

Lambda polarization at STAR & Prospects for measuring the strongest magnetic field

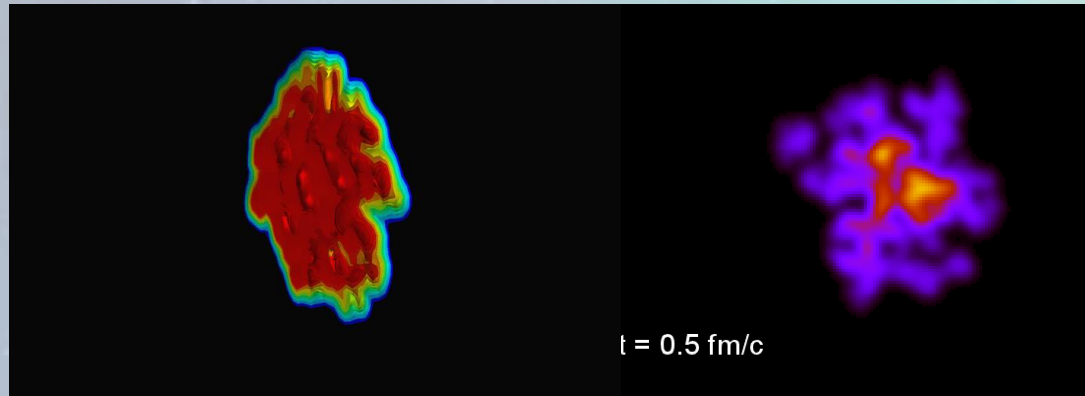
Mike Lisa
Ohio State University
for the STAR Collaboration

Outline

- Polarization
 - validation of hydro approach; possibility to measure B
 - beyond the initial observation
 - p_T , η , Φ , & centrality systematics at 200 GeV
 - longitudinal polarization
- B-field
 - fundamentally important
 - tantalizing systematic in published STAR data at BES
 - possibilities for detection in 2018 (ongoing) STAR run
 - increased statistics, detector upgrade
- Summary

Hydrodynamics –standard paradigm of H.I.C

movies by Bjorn Schenke



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

$$d_m T^{mn} = 0 \quad T^{m,n} = \epsilon u^m u^n - (p + P) D^{mn} + p^{mn}$$

$$u^m d_m P = -\frac{1}{t_P} (P + zq) - \frac{1}{2} P \frac{zT}{t_P} d_i \left[\frac{t_P}{zT} u^i \right]$$

& many more terms...

Recall fanfare when previous assumptions were overturned by data

New State of Matter Is 'Nearly Perfect' Liquid

SCIENTIFIC AMERICAN

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings—which could provide new insight into the composition of the universe just moments after the big bang—today in Florida at a meeting of the American Physical Society.



There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider.

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

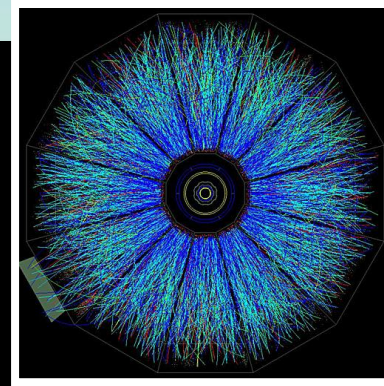
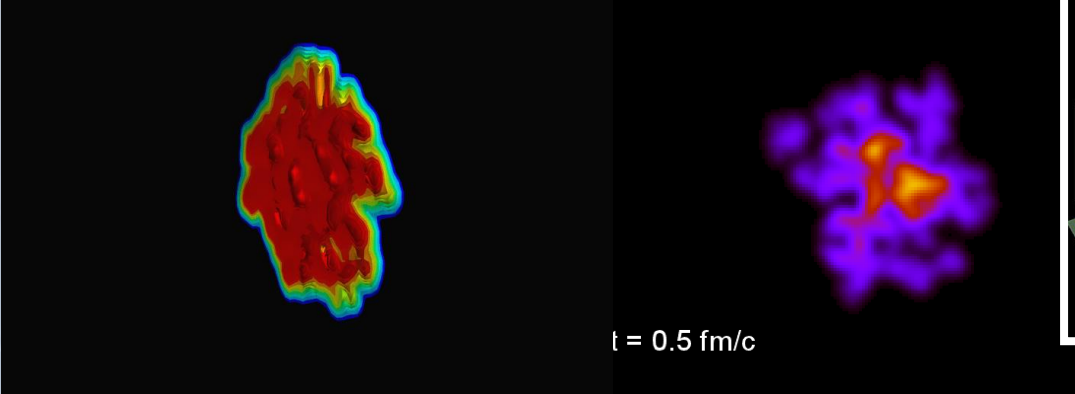
nature

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Connection to experiment – freeze-out

movies by Bjorn Schenke



emitted hadron
(color confined)

fluid cell at
freeze-out

QGP fluid:
colored quarks deconfined

System cools & expands → Freeze-out

- Cooper-Frye prescription – “physics-free”
- emitted hadrons reflect properties of their parent hydro cell (chemical potentials, thermal & collective velocities)
- **Must continue to subject paradigms under expt. scrutiny**

Local vorticity and polarization

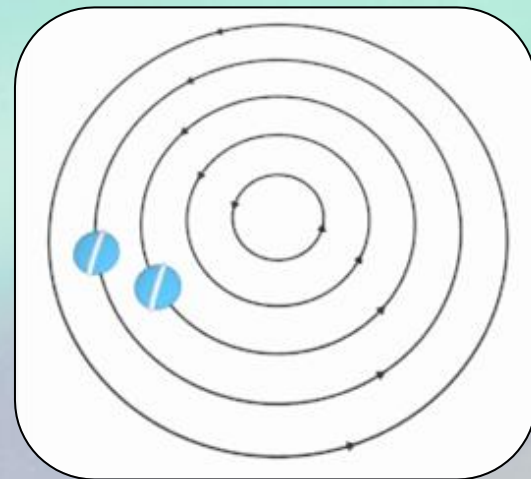
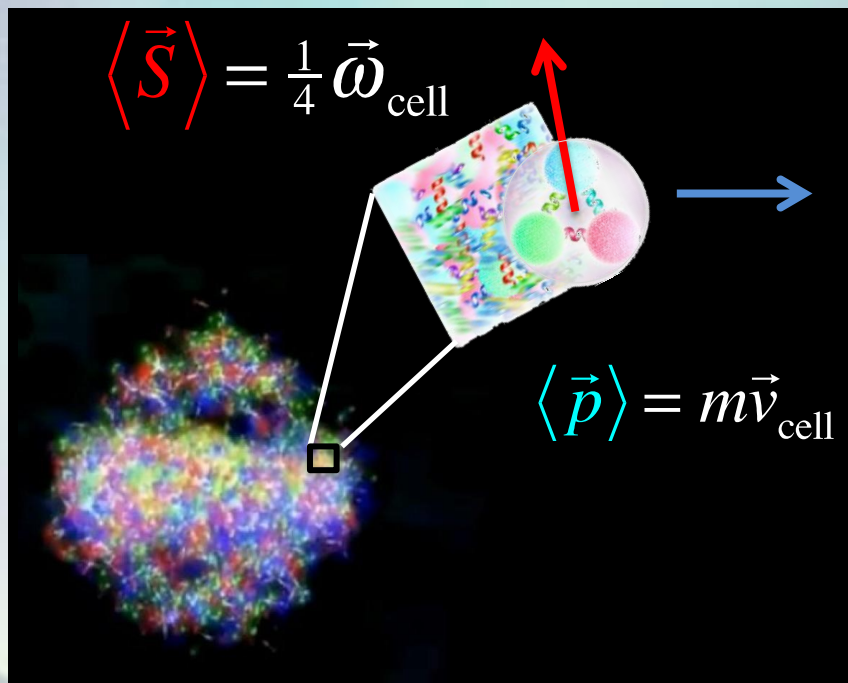
- Fine-scale vorticity *at* the “point” cell reflected in the *spin* of emitted particles

Polarization

$$\vec{P} \equiv \frac{\langle \vec{S} \rangle}{|\langle \vec{S} \rangle|}$$

first suggested by

- Betz et al. (2007)
- Becattini et al. (2008)

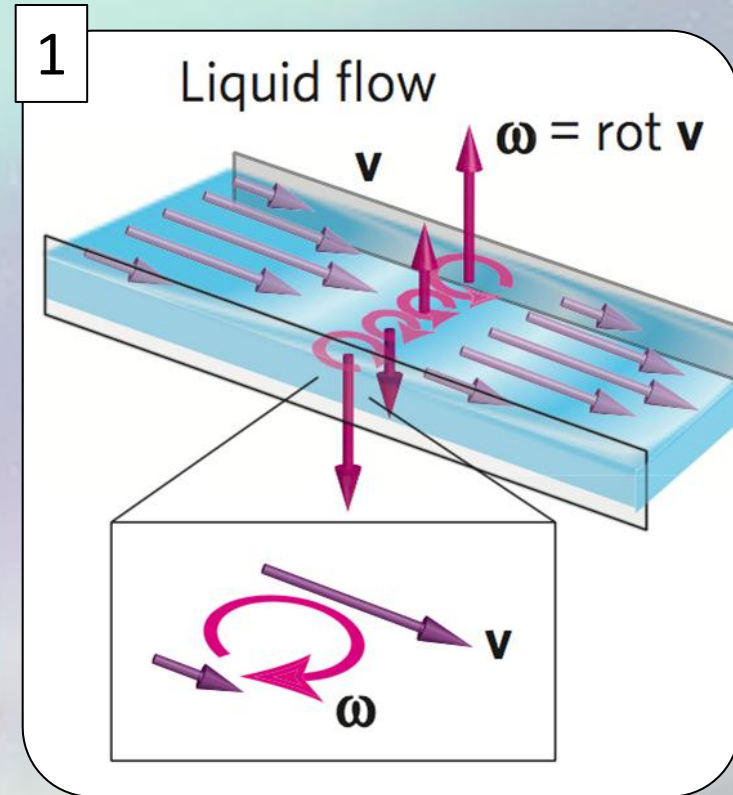


First observation of fluid vorticity-polarization coupling

“Spin hydrodynamic generation”
Takahashi, *et al.* Nat. Phys. (2016)

1. Hg flowing down a channel

- viscous forces with walls \rightarrow fluid vorticity

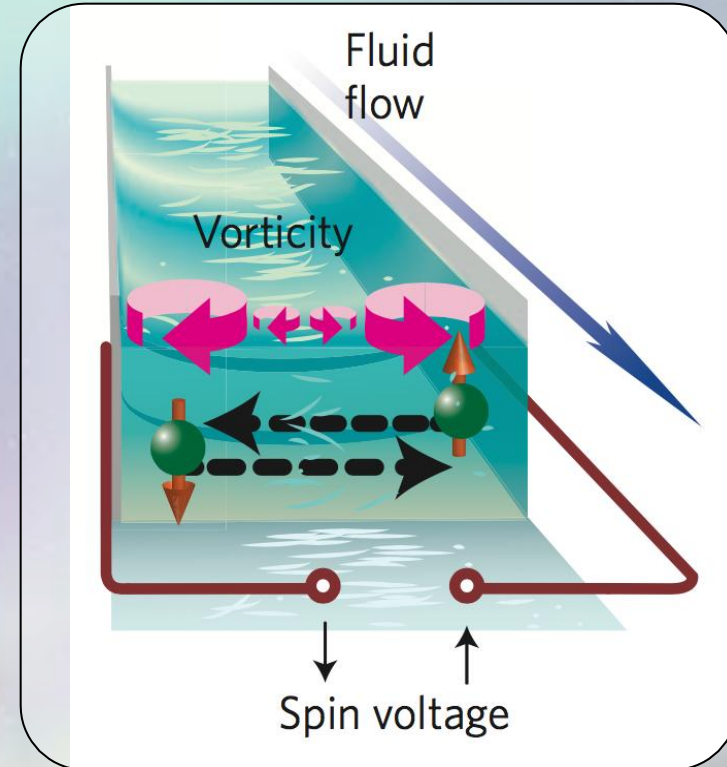


First observation of fluid vorticity-polarization coupling

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1. Hg flowing down a channel
 - viscous forces with walls \rightarrow fluid vorticity
2. mechanical **fluid vorticity** \rightarrow **e⁻ polarization**
3. Gradient across channel \rightarrow spin voltage
4. ... can be transformed into electrical voltage, generators, etc. *without magnets*

“This opens a door to the new field of fluid spintronics”



First observation of fluid vorticity-polarization coupling

“Spin hydrodynamic generation”

Takahashi, *et al.* Nat. Phys. (2016)

1. Hg flowing down a channel
 - viscous forces with walls \rightarrow fluid vorticity
2. mechanical **fluid vorticity** \rightarrow **e^- polarization**

Global hyperon polarization at local thermodynamic equilibrium with vorticity, magnetic field and feed-down

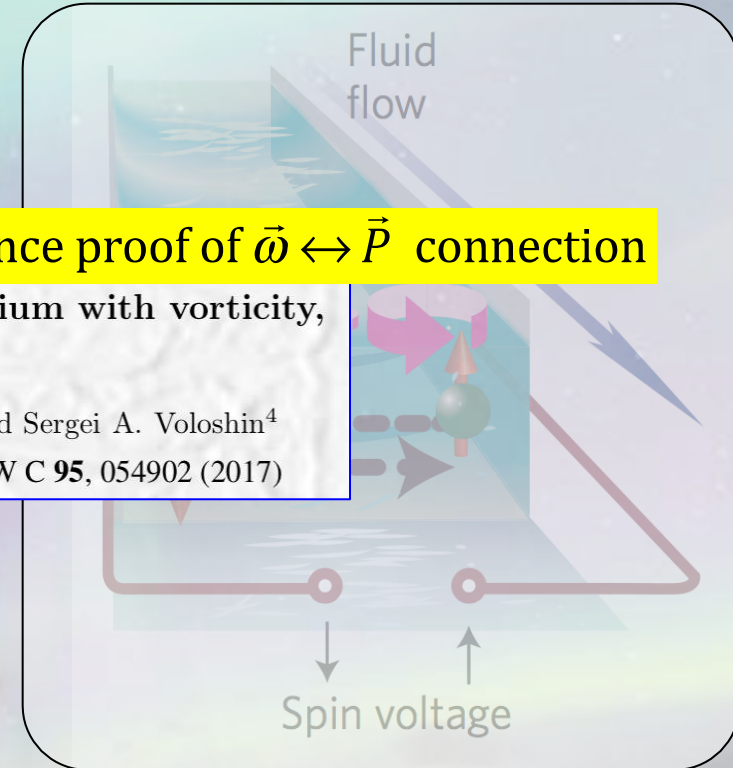
Francesco Becattini,¹ Iurii Karpenko,² Michael Annan Lisa,³ Isaac Upsal,³ and Sergei A. Voloshin⁴

PHYSICAL REVIEW C **95**, 054902 (2017)

$$P \propto e^{\left(-E + \mu_B B + \mu_Q Q + \vec{\omega} \cdot \vec{S} + \vec{\mu} \cdot \vec{B}\right)/T}$$

“This opens a door to the new field of fluid spintronics”

existence proof of $\vec{\omega} \leftrightarrow \vec{P}$ connection

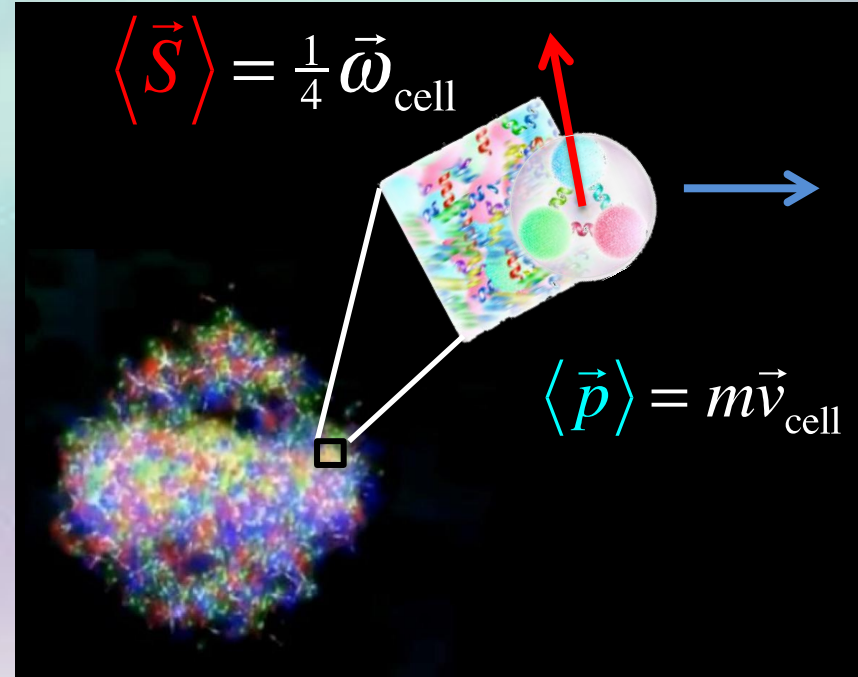
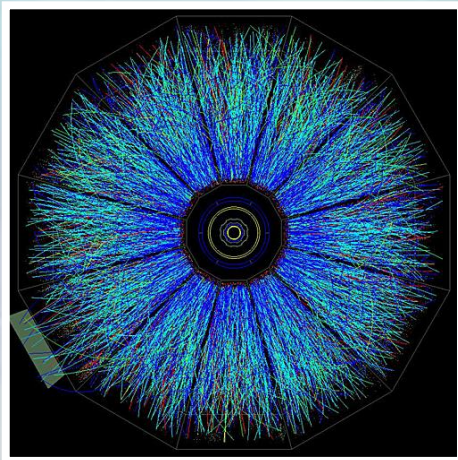


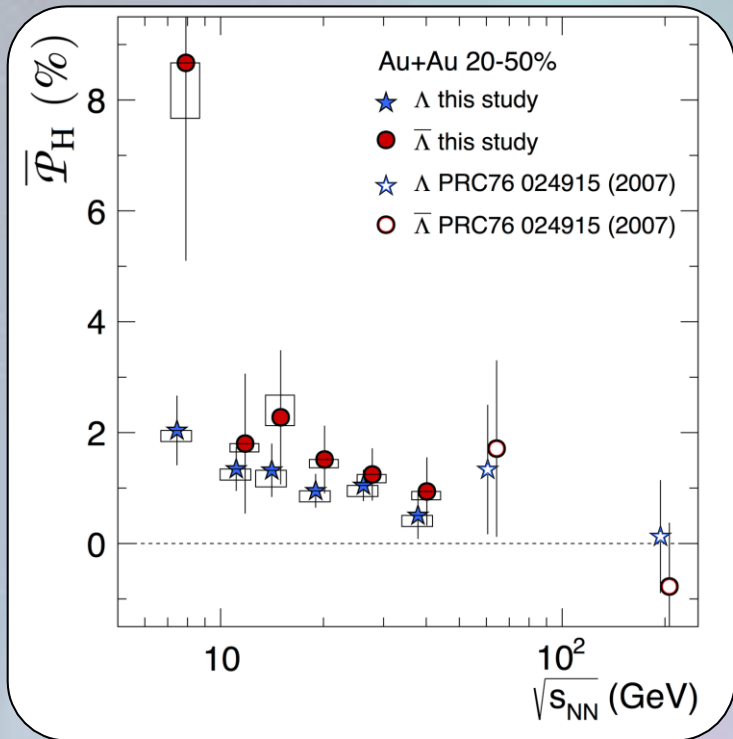
Subatomic spintronics

Barnett, Einstein, de Haas, Takahashi: $\vec{P} \propto \vec{\omega}$

- straightforward to measure both \vec{P} and $\vec{\omega}$

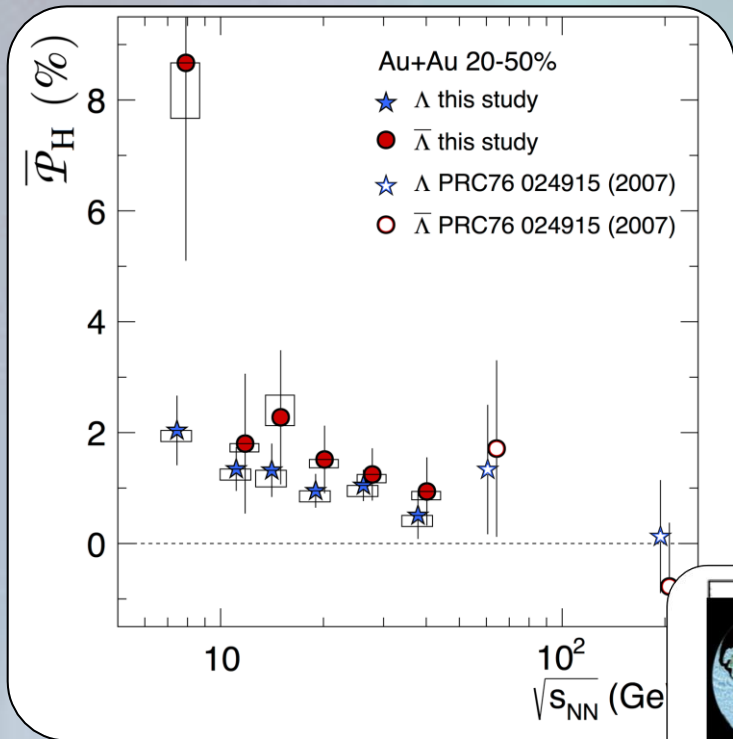
Our experimental situation is a little tougher...
...but we benefit from their validation of
the connection



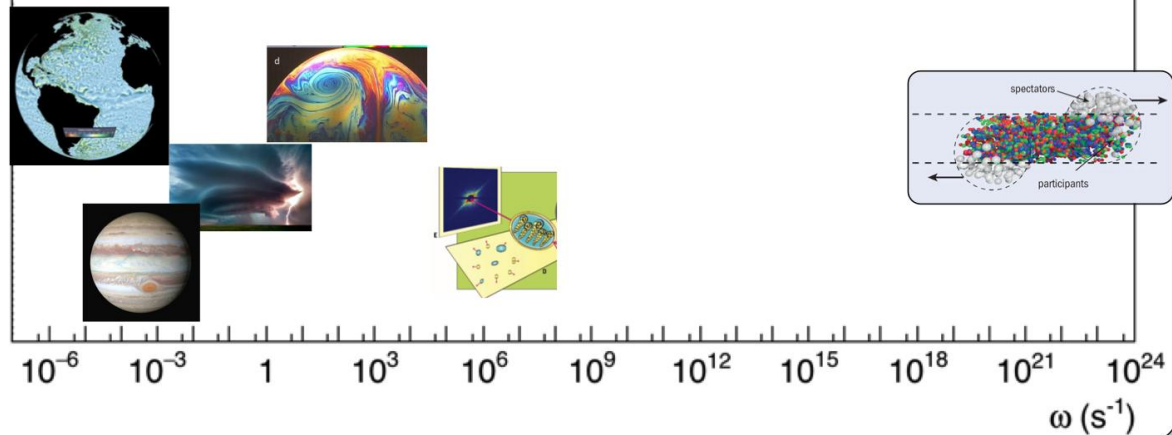


- Photogenic





- Photogenic
- Amenable to comparisons to phenomena from other fields



Brookhaven & RHI publicity...



BROOKHAVEN NATIONAL LABORATORY *Newsroom Media & Communications Office*

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Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631) 344-3174

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2017's Top-10 Discoveries and Scientific Achievements at Brookhaven National Laboratory

December 27, 2017

... and serious science

~100 related papers on arxiv

Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions 2018

19-22 March 2018 *Galileo Galilei Institute*
Europe/Rome timezone

Registration and abstract submission are now closed.

Overview

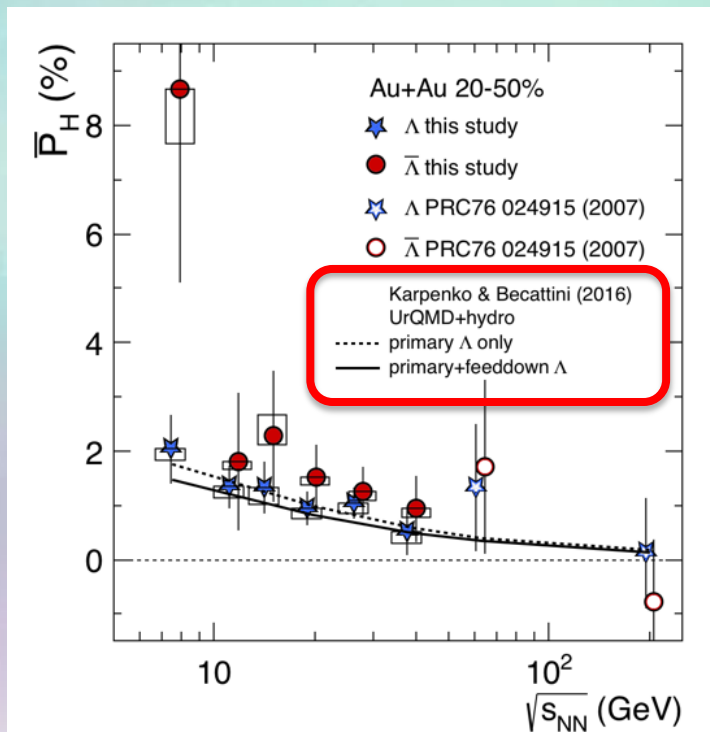
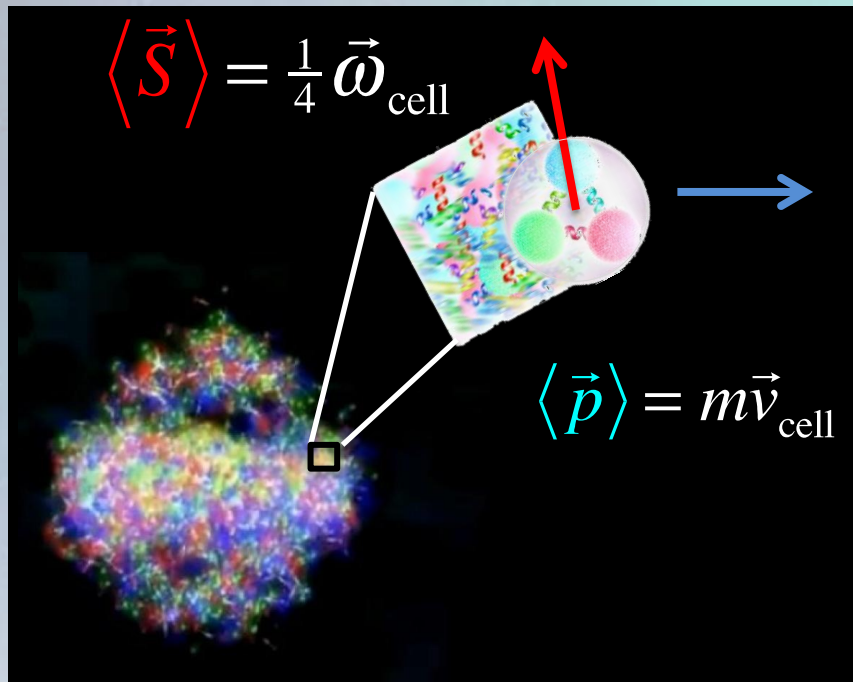
[Committees](#)
[Timetable](#)
[Program](#)
[First Circular](#)
[Second Circular](#)
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The 4th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions will be held at the Galileo Galilei Institute in Florence from March 19 through March 22, 2018. The workshop will cover recent theoretical developments and experimental measurements related to these topics.

The workshop attendance is limited to 70 participants.



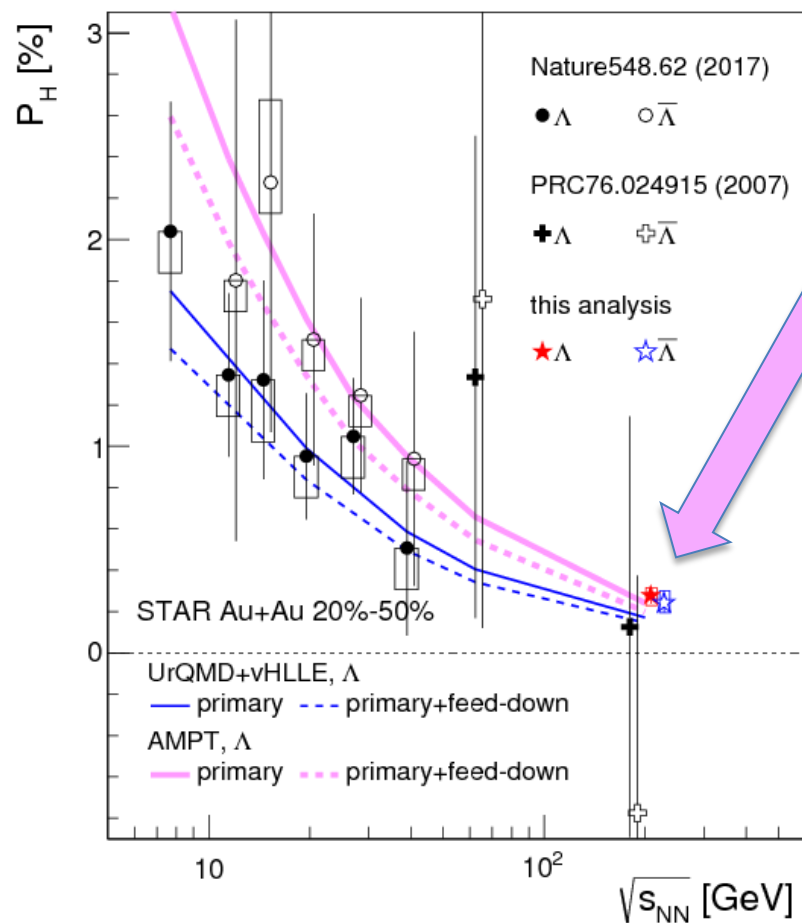
A key take-away – the approach works



- Stunning success & validation of the near-equilibrium hydro paradigm*
- More than “just” the anisotropy of fluid velocity

* which swept away the previous, erroneous paradigm with considerable fanfare

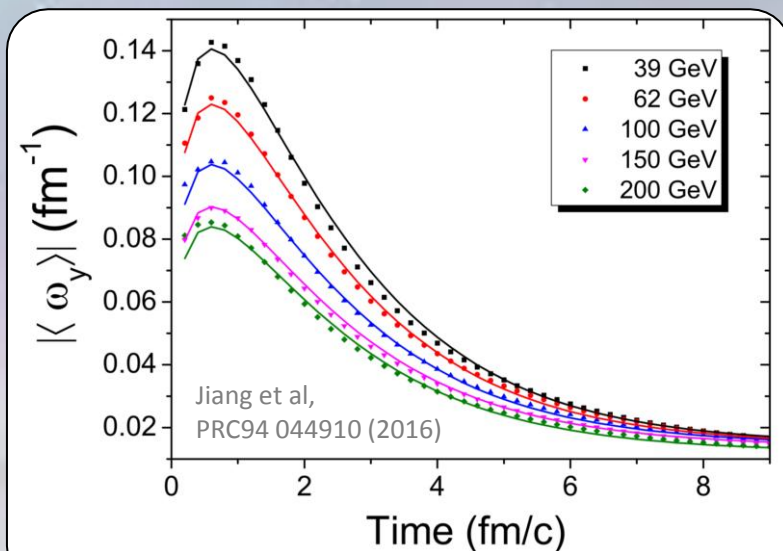




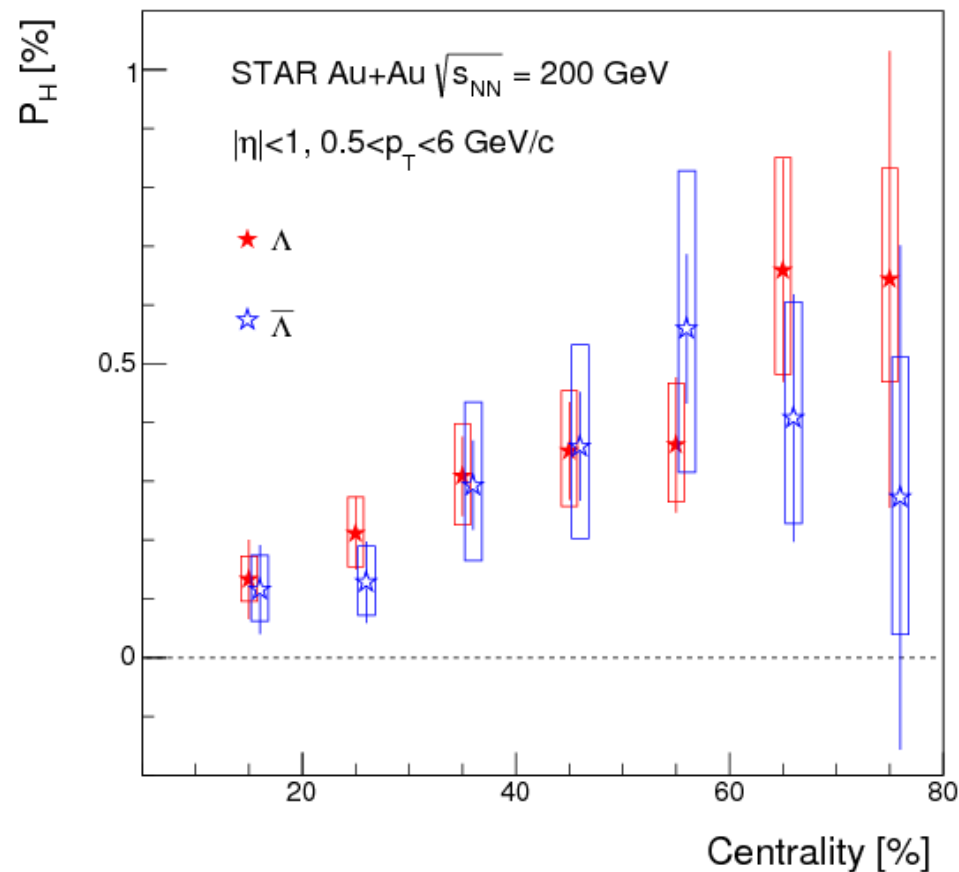
New analysis @200 GeV

High statistics analysis reveals positive signal at top RHIC energy

- consistent with established \sqrt{s} -dependence
- consistent with hydro/transport calculations
- no significant difference between Λ , anti- Λ

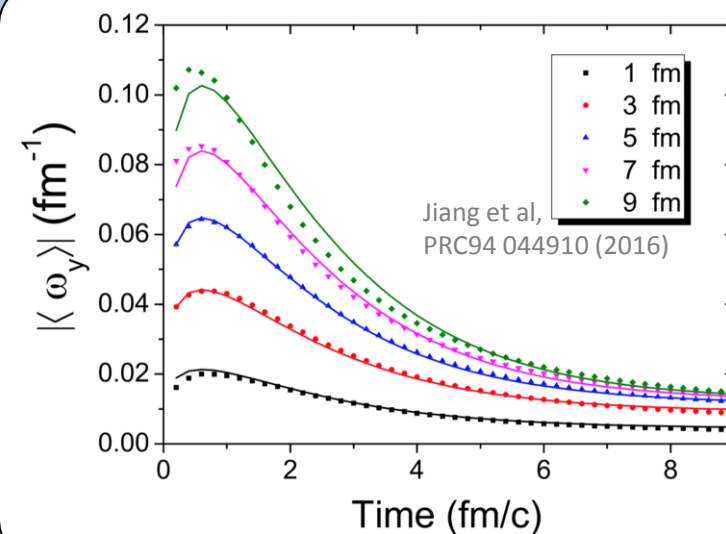


New analysis @200 GeV



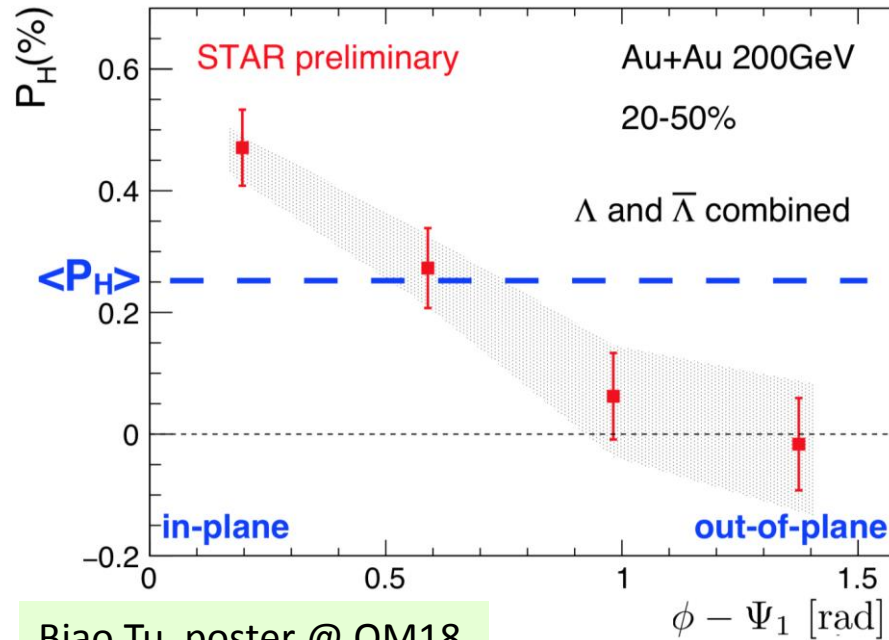
Reasonable centrality dependence

- qualitatively consistent with naive expectation & with transport



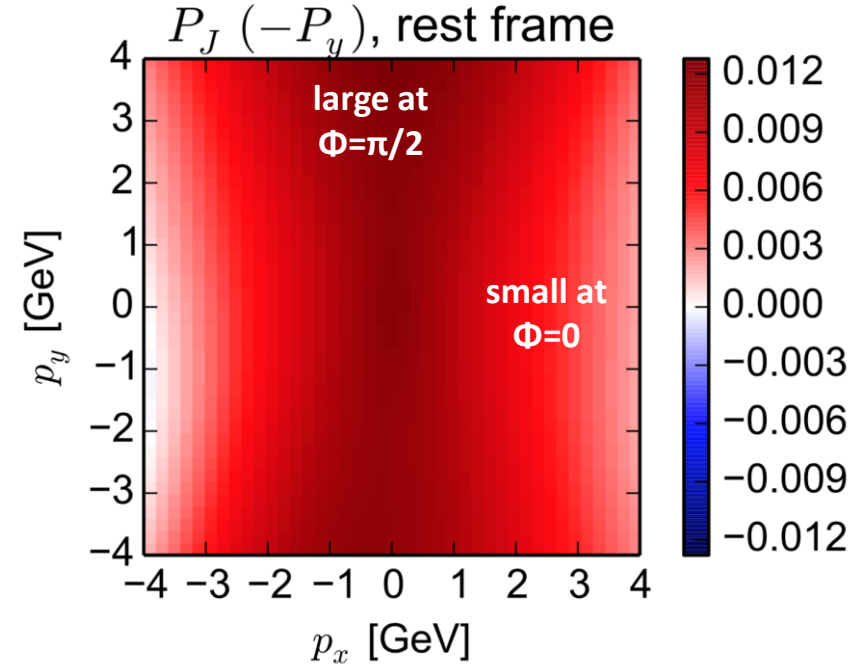
Angular substructure

Karpenko & Becattini
EPJC (2017) 77:213



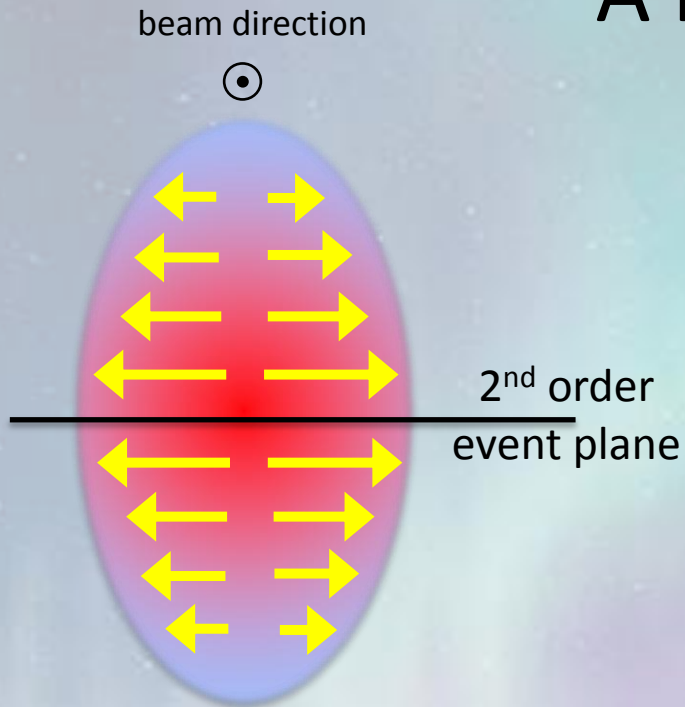
Biao Tu, poster @ QM18

- significant ϕ -dependence!
- polarization stronger in-plane

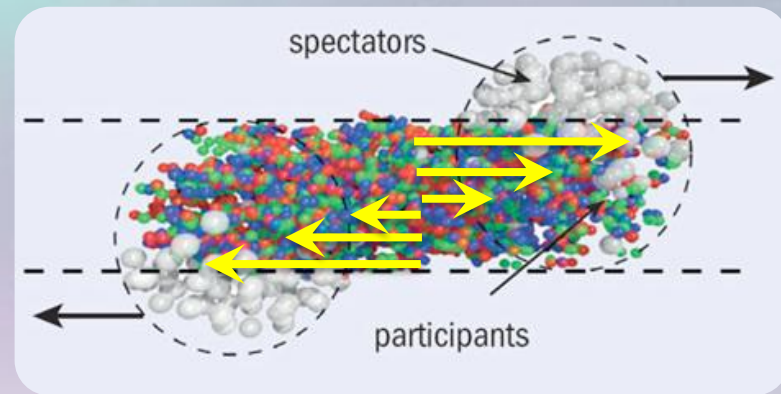


- opposite to theoretical expectation...???

A new “direction”

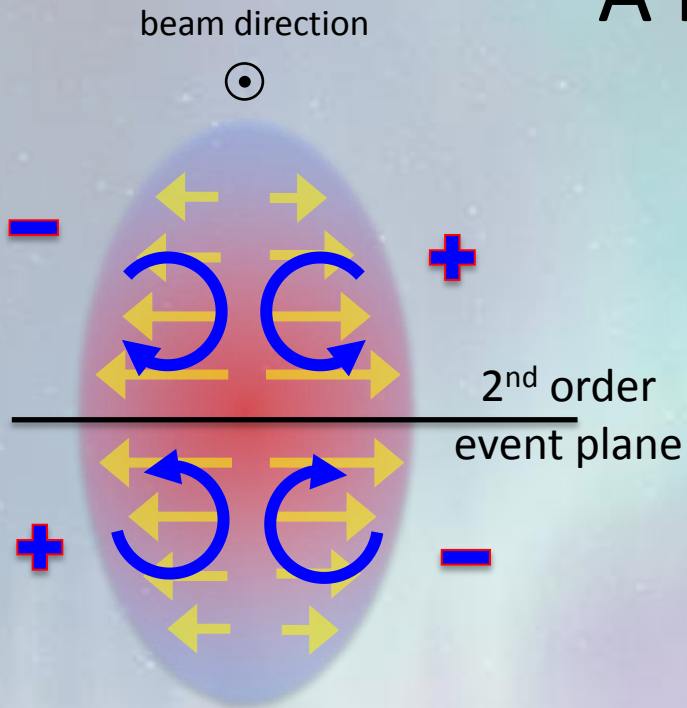


- Local velocity gradients due to elliptic flow may produce vorticity along beam direction

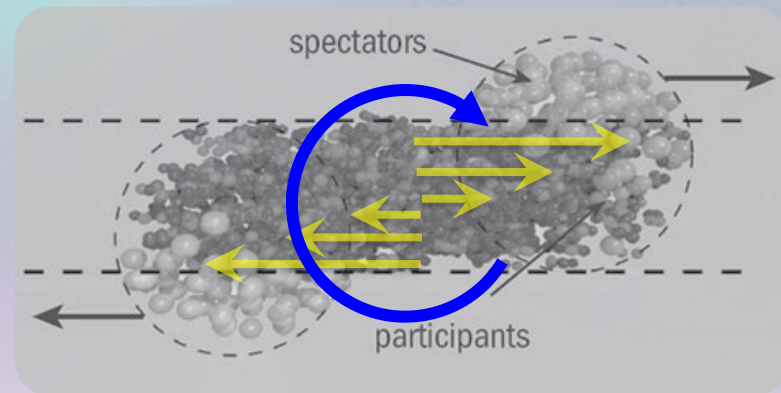


... the same mechanism that produces the vorticity transverse to the beam

A new “direction”

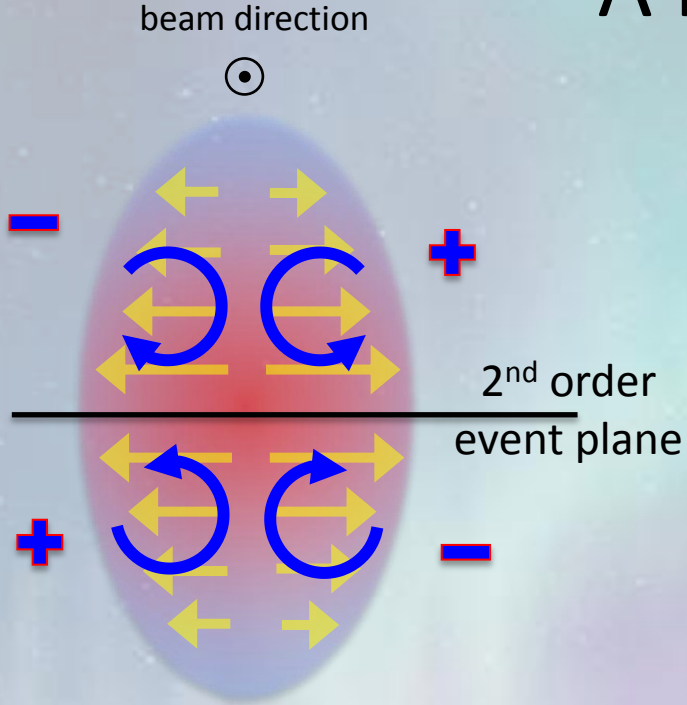


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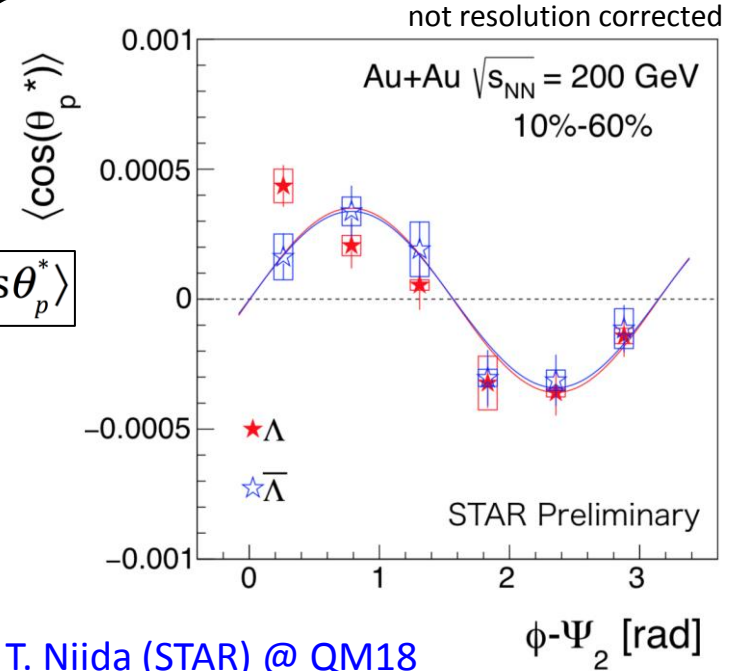
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A new “direction”



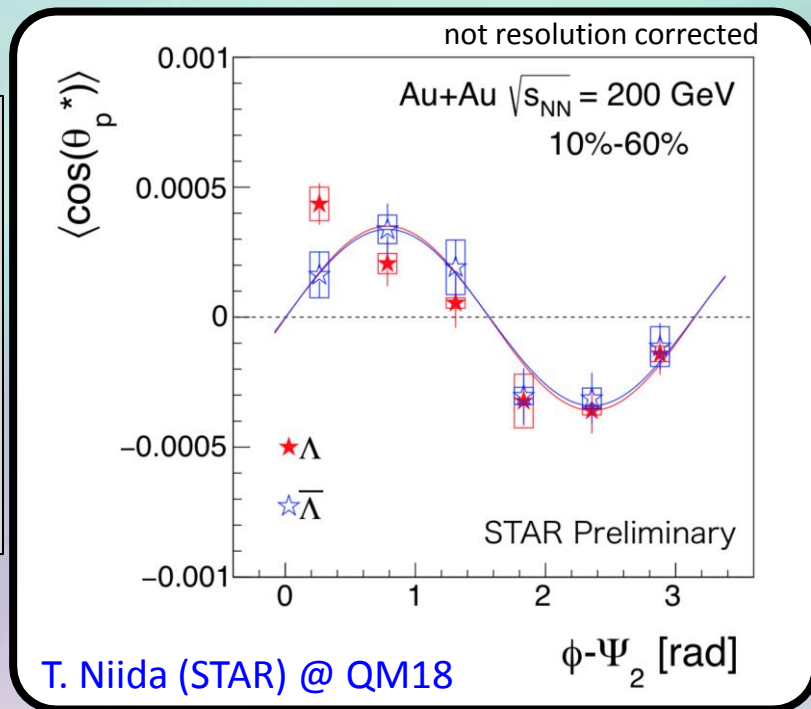
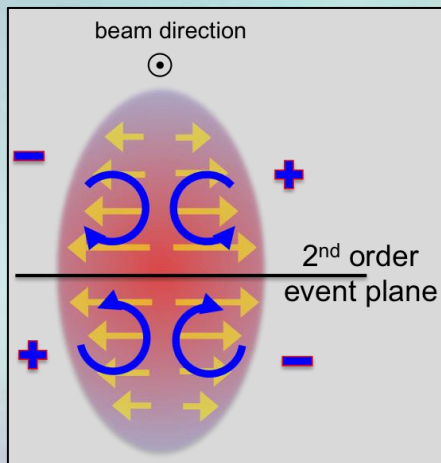
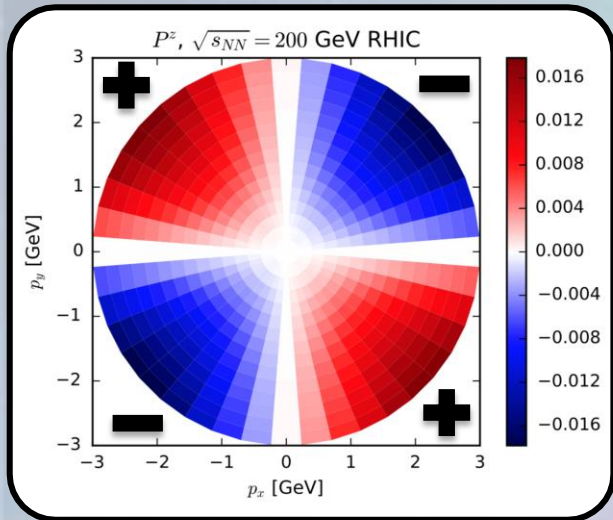
- Local velocity gradients due to elliptic flow may produce vorticity along beam direction
- Preliminary STAR results consistent with this scenario

$$\bar{P}_z \propto \langle \cos \theta_p^* \rangle$$



A new “direction”

Becattini & Karpenko PRL 120 (2018) 012302



- Local velocity gradients due to elliptic flow may produce vorticity along beam direction
- Preliminary STAR results consistent with this scenario

- Detailed hydro calculation predicts *opposite* effect
 - echoes of azimuthal discrepancy?

Summary (so far)

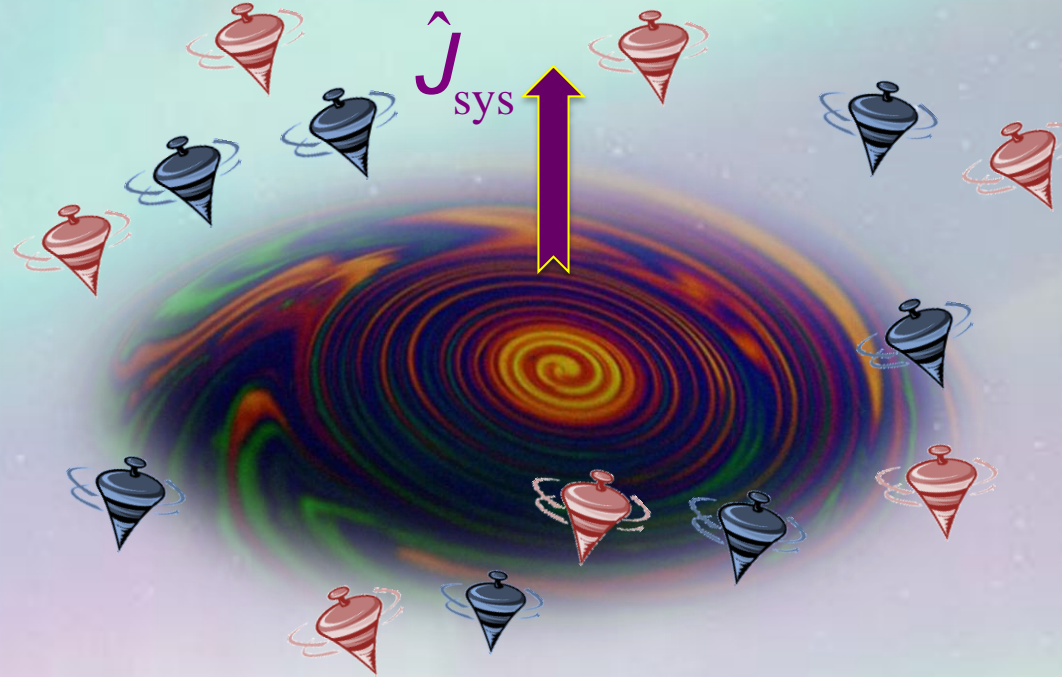
- **Polarization** : remarkable *new* validation of hydro paradigm
- **New high-statistics study at 200 GeV in STAR**: non-zero signal & new systematics
- **Systematics** (\sqrt{s} , centrality...) of global polarization consistent with *predictions*
- **Detailed substructure** (presumably) sensitive to interplay with anisotropic flow
 - azimuthal dependence of P_j – quadupole oscillation seen – *opposite of hydro prediction*
 - azimuthal dependence of P_z – quadupole oscillation seen – *opposite of hydro prediction*



Global polarization

Vortical coupling: $P \propto \omega$

$$\bar{\vec{P}}_{\Lambda} \parallel +\hat{J}_{\text{sys}} \quad \bar{\vec{P}}_{\bar{\Lambda}} \parallel +\hat{J}_{\text{sys}}$$





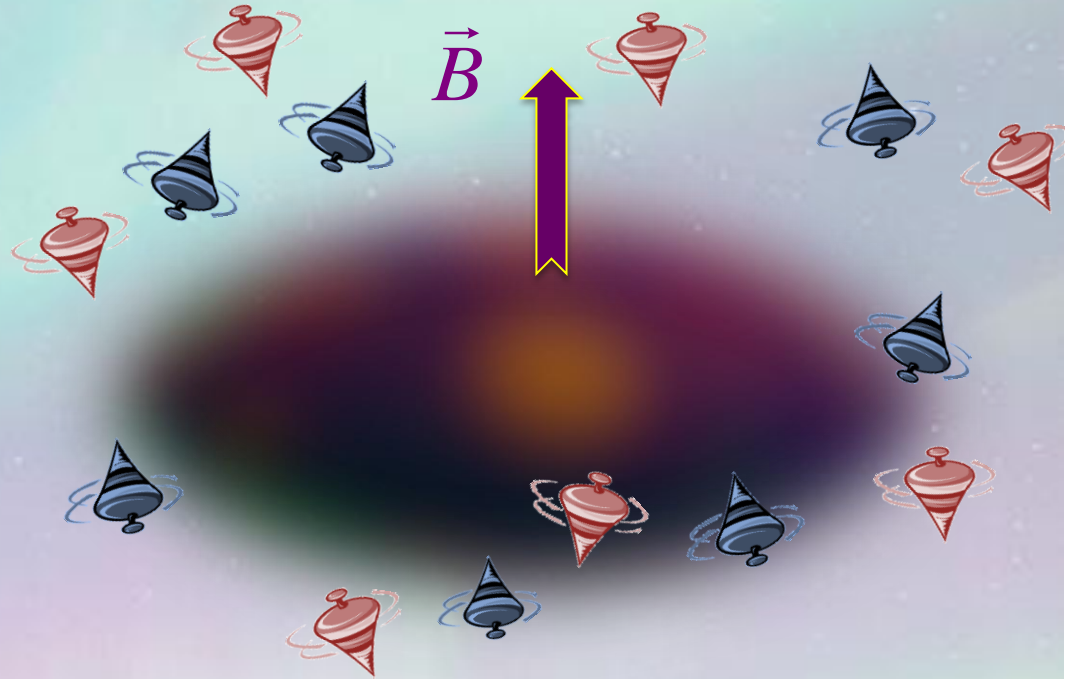
Global polarization

Vortical coupling: $P \propto \omega$

$$\vec{P}_\Lambda \parallel +\hat{J}_{\text{sys}} \quad \vec{P}_{\bar{\Lambda}} \parallel +\hat{J}_{\text{sys}}$$

Magnetic coupling: $P \propto \vec{\mu} \cdot \vec{B}$

$$\vec{P}_\Lambda \parallel -\hat{J}_{\text{sys}} \quad \vec{P}_{\bar{\Lambda}} \parallel +\hat{J}_{\text{sys}}$$



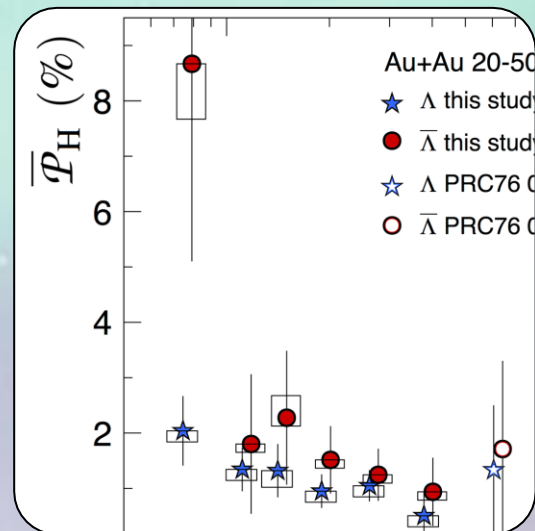


Global polarization in equilibrium paradigm

Vortical coupling: $P \propto \omega$

$$\vec{P}_{\Lambda} \parallel +\hat{J}_{\text{sys}} \quad \vec{P}_{\bar{\Lambda}} \parallel +\hat{J}_{\text{sys}}$$

“at freeze-out”



Magnetic coupling: $P \propto \vec{\mu} \cdot \vec{B}$

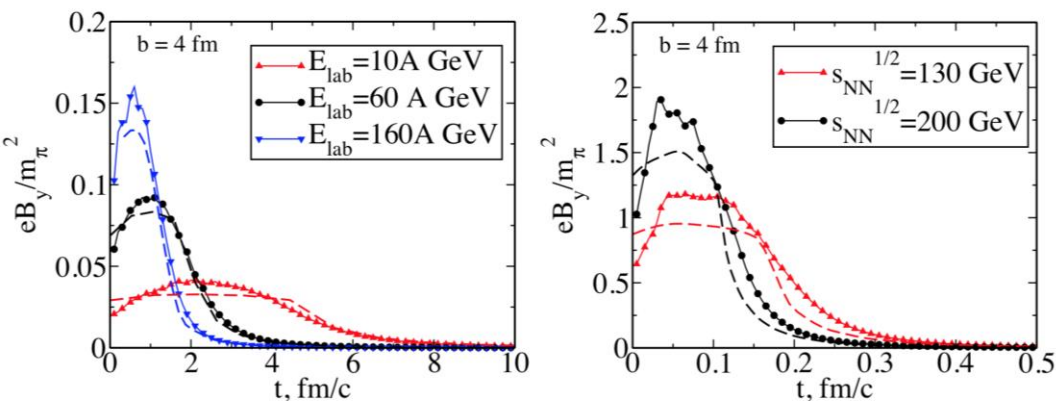
$$\vec{P}_{\Lambda} \parallel -\hat{J}_{\text{sys}} \quad \vec{P}_{\bar{\Lambda}} \parallel +\hat{J}_{\text{sys}}$$

$$\begin{pmatrix} \omega / T \\ B / T \end{pmatrix} = \underbrace{\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}}_{\text{includes feed-down}} \begin{pmatrix} P_{\Lambda}^{\text{meas}} \\ P_{\bar{\Lambda}}^{\text{meas}} \end{pmatrix}$$

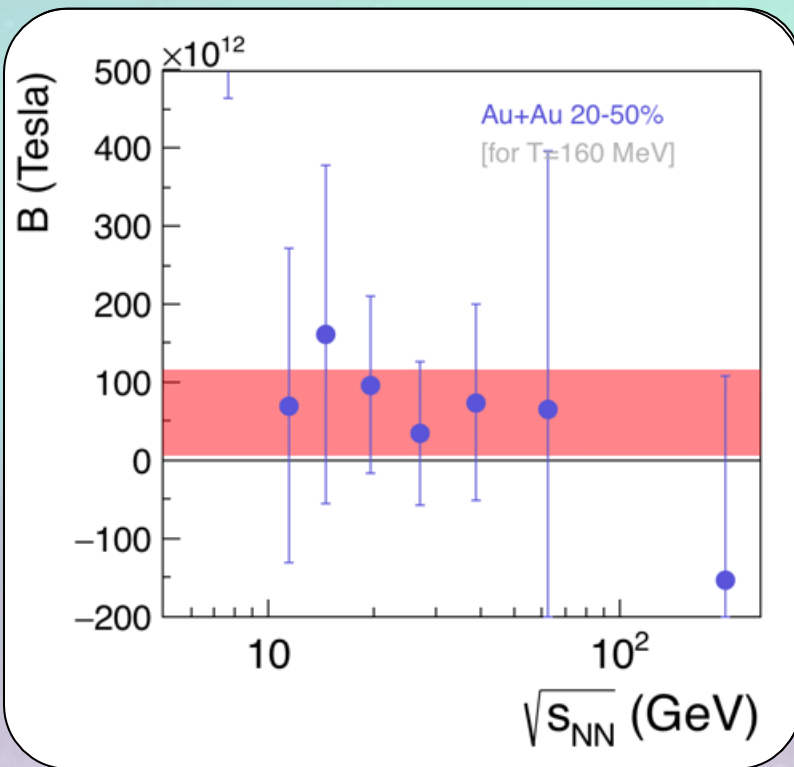
Magnetic field?

- Large statistical uncertainties
- B should change with energy^{*}, but...

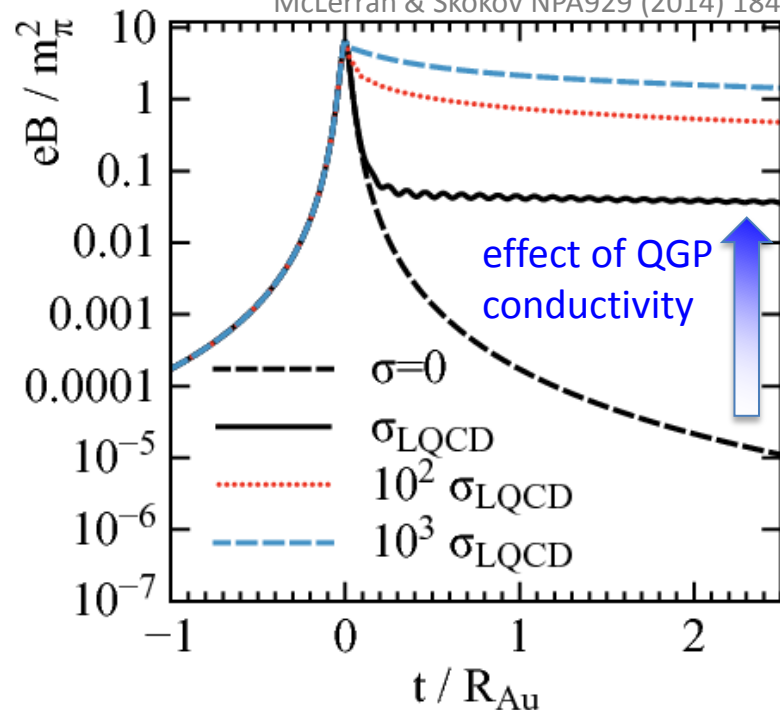
$$\langle B \rangle_{\sqrt{s}} = 6.0 \pm 5.5 \cdot 10^{13} \text{ T} \gg 0.6 \pm 0.55 m_p^2$$



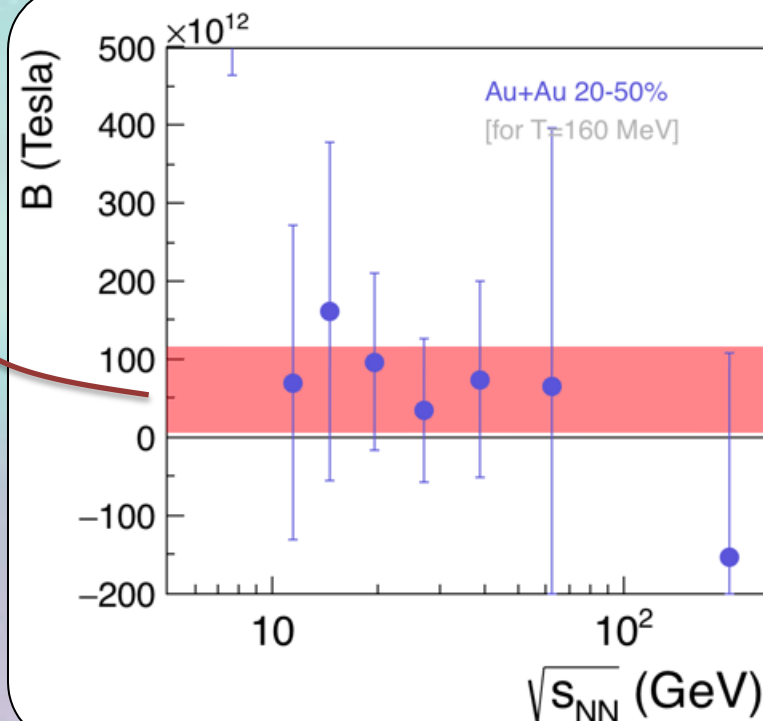
Skokov et al, Int J. Mod. Phys. E, 2009 **A24** 5925



* Interplay between timescale and magnitude \rightarrow not obvious what is energy dependence of *relevant* B...



Predicted time-dependent B-field

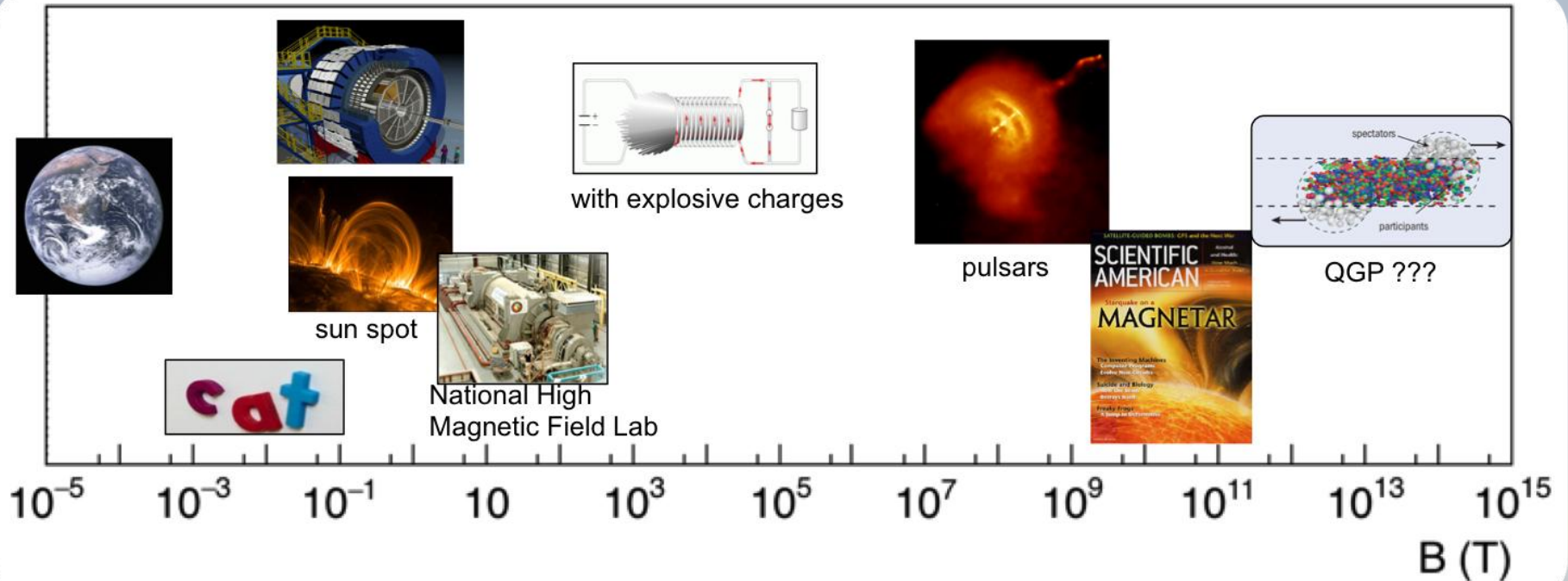
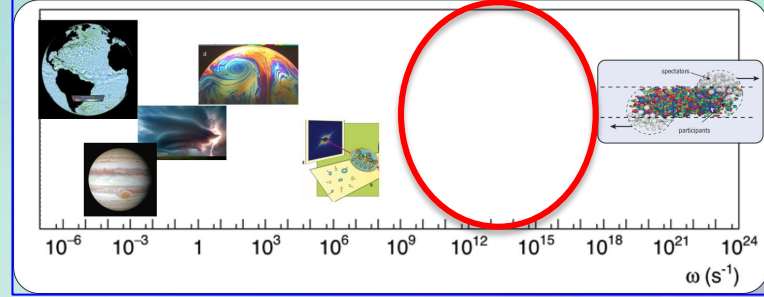


- Lifetime of extreme magnetic fields may be greatly enhanced by QGP conductivity (Lenz's Law)
- (High-stats) polarization measurements may provide a unique probe

$$m_p^2 / e \gg 10^{14} \text{ T}$$

compare

B-field, in perspective



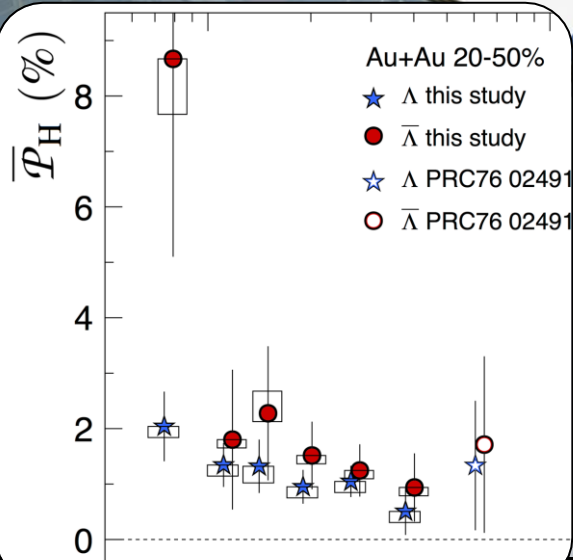
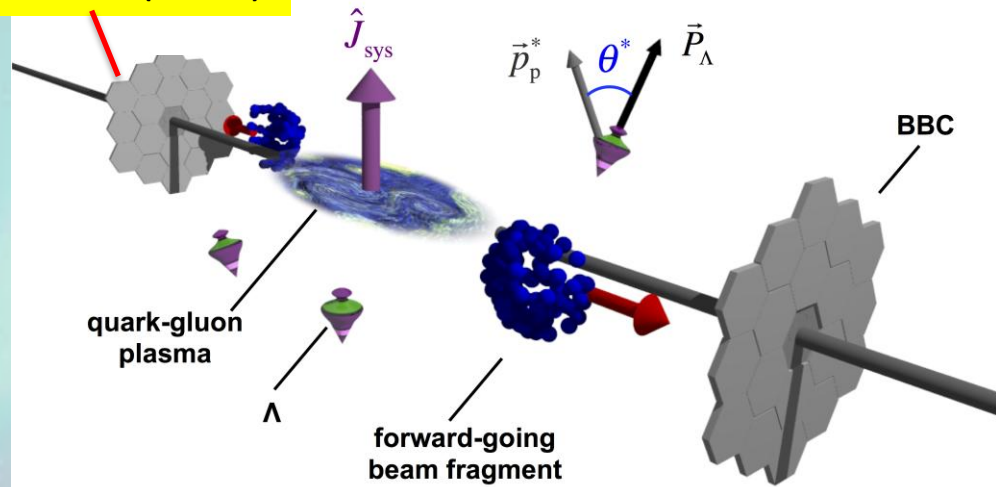
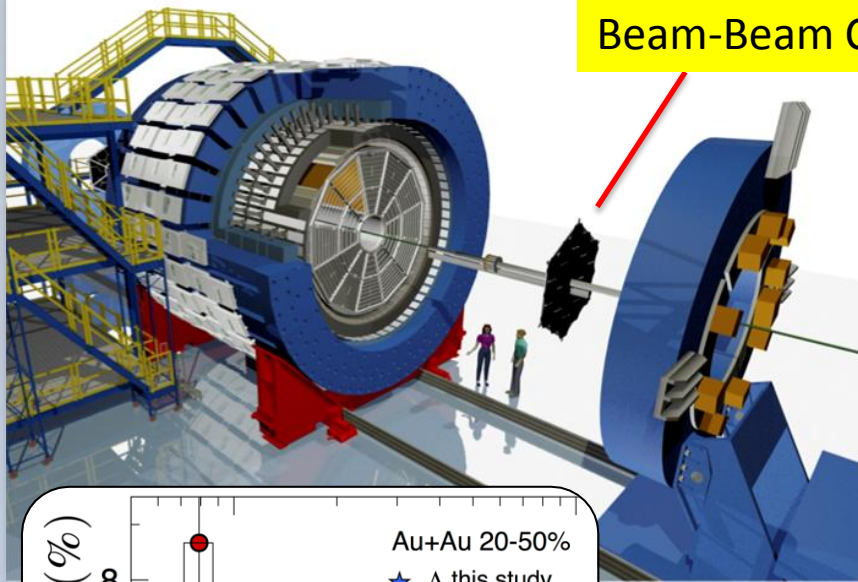
RHIC Program Advisory Committee recommendation

The PAC also strongly endorses STAR's request for a 3 week high-statistics $\sqrt{s_{NN}} = 27$ GeV Au+Au run aimed at establishing the existence of a Faraday fluid. STAR has published a landmark analysis, which for the first time measured a non-zero “global polarization” of nuclear spins for hadrons emitted from a high-energy heavy-ion collision. A collective effect like this must come from a macroscopic collective rotation of the droplet of quark-gluon plasma. By observing final- state global polarization of Lambda baryons, STAR has made a compelling case for large rotational velocities existing in equilibrated hot QCD matter. The mechanism for converting the large angular momentum of the incoming nuclei to rotational angular momentum of the fluid is currently far from understood. **The possibility of observing a Faraday fluid would represent a major discovery for the RHIC program, both as an experimental tour-de-force, and by establishing the existence of strong coherent magnetic fields in the equilibrated stages of heavy-ion collisions.** The EPD (event- plane detector) upgrade to the STAR detector is needed in order to reduce the error bars in the global polarization measurement as proposed. This upgrade is on schedule to be fully installed for Run 18, making possible the proposed run.

RHIC Program Advisory Committee recommendation

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Beam-Beam Counters (BBCs)

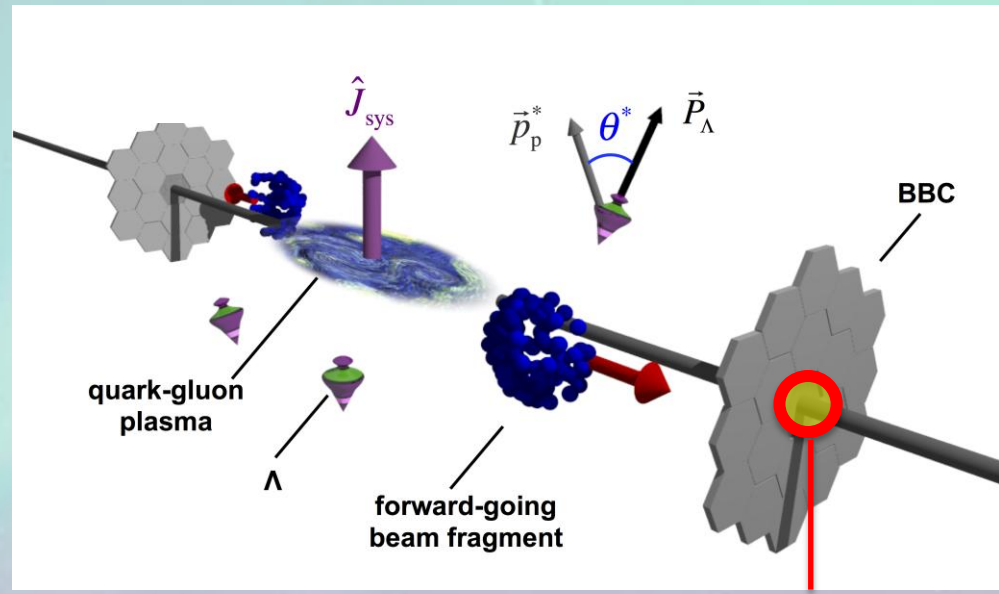
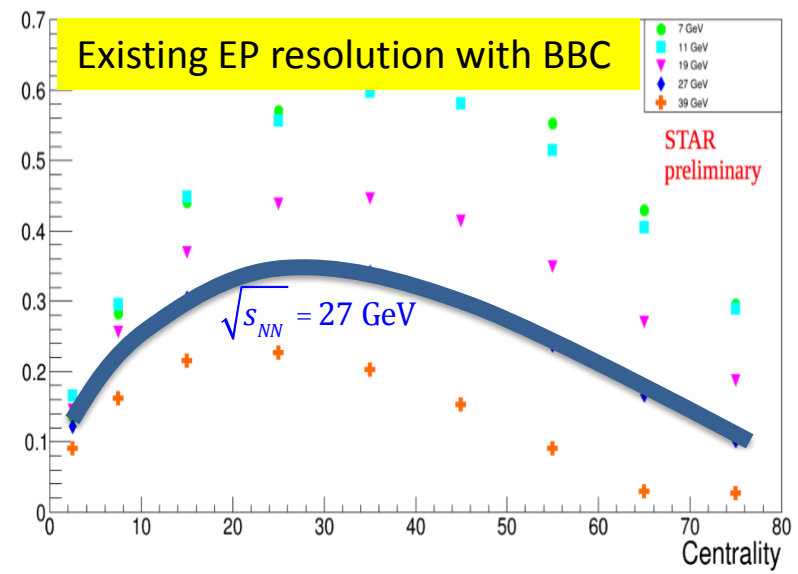


$$\overline{\mathcal{P}}_H = \frac{8}{pa} \frac{\langle \sin(f_p^* - Y_{EP}^{(1)}) \rangle}{R_{EP}^{(1)}}$$

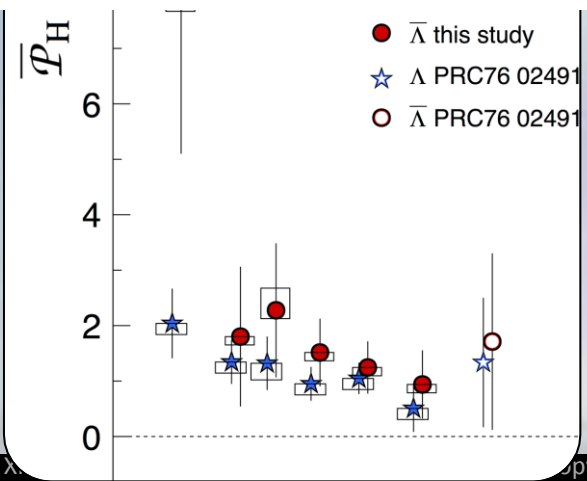
- $R_{EP}^{(1)}$ = 1st-order E.P. resolution

Event plane resolution R_{EP}^1

Existing EP resolution with BBC



In reality, we use only the inner tiles!



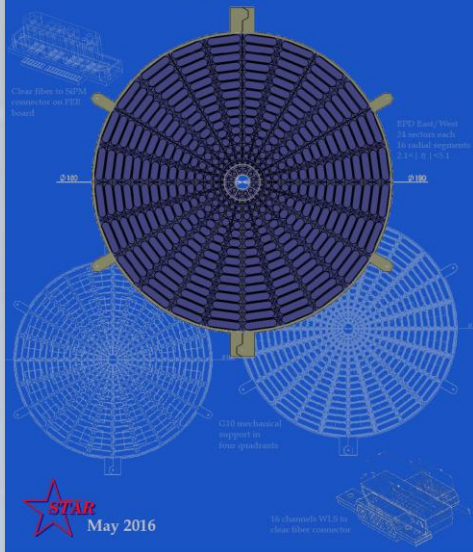
$$\overline{P}_H = \frac{8}{pa} \frac{\langle \sin(f_p^* - Y_{EP}^{(1)}) \rangle}{R_{EP}^{(1)}}$$

• $R_{EP}^{(1)}$ = 1st-order E.P. resolution

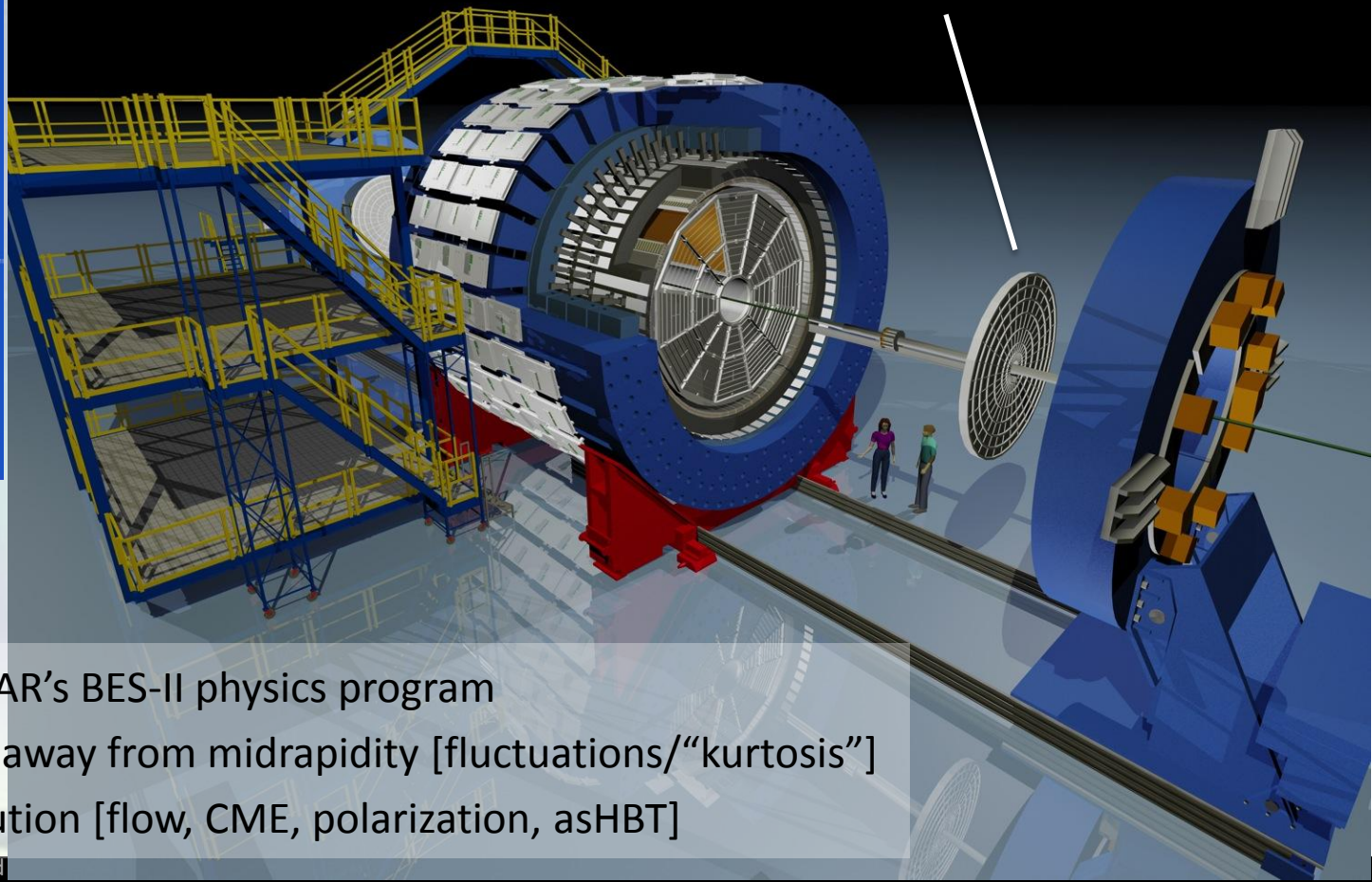
Errorbar: $d\overline{P}_H \propto \frac{1}{\sqrt{\#L}} \times \frac{1}{R_{EP}^{(1)}}$

• doubling resolution $R_{EP}^{(1)} \leftrightarrow$ quadrupling statistics

An Event Plane Detector for STAR



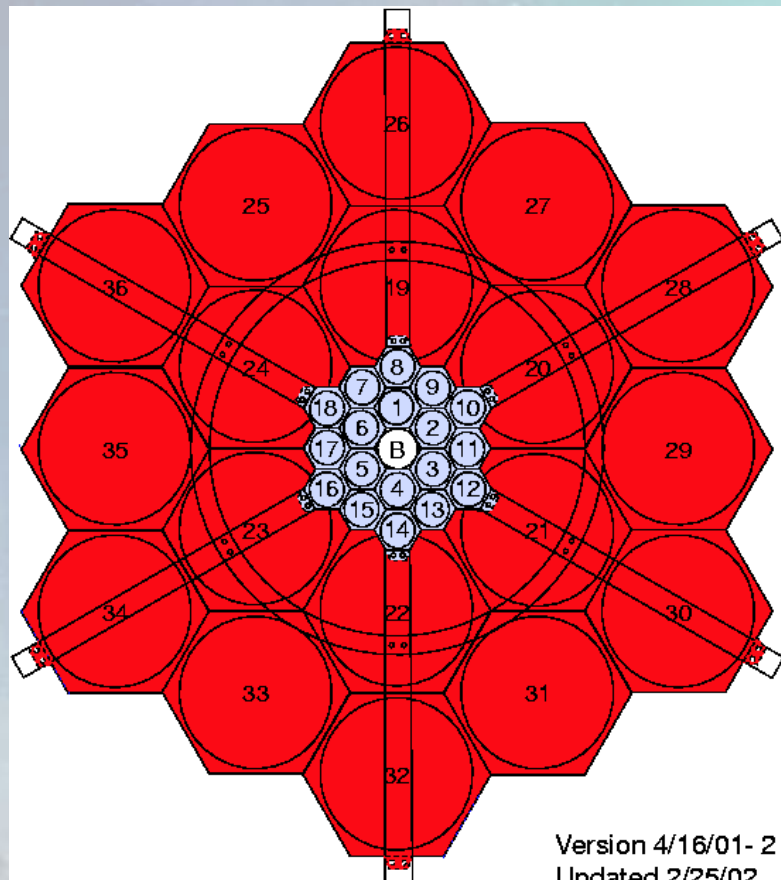
The STAR Event Plane Detector (EPD)



A major upgrade for STAR's BES-II physics program

- centrality definition away from midrapidity [fluctuations/"kurtosis"]
- enhanced E.P. resolution [flow, CME, polarization, asHBT]

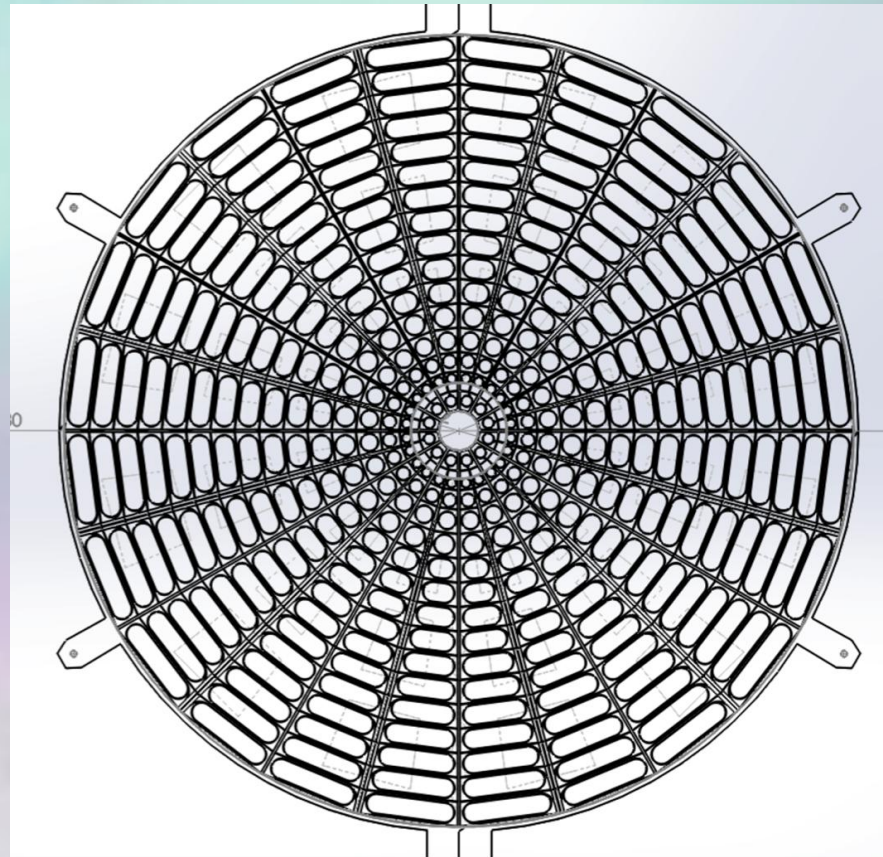
BBC inner – 16 channels / side
2 rings of hexagons

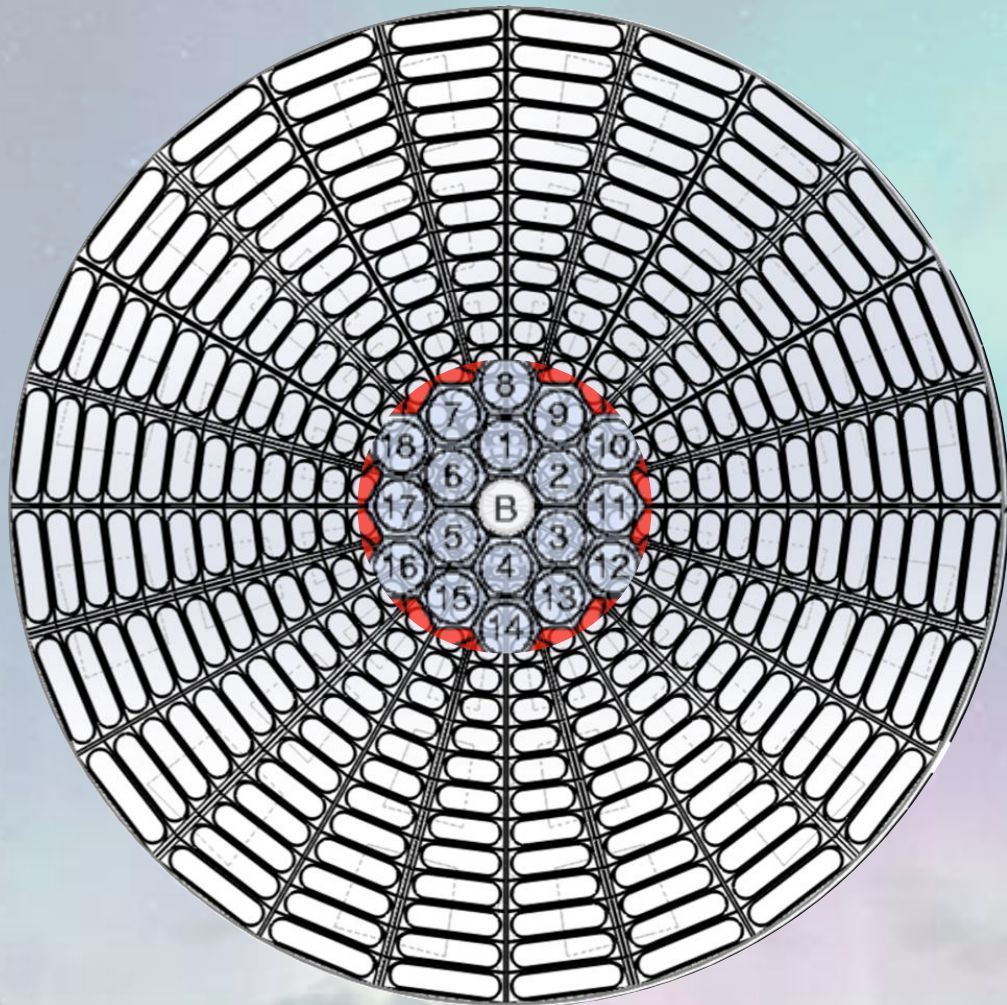


1.8 m

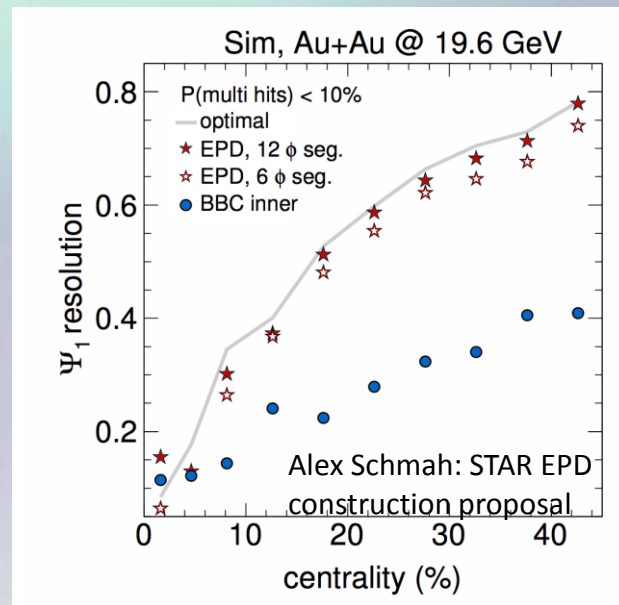


EPD – 372 tiles / side
16 eta segments x 24 phi segments

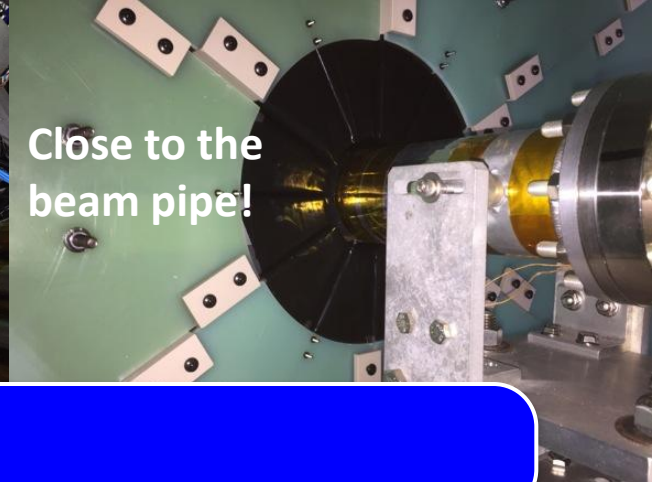
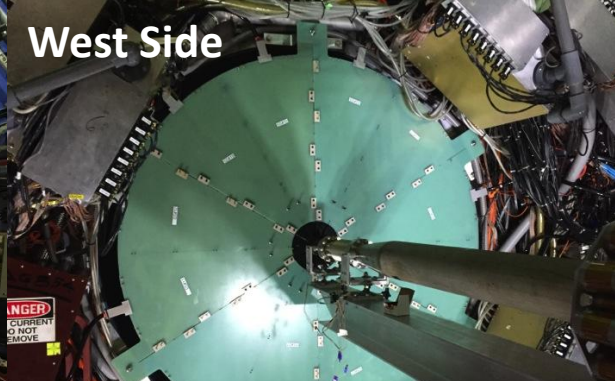
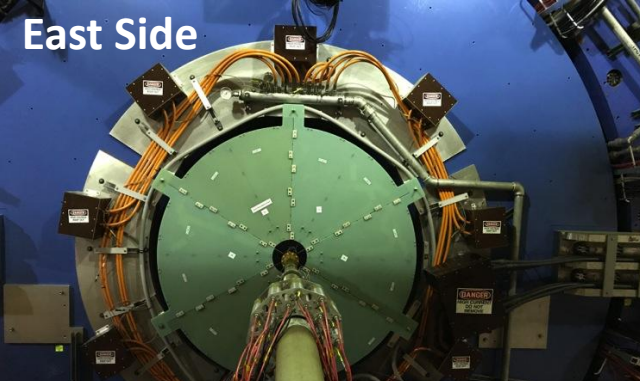




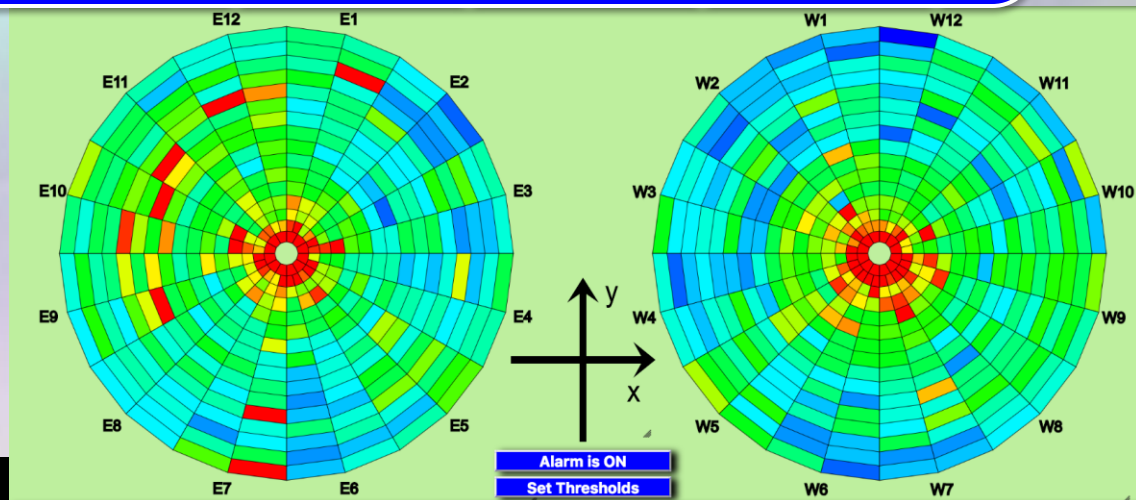
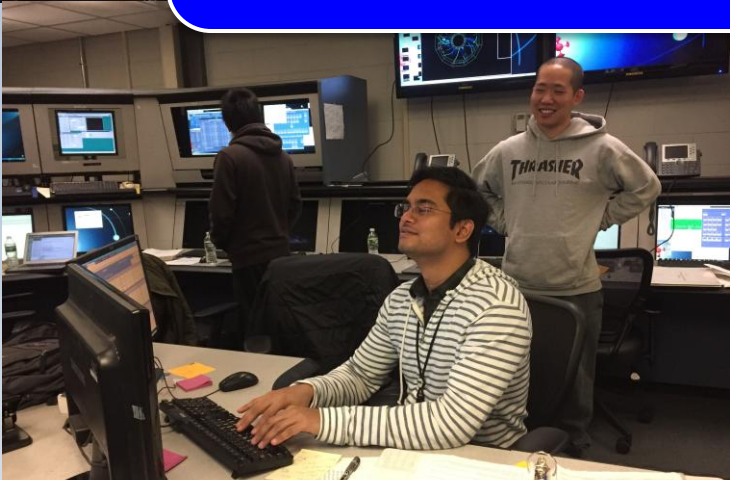
1 inner BBC tile \sim 5-7 EPD tiles



$\sim 2\times$ improved EP[1] resolution
for mid-central. [UrQMD sim.]



Installed & taking data

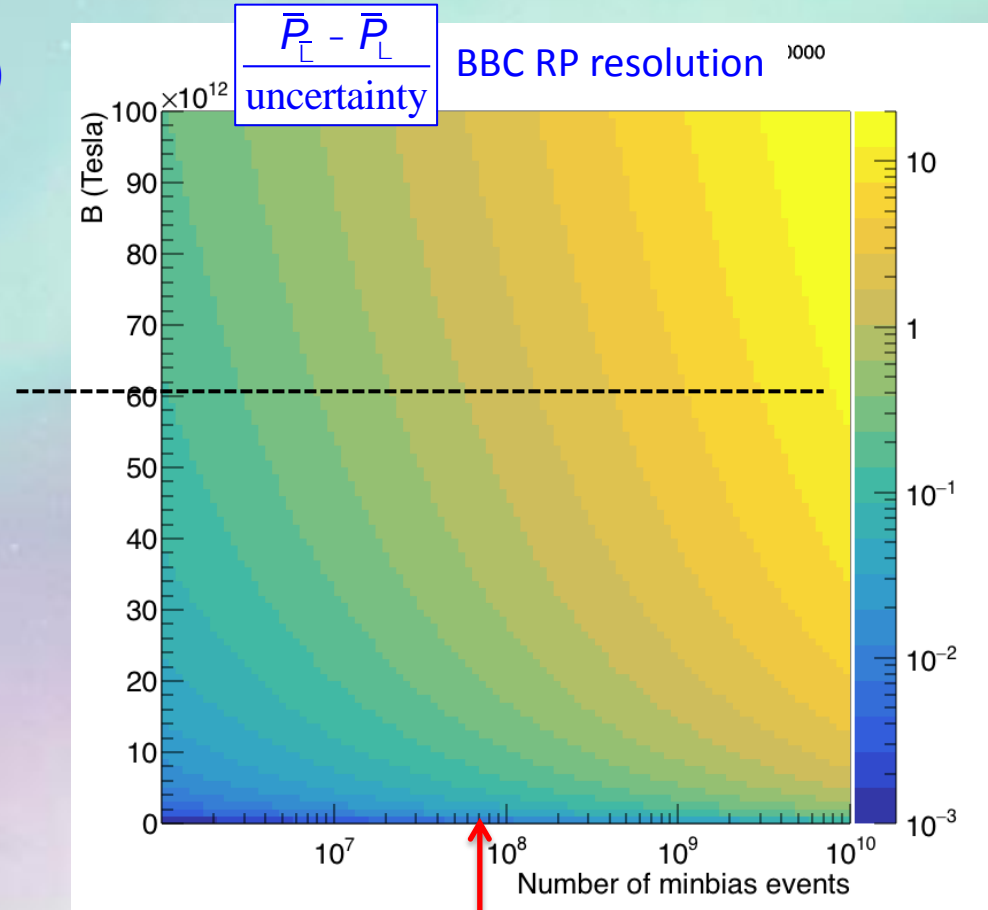
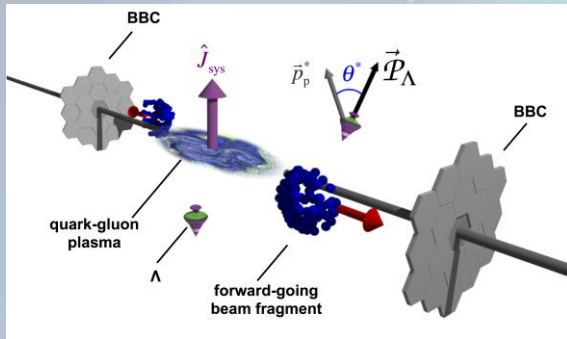


Prithwish Tribedy, “blind” shift leader
@ first Physics Ru/Zr run: 01:30 15 March 2018

Can we see the magnetic splitting? 2018 run at 27 GeV

Expect fields $\sim 10^{13}$ - 10^{14} T (for how long?)

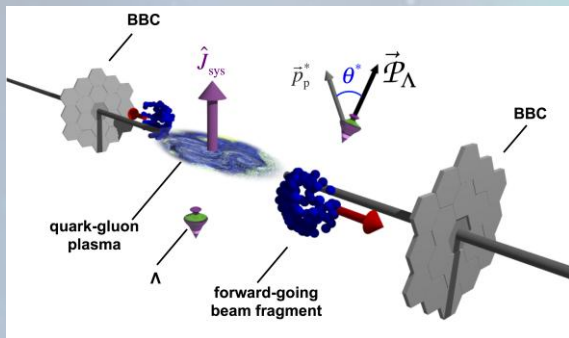
BES-I: 67×10^6 min. bias events with BBC



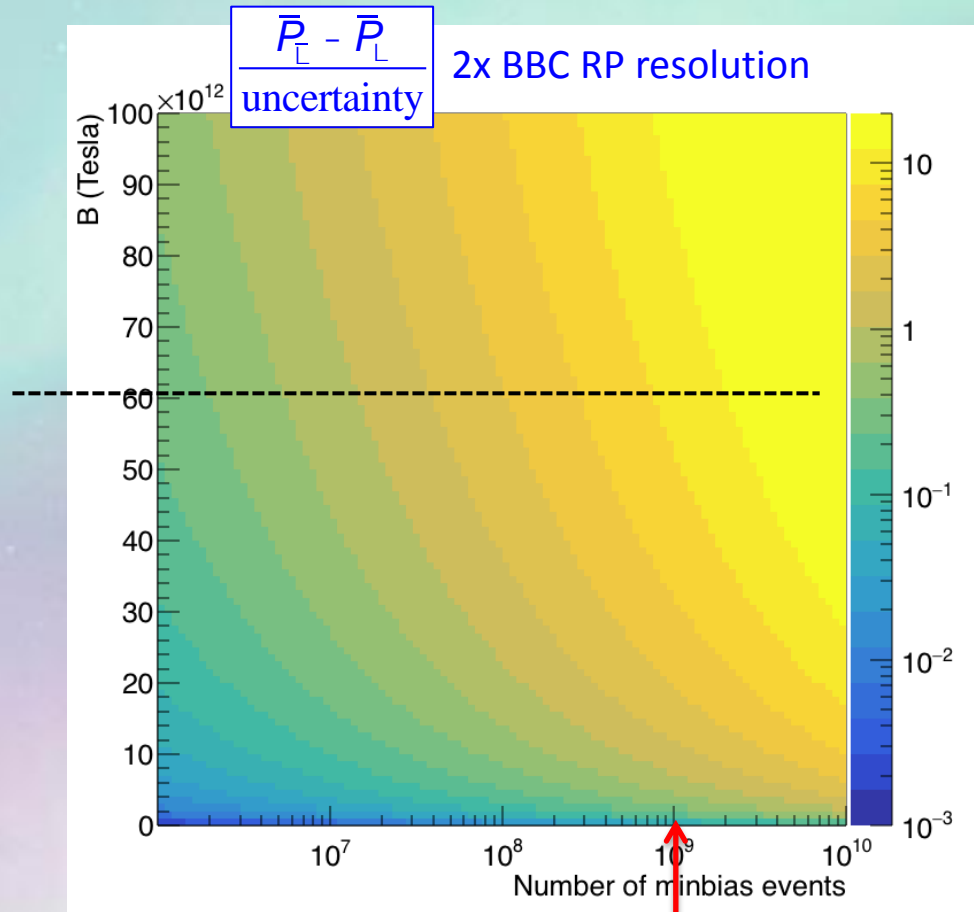
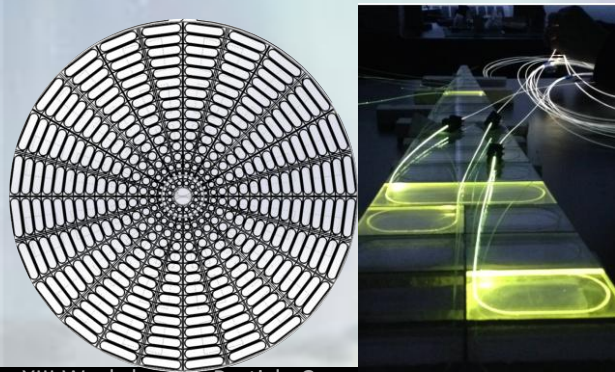
Can we see the magnetic splitting? 2018 run at 27 GeV

Expect fields $\sim 10^{13}$ - 10^{14} T (for how long?)

BES-I: 67×10^6 min. bias events with BBC



2018 : 10^9 events & detector upgrade



Summary

- **Polarization** : remarkable *new* validation of hydro paradigm
- **New high-statistics study at 200 GeV in STAR**: non-zero signal & new systematics
- **Systematics** (\sqrt{s} , centrality...) of global polarization consistent with *predictions*
- **Detailed substructure** (presumably) sensitive to interplay with anisotropic flow
 - azimuthal dependence of P_j – quadupole oscillation seen – *opposite of hydro prediction*
 - azimuthal dependence of P_z – quadupole oscillation seen – *opposite of hydro prediction*
- Possibility to measure **strongest magnetic field**: $\bar{P}_L - \bar{P}_\perp \propto B$
 - dedicated high-statistics RHIC run now ongoing: goal of 1B collisions
 - Event Plane Detector – new upgrade to improve event plane resolution