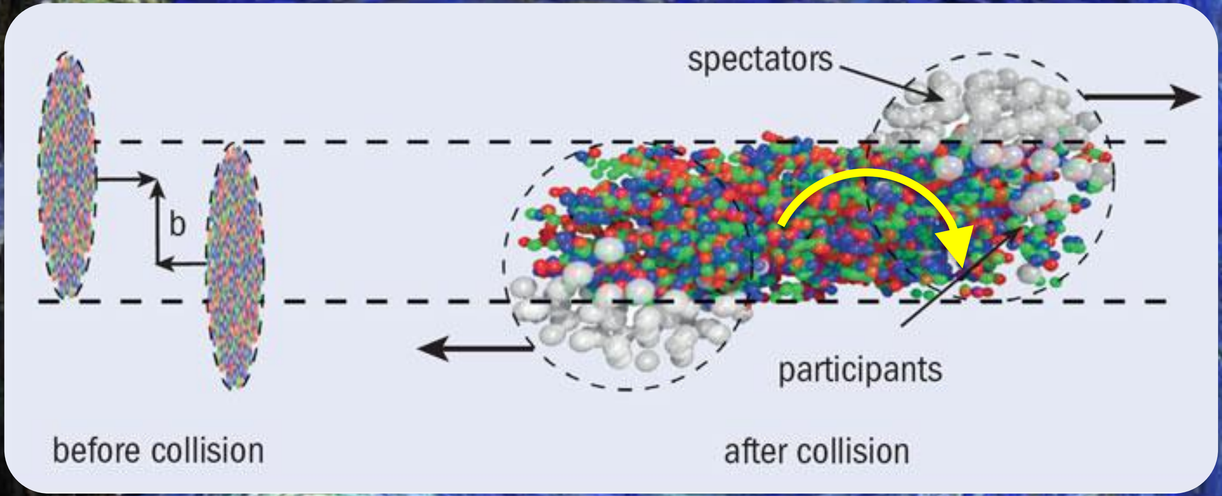
Global Λ polarization at RHIC BES energies

Mike Lisa, Ohio State University
for
Isaac Upsal, Ohio State University
for
The STAR Collaboration

Outline

- Motivation
  - angular momentum and plasma substructure
  - CME / CVE – the need for quantitative "non-chiral" input
- First observation of global hyperon polarization
  - arxiv:1701.06657, accepted by Nature
- Equilibrium-based estimate of B-field and plasma vorticity
  - Phys. Rev. C95, 054902 (2017). 1610.02506
- Larger perspective
  - relationship to other vortical fluids; Barnett effect
- More detail (requires more statistics, detector upgrade...)
  - azimuthal dependence, magnetic splitting?
- Summary & Outlook

Fluid substructure in non-central collisions – $J \sim 10^{3\text{-}4}\,\hbar$



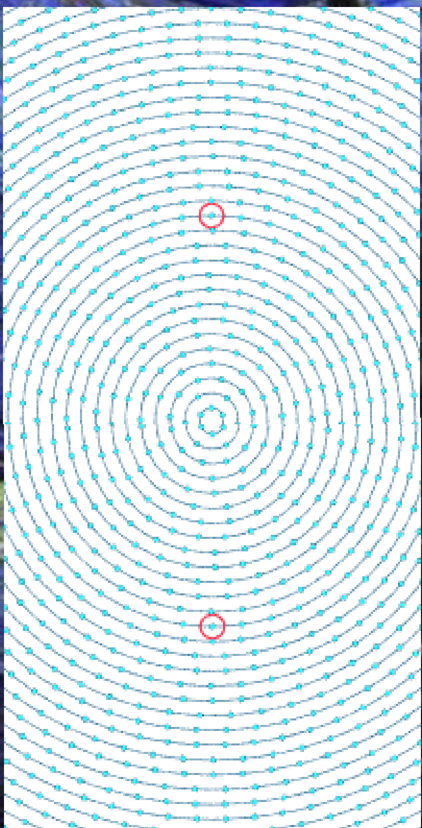
- Central concept in RHI: hydrodynamics
  - do we know the full fluid substructure?

Vorticity: $\vec{\omega} = \vec{\nabla} \times \vec{v}$

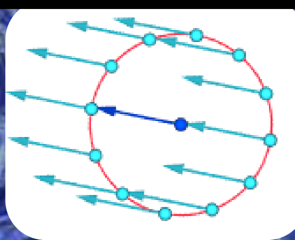
- Is angular momentum distributed thermally? "spinning QGP?"
- How would it manifest itself in data?
- Relevance to novel phenomena?

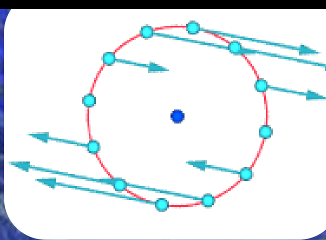
Vorticity – local rotational fluid substructure

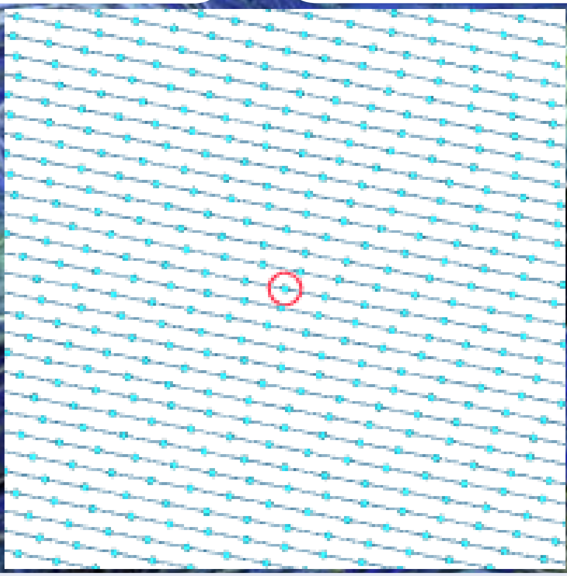
Rigid-body-like vortex
$v \mu r$

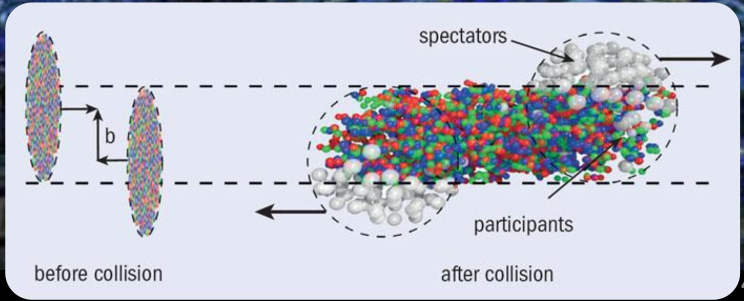


Shear vorticity
- *generated* thru viscosity in early stage
- *maintained* by low viscosity later









$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

Connection to experiment

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*

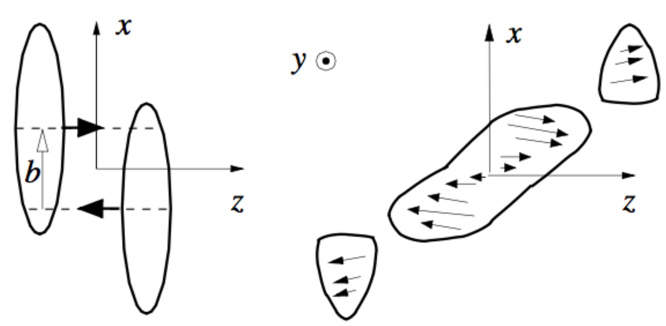
(Received 25 October 2004; published 14 March 2005)

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

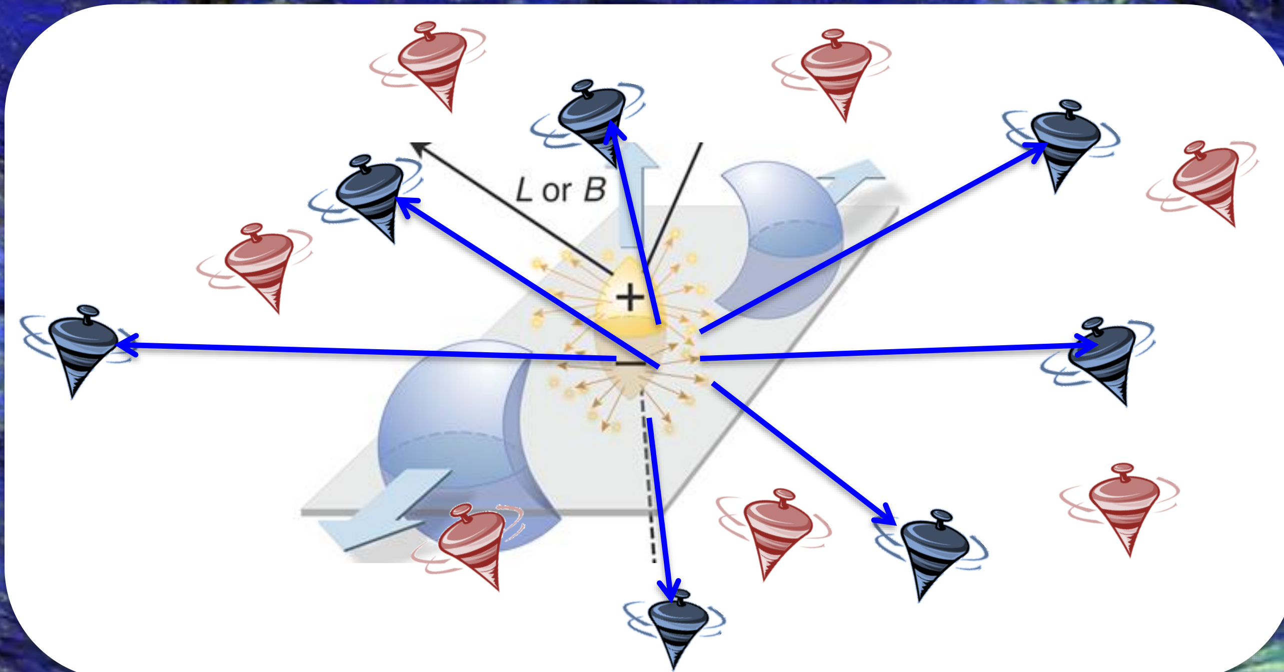
Local OAM (vorticity) transferred to spin degree of freedom of final-state hadrons

(Such transfer is rare – discussed later)



also Voloshin'04; Betz/Gyulassy/Torrieri'07; Gao'08,'12; Becattini'13,'15; Csernai'13; Jiang/Lin/Liao'16; many others

Contributors to Global Polarization



$$\overline{\vec{P}}_{\Lambda} \,||\, +\hat{J}_{\text{sys}} \qquad \overline{\vec{P}}_{\bar{\Lambda}} \,||\, +\hat{J}_{\text{sys}}$$

- Vortical:
  - fluid cell emits polarized particles $P \mu w$
  - Becattini, Csernai, Gyulassy, Gao, Liang, Torrieri, Sorin, Wang,...

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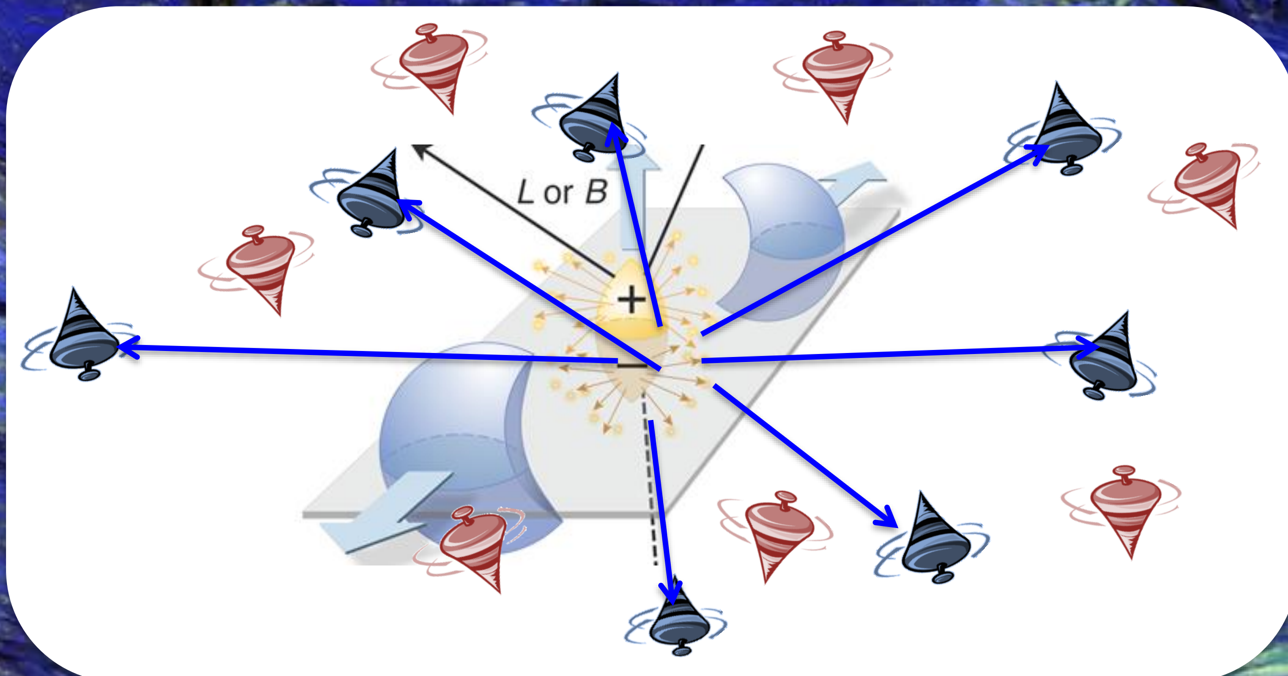


- <u>Vortical</u>:
  - fluid cell emits polarized particles P µ w
  - Becattini, Csernai, Gyulassy, Gao, Liang, Torrieri, Sorin, Wang,...

$$\overline{\vec{P}}_{\Lambda} \,||\, +\hat{J}_{sys} \qquad \overline{\vec{P}}_{\bar{\Lambda}} \,||\, +\hat{J}_{sys}$$

- <u>Magnetic coupling</u> $P \propto \vec{\mu} \cdot \vec{B}$
  - particles polarized according to magnetic moment
  - Becattini, Karpenko, MAL, Upsal, Voloshin

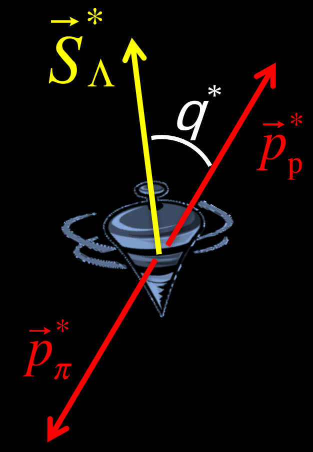
$$\overline{\vec{P}}_{\Lambda} \,||\, -\hat{J}_{sys} \qquad \overline{\vec{P}}_{\bar{\Lambda}} \,||\, +\hat{J}_{sys}$$

Ingredients needed: $\vec{P}_\Lambda$ and $\hat{J}_{\text{system}}$

Lambdas are "self-analyzing"

- reveal polarization by preferentially emitting daughter proton in the spin direction

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



$L \rightarrow p + p^{-}$

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

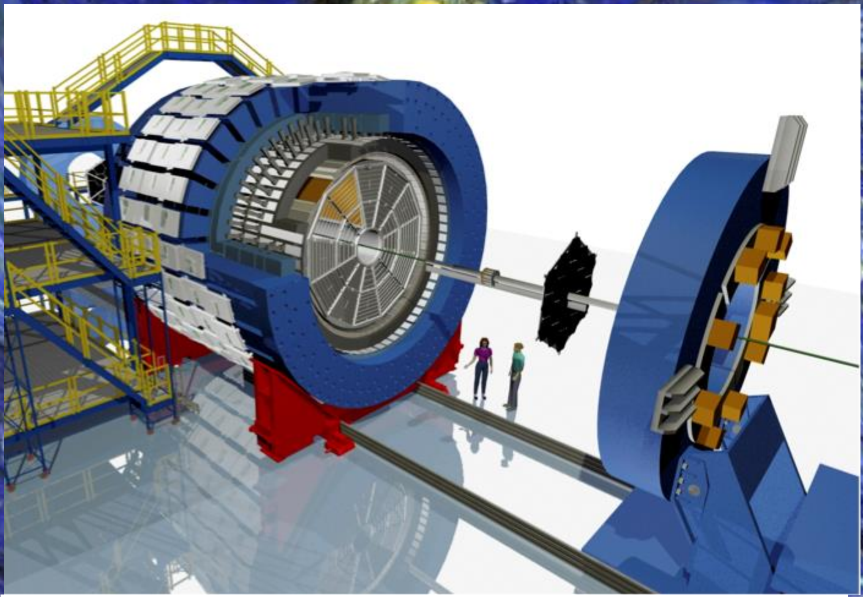
$$\frac{dW}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha \vec{P} \cdot \hat{p}^*_p\right) = \frac{1}{4\pi}\left(1 + \alpha P \cos\theta^*\right)$$

$\alpha = 0.642$ [measured]

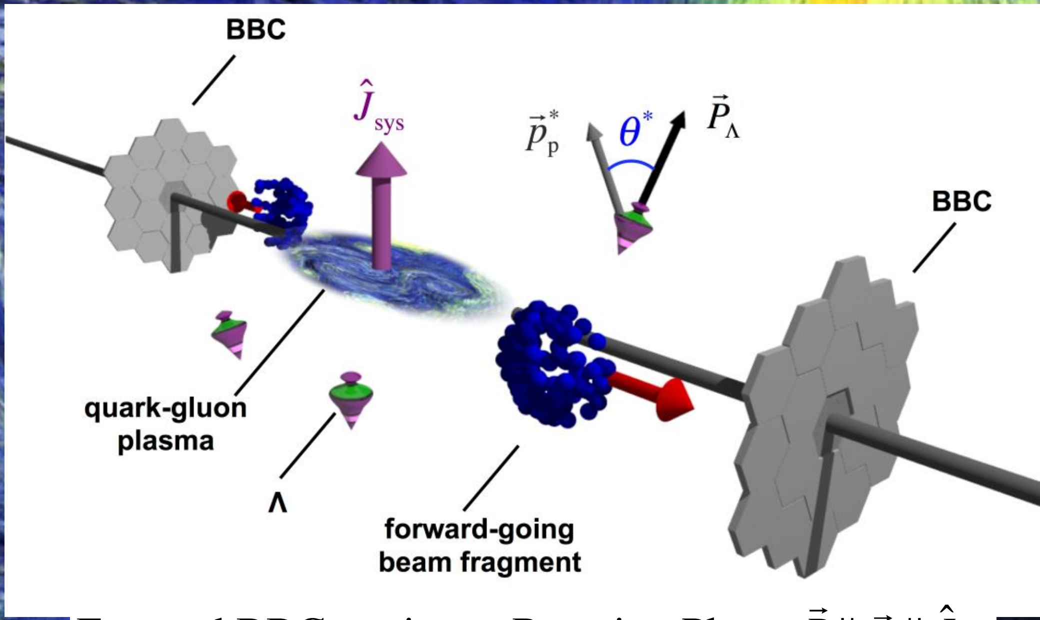
$\hat{p}^*_p$ is the daughter proton momentum direction *in* the Λ *frame*

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

Ingredients needed: $\vec{P}_\Lambda$ and $\hat{J}_{system}$



L, $\bar{\text{L}}$ reconstructed in TPC+TOF for $|y| < 1$



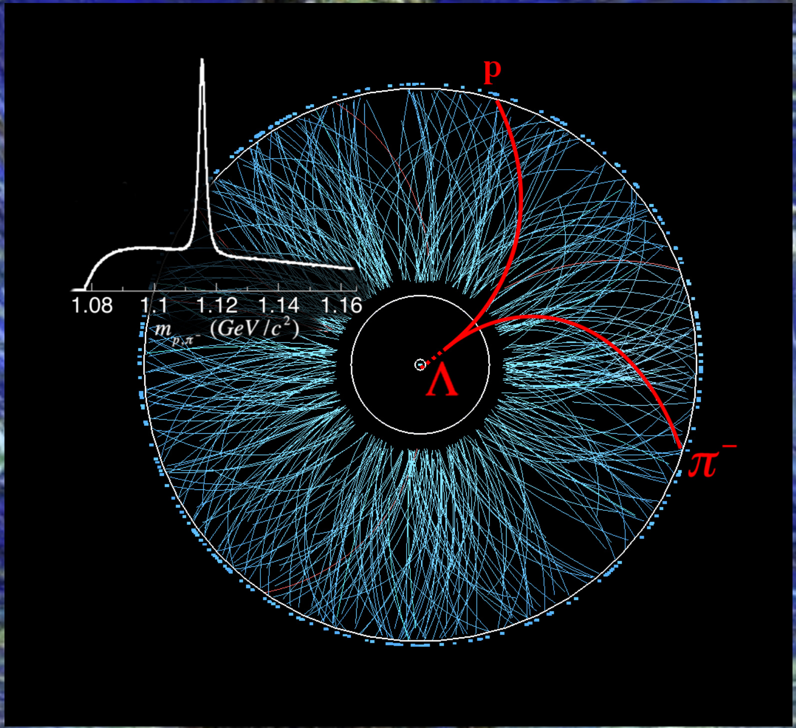
Forward BBCs estimate Reaction Plane: $\vec{B} \parallel \vec{\omega} \parallel \hat{J}_{sys}$

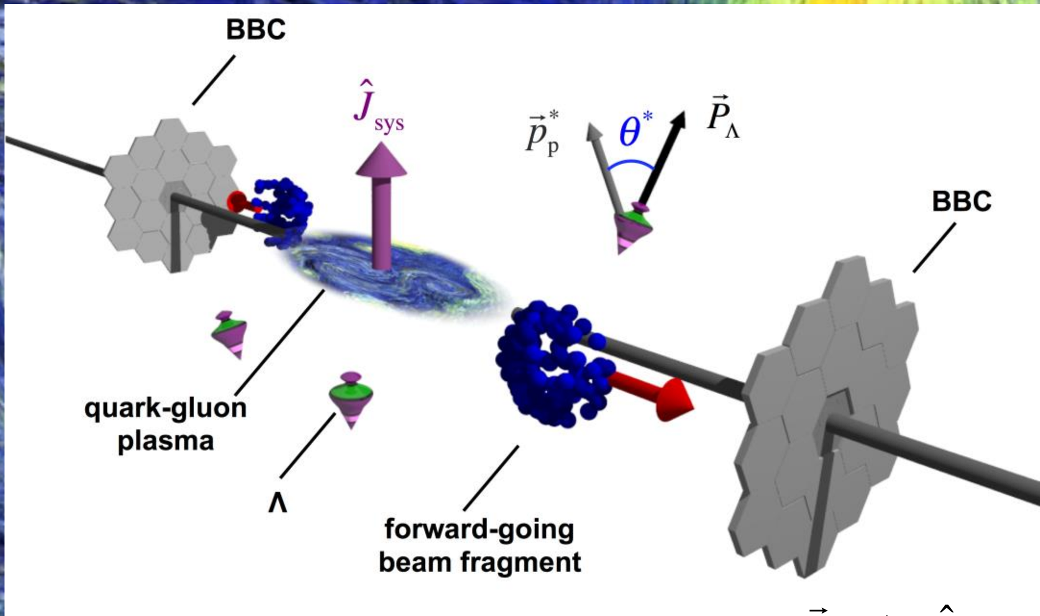
Correlate $\vec{p}^{\,*}_{p}$ and $\hat{J}_{sys}$

STAR BES energies 7.7, 11.5 14.5, 19.6, 27, 39 GeV Au+Au collisions

Also compare to previously published 62.4, 200 GeV analysis, which used ZDC for Reaction Plane

Ingredients needed: $\vec{P}_\Lambda$ and $\hat{J}_{system}$





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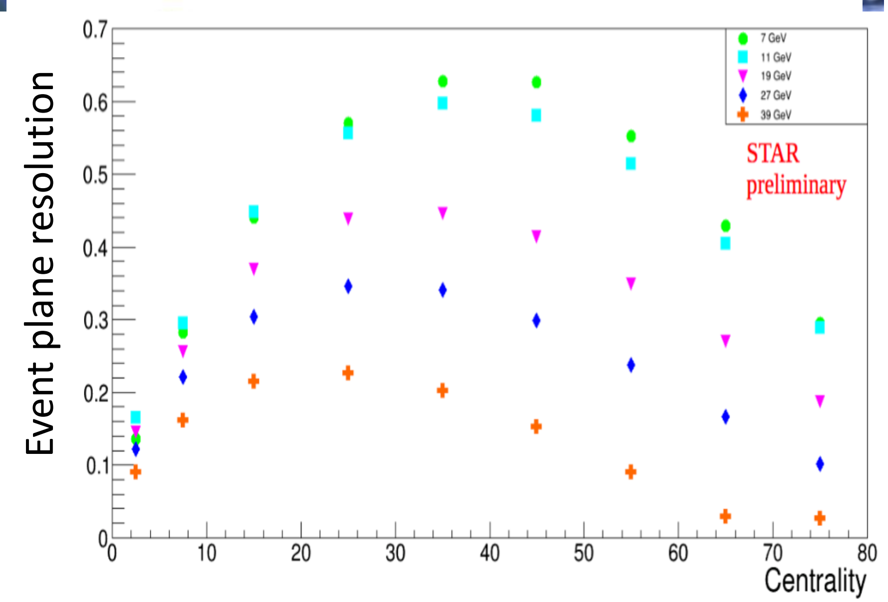
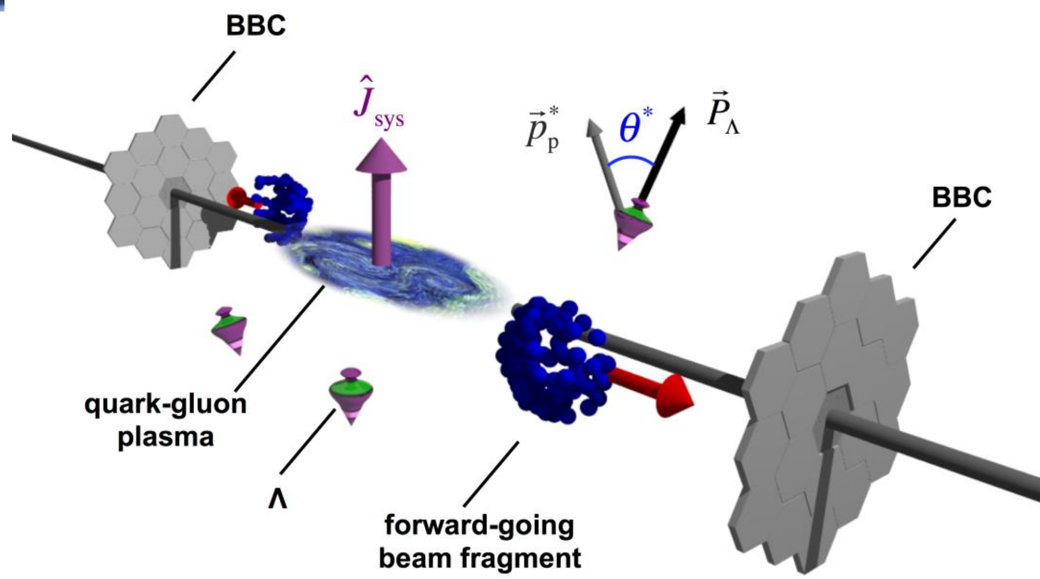




Forward BBCs estimate Reaction Plane: $\vec{B} \,||\, \vec{\omega} \,||\, \hat{J}_{\text{sys}}$

Statistics-limited: average polarization, $\bar{P}_{\text{H}} \equiv \int d\vec{\beta}_\Lambda \frac{dN}{d\vec{\beta}_\Lambda} \vec{P}\left(\vec{\beta}_\Lambda\right) \cdot \hat{J}_{\text{sys}}$

$$\bar{P}_{\text{H}} = \frac{8}{\pi\alpha} \frac{\langle \sin(\phi^*_{\text{p}} - \Psi^{(1)}_{\text{EP}}) \rangle}{R^{(1)}_{\text{EP}}}$$ where average is over events & Λs

$\Psi^{(1)}_{\text{EP}}$ is the first-order event plane (from BBCs)

$R^{(1)}_{\text{EP}}$ is the first-order event plane resolution

Event-plane resolution

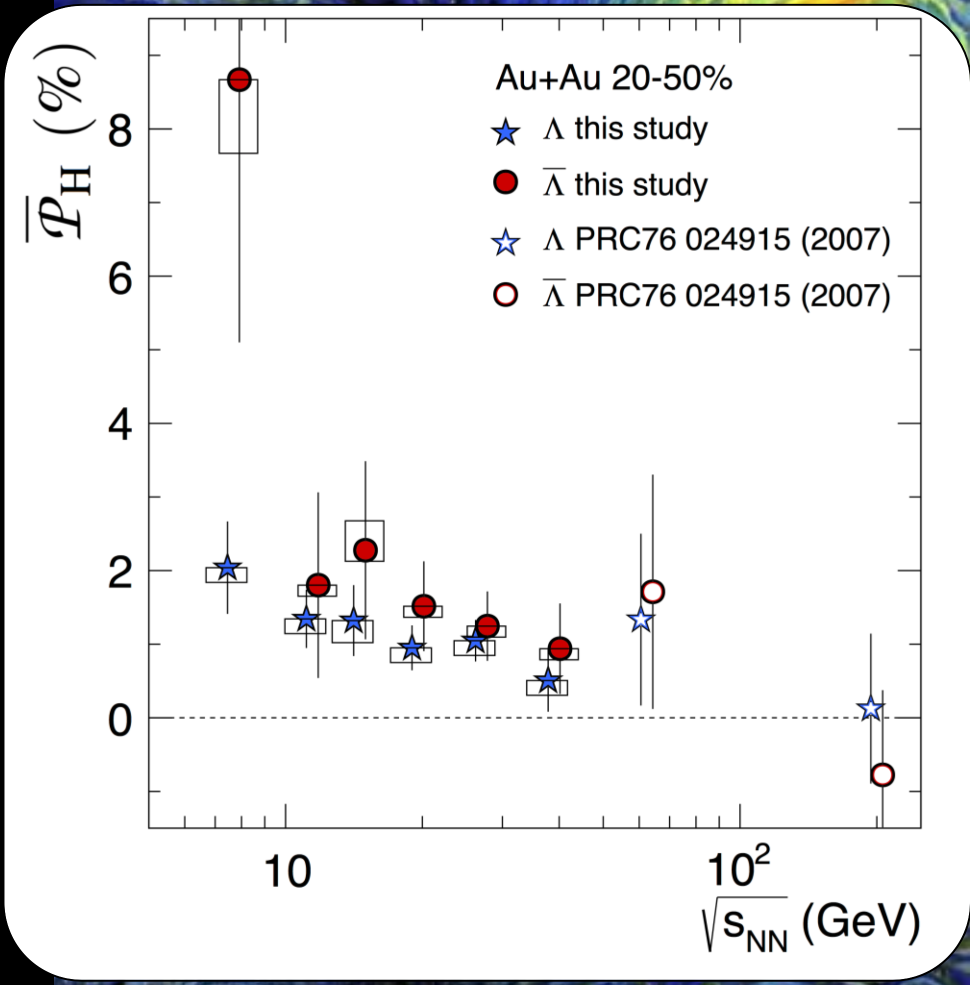
- best for mid-central collisions
- significantly worse at higher energy
- errorbars $\quad d\bar{P}_{\text{H}} \propto \left(R^{(1)}_{\text{EP}} \sqrt{\#\Lambda}\right)^{-1}$

[1] STAR, PR**C76** 024915 (2007)

Results – corrected for RP + combinatorics

First signal of global polarization in heavy ion collisions!

- systematic errors small rel statistical errors
  - mostly from combinatoric bkgd



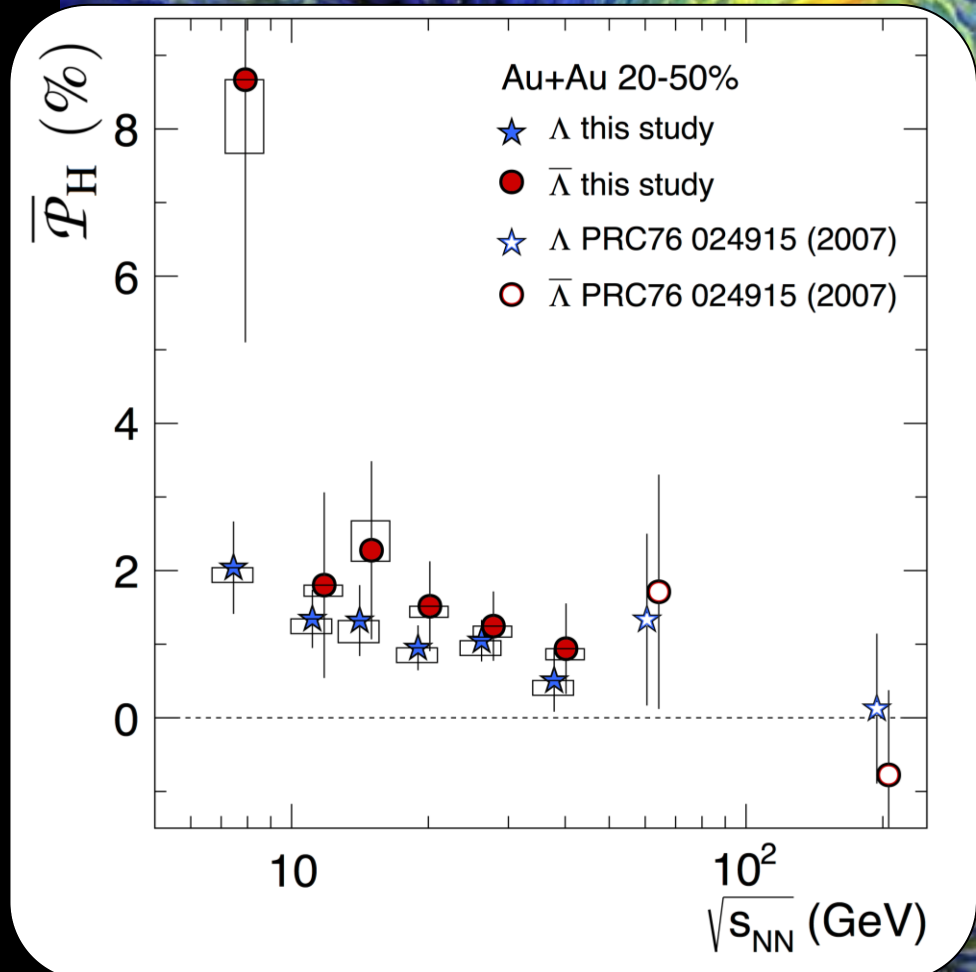
$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	14.5	19.6	27	39
Λ	3.6σ	3.5σ	2.4σ	3.1σ	3.5σ	1.1σ
anti-Λ	2.2σ	2.1σ	1.1σ	2.4σ	2.9σ	1.6σ

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

Preliminary results – corrected for RP + combinatorics

First signal of global polarization in heavy ion collisions!

- systematic errors small rel statistical errors
  - mostly from combinatoric bkgd
- $\overline{P}_{\Lambda} > 0$, $\overline{P}_{\bar{\Lambda}} > 0$: vorticity mechanism dominant
- $\overline{P}_{\bar{\Lambda}} > \overline{P}_{\Lambda}$: *suggests* additional magnetic effect
- Signal falls with energy (maybe...)
  - previous "null result" in line with trend
  - *Transport models predict falling vorticity*



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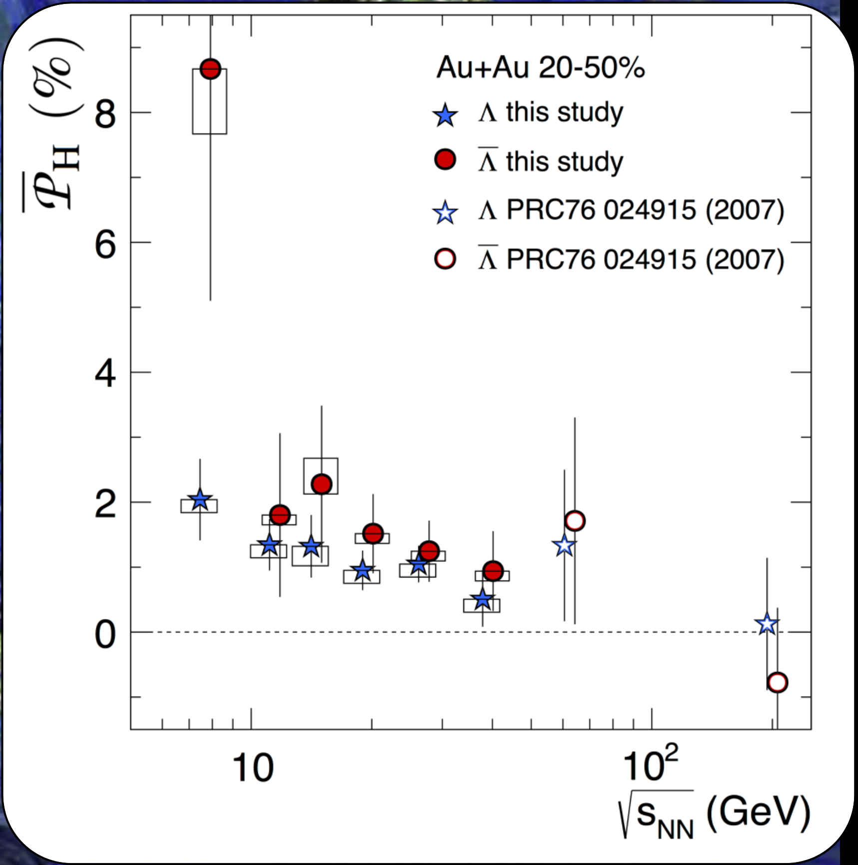
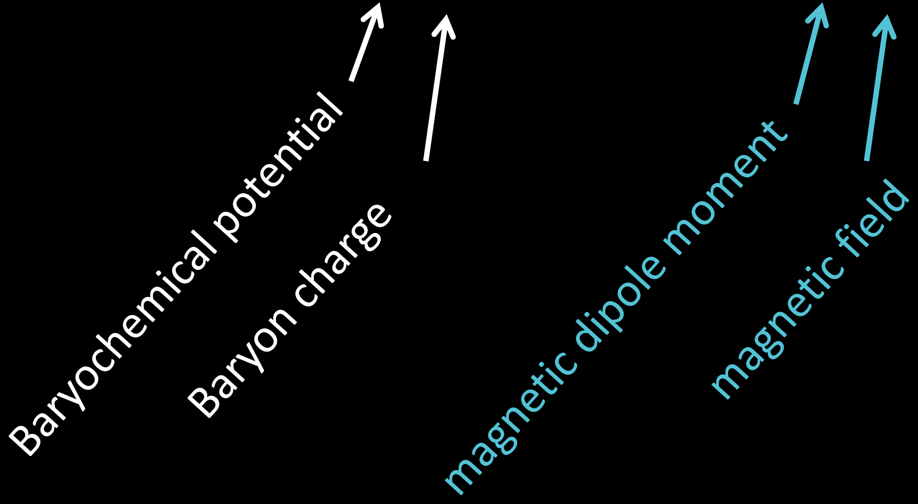
	BES average
Λ	6.8σ
anti-Λ	3.7σ

Extracting Vortical and Magnetic Contributions



- The data reveal a dominant *common* component and suggest a small splitting
- Magneto-hydro equilibrium interpretation

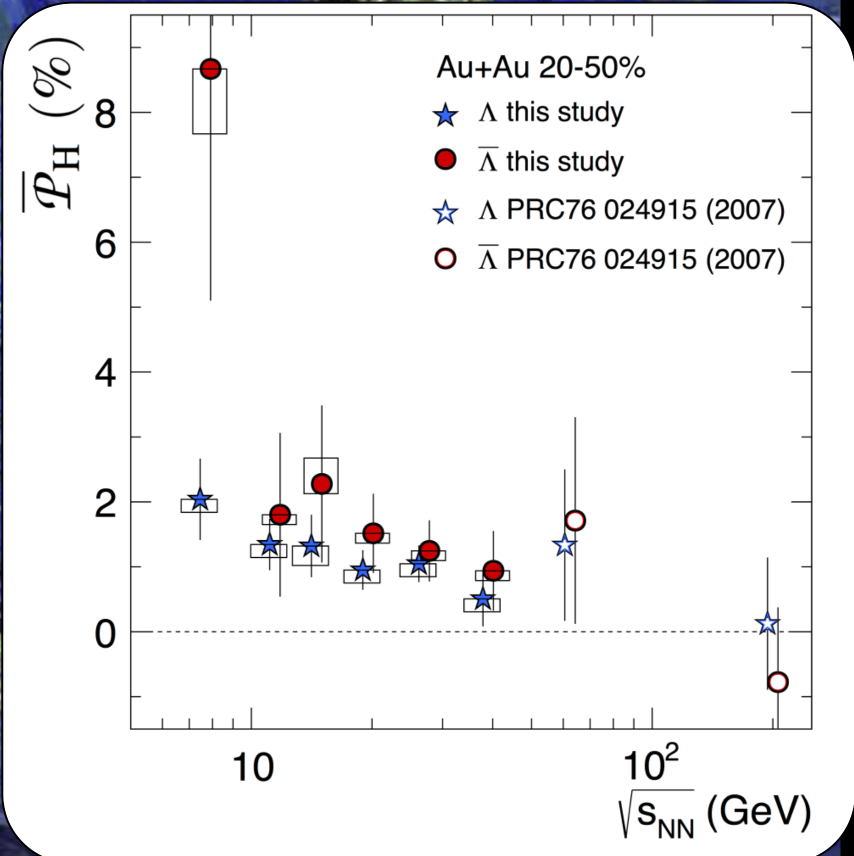
$$P \sim \exp(-E/T + \mu_B B/T + \vec{\omega}\cdot\vec{S}/T + \vec{\mu}\cdot\vec{B}/T)$$



Becattini, Karpenko, ML, Upsal, Voloshin PRC95, 054902 (2017). 1610.02506

* coupling to μ_B may produce similar [Becattini, Wang, Sorin...]

Extracting Vortical and Magnetic Contributions



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- Magneto-hydro equilibrium interpretation

$$P \sim \exp(-E/T + \mu_B B/T + \vec{\omega}\cdot\vec{S}/T + \vec{\mu}\cdot\vec{B}/T)$$

  - 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 the average: $\frac{\omega}{T} = P_{\Lambda} + P_{\bar{\Lambda}}$
  - B-field from the difference*: $\frac{B}{T} = \frac{1}{2\mu_{\Lambda}}\left(P_{\Lambda} - P_{\bar{\Lambda}}\right)$

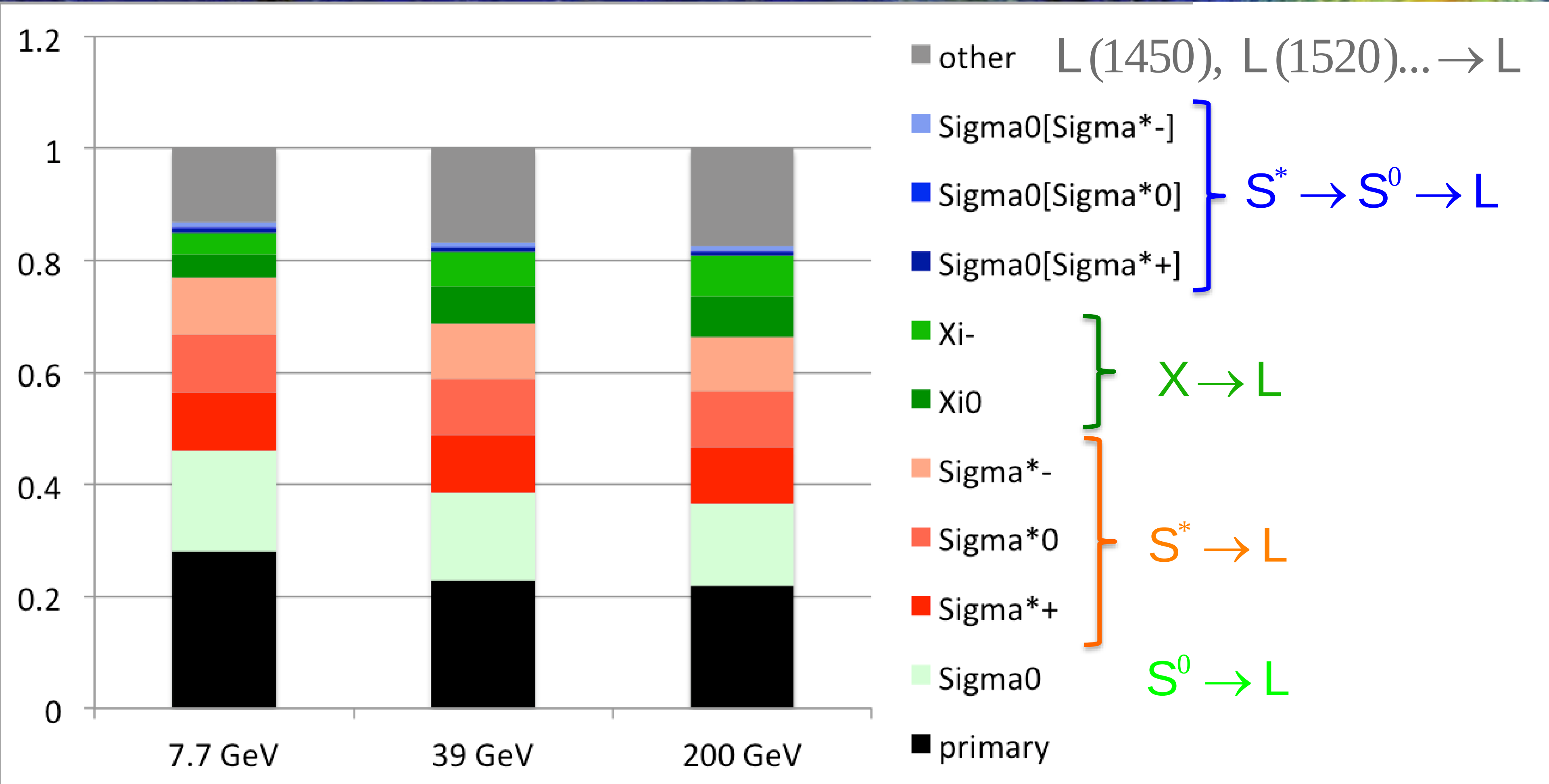
But even with topological cuts, significant feeddown from Σ^0, $\Xi^{0/-}$, $\Sigma^{*\pm/0}$...

... which themselves will be polarized...

Becattini, Karpenko, ML, Upsal, Voloshin PRC95, 054902 (2017). 1610.02506

* coupling to μ_B may produce similar [Becattini, Wang, Sorin...]

Extracting Vortical and Magnetic Contributions



But even with topological cuts, significant feeddown from S^0, $X^{0/-}$, $S^{*\pm/0}$...

... which themselves will be polarized...

Becattini, Karpenko, ML, Upsal, Voloshin PRC95, 054902 (2017). 1610.02506

Feed-down effects

$$\begin{pmatrix} \frac{\varpi}{T} \\ \frac{B}{T} \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_{R}\left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)S_R\left(S_R+1\right) & \frac{2}{3}\sum_{R}\left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)\left(S_R+1\right)m_R \\ \frac{2}{3}\sum_{\bar{R}}\left(f_{\bar{\Lambda}\bar{R}}C_{\bar{\Lambda}\bar{R}} - \frac{1}{3}f_{\bar{\Sigma}^0 \bar{R}}C_{\bar{\Sigma}^0 \bar{R}}\right)S_{\bar{R}}\left(S_{\bar{R}}+1\right) & \frac{2}{3}\sum_{\bar{R}}\left(f_{\bar{\Lambda}\bar{R}}C_{\bar{\Lambda}\bar{R}} - \frac{1}{3}f_{\bar{\Sigma}^0 \bar{R}}C_{\bar{\Sigma}^0 \bar{R}}\right)\left(S_{\bar{R}}+1\right)m_{\bar{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_{\Lambda}^{\mathrm{meas}} \\ P_{\bar{\Lambda}}^{\mathrm{meas}} \end{pmatrix}$$

$f_{\Lambda R}$ = fraction of Λs that originate from parent $R \to \Lambda$

$C_{\Lambda R}$ = coefficient of spin transfer from parent R to daughter Λ

$f_{\Sigma^0 R}$ = fraction of Λs that originate from parent $R \to \Sigma^0 \to \Lambda$

$C_{\Sigma^0 R}$ = coefficient of spin transfer from parent R to daughter Σ^0

From THERMUS

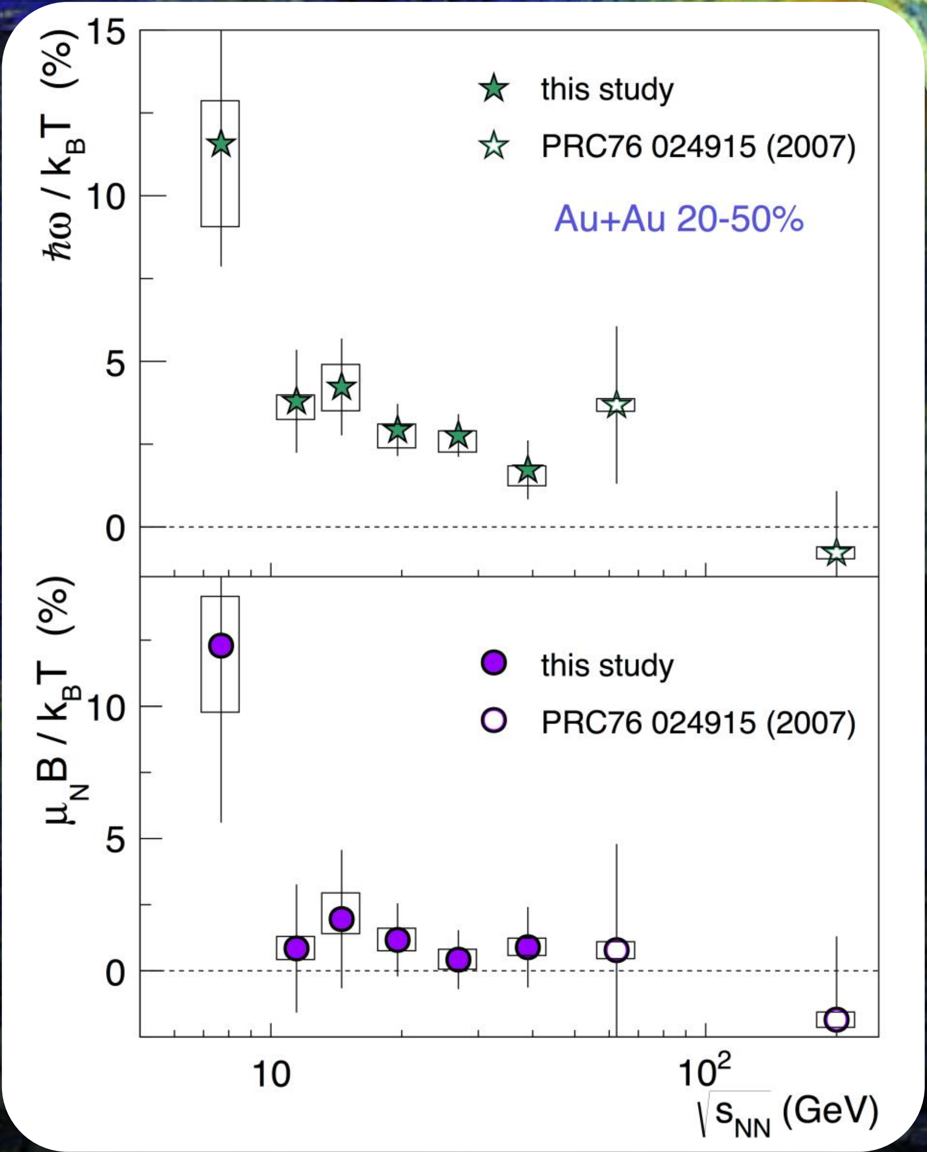
Decay	C
parity-conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+\ 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+\ 0^-$	1/3
parity-conserving: $3/2^- \to 1/2^+\ 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	+0.900
$\Xi^- \to \Lambda + \pi^-$	+0.927
$\Sigma^0 \to \Lambda + \gamma$	-1/3

TABLE I. Polarization transfer factors C (see eq. (31)) for important decays $X \to \Lambda(\Sigma)\pi$

Becattini, Karpenko, ML, Upsal, Voloshin PRC95, 054902 (2017). 1610.02506

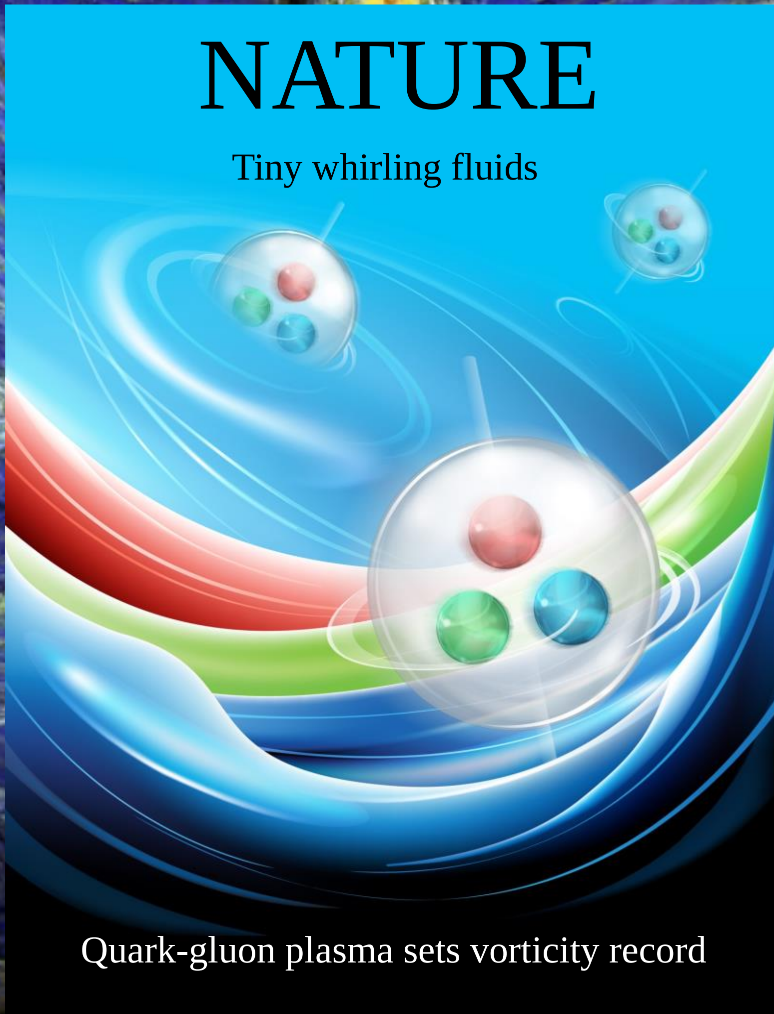
Extracted Physical Parameters

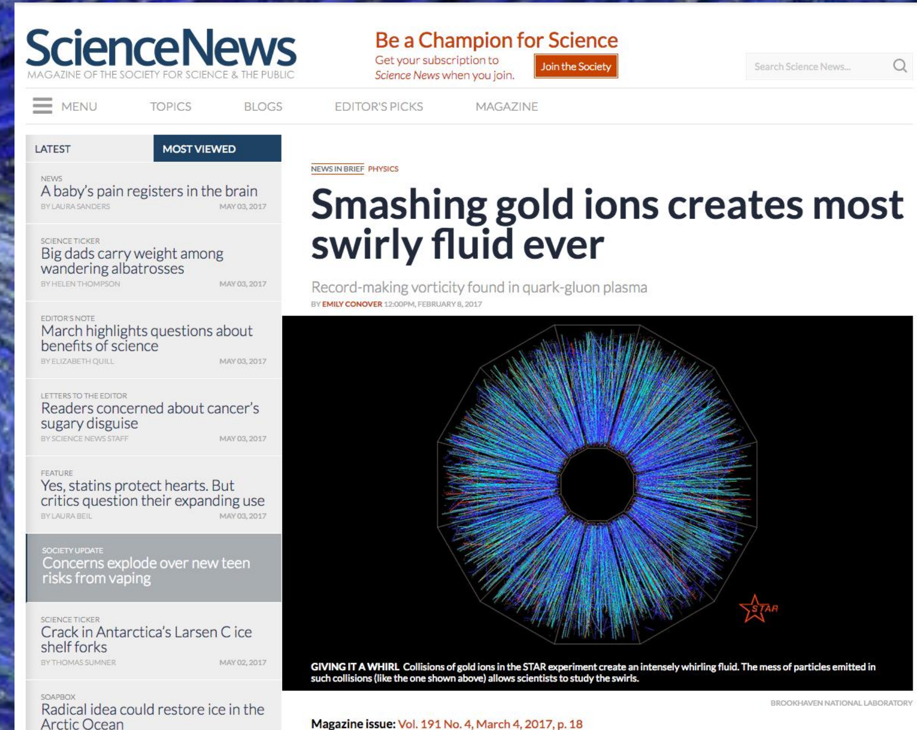
- Significant vorticity signal
  - (probably) falling with energy, despite increasing $J_{collision}$
  - $P_{\Lambda\,primary} = \frac{\omega}{2T} \approx 5\%$
- Magnetic field
  - positive value as expected, but... consistent with zero for all energies
  - (2σ effect for *average* of BES energies)
  - Higher statistics dataset for 27 GeV in run 2018 → hope for 5σ measurement



$\sqrt{s_{NN}}$	7.7	11.5	14.5	19.6	27	39	62.4
P_V	2.7σ	3.0σ	1.9σ	3.5σ	4.5σ	2.1σ	1.6σ

BES ave
5.4σ





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Smashing gold ions creates most swirly fluid ever

Record-making vorticity found in quark-gluon plasma

BY EMILY CONOVER 12:00PM, FEBRUARY 8, 2017

STAR

GIVING IT A WHIRL Collisions of gold ions in the STAR experiment create an intensely whirling fluid. The mess of particles emitted in such collisions (like the one shown above) allows scientists to study the swirls.

BROOKHAVEN NATIONAL LABORATORY

Magazine issue: Vol. 191 No. 4, March 4, 2017, p. 18

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Whirlpools might have stirred up baby universe's soup

Computer simulations suggest possibility of vortices in quark-gluon plasma

BY EMILY CONOVER 7:00AM, NOVEMBER 18, 2016

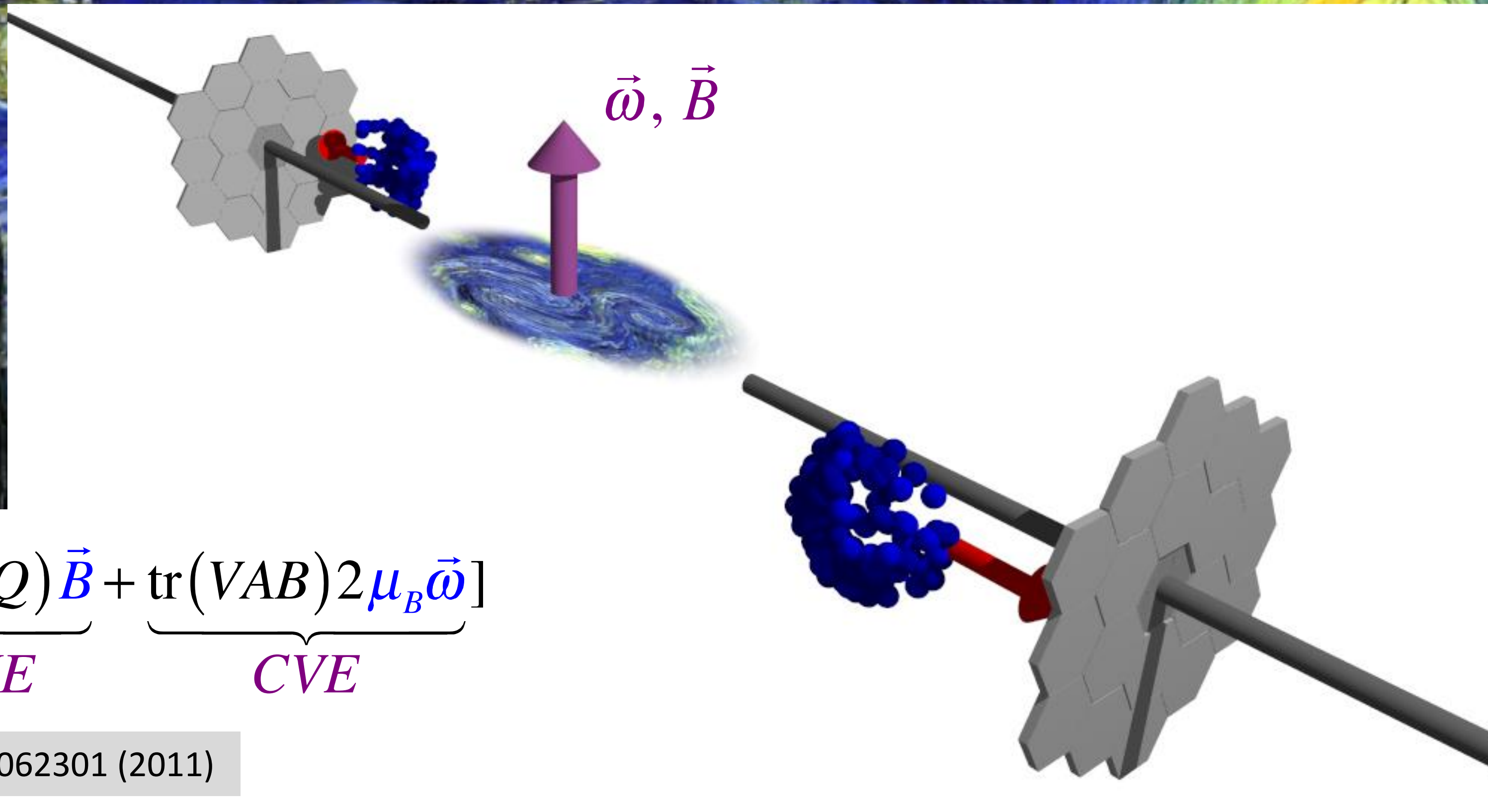
HOT STUFF A collision of two heavy ions produces an extremely hot, dense state of matter called quark-gluon plasma (illustration shown). Computer simulations indicate that swirling patterns could form in this material.

CERN

Magazine issue: Vol. 190, No. 12, December 10, 2016, p. 9

https://www.sciencenews.org/article/whirlpools-might-have-stirred-baby-universes-soup
https://www.sciencenews.org/article/smashing-gold-ions-creates-most-swirly-fluid-ever

Relevance to Chiral Phenomena



$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\underbrace{\mathrm{tr}(VAQ)\vec{B}}_{CME} + \underbrace{\mathrm{tr}(VAB)2\mu_B\vec{\omega}}_{CVE}]$$

Kharzeev & Son PRL**106** 062301 (2011)

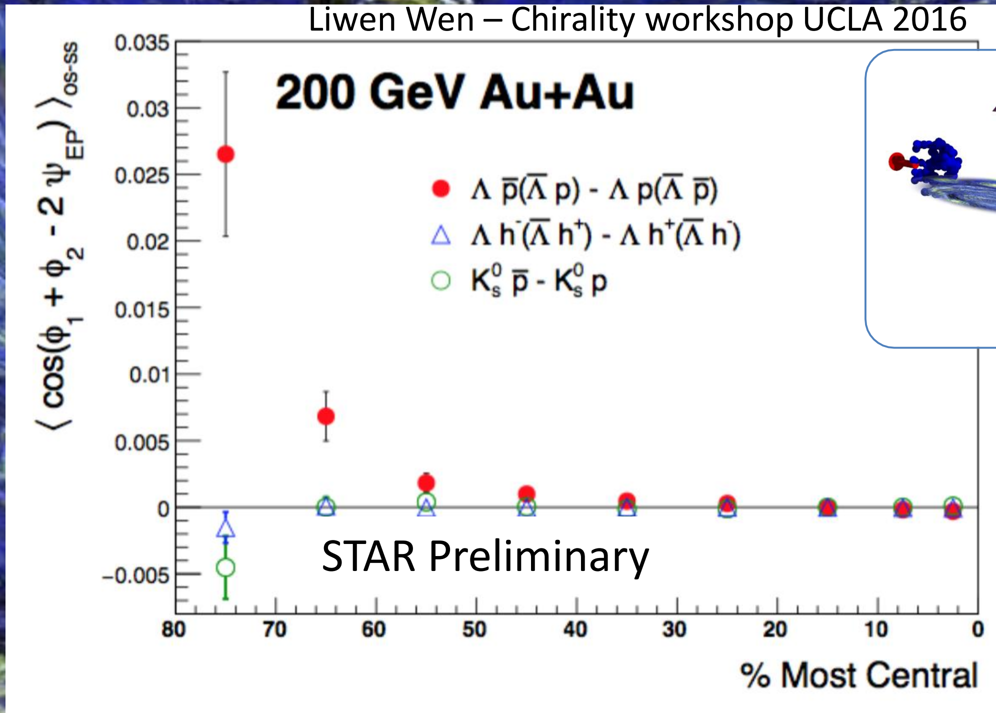
$SU(3)$:

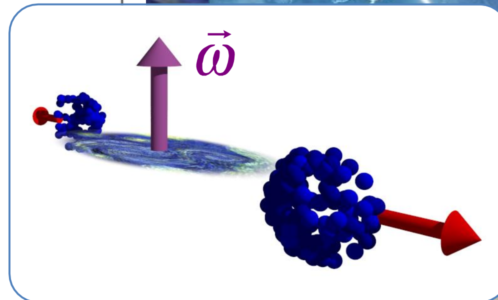
$$J_E = \frac{N_c \mu_5}{3\pi^2} B \quad \rightarrow \text{separation of +/- along } \vec{B}$$

$$J_B = \frac{N_c \mu_5}{\pi^2} \mu_B \omega \quad \rightarrow \text{separation of B/}\bar{\text{B}} \text{ along } \vec{\omega}$$

If chiral symmetry is restored, μ_5 characterizes the fluctuation into a QCD vacuum with different topological (Chern-Simons) number

Chiral Vortical Effect

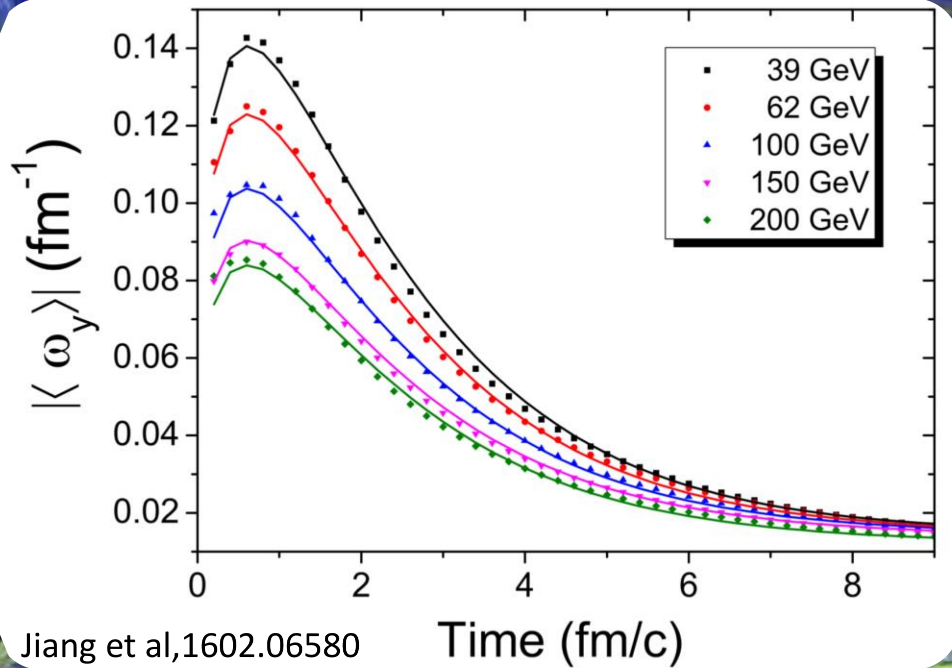




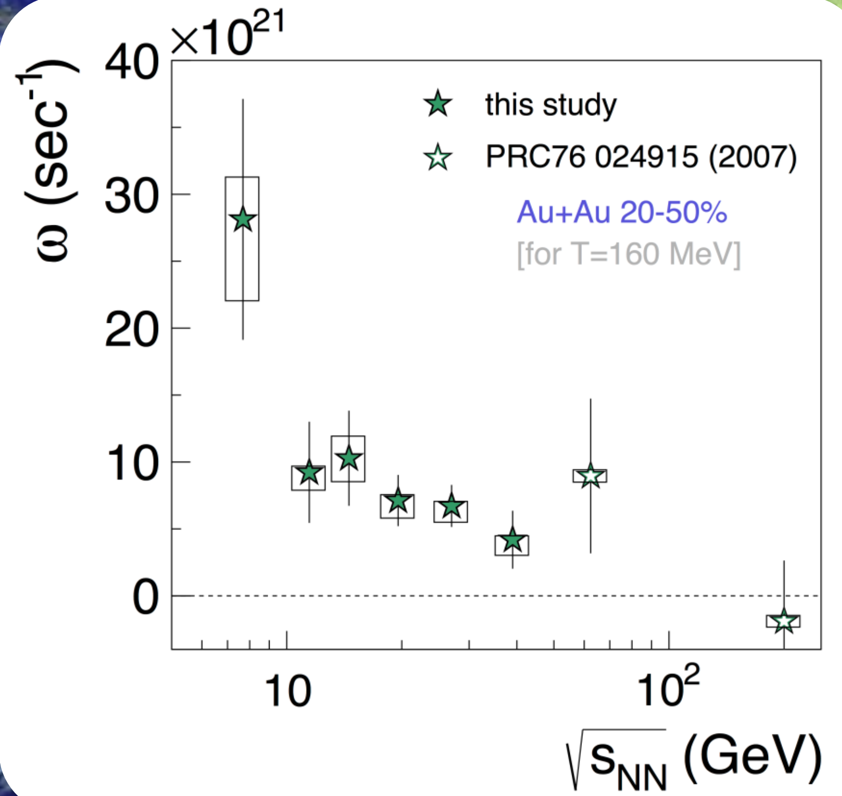
$$J_B = \frac{N_c \mu_5}{\pi^2} \mu_B \omega \quad \rightarrow \text{separation of B/}\bar{\text{B}}\text{ along } \vec{\omega}$$

- (Some) effect observed (preliminary) - Magnitude, sign fluctuates event-to-event, according to μ_5 .

Chiral Vortical Effect



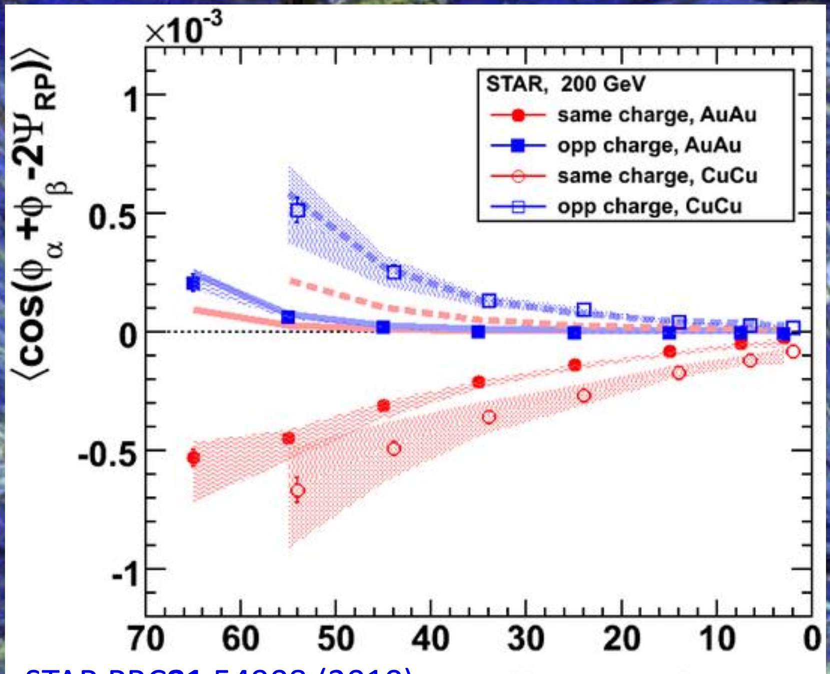
Jiang et al,1602.06580



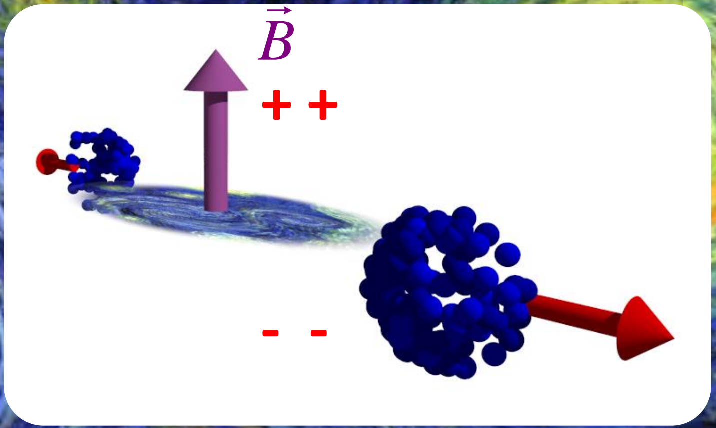
$$J_B = \frac{N_c \mu_5}{\pi^2} \mu_B \omega \quad \rightarrow \text{separation of } B/\bar{B} \text{ along } \vec{\omega}$$

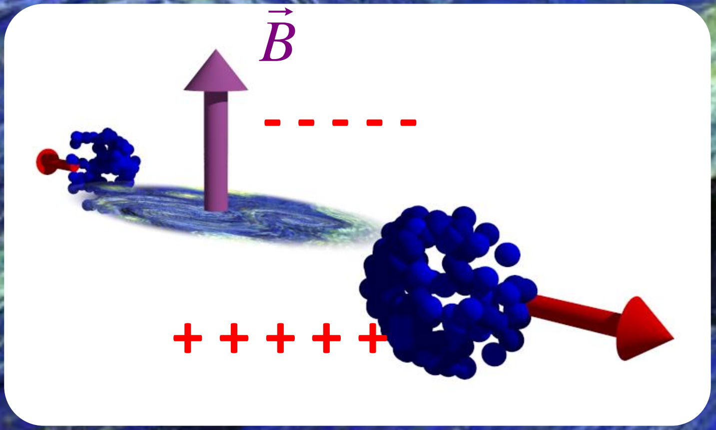
- Effect observed (preliminary) - Magnitude, sign fluctuates according to μ_5 .
- **Connection w/ underlying physics uncalibrated**
- Interpretation of STAR result: ω~0.02-0.09 fm^{-1}
  - in expected range (see also Csernai 2014)

Chiral Magnetic Effect



STAR PRC**81** 54908 (2010)



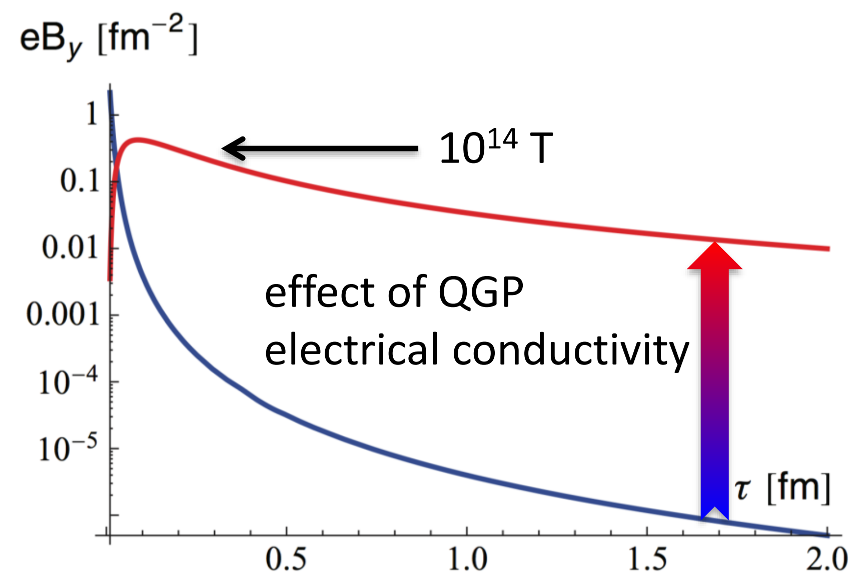


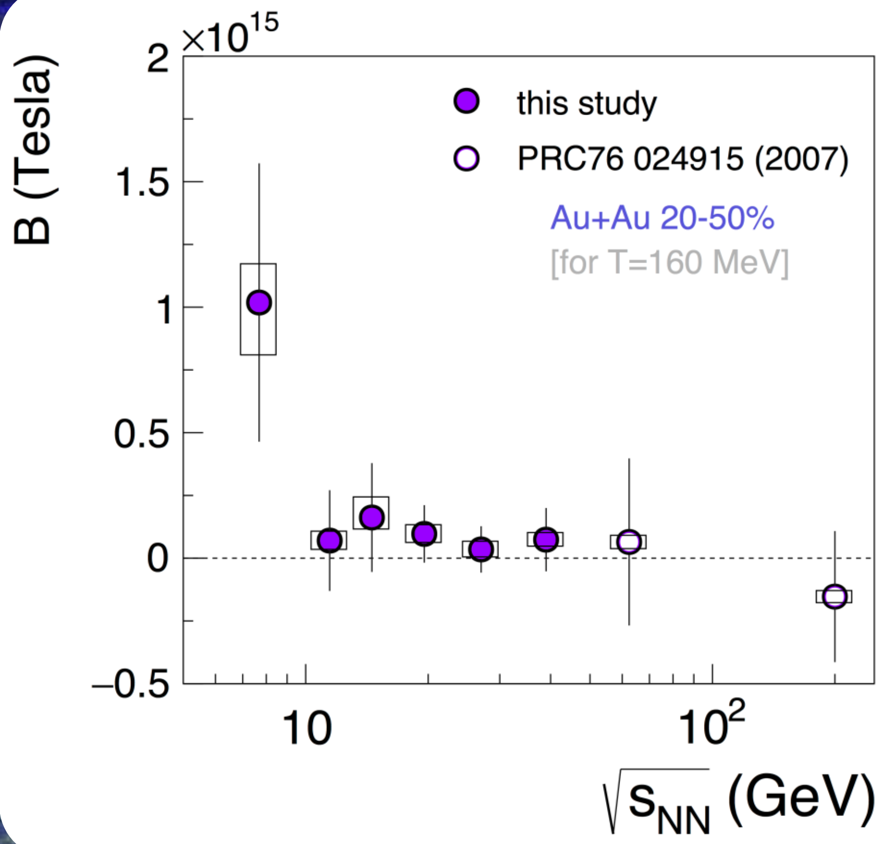
$$J_E = \frac{N_c \mu_5}{3\pi^2} B \qquad \rightarrow \text{separation of +/- along } \vec{B}$$

- (Some) effect observed: Magnitude, sign fluctuates event-to-event, according to μ_5 .

Chiral Magnetic Effect

Gursoy, Kharzeev & Rajagopal PRC**89** 054905 (2014)





$$J_E = \frac{N_c \mu_5}{3\pi^2} B \qquad \rightarrow \text{separation of +/- along } \vec{B}$$

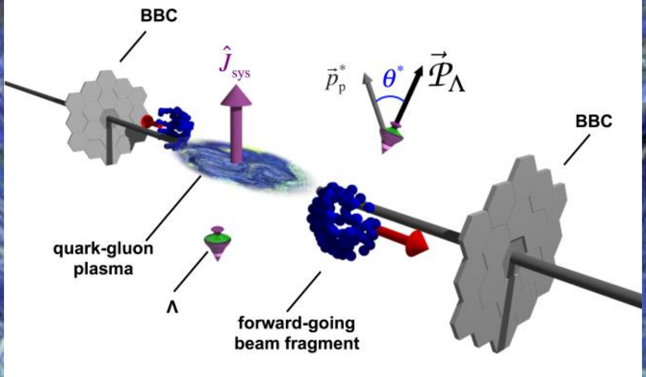
- (Some) effect observed: Magnitude, sign fluctuates event-to-event, according to μ_5 .
- Connection with underlying physics complicated by **orders-of-magnitude uncertainty in B-field & time-dependence**
- STAR result: consistent with B=0
  - reducing error bars may be interesting! (B~$10^{13\text{-}14}$ T?)

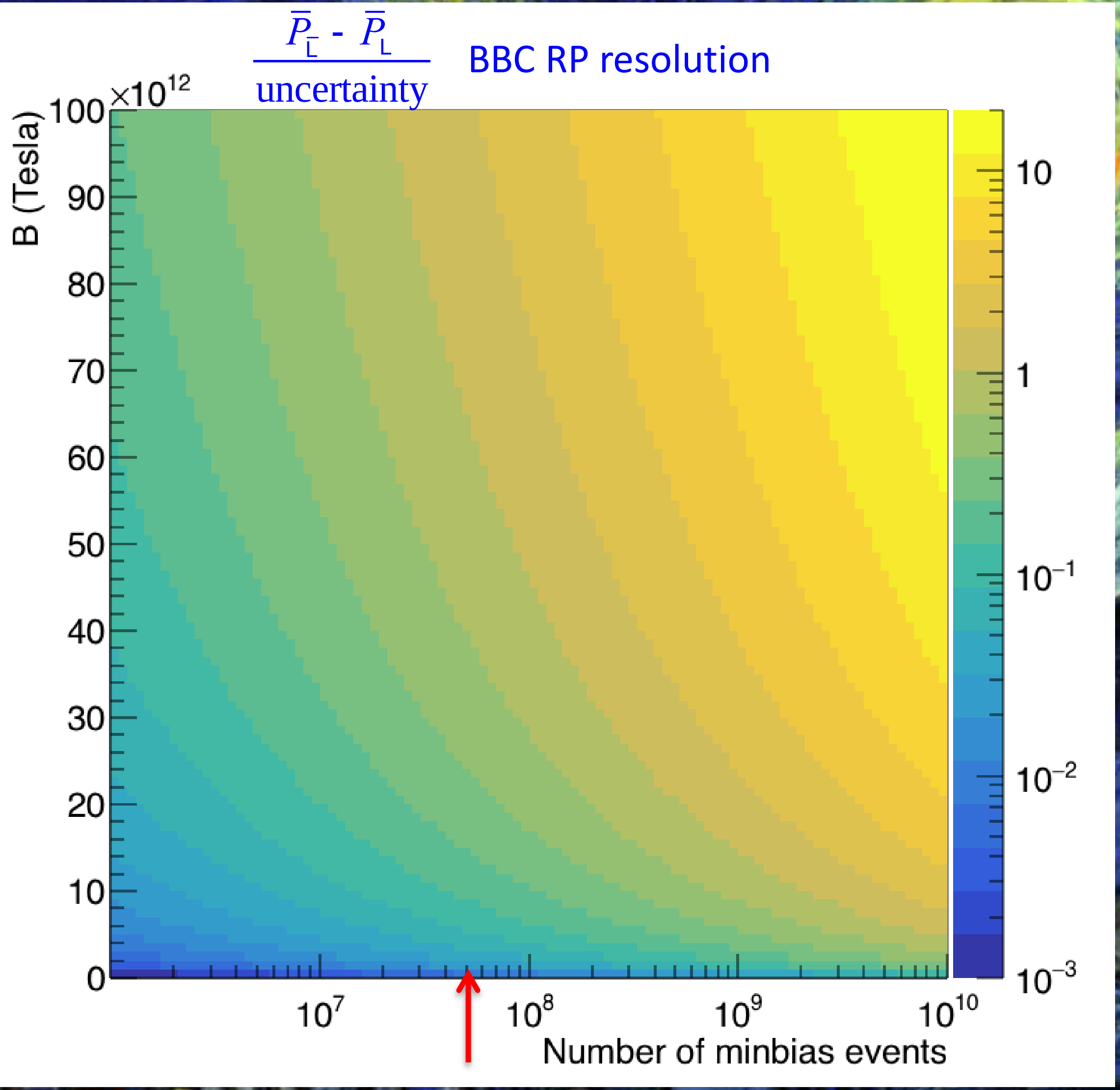
$m_p^2 = 2\times 10^4\ \text{MeV}^2 = 10^{14}\ \text{T}$

$1\ \text{fm}^{-2} = 2\, m_p^2$

Magnetic splitting? Higher-statistics run at 27 GeV

BES-I: 67x10^6 min. bias events

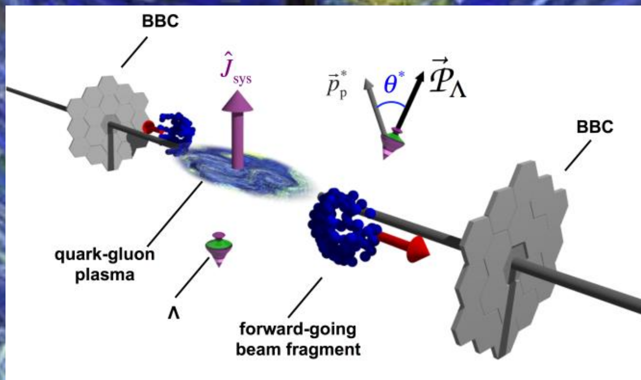




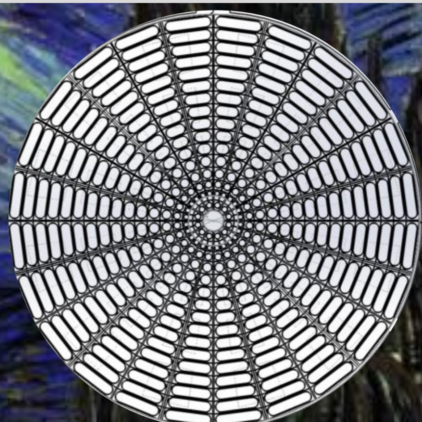
- Fields on order 10^{13}-10^{14} T expected (for how long...?)
- Increased statistics and RP resolution could allow clear measurement of magnetic splitting

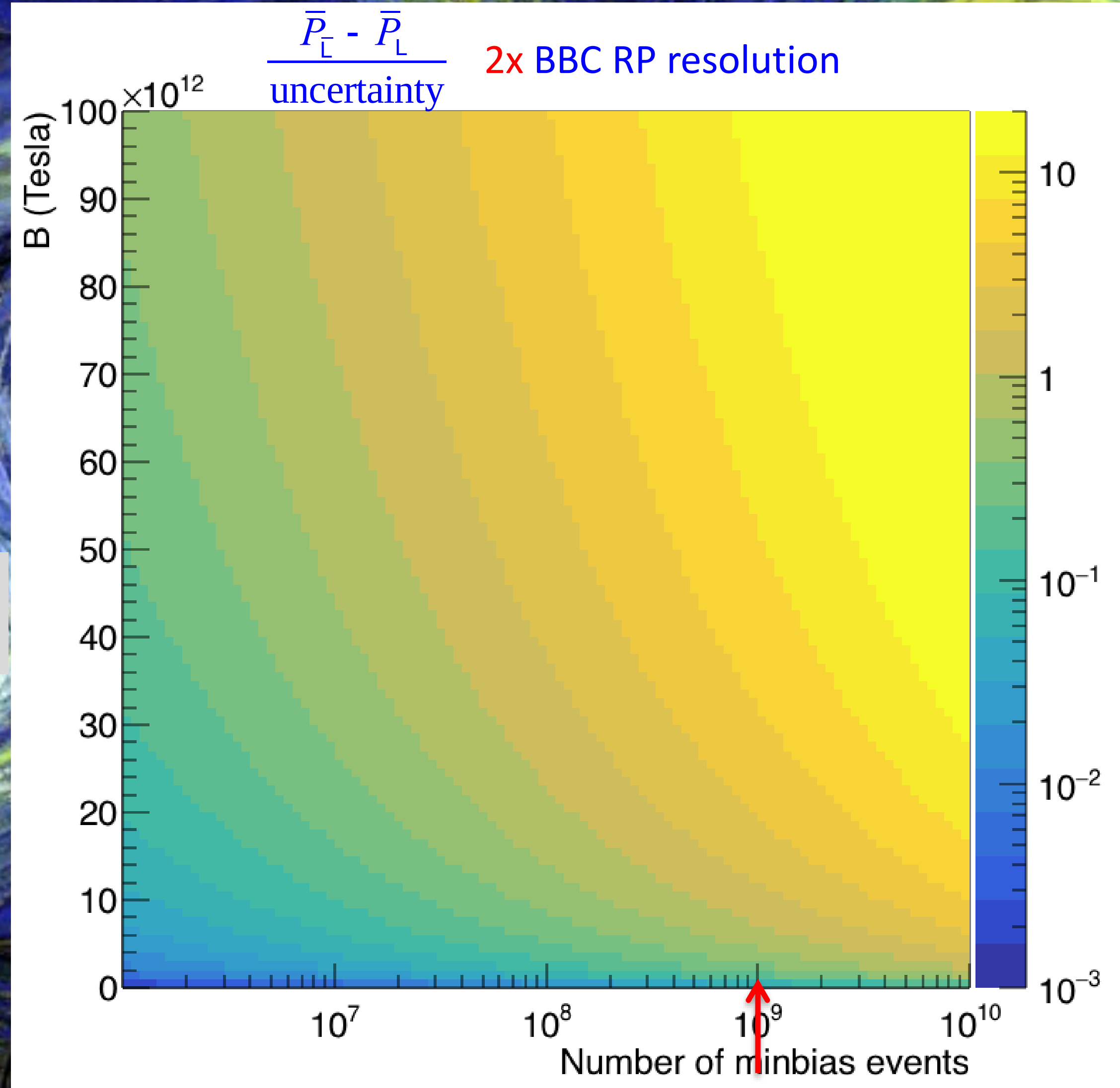
Magnetic splitting? Higher-statistics run at 27 GeV

BES-I: 67x10⁶ min. bias events



2018 proposal: 10^9 min. bias events
and EPD upgrade detector (talk Friday)



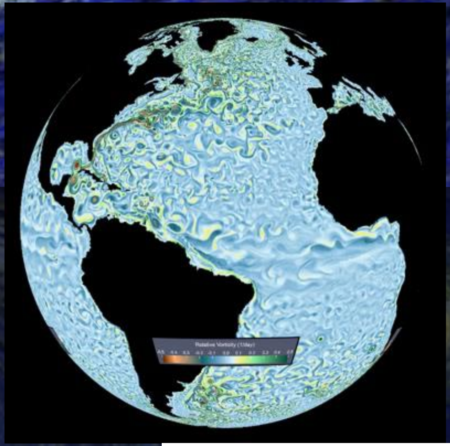


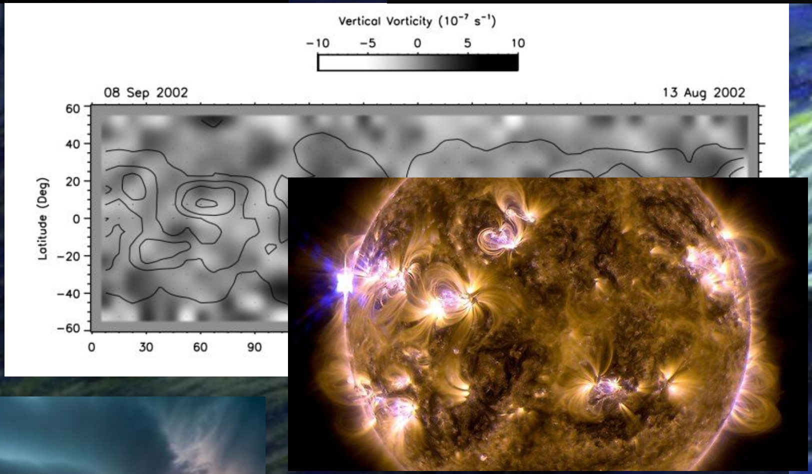
- Fields on order 10^{13}-10^{14} T expected (for how long...?)
- Increased statistics and RP resolution could allow clear measurement of magnetic splitting

BROADER CONTEXT…

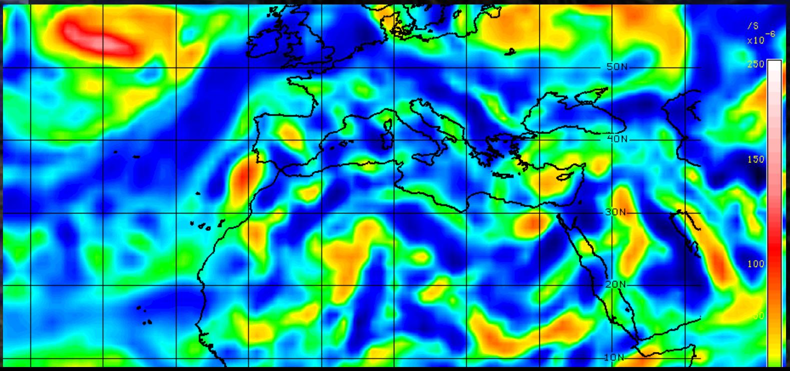
World records

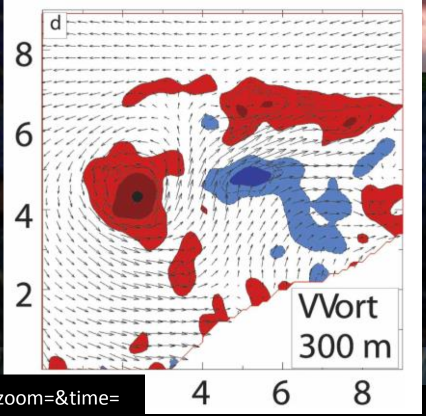
- ocean flows: $\omega \sim 10^{-5}\ s^{-1}$
- terrestrial atmosphere: $\omega \sim 10^{-4}\ s^{-1}$
- core of supercell tornado : $\omega \sim 10^{-1}\ s^{-1}$
- solar subsurface flow: : $\omega \sim 10^{-6}\ s^{-1}$
- high vorticity ($10^{-4}\ s^{-1}$) in the “collar” of Jupiter’s Great Red Spot
- Heated, rotating soap bubbles ($10^{2}\ s^{-1}$)



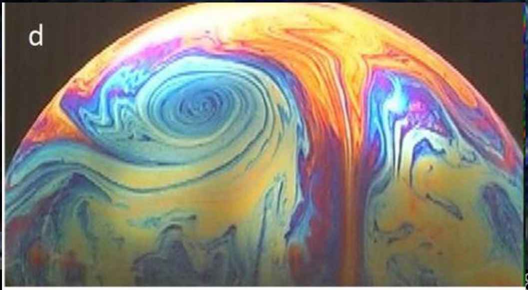


Atmospheric vorticity as of 5:00 today





Heated soap bubble



http://tropic.ssec.wisc.edu/real-time/windmain.php?&basin=europe&sat=wm7&prod=vor&zoom=&time=

World records

- ocean flows: ω ~ 10^{-5} s^{-1}
- terrestrial atmosphere: ω ~ 10^{-4} s^{-1}
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- solar subsurface flow: : ω ~ 10^{-6} s^{-1}
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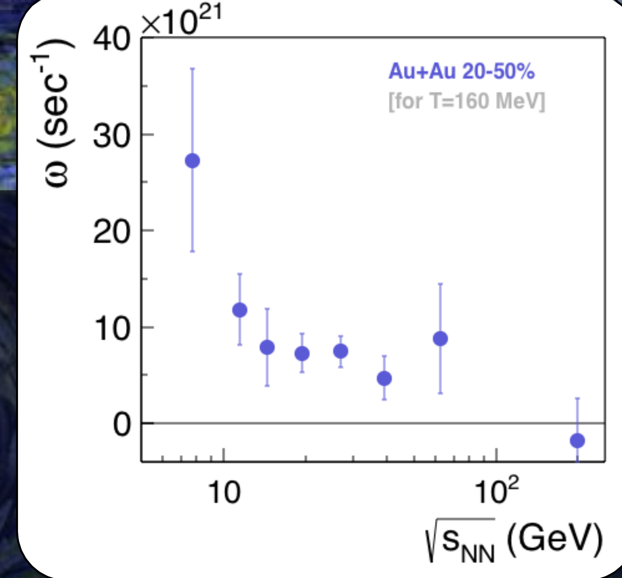
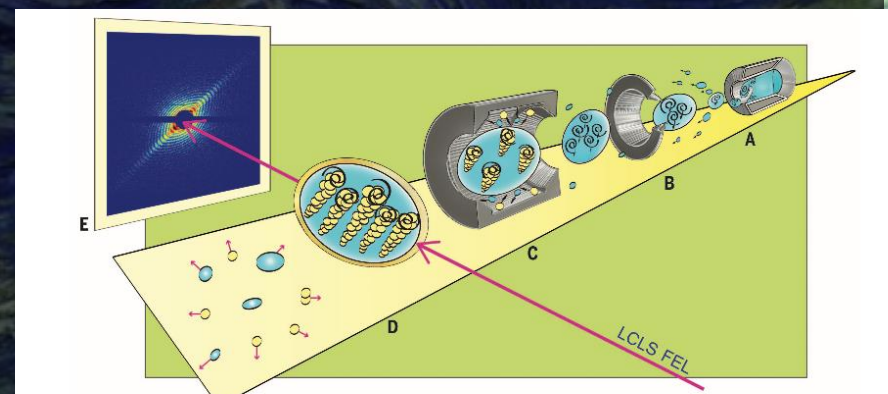




- Max vorticity in bulk superfluid He-II: ω ~ 150 s^{-1}
  - R. Donnelly, Ann. Rev. Fluid Mech. 25, 325 (1993)
- Max vorticity in nanodroplets of superfluid He-II: 10^6 s^{-1}
  - Gomez et al, Science 345 (2014) 903

RHIC produces the least viscous fluid.

RHIC produces the most vortical fluid!

2016 - Birth of fluid spintronics

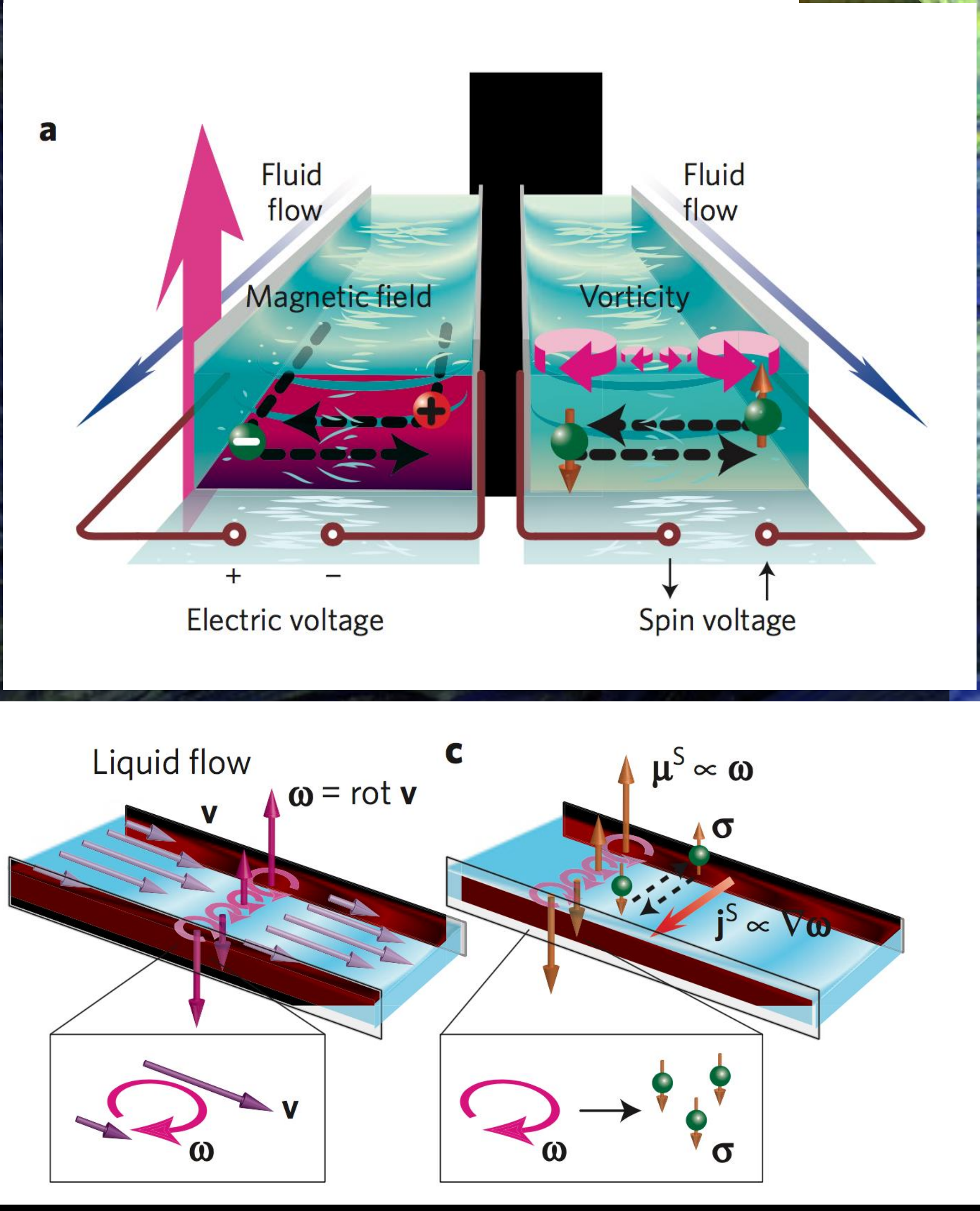
Recent discovery in flowing Hg:

- vorticity generation in flowing fluid due to anisotropy and viscosity
- transfer of macroscopic fluid vorticity to quantum spin

→ spin voltage and spin current across channel (sim Hall effect)

→ voltage & power generation

Takahashi et al, Nature Physics **12** (2016) 52



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Takahashi et al, Nature Physics **12** (2016) 52

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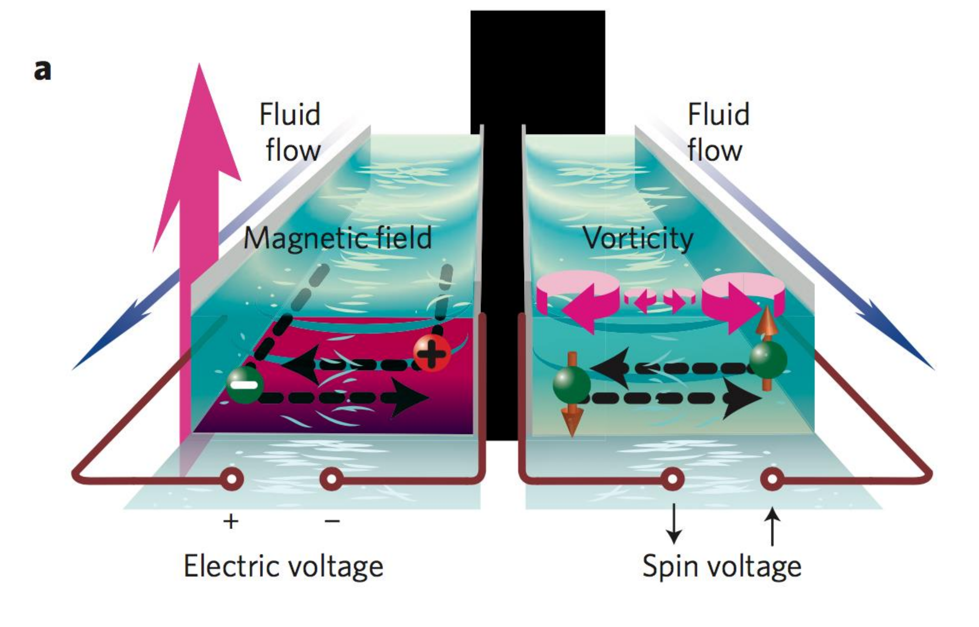

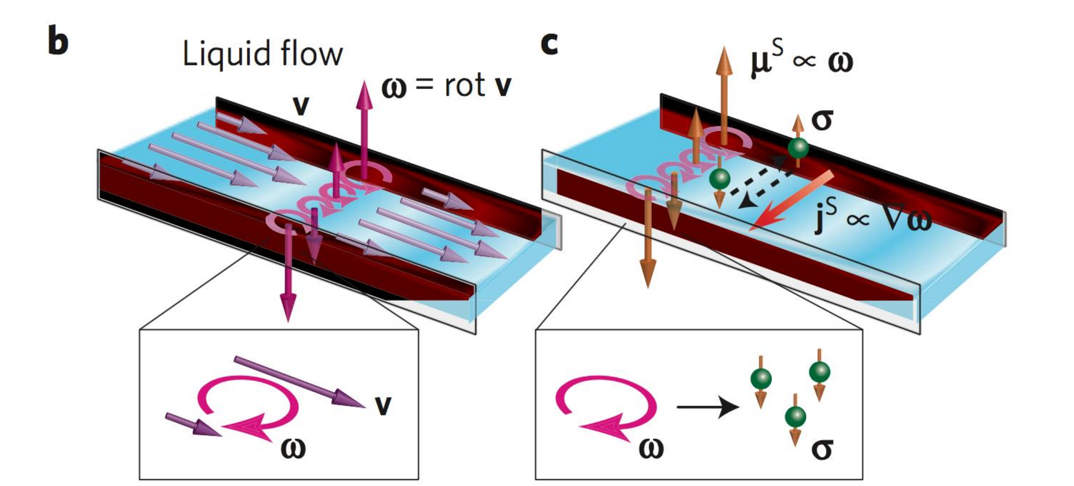

Macroscopic rotation to quantum alignment

- Transfer of macro-rotation to (quantum) spin alignment, quite rare!
- First observation: S. J. Barnett, Magnetization by Rotation

Second Series. *October, 1915* *Vol. VI., No. 4*

THE

PHYSICAL REVIEW.

MAGNETIZATION BY ROTATION.[1]

BY S. J. BARNETT.

A full account of the work summarized here, and presented to the American Physical Society at its meetings of last December and April, will be published in the *Physical Review*.

S. J. BARNETT

THE OHIO STATE UNIVERSITY

Recent investigations

PHYSICAL REVIEW B **92**, 174424 (2015)

Barnett effect in paramagnetic states

Masao Ono,[1,2,*] Hiroyuki Chudo,[1,2] Kazuya Harii,[1,2] Satoru Okayasu,[1,2] Mamoru Matsuo,[1,2] Jun'ichi Ieda,[1,2] Ryo Takahashi,[1,2,3,4] Sadamichi Maekawa,[1,2] and Eiji Saitoh[1,2,3,4]

[1]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*
[2]*ERATO, Japan Science and Technology Agency, Sendai 980-8577, Japan*
[3]*WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[4]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

(Received 16 June 2015; revised manuscript received 27 October 2015; published 30 November 2015)

We report the observation of the Barnett effect in paramagnetic states by mechanically rotating gadolinium (Gd) metal with a rotational frequency of up to 1.5 kHz above the Curie temperature. An *in situ* magnetic measurement setup comprising a high-speed rotational system and a fluxgate magnetic sensor was developed for the measurement. Temperature dependence of the observed magnetization follows that of paramagnetic susceptibility, indicating that any emergent magnetic field is proportional to the rotational frequency and is independent of temperature. From the proportionality constant of the emergent field, the gyromagnetic ratio of Gd is calculated to be $-29 \pm 5\,\mathrm{GHz/T}$. This study revisits the primordial issue of magnetism with modern technologies to shed new light on the fundamental spin-rotation coupling.

DOI: 10.1103/PhysRevB.92.174424 PACS number(s): 75.80.+q, 71.20.Eh, 71.18.+y

Recent investigations

PHYSICAL REVIEW B **92**, 174424 (2015)

Barnett effect in paramagnetic states

Masao Ono,[1,2,*] Hiroyuki Chudo,[1,2] Kazuya Harii,[1,2] Satoru Okayasu,[1,2] Mamoru Matsuo,[1,2] Jun'ichi Ieda,[1,2]
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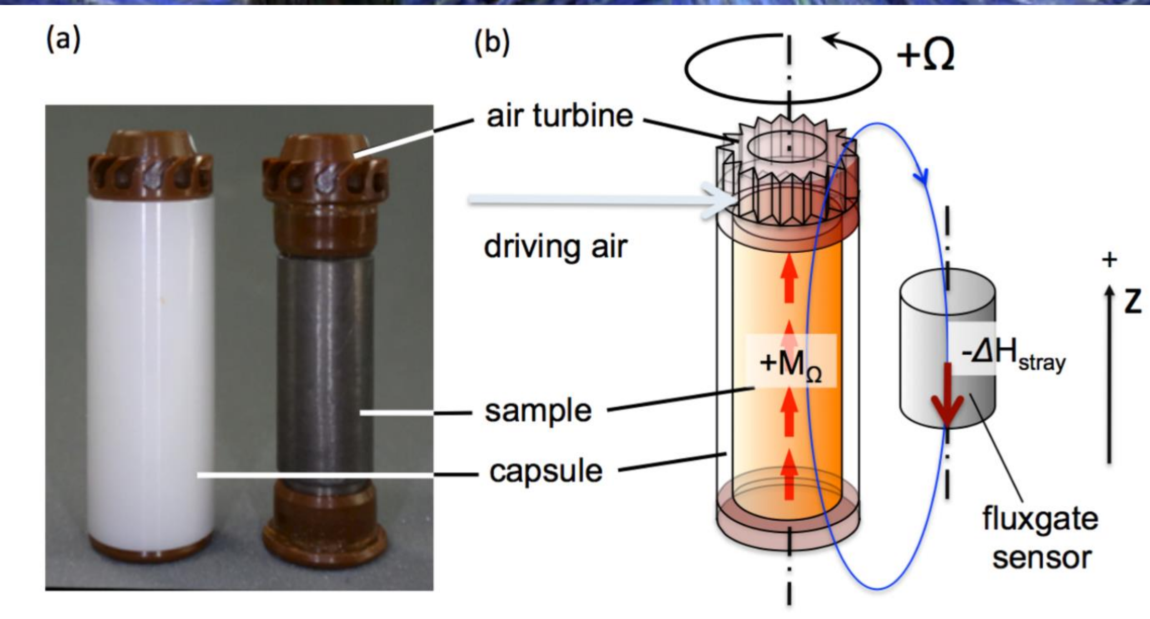


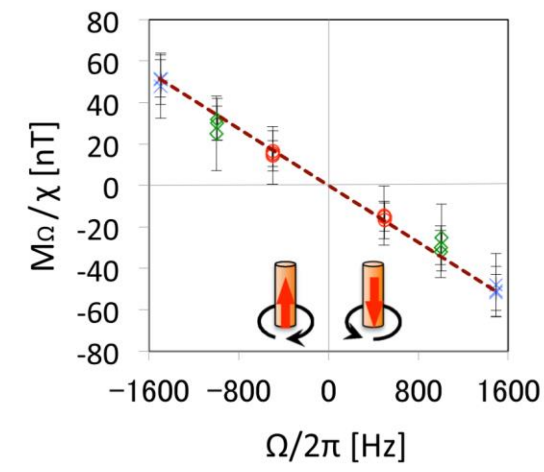
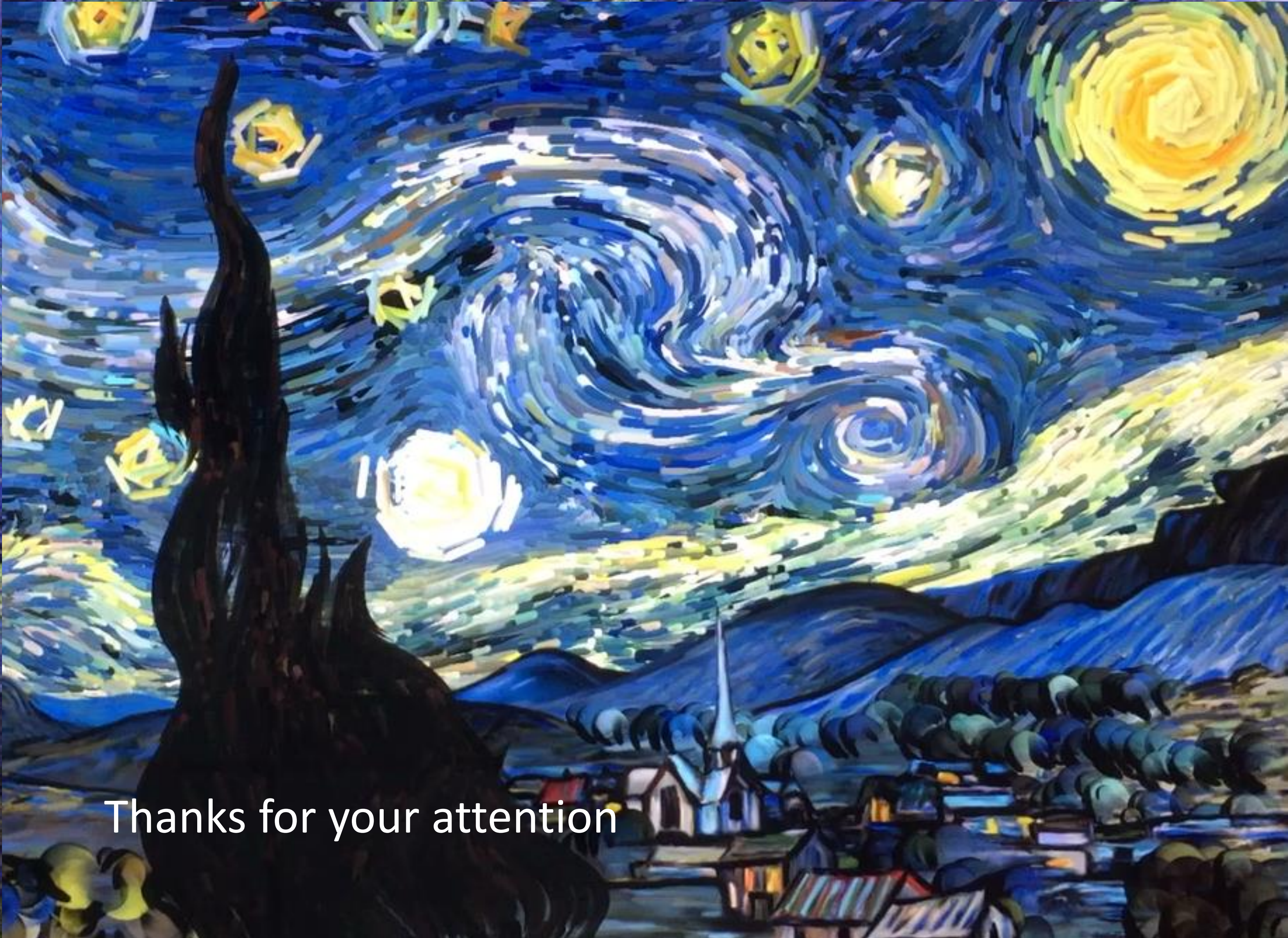


FIG. 4. (Color online) Rotational frequency dependence of M_Ω/χ. The dotted line is the linear fit of all experimental results in the temperature range of 297–305 K. The inverse of the slope of this fitting line is -29 ± 5 GHz/T.

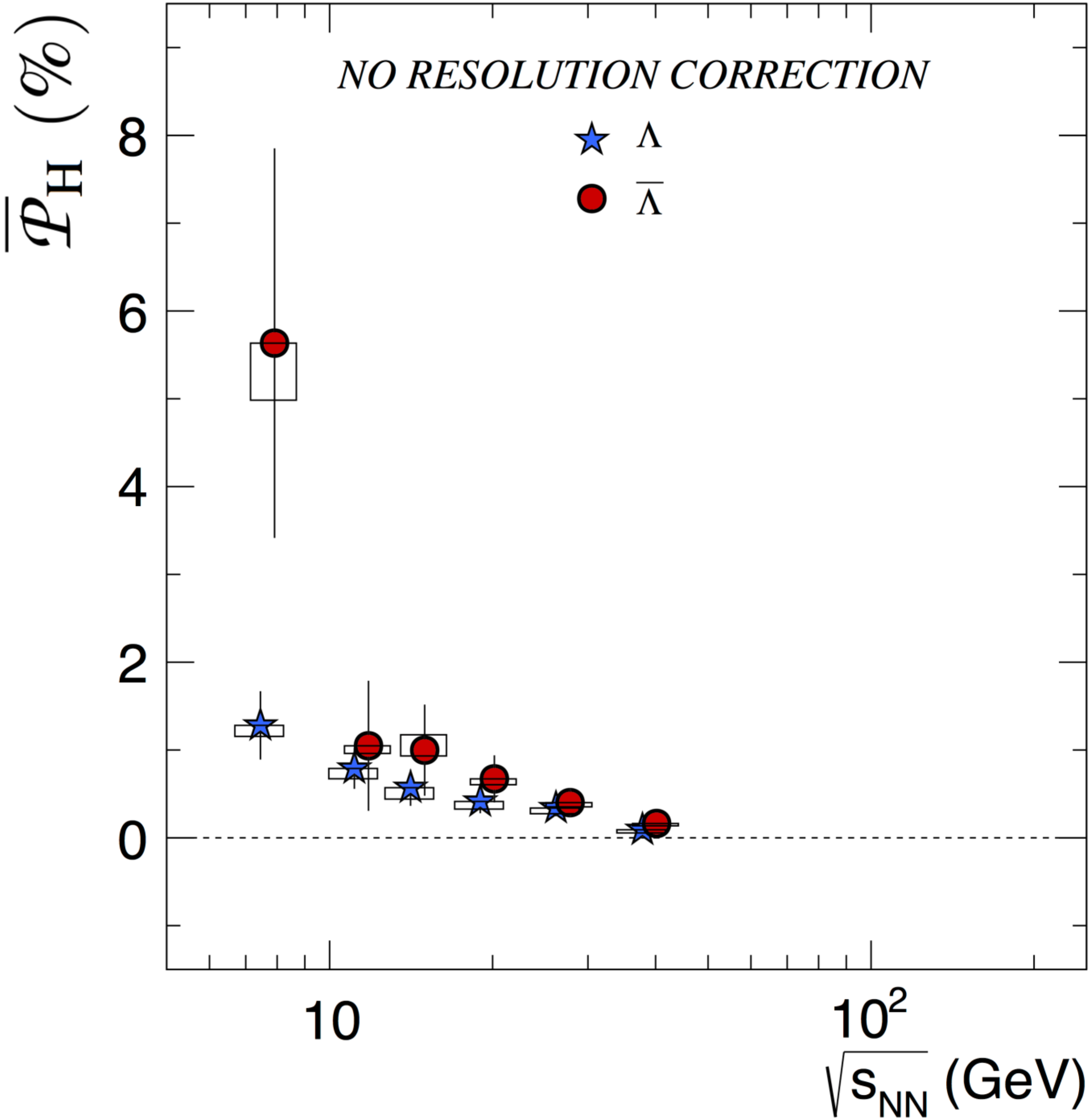
Summary

- Non-central heavy ion collisions create QGP with high vorticity
  - fundamental feature of *any* fluid, unmeasured until now
- Huge and rapidly-changing B-field in non-central collisions
  - theoretical predictions vary by orders of magnitude
- Global hyperon polarization: unique probe of vorticity & B-field
  - non-exotic, non-chiral
- STAR has made the first observation of global Λ polarization
  - ~5-6 sigma effect energy-averaged
- Interpretation in statistical magnetic-vortical model:
  - clear vortical component of expected sign, magnitude for $\sqrt{s_{NN}} < 30$ GeV
  - magnetic component of expected sign, magnitude *hinted at*, but ~0
- Fluid at RHIC
  - highest vorticity fluid
  - rare example of macro-quantum rotation transfer

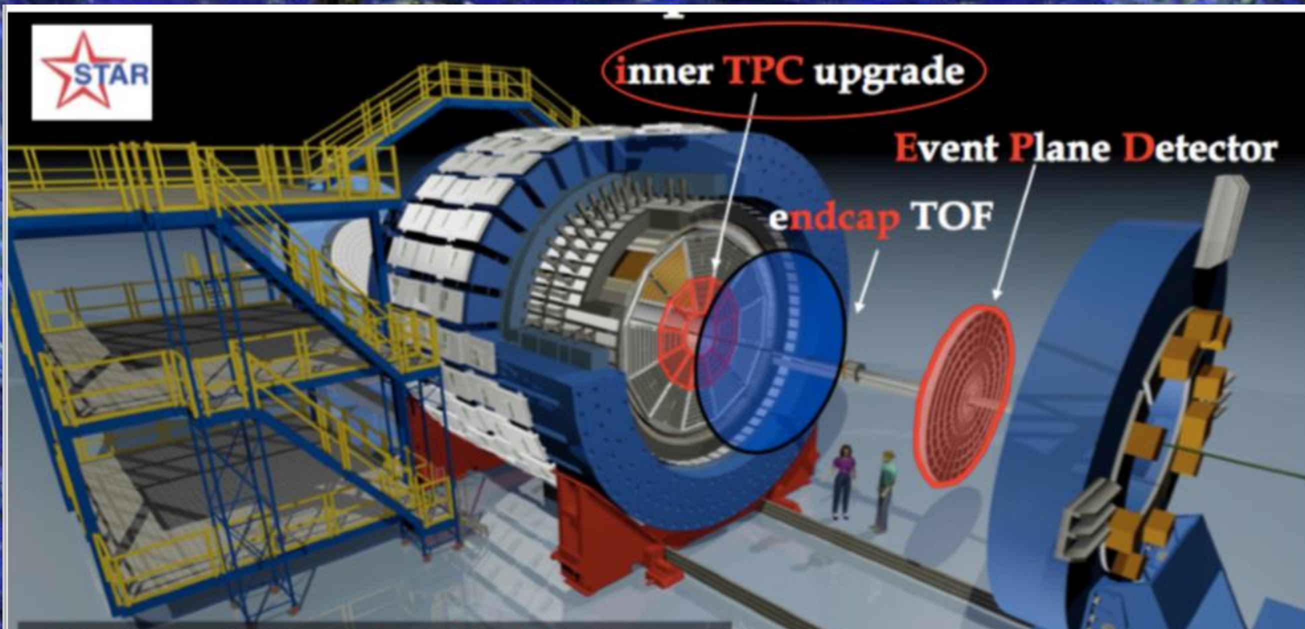


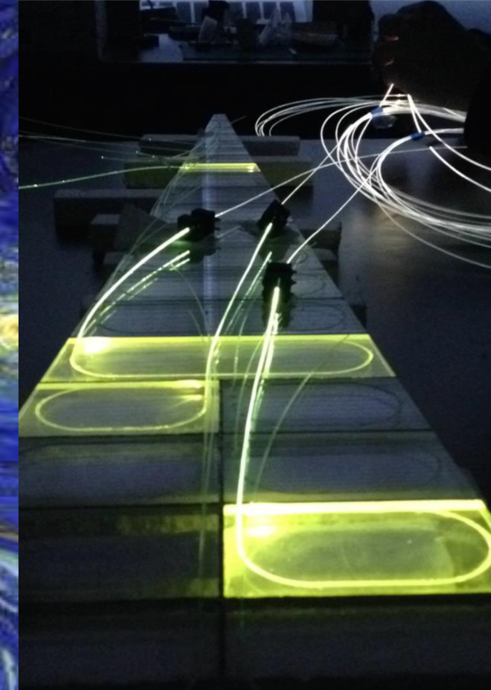
Thanks for your attention

END


NO RESOLUTION CORRECTION
Λ
$\bar{\Lambda}$
$\overline{\mathcal{P}}_{\mathrm{H}}$ (%)
8
6
4
2
0
10
10^2
$\sqrt{s_{NN}}$ (GeV)

Next steps – experimental: BES II





$$d\bar{P}_{\mathrm{H}} \ \mu \left(R_{\mathrm{EP}}^{(1)} \sqrt{\#\mathrm{L}} \right)^{-1}$$

$\sqrt{S_{NN}}$ (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

- Dedicated high-statistics running
- Collider (e-cooling) & detector upgrades
- Finer-grained measurements
- Better control on initial conditions (RP)
- Forward tracking/PID
- fixed-target mode – full coverage of FAIR energies
- Detector upgrades

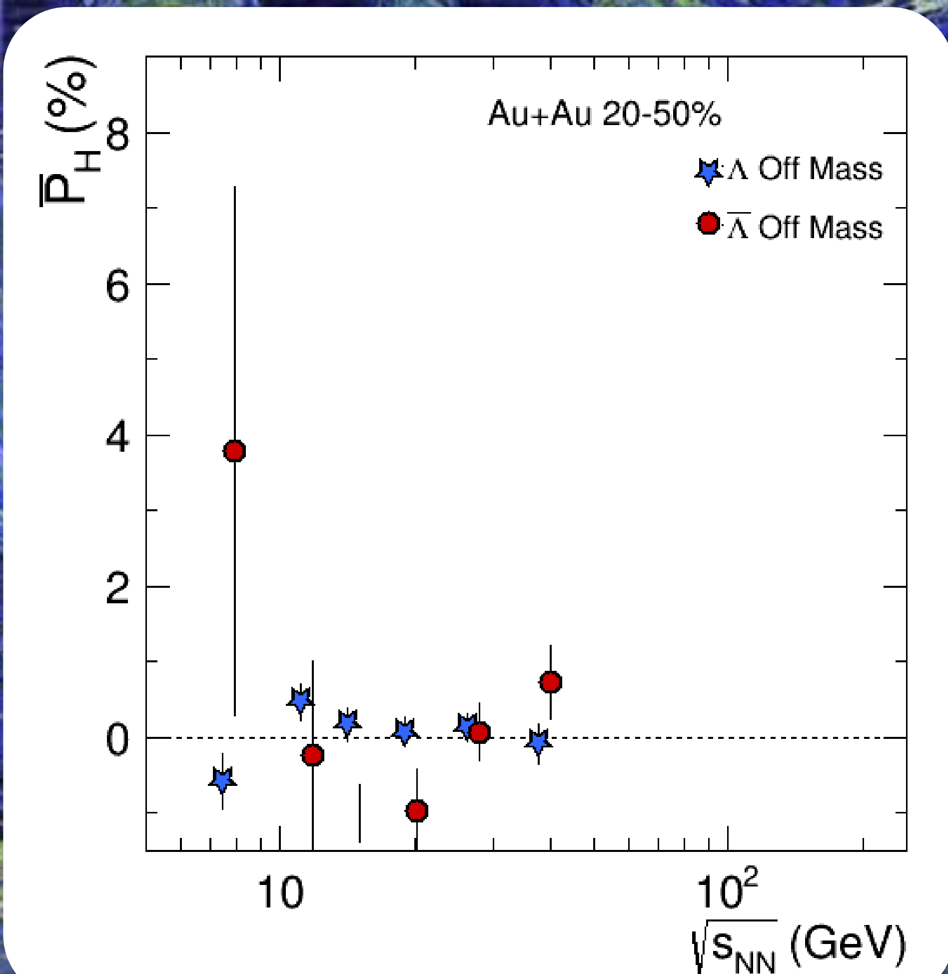
World record?

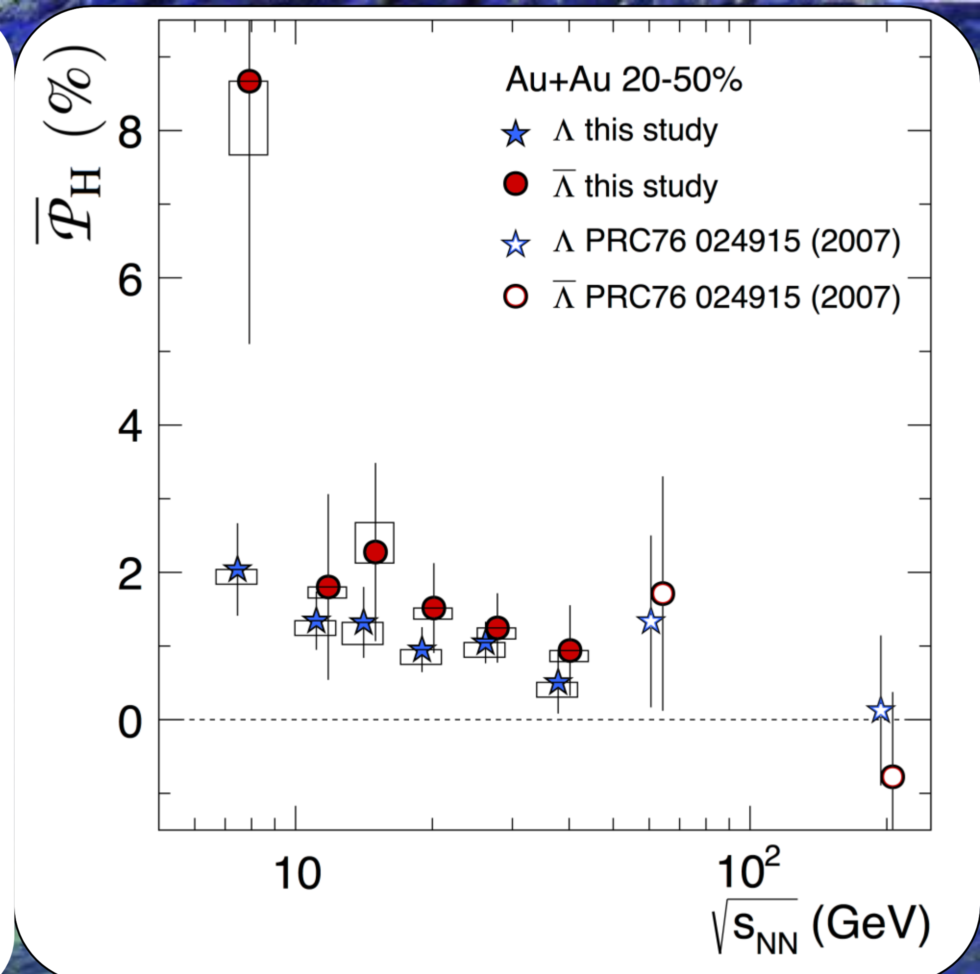
Scaled by Temperature (thermal vorticity)

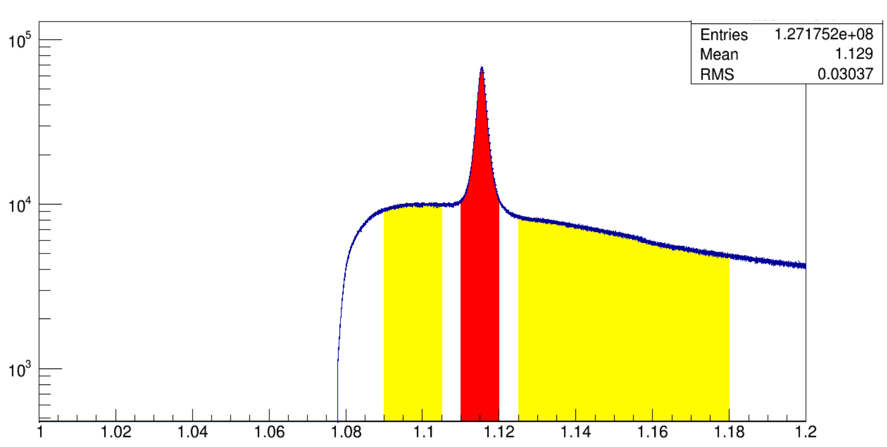
fluid	vorticity ω [/s]	temp (K)	kB*T [eV]	hbar*ω/kBT
QGP	1.00E+22		1.60E+08	4.13E-02
He-II nanodroplets	1.00E+07	5	4.30E-04	1.53E-05
He-II turbulence	1.50E+02	3	2.58E-04	3.84E-10
heated soap bubble	1.00E+02	300	2.58E-02	2.56E-12
supercell tornado	1.00E-01	300	2.58E-02	2.56E-15
Jupiter Red Spot	1.00E-04	1600	1.38E-01	4.80E-19
atmospheric	1.00E-05	300	2.58E-02	2.56E-19
solar subsurface	1.00E-07	6500	5.59E-01	1.18E-22

Scaled by spatial scale

system	vorticity (/s)	size (m)	product (m/s)
ocean	1.00E-05	1.00E+06	1.00E+01
atmosphere	1.00E-04	1.00E+06	1.00E+02
solar subsurface	1.00E-06	1.00E+08	1.00E+02
Jupiter collar	1.00E-04	1.00E+07	1.00E+03
hot soap	1.00E+02	1.00E-02	1.00E+00
nanodroplets	1.00E+06	1.00E-09	1.00E-03
QGP	1.00E+21	1.00E-15	1.00E+06







Off-mass check:

- statistics challenged
- dominant source of systematic uncertainty
  - → syst. errors should go down with stats
- several other tests done ("cleaner/dirtier cuts, etc.)

Accounting for polarized feeddown

PRIMARY + FEED-DOWN POLARIZATION

VORTICAL COMPONENT

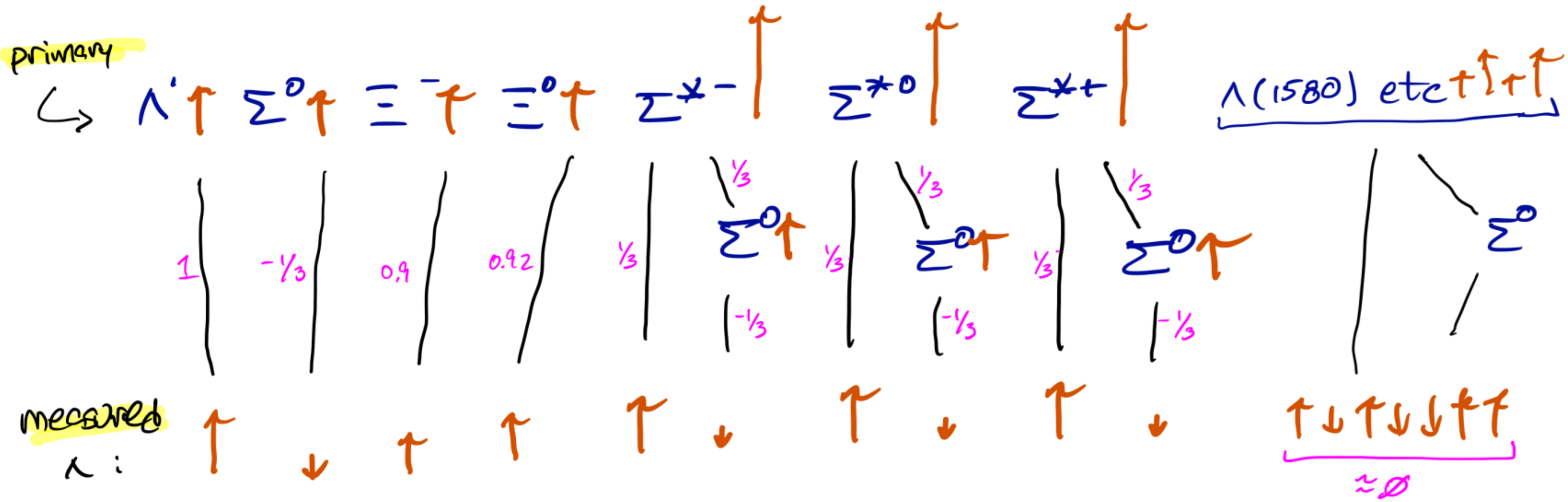
primary

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

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

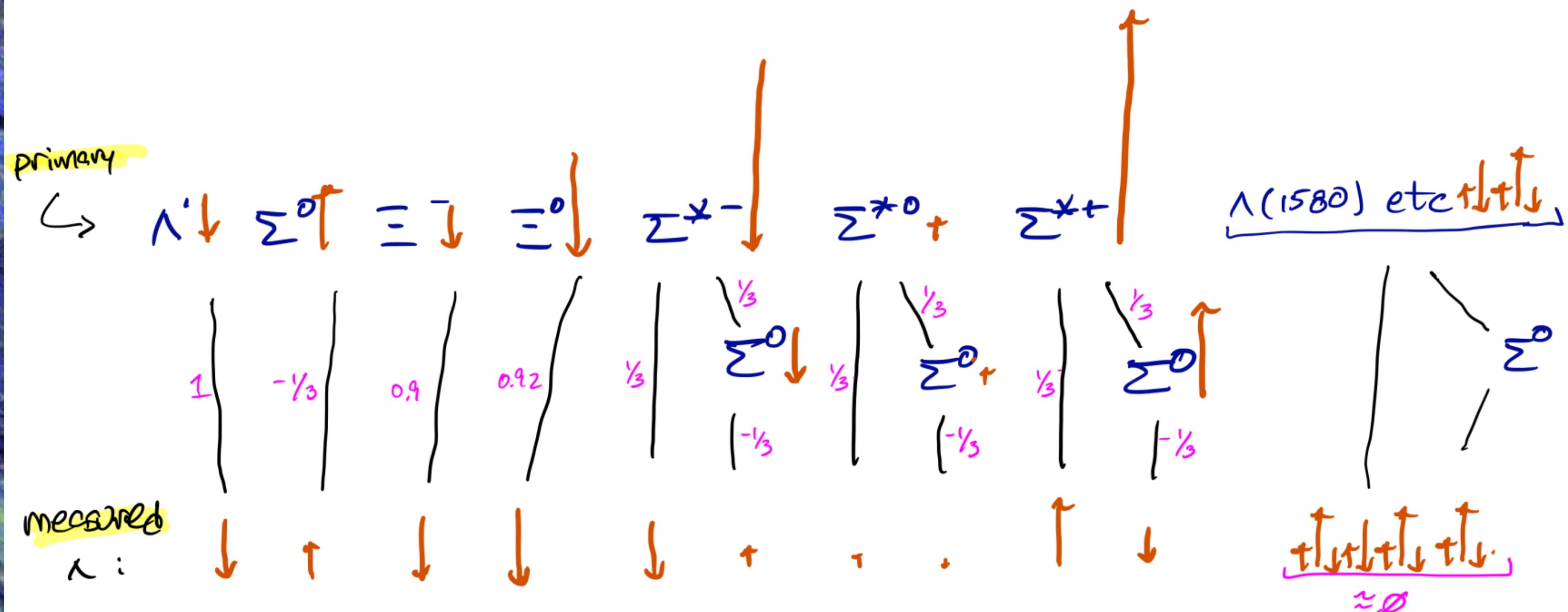
	J^π	μ
Σ^{*-}	$3/2^+$	-2.41
Σ^{*0}	$3/2^+$	$+0.30$
Σ^{*+}	$3/2^+$	$+3.02$

Becattini, Karpenko, ML, Upsal, Voloshin PRC95, 054902 (2017). 1610.02506

Accounting for polarized feeddown

PRIMARY + FEED-DOWN POLARIZATION

MAGNETIC COMPONENT



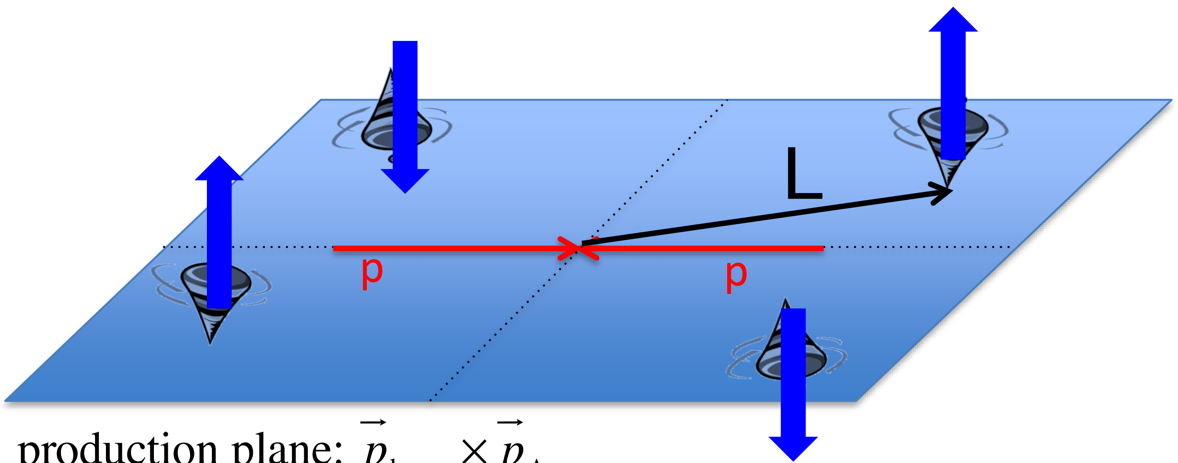
	J^π	μ		J^π	μ
Λ	$1/2^+$	-0.613	Σ^{*-}	$3/2^+$	-2.41
Σ^0	$1/2^+$	$+0.79$	Σ^{*0}	$3/2^+$	$+0.30$
Ξ^-	$1/2^+$	-0.651	Σ^{*+}	$3/2^+$	$+3.02$
Ξ^0	$1/2^+$	-1.25			

Becattini, Karpenko, ML, Upsal, Voloshin PRC95, 054902 (2017). 1610.02506

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: $\vec{p}_{\rm beam} \times \vec{p}_\Lambda$

- Vortical:

$$\overline{\vec{P}}_\Lambda \,||\, +\hat{J}_{\rm sys} \qquad \overline{\vec{P}}_{\bar{\Lambda}} \,||\, +\hat{J}_{\rm sys}$$

- Magnetic coupling:

$$\overline{\vec{P}}_\Lambda \,||\, -\hat{J}_{\rm sys} \qquad \overline{\vec{P}}_{\bar{\Lambda}} \,||\, +\hat{J}_{\rm sys}$$

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

$$\overline{\vec{P}}_\Lambda = \overline{\vec{P}}_{\bar{\Lambda}} = 0$$

Topologically-dependent efficiency

Spin-orientation-dependent efficiency (!)

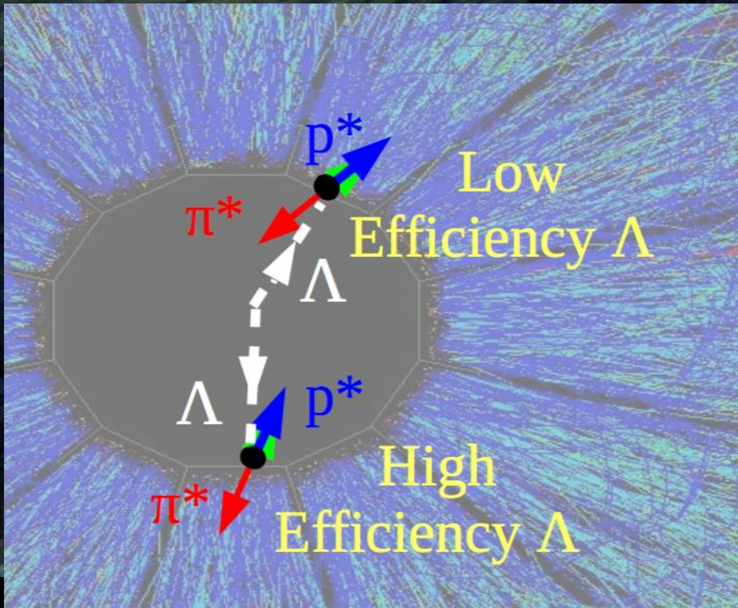
In Lambda frame, proton & pion have equal-magnitude momentum, but not in STAR frame

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

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



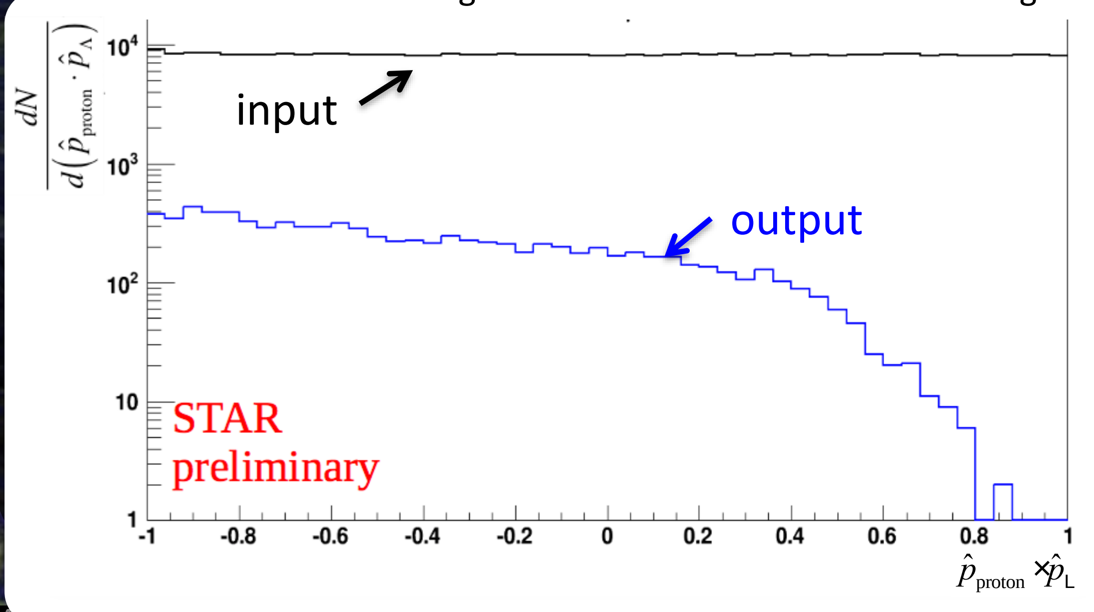
Topologically-dependent efficiency

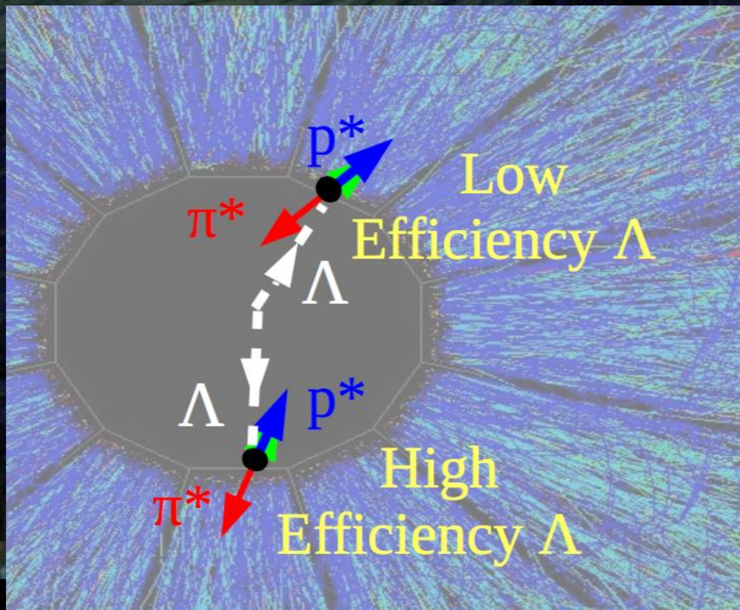
Spin-orientation-dependent efficiency (!)

- 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 $\bar{P}_H$

HIJING events through simulated STAR detector & tracking





Effect of baryochemical potential

Fang, Pang, Wang, Wang, PRC 94 (2016) 024904

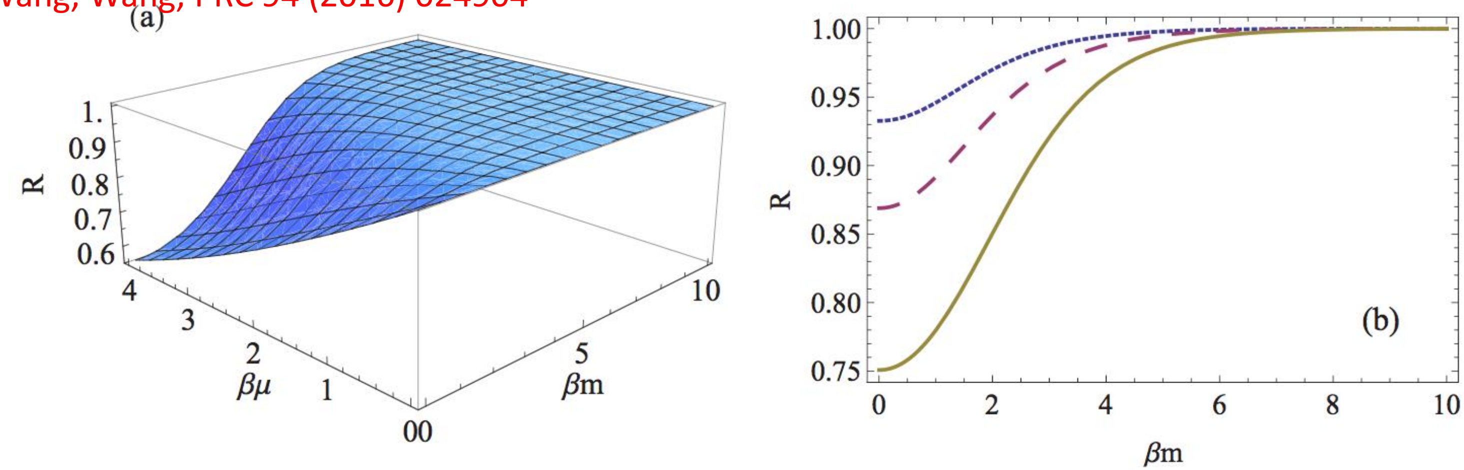
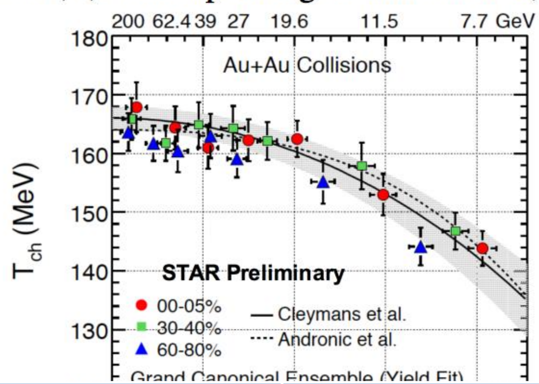


FIG. 4. The ratio R of the integrated polarization per particle in Eq. (56) for fermions to antifermions. (a) R as a function of βm and $\beta\mu$. (b) R as functions of βm at three values $\beta\mu = 0.5, 1, 2$ corresponding to short-dashed, long-dashed, and solid lines, respectively.

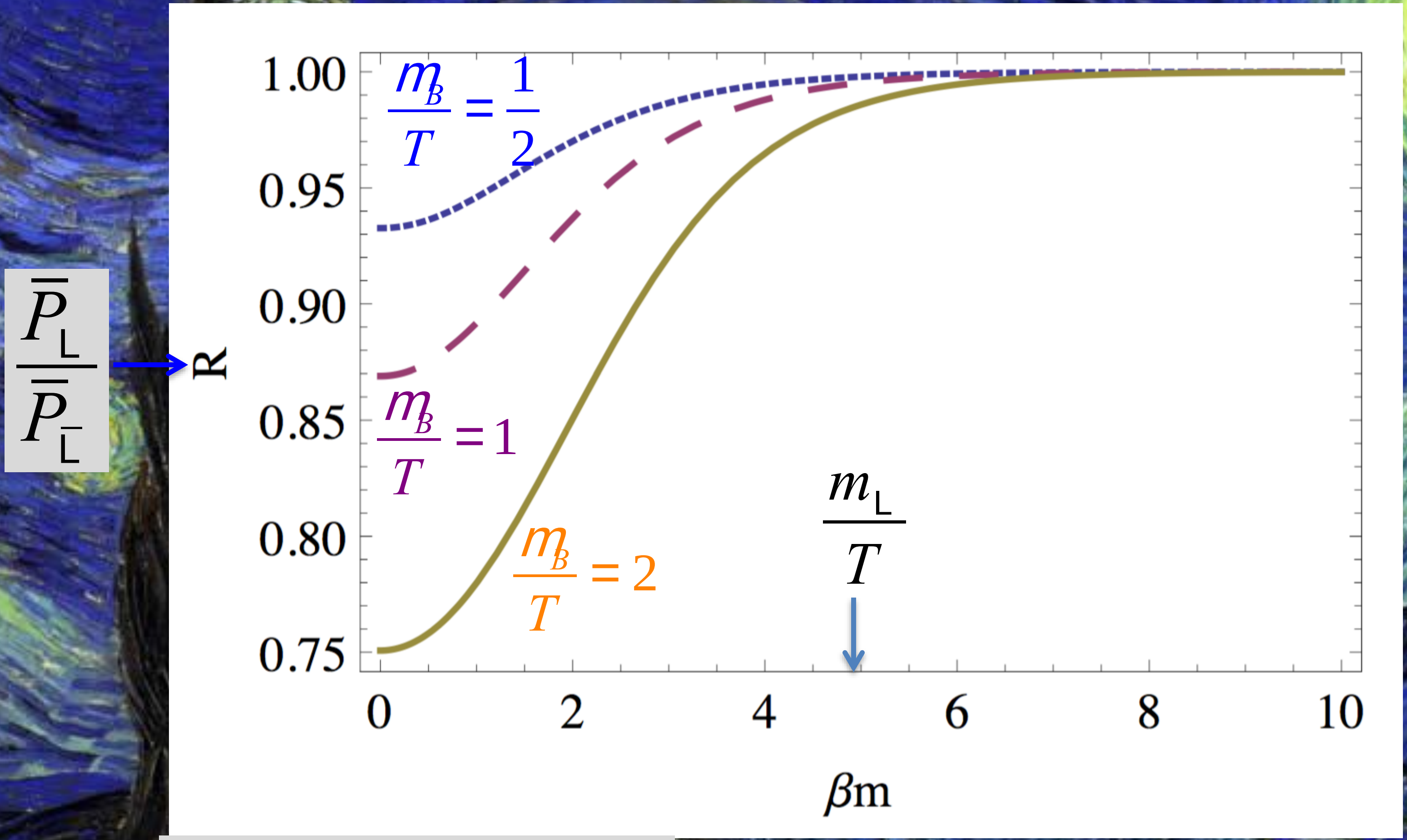
$$b = \frac{1}{T}$$

$$\left.\begin{aligned} bm &\approx \frac{150\ \text{MeV}}{150\ \text{MeV}} = 1 \\ bm &\approx \frac{1100\ \text{MeV}}{150\ \text{MeV}} \approx 7 \end{aligned}\right\} 1 - \tfrac{1}{R} < 1\%$$



root(s)	P Lambda	P anti Lambda	1-1/R
15	1.167	1.42	20%
19	0.955	1.45	50%
27	1.03	1.41	40%

Splitting effect of finite μ_B



Fang et al, arxiv:1604.0403