

RHIC 25:

A quarter century of discovery

May 20-23, 2025

Topical Workshops: May 20-21

Plenary Sessions: May 22-23

RHIC 25 Symposium: May 22, 4:30pm

RHIC/AGS Users' Executive Committee

Peter Steinberg, Chair Elect

Anders Knospe, Chair

Marzia Rosati, Past Chair

Meeting Coordinators

Kelly Guiffreda
guiffreda@bnl.gov

Teri Lazar
tlazar@bnl.gov



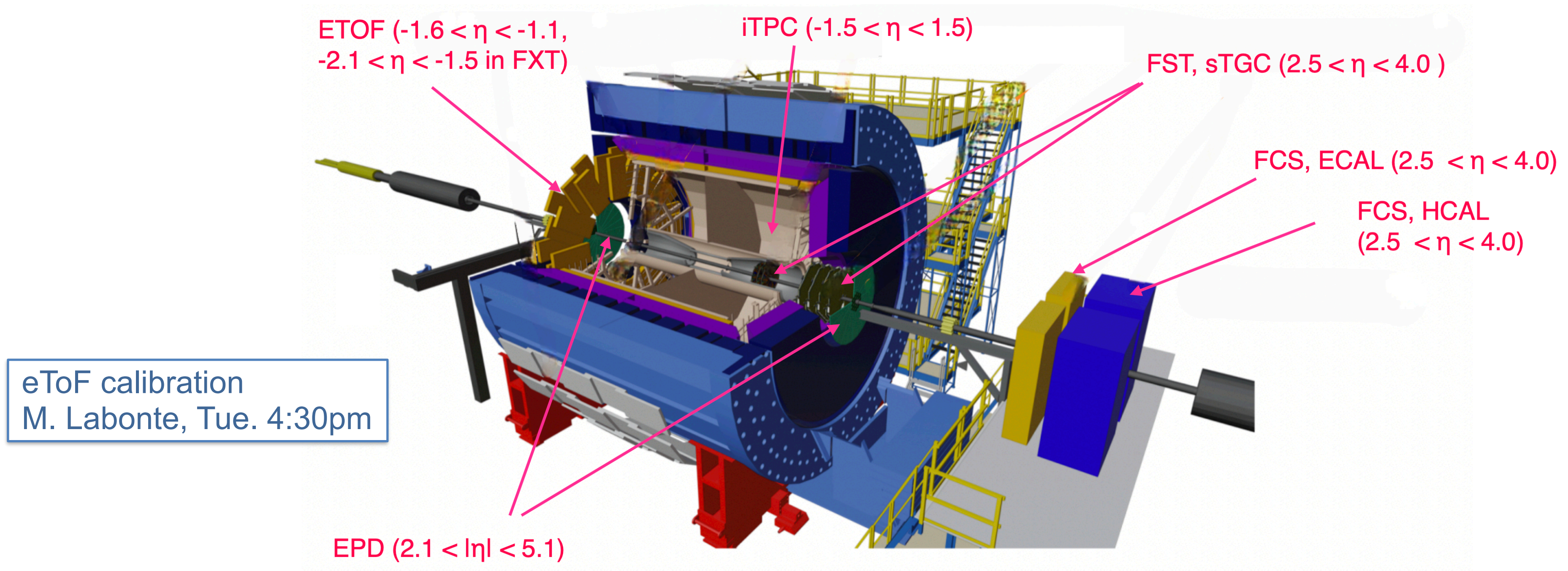
RICE

STAR Highlights

Chenliang Jin
(Rice University)
for the STAR Collaboration
05/22/2025



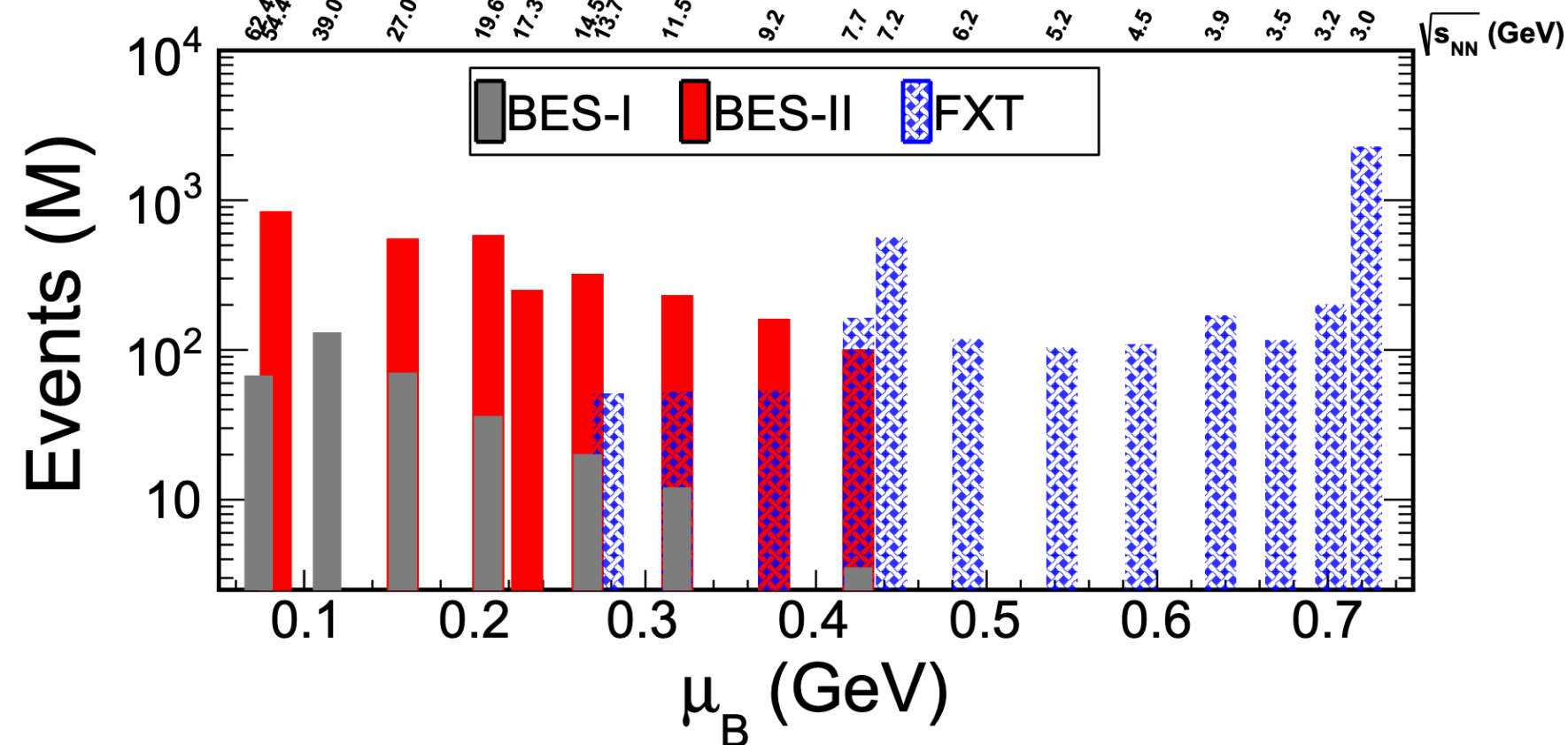
STAR detector



STAR BES-II and Forward Upgrades: Enhanced acceptance and expanded physics opportunities.

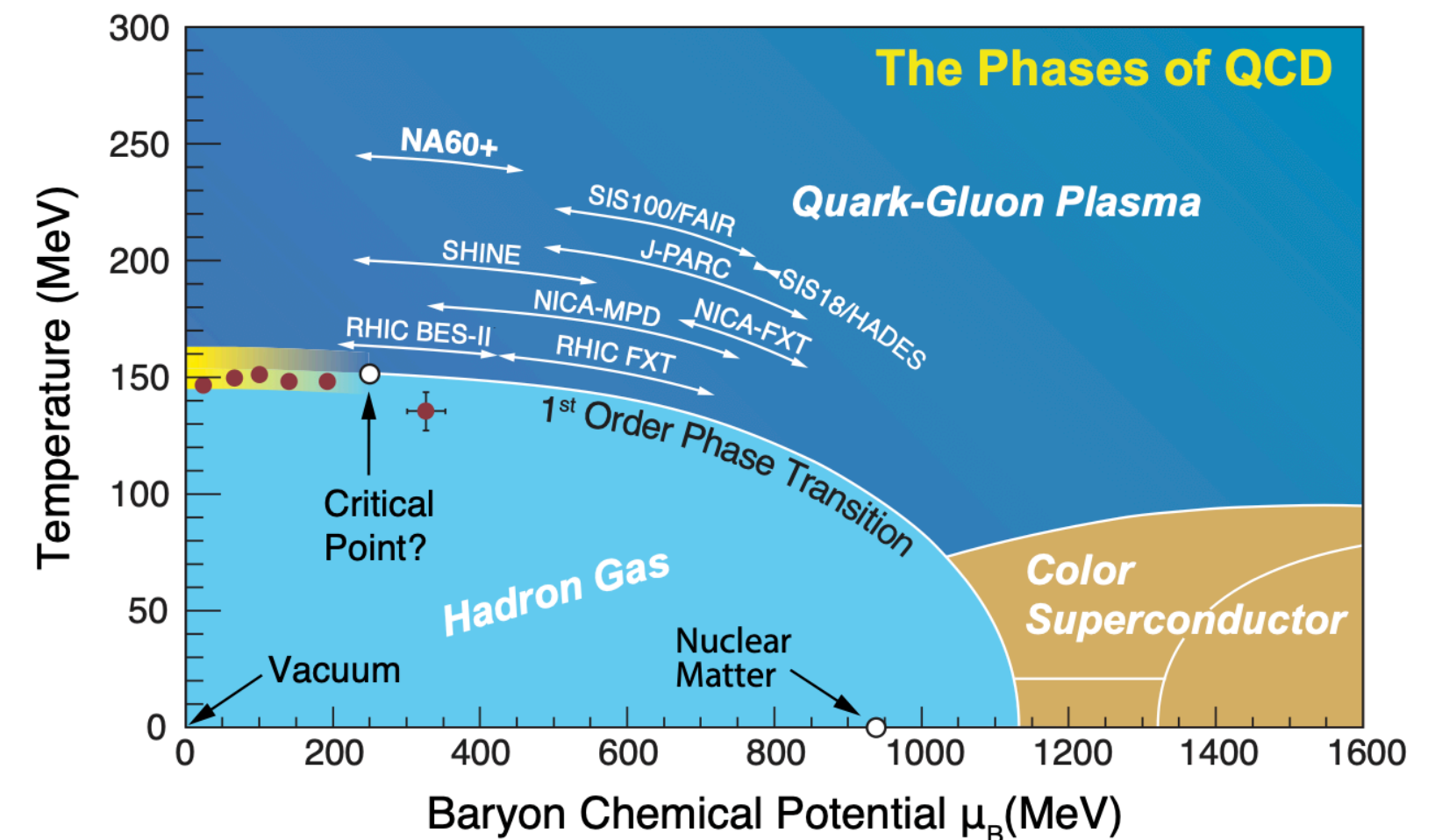
STAR datasets

- High statistics BES-II datasets covering large baryon chemical potential range: $100 < \mu_B < 760$ MeV.
- Varied collision systems: U+U, Au+Au, Ru+Ru/Zr+Zr, O+O, d+Au, p+Au, (polarized) p+p, etc.



Experimental overview of the BES-II
L. Ruan, Tue. 9:00am

Odyniec, G. (2022). Probing the QCD Phase Diagram with Heavy-Ion Collision Experiments.

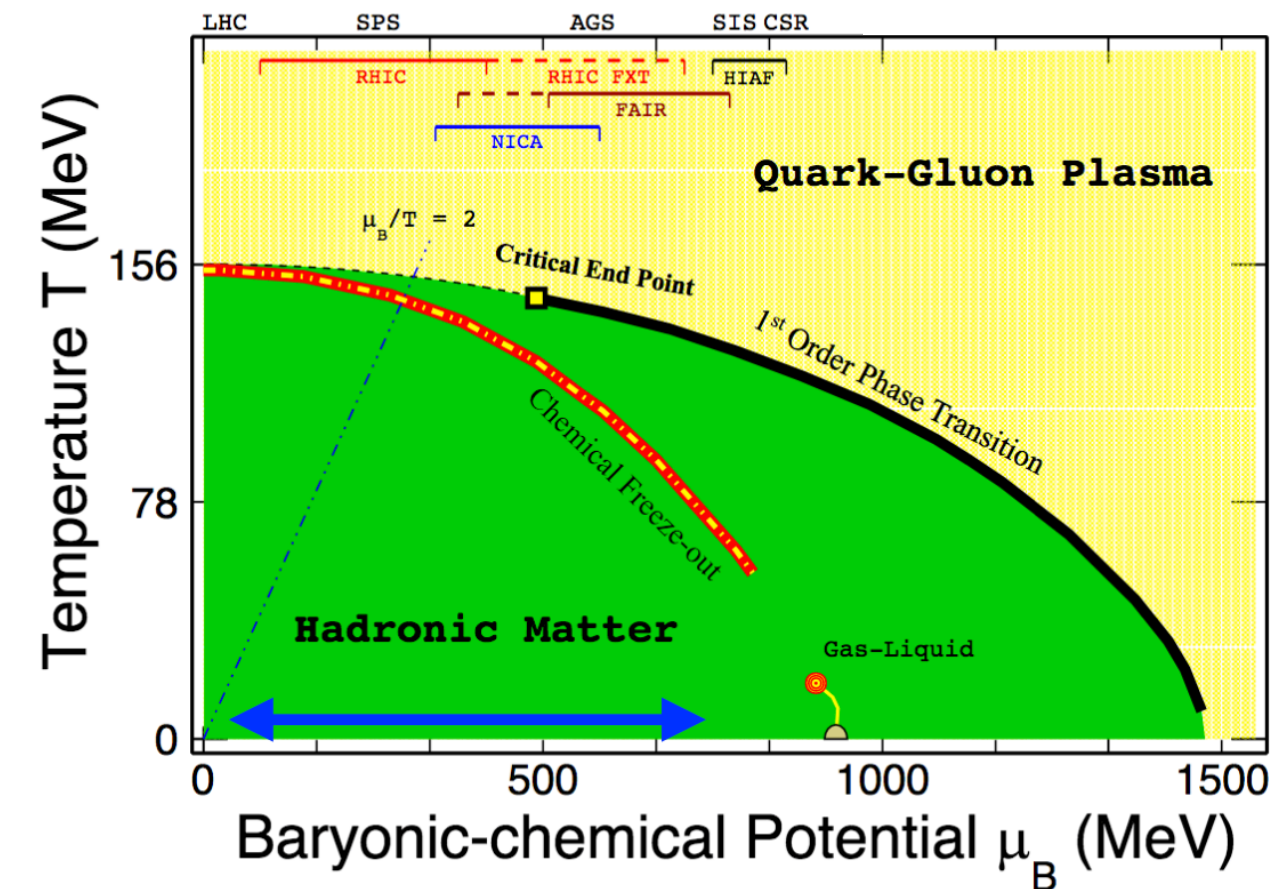


Outline

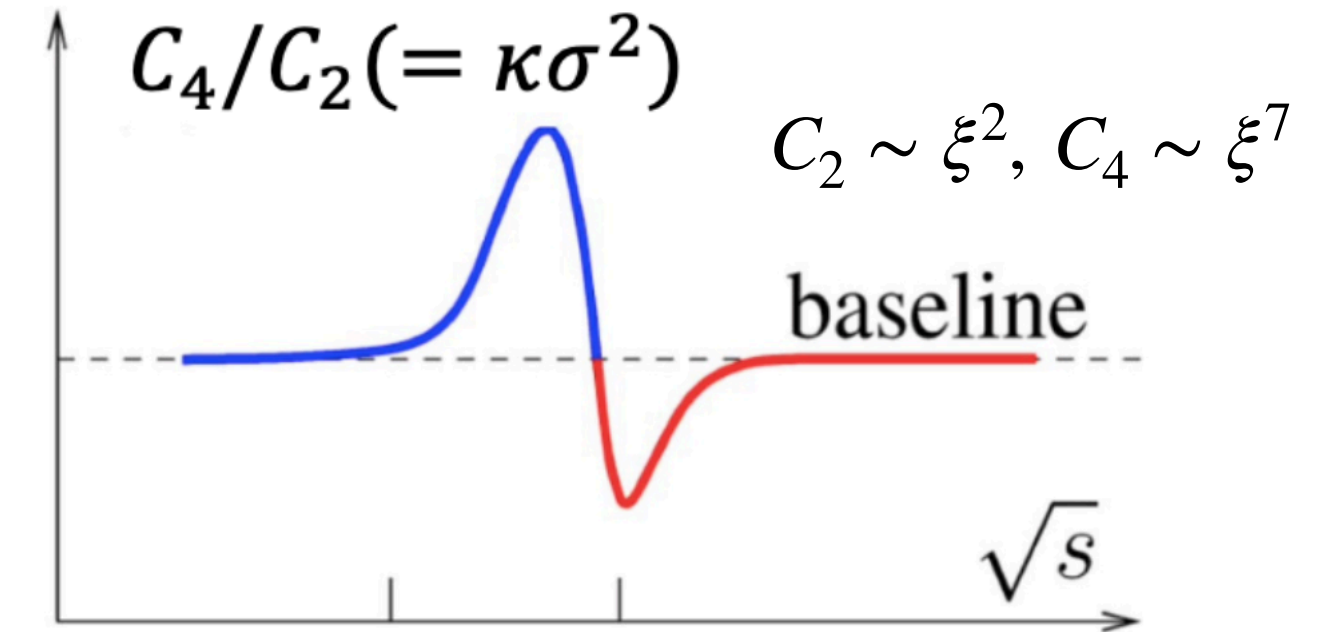
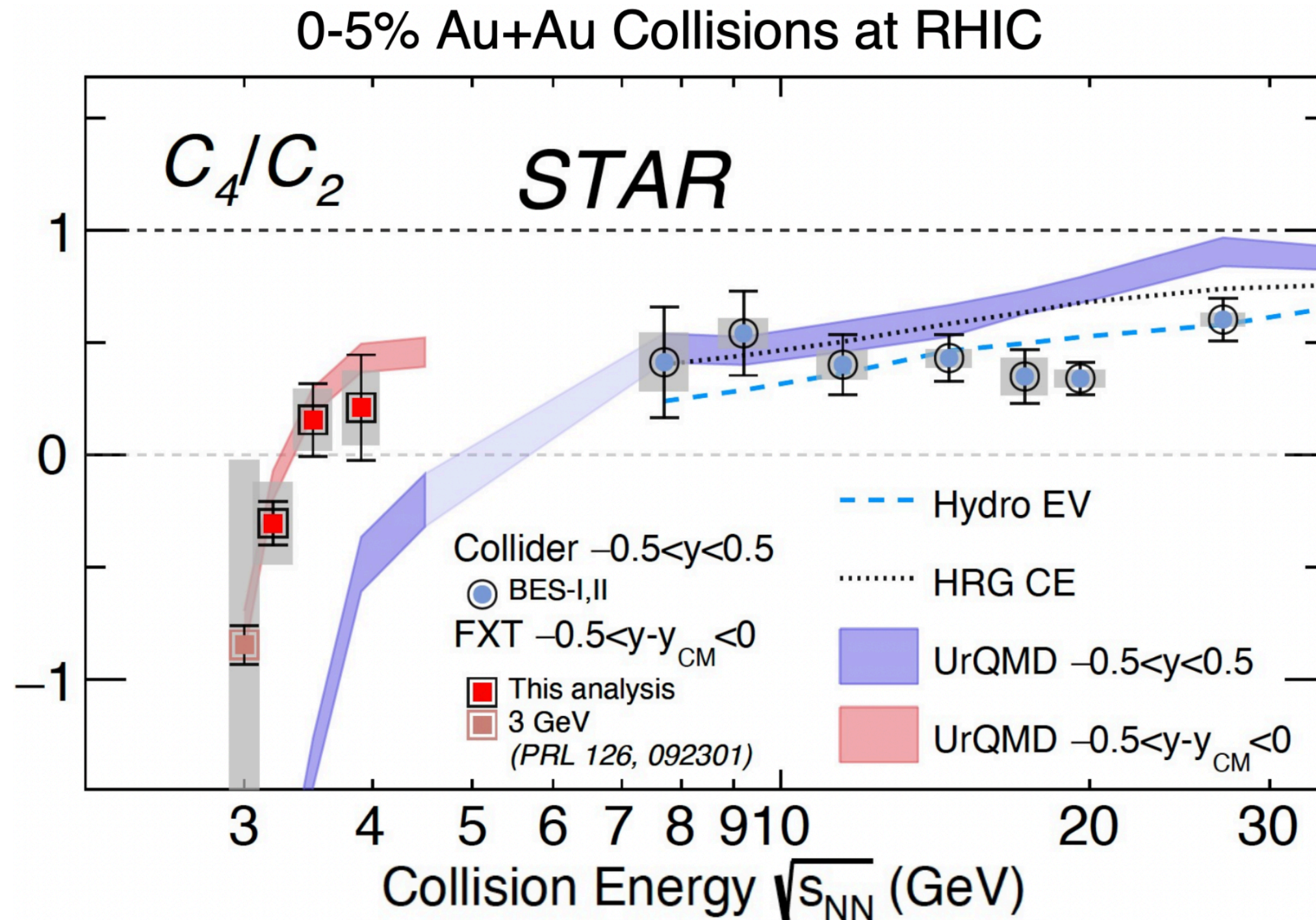
- **QCD Phase Structure**
- **Flow**
- **Heavy Flavor & Jets**
- **EM Probes**
- **Spin & Polarization**

Outline

- QCD Phase Structure: critical point.
- Flow
- Heavy Flavor & Jets
- EM Probes
- Spin & Polarization



Net-proton higher order cumulants



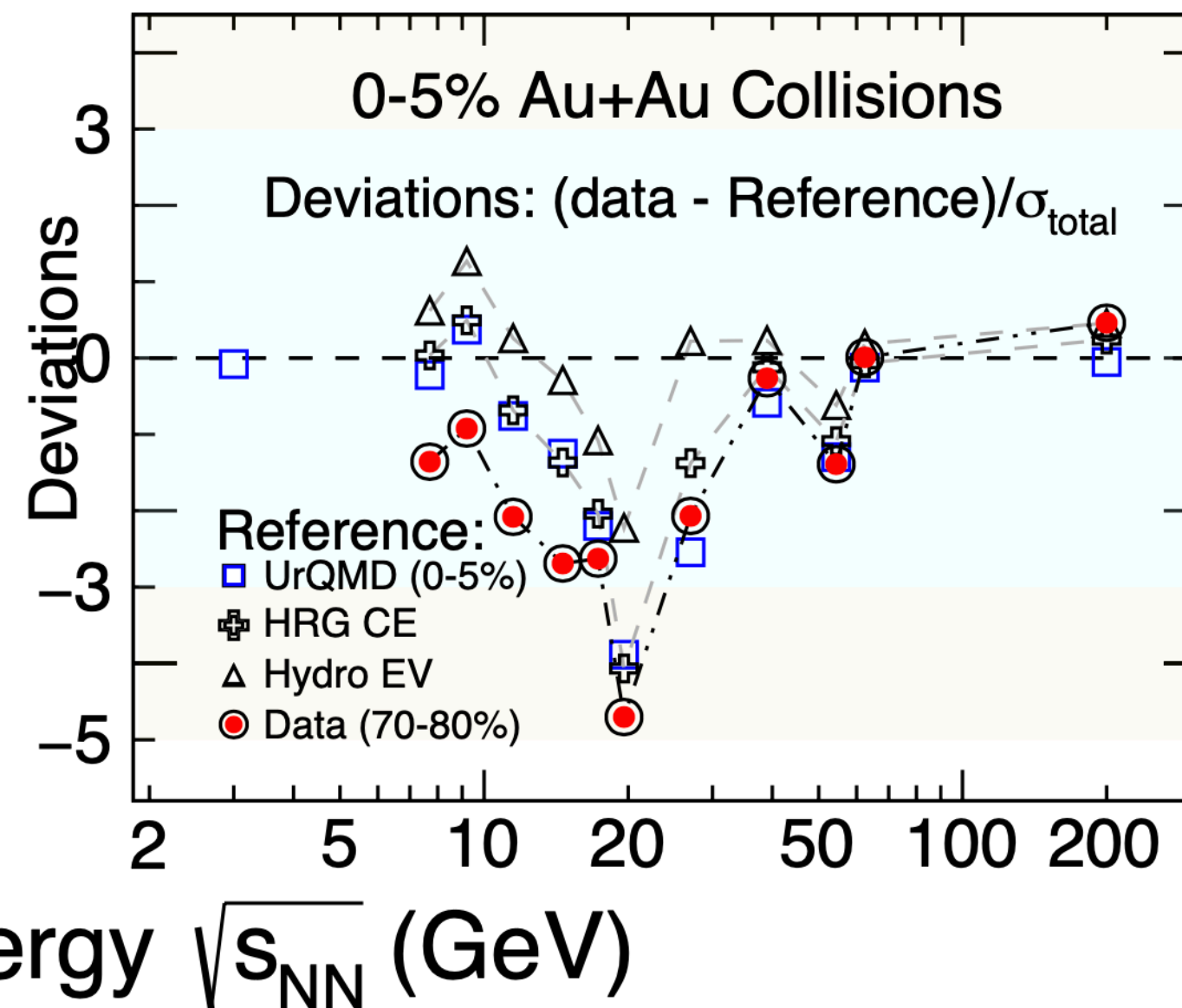
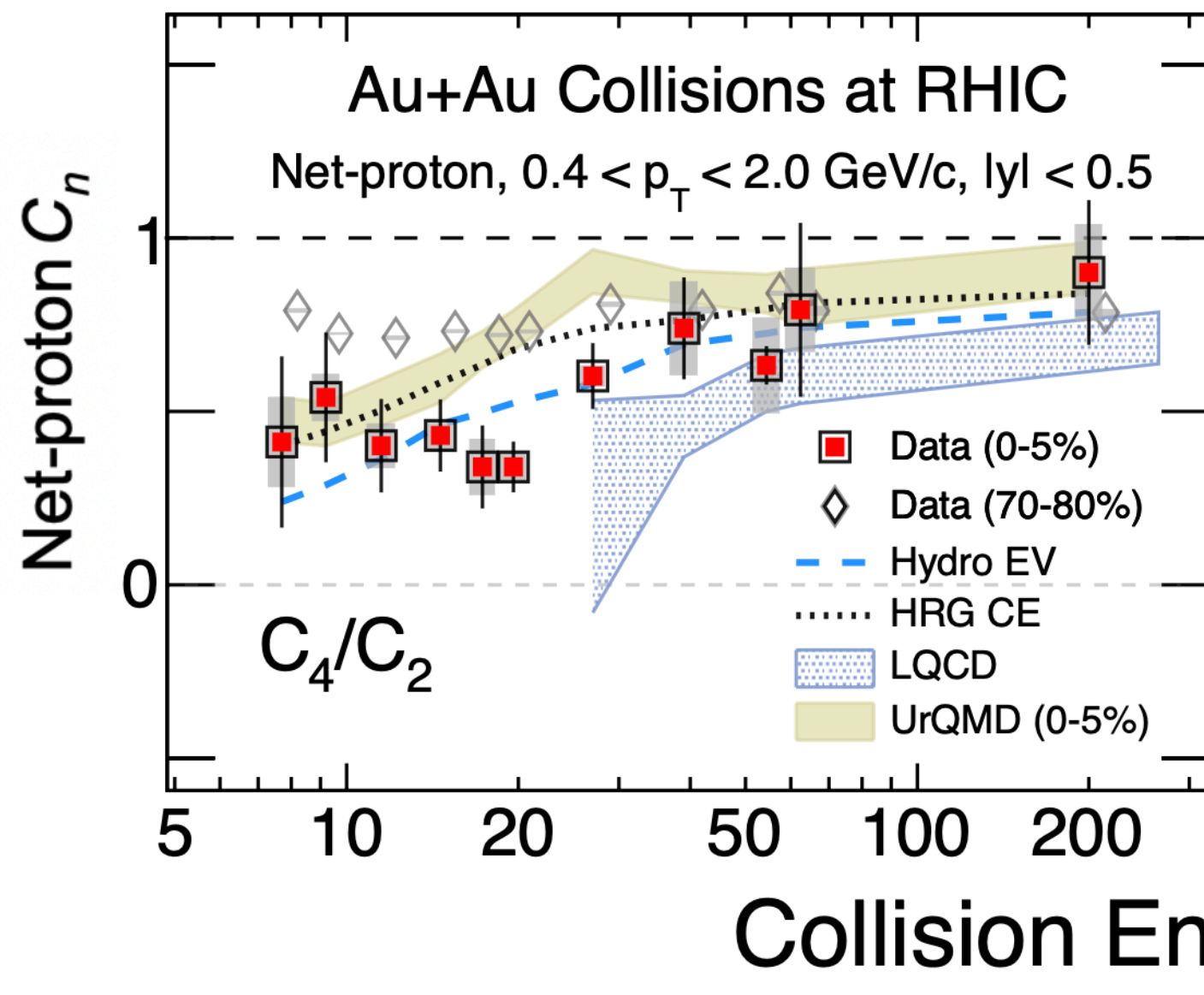
- Precision measurements of high-order (factorial) cumulants for collision energies from 7.7 to 19.6 GeV and FXT energies at 3.2, 3.5, and 3.9 GeV.
- In 3.2 - 3.9 GeV, C_4/C_2 is consistent with UrQMD. Deviations can be seen at higher energies.

Net-proton higher order cumulants

Z. Sweger, Tue. 9:30am

- Precision measurements: statistical uncertainty is reduced by factor of 4.5 and systematic uncertainty is reduced by 3-4.

STAR: arXiv: 2504.00817



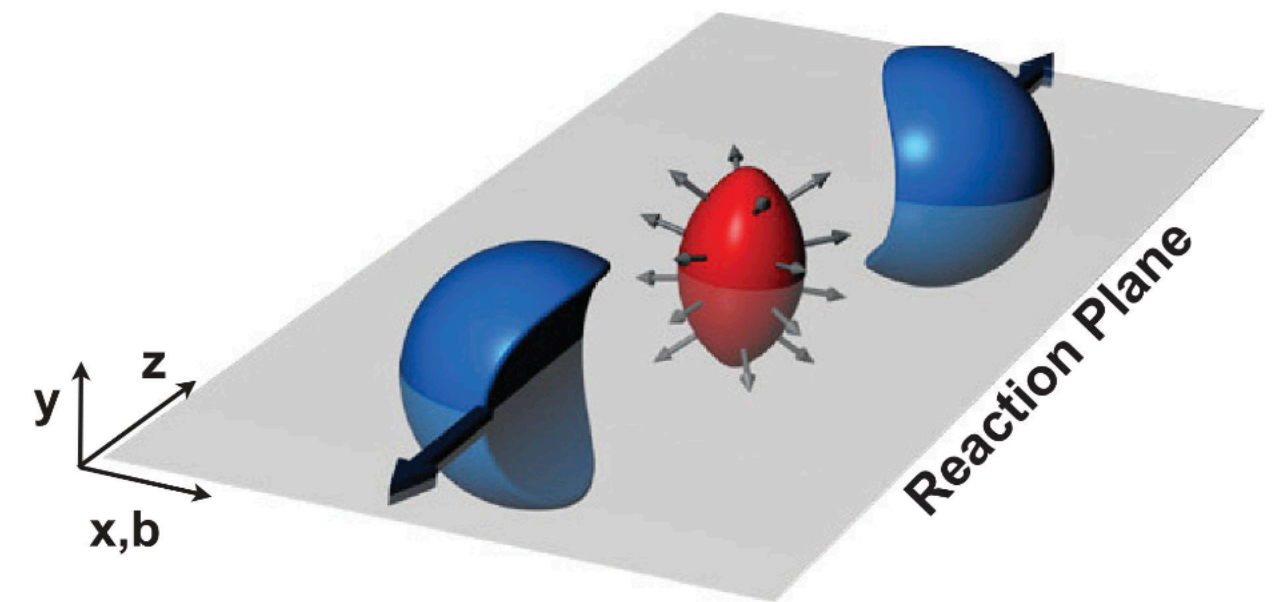
2 - 5 σ deviation
from calculations
without CP.

The largest
deviation occurs at
 $\sqrt{s_{NN}} = 19.6$ GeV.

Outline

- QCD Phase Structure
- **Flow: azimuthal anisotropy & nuclear imaging.**
- Heavy Flavor & Jets
- EM Probes
- Spin & Polarization

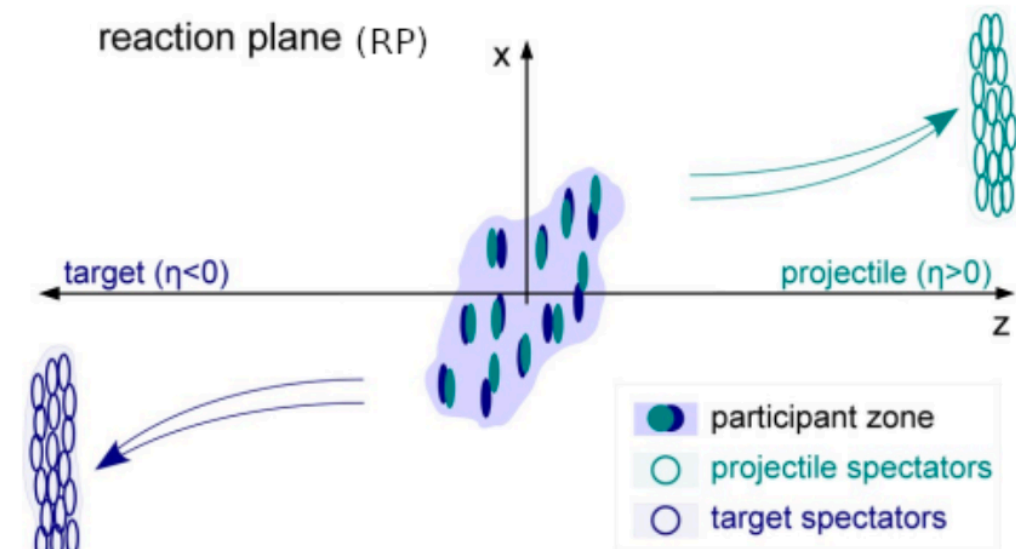
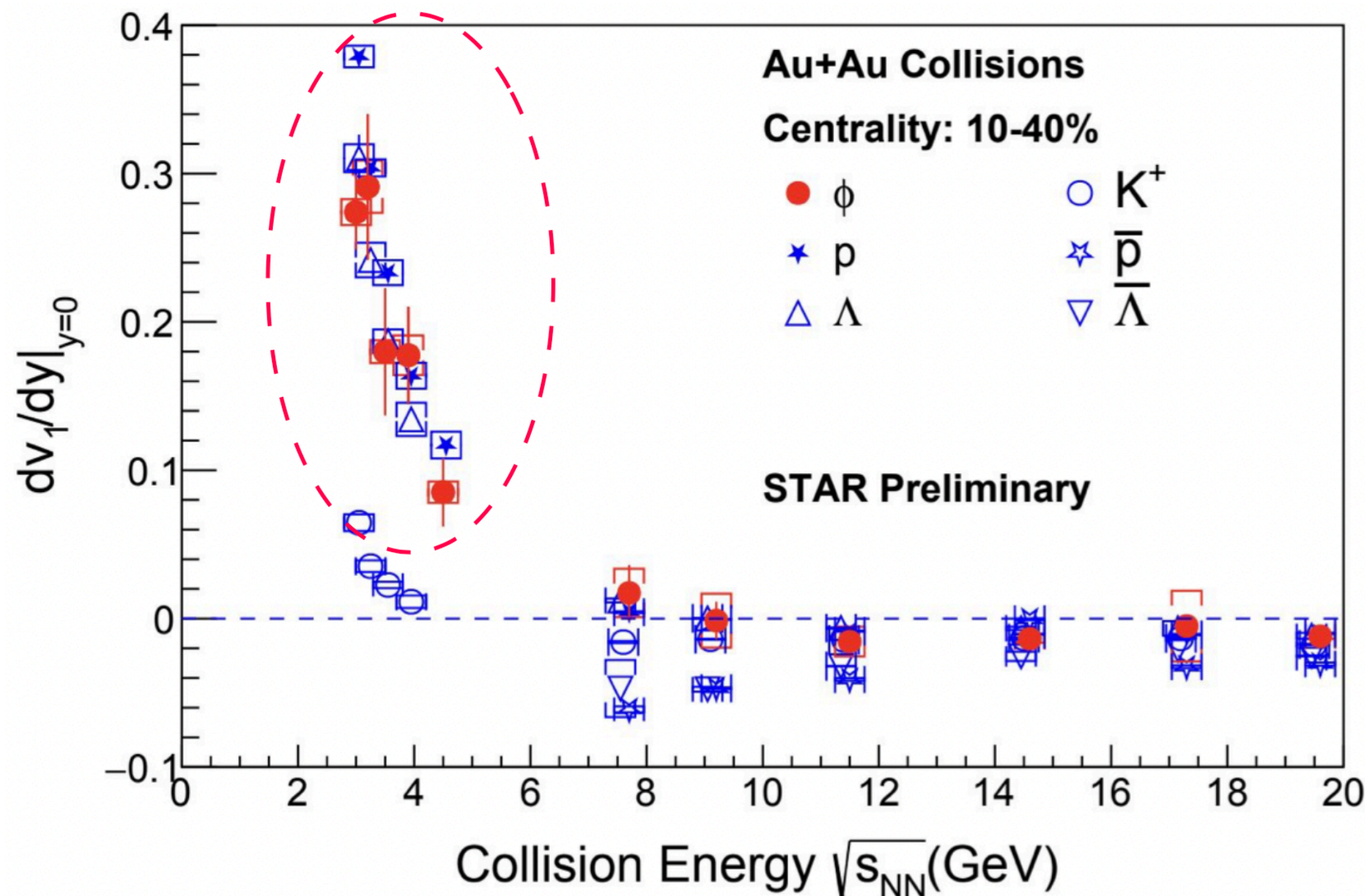
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$



Anisotropic Flow: directed flow (v_1)

S. Sharma, Wed. 4:00pm

Anisotropic flow is sensitive to the equation of state and early times in the evolution of the system.

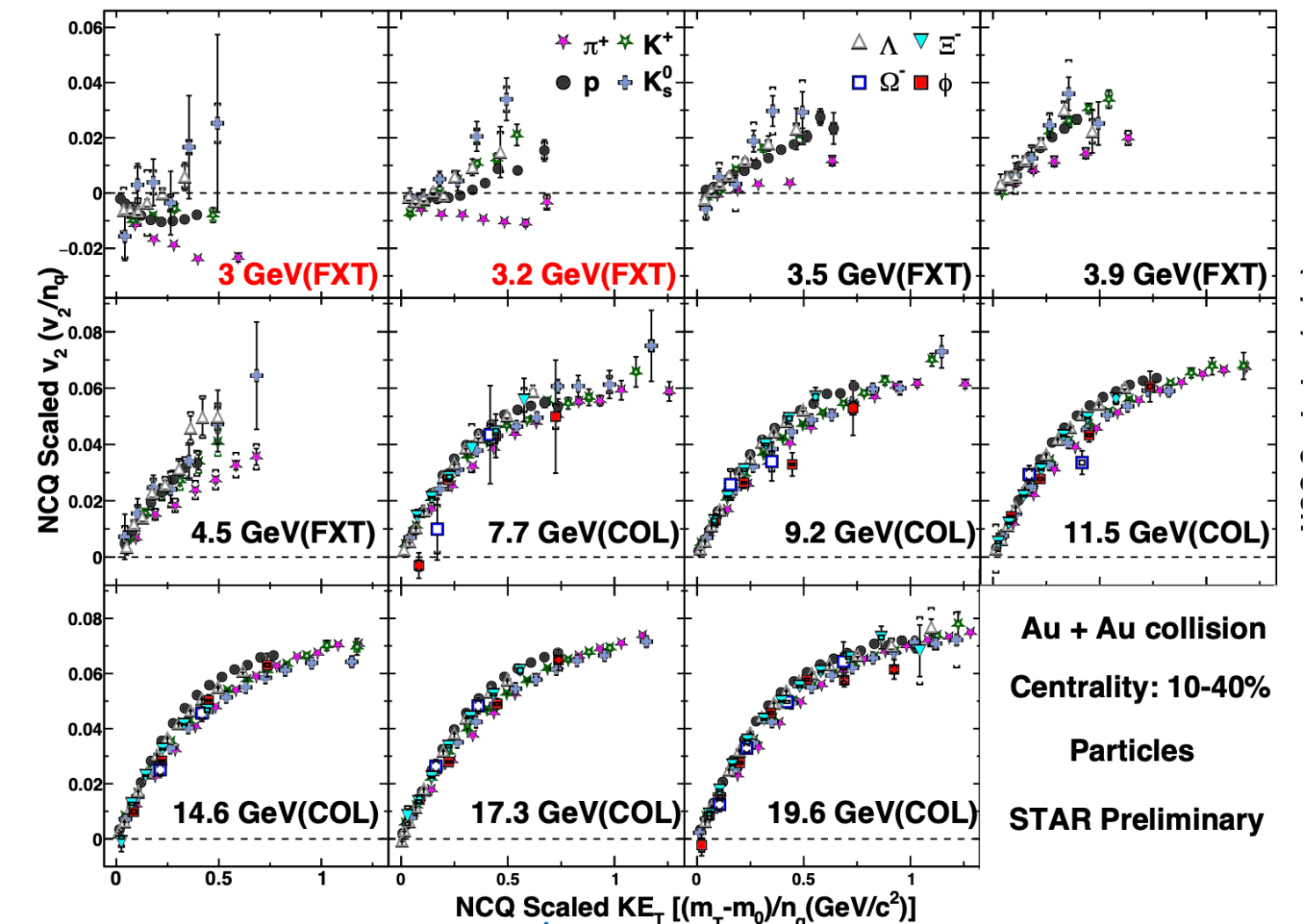
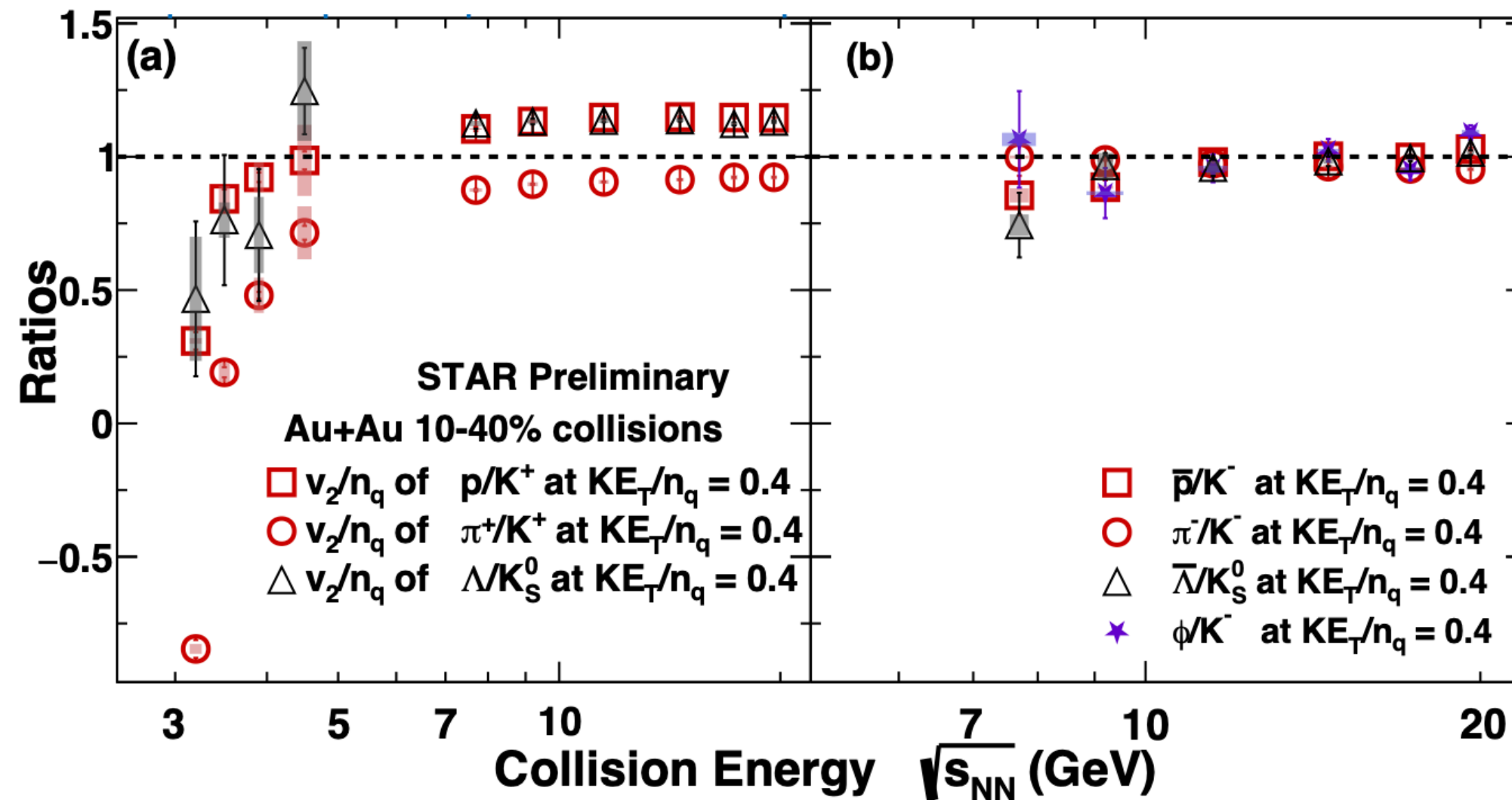


- The v_1 slope of ϕ meson shows **unexpected similar trends** to that of p and Λ in high μ_B region.
- Kaons show sign change as protons with minimum between 4.5 and 7.7 GeV.

Anisotropic Flow: elliptic flow (v_2)

S. Sharma, Wed. 4:00pm

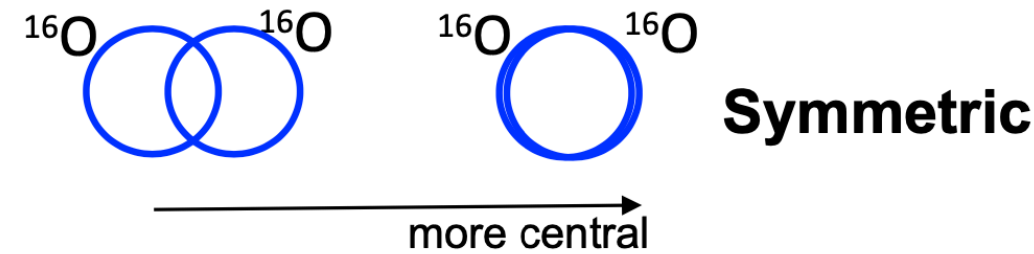
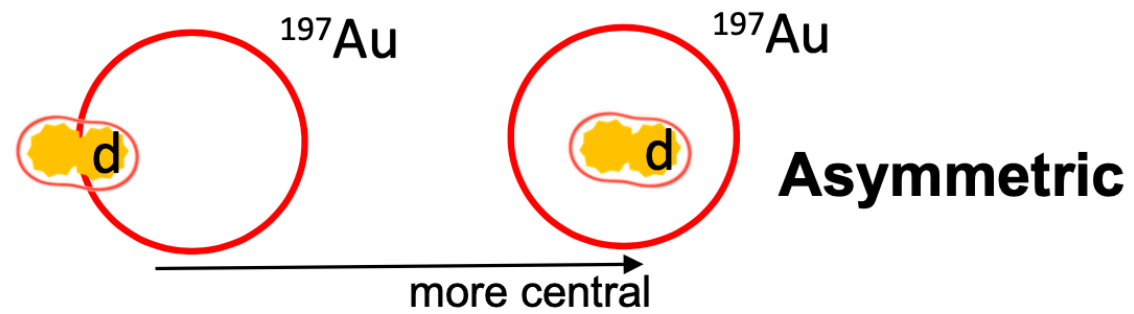
- NCQ scaling completely **breaks** below 3.2 GeV indicates dominance of hadronic interactions.
- Partonic collectivity at 7.7 GeV and above.



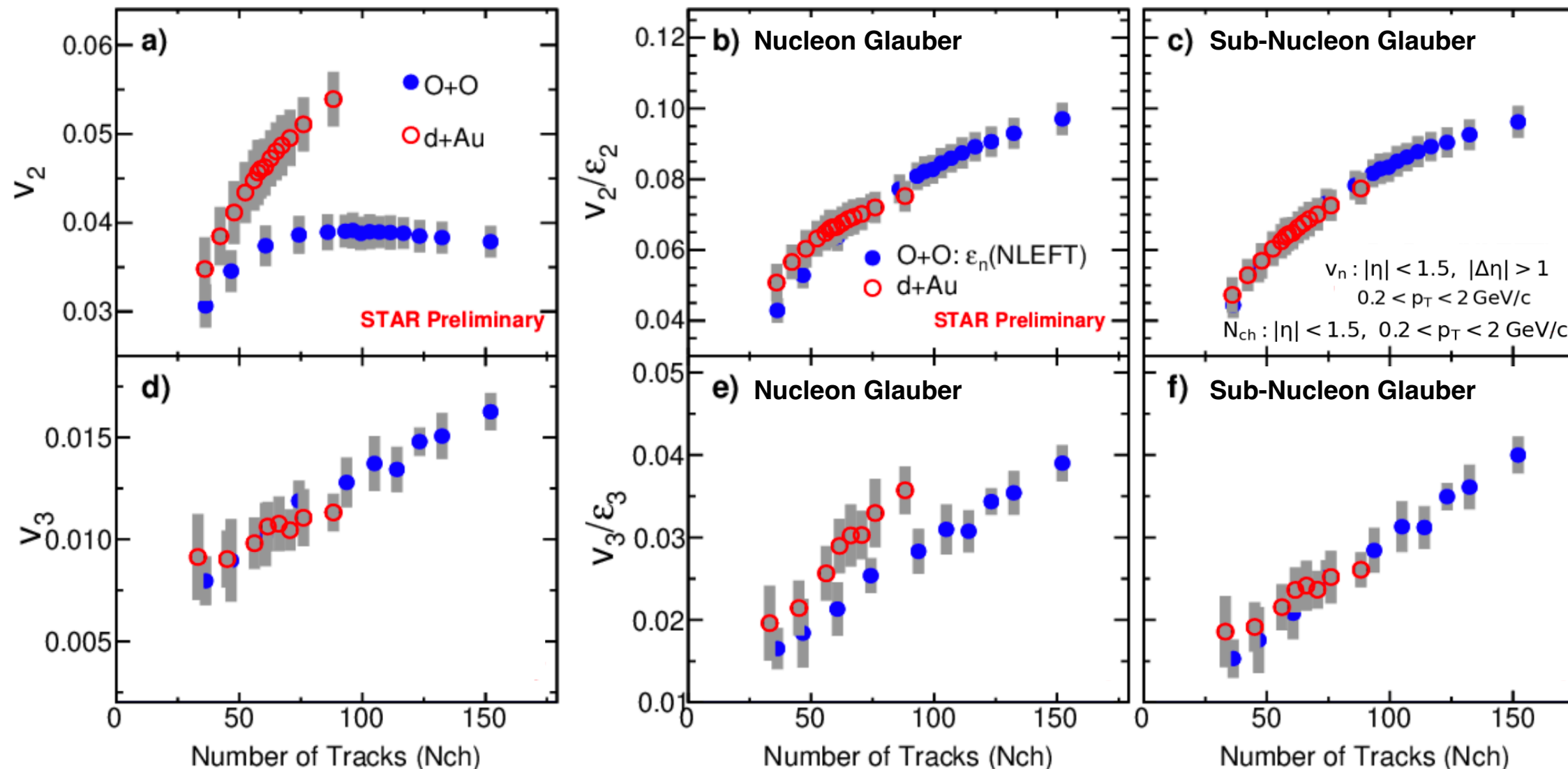
NCQ scaling: number of constituent quark scaling.
Hadron flows follow the same scaling.

Origin of anisotropy in small systems

S. Paul, Wed. 2:00pm



$$\varepsilon_2(d+Au) > \varepsilon_2(O+O)$$



- v_2/ε_2 : d+Au and O+O show **consistent** collective response to geometry.
- Both v_2 and v_3 scale well with eccentricities from **sub-nucleon Glauber**.
- Wildly different initial geometries are converted to the final state flow.
- Hallmark of collective response **from QGP** in small systems.

Nuclear imaging in HIC

- Nuclear structure leaves imprints on v_n and $v_n - p_T$ correlations.
- Extract U+U shape parameters β_2 and γ :
 - **Large quadrupole deformation**, consistent with low-energy measurements and indication of **small triaxiality** in U+U ground state.

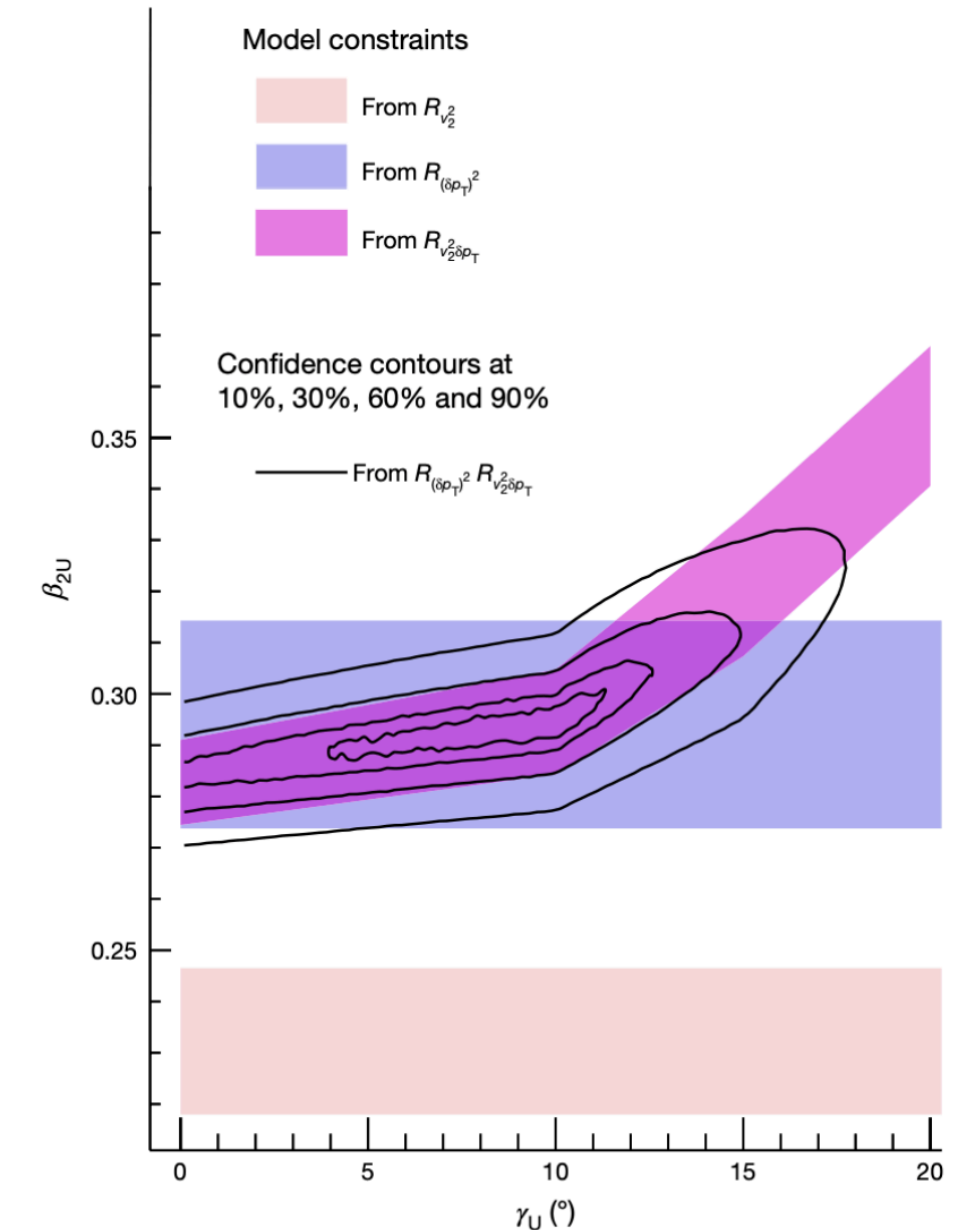
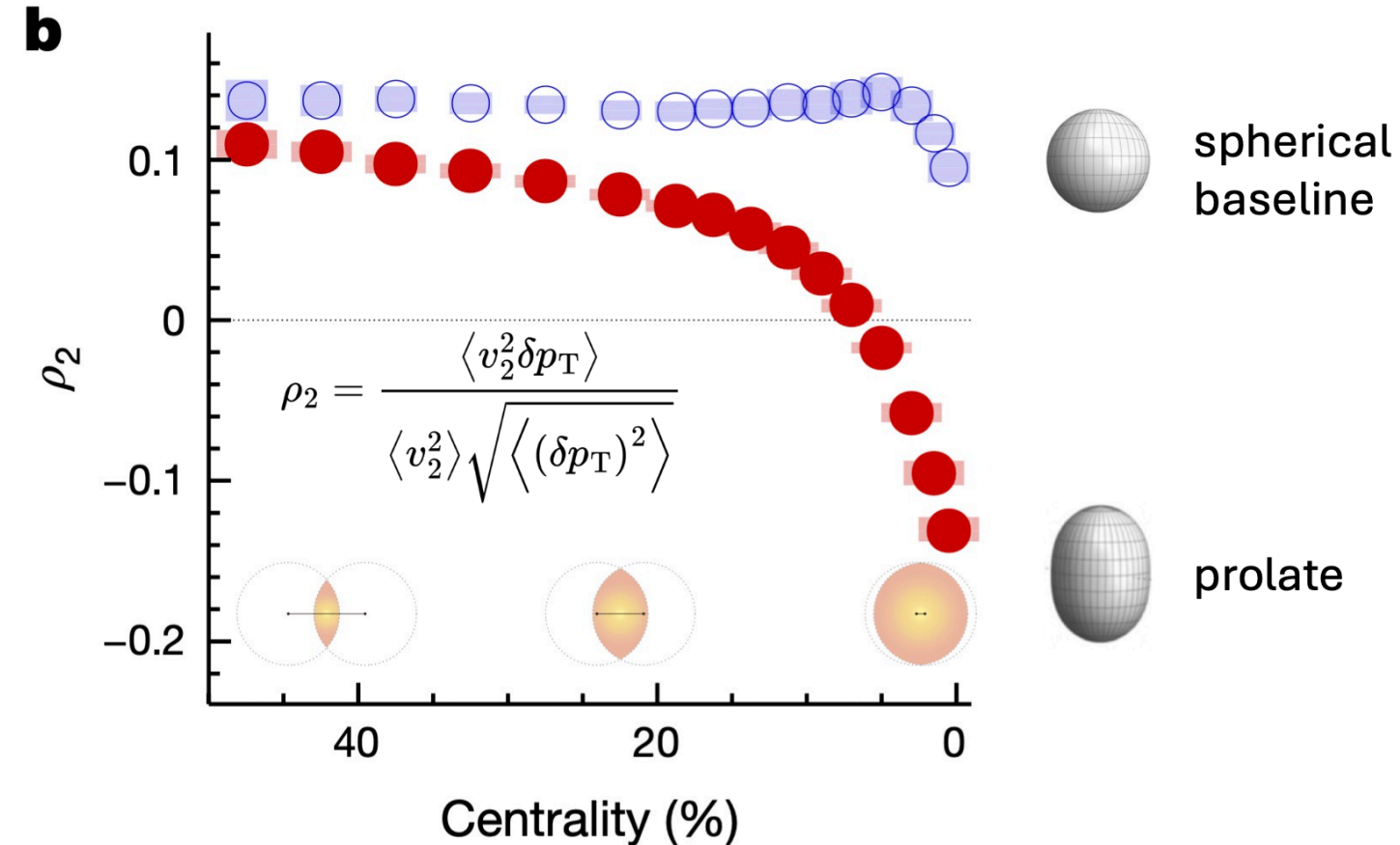
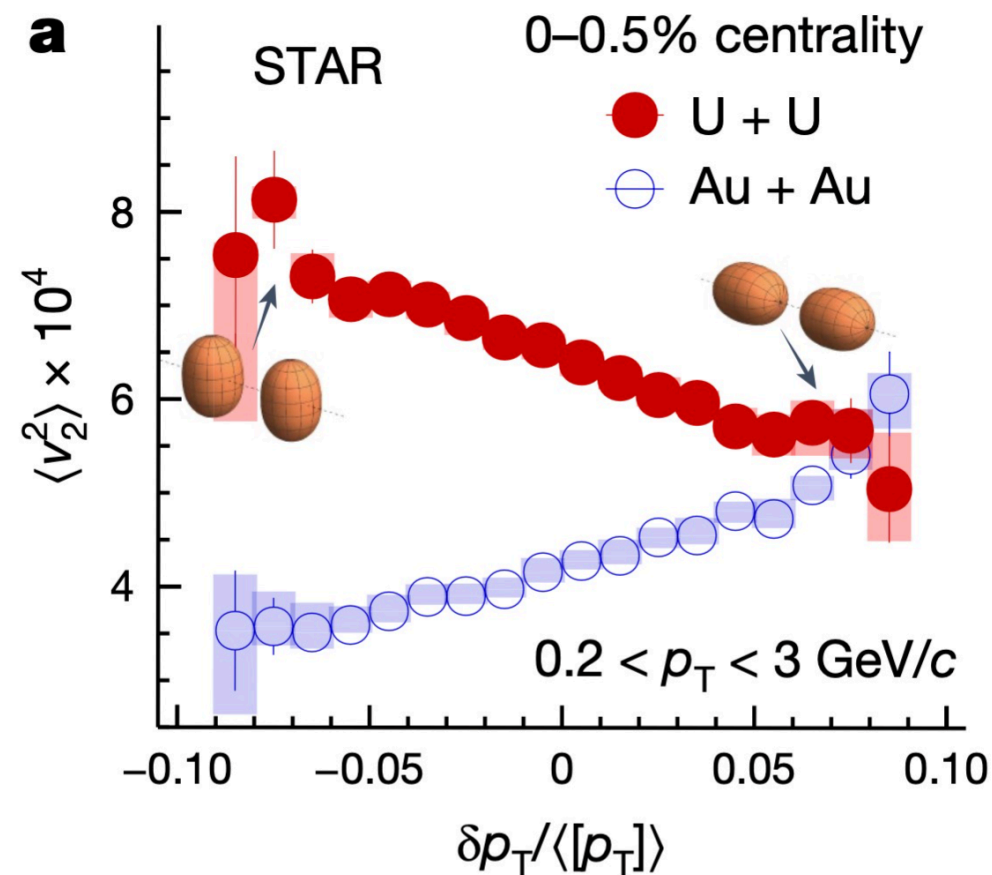
$$\rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{(r-R(\theta, \phi))/a_0}}$$

$$R(\theta, \phi) = R_0(1 + \beta_2[\cos \gamma Y_{2,0}(\theta, \phi) + \sin \gamma Y_{2,2}(\theta, \phi)] + \beta_3 Y_{3,0}(\theta, \phi))$$

$$\beta_{2U} = 0.297 \pm 0.015$$

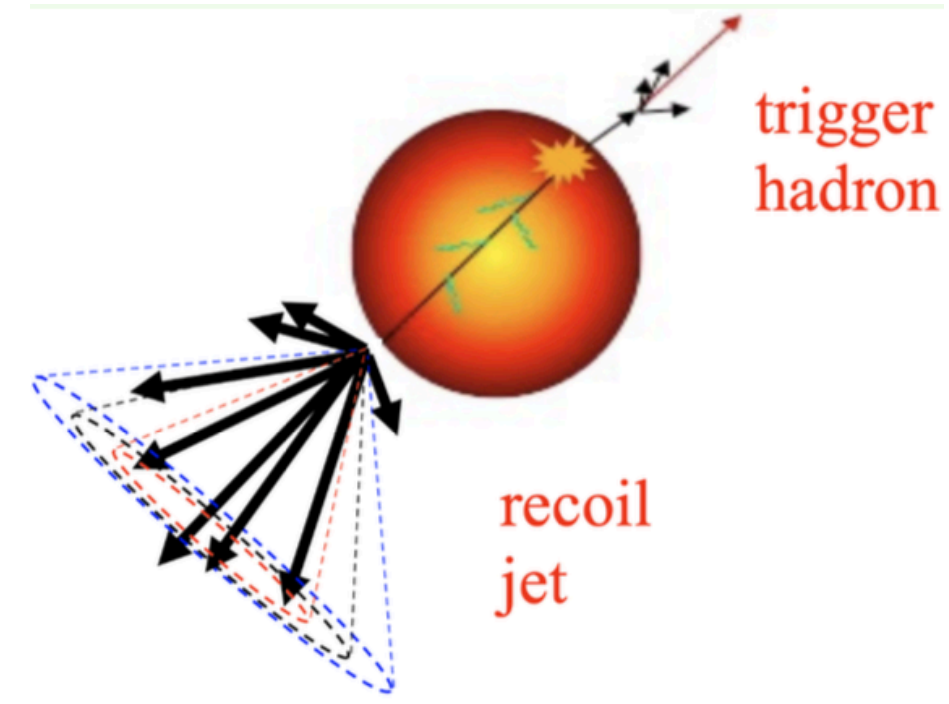
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

STAR, Nature 635, 67-72 (2024)



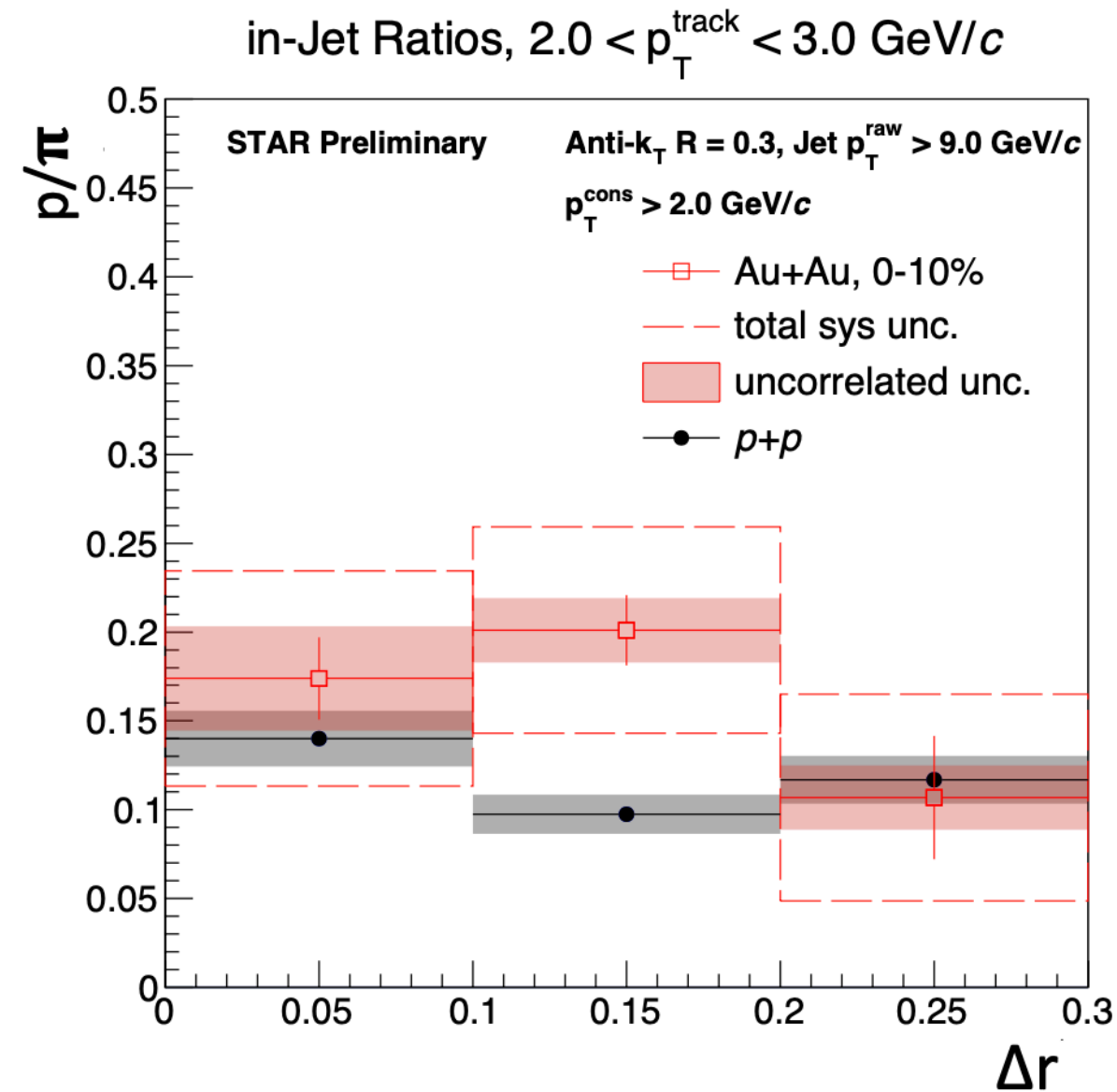
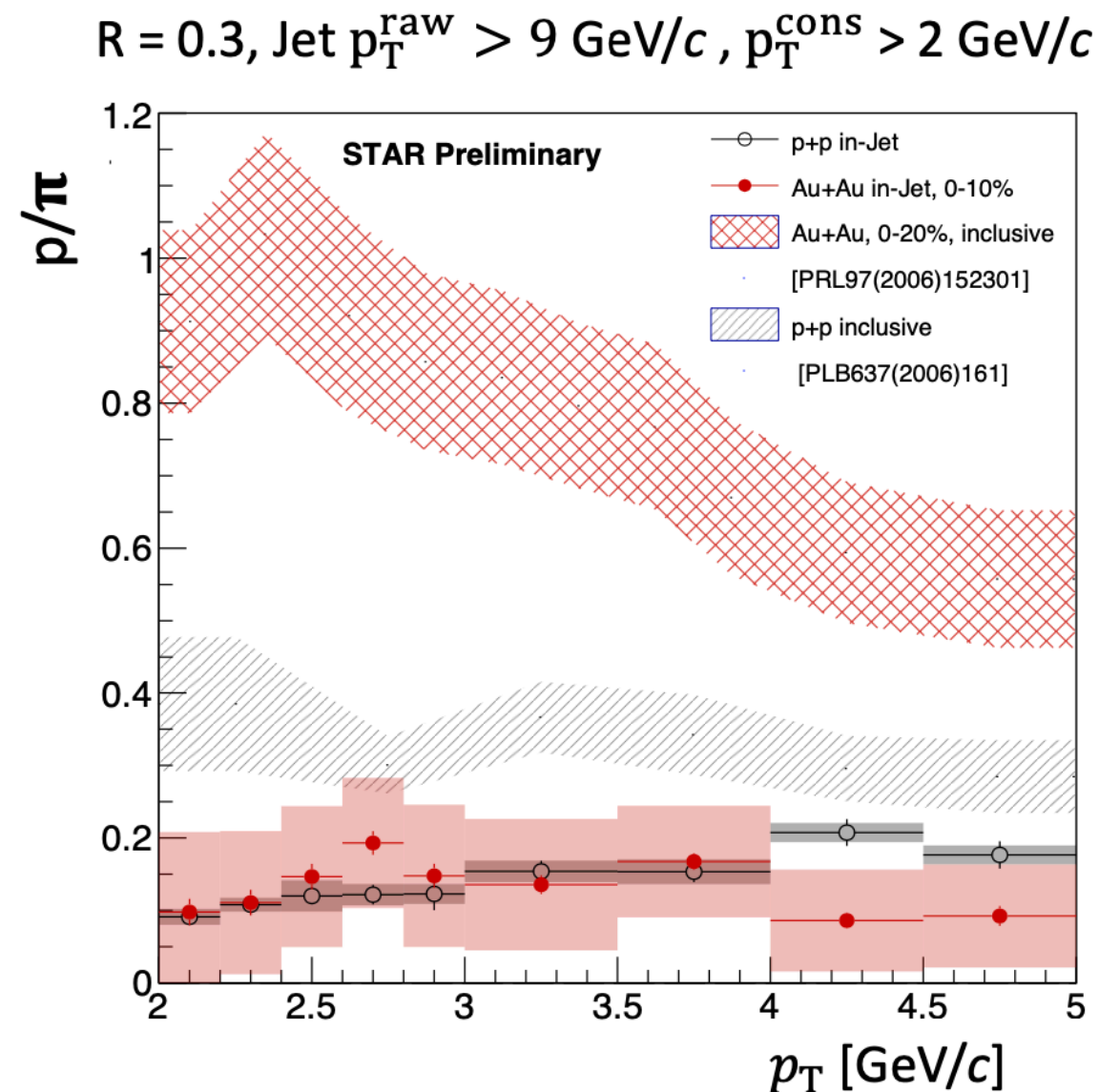
Outline

- QCD Phase Structure
- Flow
- **Heavy Flavor & Jets: hadronization and jet quenching.**
- EM Probes
- Spin & Polarization



Baryon to Meson ratio in jets

A. Tamis, Wed. 9:50am



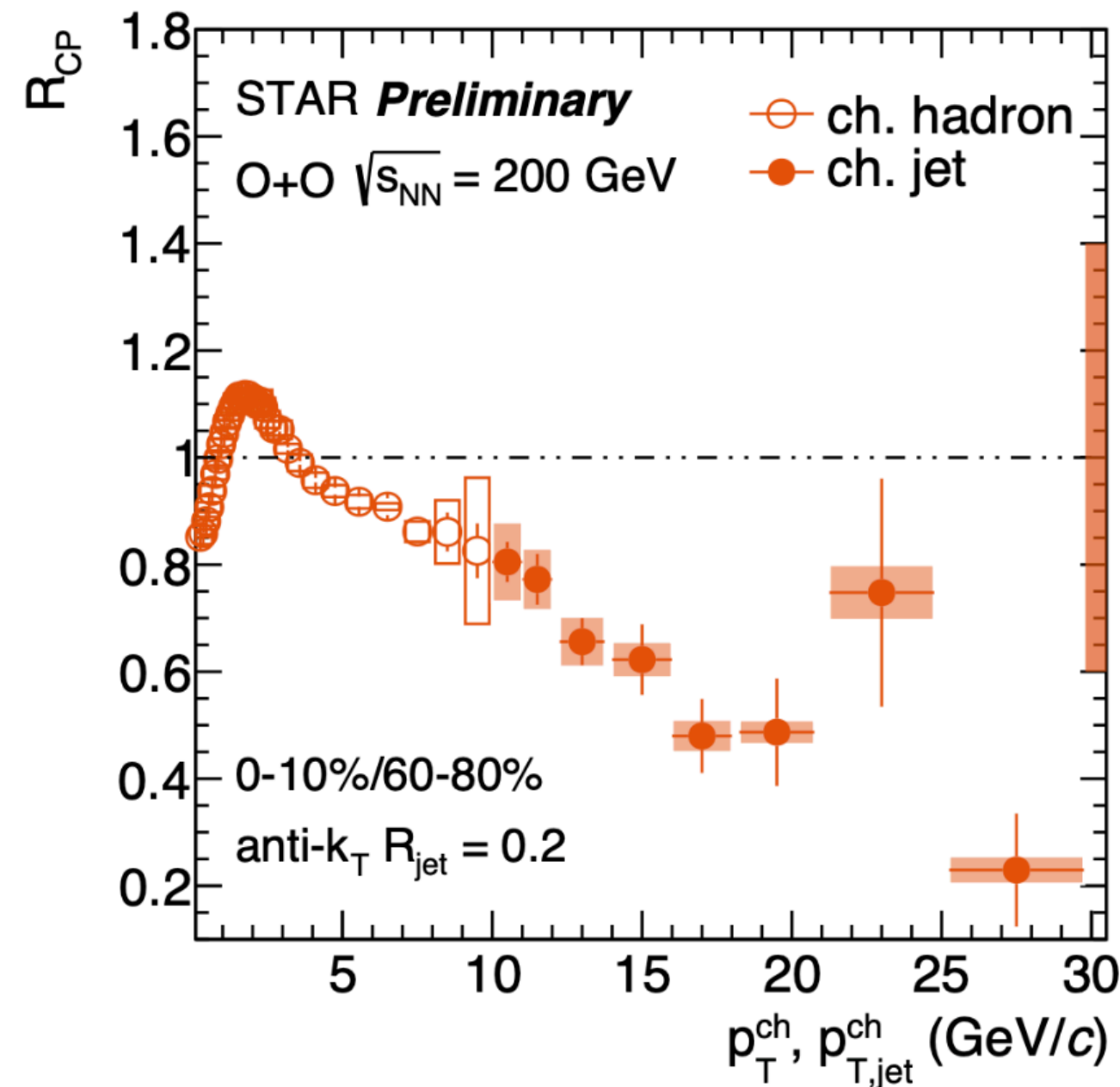
- For measured kinematics, **no significant modification** of p/π yield ratio within jets between p+p and Au+Au.
- **No baryon enhancement** observed over momentum range scanned, except hint at $\Delta R = 0.15$.
- Inclusive baryon to meson ratios **enhanced** in A+A compared to p+p.
- Coalescence hadronization in QGP.
- How about the B/M ratio within jets?

Jet quenching in O+O

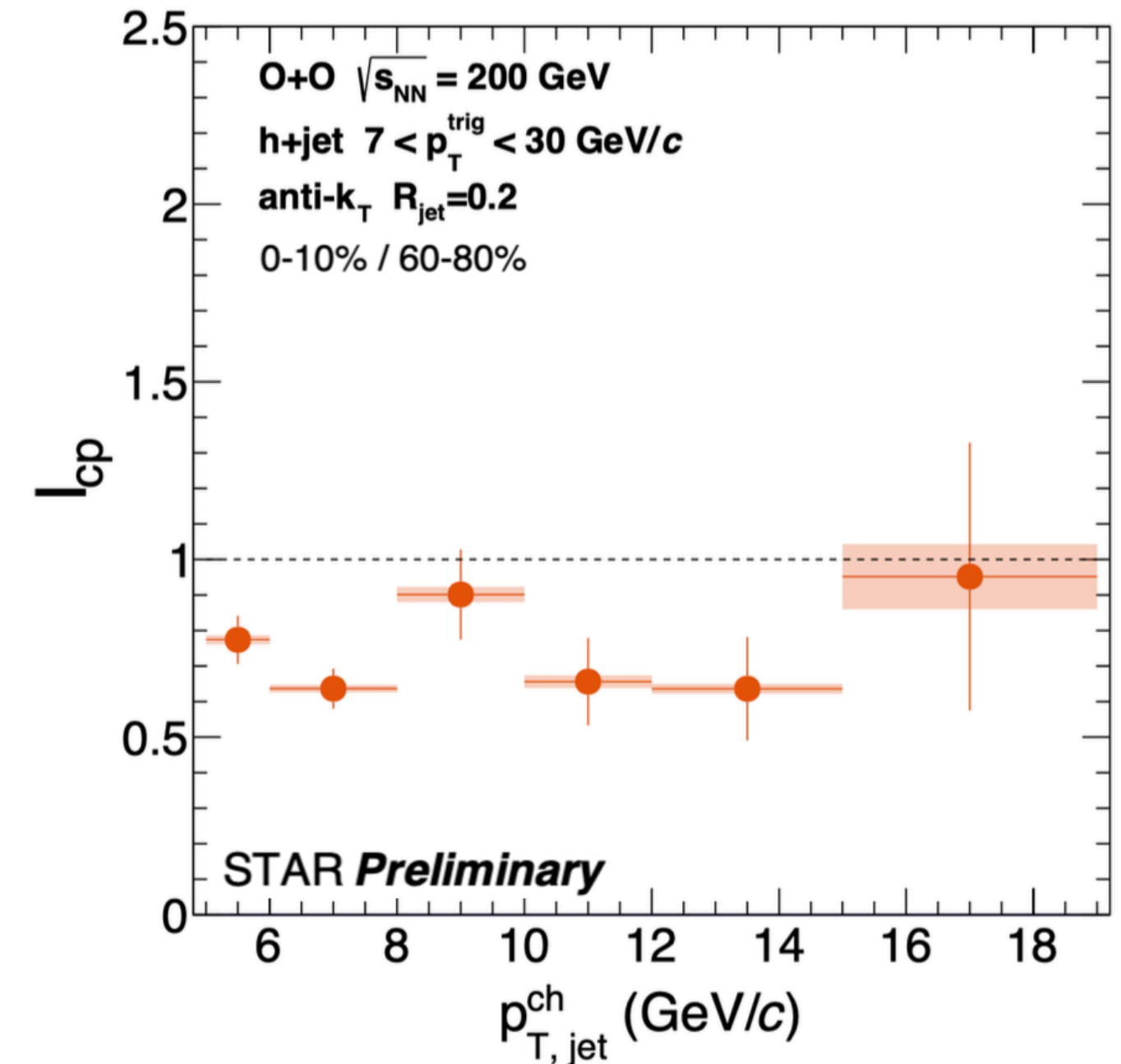
A. Tamis, Wed. 9:50am

- Jet quenching in small system?
- No significant radial dependence.
- Effects other than quenching may be present.

Inclusive hadrons and jets



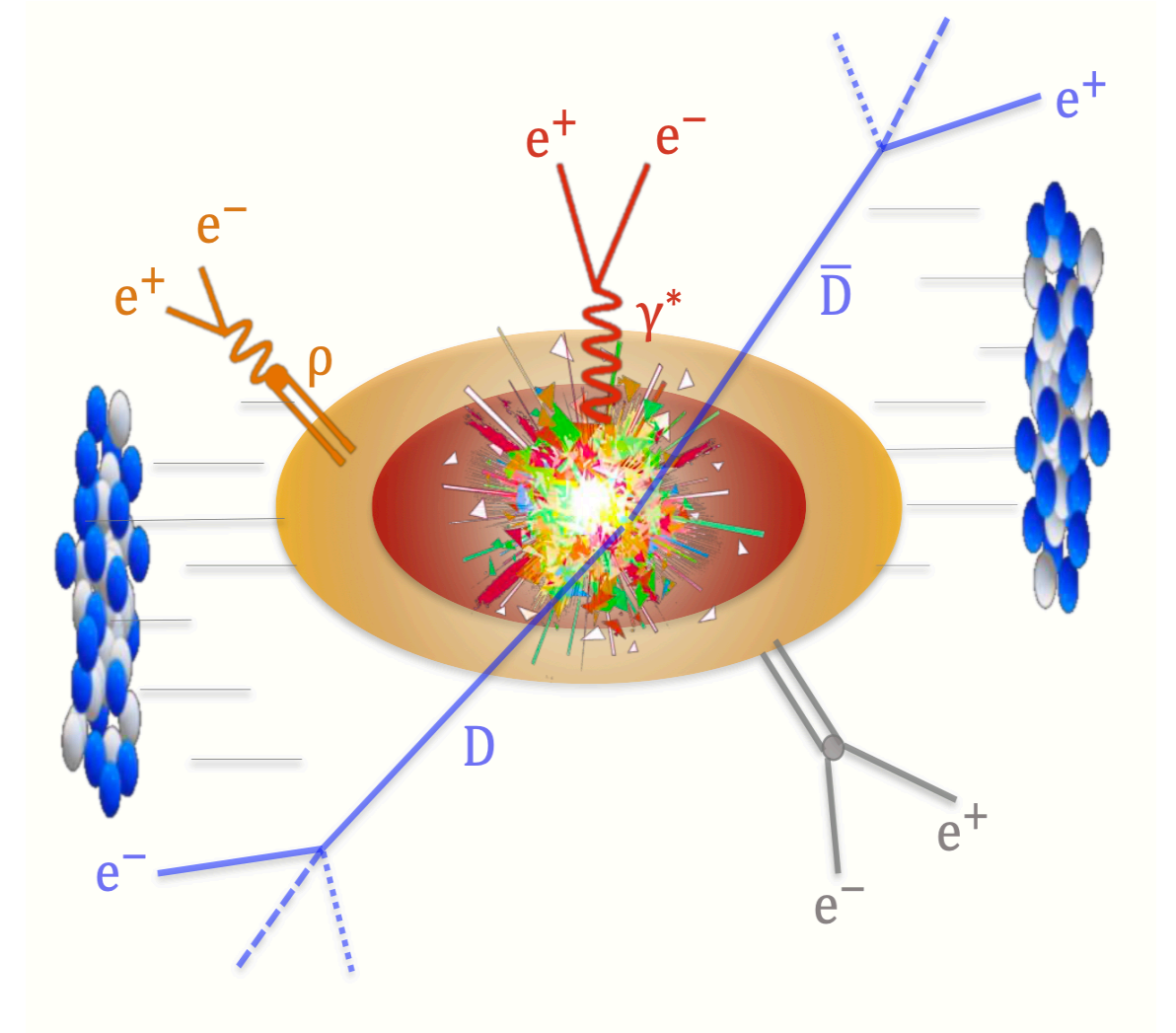
Semi-inclusive h+jets



Hint of high- p_T jet suppression in O+O collisions.

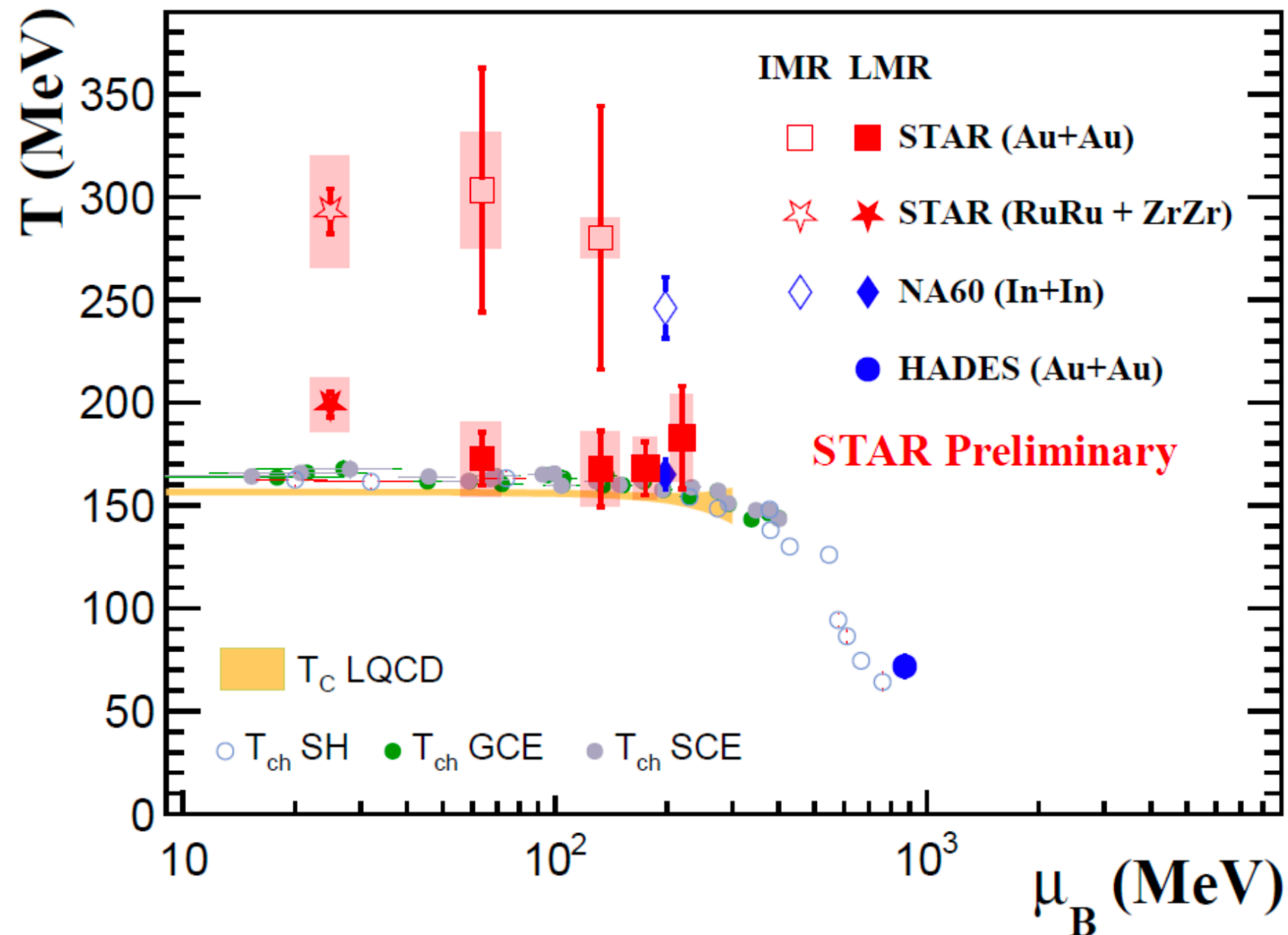
Outline

- QCD Phase Structure
- Flow
- Heavy Flavor & Jets
- **EM Probes: spectrometer & thermometer.**
- Spin & Polarization

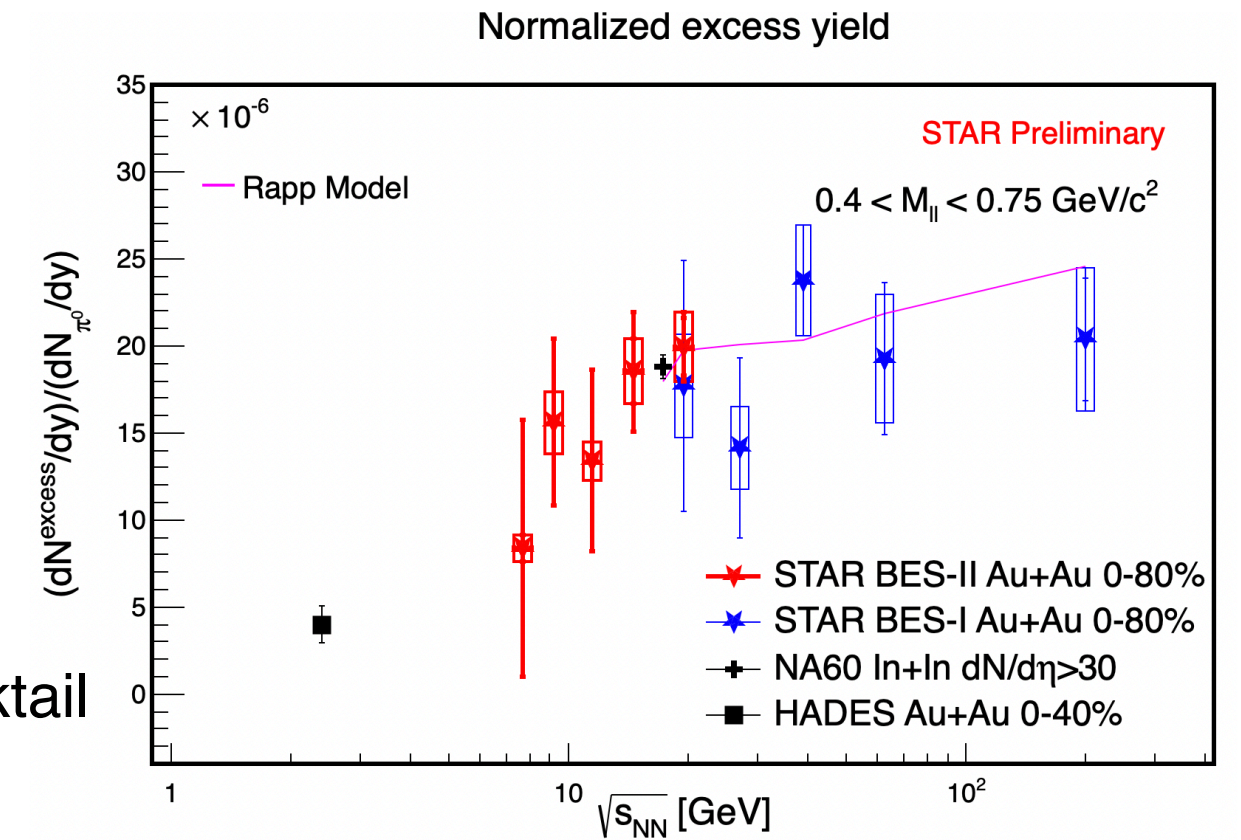


Thermal dielectrons

Normalized integrated excess yield: hint of **decreasing trend** towards lower collision energy.

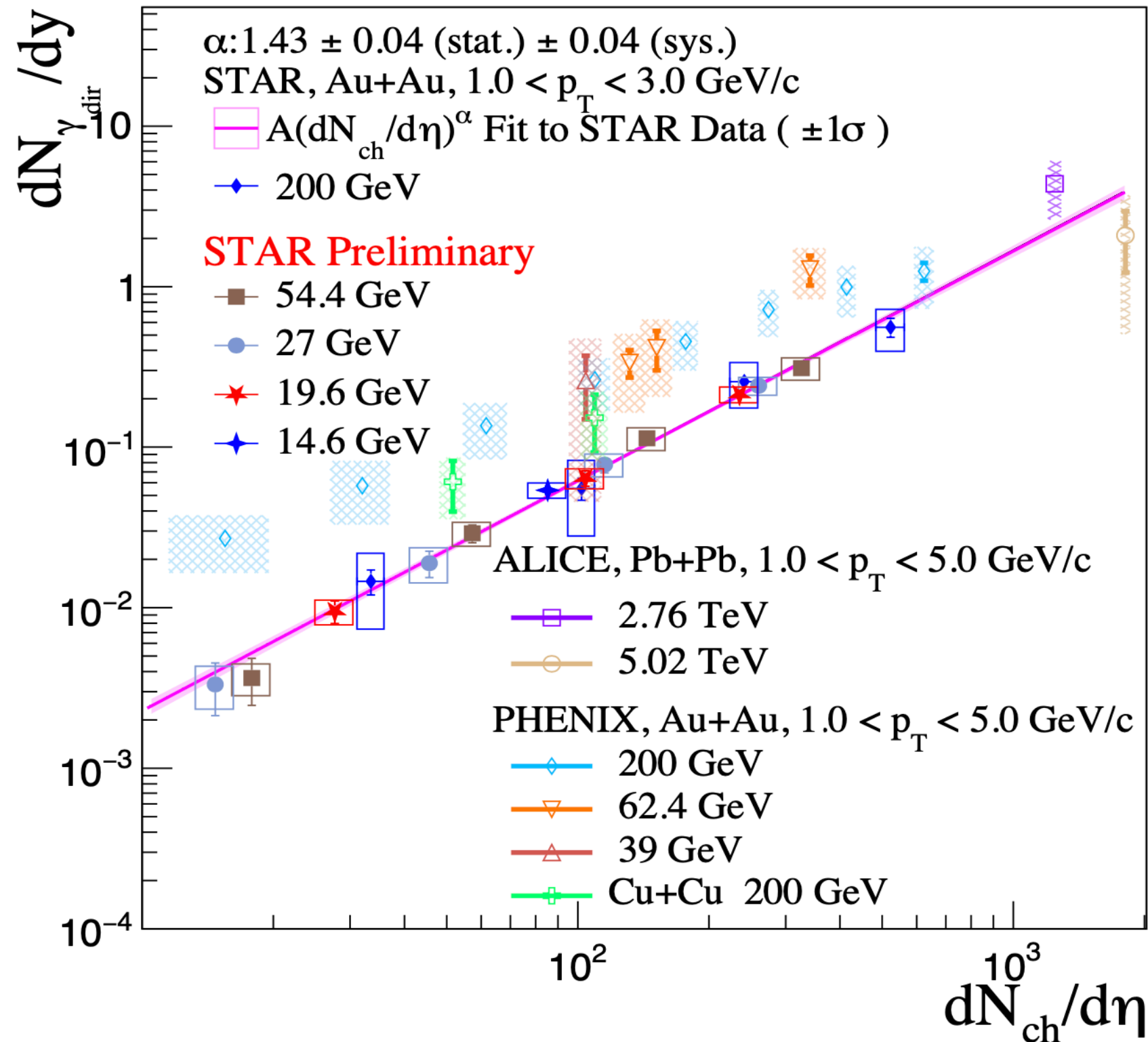


Excess = data - cocktail



- Low Mass Range:
 - T is close to both T_{ch} and T_{pc} .
 - Results indicate the thermal radiation from hadronic gas is mainly produced **around the phase transition**.
- Intermediate Mass Range:
 - T is higher than both T_{ch} and T_{pc} .

Direct virtual photons

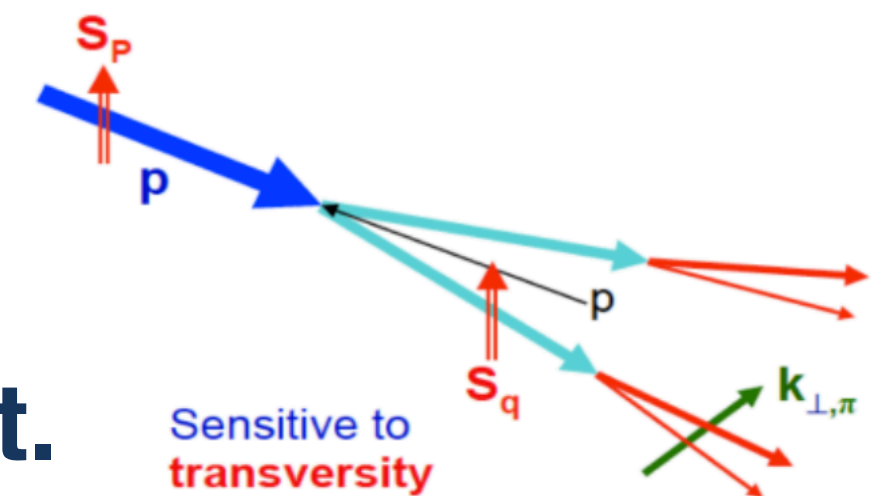
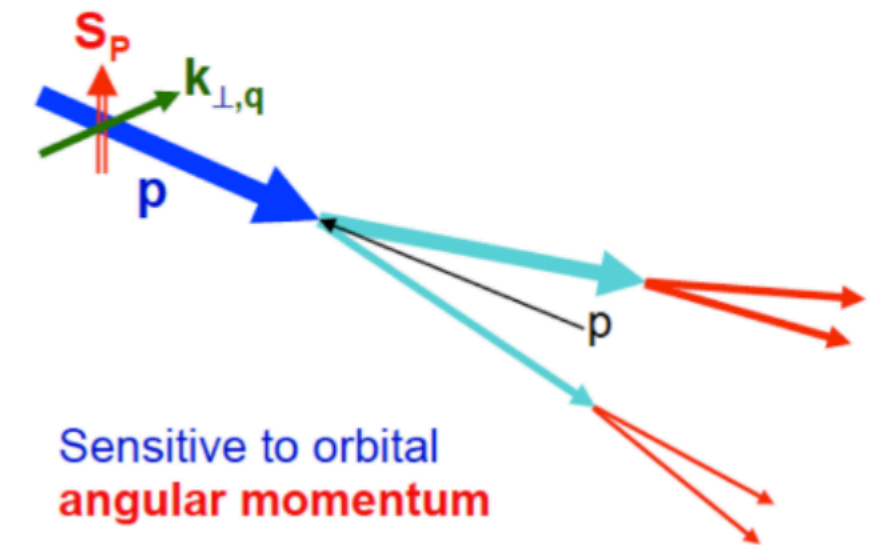


- Yield of direct photons vs. multiplicity from 14.6 to 200 GeV.
- Common scale factor for yields from 14.6 to 200 GeV measurements by STAR.

$$\alpha = 1.43 \pm 0.04 \pm 0.04$$

Outline

- QCD Phase Structure
- Flow
- Heavy Flavor & Jets
- EM Probes
- **Spin & Polarization: Sivers effect & Collins effect.**

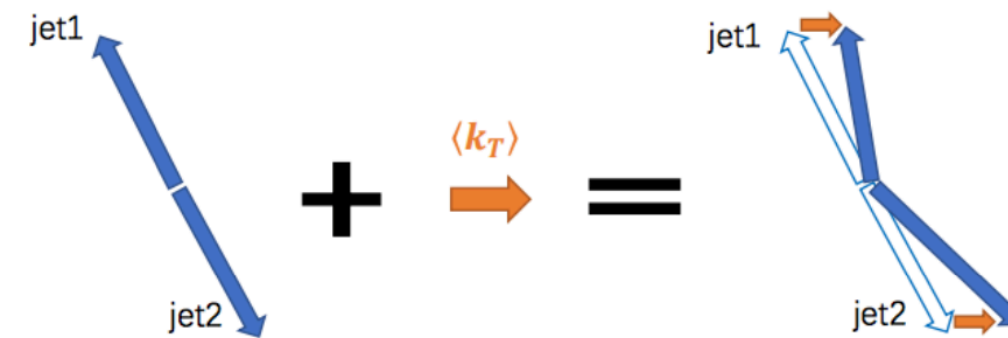
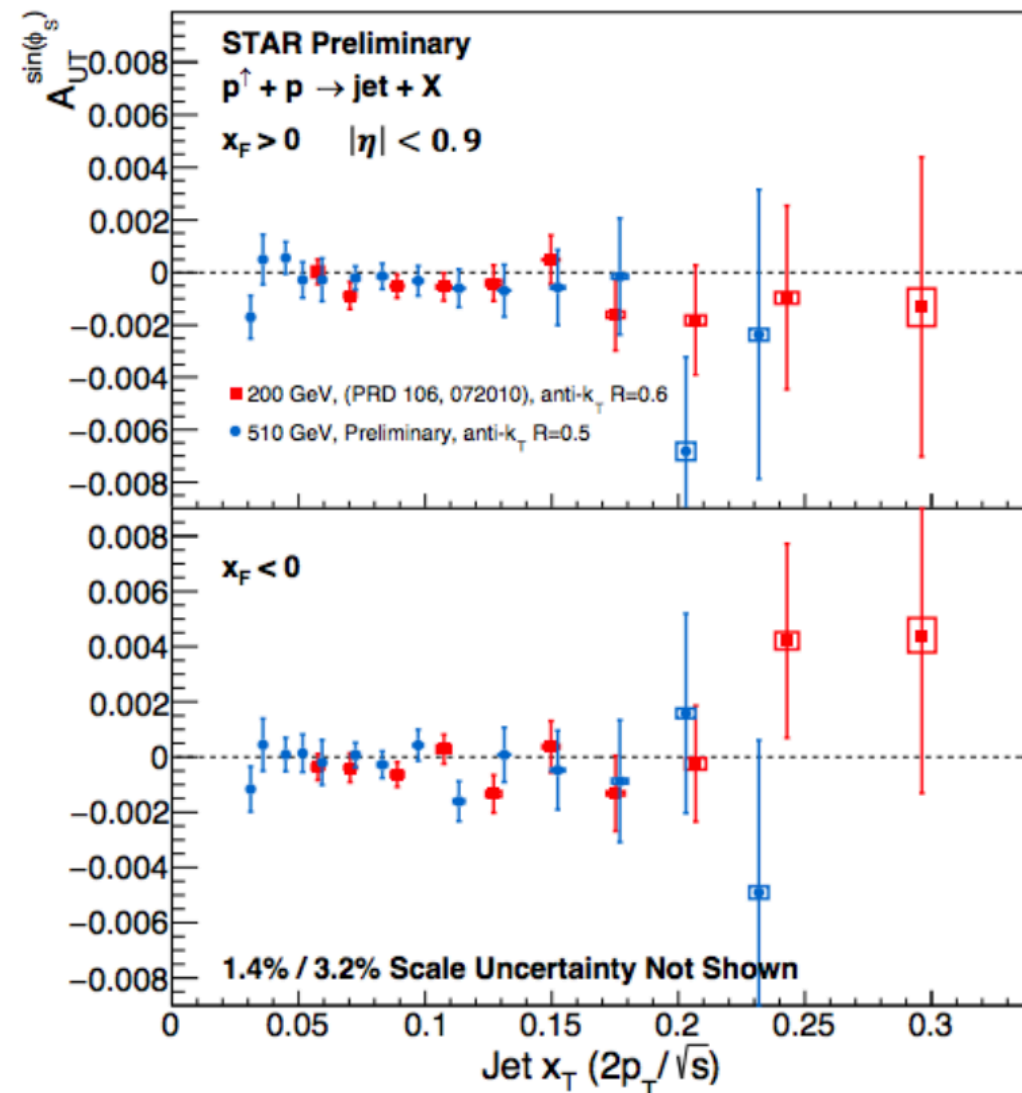


Measurements of A_N with jets

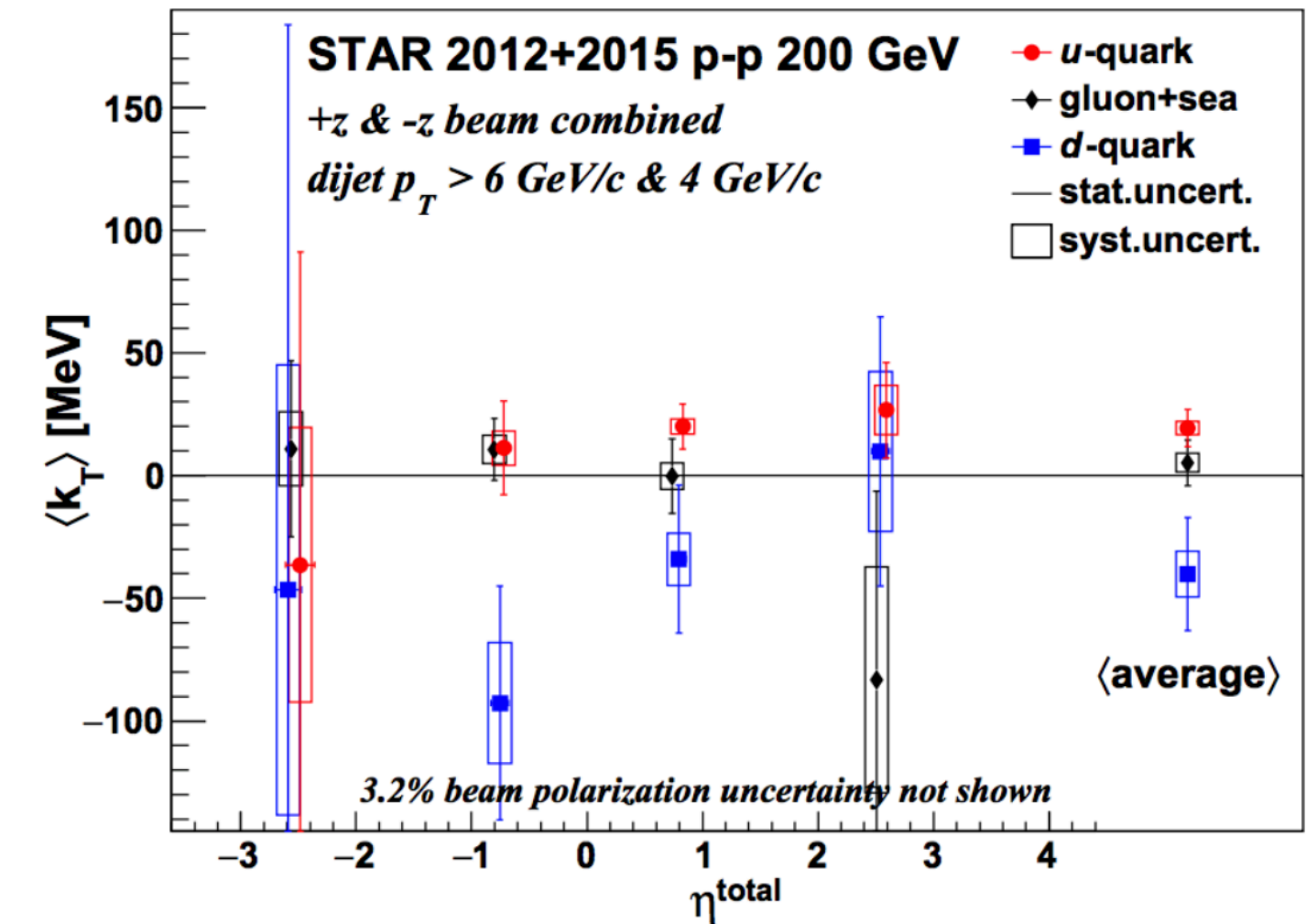
J. Nam, Tue. 11:25am

STAR, arXiv:2305.10359

Inclusive Jet A_N



Parton $\langle k_T \rangle$ can be extracted from azimuthal decorrelation from back-to-back topology in **dijet** production

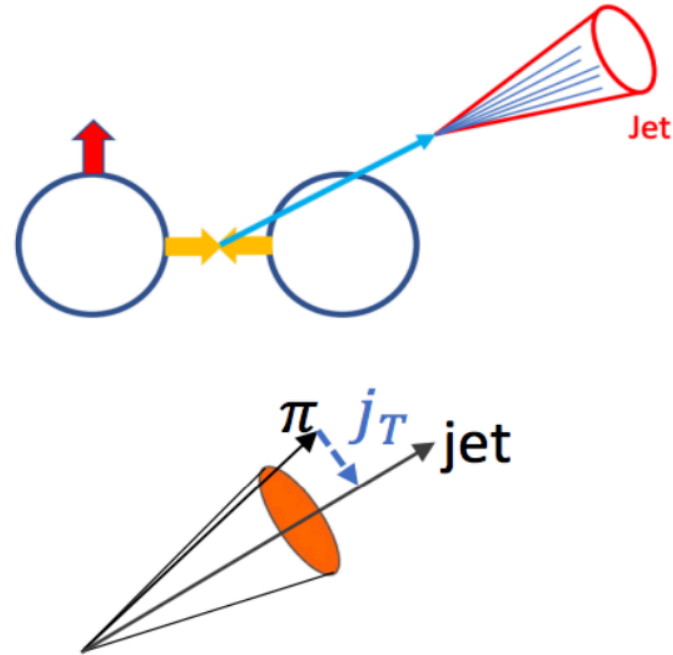


- Inclusive jet A_N consistent with 0, unlike in SIDIS: pQCD suggests **cancellations** of u and d quarks at **initial** and **final** states.
- First hint of non-zero Sivers effect in dijet at pp collisions.

$$2\langle k_T^u \rangle \approx \langle k_T^d \rangle, \quad \langle k_T^{g+\text{sea}} \rangle \approx 0$$

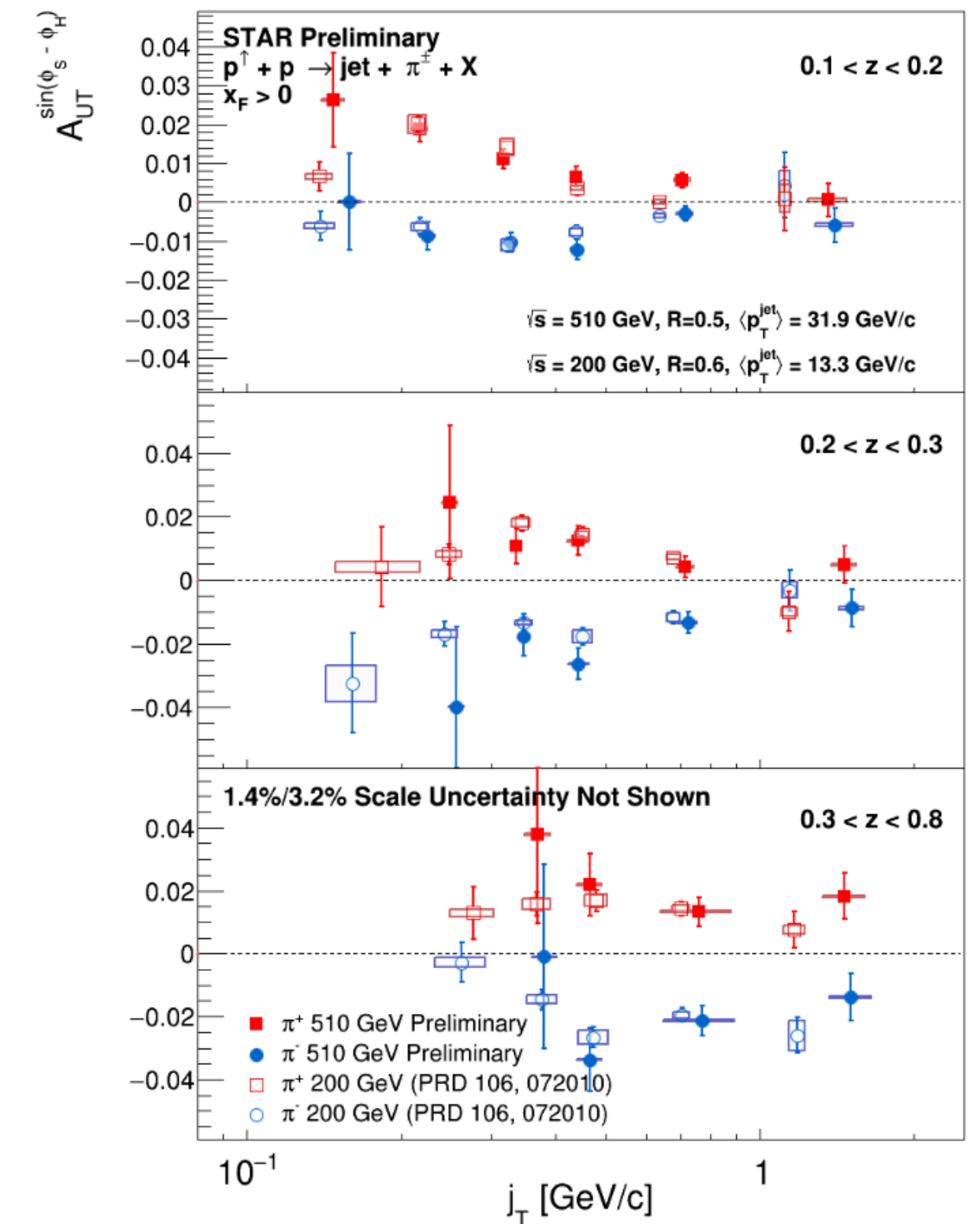
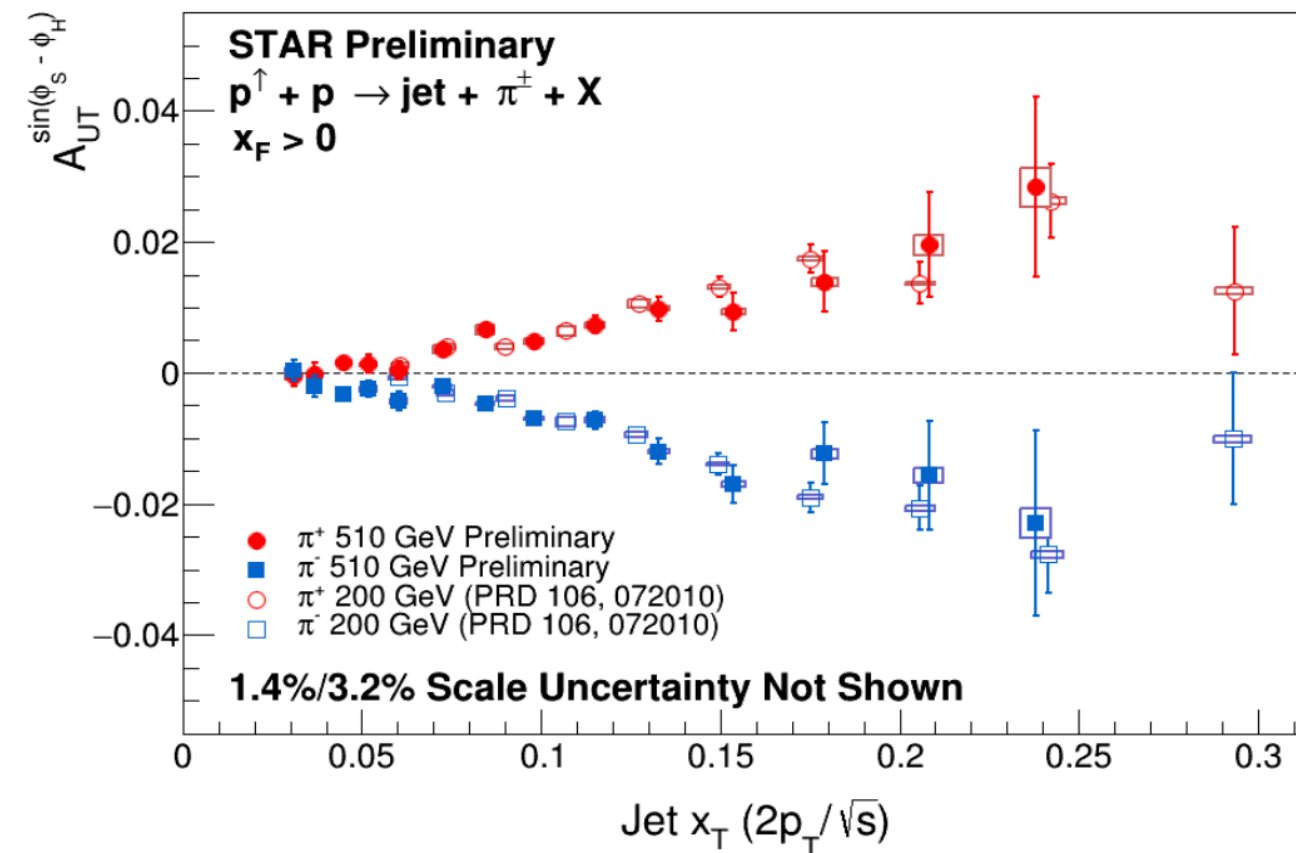
Investigation of Collins effect

J. Nam, Tue. 11:25am



$$A_{UT}^{Collins} \propto h_1(x) \otimes H_1^\perp(z, j_T)$$

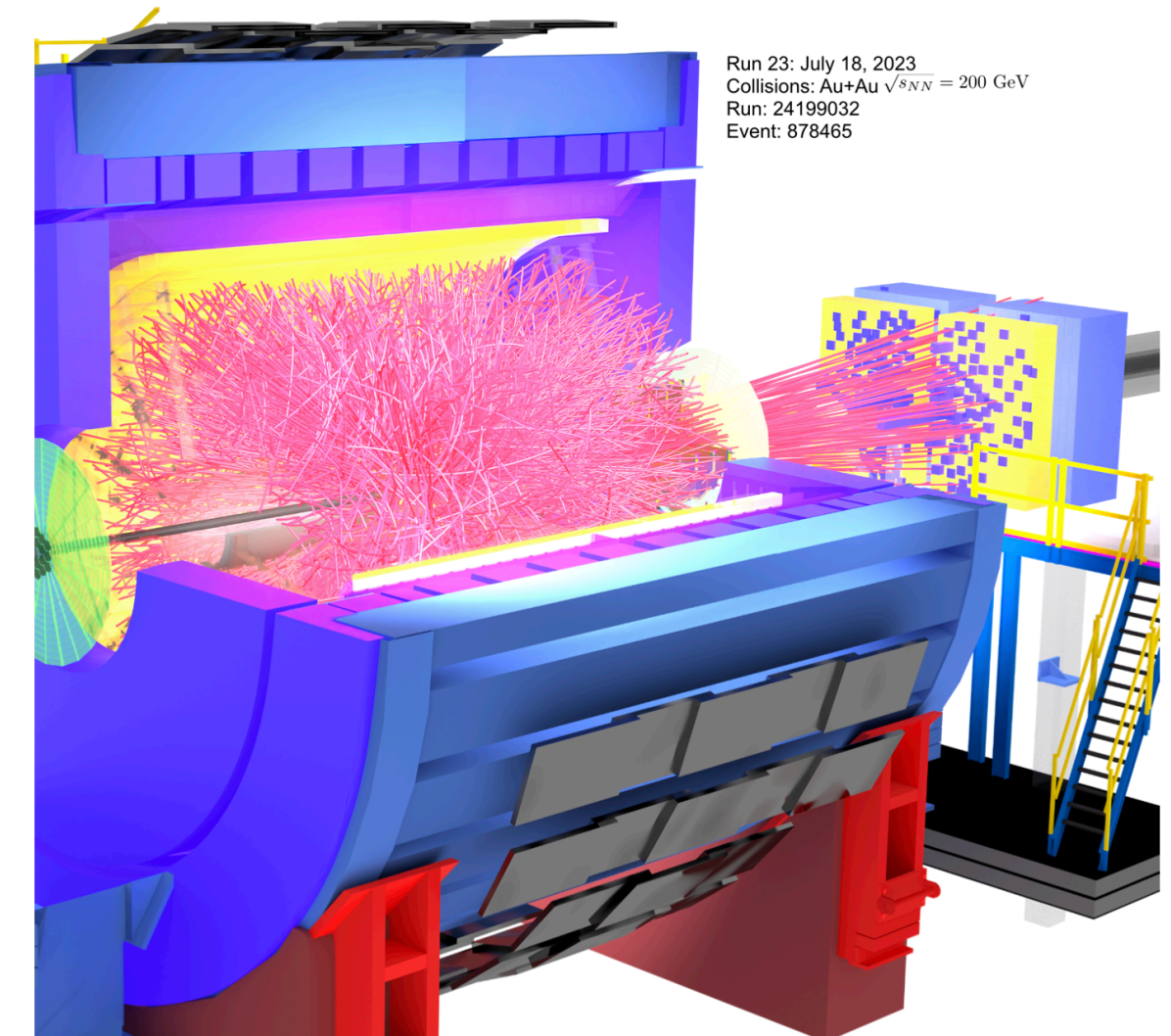
Transversity \otimes Collins FF



- Hadron-jet correlation measurements: a more direct probe of **transversity** than SIDIS: Collinear (pp, $h_1(x)$) vs. TMD (SIDIS, $h_1(x, k_T)$)
- By varying z and j_T , STAR simultaneously explores both the **transversity** distribution and the **Collins FF**.

Summary

- Detector fully **upgraded** with BES-II and Forward capabilities — expanding acceptance and precision.
- STAR delivers important results across key QCD physics topics.
- 2023–2025: **high-statistics** data with the full STAR detector.
 - building the bridge to the **future EIC**.
- Expect many more exciting results spanning diverse topics for many years to come.



A quarter-century of pushing the boundaries in high-energy nuclear physics research.

We thank C-AD for successful and reliable beam operations, and SDCC & NERSC for their excellent computing support.



**Thank you for
your attention**

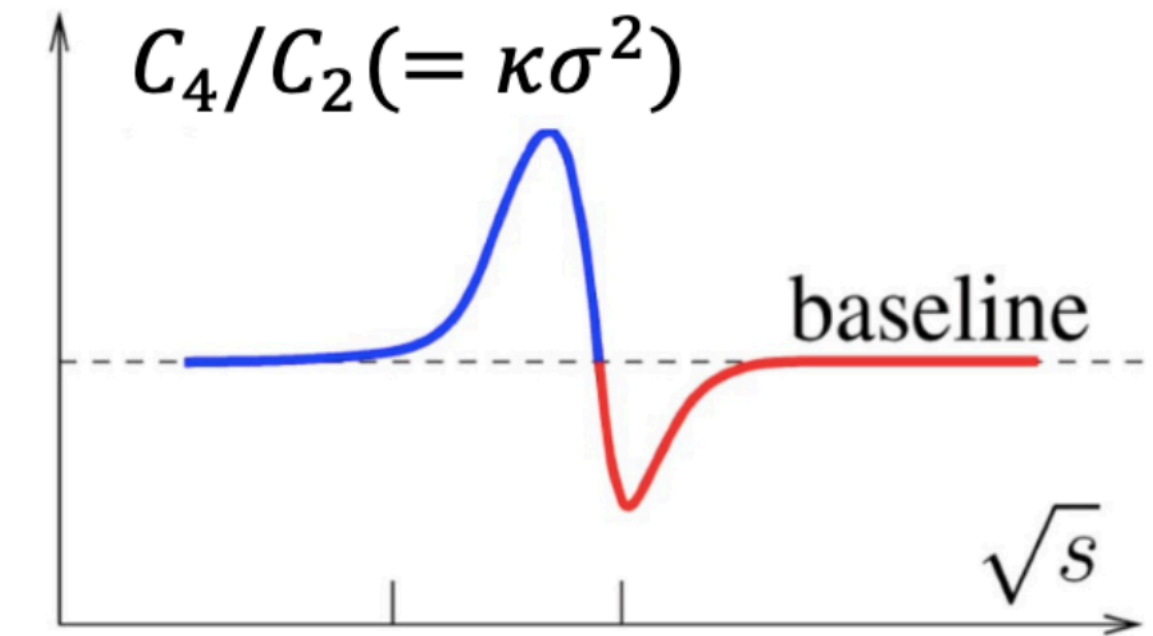
STAR Collaboration Meeting, 03/27/2025

Back Up

Net-proton higher order cumulants

Z. Sweger, Tue. 9:30am

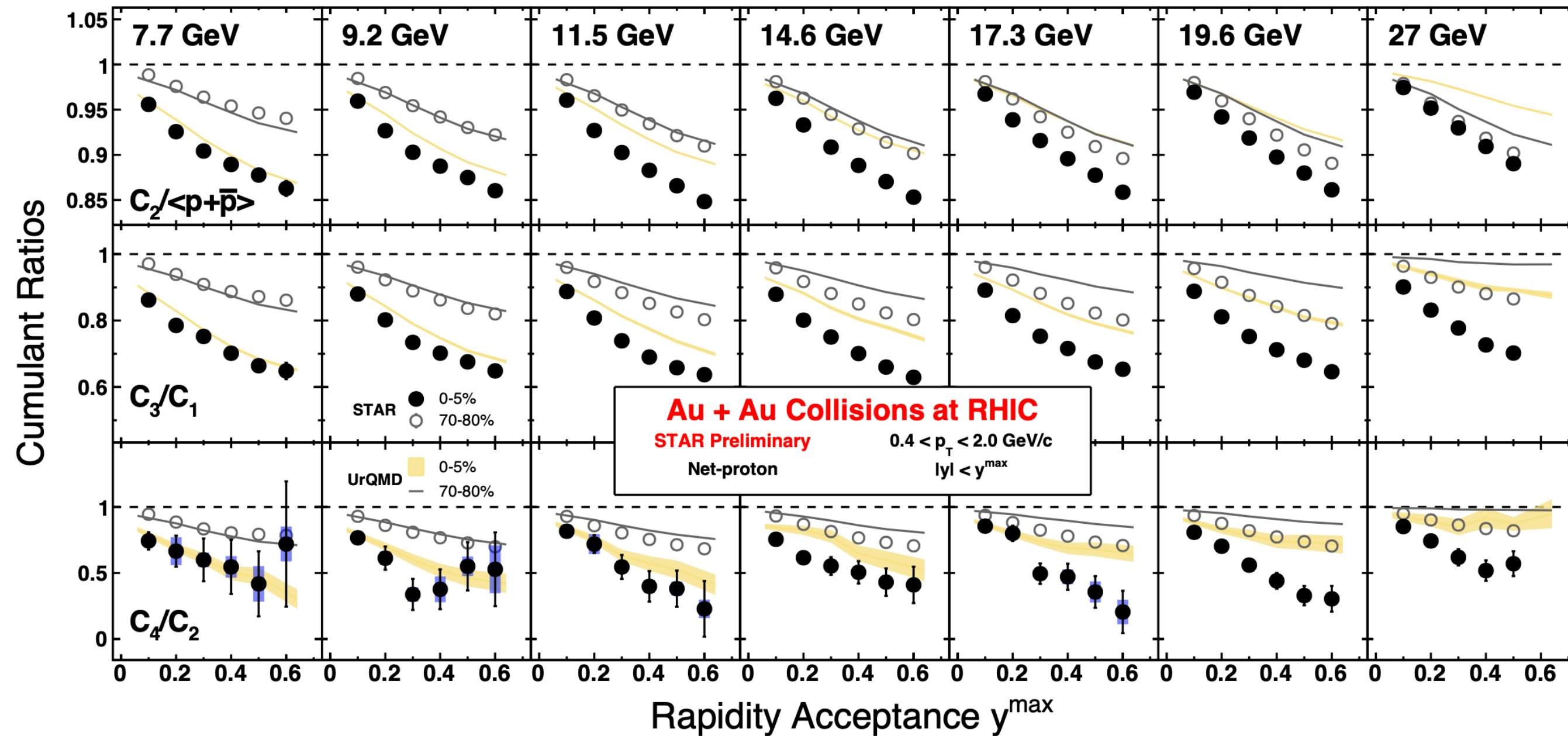
- Higher-order cumulants of conserved charges serve as an important probe in the search for QCD critical end point.
- Cumulants are related to the **correlation length ξ** . ξ diverges at the critical point.



$$C_2 \sim \xi^2, C_4 \sim \xi^7$$

Non-monotonic energy dependence of C_4/C_2 for the conserved baryon number indicates the existence of a critical region.

Net-proton cumulant ratios: rapidity scan

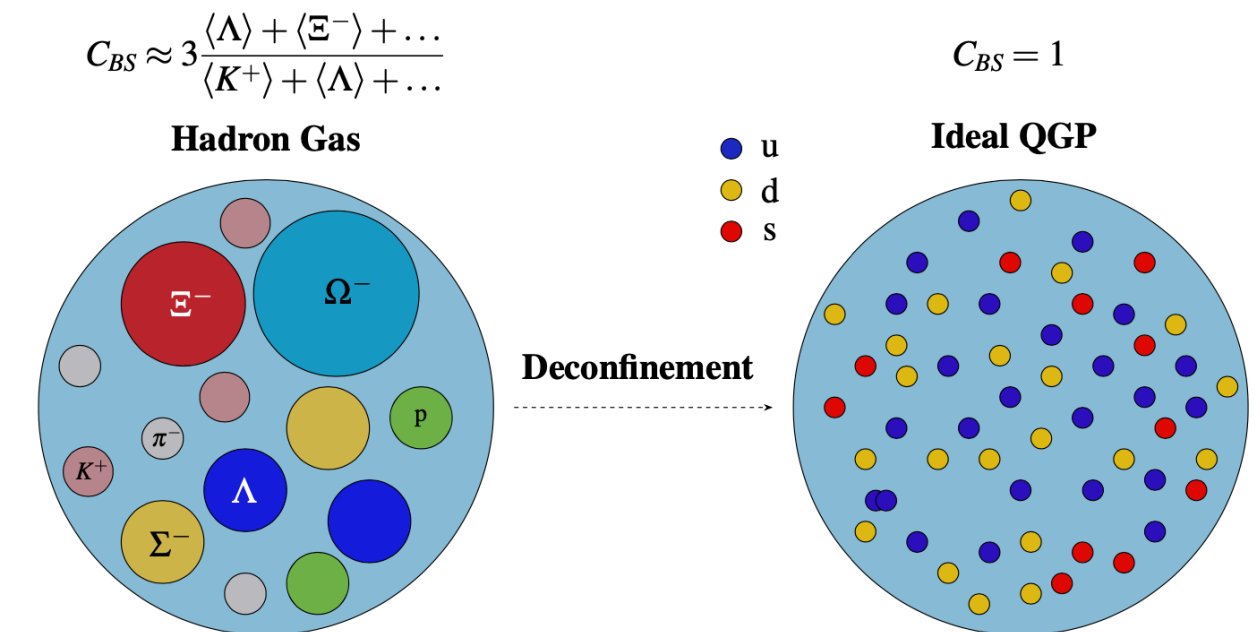
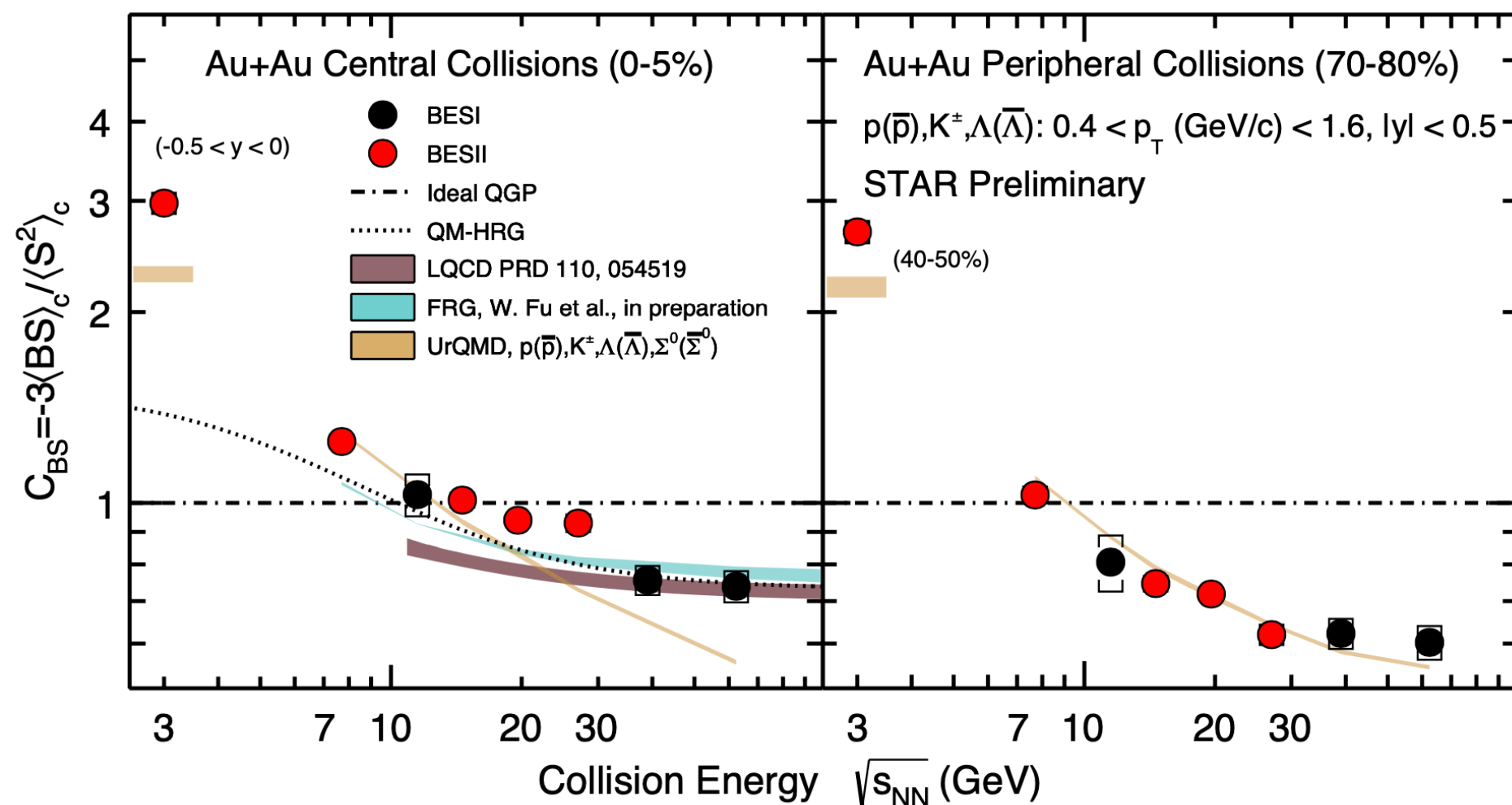


Widening $y(p_T)$ windows of measurement enhances potential critical contributions

- Cumulant ratios decrease smoothly along rapidity window
- Deviation from UrQMD **increases with y acceptance.**

Baryon - Strangeness correlations: C_{BS}

- Central Collisions: higher energies consistent with FRG and LQCD, lower energies agree with UrQMD, **the intermediate energies** cannot be reproduced by either of the calculations.
- Peripheral collisions: agree with UrQMD at all energies.

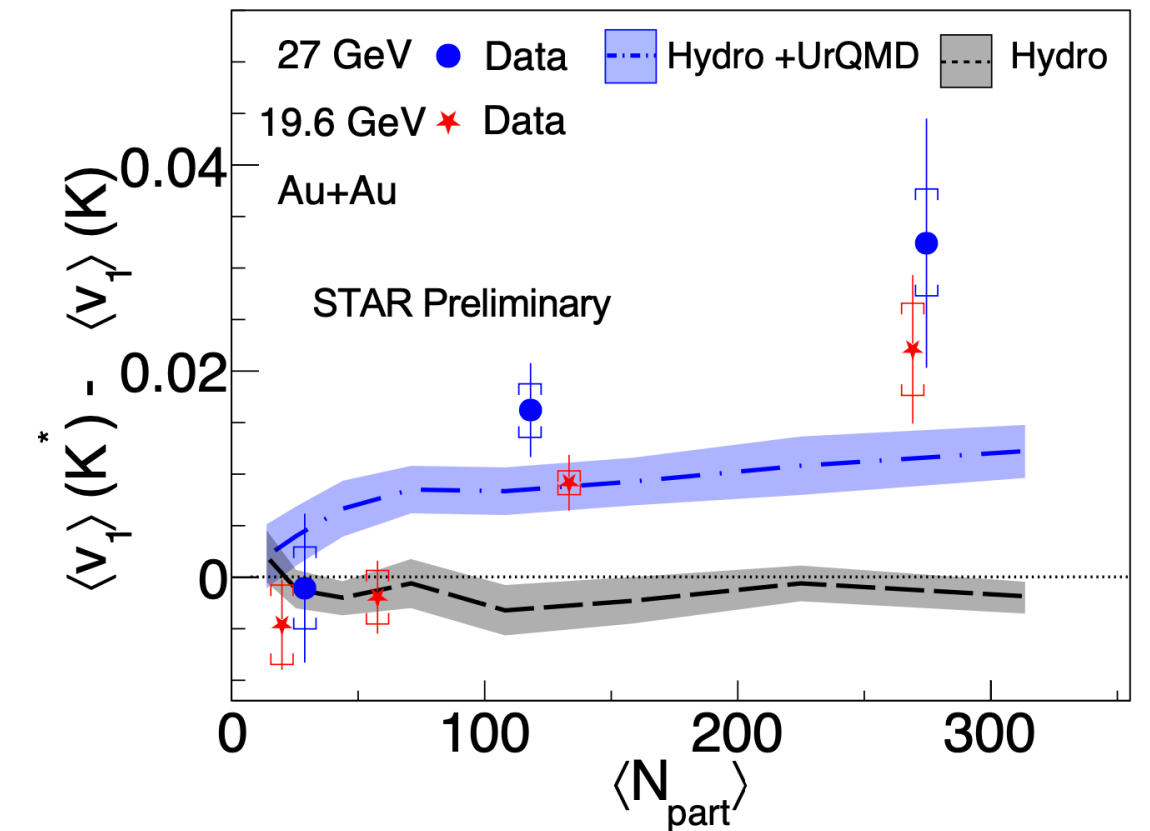
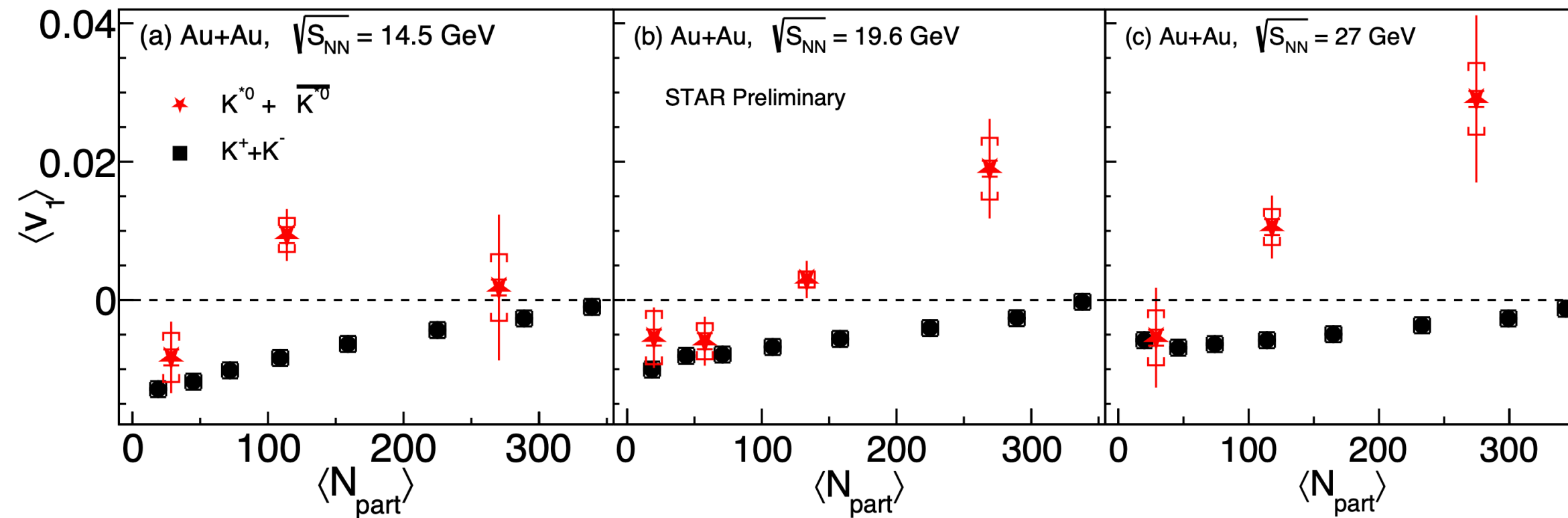


$$C_{BS} = -3 \frac{\langle BS \rangle_c}{\langle S^2 \rangle_c} = -3 \frac{\langle BS \rangle - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2}$$

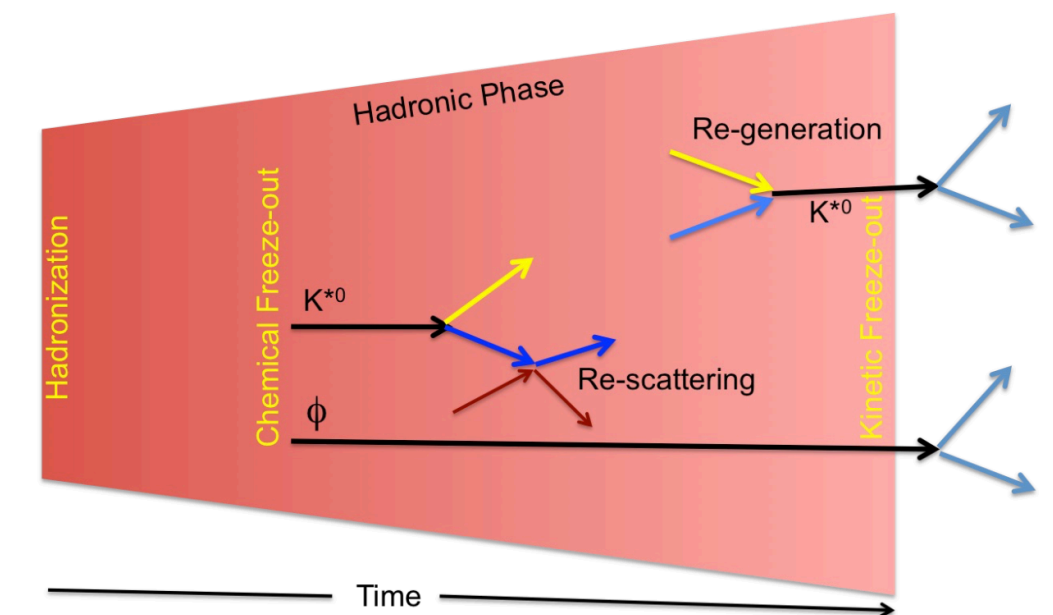
C_{BS} is proposed to diagnose the **change of phases** in the matter created in the heavy-ion collisions.

Directed flow of K^{*0}

MD Nasim, Tue. 2:00pm



- K^{*0} is an ideal probe to study hadronic interactions after freeze-out.
- $K^{*0} v_1$ **changes sign** from peripheral to central collisions, unlike charged kaons.
- Model comparison suggests **re-scattering** causes asymmetric loss of K^{*0} yield in momentum space.



Nuclear imaging in HIC

- Nuclear structure leaves imprints on v_n and $v_n - p_T$ correlations.
- Compare similar-sized systems U+U, Au+Au to gain insights on nuclear structure.

$$\rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{(r-R(\theta, \phi))/a_0}}$$

$$R(\theta, \phi) = R_0(1 + \beta_2[\cos \gamma Y_{2,0}(\theta, \phi) + \sin \gamma Y_{2,2}(\theta, \phi)] + \beta_3 Y_{3,0}(\theta, \phi))$$

$\beta_2 \rightarrow$ quadrupole deformation

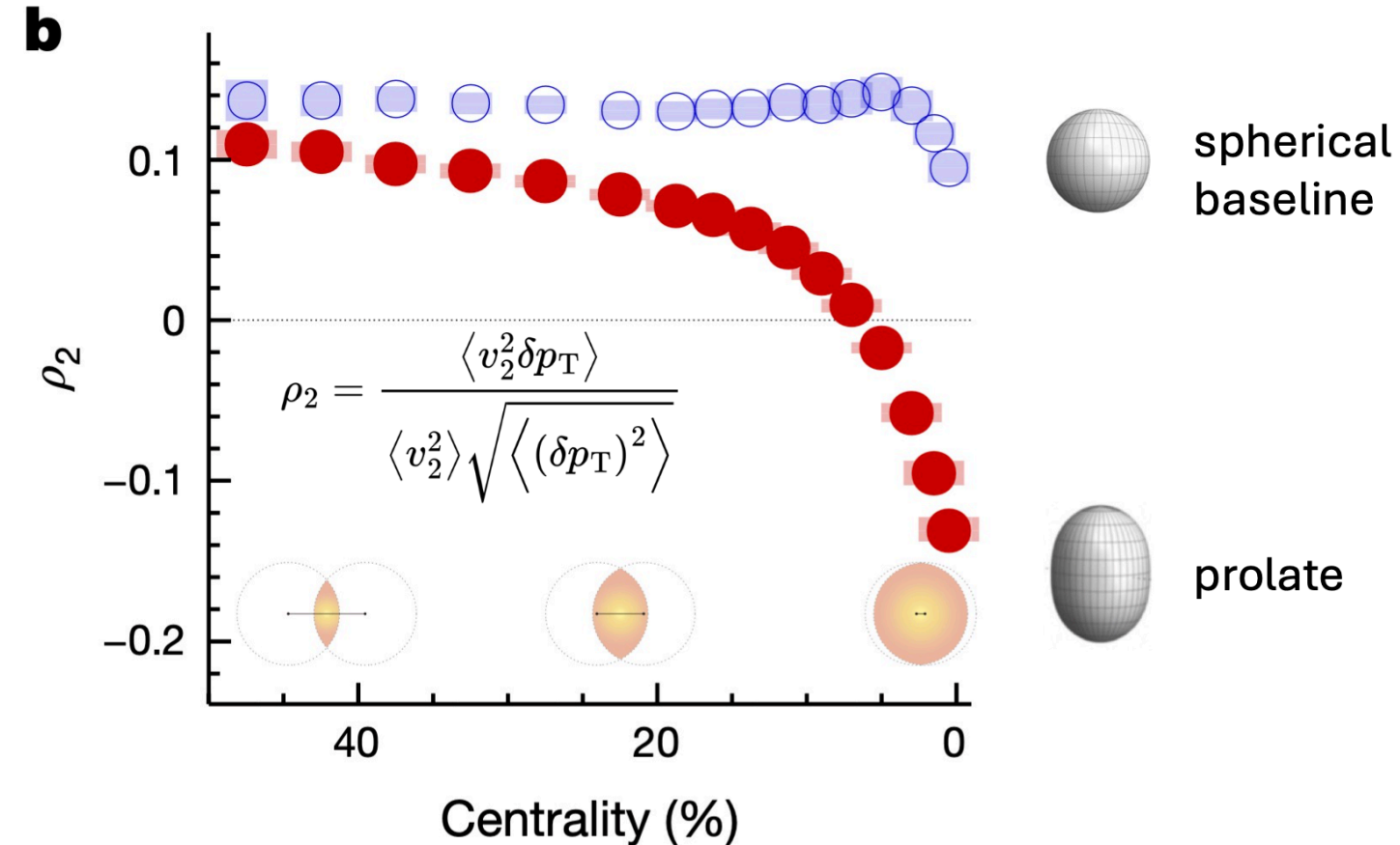
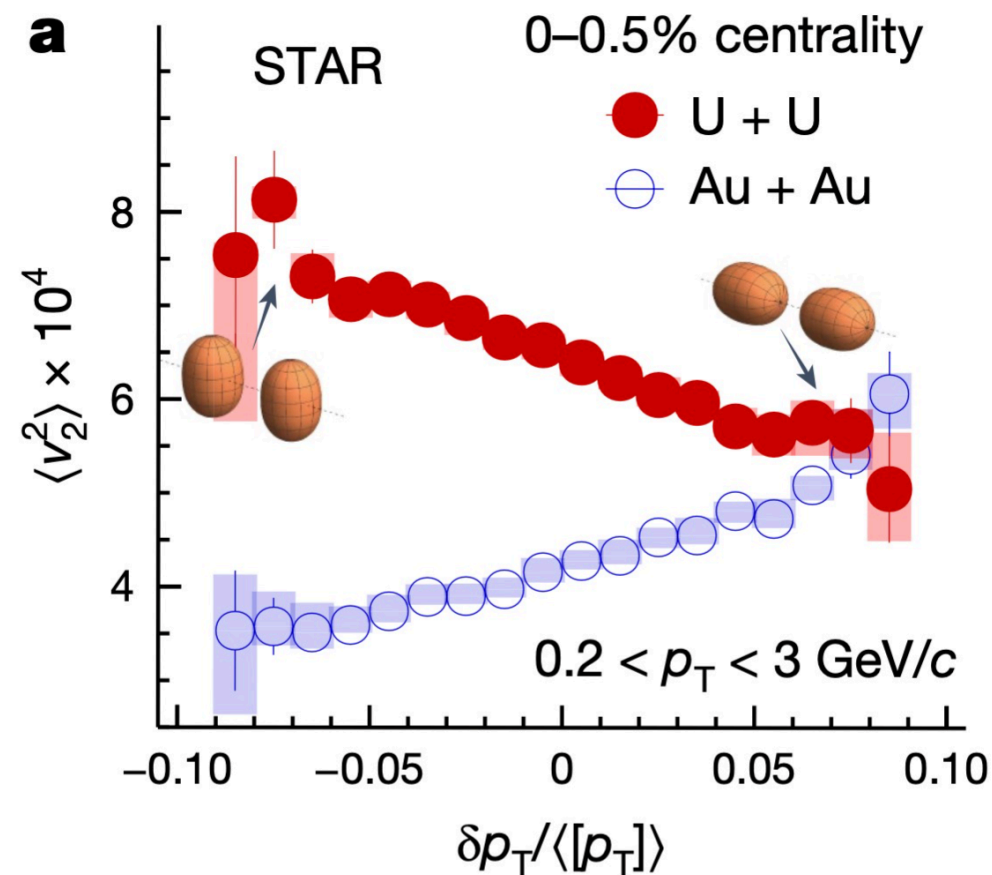
$\beta_3 \rightarrow$ octupole deformation

$\gamma \rightarrow$ triaxiality

$a_0 \rightarrow$ surface diffuseness

$R_0 \rightarrow$ nuclear size

STAR, Nature 635, 67-72 (2024)

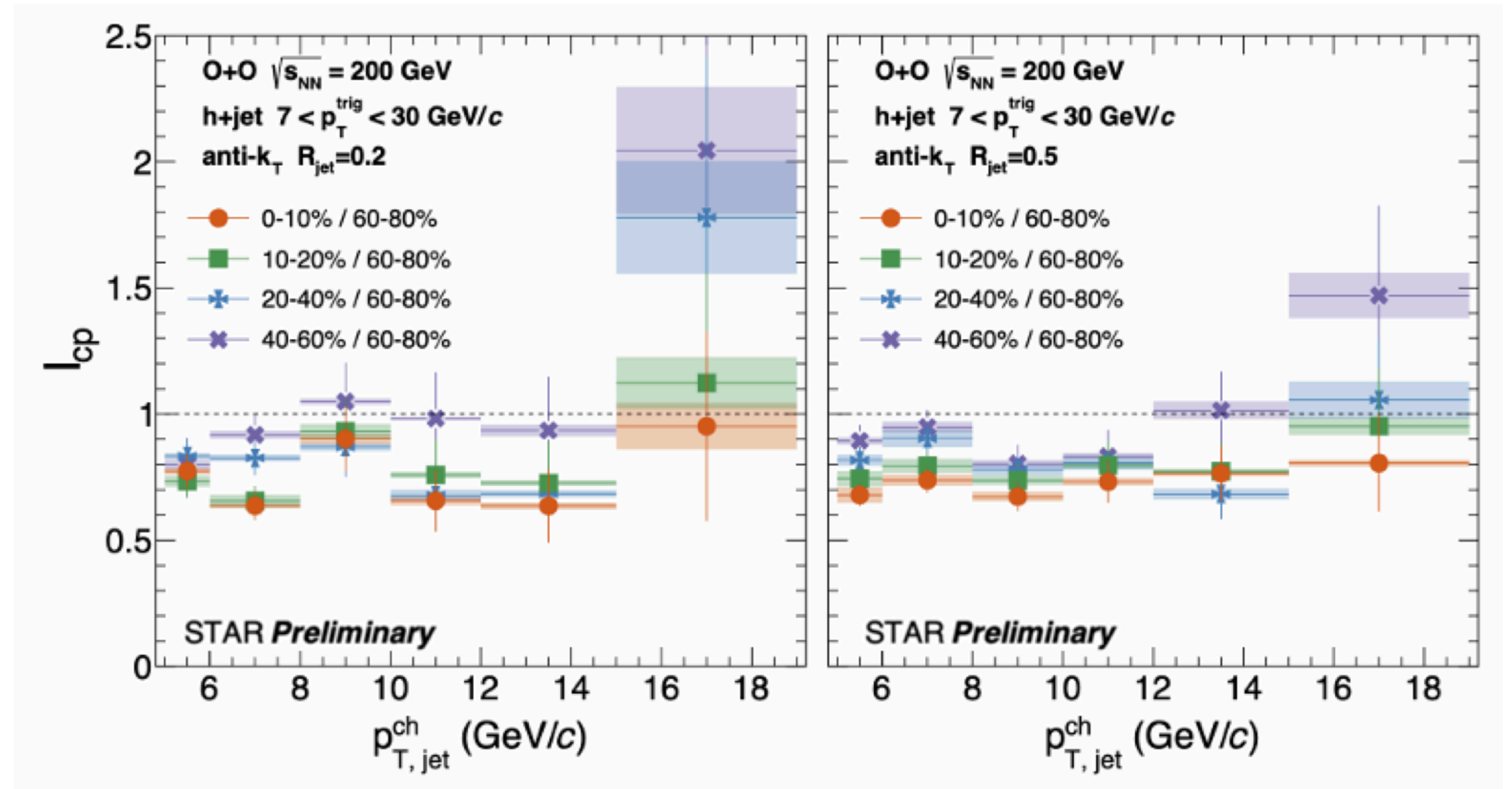


$$\begin{aligned} \langle v_2^2 \rangle &= a_1 + b_1 \beta_2^2 \\ \langle (\delta p_T)^2 \rangle &= a_2 + b_2 \beta_2^2 \\ \langle v_2^2 \delta p_T \rangle &= a_3 - b_3 \beta_2^3 \cos(3\gamma) \end{aligned}$$

Jet quenching in O+O

A. Tamis, Wed. 9:50am

- Jet quenching in small system?
- **No significant radial dependence.**
- Effects other than quenching may be present.



Hint of high- p_T jet suppression in O+O collisions.

