

Experimental Review on Bulk Properties and Light/Strange Hadron Production in Heavy-Ion Collisions

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



QCD Phase Diagram

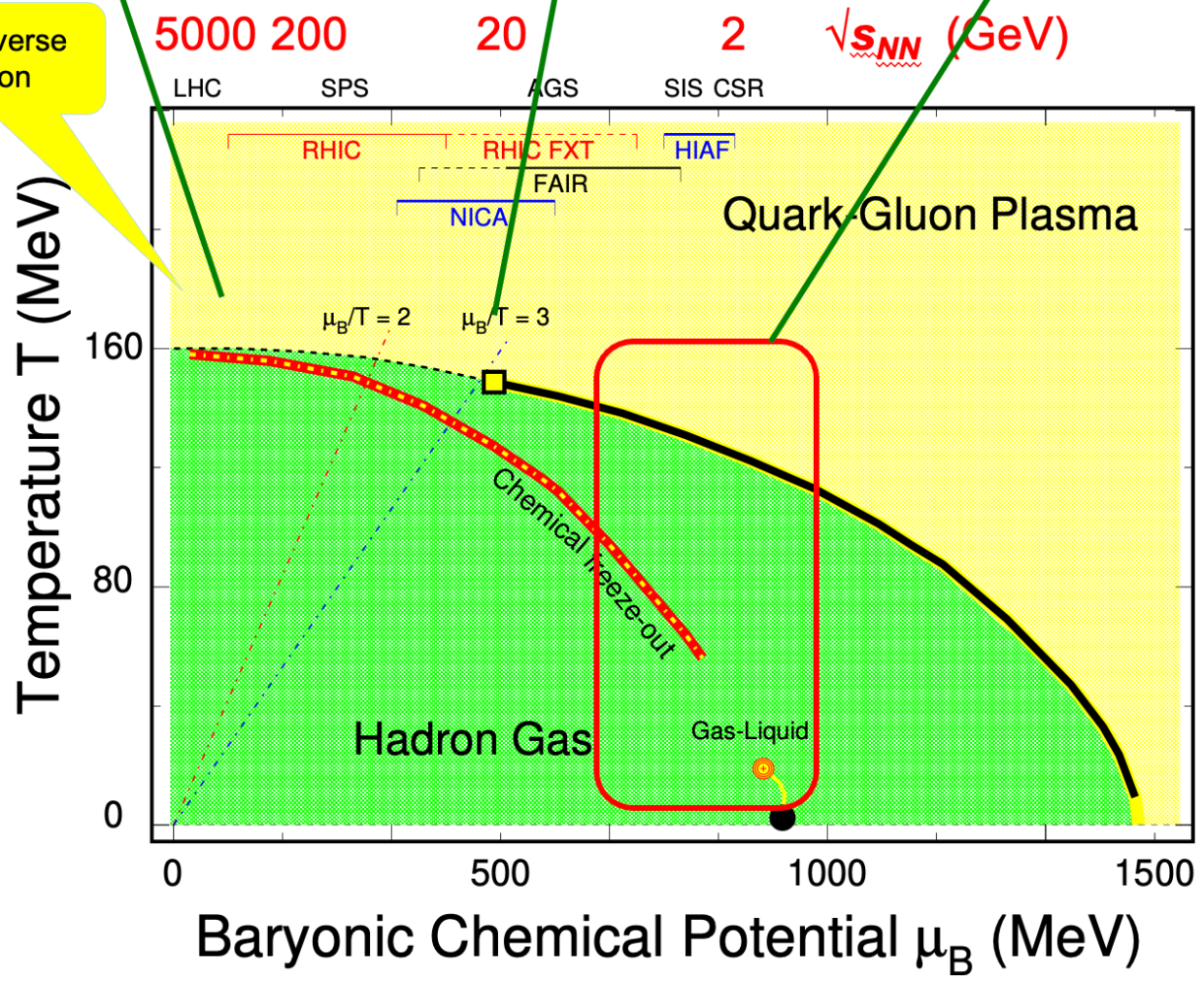
- 1

 T_{ini}, T_C
LHC, RHIC
- 2

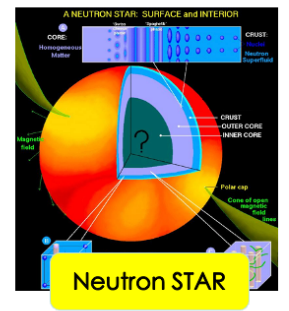
 T_E
RHIC, SPS
- 3

Large μ_B
FAIR, NICA, CSR

Early universe evolution



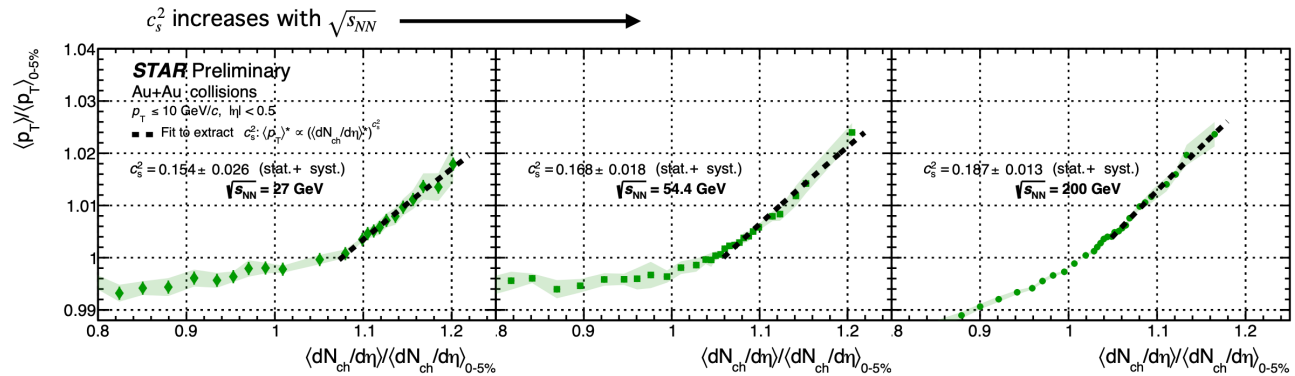
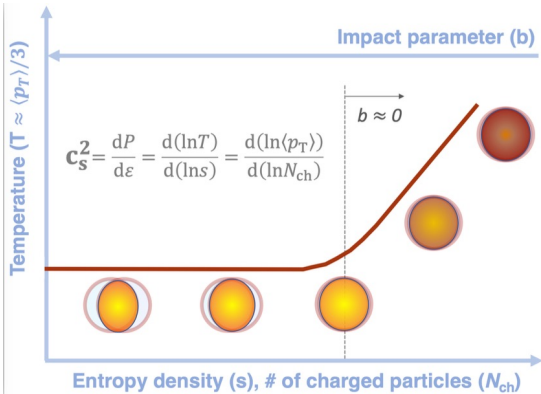
- Low Baryon Density (High energy):
The properties of QGP
- High Baryon Density (BES):
QCD Phase transition



High Baryon Density
→

X. Luo, S. Shi, N. Xu and Y. Zhang,
Particle 3, 278 (2020)

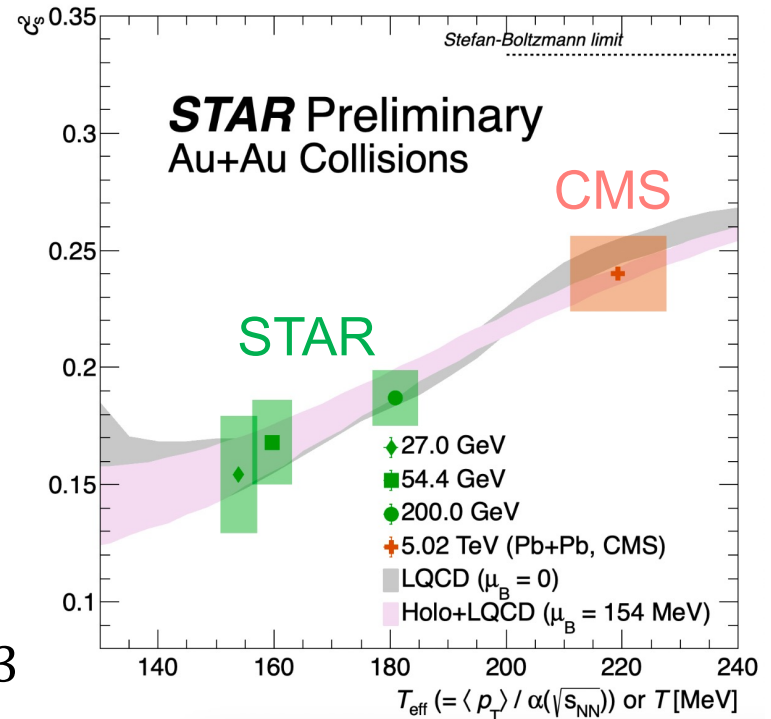
Extracting speed of sound with $\langle p_T \rangle$



Caleb Broodo for STAR, SQM2026

- First extraction of T -dependence of speed of sound from the $\langle p_T \rangle$ measurements in ultra-central collisions
- Results consistent with Lattice QCD

$$T_{eff} \sim \langle p_T \rangle / 3$$

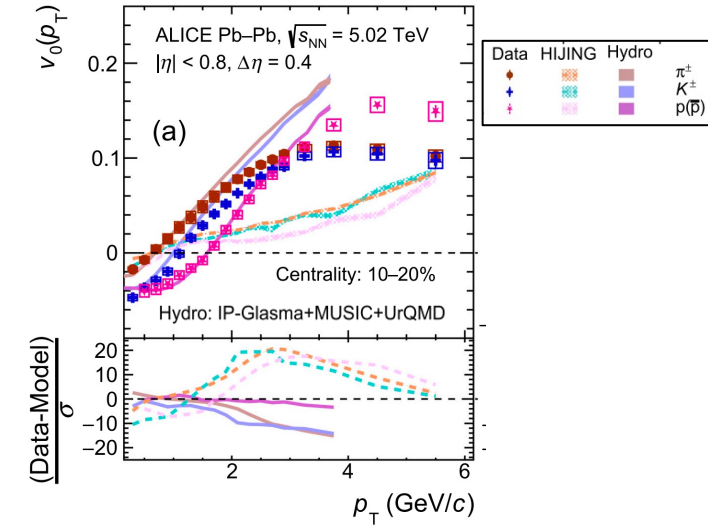
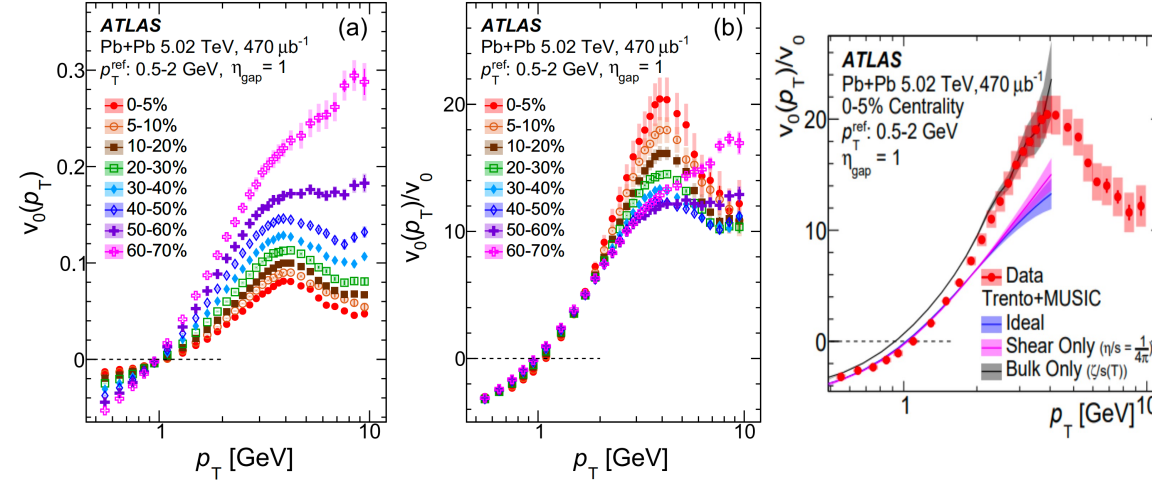


$v_0(p_T)$: A radial-flow probe of bulk viscosity

Aman Dimri for ATLAS, SQM2026

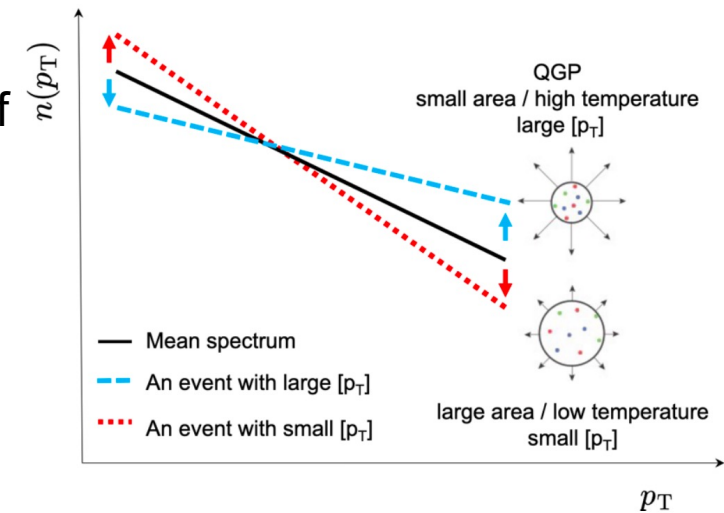
ATLAS, Phys. Rev. Lett. 136, 032301 (2026)

ALICE, Phys. Rev. Lett. 136, 032302 (2026)



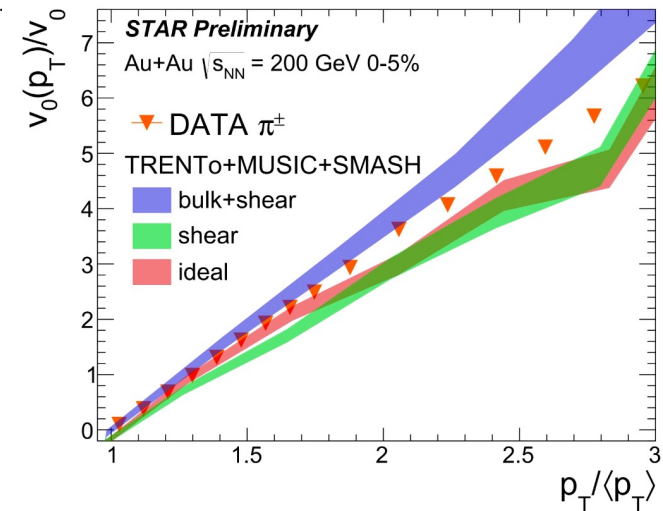
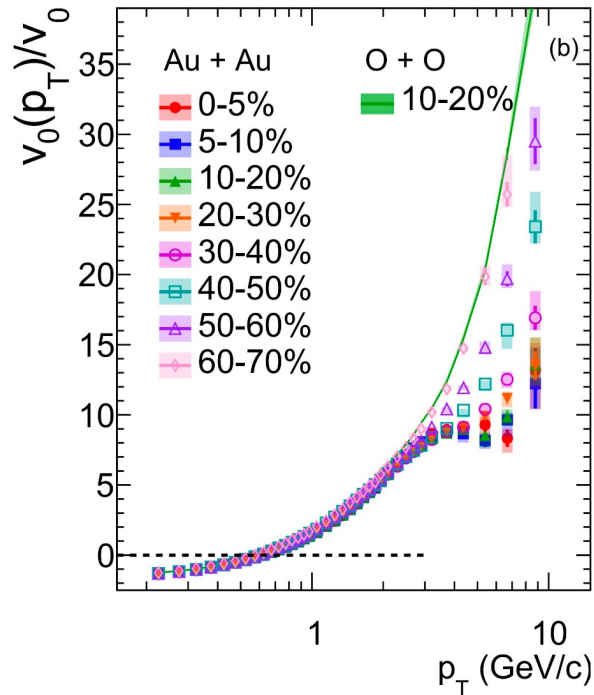
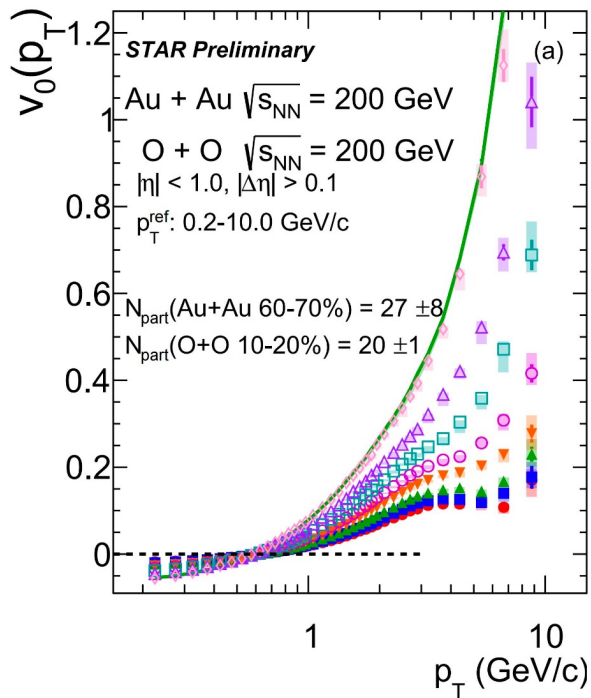
$$\frac{\langle \delta n(p_T) \delta [p_T] \rangle}{\langle n(p_T) \rangle \langle [p_T] \rangle} = v_0(p_T) v_0, \text{ with } v_0 = \sqrt{\langle (\delta [p_T])^2 \rangle} / \langle [p_T] \rangle$$

- Quantify the correlation between the fluctuation of yield fraction in one p_T bin ($n(p_T)$) and that of event-wise mean- p_T ($[p_T]$)
- Sensitive to bulk viscosity
- Mass ordering observed for $v_0(p_T)$ at low p_T
- Baryon-meson splitting at intermediate p_T



$v_0(p_T)$: System-size dependence at 200 GeV

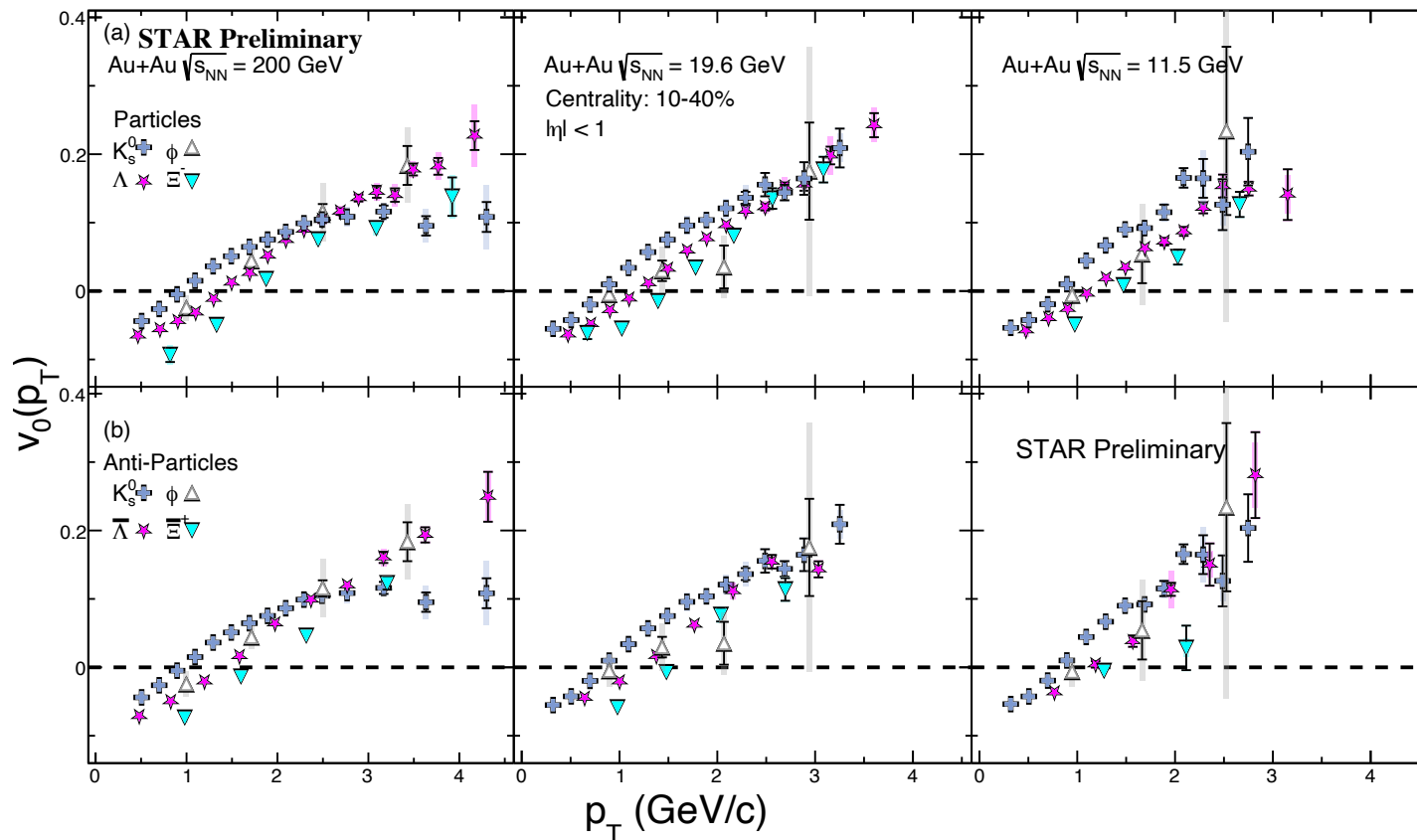
Zaining Wang for STAR, SQM2026



- $v_0(p_T)$ captures system-size dependent radial flow fluctuations with coherent hydrodynamic response
- Intermediate p_T region show clear sensitivity to bulk viscosity

$v_0(p_T)$: (Multi-)strange hadrons at RHIC

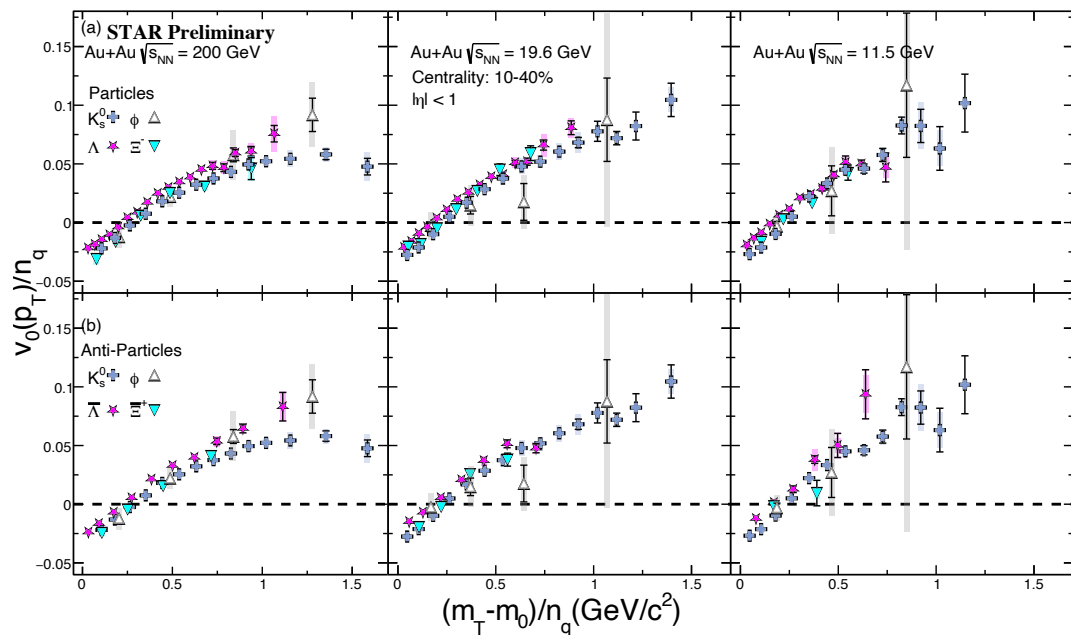
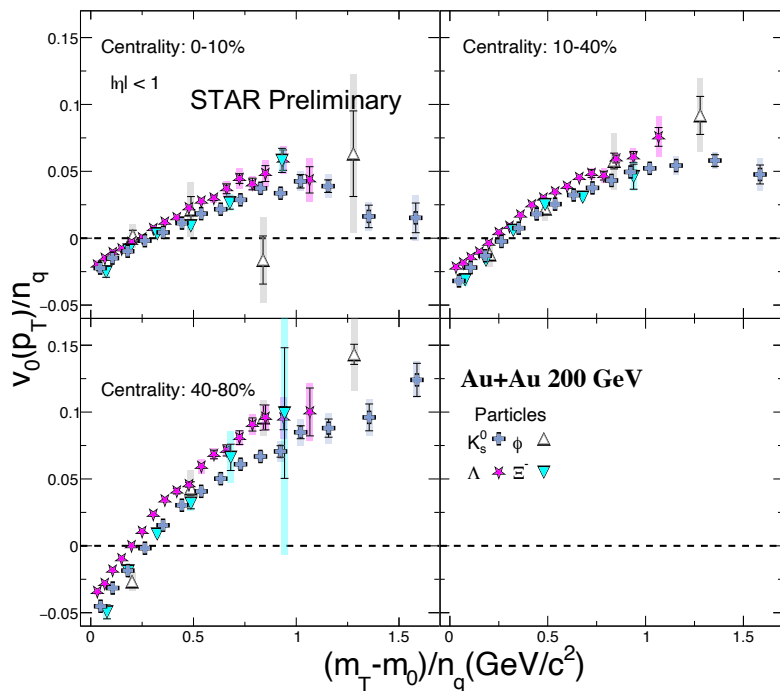
Yuli Kong for STAR, SQM2026



- At low p_T (< 2 GeV/c): mass ordering
- At intermediate p_T (2 - 4 GeV/c):
baryon-meson splitting between Λ and K_s^0 at 200 GeV
limited by statistical precision at 19.6 and 11.5 GeV

$v_0(p_T)$: NCQ scaling test at RHIC

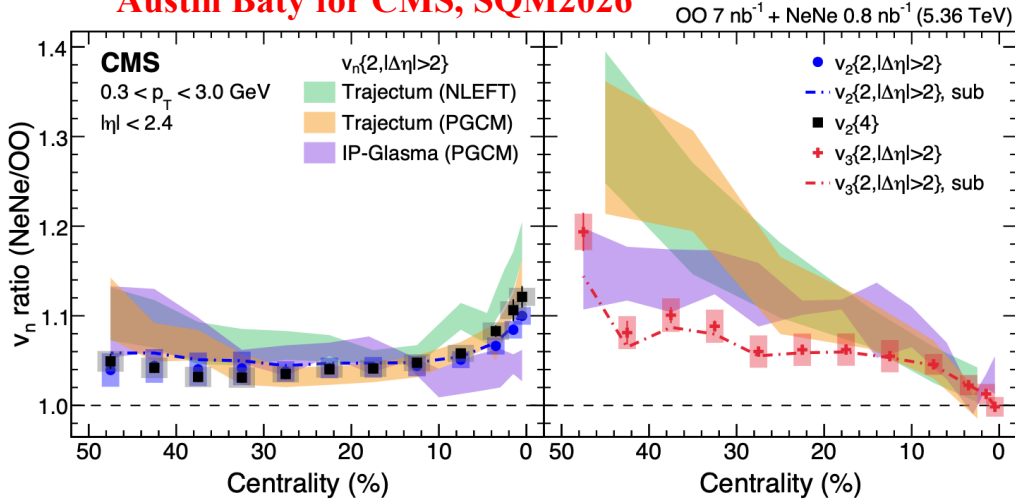
Yuli Kong for STAR, SQM2026



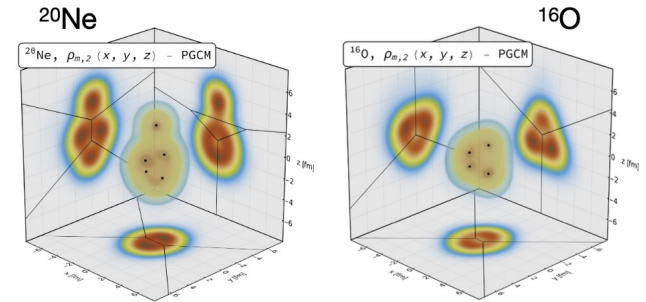
➤ Better NCQ scaling in more central collisions at 200 GeV

Anisotropic flow in OO/NeNe collisions

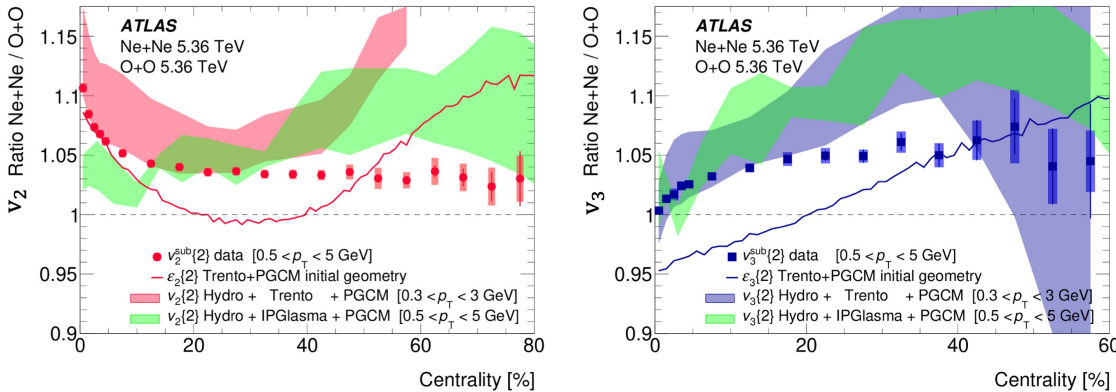
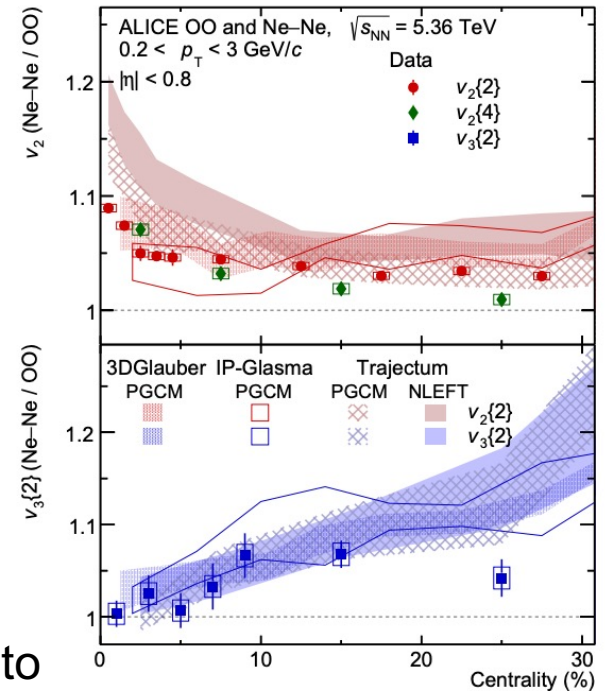
Austin Baty for CMS, SQM2026



Phys. Rev. Lett. 135, 012302



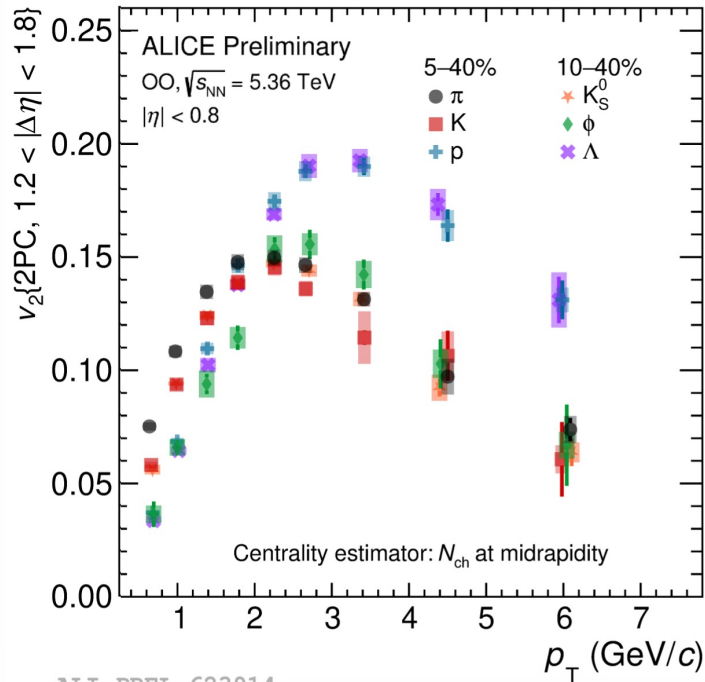
Vojtech Machacek for ALICE, SQM2026



Soumya Mohapatra for ATLAS, SQM2026

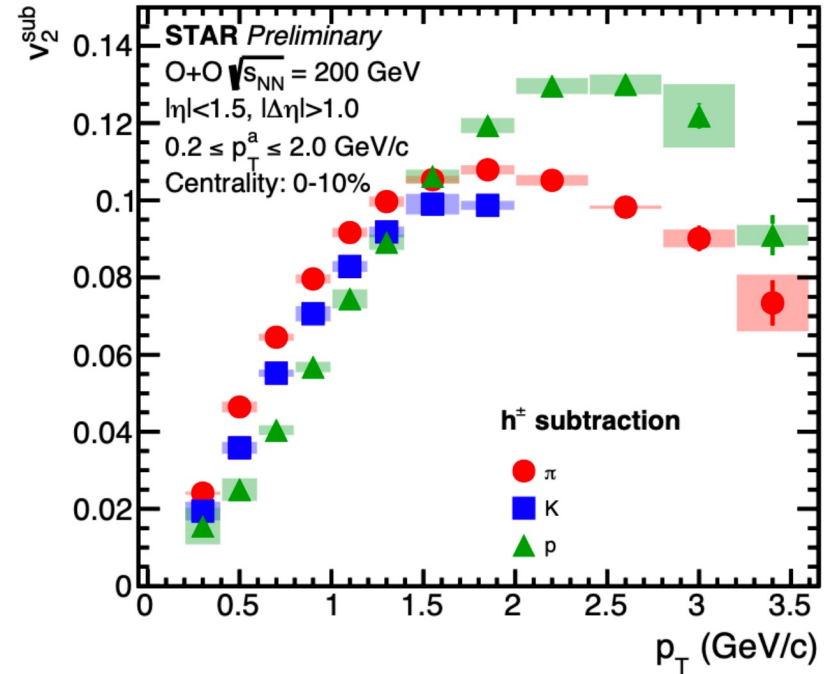
- v_n ratios sensitive to initial-state geometry/nuclear deformation
- dN/dη, <p_T> and more flow observables measured to compare with hydro models

v_2 : Light-ion collisions



ALI-PREL-623914

Preet Bhanjan Pati for ALICE, SQM2026

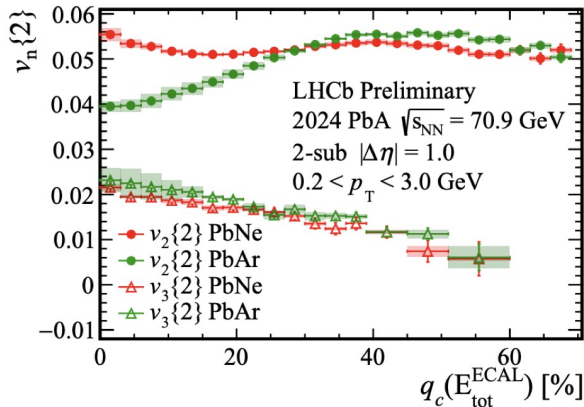


Souvik Paul for STAR, SQM2026

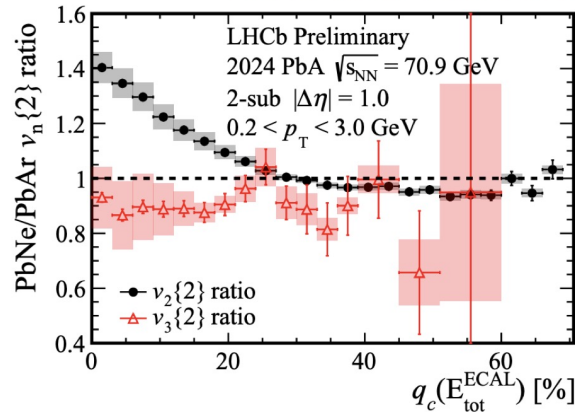
- Signature of partonic collectivity persists in light-ion collisions
- Baryon-meson splitting persists to higher p_T in higher energy collisions

SMOG2 @ LHCb: a bowling alley

$-2.3 < y^* < 0.7$

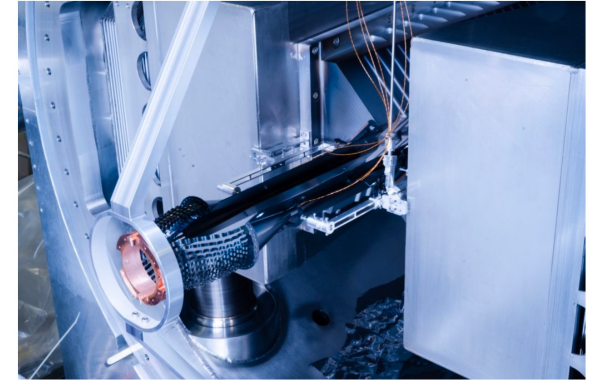


LHCb-CONF-2025-001

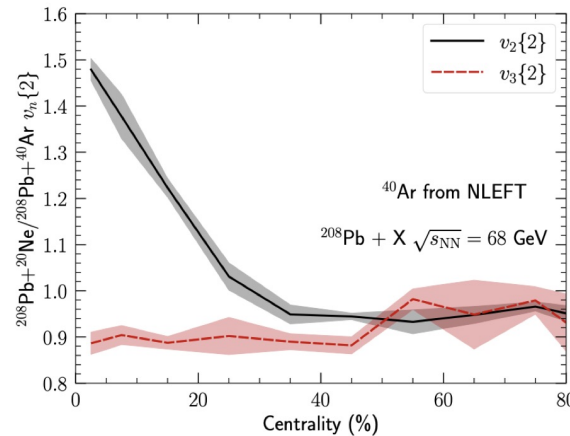
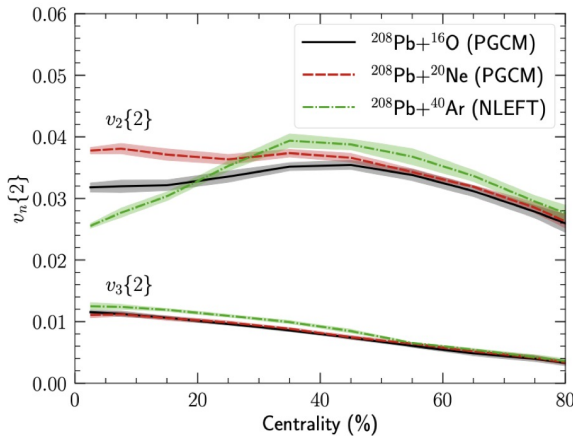


Cesar Luiz Da Silva for LHCb, SQM2026

System for measuring overlap with gas 2



Phys. Rev. Accel. Beams 27, 111001 (2024)



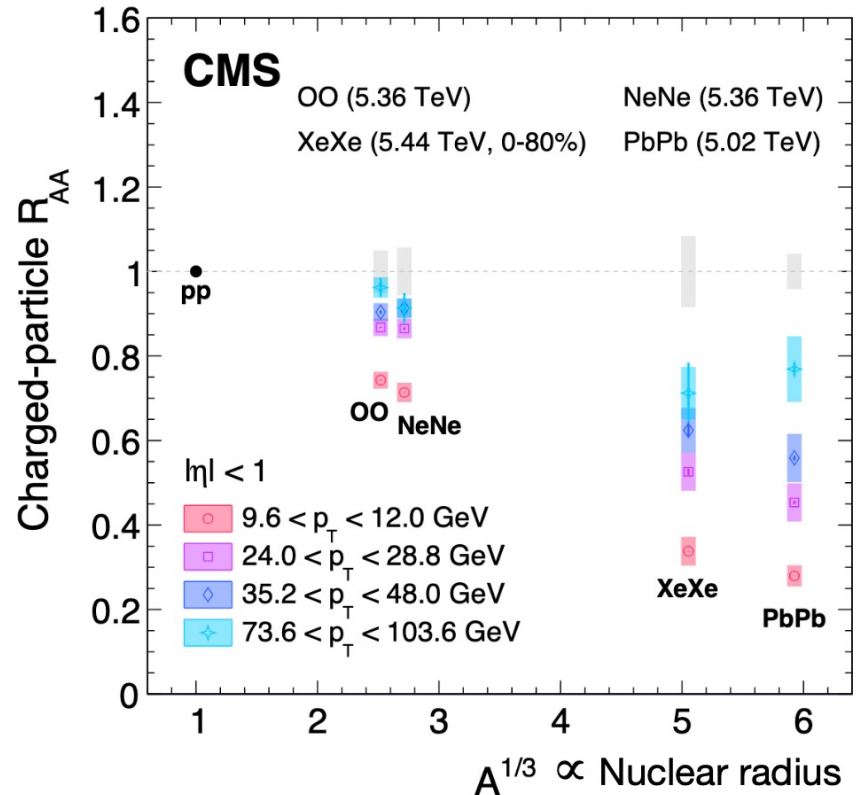
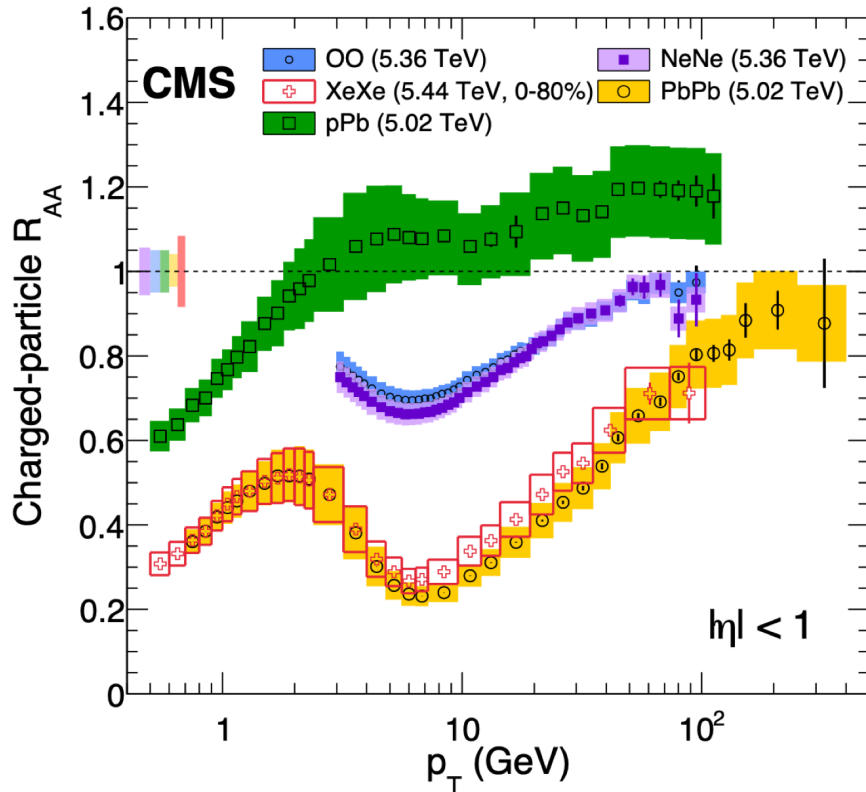
Phys. Rev. Lett. 134 (2025) 082301
QM2025



- Clearly consistent with the predicted Ne bowling-pin shape, and confirms its major effect on collective dynamics
- Great potential to further probe the α -cluster structure in light nuclei with flow observables

System size dependence of energy loss

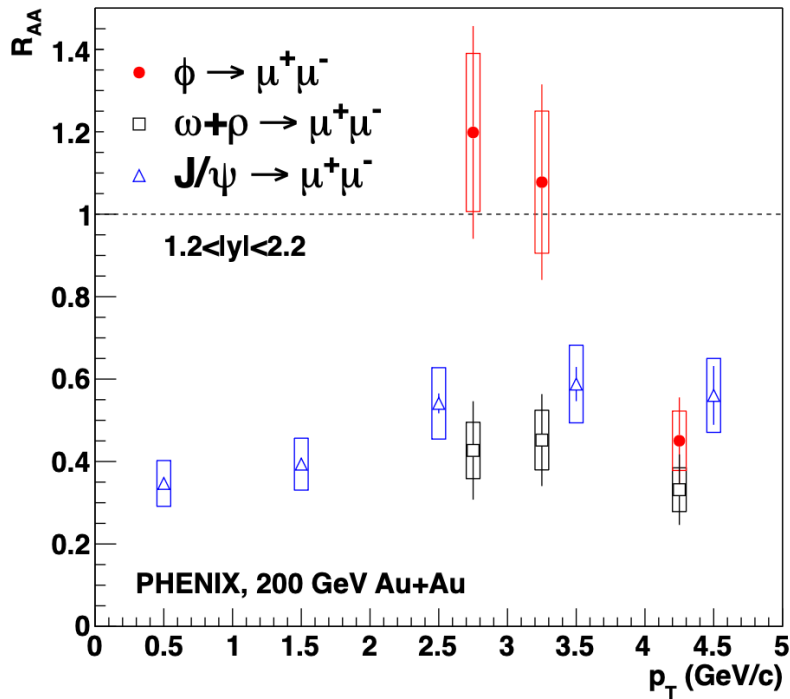
Vipul Pant for CMS, SQM2026



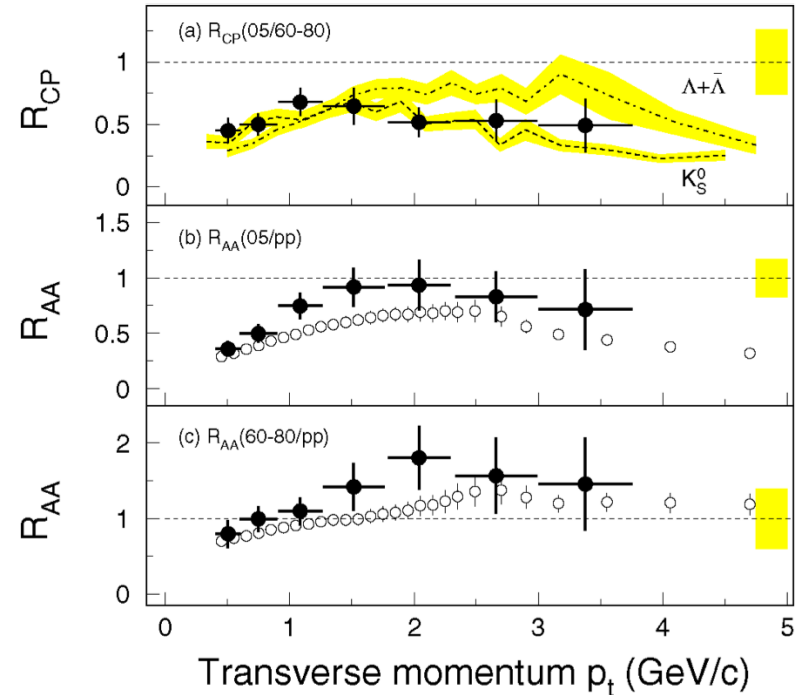
- R_{AA} in OO and NeNe shows significant suppression that is consistent with energy loss models
- Slightly stronger suppression in NeNe than in OO
- A-dependent suppression hierarchy

R_{AA} for ϕ in Au+Au 200 GeV

Chaitanya Prasad for PHENIX, SQM2026



STAR, Phys. Lett. B 612 (2005) 181

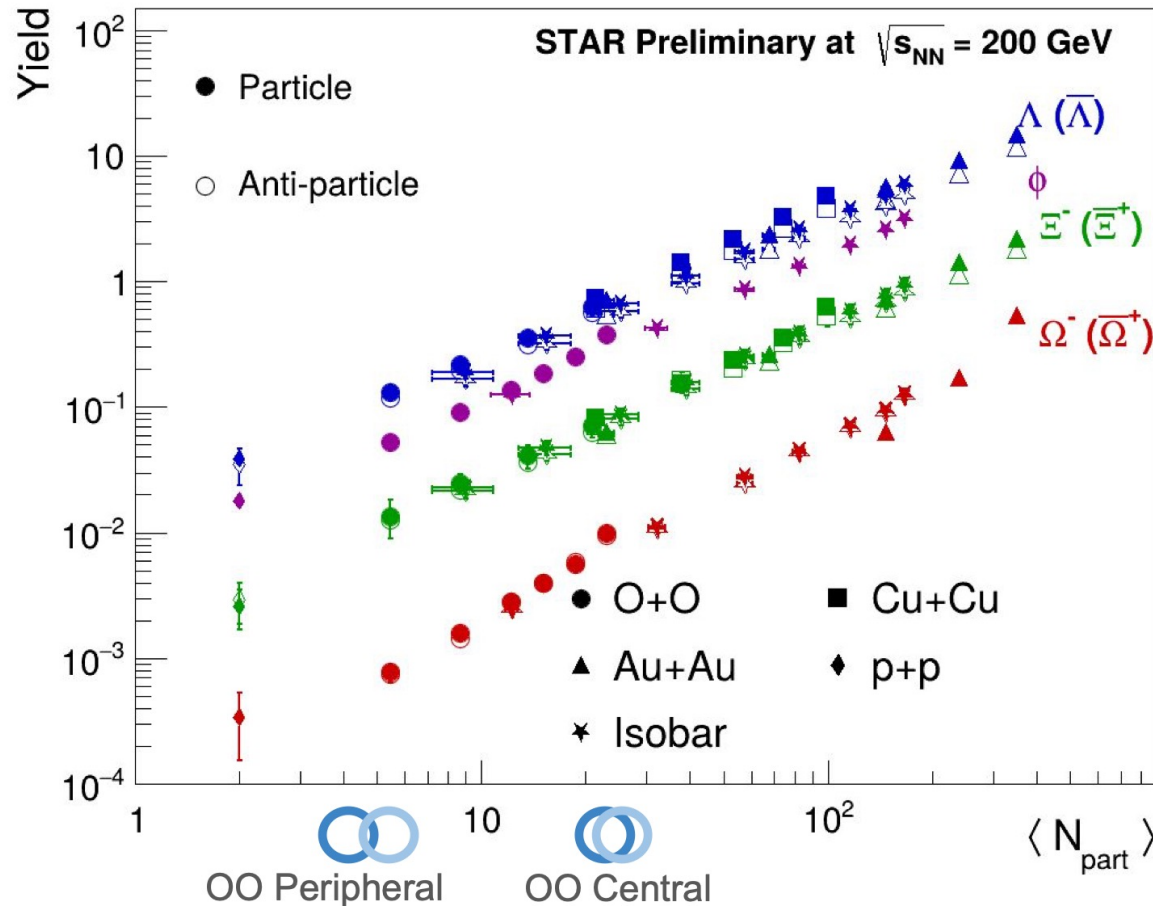


- R_{AA} of ϕ in Au+Au 200 GeV shows enhancement at intermediate p_T
- Strangeness enhancement in AA with respect to pp

Strange hadron yields for different systems

Iris Ponce for STAR, SQM2026

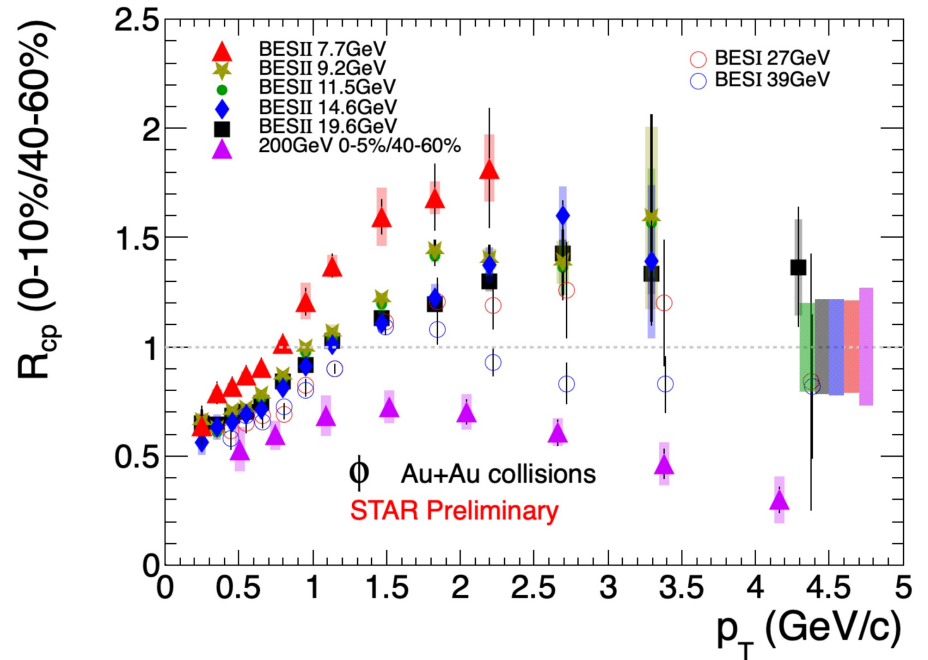
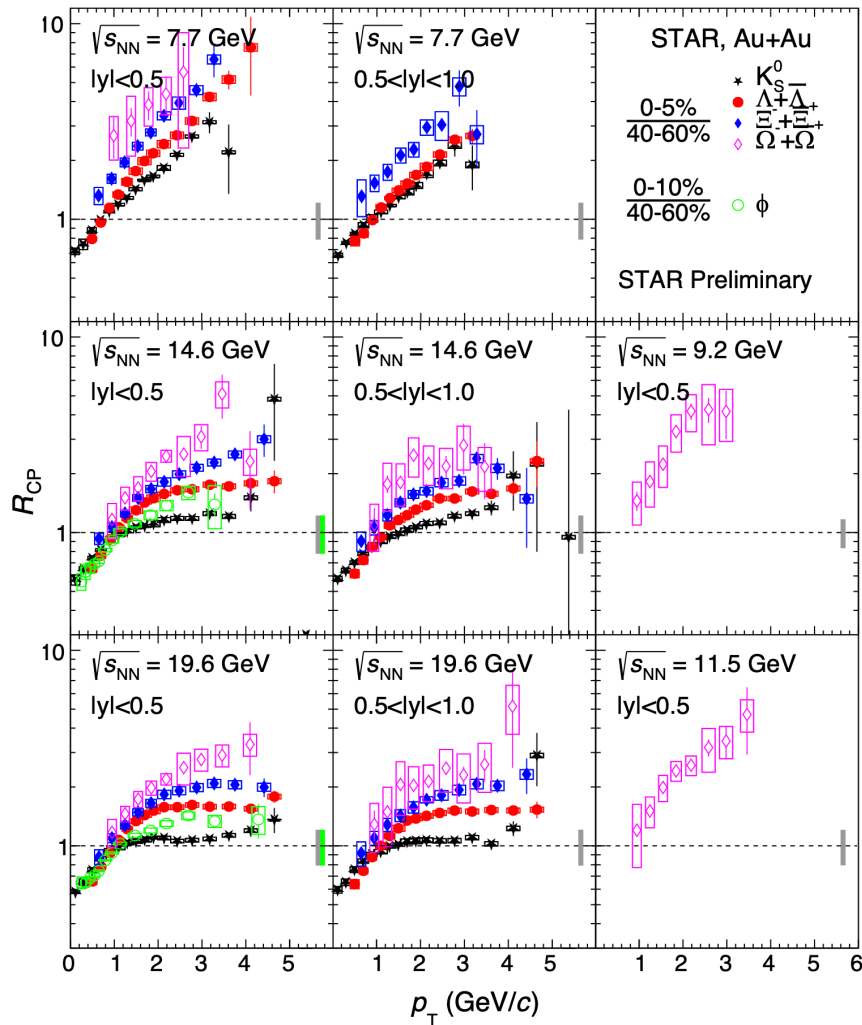
More discussions in Sruthy Das's talk (Fri)



- Yield smoothly scales with $\langle N_{part} \rangle$ independent of collision systems

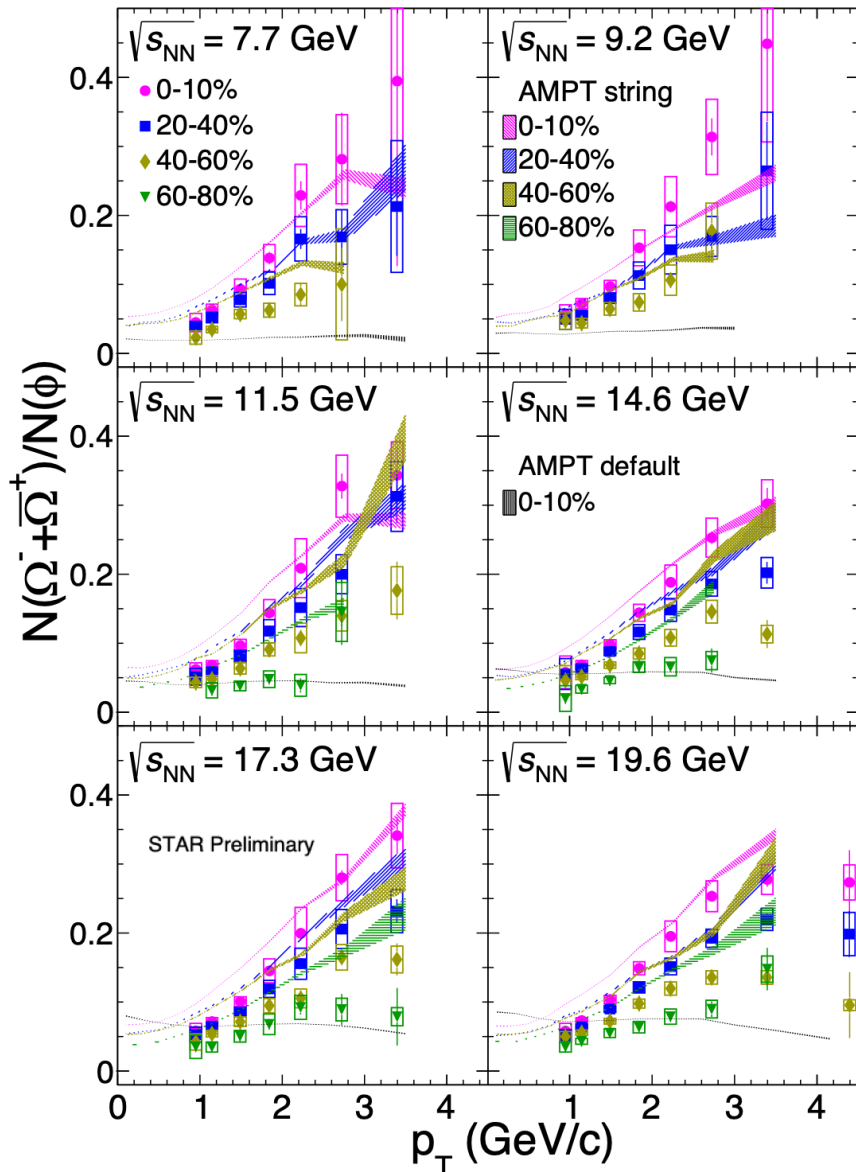
R_{CP} for strange hadrons and ϕ in BESII

Weiguang Yuan for STAR, SQM2026



- Interplay of multiple mechanisms towards high baryon density region (strangeness enhancement, radial flow, ...)

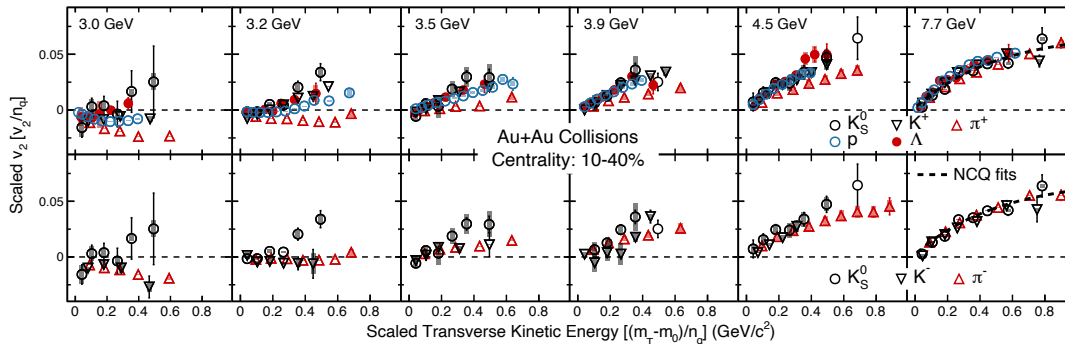
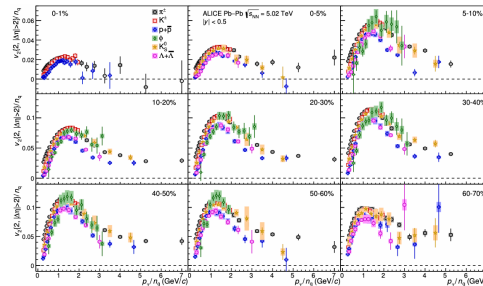
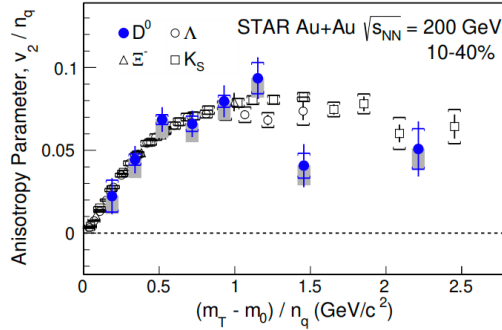
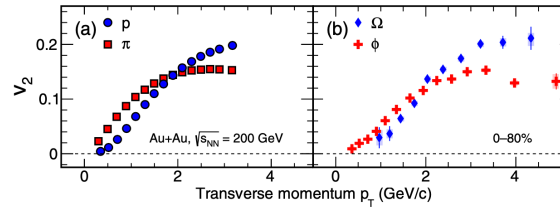
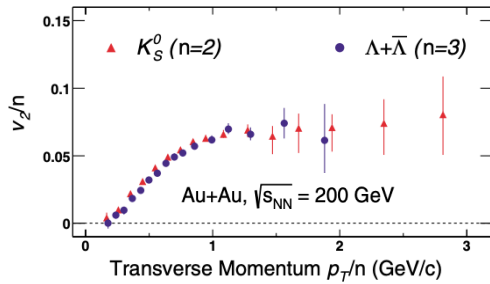
Ω/ϕ ratio in BESII



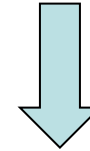
Weiguang Yuan for STAR, SQM2026

- Clean probe to deconfined phase
- Strongly enhanced production of Ω baryon at intermediate p_T compared to ϕ meson, from peripheral to central collisions at all energies
- Default AMPT model (hadronic transport) do not show enhancement
- The string-melting version, assuming Ω and ϕ production via strange quark coalescence, reproduce the data well
- The good data/model agreement suggests deconfinement in central AA collisions at $\sqrt{s_{NN}} \geq 7.7$ GeV

Onset of v_2 NCQ scaling in BESII



- First observation of NCQ scaling at 200 GeV
STAR, Phys. Rev. Lett. 92, 052302 (2004)



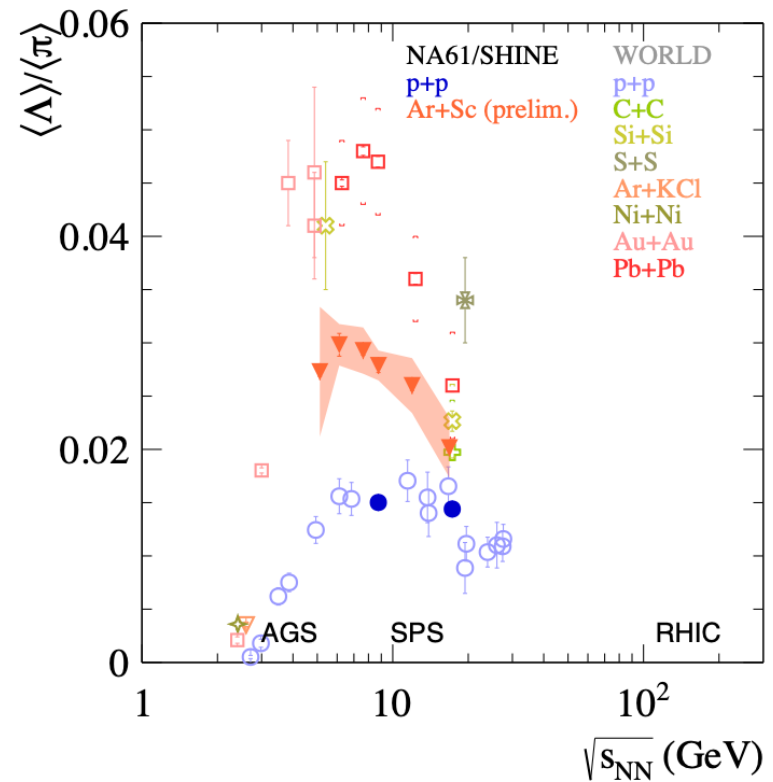
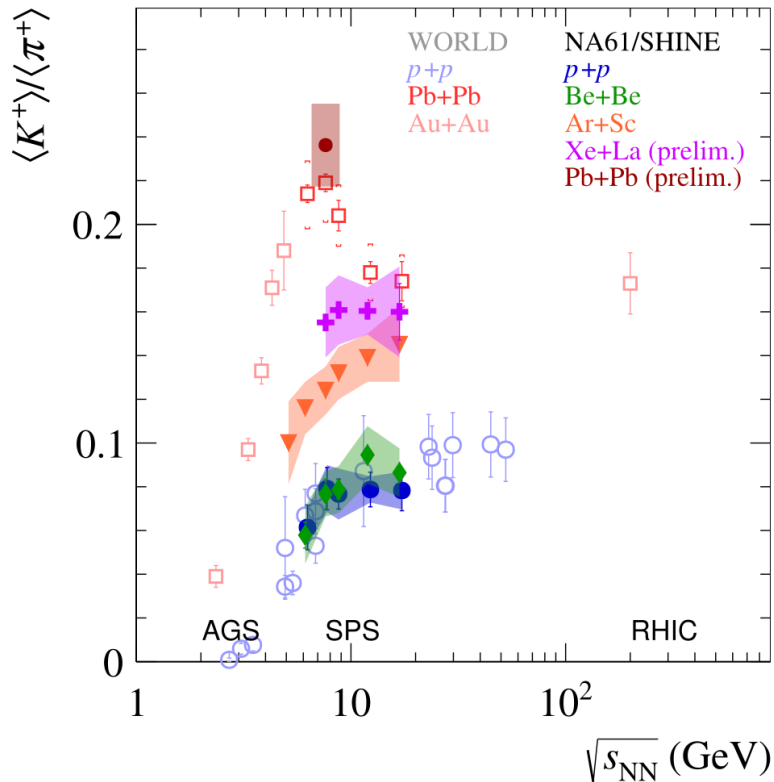
- NCQ scaling for the multi-strange hadrons and D meson at 200 GeV and LHC energy
Partonic collectivity
STAR, Phys. Rev. Lett. 116, 062301 (2016)
Phys. Rev. Lett. 118, 212301 (2017)
ALICE, JHEP 09, 006 (2018)



- NCQ scaling gradually restores from 3.2-4.5 GeV
STAR, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Lett. B 827 (2022) 137003
Phys. Rev. Lett. 135, 072301 (2025)

K^+/π^+ ratio at SPS

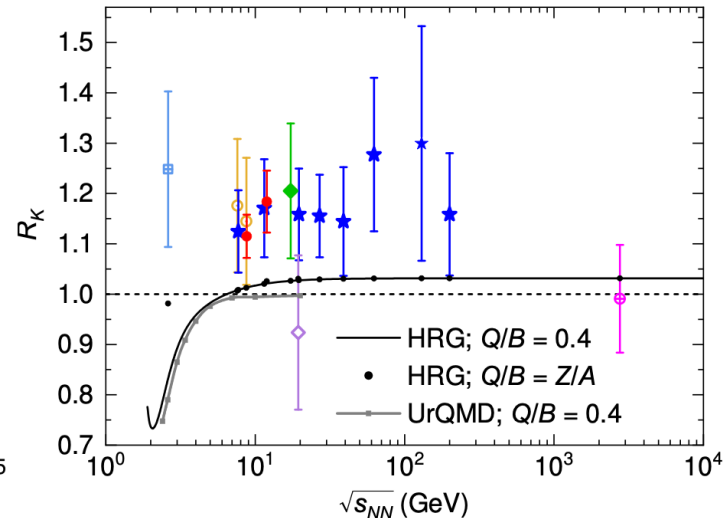
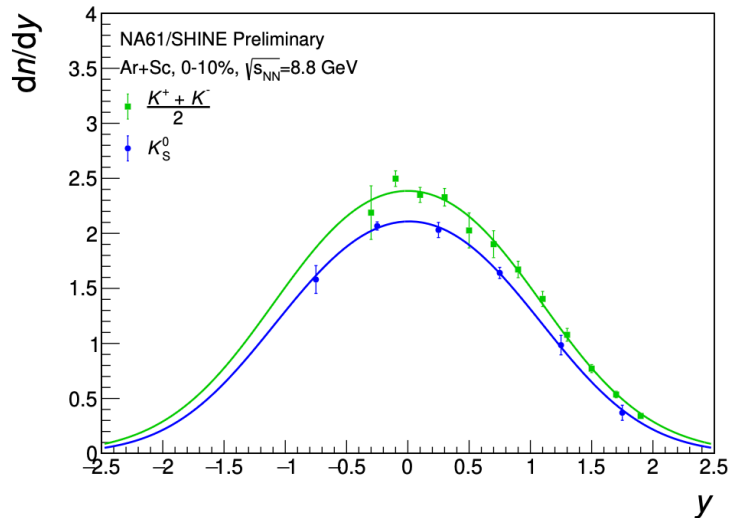
Maciej Lewicki for NA61/SHINE, SQM2026



- Sharp peak in K^+/π^+ ratio observed by NA49 confirmed by NA61/SHINE.
- Significant system size dependence of this ratio

Excess of charged over neutral kaons

Maciej Lewicki for NA61/SHINE, SQM2026

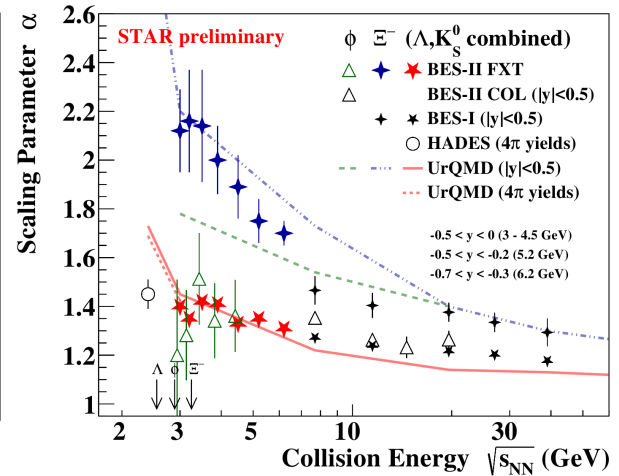
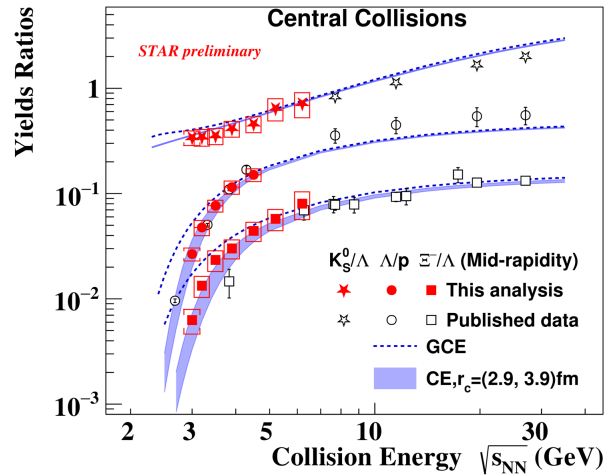
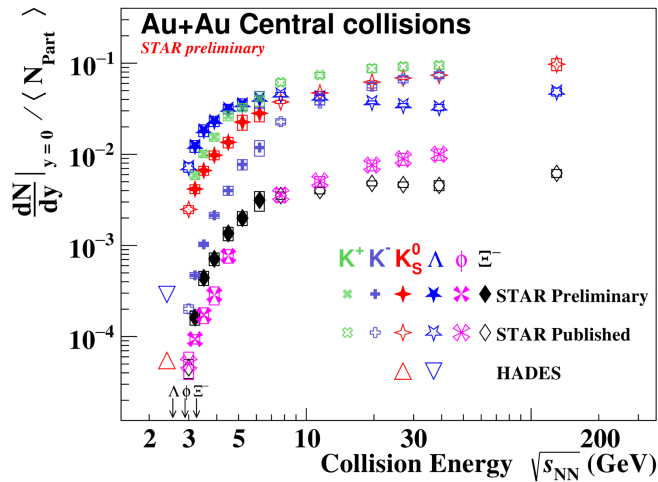


$$R_K = \frac{K^+ + K^-}{2 K_S^0}$$

- HADES; Ar+KCl; 4π
- ★ STAR; Au+Au; $y \approx 0$
- NA49; Pb+Pb; 4π
- NA61/SHINE; Ar+Sc; $y \approx 0$
- ◆ CERES; Pb+Au; $y \approx 0$
- ◇ NA35; S+S; 4π
- ALICE; Pb+Pb; $y \approx 0$

➤ The new results from Ar+Sc at 8.8 GeV confirms the excess of charged kaons over neutral kaons

Strangeness in high baryon density



STAR: PLB 831, 137152 (2022); JHEP 10 (2024) 139

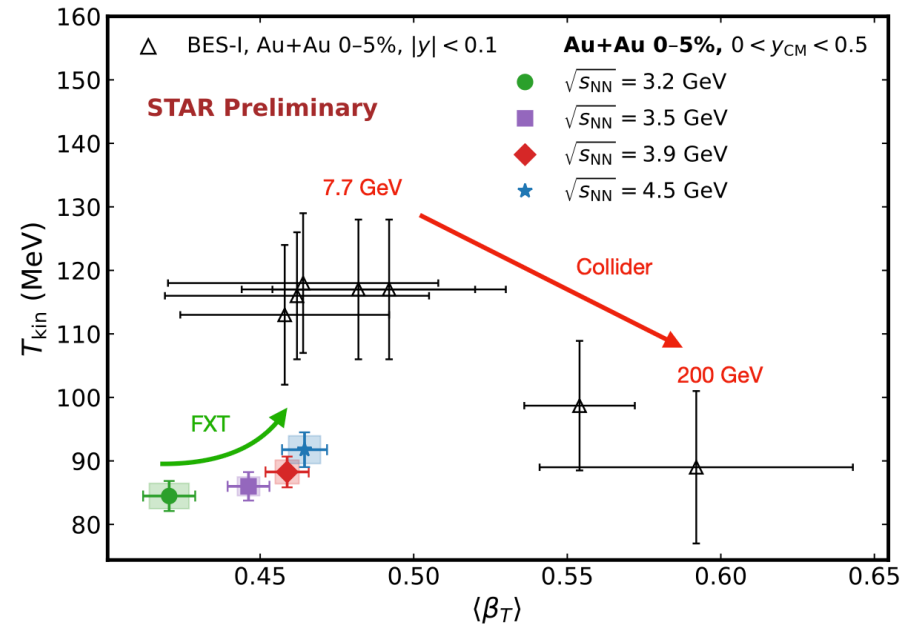
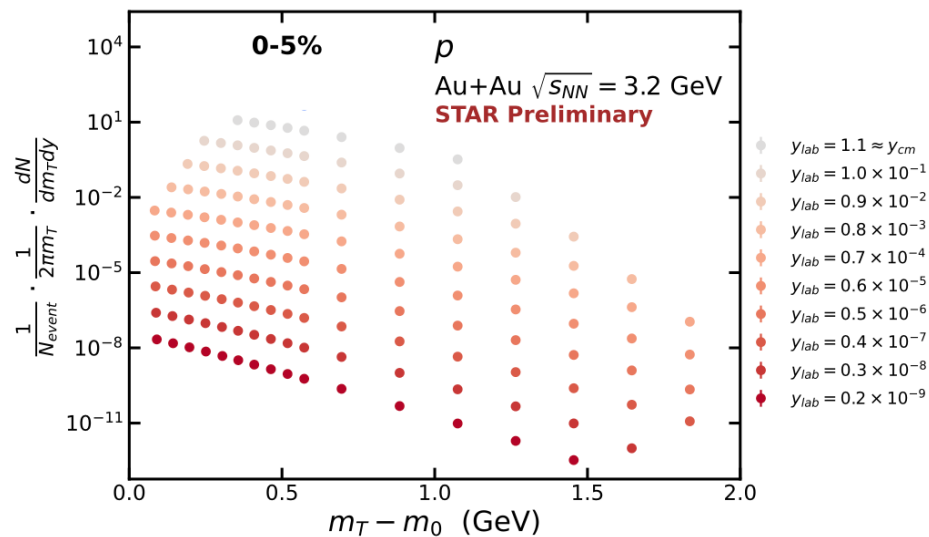
α : Centrality scaling parameter of particle yields Yields = kN_{part}^α

- First measurement of Ξ^- yield near threshold in Au+Au collisions
- α value for Ξ^- in high baryon density region significantly larger than for Λ , K_S^0 , ϕ
- Strange hadron yields in high baryon density region: Canonical ensemble describes data better than Grand-Canonical ensemble

Nuclear matter property in HBDR: hadronic interactions dominate

Kinetic freeze-out in high baryon density

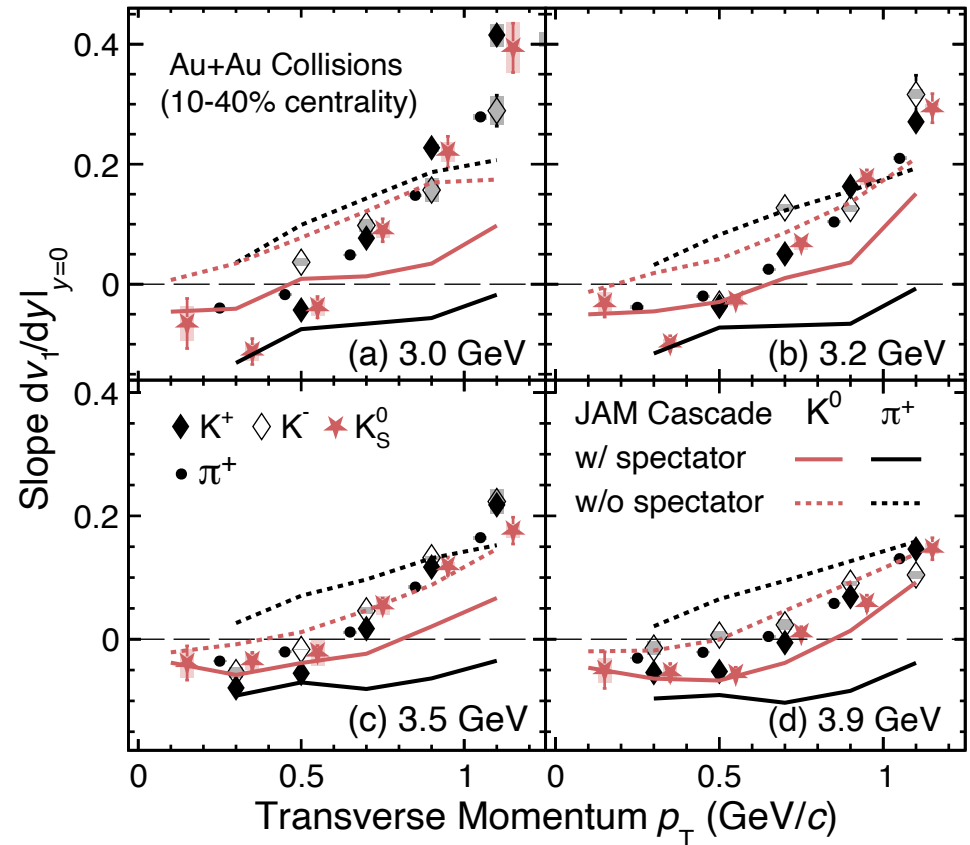
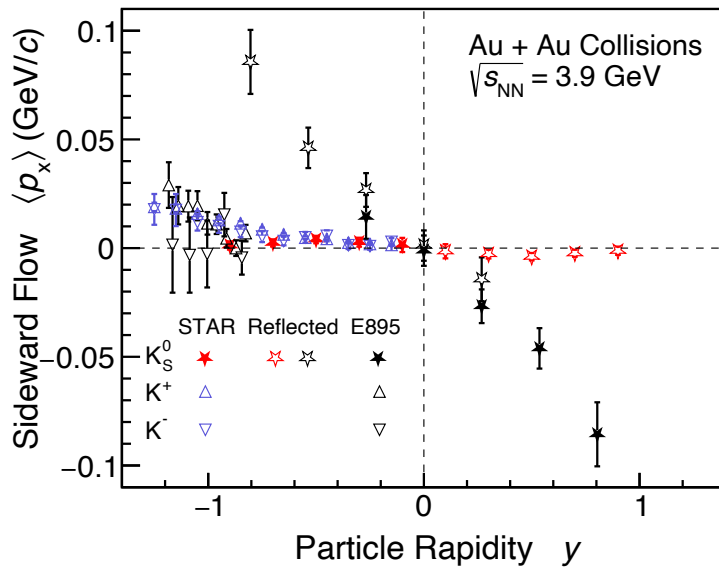
Mathias Labonté for STAR, SQM2026



- Fit π, K, p simultaneously with a blast wave function to extract kinetic freeze-out parameters
- Both T_{kin} and $\langle \beta_T \rangle$ increases with energy in FXT energy range

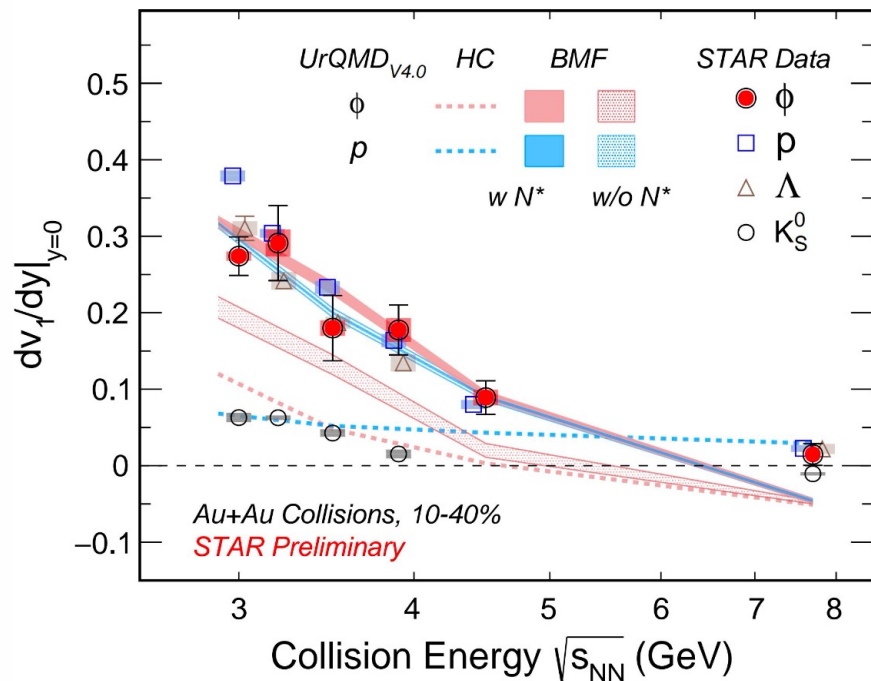
Kaon v_1 in high baryon density

STAR: arxiv: 2503.23665, accepted by PLB
E895, Phys. Rev. Lett. 85, 940 (2000)



- K_S^0 anti-flow: STAR measurement 8 times smaller than E895
- 20 years of kaon potential theories need re-examination

ϕ v_1 in high baryon density



- ϕ v_1 at 3-4.5 GeV –
UrQMD with mean-field:
 - Proton data: reproduced
 - ϕ data: not reproduced (fails without high-mass resonances)

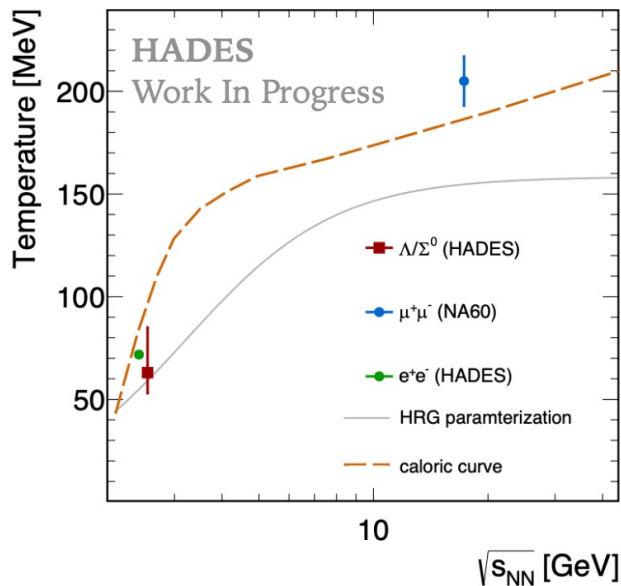
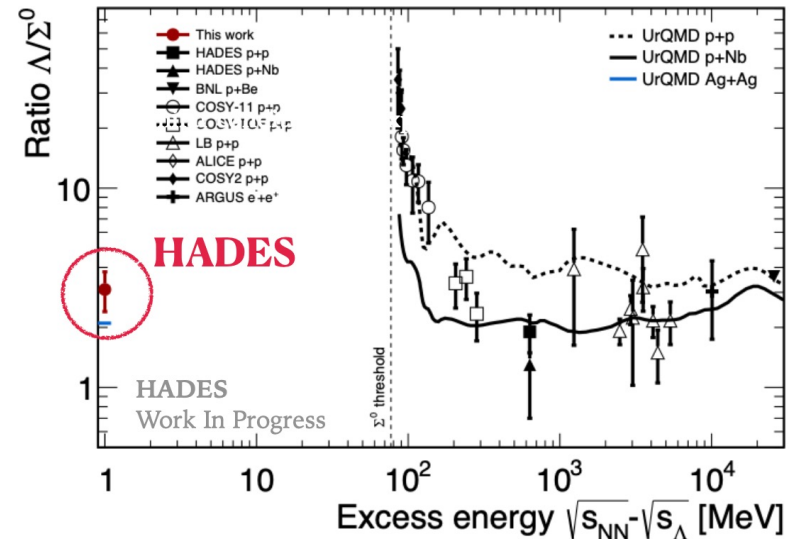
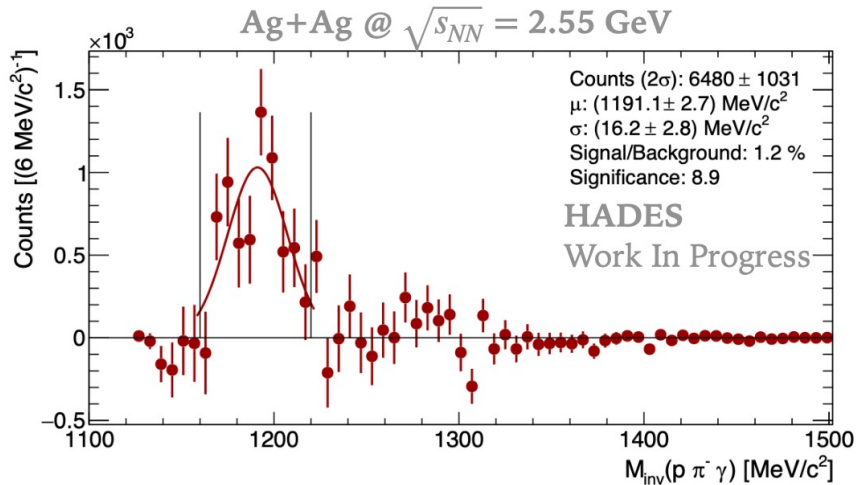
- **Key implication:**

- High-mass baryon resonances (N^*) may drive ϕ production & its baryon-like flow

- **Why ϕ shows strong flow but other mesons don't?**
→ Possibly due to small ϕ - N cross section

Guangyu Zheng for STAR, SQM2026

Λ/Σ ratio as hyperonic thermometer



Jan Orliński for HADES, SQM2026

- Extrapolated measurement by HADES of $R(\Lambda/\Sigma) = 3.1 \pm 0.8$
- Temperature extracted with thermal model

$$T = 63_{-10}^{+20} \text{ MeV}$$

Summary

➤ RHIC and LHC energies:

- $\langle p_T \rangle$ in **ultra-central-collisions**: T-dependence of speed of sound
- $v_0(p_T)$: a new radial-flow probe of bulk viscosity
- $v_n\{m\}$ in **light-ion/heavy-light-ion collisions**: medium response to initial geometry / probe of light nuclei shape
- R_{AA} : onset of jet-quenching in light-ion collisions

➤ RHIC BESII energies:

- **NCQ scaling on v_2** : onset at ~ 4.5 GeV
- **Ω/ϕ enhancement**: persists at 7.7 GeV
- **“Horn” in K^+/π^+** : confirmed at 7.6 GeV

➤ RHIC FXT/AGS/SIS energies:

- **Kaon anti-flow**: spectator shadowing – kaon potential theories need re-examination
- **Strong ϕ v_1** : High-mass baryon resonances (N^*) may drive ϕ production

Thank you!