Global Hyperon Polarization in Heavy-Ion Collisions at RHIC-STAR

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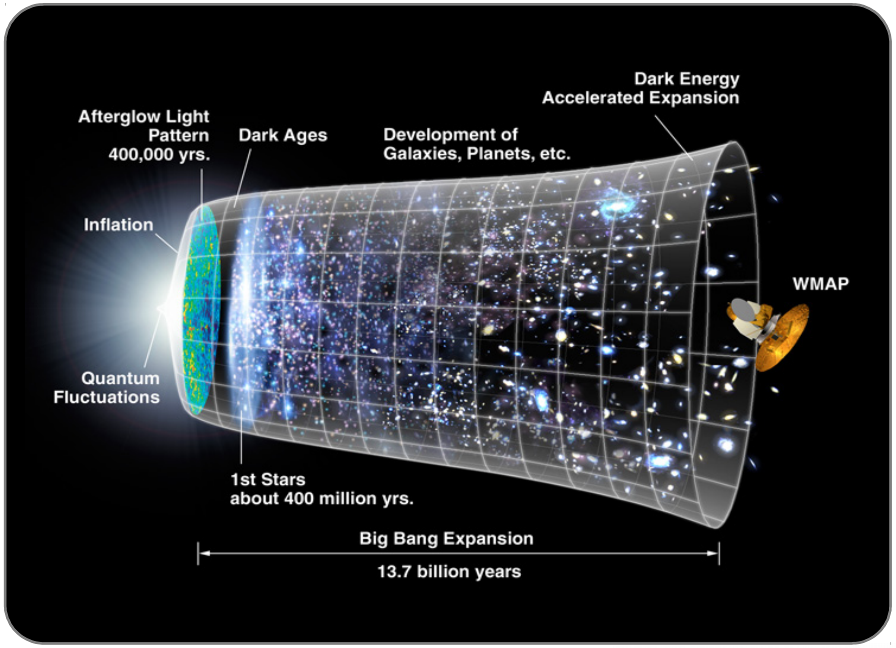
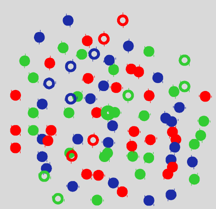
SDU/BNL
09/05/18

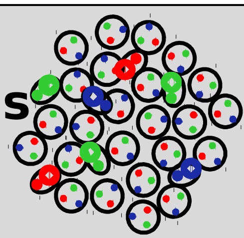
QCD: Early universe

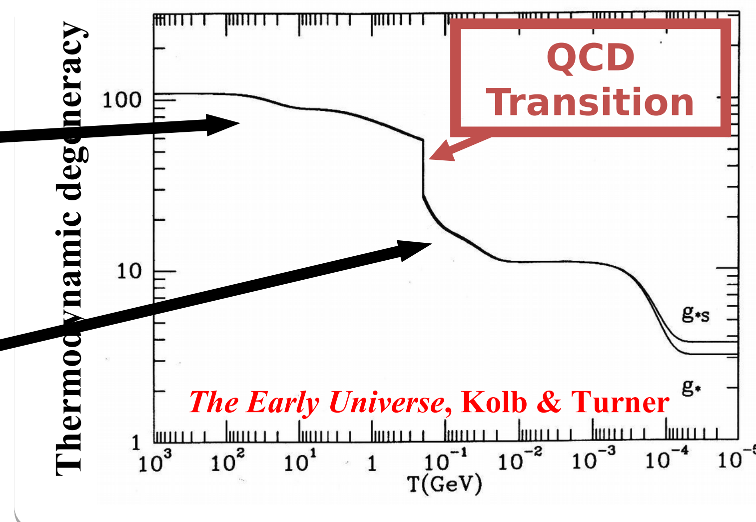


Deconfined color charges
Quark-gluon plasma



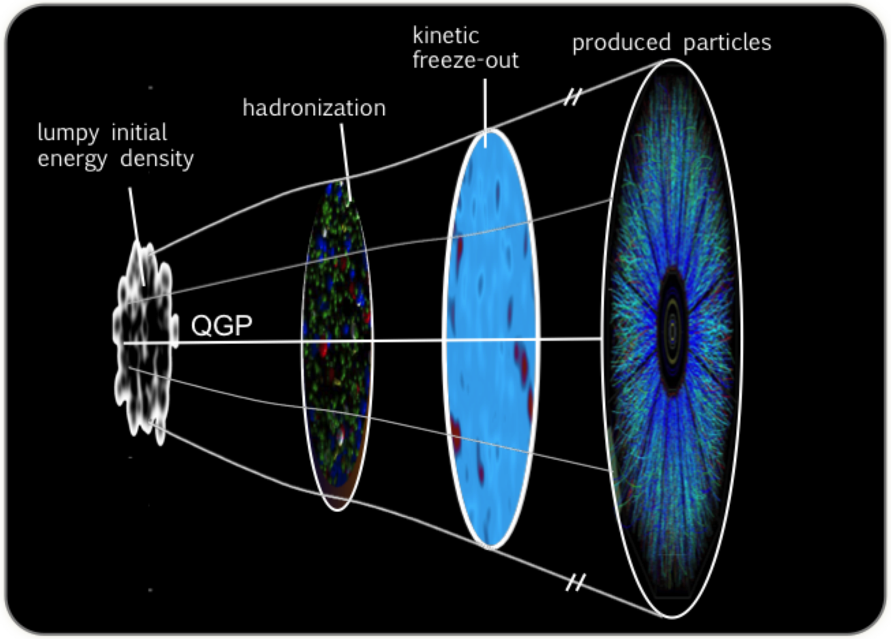
Color confined inside
net-color-neutral **hadrons**
(e.g. proton)





2

QCD: Heavy-ion physics

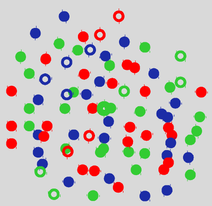


Lattice QCD calculation:

- T<150 MeV : interacting hadrons
- T>150 MeV : deconfined quarks

* (150 MeV = 2x10^{12} K ~ 10^{5} $T_{\perp}$)

Deconfined color charges
Quark-gluon plasma



Color confined inside
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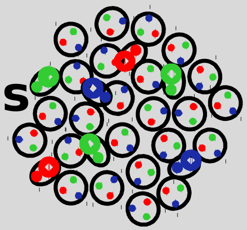
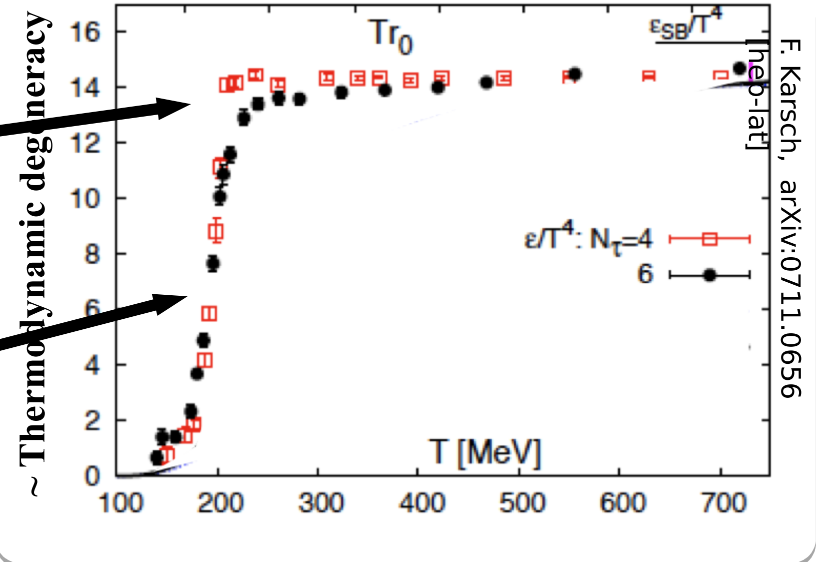
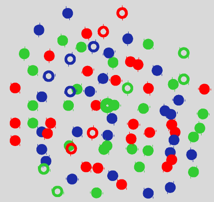


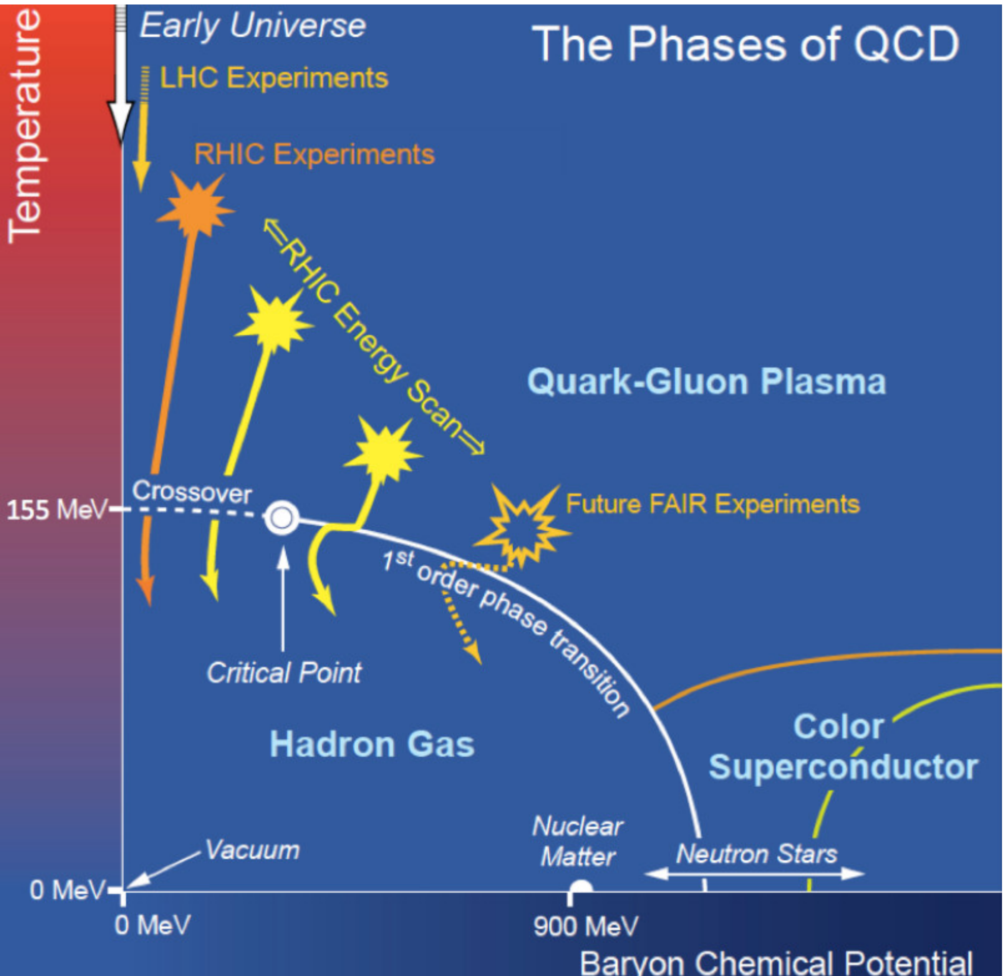


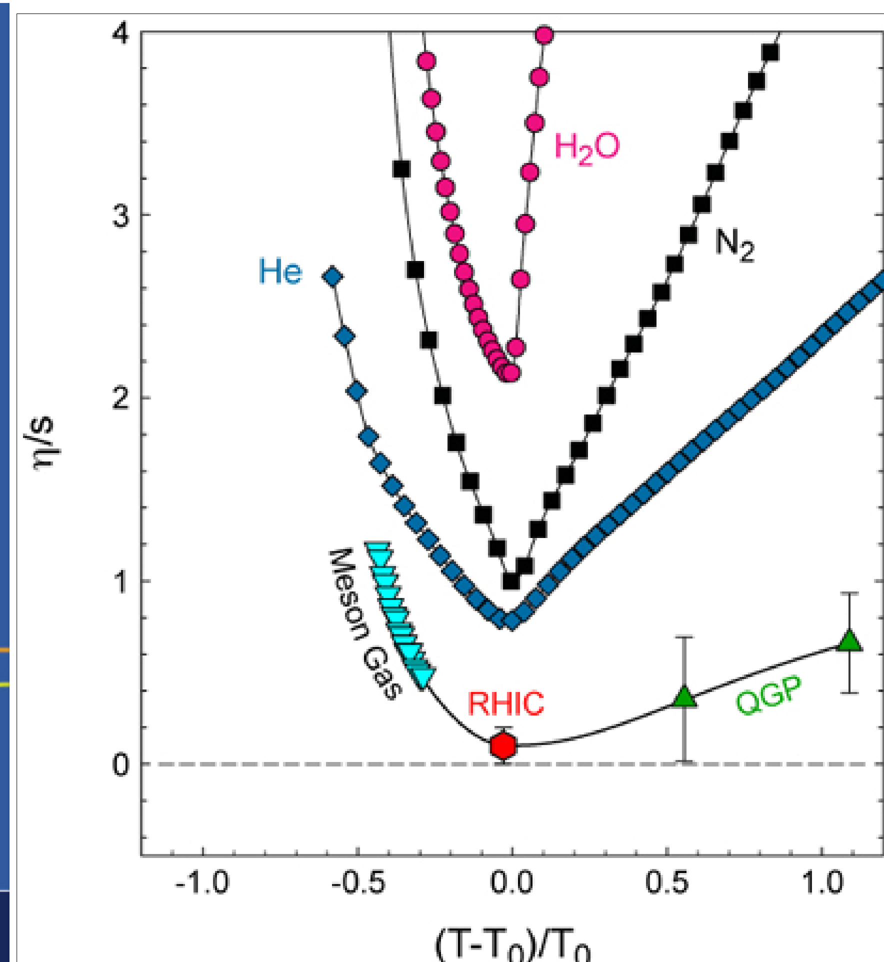
Nuclear matter phase diagram

Deconfined color charges
Quark-gluon plasma

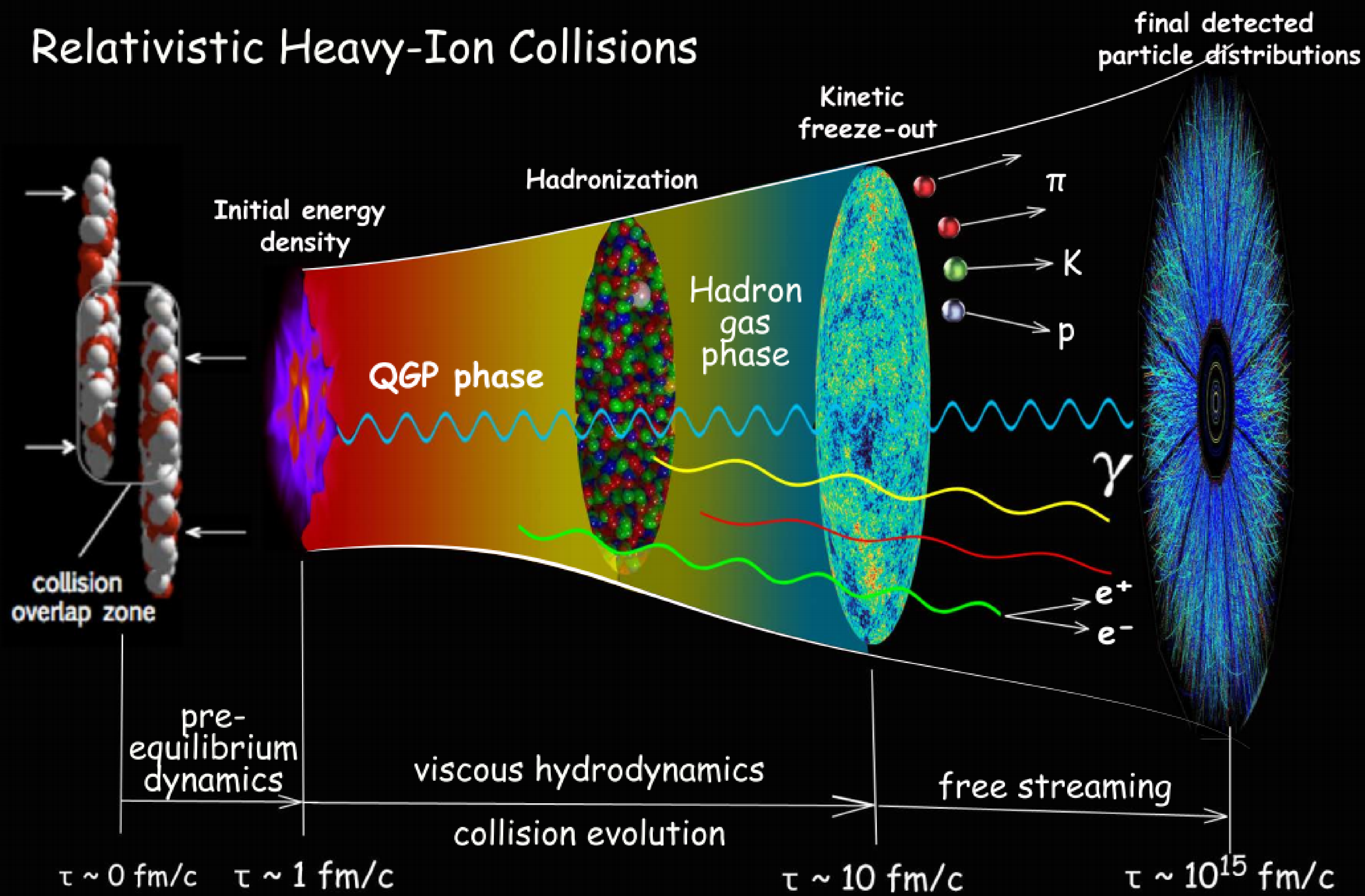


The QGP is very nearly a perfect fluid



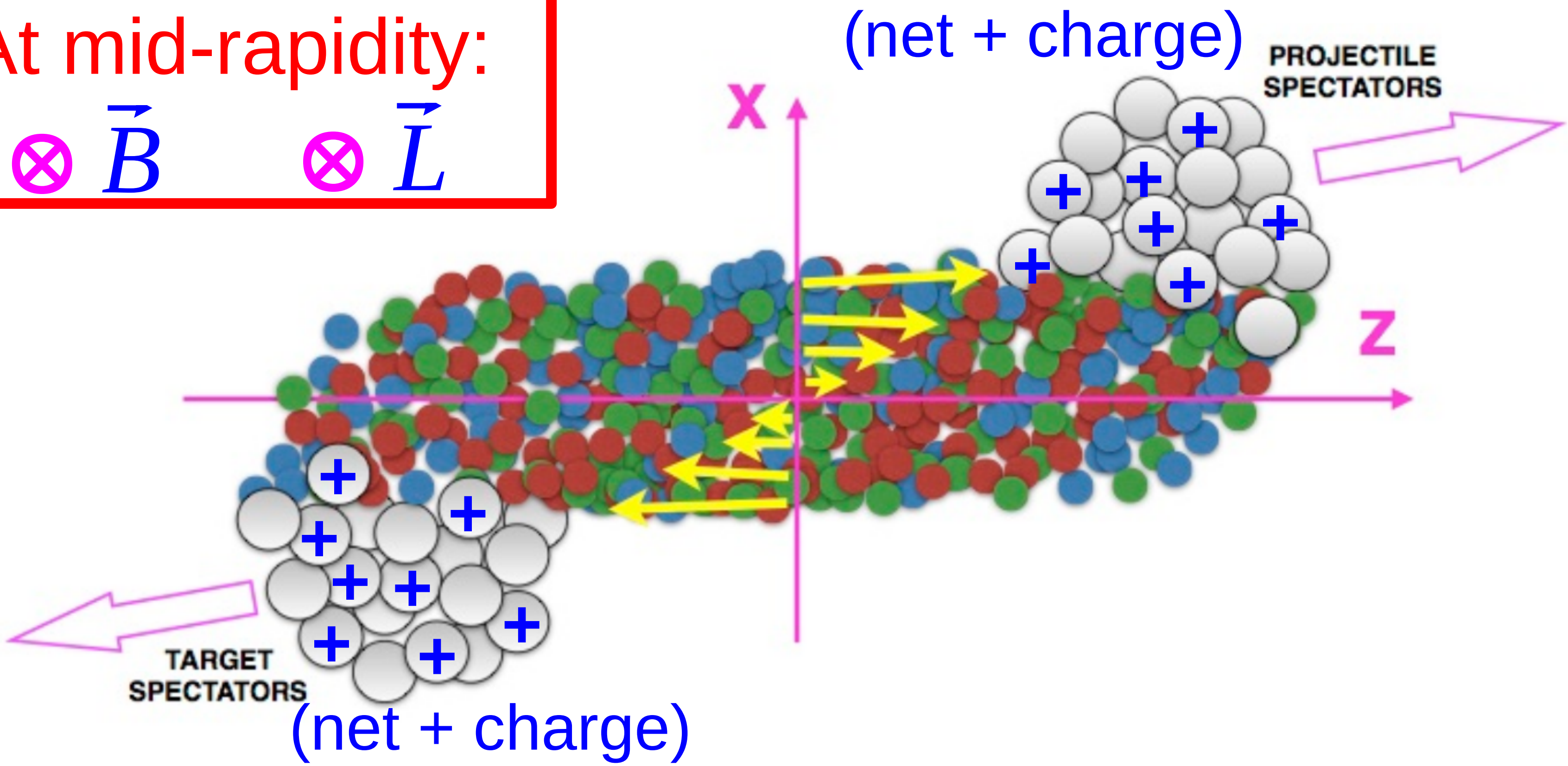


Relativistic Heavy-Ion Collisions



At mid-rapidity:

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



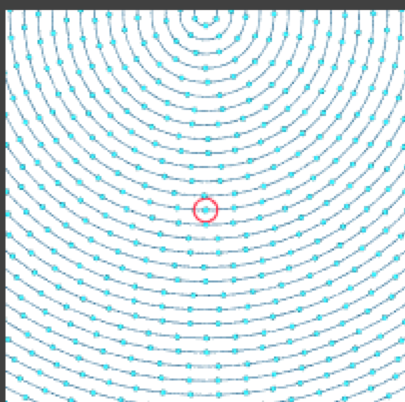
- |L| ~ 10^3 ħ in non-central collisions
- How much is transferred to particles at mid-rapidity?
- Does angular momentum get distributed thermally?
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} \equiv \frac{1}{2} \vec{\nabla} \times \vec{v}$
- How would it manifest itself in data?

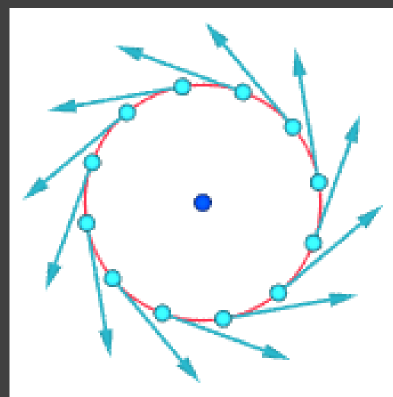
Vortices

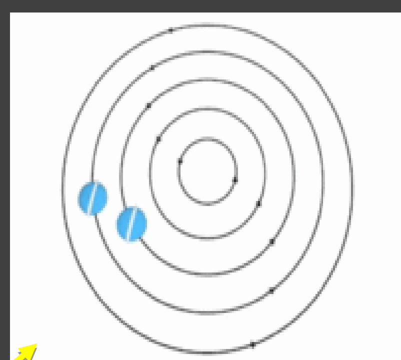
Classical Vorticity: $\vec{\omega} \equiv \frac{1}{2} \vec{\nabla} \times \vec{v}$

Rigid-body-like Vortex

$v \propto r$

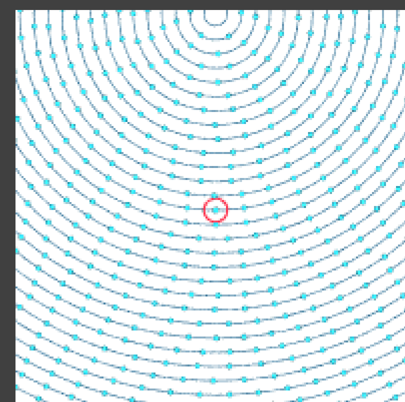


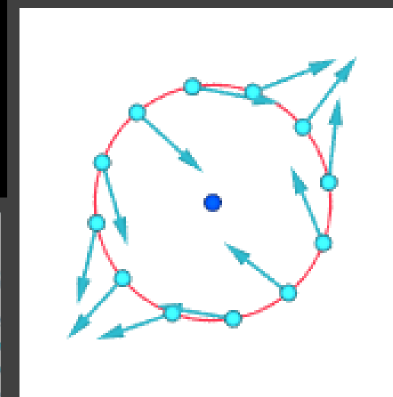


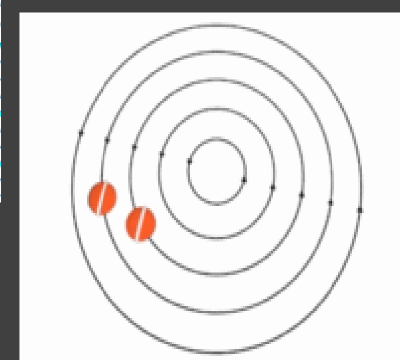


Irrotational vortex

$v \propto 1/r$

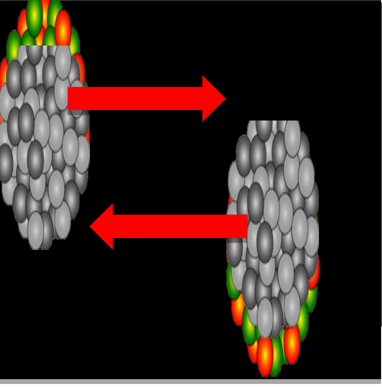






Like the moon, always the same side toward Earth

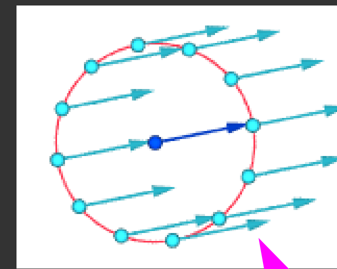
Notice the rotation, or lack thereof, in the fluid elements

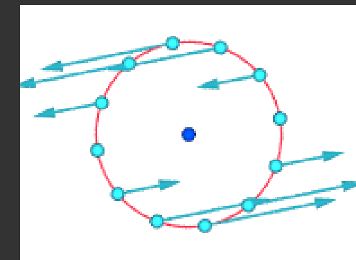


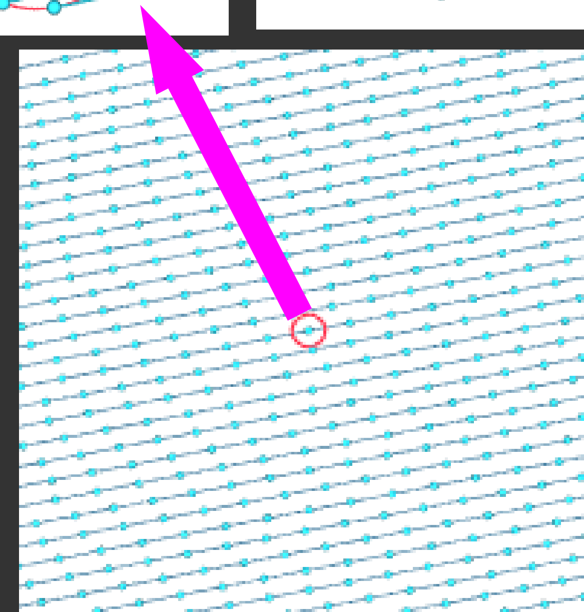
HIC Vorticity formation

In collision c.m. frame

Local fluid cell frame



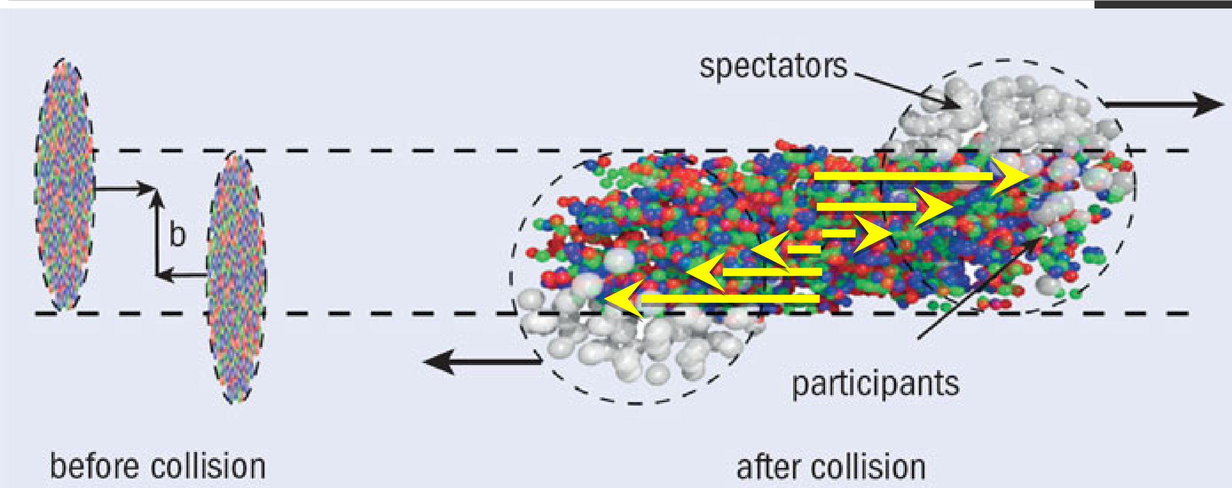




Localized vortex generation via baryon stopping

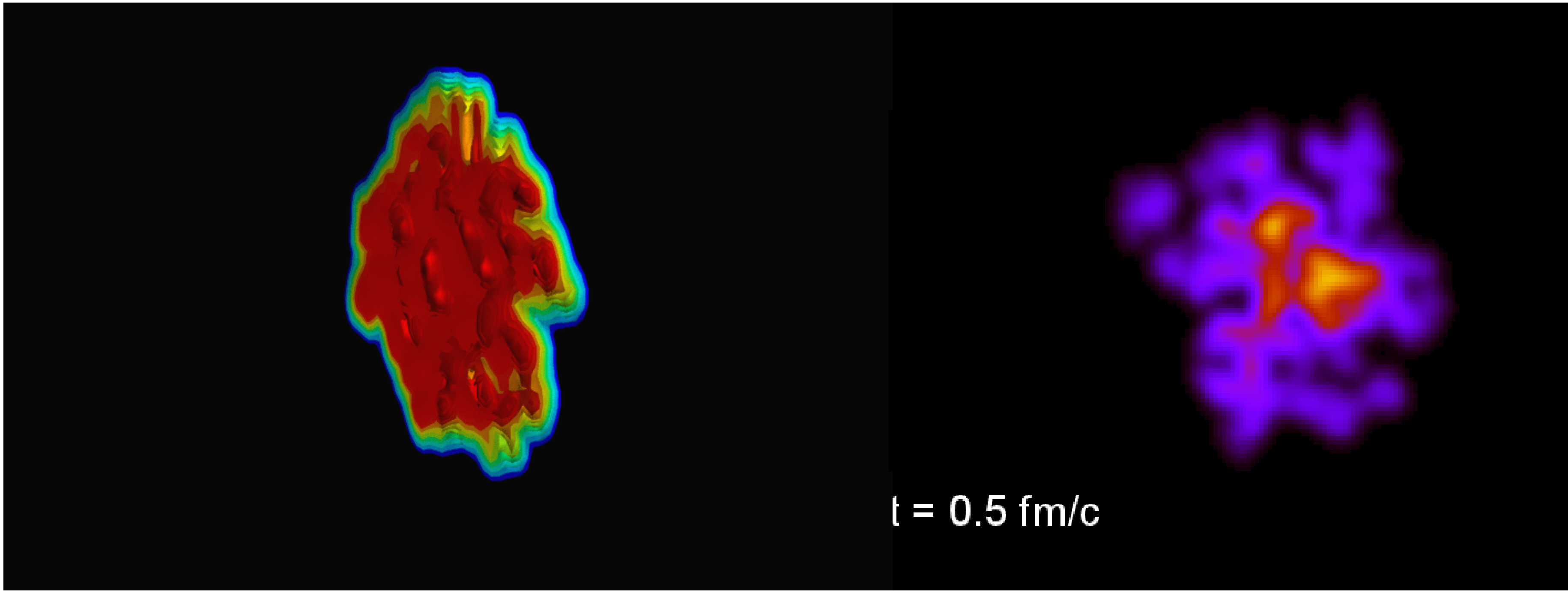
Viscosity dissipates vorticity to fluid at larger scale

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



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

Hydrodynamic evolution



movies by Bjorn Schenke

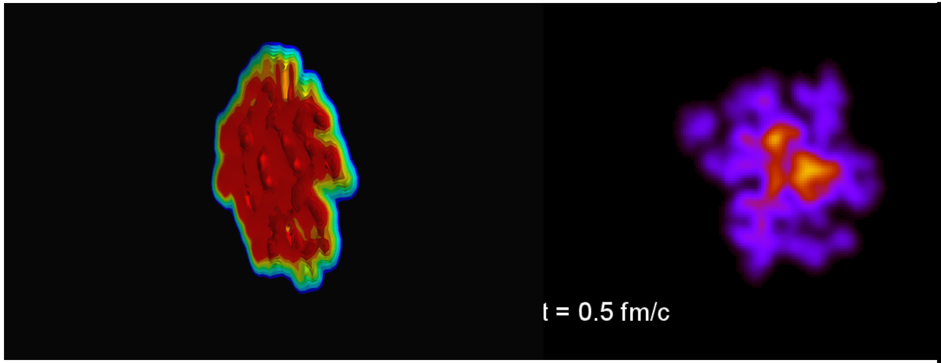
From a (lumpy) initial state, solve hydro equations:

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

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

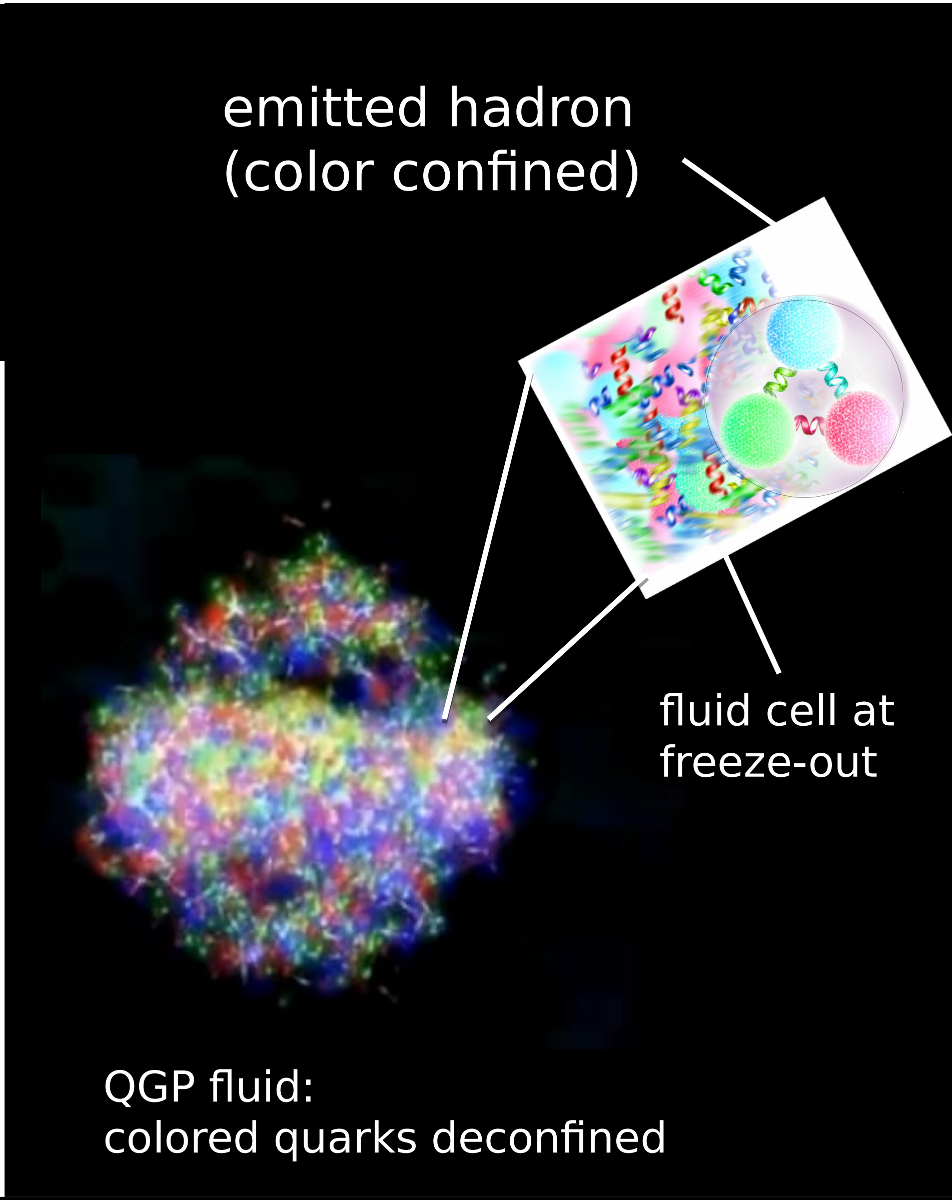
& many more terms...

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



Theory Background

PRL 94, 102301 (2005) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2005

Globally Polarized Quark-Gluon Plasma in Noncentral $A + A$ Collisions

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]

[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*

[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

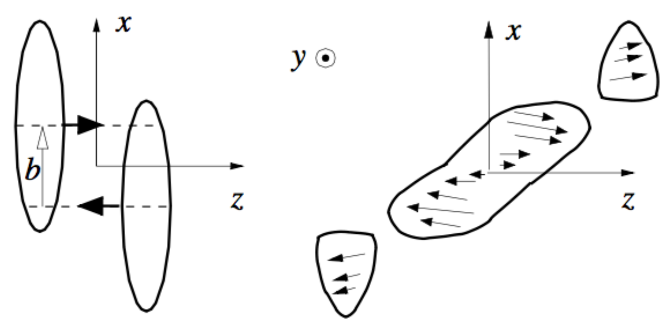
(Received 25 October 2004; published 14 March 2005)

Produced partons have a large local relative orbital angular momentum along the direction opposite to the reaction plane in the early stage of noncentral heavy-ion collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark polarization will lead to many observable consequences, such as left-right asymmetry of hadron spectra and global transverse polarization of thermal photons, dileptons, and hadrons. Hadrons from the decay of polarized resonances will have an azimuthal asymmetry similar to the elliptic flow. Global hyperon polarization is studied within different hadronization scenarios and can be easily tested.

DOI: 10.1103/PhysRevLett.94.102301 PACS numbers: 25.75.Nq, 13.88.+e, 12.38.Mh

Local OAM (vorticity) transferred to spin degree of freedom of final-state hadrons

(Such transfer is rare – discussed below)



Theory work – broad and incomplete overview

- Voloshin, arxiv:nucl-th/0410089
- Liang and Wang, PRL94 102301 (2005) [errat-*ibid* **96** (2006) 039901
- Liang and Wang PLB629 (2005) 20 (2005)
- Betz, Gyulassy, Torrieri PRC76 044901 (2007)
- Gao et al, PRC**77** 044902 (2008)
- Gao et al, PRL **109** 232301 (2012)
- 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
- Jiang, Lin, and Liao, arxiv:1602.06580

- many others ....

Barnett effect

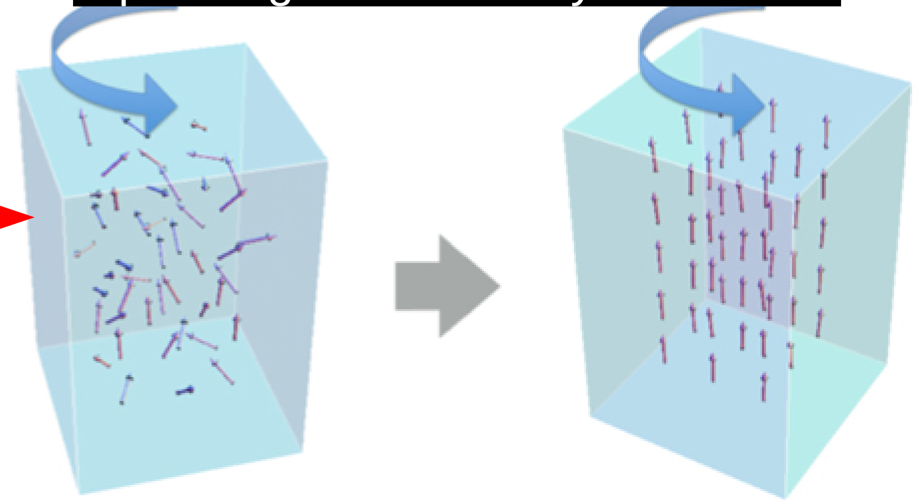
- Nice parallel in **<u>Barnett effect</u>**
- **<u>BE</u>**: uncharged object rotating with angular velocity ω magnetizes

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

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

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

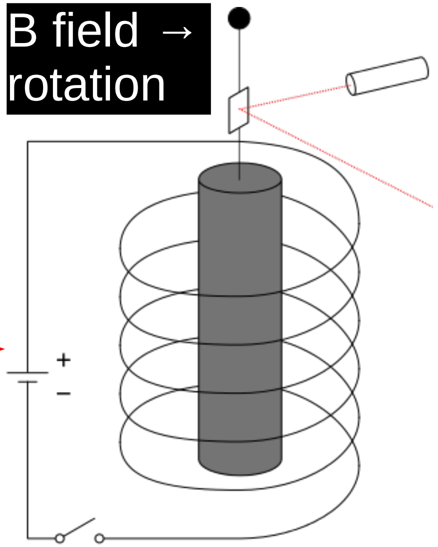
Spins align with vorticity → B field



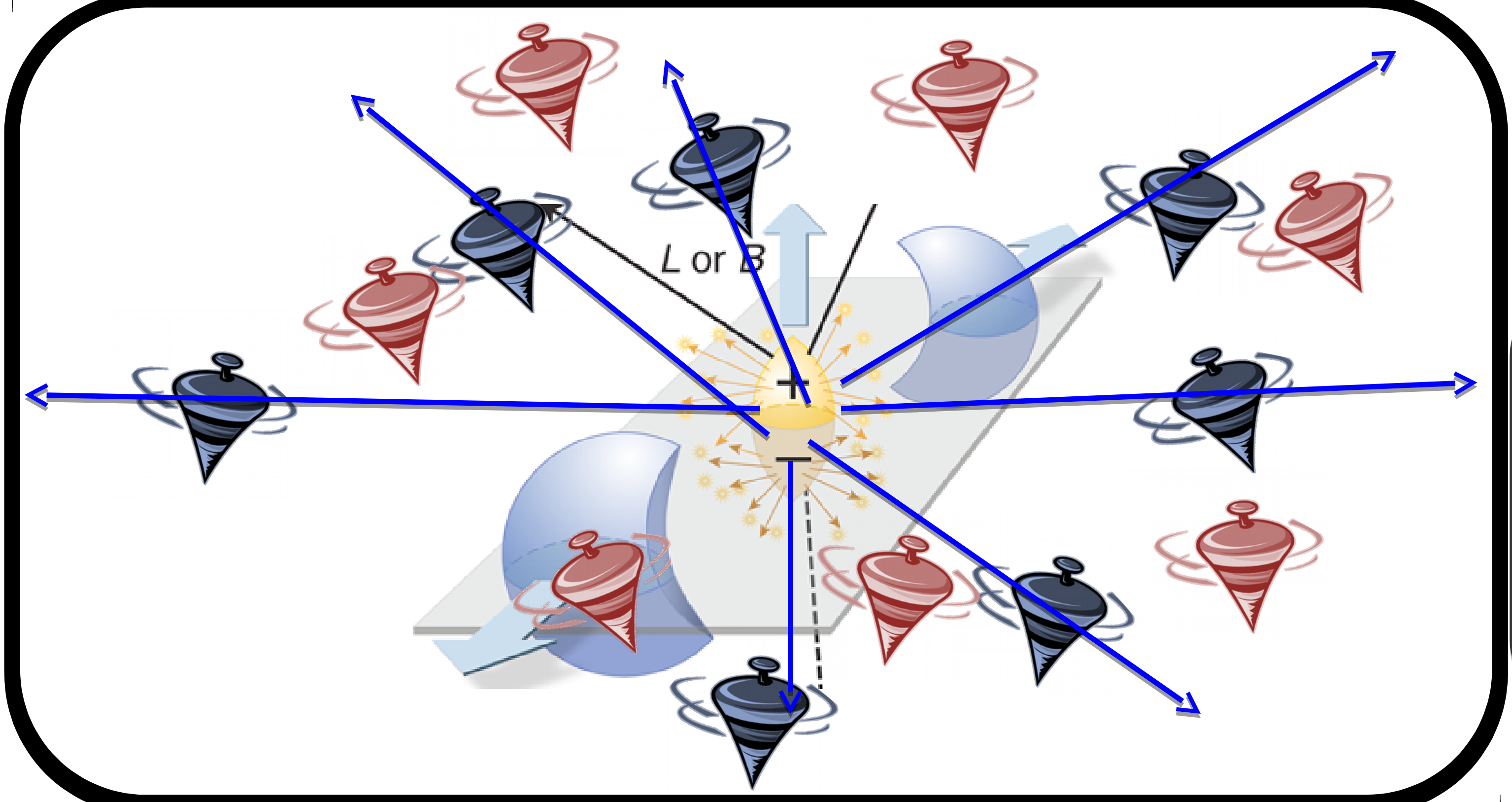
- **<u>Einstein-de Haas effect</u>**, (only published experiment of Einstein!)
- **<u>EdHE</u>**:Magnetic field induces rotation

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

B field → rotation

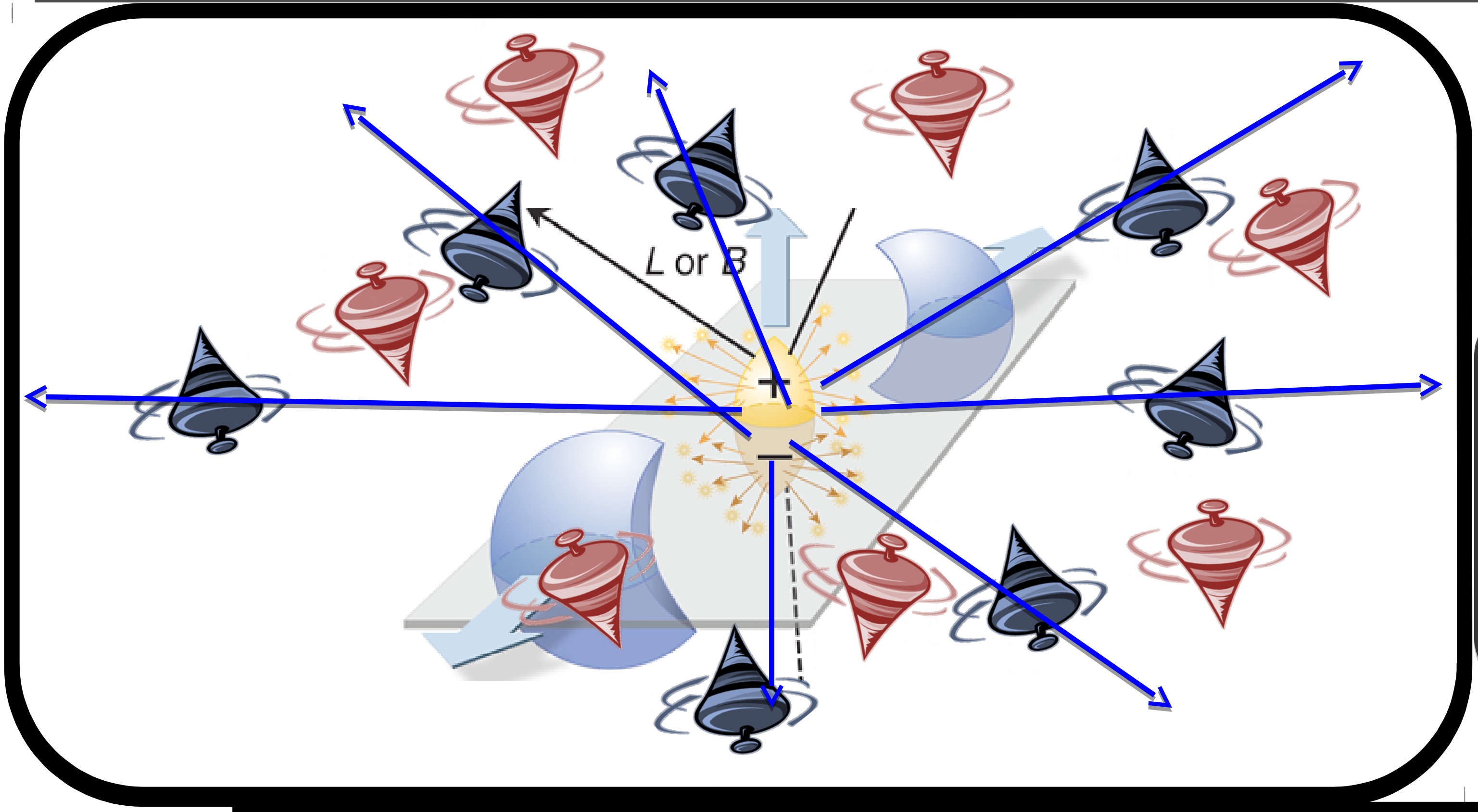


Vorticity → Global Polarization



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

Magnetic field → Global Polarization

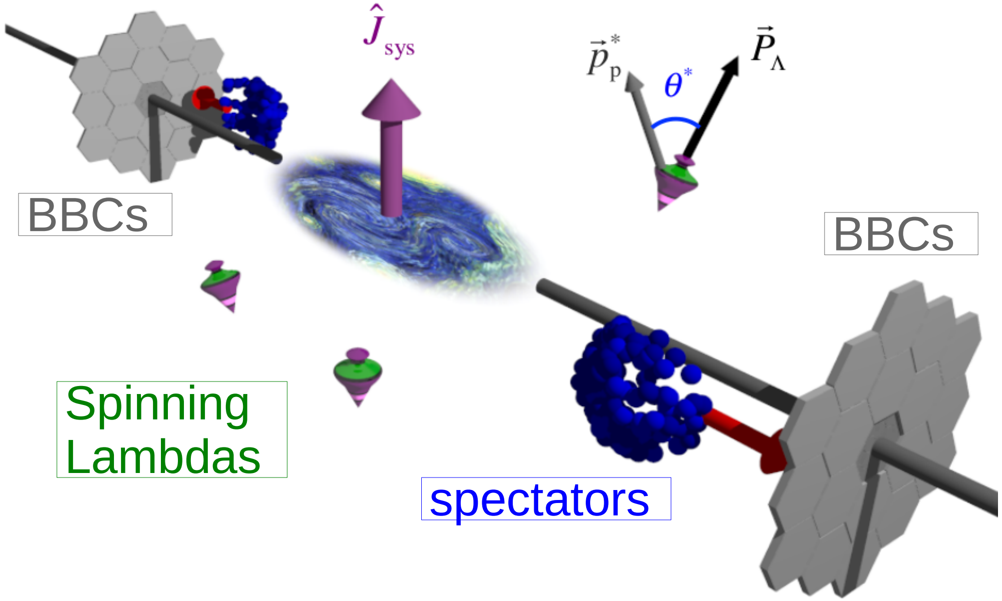


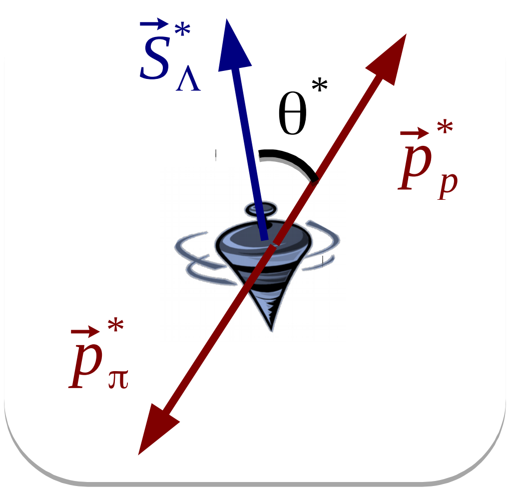
Both may contribute

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

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:

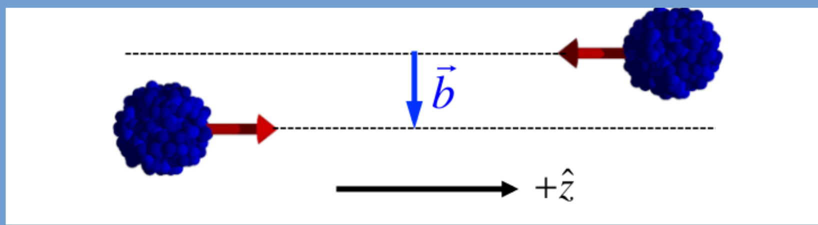
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\,\vec{P}\cdot\hat{p}_p^*\right) = \frac{1}{4\pi}\left(1+\alpha\,P\cos\theta^*\right)$$

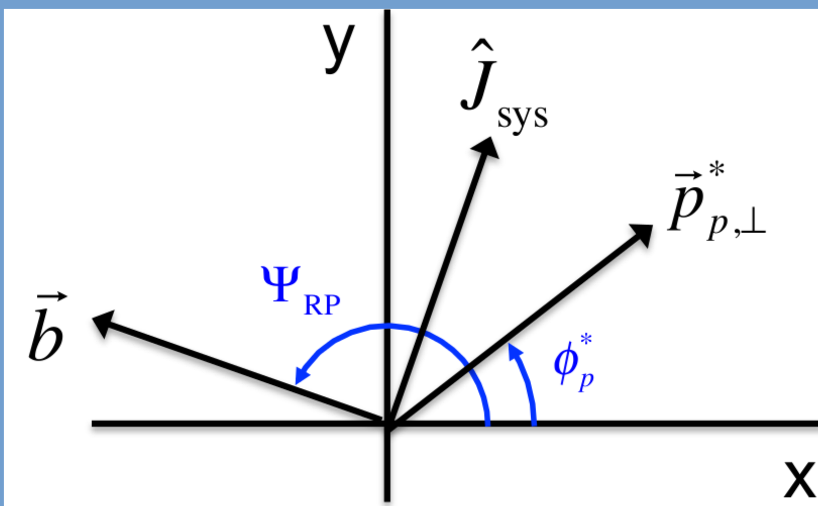
$\alpha = 0.642 \pm 0.013$ [measured]

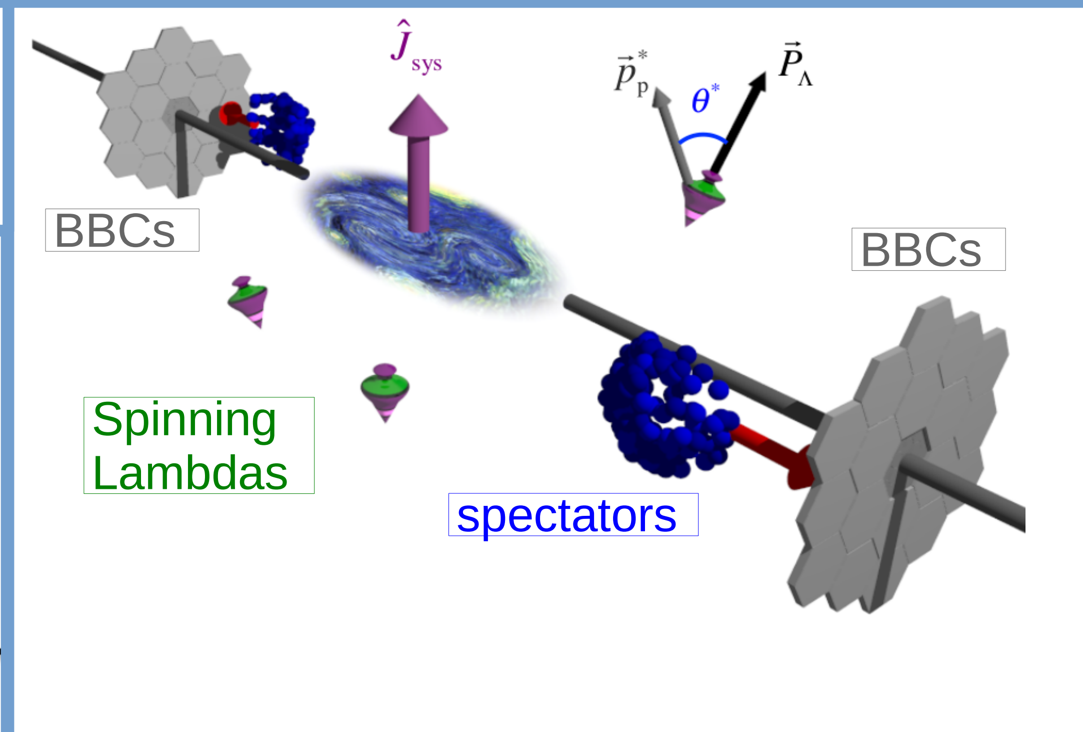
$\hat{p}_p^*$ is the daughter proton momentum direction *in the Λ frame* (note that this is opposite for $\overline{\Lambda}$)

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

How to quantify the effect (II)







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

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

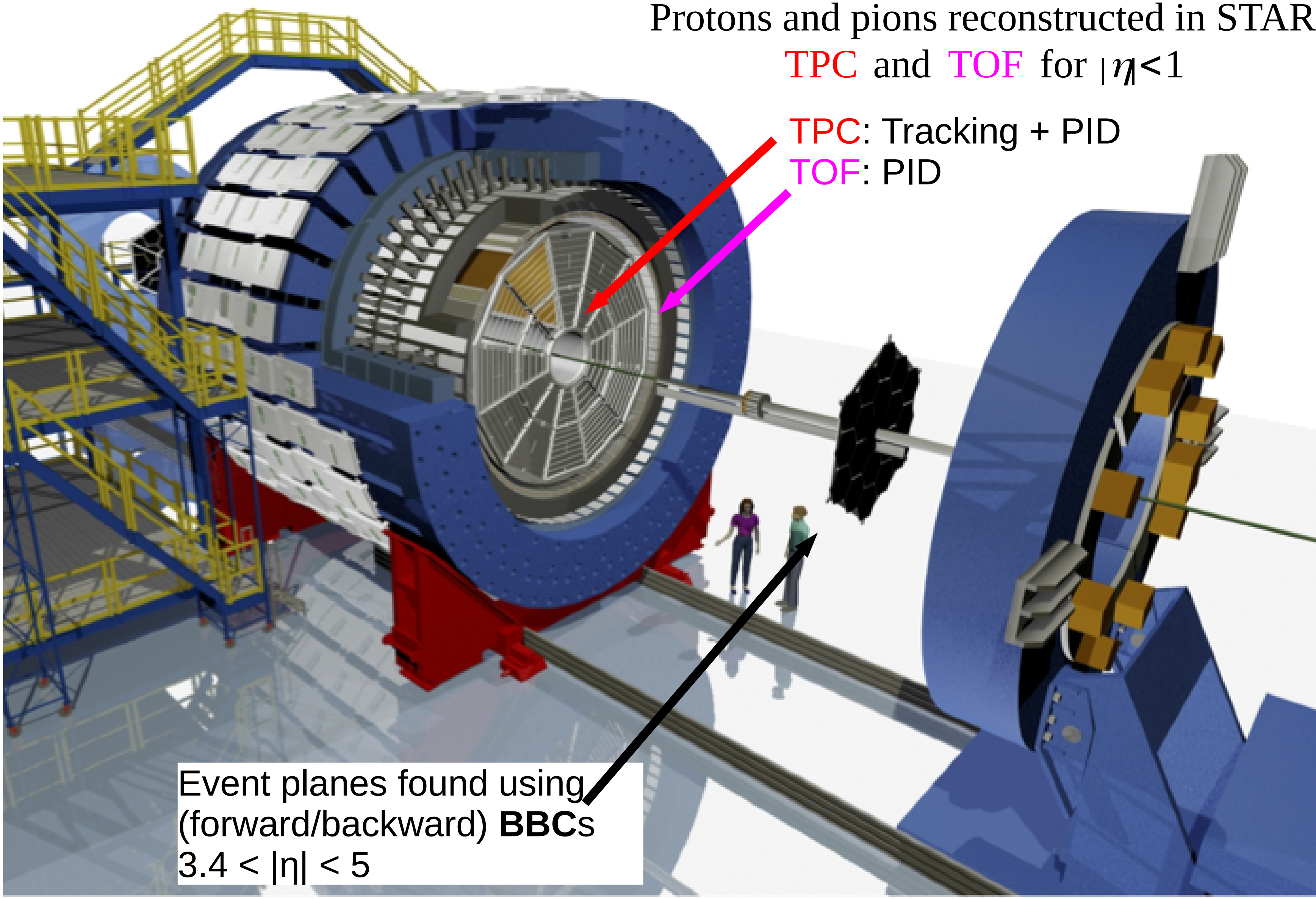
$P_{AVE} = \frac{8}{\pi\alpha} \frac{\langle \sin(\phi_{\hat{b}} - \phi^*_p) \rangle}{R^{(1)}_{EP}}$ ** where the average is performed over events and Λs

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

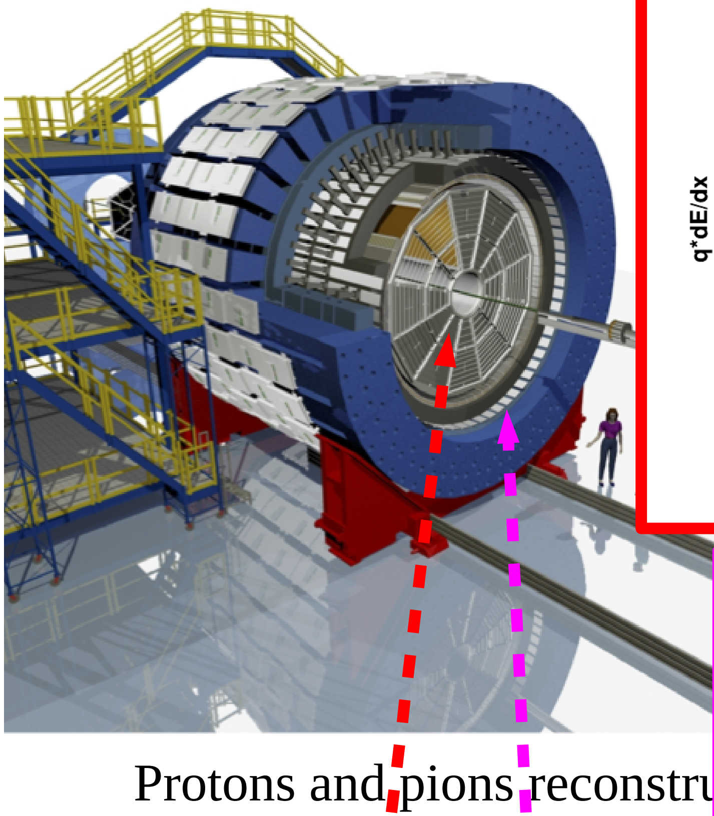
** if $v_1 \cdot y > 0$ in BBCs $\phi_{\hat{b}} = \Psi_{EP}$, if $v_1 \cdot y < 0$ in BBCs $\phi_{\hat{b}} = \Psi_{EP} + \pi$

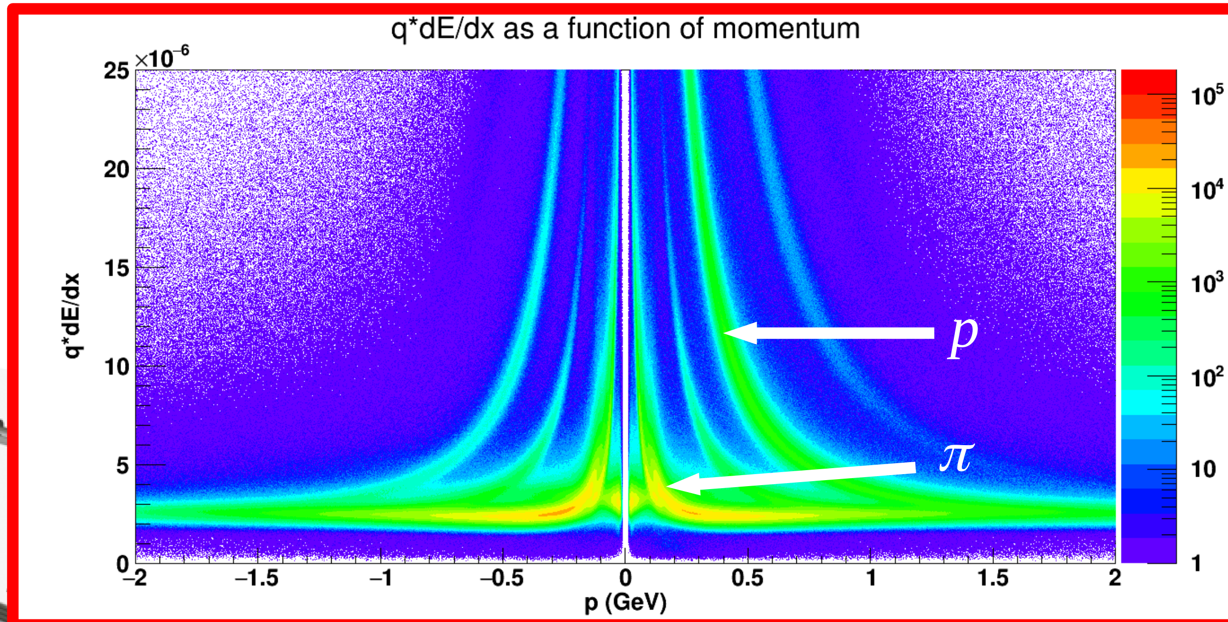
Ingredients: Using STAR

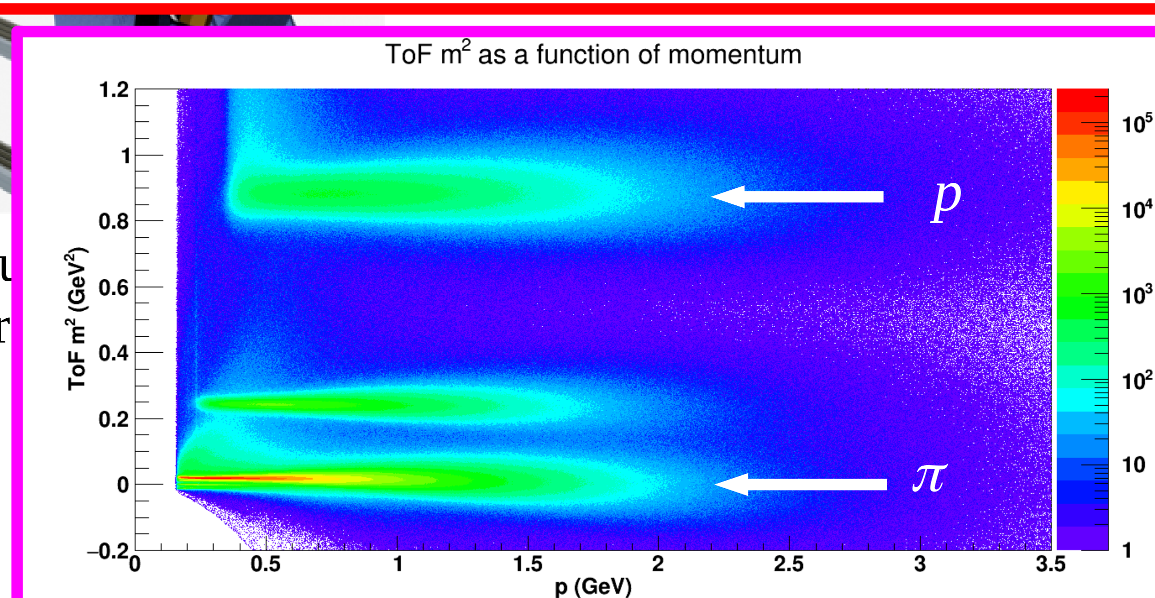
Protons and pions reconstructed in STAR TPC and TOF for $|\eta|<1$



Ingredients: Using STAR (PID)



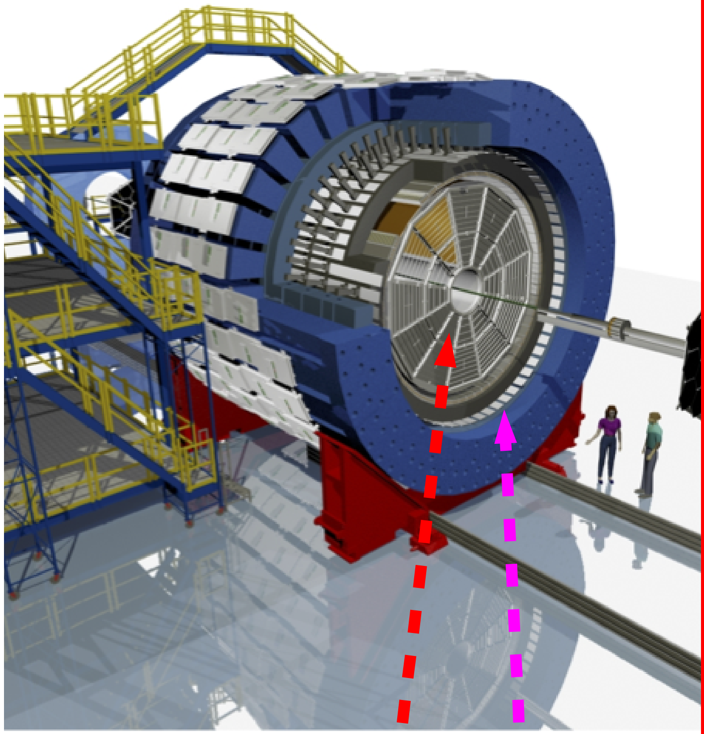




Protons and pions reconstru
TPC and TOF for

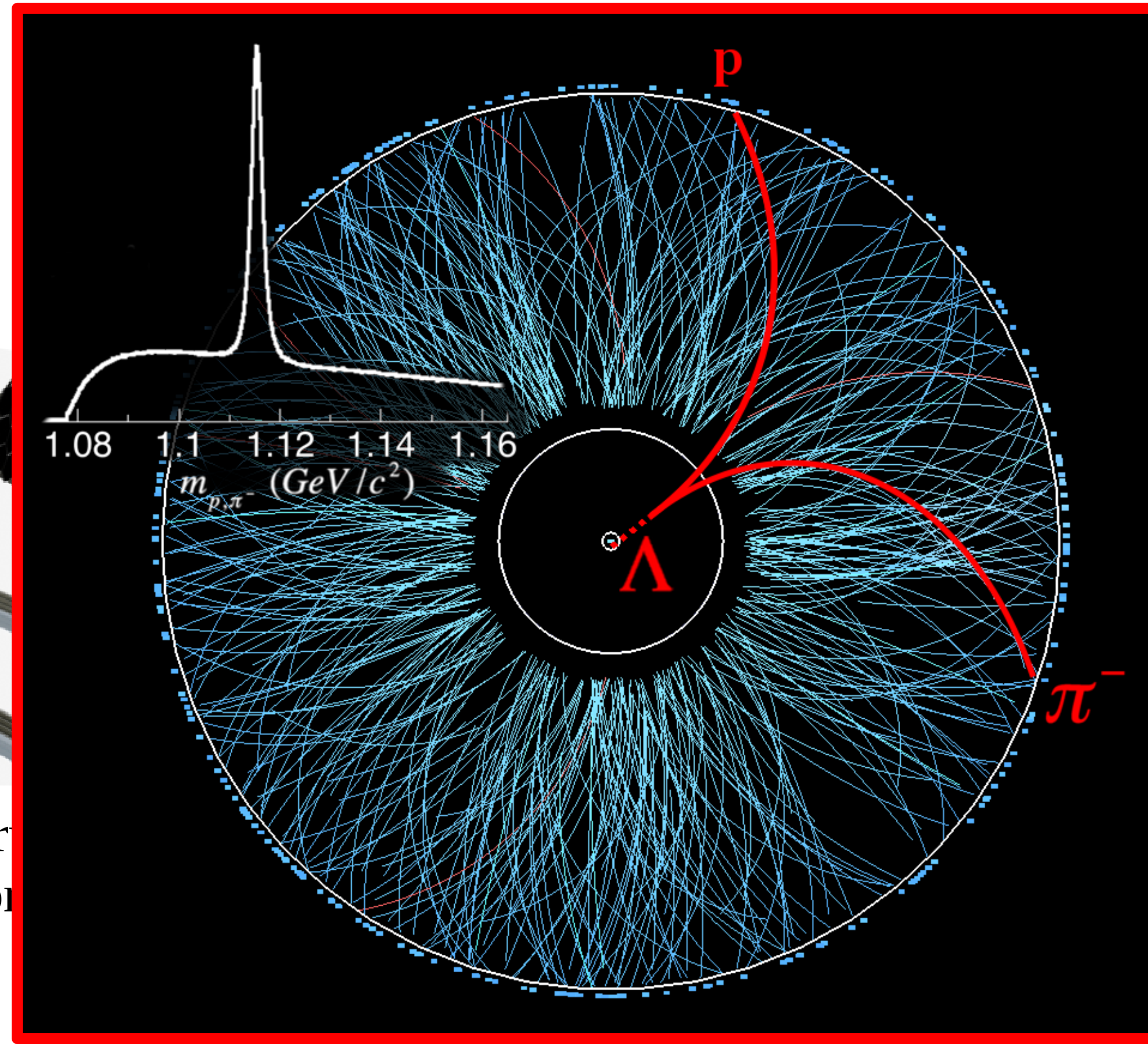
TPC: Tracking + PID
TOF: PID

Ingredients: Using STAR (tracking)



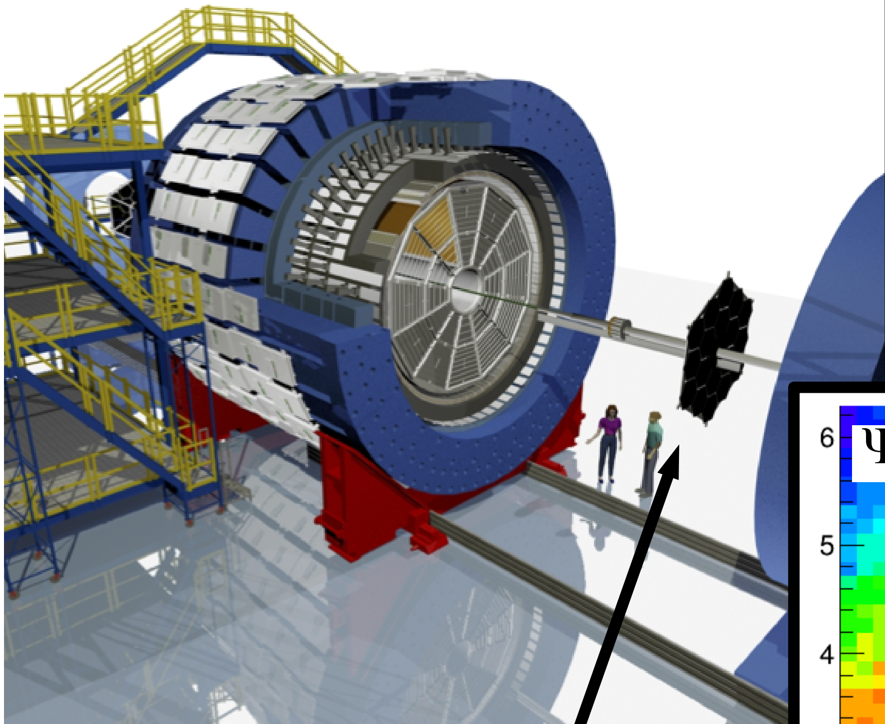
Protons and pions reconstr
TPC and TOF fo

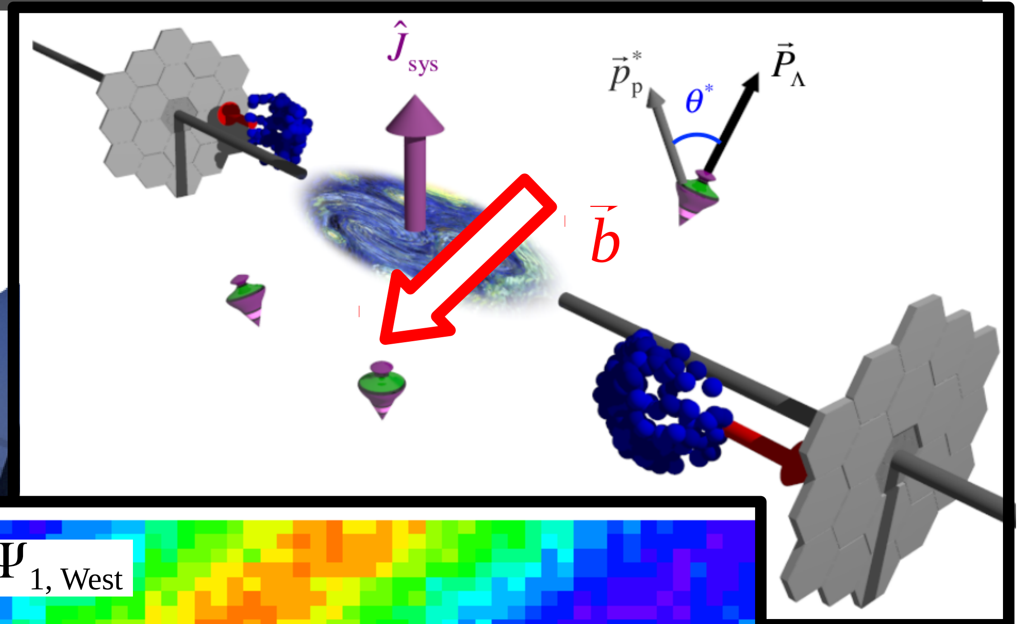
TPC: Tracking + PID
TOF: PID

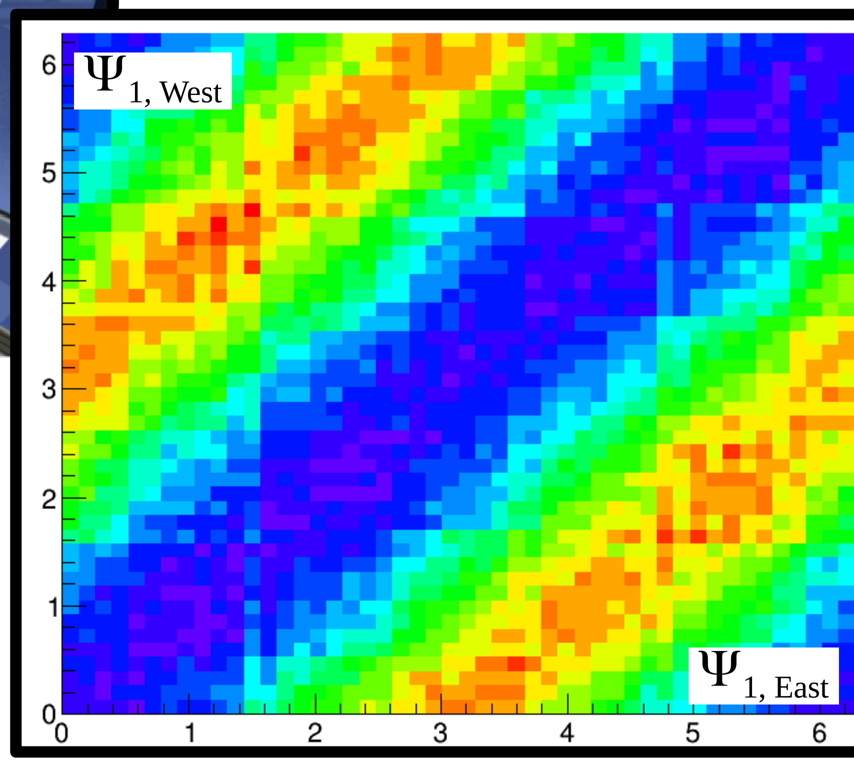


Lambdas are found topologically using identified protons and pions

Ingredients: Using STAR (Event Plane)



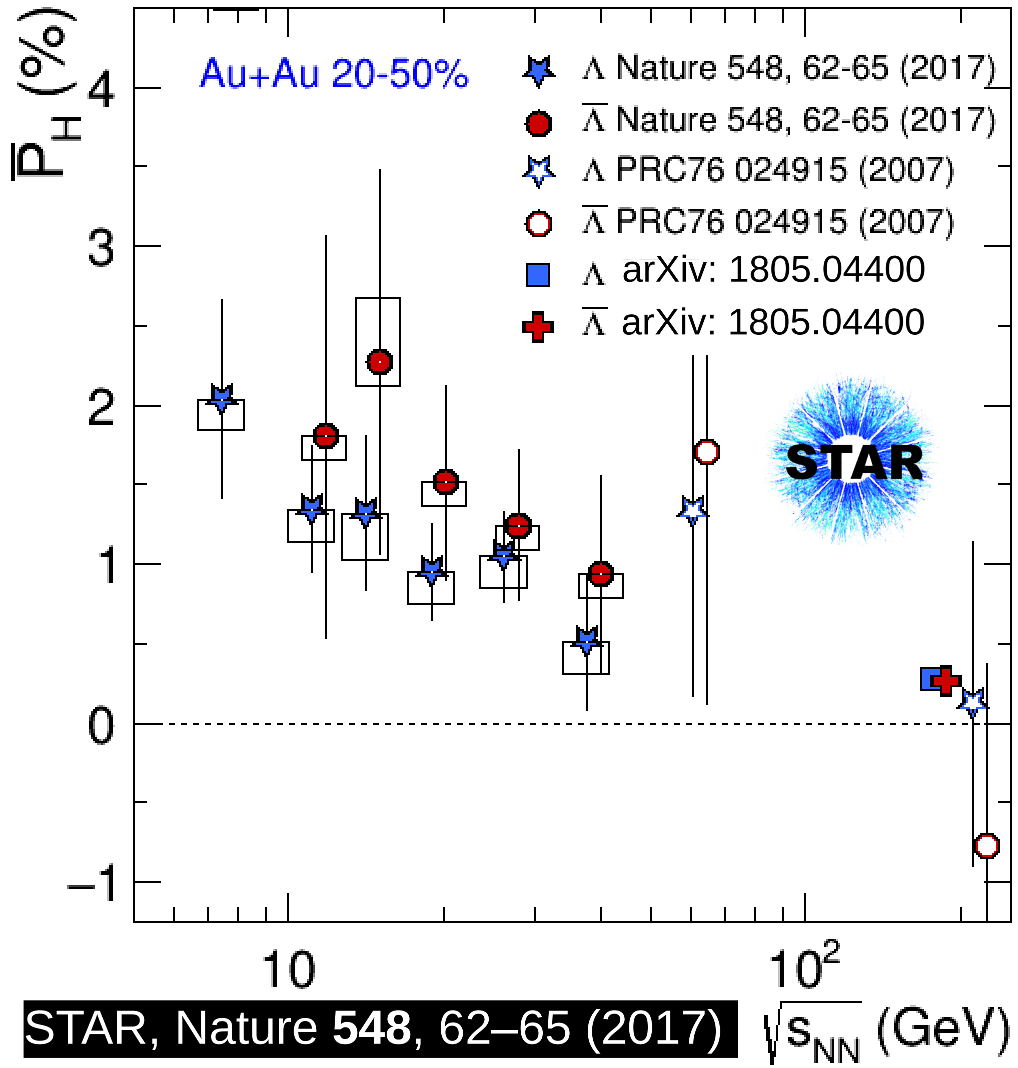




Event planes found using (forward/backward) BBCs
3.4 < |η| < 5

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

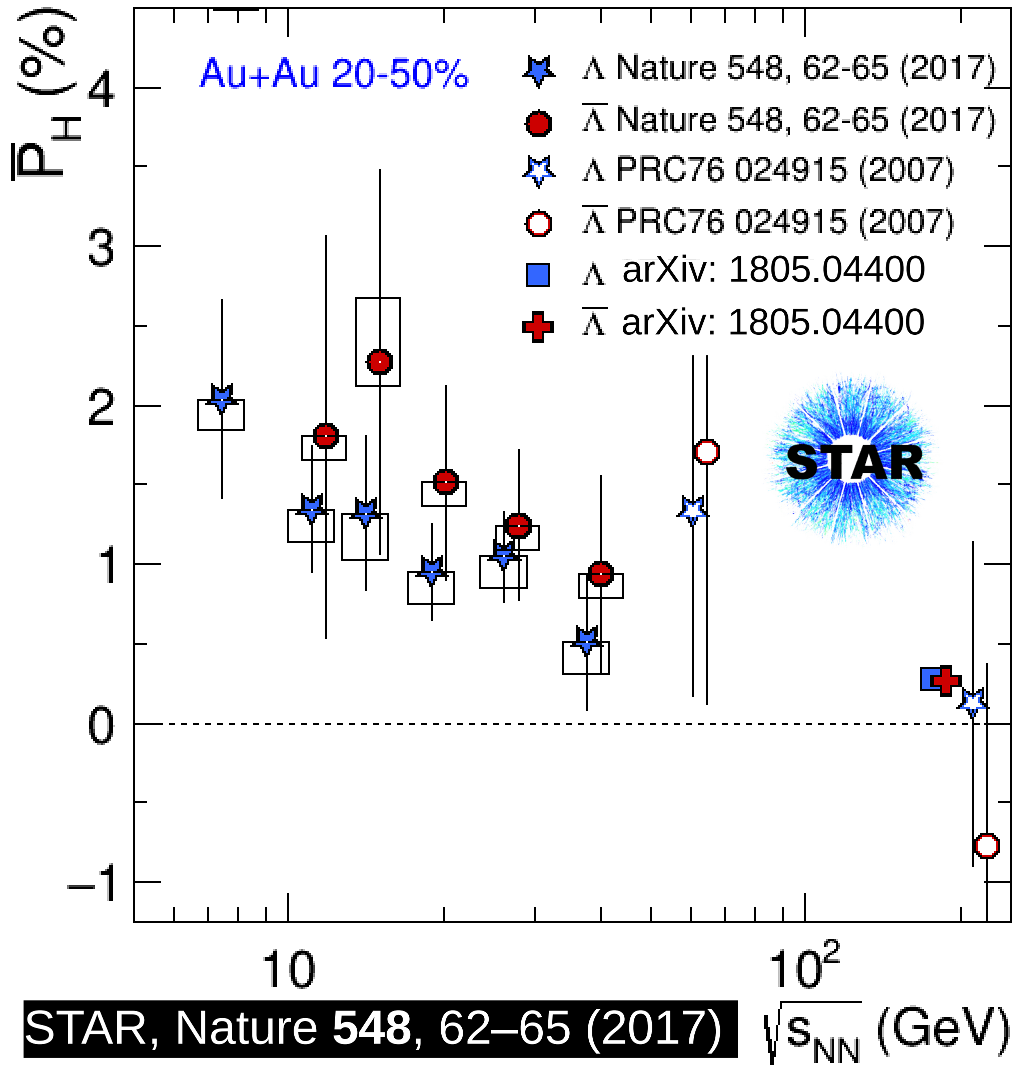
- Measured Lambda and Anti-

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

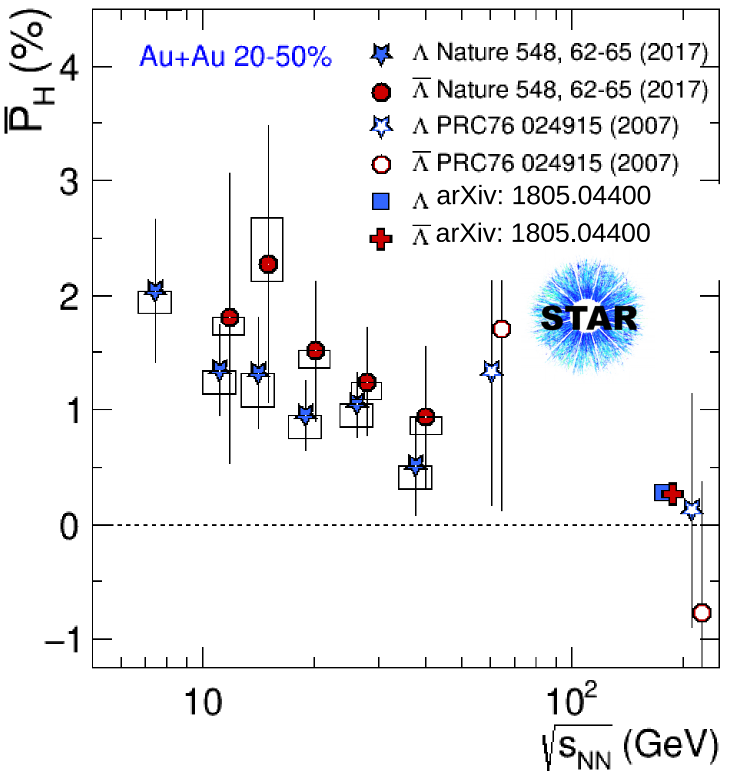
- $\overline{P}_H(\bar{\Lambda}) > \overline{P}_H(\Lambda)$ would imply magnetic coupling



STAR, Nature **548**, 62–65 (2017)

STAR, arXiv: 1805.04400

Vortical and Magnetic Contributions



STAR, Nature **548**, 62–65 (2017)

STAR, arXiv: 1805.04400

- 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:

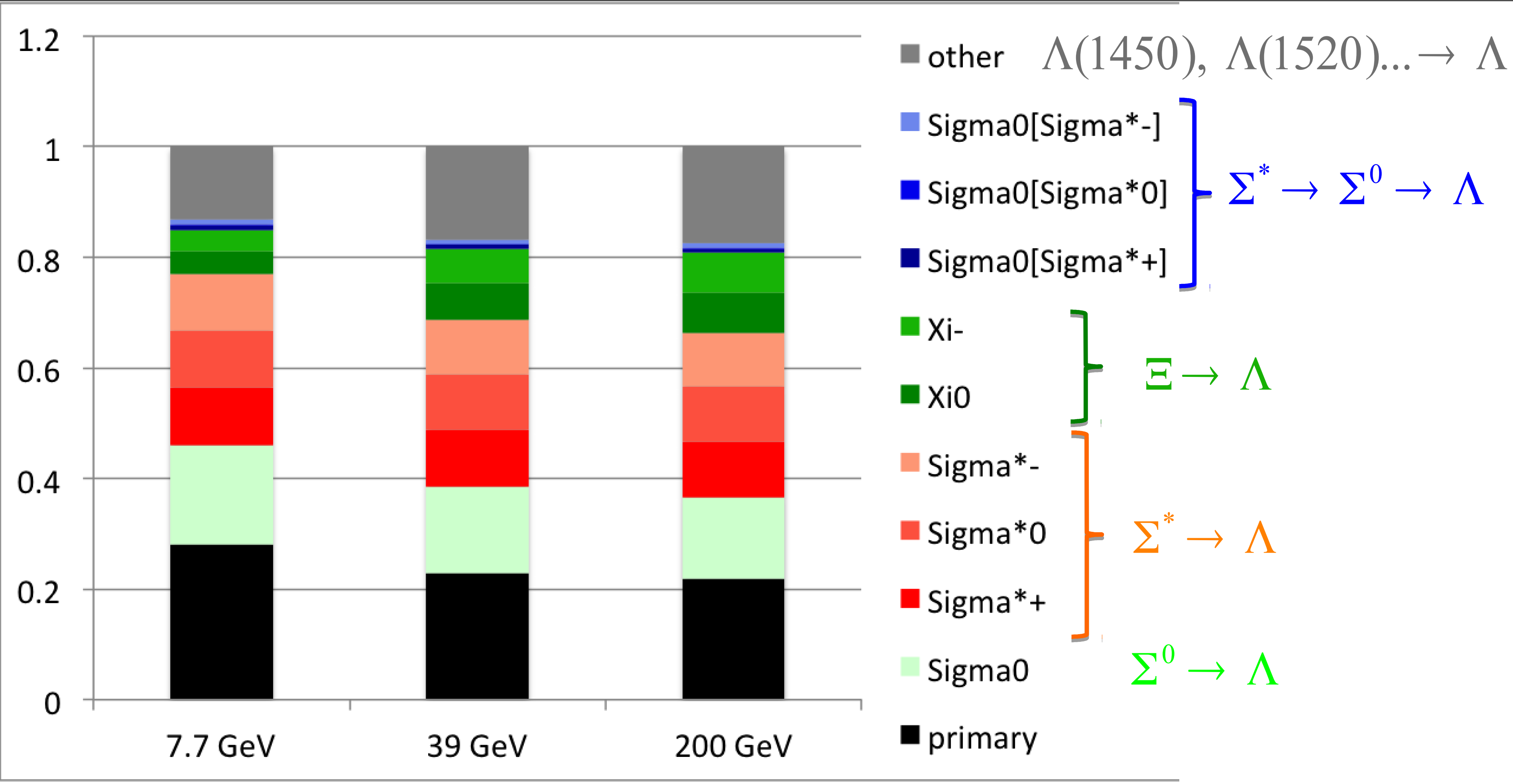
$$\frac{B}{T} = \frac{1}{2\mu_\Lambda}\left(P_{\bar{\Lambda}} - P_\Lambda\right)$$

** $\hbar = k_B = 1$

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



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

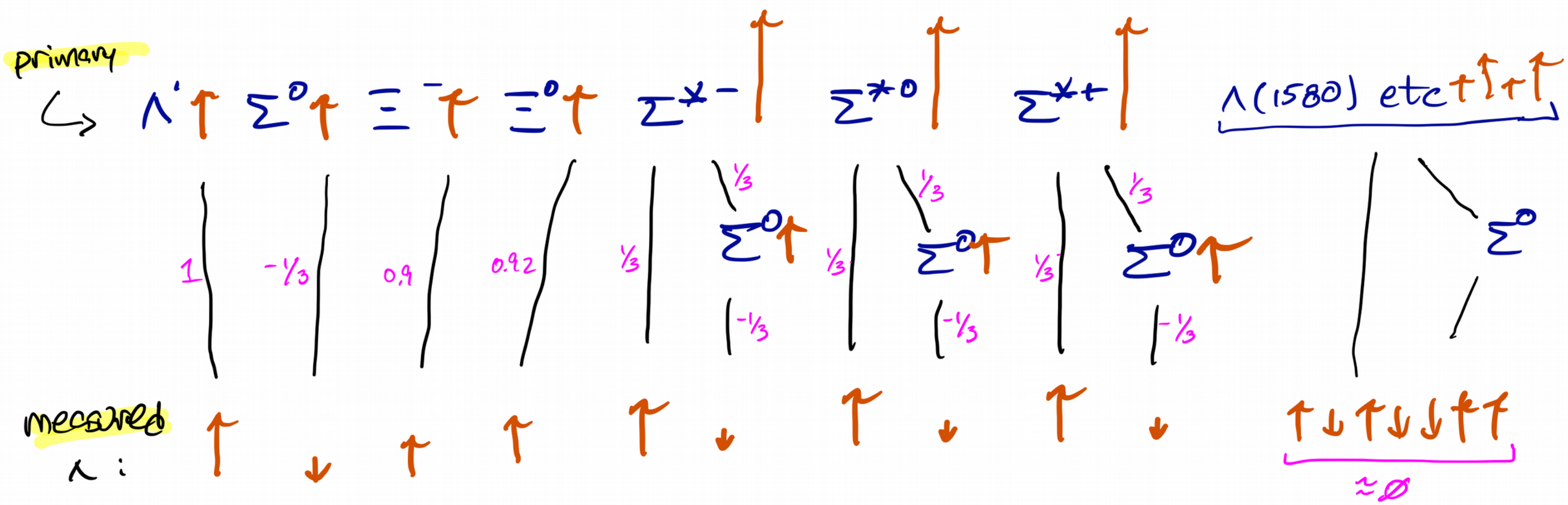
primary

↳ 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
Λ	$1/2^+$	-0.613
Σ^0	$1/2^+$	$+0.79$
Ξ^-	$1/2^+$	-0.651
Ξ^0	$1/2^+$	-1.25

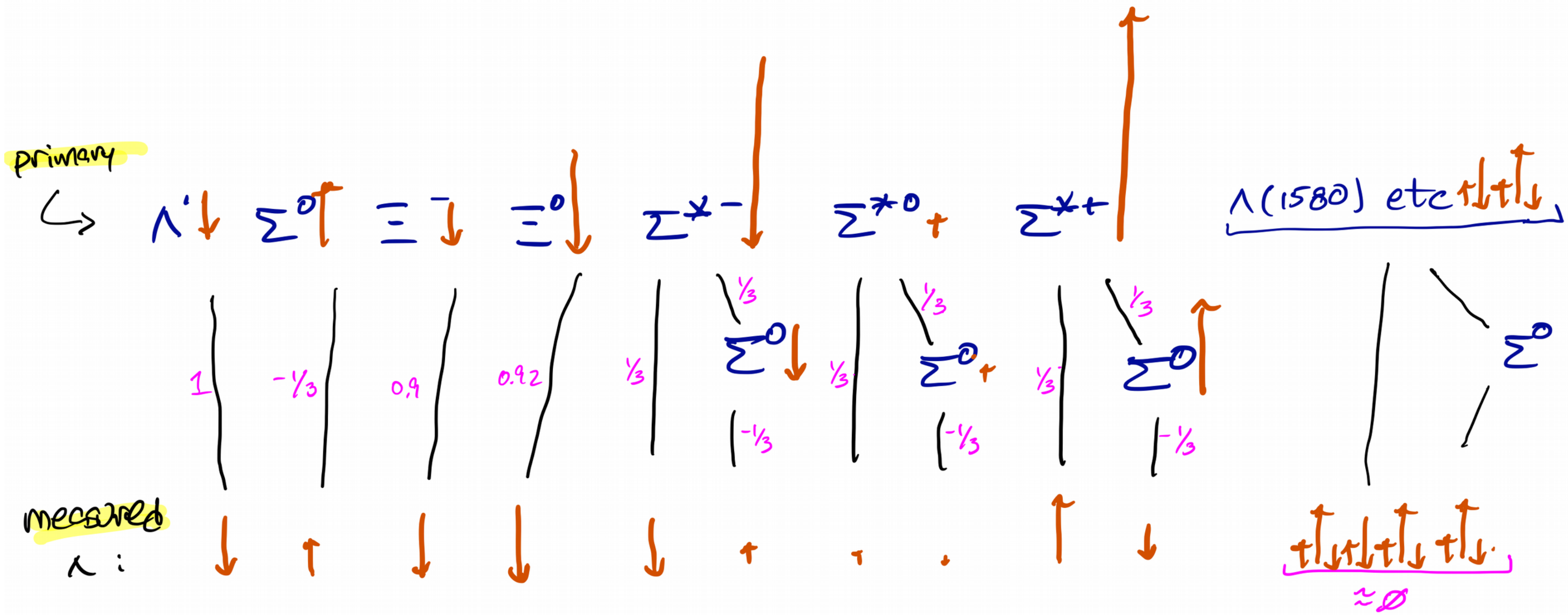
	J^π	μ
Σ^{*-}	$3/2^+$	-2.41
Σ^{*0}	$3/2^+$	$+0.30$
Σ^{*+}	$3/2^+$	$+3.02$

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

Accounting for polarized feeddown

PRIMARY + FEED-DOWN POLARIZATION

MAGNETIC COMPONENT



	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			

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 $R \to \Lambda$
- $C_{\Lambda R}=$ 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)

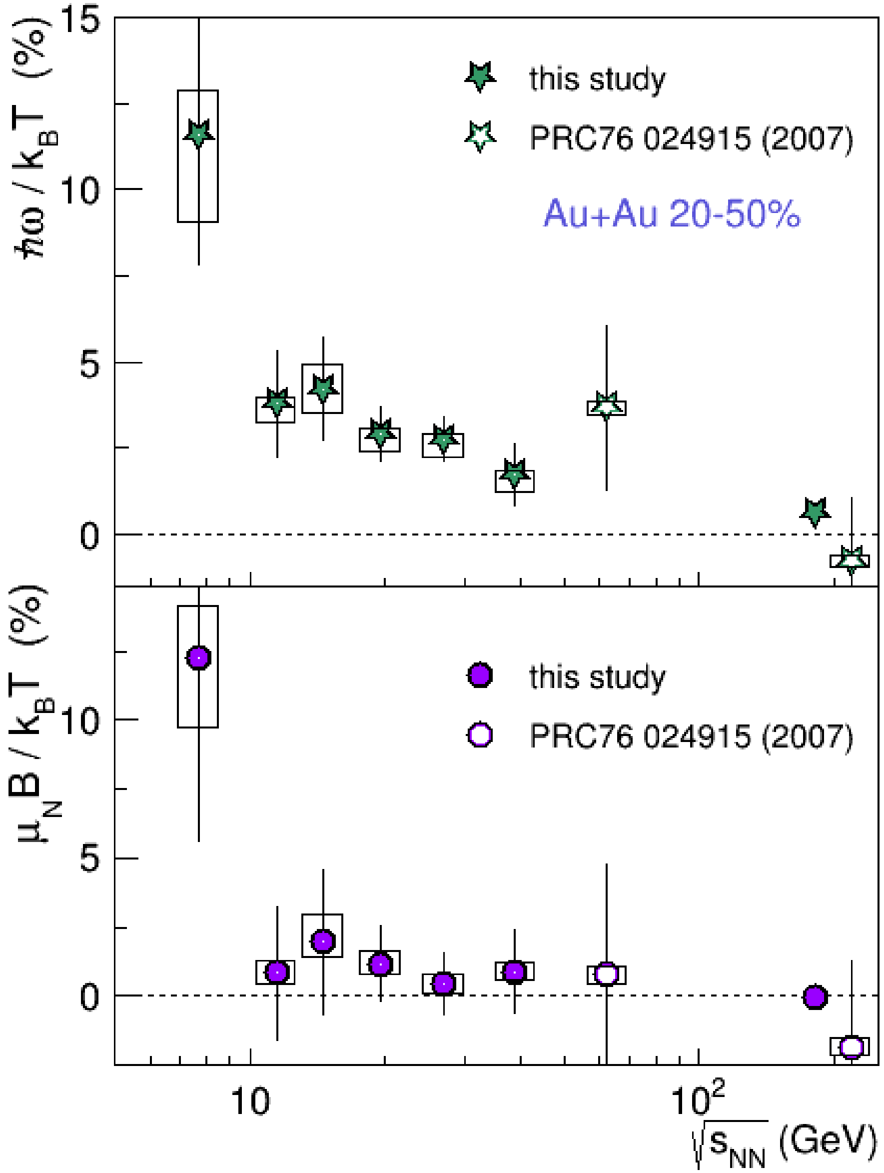
Decay	C
parity-conserving: $1/2^+ \to 1/2^+ \; 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+ \; 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+ \; 0^-$	$1/3$
parity-conserving: $3/2^- \to 1/2^+ \; 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$	-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
  - $P_{\Lambda_{primary}} = \frac{\omega}{2T} \sim 5\%$
- 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

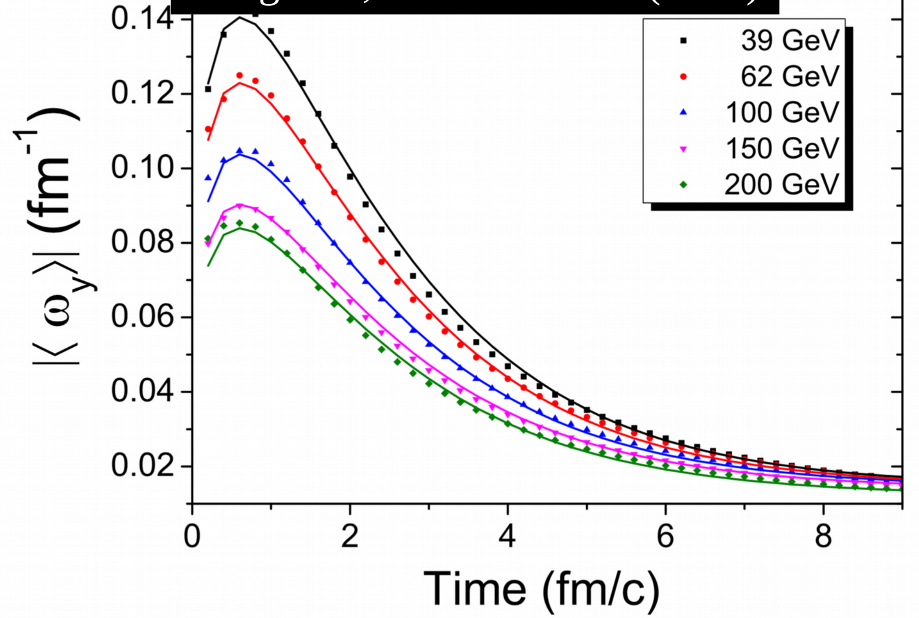
- Thermal vorticity:

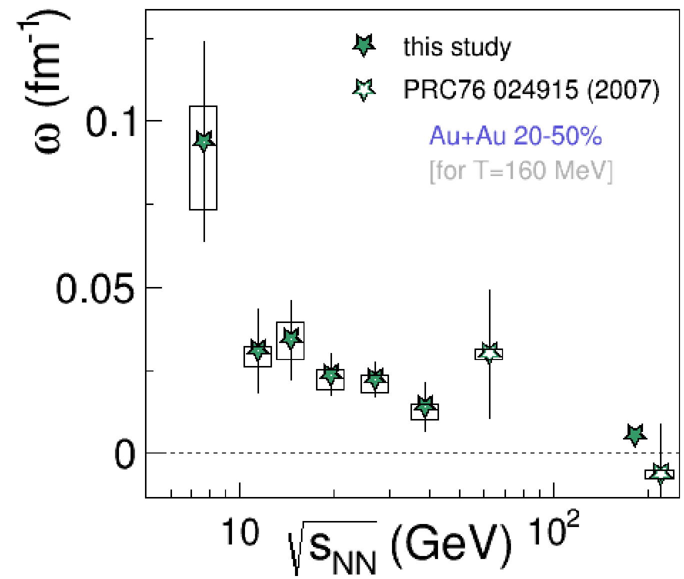
$$\frac{\omega}{T} \approx 2 - 10\,\%$$

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

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

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





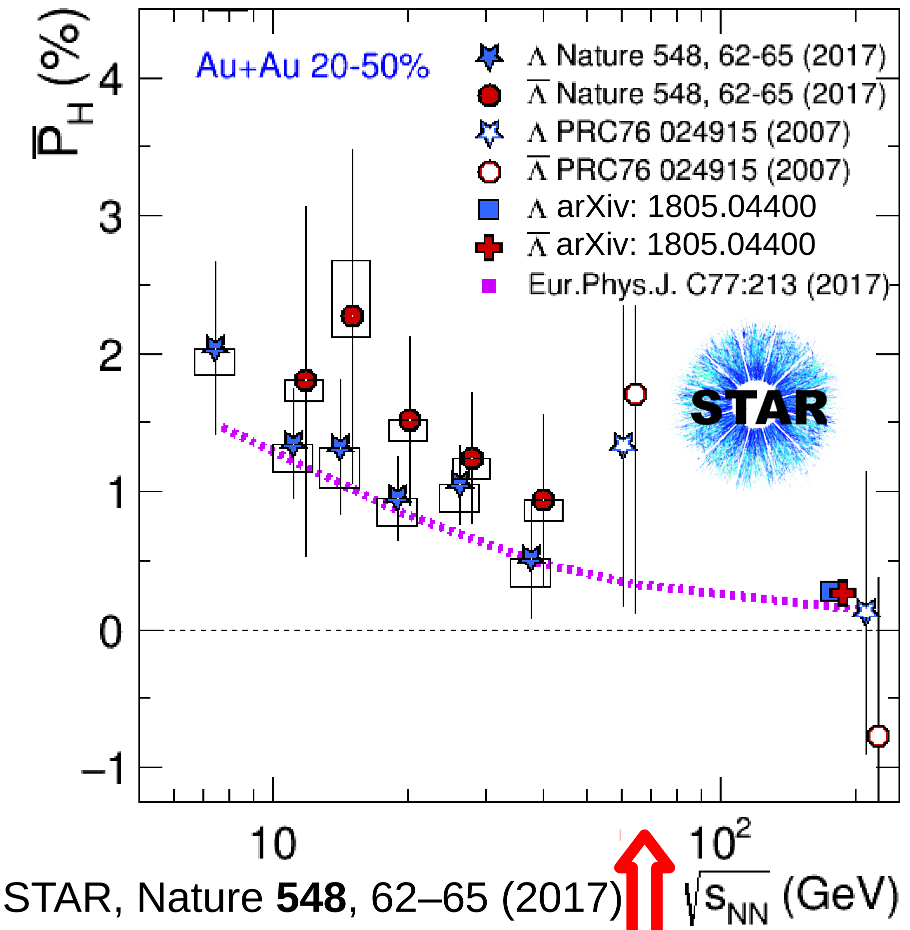
Csernai et al, PRC**90** 021904(R) (2014)

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.

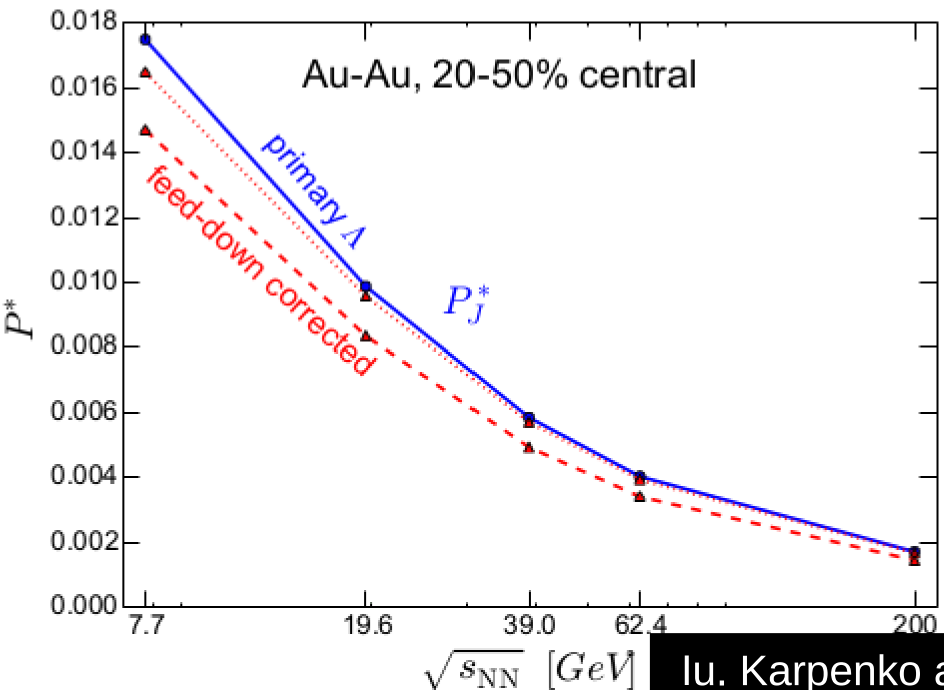
t (fm/c)	Vorticity (classical) (c/fm)	Thermal vorticity (relativistic) (1)
0.17	0.1345	0.0847
1.02	0.1238	0.0975
1.86	0.1079	0.0846
2.71	0.0924	0.0886
3.56	0.0773	0.0739

Polarization ~ theory expectation (I)

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



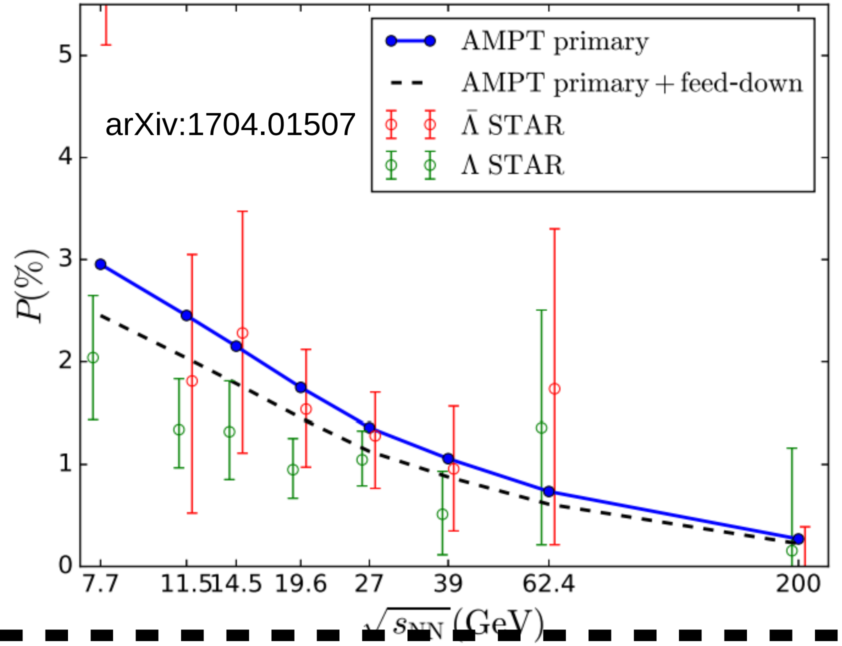
STAR, Nature **548**, 62–65 (2017)



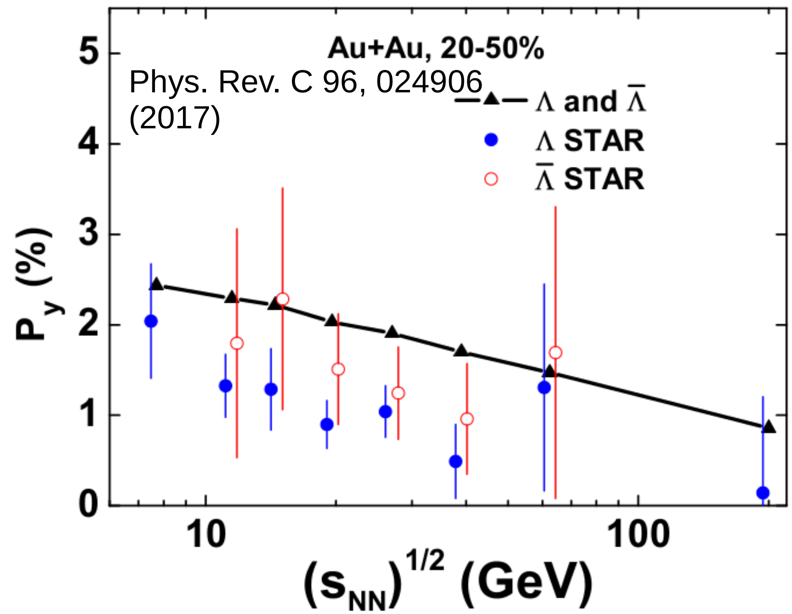
Compare "feed-down corrected" curve in dashed magenta line

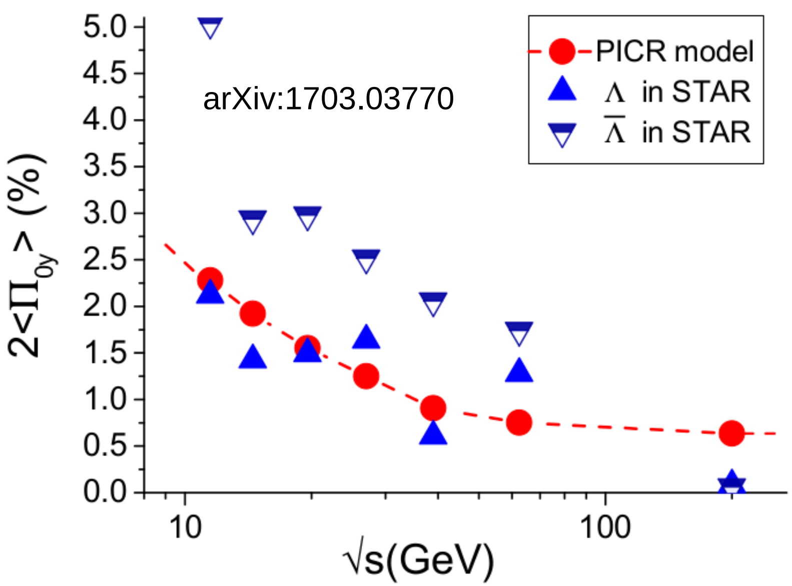
Iu. Karpenko and F. Becattini Eur. Phys. J. C (2017) 77: 213

Polarization ~ theory expectation (II)

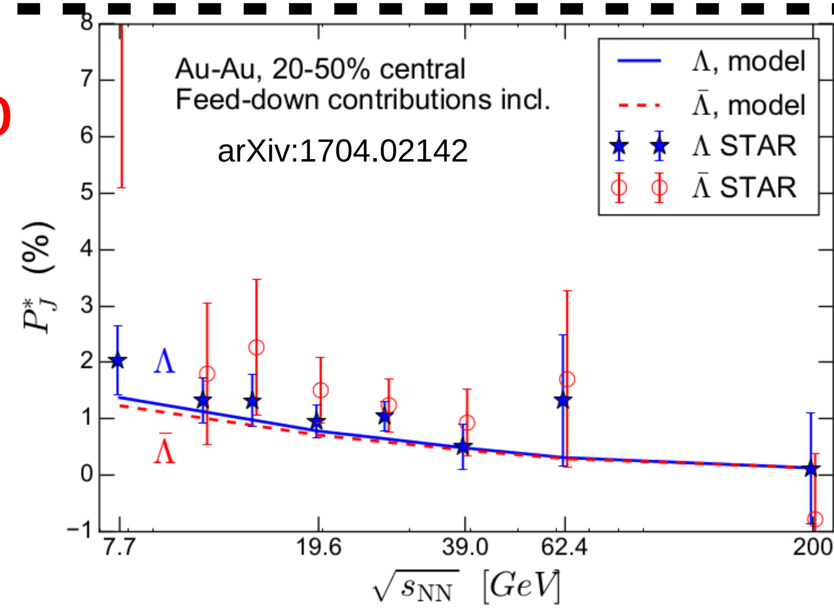


AMPT





Hydro

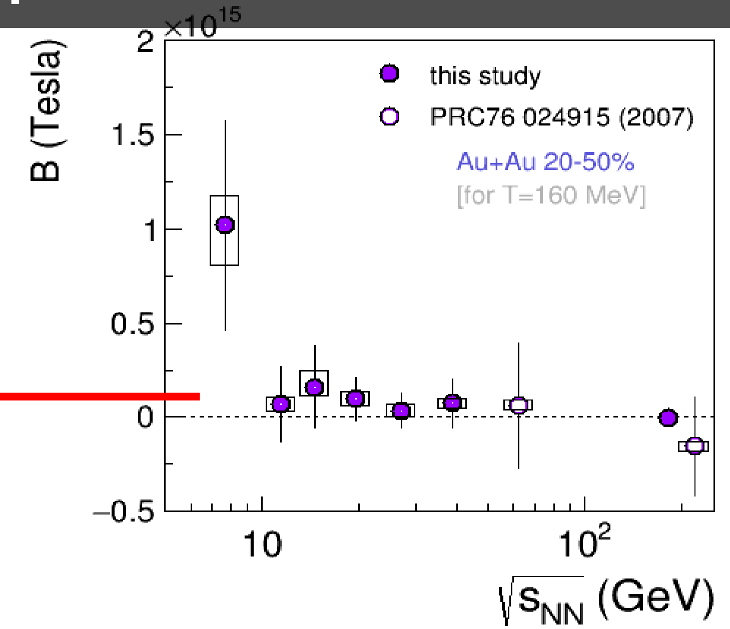


B-Field ~ theory expectation

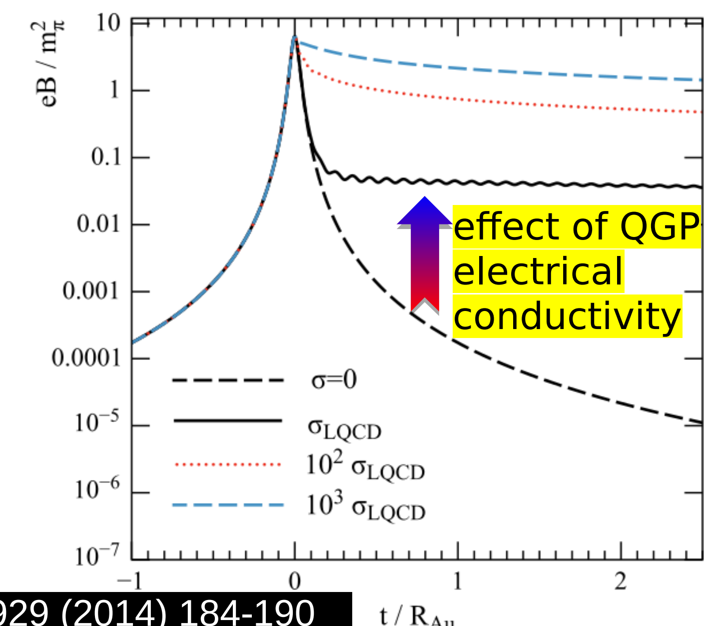
Magnetic field:

- Expected sign

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

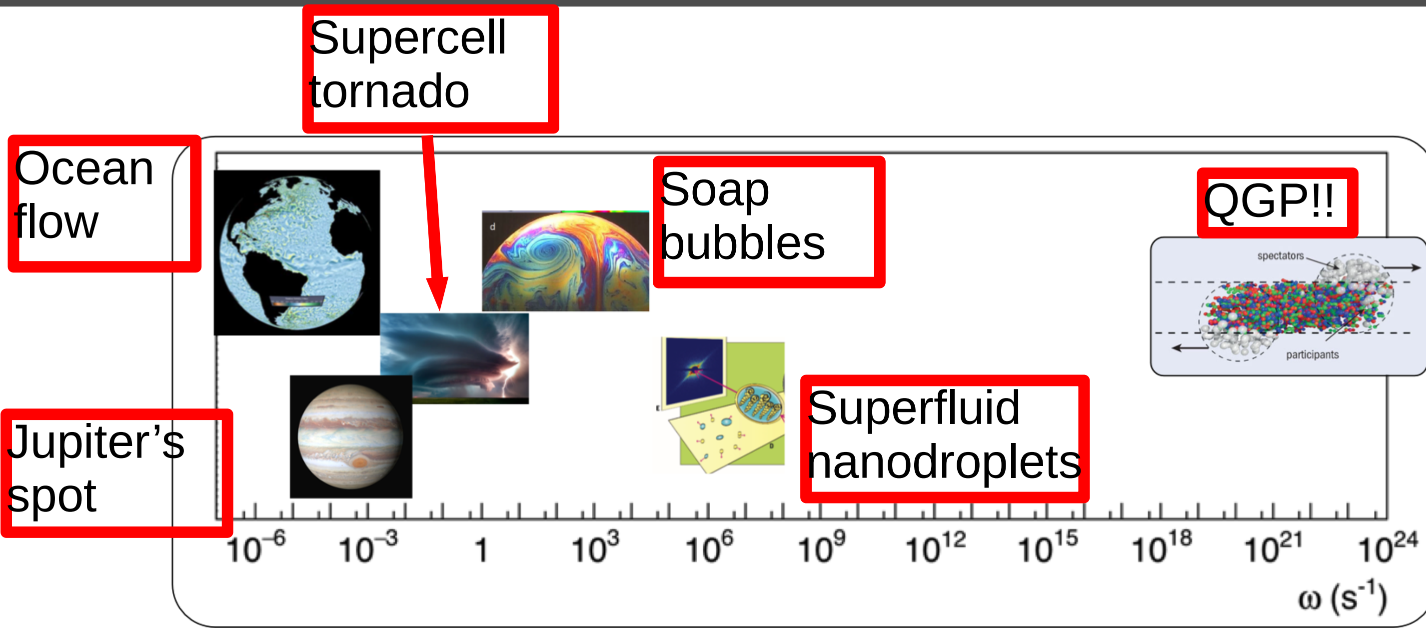


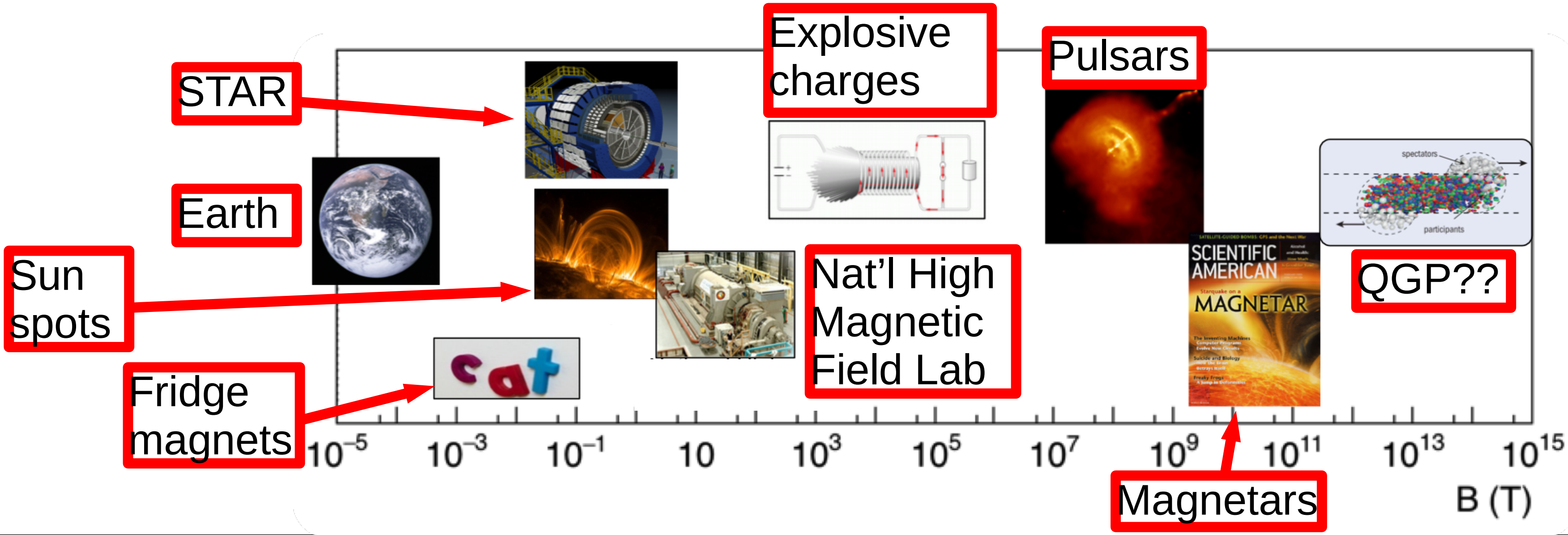
- Magnitude at high end of theory expectation (expectations vary by orders of magnitude)
- But... consistent with zero
  - A definitive statement requires improved statistics/EP determination



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

Comparison of QGP superlatives

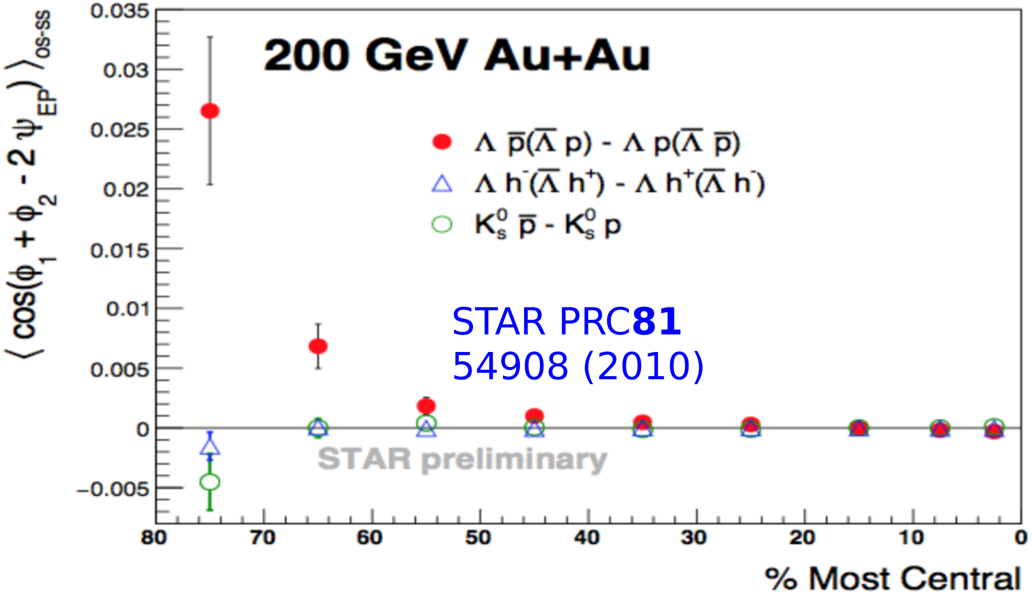




Connection: CVE

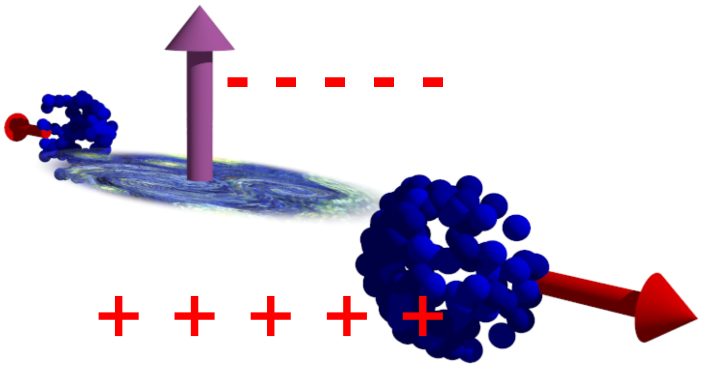
- Polarization not inherently chiral
- Large uncertainty term, μ_5, in the delta correlator (related to Chern–Simons)
- For neutral baryons (Lambdas) correlator predicts separation of B# along vorticity, ω

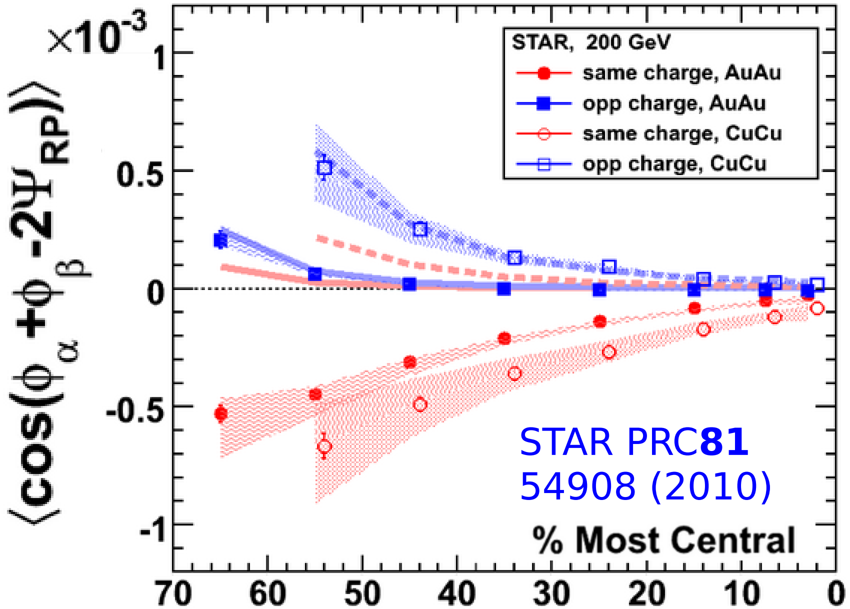
$$J_E = \frac{N_c \mu_5}{3\pi^2} \mu_B \omega$$



- 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

- 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

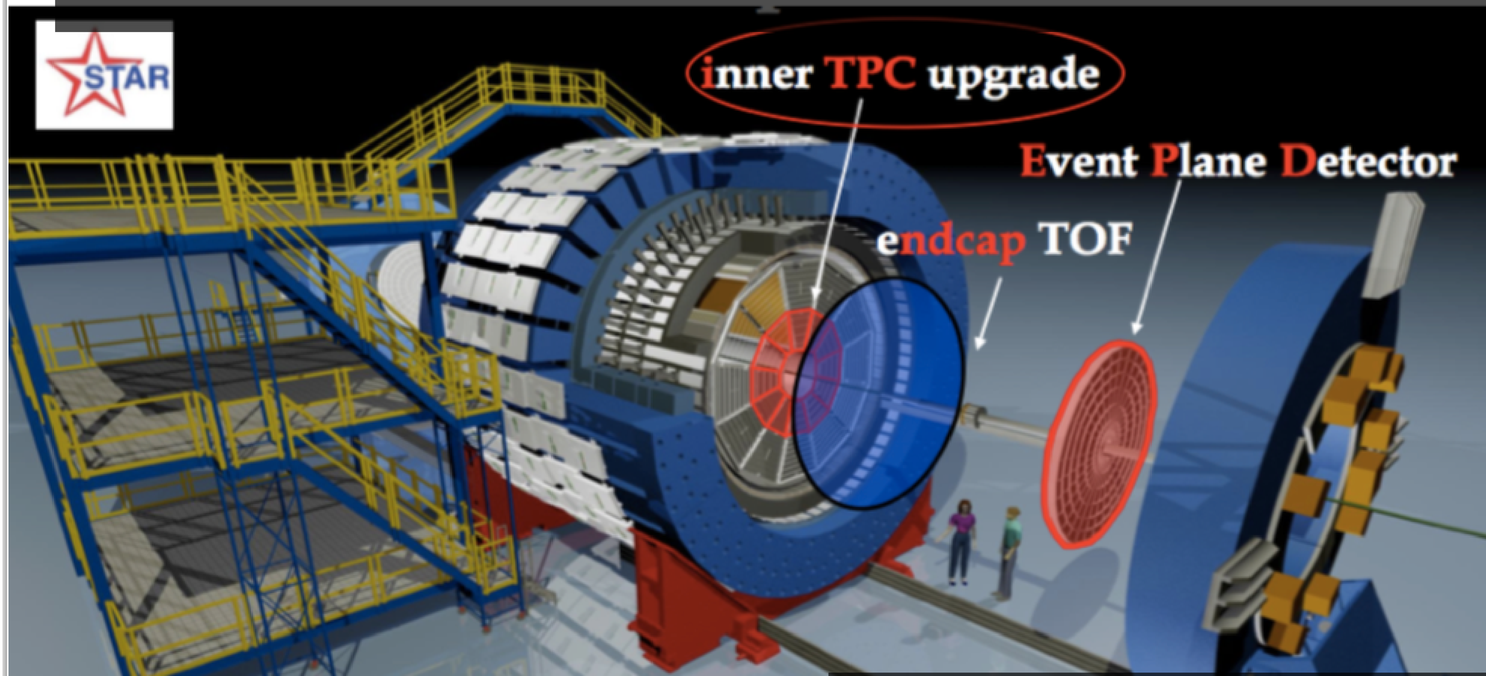
Summary II

- 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

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 $\mathcal{L}$ (1×10^{25}/cm^{2}sec)		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**

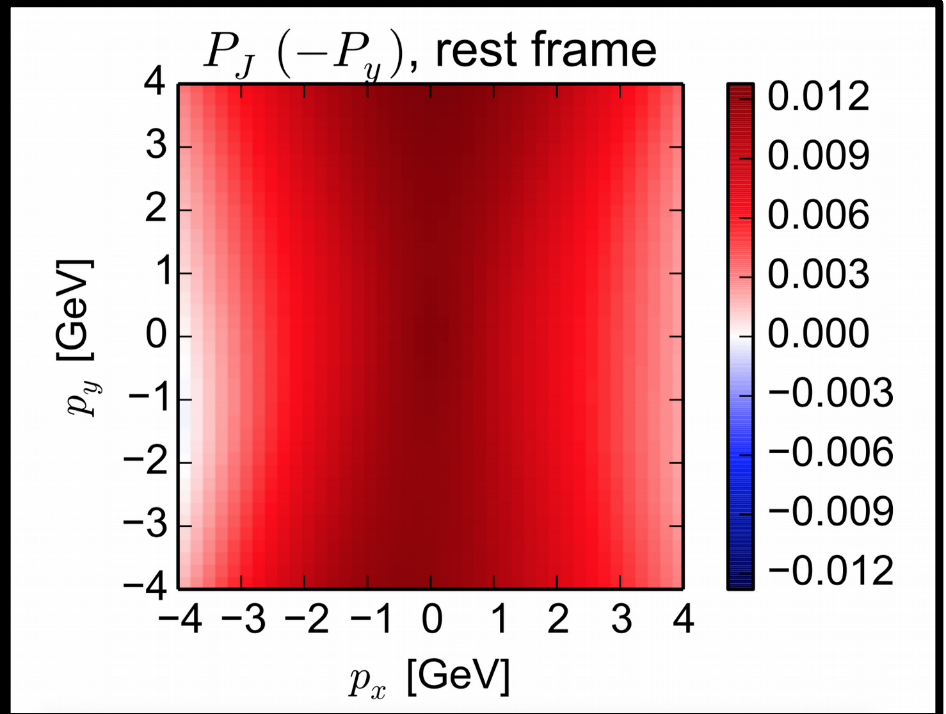
BES-II ~ 2019-2020

- 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

END

Azimuthal dependence (I)

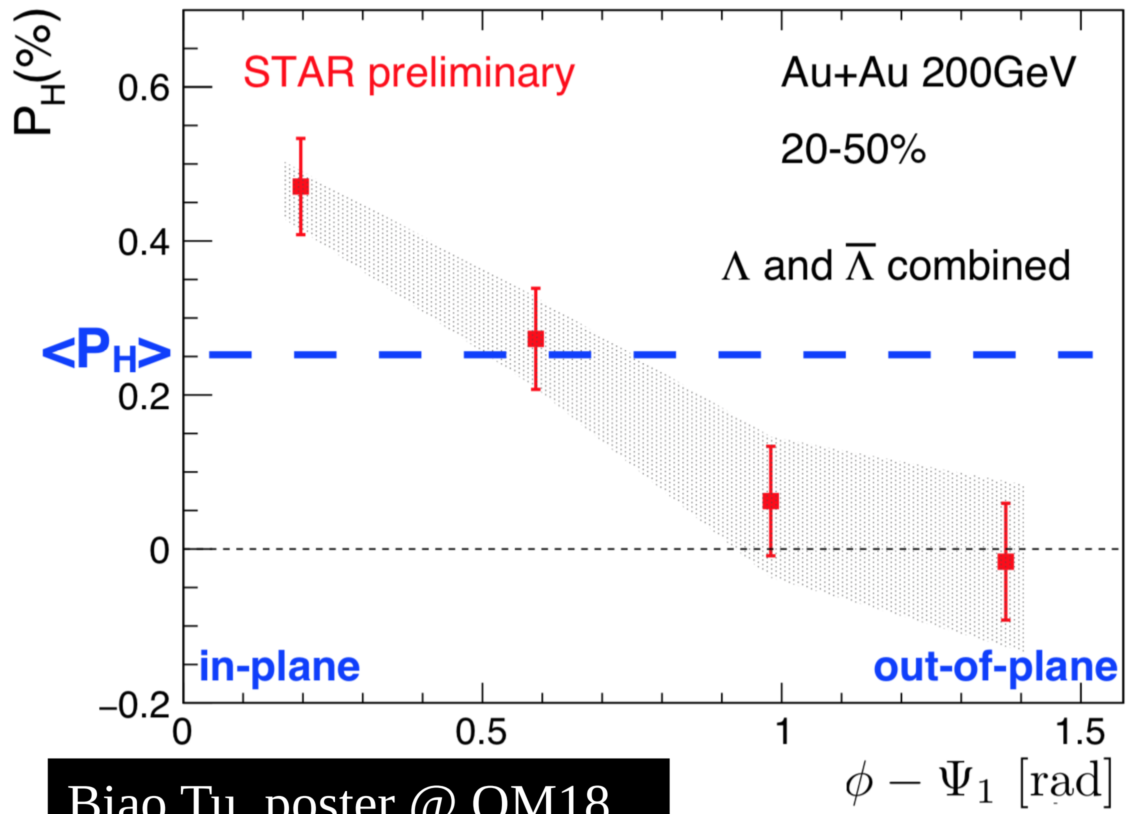
- Naively collision starts with strongest vorticity gradient in plane
- A model predicts the opposite dependence
- The dependence of P_H on $\phi_\Lambda - \Psi_1$ tests spin local thermal equilibrium and model initial conditions



Karpenko & Becattini EPJC (2017) 77:213

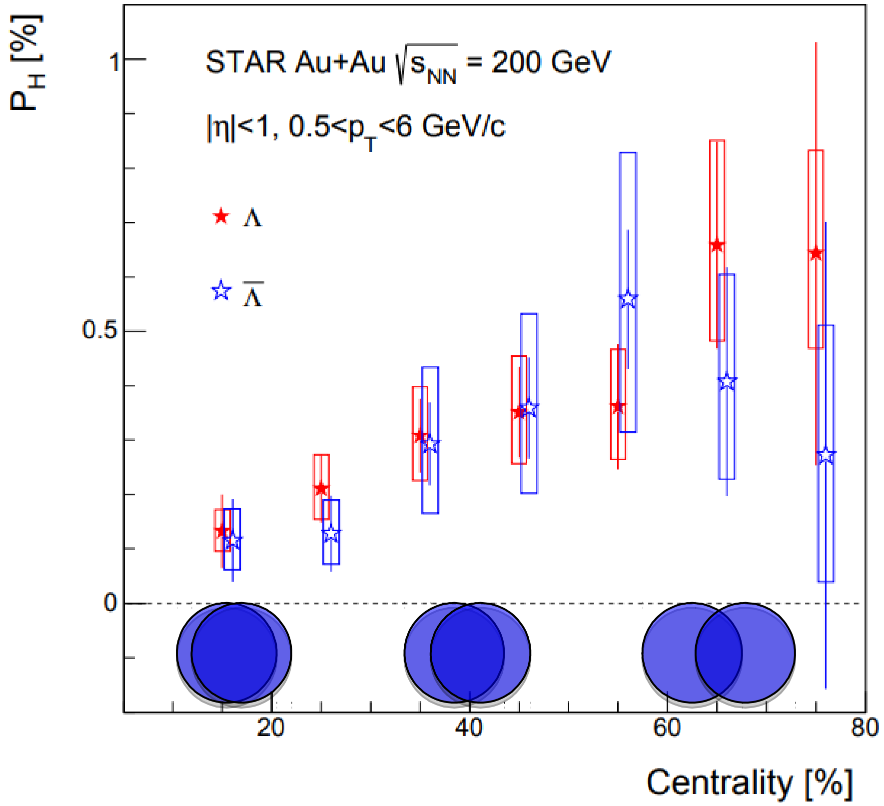
Azimuthal dependence (II)

- 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

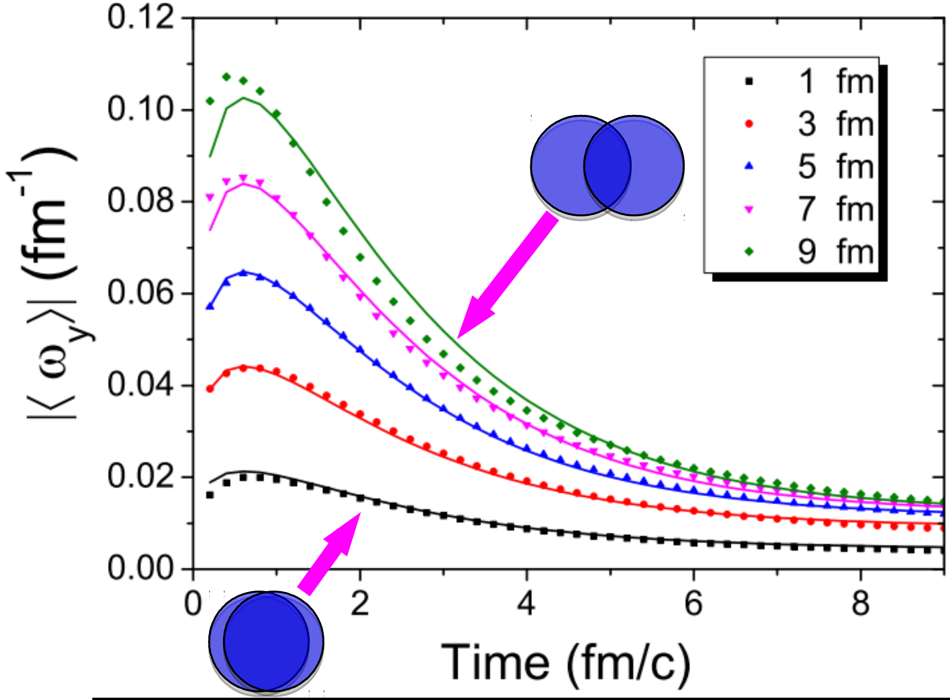


Biao Tu, poster @ QM18

Centrality



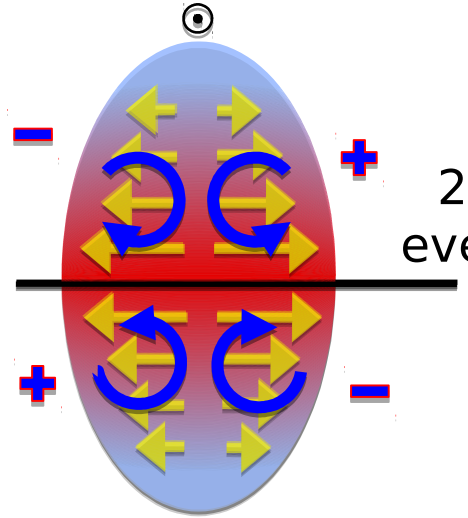
STAR, arXiv: 1805.04400



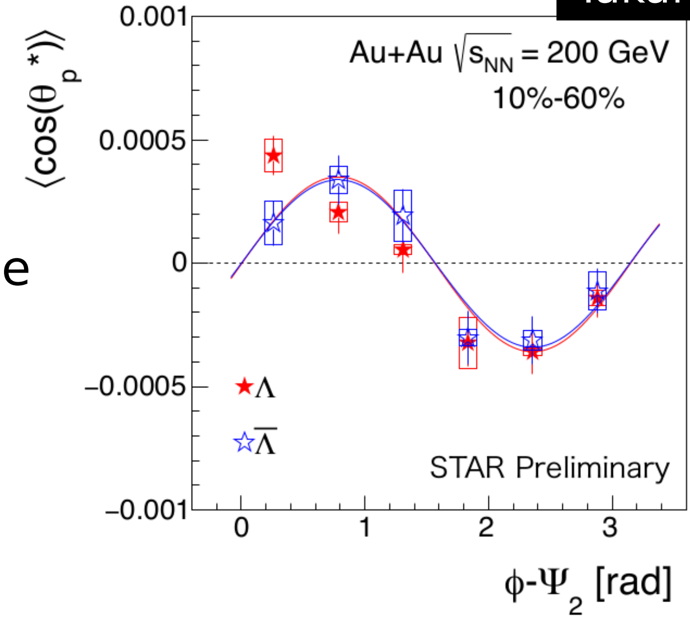
Jiang et al, PRC90 021904(R) (2014)

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

Polarization along the beam direction

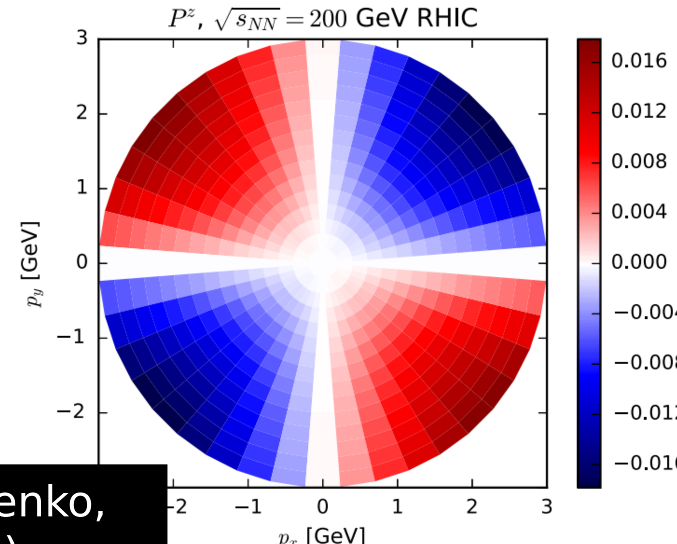


Takafumi Niida, talk @ QM18



- 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)

- 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.

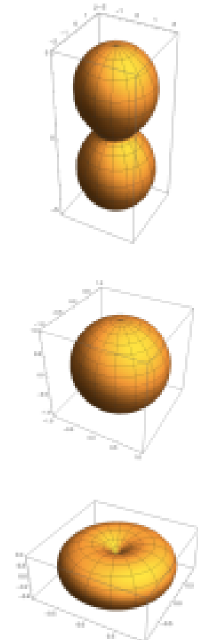
- A deviation of ρ_{00} from 1/3 signals net spin alignment.

Region of recombination of polarized quarks

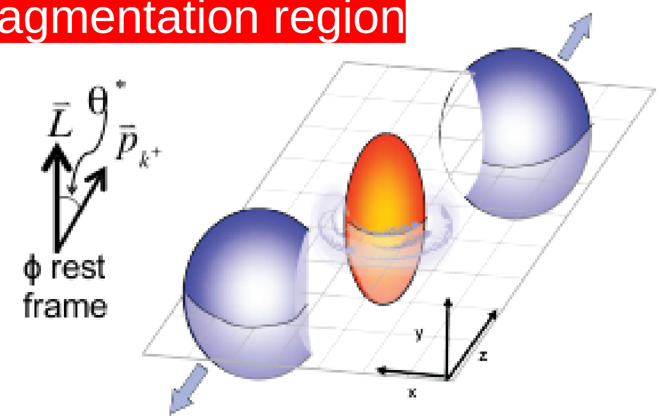
$\rho_{00} > 1/3$:

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

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



Polarized quark fragmentation region

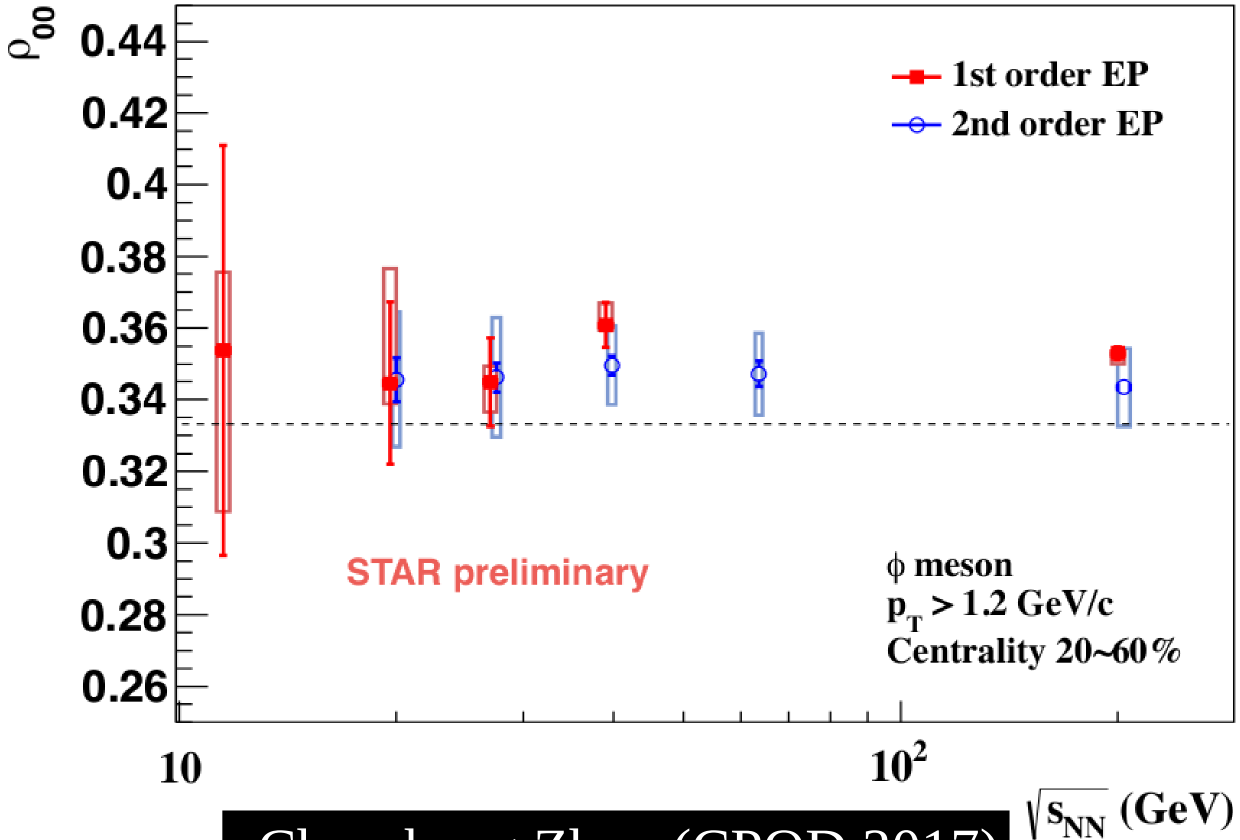


*K. Schilling el al., Nucl. Phys. B 15, 397 (1970)

Chensheng Zhou (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



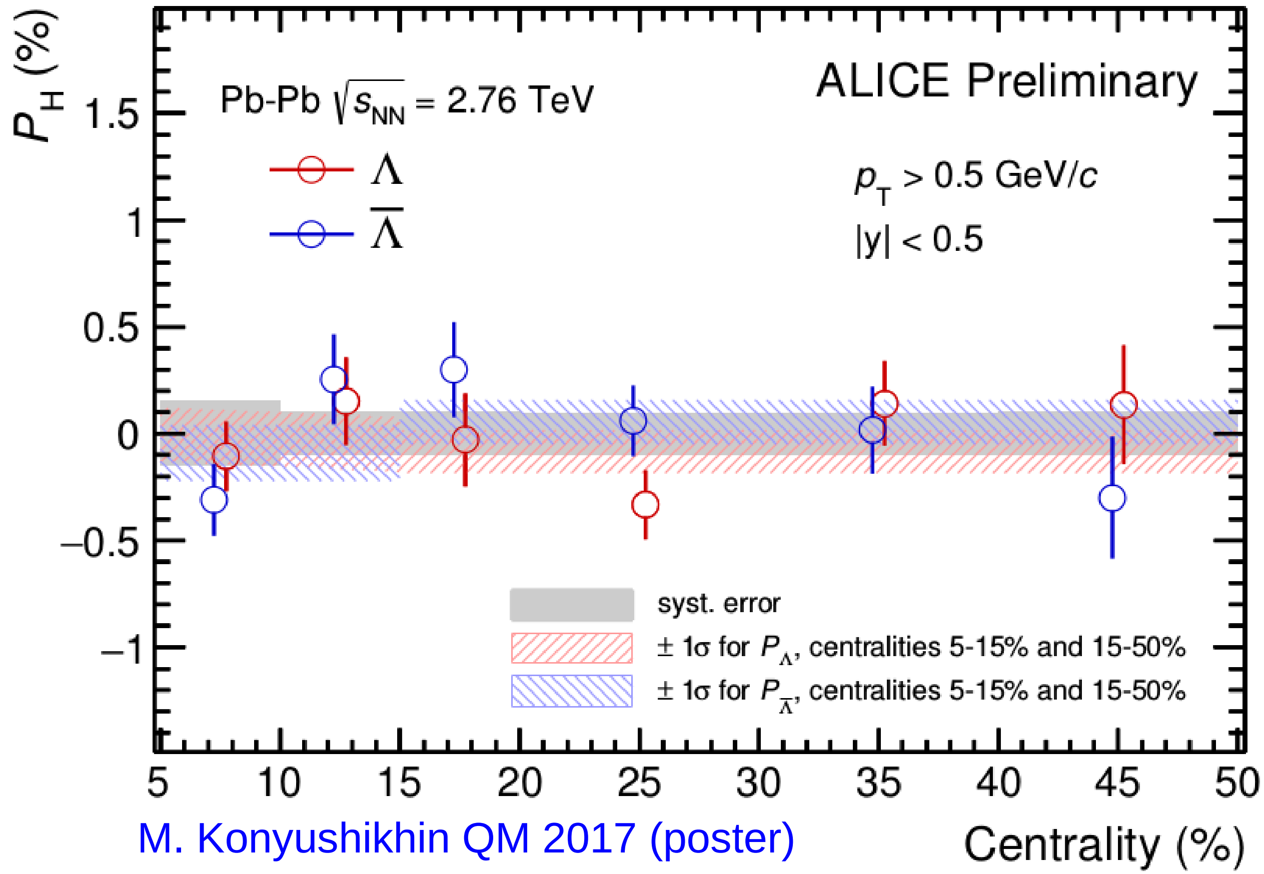
Chensheng Zhou (CPOD 2017)

ALICE Results

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

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

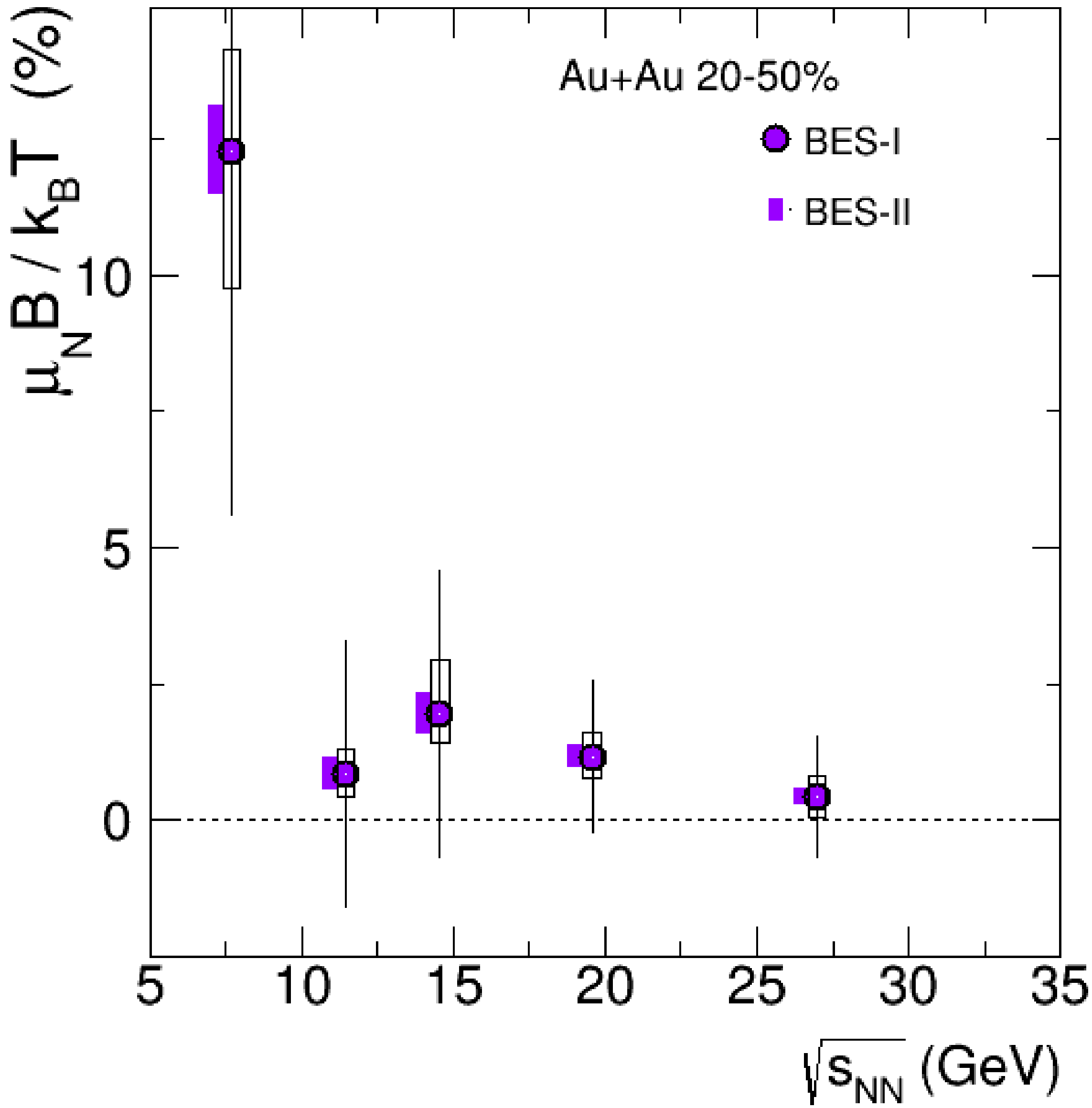
$$\text{15-50\% centrality} = \begin{cases} P_\Lambda = -0.0008 \pm 0.0010(\text{stat}) \pm 0.0004(\text{syst}) \\ P_{\bar{\Lambda}} = 0.0005 \pm 0.0010(\text{stat}) \pm 0.0003(\text{syst}) \end{cases}$$



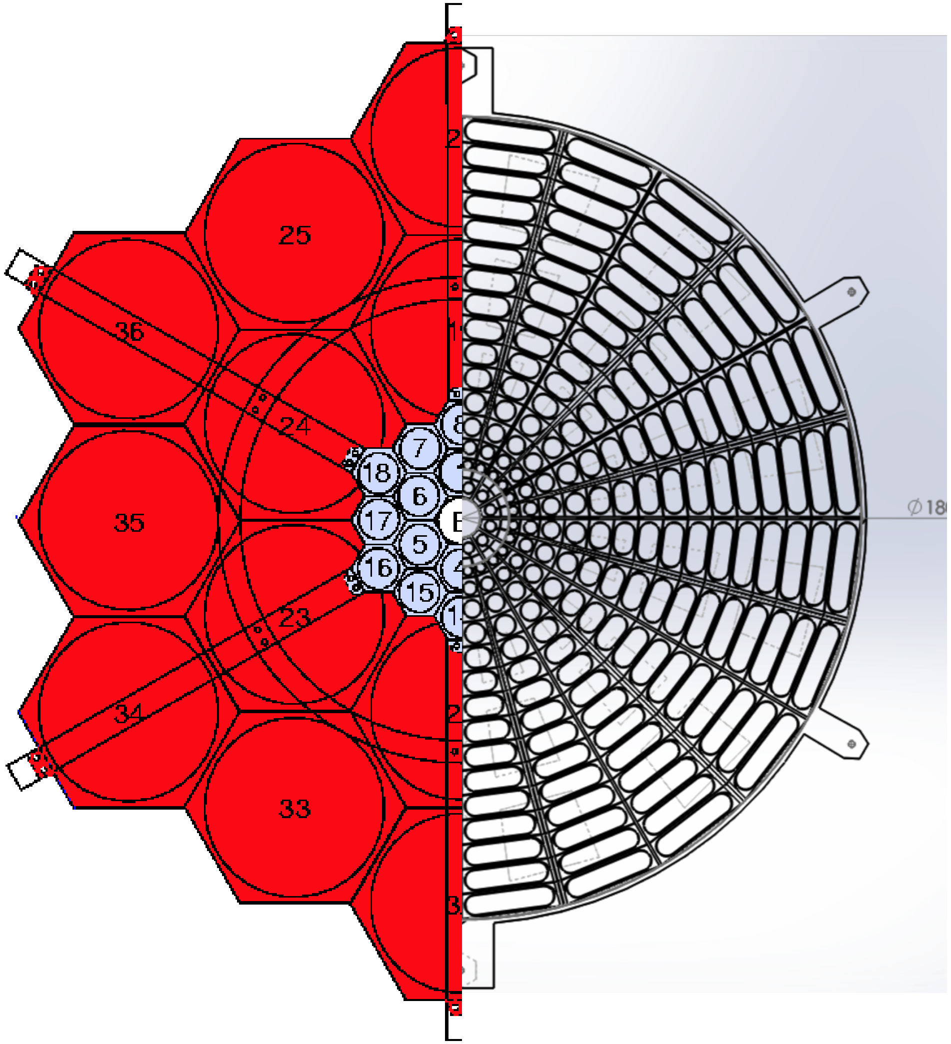
M. Konyushikhin QM 2017 (poster)

B field BES II Projection

- 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



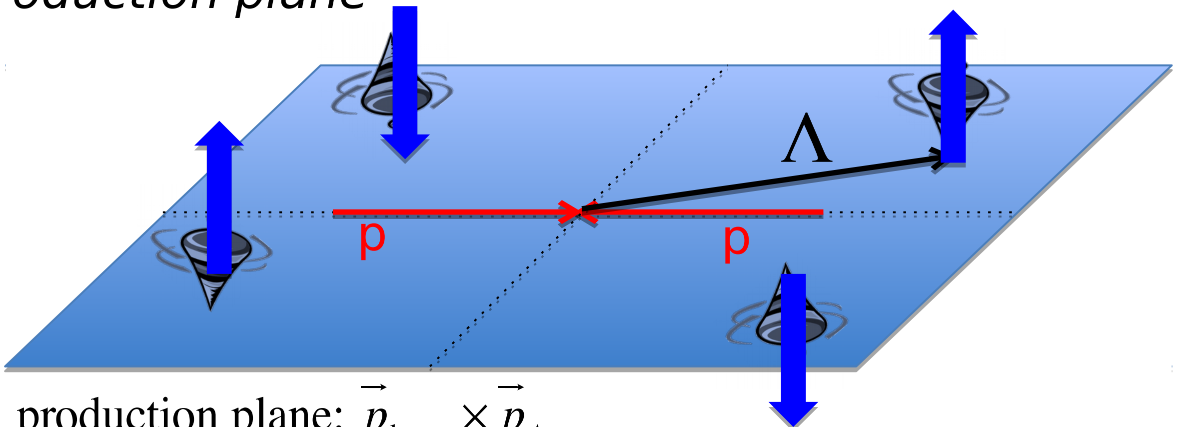
EPD BBC comparison



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

Topological dependent efficiency (I)

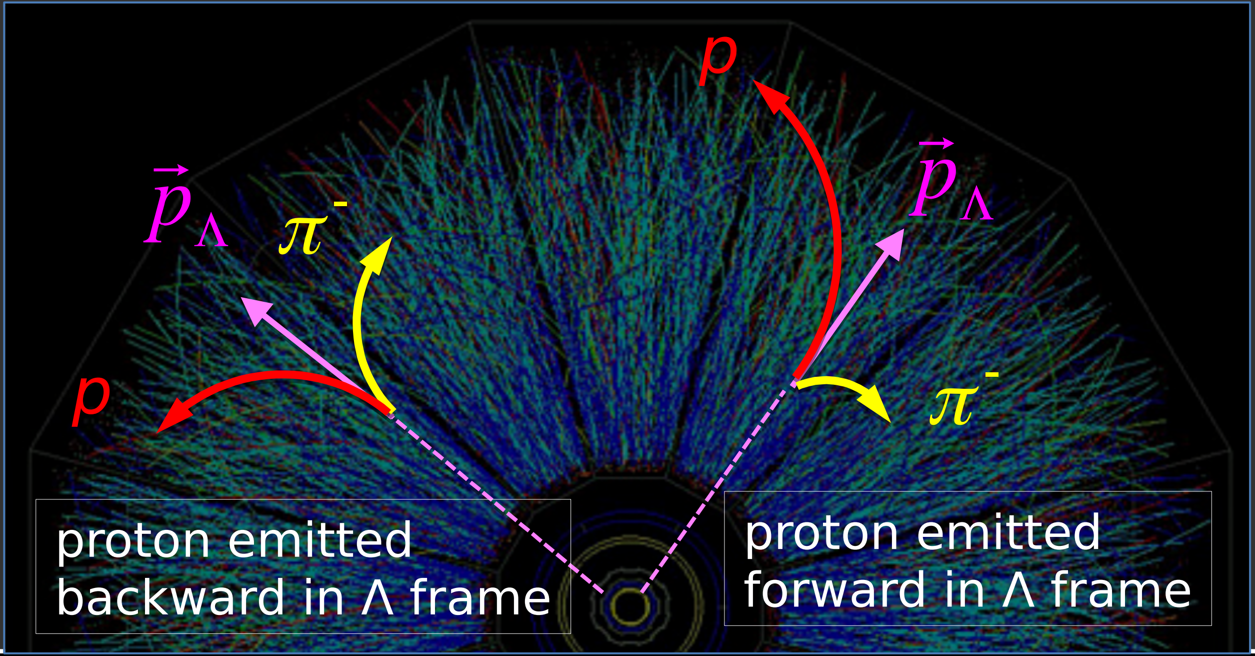
In Lambda frame, proton & pion have equal-magnitude momentum, but not in STAR frame

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

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

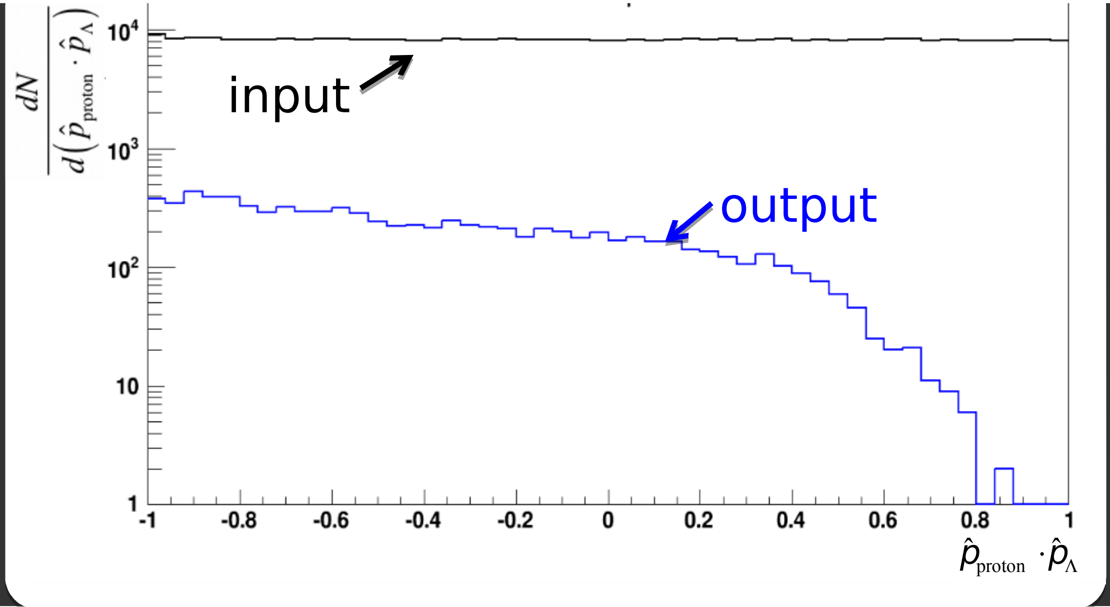


Topological dependent efficiency (II)

- 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 $\bar{P}_H$

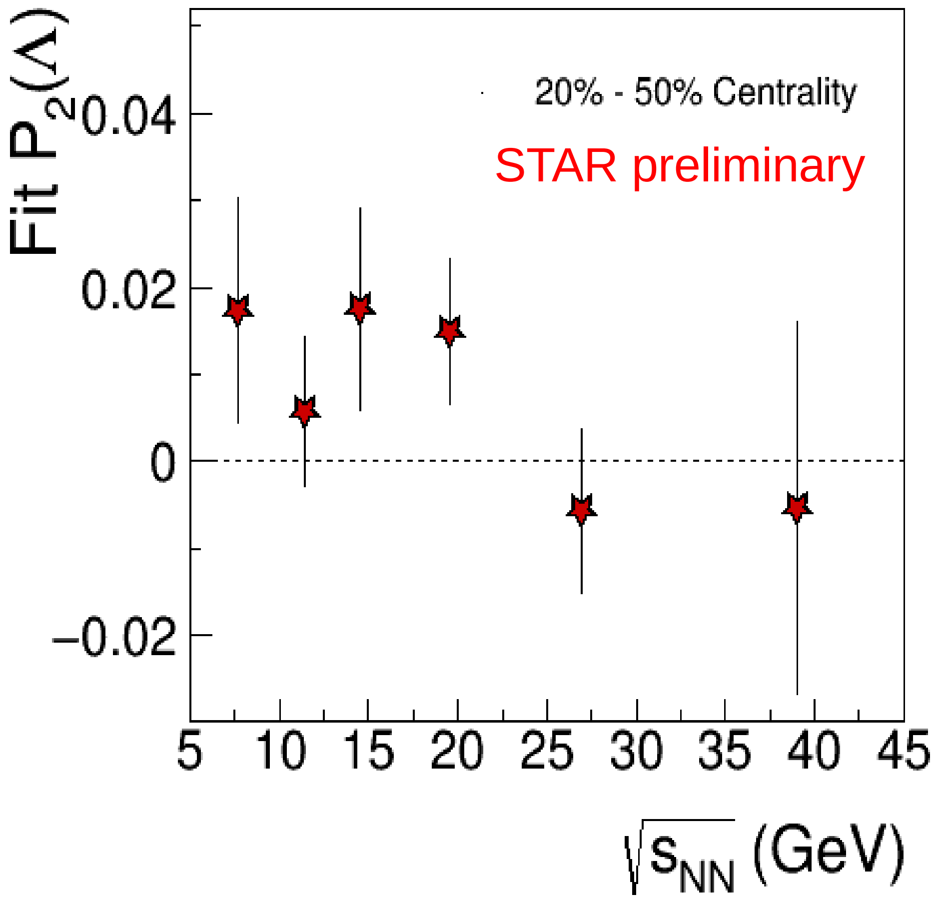
HIJING events through simulated STAR detector & tracking



Azimuthal dependence (BES)

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

- 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 $\phi_\Lambda - \Psi_1$ (second order)
- Uncertainties for Anti-Lambda results larger than plot range



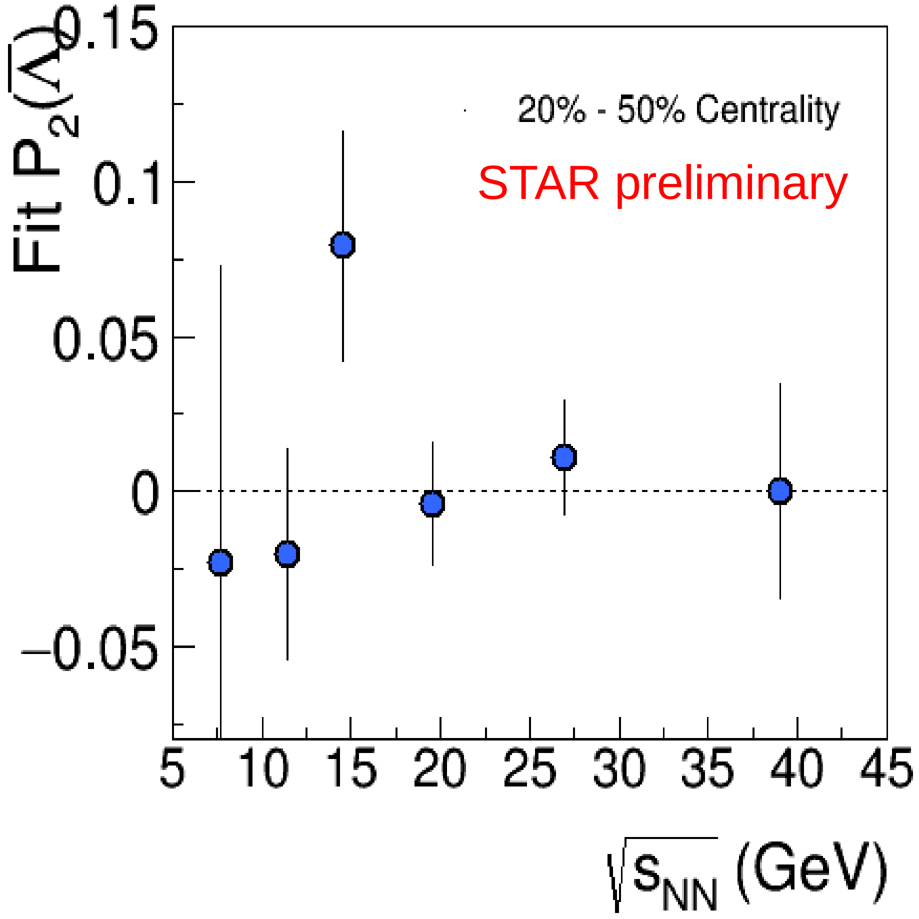
Azimuthal dependence (BES)

- 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 $\phi_\Lambda - \Psi_1$ (second order)

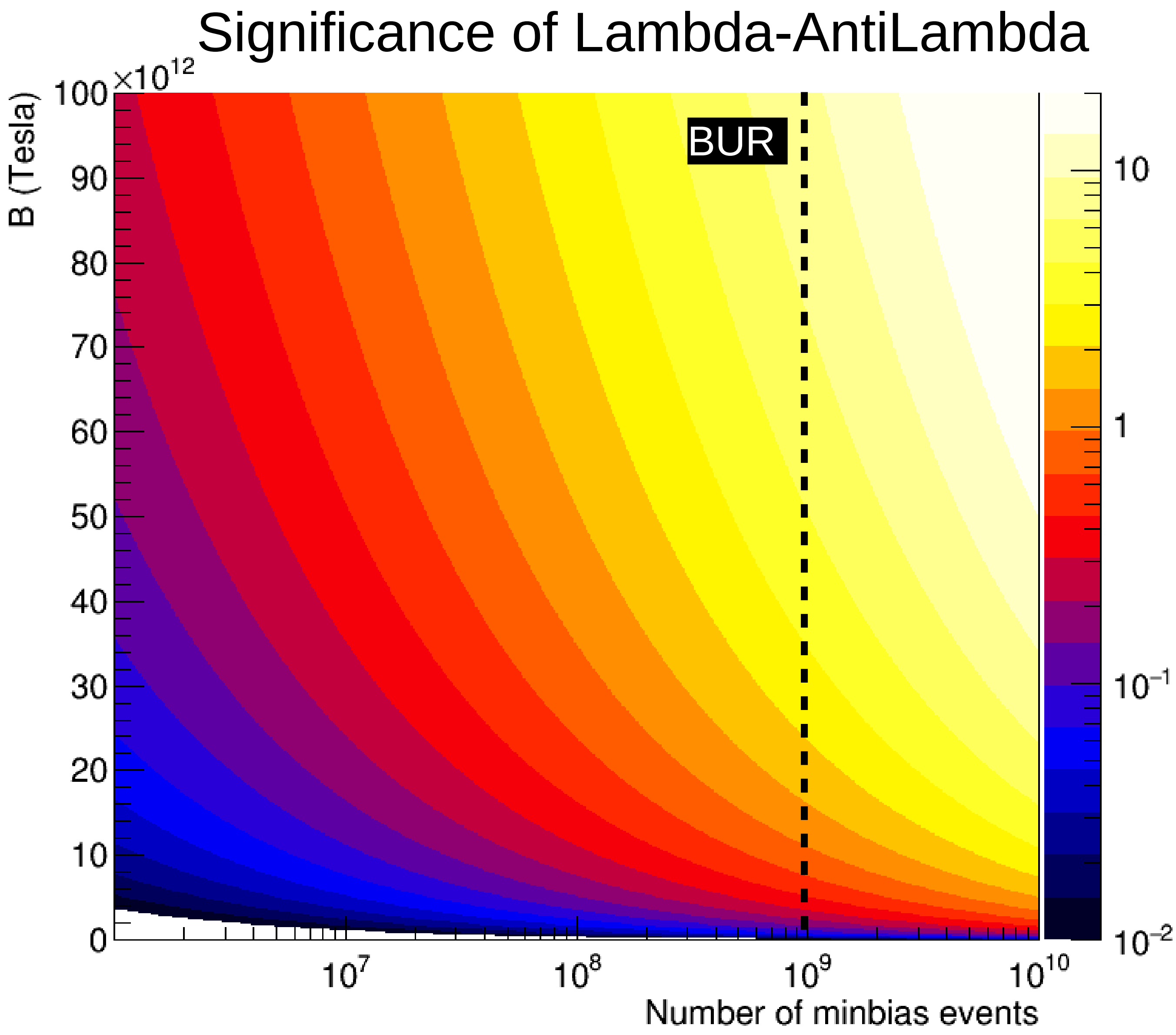
- Errors for Anti-Lambda results are too large to display

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



27GeV (2018) Magnetic Search $\left(P_{\bar{\Lambda}} - P_{\Lambda}\right)$

- 27GeV (based on BES I error bars)
- Assuming $R_{EPD} = 2R_{BBC}$
- Z axis depicts the significance of the gap in between the Lambda and AntiLambda Polarizations



EPD BBC comparison (I)