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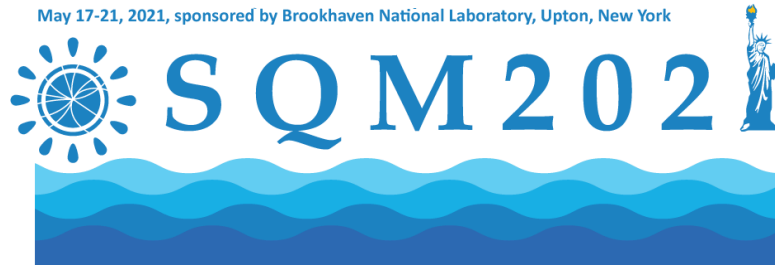


# Recent milestones from STAR: new developments and open questions

Rongrong Ma (For the STAR Collaboration)  
Brookhaven National Laboratory

The 19th International Conference on Strangeness in Quark Matter

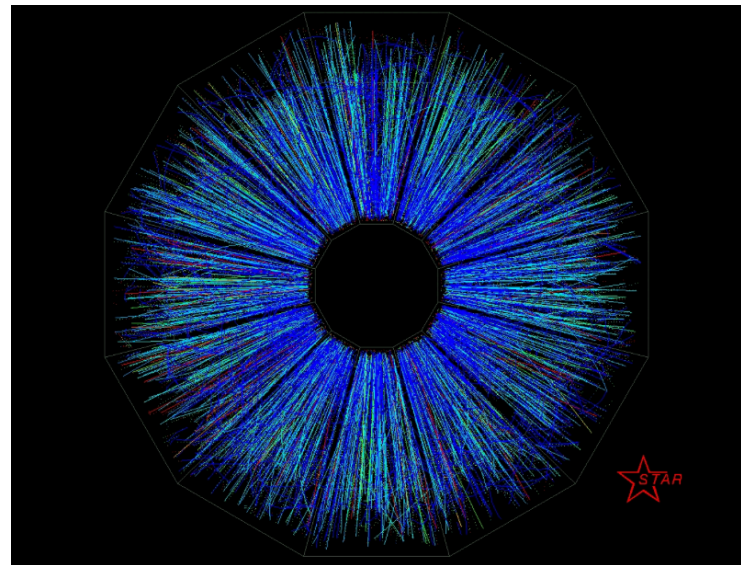
May 17-21, 2021, sponsored by Brookhaven National Laboratory, Upton, New York





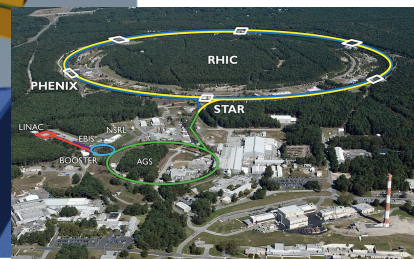
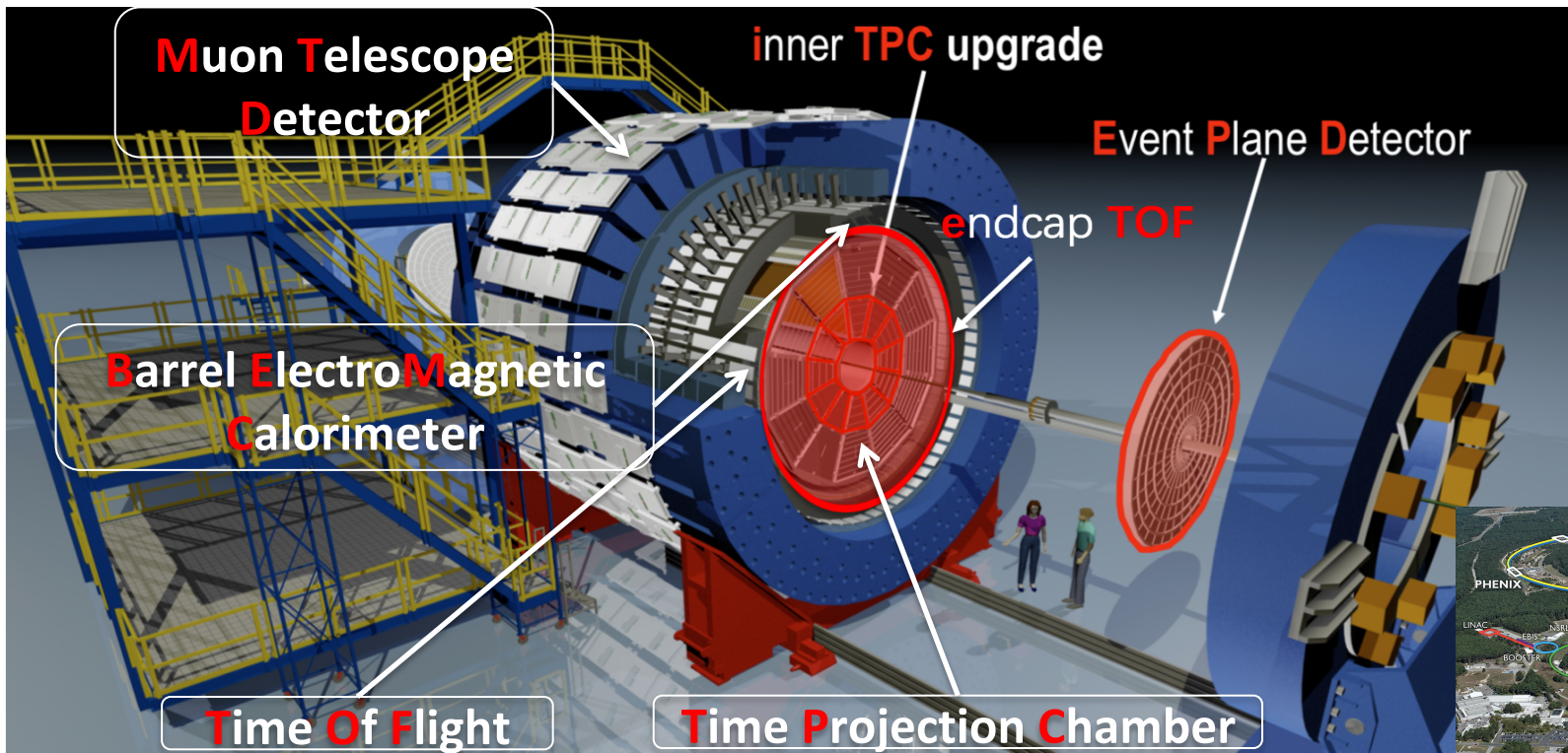
# Outline

- Initial stage electromagnetic field
  - Photon-photon process
  - Chiral magnetic effect
- Quark-Gluon Plasma (QGP) dynamics
  - $\Lambda$  global polarization
  - Net-proton cumulants
  - Baryon-baryon correlations
  - Understand  $f_0(980)$

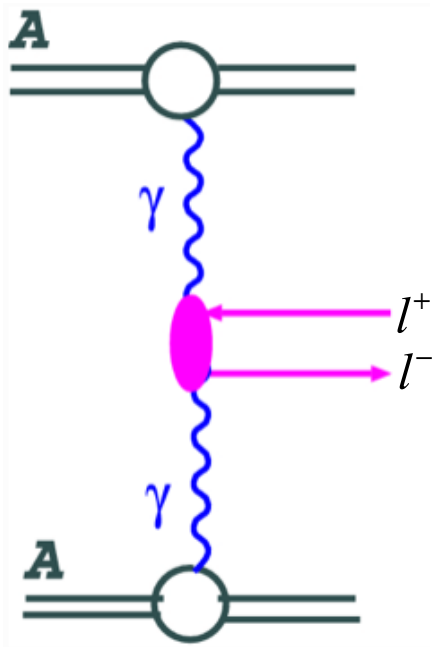




# STAR Detector at RHIC



# Initial Strong EM Fields



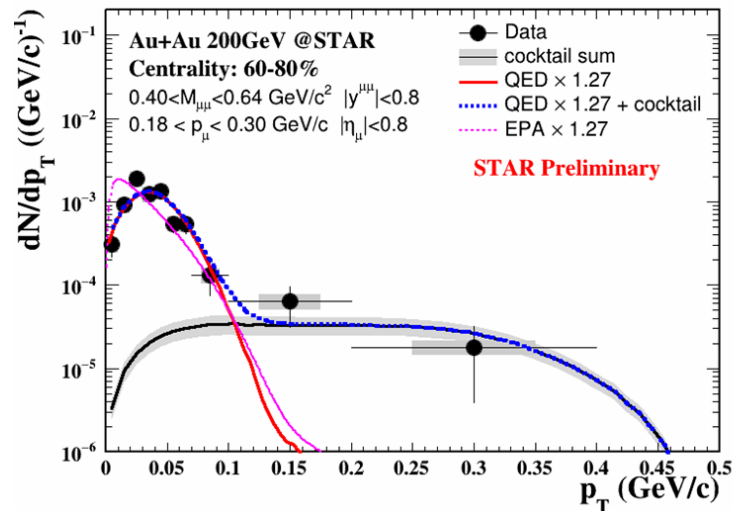
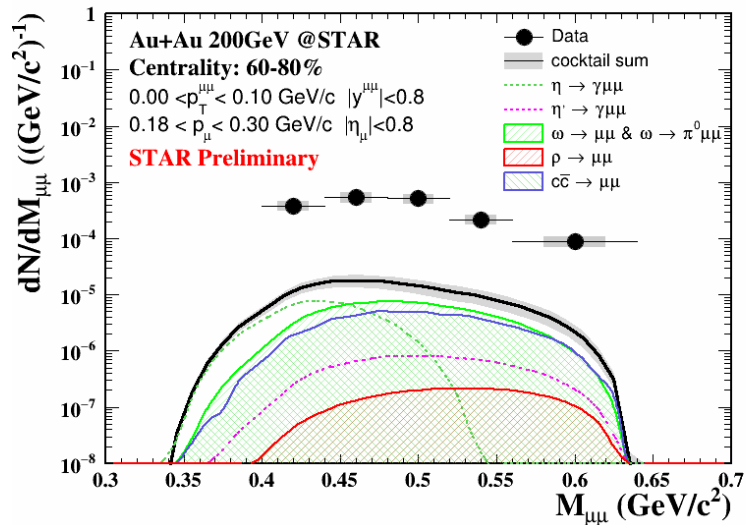
- In relativistic HI collisions, charged nuclei produce highly contracted EM fields
  - Photon flux proportional to  $Z^2$
  - Linearly polarized
- Coherent  $\gamma\gamma \rightarrow e^+e^-$  processes observed in UPC and peripheral Au+Au collisions
  - Excess pair production at  $p_T < 0.15$  GeV/c
  - $\cos(4\Delta\phi)$  modulation

$$\Delta\phi[(\vec{p}_1 + \vec{p}_2), (\vec{p}_1 - \vec{p}_2)]$$

# First Measurement of $\gamma+\gamma \rightarrow \mu^+\mu^-$

J. Zhou  
Tue. 9:50(C)

Au+Au @ 200 GeV 60-80%



- Significant excess above hadronic cocktail
- Excess concentrated below  $p_T = 0.1 \text{ GeV/c} \rightarrow$  coherent production
- Compatible with QED calculation

W. Zha, et al., PLB 800 (2020) 135089

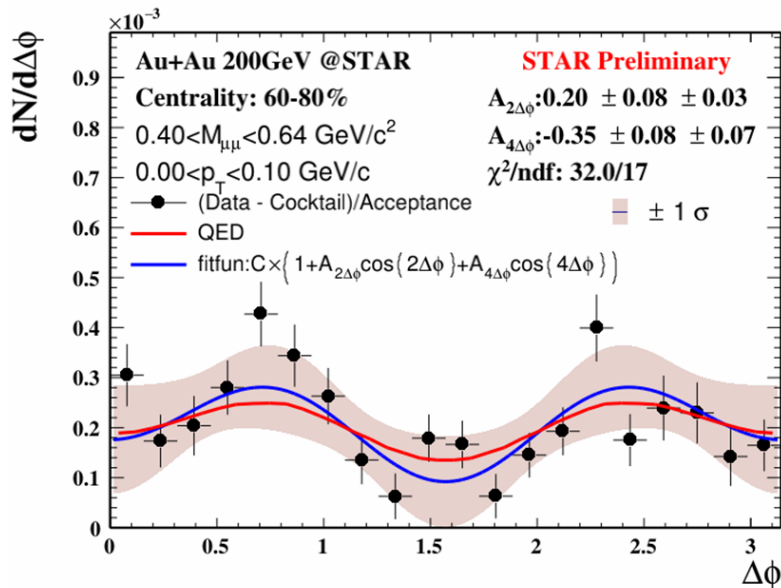


# Measurement of $\cos(2\Delta\phi)$ Modulation



J. Zhou  
Tue. 9:50(C)

$$\Delta\phi[(\vec{p}_1 + \vec{p}_2), (\vec{p}_1 - \vec{p}_2)]$$

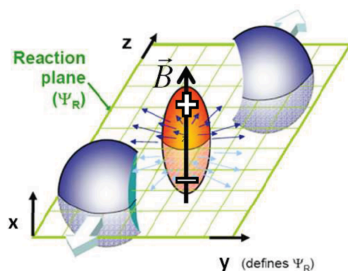


- $\cos(2\Delta\phi)$  modulation measured with  $2.3\sigma$  significance
  - Asymmetry proportional to  $m^2/p_T^2$
- Confirms the  $\cos(4\Delta\phi)$  modulation observed in electron channel
- 2014 data are used now. Will combine with 2016 data

W. Zha, et al., PLB 800 (2020) 135089



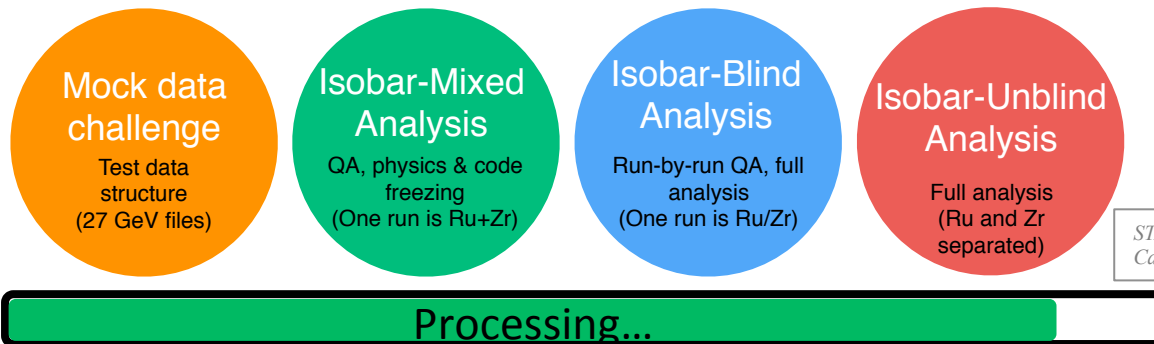
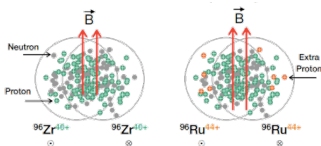
# Chiral Magnetic Effect (CME)



- CME: a novel phenomenon predicted in HI collisions
  - Prerequisite: chiral imbalance+ magnetic field
  - Consequence: charge separation along  $B$  field

- Experimental search is challenging due to overwhelming background → Isobar

## Isobar Blind Analysis



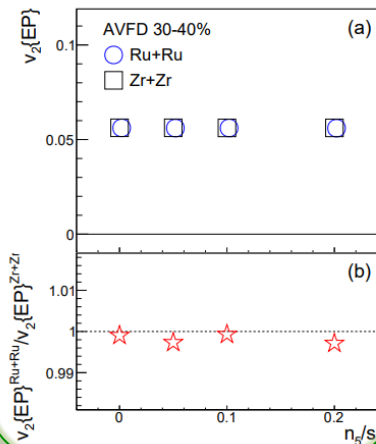
STAR, arXiv:1911.00596  
Cartoon: arXiv:2009.01230



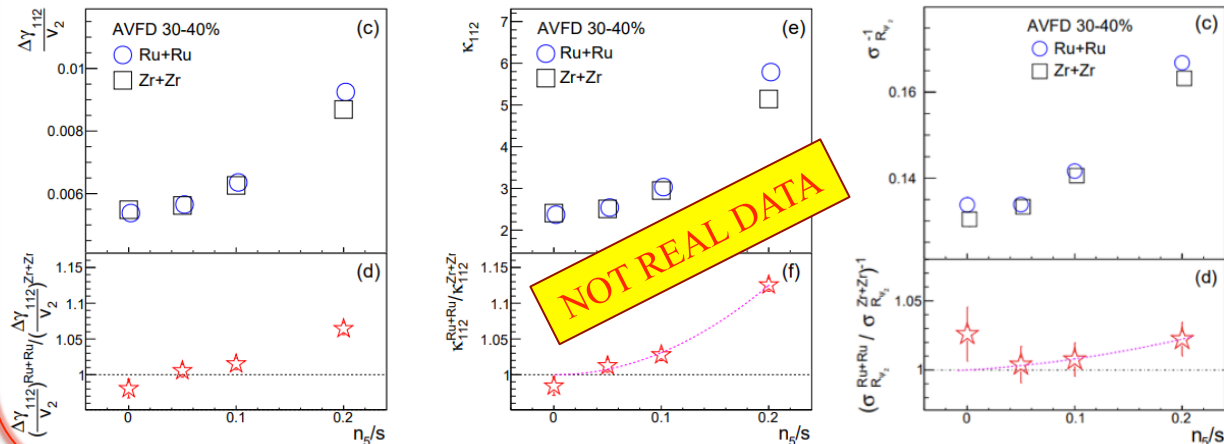
# Analyze AVFD Events with Frozen Code

Y. Hu  
Wed. 10:30(C)

## Background



## Signal



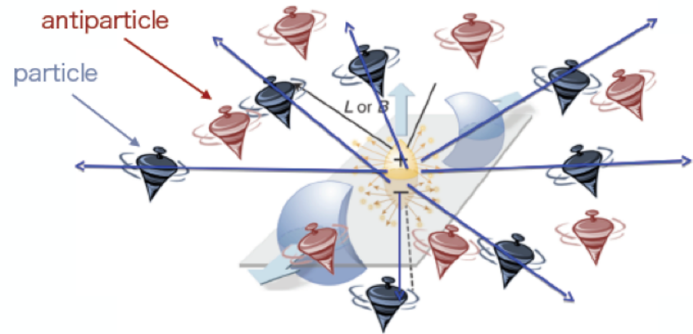
- Test response of different observables in frozen code to CME signal and difference between Ru+Ru and Zr+Zr using e-b-e AVFD (Anomalous Viscous Fluid Dynamics)
  - $n_s/s$  indicates CME signal strength
- Same sensitivity (inclusive  $\Delta\gamma$ ,  $R_2$ ) when put on same footing

S. Choudhury, arXiv:2105.06044  
 AVFD:  
 S. Shi, et al., *Annals Phys.*394 (2018) 50  
 Y. Jiang, et al., *CPC42* (2018) 011001  
 S. Shi, et al., *PRL* 125 (202) 242301

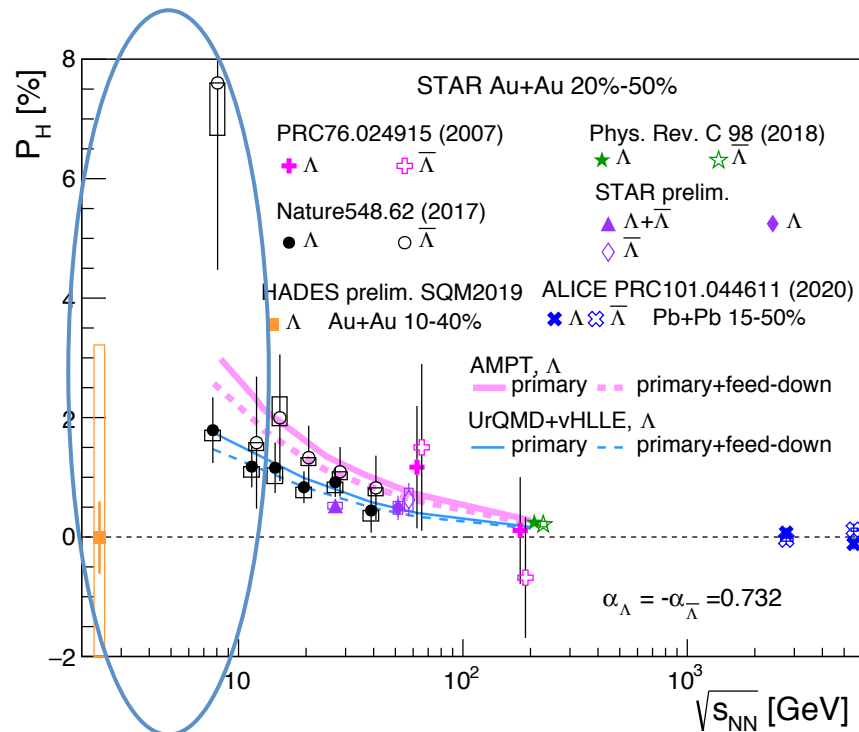




# $\Lambda$ Global Polarization

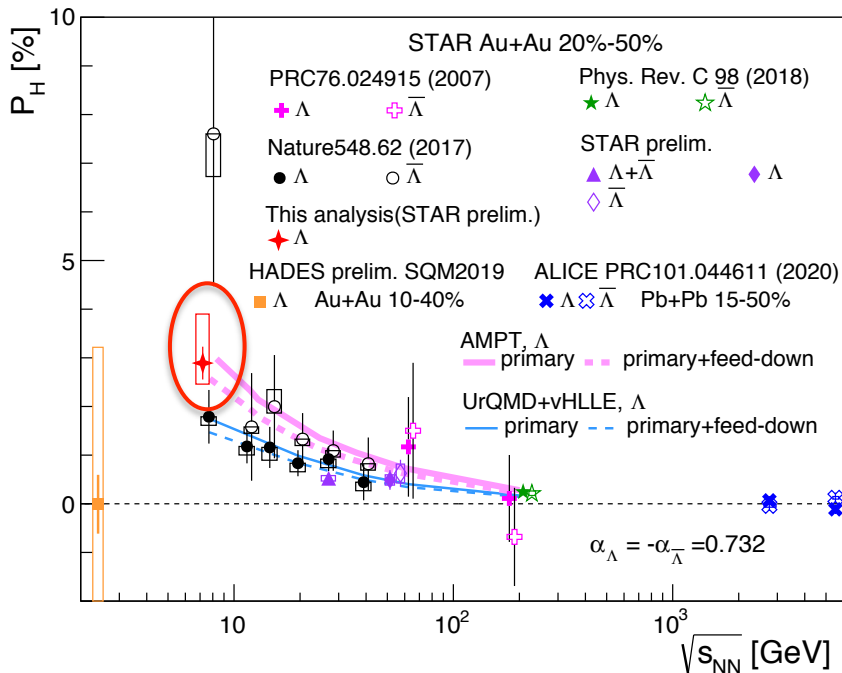


- **Magnetic field**  $\rightarrow$   $\Lambda$  and anti- $\Lambda$  align in **opposite** directions
- **Fluid vorticity**  $\rightarrow$   $\Lambda$  and anti- $\Lambda$  align in **same** direction





# $\Lambda P_H$ at 7.2 GeV Au+Au



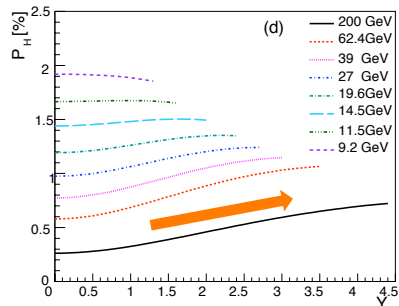
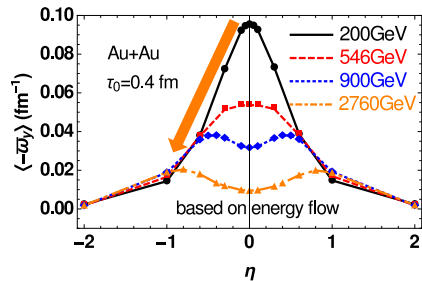
- *First measurement at  $\sqrt{s_{NN}} = 7.2$  GeV Au+Au (FXT)*
- **Positive polarization for  $\Lambda$** 
  - $0.6 < y + |y_{beam}| < 1.8$
- Follow the world data trend
  - Increasing polarization with decreasing collision energy

K. Okubo  
Thu. 10:10(B)

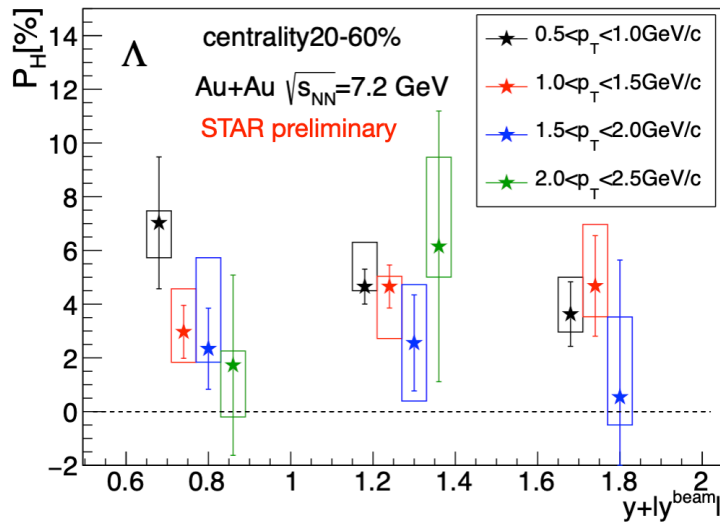


# Rapidity Dependence of $\Lambda P_H$

W-T Deng, X-G Huang, PRC 93 (2016) 064907



Z-T Liang, et. al, arXiv: 1912.10223



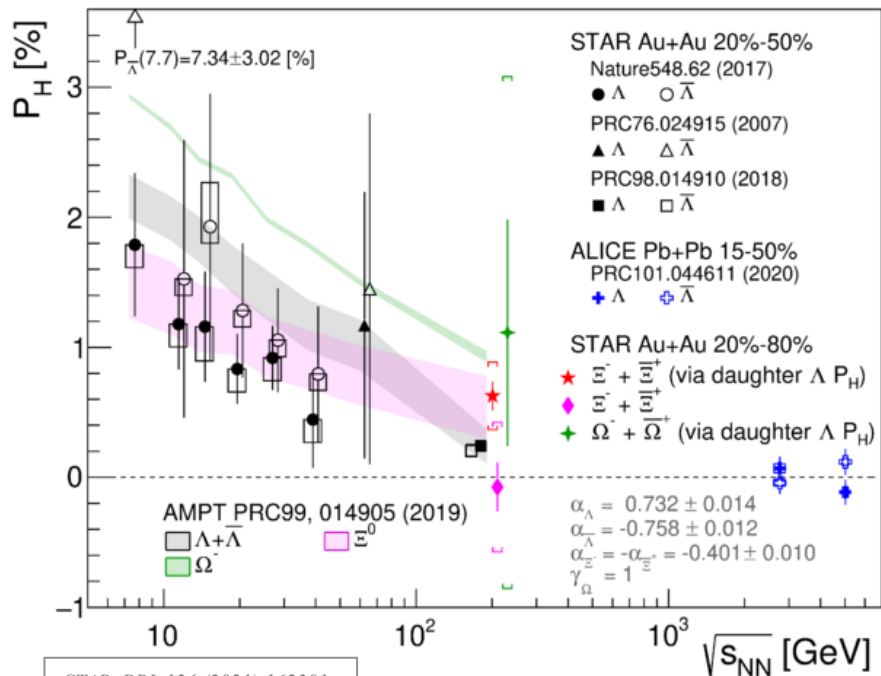
K. Okubo  
Thu. 10:10(B)

- No significant rapidity dependence ( $\Delta y \sim 1.2$ ) within uncertainties



BES-II larger  
rapidity coverage

# Extend Measurements to $\Xi$ and $\Omega$



STAR, PRL 126 (2021) 162301

- *First measurement of  $\Xi$  and  $\Omega$  global polarization in 200 GeV Au+Au collisions*
  - Important addition to  $\Lambda$  results
- Within 20-80%,  $|y| < 1$ ,  $p_T > 0.5$  GeV/c
  - $\langle P_\Lambda \rangle$  (%) =  $0.24 \pm 0.03(\text{stat}) \pm 0.03(\text{syst})$
  - $\langle P_\Xi \rangle$  (%) =  $0.47 \pm 0.10(\text{stat}) \pm 0.23(\text{syst})$
  - $\langle P_\Omega \rangle$  (%) =  $1.11 \pm 0.87(\text{stat}) \pm 1.97(\text{syst})$
- Consistent with picture of system fluid vorticity

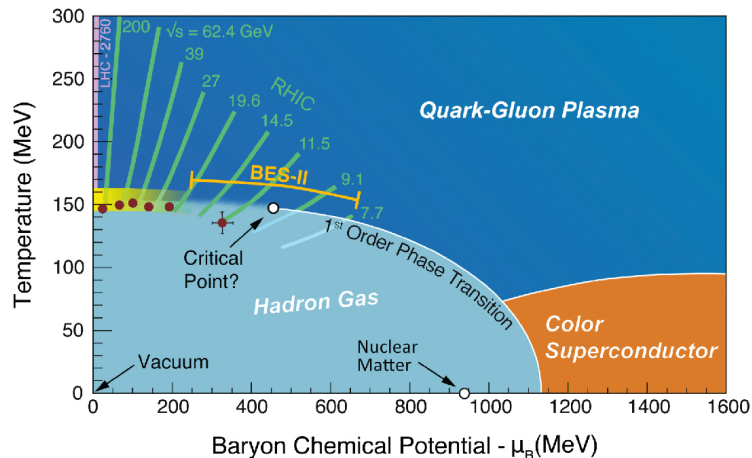


More statistics  
in 2023+25



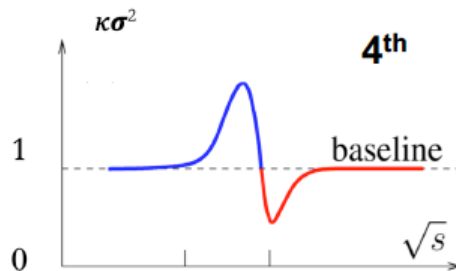
# Search for Critical Point (CP)

Courtesy: S. Mukherjee



- Finding the conjectured critical point is one of the main goals of the BES program at RHIC
- Cumulants of conserved quantities (Q, B, S) are sensitive to the correlation length, which diverges at CP
  - Need to survive the medium evolution

$$s\sigma = \frac{C_3}{C_2} \quad \kappa\sigma^2 = \frac{C_4}{C_2}$$

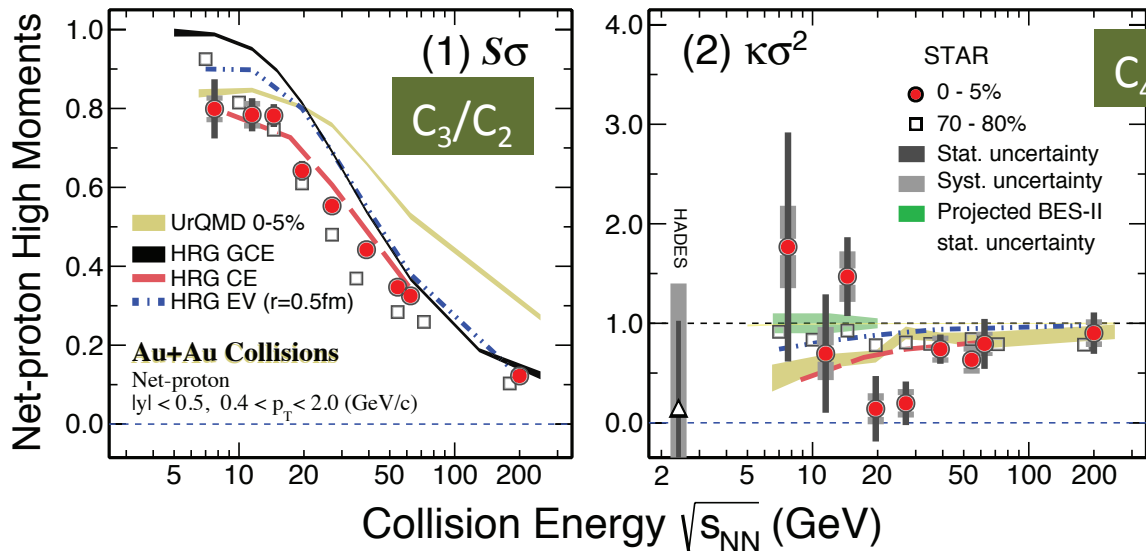


M. A. Stephanov, PRL 102 (2009) 032301  
 M. A. Stephanov, PRL 107 (2011) 052301



# Higher Moments Ratio vs. $\sqrt{s_{NN}}$ (BES-I)

Y. Zhang  
Tue. 11:30(A)



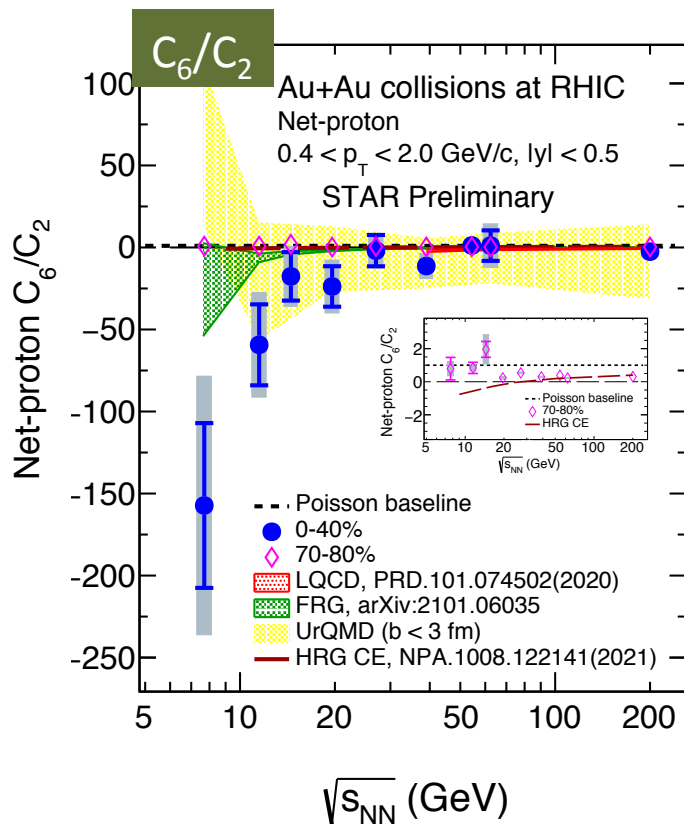
- Milestone measurement from BES-I
- Non-monotonic behavior of  $\kappa\sigma^2$  vs.  $\sqrt{s_{NN}}$  in 0-5% central collision with 3.1 $\sigma$



BES-II with upgrades and more statistics



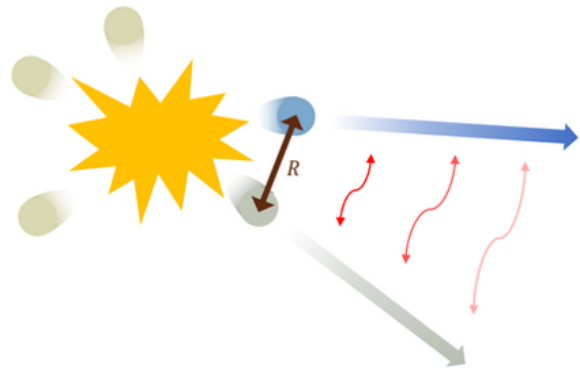
# Even Higher Order



- Higher order is more sensitive to correlation length
- Smooth trend vs.  $\sqrt{s_{NN}}$
- In 0-40%, negative  $C_6$  values at most  $\sqrt{s_{NN}}$  values
  - Positive for 70-80%

Y. Zhang  
Tue. 11:30(A)

# Femtoscscopy: Short-Range Correlation



- Study the spatial and temporal extent of the emission source
  - Quantum statistics; final-state interactions
- Y-Y and Y-N interactions are essential inputs for understanding EoS of neutron stars
- Observable: two-particle correlation

$$C(q) = \frac{A(q)}{B(q)}$$

$q$  – relative momentum between two particles

$A(q)$  – signal correlation from same events

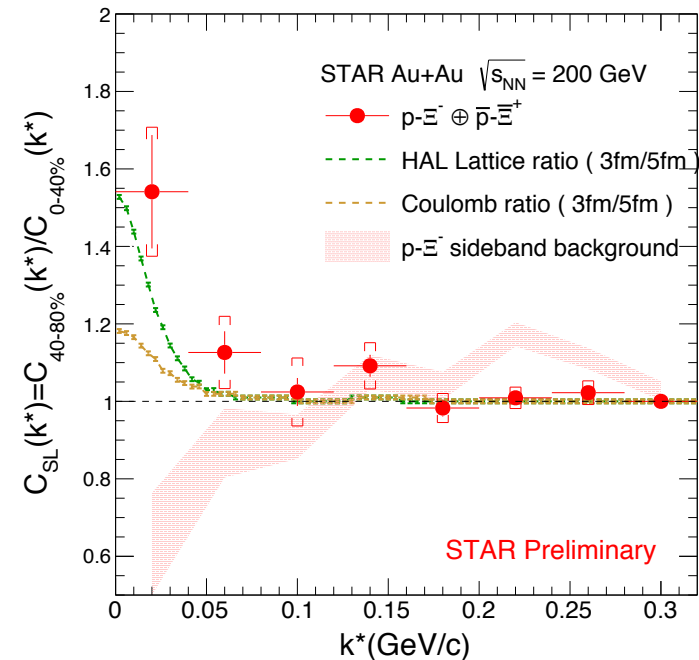
$B(q)$  – background correlation from mixed events





# 200 GeV Au+Au: $p$ - $\Xi^-$ Correlation

M. Isshiki  
Wed. 10:30(B)

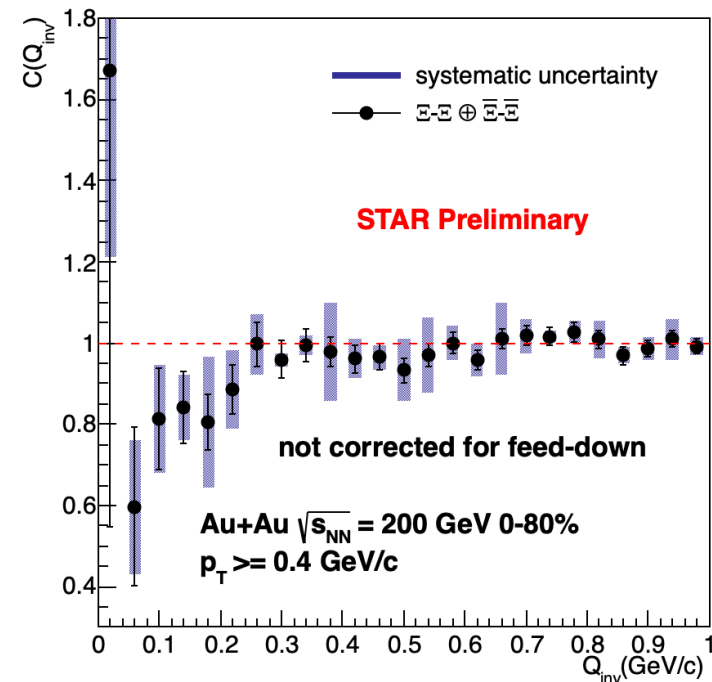


$$C_{SL}(k^*) = \frac{C(k^*)_{40-80\%}}{C(k^*)_{0-40\%}}$$

- *First measurement of  $p$ - $\Xi^-$  correlation in Au+Au*
- Stronger correlation in peripheral than central collisions (system size)
- Peripheral/central: **attractive strong interaction at  $k^* < 0.1$  GeV/c beyond Coulomb interaction and background**
- Consistent with lattice-QCD calculation

K. Morita, et al., PRC 94 (2016) 031901  
T. Hatsuda, NPA 967 (2017) 856

# 200 GeV Au+Au: $\Xi$ - $\Xi$ Correlation



- *First measurement of  $\Xi$ - $\Xi$  correlation in Au+Au collisions*
- Indication of negative correlation at small  $Q_{inv}$
- Need to understand feed-down contribution and Coulomb effect

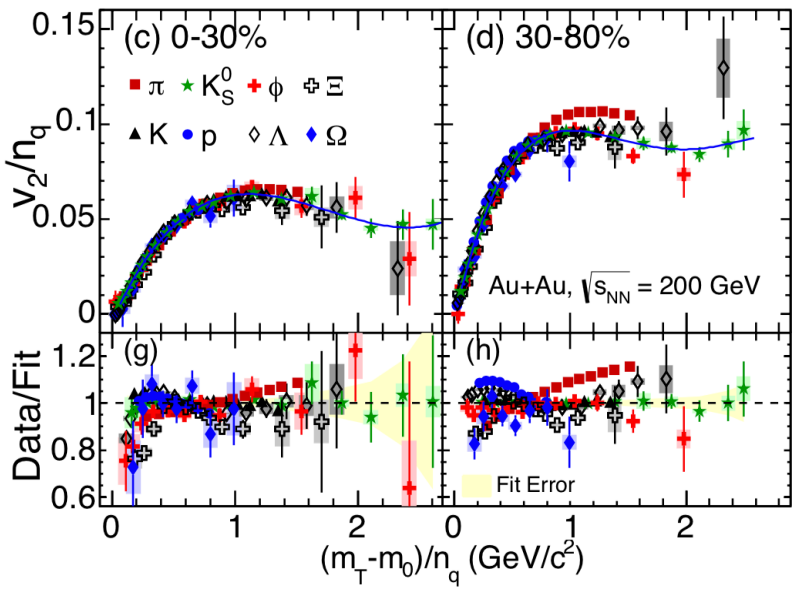


More statistics  
in 2023+25

M. Isshiki  
Wed. 10:30(B)

# What is Quark Content of $f_0(980)$ ?

STAR, PRL 116 (2016) 062301



J. Zhao  
Wed. 09:50(A)

- Use NCQ scaling of elliptic flow as a tool

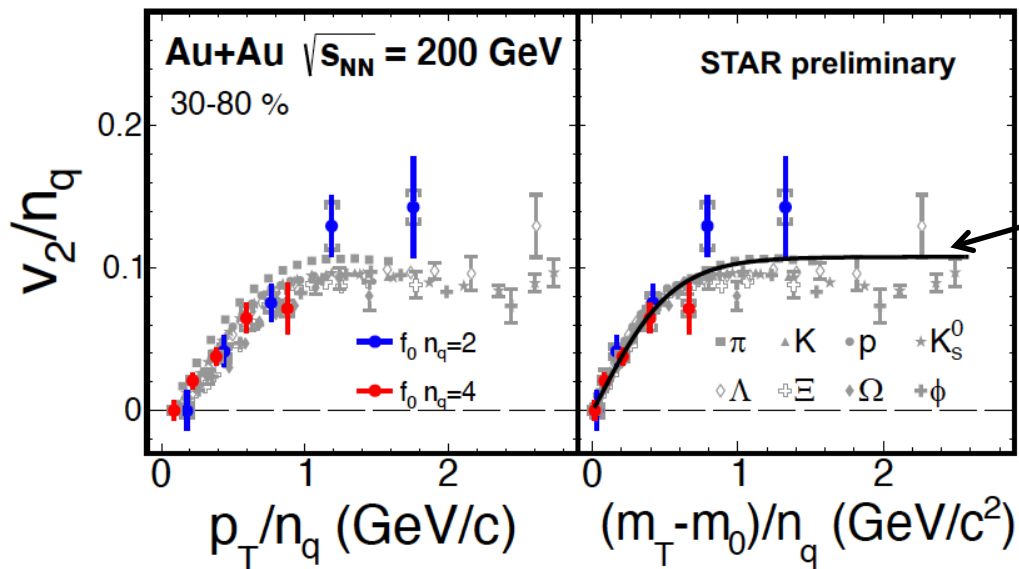


# NCQ Scaling of $f_0(980) v_2$

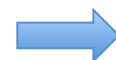


STAR, PRL 116 (2016) 062301

J. Zhao  
Wed. 09:50(A)



- $f_0(980) n_q$ :  $3.0 \pm 0.7(\text{stat}) \pm 0.5(\text{syst})$  from best fit to common trend
- A mixture of 2q and 4q states?



More statistics  
in 2023+25



# Summary and Outlook

- **STAR continues the mission of understanding QCD diagram**
  - Non-monotonic behavior in net-proton high moments ratio vs.  $\sqrt{s_{NN}}$
  - CME search challenging due to background. Dedicated Isobar data
  - Positive  $\Lambda$  global polarization measured at 7.2 GeV
- **STAR expands the horizon: use HI/QGP as a lab**
  - Excess low- $p_T$  muon pair from coherent photoproduction. Photon polarization reflected in pair kinematics
  - Positive  $p$ - $\Xi^-$  and negative  $\Xi$ - $\Xi$  correlations. Input for astrophysics
  - $f_0(980)$  quark content:  $3.0 \pm 0.7(\text{stat}) \pm 0.5(\text{syst})$
- *Coming up soon: Isobar, BES-II and O+O results*



# List of STAR Talks

- Production of pions, kaons, (anti-)protons and (multi-)strange hadrons production in Au+Au collisions at  $\sqrt{s_{NN}} = 54.4$  GeV using the STAR detector – [Yan Huang – Tue. 09:30 \(B\)](#)
- Low- $p_T$   $\mu^+\mu^-$  pair production in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV at STAR – [Jian Zhou - Tue. 09:50 \(C\)](#)
- Azimuthal anisotropy measurement of multi-strange hadrons in Au+Au collisions at  $\sqrt{s_{NN}} = 27$  GeV and 54.4 GeV at STAR – [Prabhupada Dixit – Tue. 10:10 \(A\)](#)
- Higher-Order Cumulants of Net-Proton Multiplicity Distribution from RHIC-STAR – [Yu Zhang – Tue. 11:30 \(A\)](#)
- Light and strange hadron production and anisotropic flow measurement in Au+Au collisions at  $\sqrt{s_{NN}} = 3$  GeV from STAR – [Guannan Xie – Tue. 12:30 \(B\)](#)
- NCQ scaling of  $f_0(980)$  elliptic flow in 200 GeV Au+Au collisions by STAR and its constituent quark content – [Jie Zhao – Wed. 09:50 \(A\)](#)
- Measurements of electrons from heavy-flavor hadron decays in 27, 54.4, and 200 GeV Au+Au collisions in STAR – [Shenghui Zhang – Wed. 09:50 \(D\)](#)
- Measurements of  $\Lambda\Lambda$ ,  $\Xi-\Xi$  and  $p-\Xi$  Correlation in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV at RHIC-STAR – [Moe Isshiki – Wed. 10:30 \(B\)](#)
- CME Search at STAR – [Yu Hu – Wed. 10:30 \(C\)](#)
- Measurement of global polarization of Lambda hyperons in Au+Au  $\sqrt{s_{NN}} = 7.2$  GeV Fixed-target collisions at RHIC-STAR experiment – [Kosuke Okubo – Thu. 10:10 \(B\)](#)
- Study of Charge Symmetry Breaking in  $A = 4$  hypernuclei in  $\sqrt{s_{NN}} = 3$  GeV Au+Au collisions at RHIC – [Tianhao Shao – Fri. 09:30 \(B\)](#)
- Recent  $J/\psi$  results in p+p and Au+Au collisions from STAR – [Kaifeng Shen – Fri. 10:10 \(D\)](#)
- Light Hyper-Nuclei Production in 3 GeV Au+Au Collisions at RHIC – [Chenlu Hu – Fri. 10:30 \(B\)](#)