Understanding QCD Matter Through Heavy-Ion Collisions at STAR

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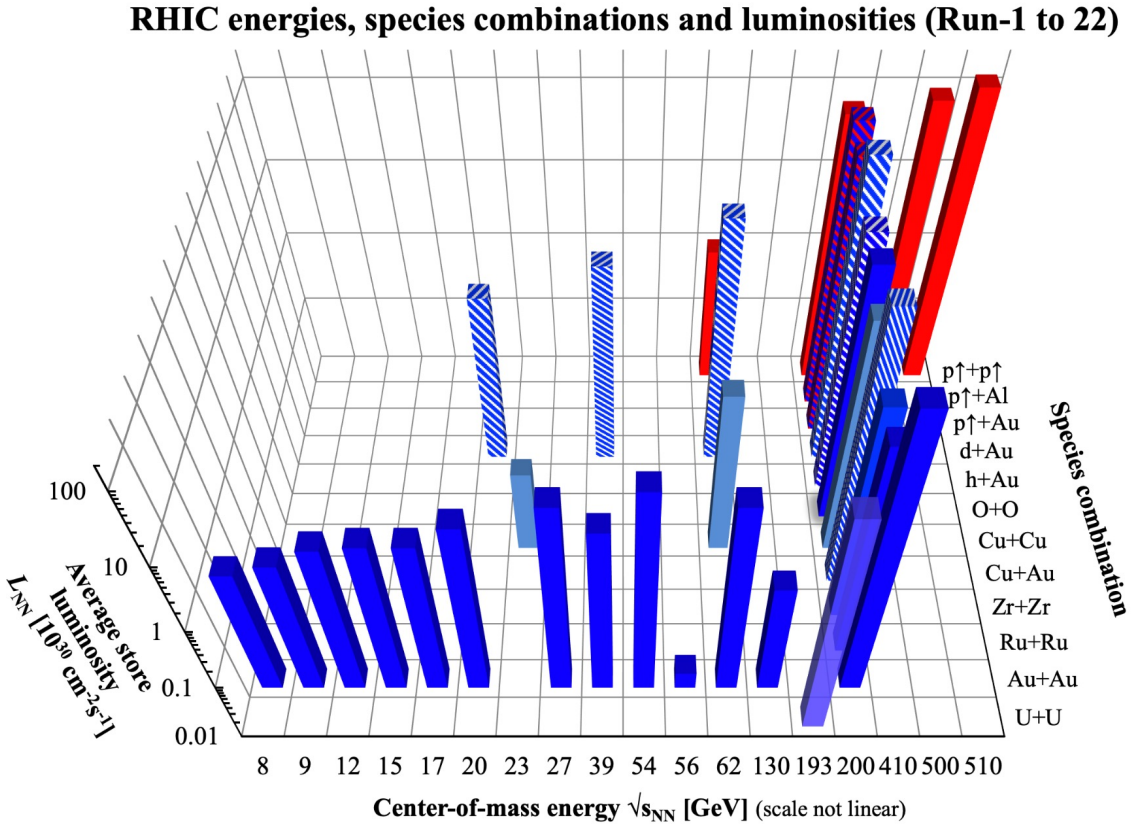
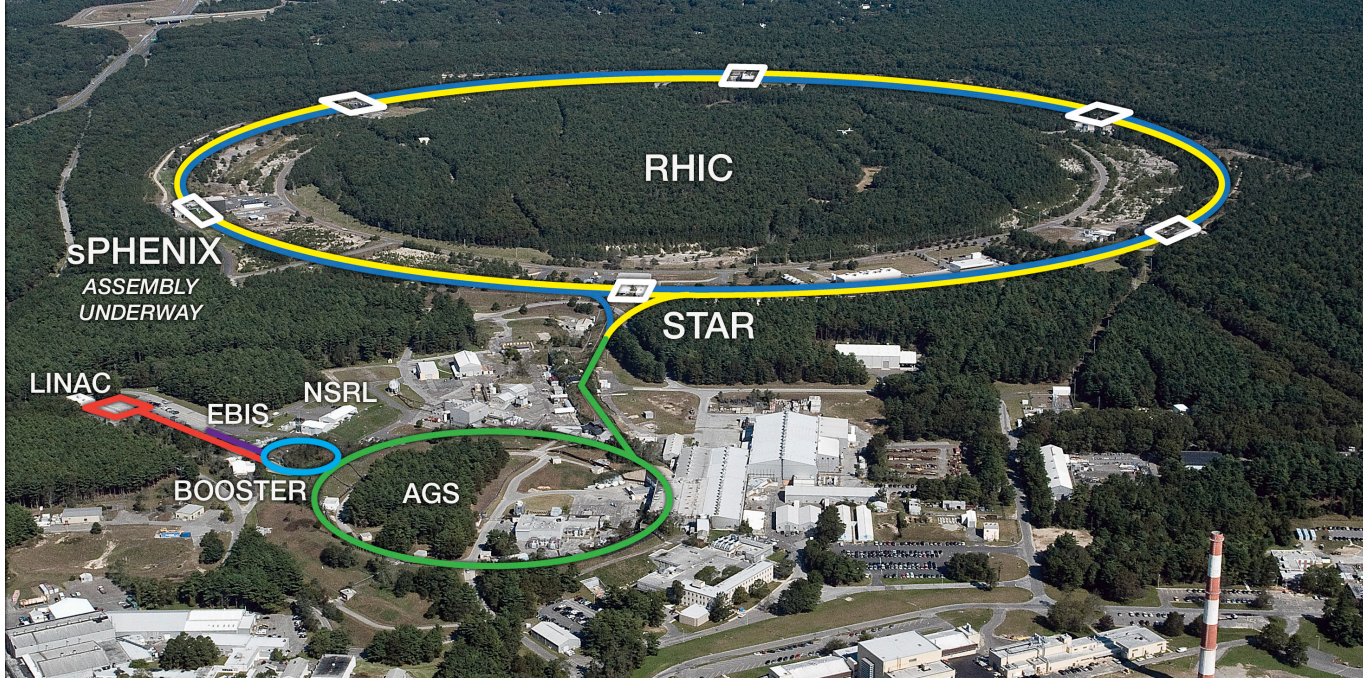
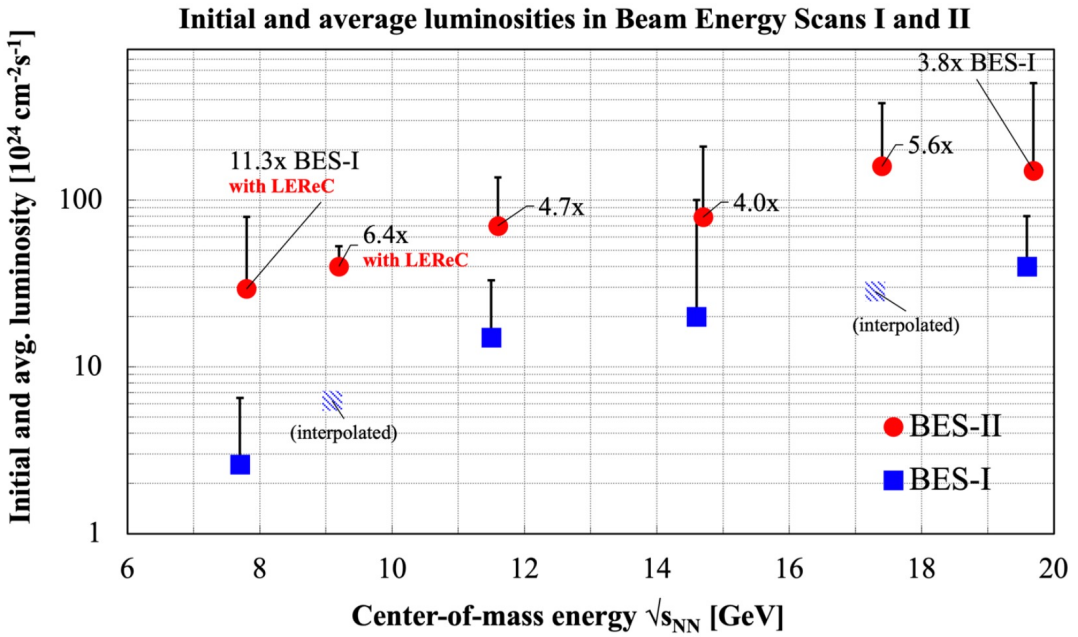
RHIC


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
p↑+p↑
p↑+Al
p↑+Au
d+Au
h+Au
O+O
Cu+Cu
Cu+Au
Zr+Zr
Ru+Ru
Au+Au
U+U
Species combination
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)


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}]
100
10
1
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
6 8 10 12 14 16 18 20
Center-of-mass energy $\sqrt{s_{NN}}$ [GeV]

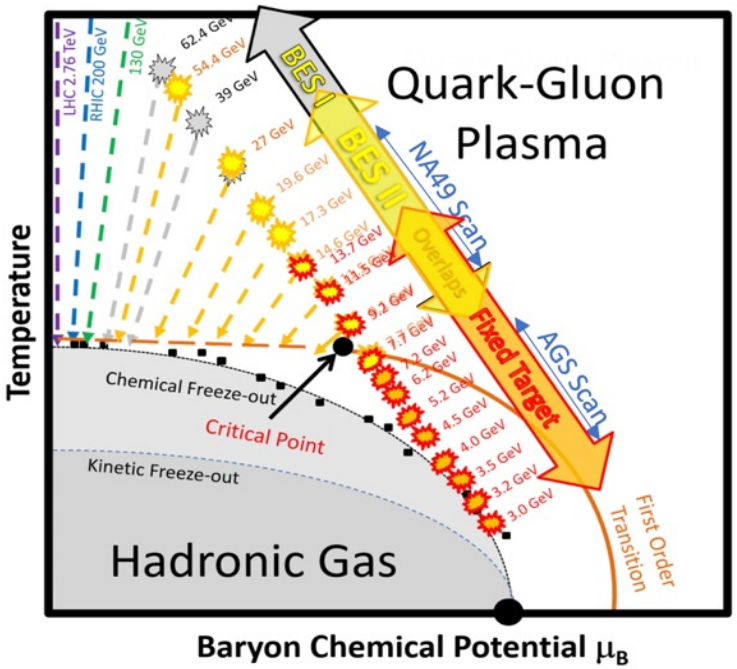
STAR Physics Focus

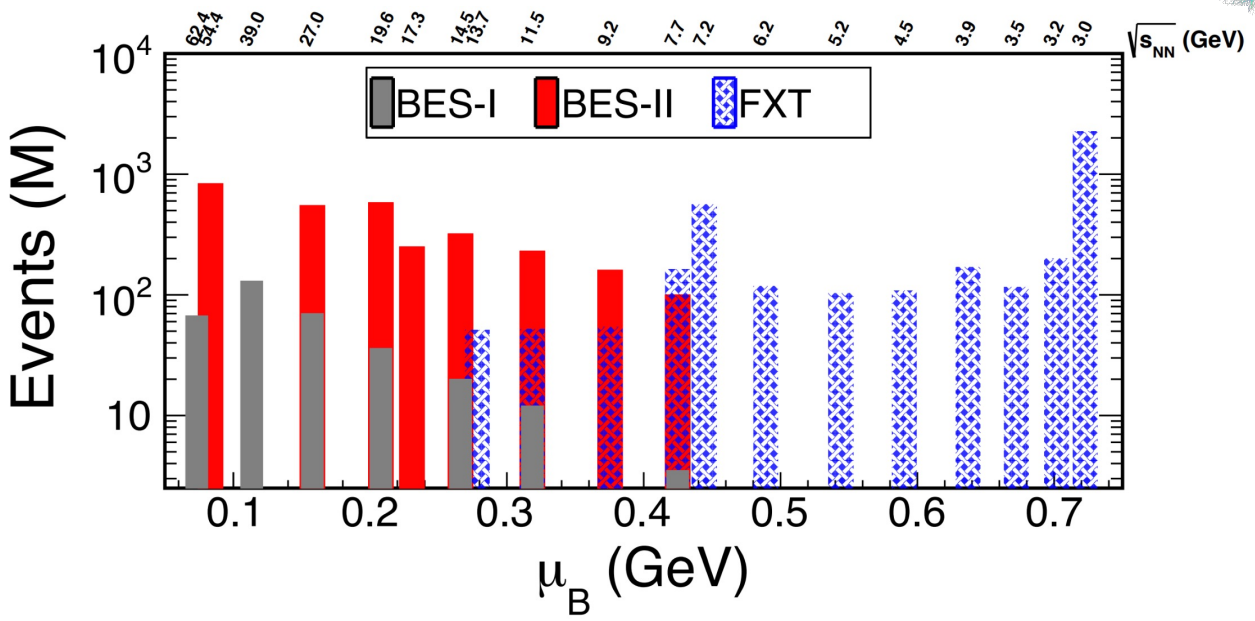
Motivation

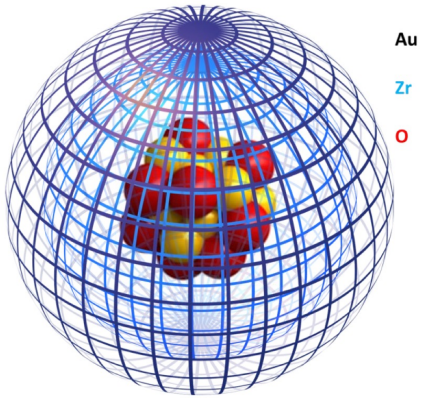
Probing the QCD phase diagram
- Nature of phase transitions
- Critical point

Properties of partonic / high μ_B matter
- Vorticity and its system size dependence.

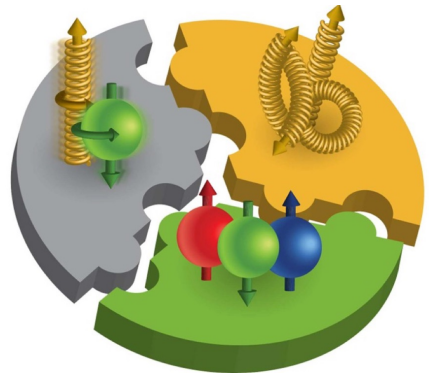
Proton spin - not discussed in this talk





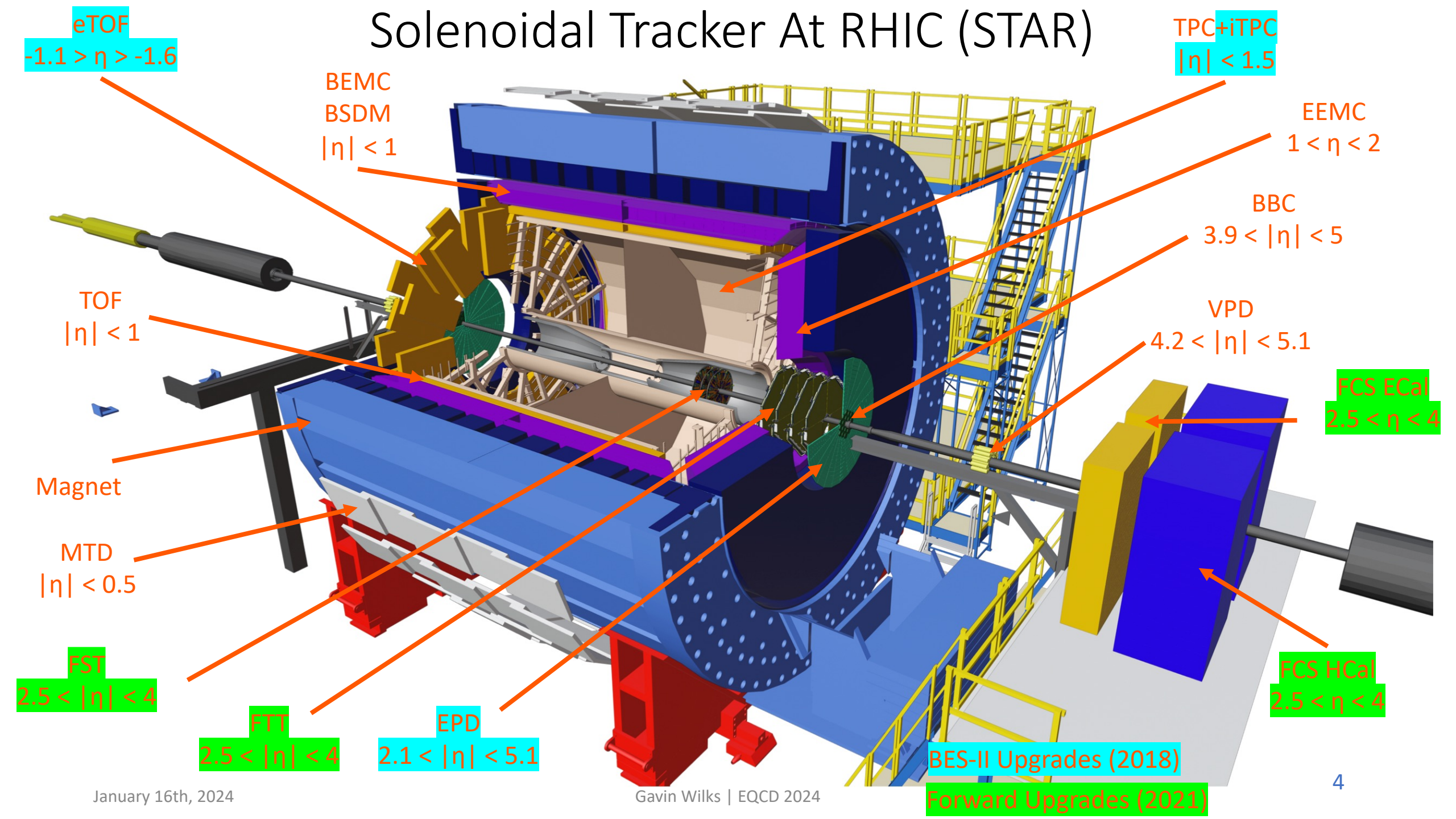


System Size Dependence



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.

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Cumulants

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

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 remove volume dependence

$$\frac{C_5}{C_1} \propto \frac{\chi_5}{\chi_1}$$
$$\frac{C_6}{C_2} \propto \frac{\chi_6}{\chi_2}$$

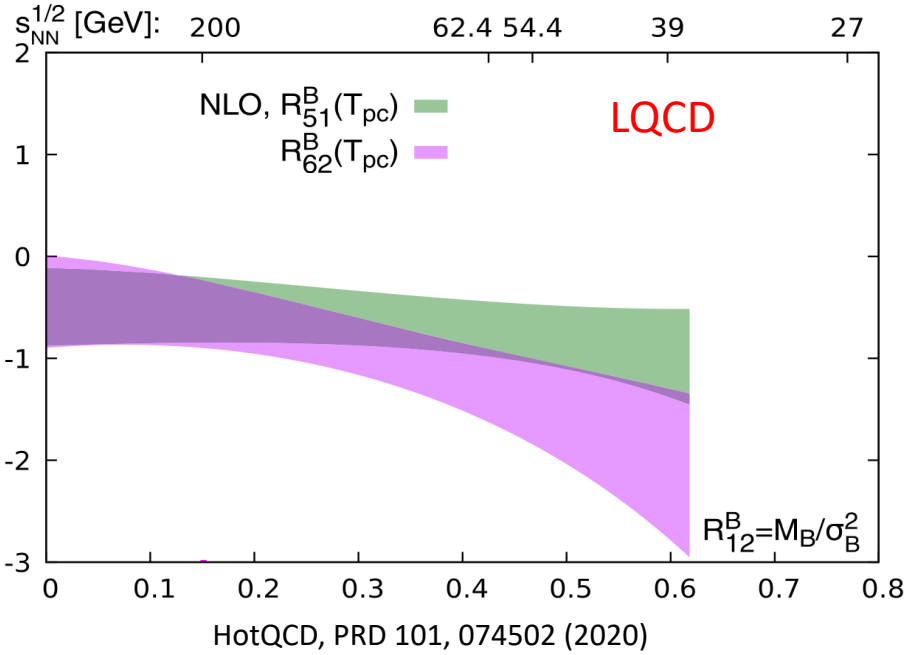
- Cumulant ratios are related to the susceptibilities.
- Higher order cumulants are increasingly sensitive to the nature of the QCD phase transition.

Cumulants and Crossover Phase Transition

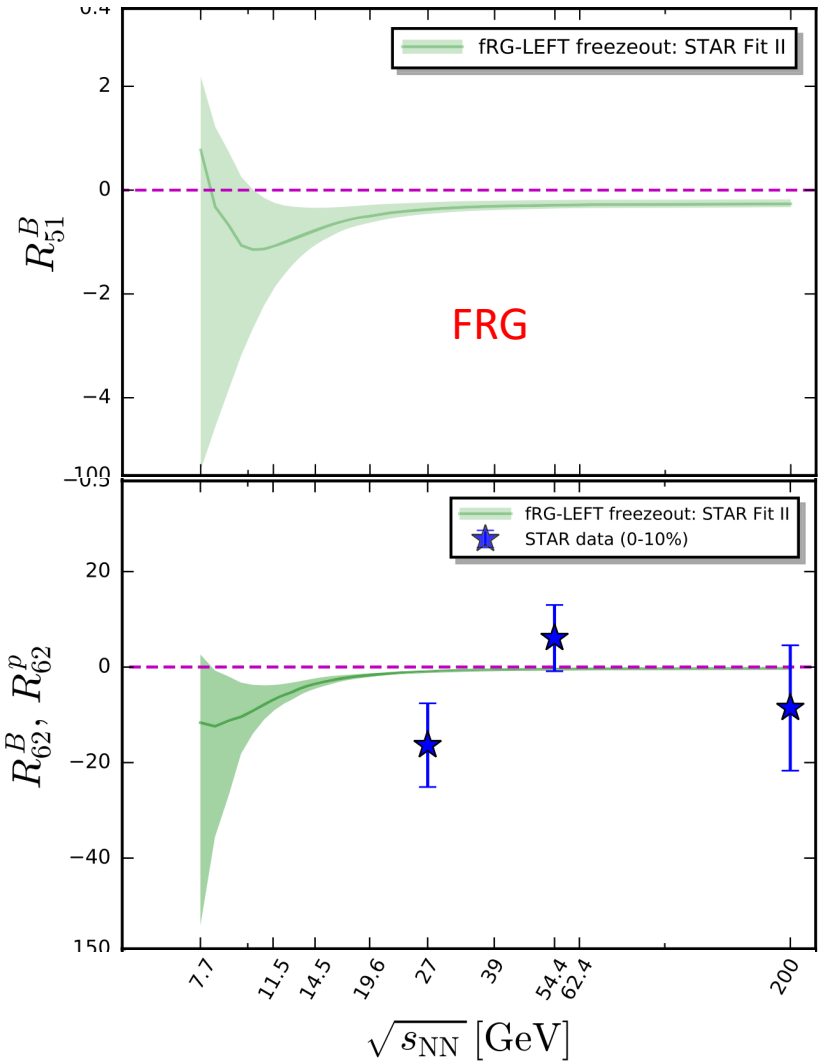
C_5/C_1 and C_6/C_2

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

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



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



Cumulant Ratios [BES-I, FXT]

0-40% Centrality

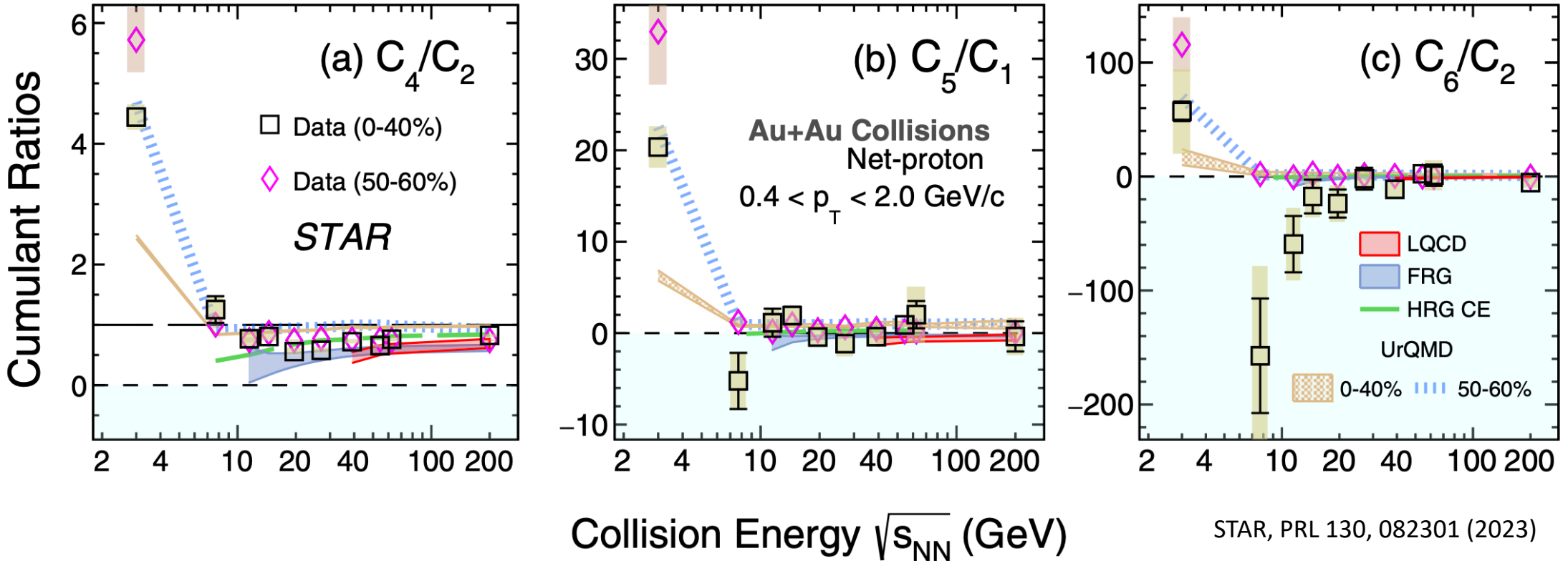
C_4/C_2: Positive for all energies
C_5/C_1: Weak dependence on energy except for large positive value at 3 GeV.
C_6/C_2:

- 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)

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- STAR Forward Upgrade.

Light nuclei yield ratios [BES-I]

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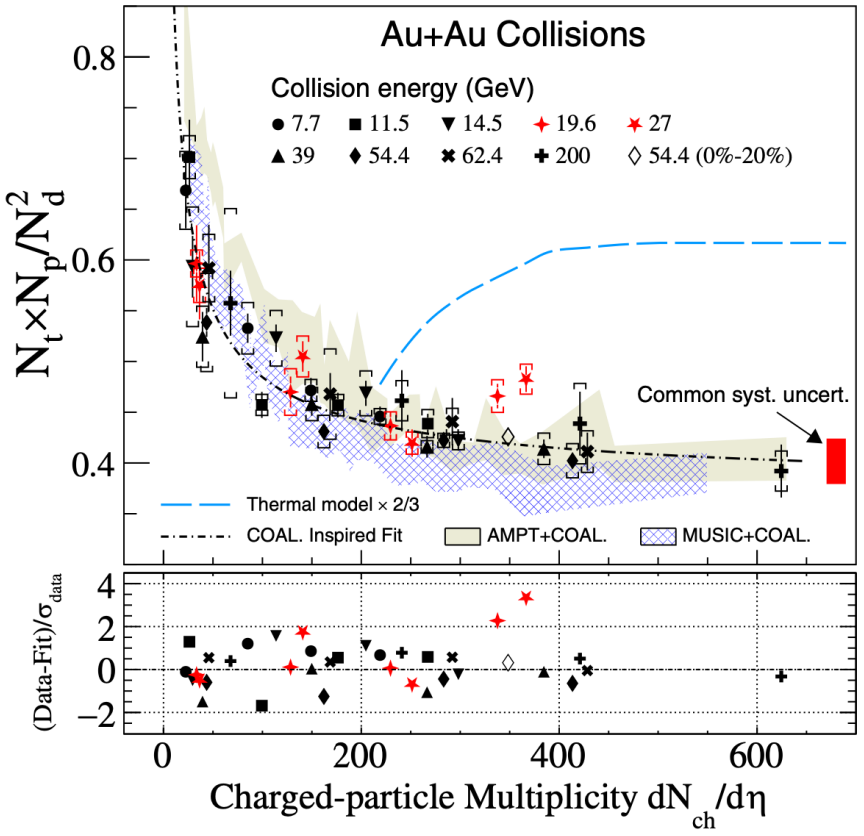
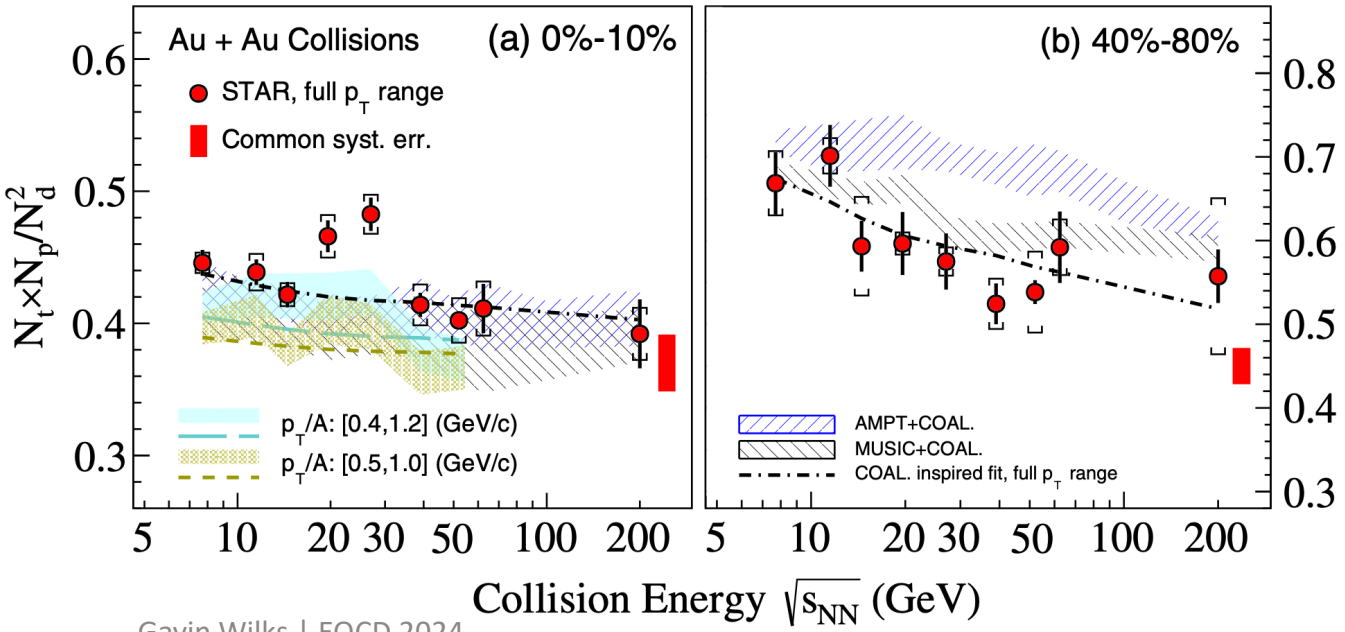


- Coalescence (COAL.) model: light nuclei are formed by the coalescence of protons and neutrons in late stages of heavy-ion collisions.
  - $N_t \times N_p / N_d^2$ is sensitive to neutron density fluctuations.
  - Promising observable to search for first-order phase transition / CP.
- 19.6 & 27 GeV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



Data shows monotonic decrease with increasing N_{ch}

- Consistency with COAL. model.

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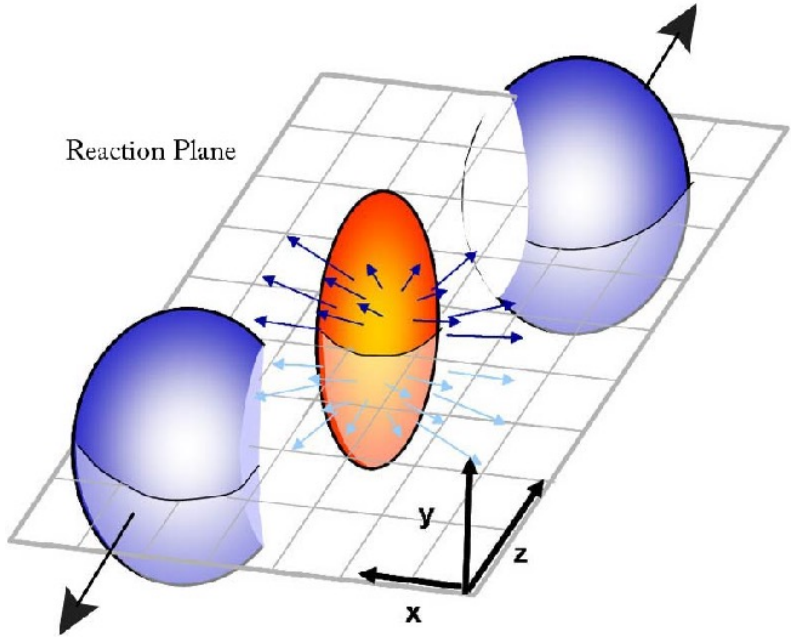
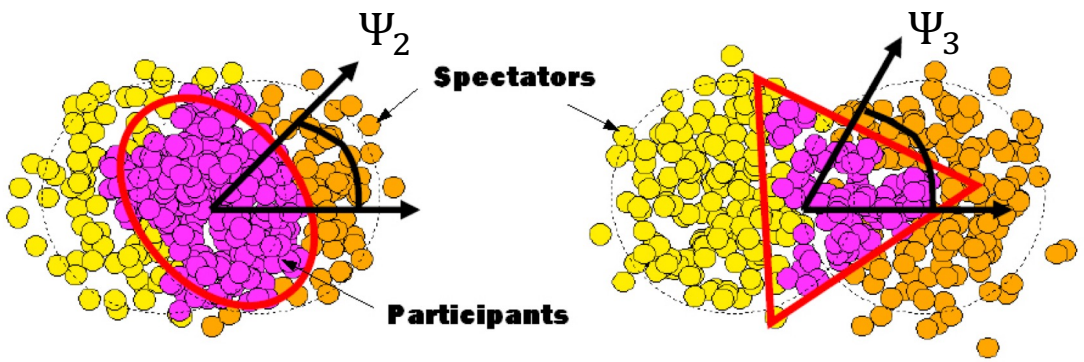
Event Plane and Anisotropic Flow

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

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

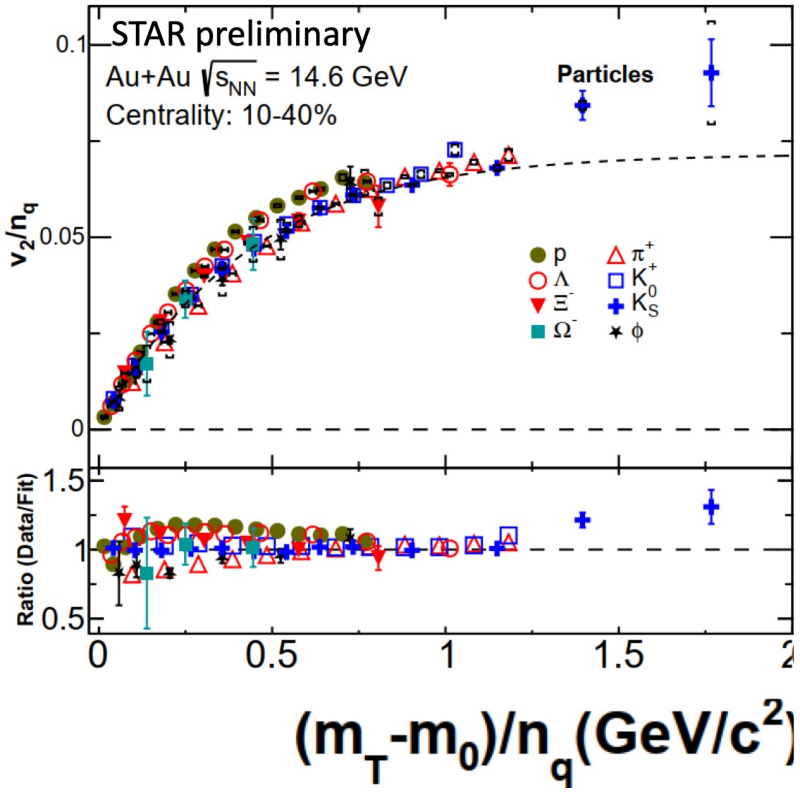
- Ψ_n characterizes the nth order event plane.
- v_n characterizes the nth order anisotropic flow of the QGP.
  - v_2, elliptic flow, particle yields are higher along 1 **axis** in azimuthal distribution.
  - v_3, triangular fow, particle yields are higher along 3 **directions** with equal angular separation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



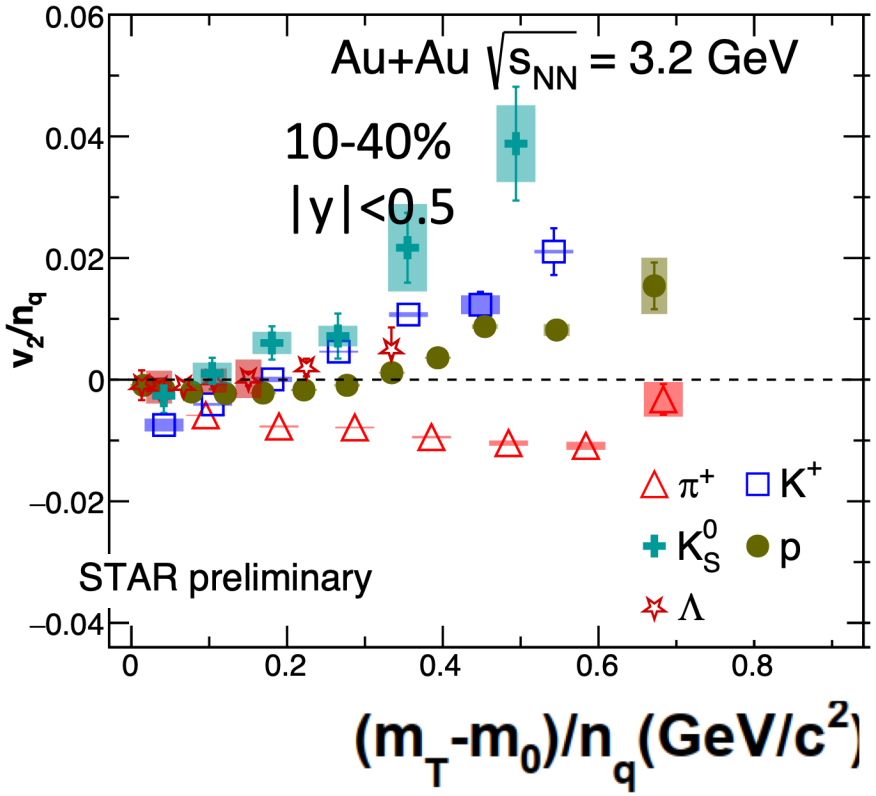


NCQ scaling of elliptic flow [BES-II, FXT]

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

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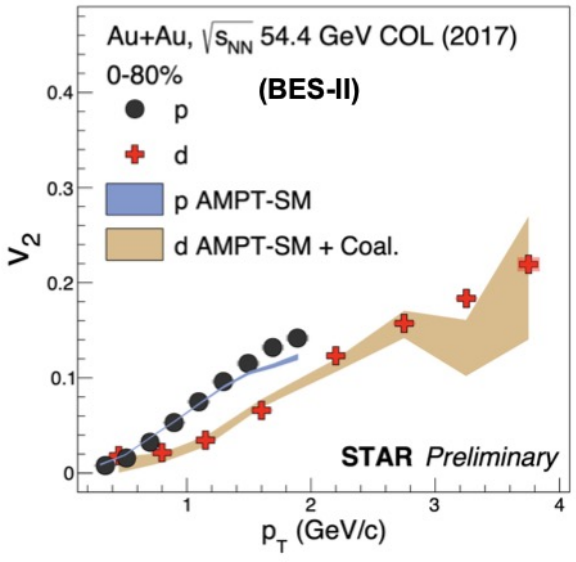
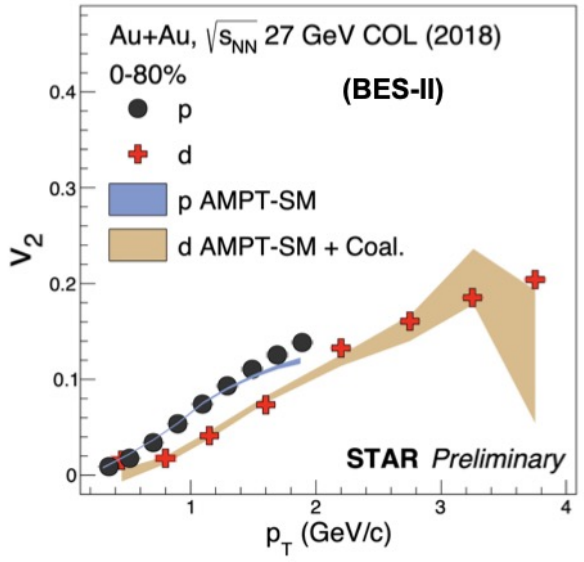
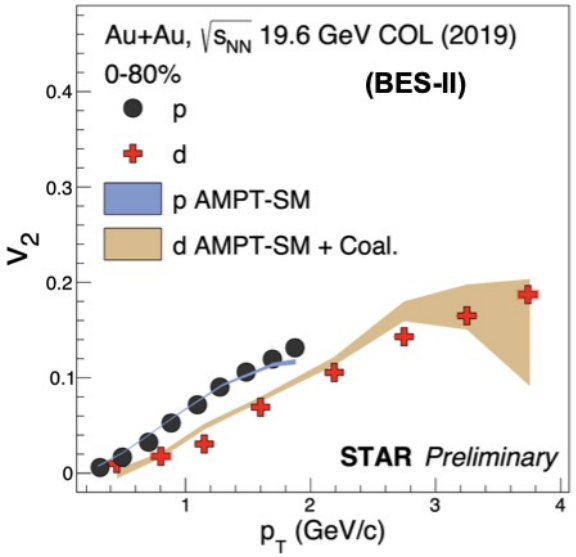
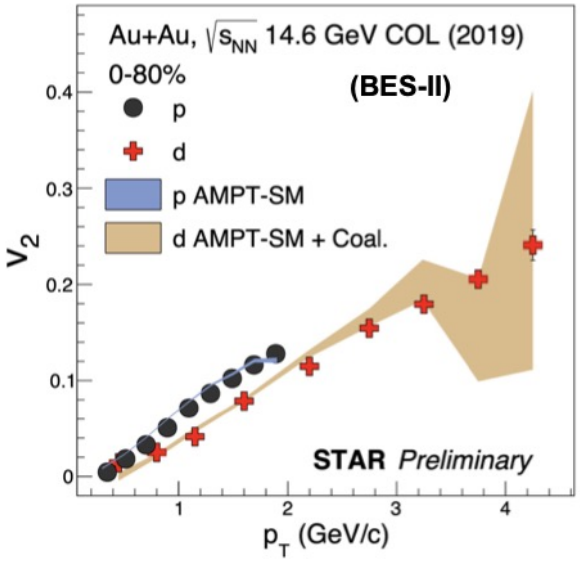
Light nuclei elliptic flow (v_2) [BES-II]

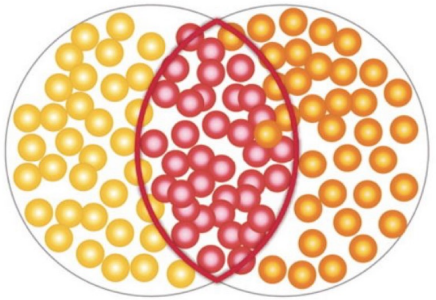








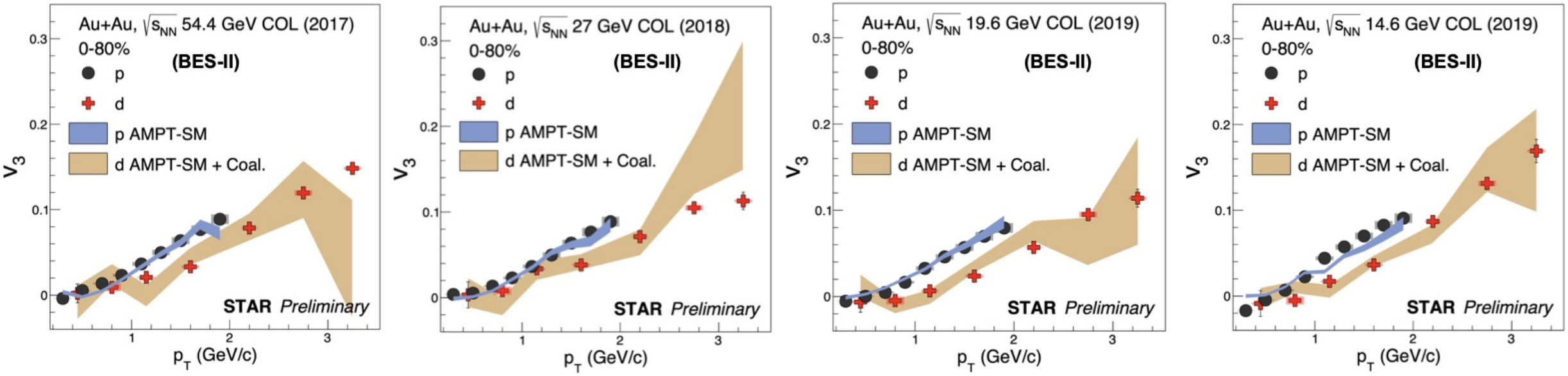
- In BES-II, we observe 20-30% deviation of light nuclei v_2 from mass number scaling, the naïve expectation from coalescence production.
  - Consistent with ALICE measurements in PRC 102, 055203 (2020).
- AMPT+Coal. well describes the v_2 of *d*.



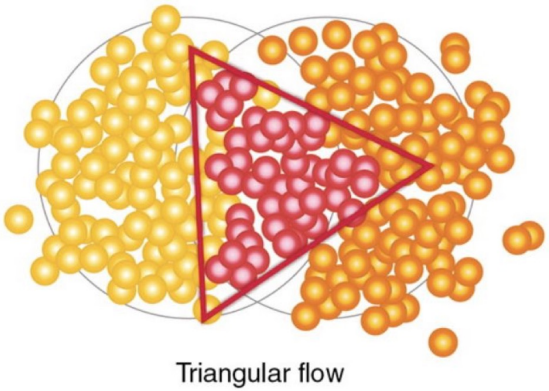
Elliptic flow

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_3: Phys. Rev. C 93, 014907 (2016); Phys. Rev. C 88, 014902 (2013); Phys. Lett. B 827, 137003 (2022)

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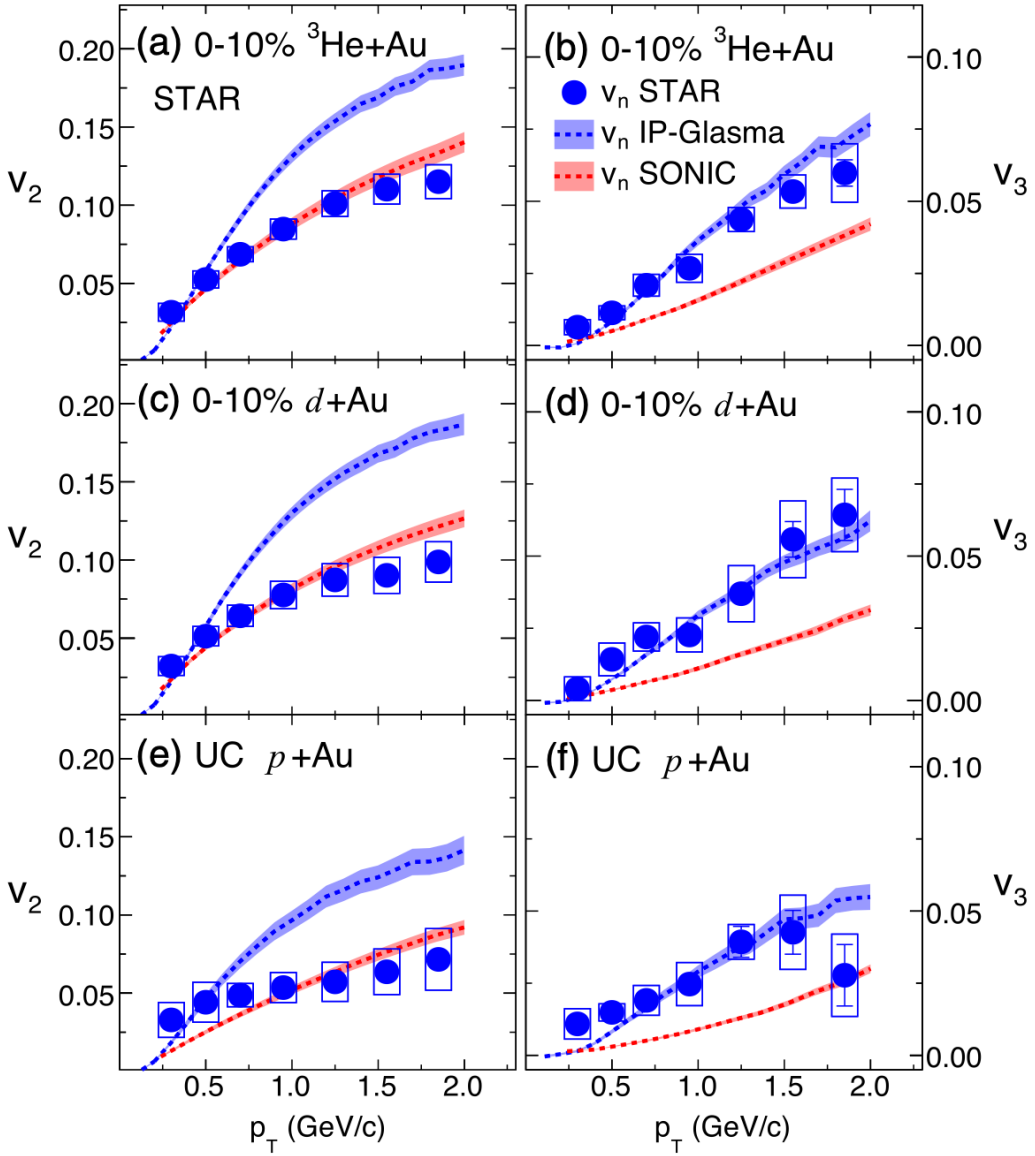
Anisotropies in highly asymmetric collisions



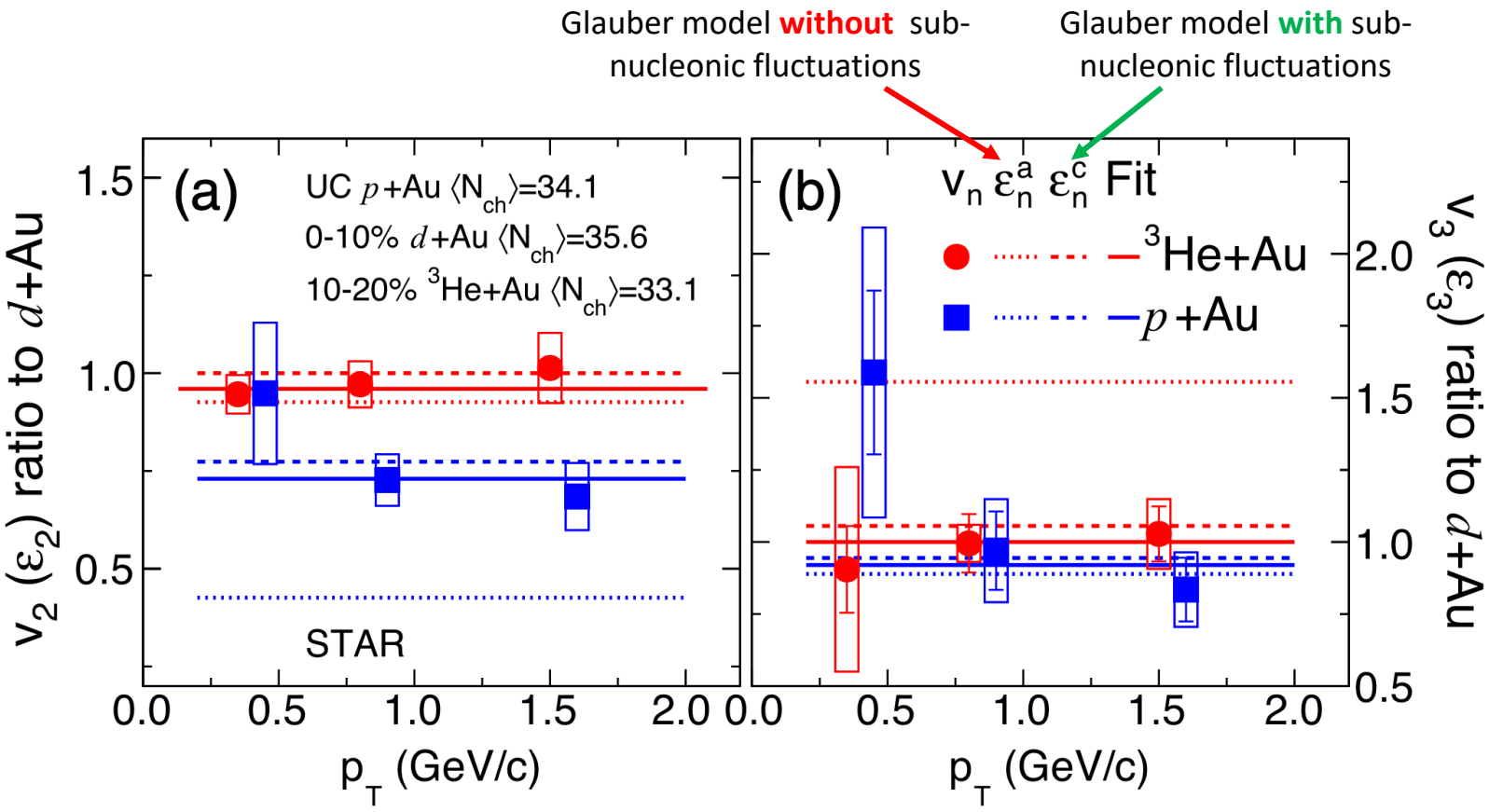
STAR, PRL 130, 242301 (2023)

- 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

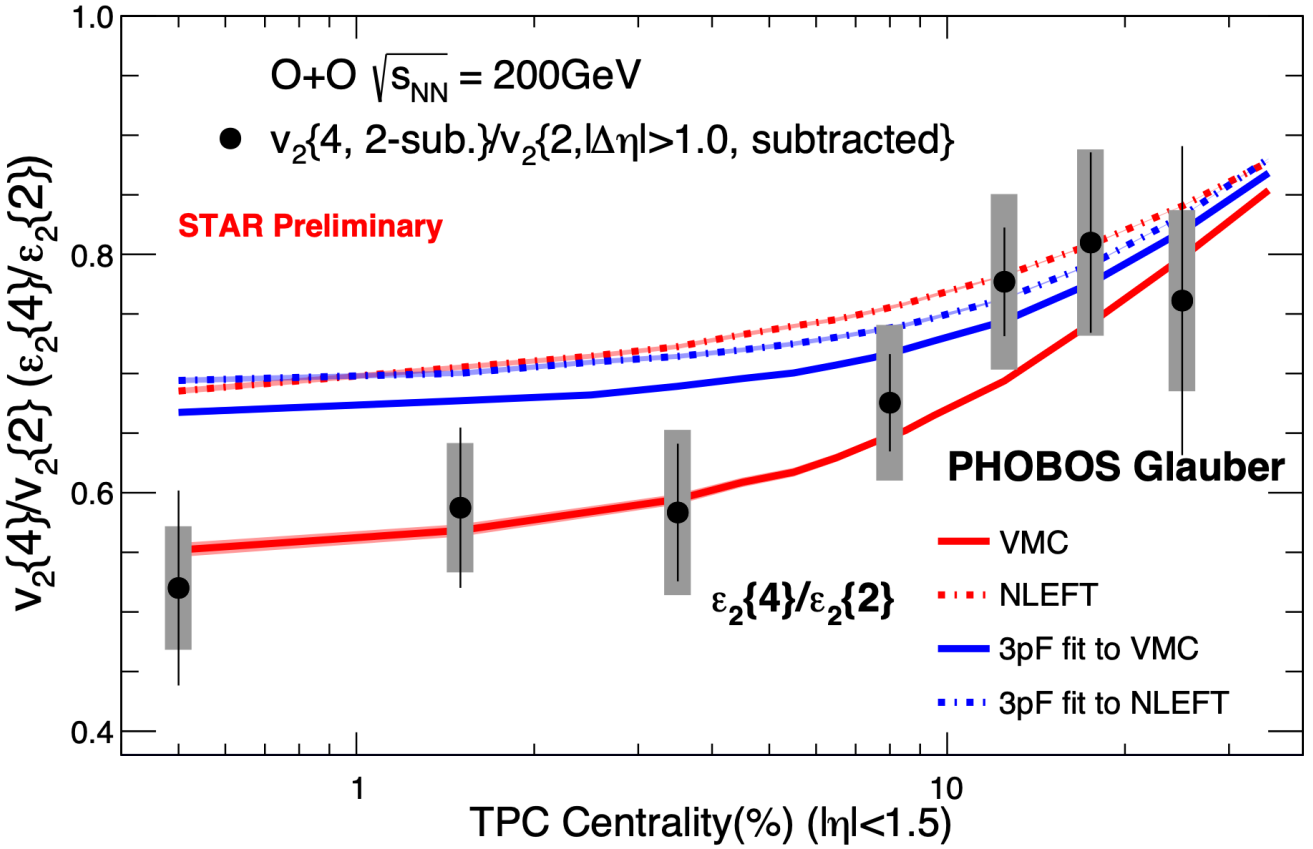


- Measurements are consistent with a significant influence from sub-nucleonic eccentricity fluctuations.

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)

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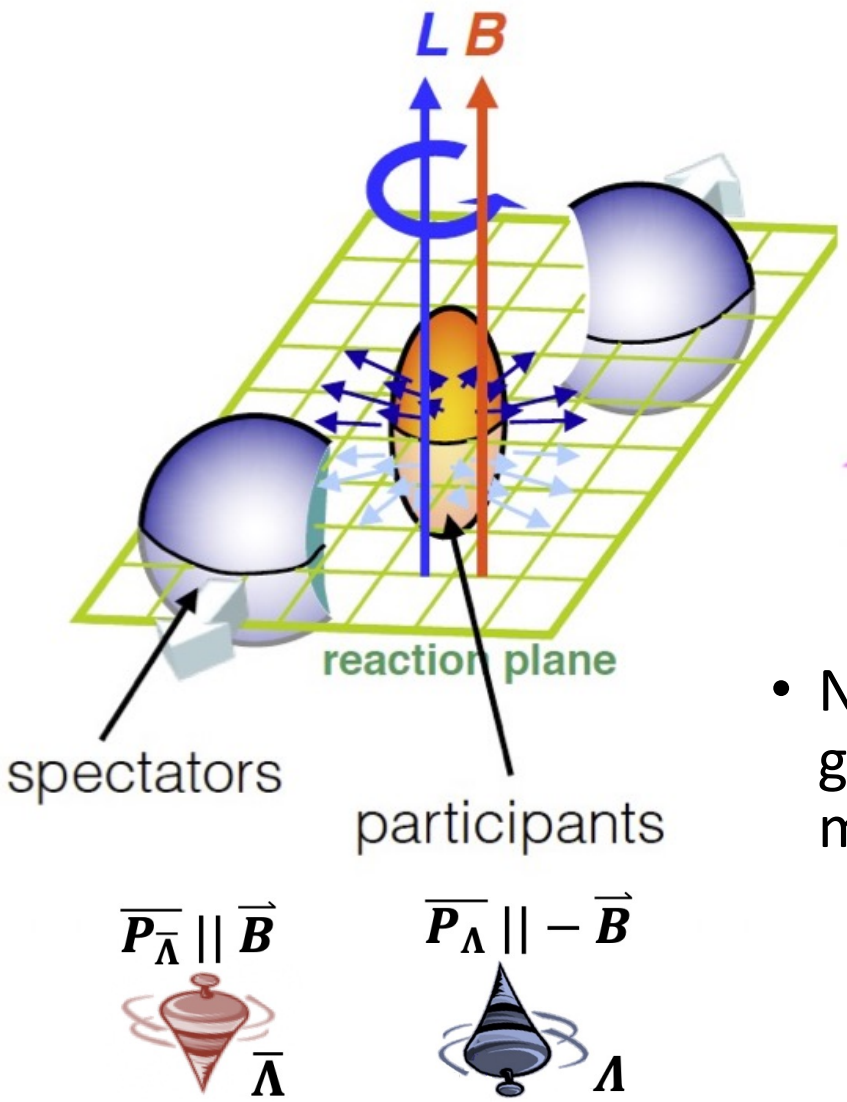
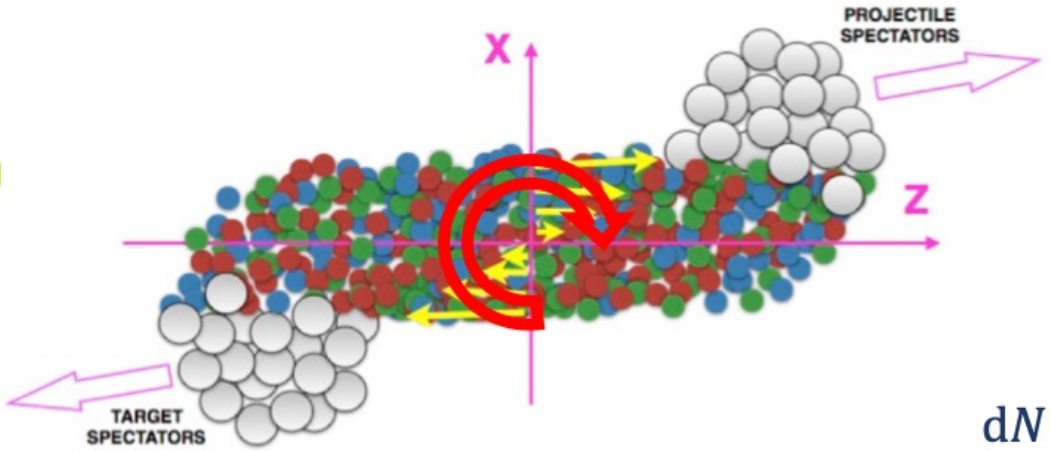
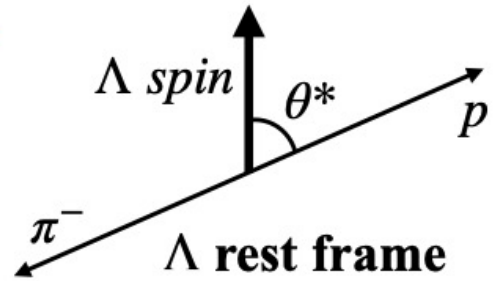
Hyperon Polarization







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

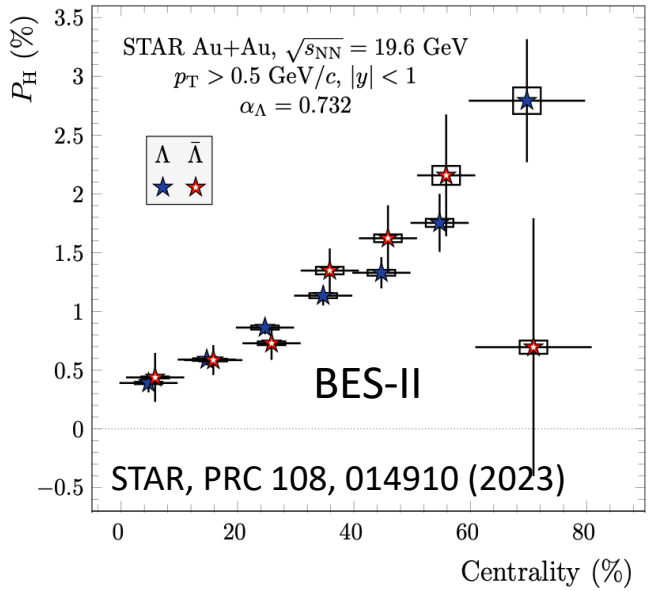
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_\Lambda P_\Lambda cos\theta^*)$$

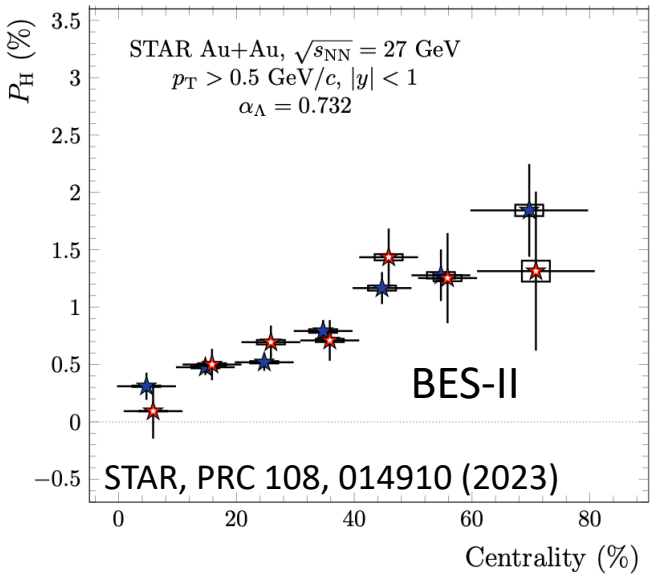
$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{1}{A_0} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{Res(\Psi_1)}$$

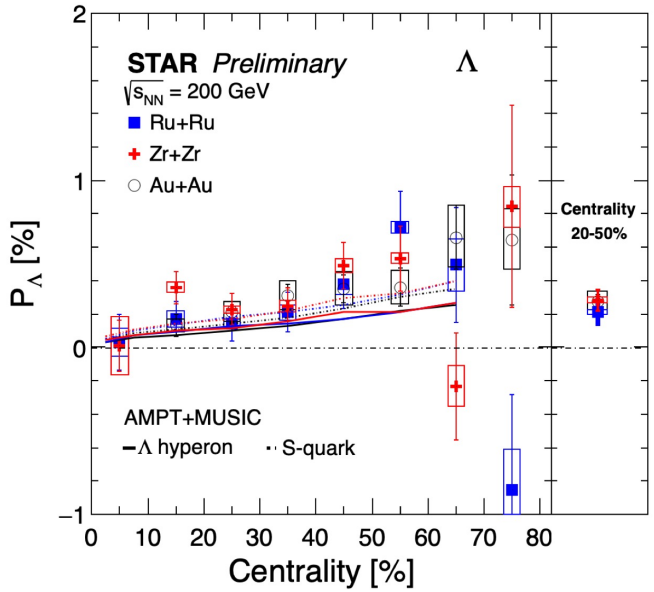
$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$
A_0: Acceptance correction factor
Ψ_1: First-order event plane angle
$Res(\Psi_1)$: Event plane resolution

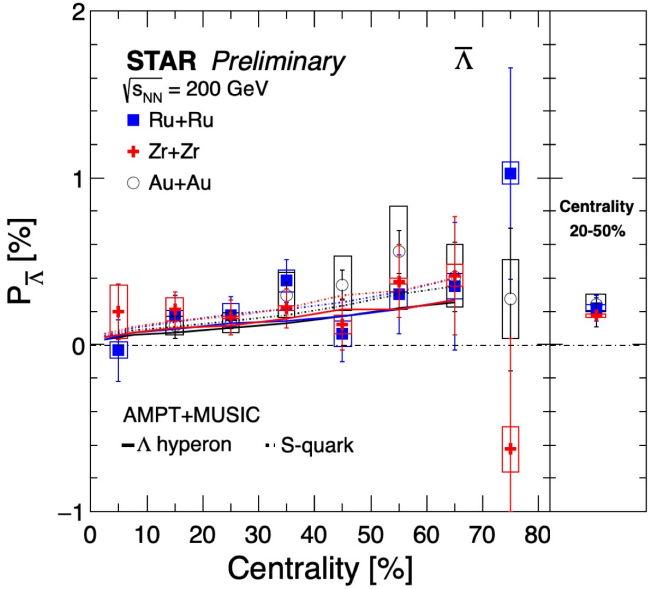
Liang et al., PLB 629, 20–26 (2005).

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







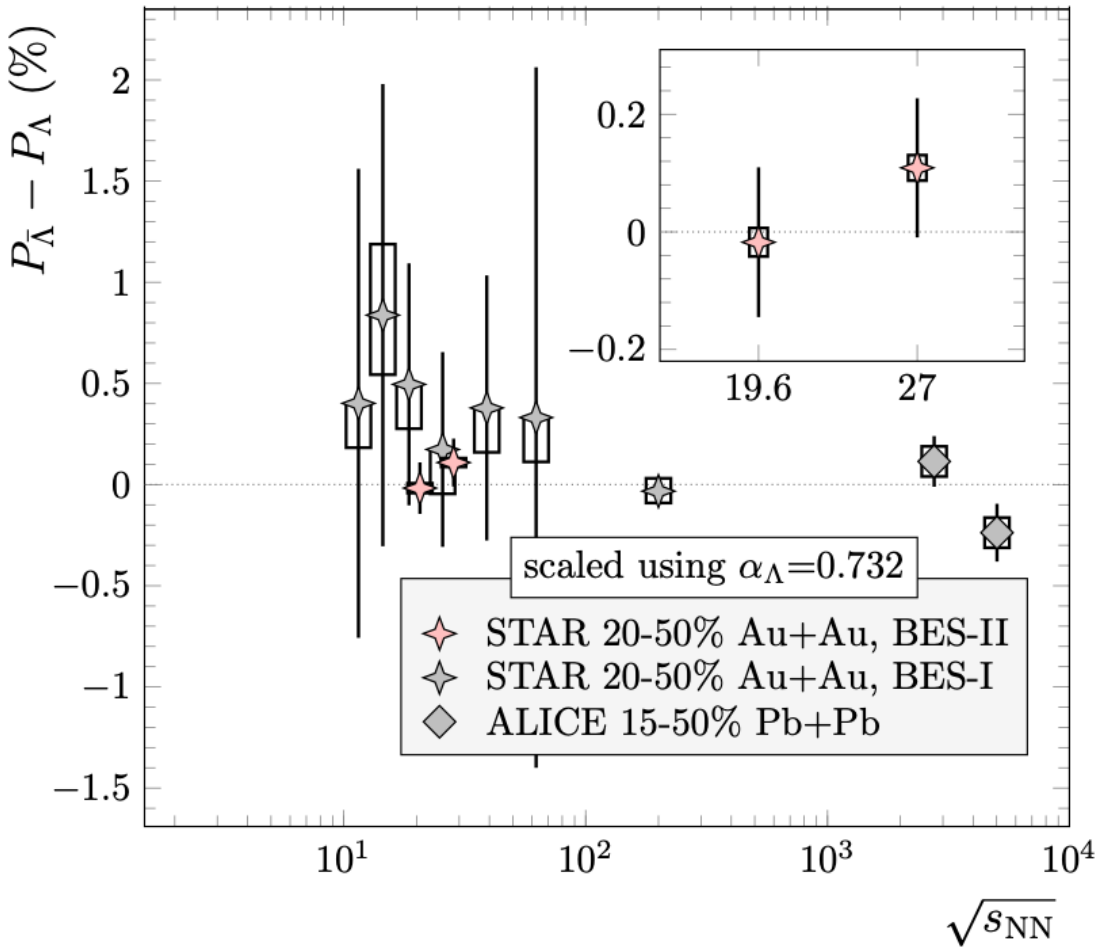


- Significant centrality dependence of global polarization observed.
- BES-II and BES-I are consistent.
  - BES-II with 10x more statistics.

- 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]



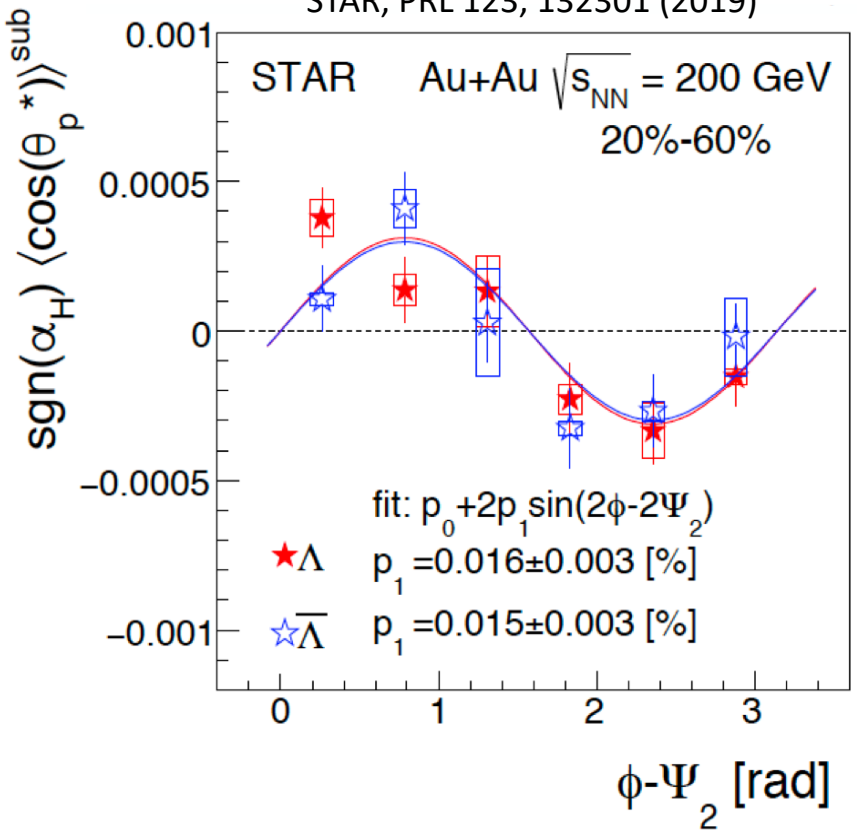
STAR, PRC 108, 014910 (2023)

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

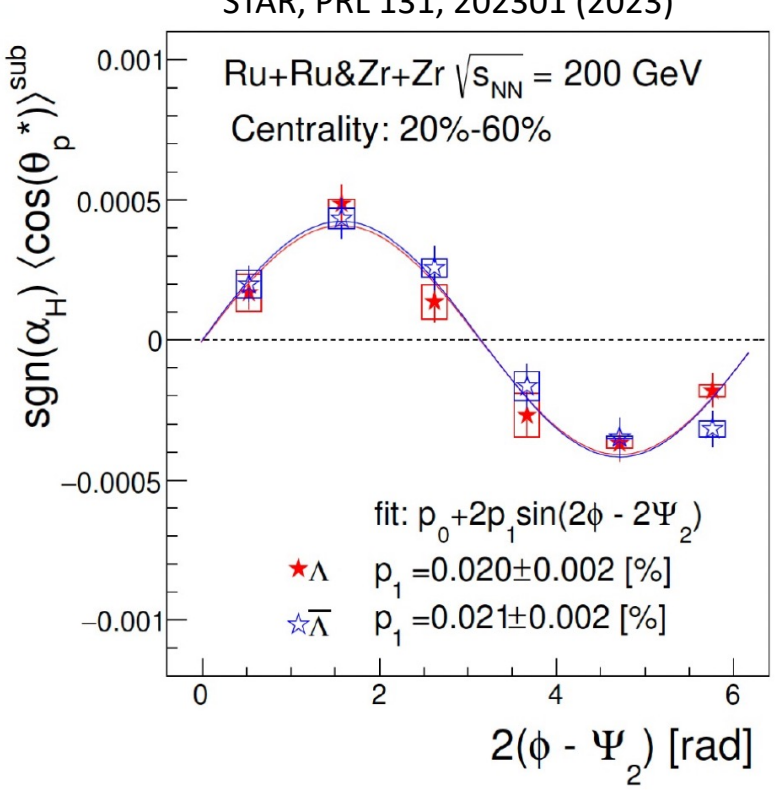
- No significant splitting of $\Lambda/\bar{\Lambda}$ observed.
- Upper limit on late-stage magnetic field:
  - 19.6 GeV: B < 9.5 x 10^{12} T (95%)
  - 27 GeV: B < 1.4 x 10^{13} T (95%)

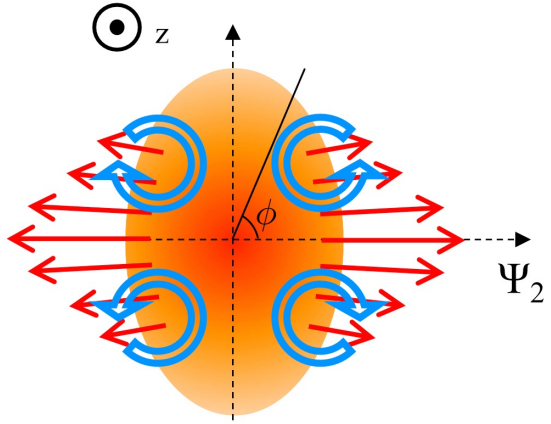
Local Λ Polarization (Ψ_2)

STAR, PRL 123, 132301 (2019)

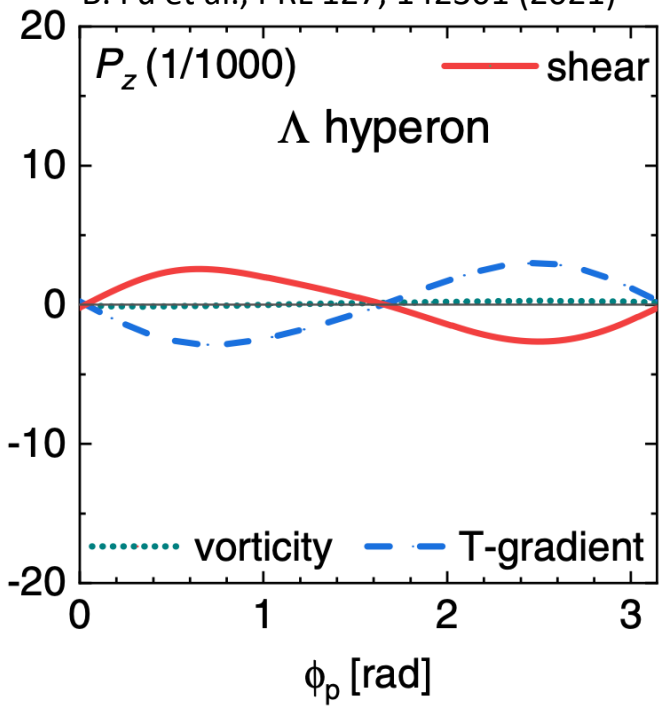


STAR, PRL 131, 202301 (2023)





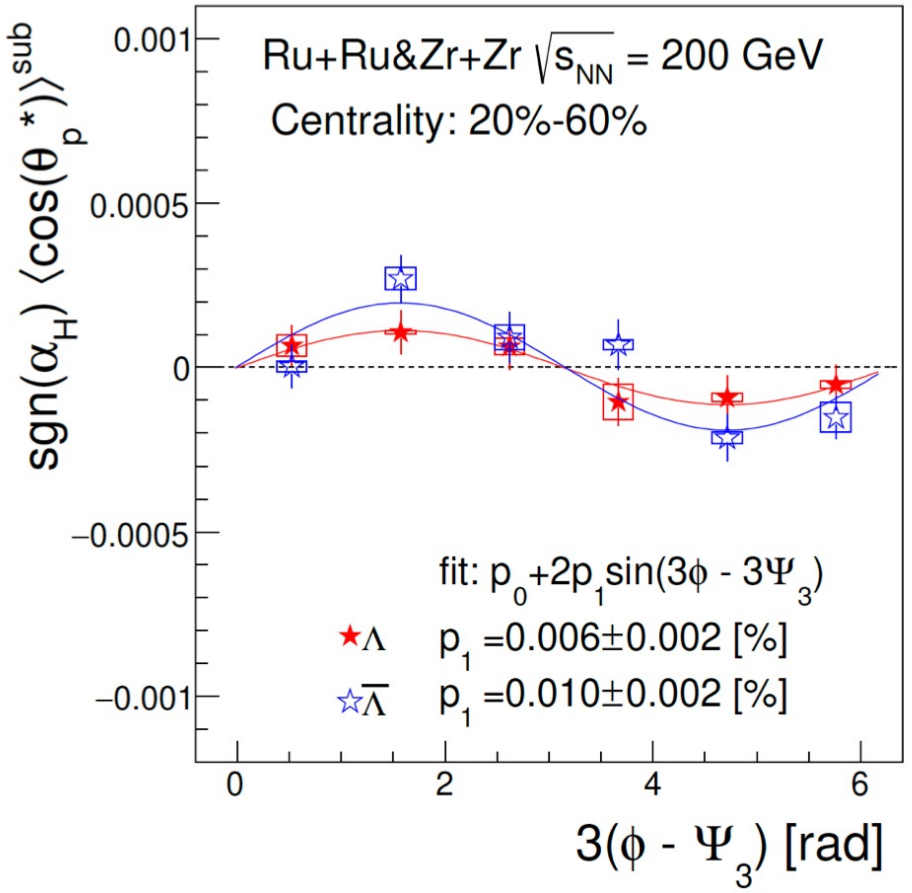
B. Fu et al., PRL 127, 142301 (2021)

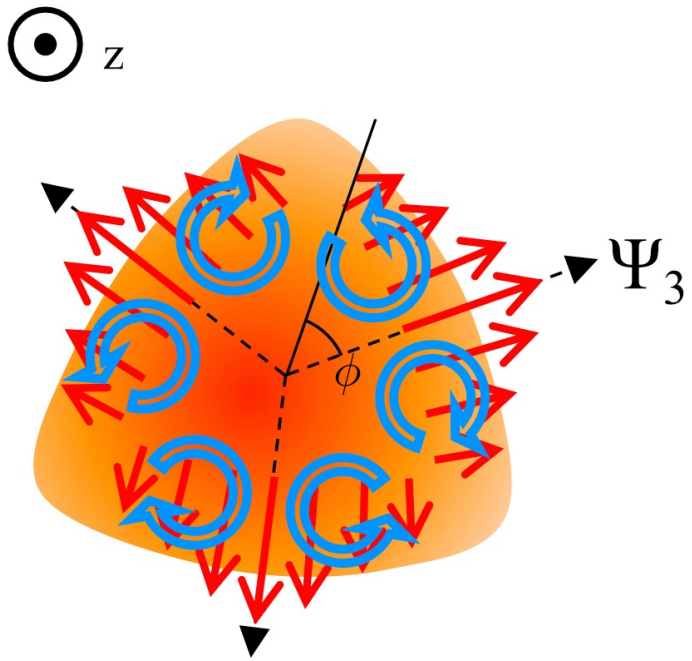


- Shear contributions from vorticity generated by elliptic flow can accommodate the current data.
- Consistent for Au+Au and isobar collisions at mid-centrality.
  - No system size dependence.

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.

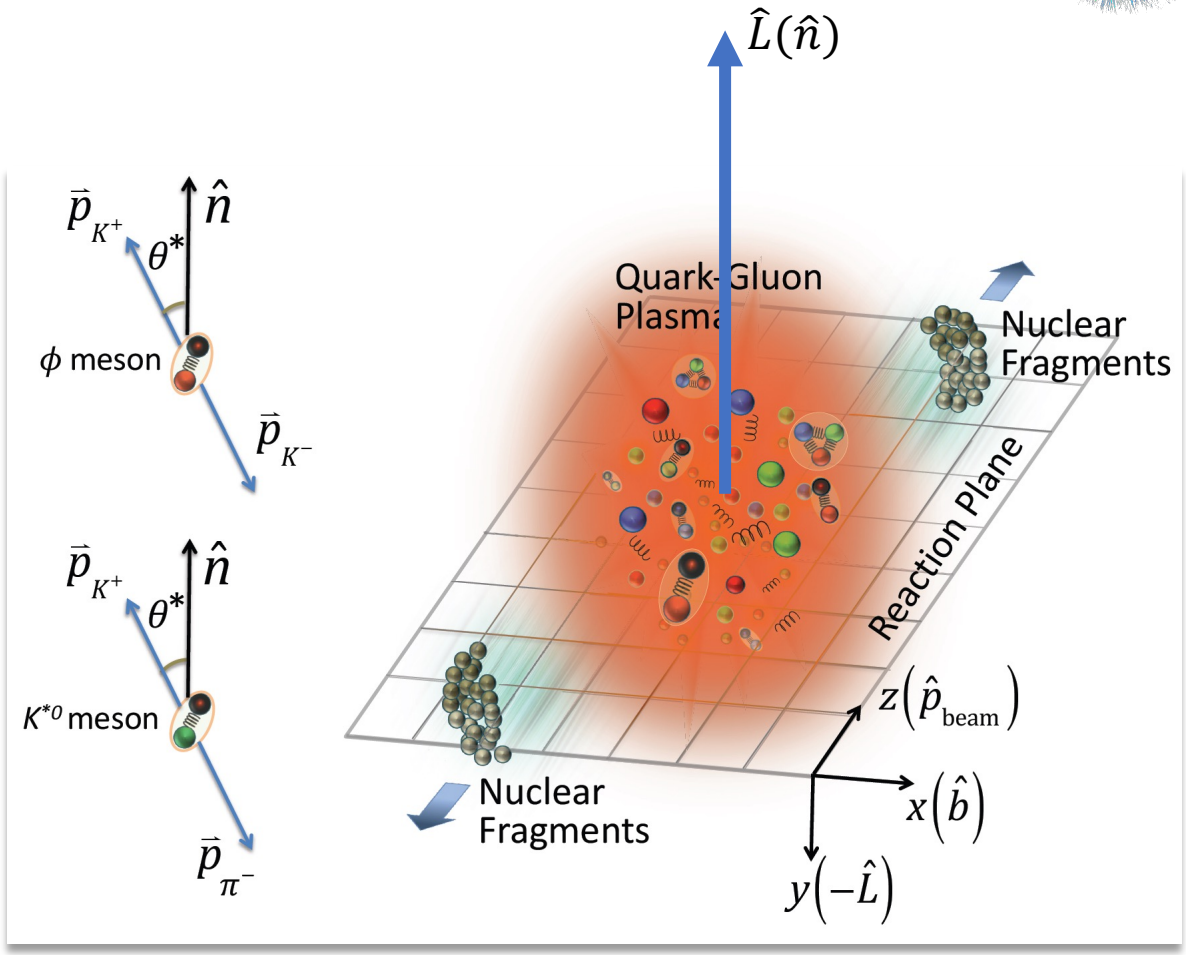
θ^*: angle between K$^+$ daughter momentum and polarization axis in parent's rest frame.

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.

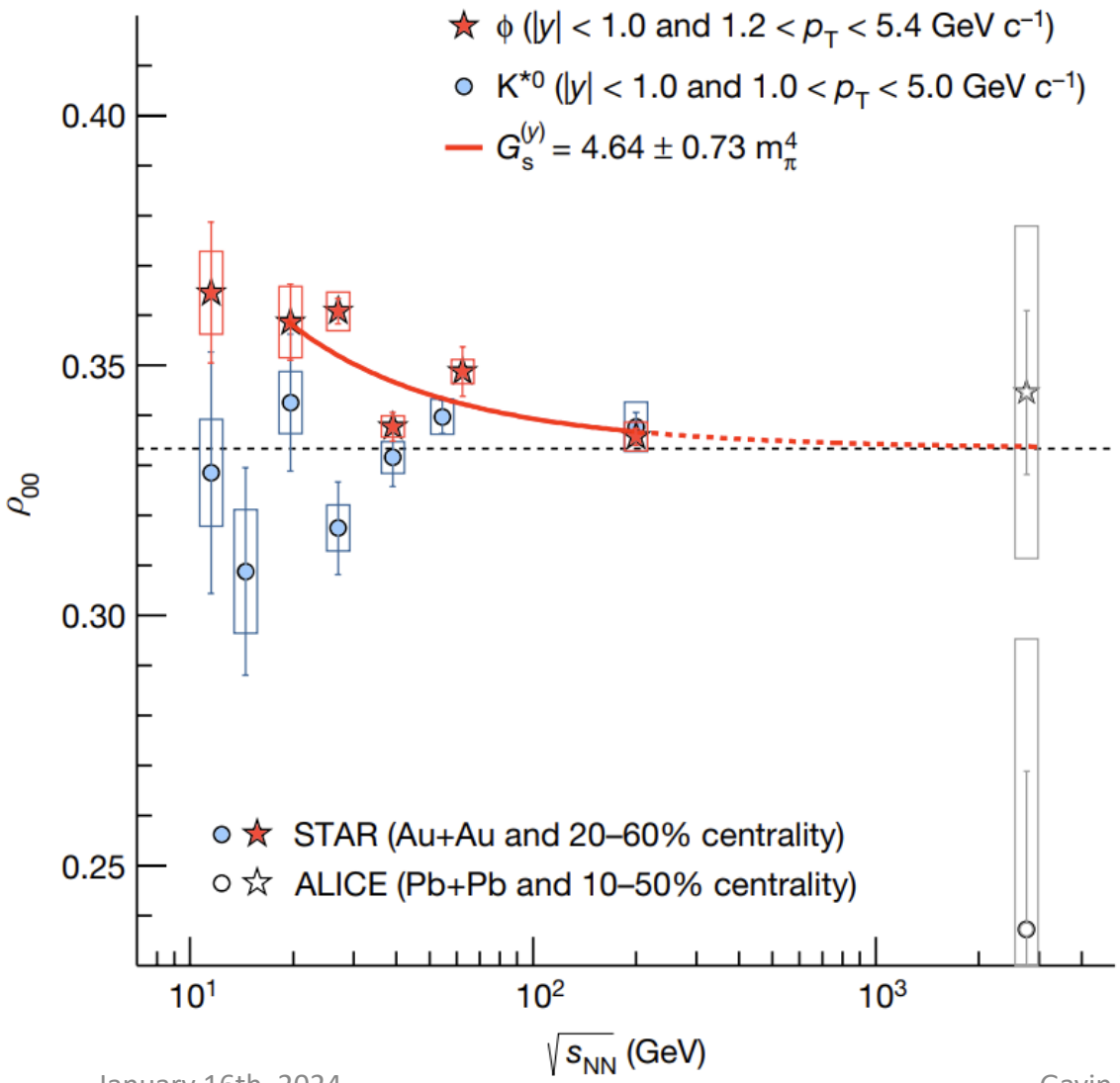


STAR, Nature 614 (2023) 7947.

[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 $\bar{s}$.

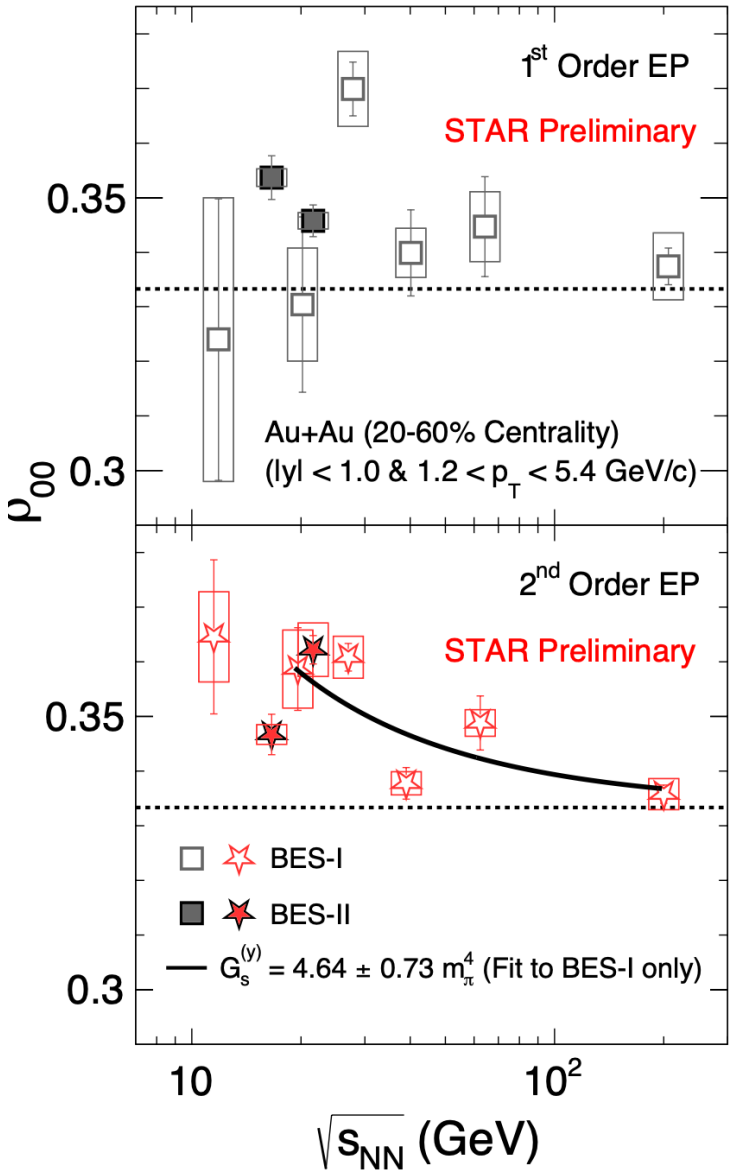
Potential Contributions to ϕ-meson ρ_{00}

Physics Mechanism	ρ_{00}	
Fragmentation of polarized quarks[1]	$\leqslant 1/3$	~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.

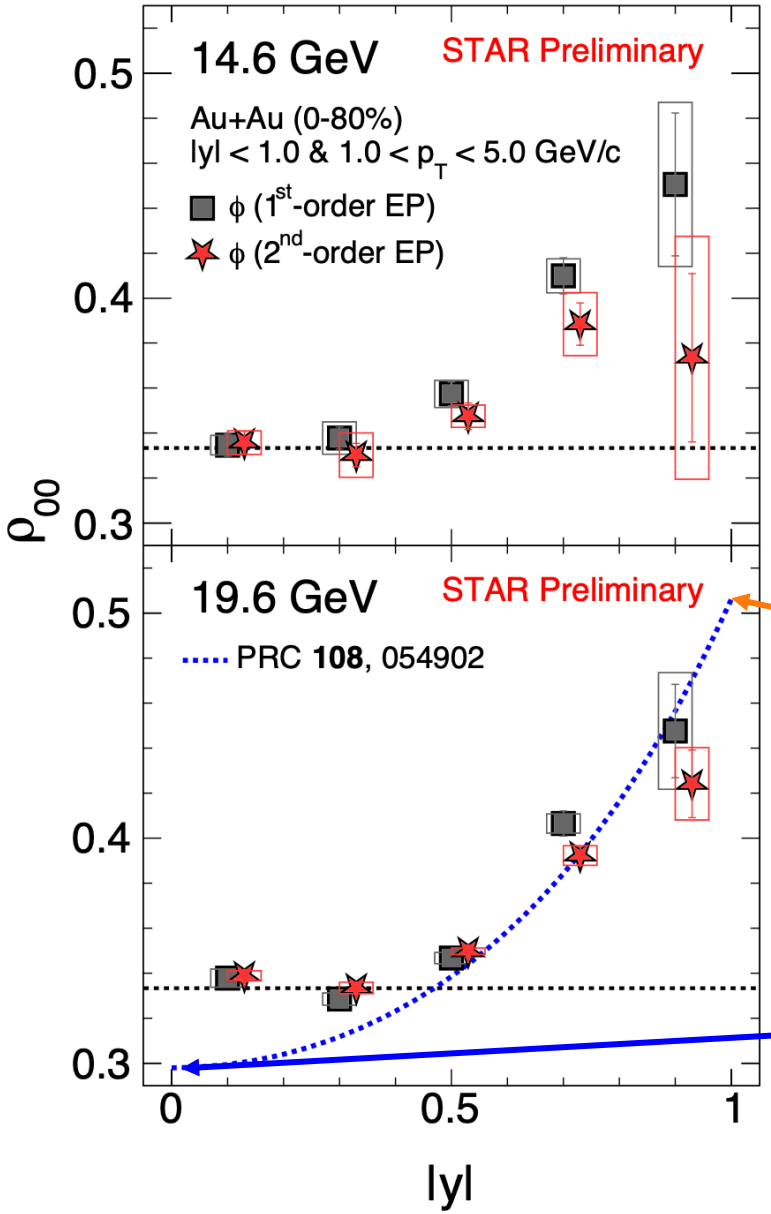
ϕ-meson $\sqrt{s_{NN}}$-dependent ρ_{00} [BES-I, BES-II]



- 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.

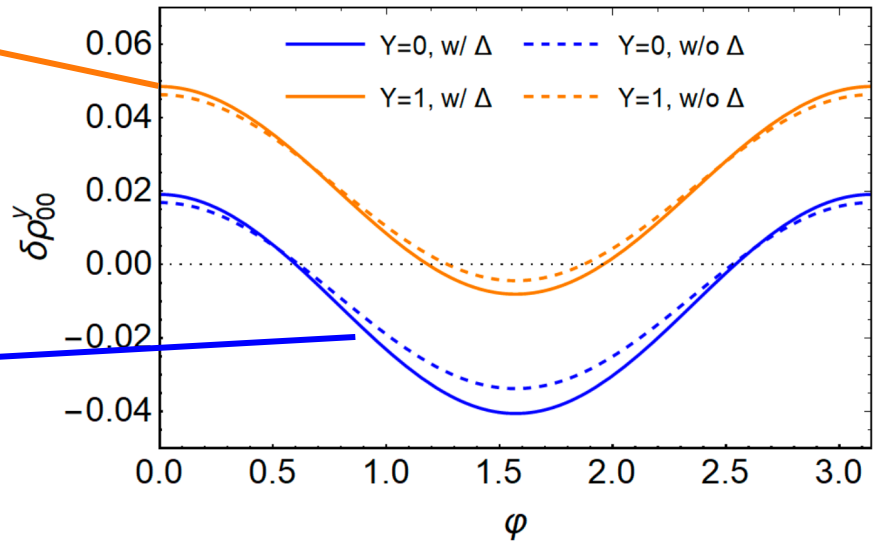
ϕ-meson rapidity-dependent ρ_{00} [BES-II]



- 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 $\rho_{00} < 1/3$.

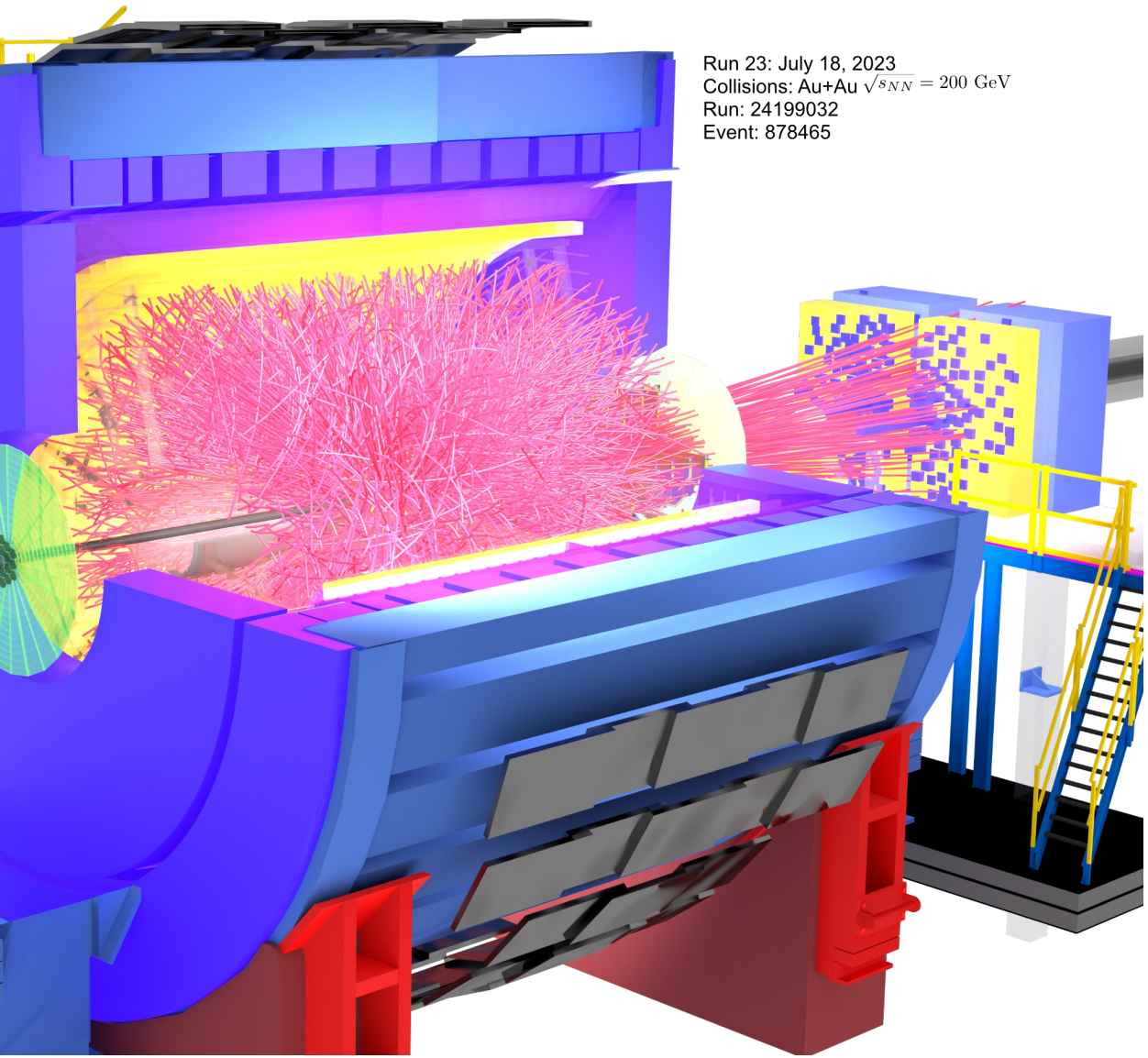
Integrated over φ

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

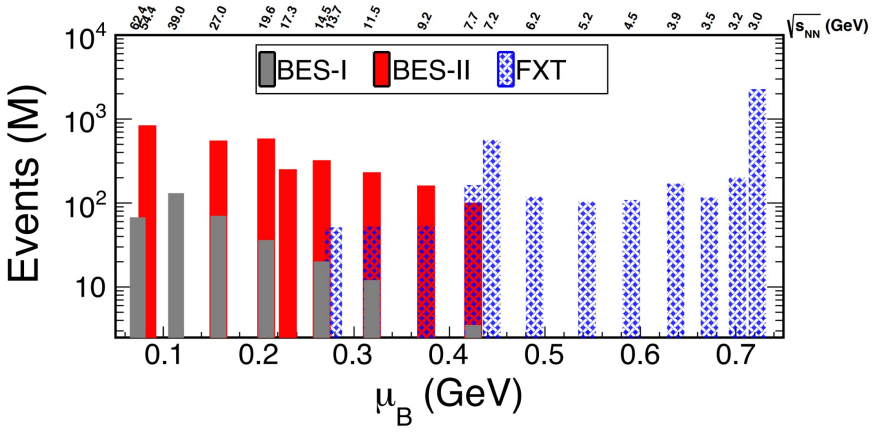
Forward Calorimeter System (FCS):

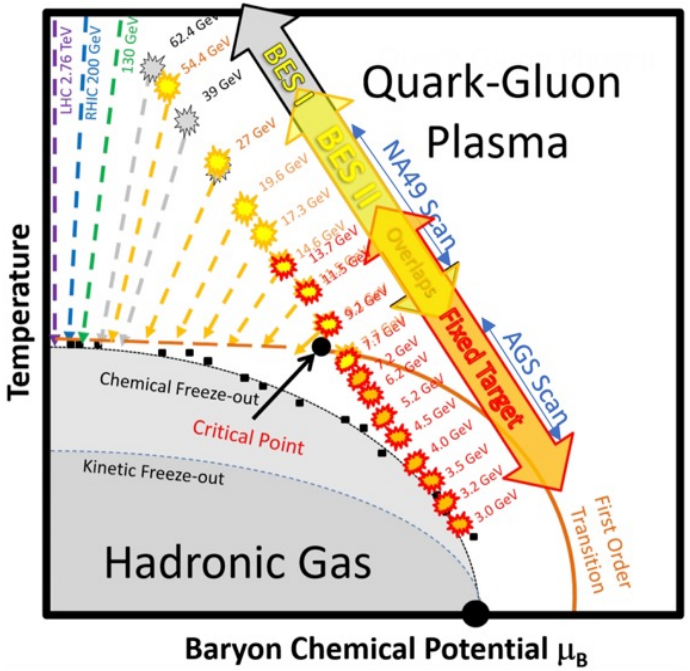
Forward Electromagnetic Calorimeter (ECal)
Forward Hadronic Calorimeter (HCal)

- 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 1st 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!