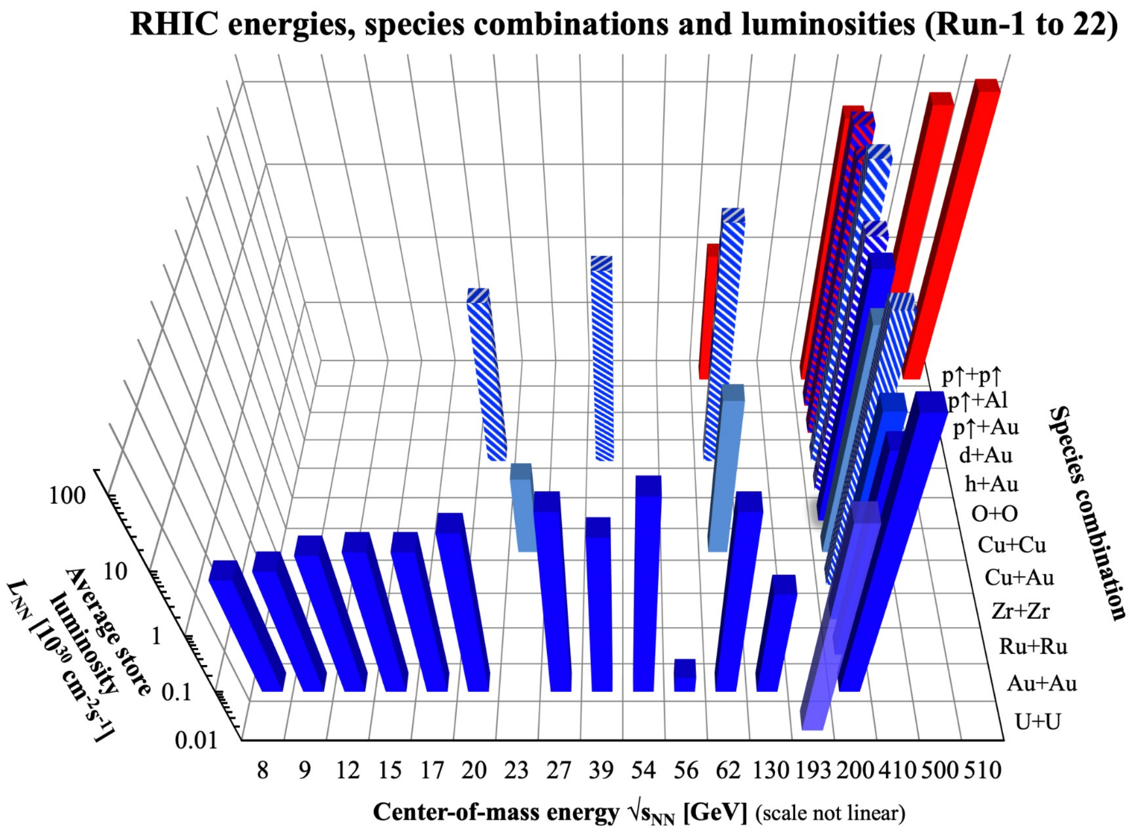
Understanding QCD Matter Through Heavy-Ion Collisions at STAR

Gavin Wilks (for the STAR Collaboration)
University of Illinois at Chicago

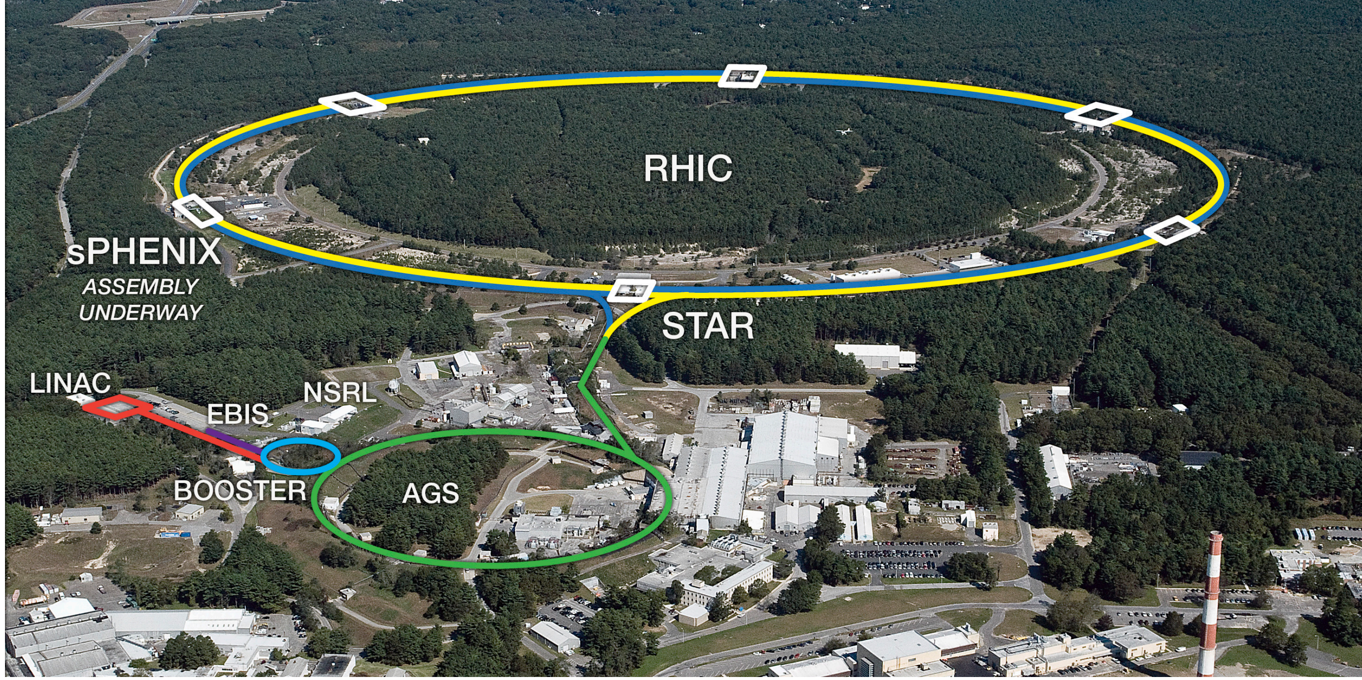
January 16th, 2024

This work is supported in part by the DOE Office of Science

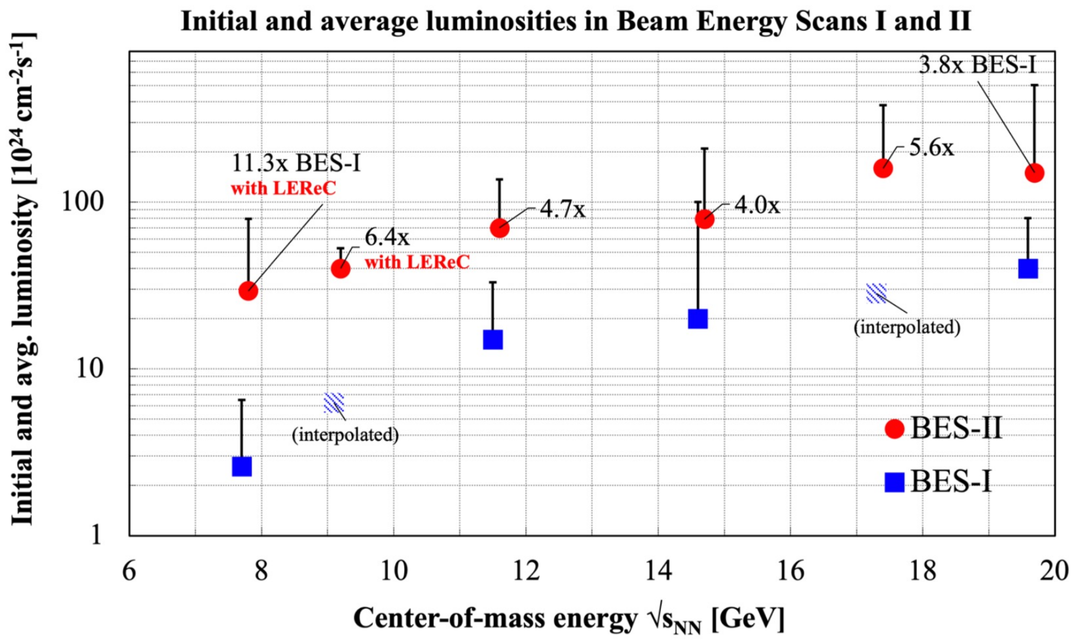
RHIC



RHIC energies, species combinations and luminosities (Run-1 to 22)
Average store luminosity L_{NN} [10^{30} cm^{-2}s^{-1}]
100
10
1
0.1
0.01
8 9 12 15 17 20 23 27 39 54 56 62 130 193 200 410 500 510
Center-of-mass energy $\sqrt{s_{NN}}$ [GeV] (scale not linear)
Species combination
p↑+p↑
p↑+Al
p↑+Au
d+Au
h+Au
O+O
Cu+Cu
Cu+Au
Zr+Zr
Ru+Ru
Au+Au
U+U



RHIC
sPHENIX
ASSEMBLY UNDERWAY
STAR
LINAC
EBIS
NSRL
BOOSTER
AGS



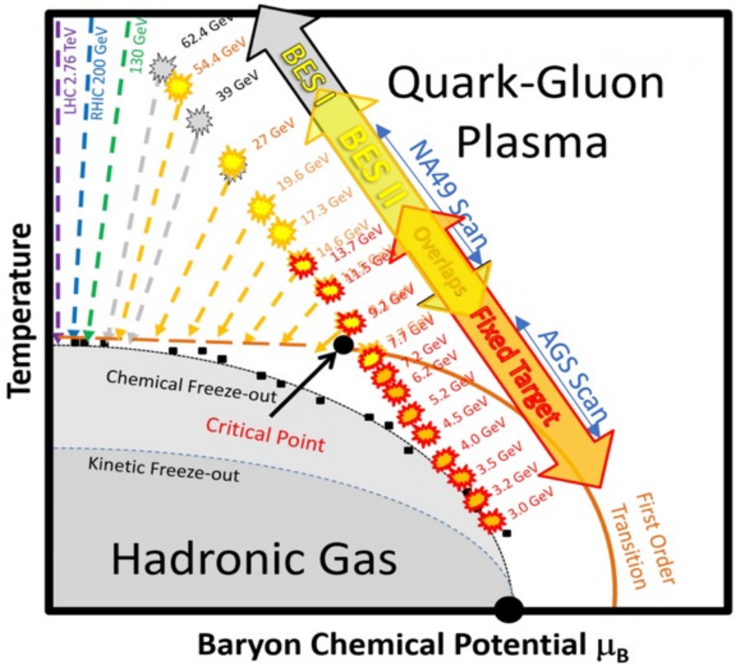
Initial and average luminosities in Beam Energy Scans I and II
Initial and avg. luminosity [10^{24} cm^{-2}s^{-1}]
1
10
100
6 8 10 12 14 16 18 20
Center-of-mass energy $\sqrt{s_{NN}}$ [GeV]
11.3x BES-I
with LEReC
6.4x
with LEReC
4.7x
4.0x
5.6x
3.8x BES-I
(interpolated)
(interpolated)
BES-II
BES-I

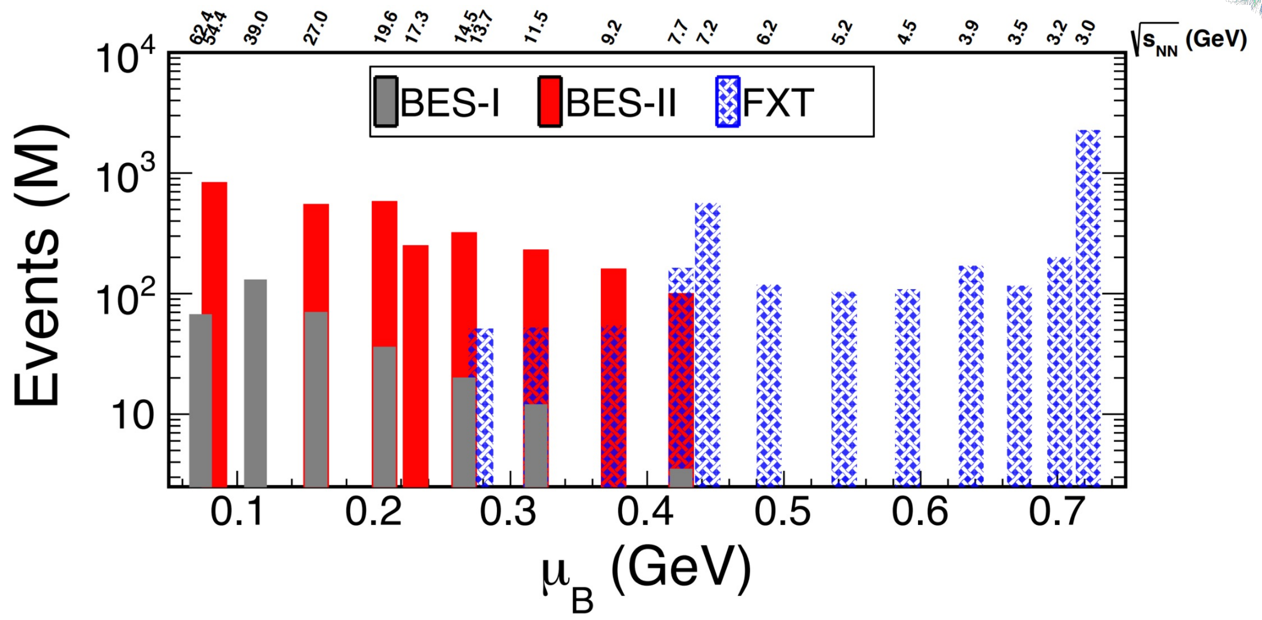
STAR Physics Focus

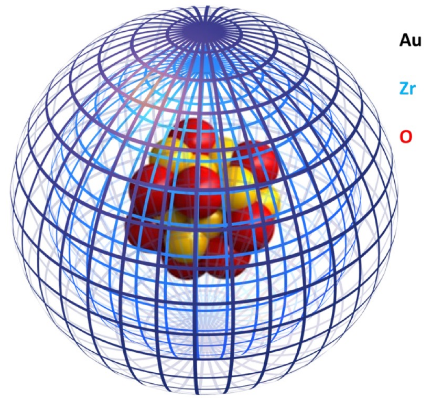
Motivation

Probing the QCD phase diagram
- Nature of phase transitions
- Critical point

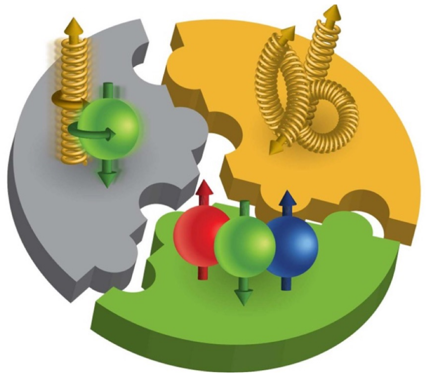
Properties of partonic / high μ_B matter
- Vorticity and its system size dependence.
- Proton spin - not discussed in this talk





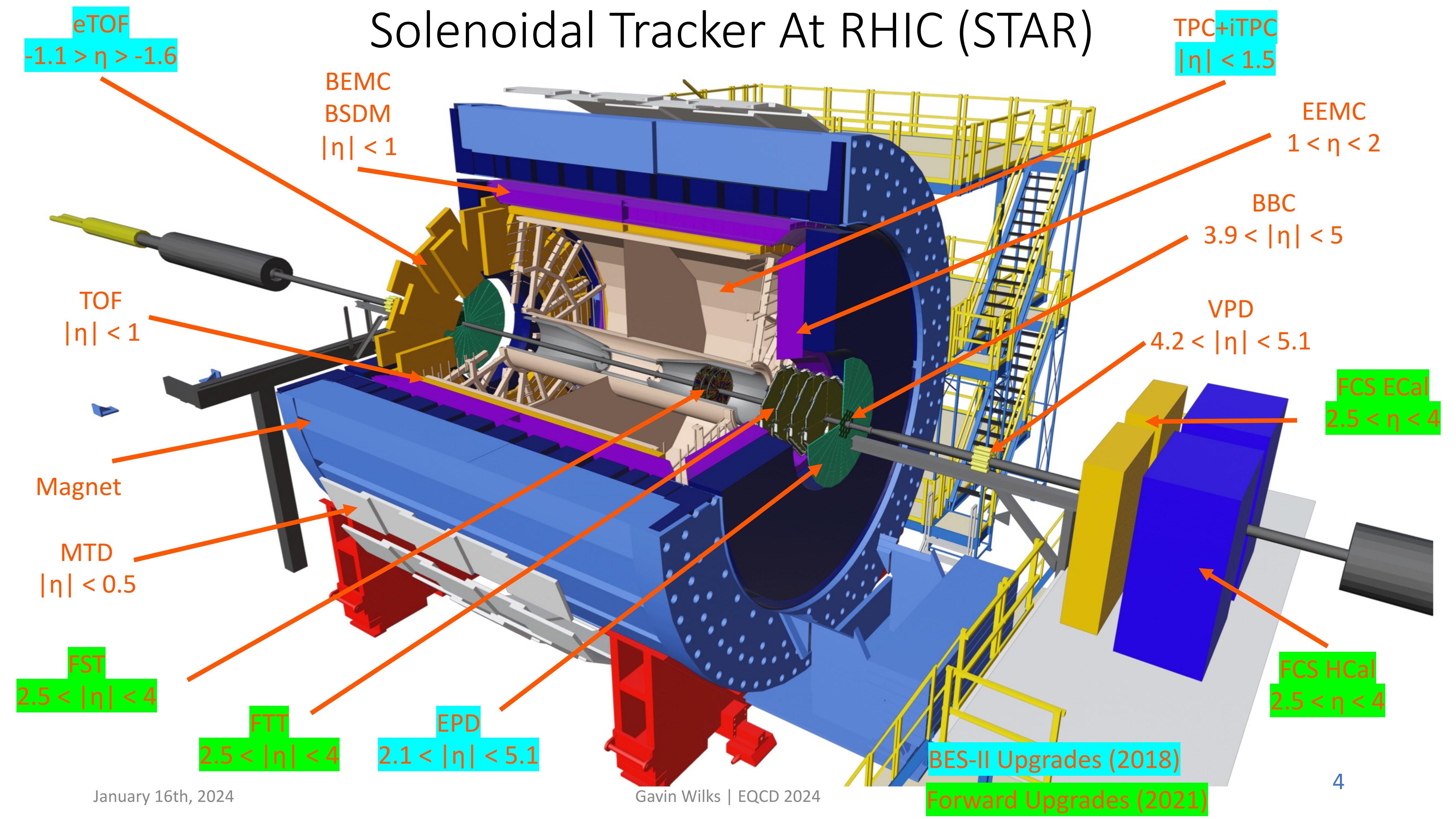


System Size Dependence



Proton Spin

Solenoidal Tracker At RHIC (STAR)



Outline

Probing the QCD phase diagram.

- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

Properties of partonic and high μ_B matter.

- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

- STAR Forward Upgrade.

Outline

Probing the QCD phase diagram.

- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

Properties of partonic and high μ_B matter.

- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

- STAR Forward Upgrade.

Cumulants

Cumulant ratios remove volume dependence

$$\frac{C_5}{C_1} \propto \frac{\chi_5}{\chi_1}$$

$$\frac{C_6}{C_2} \propto \frac{\chi_6}{\chi_2}$$

$$C_1 = \langle N \rangle$$
$$C_2 = \langle (\delta N)^2 \rangle$$
$$C_3 = \langle (\delta N)^3 \rangle$$

N: Net-proton multiplicity

C_n: n^{th} order cumulant

$\delta N = N - \langle N \rangle$

$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$
$$C_5 = \langle (\delta N)^5 \rangle - 10\langle (\delta N)^3 \rangle \langle (\delta N)^2 \rangle$$
$$C_6 = \langle (\delta N)^6 \rangle - 15\langle (\delta N)^4 \rangle \langle (\delta N)^2 \rangle - 10\langle (\delta N)^3 \rangle^2 + 30\langle (\delta N)^2 \rangle^3$$

- Cumulant ratios are related to the susceptibilities.
- Higher order cumulants are increasingly sensitive to the nature of the QCD phase transition.

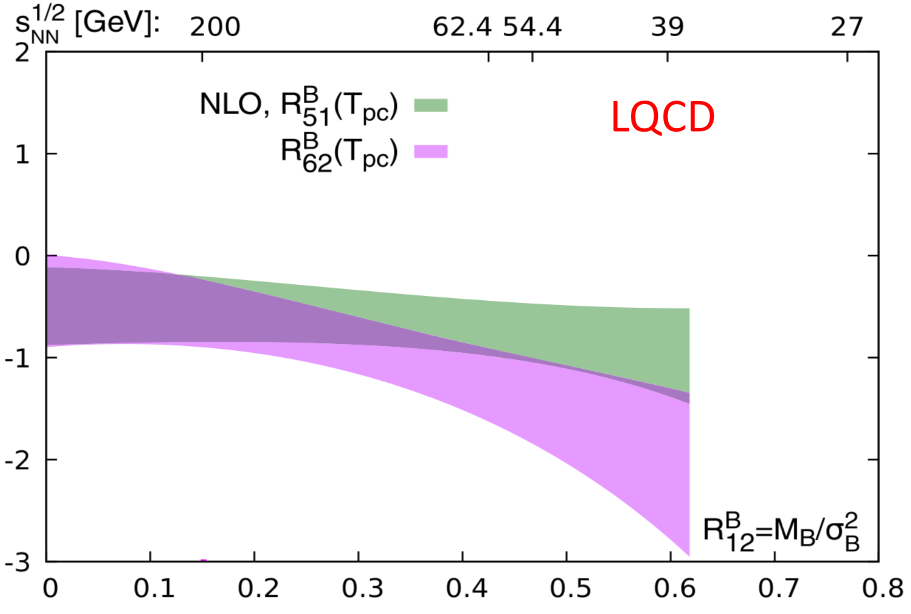
Cumulants and Crossover Phase Transition

STAR

C_5/C_1 and C_6/C_2

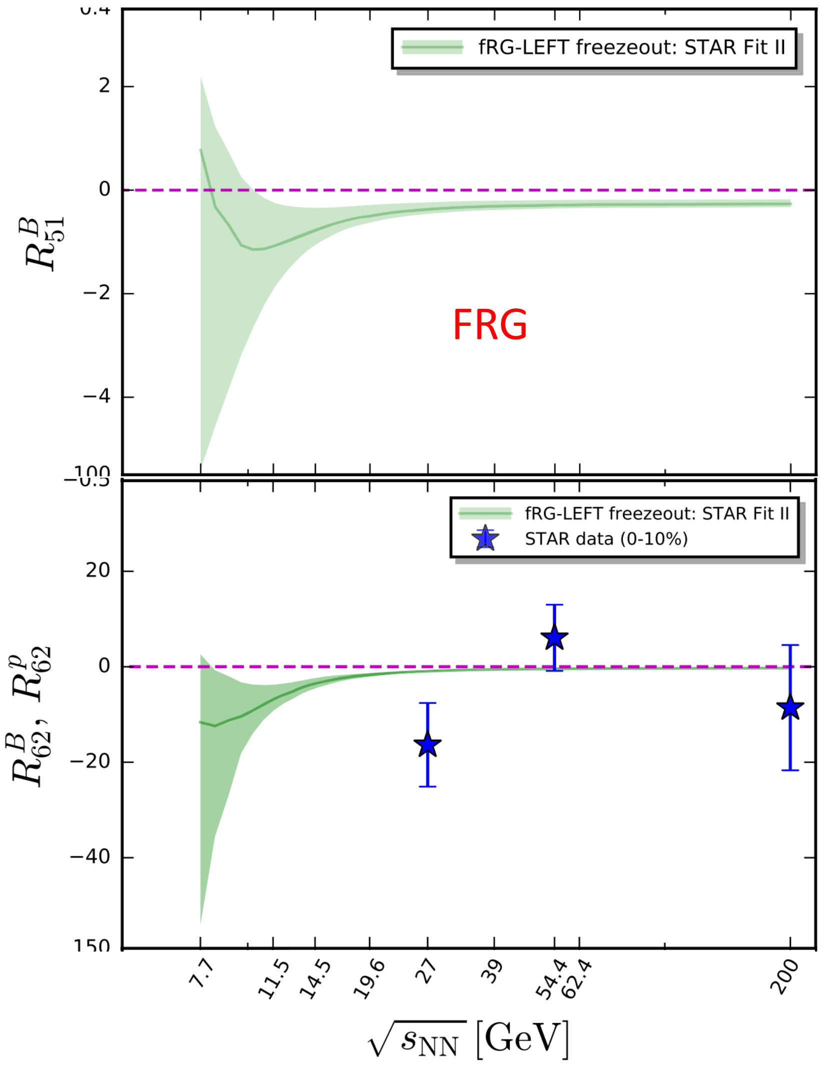
LQCD, FRG predict: $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$

- **Positive** for HRG and UrQMD
  - no QCD transition
- **Negative** for LQCD and FRG (Functional Renormalization Group)
  - Includes crossover phase transition.



HotQCD, PRD 101, 074502 (2020)

$$R_{62} = C_6/C_2$$
$$R_{51} = C_5/C_1$$



W. Fu et. al., PRD 104, 094047 (2021)

Cumulant Ratios [BES-I, FXT]

0-40% Centrality

C_4/C_2: Positive for all energies

C_5/C_1: Weak dependence on energy except for large positive value at 3 GeV.

C_6/C_2:

- 7.7-200 GeV: Increasingly negative with decreasing energy – consistent with calculations that include a cross-over transition.
- 3 GeV is positive and agrees with UrQMD.

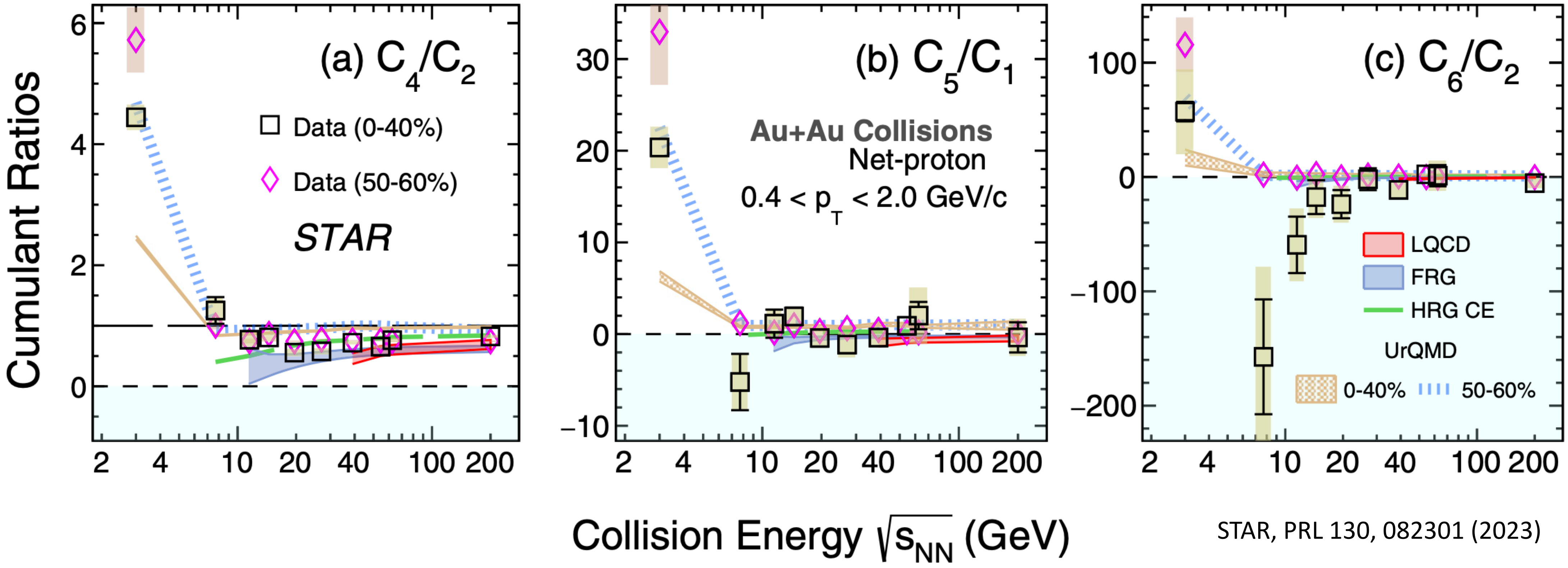
50-60% Centrality

C_4/C_2: Positive for all energies

C_5/C_1: Positive/zero for all energies

C_6/C_2: Positive/zero for all energies

- No phase transition indicated.



STAR, PRL 130, 082301 (2023)

Outline

Probing the QCD phase diagram.

- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

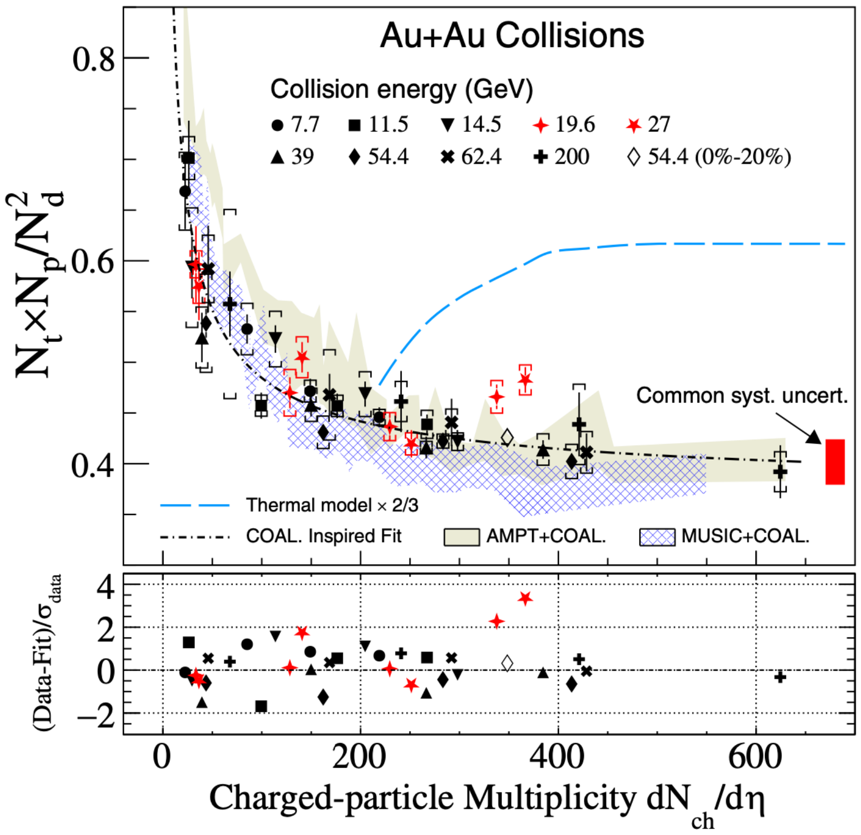
Properties of partonic and high μ_B matter.

- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

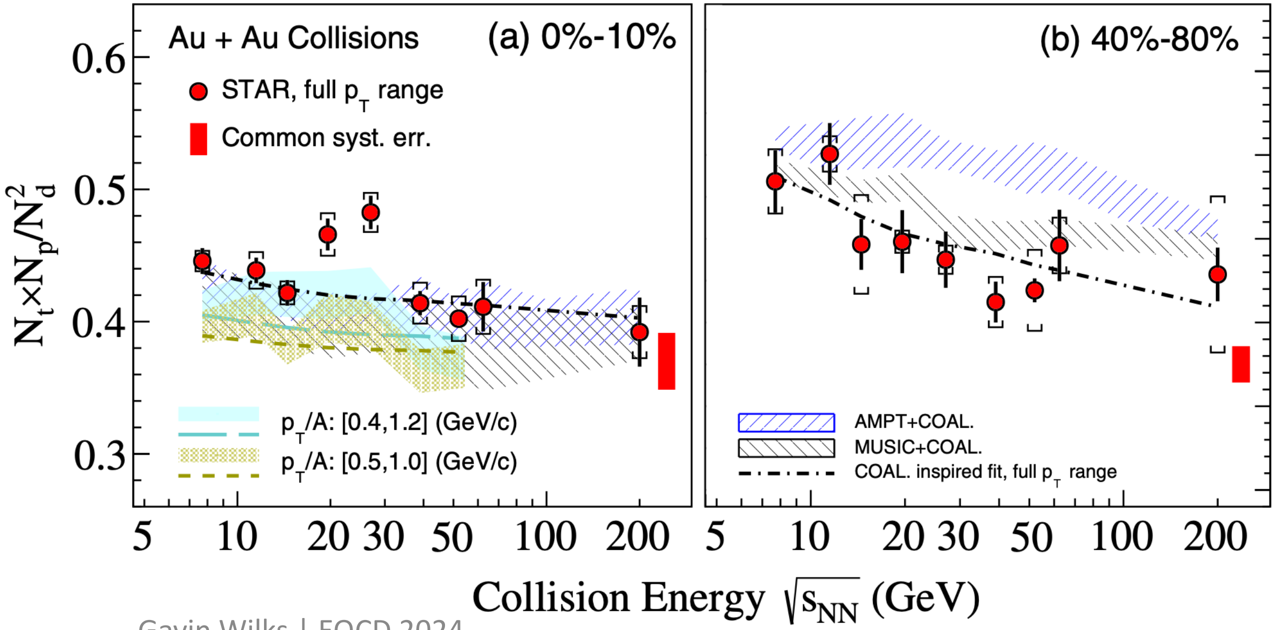
- STAR Forward Upgrade.

Light nuclei yield ratios [BES-I]

STAR, PRL 130, 202301 (2023)



- Coalescence (COAL.) model: light nuclei are formed by the coalescence of protons and neutrons in late stages of heavy-ion collisions.
  - $N_t{\times}N_p/N_d^2$ is sensitive to neutron density fluctuations.
  - Promising observable to search for first-order phase transition / CP.
- 19.6 & 27 GeV enhancement due to large baryon density fluctuations near CP?



Data shows monotonic decrease with increasing N_{ch}

- Consistency with COAL. model.

Outline

Probing the QCD phase diagram.

- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

Properties of partonic and high μ_B matter.

- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

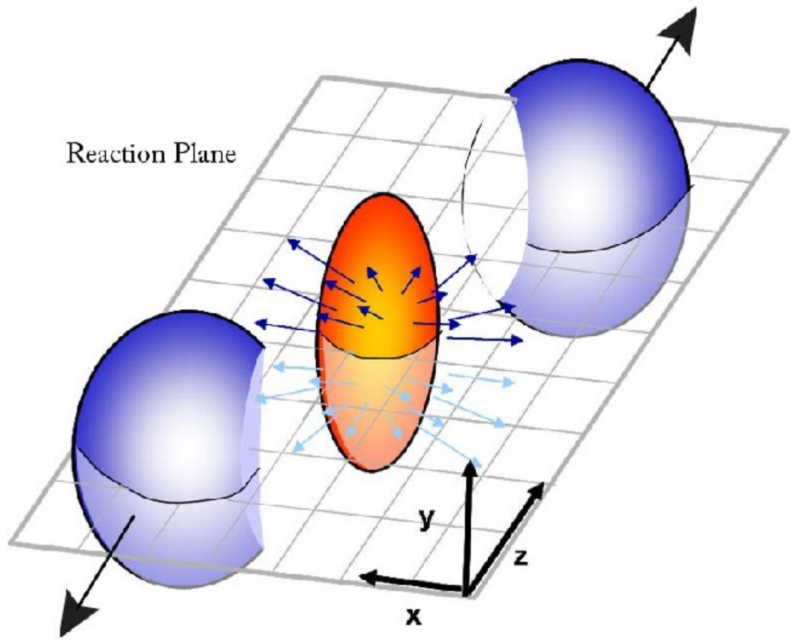
- STAR Forward Upgrade.

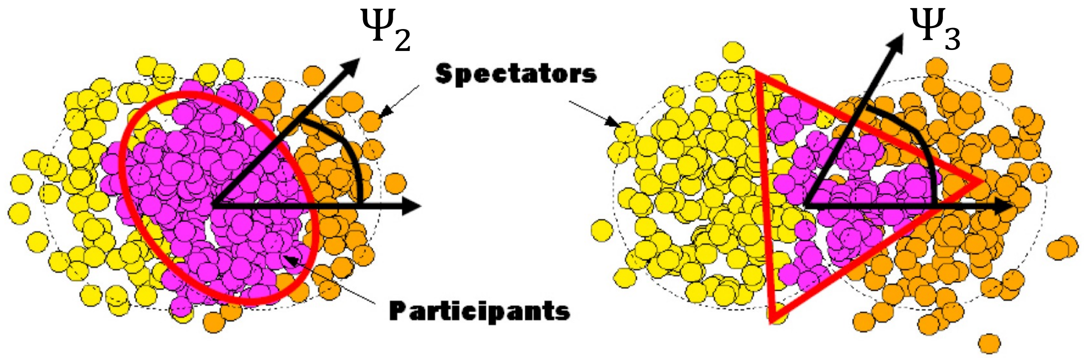
Event Plane and Anisotropic Flow

- We can use Fourier analysis to describe the azimuthal particle distribution.

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos\big(n(\varphi - \Psi_n)\big)$$

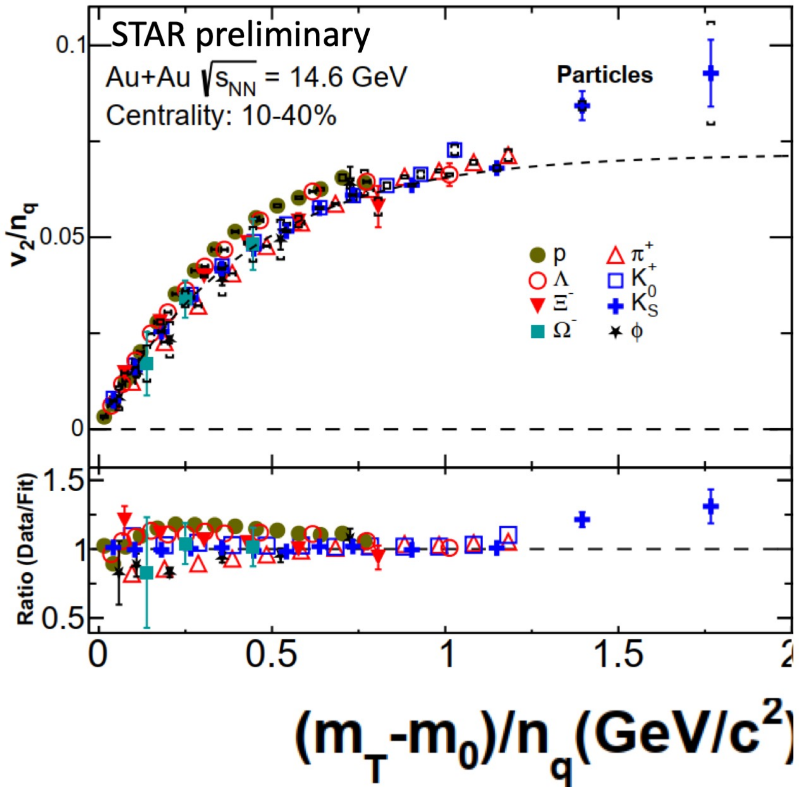
- Ψ_n characterizes the nth order event plane.
- v_n characterizes the nth order anisotropic flow of the QGP.
  - v_2, elliptic flow, particle yields are higher along 1 **axis** in azimuthal distribution.
  - v_3, triangular fow, particle yields are higher along 3 **directions** with equal angular separation in azimuthal distribution.
- v_n coefficients can be compared to hydrodynamic models.
  - QGP behaves as a near perfect liquid.



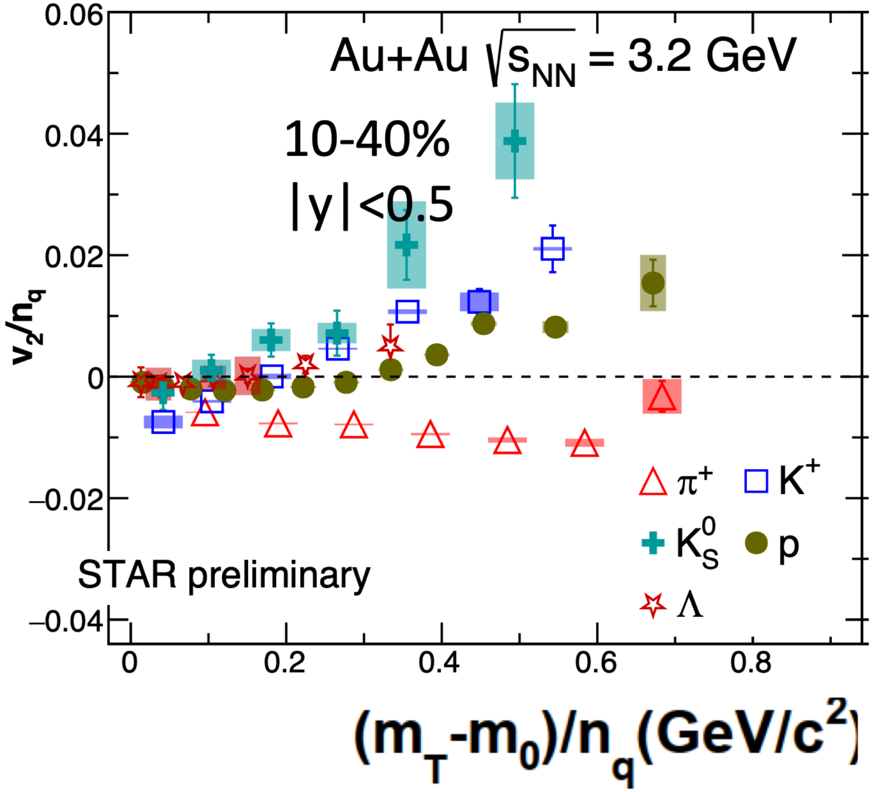


NCQ scaling of elliptic flow [BES-II, FXT]

$\sqrt{s_{NN}} = 14.6$ GeV



$\sqrt{s_{NN}} = 3.2$ GeV



- NCQ scaling of v_2 is seen at $\sqrt{s_{NN}} \geq 14.6$ GeV.
  - Scaling is violated at 3.2 GeV.
  - Consistent with a disappearance of partonic collectivity.

Outline

Probing the QCD phase diagram.

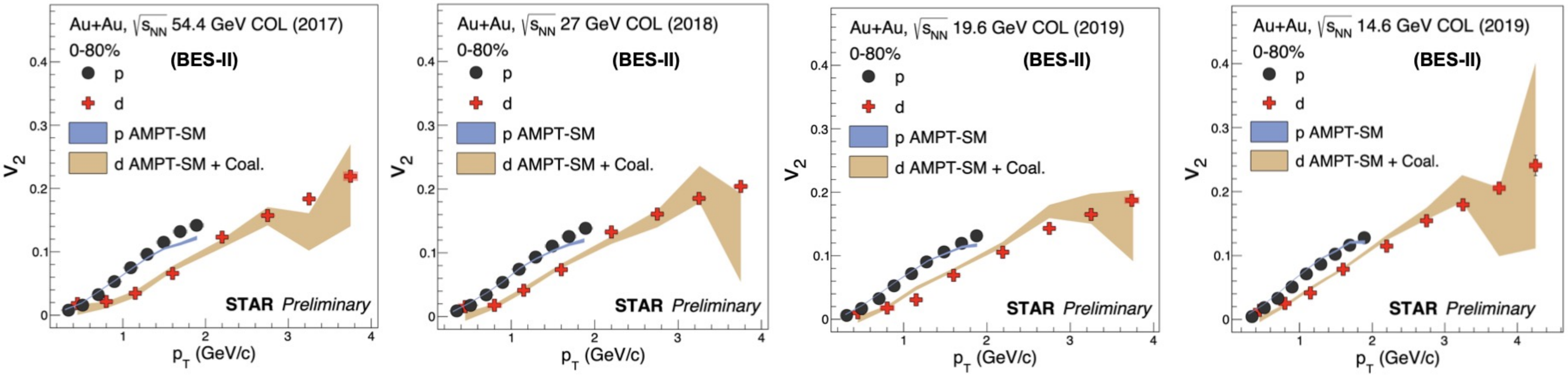
- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

Properties of partonic and high μ_B matter.

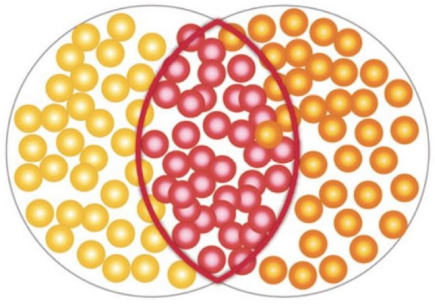
- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

- STAR Forward Upgrade.

Light nuclei elliptic flow (v_2) [BES-II]



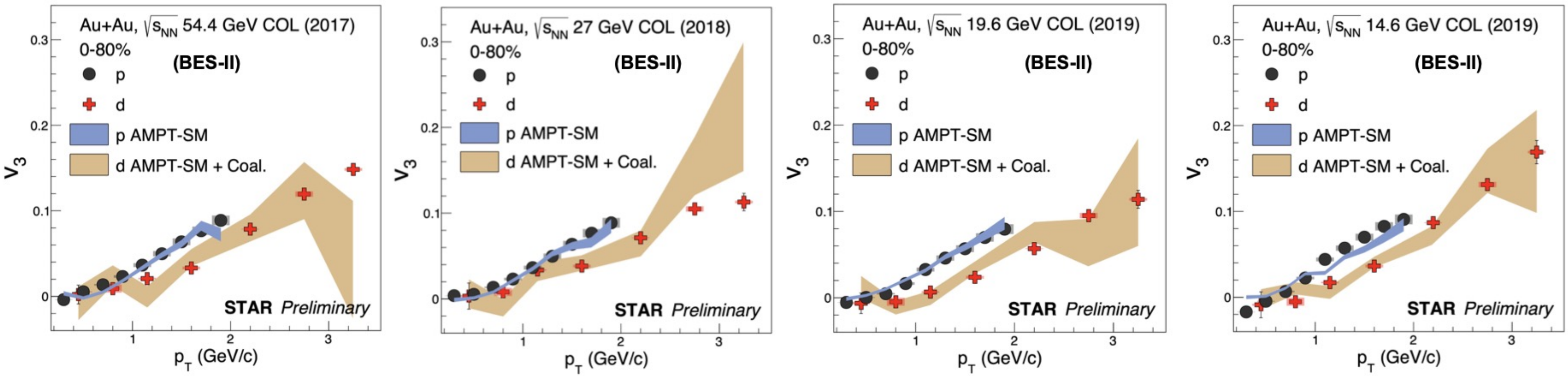
- In BES-II, we observe 20-30% deviation of light nuclei v_2 from mass number scaling, the naïve expectation from coalescence production.
    - Consistent with ALICE measurements in PRC 102, 055203 (2020).
- AMPT+Coal. well describes the v_2 of *d*.



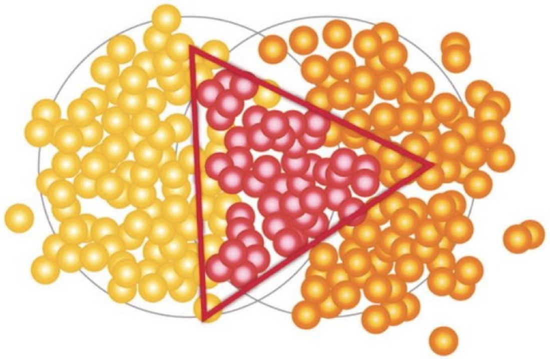
Elliptic flow

PRC 72, 064901 (2005) Nucl. Phys. A 729 (2003) 809–834
Proton v_2: Phys. Rev. C 93, 014907 (2016); Phys. Rev. C 88, 014902 (2013); Phys. Lett. B 827, 137003 (2022)

Light nuclei triangular flow (v_3) [BES-II]



- v_3 of *d* shows agreement with mass number scaling.
  - Consistent with ALICE measurements in PRC 102, 055203 (2020).
- AMPT+Coal. well describes the v_3 of *d*.



Triangular flow

PRC 72, 064901 (2005) Nucl. Phys. A 729 (2003) 809–834

Proton v_2: Phys. Rev. C 93, 014907 (2016); Phys. Rev. C 88, 014902 (2013); Phys. Lett. B 827, 137003 (2022)

Outline

Probing the QCD phase diagram.

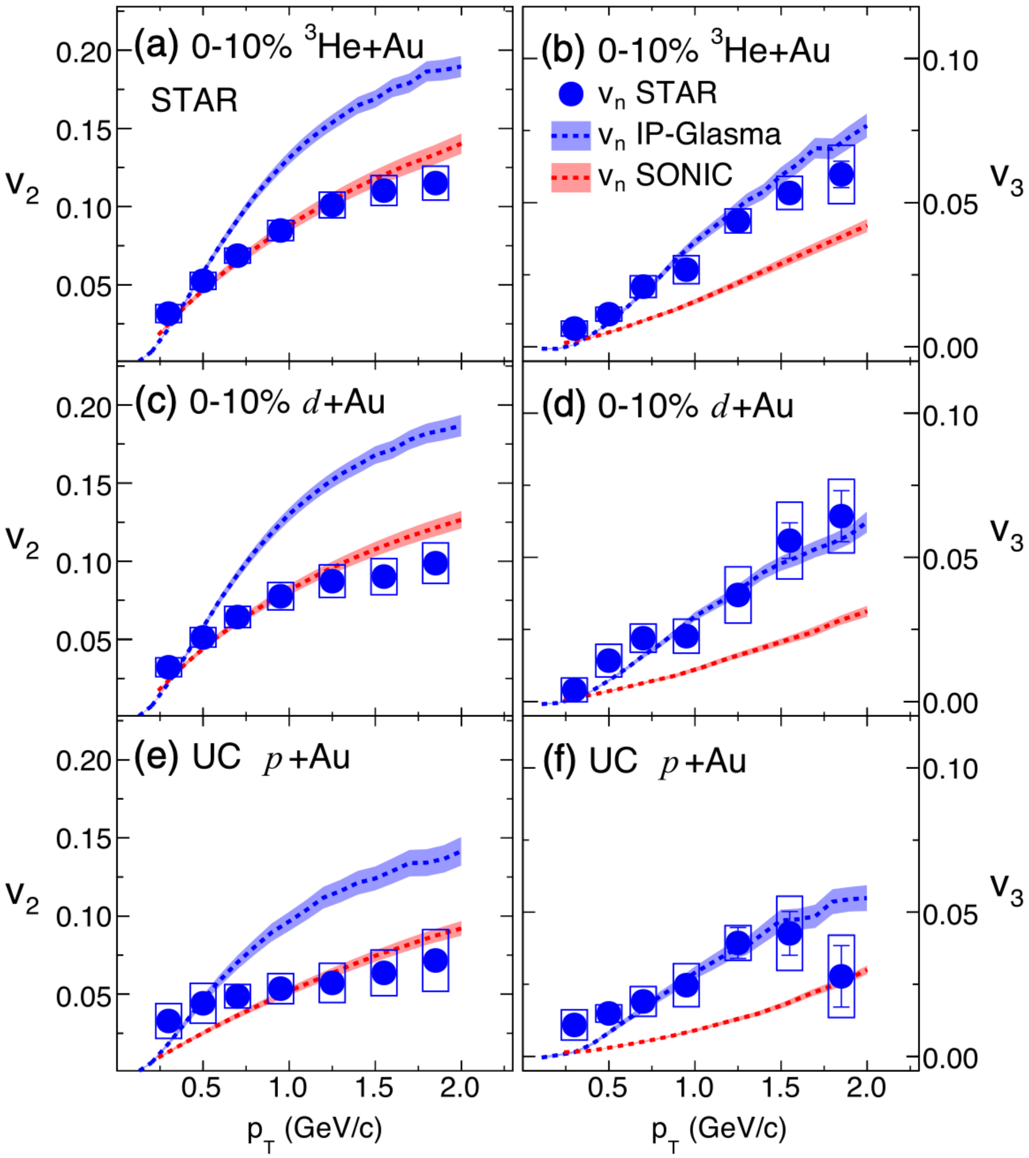
- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

Properties of partonic and high μ_B matter.

- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

- STAR Forward Upgrade.

Anisotropies in highly asymmetric collisions



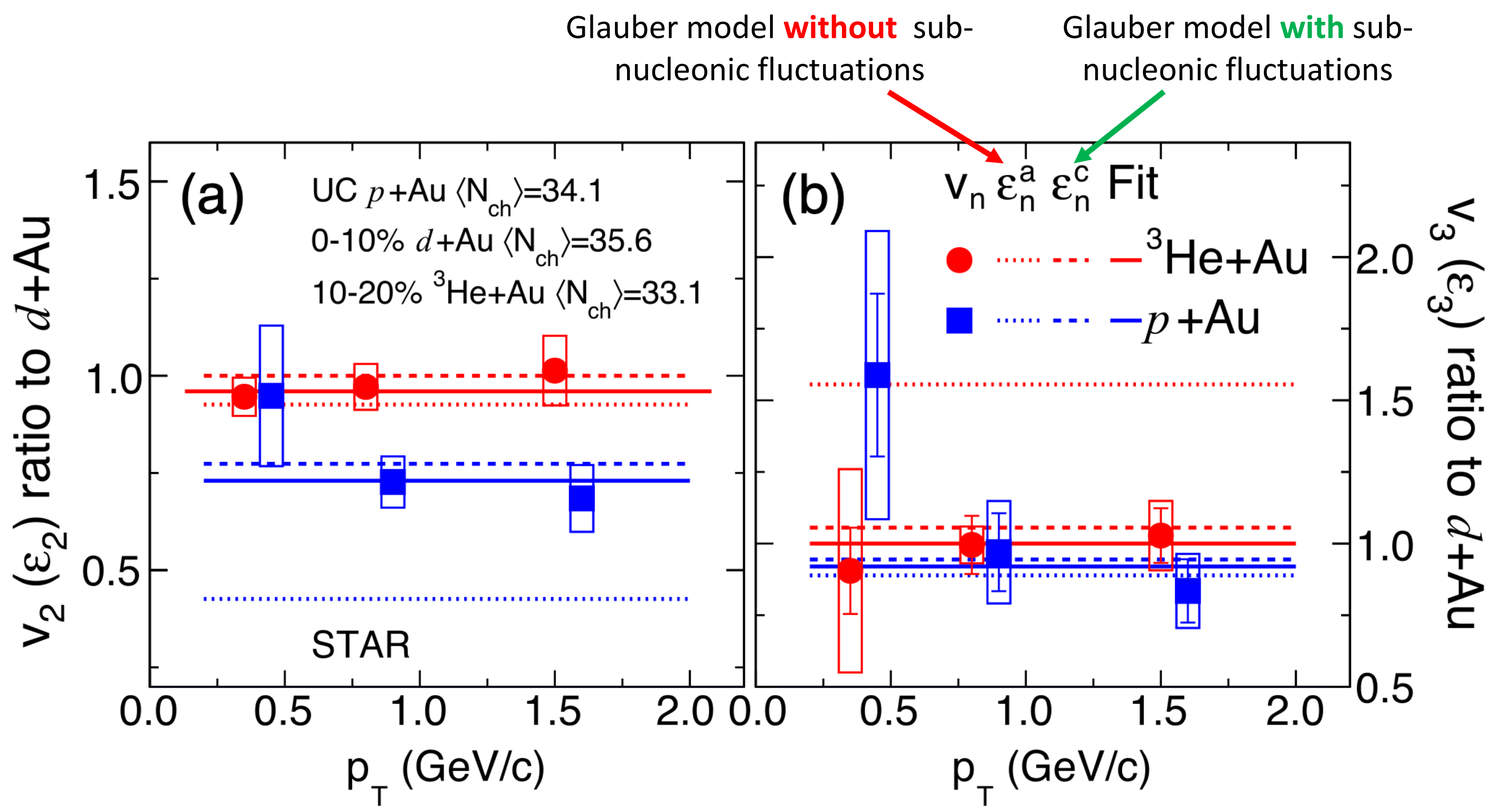
STAR, PRL 130, 242301 (2023)

- Eccentricities from two particle correlations $\varepsilon_2\{2\}$ and $\varepsilon_3\{2\}$ are related to $v_2\{2\}$ and $v_3\{2\}$, respectively.
  - Provide model constraint on the specific shear viscosity in large- to moderate-sized systems.
  - Sub-nucleonic fluctuations. (inhomogeneous gluon field)

Hydrodynamic Models

- SONIC:
  - No sub-nucleonic fluctuations.
  - Succeeds(Fails) in describing $v_2(v_3)\{2\}$.
- IP-Glasma+MUSIC:
  - Includes sub-nucleonic fluctuations.
  - Succeeds(Fails) in describing $v_3(v_2)\{2\}$.

Anisotropies in highly asymmetric collisions

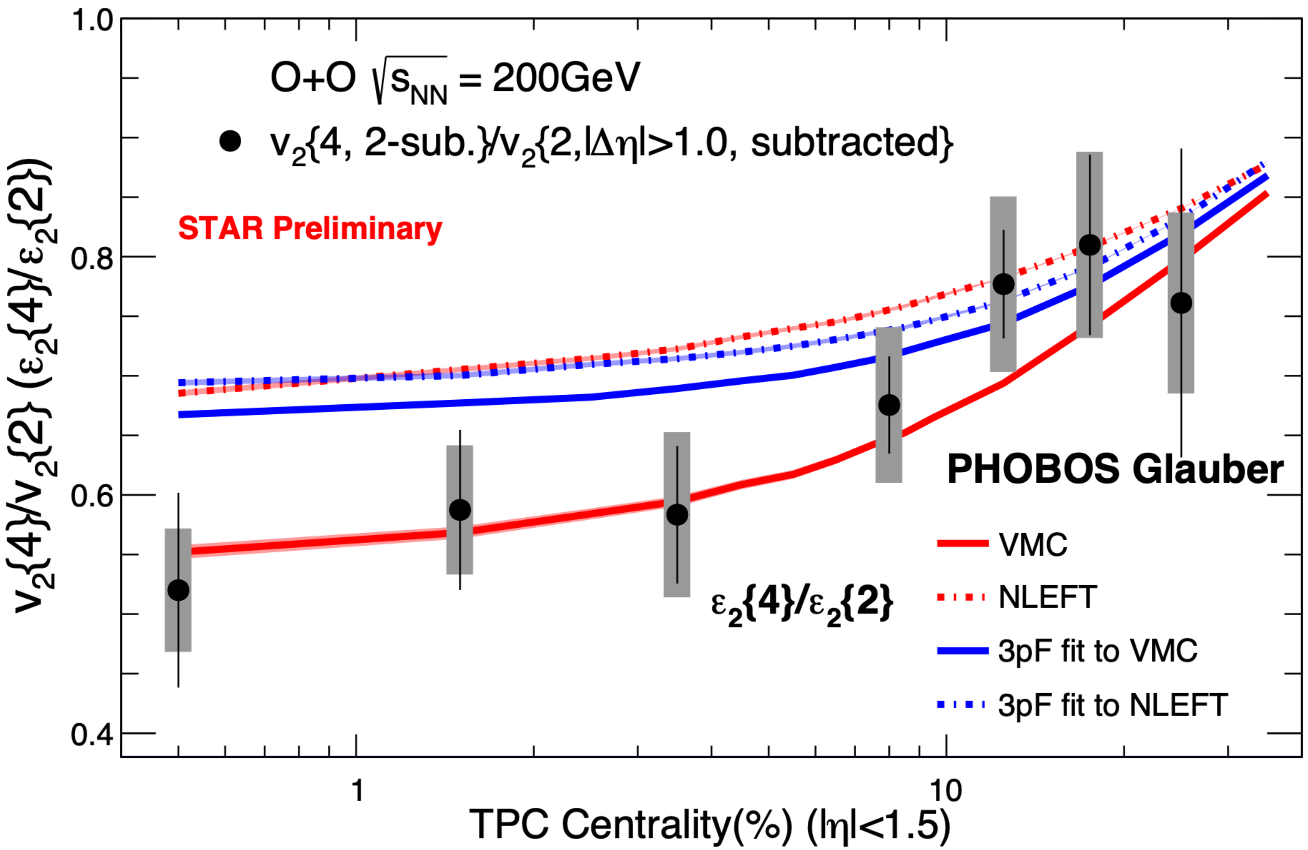


- Measurements are consistent with a significant influence from sub-nucleonic eccentricity fluctuations.

STAR, PRL 130, 242301 (2023)

Anisotropies in small symmetric collisions

- The eccentricity ratio from 4- to 2-particle correlations, $\varepsilon_2\{4\}/\varepsilon_2\{2\}$, give insight to initial geometry fluctuations.
- $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from VMC matches data well, suggesting that $v_2\{4\}/v_2\{2\}$ can serve as a useful tool in studying nucleon-nucleon correlations in light nuclei collisions.



Phobos Glauber: Alver et al., arXiv:0805.4411 [nucl-ex] (2008)
VMC: Gezerlis et al., PRL 111, 032501 (2013)
NLEFT: Elhatisari et al., PRL 119, 222505 (2017)

Outline

Probing the QCD phase diagram.

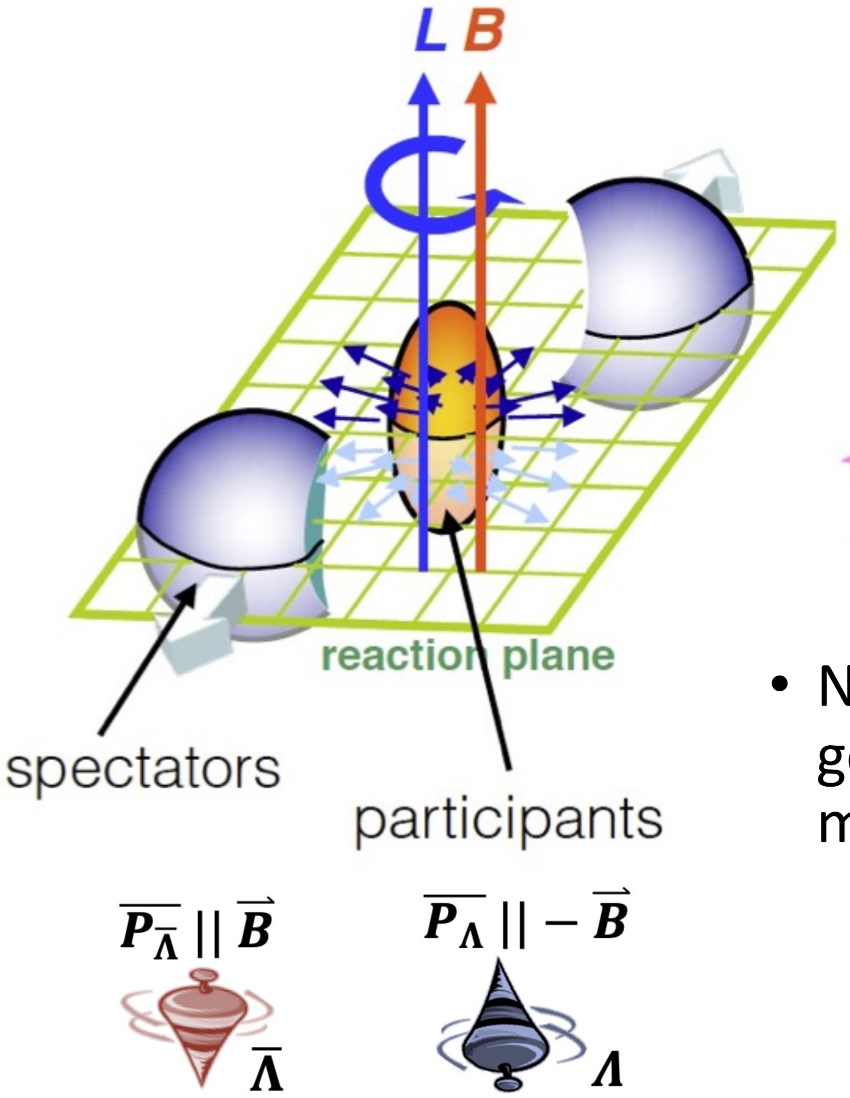
- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

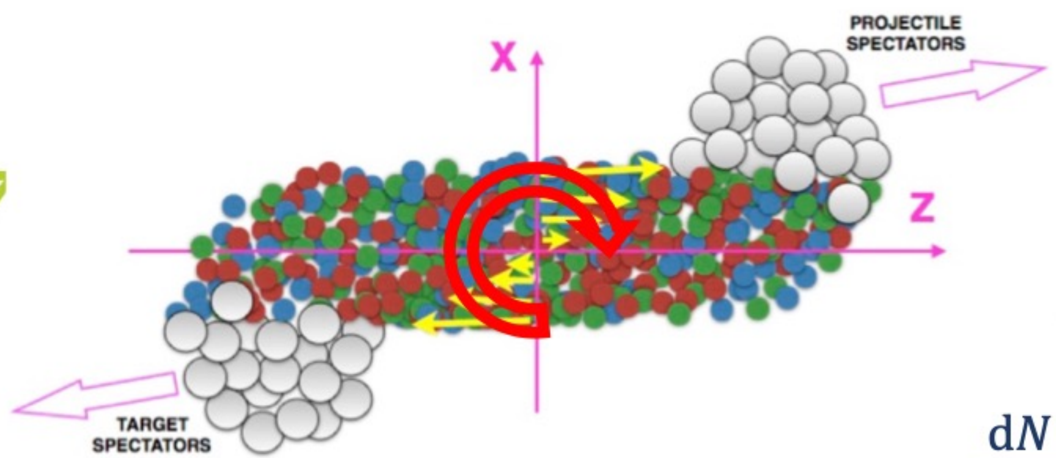
Properties of partonic and high μ_B matter.

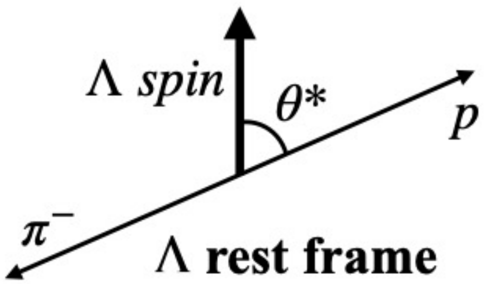
- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

- STAR Forward Upgrade.

Hyperon Polarization







$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_\Lambda P_\Lambda cos\theta^*)$$

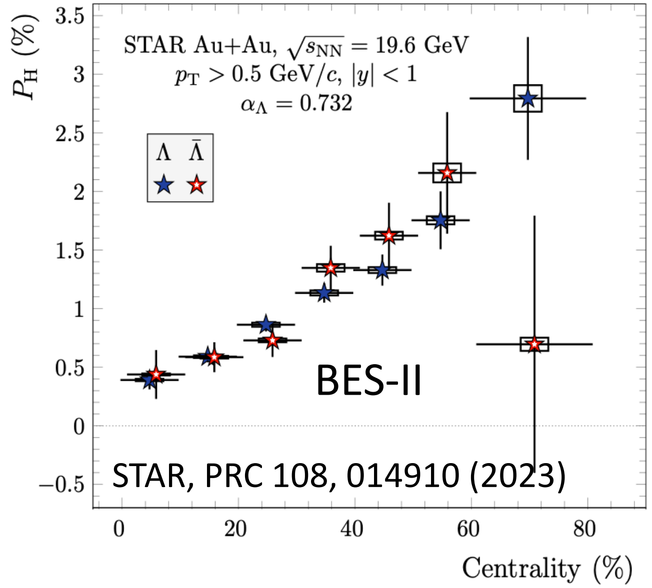
$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{1}{A_0}\frac{\langle \sin(\Psi_1 - \phi_p^*)\rangle}{Res(\Psi_1)}$$

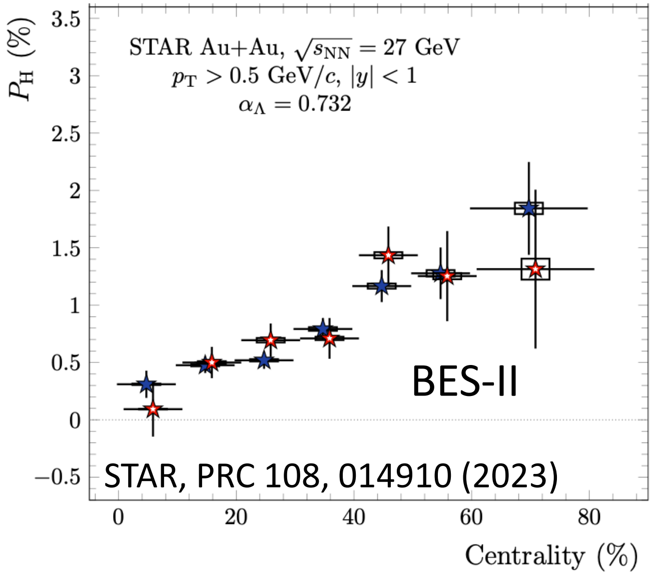
$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$
A_0: Acceptance correction factor
Ψ_1: First-order event plane angle
$Res(\Psi_1)$: Event plane resolution

- Non-central heavy-ion collisions generate large orbital angular momentum (OAM).
  - Leads to global polarization.

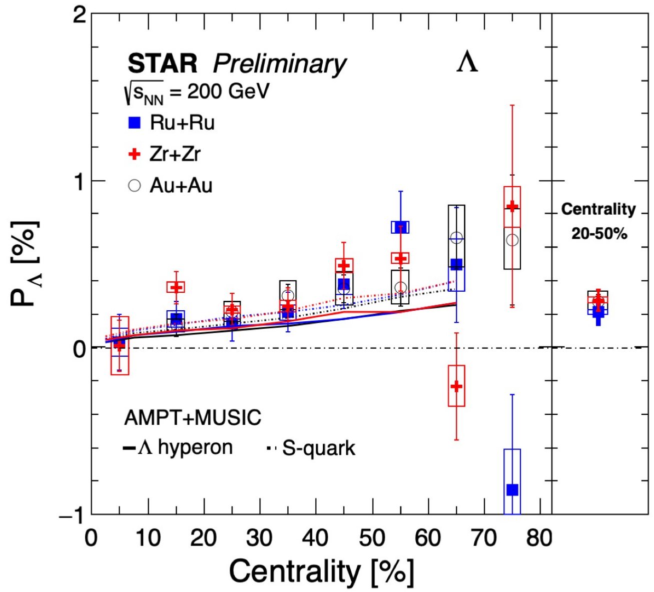
Liang et al., PLB 629, 20–26 (2005).

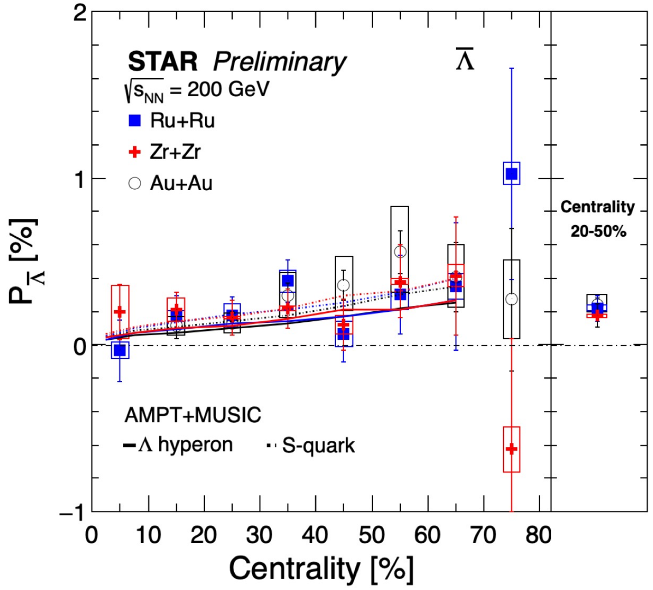
Global Λ Polarization (Centrality) [BES-I, BES-II]





- Significant centrality dependence of global polarization observed.
- BES-II and BES-I are consistent.
  - BES-II with 10x more statistics.

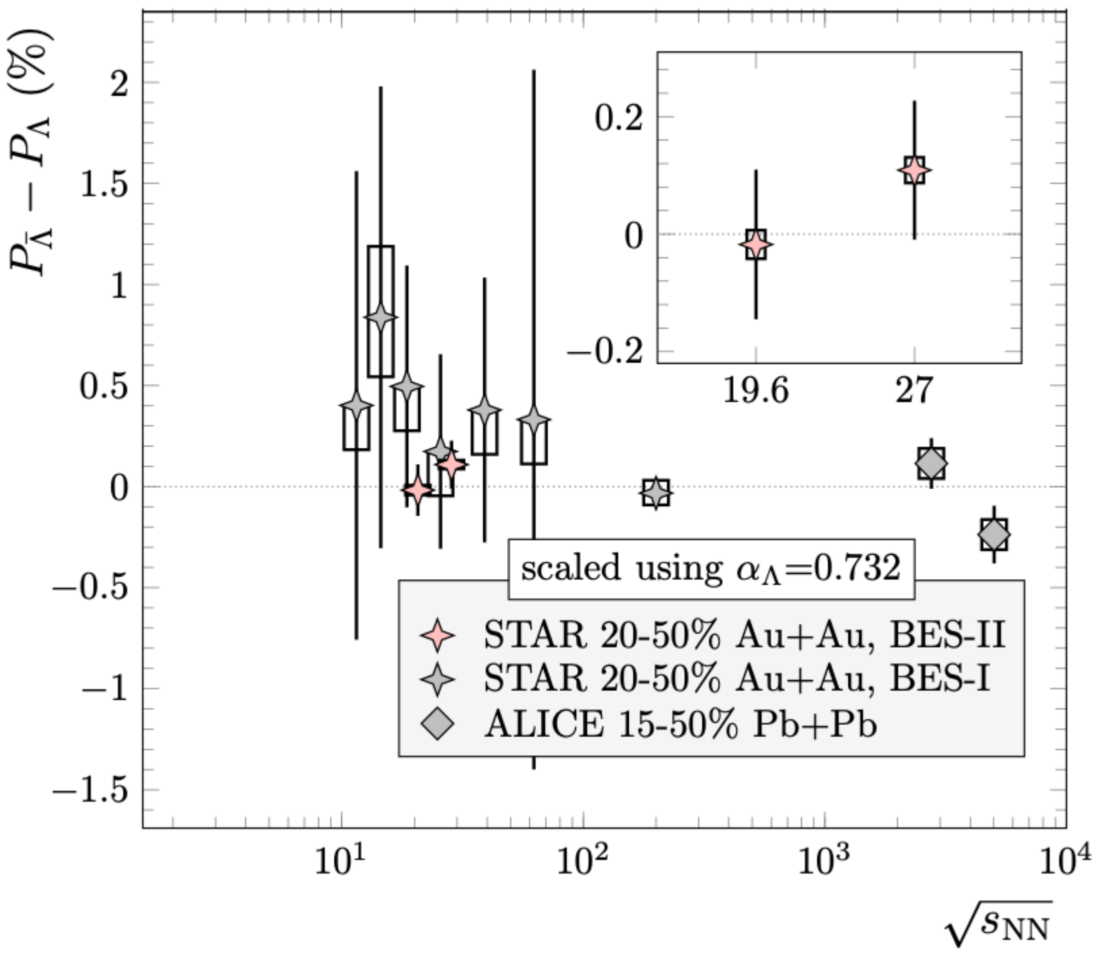




- Global polarization of Λ and $\bar{\Lambda}$ are consistent in isobar and Au+Au collisions.
  - There are no magnetic field driven effects on Λ polarization observed within current statistical precision.

Model results from B. Fu et al., arXiv:2201.12970

Global Λ Polarization ($\sqrt{s_{NN}}$) [BES-I, BES-II]



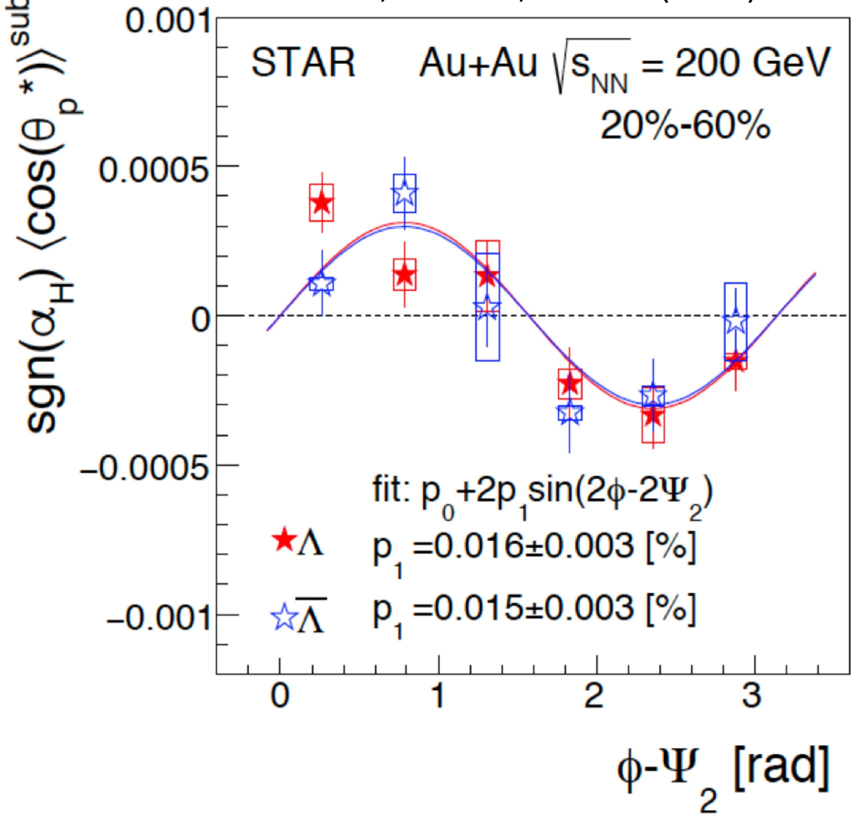
STAR, PRC 108, 014910 (2023)

Au+Au	19.6 GeV	27 GeV
$P_{\bar{\Lambda}} - P_{\Lambda}$ (%)	-0.018 $\pm 0.127(stat.)$ $\pm 0.024(sys.)$	0.109 $\pm 0.118(stat.)$ $\pm 0.022(sys.)$

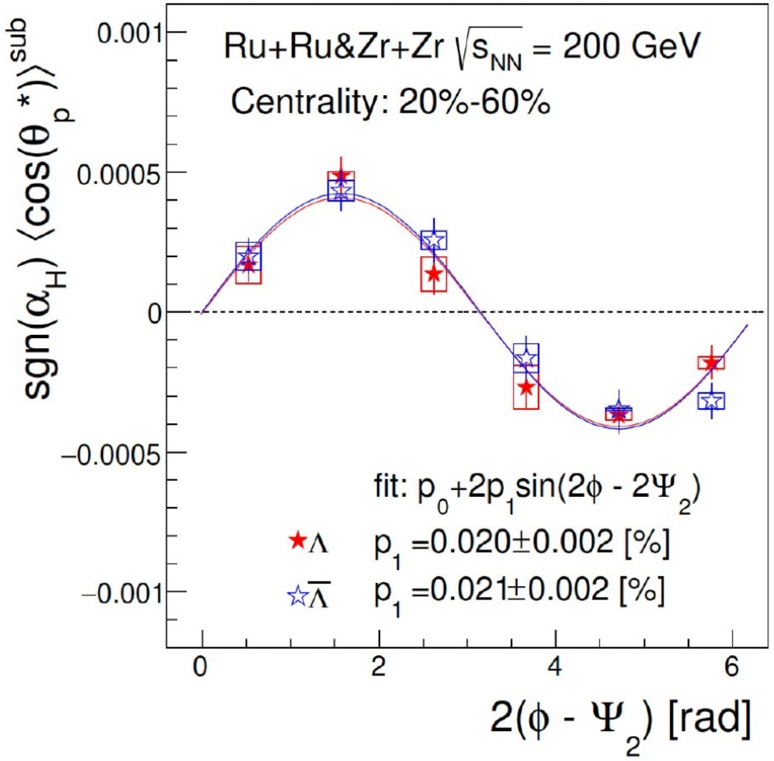
- No significant splitting of $\Lambda/\bar{\Lambda}$ observed.
- Upper limit on late-stage magnetic field:
  - 19.6 GeV: B < 9.5 x 10^{12} T (95%)
  - 27 GeV: B < 1.4 x 10^{13} T (95%)

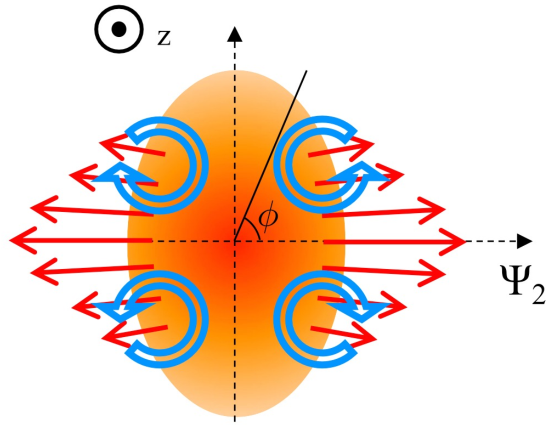
Local Λ Polarization (Ψ_2)

STAR, PRL 123, 132301 (2019)

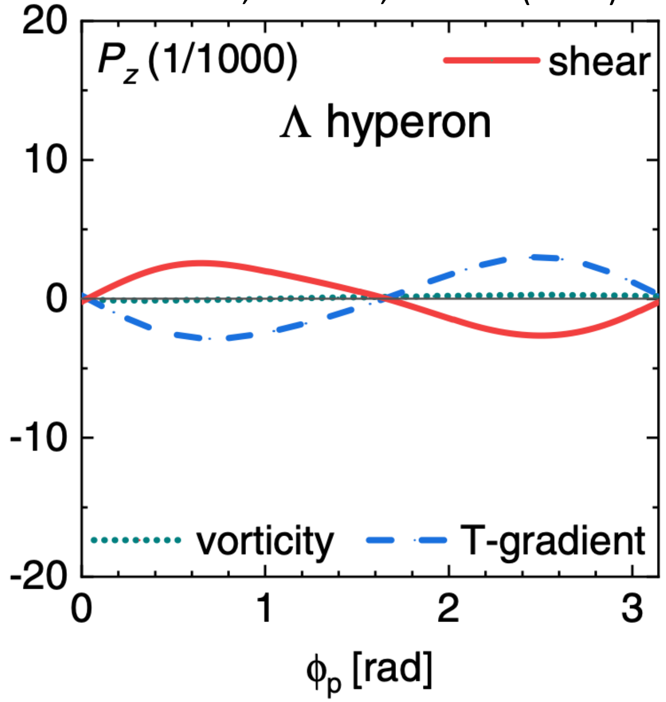


STAR, PRL 131, 202301 (2023)





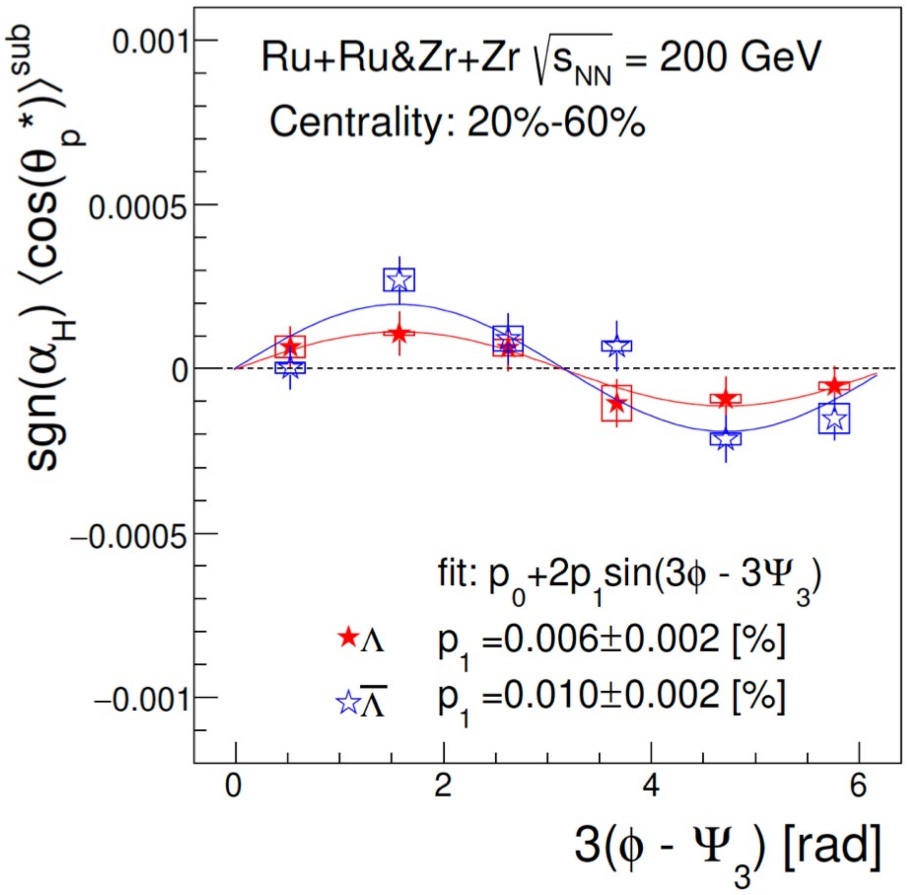
B. Fu et al., PRL 127, 142301 (2021)

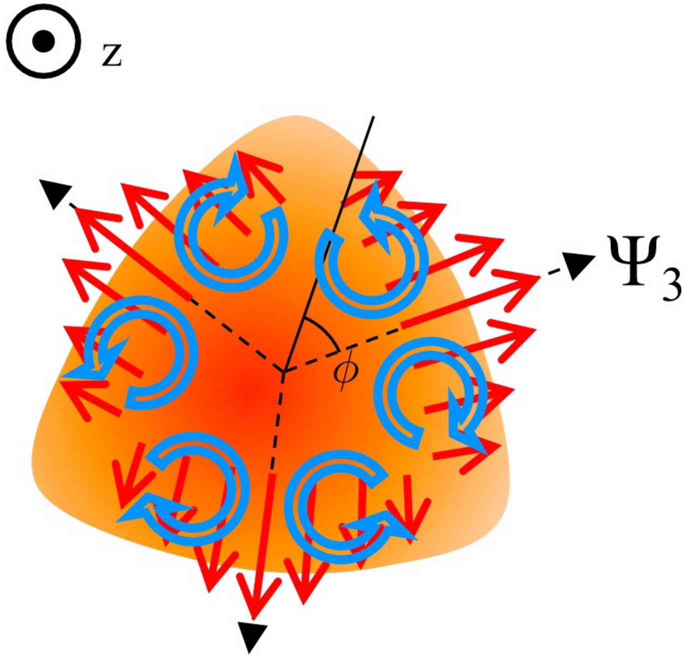


- Shear contributions from vorticity generated by elliptic flow can accommodate the current data.
- Consistent for Au+Au and isobar collisions at mid-centrality.
  - No system size dependence.

Local Λ Polarization (Ψ_3)

STAR, PRL 131, 202301 (2023)





- Shear contributions from vorticity generated by triangular flow can accommodate the current data.
- First observation of local polarization with respect to 3rd order event plane.

Outline

Probing the QCD phase diagram.

- 5^{th} and 6^{th} order net-proton cumulants. (BES-I)
- Triton production and yield ratios. (BES-I, FXT)

Properties of partonic and high μ_B matter.

- Probing the nuclear matter equation of state and partonic collectivity.
  - NCQ scaling violation of elliptic flow. (BES-II, FXT)
- Light nuclei production mechanism.
  - Elliptic and triangular flow of light nuclei. (BES-II)
- Sub-nucleon fluctuations and nuclear structure.
  - Elliptic and triangular anisotropies in central highly asymmetric collision systems.
  - Elliptic anisotropies in central small symmetric collision systems.
- Probing the vorticity and shear viscosity of QGP.
  - Hyperon polarization. (BES-I, BES-II)
  - Global spin alignment of ϕ and K^{*0} vector mesons. (BES-I, BES-II)

- STAR Forward Upgrade.

Global Spin Alignment

ρ_{00}: 00th element of the spin density matrix.

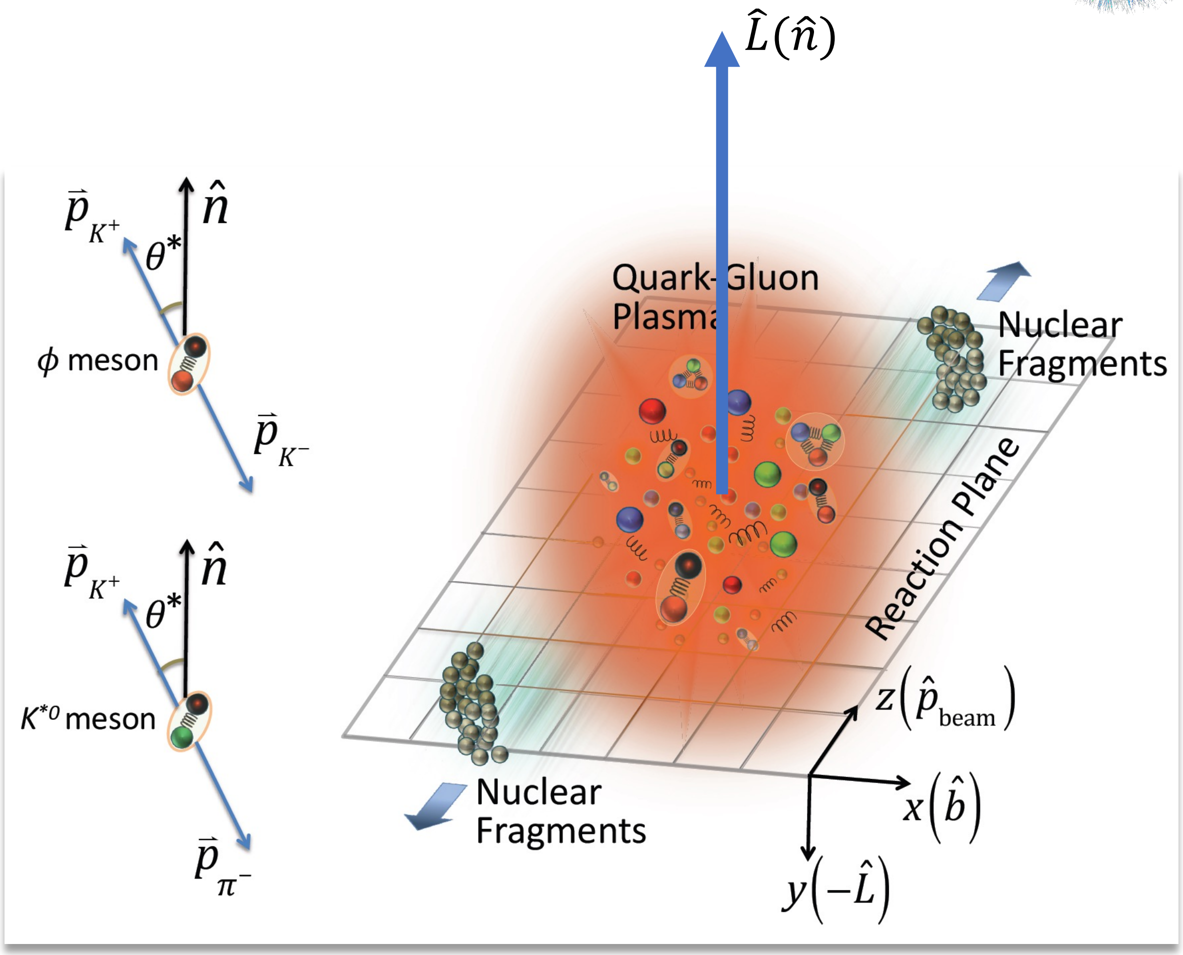
θ^*: angle between K+ daughter momentum and polarization axis in parent's rest frame.

ρ_{00} is found by fitting the parent particle's yield (N) vs cos(θ*).[1]

$$\frac{dN}{dcos\theta^*} = N_0 \times [(1 - \rho_{00}) + (3\rho_{00} - 1)cos^2\theta^*]$$

$\rho_{00} \neq 1/3$ indicates spin alignment.

- The θ^* angle is calculated with respect to the normal of the first or second order event plane, which estimate the angular momentum direction.

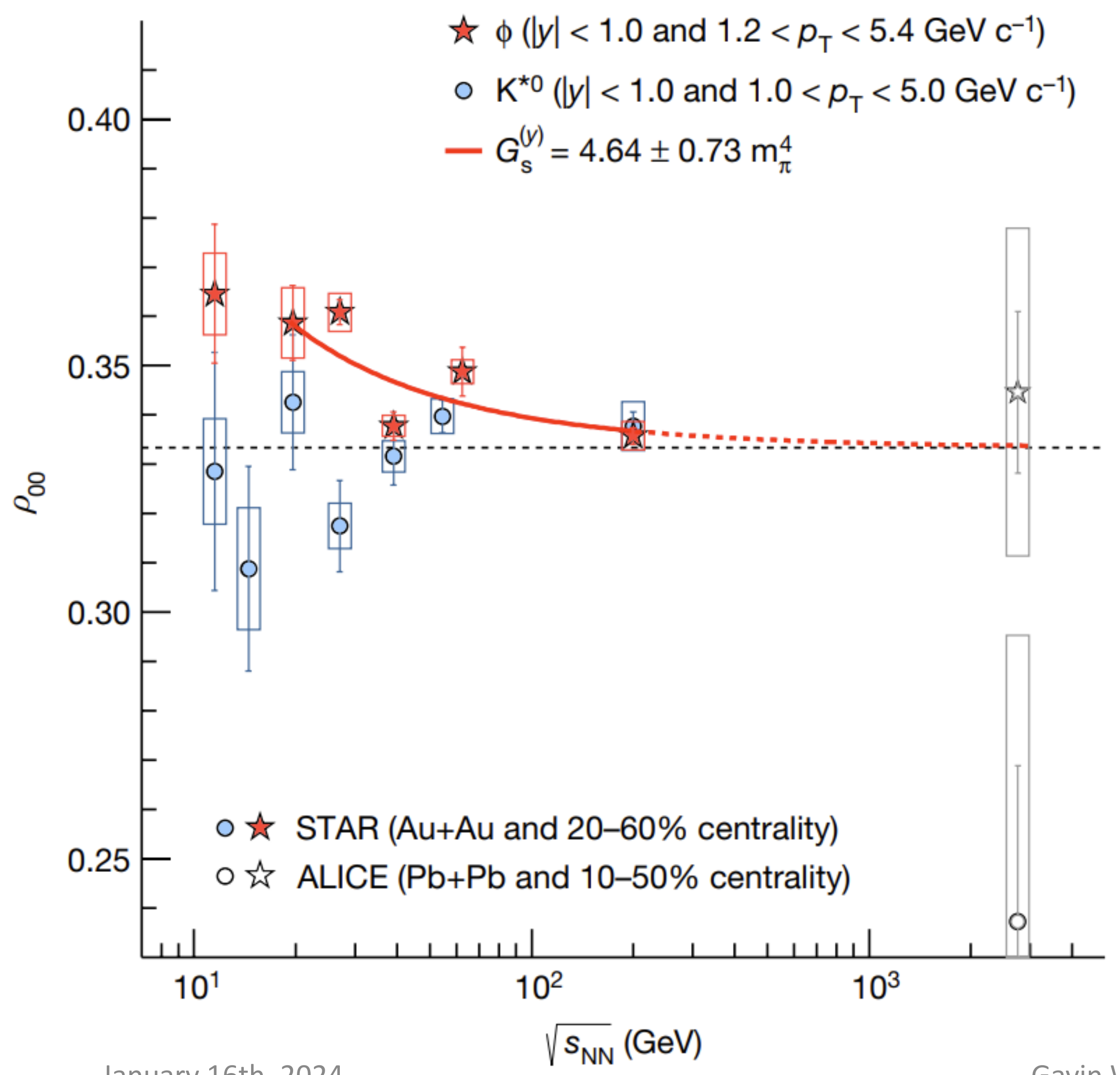


STAR, Nature 614 (2023) 7947.

[1] Schilling et al., Nucl. Phys.B 18, 332 (1970).

ρ_{00} of vector mesons [BES-I]

STAR, Nature 614 (2023) 7947.



- Significant positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured for the first time at mid-central collisions.
- ρ_{00} ~ 1/3 for K^{*0} at mid-central collisions.
  - Mean lifetime is ~10x smaller than ϕ (different in medium interactions).
  - Fluctuations in vector meson fields for d and $\bar{s}$ expected to be weaker than s and $\bar{s}$.

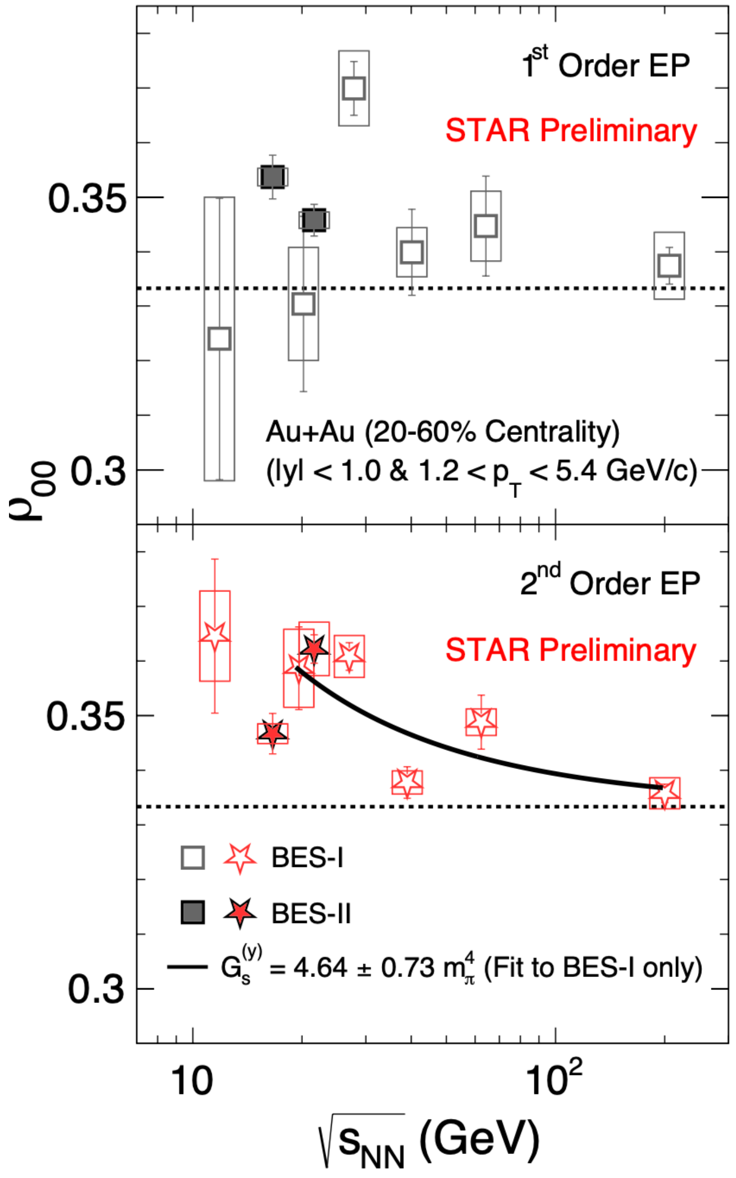
Potential Contributions to ϕ-meson ρ_{00}

Physics Mechanism	ρ_{00}	
Fragmentation of polarized quarks[1]	$\lessgtr$ 1/3	~10^{-5}
Quark coalescence Magnetic components of EM and vorticity fields[1,2,3]	< 1/3	~10^{-5}
Electric part of vorticity tensor[2]	< 1/3	~10^{-4}
Electric field[2]	> 1/3	~10^{-5}
Helicity polarization[4]	< 1/3	
Locally fluctuating axial charge currents[5]	< 1/3	
Local vorticity loop + coalescence[6]	< 1/3	
Vector meson strong force field[2,7]	> 1/3	

- Significant positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured at midcentral collisions from BES-I.[8]
- Unable to be explained by conventional polarization mechanisms.
- Supported by a theoretical model considering a ϕ-meson strong force field.
  - Couples to s and $\bar{s}$ quarks.

[1] Liang et al., PLB 629, 20–26 (2005).
[2] Sheng et al., PRD 101, 096005 (2020).
[3] Yang et al., PRC 97, 034917 (2018).
[4] Gao et al., PRD 104, 076016 (2021).
[5] Müller et al., PRD 105, L011901 (2022).
[6] Xia et al., PLB 817, 136325 (2021).
[7] Sheng et al., PRD 102, 056013 (2020).
[8] STAR, Nature 614 (2023) 7947.

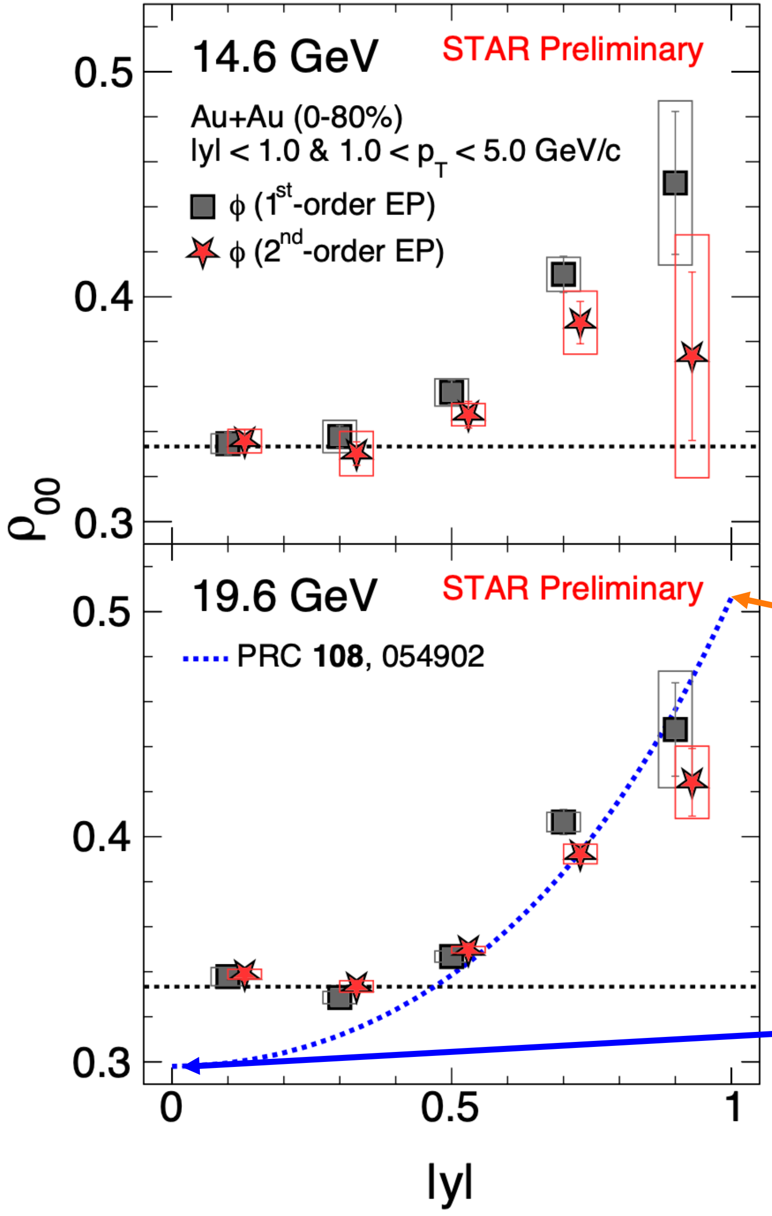
ϕ-meson $\sqrt{s_{NN}}$-dependent ρ_{00} [BES-I, BES-II]



- Significant ϕ-meson global spin alignment confirmed in 14.6 and 19.6 GeV mid-central Au+Au collisions from BES-II.
- Significant for both orders of EP.
- Consistent with BES-I at 19.6 GeV, but with higher precision.

STAR, Nature 614 (2023) 7947.
Sheng et al., PRD 101 (2020) 9, 096005.
Sheng et al., PRD 102 (2020) 5, 056013.

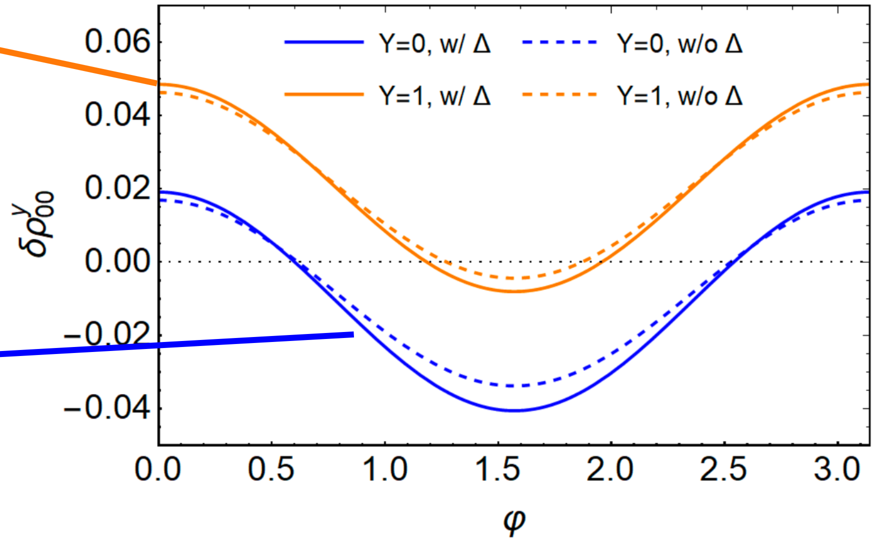
ϕ-meson rapidity-dependent ρ_{00} [BES-II]



- Anisotropy of field fluctuations leads to $\rho_{00} \neq 1/3$.
- If ϕ-meson field fluctuations are stronger along quantization axis, then $\rho_{00} > 1/3$.
- Motion of ϕ-meson in lab frame leads to increases in field fluctuations perpendicular to the motion after boosting into the ϕ-meson rest frame.
- If |y| = 0, all motion is within transverse plane and any motion in y-direction will contribute to $\rho_{00} < 1/3$.

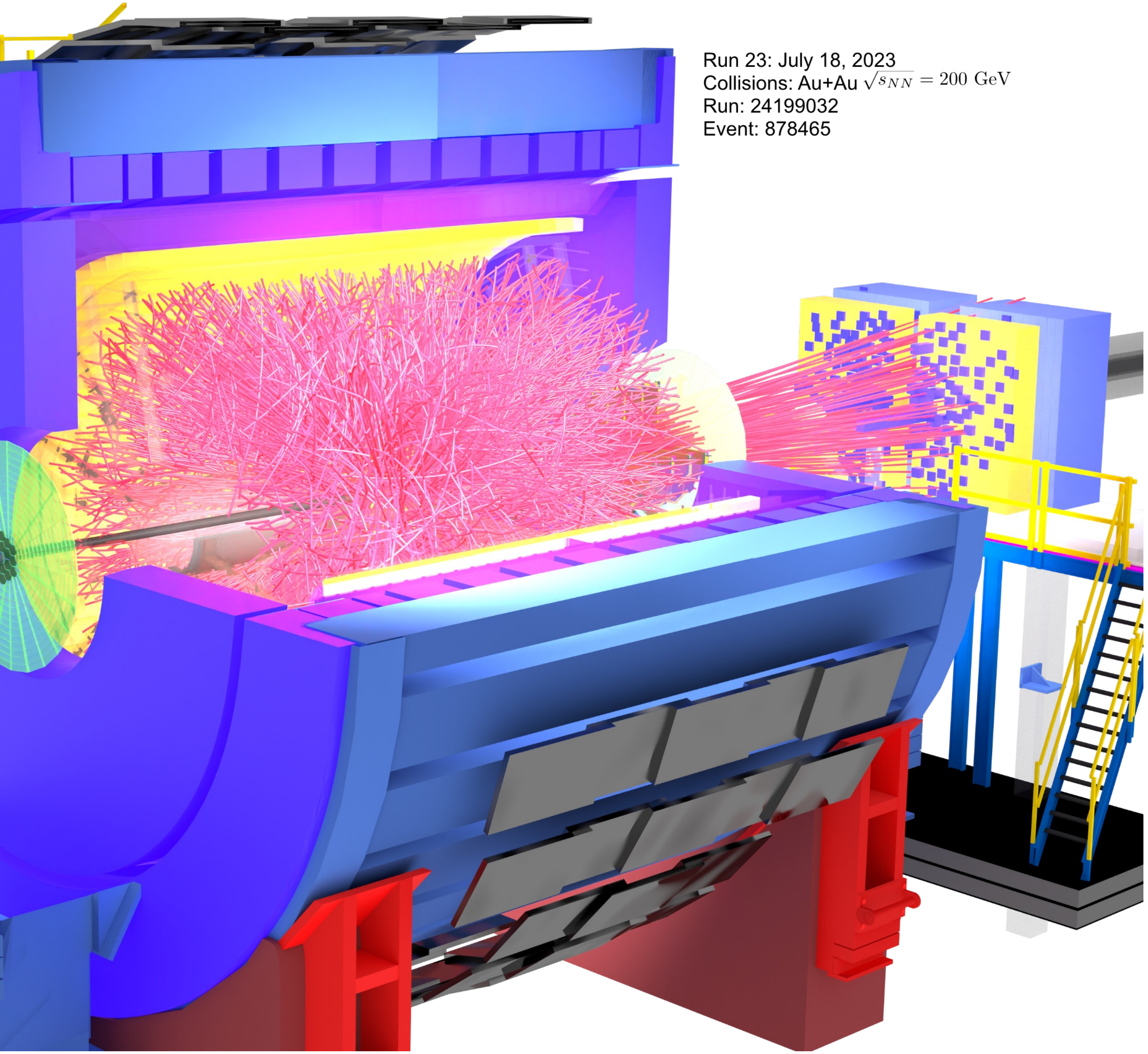
Integrated over φ

Integrated over φ



Sheng et al., PRC 108, 054902 (2023).

Forward Upgrade



Forward Tracking System:
Forward Silicon Tracker (FST)
Forward small-strip Thin Gap Chamber Tracker (FTT)

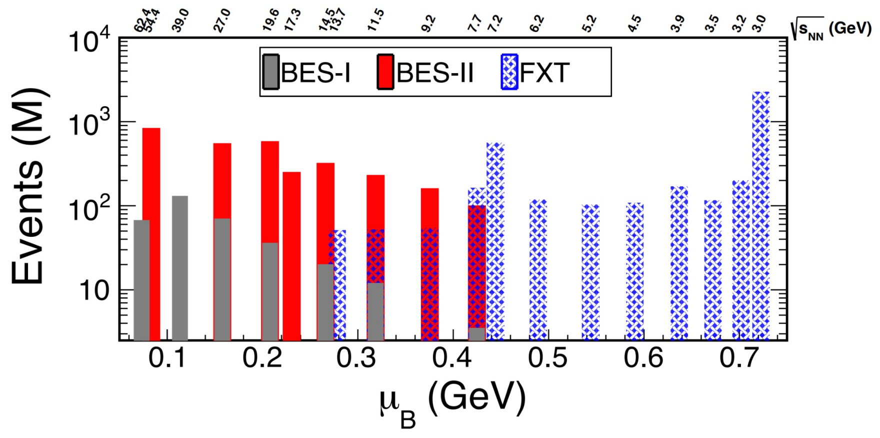
- Charge separation
- $\delta p_T/p_T$ ~ 20-30% for $0.2 < p_T < 2$ GeV/c

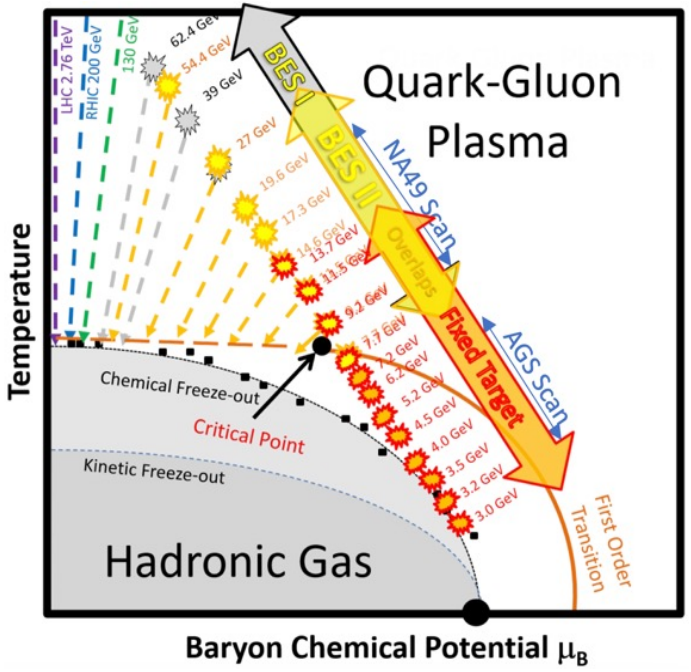
Forward Calorimeter System (FCS):
Forward Electromagnetic Calorimeter (ECal)
Forward Hadronic Calorimeter (HCal)

- Good e/h separation
- Photon, π^0 identification
- ECal: ~10%/$\sqrt{E}$ for pp and pA, ~20%/$\sqrt{E}$ for AA
- ECal: ~50%/$\sqrt{E}$ for pp and pA

- Precision forward physics (Cold QCD/Hot QCD):
  - Gluon PDFs, Saturation tests, Sivers asymmetries.
  - Viscosity temperature dependence, Longitudinal decorrelation, global Λ polarization rapidity dependence

Outlook





- Upgrades to STAR detector since BES-I for both mid- and forward-rapidity.
- BES-II and FXT program provide several new data sets at collision energies down to 3 GeV.
  - Many ongoing analyses.
- Run 23 recorded 1^{st} top energy Au+Au with all upgrades.
  - 6.5 B events before unexpected RHIC shutdown.
  - High statistics p+p/p+Au/Au+Au planned for runs in 2024-2025.

Summary

Search for the QCD critical point and phase transitions

- C_6/C_2 in 7.7-200 GeV shows increasingly negative values with decreasing energy – consistent with calculations that include a cross-over transition.
- $N_t \times N_p / N_d^2$ from data shows consistency with coalescence model.

Probing the nuclear matter equation of state through anisotropies

- NCQ scaling of v_2 is violated at 3.2 GeV – consistent with a disappearance of partonic collectivity.
- In BES-II, we observe 20-30% deviation of light nuclei v_2 from mass number scaling.
  - AMPT+Coal. well describes the v_2 and v_3 of *d.*

Probing the vorticity and shear viscosity of QGP

- Global and local Λ polarization are consistent for Au+Au and isobar collisions.
  - No system size dependence and there is no indication of significant magnetic field effects.
- Event plane dependent local Λ polarization is consistent with shear contributions.
- Significant positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured for the first time at mid-central collisions – accommodated by ϕ-mean field.
  - First rapidity dependent results agree with trend from the model for |y| > 0.5.

Precision forward physics with the STAR forward upgrade!