$\vec{S}_\Lambda = \vec{S}^*_\Lambda + \frac{\gamma^2}{\gamma+1}\left(\vec{\beta}\cdot\vec{S}^*_\Lambda\right)\vec{\beta}$$

$\vec{\beta}$ boosts from Λ frame to system c.m.

Results shown today

- *not* corrected for reaction plane resolution (i.e. smearing of L)
  ➔ final result will be larger when correction is applied
- extracted assuming Lambda spin direction *equals* proton momentum direction
  ➔ final result will be larger when this simplifying assumption removed

Important analysis details

Relevant quantity

$\vec{S}_\Lambda \cdot \hat{L}$

Spin-orientation-dependent efficiency (!)

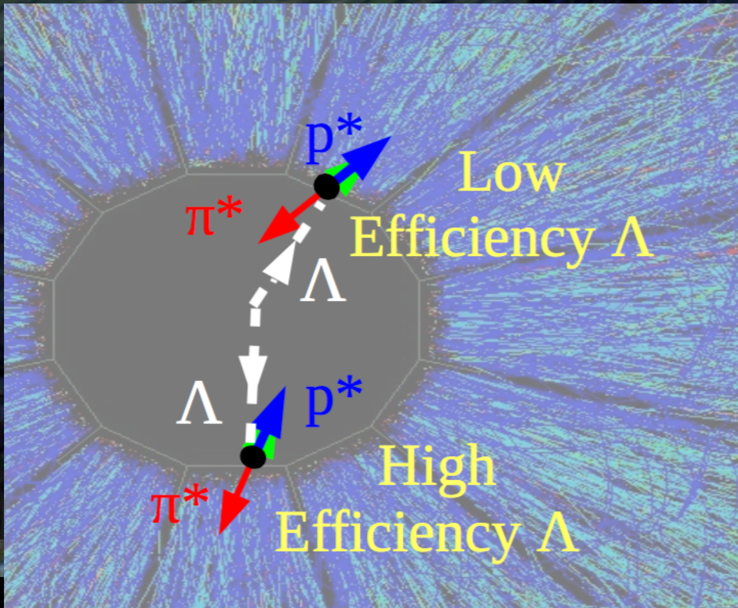
In Lambda frame, proton & pion have equal-magnitude momentum, but not in STAR frame

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

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



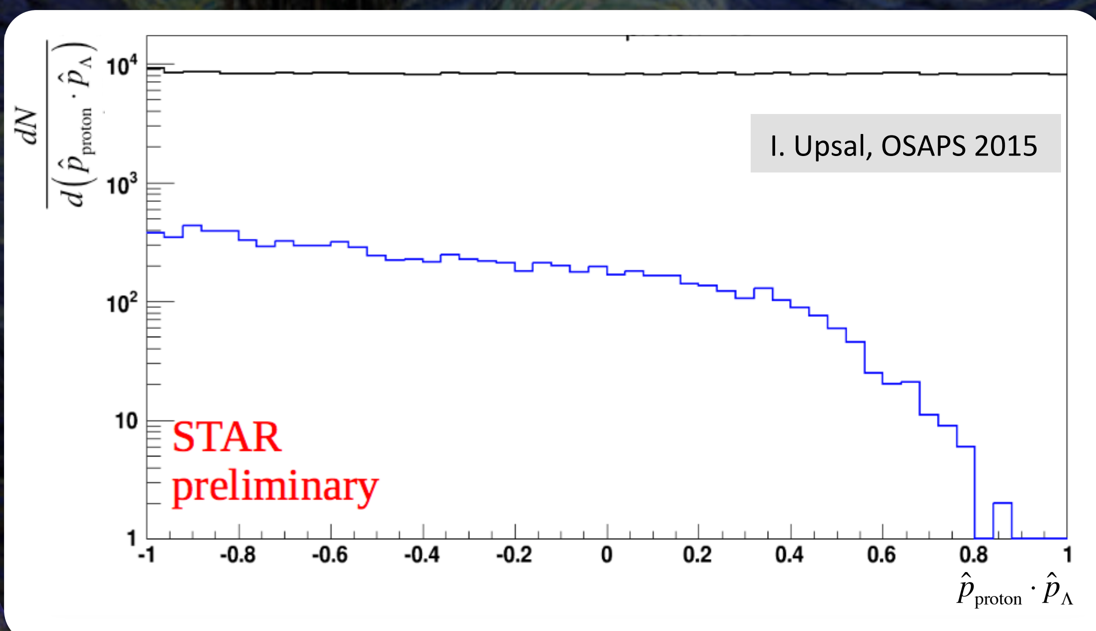
Important analysis details

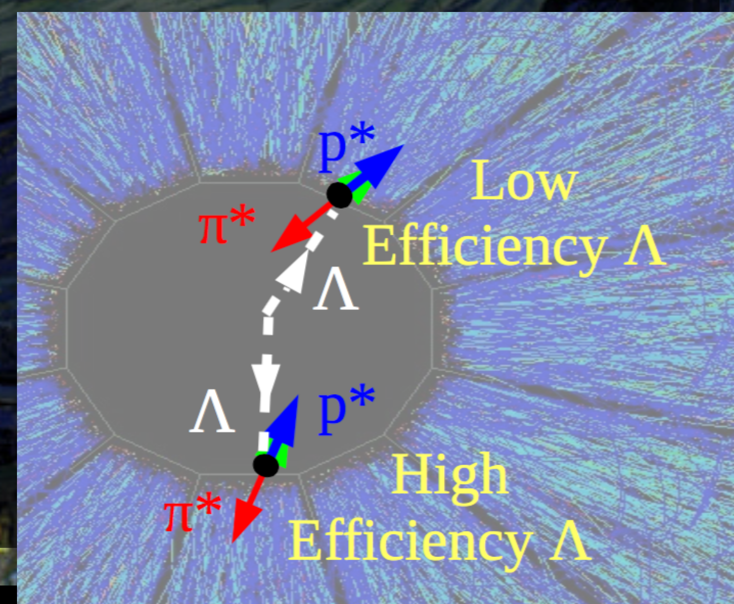
Relevant quantity

$\vec{S}_\Lambda \cdot \hat{L}$

Spin-orientation-dependent efficiency (!)

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





How to quantify the effect?

Relevant quantity

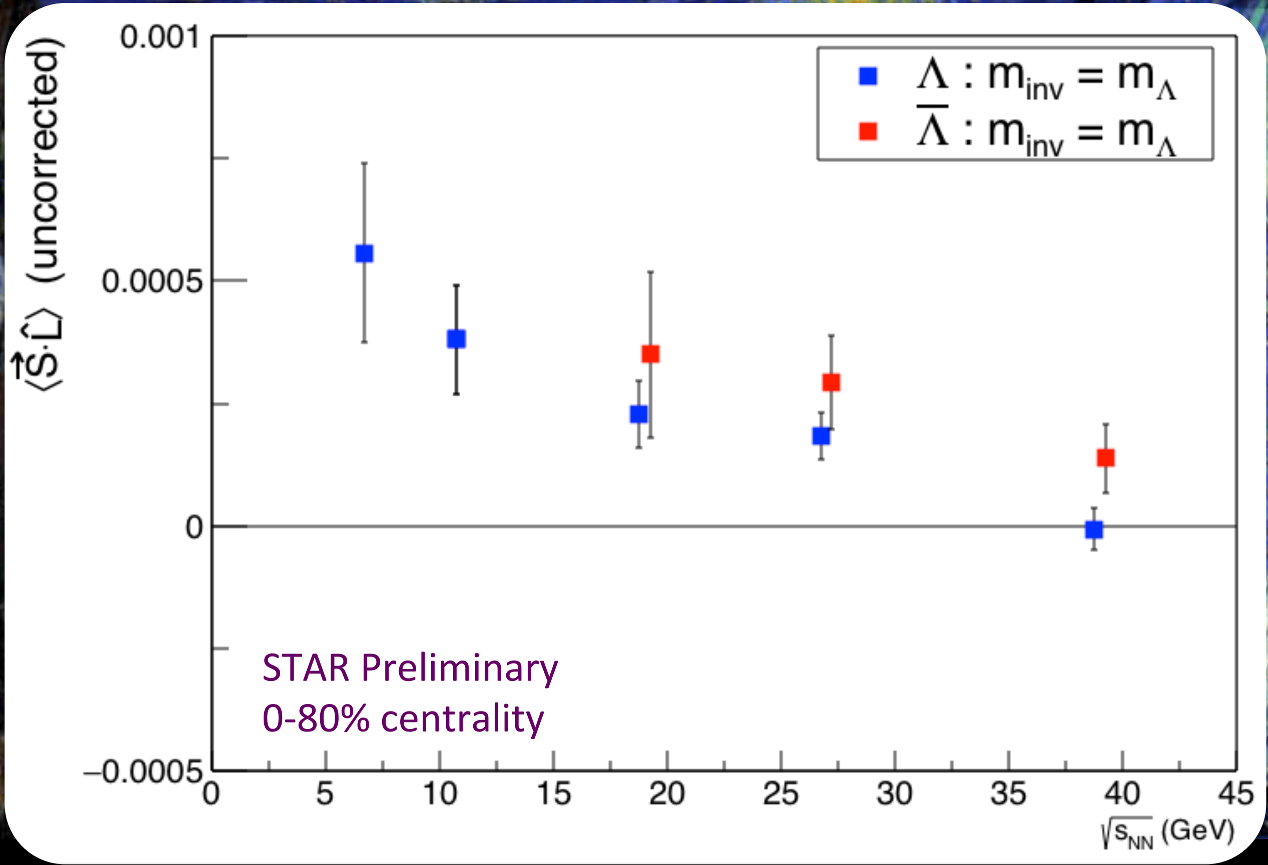
$\vec{S}_\Lambda \cdot \hat{L}$

$\left\langle \vec{S}_\Lambda \cdot \hat{L} \right\rangle$ seems an obvious choice

- May depend on pT, phi, (rapidity?)
  - Csernai & Becatinni...

- There are other (perhaps better) ways to quantify, but no time to discuss today...

Preliminary results



- First clear positive signal of global polarization in heavy ion collisions!

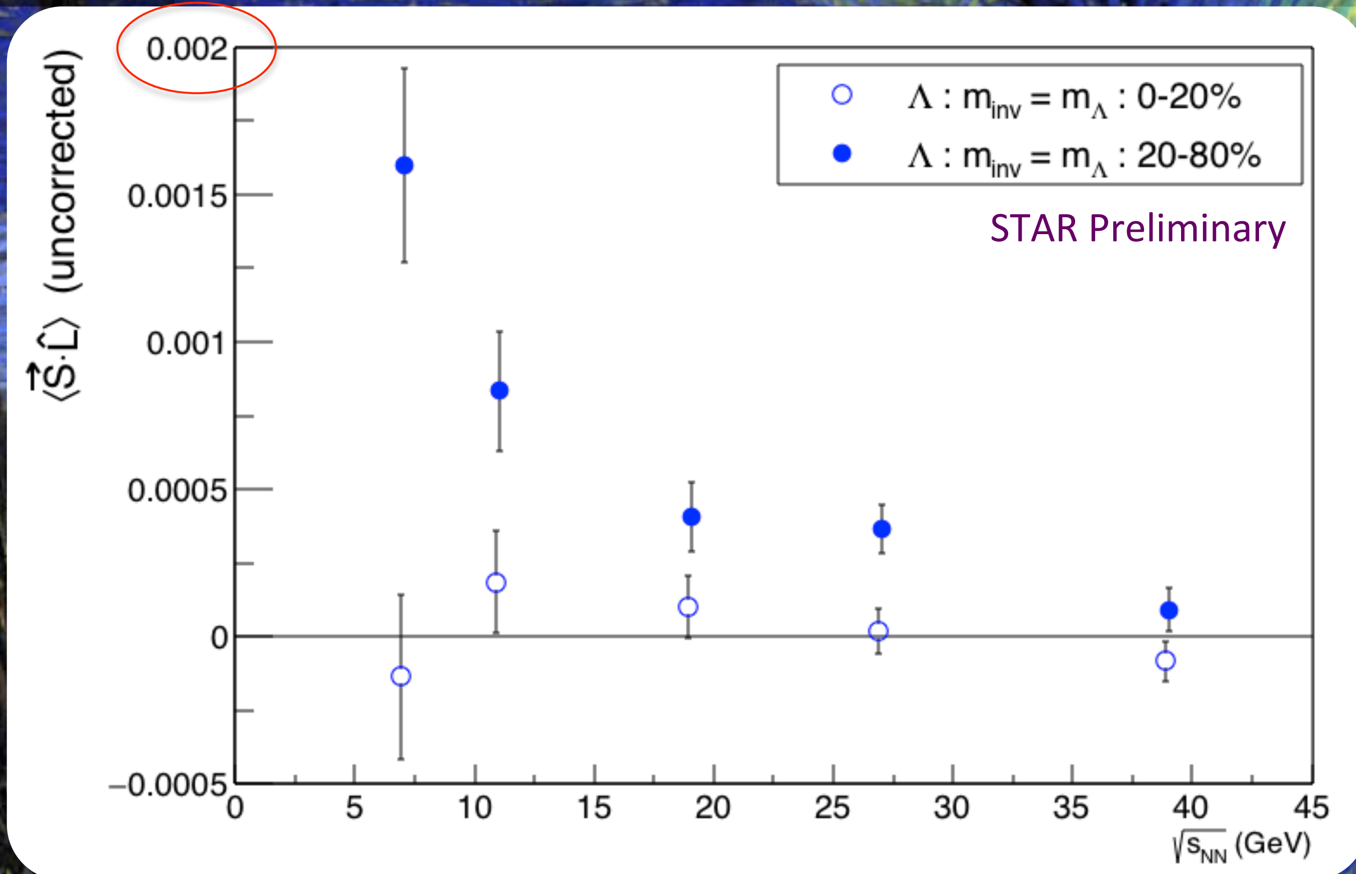
$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	19.6	27	39
Λ	3.1σ	3.4σ	3.3σ	3.8σ	-0.2σ
anti-Λ	-	-	2.1σ	3.0σ	2.0σ

Marginal significance for *one* energy.
Ensemble & trend adds confidence.

- Both Lambdas and AntiLambdas show positive polarization → vorticity and/or spin-orbit
  - increased AntiLambdas polarization could arise from (electro)magnetic contribution, but errorbars...
- Cannot interpret energy dependence until resolution correction is done

Preliminary results

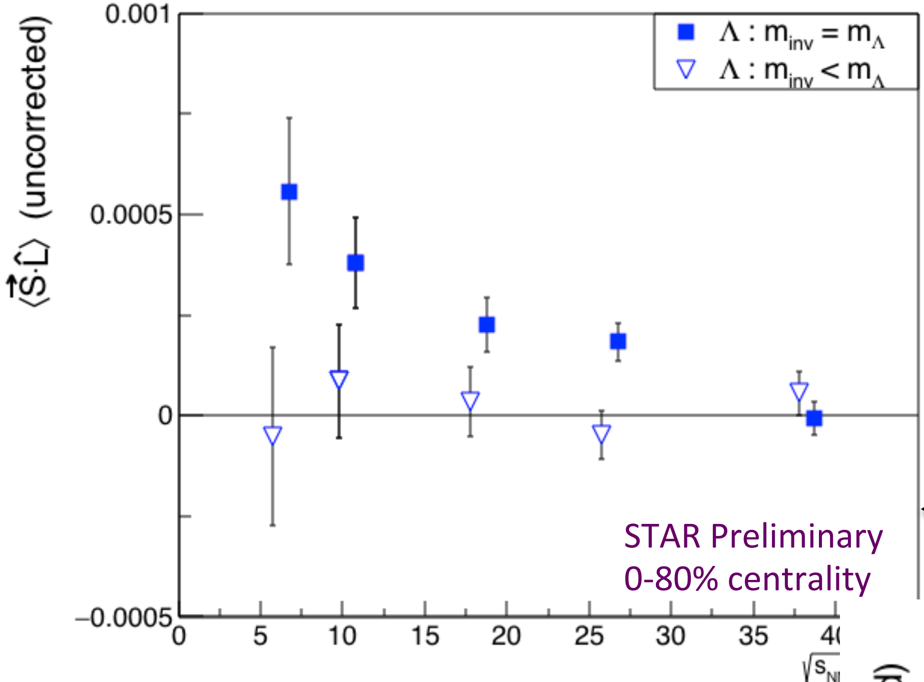
Note expanded scale

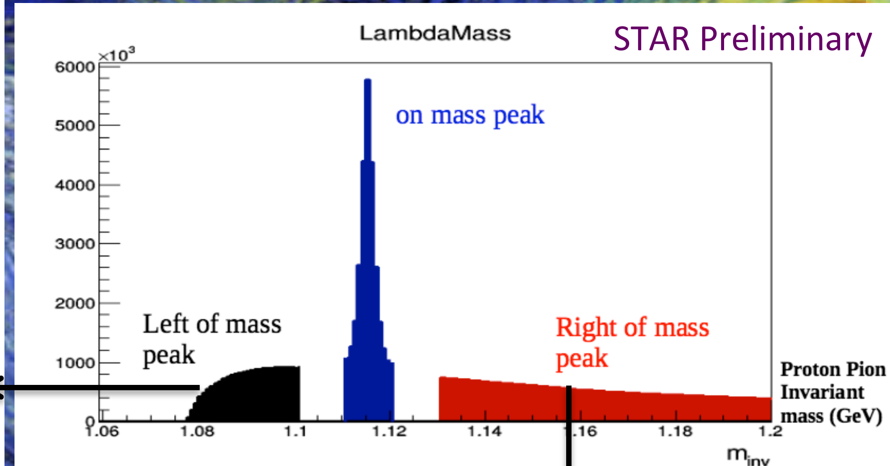


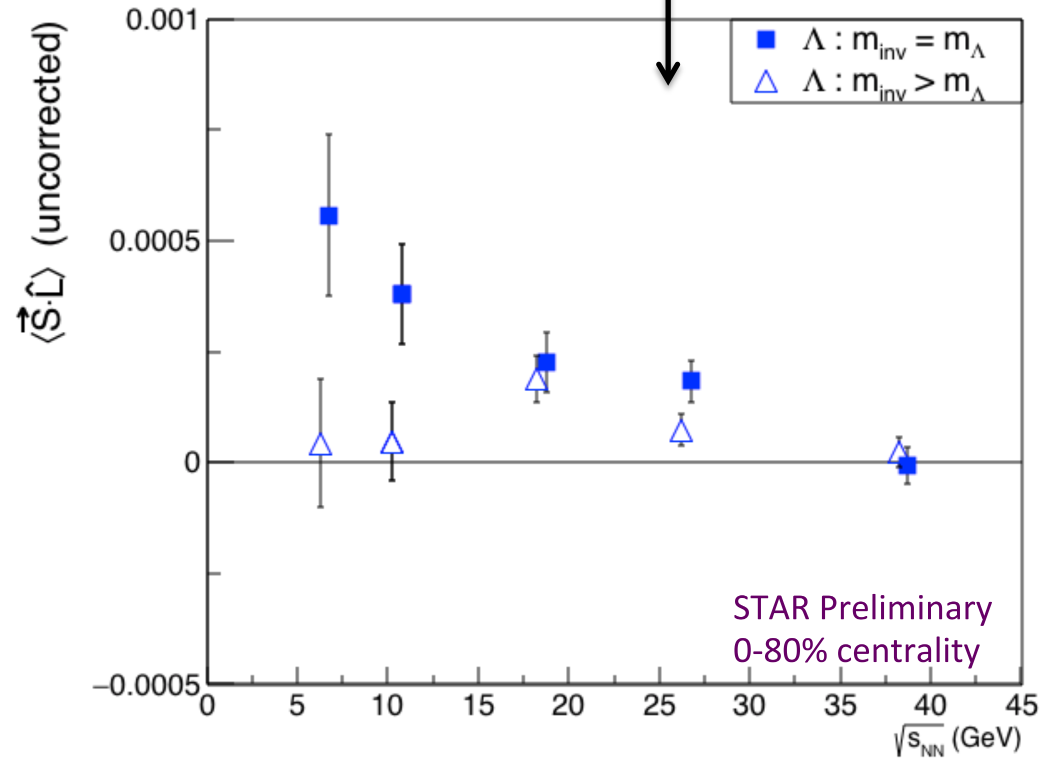
- Raw signal larger for peripheral collisions. Not unreasonable, but...
- ...cannot interpret centrality dependence until resolution correction is done

$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	19.6	27	39
20-80%	4.9σ	4.1σ	3.4σ	4.4σ	1.26σ

Test off mass peak







One high-mass points is significantly (3.5 sigma) above zero. →
(another is 2 sigma)

not understood.
may be (large) fluctuation?

Summary

- Large angular momentum in noncentral 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
  - At a microscopic level, achieved QCD spin-orbit coupling transfers
- Global hyperon polarization probes this (largely unexplored) physics
- STAR has seen the first positive signal of global hyperon polarization
  - 3σ to 5σ signal for Λ's at each energy below 39 GeV
- Resolution corrections in progress
  - clear picture of energy & centrality dependence requires this correction
- "null test" : troubling (3 sigma) signal on one side of the peak at one energy
  - red flag? fluctuation?
  - under investigation

Thanks for your attention


END

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

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

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

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

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.**