The 22nd International Conference on
Strangeness in Quark Matter
22-27 March, 2026, Los Angeles, CA

STAR Highlight II: Study of Small Systems and the Search for New, Exotic Physics

Jiangyong Jia for the STAR collaboration

Stony Brook University and BNL

Stony Brook University
Brookhaven National Laboratory
Office of Science | U.S. Department of Energy
Supported in part by the U.S. DEPARTMENT OF ENERGY
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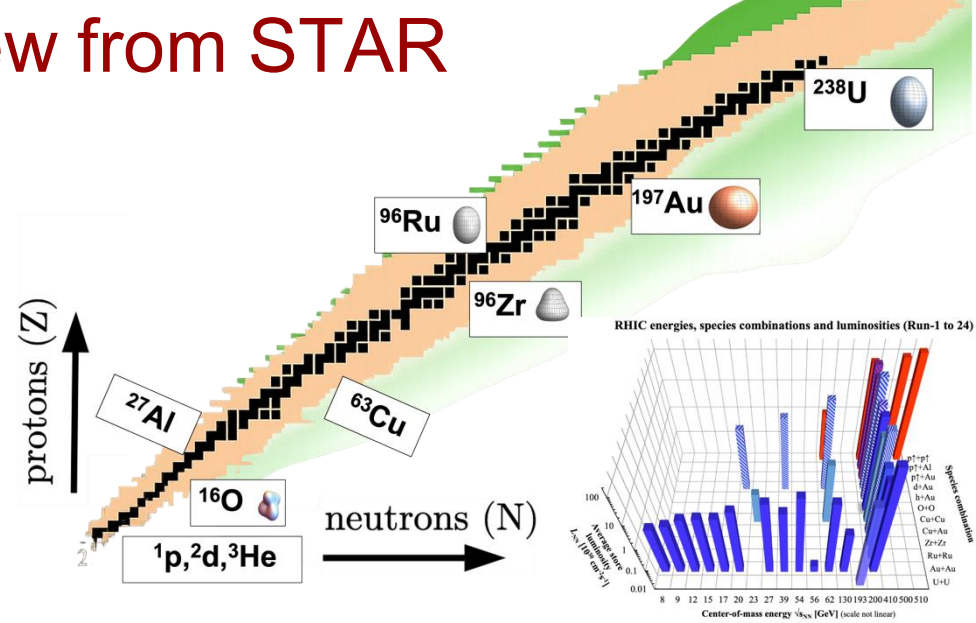
STAR collaboration

25 years of RHIC: what's new from STAR

~30 energies in Au+Au
12 species combinations

- Enable a rich physics program
- Will keep us busy for 10+ years



- Exotic searches and UPC physics
  - Unstable nuclei (^{4}Li, ^{5}Li), muonic atoms (K-μ), coherent photoproduction
- The onset of QGP signature in O+O collisions
  - Jet quenching, quarkonium, thermal radiation, anisotropic flow.
- New measurements of radial flow and its fluctuations
  - c_s^2 extraction, mean-p_T fluctuations, sensitivity to bulk viscosity
- Polarization and spin correlations
  - ϕ spin density matrix, s-$\bar{s}$ correlations

Exotic searches and UPC physics

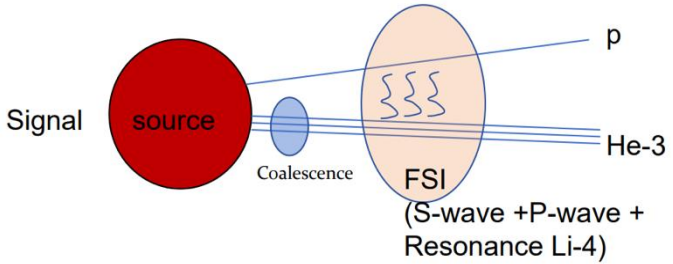
Unstable ^{4}Li and ^{5}Li in dense medium at 3 GeV

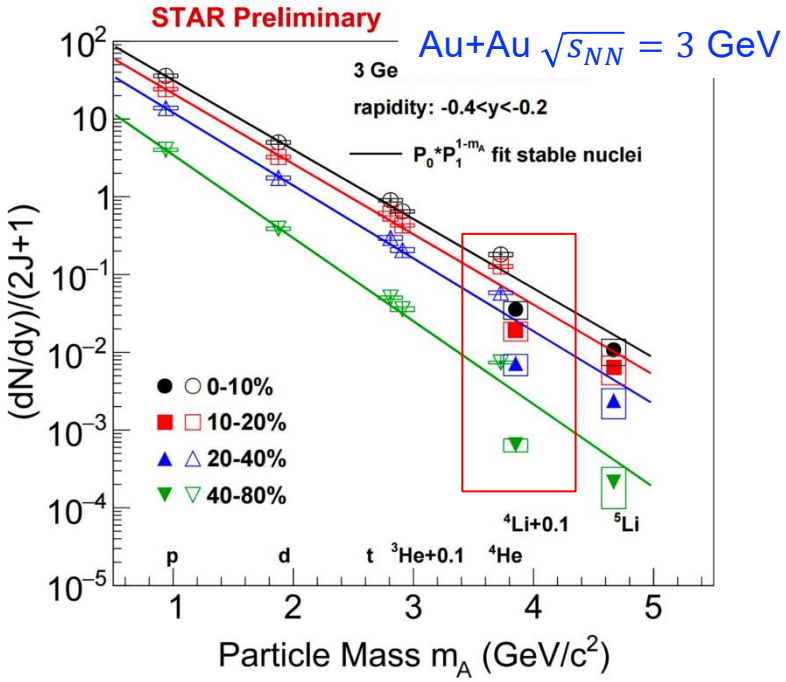
Talk: Junlin Wu (Tue)

$^4Li \rightarrow {}^3He + p$ τ~30fm/c

$^5Li \rightarrow {}^4He + p$ τ~120fm/c

The coalescence into transient resonances is coupled with the scattering process





Novel method developed to correct for FSI interactions

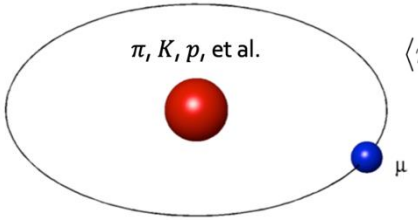
Yield of ^{4}Li is significantly lower than that of ^{4}He. i.e. deviation from coalescence baseline

Unstable light nuclei provide a unique way to test light-ion production mechanism

Evidence of muonic atom: K-μ

Talk: Xiaofeng Wang (Tue)

A muon-hadron bound state



$$\langle r^{\mathrm{orbit}} \rangle \simeq \frac{\hbar}{Z\alpha\, m_r c}\, n^2$$

Joseph I. Kapusta and Agnes Mocsy, Phys. Rev. C 59, 2937–2940 (1999);
Xiaofeng Wang et al. Phys. Lett. B 861,139242(2025)

- Yield is enhanced in HIC via EM coalescence.

$$\frac{dN_a}{dyd^2p_{T,a}} = \frac{4\pi}{3}(2\alpha\hbar c/r_0)^{3/2} m_{\mathrm{red}}^{1/2} \frac{dN_h}{dyd^2p_{T,h}} \frac{dN_l}{dyd^2p_{T,l}}$$

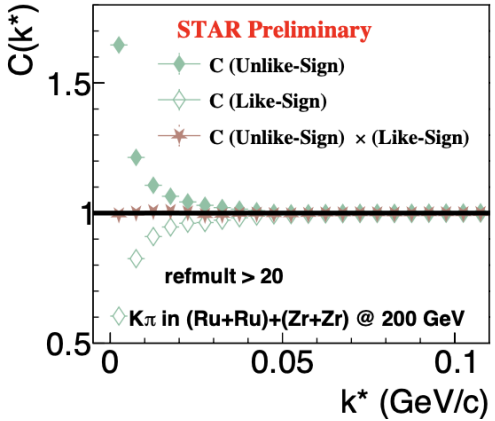
- Sensitive to yield of soft μ from QGP radiation (p_T~0.2 GeV/c)
- Dissociation in material in flight → shift in M_{inv}

$$\delta m \equiv M_{inv} - m_\mu - m_{hadron}$$

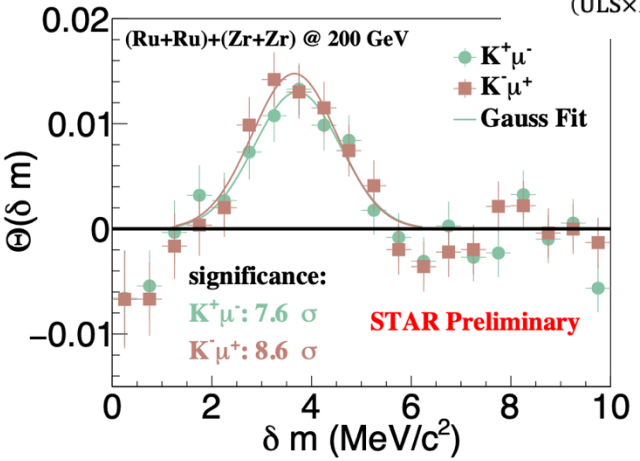
- Measure muonic atoms via K-μ momentum correlations

$$\Theta \equiv \frac{(\mathrm{ULS}\times\mathrm{LS})_{same\ event}}{(\mathrm{ULS}\times\mathrm{LS})_{mixed\ event}} - 1$$

Suppress coulomb correlation via ULS x LS



Ru+Ru, Zr+Zr
$\sqrt{s_{NN}} = 200$ GeV

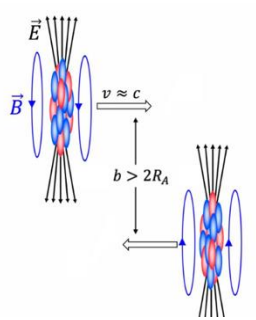


Significant signal observed, work ongoing to understand acceptance corrections

J/ψ and K^+K^- photoproduction in UPC

Talk : Zengzhi Li (Wed)

Poster : Luobing Wang (Wed)



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Photon-photon

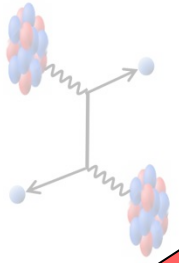

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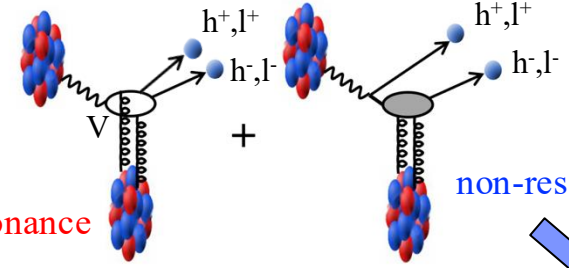
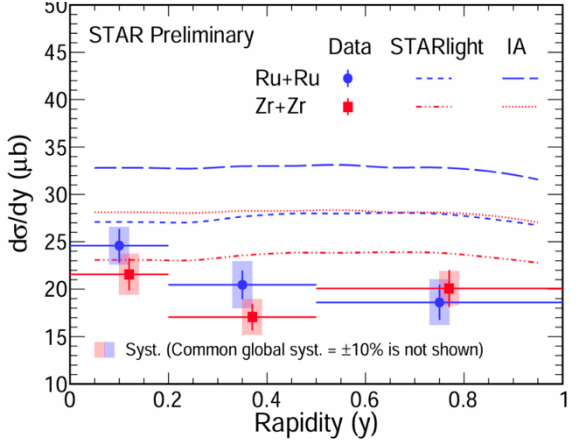
Photo-nuclear



resonance

non-resonance: Drell-Soding

$\gamma^*+A \rightarrow J/\psi + A^* \rightarrow e^+e^- + A^*$

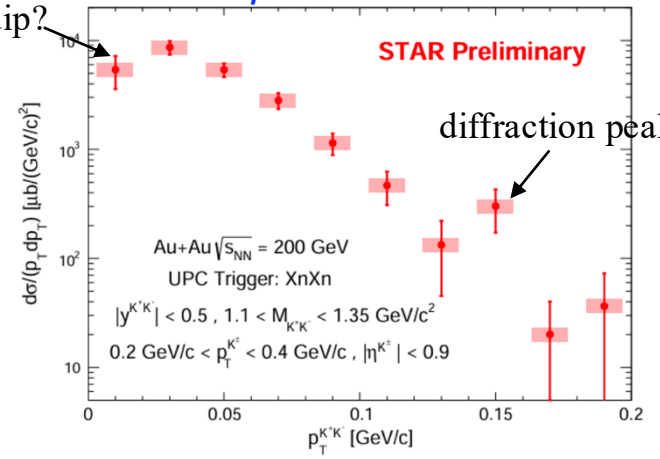


Coherent J/ψ yields suggest strong suppression compared to baseline models

$\gamma^*+A \rightarrow K^+ + K^- + A^*$

Interference dip?

diffraction peak?



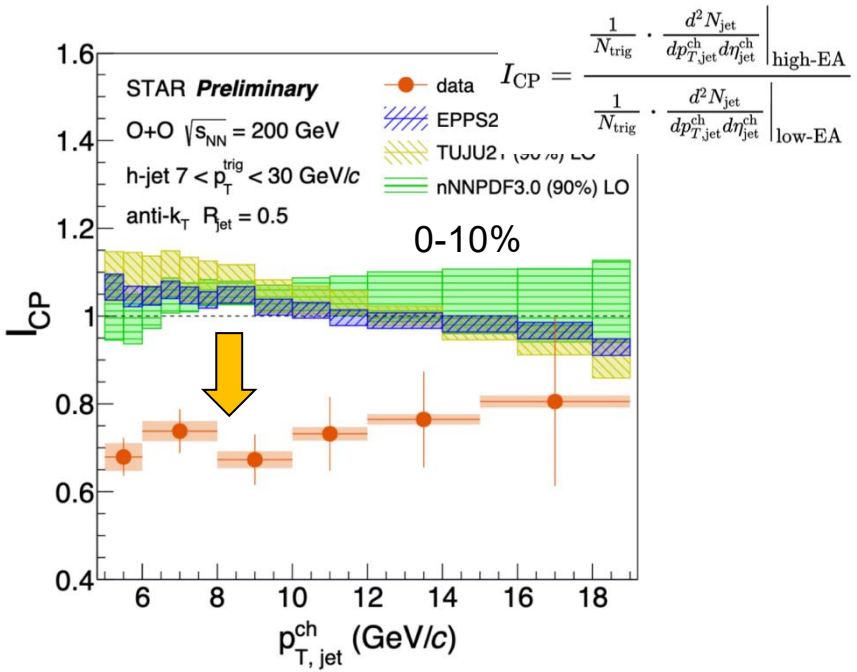
Most precise measurement of coherent non-resonant K+K- production

Search for onset of QGP signature in O+O

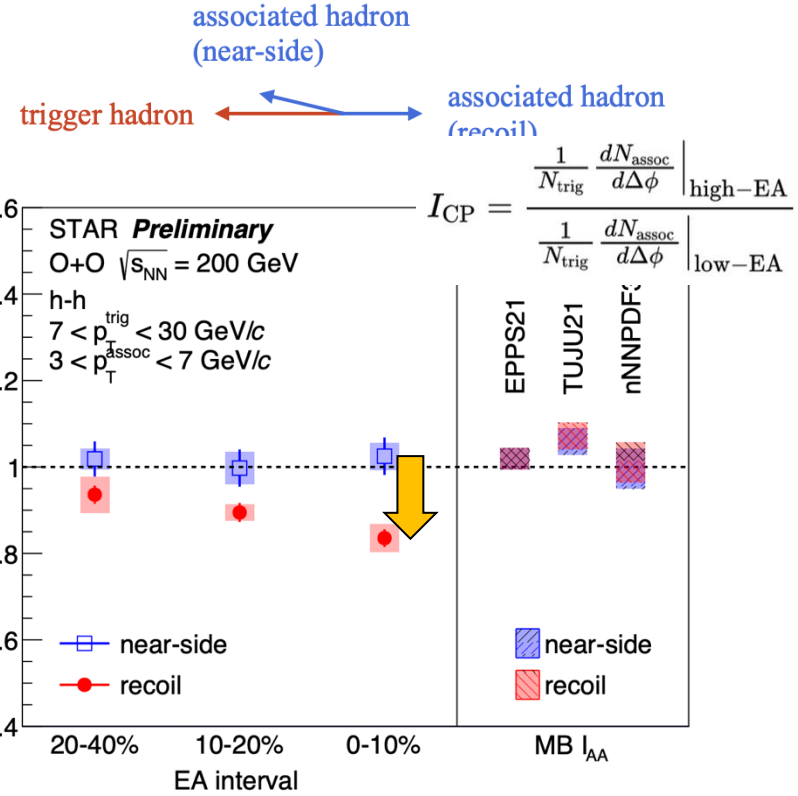
Evidence of jet quenching in O+O

Sijie Zhang Light Ion Workshop 2025

hadron-jet correlations



hadron-hadron correlations



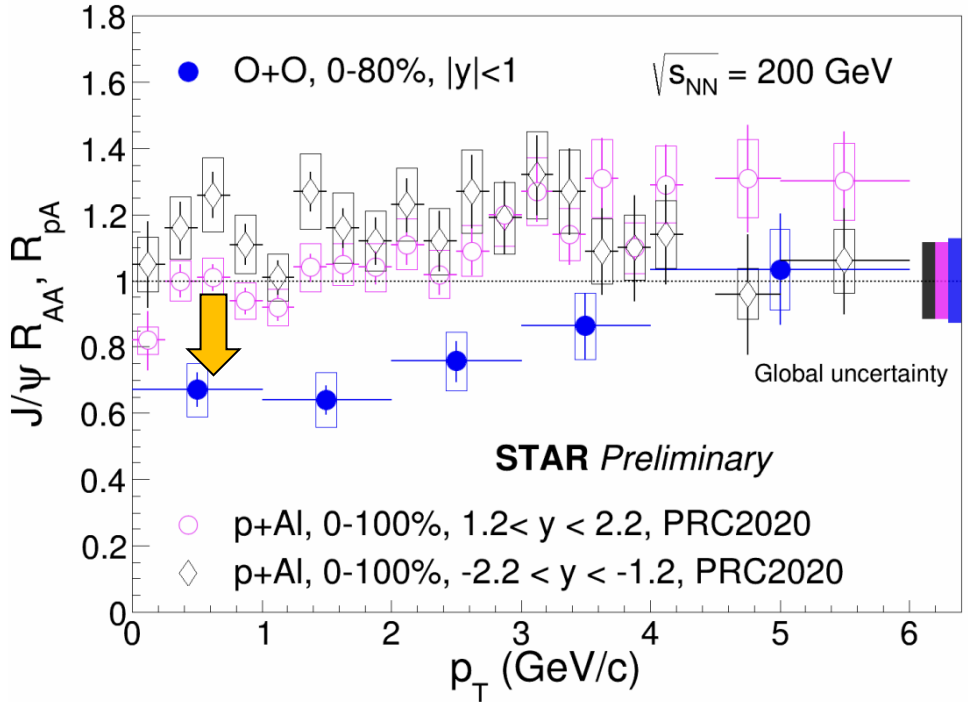
Event activity (EA) defined in forward detectors to reduce bias

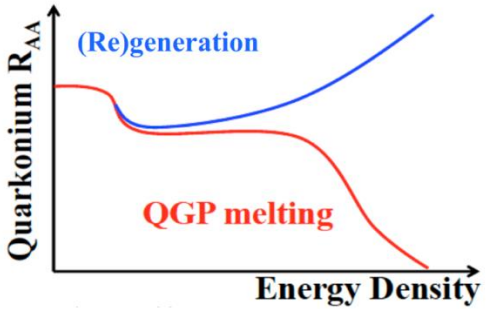
J/ψ production in O+O

Talk: Aoke Zhang (Wed)

Sensitive to both hot QGP medium and cold nuclear matter effects.

- O+O has small CNM effects, provides an important anchor point.





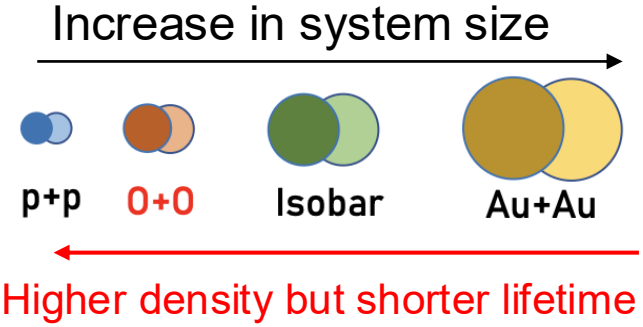
System size

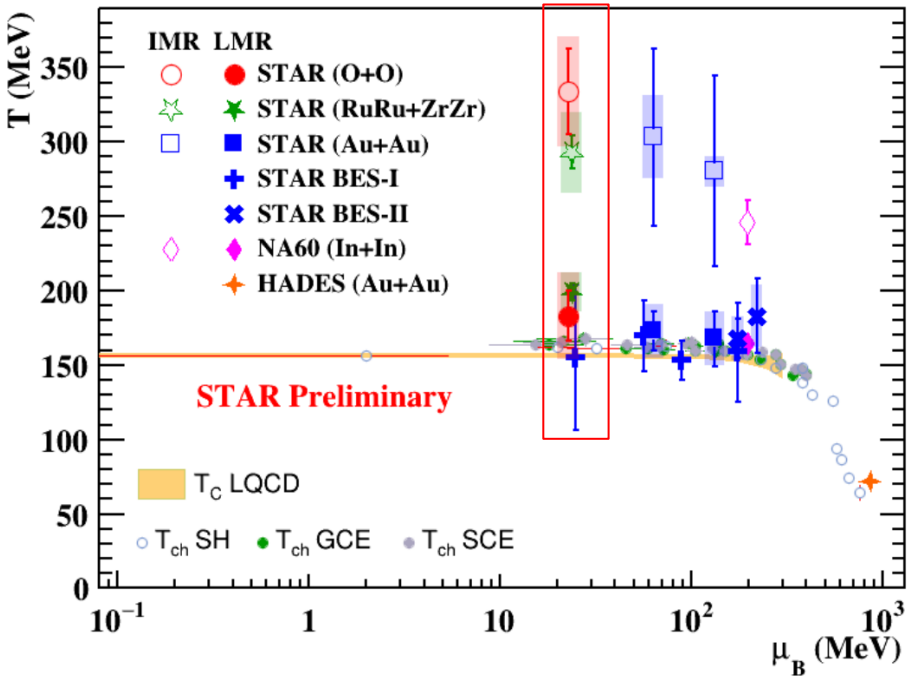
Clear suppression beyond the expected CNM effects→ hot medium effect?

Dilepton production in O+O

Talk: Zihan Liu (Tue)

Dileptons are thermometer of QGP



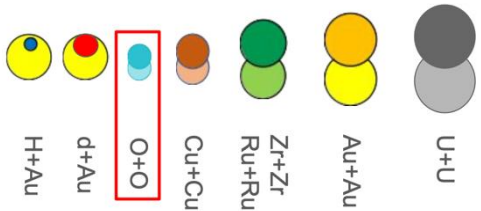


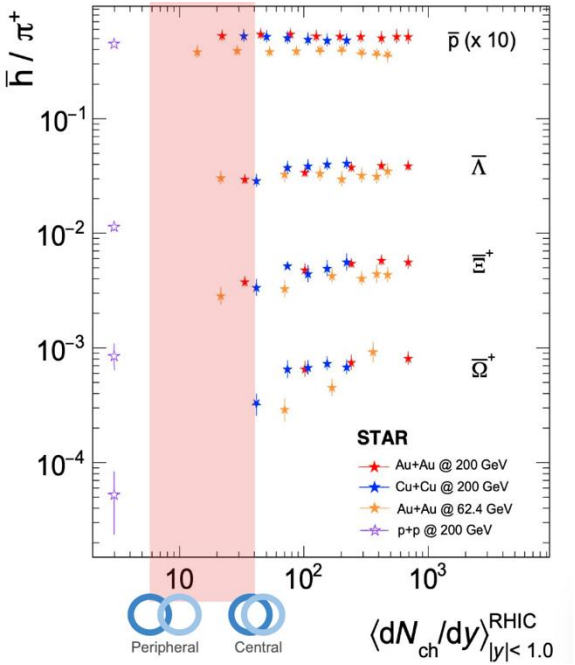
Temperature measured in LMR (near phase transition) and IMR (QGP dominant)
Temperature in O+O is as high as in large isobar systems

Consistent with thermal radiation from the QGP medium

Strangeness production in O+O

Talk: Iris Ponce (Tue)



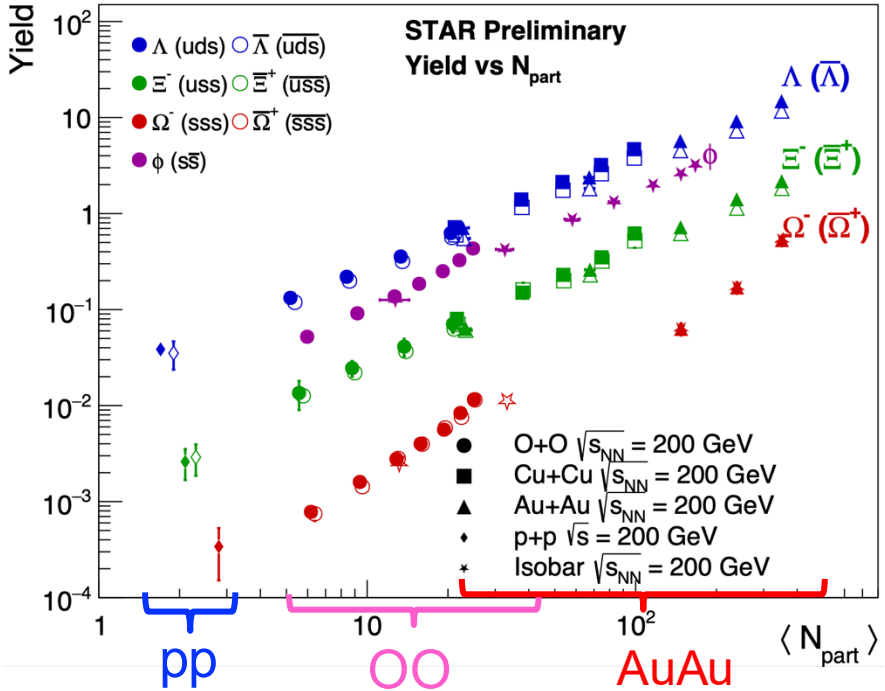


Motivation:

- strangeness/pion ratios increase with N_{ch} at RHIC, like LHC.
- but large gap at onset region, which O+O data can fill.

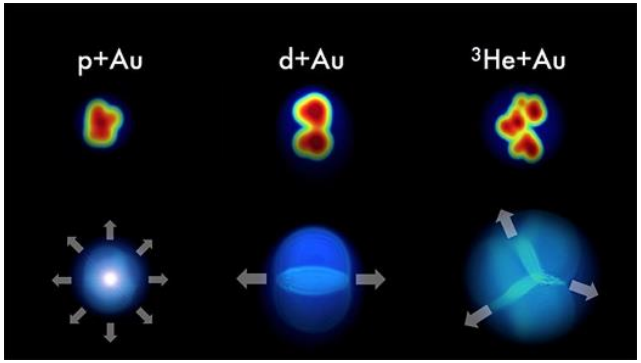
Result:

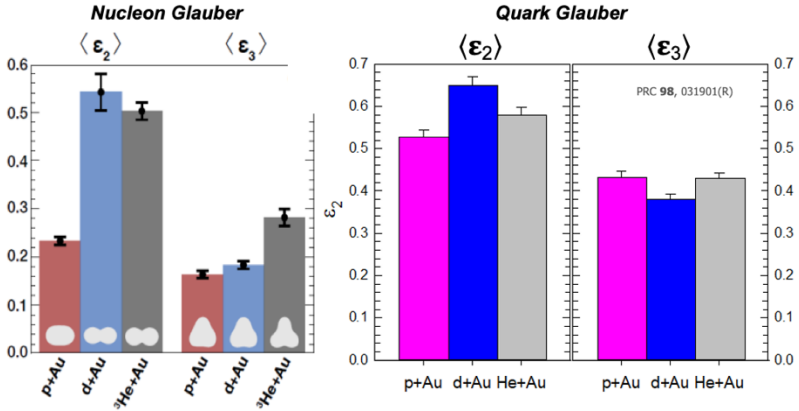
- Yields of Ω/ϕ, $\bar{\Lambda}/\Lambda$, Ξ^-/Ξ^+,Ω^-/Ω^+ …vs N_{part}
- We see smooth transition from small to large systems



Flow in small systems

Goal: Show that flow is driven by initial-state geometry though QGP response





Challenge: p/d/^{3}He+Au ordering reflects interplay between nucleonic and subnucleonic fluctuations

$$\varepsilon_2^{^3\mathrm{HeAu}} \approx \varepsilon_2^{d\mathrm{Au}} > \varepsilon_2^{p\mathrm{Au}} \qquad \varepsilon_2^{^3\mathrm{HeAu}} \approx \varepsilon_2^{d\mathrm{Au}} \gtrsim \varepsilon_2^{p\mathrm{Au}}$$
$$\varepsilon_3^{^3\mathrm{HeAu}} \approx \varepsilon_3^{d\mathrm{Au}} > \varepsilon_3^{p\mathrm{Au}} \qquad \varepsilon_3^{^3\mathrm{HeAu}} \approx \varepsilon_3^{d\mathrm{Au}} \approx \varepsilon_3^{p\mathrm{Au}}$$

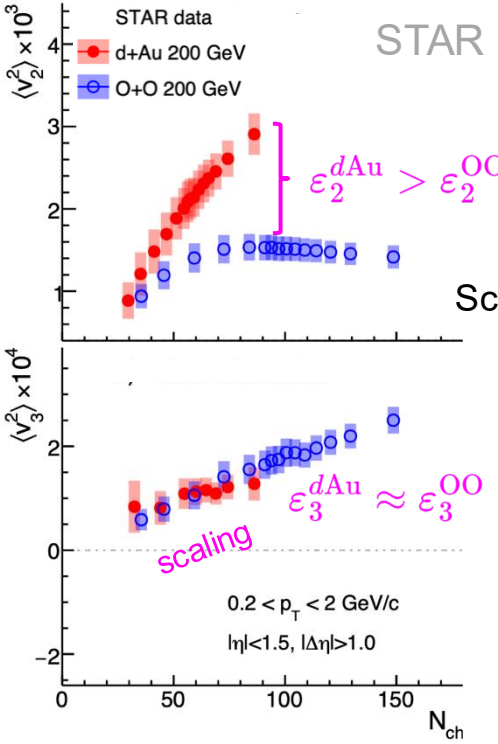
Constrain subnucleonic fluctuations by comparing d+Au with ^{16}O+^{16}O

NB: Nucleon configurations of deuteron or ^{16}O are well constrained in ab initio models.

Compare d+Au and O+O flow data

Poster: Chunjian Zhang (Wed)

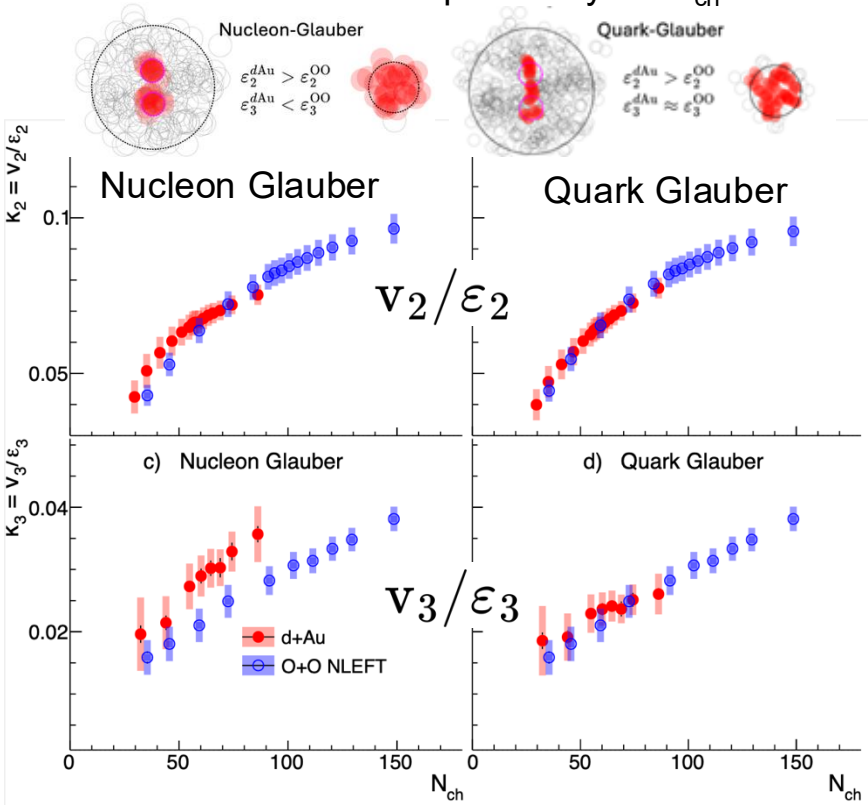
Characteristic ordering driven by geometry is observed



STAR 2510.19645

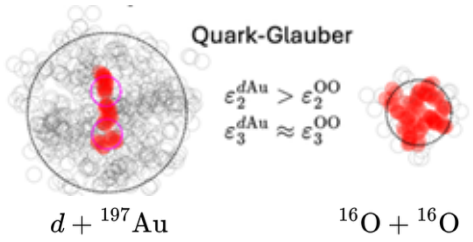
Scale by eccentricity

$k_n = v_n/\varepsilon_n$ reflecting hydrodynamic response, should depend only on N_{ch}



Better scaling achieved when considering substructure fluctuations

Compare d+Au and O+O elliptic flow fluctuations



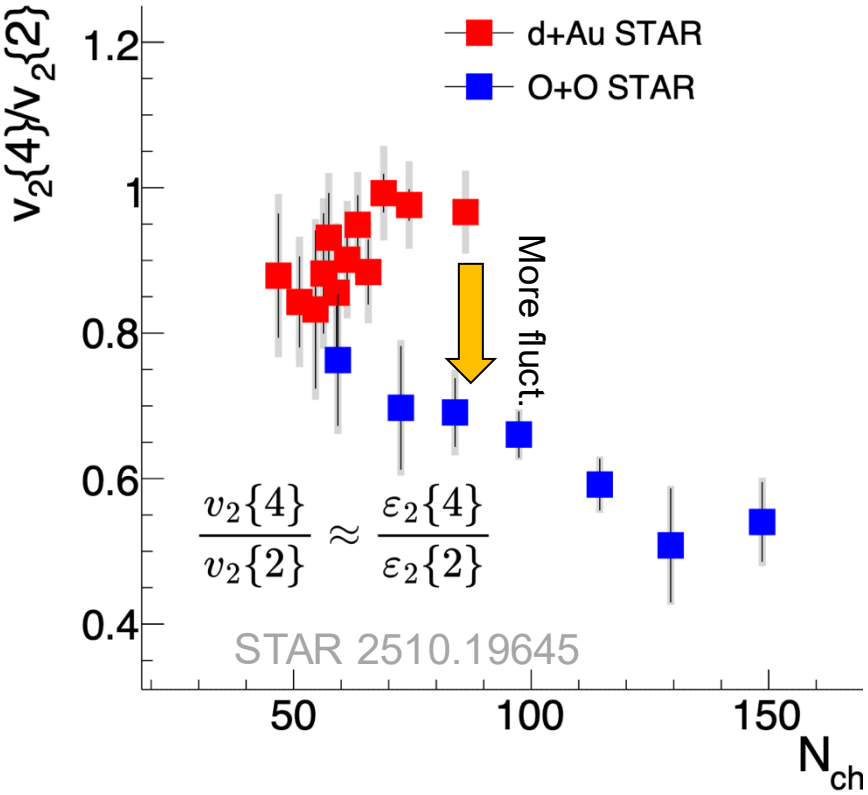
Small fluctuations in dAu

$$\frac{v_2^{dAu}\{4\}}{v_2^{dAu}\{2\}} \approx \frac{\varepsilon_2^{dAu}\{4\}}{\varepsilon_2^{dAu}\{2\}} \approx 0.9$$

Large fluctuations in OO

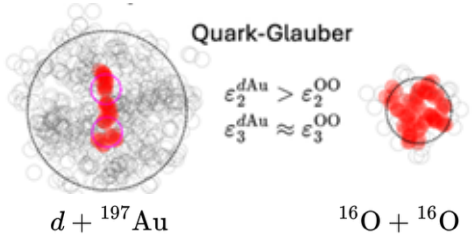
$$\frac{v_2^{OO}\{4\}}{v_2^{OO}\{2\}} \approx \frac{\varepsilon_2^{OO}\{4\}}{\varepsilon_2^{OO}\{2\}} \sim 0.6$$

Compare to ATLAS data
(re-match to STAR centrality)



Fluctuations universal with $\sqrt{s_{NN}}$ despite x10 (x3) increase in energy (multiplicity)

Compare d+Au and O+O elliptic flow fluctuations



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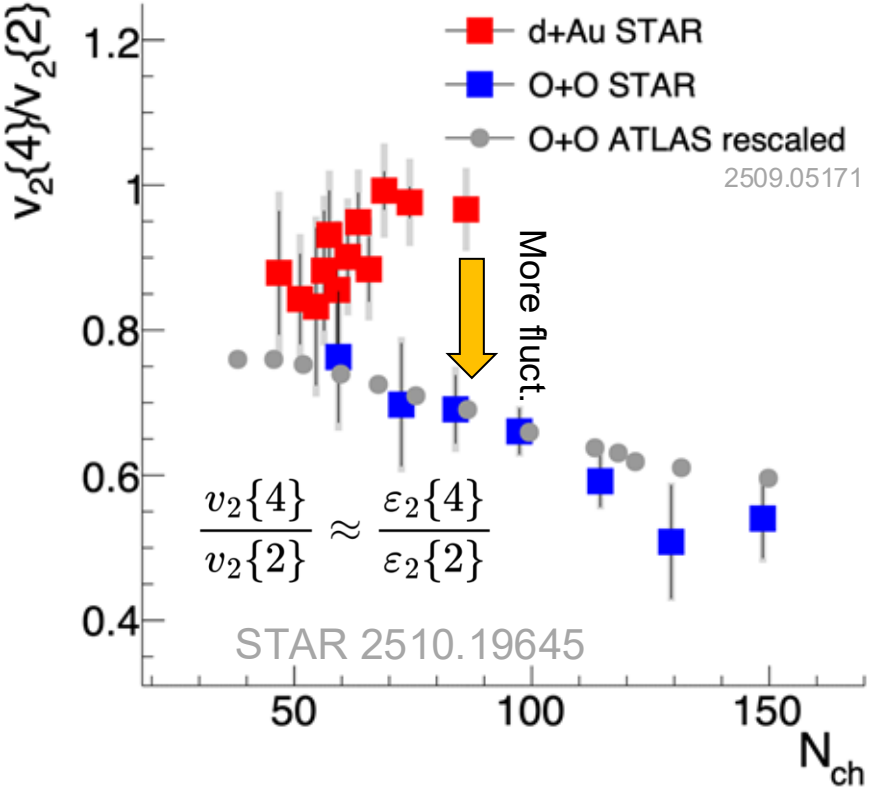
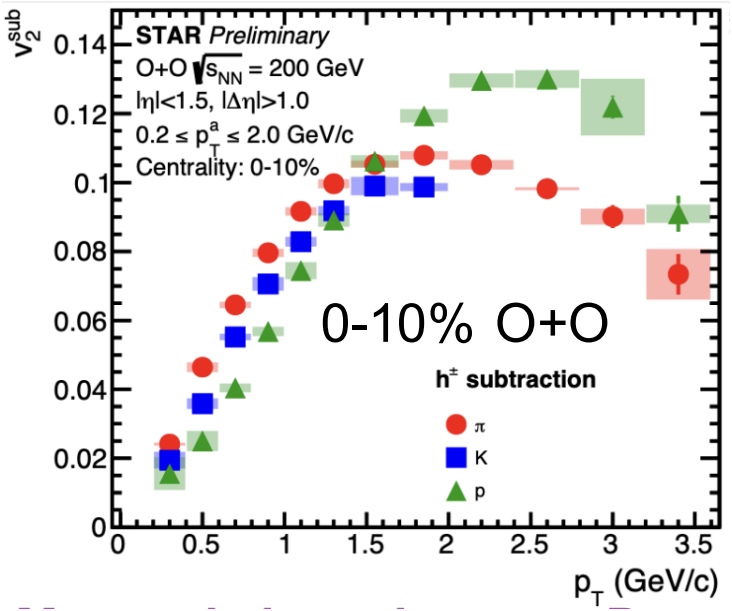


Fluctuations universal with $\sqrt{s_{NN}}$ despite x10 (x3) increase in energy (multiplicity)

π/K/p elliptic flow in central O+O collisions

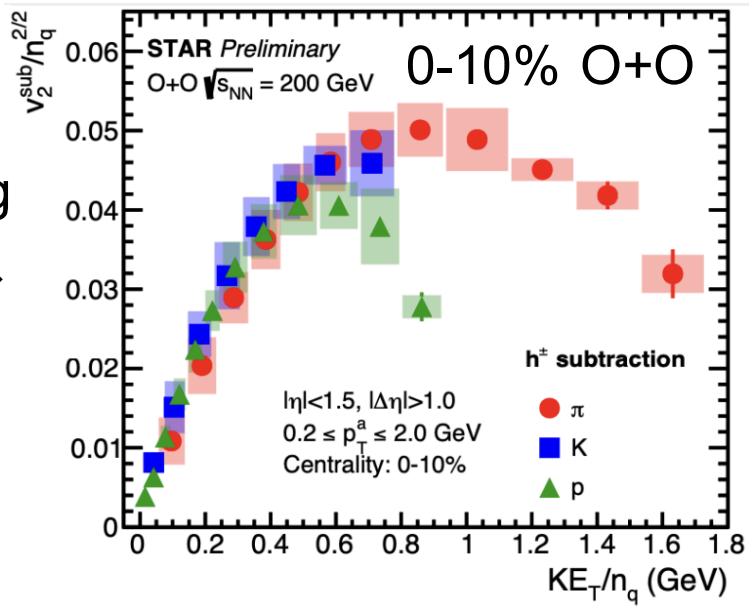
Poster: Souvik Paul (Wed)

v_2 for π/K/p (non-flow subtracted)



NCQ-scaling

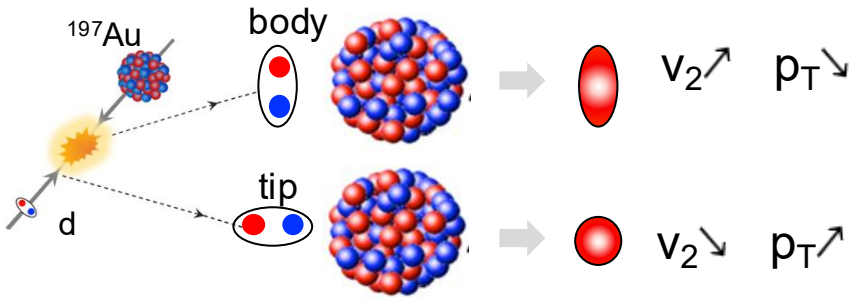
Scaled by number of quarks



- Significant hierarchy for identified particles expected for v_2.
- Follow NCQ-scaling at low p_T, but deviation at higher p_T.

Impact of prolate shape of deuteron

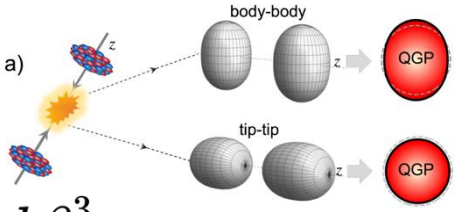
Poster: Zaining Wang (Wed)



smaller $\langle v_2^2 \delta p_T \rangle$

$$\langle v_2^2 \delta p_T \rangle = a - b\beta_2^3$$

Similar to U+U collisions



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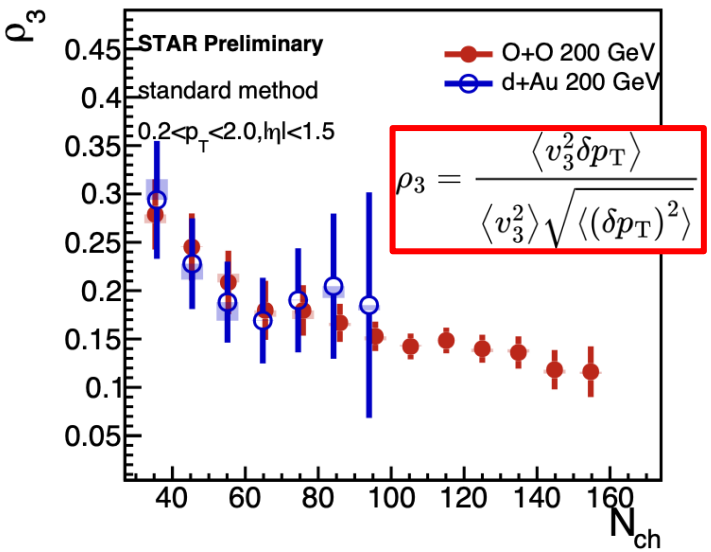
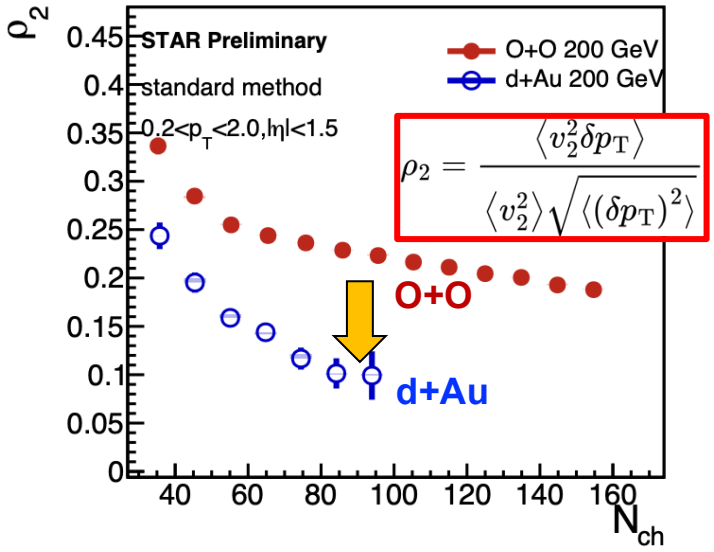


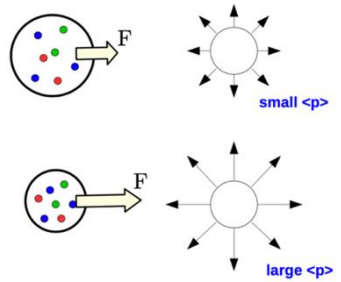


Behavior of $\langle v_2^2 \delta p_T \rangle$ consistent with QGP response to the prolate shape of deuteron

Radial flow and its fluctuations

Radial flow observables

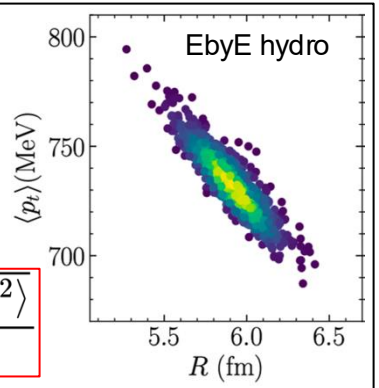
Large event-by-event fluctuations



$$p_T \approx p_T^{\mathrm{th}} + m\langle v_T \rangle$$

Response to size fluctuations

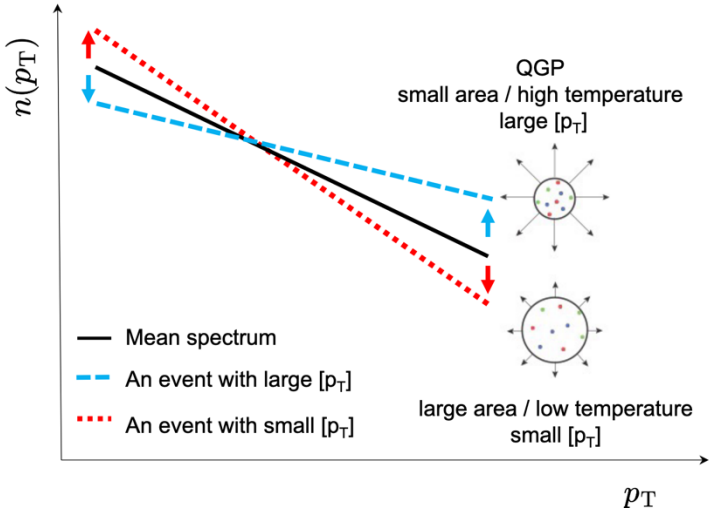
$$\delta p_{\mathrm{T}}/\langle [p_{\mathrm{T}}] \rangle \approx -\delta R/\langle R \rangle$$



Integral: $\langle [p_{\mathrm{T}}] \rangle$, $v_{0,\mathrm{int}} \equiv \dfrac{\sqrt{\langle (\delta [p_{\mathrm{T}}])^2 \rangle}}{\langle [p_{\mathrm{T}}] \rangle}$

Fluctuation of local yield $\delta n(p_T)$ and $\delta[p_T]$ are correlated→ measure $\langle \delta n(p_T) \delta[p_T] \rangle$.

differential: $v_0\,(p_{\mathrm{T}}) v_{0,\mathrm{int}} = \dfrac{\langle \delta n(p_{\mathrm{T}}) \delta\,[p_{\mathrm{T}}] \rangle}{\langle n(p_{\mathrm{T}}) \rangle \langle [p_{\mathrm{T}}] \rangle}$



Extraction of speed of sound from $\langle p_T \rangle$

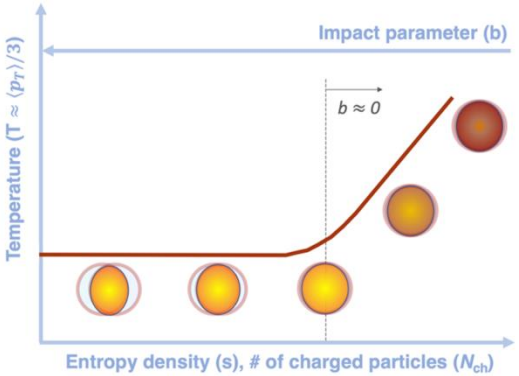
Talk: Caleb Broodo (Tue)

$\langle p_T \rangle$ increase with N_{ch} in UCC are related to the Temperature fluctuations → c_s^2

(1)
$$c_s^2 = \frac{dP}{d\varepsilon} \approx \frac{d(\ln \langle p_T \rangle)}{d(\ln N_{ch})}$$
1908.09728

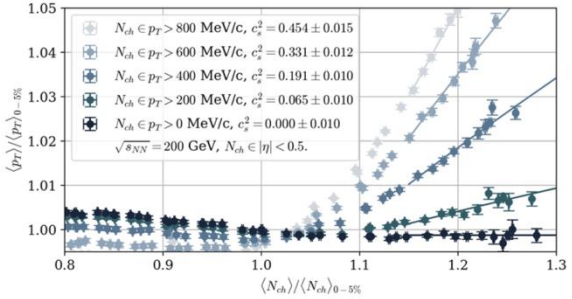
or

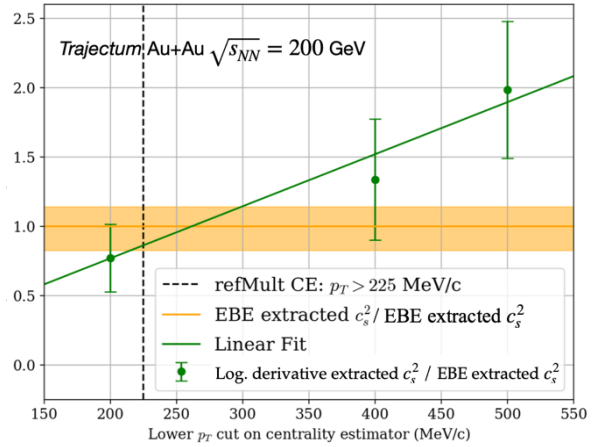
(2) e-by-e model fluctuations
$$\frac{\Delta_{p_T}}{\langle p_T \rangle} = c_s^2 \frac{\Delta_N + \delta}{N}$$
2501.02777



Enforcing the following consistency in Trajectum model:
- c_s^2 obtained via (2) by imposing constraint $\{\delta^3\}=0$
- c_s^2 obtained via (1) for N_{ch} defined with $p_T > p_{Tmin}$
- vary p_{Tmin} for N_{ch} until (1) agree with (2)

Relation (1) is broken by acceptance effects in defining centrality estimator N_{ch}.



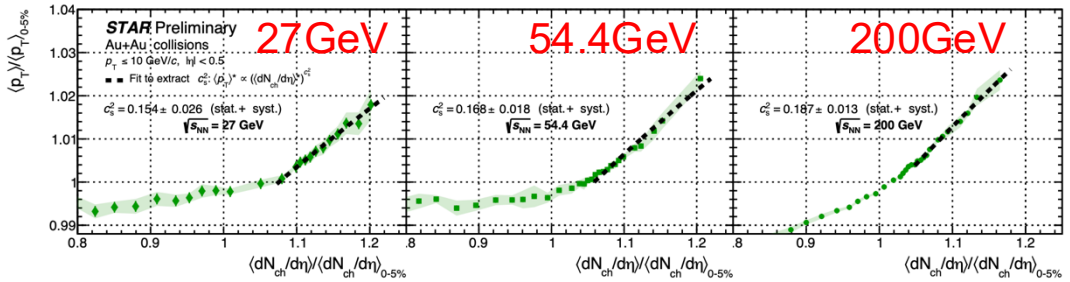


suggests $p_{T,min}$ =0.225 GeV for centrality estimator

Extraction of speed of sound from $\langle p_T \rangle$

Talk: Caleb Broodo (Tue)

Extract c_s^2 in three energies:

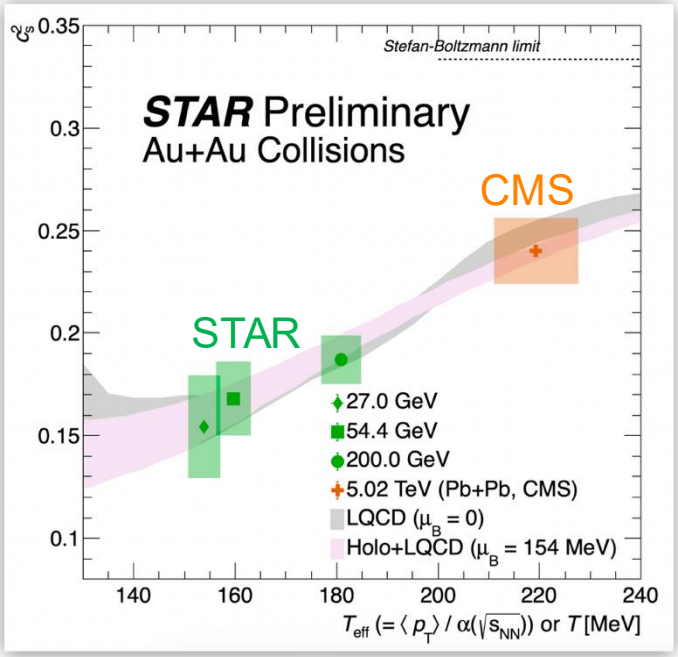


To estimate T_{eff}:

- First estimate $\langle p_T \rangle$ by extrapolating to zero p_T.
- $T_{eff} = \alpha \langle p_T \rangle / 3$, α estimated from hydro model, close to 1

2403.06052

First extraction of temperature dependence of c_s.
Result consistent with LQCD!



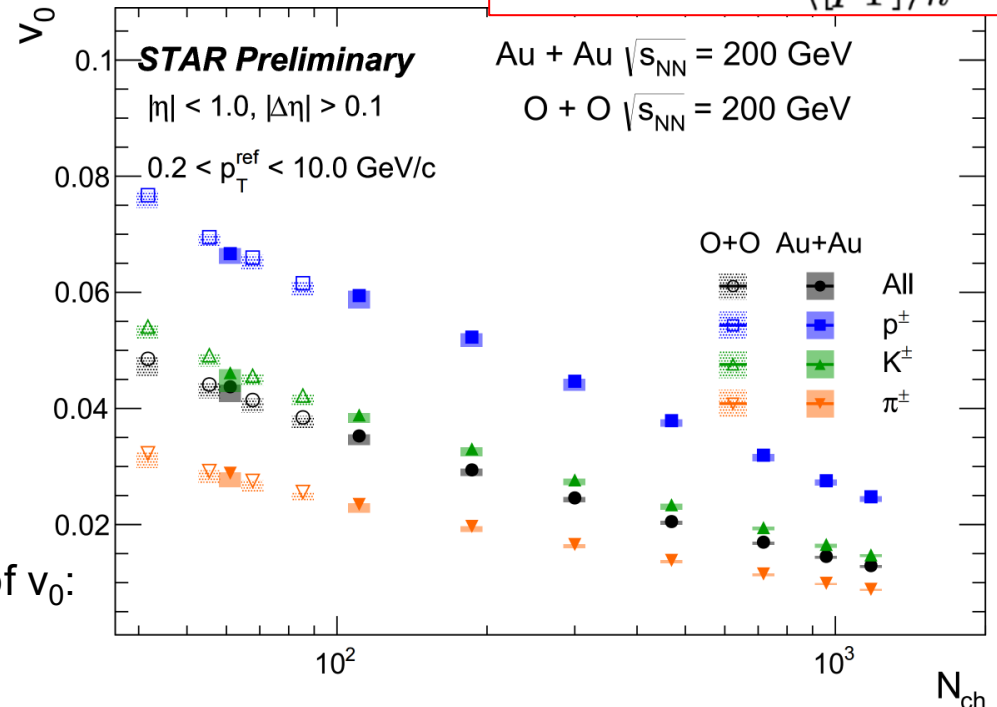
v_0: Integral p_T fluctuation at 200 GeV

Talk: Zaining Wang (Tue)

- Measured for charged hadrons, protons, kaons and pions in OO to AuAu.
- larger fluctuation signals for heavier particles.
- v_0 follows an approximate power scaling $v_0 \sim 1/\sqrt{N_{ch}}$.

Expected for independent source model

$$v_{0,\mathrm{PID}} = \frac{\langle \delta[p_T]_{\mathrm{PID}} \delta[p_T]_h \rangle}{\langle [p_T] \rangle_h}$$



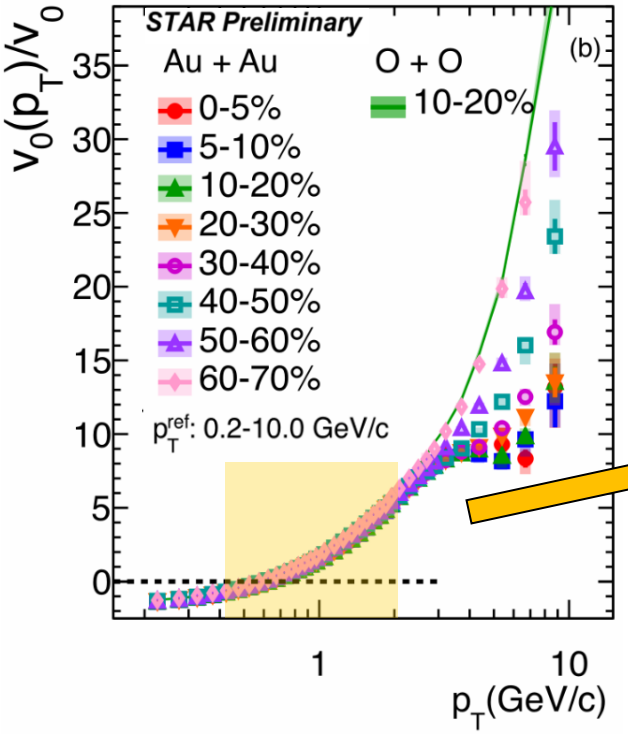
Also see Rutik's talk for $\sqrt{s_{NN}}$ dependence of v_0:

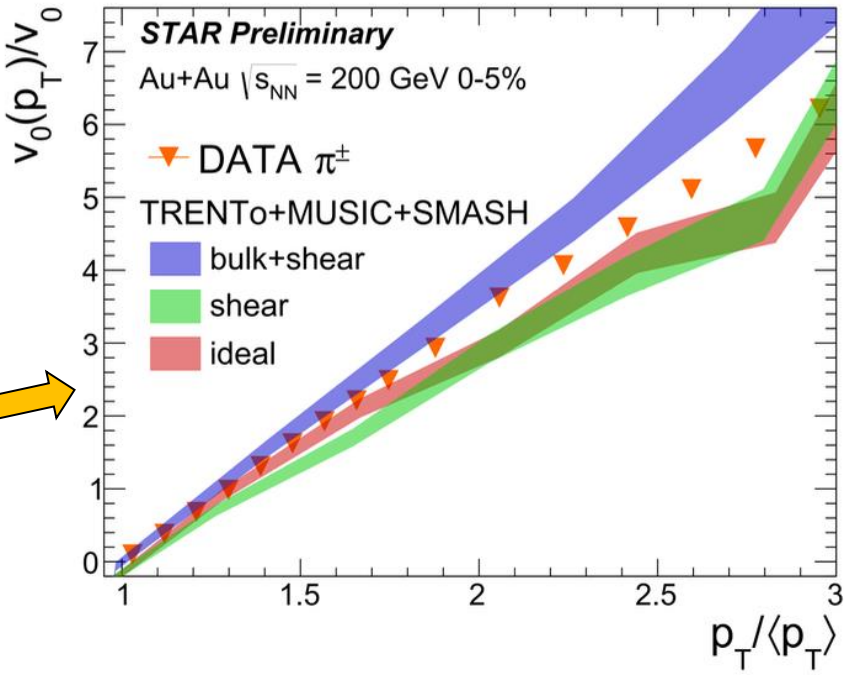
Talk: Rutik Manikandhan (Tue)

$v_0(p_T)$: p_T -differential fluctuations at 200 GeV

Talk: Zaining Wang (Tue)

$v_0(p_T)$ and v_0 are driven by size fluctuations, use $v_0(p_T)/v_0$ to take out overall fluctuations





Universal shape scaling across centrality and systems, except at high p_T

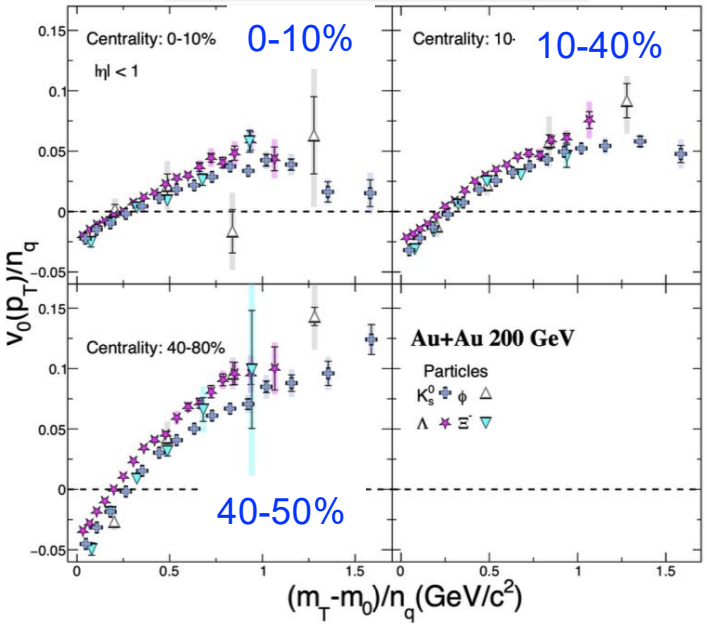
Intermediate p_T region shows clear sensitivity to bulk viscosity.

$v_0(p_T)$: strange hadron and its $\sqrt{s_{NN}}$ dep.

Talk: Yuli Kong (Tue)

PID (strange meson and baryons) dependence allows a detailed test of NCQ scaling

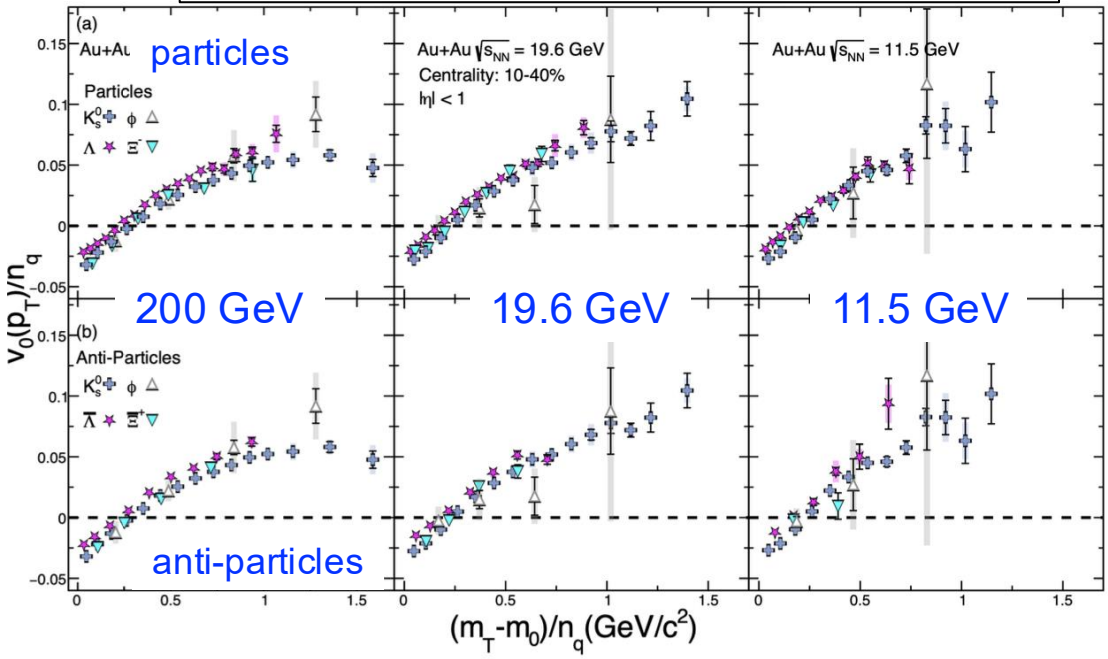
Centrality dependence at 200 GeV



deviation in more peripheral collisions

Look forward to theory predictions!

Energy dependence in 10-40% centrality collisions



approximately hold in broad $\sqrt{s_{NN}}$ range

signal also change weakly with $\sqrt{s_{NN}}$

Polarization and spin correlations

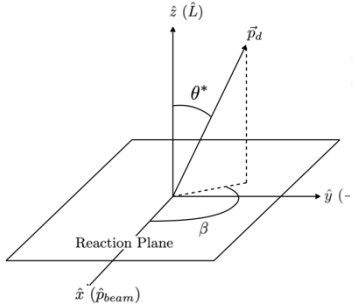
ϕ-meson spin alignment via $\phi(s\bar{s}) \rightarrow K^+K^-$

Talk: Gavin Wilks (Tue)

spin-density matrix

$$\rho = \begin{pmatrix} \rho_{-1-1} & \rho_{-1,0} & \rho_{-11} \\ \rho_{0-1} & \rho_{00} & \rho_{01} \\ \rho_{1-1} & \rho_{10} & \rho_{11} \end{pmatrix}$$

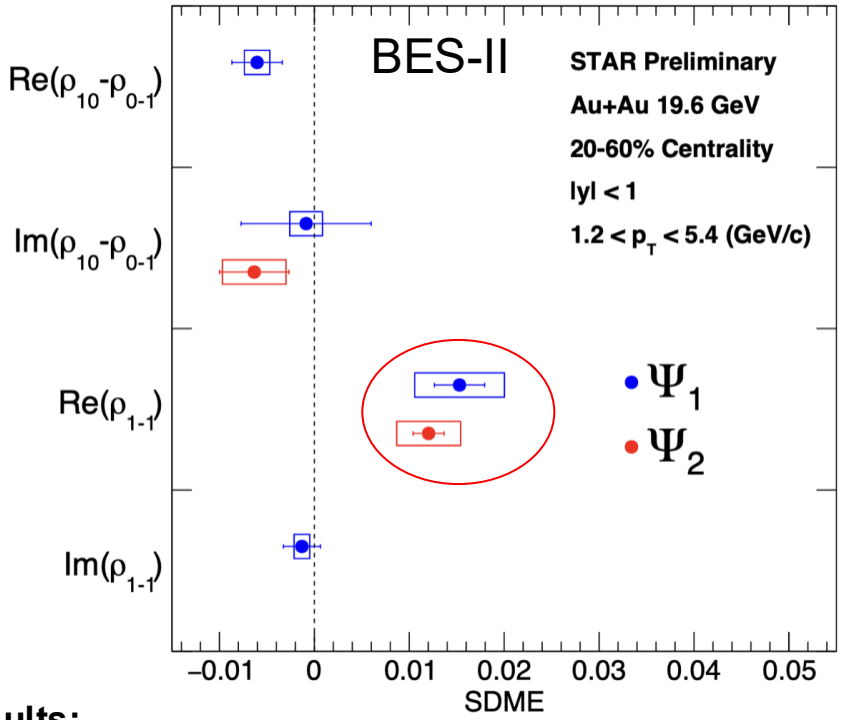
coordinate choice



general 2D distribution of daughter K

$$\frac{d^2N}{d\cos\theta^* d\beta} = \frac{3}{8\pi}\big[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* - \sqrt{2}\mathrm{Re}\,(\rho_{10}-\rho_{0-1})\sin 2\theta^*\cos\beta + \sqrt{2}\mathrm{Im}\,(\rho_{10}-\rho_{0-1})\sin 2\theta^*\sin\beta - 2\mathrm{Re}\,(\rho_{1-1})\sin^2\theta^*\cos 2\beta + 2\mathrm{Im}\,(\rho_{1-1})\sin^2\theta^*\sin 2\beta\big],$$

$\rho_{00} - 1/3 \sim 0.02$ at 19.6 GeV BES-I from Nature 614 244,2023



Motivation:

- Previous measurements assume off-diagonal terms are zero and only measure θ^* dep.$\rightarrow\rho_{00}$.
- Extend the measurement to both θ^* and β dependence to access the off-diagonal terms.
- ϕ has contribution from both s-$\bar{s}$ global polarization and spin correlations.

Results:

- First measurement in Au+Au with full 2D correction
- First evidence of non-zero off-diagonal term ρ_{1-1}!
- Signal is large, suggests non-zero s-$\bar{s}$ spin correlations.

s-$\bar{s}$ spin correlations

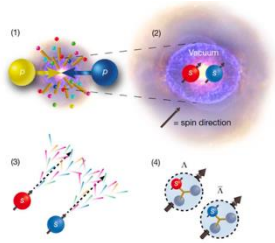
Talk: Tong Fu (Tue)

$$\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$$

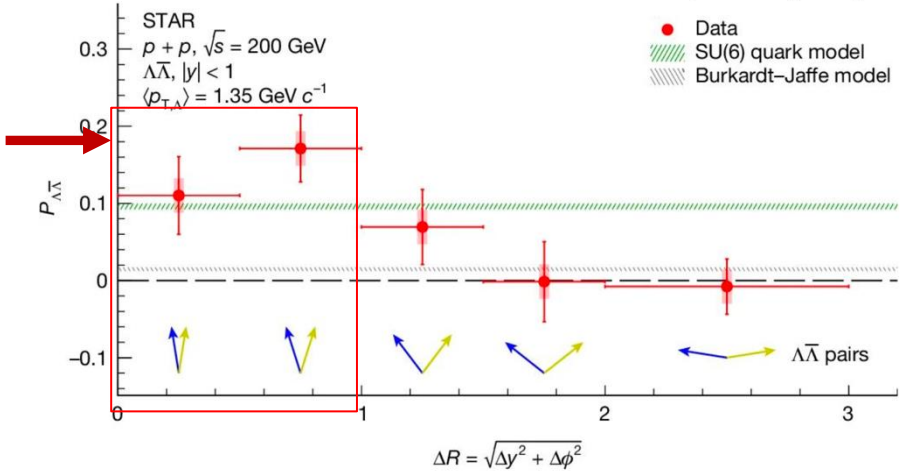
Such spin correlations was in fact observed in p+p collisions!

Measurement of $\Lambda\bar{\Lambda}$ correlation suggest maximum $s\bar{s}$ spin correlations:

Properties of QCD vacuum: $J^{PC} = 0^{++}$



STAR Collaboration. Nature 650, 65–71 (2026).



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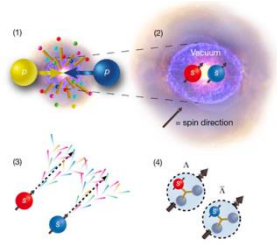
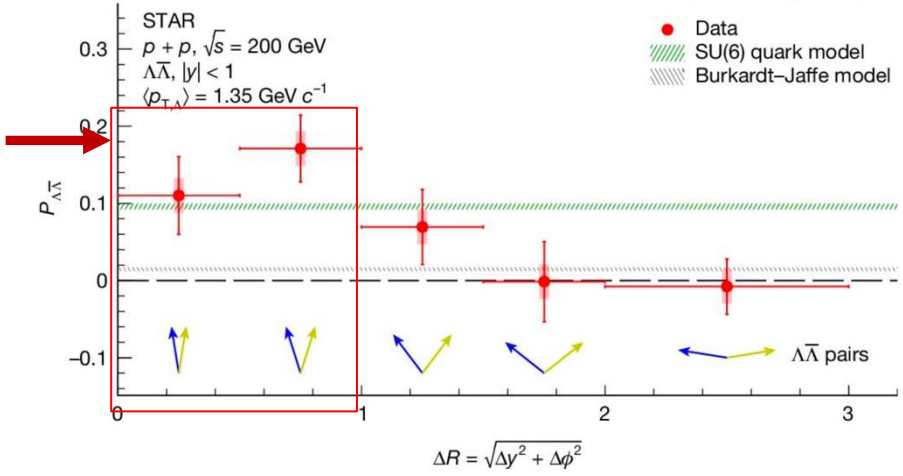
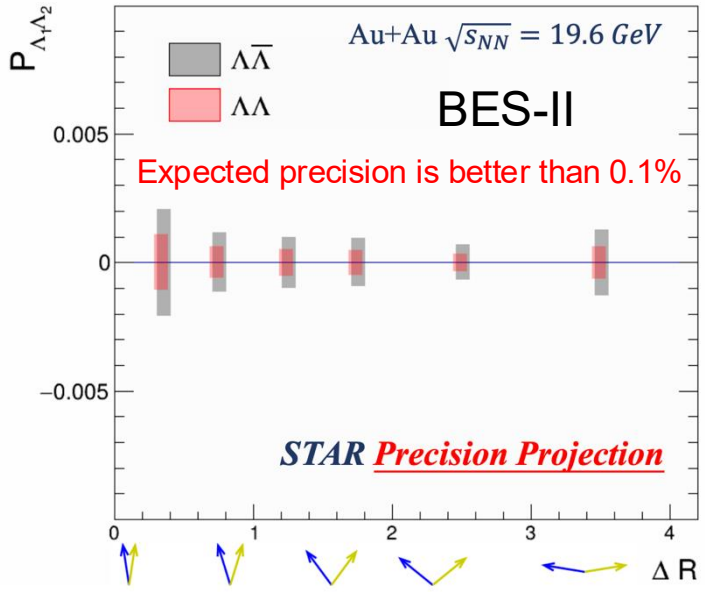


What happens to QCD vacuum at finite temperature?

Measurement of $\Lambda\bar{\Lambda}$ correlation is ongoing.

STAR Collaboration. Nature 650, 65–71 (2026).





Summary

STAR's rich datasets, 40+ species combinations or energies, are a gold mine for a diverse physics program

- First observations of ^{4}Li, ^{5}Li, muonic atom, precision photonuclear J/ψ, $K^{+}K^{-}$ measurement.
- Multiple independent probes provide strong evidence for QGP formation in central O+O.
- New utilities of radial flow to probe speed of sound and bulk viscosity.
- First measurement of off-diagonal spin density-matrix and spin-spin correlations for s-$\bar{s}$

More discoveries in the decades to come.

List of STAR Presentations

Parallel Talks:

TITLES	PRESENTER	DAY/SESSION (with LINK)
1. Strange hadron production in different collision systems at sNN = 200 GeV at STAR Beam Energy Scan-II at STAR	Iris Ponce	Tue, PI
2. Exploring Strangeness Production across Beam Energies in Au+Au Collisions at STAR	Weiguang Yuan	Tue, PI
3. Measurement of Charge Symmetry Breaking in A = 4 hypernuclei in sNN = GeV Au+Au collisions at RHIC	Tianhao Shao	Tue, PI
4. Production of Unstable Light Nuclei in Au+Au Collisions at sNN = GeV with the STAR Detector	Chenlu Hu	Tue, PI
5. Light hadron production measurements with Au+Au Collisions from sNN = 3.2 -4.5 GeV with STAR	Mathias Labonte	Tue, PII
6. Extracting the Speed of Sound from Mean Transverse Momentum Measurements in Au+Au Collisions from RHIC-BESII	Caleb Broodo	Tue, PII
7. Radial Flow of Strange and Multi-strange Hadrons in Heavy-Ion Collisions at RHIC–STAR	Yuli Kong	Tue, PII
8. Collision Energy and System Size Dependent Radial Flow Fluctuations at RHIC	Zaining Wang	Tue, PII
9. Measurement of thermal dielectron production in O+O collisions at sNN = 200 GeV with the STAR experiment	Zihan Liu	Tue, PIII
10. Hyperon Spin Observables in Au+Au Collisions at RHIC BES-II: Global and Local Polarization, Spin Correlations	Tong Fu	Tue, PIV
11. Differential measurements of phi-meson global spin alignment and off-diagonal spin density matrix elements in Au+Au	Zhenyu Ye	Tue, PIV
12. Measurements of Local Polarization of Hyperons with Event Shape Engineering in Au+Au collisions at RHIC-STAR	Taiki Kondo	Tue, PIV
13. Non-Monotonicity of pT Correlations in Au + Au Collisions at RHIC	Rutik Manikandhan	Tue, PV
14. Observation of Strong Directed Flow for phi meson in High Baryon Density Region at RHIC	Guangyu Zheng	Tue, PV
15. Third-body-corrected Two-Pion Femtoscopic Correlations in Au+Au Collisions at high baryon density	Youquan Qi	Tue, PV
16. Measurements of p-Xi Correlation Functions in Au+Au Collisions from STAR Beam Energy Scan II	Jing An	Tue, PVI
17. p-p-Lambda Correlation in 3 GeV Au+Au Collisions with the STAR Detector	Jing Gu	Tue, PVII
18. Observation of a Strange Muonic Atom and Its Antimatter in Heavy-Ion Collisions at STAR	Zhangbu Xu	Tue, PVIII
19. Exploring System-Size and Energy Dependence of J/Psi production with the STAR experiment	Kaifeng Shen	Wed, PII
20. Fluctuations and Correlations of Conserved Charges in Isobar Collisions at sNN = 200 GeV with STAR Detector	Hanwen Feng	Wed, PVI

List of STAR Presentations

Posters:

TITLES	PRESENTER	DAY/SESSION (with LINK)
1. Search for dark photons in pi0/eta Dalitz decays with the STAR detector	Kaifeng Shen	Wed
2. Bulk Properties of the medium in Ru+Ru and Zr+Zr Collisions at sNN = 200 GeV with STAR detector	Chun Yuen Tsang	Wed
3. J/Psi production as a function of event activity in p+p collisions at s = 500 GeV at STAR	Brennan Schaefer	Wed
4. Accessing the shape of cluster pattern in O+ O and d+Au collisions from STAR experiment	Zaining Wang	Wed
5. Anisotropic Flow of Identified Hadrons in O+O Collisions at sNN = 200 GeV	Santanu Prodhan	Wed
6. Study of charge and baryon transport in O+O and Au+Au collisions at sNN = 200 GeV with STAR experiment	Wendi Lu	Wed
7. Search for Exotic Particles in Multi-Prong Central Exclusive Production in pp Collisions at the STAR Experiment	Aranya Giri	Wed
8. Measurement of coherent K+K- photoproduction in Au+Au ultra-peripheral collisions at sNN = 200 with the STAR	Luobing Wang	Wed
9. π/K/p/φ flow in O+O and d+Au collisions	Souvik Paul	Wed
10. Engineering the shapes of quark-gluon plasma droplets by comparing anisotropic flow in small symmetric and asymmetric collision systems	Chunjian Zhang	Wed
11. The underlying event and global event-structure observables in p+p collisions at STAR	Oliver Matonoha	Wed