Global Lambda polarization measurements in BES

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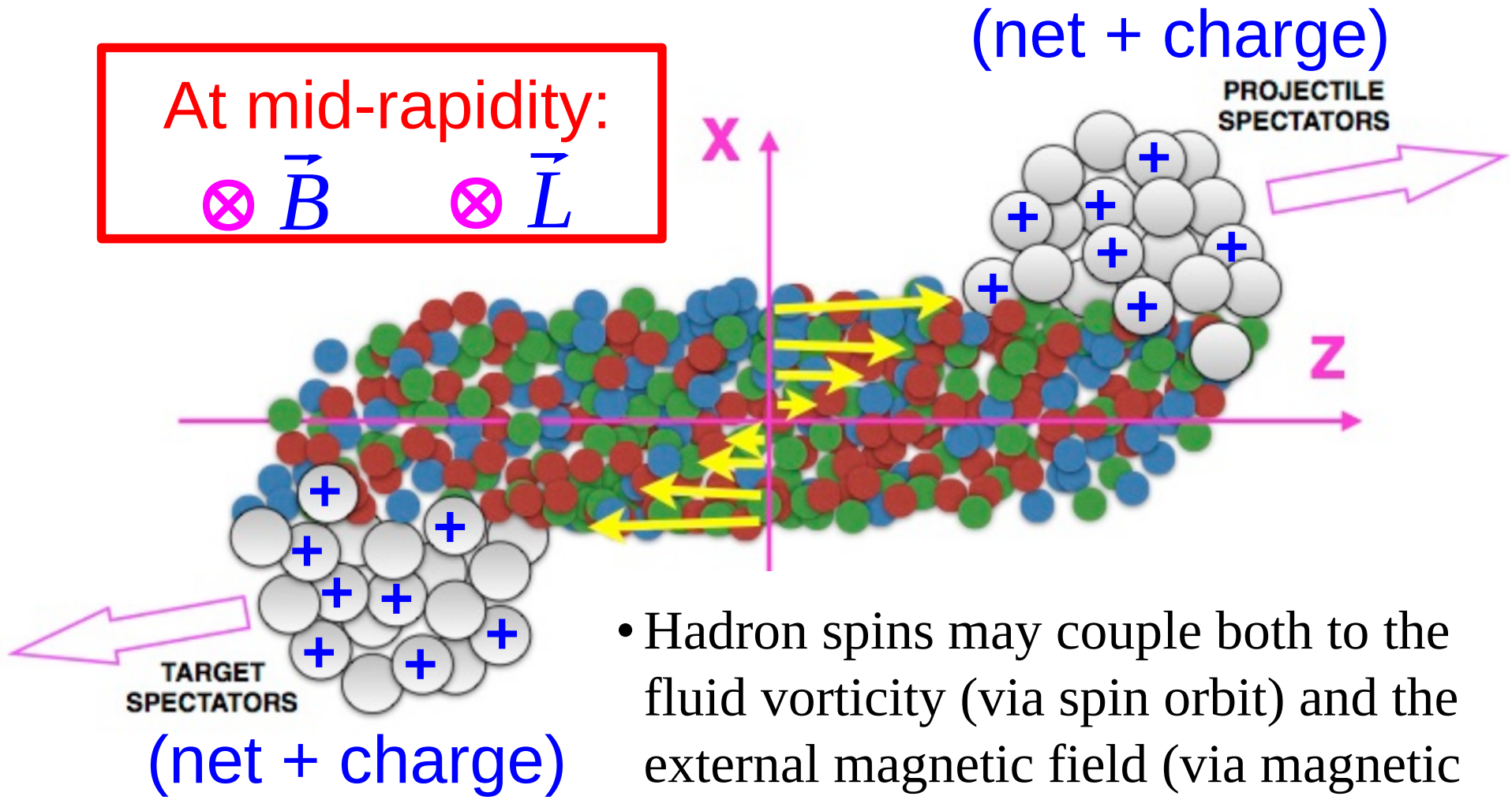
For the STAR Collaboration
06/12/18

At mid-rapidity:

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

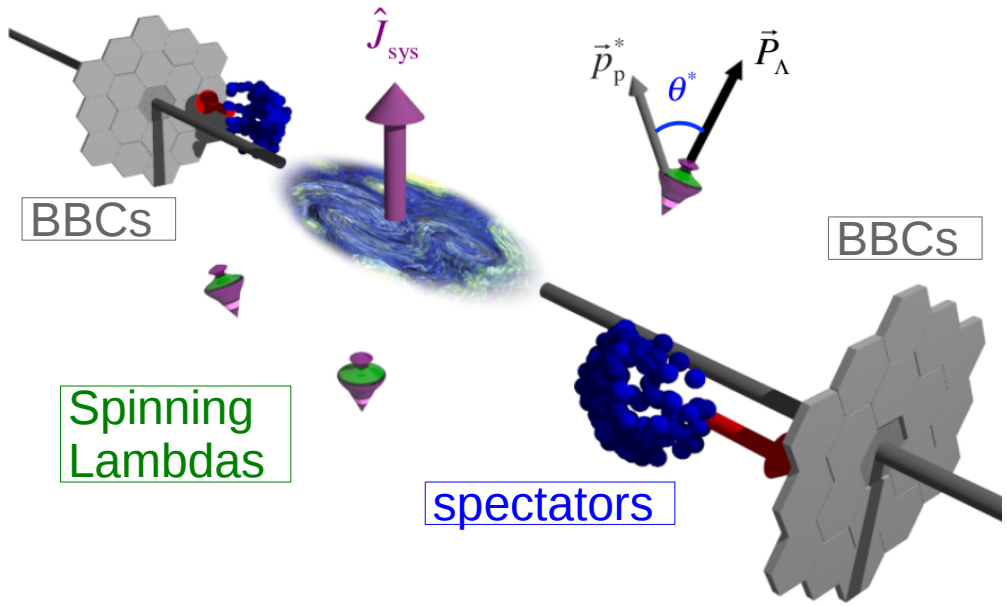


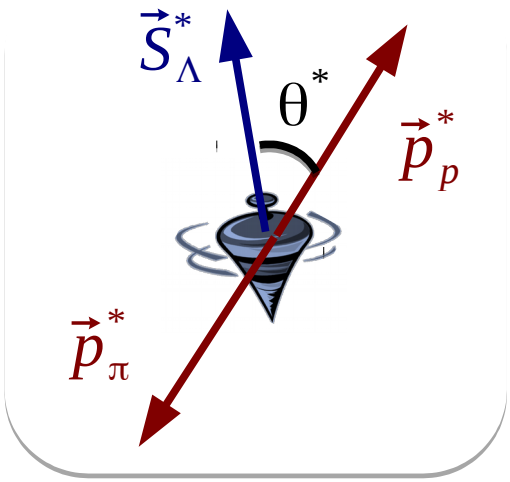
- Hadron spins may couple both to the fluid vorticity (via spin orbit) and the external magnetic field (via magnetic moment)

- In this talk I'll focus on the $\Lambda/\overline{\Lambda}$ baryon system

How to quantify the effect (I)

- Lambdas are "self-analyzing"
  - Reveal polarization by preferentially emitting daughter proton in spin direction





Λs with Polarization $\vec{P}$ follow the distribution:

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

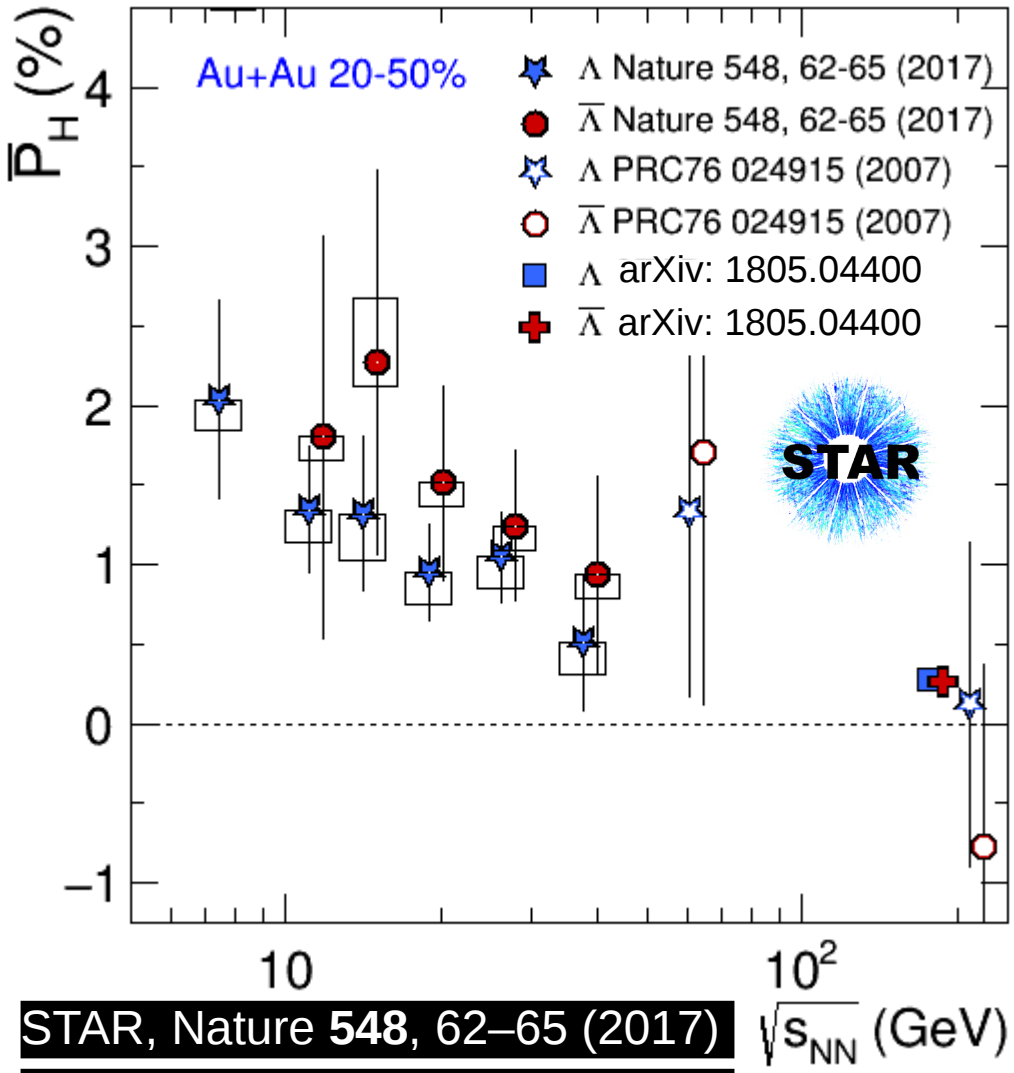
$\alpha = 0.642 \pm 0.013$ [measured]

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

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

Global polarization measure

- Measured Lambda and Anti-Lambda polarization
- Includes results from previous STAR null result (2007) and more recent result
- $\overline{P}_H(\Lambda)$ and $\overline{P}_H(\bar{\Lambda})>0$ implies positive vorticity
- $\overline{P}_H(\bar{\Lambda})>\overline{P}_H(\Lambda)$ could imply magnetic coupling, hint at low energies

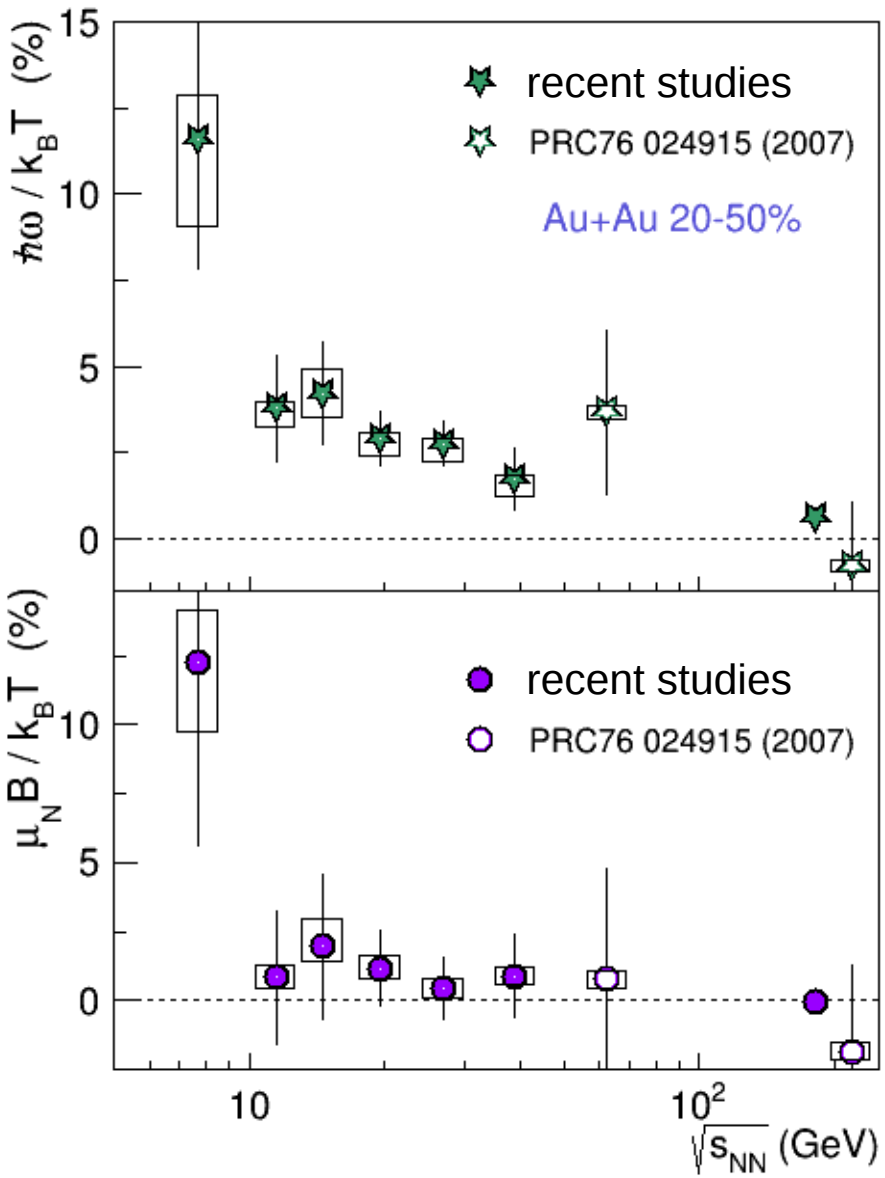


STAR, Nature **548**, 62–65 (2017)

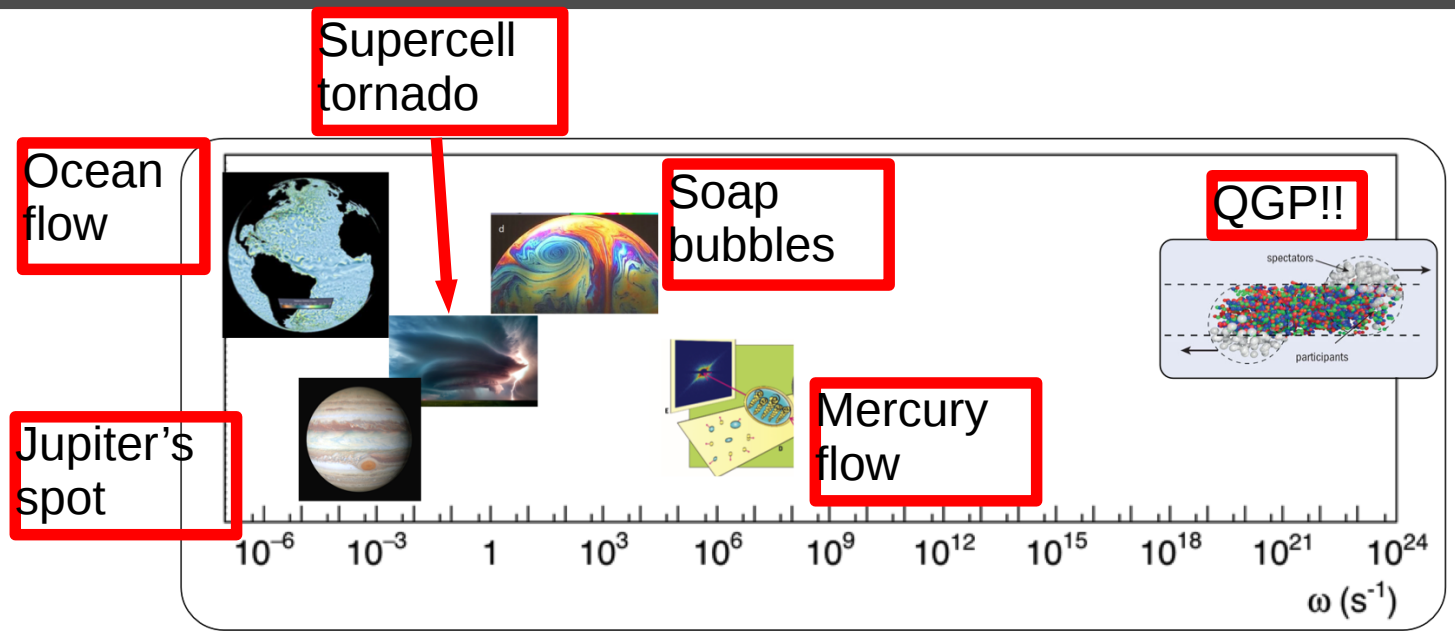
STAR, arXiv: 1805.04400

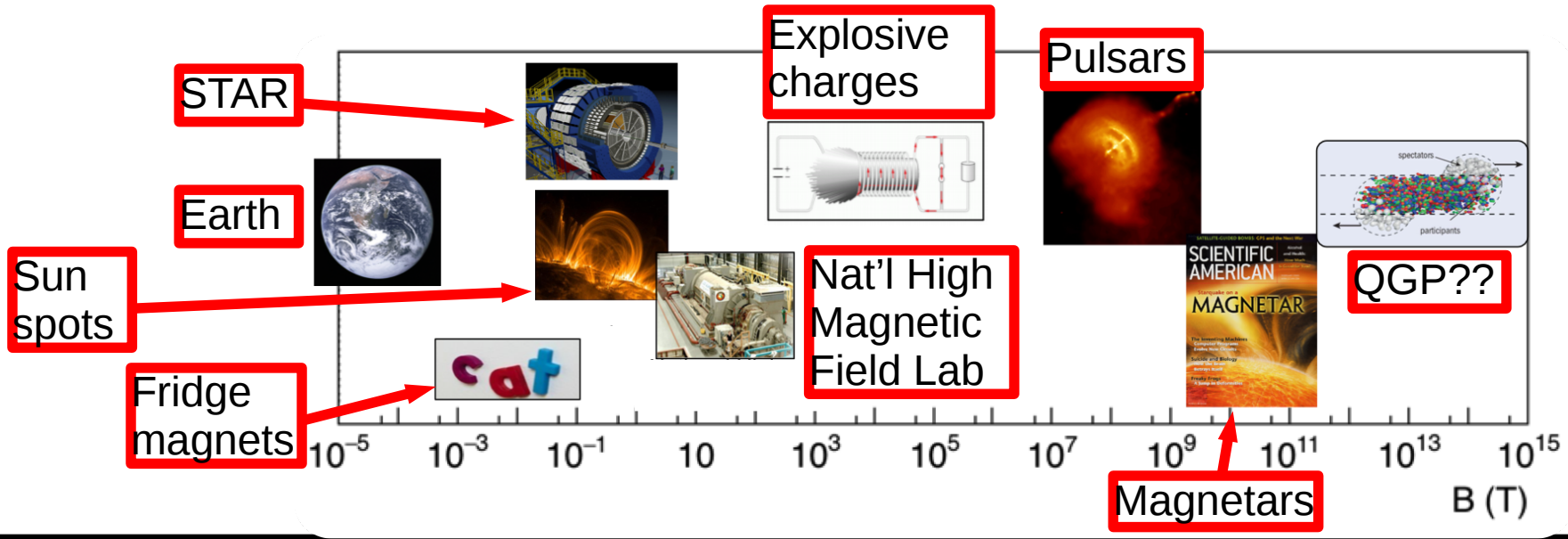
Extracted physical parameters

- Magnetic field and vorticity can be extracted for some thermal medium of temperature T
- Significant vorticity (ω) signal
  - Hints at falling with energy, despite increasing J_{sys}
  - 6σ average for 7.7-39 GeV
  - $P_{\Lambda_{\text{primary}}} = \frac{\omega}{2T} \sim 5\%$
- Hint of a magnetic field (B)
  - $\mu_N \equiv \frac{e\hbar}{2m_p}$, where m_p is the proton mass
  - positive value, 1.5σ average for 7.7-39 GeV

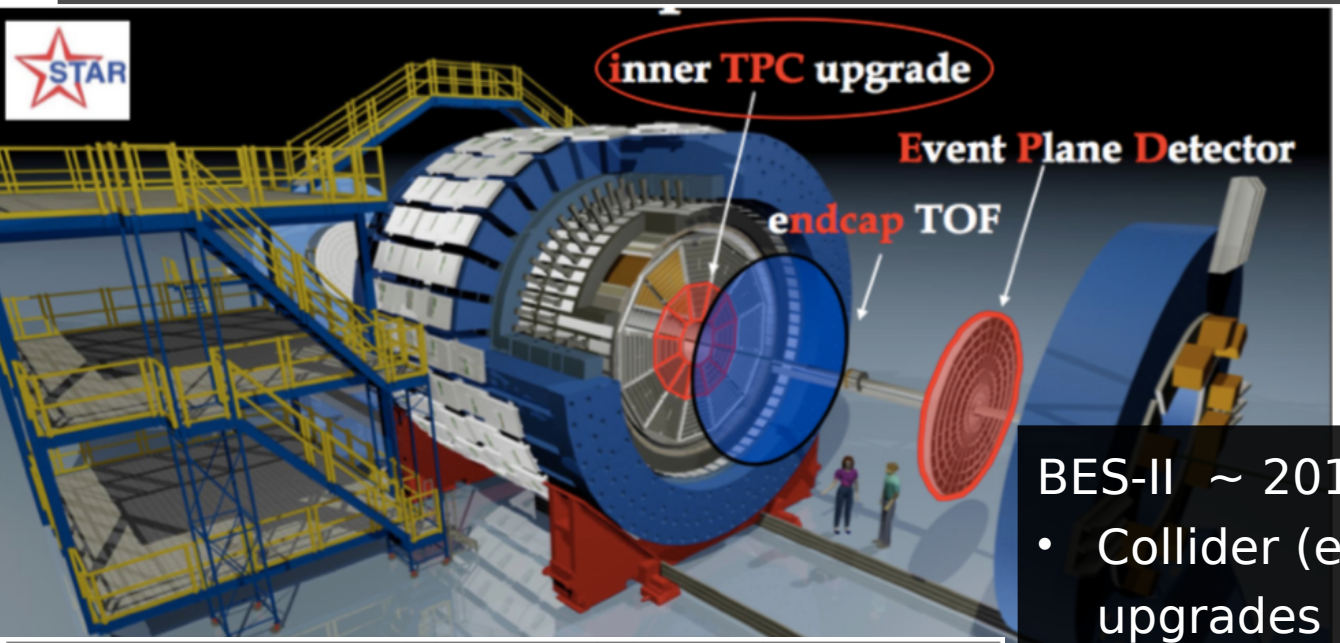


Comparison of QGP superlatives





BES-II: 2019-2020

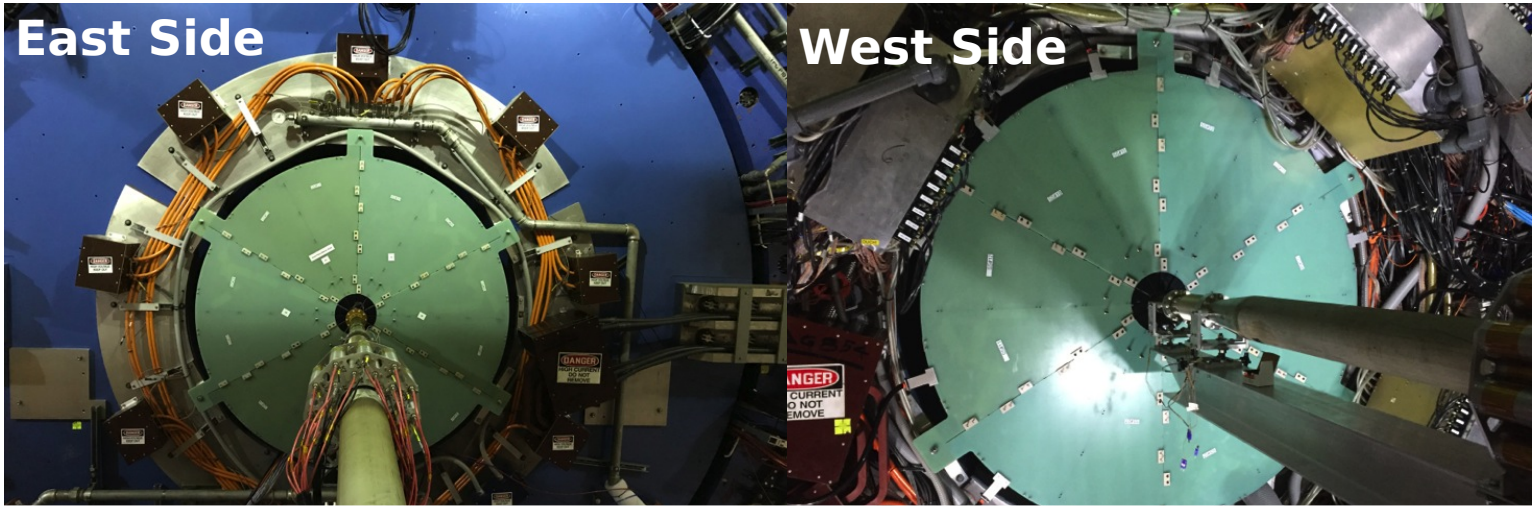


Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2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

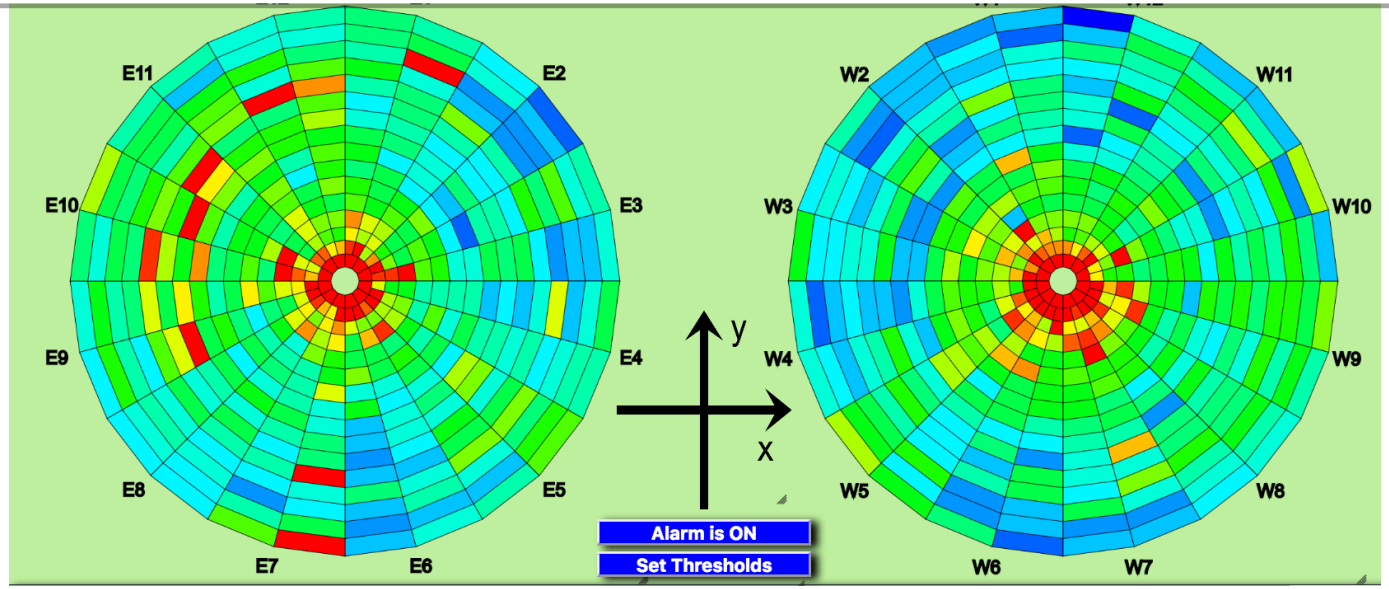
BES-II ~ 2019-2020

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

EPD fully installed for 2018 run

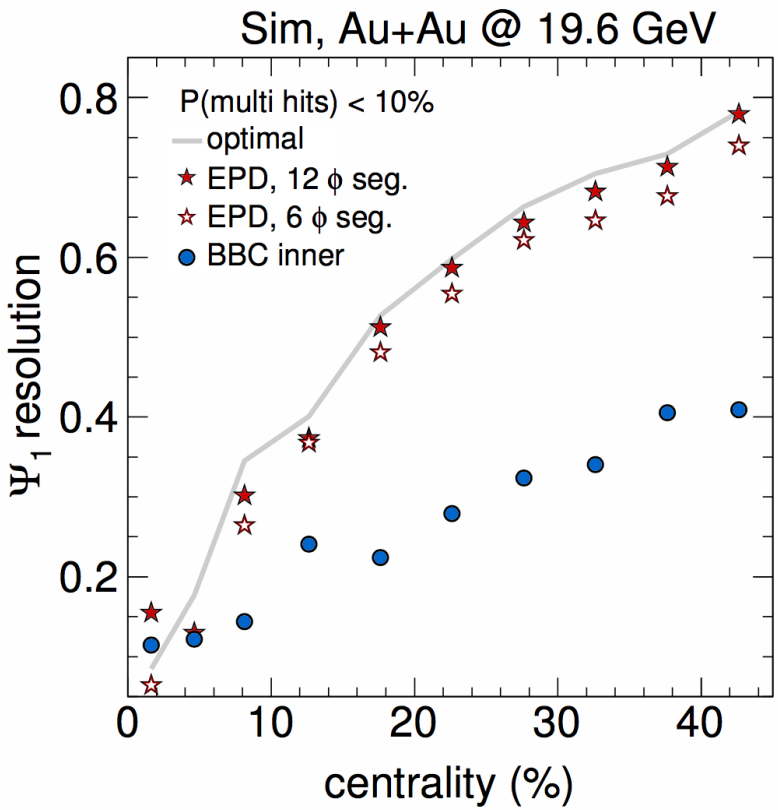


Installed & taking data



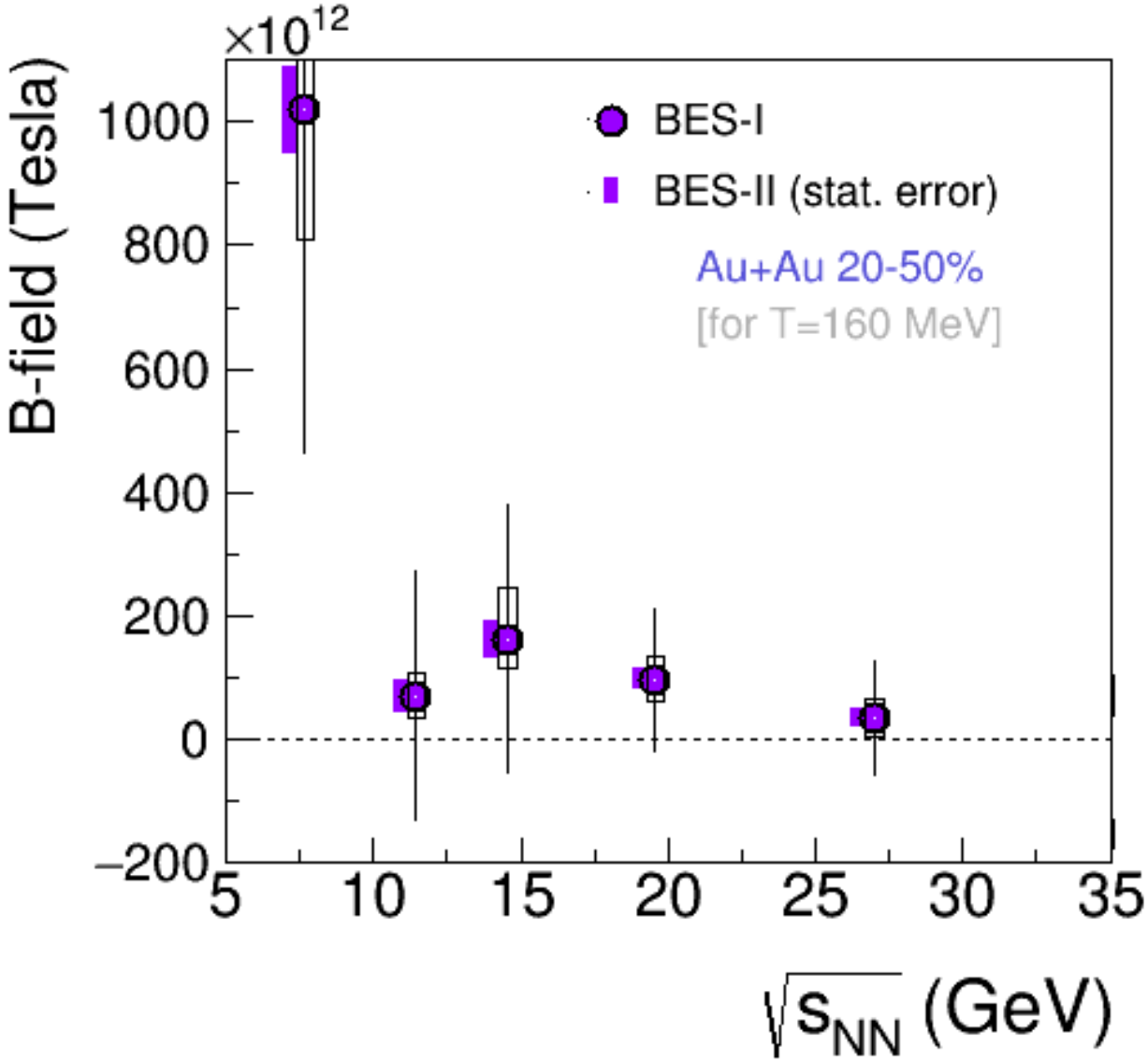
What about event planes?

- Improved φ segmentation increases resolution
- Greater η segment reduces systematics and separates produced from transported particles
- Polarization proportional to inverse of the resolution, stat. error decreases linearly with resolution
  - 2x resolution improvement = 4x more statistics
- Early simulations predicted 2x resolution improvement
- More recent (very preliminary) studies on 27 GeV data have a 45% improvement



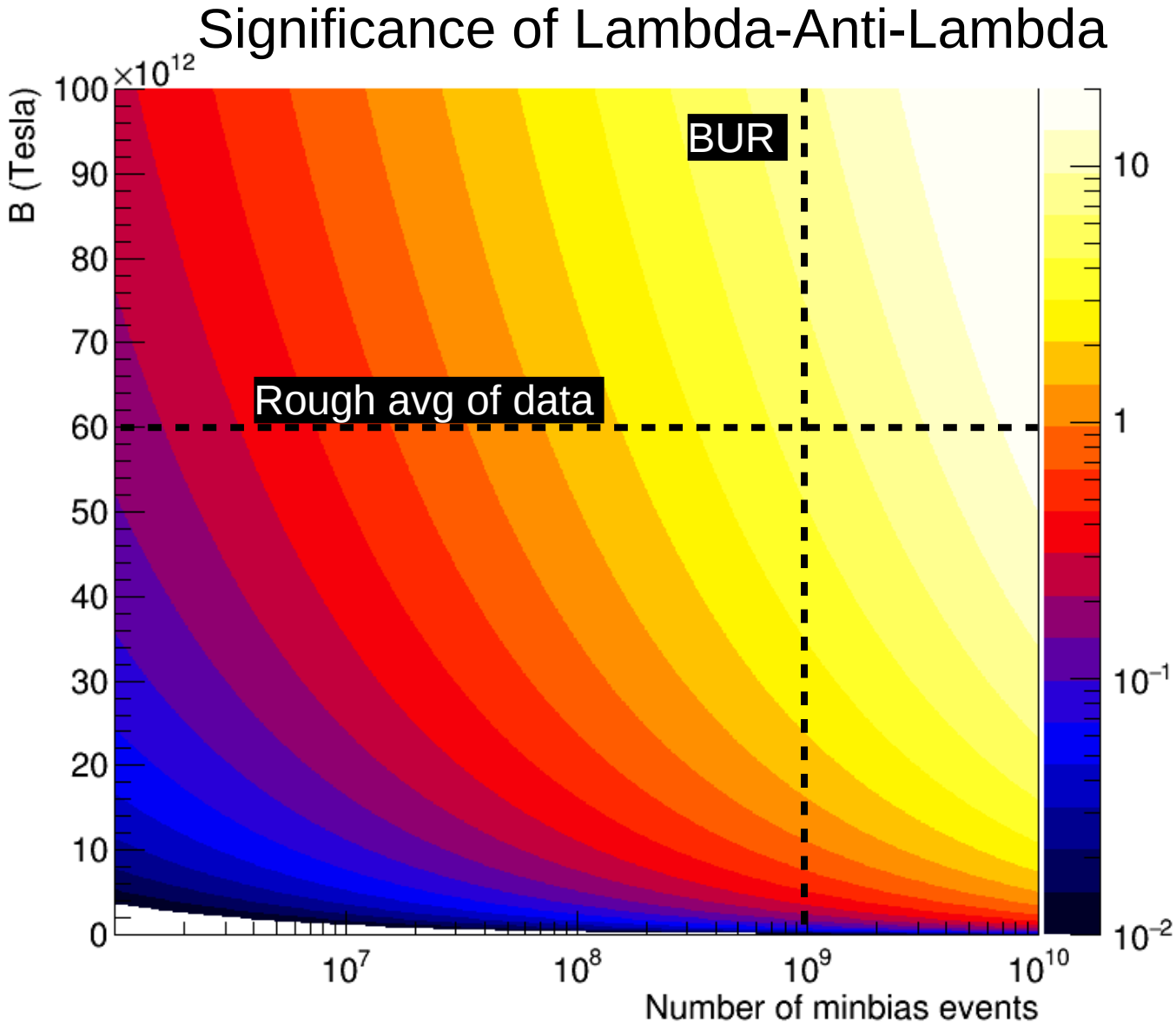
B field BES-II Projection

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



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

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

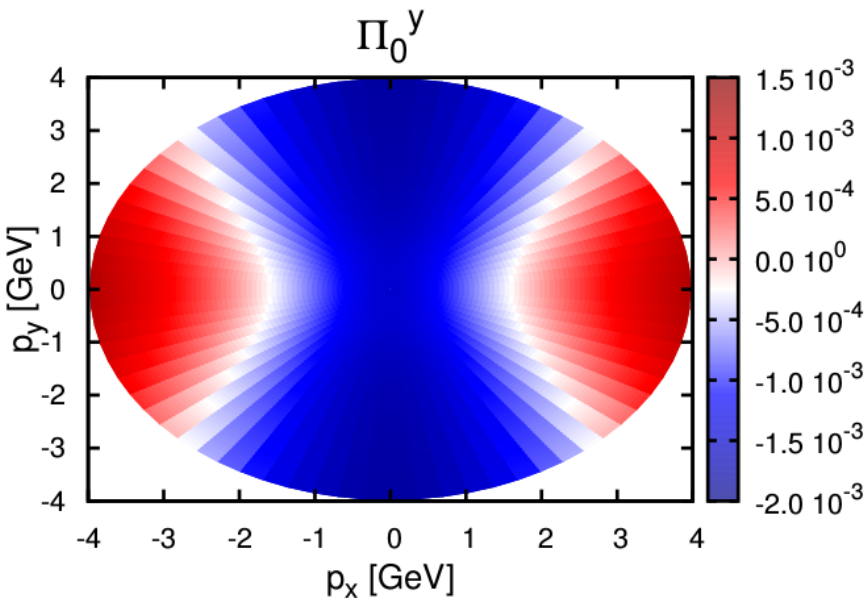


What else is possible? See 200 GeV

- The very high precision 200 GeV datapoint proves energy dependence of the polarization
- In this datapoint there is no hint of a magnetic splitting
- The high precision allows for important studies of signal dependence on
  - Particle p_T
  - Particle rapidity
  - Particle emission angle
  - System centrality
- New measurement techniques have also been opened up
  - Polarization dependence on system charge asymmetry, which is related to chiral effects
  - Polarization along the beam direction

Azimuthal dependence (I)

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

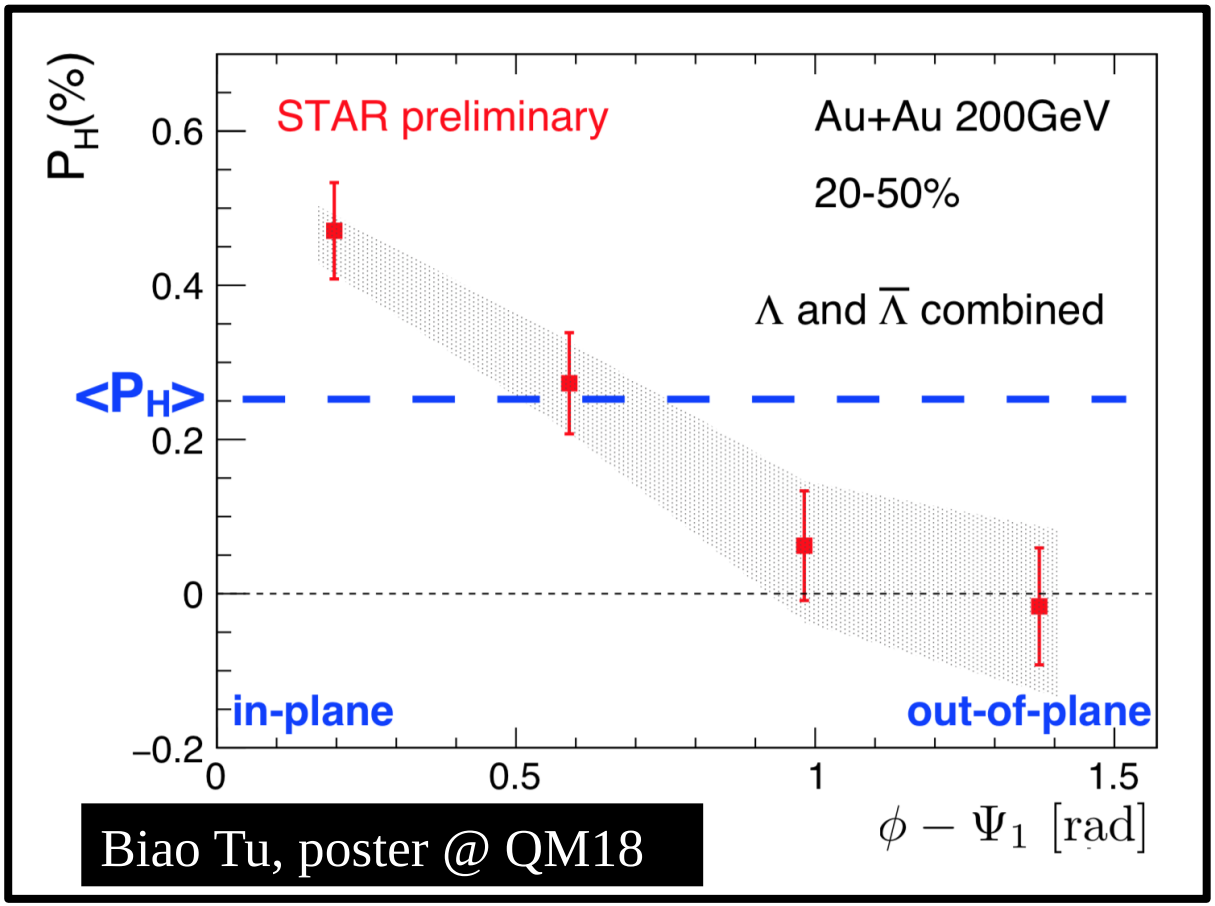


Becattini, F., Inghirami, G., Rolando, V. et al. Eur. Phys. J. C (2015) 75: 406

*Note that Π_0^y depicts the vorticity projected on the direction opposite to that of the system angular momentum

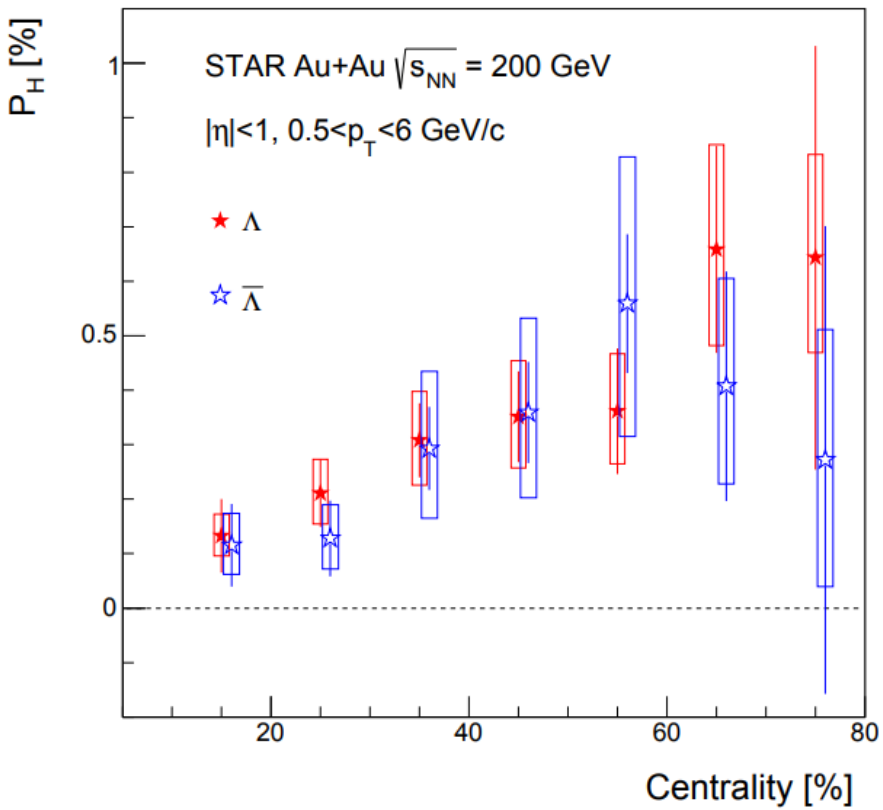
Azimuthal dependence (II)

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

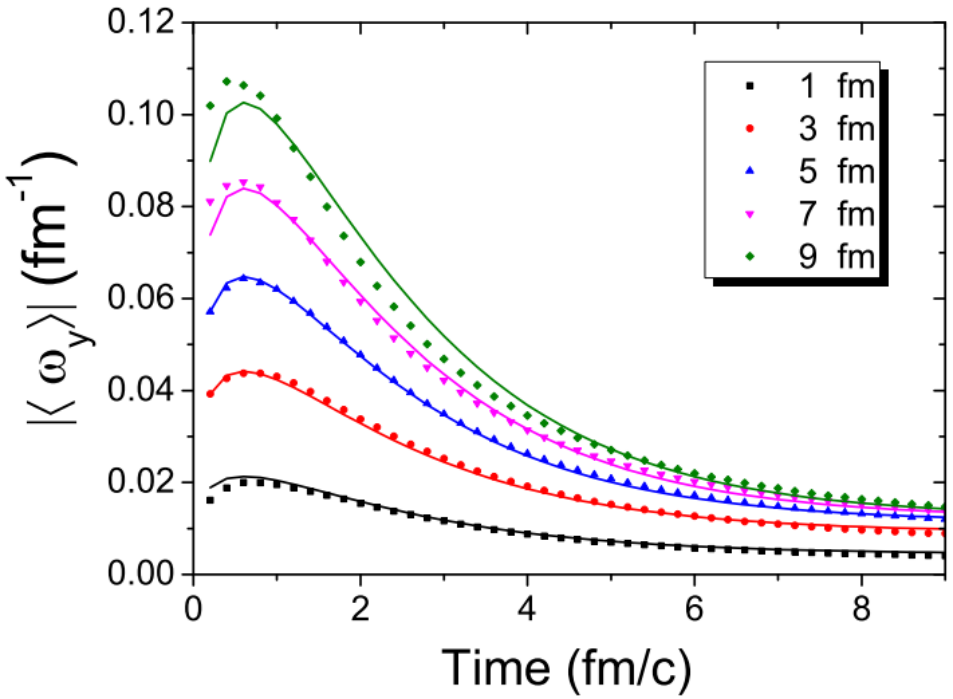


Biao Tu, poster @ QM18

Centrality



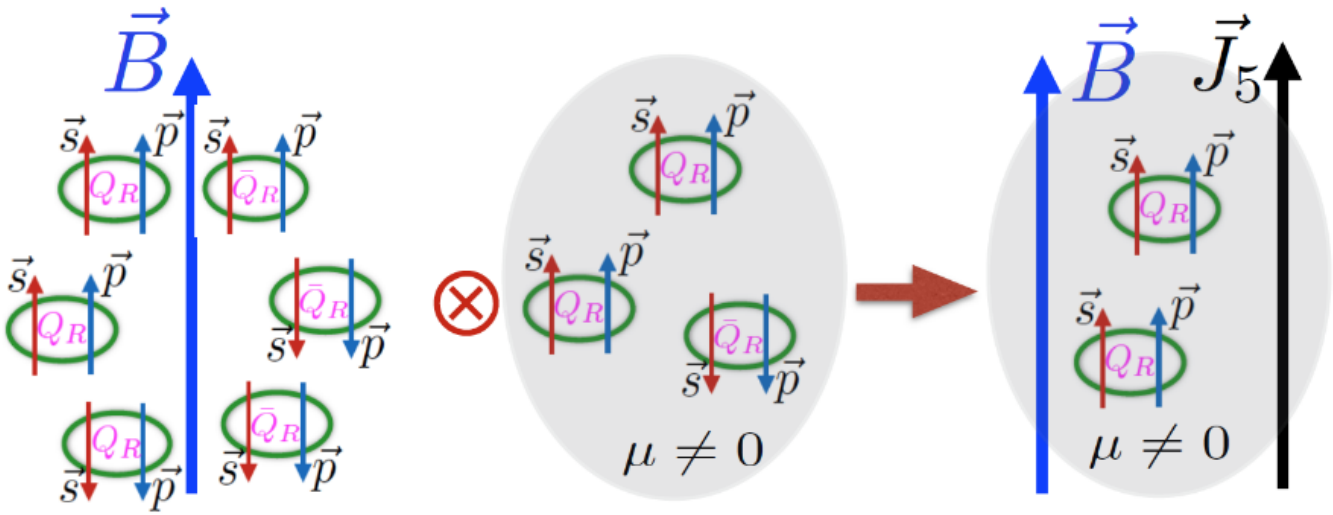
STAR, arXiv: 1805.04400



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

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

Polarization sensitivity to chiral effects (I)



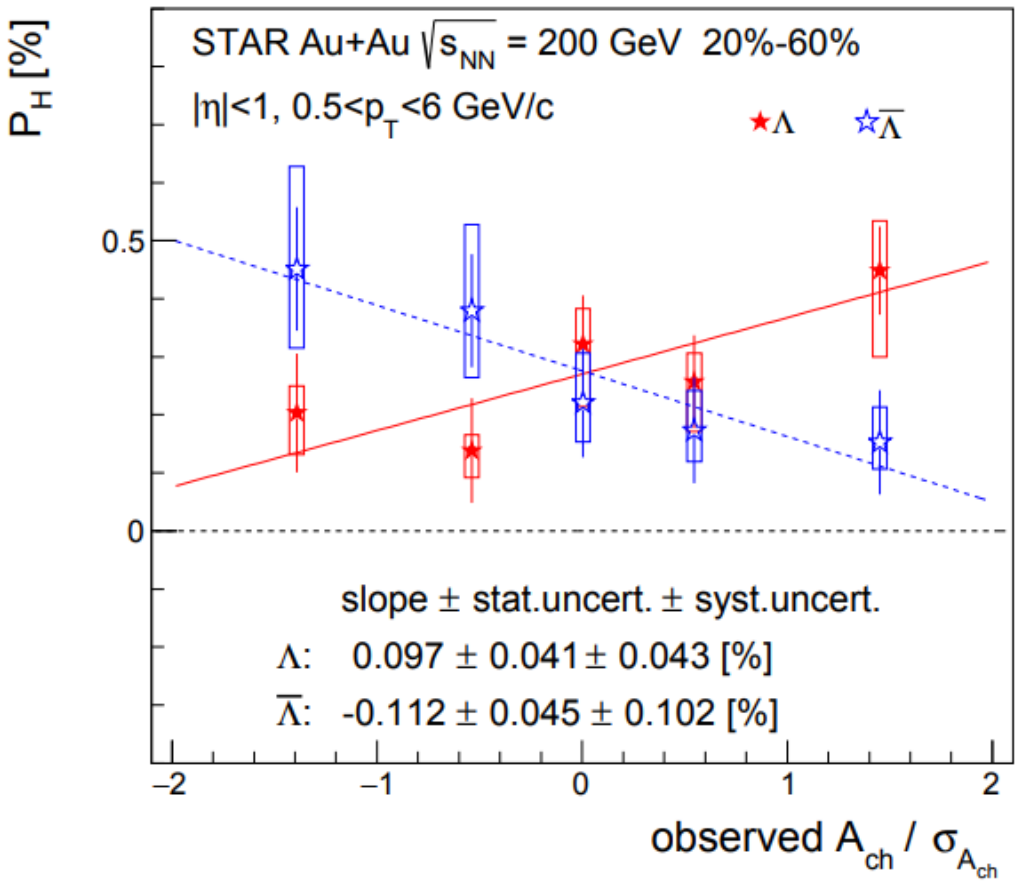
*Note that only the situation of an abundance of right handed quarks is depicted

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

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

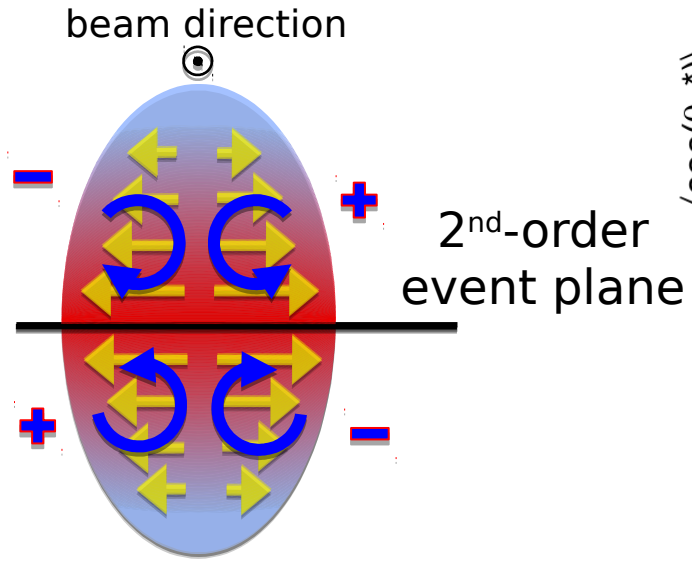
Polarization sensitivity to chiral effects (II)

- Hint of a signal slope
  - Lambda and Anti-Lambda have opposite-sign slopes
- Isobaric collision systems are a unique environment to test this effect

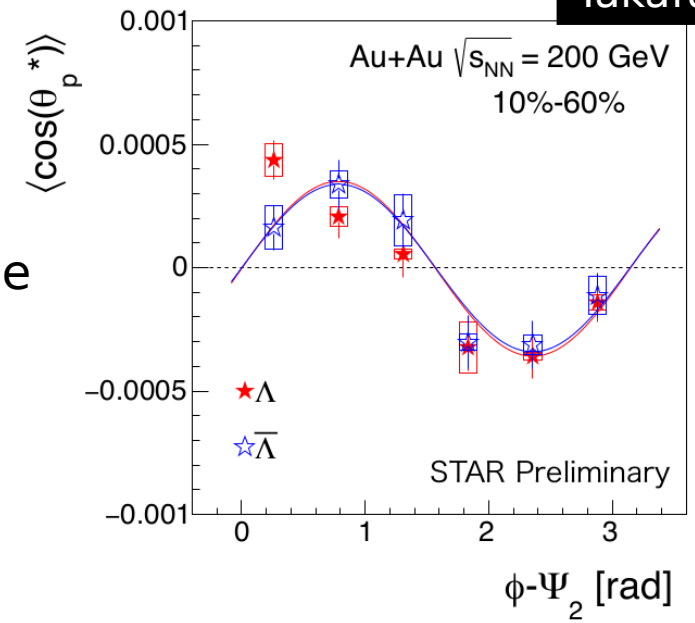


STAR, arXiv: 1805.04400

Polarization along the beam direction

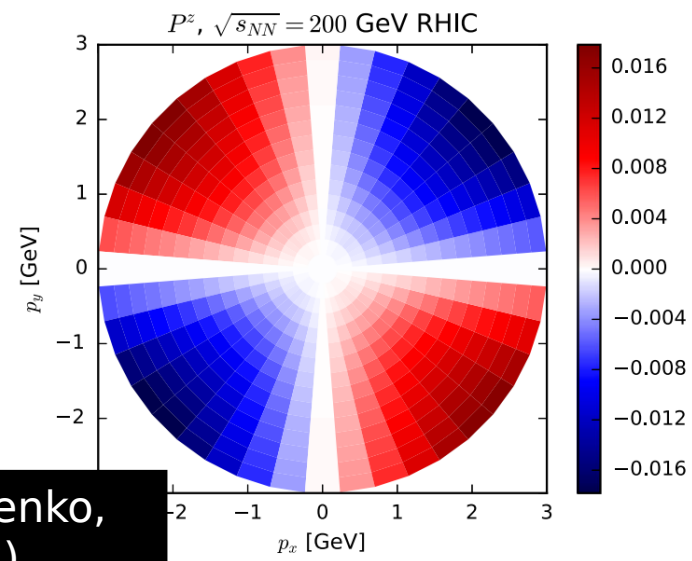


Takafumi Niida, talk @ QM18



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

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



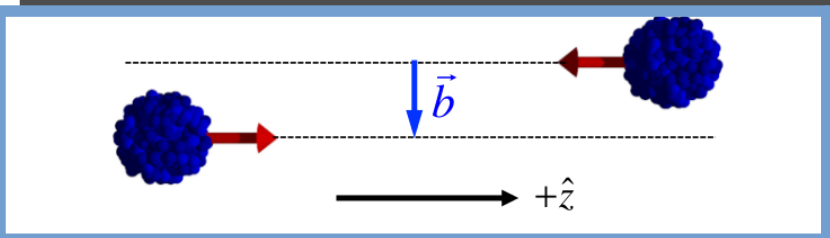
S. Voloshin, EPJ Web Conf. 17 (2018) 10700

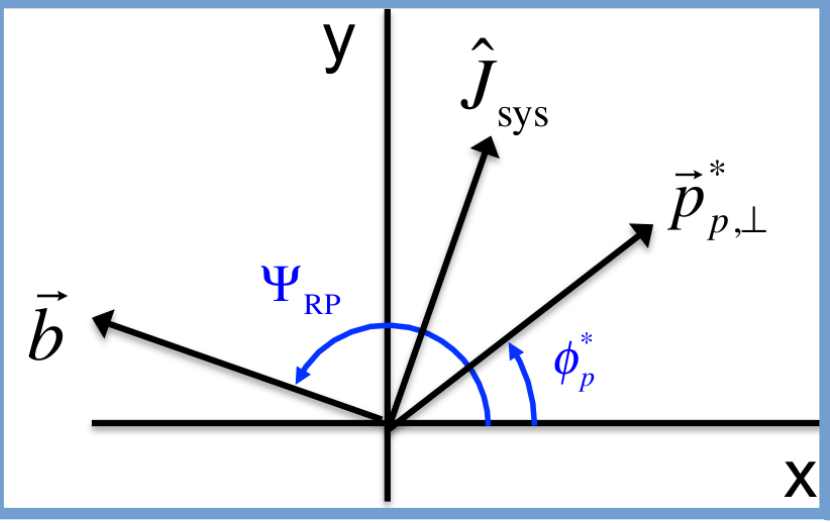
F. Becattini and I. Karpenko, PRL.120.012302 (2018)

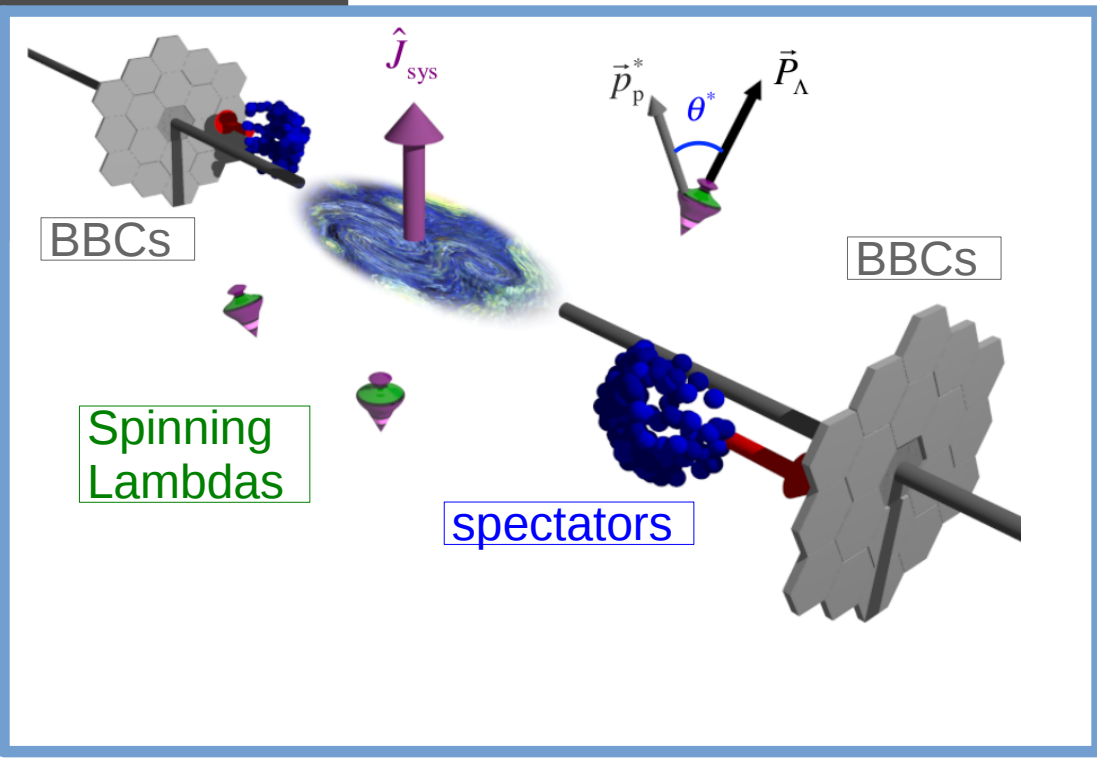
Conclusions

- Polarization may be a promising way to measure the magnetic field
  - RHIC BES-II may be the only program ready to measure it
- Recent high statistics 200 GeV measurements from STAR demonstrate a whole suite of measurements not previously available
  - Some have significant tension with hydrodynamic models
- STAR FXT program allows for significant increase in $\sqrt{s_{NN}}$ coverage
  - Could we see a turnover in the $\sqrt{s_{NN}}$ trend?
  - Higher energy beams on FXT mean far forward measurements

How to quantify the effect (II)







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

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

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

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

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

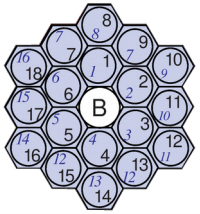
EPD-BBC comparison

BBC

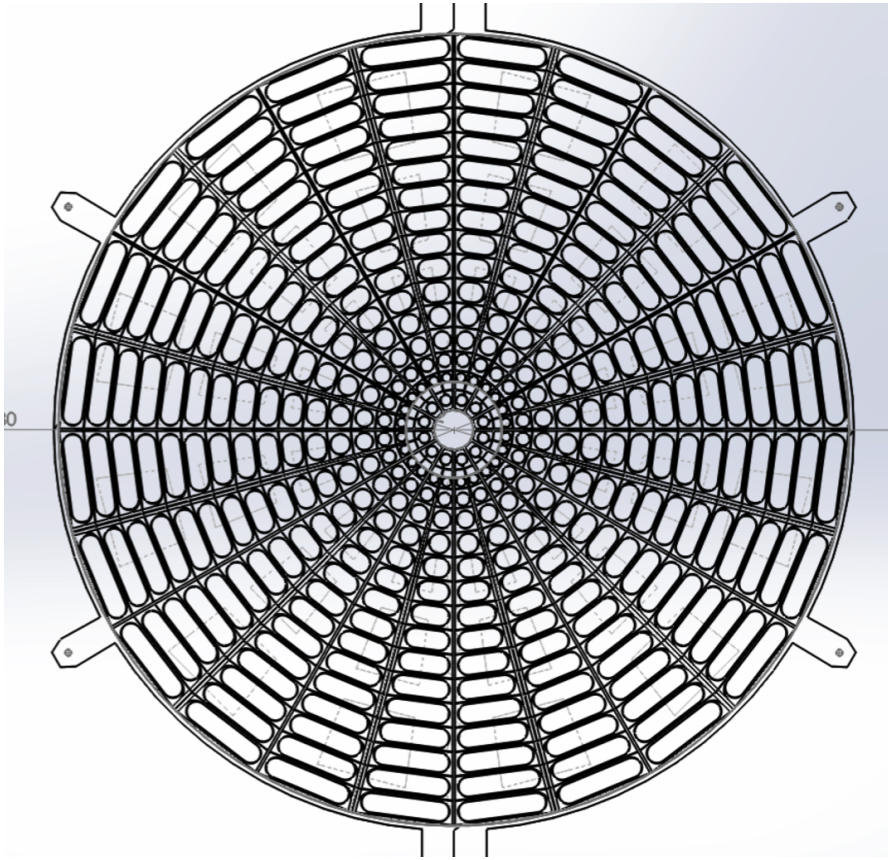
- 16 channels/side
- 2 η rings
- 3.6 < |η| < 5.0

EPD

- 372 tiles/side
- 16 η rings
- 24 φ segments
- 2.1 < |η| < 5.1

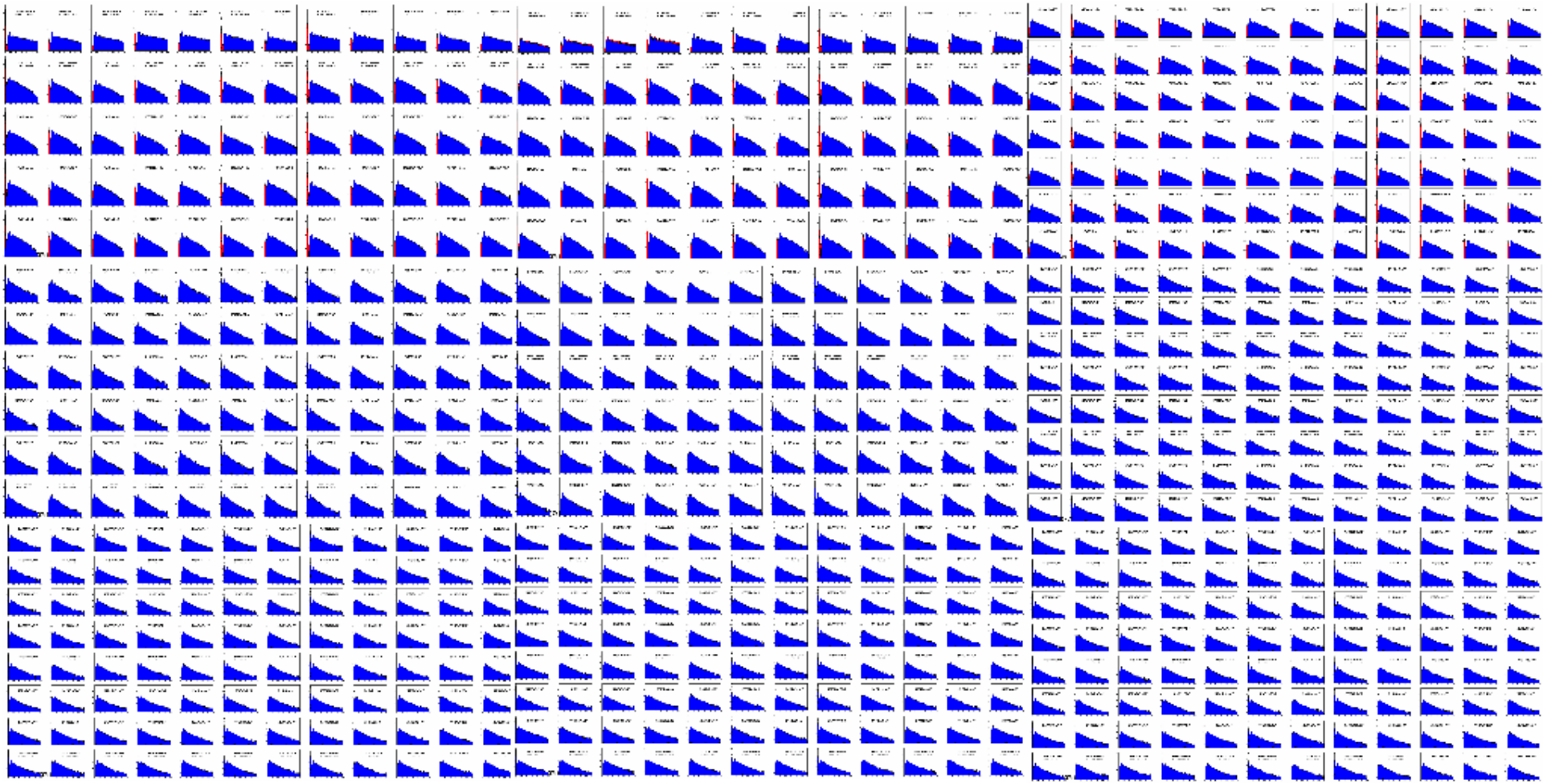


1.8 m



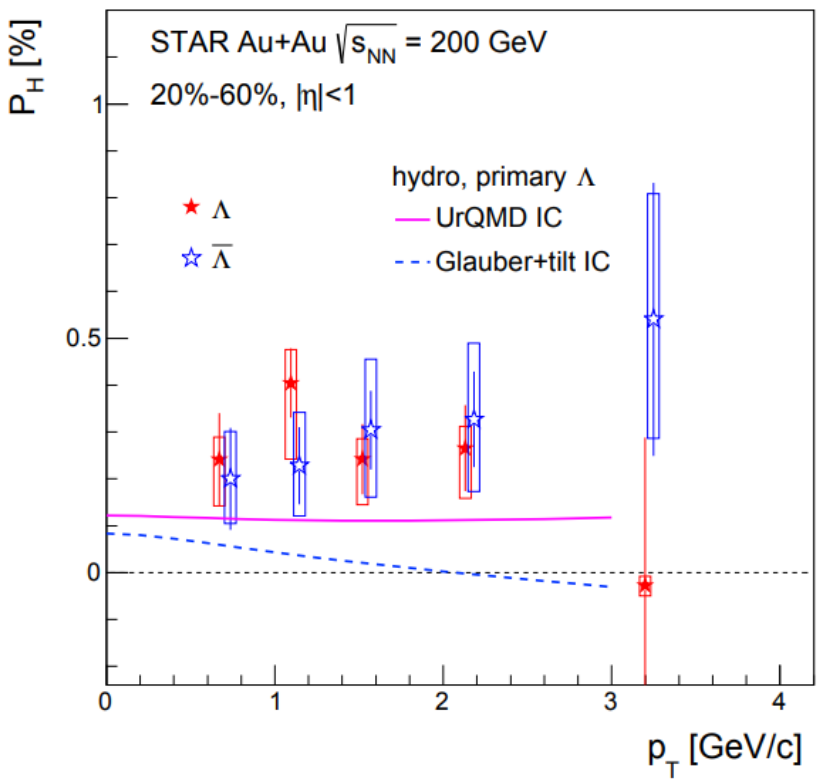
EPD-BBC comparison

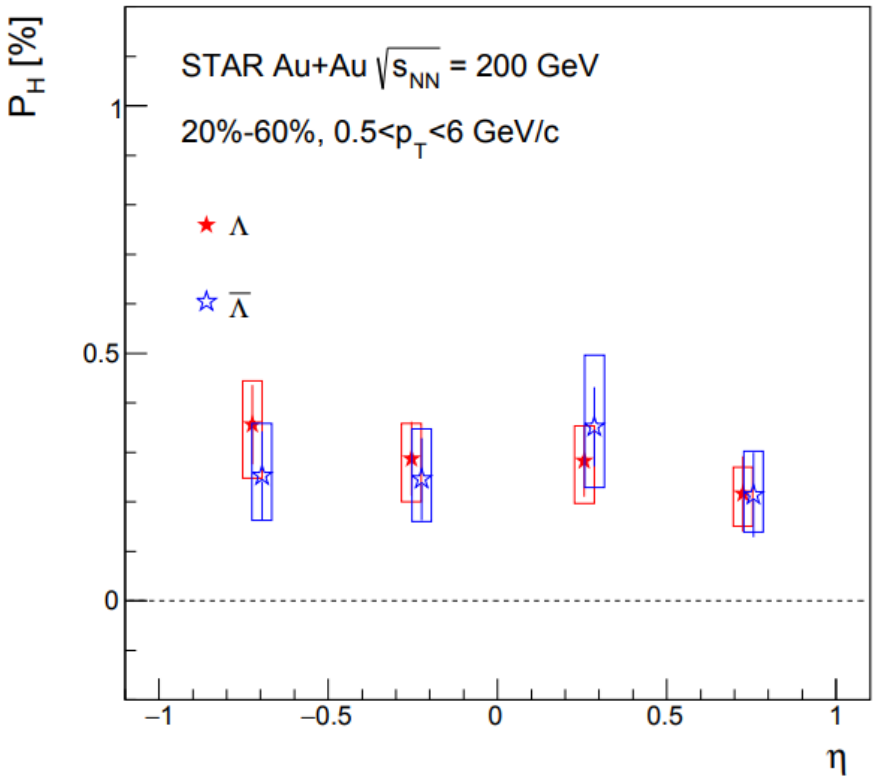
Run 19076023 – 07:32 17 May – 744 ADC spectra



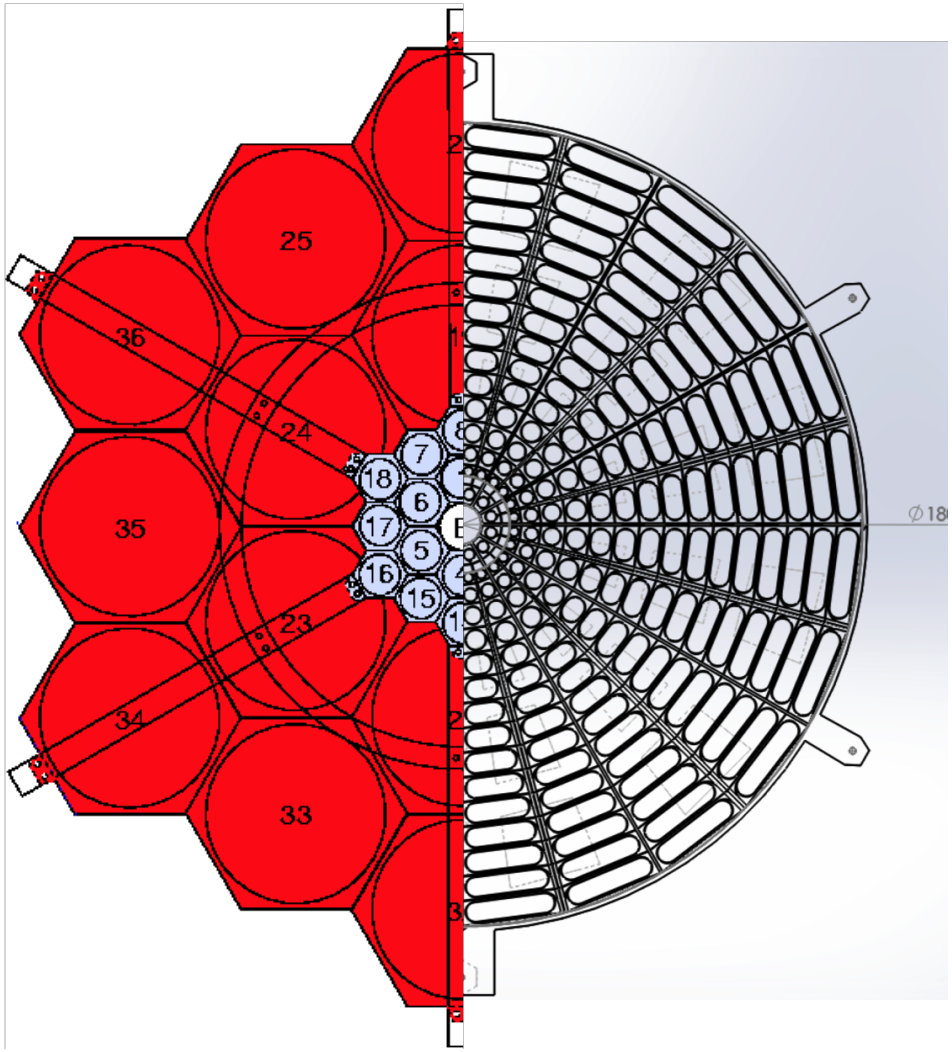
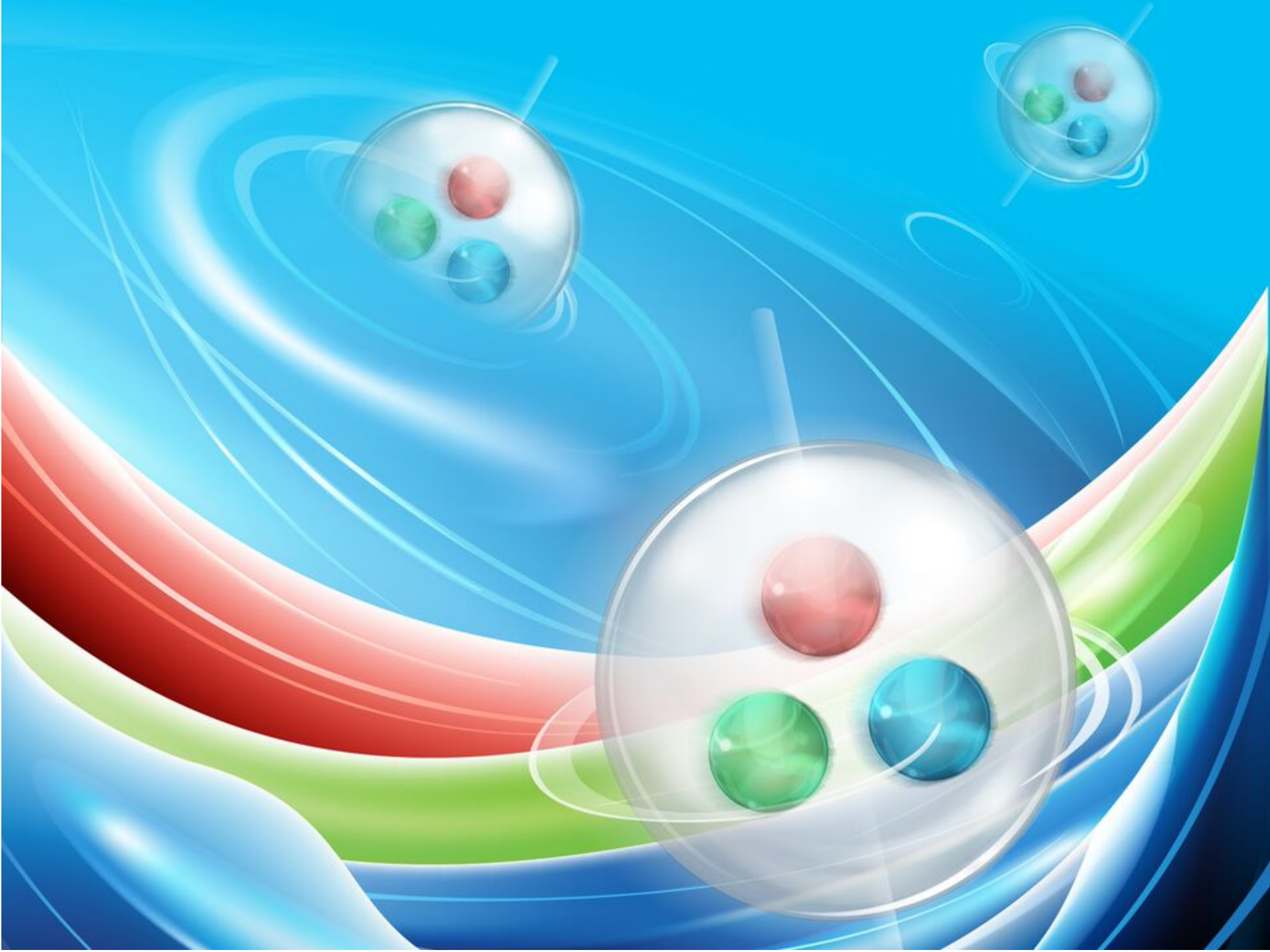
Extremely uniform performance

Momentum and pseudorapidity





STAR, arXiv: 1805.04400

- No dependence seen on transverse momentum or psuedorapidity

EPD BBC comparison