Measuring the strongest magnetic field: Prospects at RHIC

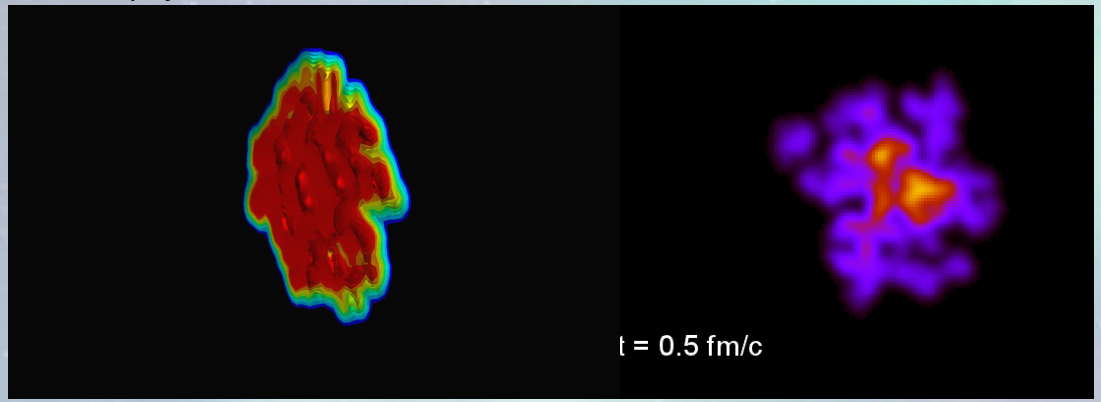
Mike Lisa
Ohio State University
for the STAR Collaboration

Outline

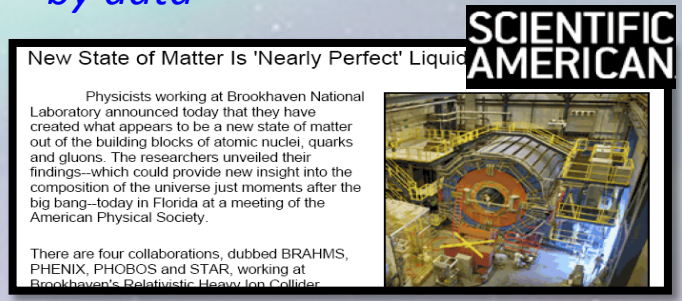
- Polarization
  - validation of hydro approach; possibility to measure B
- B-field
  - key for CME
  - “closure relation?
  - hint in published STAR data
- Run 2018
  - focus; upgrades; possibilities

Hydrodynamics –standard paradigm of H.I.C

movies by Bjorn Schenke



Recall fanfare when previous assumptions were overturned *by data*

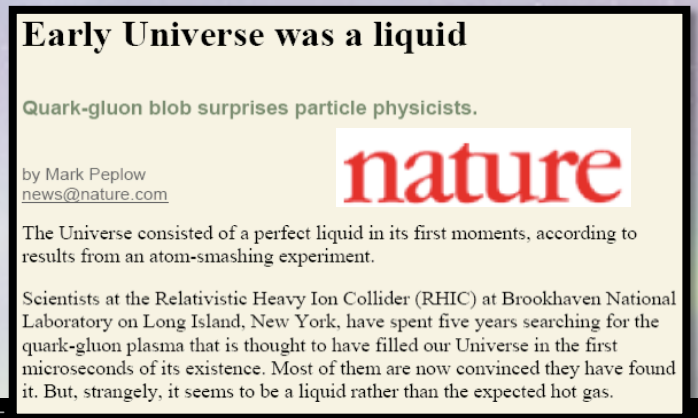


From a (lumpy) initial state, solve hydro equations:

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

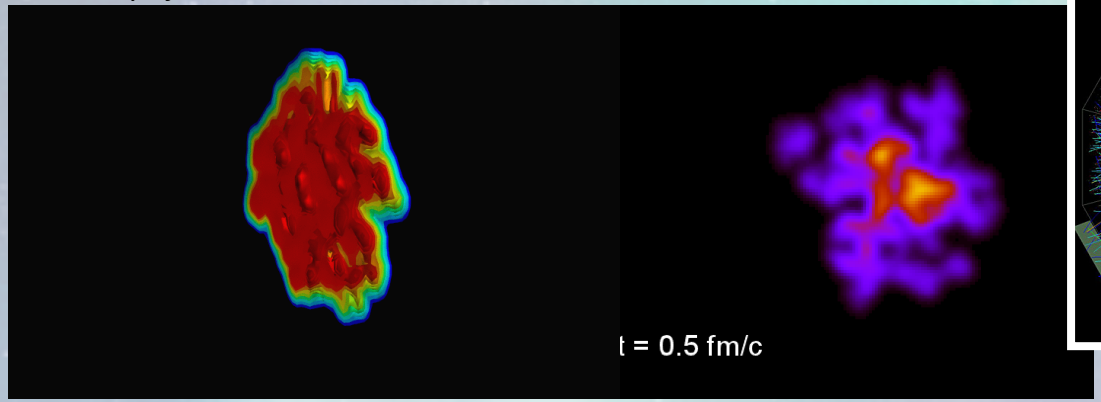
$$u^\mu d_\mu \Pi = -\frac{1}{\tau_\Pi}(\Pi + \zeta\theta) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi} d_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

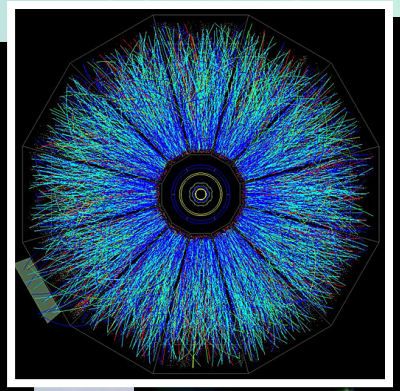
& many more terms...



Connection to experiment – freeze-out

movies by Bjorn Schenke





System cools & expands → Freeze-out

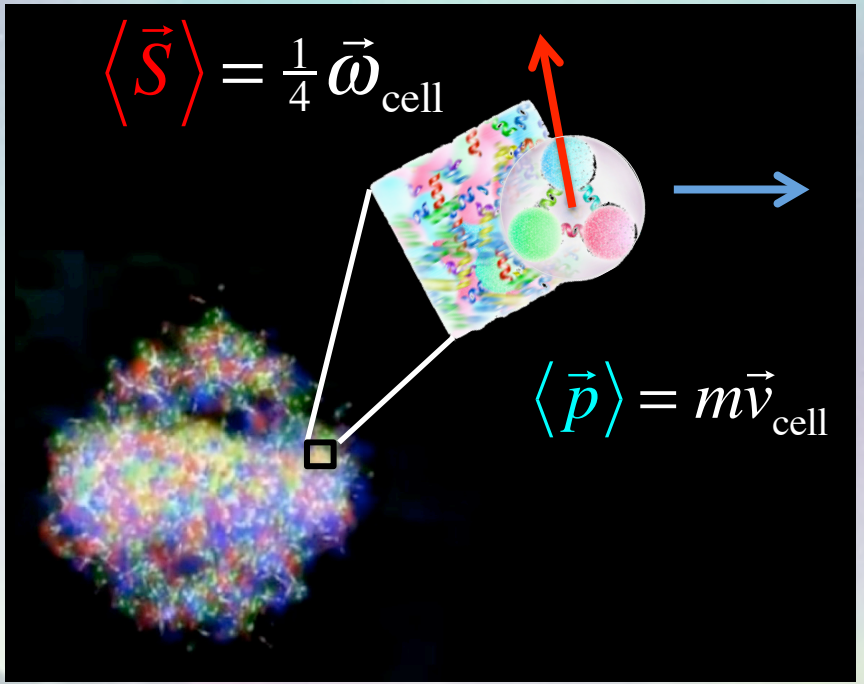
- Cooper-Frye prescription – "physics-free"
- emitted hadrons reflect properties of their parent hydro cell (chemical potentials, thermal & collective velocities)
- Must continue to subject paradigms under expt. scrutiny

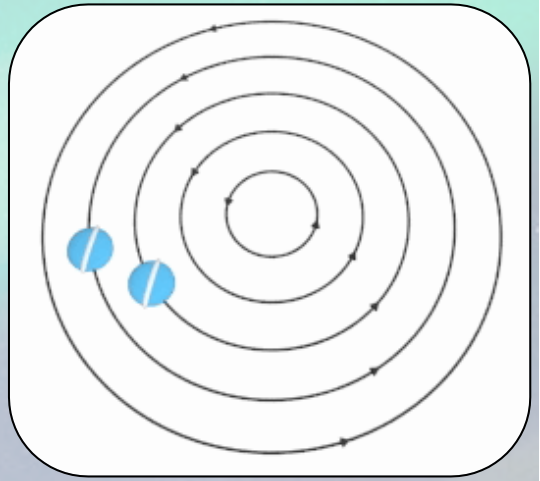
Local vorticity and polarization

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

Polarization

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





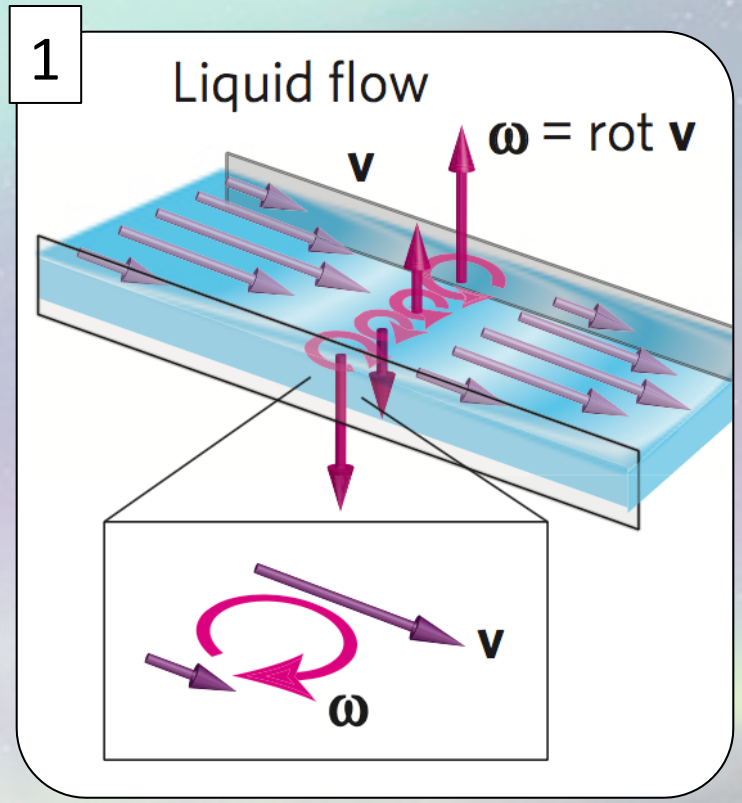
first suggested by

- 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 → fluid vorticity

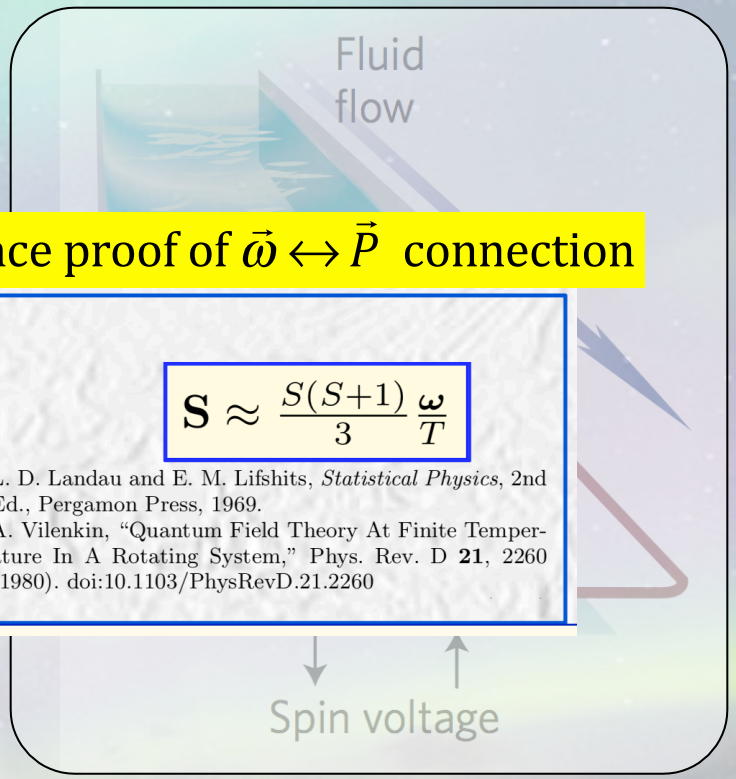


First observation of fluid vorticity-polarization coupling

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

1. Hg flowing down a channel
   - viscous forces with walls → fluid vorticity

2. mechanical **fluid vorticity → e⁻ polarization**



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

Nonrelativistic statistical mechanics

$$p(T, \mu_i, \mathbf{B}, \boldsymbol{\omega}) \propto \exp[(-E + \mu_i Q_i + \boldsymbol{\mu} \cdot \mathbf{B} + \boldsymbol{\omega} \cdot (\mathbf{S} + \mathbf{L}))/T]$$

$$\mathbf{S} \approx \frac{S(S+1)}{3} \frac{\boldsymbol{\omega}}{T}$$

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. Voloshin[4]

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

[28] L. D. Landau and E. M. Lifshits, *Statistical Physics*, 2nd Ed., Pergamon Press, 1969.
[29] A. Vilenkin, "Quantum Field Theory At Finite Temperature In A Rotating System," Phys. Rev. D **21**, 2260 (1980). doi:10.1103/PhysRevD.21.2260

"This opens a door to the new field of fluid spintronics"

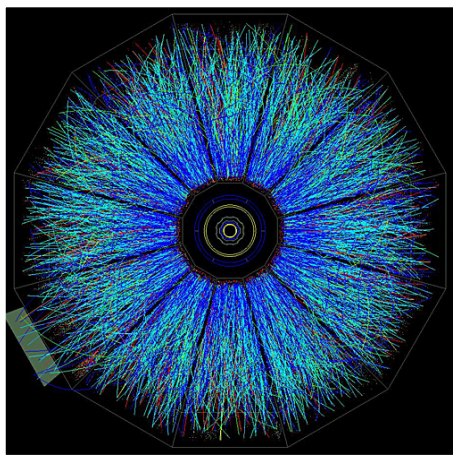
Subatomic spintronics

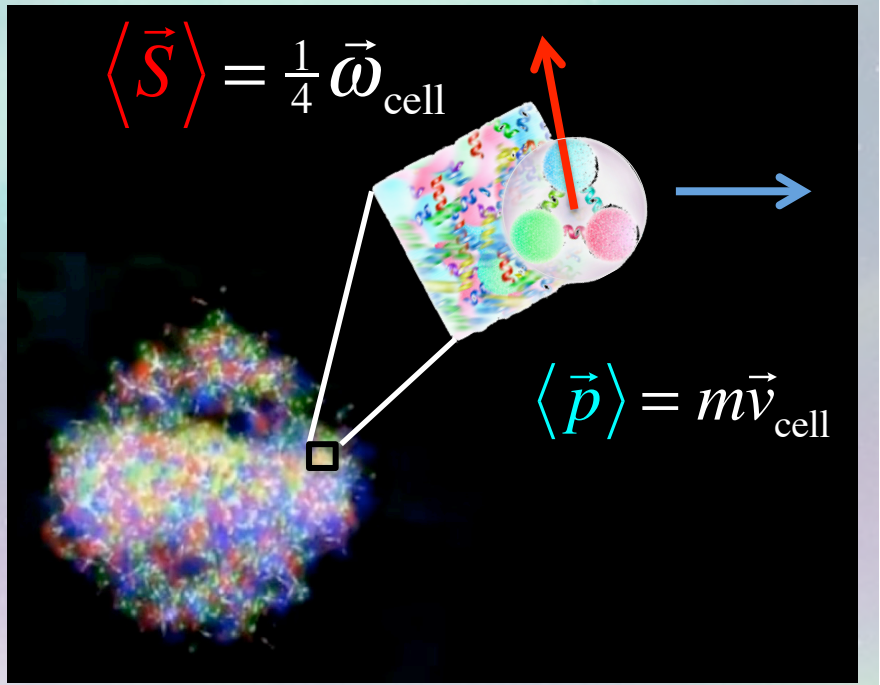
Barnett, Einstein, de Haas, Takahashi: $\vec{P} \propto \vec{\omega}$

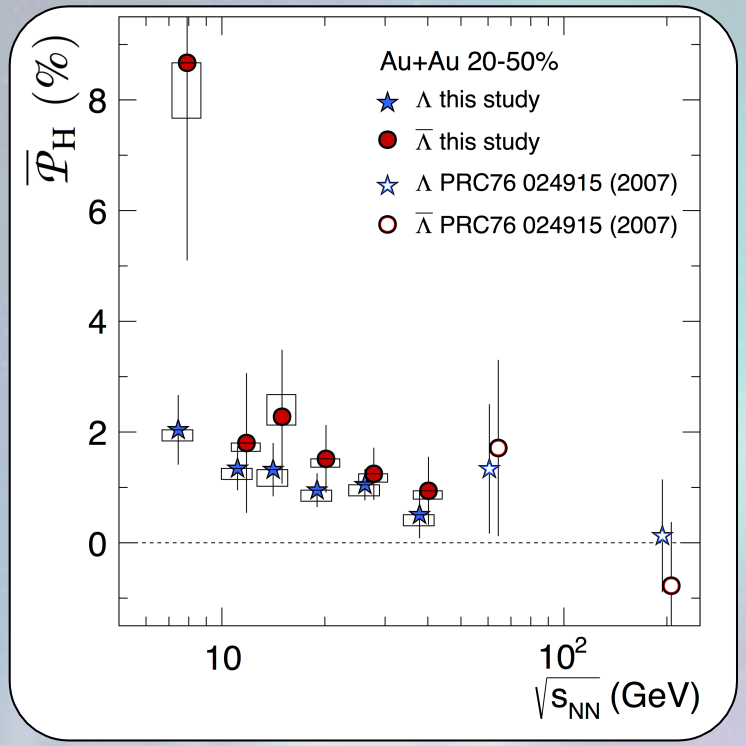
- straightforward to measure both $\vec{P}$ and $\vec{\omega}$

Our experimental situation is a little tougher...

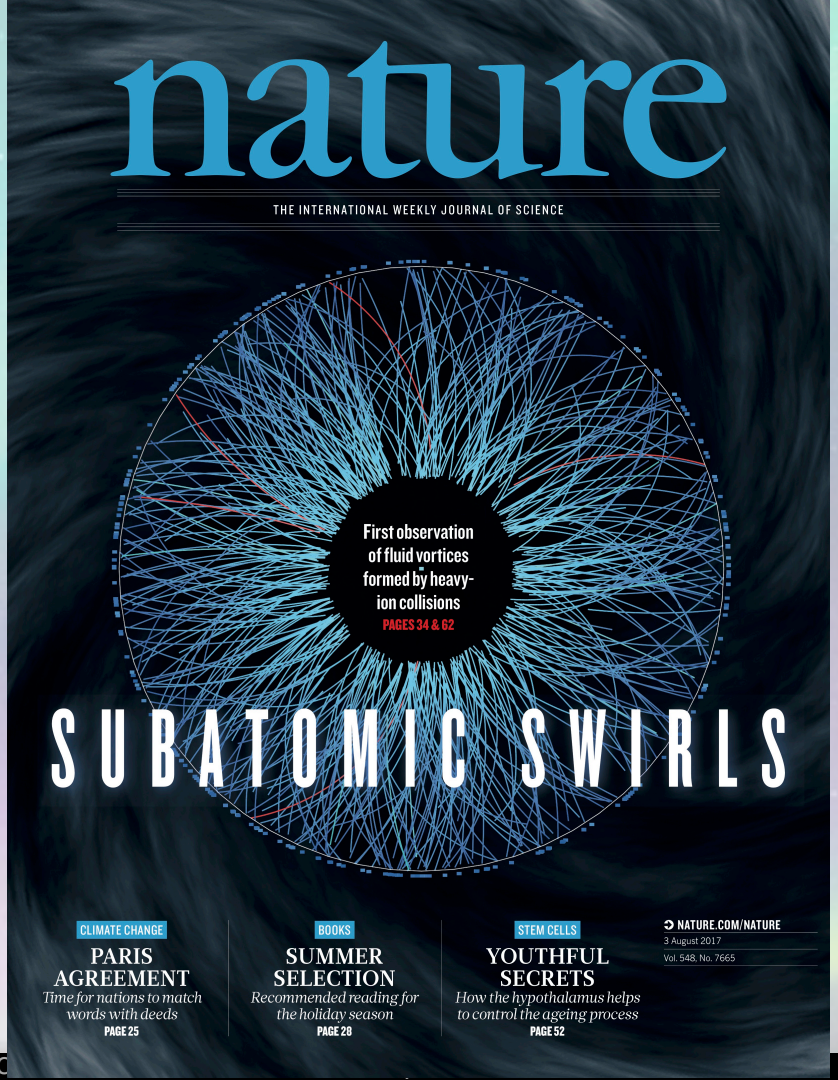
...but we benefit from their validation of the connection






Au+Au 20-50%
Λ this study
$\overline{\Lambda}$ this study
Λ PRC76 024915 (2007)
$\overline{\Lambda}$ PRC76 024915 (2007)
$\overline{P}_H$ (%)
8
6
4
2
0
10
10^2
$\sqrt{s_{NN}}$ (GeV)

- Photogenic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First observation of fluid vortices formed by heavy-ion collisions
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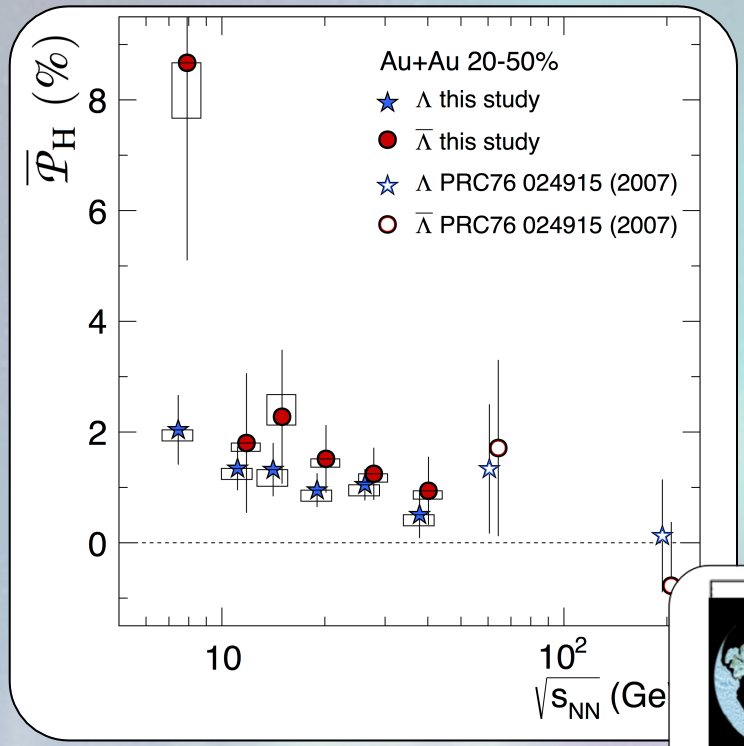
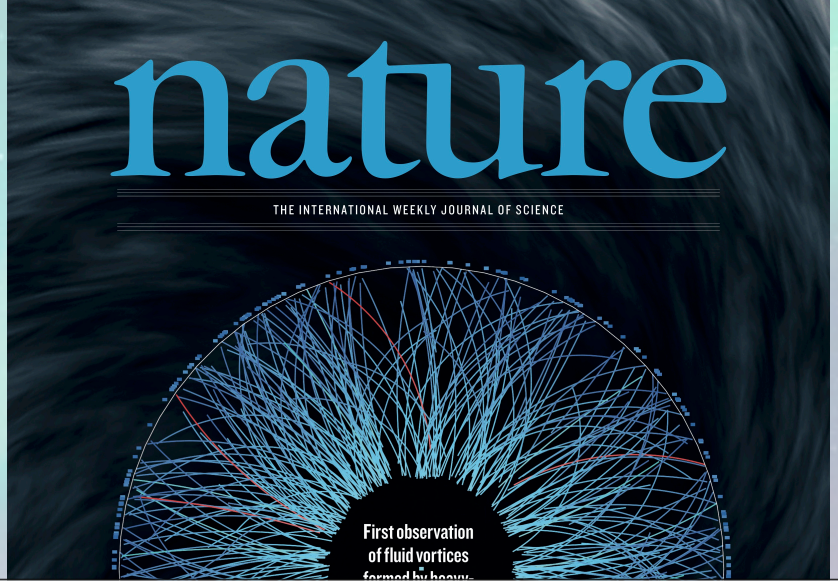
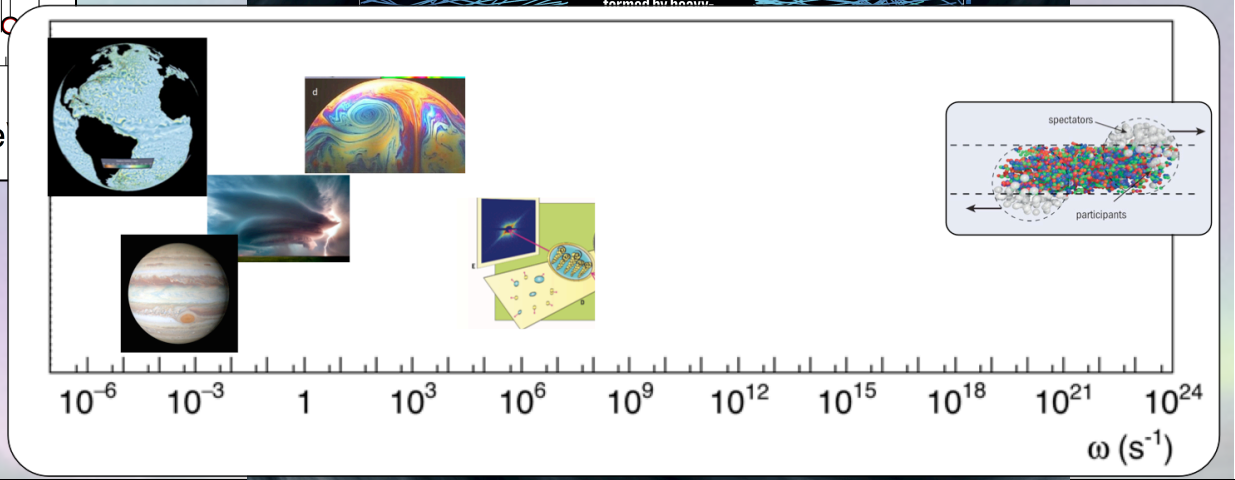




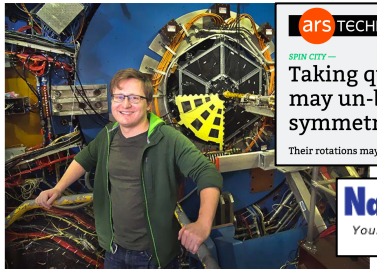


- Photogenic
- Amenable to comparisons to phenomena from other fields

'Perfect Liquid' Quark-Gluon Plasma is the Most Vortical Fluid

Swirling soup of matter's fundamental building blocks spins ten billion trillion times faster than the most powerful tornado, setting new record for "vorticity"

August 2, 2017



Ohio State University graduate student Isaac Upsal helped lead the analysis of results from the STAR detector that revealed a "vorticity" record for the quark-gluon plasma created in collisions at the Relativistic Heavy Ion Collider (RHIC).

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Taking quark-gluon plasma for a spin may un-break a fundamental symmetry

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'Perfect liquid' quark-gluon plas most vortical fluid

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PHYSICS | RICE UNIVERSITY

Fluid spins trillions of times faster than

The Telegraph India

Wednesday , August 9 , 2017

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'Perfect liquid' quark-gluon plasma is the most vortical fluid

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Primordial particle soup smashes spin-speed record

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夸克胶子等离子体“整体极化”理论获证

最新发现与创新

科技日报济南8月3日电 （记者王延斌 通讯员车慧卿）宇宙在最初诞生

万分之几秒内以“夸克胶子等离子体”的形式存在，这种类似“电浆”的状态

为是固体、液体、气体之后的第四种物质形态。近日，我国科学家首次提出的

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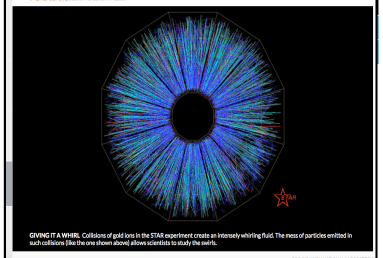
Smashing gold ions creates most swirly fluid ever

Record-making vorticity found in quark-gluon plasma

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



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.

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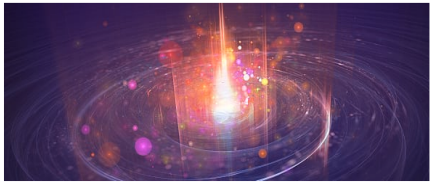
Gehirn&

Der schnellste Wirbel des Universums?

Den schnellsten bisher gemessenen Wirbel erzeugten Physiker in einem Teilchenbeschleuniger. Die Flüssigkeit ist dabei ein Plasma aus fundamentalen Teilchen: Quarks und Gluonen.

von Manon Bischoff



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INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 57 NUMBER 9 NOVEMBER 2017

HEAVY IONS

Fastest spinning fluid clocked by RHIC

Experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory have found that droplets of quark–gluon plasma (QGP) can spin faster than any other fluid. The immensely hot and fast-expanding QGP is already known to behave as a near "perfect" liquid, exhibiting a viscosity lower than any other. Now, researchers on RHIC's STAR experiment report that the vorticity (or curl) of the fluid produced in RHIC's relativistic heavy-ion collisions is about 9×10^{21} s^{-1}. That exceeds

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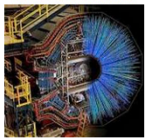
Perfect liquid quark-gluon plasma is the most vortical fluid

ENERGY DAILY the power of earth and beyond

Friday, 4 August 2017 (22 days ago)



Upton, NY (SPX) Aug 03, 2017

Particle collisions recreating the quark-gluon plasma (QGP) that filled the early universe reveal that droplets of this primordial soup swirl far faster than any other fluid. The new analysis of data from the Relativistic Heavy Ion Collider (RHIC) - a U.S. Department of Energy Office of Science User Facility for nuclear physics research at Brookhaven National Laboratory -

Brookhaven & RHI publicity...

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

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.

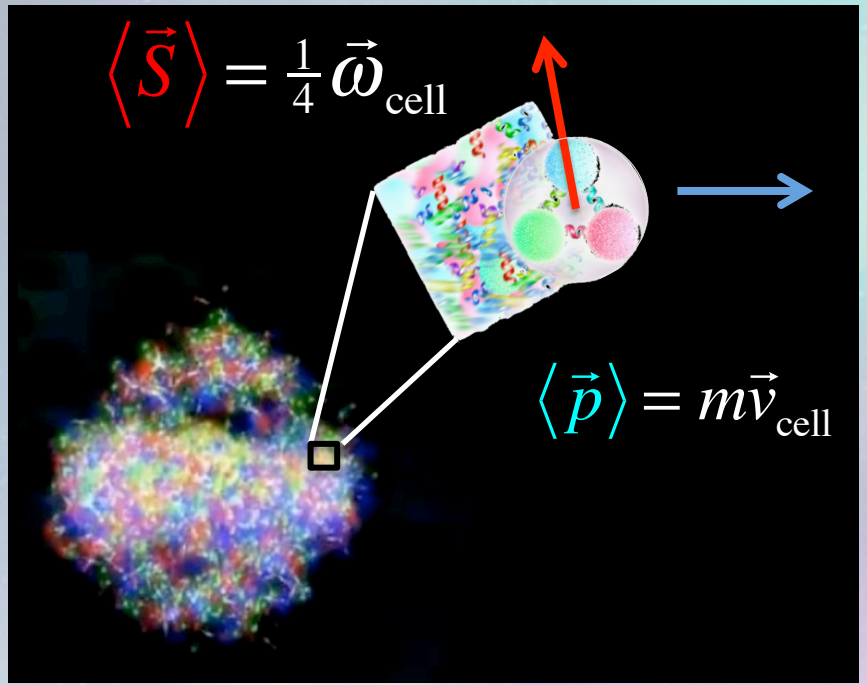
- **Overview**
- Committees
- Timetable
- Program
- First Circular
- Second Circular
- Third Circular
- Important Dates
- Call for Abstracts
  - View my abstracts

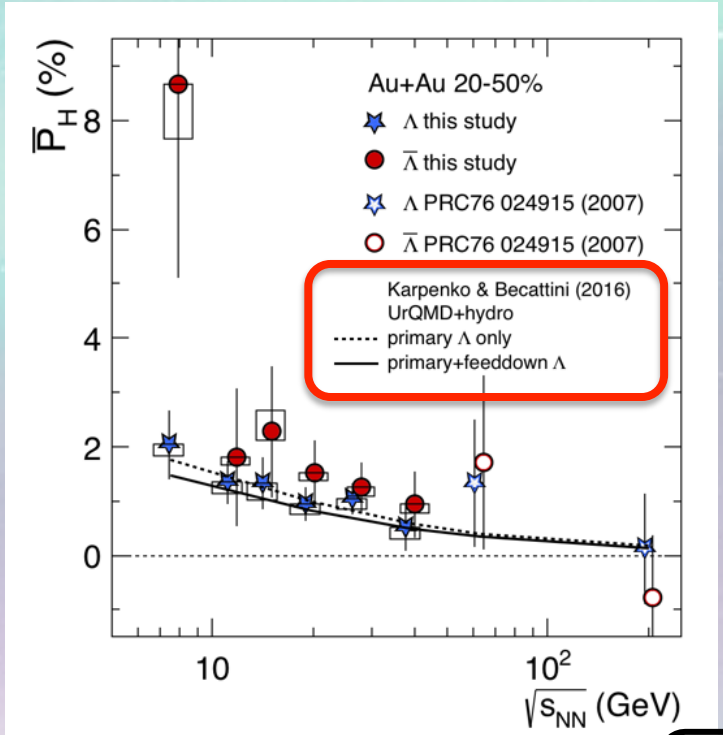
The **4th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions** will be held at the Galileo Galilei Institute in Florence from March 19 through March 22, 2018. The workshop will cover recent theoretical developments and experimental measurements related to these topics.

The workshop attendance is limited to 70 participants.

INFN Istituto Nazionale di Fisica Nucleare

A key take-away – the approach works





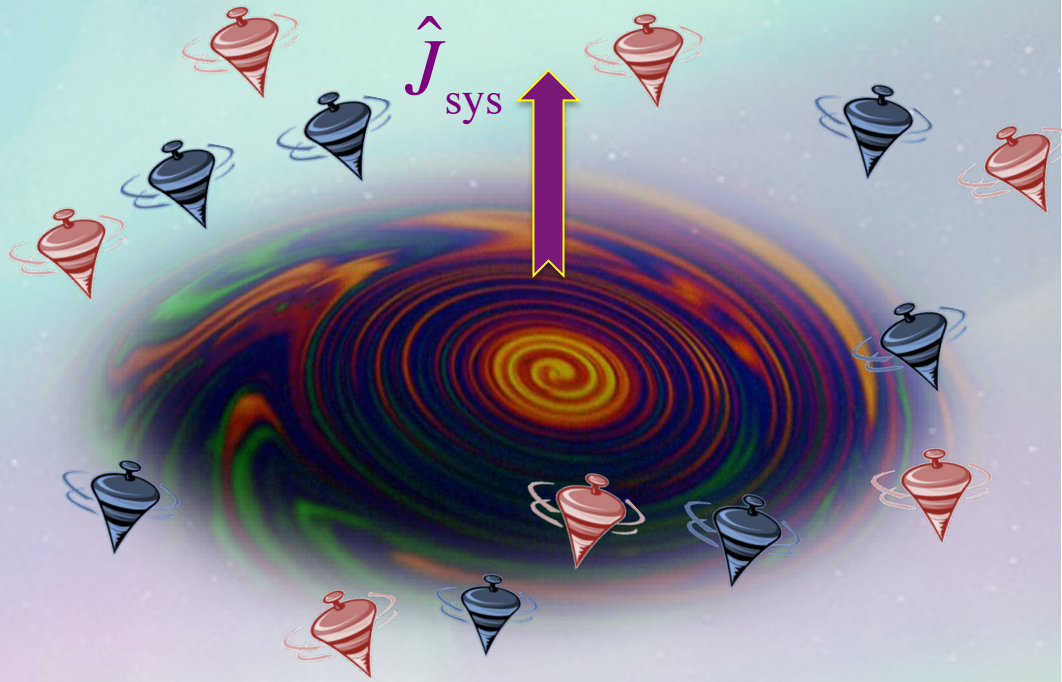
- Stunning success & validation of the near-equilibrium hydro paradigm*
- More than "just" the anisotropy of fluid velocity

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

Global polarization

Vortical coupling: $P \propto \omega$

$$\vec{\overline{P}}_{\Lambda} \parallel +\hat{J}_{\text{sys}} \qquad \vec{\overline{P}}_{\overline{\Lambda}} \parallel +\hat{J}_{\text{sys}}$$



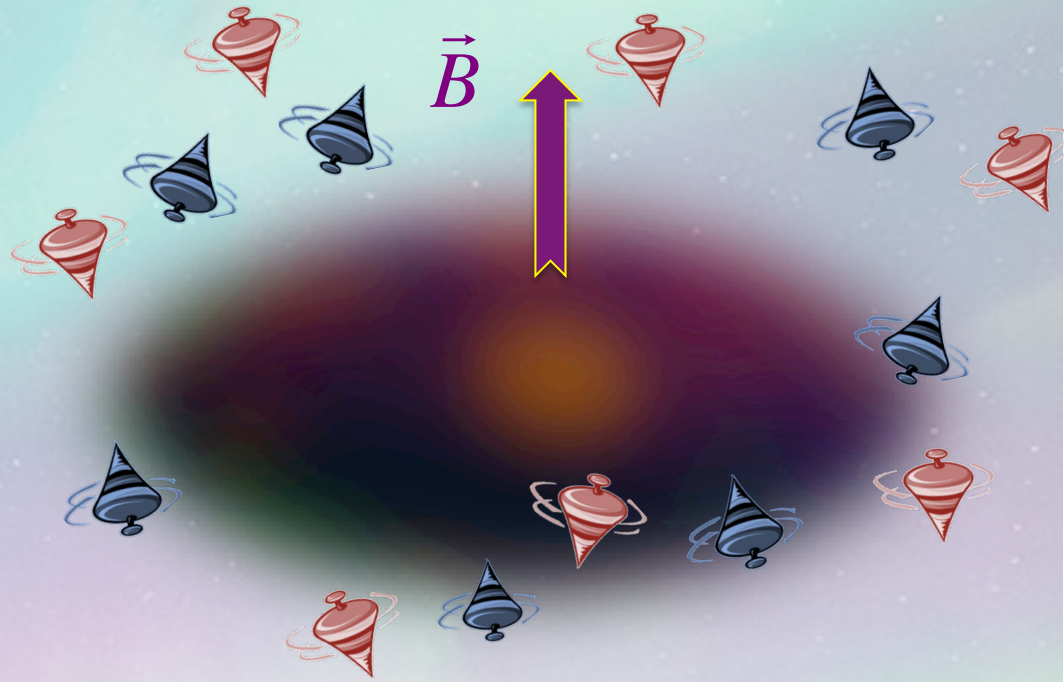
Global polarization

Vortical coupling: $P \propto \omega$

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

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

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



Global polarization in equilibrium paradigm

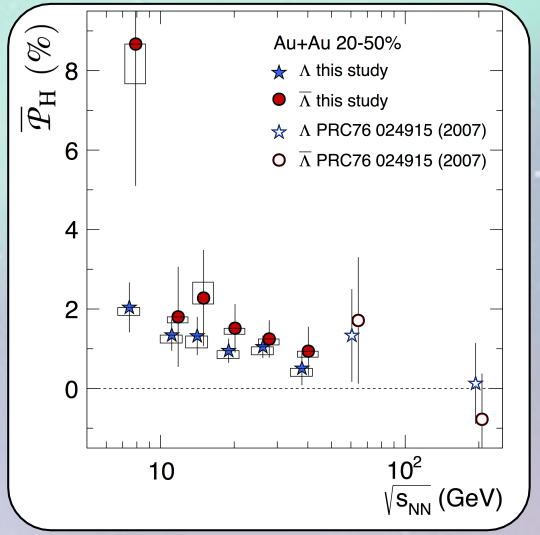
Vortical coupling: $P \propto \omega$

$\vec{P}_{\Lambda} \parallel +\hat{J}_{\rm sys} \qquad \vec{P}_{\bar{\Lambda}} \parallel +\hat{J}_{\rm sys}$

"at freezeout"

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

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



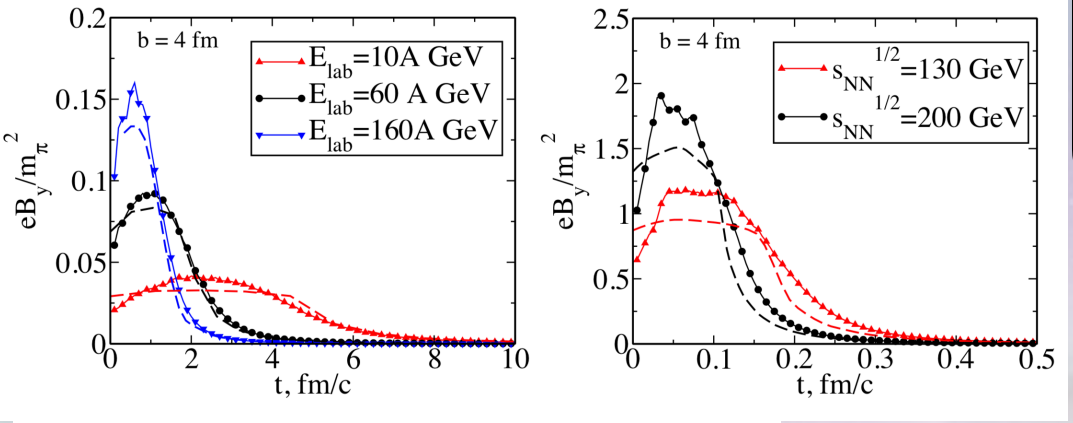
$$\begin{pmatrix} \omega/T \\ B/T \end{pmatrix} = \underbrace{\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}}_{\text{includes feed-down}} \begin{pmatrix} P_{\Lambda}^{\rm meas} \\ P_{\bar{\Lambda}}^{\rm meas} \end{pmatrix}$$

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

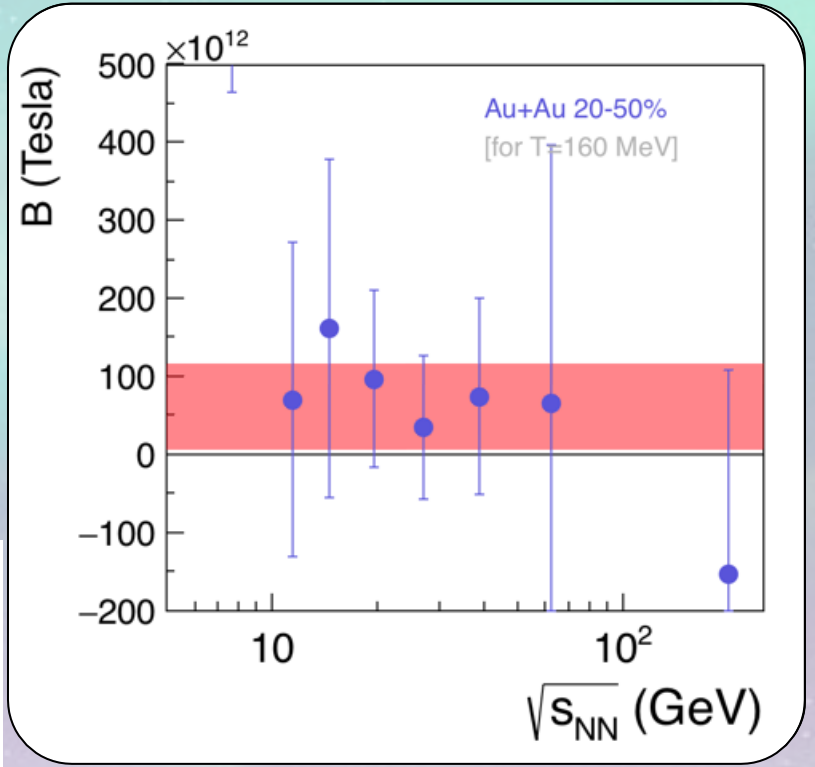
Magnetic field?

- Statistical uncertainties preclude claim
- B should change with energy*, but...

$$\langle B \rangle_{\sqrt{s}} = 6.0 \pm 5.5 \times 10^{13}\ \mathrm{T} \approx 0.6 \pm 5.5\ m_\pi^2$$

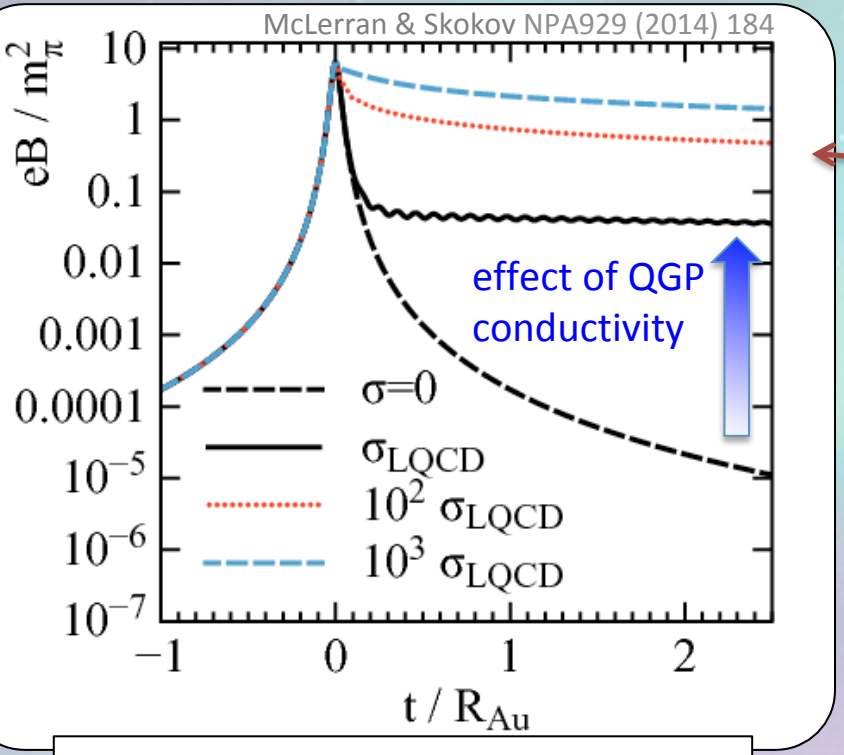


Skokov et al, Int J. Mod. Phys. E, 2009 **A24** 5925

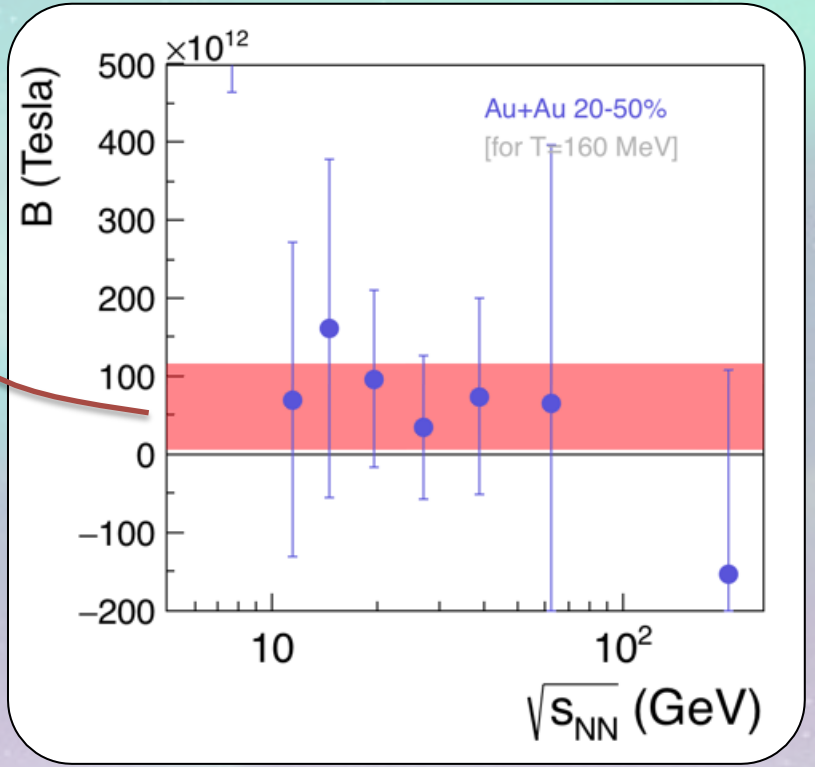


* Interplay between timescale and magnitude → not obvious what is energy dependence of *relevant* B...

McLerran & Skokov NPA929 (2014) 184



Predicted time-dependent B-field

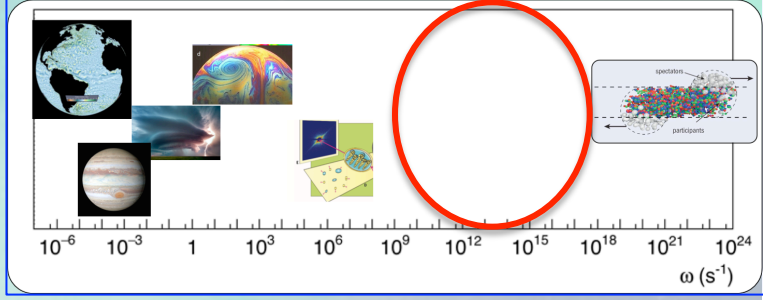


- Lifetime of extreme magnetic fields may be greatly enhanced by QGP conductivity (Lenz's Law)
- (High-stats) polarization measurements may provide a unique probe

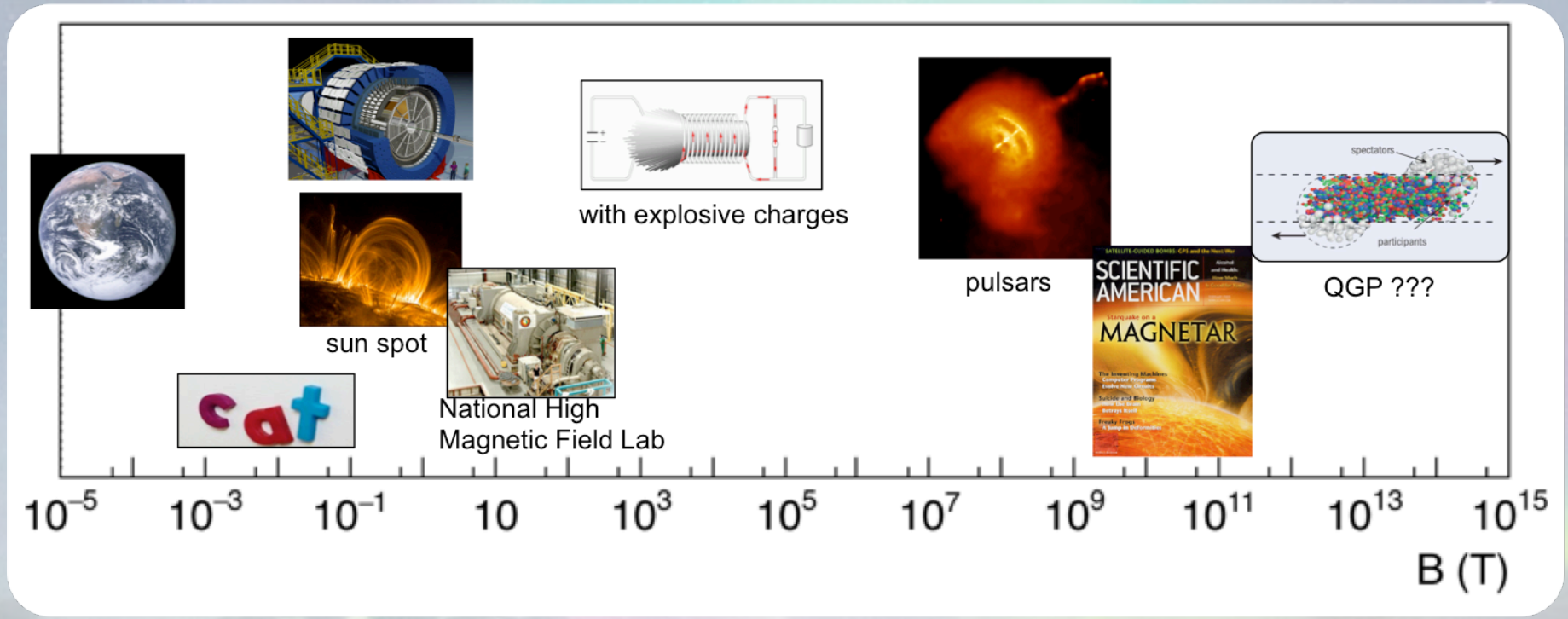
$m_\pi^2 / e \approx 10^{14}$ T

Similar result from Shi Pu's talk using more realistic calculation

compare



B-field, in perspective



RHIC Program Advisory Committee recommendation

The PAC also strongly endorses STAR's request for a 3 week high-statistics √sNN = 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.

Can we “close” the overconstrained system?

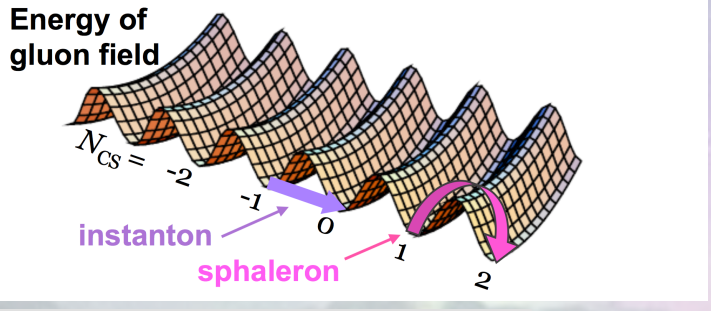
$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\underbrace{\mathrm{tr}(VAQ)\vec{B}}_{CME} + \underbrace{\mathrm{tr}(VAB)2\mu_B\vec{\omega}}_{CVE}]$$

μ_5 : characterizes fluctuations in N_{CS}

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

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

$$\Gamma = \frac{1}{2}\lim_{t\to\infty}\lim_{V\to\infty}\int_0^t \langle (q(x)q(0) + q(0)q(x))\rangle d^4x$$



6 variables: $B, \omega, \mu_B, \mu_5, J_E, J_B$

2 equations

ω measured

μ_B measured

J_E measured??

J_B ??

B Try!

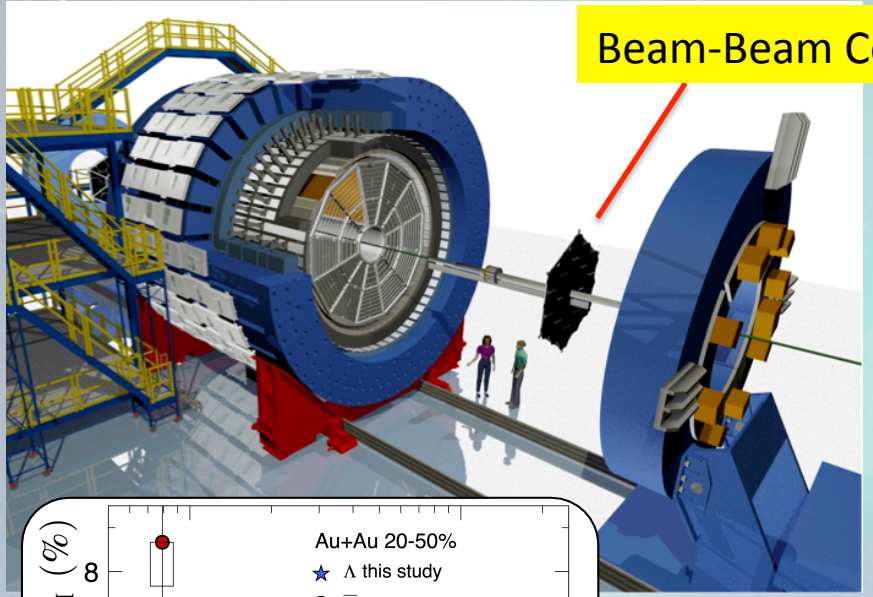
- Experimental test: “Blinding”
- Theoretical test: Consistency in overconstrained system

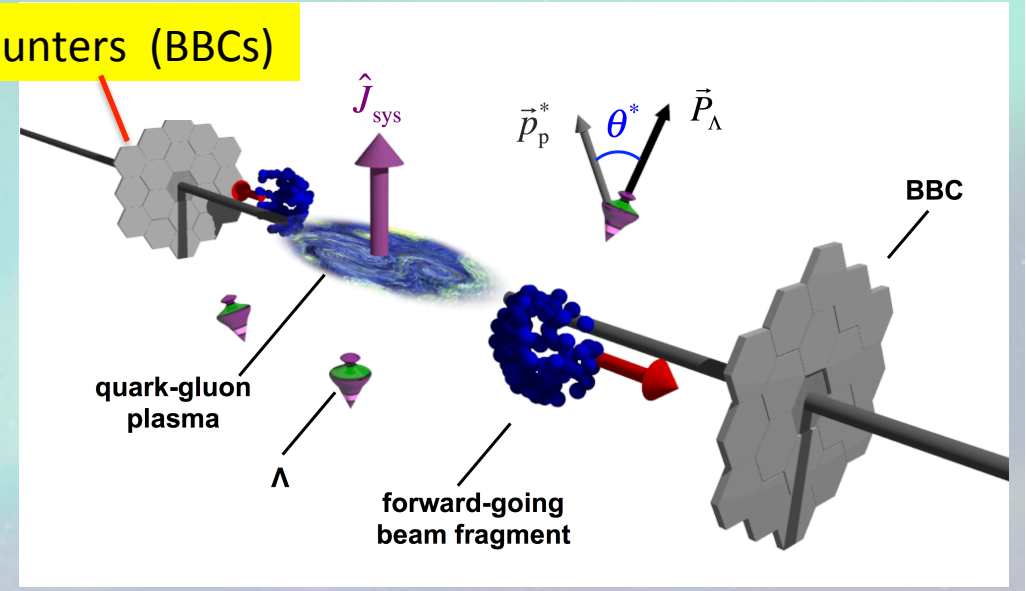
Kharzeev & Son PRL**106** 062301 (2011)

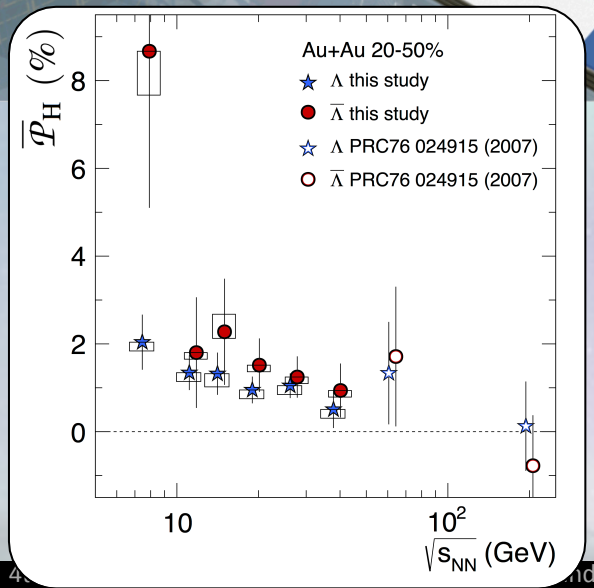
RHIC Program Advisory Committee recommendation

The PAC also strongly endorses STAR's request for a 3 week high-statistics √sNN = 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.**

Beam-Beam Counters (BBCs)

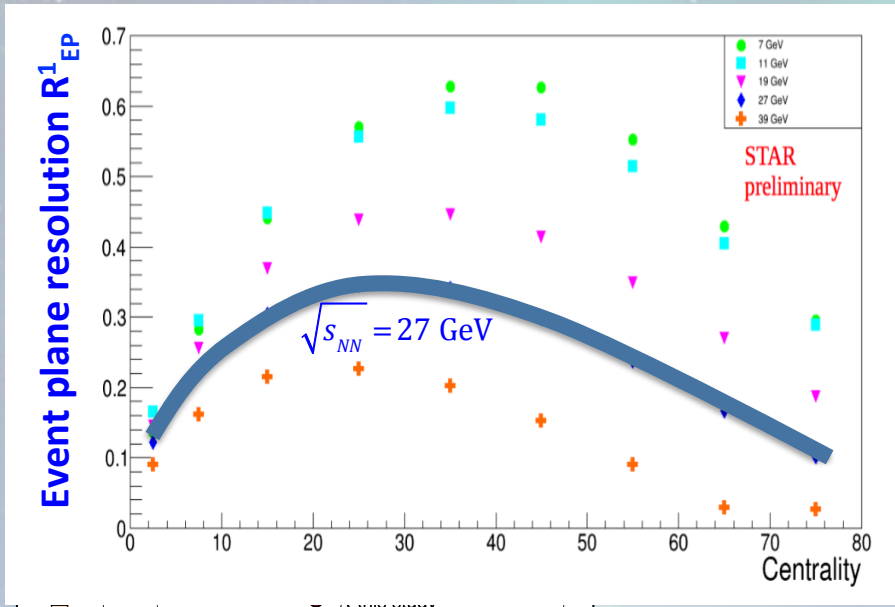


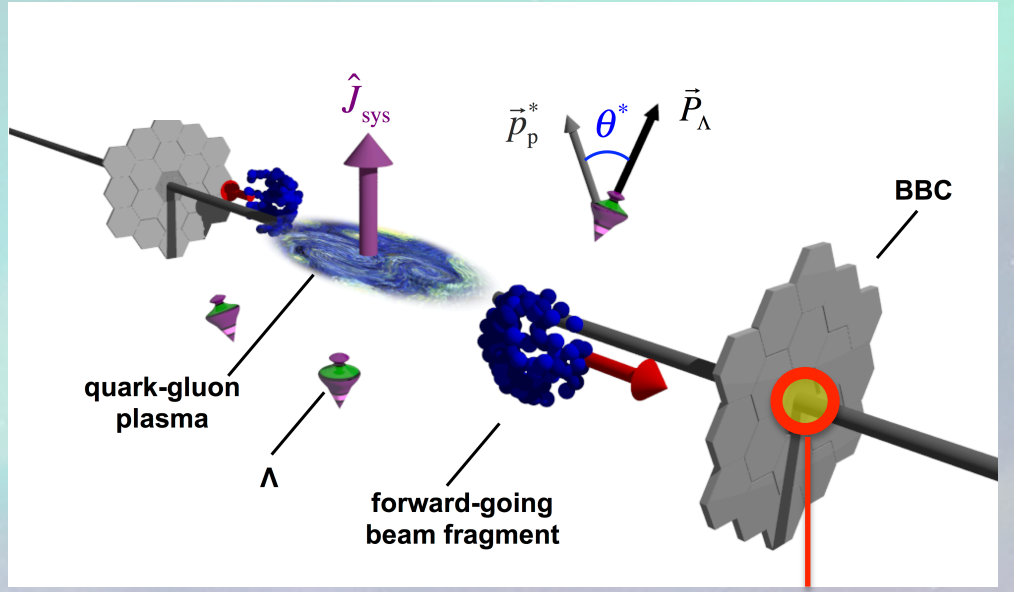




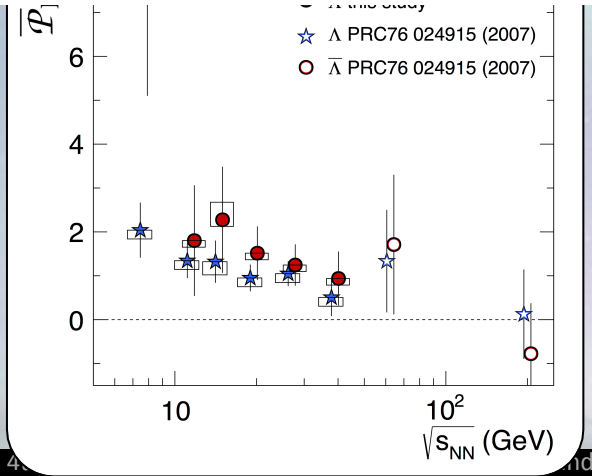
$$\overline{P}_H = \frac{8}{\pi\alpha} \frac{\langle \sin(\phi^*_p - \Psi^{(1)}_{EP}) \rangle}{R^{(1)}_{EP}}$$

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





In reality, we use only the inner tiles!



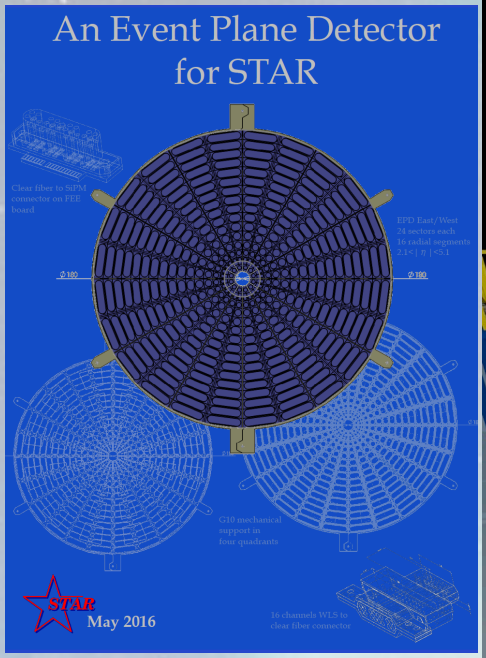
$$\overline{P}_{\mathrm{H}} = \frac{8}{\pi\alpha} \frac{\langle \sin(\phi^*_{\mathrm{p}} - \Psi^{(1)}_{\mathrm{EP}}) \rangle}{R^{(1)}_{\mathrm{EP}}}$$

- $R^{(1)}_{\mathrm{EP}}$ = 1st-order E.P. resolution

Errorbar: $\delta\overline{P}_H \propto \frac{1}{\sqrt{\#\Lambda}} \times \frac{1}{R^{(1)}_{EP}}$

- doubling resolution $R^{(1)}_{EP} \leftrightarrow$ quadrupling statistics

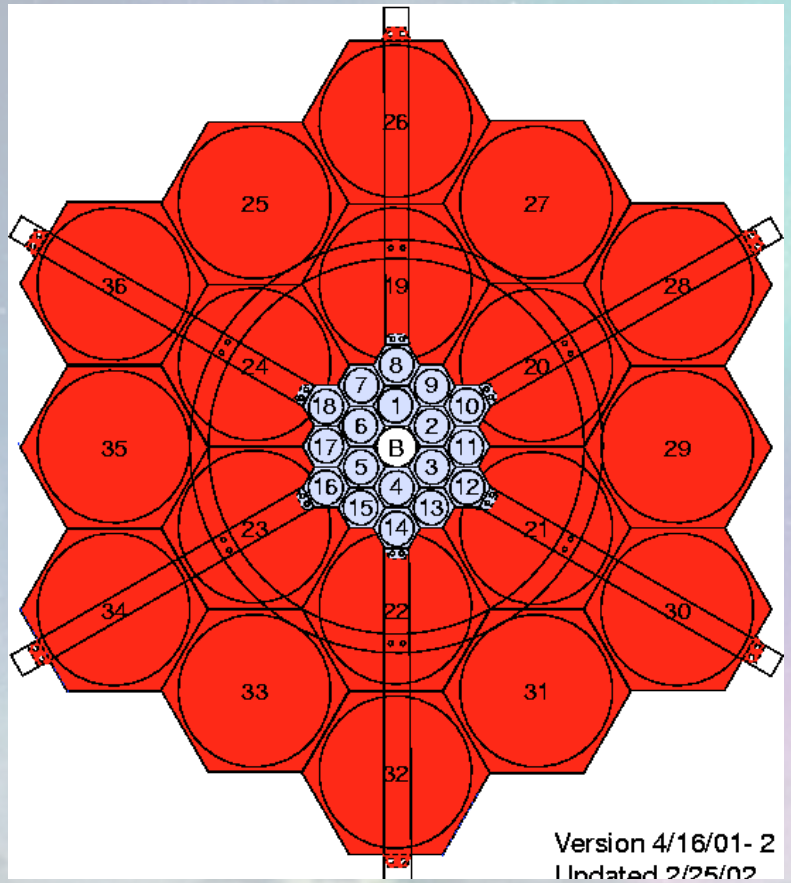
STAR Event Plane Detector (EPD)



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

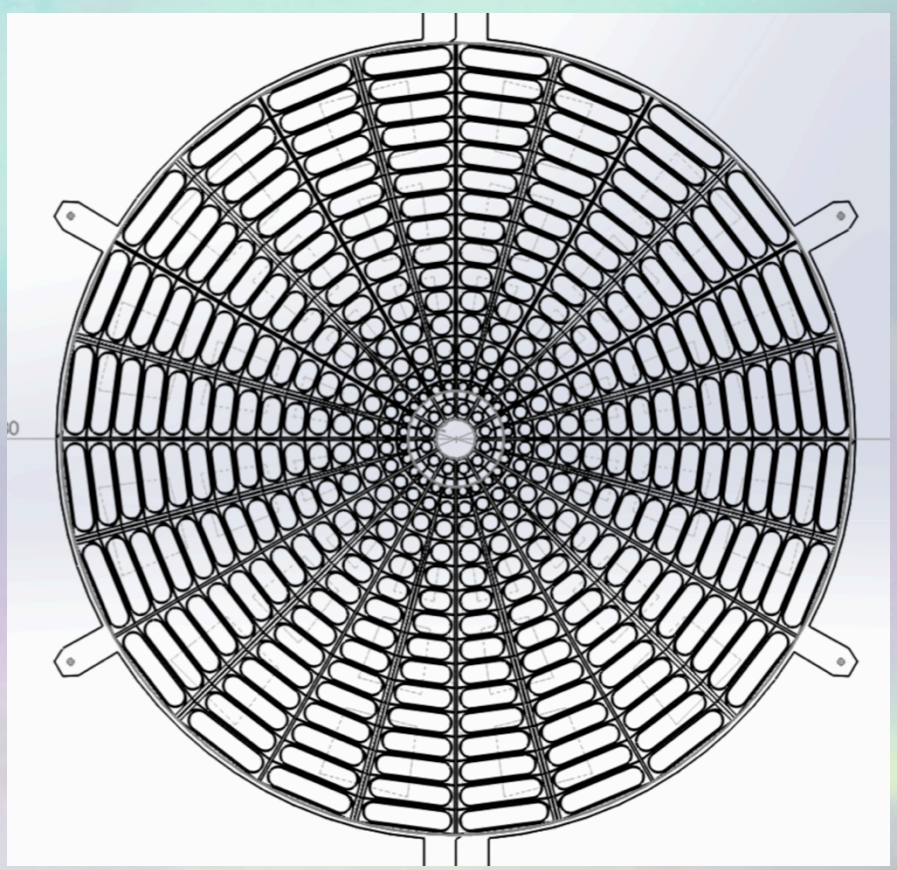
- centrality definition away from midrapidity [fluctuations/"kurtosis"]
- enhanced E.P. resolution [flow, CME, polarization, asHBT]

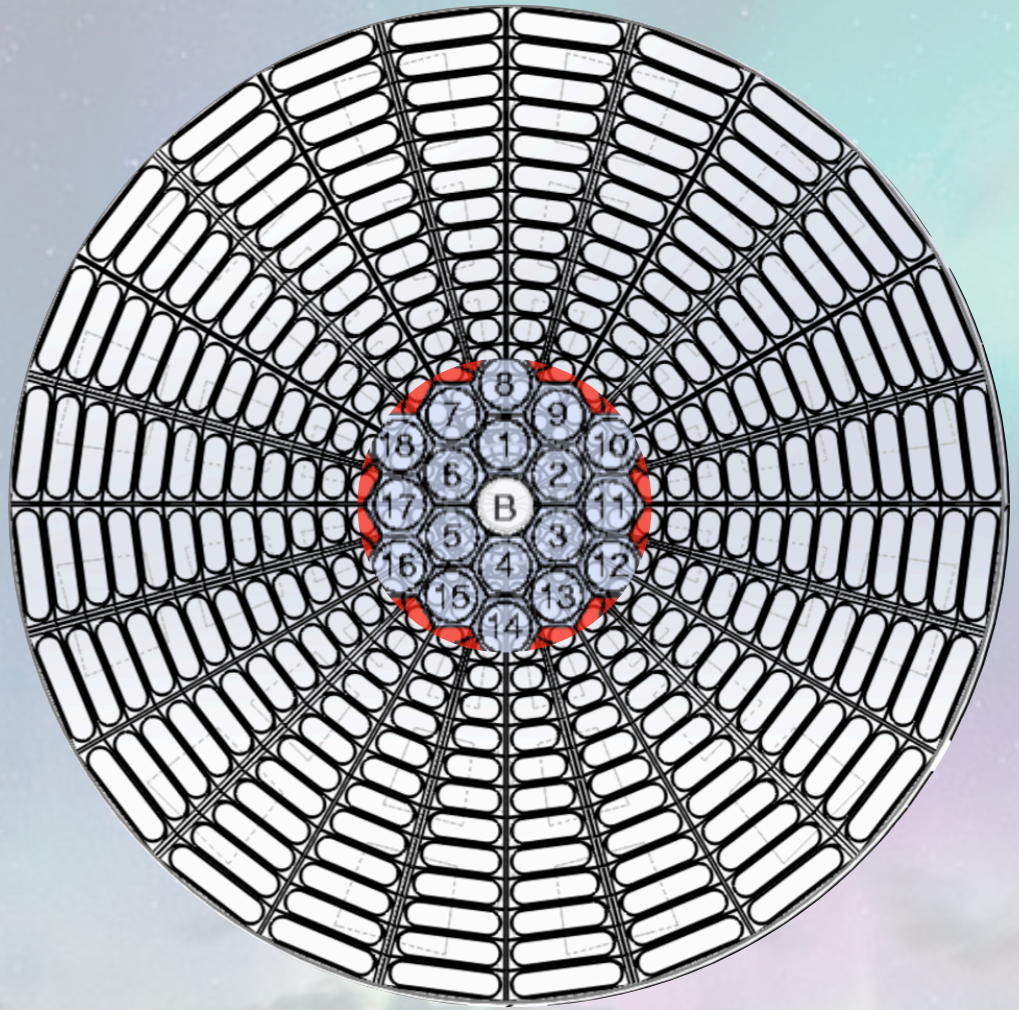
BBC inner – 16 channels / side
2 rings of hexagons



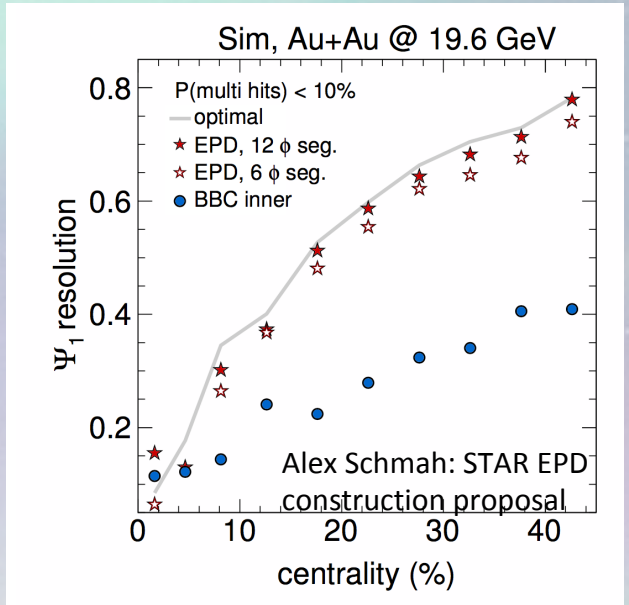
1.8 m

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

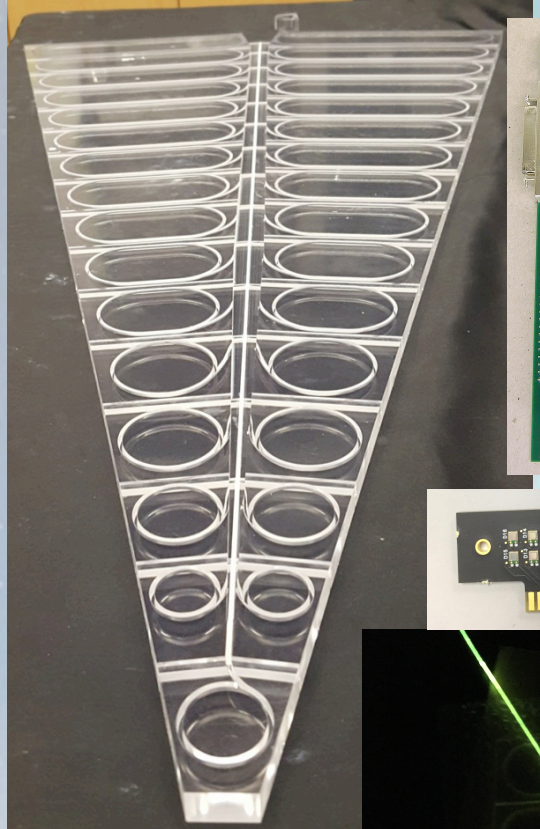


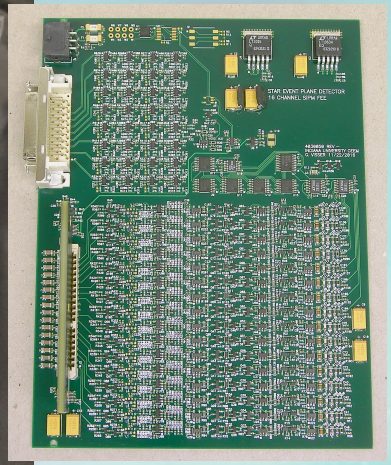


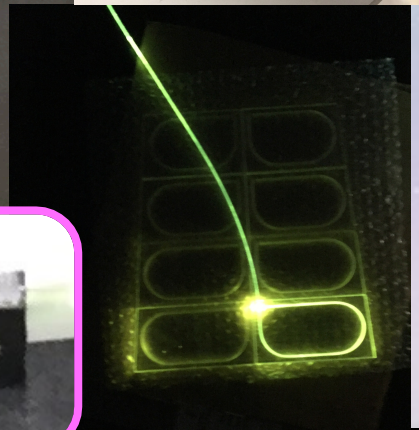
1 inner BBC tile ~ 5-7 EPD tiles

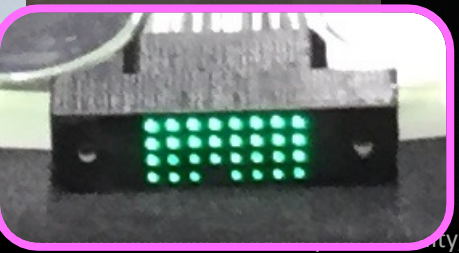


~2x improved EP[1] resolution for mid-central. [UrQMD sim.]

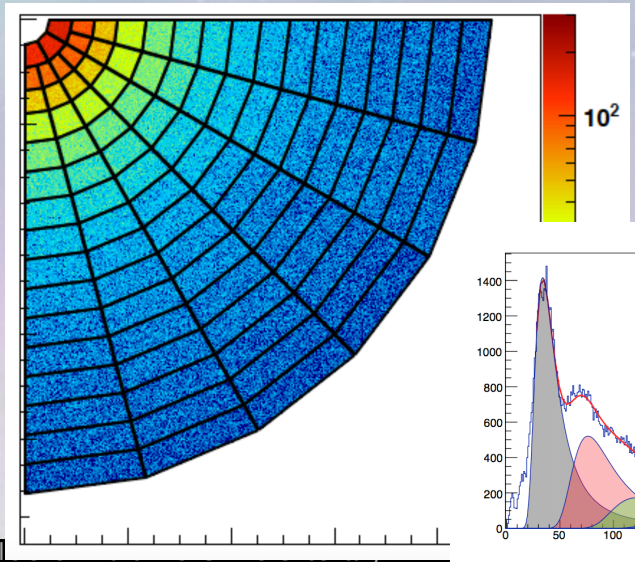


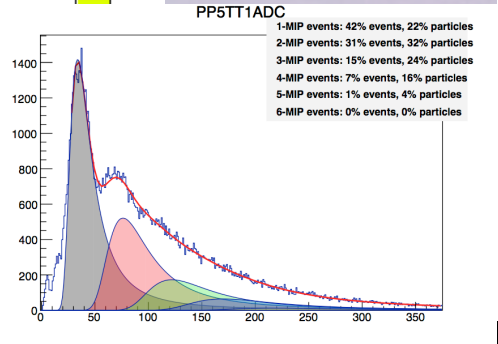






- 1.2 cm-thick scintillator tiles
- WLS fibers → SiPMs → custom FEE
- constructed at OSU & Lehigh U.
- major contributions from USTC, Shandong, NCKU, MEPhI
- electronics by IU, USTC, BNL
- 1/8 engineering run in 2017



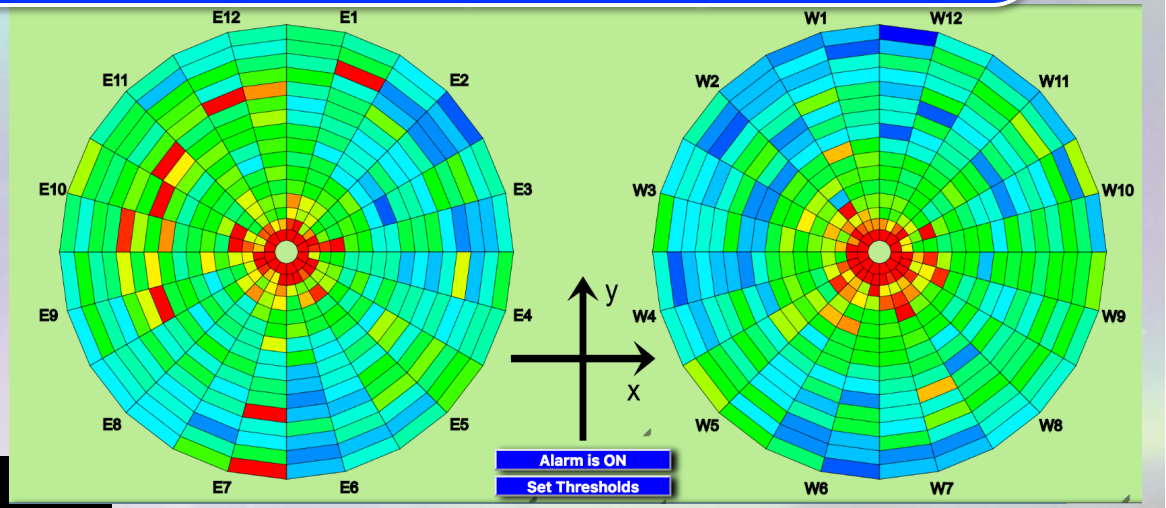


East Side

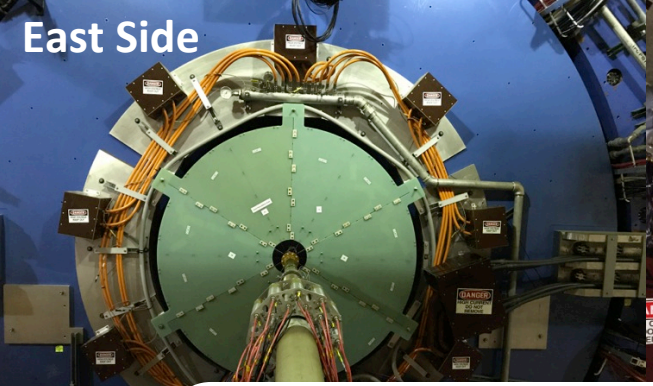
West Side

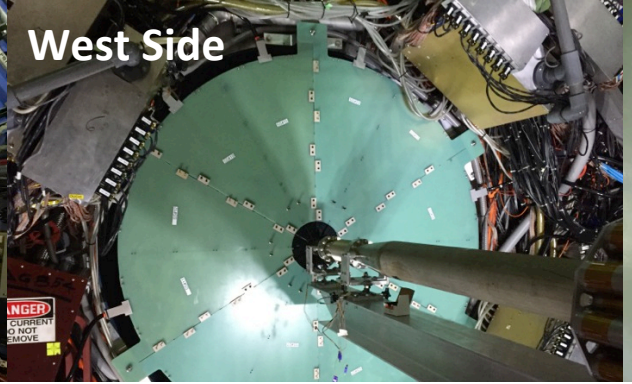
Close to the beam pipe!

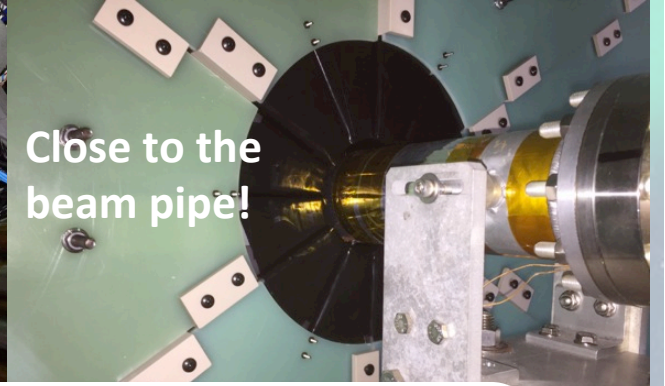
Installed & (last week!) fully commissioned with beam



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

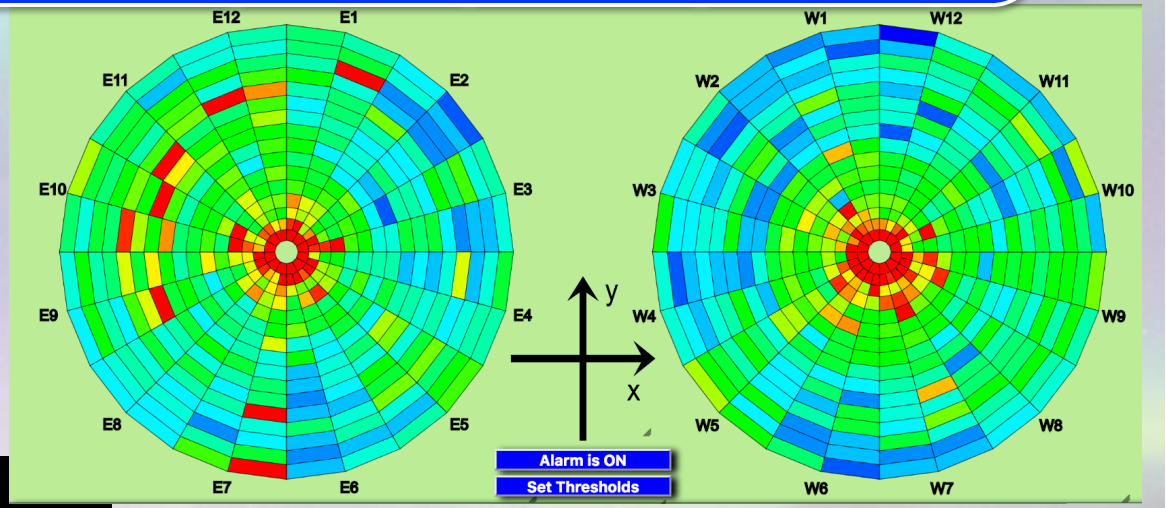




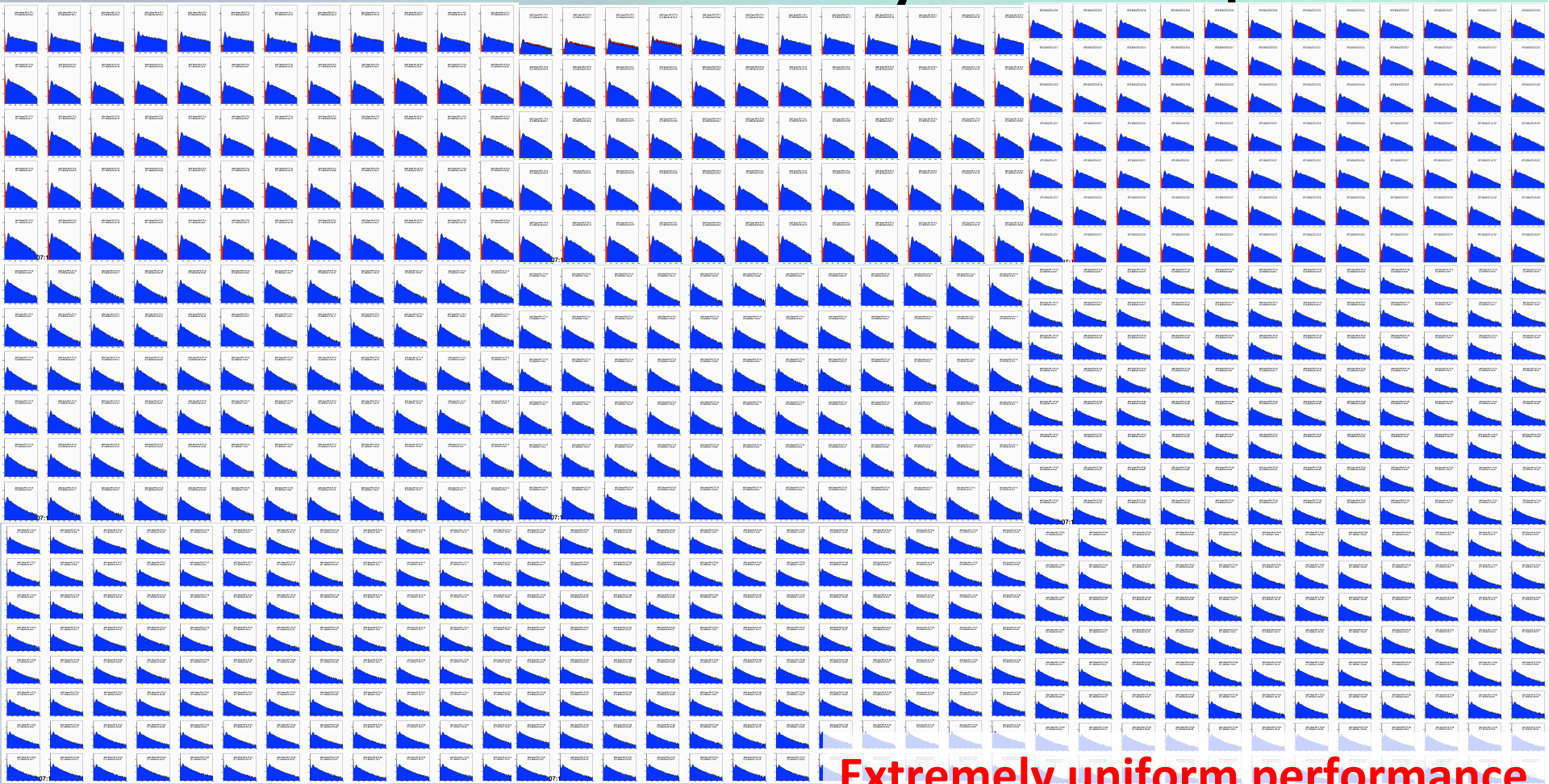


Until now, STAR has been “blind/impaired” in this important region

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



Run 19076023 – 07:32 17 May – 744 ADC spectra



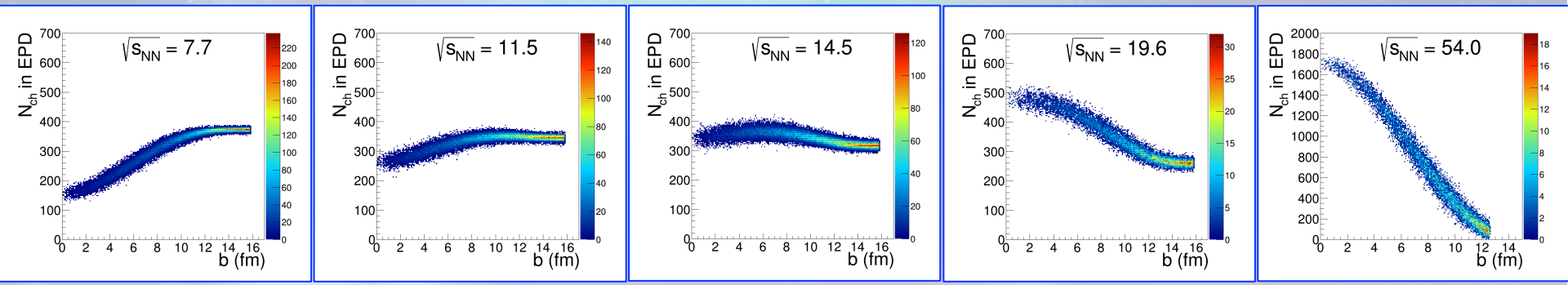
Extremely uniform performance

A challenge: centrality over wide range of collision energies

Using multiplicity in EPD

spectator dominance

participant dominance



!! “cancellation” in important energy region

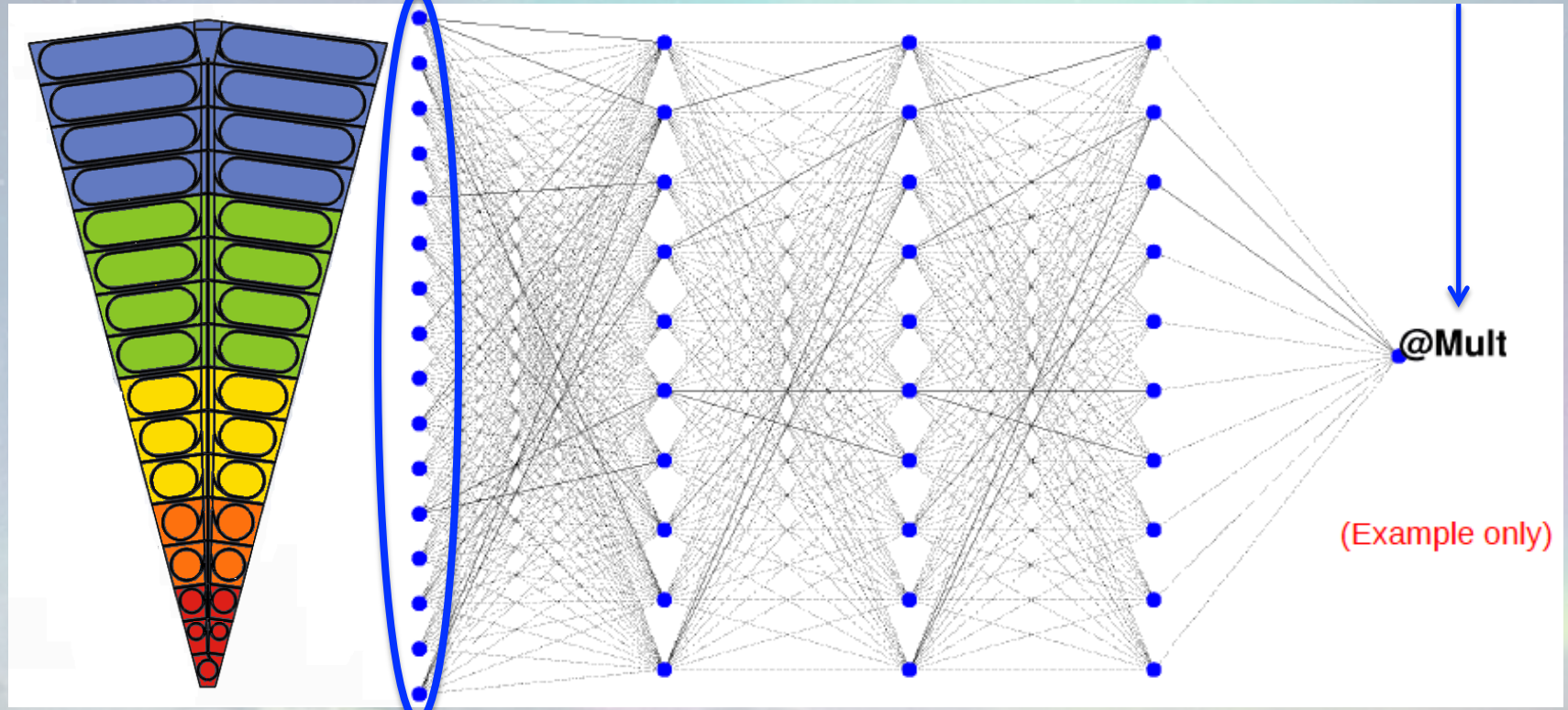
George Halal

UrQMD

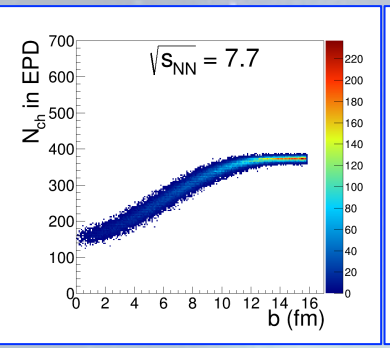
Multi-variable problem – try neural nets

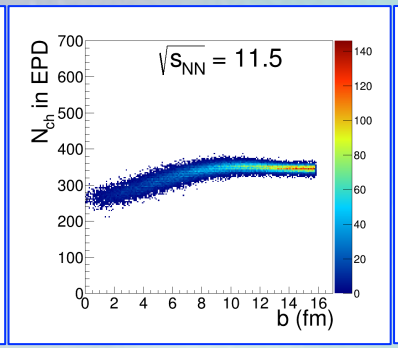
Input neurons = groups of tile ADCs

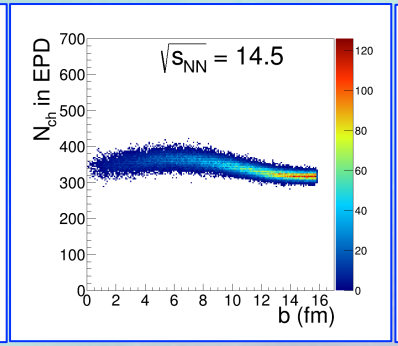
output = centrality measure
(b from model / mult from TPC)

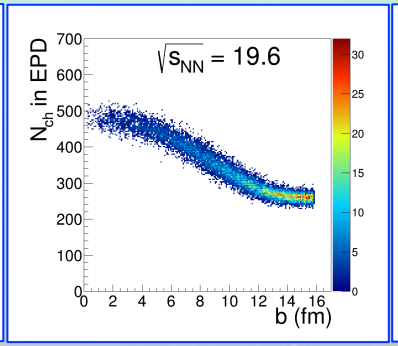


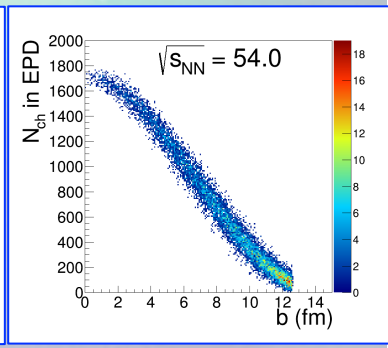
A challenge: centrality over wide range of collision energies

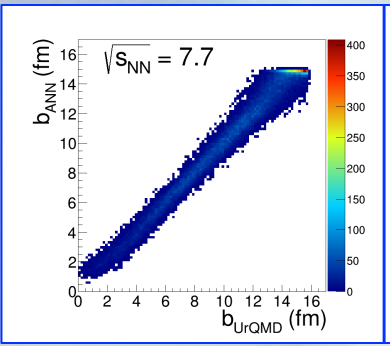


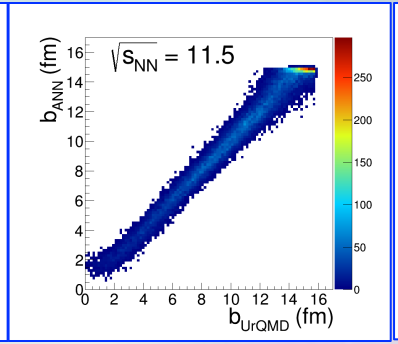


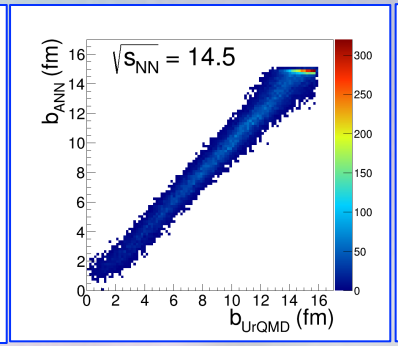


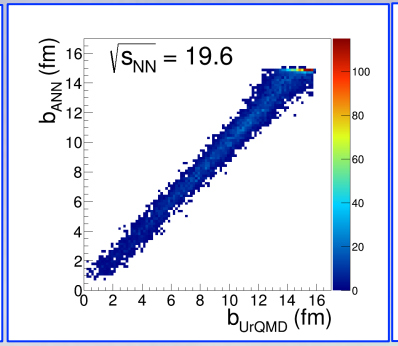


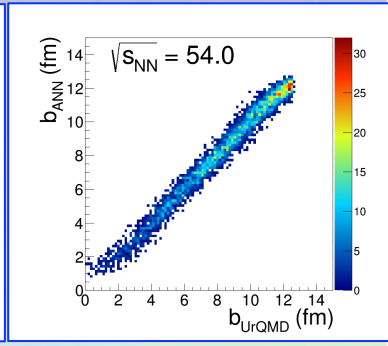












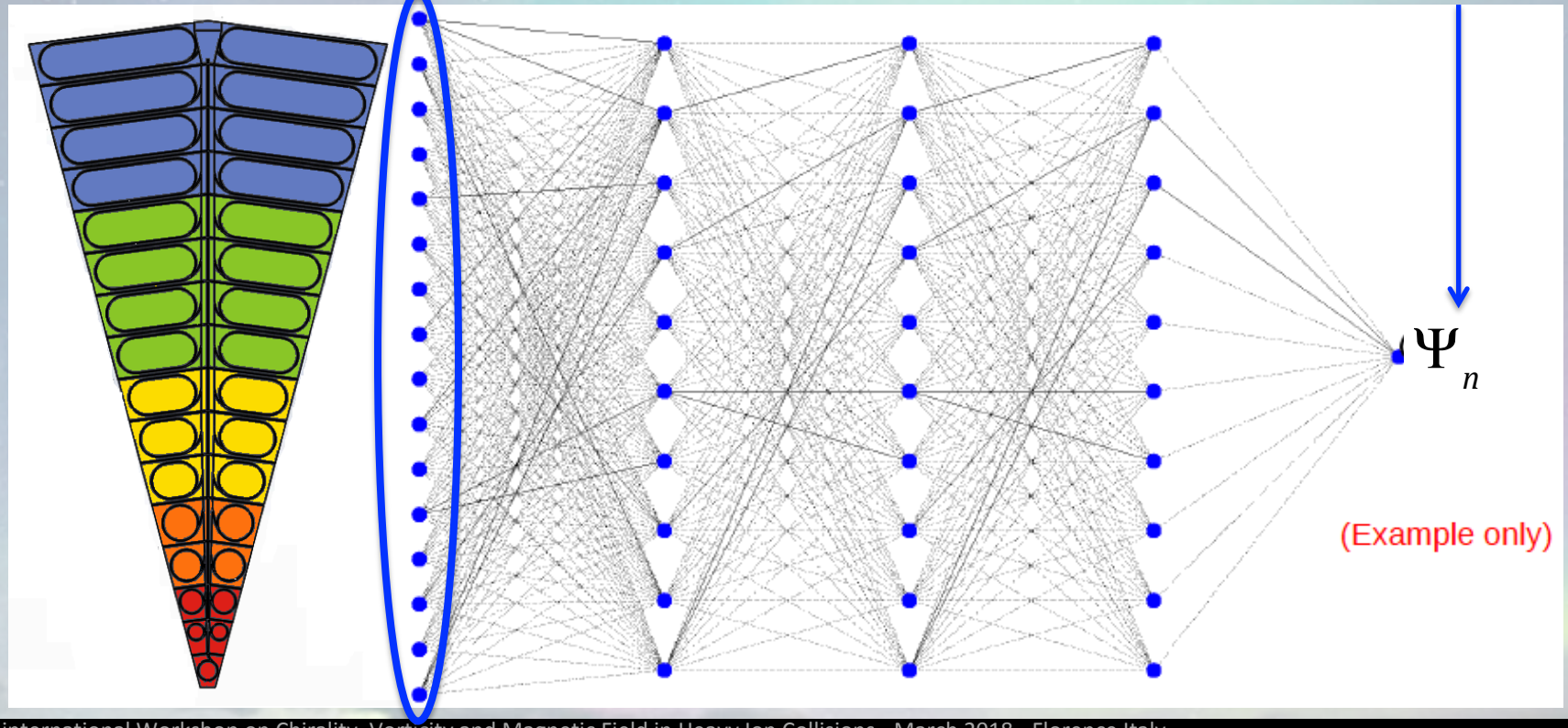
George Halal

UrQMD

Similar for E.P. - *In progress*

Input neurons = groups of tile ADCs (& Q-vectors)

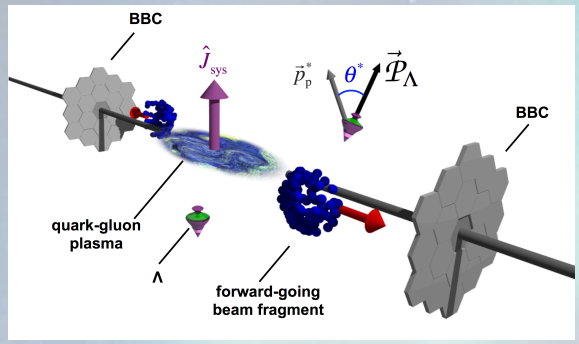
output = Event Plane
train on Ψ of *other* EPD)

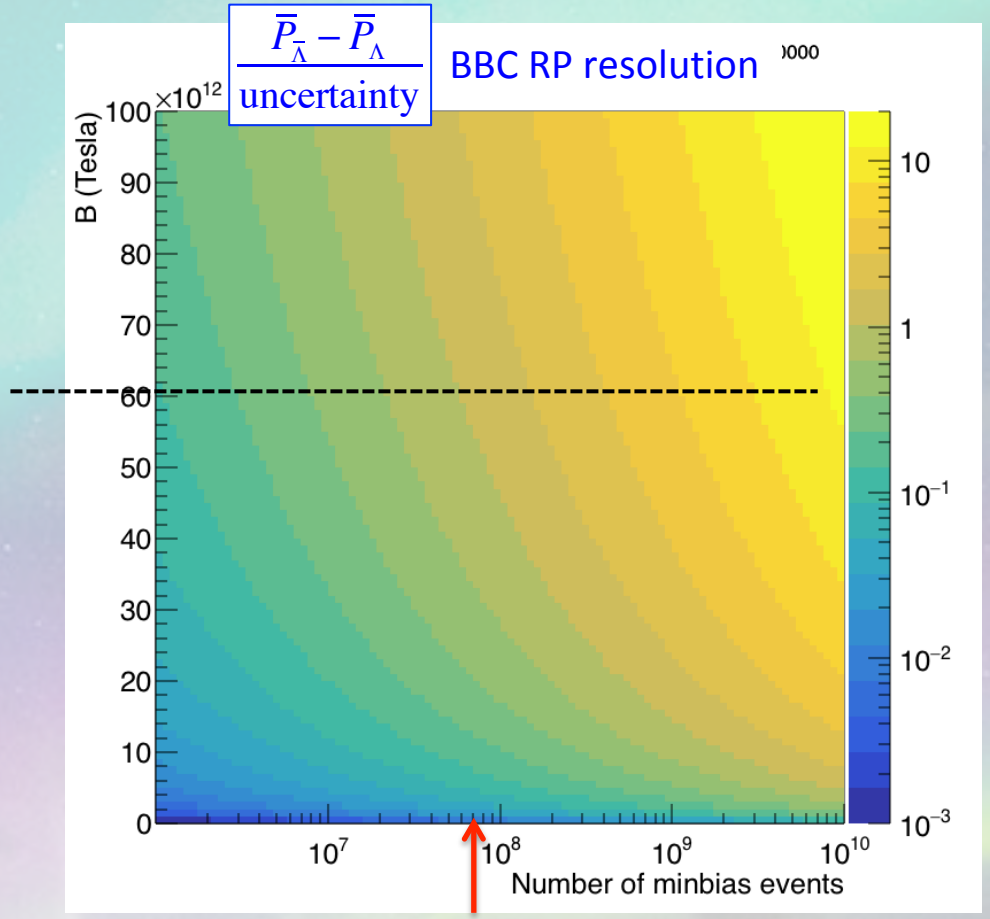


Can we see the magnetic splitting? 2018 run at 27 GeV

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

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





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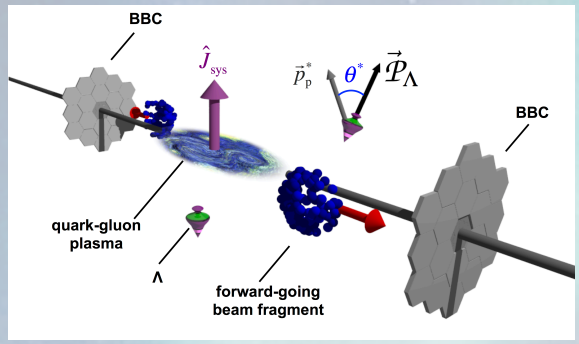
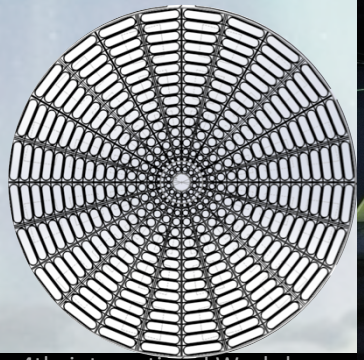
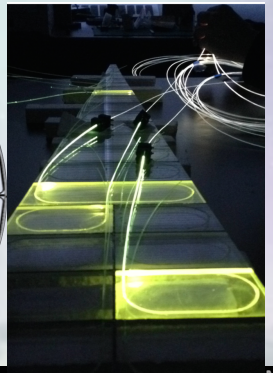
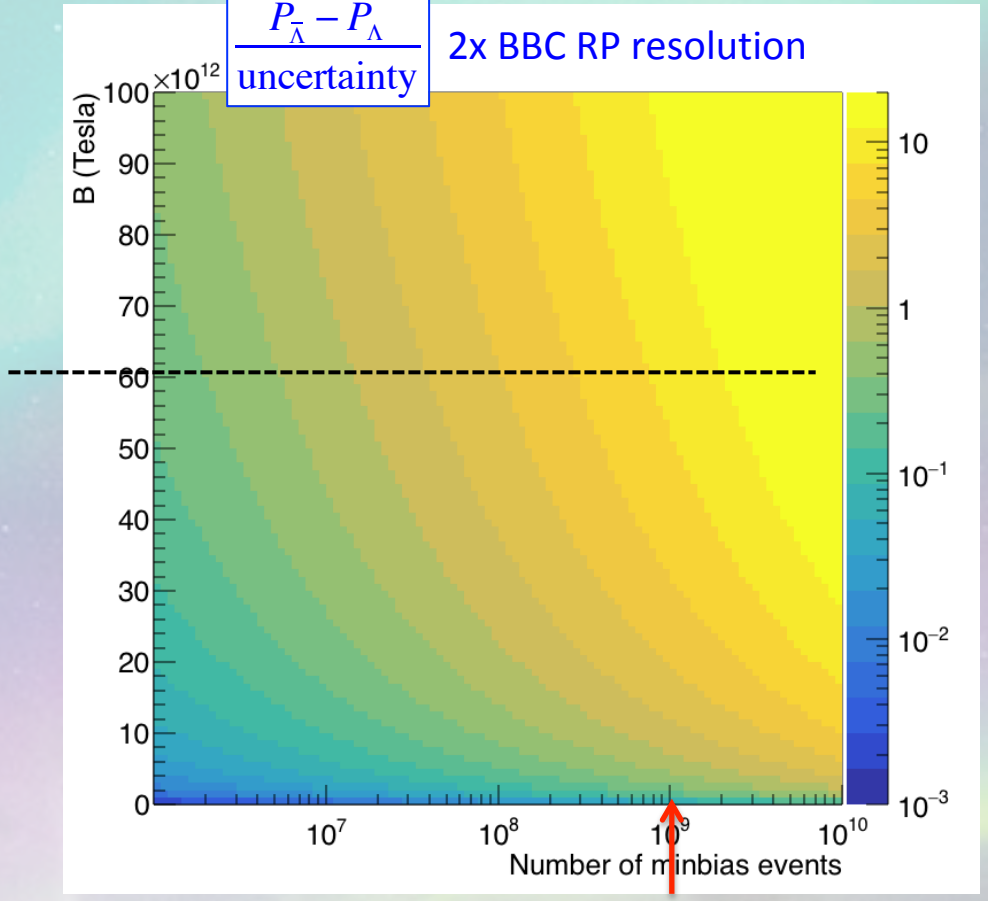


2018 : 10^9 events & detector upgrade







Summary

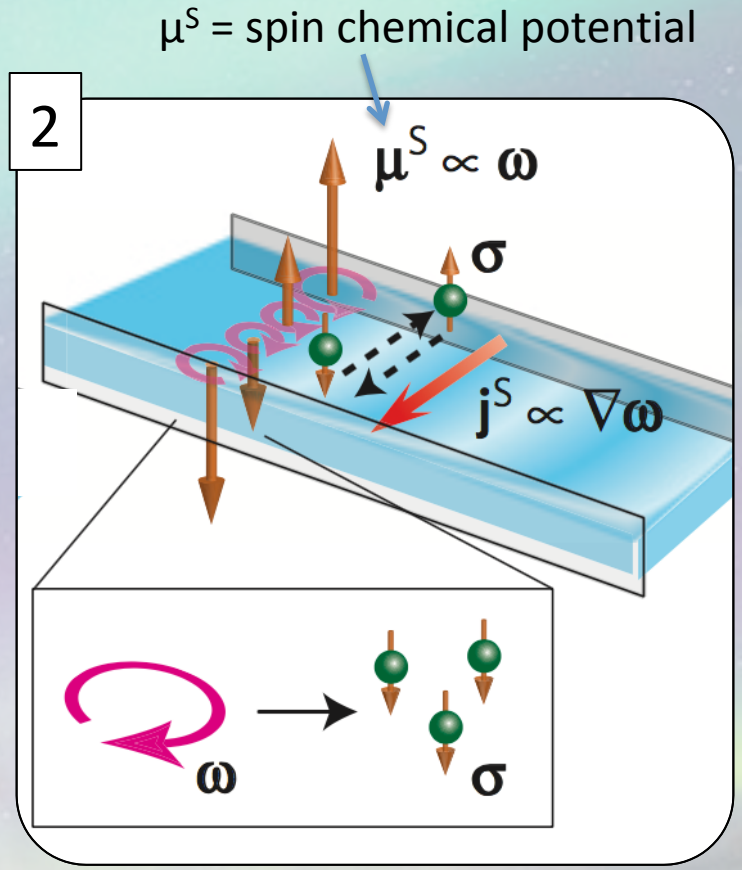
- Vorticity measurement provides new, important validation of hydro paradigm
  - Don't take that for granted!
- Polarization "splitting" may provide independent, non-chiral measurement of B-field
  - establishes conditions for CME, CMW, etc
  - close an overconstrained theory formalism?
- STAR/RHIC Run 2018 has begun – ***CME / B-field are main priorities***
  - substantial investment
  - machine upgrades provide unprecedented luminosity / flexibility (Zr/Ru)
- Event Plane Detector
  - major upgrade to STAR provides new sensitivity in an important region
  - integral component of polarization & CME measurements
  - **physics-ready on Day One**

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 → fluid vorticity

2. mechanical fluid vorticity → e^- polarization



First observation of fluid vorticity-polarization coupling

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

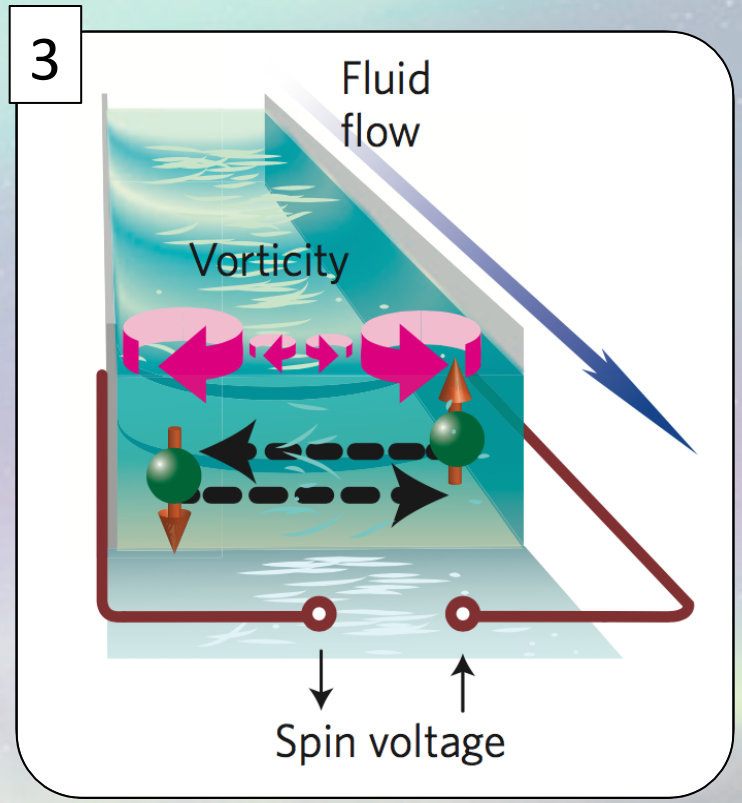
1. Hg flowing down a channel
   - viscous forces with walls → fluid vorticity

2. mechanical fluid vorticity → e^- polarization

3. Gradient across channel → spin voltage

4. ... can be transformed into electrical voltage, generators, etc. *without magnets*

"This opens a door to the new field of fluid spintronics"



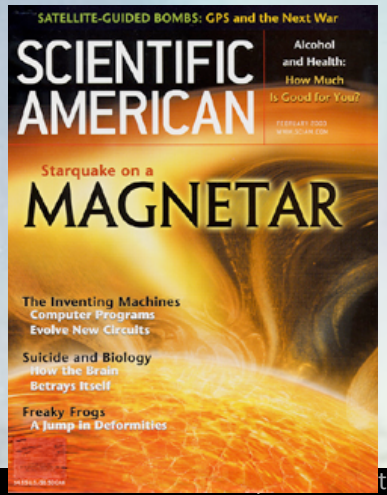
Magnetic field?

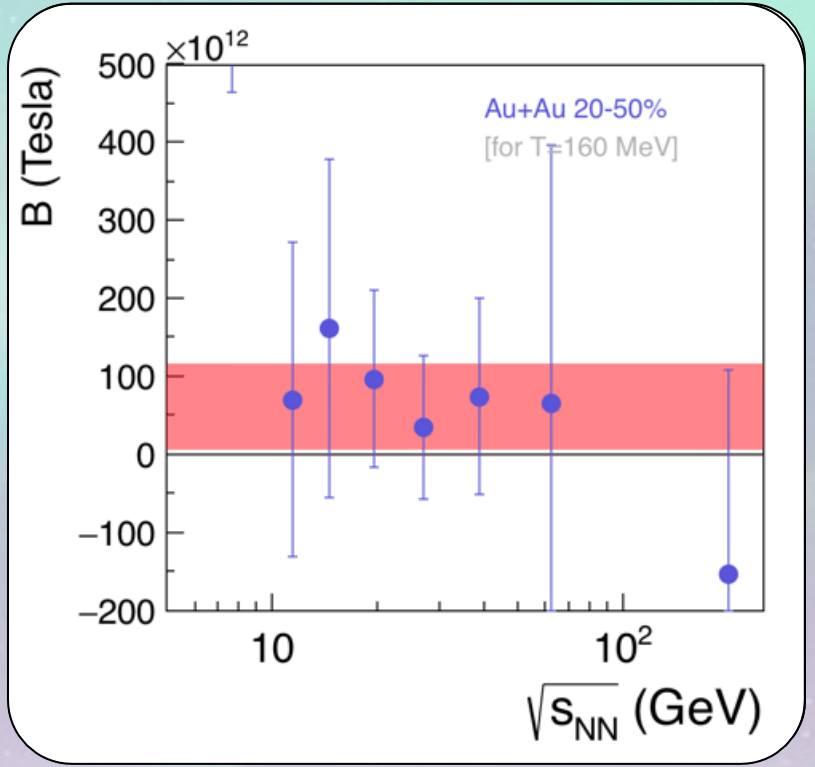
- Statistical uncertainties preclude claim
- B should change with energy, but...

$$\langle B \rangle_{\sqrt{s}} = 6.0 \pm 5.5 \times 10^{13}\ \mathrm{T} \approx 0.6 \pm 5.5\ m_\pi^2$$

- Highest fields in the known universe:

  Magnetars ~ 10^{10}-10^{11} T





McGill Online Magnetar Catalog: ApJS 212 (2014)
http://www.physics.mcgill.ca/~pulsar/magnetar/main.html