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

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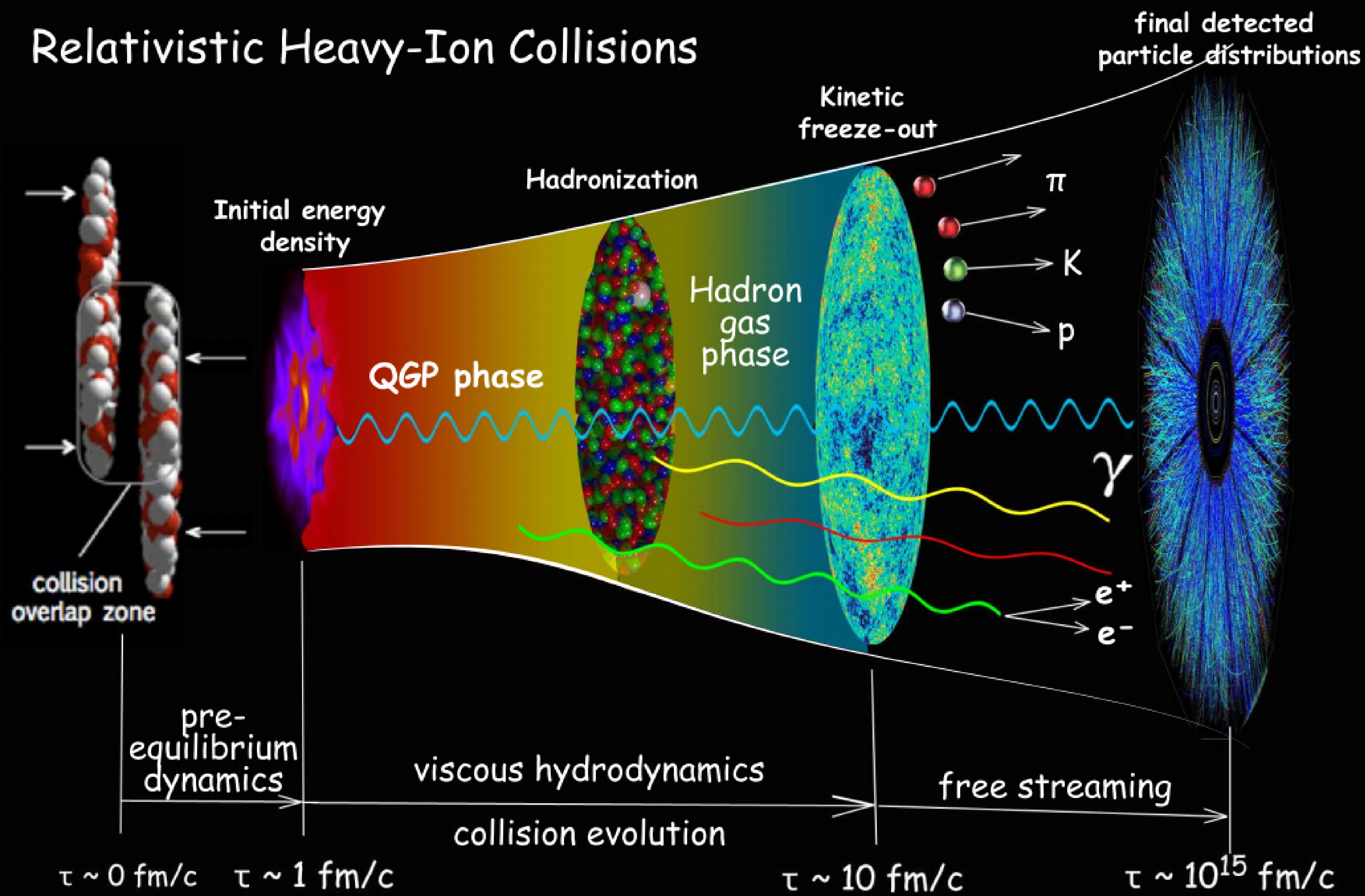
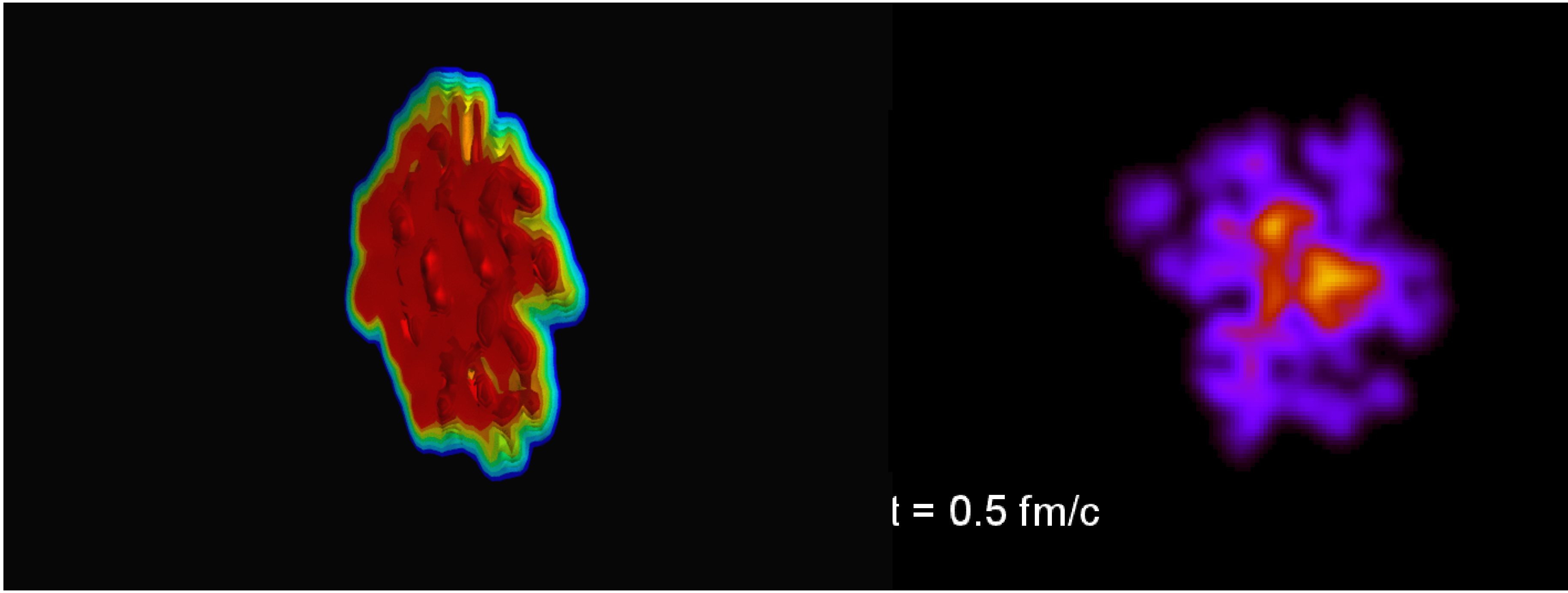
06/27/18

Relativistic Heavy-Ion Collisions



Hydrodynamic evolution



movies by Bjorn Schenke

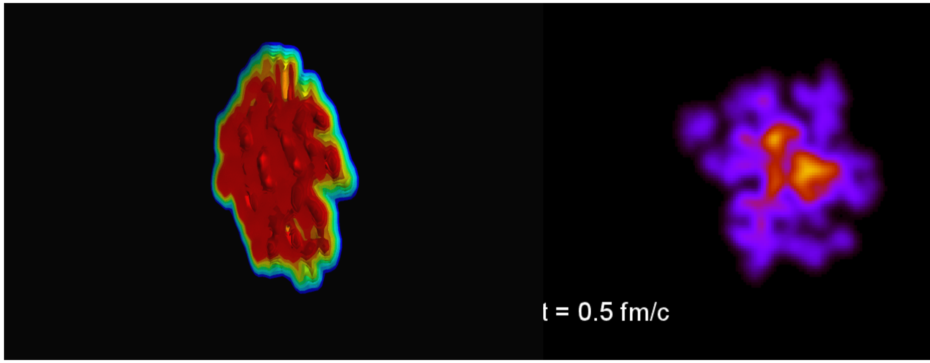
From a (lumpy) initial state, solve hydro equations:

$$d_\mu T^{\mu\nu} = 0 \qquad T^{\mu,\nu} = e u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$u^\mu d_\mu \Pi = -\frac{1}{\tau_\Pi}(\Pi + \zeta\theta) - \frac{1}{2}\Pi \frac{\zeta T}{\tau_\Pi} d_\lambda \left(\frac{\tau_\Pi}{\zeta T} u^\lambda \right)$$

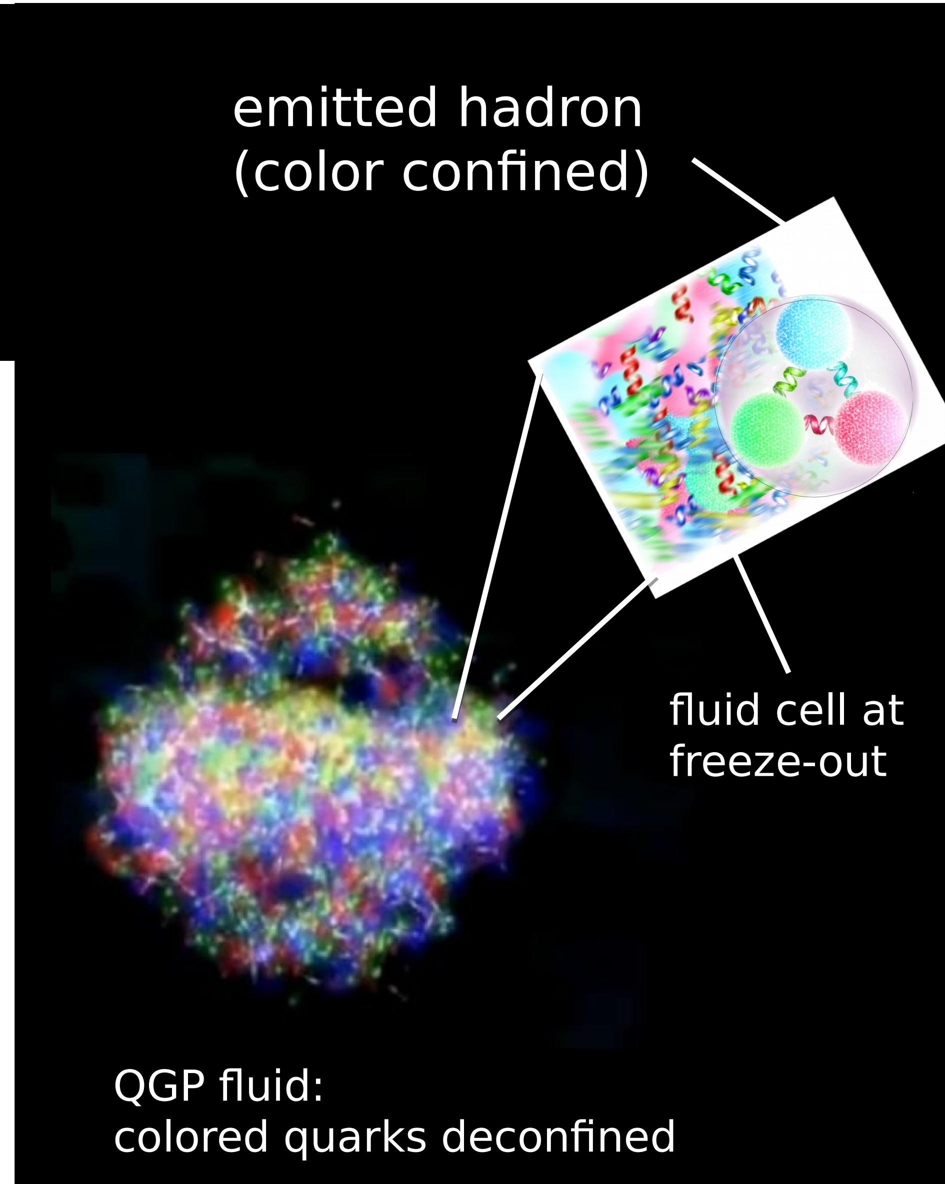
& many more terms...

Final state particles from hydro



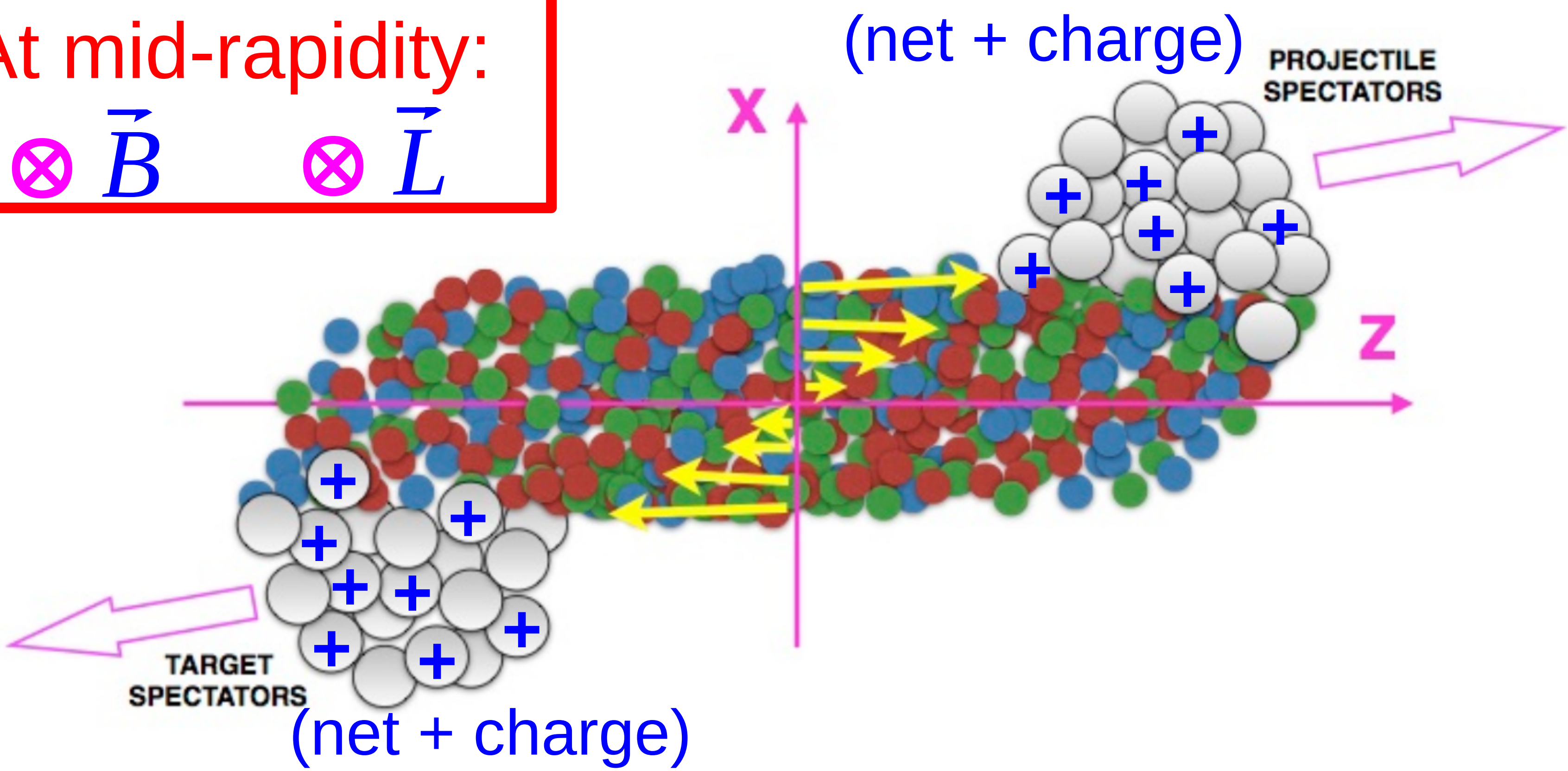
System cools & expands → Hadronization & “Freeze-out”

- emitted particles reflect properties of parent fluid cell (Cooper-Frye)
  - chemical potentials, thermal & collective velocities



At mid-rapidity:

$\otimes \vec{B} \quad \otimes \vec{L}$



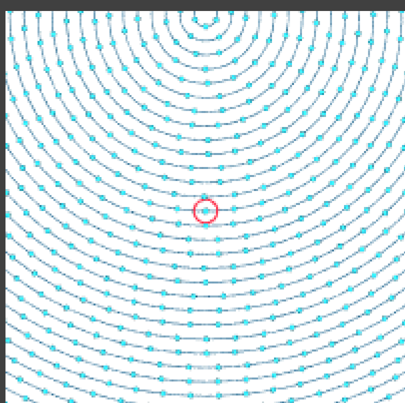
- |L| ~ 10^3 ħ in non-central collisions
- How much is transferred to particles at mid-rapidity?
- Does angular momentum get distributed thermally?
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} \equiv \frac{1}{2} \vec{\nabla} \times \vec{v}$
- How would it manifest itself in data?

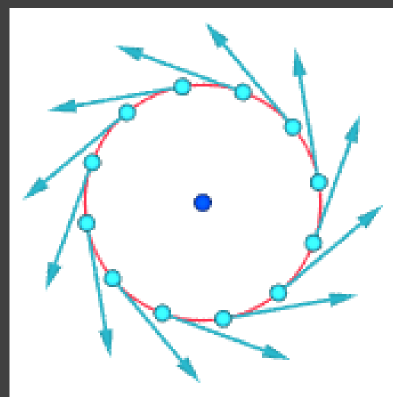
Vortices

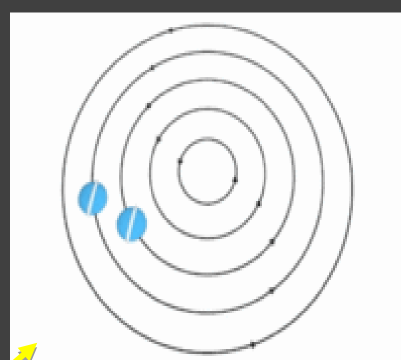
Classical Vorticity: $\vec{\omega} \equiv \frac{1}{2}\vec{\nabla}\times\vec{v}$

Rigid-body-like Vortex

$v \propto r$

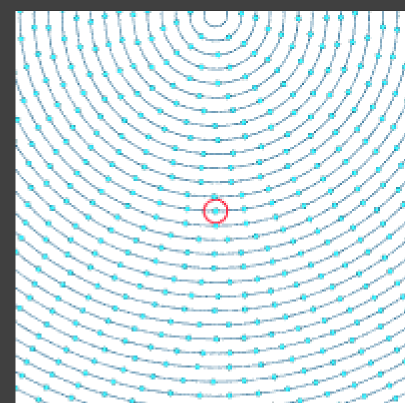


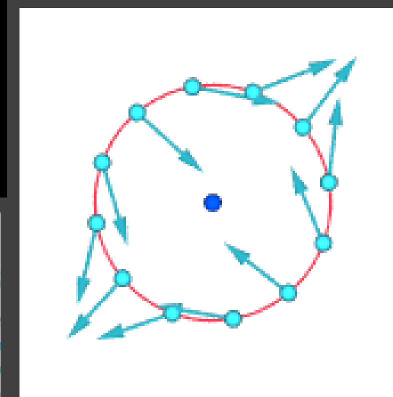


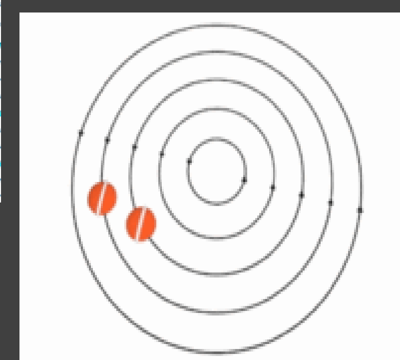


Irrotational vortex

$v \propto 1/r$

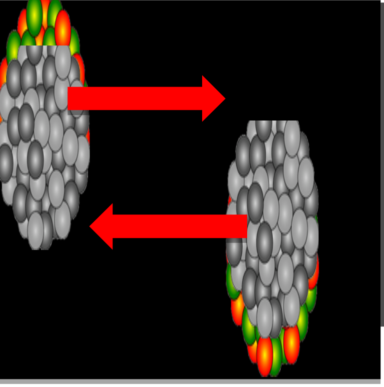






Like the moon, always the same side toward Earth

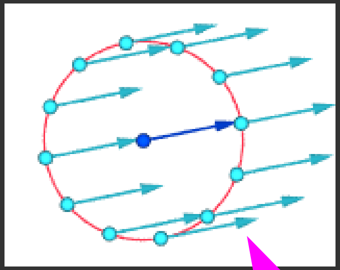
Notice the rotation, or lack thereof, in the fluid elements

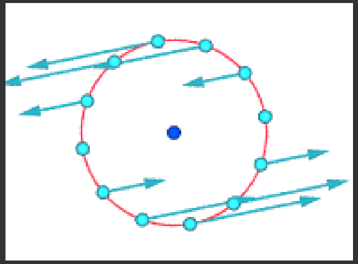


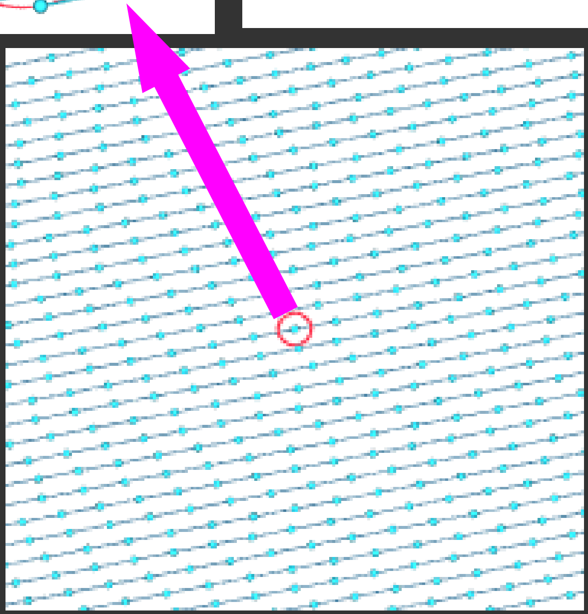
HIC Vorticity formation

In collision c.m. frame

Local fluid cell frame





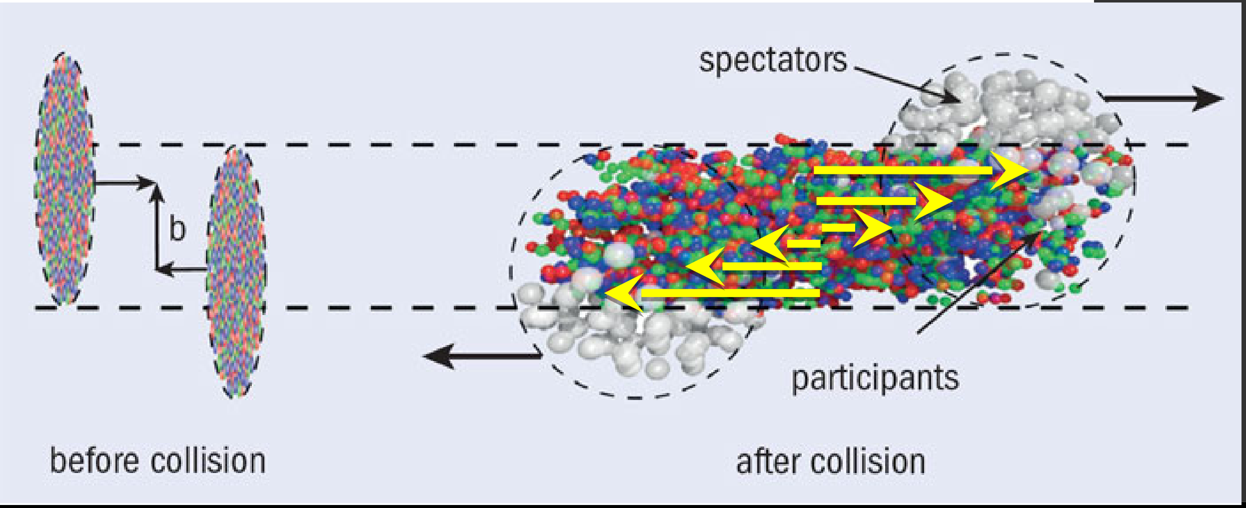


Localized vortex generation via baryon stopping

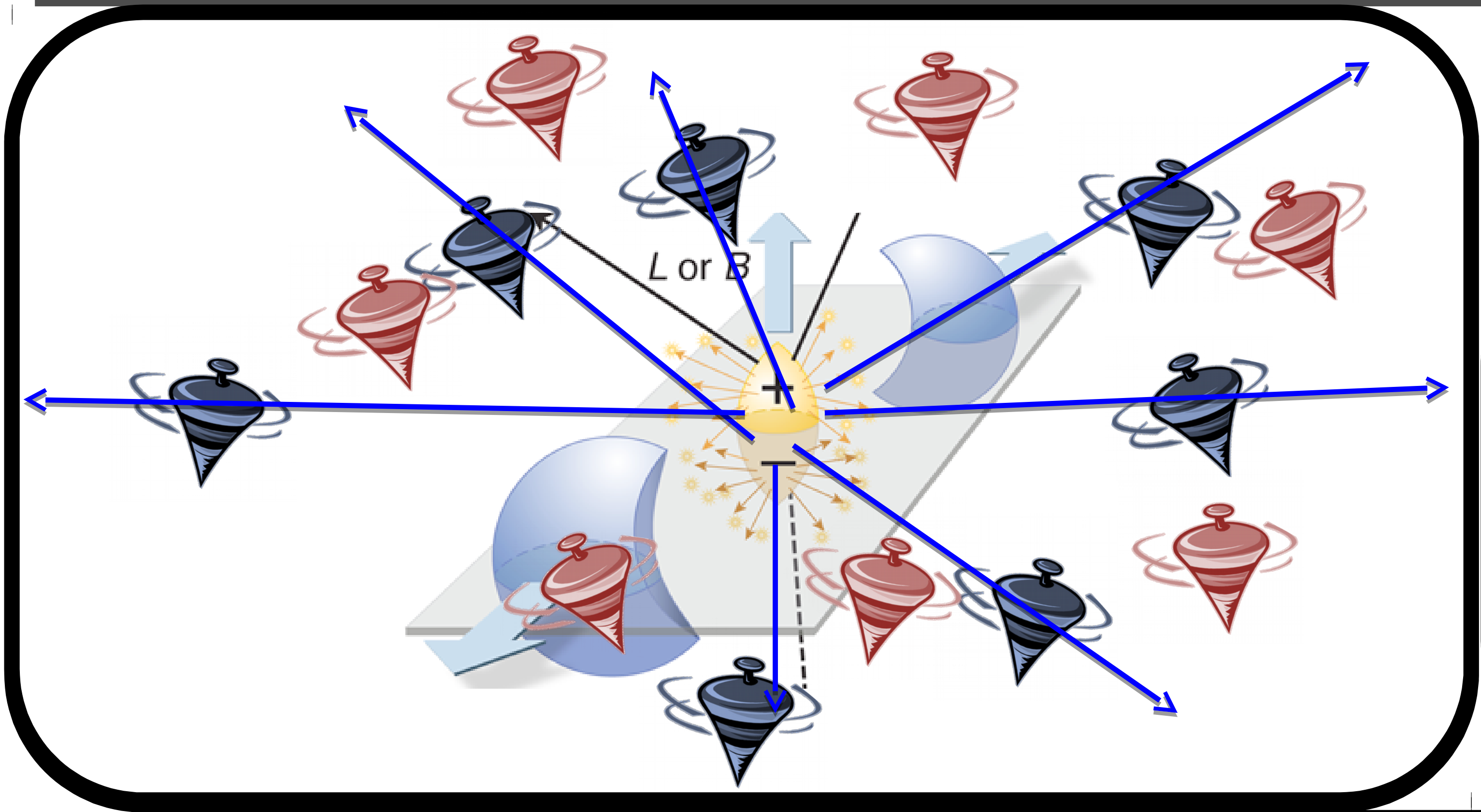
Viscosity dissipates vorticity to fluid at larger scale

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

$$\omega = \tfrac{1}{2}\nabla \times \vec{v} \approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$

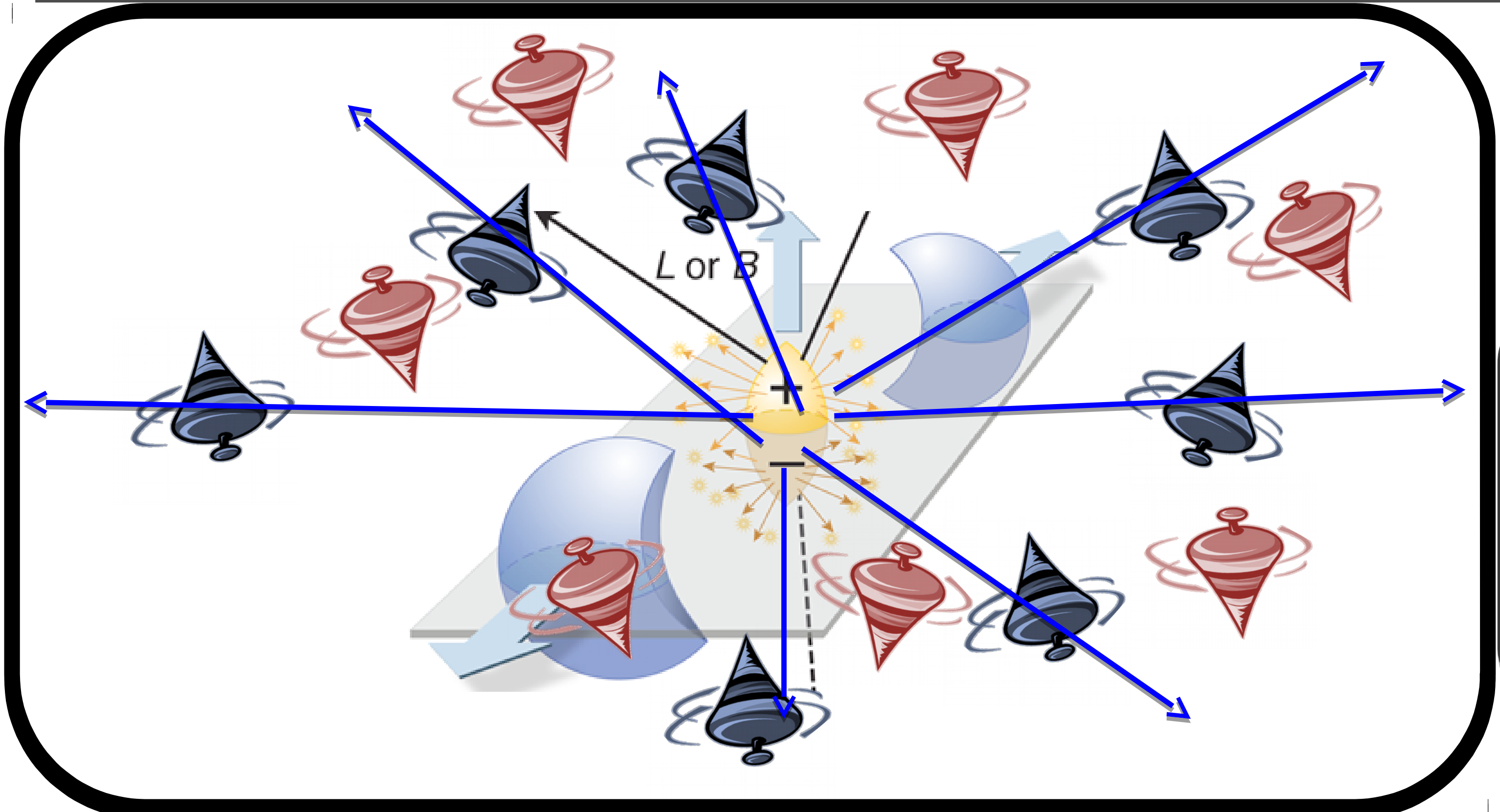


Vorticity → Global Polarization



- 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

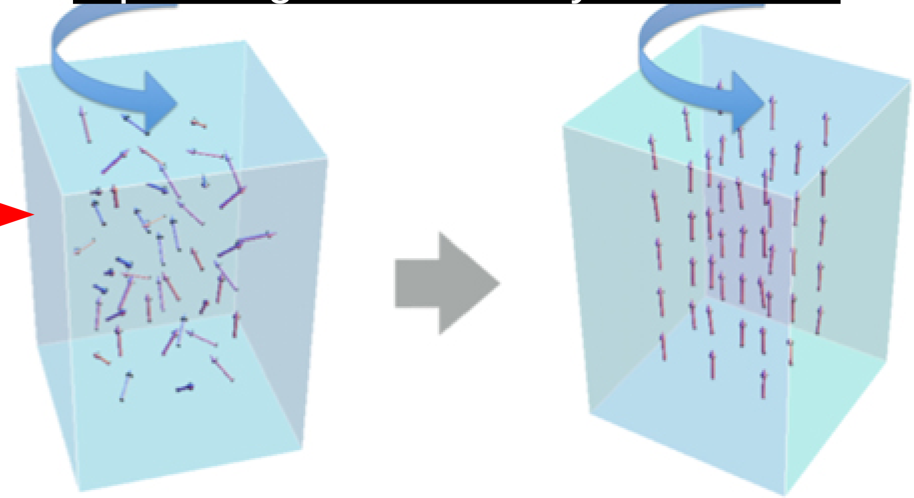
- Nice parallel in **Barnett effect**
- **BE**: uncharged object rotating with angular velocity ω magnetizes

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

- γ = gyromagnetic ratio, χ = magnetic susceptibility.
- Inverse of Einstein-de Haas effect,

Science 15 42 (1915); Phys. Rev. 6, 239–270 (1915)

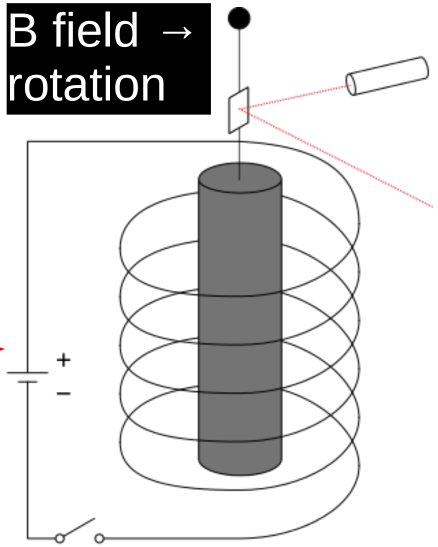
Spins align with vorticity → B field



- **Einstein-de Haas effect**, (only published experiment of Einstein!)
- **EdHE**:Magnetic field induces rotation

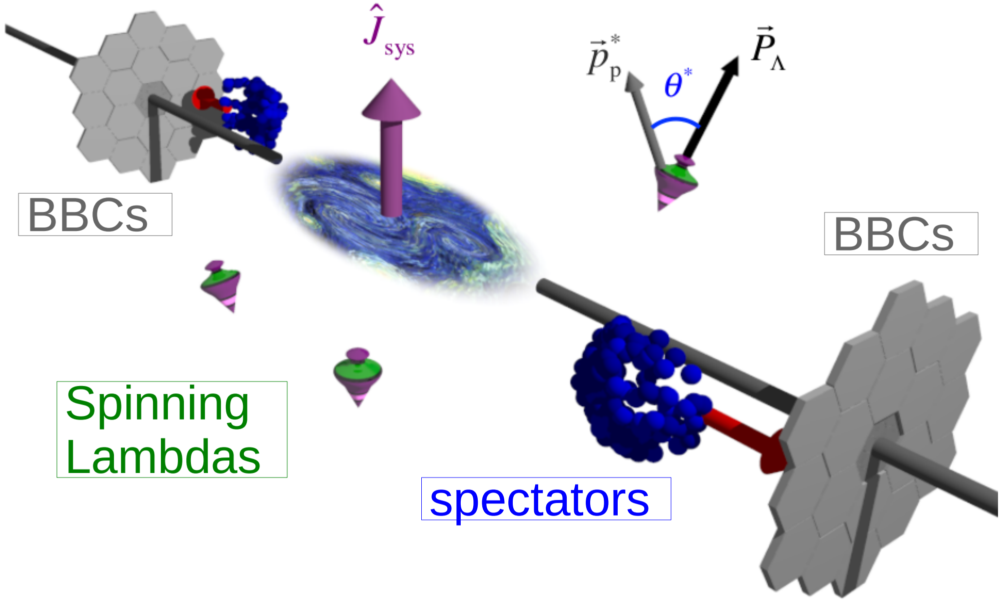
Physical Review (Series I), Vol. 26, Issue 3, pp. 248–253 (1908)

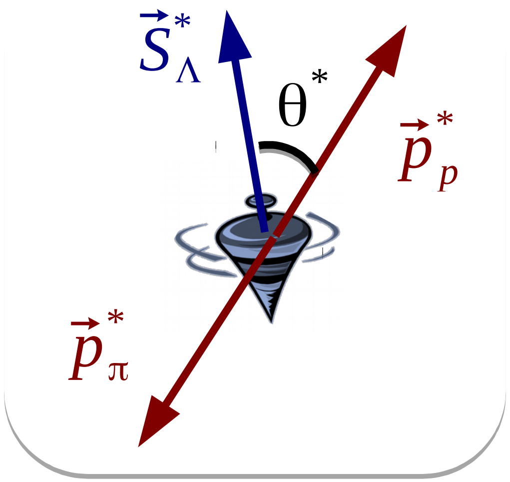
B field → rotation



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]

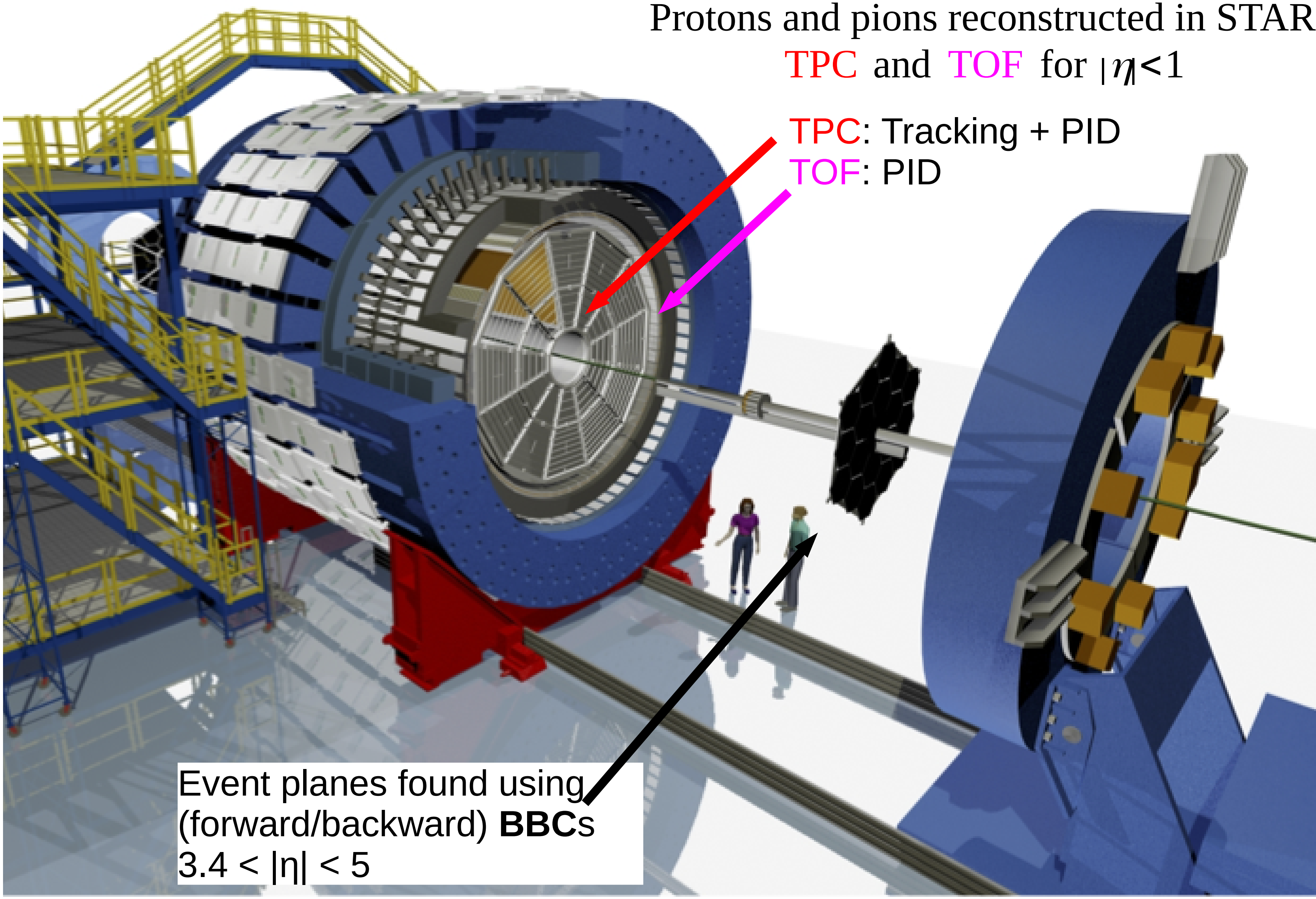
$\hat{p}_p^*$ is the daughter proton momentum direction *in the Λ frame* (note that this is opposite for $\overline{\Lambda}$)

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

Ingredients: Using STAR

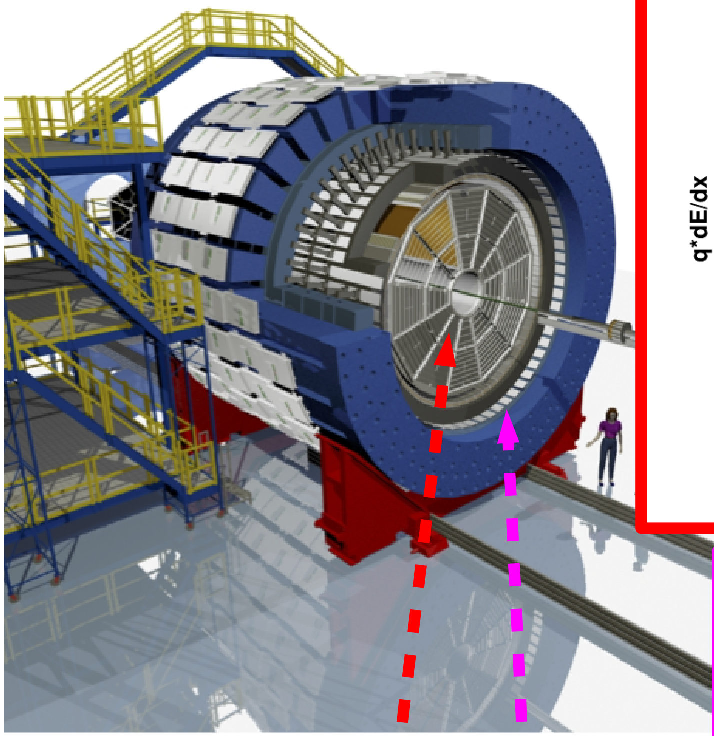
Protons and pions reconstructed in STAR TPC and TOF for $|\eta|<1$

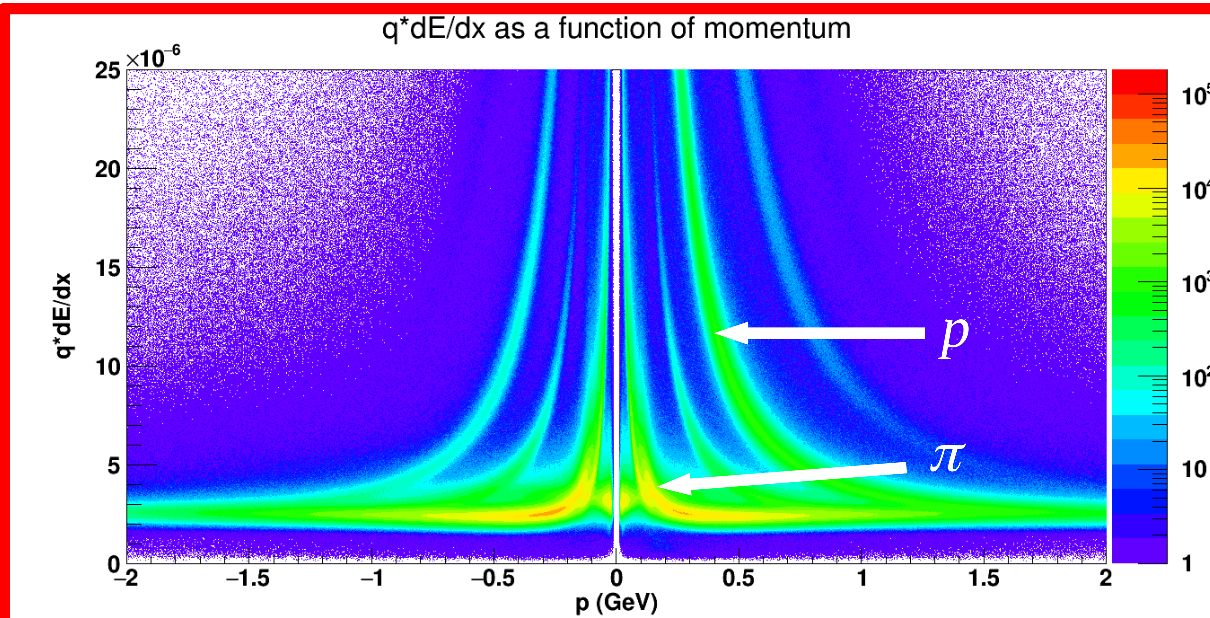
TPC: Tracking + PID
TOF: PID



Event planes found using (forward/backward) **BBC**s
$3.4 < |\eta| < 5$

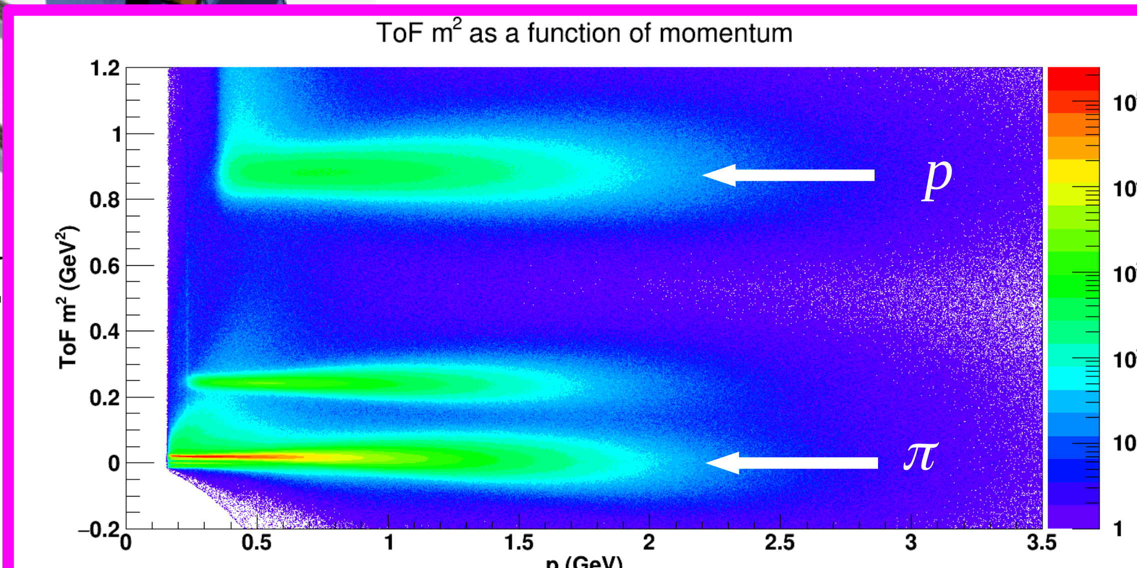
Ingredients: Using STAR (PID)





Protons and pions reconstru

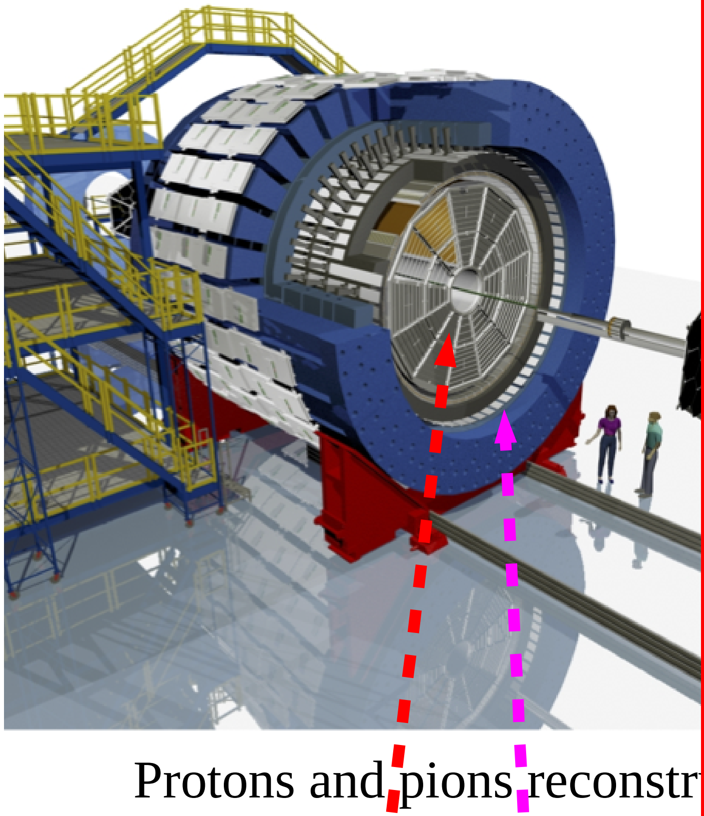
TPC and TOF for



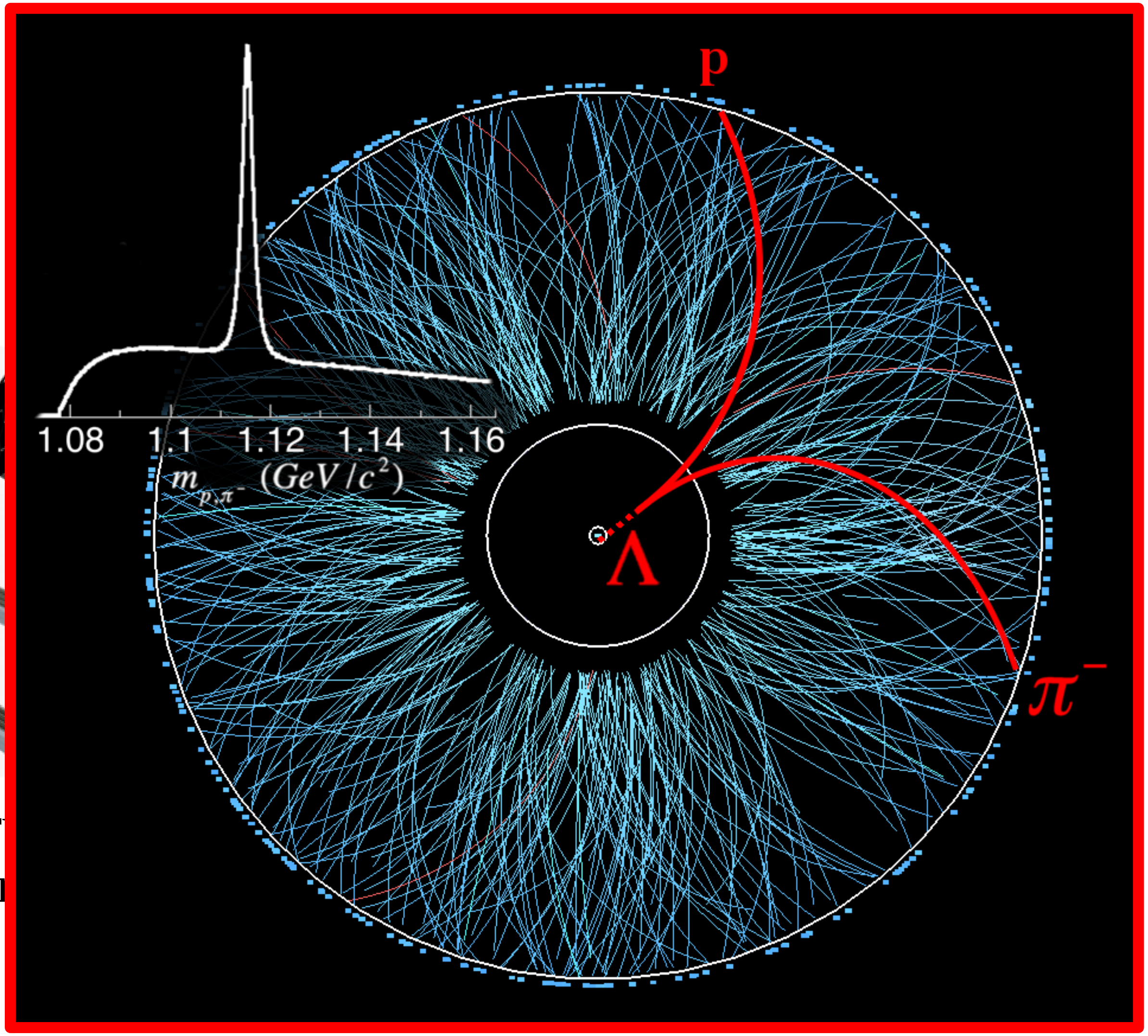
TPC: Tracking + PID

TOF: PID

Ingredients: Using STAR (tracking)



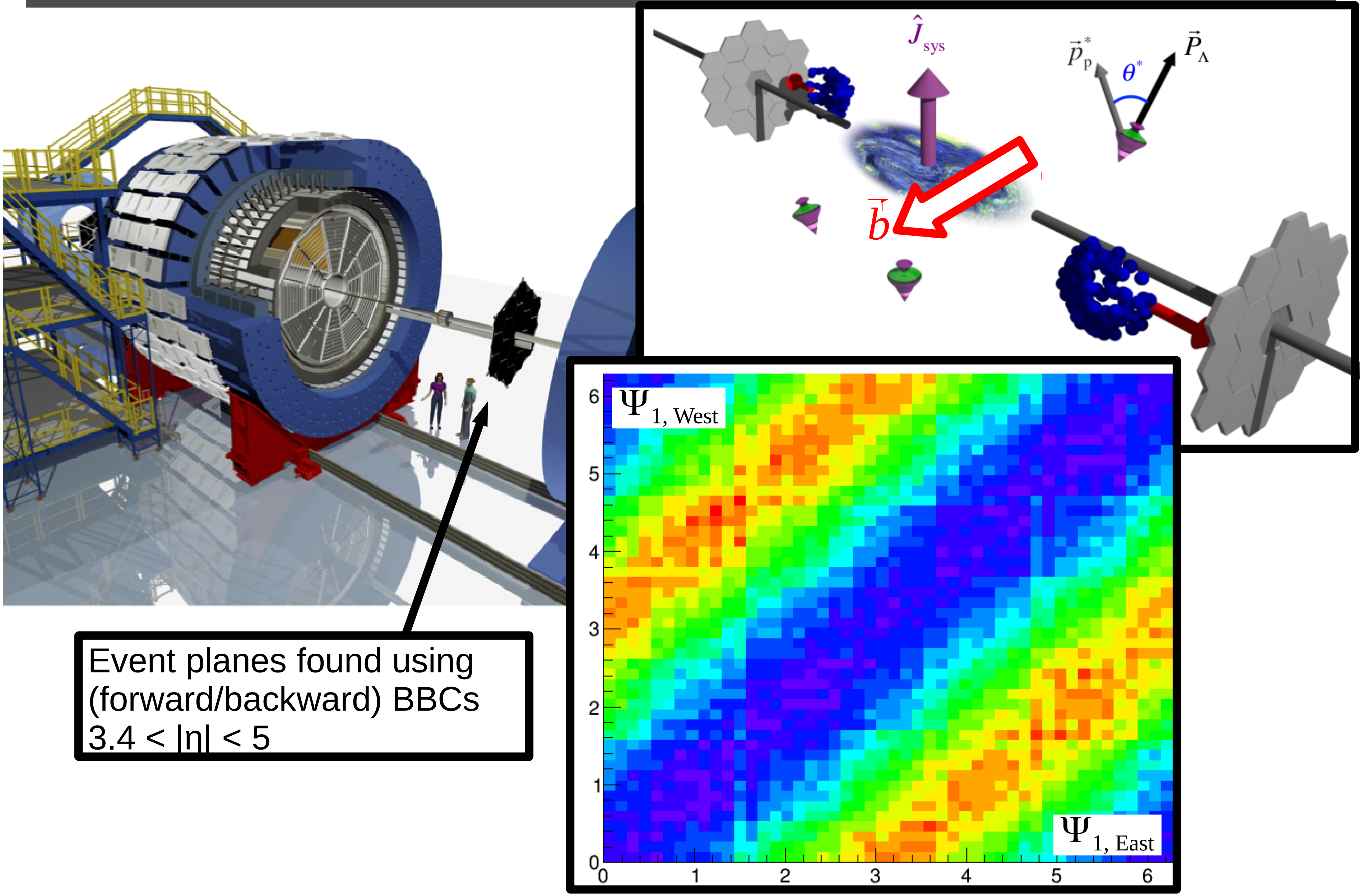
Protons and pions reconstr
TPC and TOF fo



TPC: Tracking + PID
TOF: PID

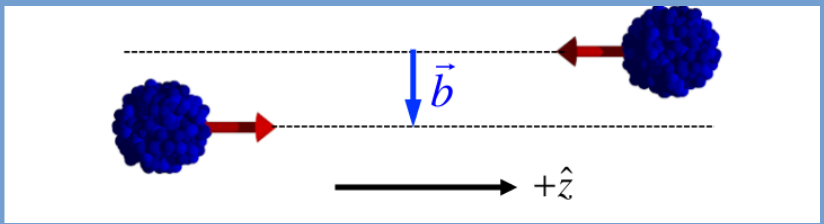
Lambdas are found topologically using identified protons and pions

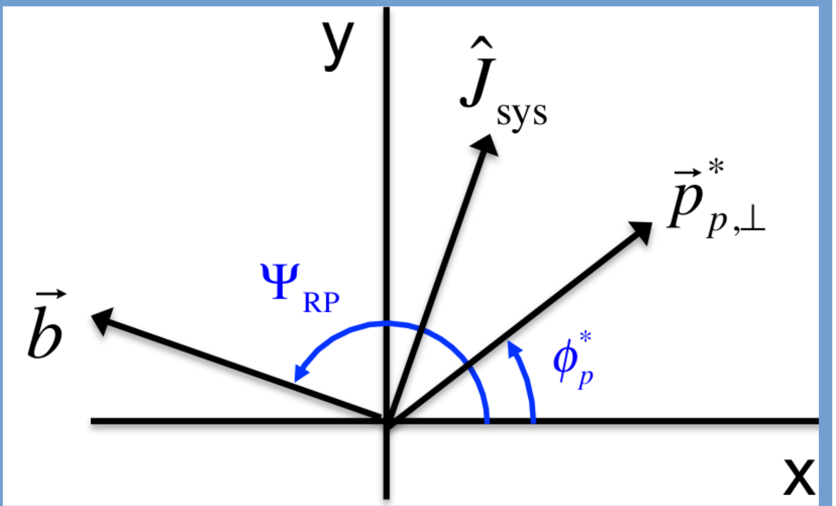
Ingredients: Using STAR (Event Plane)

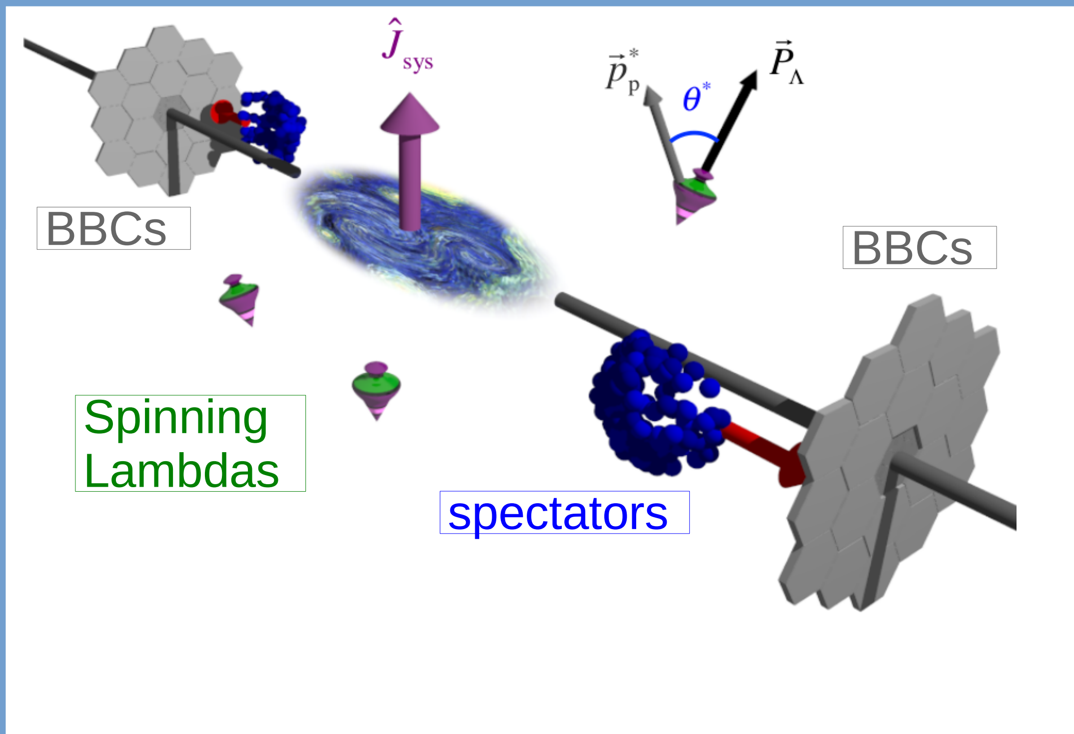


Event planes found using (forward/backward) BBCs $3.4 < |\eta| < 5$

How to quantify the effect (II)







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

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

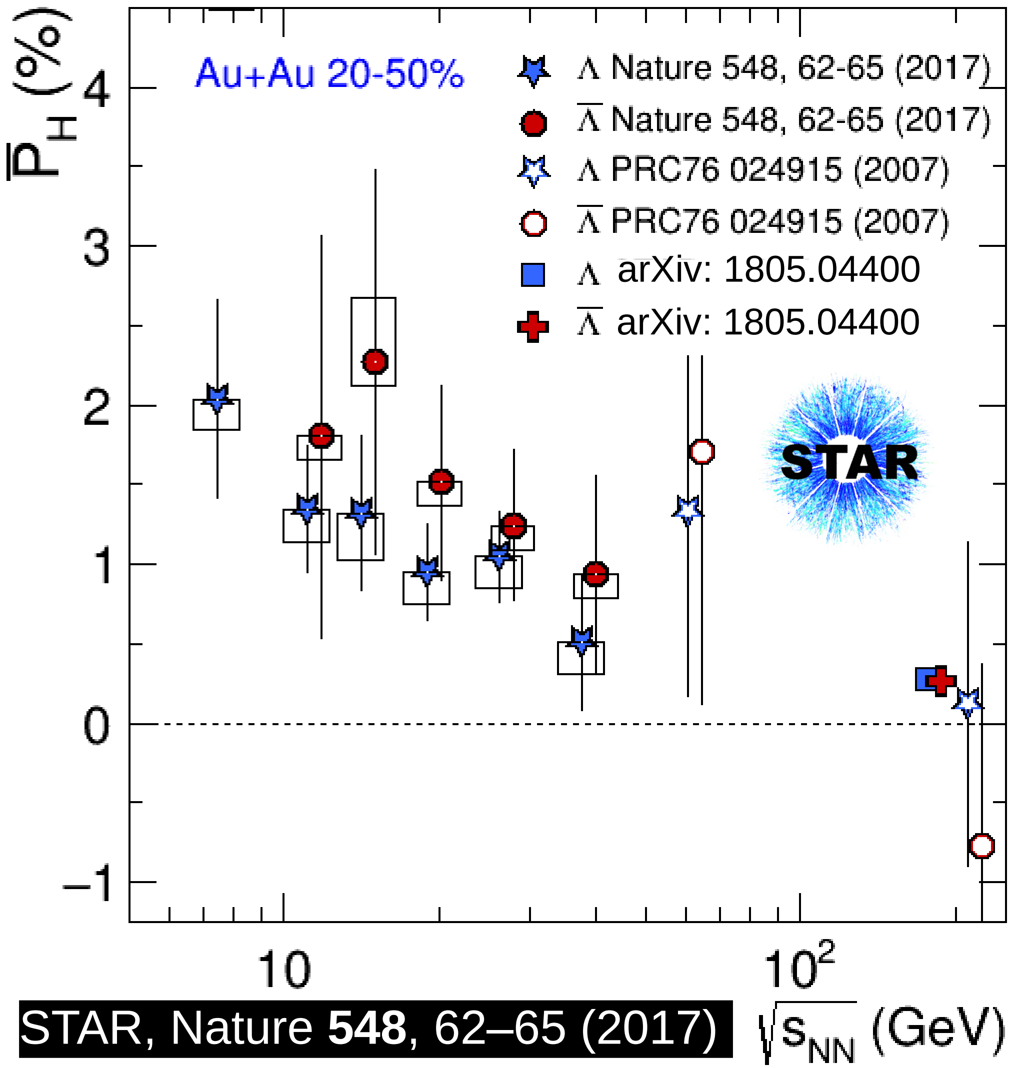
$P_{AVE} = \frac{8}{\pi\alpha} \frac{\langle \sin(\phi_{\hat{b}} - \phi^*_p) \rangle}{R^{(1)}_{EP}}$ ** where the average is performed over events and Λs

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

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

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)

STAR, arXiv: 1805.04400

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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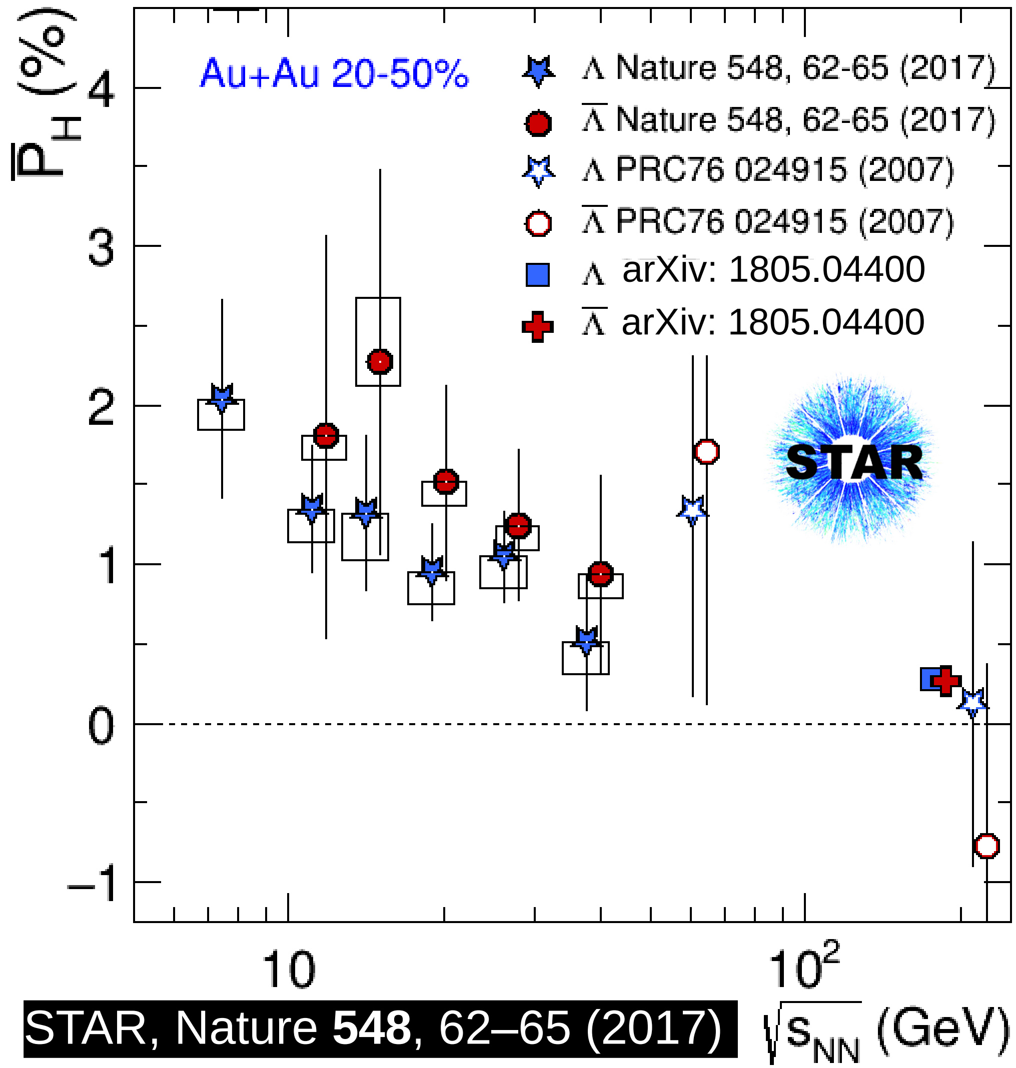

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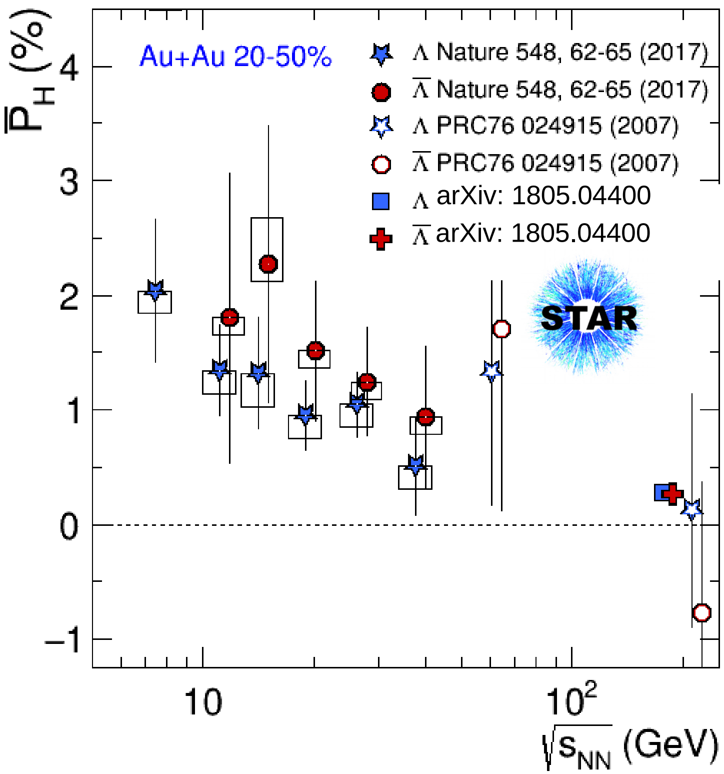
Vortical and Magnetic Contributions



STAR, Nature **548**, 62–65 (2017)

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- 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:

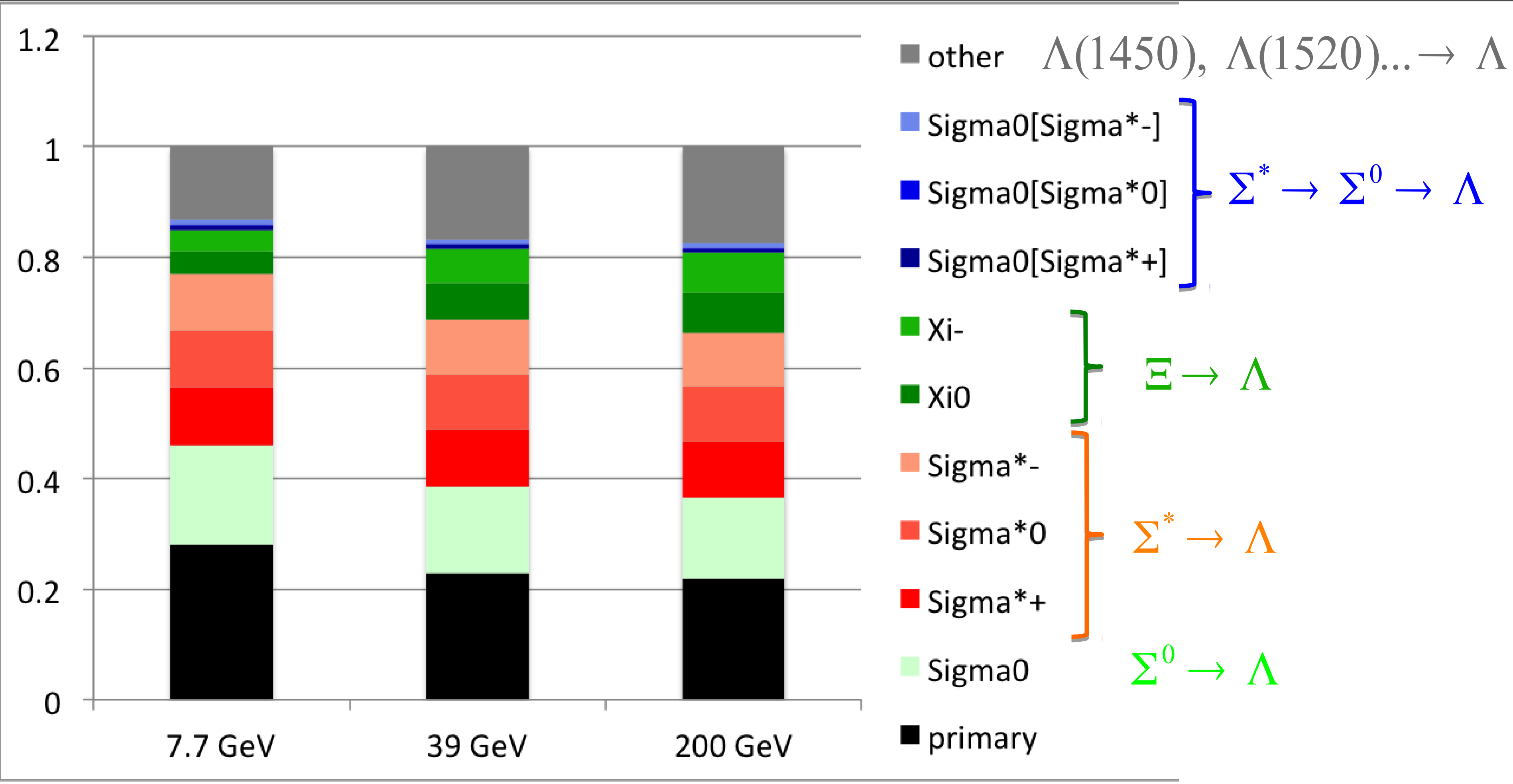
$$\frac{B}{T} = \frac{1}{2\mu_\Lambda}\left(P_{\bar{\Lambda}} - P_\Lambda\right)$$

** $\hbar = k_B = 1$

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

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

Vortical and Magnetic Contributions



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

Accounting for polarized feeddown

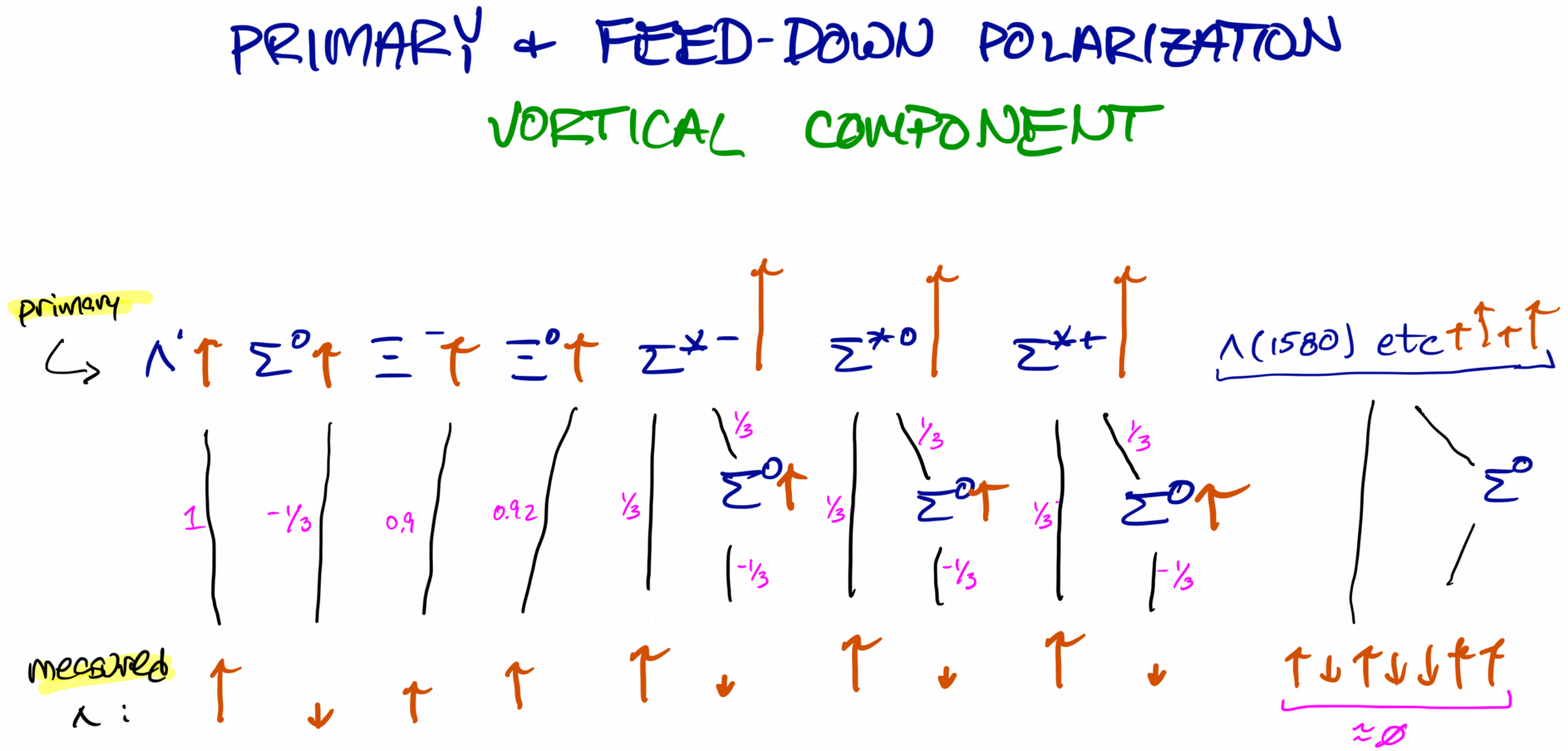
PRIMARY & FEED-DOWN POLARIZATION

VORTICAL COMPONENT

primary

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

Accounting for polarized feeddown



	J^π	μ
Λ	$1/2^+$	-0.613
Σ^0	$1/2^+$	$+0.79$
Ξ^-	$1/2^+$	-0.651
Ξ^0	$1/2^+$	-1.25

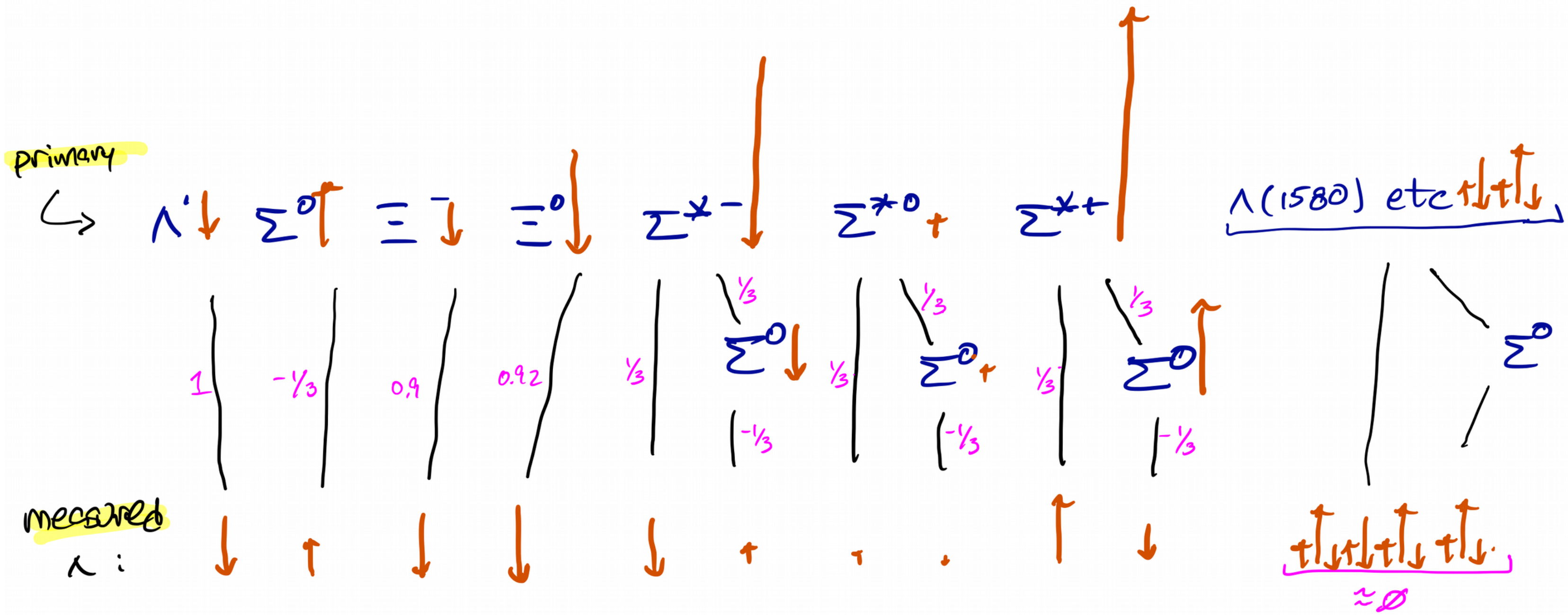
	J^π	μ
Σ^{*-}	$3/2^+$	-2.41
Σ^{*0}	$3/2^+$	$+0.30$
Σ^{*+}	$3/2^+$	$+3.02$

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

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

- $f_{\Lambda R}$ = fraction of Λs that originate from parent $R \rightarrow \Lambda$ ⇒ From a statistical hadronization model with STAR measurements as parameter inputs (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

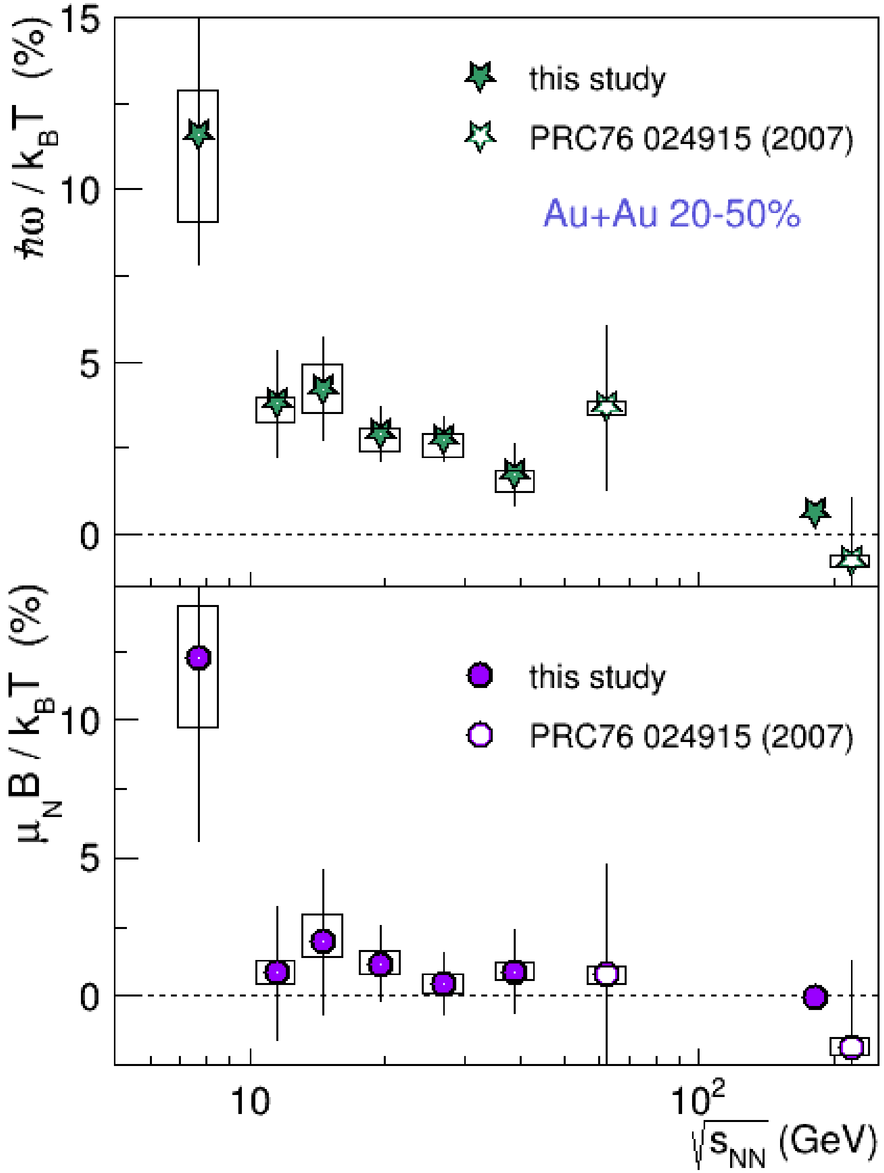
Decay	C
parity-conserving: $1/2^+ \rightarrow 1/2^+ \ 0^-$	$-1/3$
parity-conserving: $1/2^- \rightarrow 1/2^+ \ 0^-$	1
parity-conserving: $3/2^+ \rightarrow 1/2^+ \ 0^-$	$1/3$
parity-conserving: $3/2^- \rightarrow 1/2^+ \ 0^-$	$-1/5$
$\Xi^0 \rightarrow \Lambda + \pi^0$	$+0.900$
$\Xi^- \rightarrow \Lambda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

** $\hbar = k_B = 1$

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

Extracted Physical Parameters

- Significant vorticity signal
  - Falling with energy, despite increasing J_{sys}
  - 6σ average for 7.7-39 GeV
  - $P_{\Lambda_{\text{primary}}} = \frac{\omega}{2T} \sim 5\%$
- Magnetic field
  - $\mu_N \equiv \frac{e\hbar}{2m_p}$, where m_p is the proton mass
  - positive value, 1.5σ average for 7.7-39 GeV



Vorticity ~ theory expectation

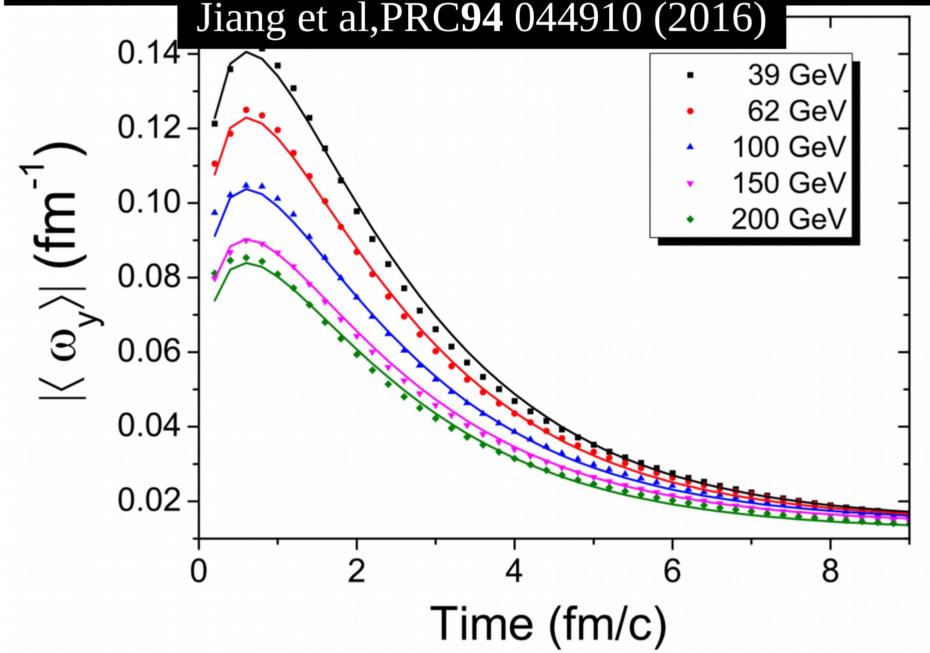
- Thermal vorticity:

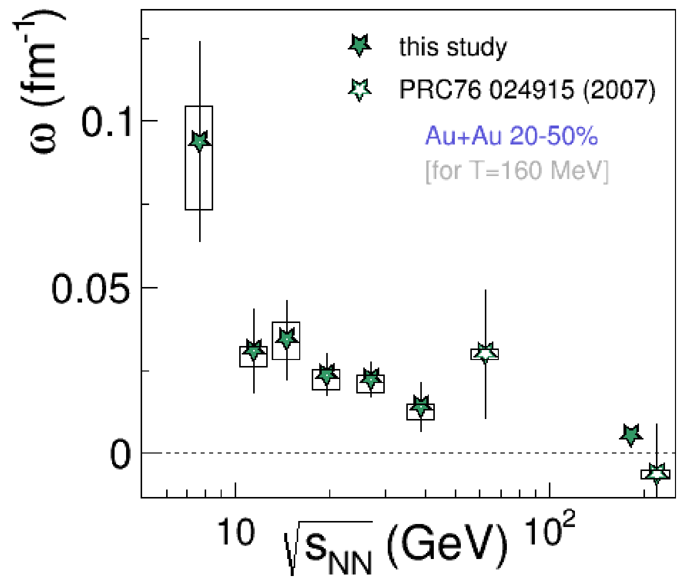
$$\frac{\omega}{T} \approx 2-10\,\%$$

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

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

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





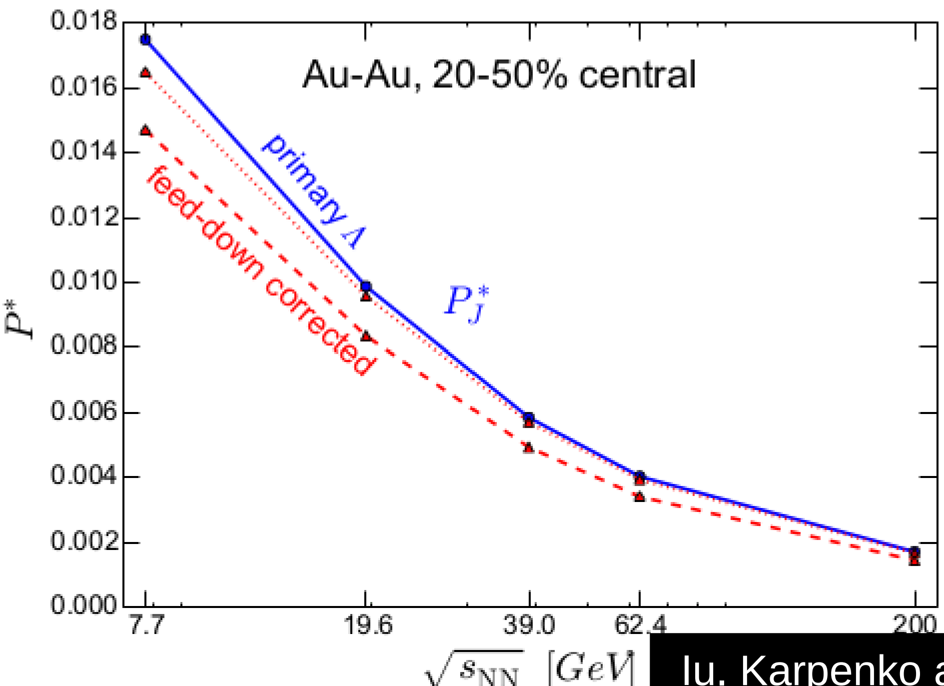
Csernai et al, PRC**90** 021904(R) (2014)

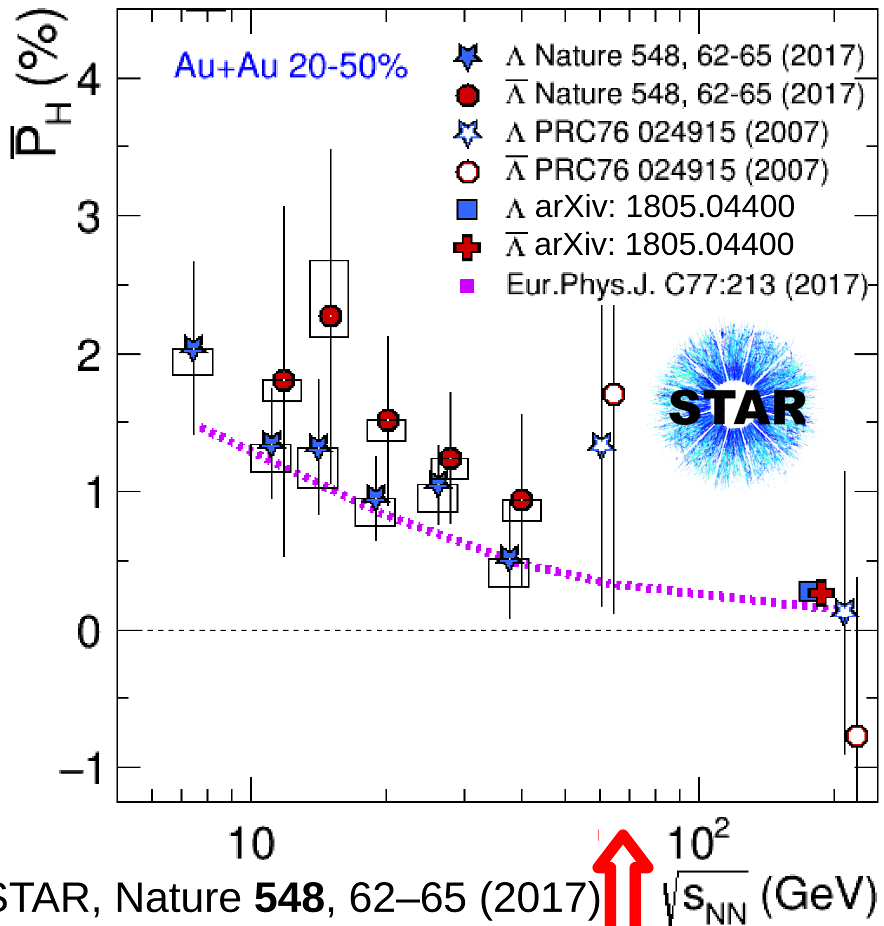
TABLE I. Time dependence of average vorticity projected to the reaction plane for heavy-ion reactions at the NICA energy of $\sqrt{s_{NN}} = 4.65 + 4.65$ GeV.

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 (I)

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



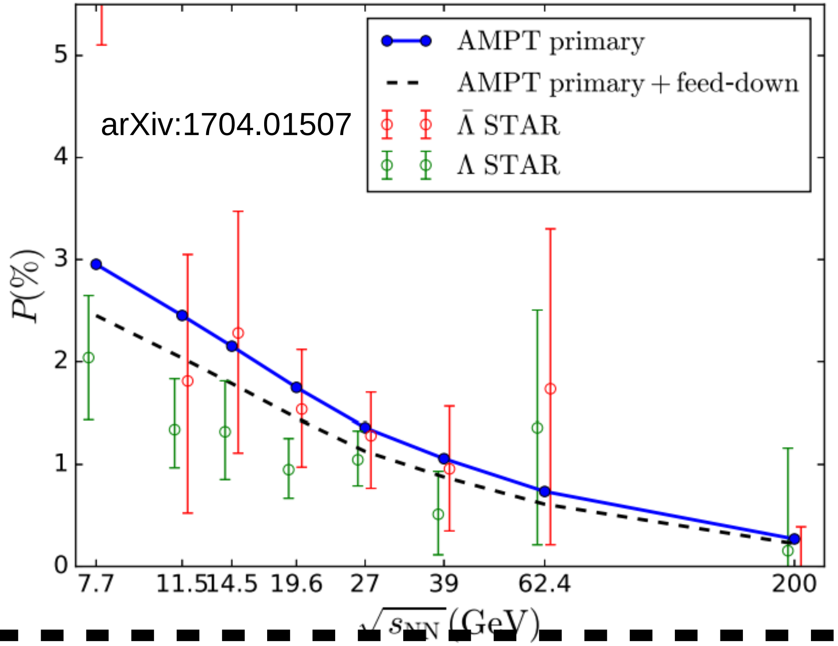


STAR, Nature **548**, 62–65 (2017)

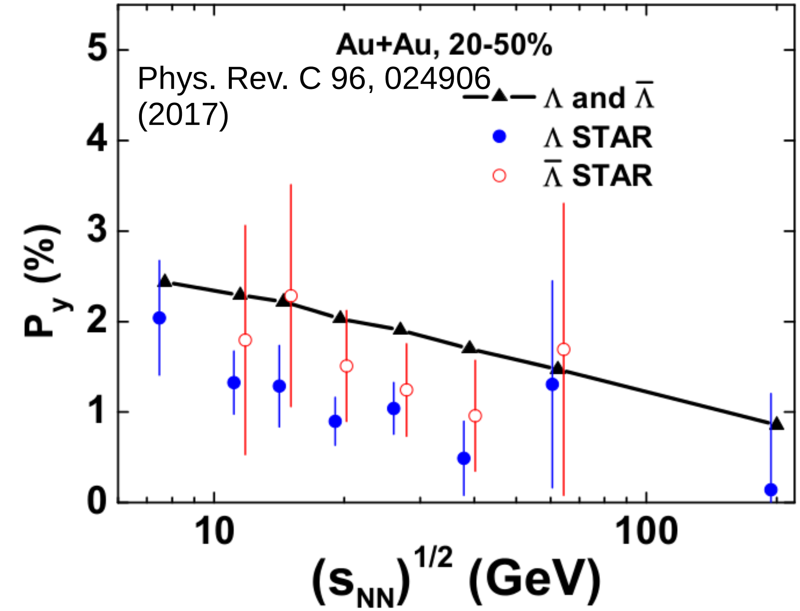
Compare "feed-down corrected" curve in dashed magenta line

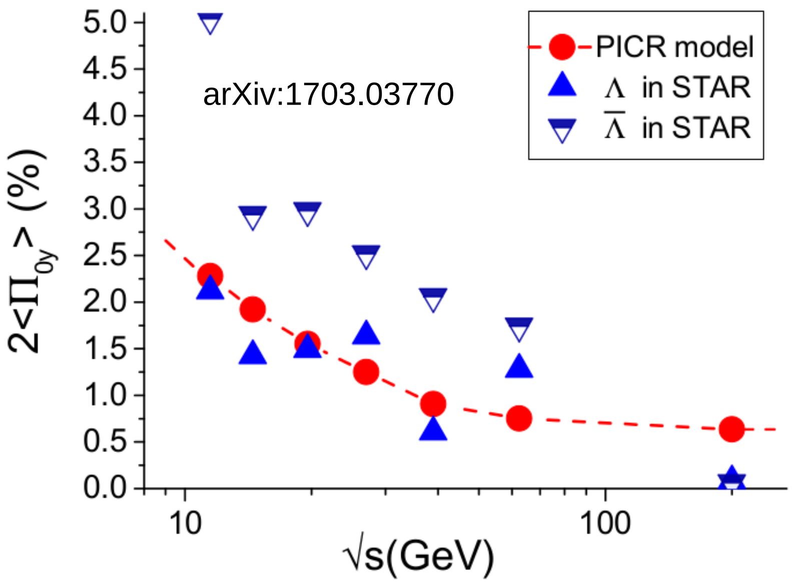
Iu. Karpenko and F. Becattini Eur. Phys. J. C (2017) 77: 213

Polarization ~ theory expectation (II)

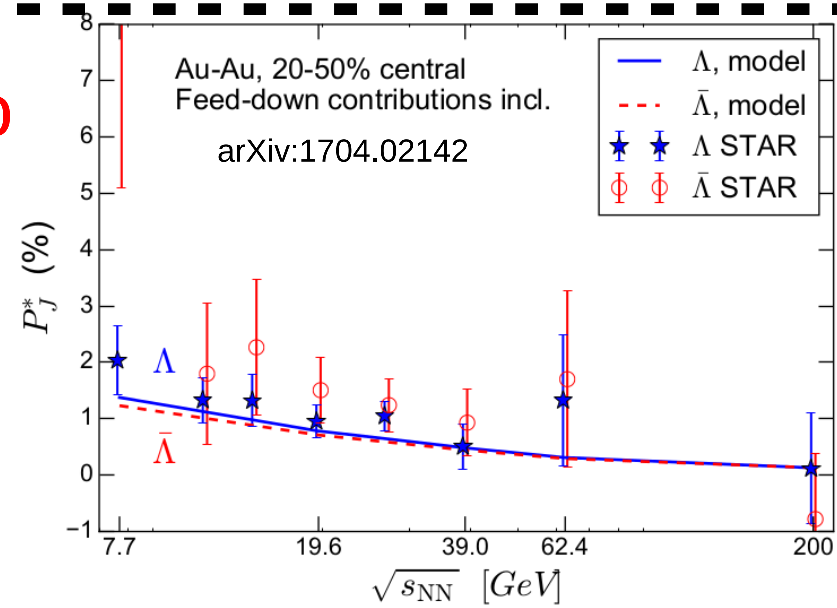


AMPT





Hydro



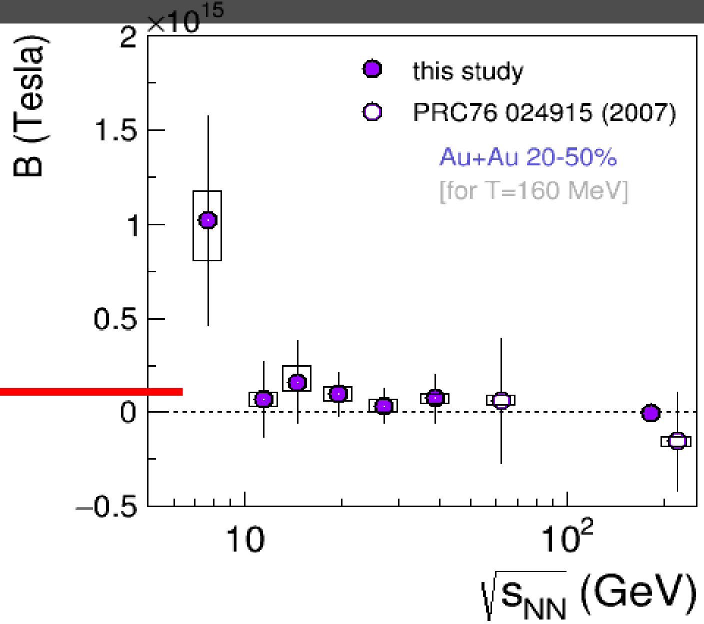
B-Field ~ theory expectation

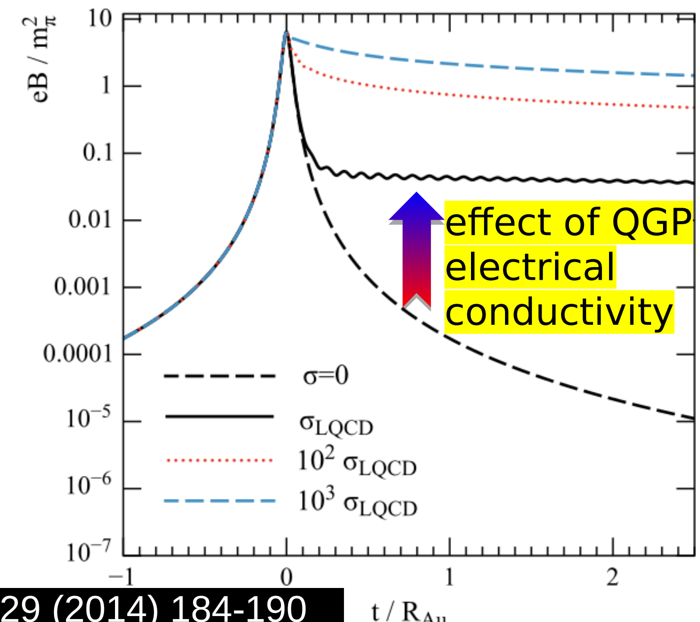
Magnetic field:

- 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

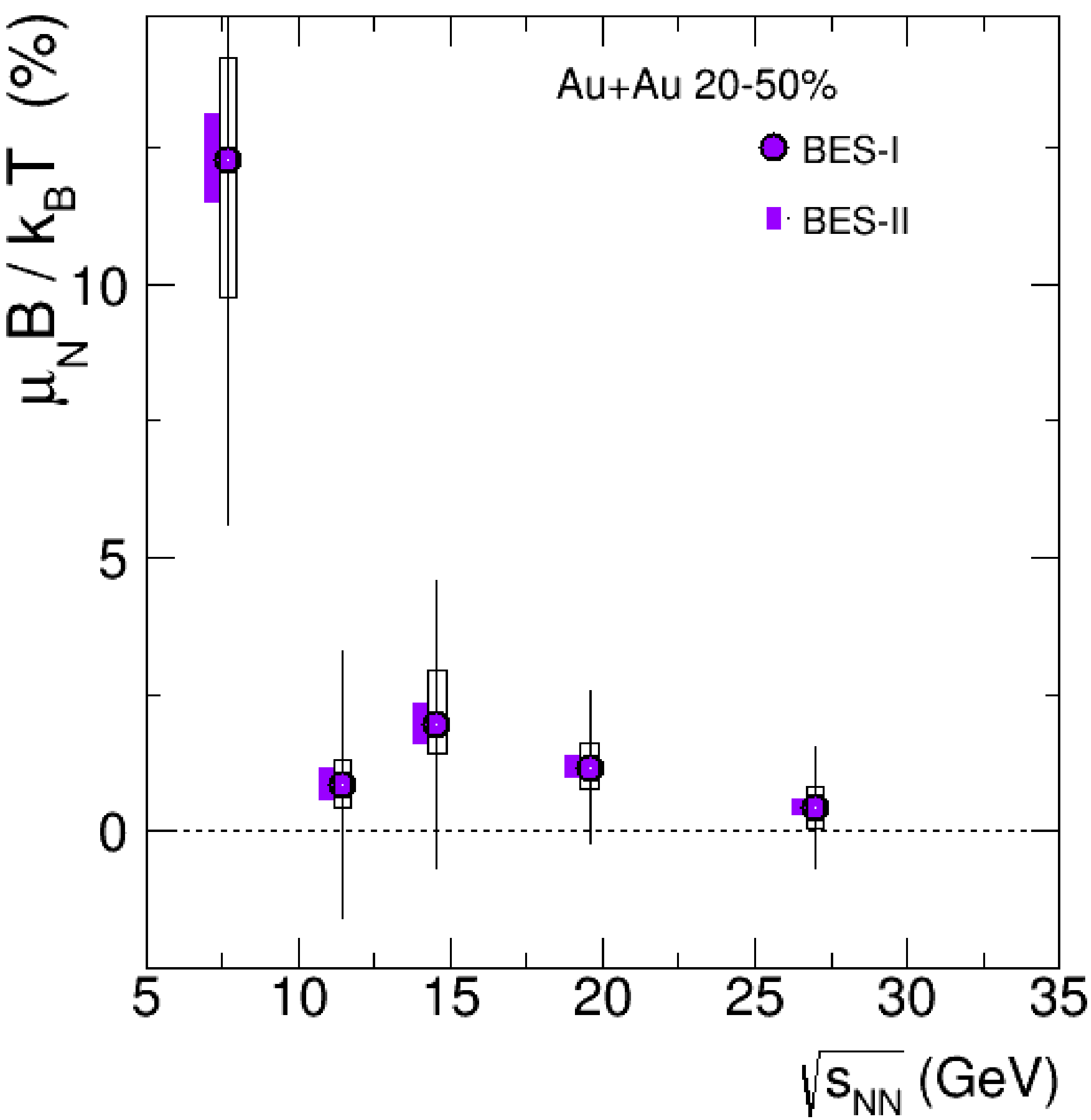




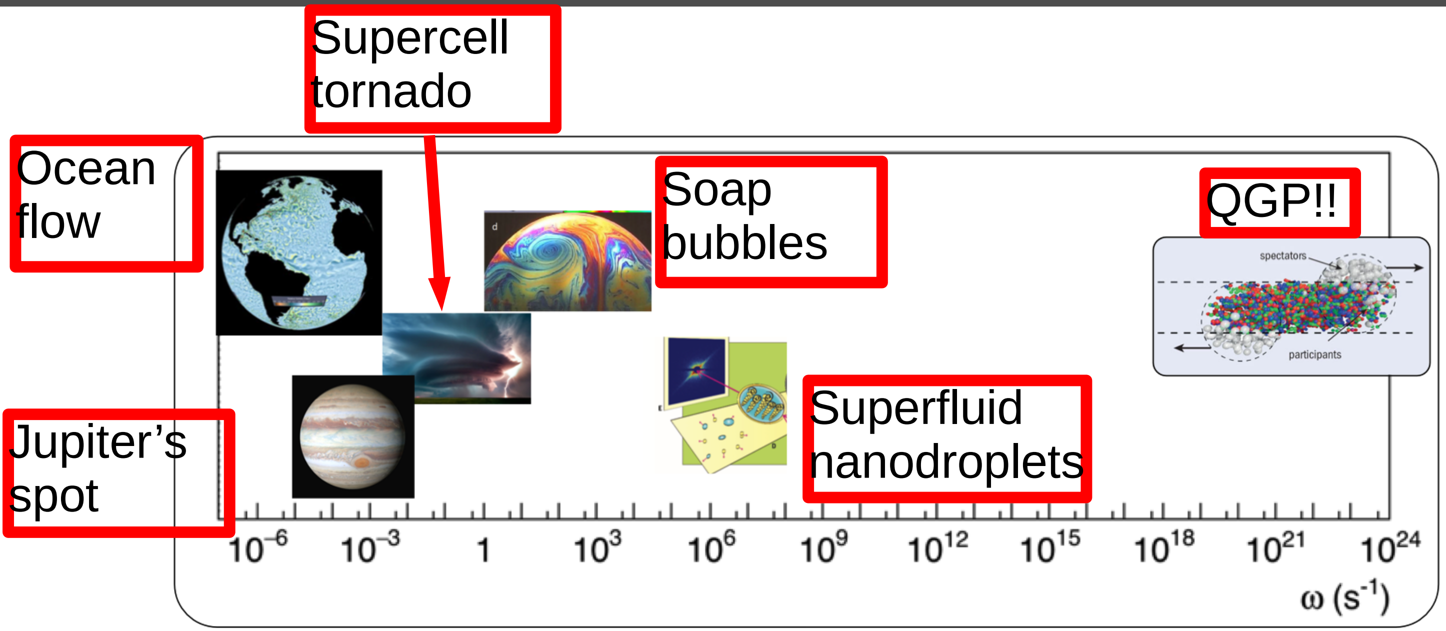
L. McLerran, V. Skokov Nucl.Phys. A929 (2014) 184-190

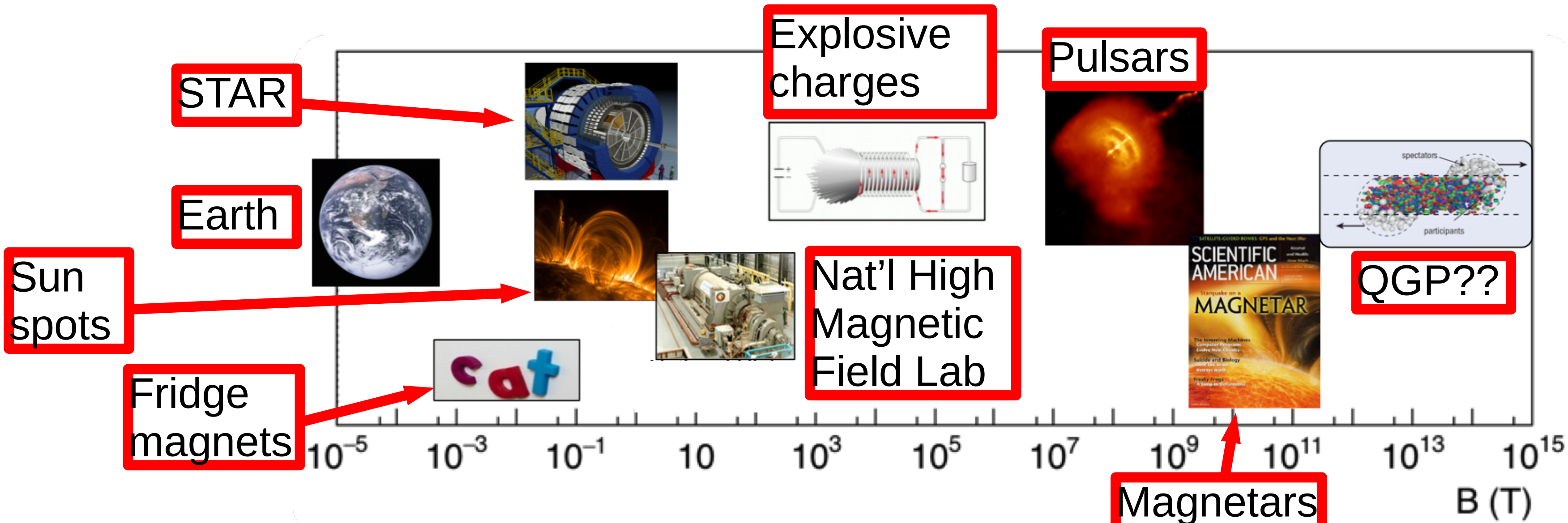
B field BES II Projection

- Using statistics from the BES-II + 27 GeV BUR (excepting 9.1 GeV)
- Assuming present centerpoints 9.6σ result
  - Clearly 7 GeV is a statistical blip
- If only 11-27 GeV are used maybe expect ~6σ result for BES-II



Comparison of QGP superlatives

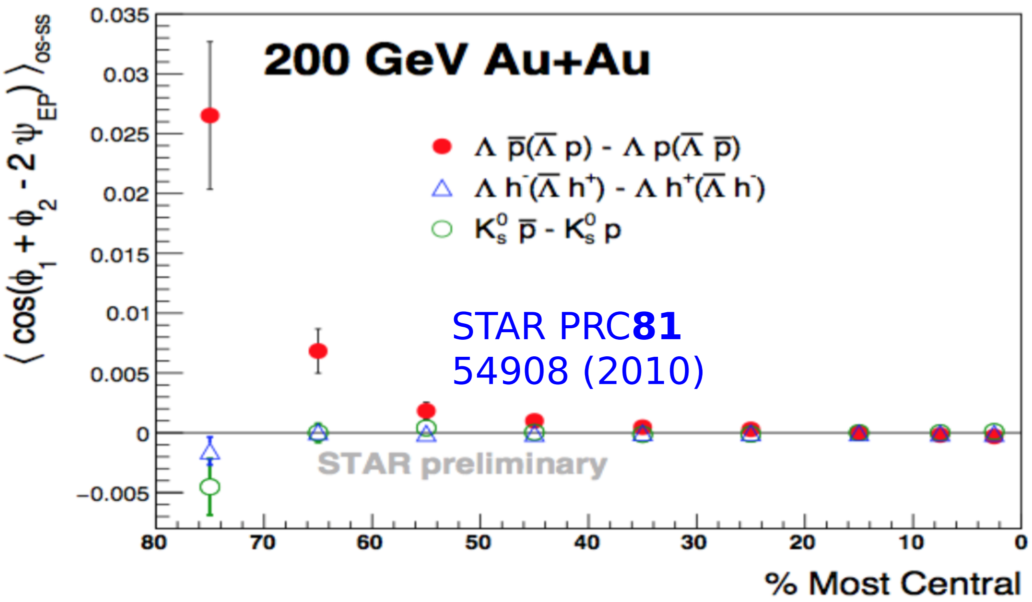




Connection: CVE

- 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

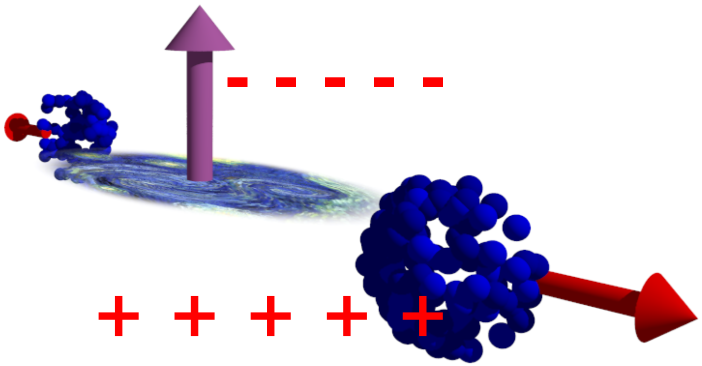
$$J_E = \frac{N_c \mu_5}{3\pi^2} \mu_B \omega$$

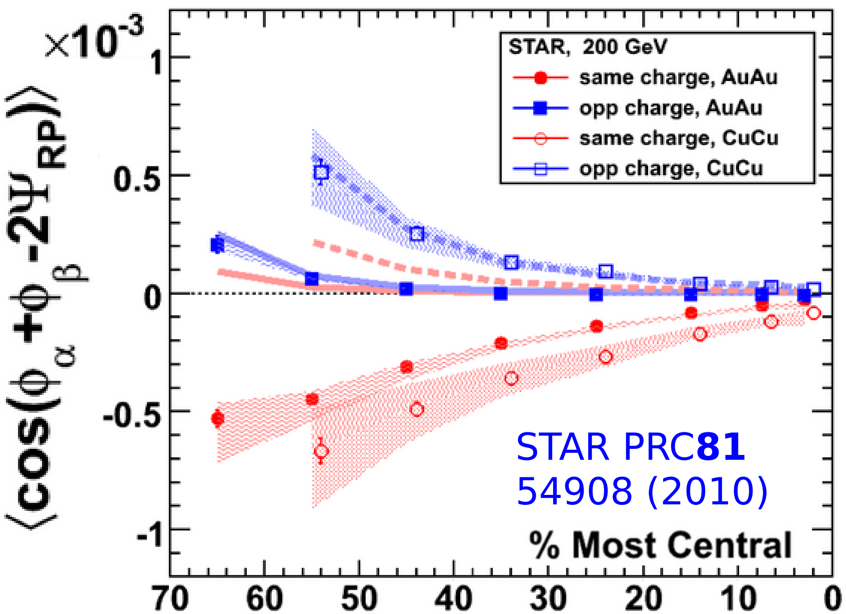


Connection: CME

- 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

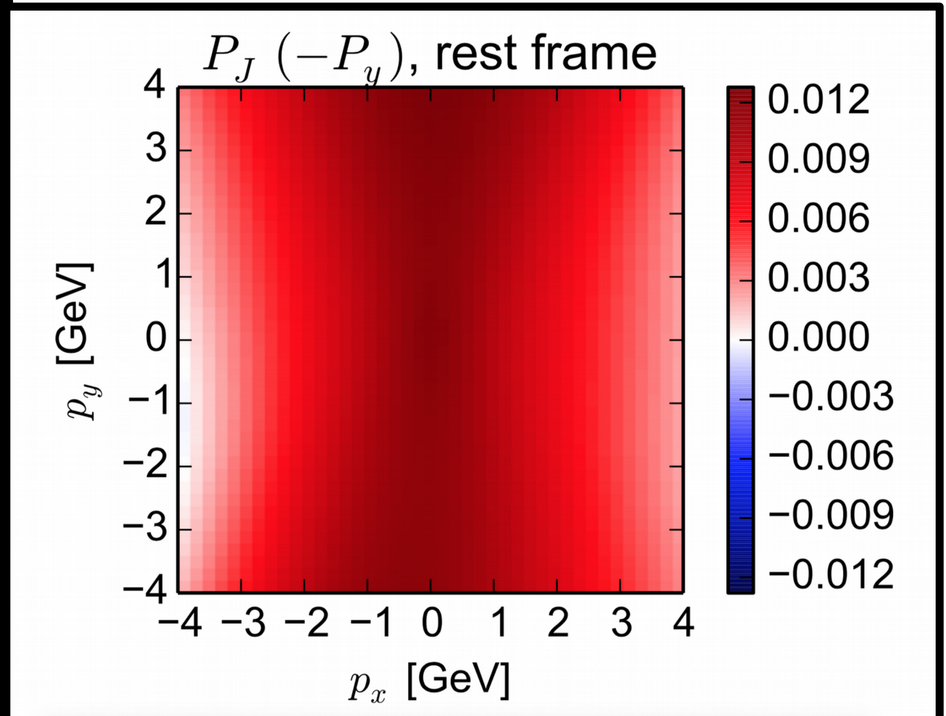
$$J_E = \frac{N_c \mu_5}{3\pi^2} B$$





Azimuthal dependence (I)

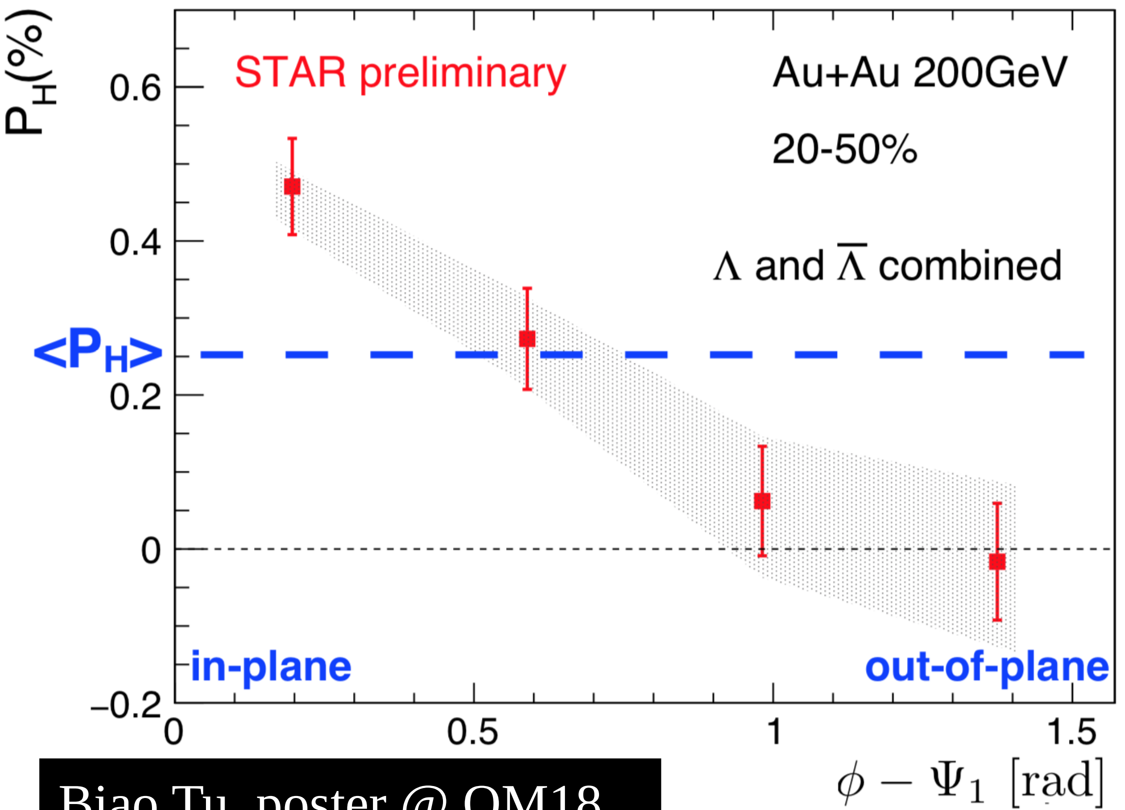
- Naively collision starts with strongest vorticity gradient in plane
- A model predicts the opposite dependence
- The dependence of P_H on $\phi_\Lambda - \Psi_1$ tests spin local thermal equilibrium and model initial conditions



Karpenko & Becattini EPJC (2017) 77:213

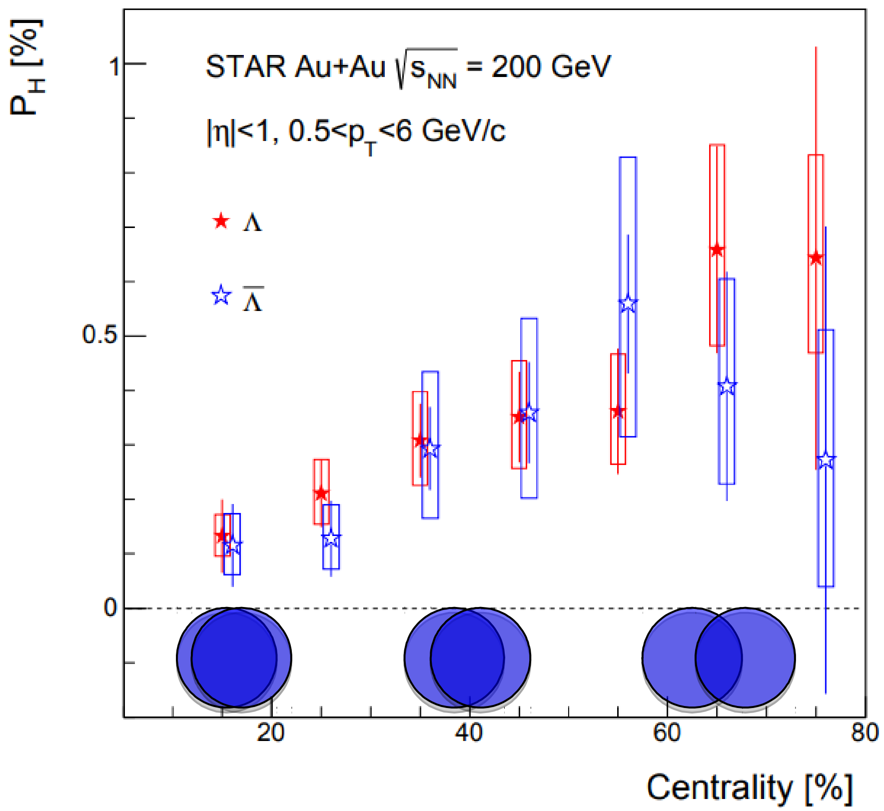
Azimuthal dependence (II)

- In opposition to the model prediction STAR sees a *larger* polarization in in-plane than in out-of-plane
- Represents an important tension in the measurement

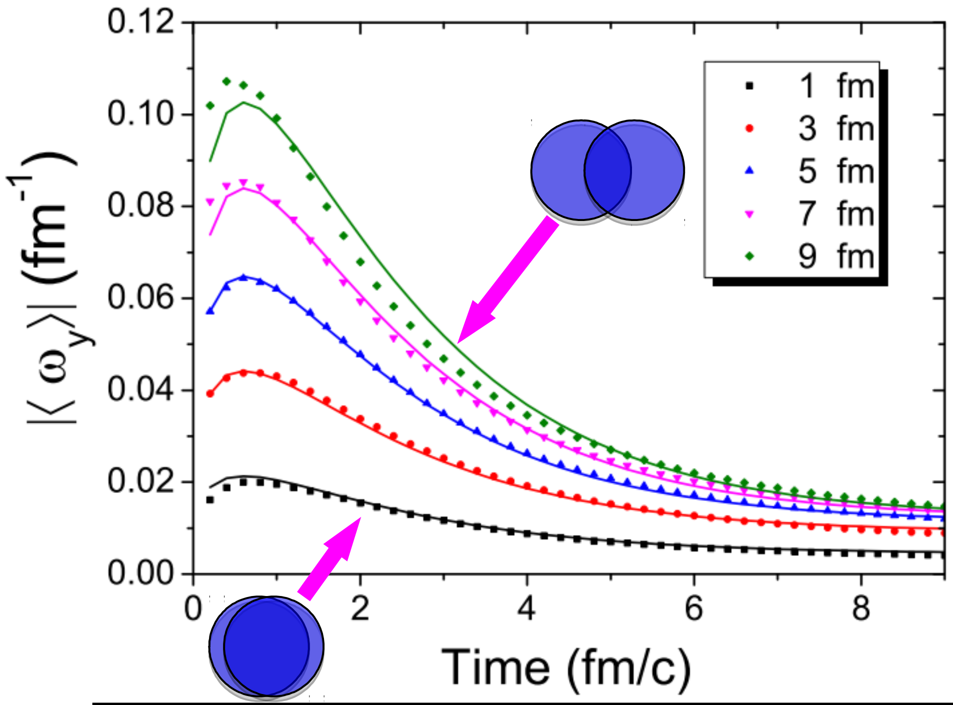


Biao Tu, poster @ QM18

Centrality



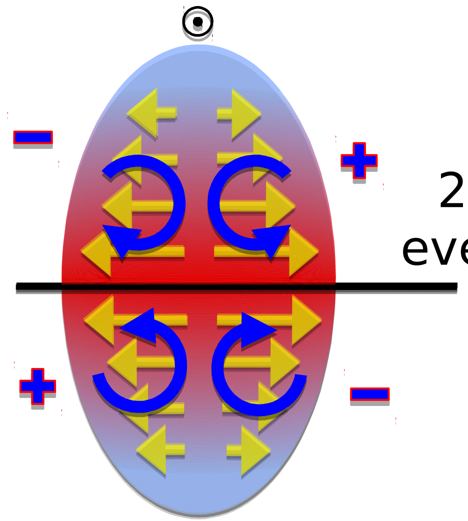
STAR, arXiv: 1805.04400

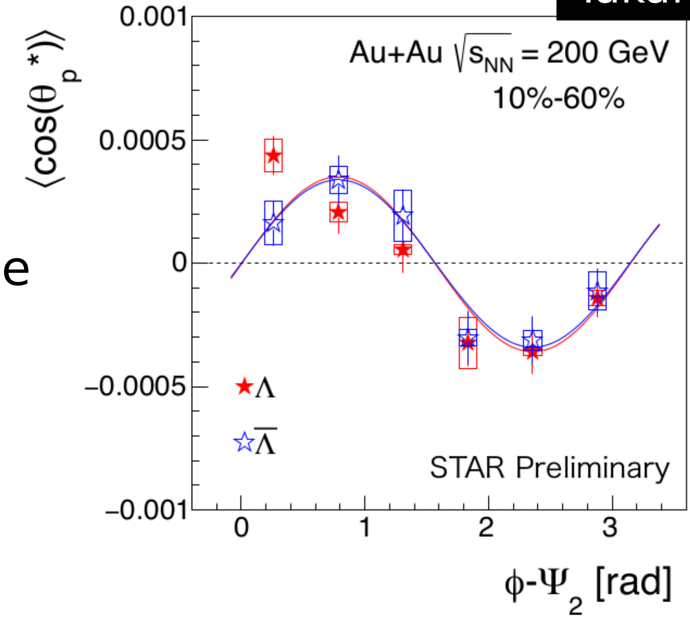


Jiang et al, PRC90 021904(R) (2014)

- Signal increasing with decreasing centrality falls well in line with theory

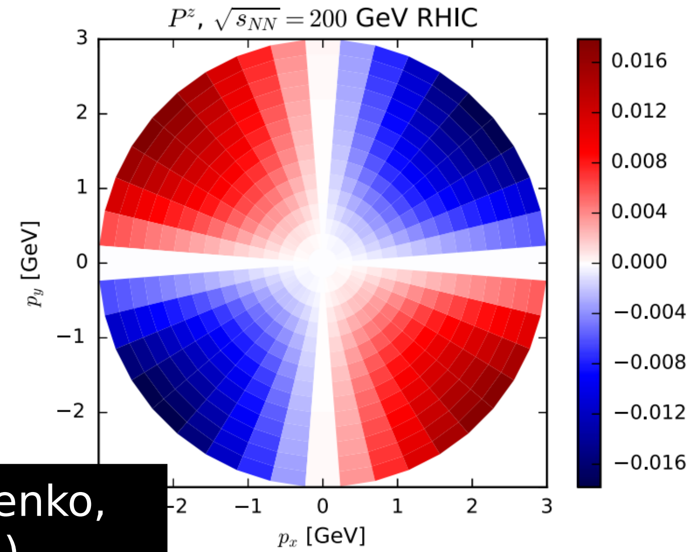
Polarization along the beam direction





- Clear signal at 200 GeV
- Signal qualitatively disagrees with hydro model

- Local velocity gradients due to elliptic flow may produce vorticity along beam direction
- This is a brand new area to look!
- Look for sinusoidal polarization structure projected onto the beam direction



S. Voloshin, EPJ Web Conf. 17 (2018) 10700

F. Becattini and I. Karpenko, PRL.120.012302 (2018)

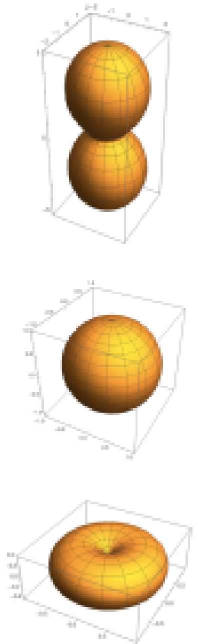
Phi Meson Polarization (I)

Region of recombination of polarized quarks

$\rho_{00} > 1/3$:

$\rho_{00} = 1/3$:

$\rho_{00} < 1/3$:



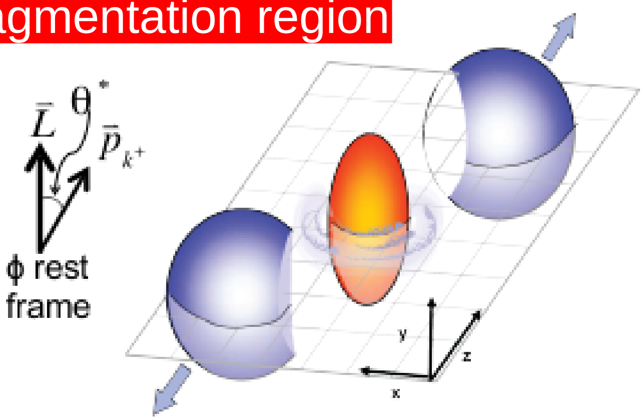
Polarized quark fragmentation region

- Spin alignment can be determined from the angular distribution of the decay products*:

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

where N_0 is the normalization and θ^* is the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

- A deviation of ρ_{00} from 1/3 signals net spin alignment.

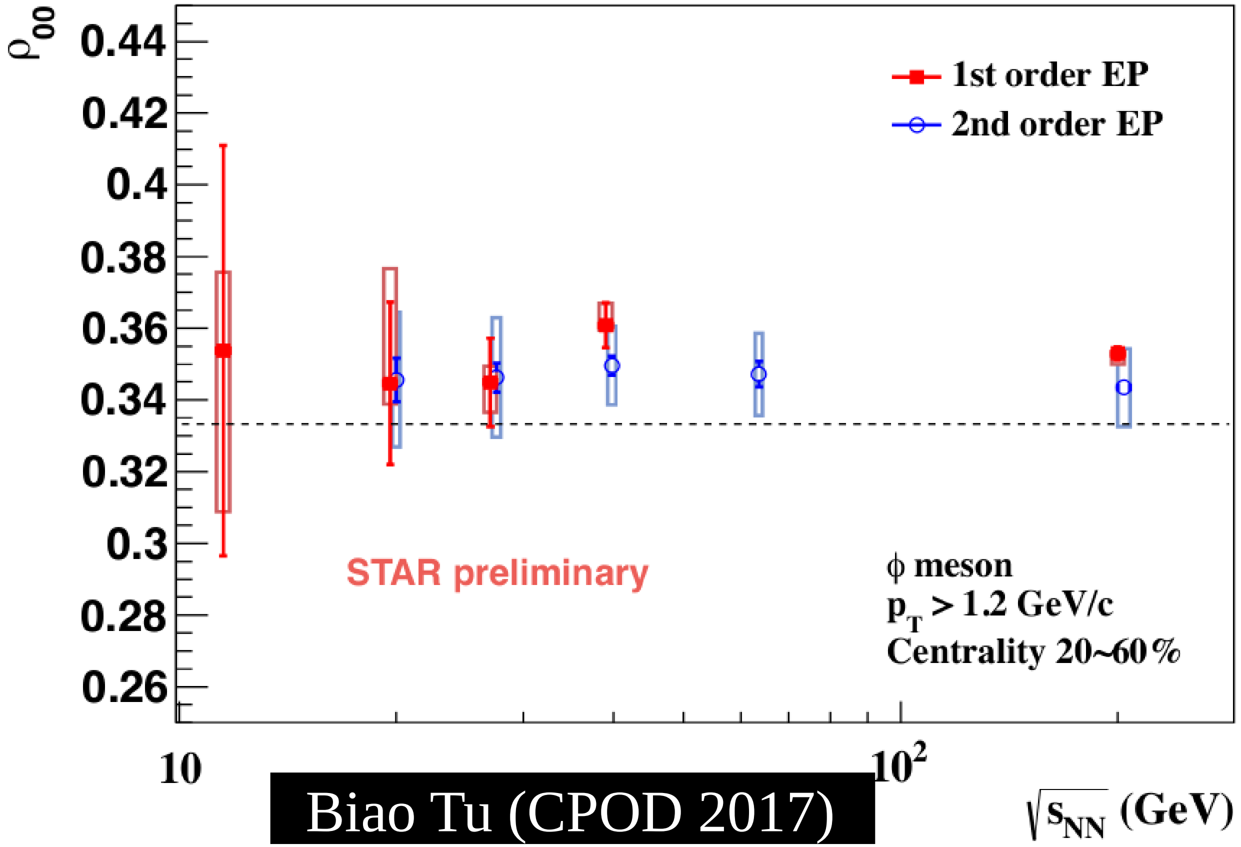


*K. Schilling el al., Nucl. Phys. B 15, 397 (1970)

Biao Tu (CPOD 2017)

Phi Meson Polarization (II)

- Polarization measure is made WRT both the first and second order event planes
- Significant deviation from 1/3 is seen for higher energies



Biao Tu (CPOD 2017)

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 $\sqrt{s_{NN}}$
- Polarization along beam direction has qualitative tension
- Systematic dependences may offer more insight into modeling
  - sign tension for azimuthal dependence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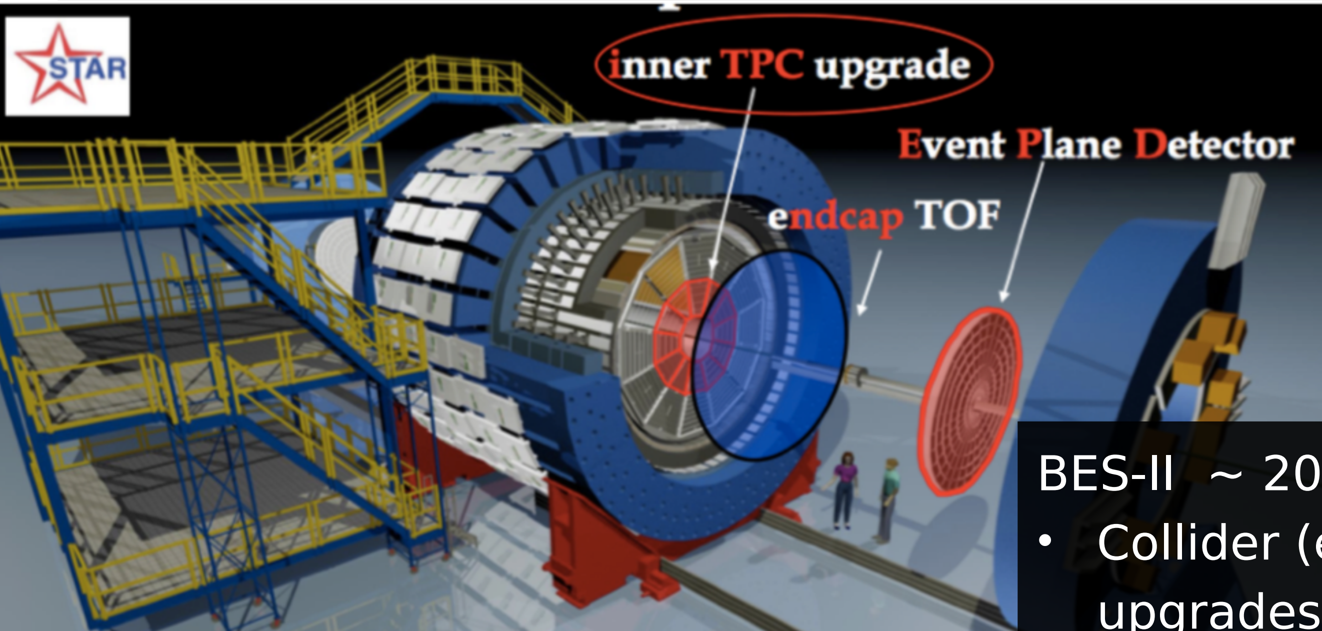
BES-II: 2019-2020



Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2 days	100M
9.8	4.5 (FXT)	589	2 days	100M
7.3	3.9 (FXT)	633	2 days	100M
5.75	3.5 (FXT)	666	2 days	100M
4.55	3.2 (FXT)	699	2 days	100M
3.85	3.0 (FXT)	721	2 days	100M

BES-II ~ 2019-2020

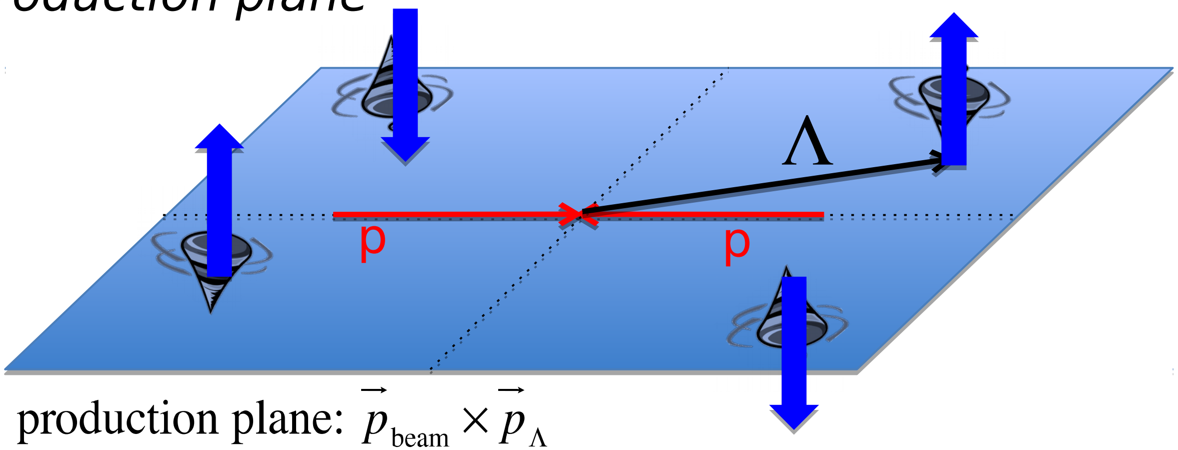
- Collider (e-cooling) & detector upgrades
- Finer-grained measurements
  - what drives energy dependence of P?
- Increase statistics by an order of magnitude
  - stat. errors reduced by ~3
- Improve the avg. 1st-order EP resolution by 2x
  - stat. errors reduced 2x

Production Plane – NOT 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*

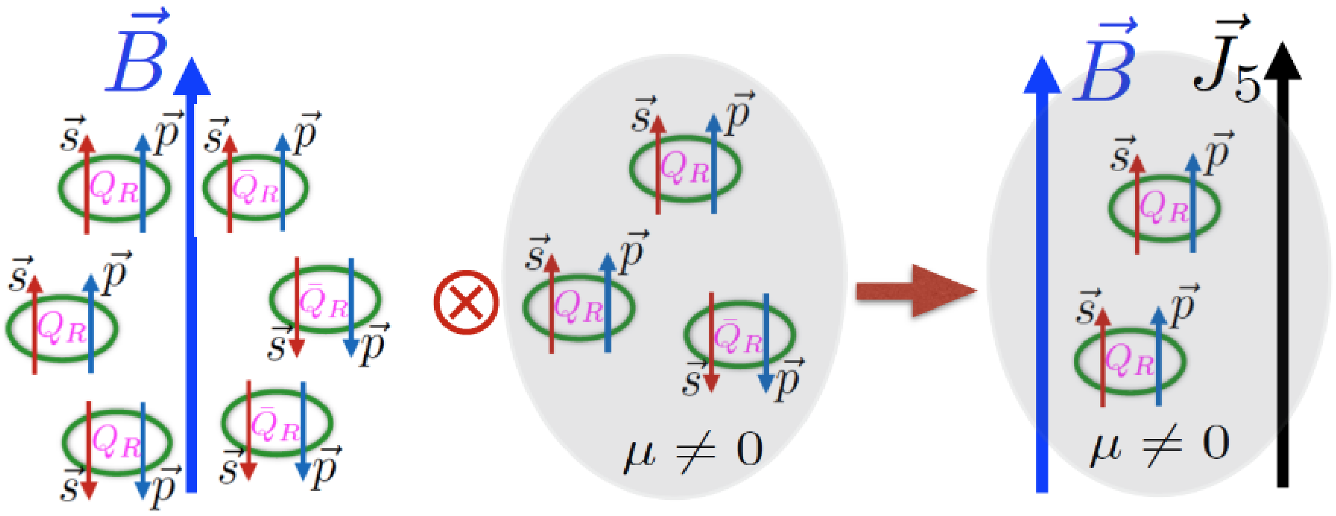


production plane: $\vec{p}_{\mathrm{beam}} \times \vec{p}_{\Lambda}$

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
- Polarization w/ *production* plane:
  - No integrated effect at midrapidity for Lambda
  - No (known) effect *at all* for AntiLambdas

Polarization sensitivity to chiral effects (I)



*Note that only the situation of an abundance of right handed quarks is depicted

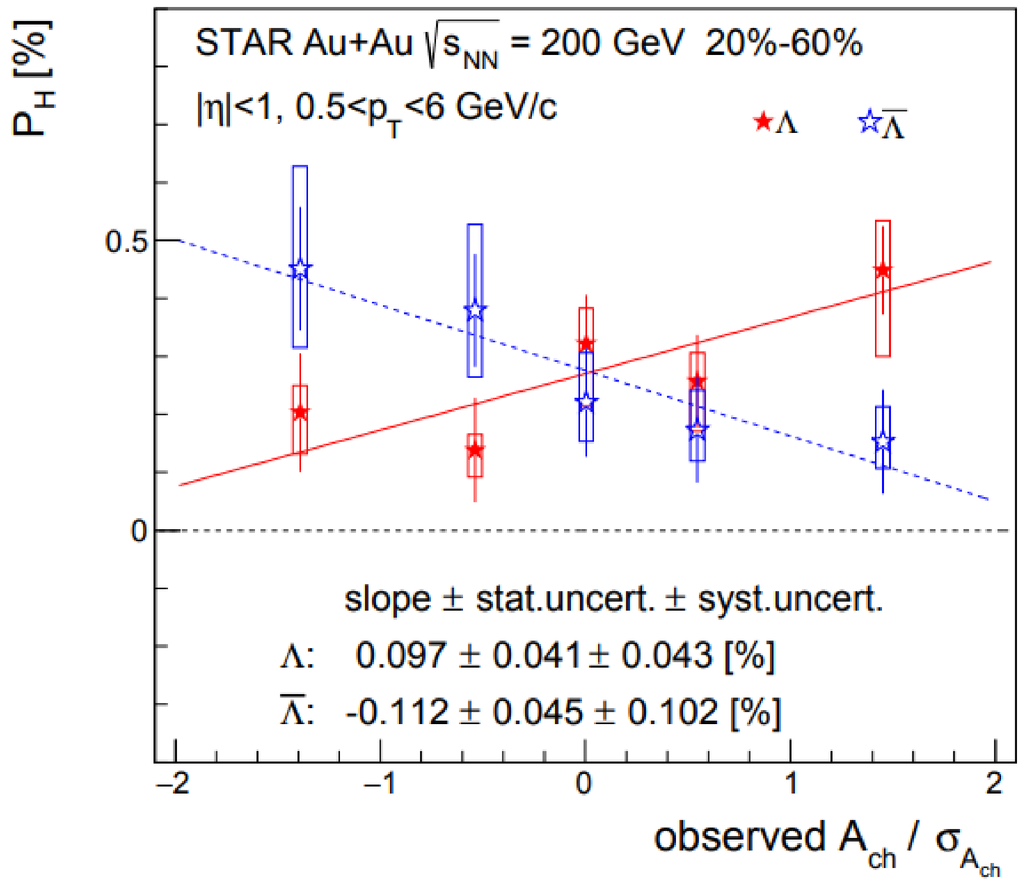
- The Chiral Separation Effect (CSE) is an expected axial current along the direction of an external magnetic field
- It has been postulated that the current of axial charges may contribute to the global polarization and effect a dependence of the polarization on charge asymmetry

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-}$$

Polarization sensitivity to chiral effects (II)

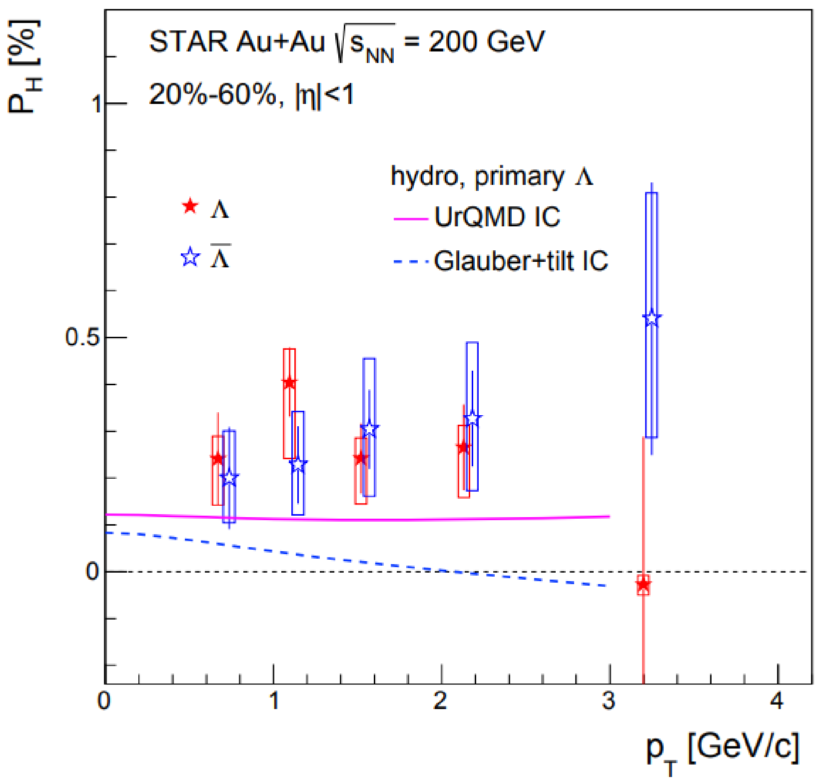
- Hint of a signal slope
  - Lambda and Anti-Lambda have opposite-sign slopes

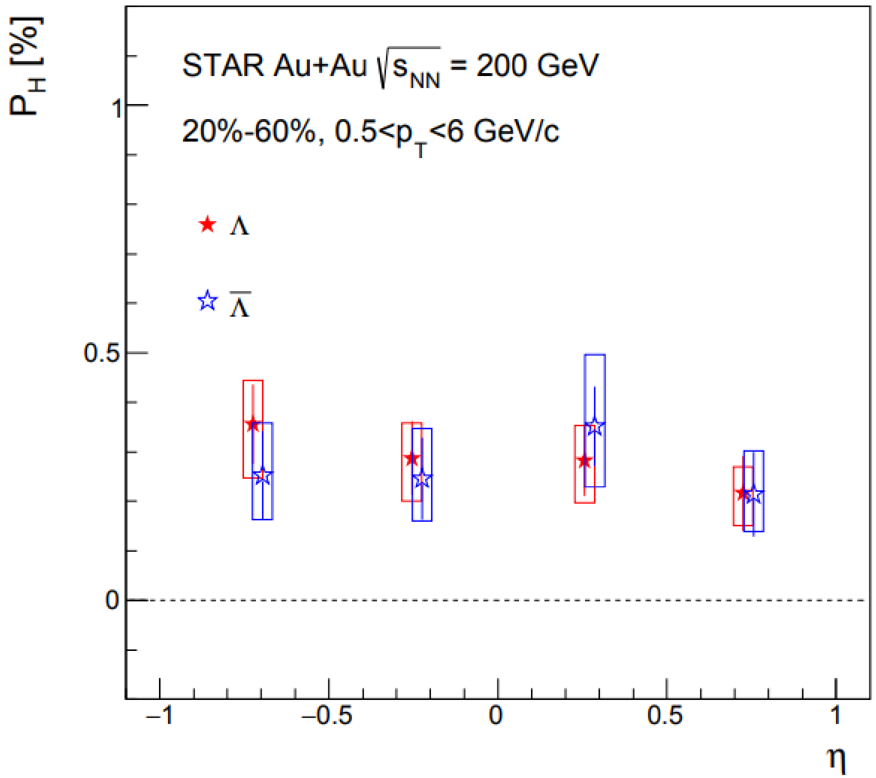
- Isobaric collision systems are a unique environment to test this effect



STAR, arXiv: 1805.04400

Momentum and pseudorapidity





STAR, arXiv: 1805.04400

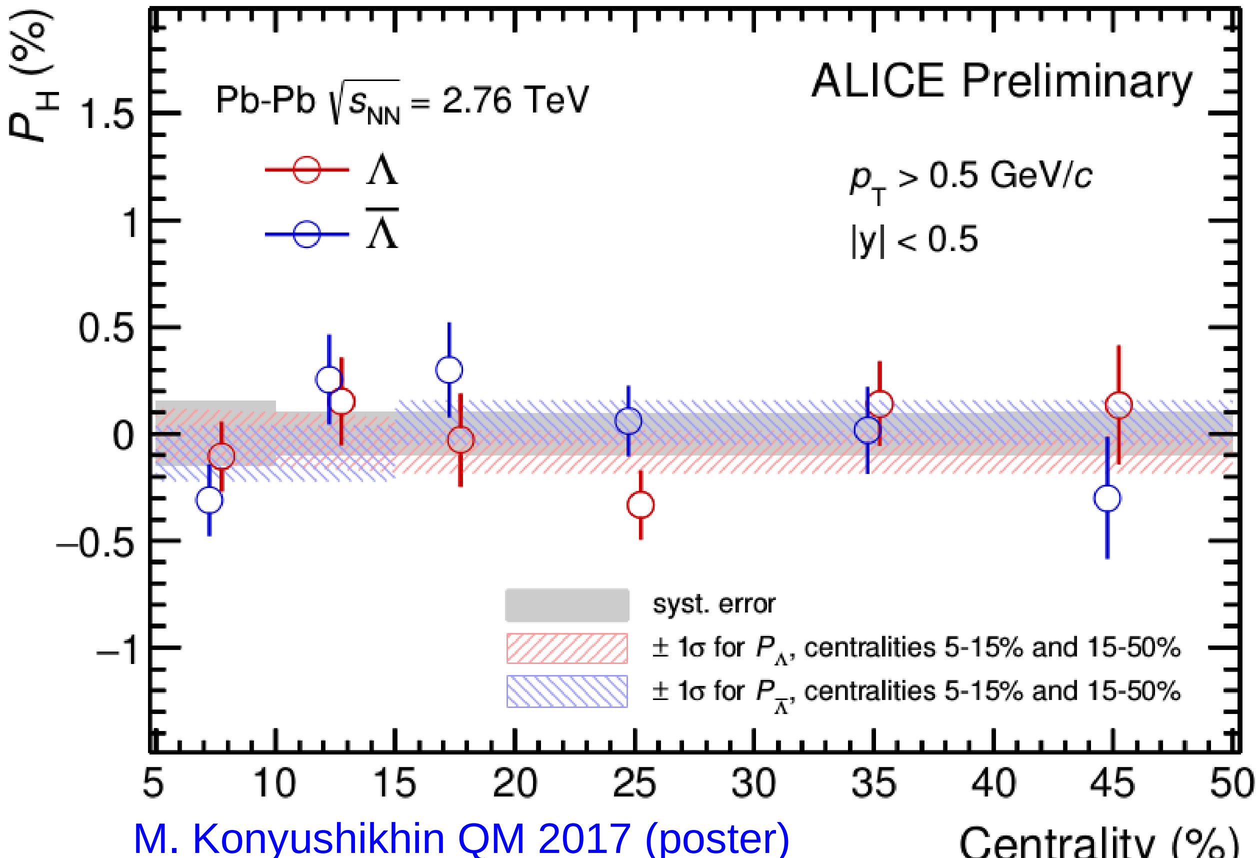
- No dependence seen on transverse momentum or psuedorapidity

ALICE Results

- At 2.76TeV ALICE sees a null result
- Strongly supports vorticity falling with beam energy
- No hint of Lambda-AntiLambda difference

$$5\text{-}15\%\ \text{centrality} = \begin{cases} P_\Lambda = -0.0001 \pm 0.0013(\text{stat}) \pm 0.0004(\text{syst}) \\ P_{\bar{\Lambda}} = -0.0009 \pm 0.0013(\text{stat}) \pm 0.0008(\text{syst}) \end{cases}$$

$$15\text{-}50\%\ \text{centrality} = \begin{cases} P_\Lambda = -0.0008 \pm 0.0010(\text{stat}) \pm 0.0004(\text{syst}) \\ P_{\bar{\Lambda}} = \ \ \ 0.0005 \pm 0.0010(\text{stat}) \pm 0.0003(\text{syst}) \end{cases}$$



M. Konyushikhin QM 2017 (poster)

EPD BBC comparison