STAR 25 YEARS

RICE

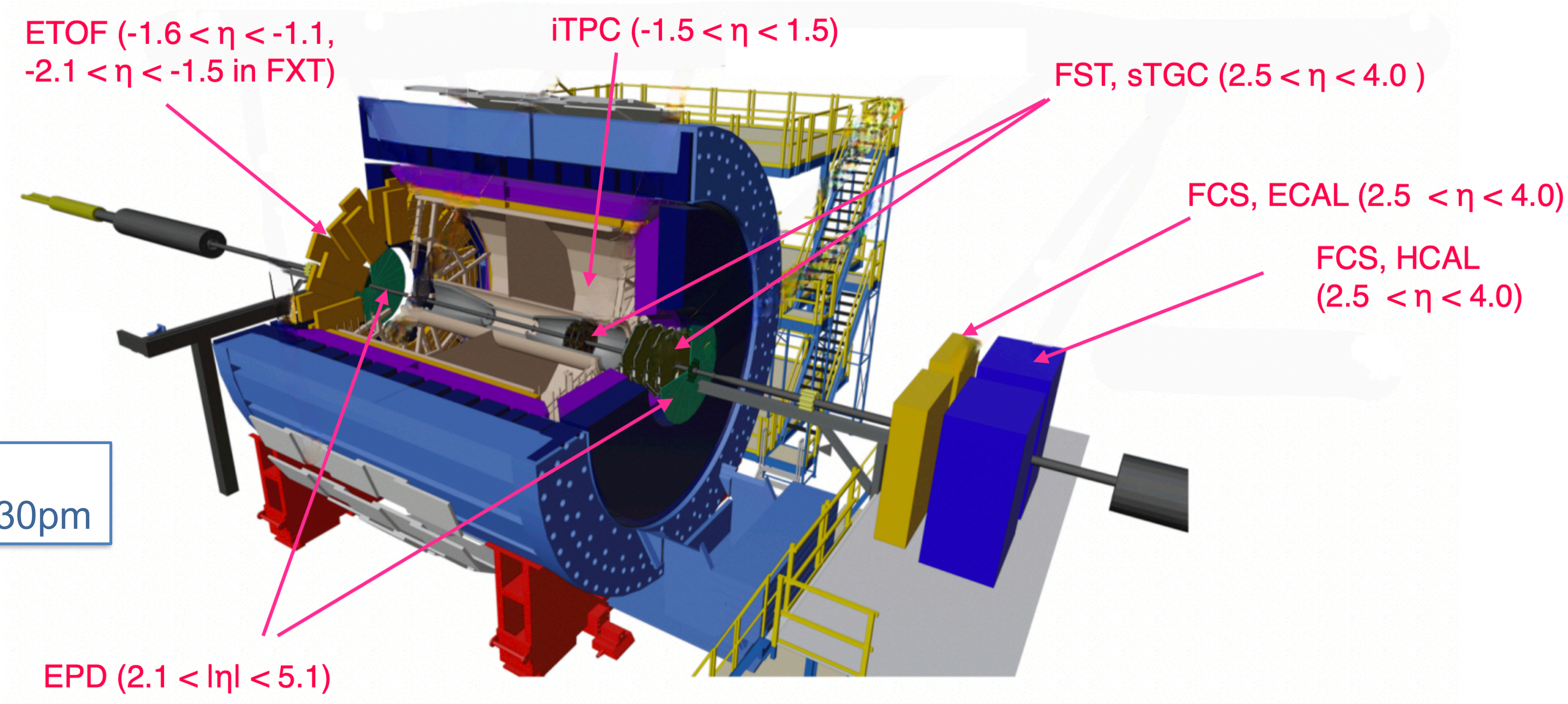
STAR Highlights

Chenliang Jin
(Rice University)
for the STAR Collaboration

05/22/2025

Supported in part by the
U.S. DEPARTMENT OF ENERGY | Office of Science

STAR detector



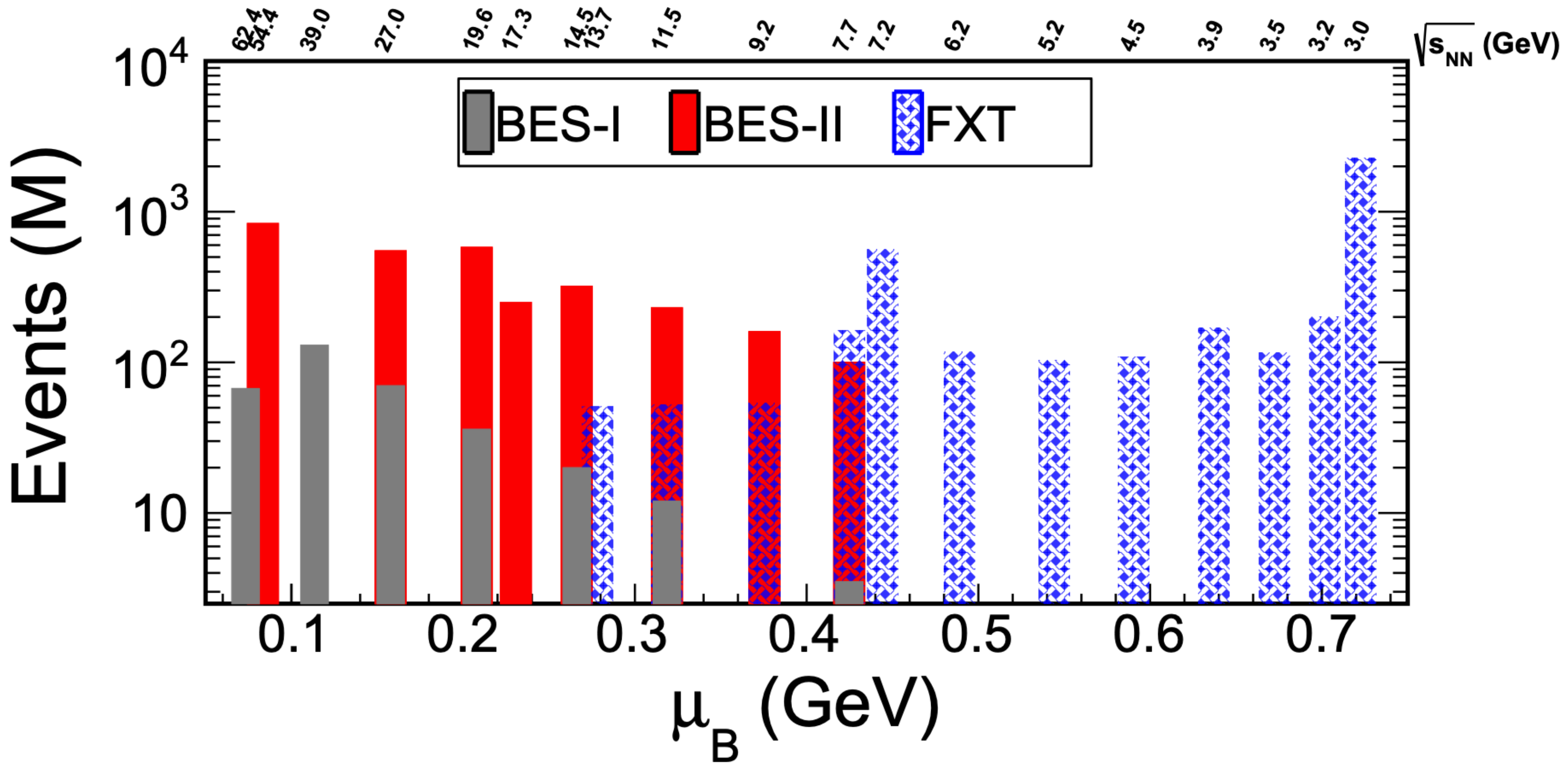
eToF calibration
M. Labonte, Tue. 4:30pm

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

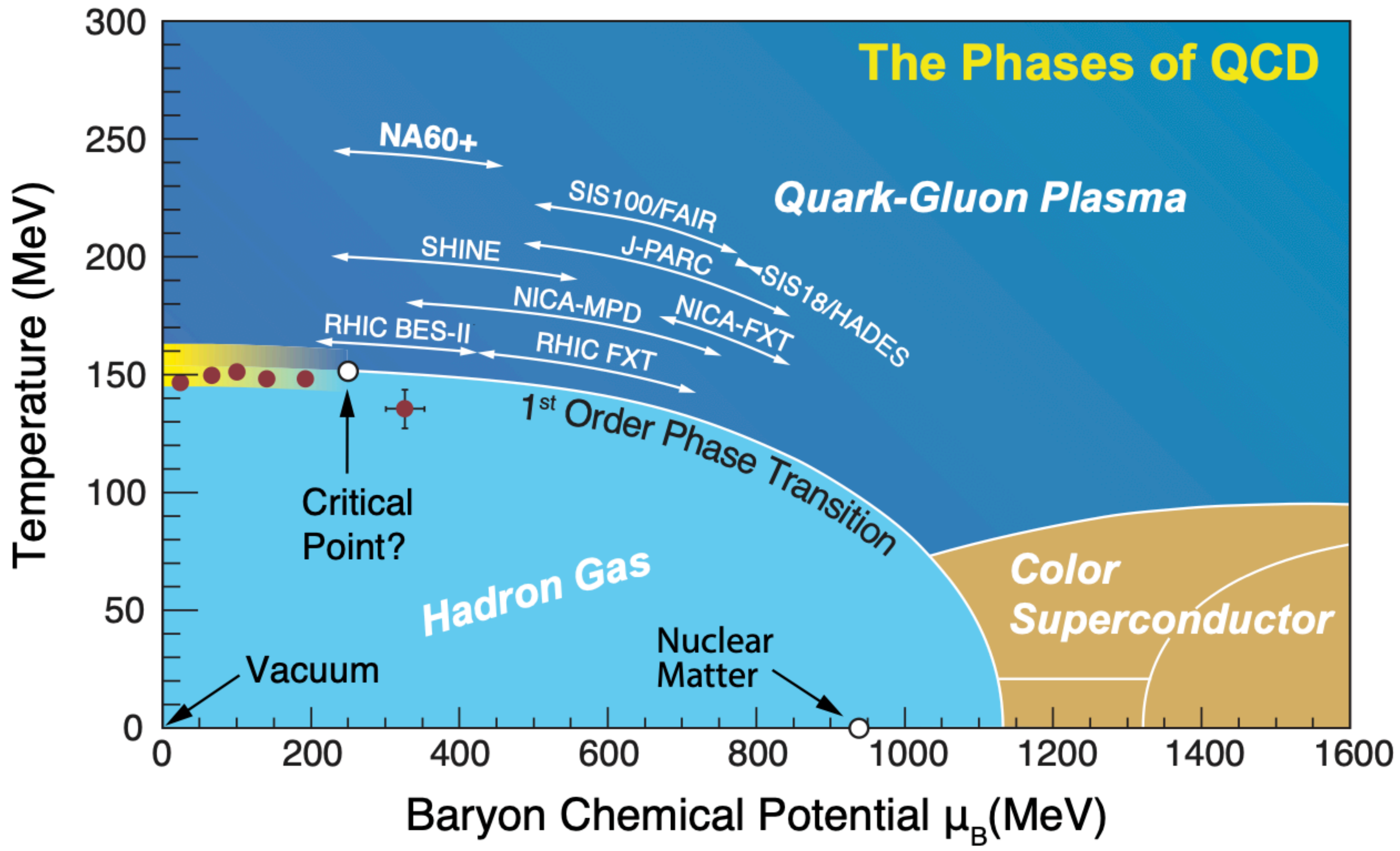
STAR datasets

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

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



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

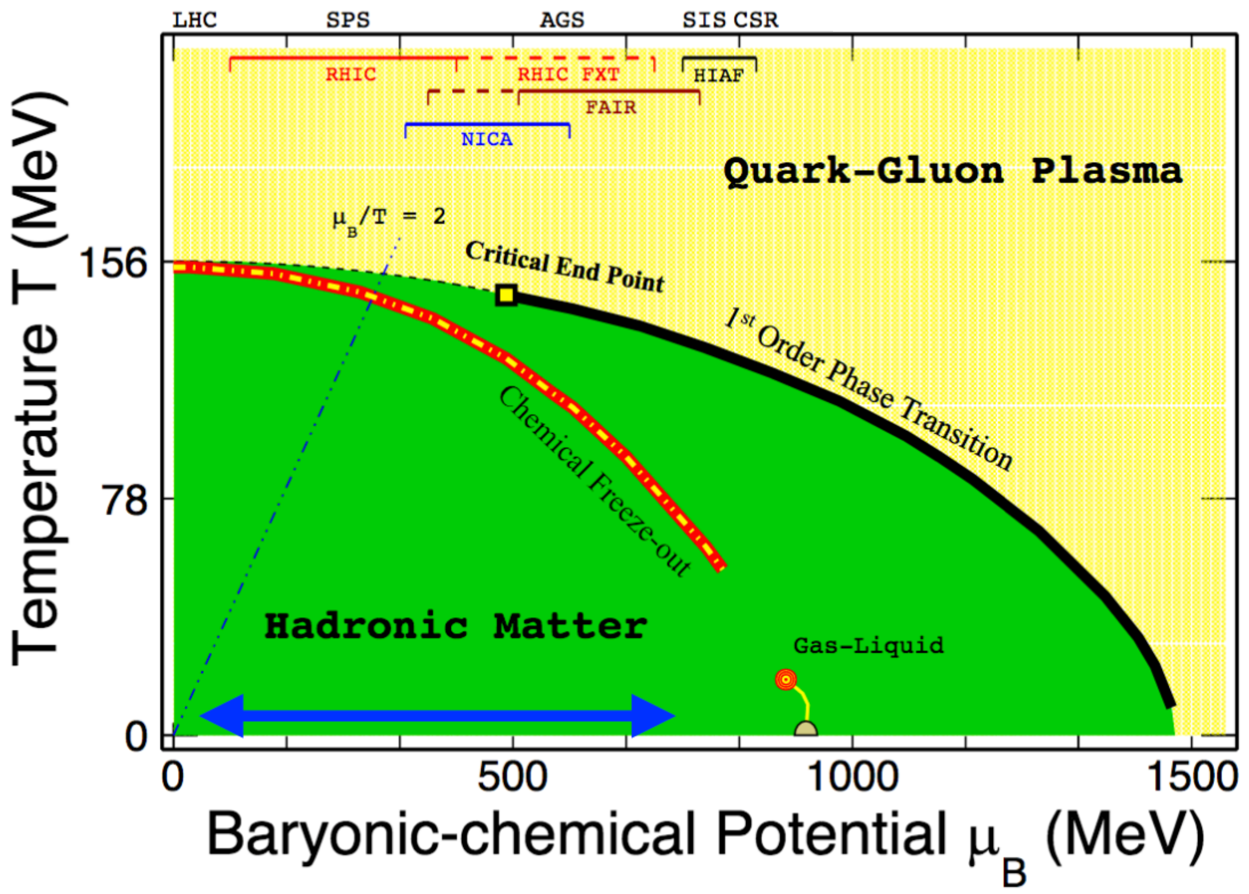


Outline

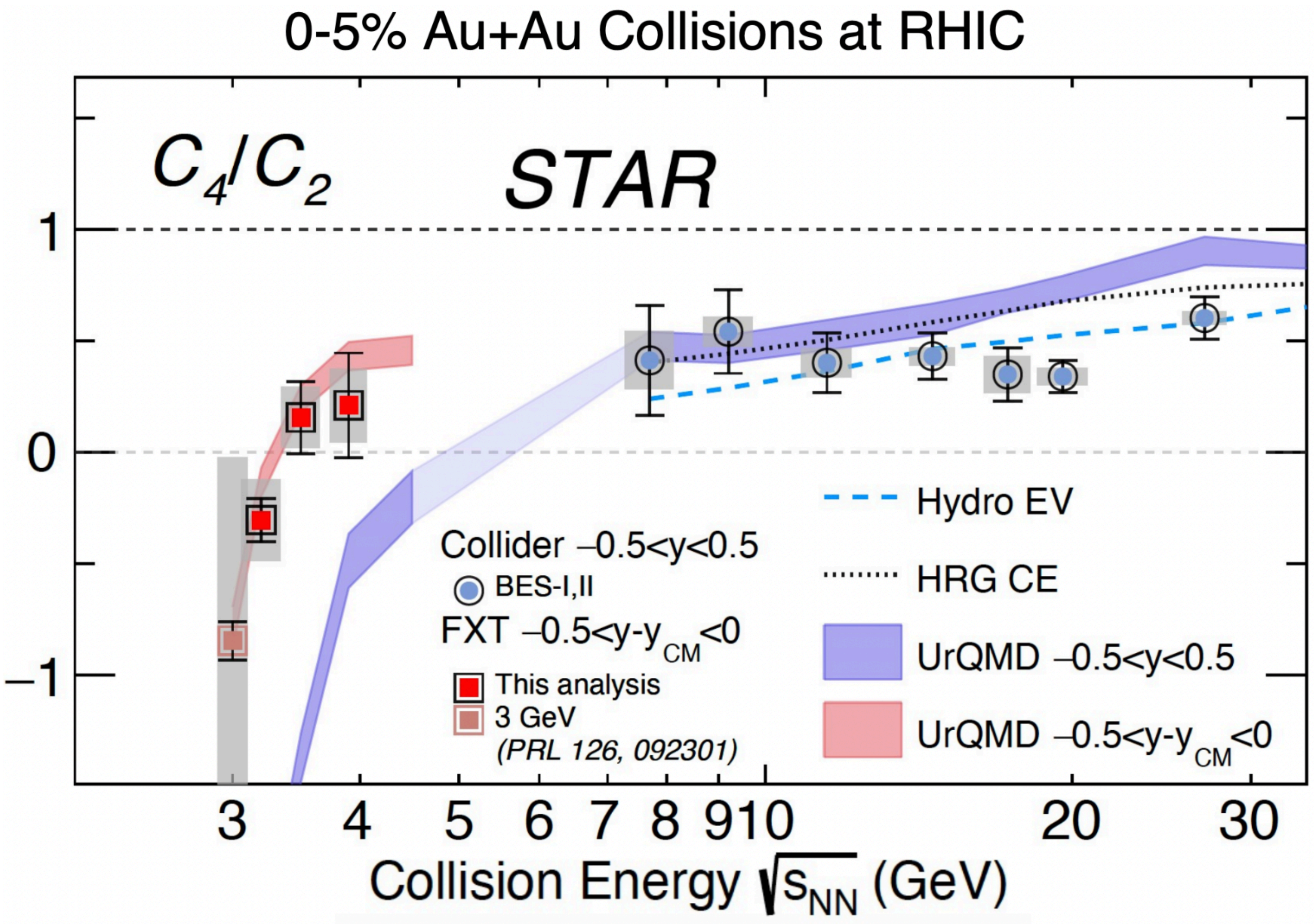
- QCD Phase Structure
- Flow
- Heavy Flavor & Jets
- EM Probes
- Spin & Polarization

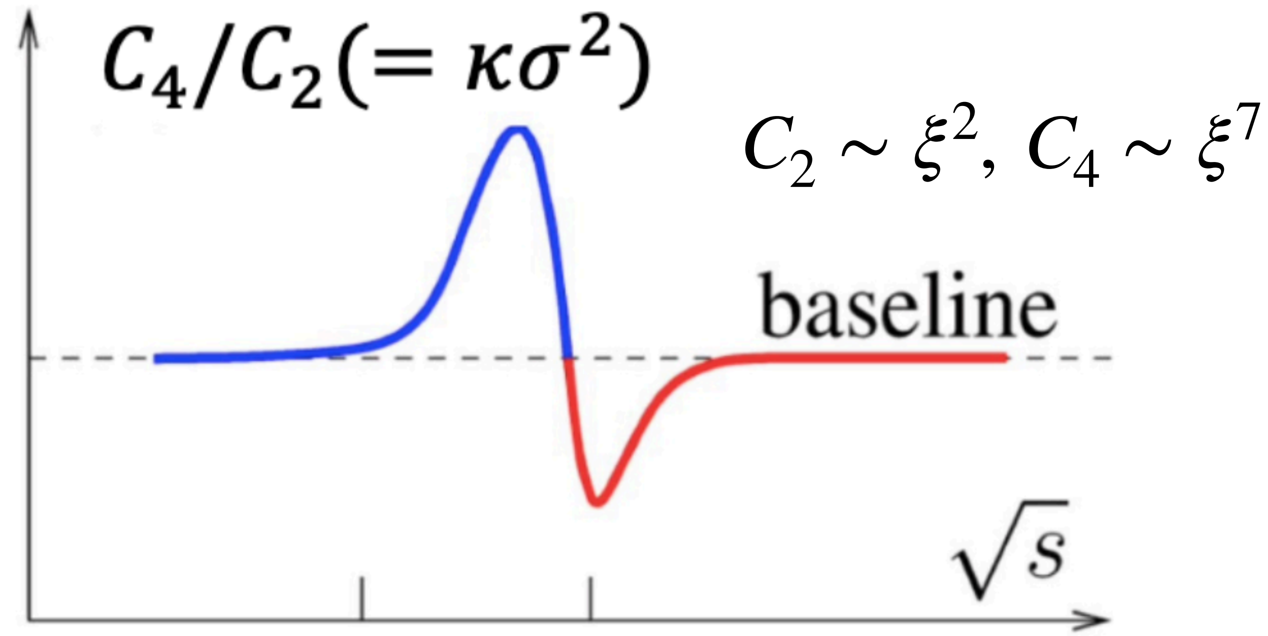
Outline

- **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.

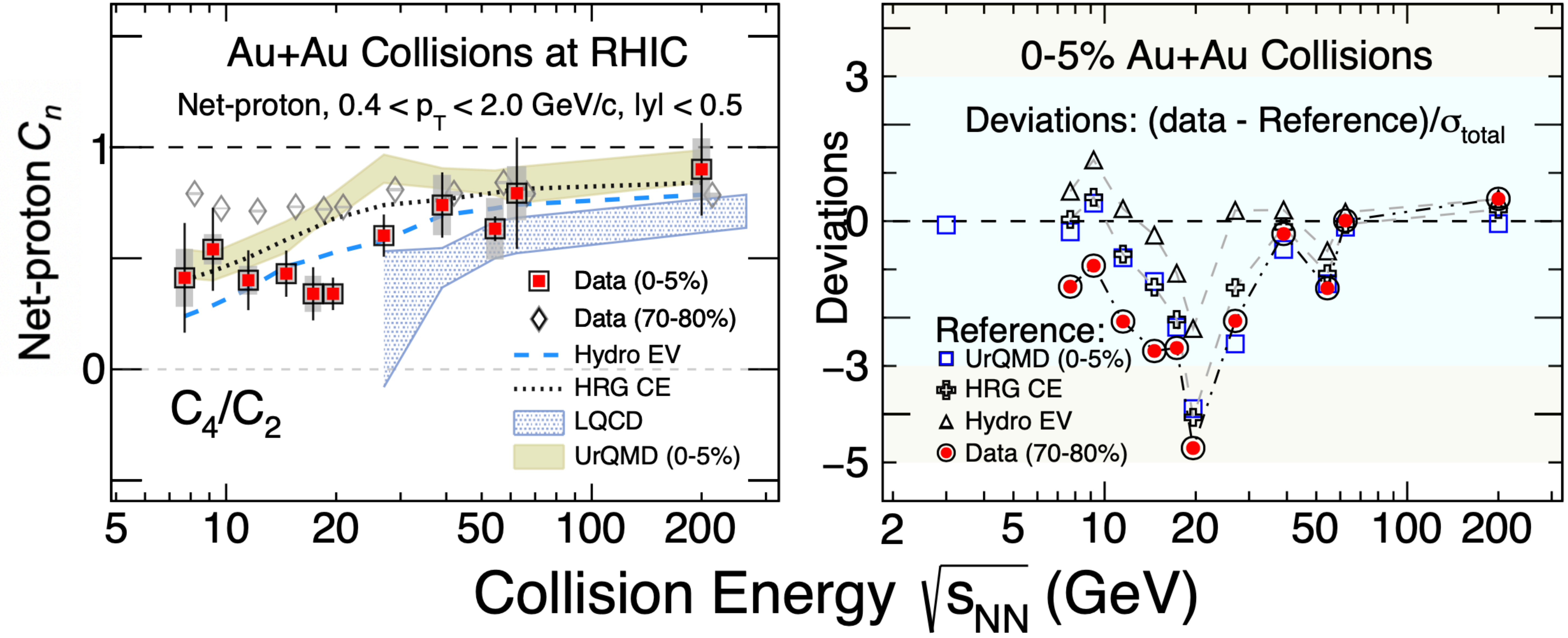
- In 3.2 - 3.9 GeV, C_4/C_2 is consistent with UrQMD. Deviations can be seen at higher energies.

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



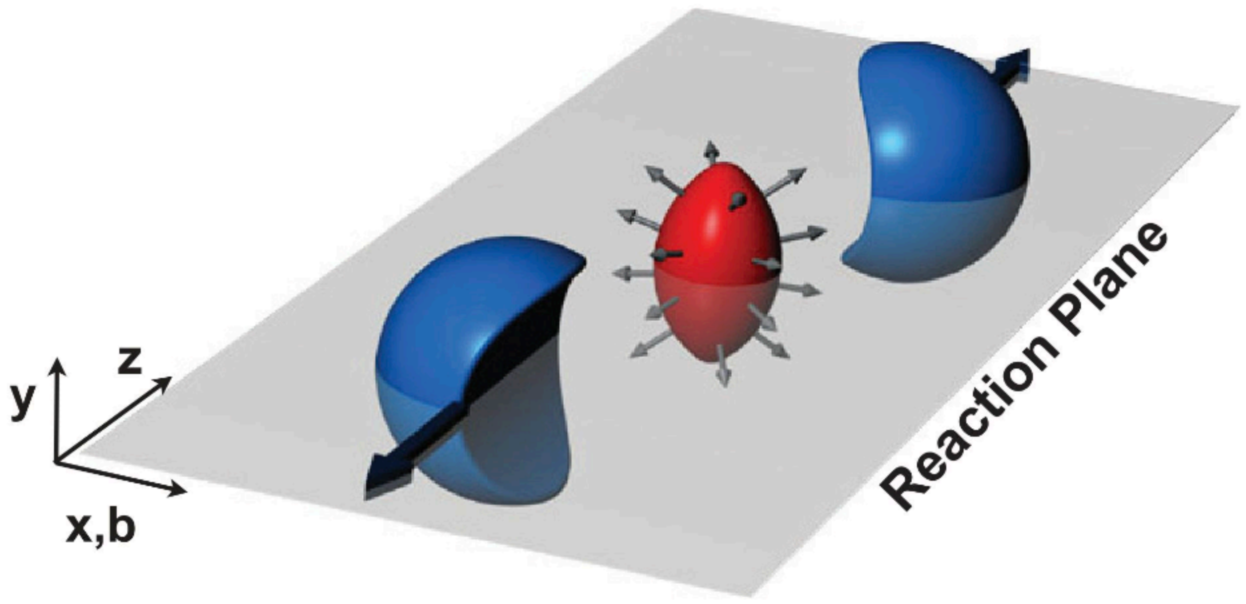
2 - 5σ deviation from calculations without CP.

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

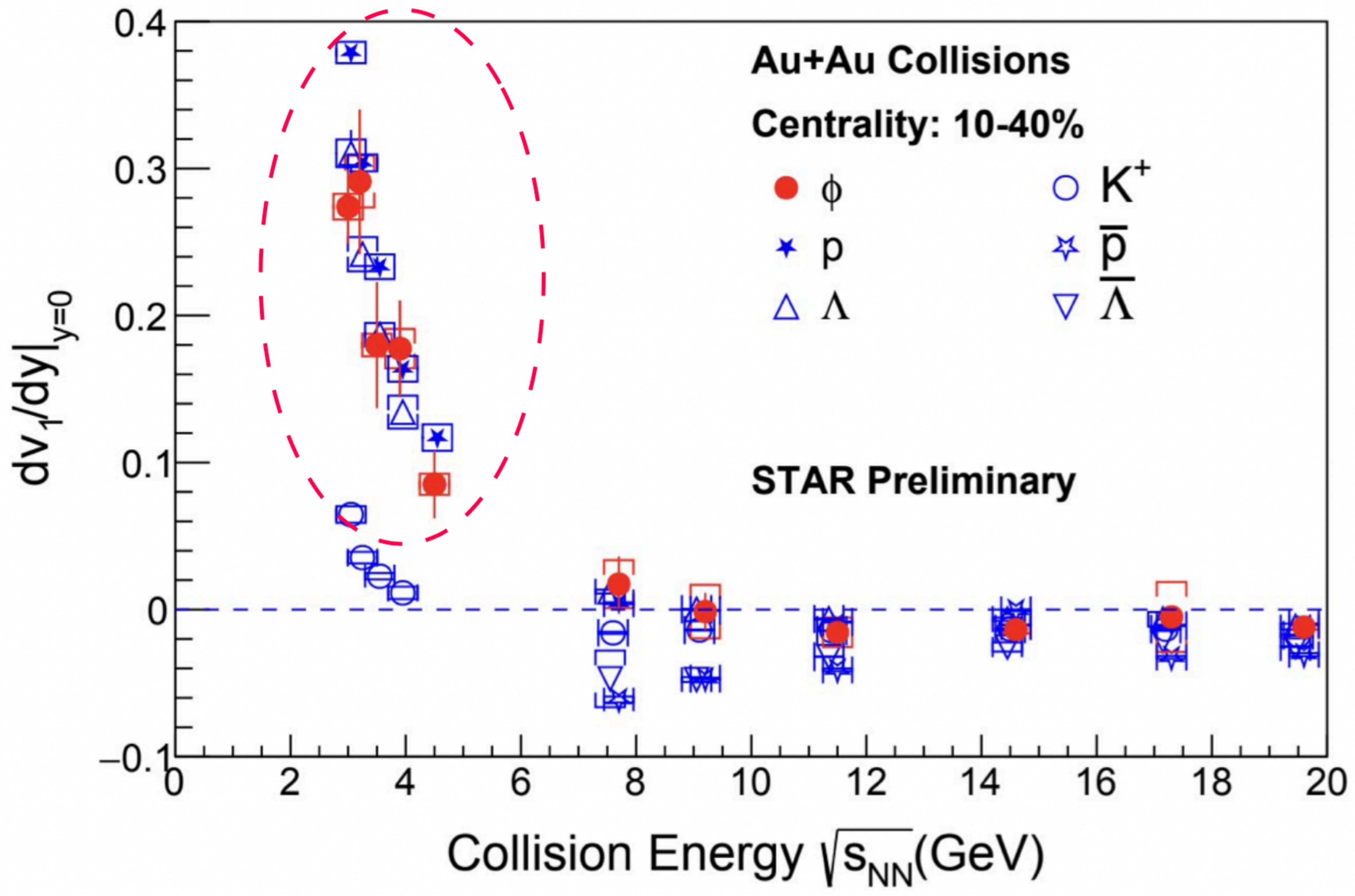
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

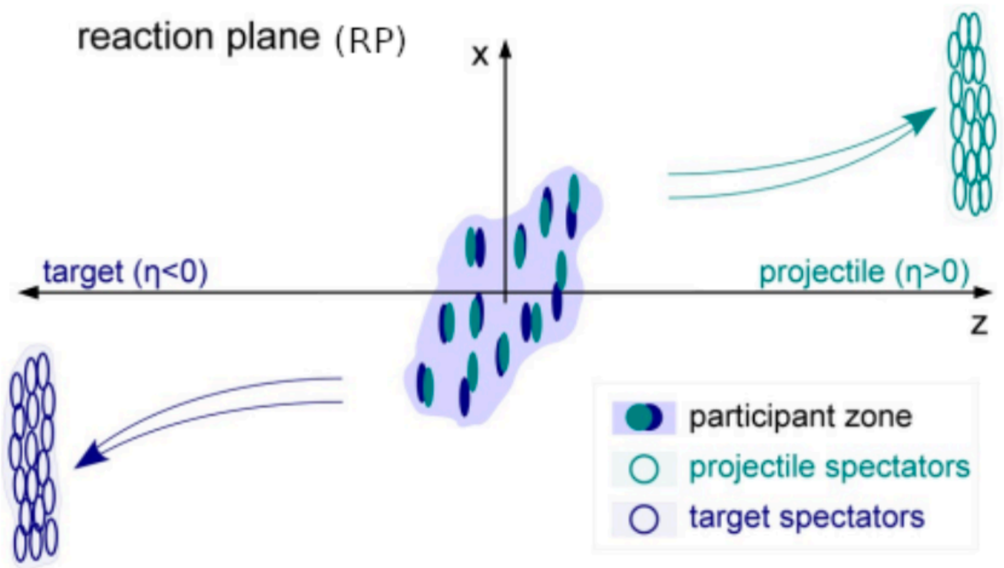


Anisotropic Flow: directed flow (v_1)

S. Sharma, Wed. 4:00pm

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



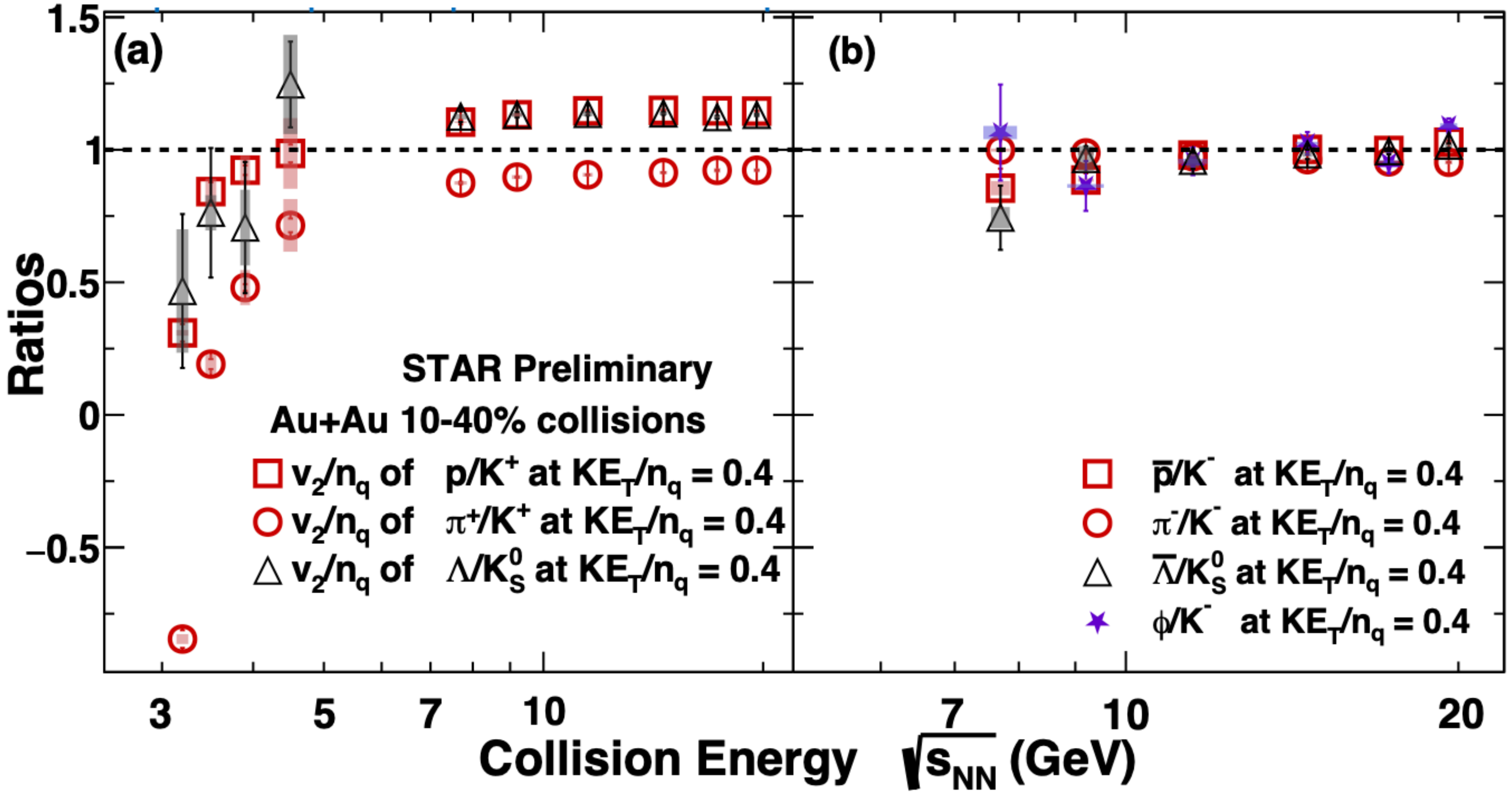


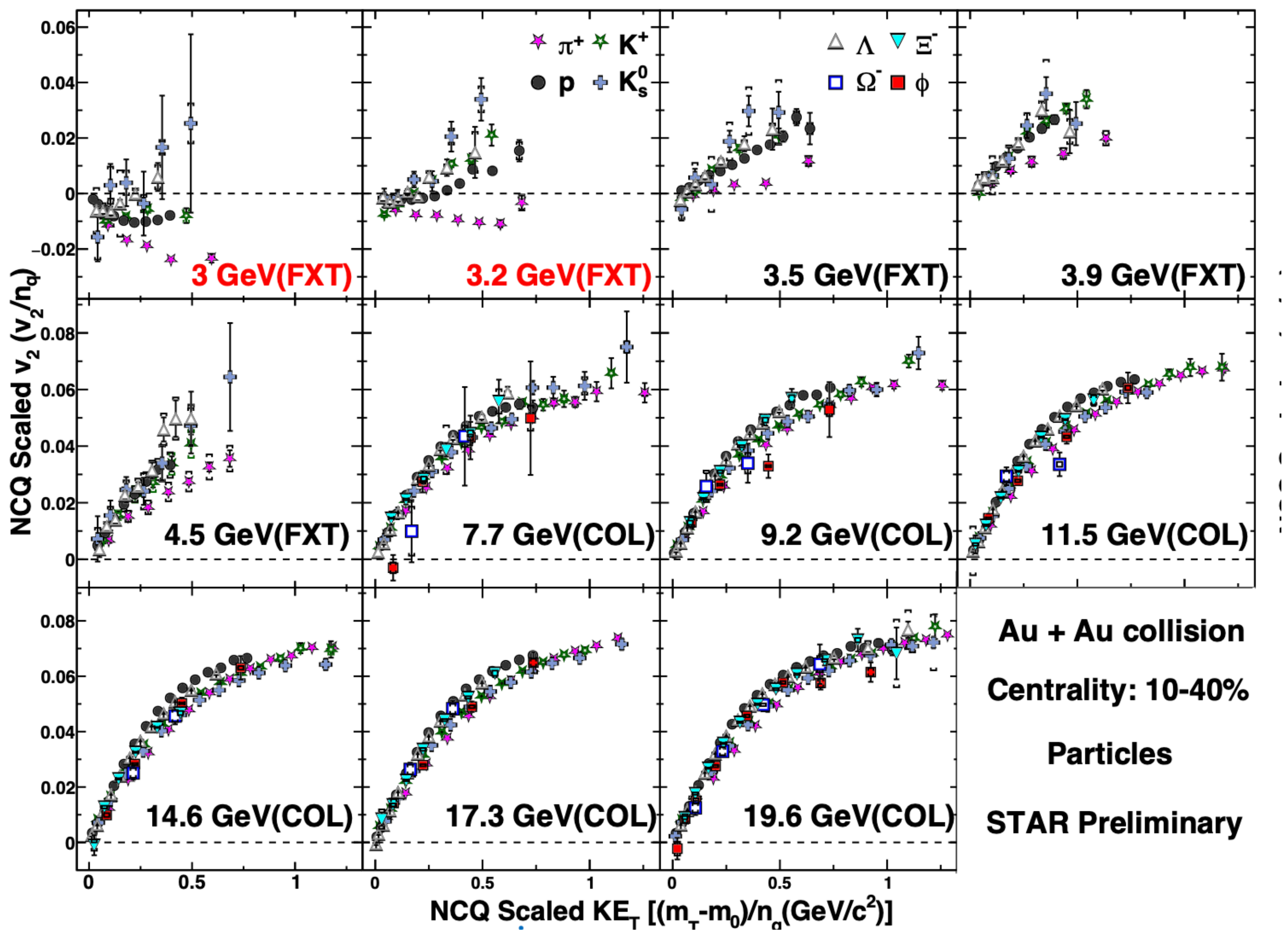
- The v_1 slope of φ meson shows unexpected similar trends to that of p and Λ in high μ_B region.
- Kaons show sign change as protons with minimum between 4.5 and 7.7 GeV.

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.



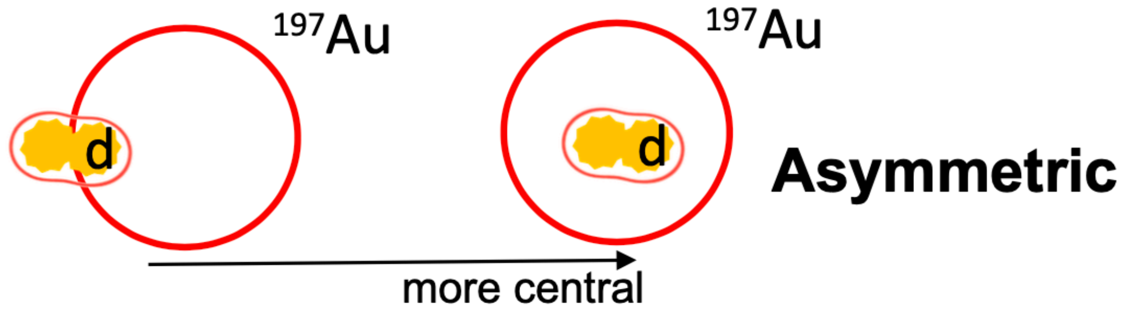


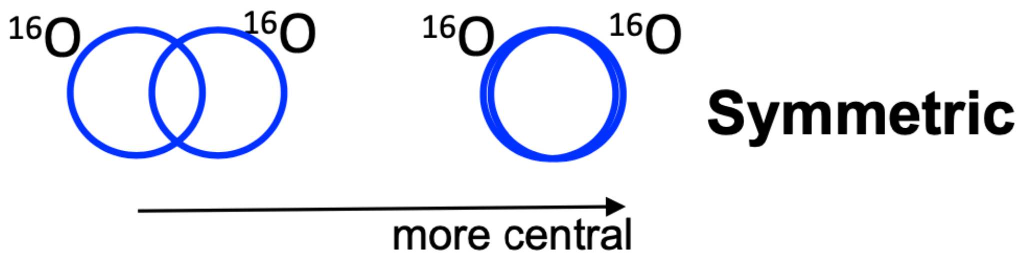
NCQ scaling: number of constituent quark scaling.

Hadron flows follow the same scaling.

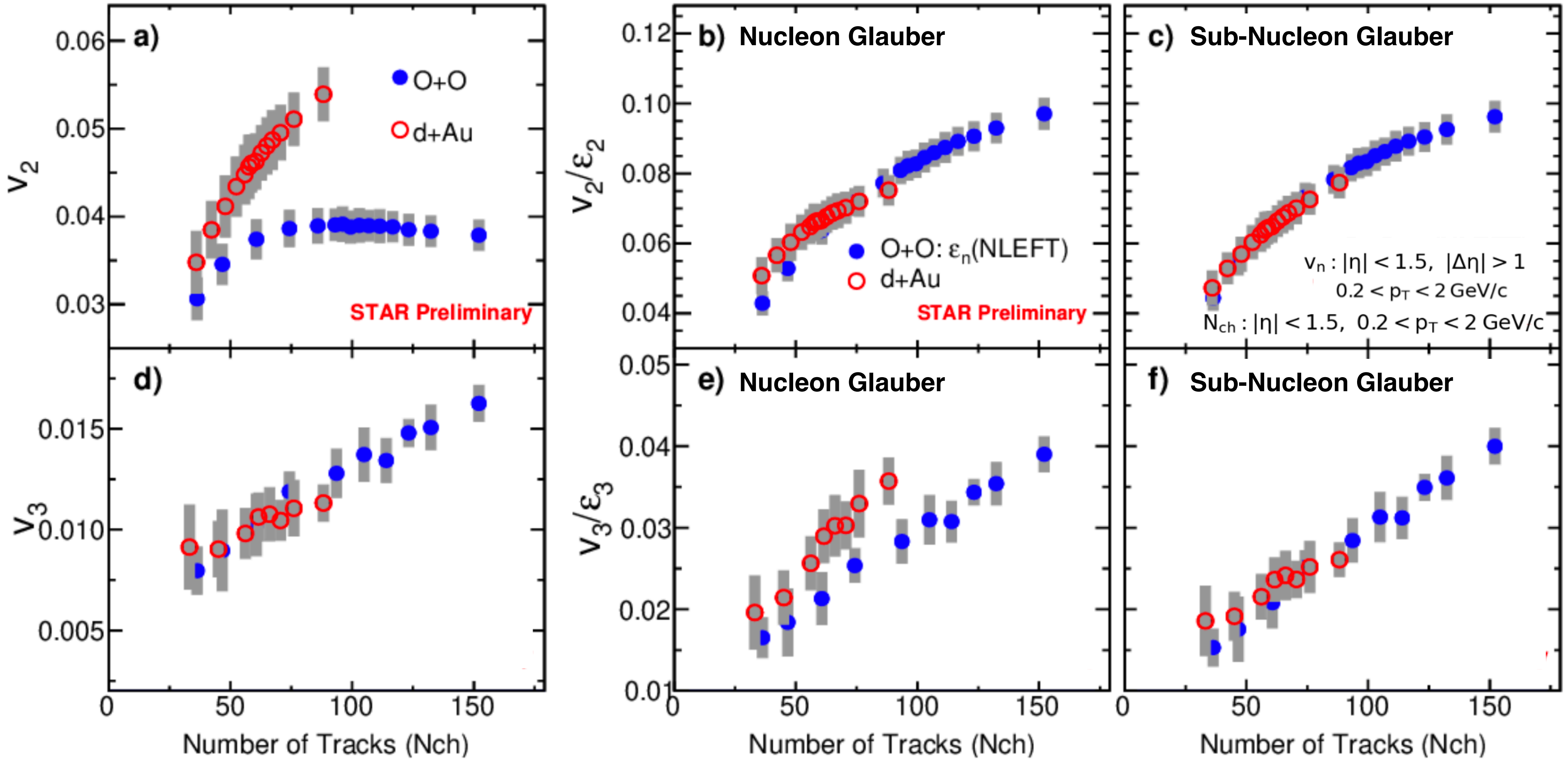
Origin of anisotropy in small systems

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

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

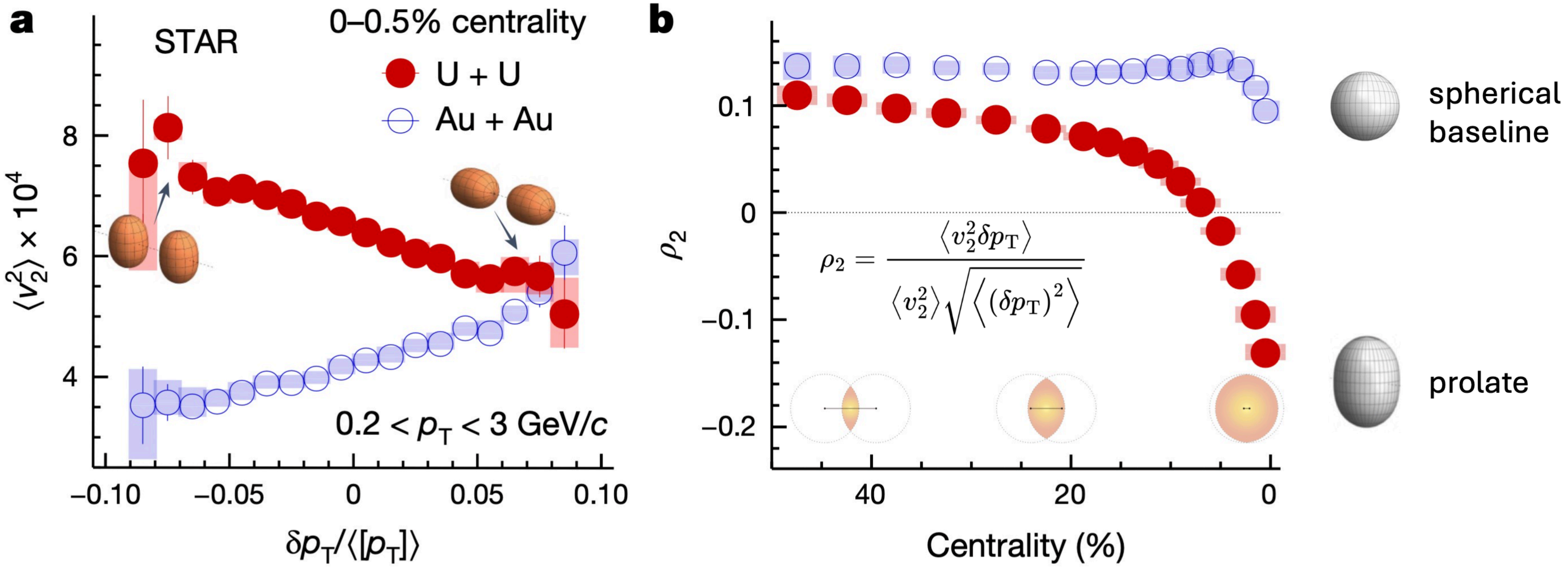
$$R(\theta,\phi) = R_0(1+\beta_2[\cos\gamma Y_{2,0}(\theta,\phi)+\sin\gamma Y_{2,2}(\theta,\phi)]+\beta_3 Y_{3,0}(\theta,\phi))$$

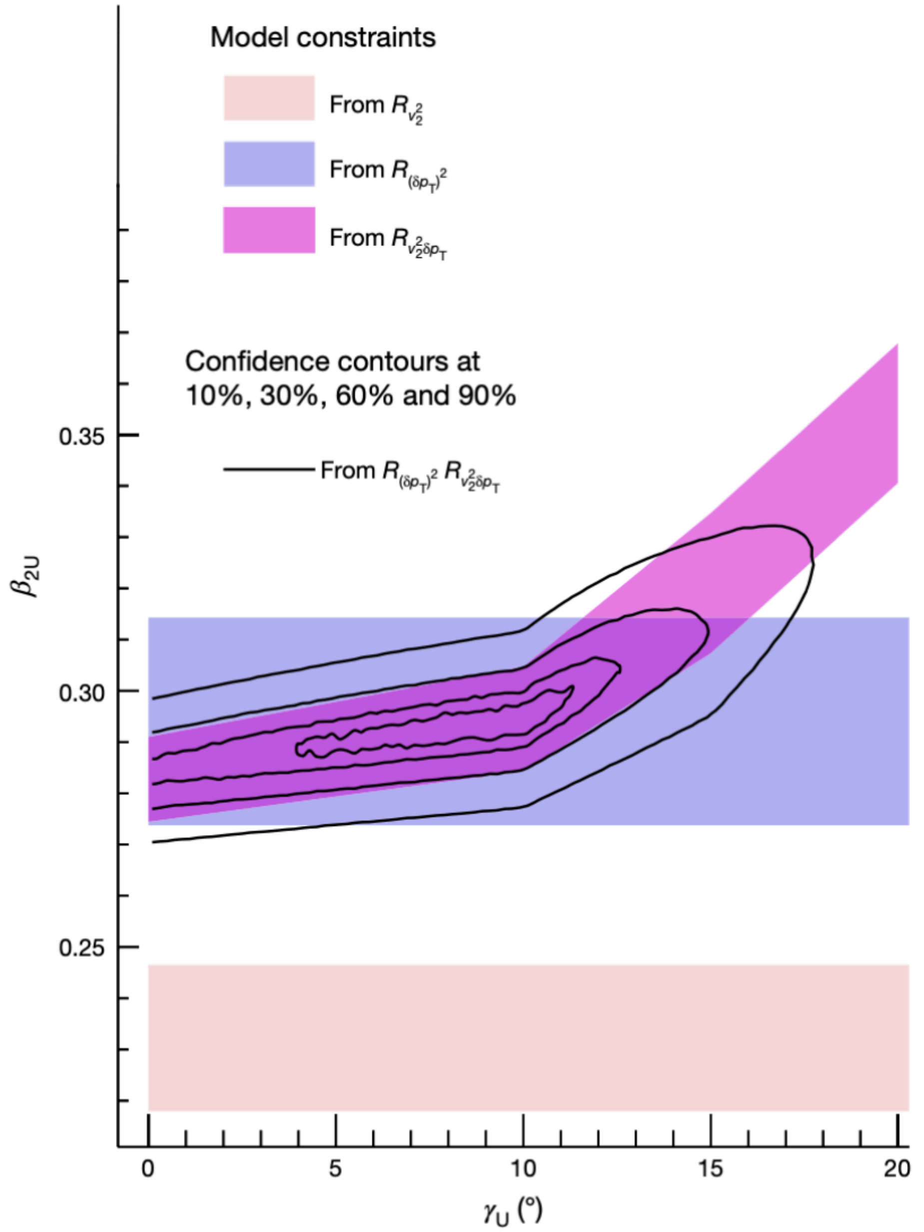
- Nuclear structure leaves imprints on v_n and v_n - p_T correlations.
- Extract U+U shape parameters β_2 and γ:
  - Large quadrupole deformation, consistent with low-energy measurements and indication of small triaxiality in U+U ground state.

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

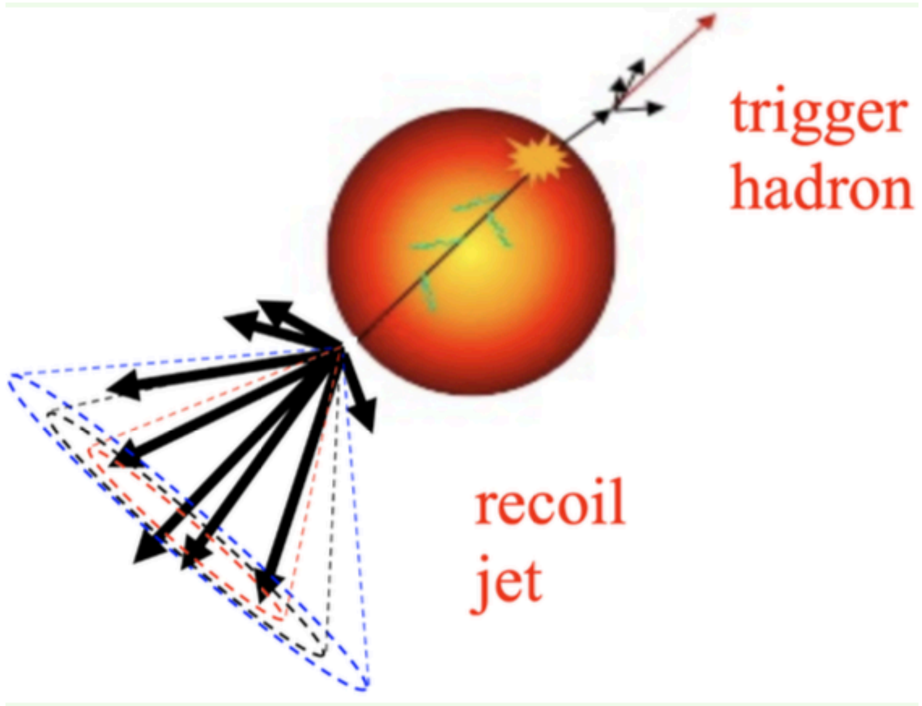
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

STAR, Nature 635, 67-72 (2024)





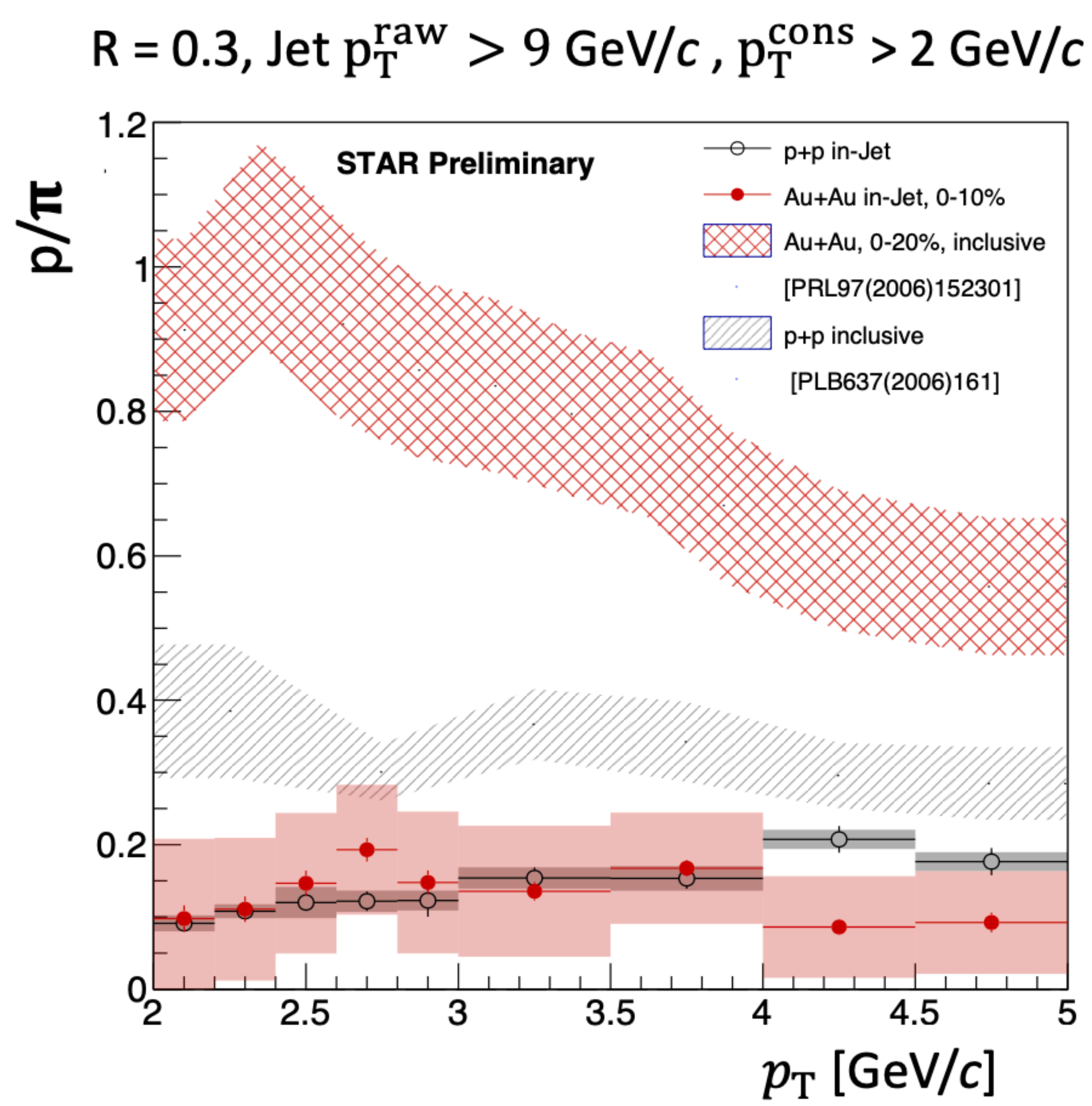
Outline

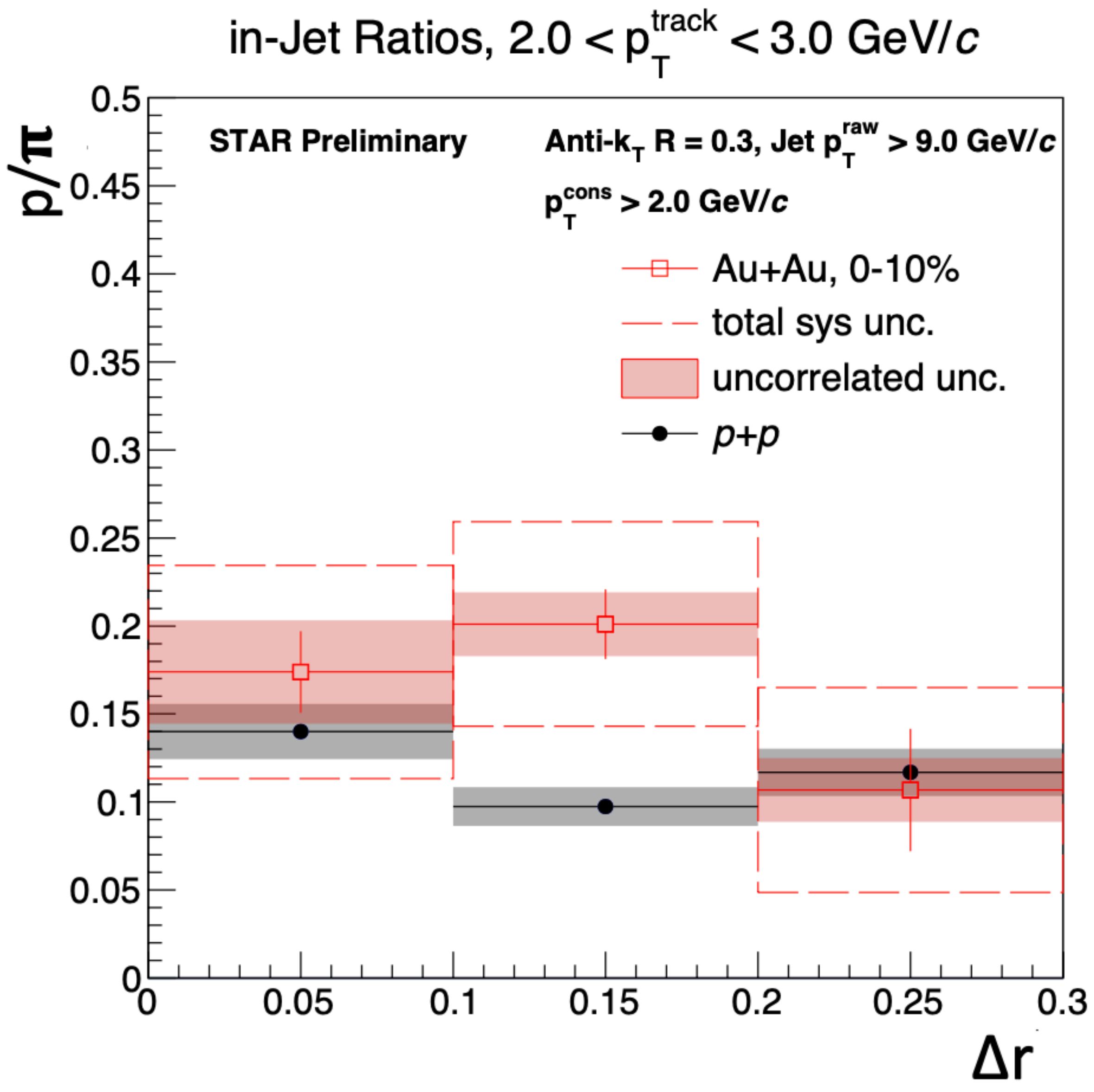


- QCD Phase Structure
- Flow
- **Heavy Flavor & Jets: hadronization and jet quenching.**
- EM Probes
- Spin & Polarization

Baryon to Meson ratio in jets

A. Tamis, Wed. 9:50am





- 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?

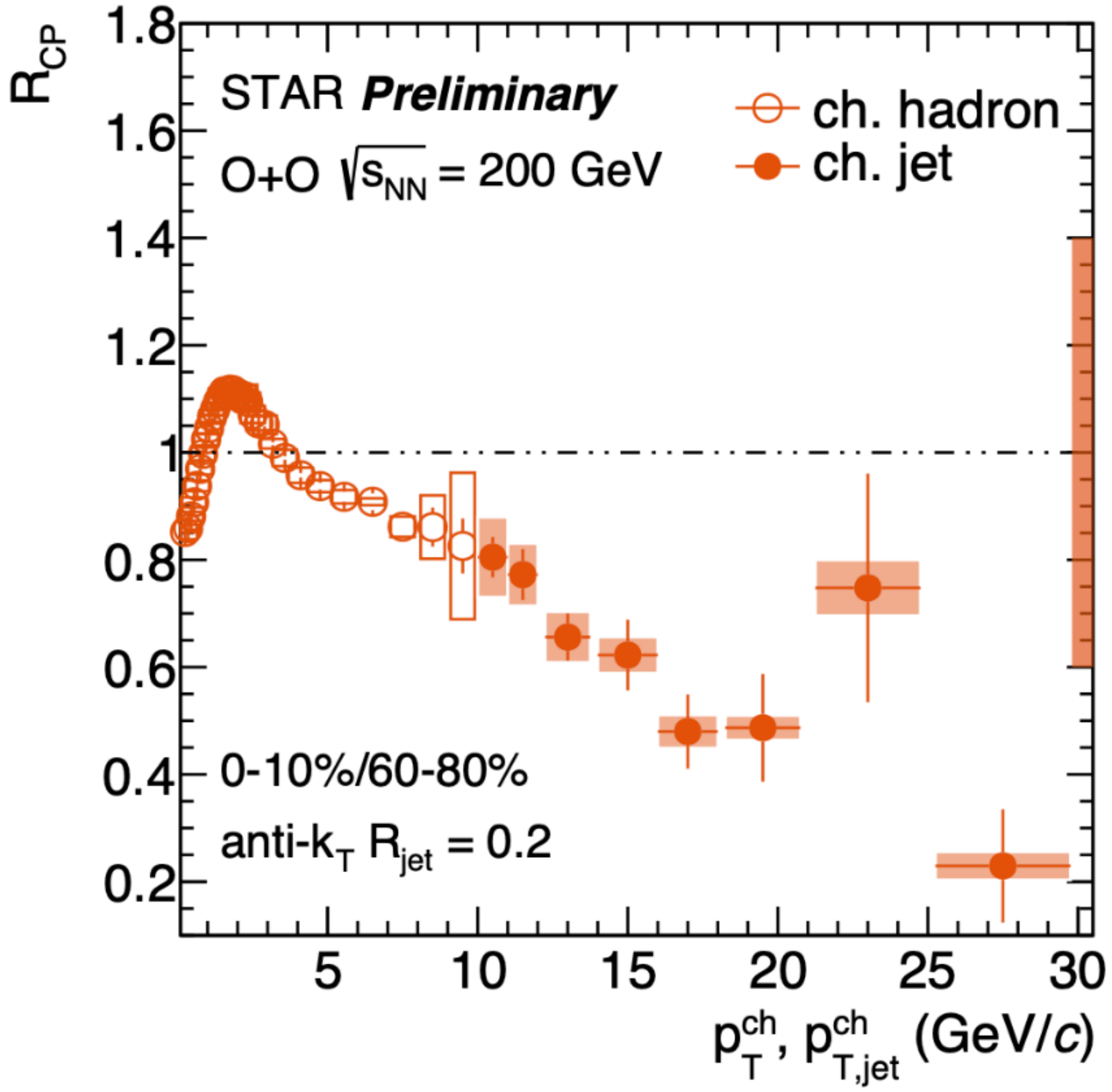
- For measured kinematics, no significant modification of p/π yield ratio within jets between p+p and Au+Au.
- No baryon enhancement observed over momentum range scanned, except hint at ΔR = 0.15.

Jet quenching in O+O

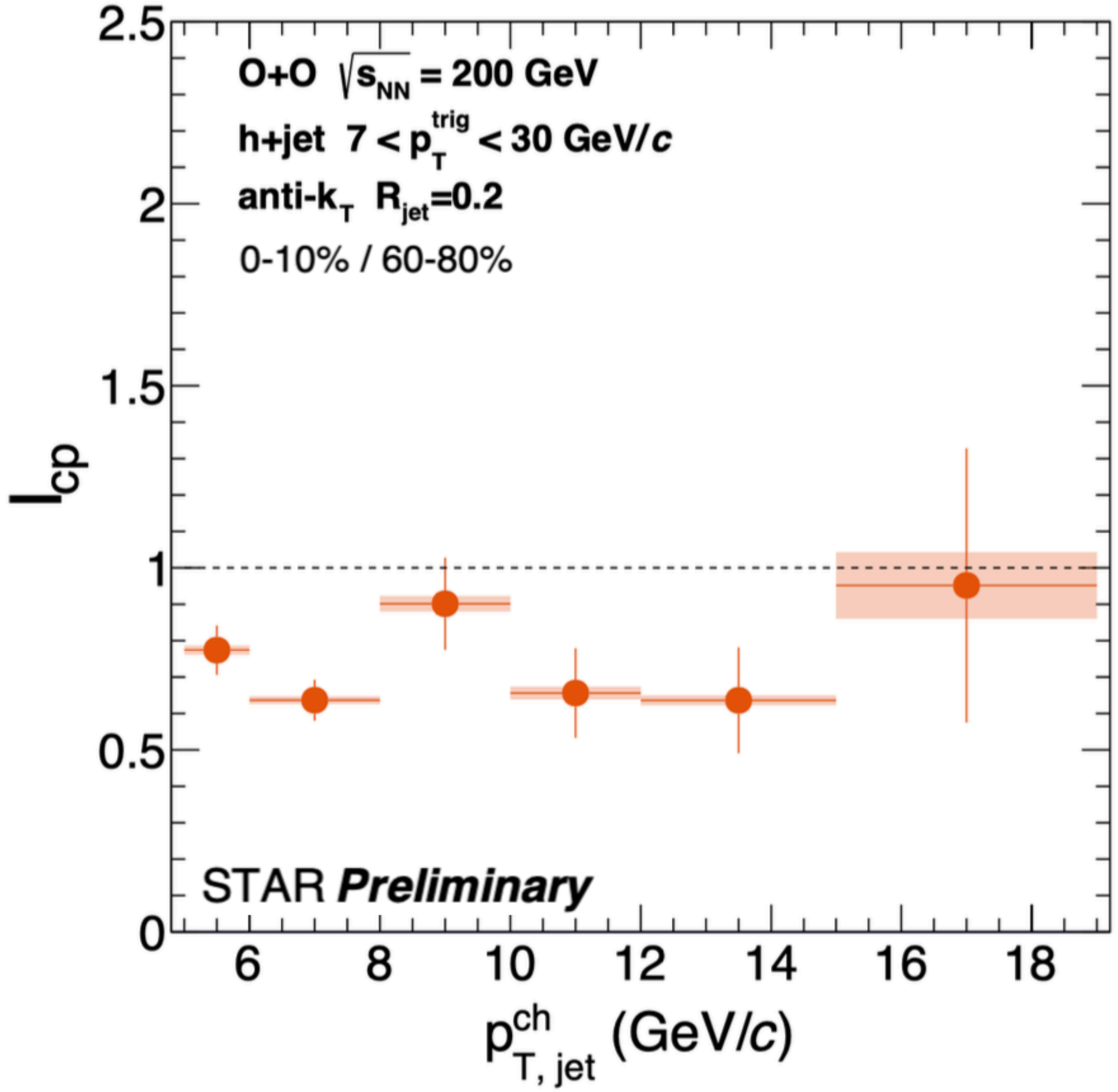
A. Tamis, Wed. 9:50am

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

Inclusive hadrons and jets



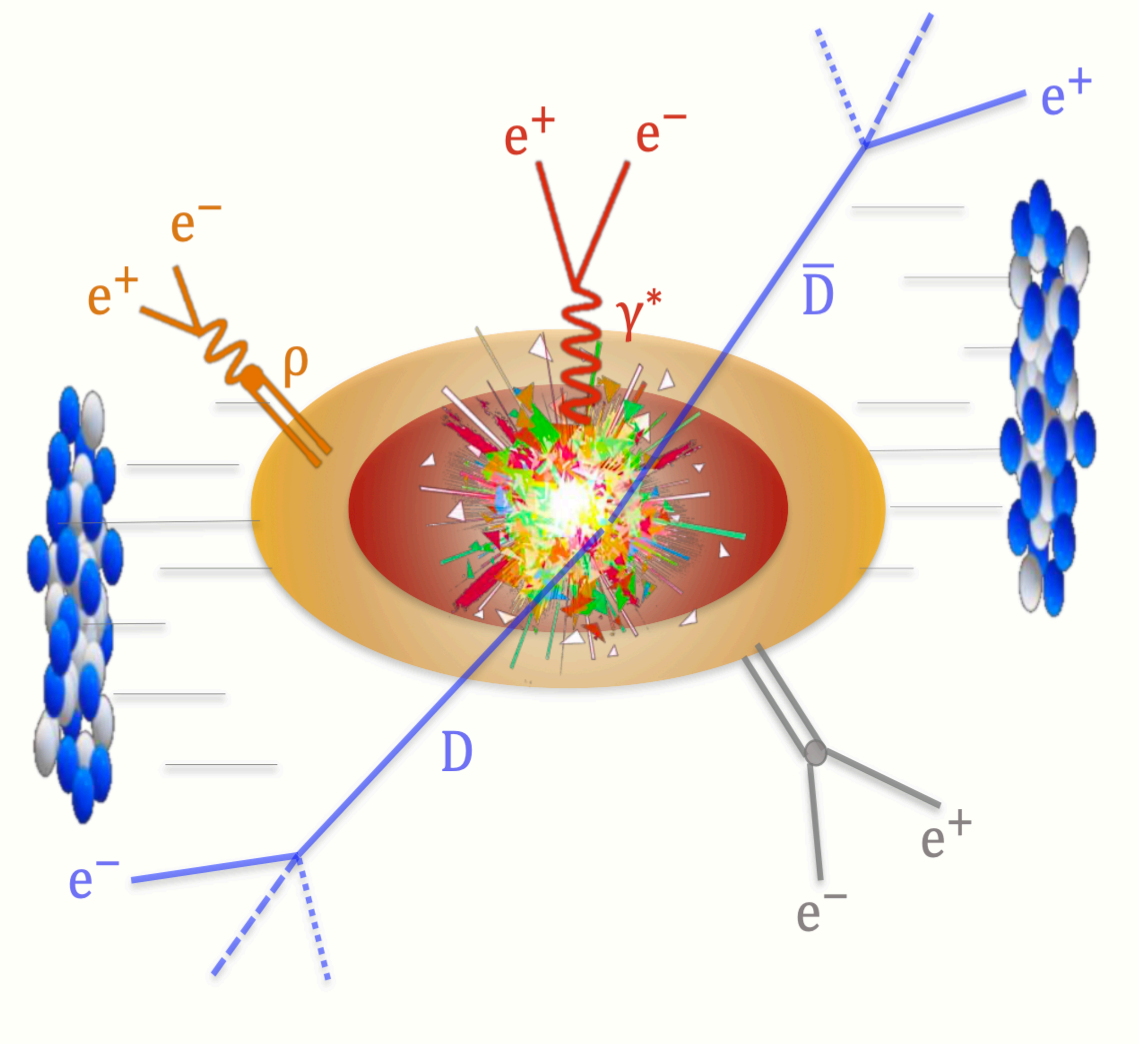
Semi-inclusive h+jets



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

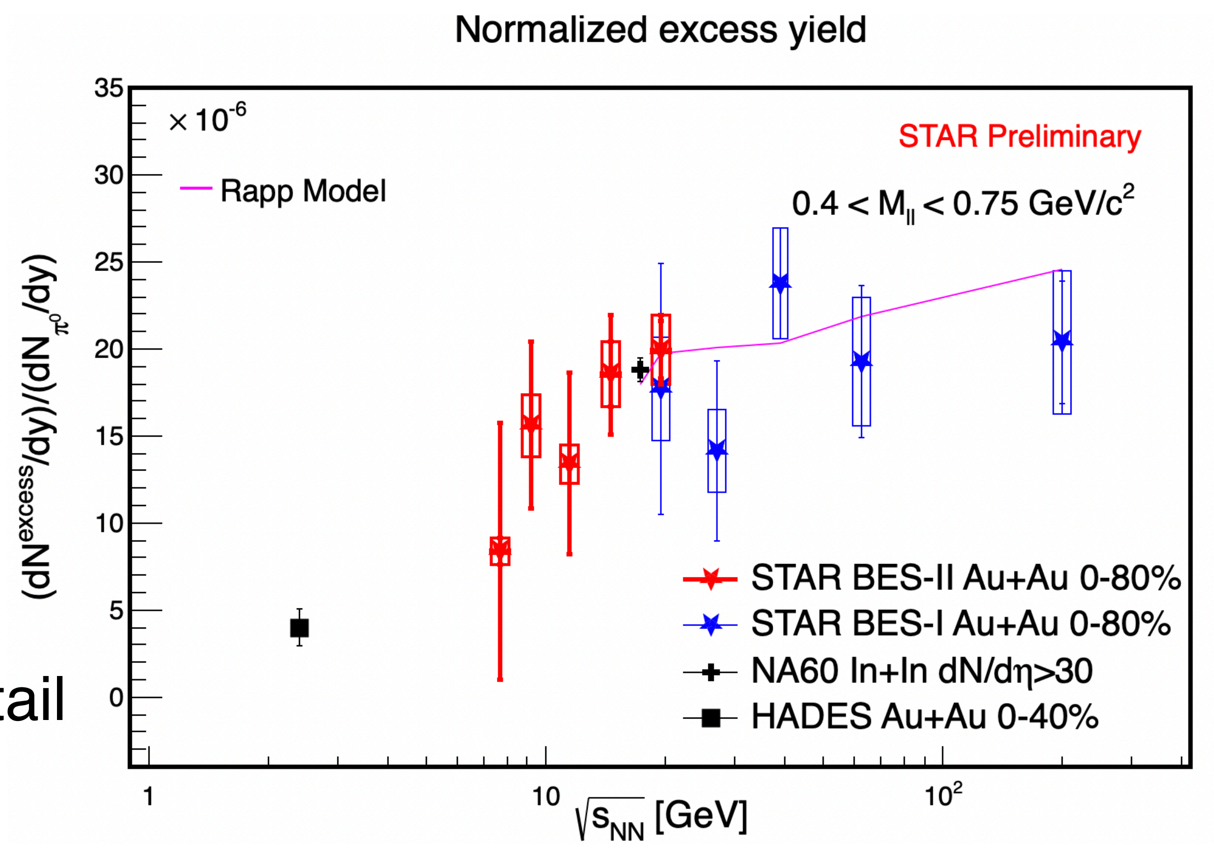
Outline

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

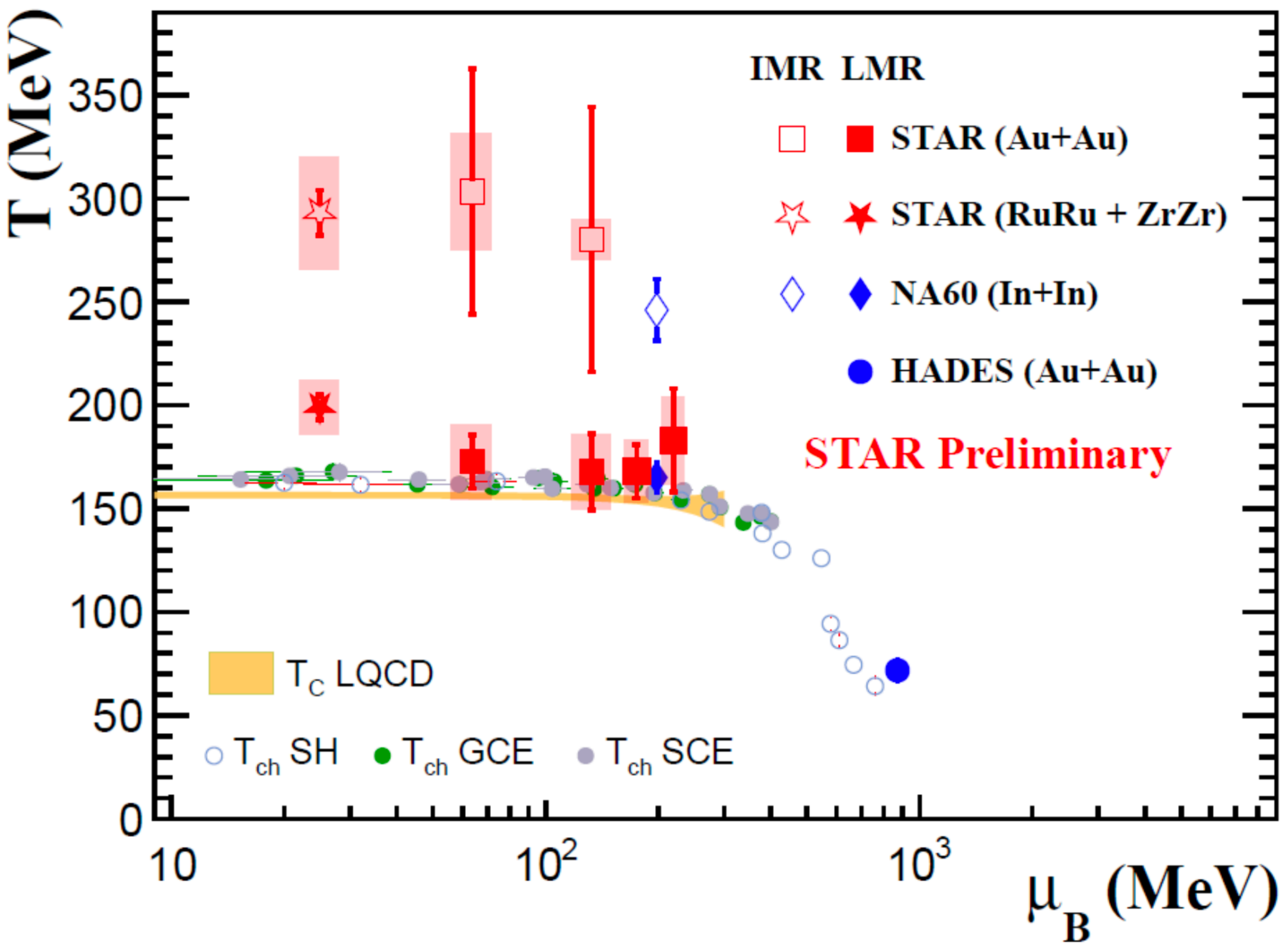


Thermal dielectrons

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

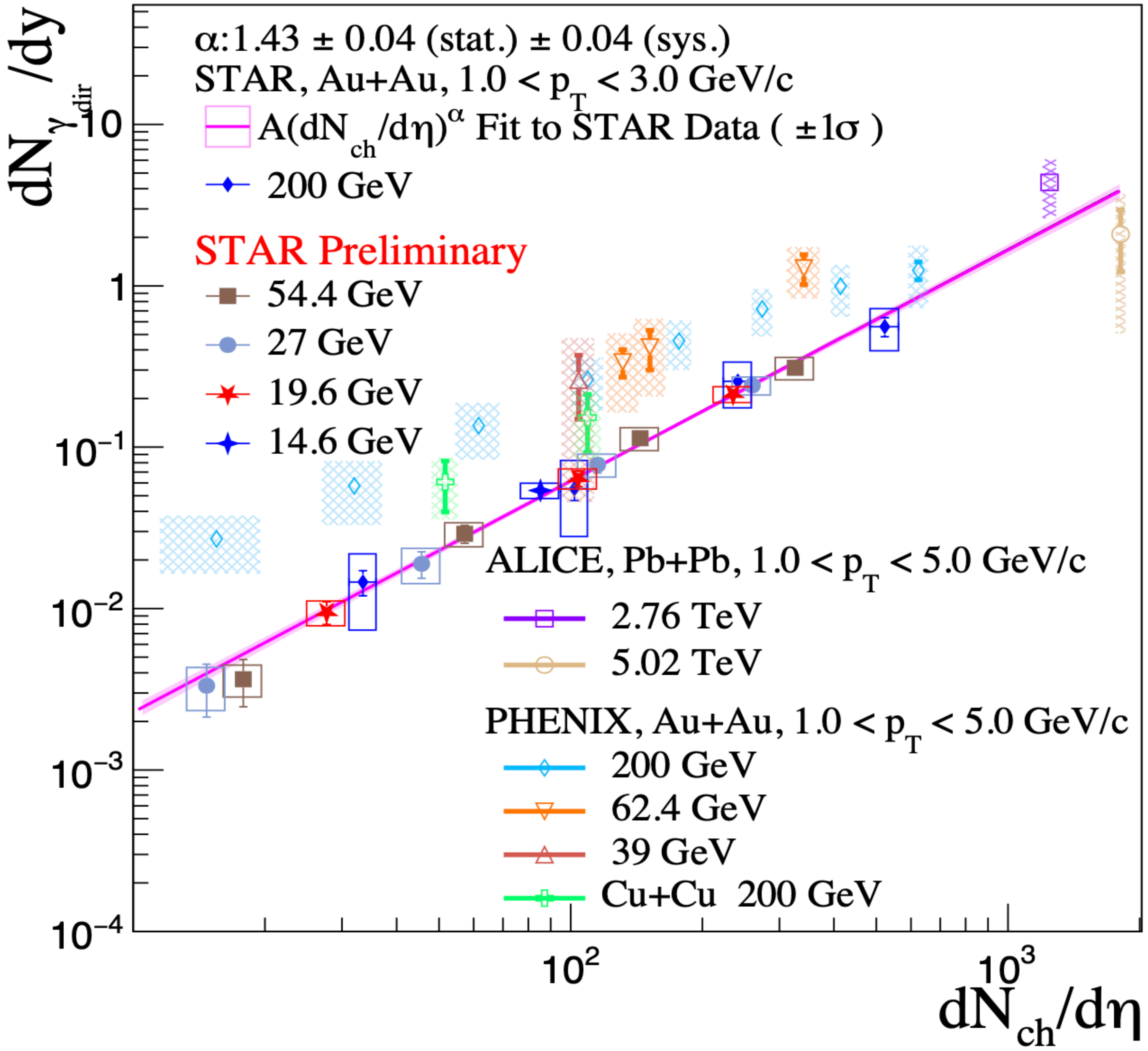


Excess = data - cocktail



- 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

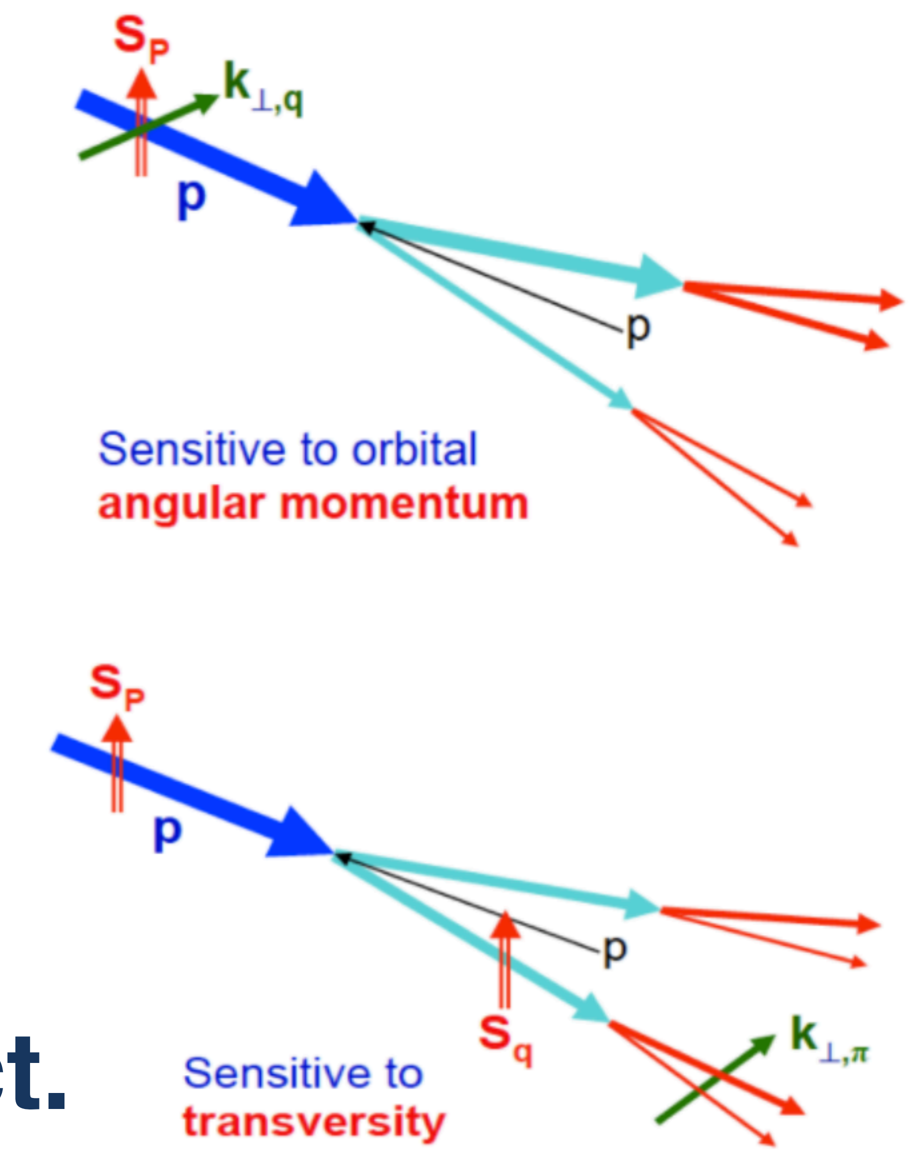


- Yield of direct photons vs. multiplicity from 14.6 to 200 GeV.
- Common scale factor for yields from 14.6 to 200 GeV measurements by STAR.

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

Outline

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

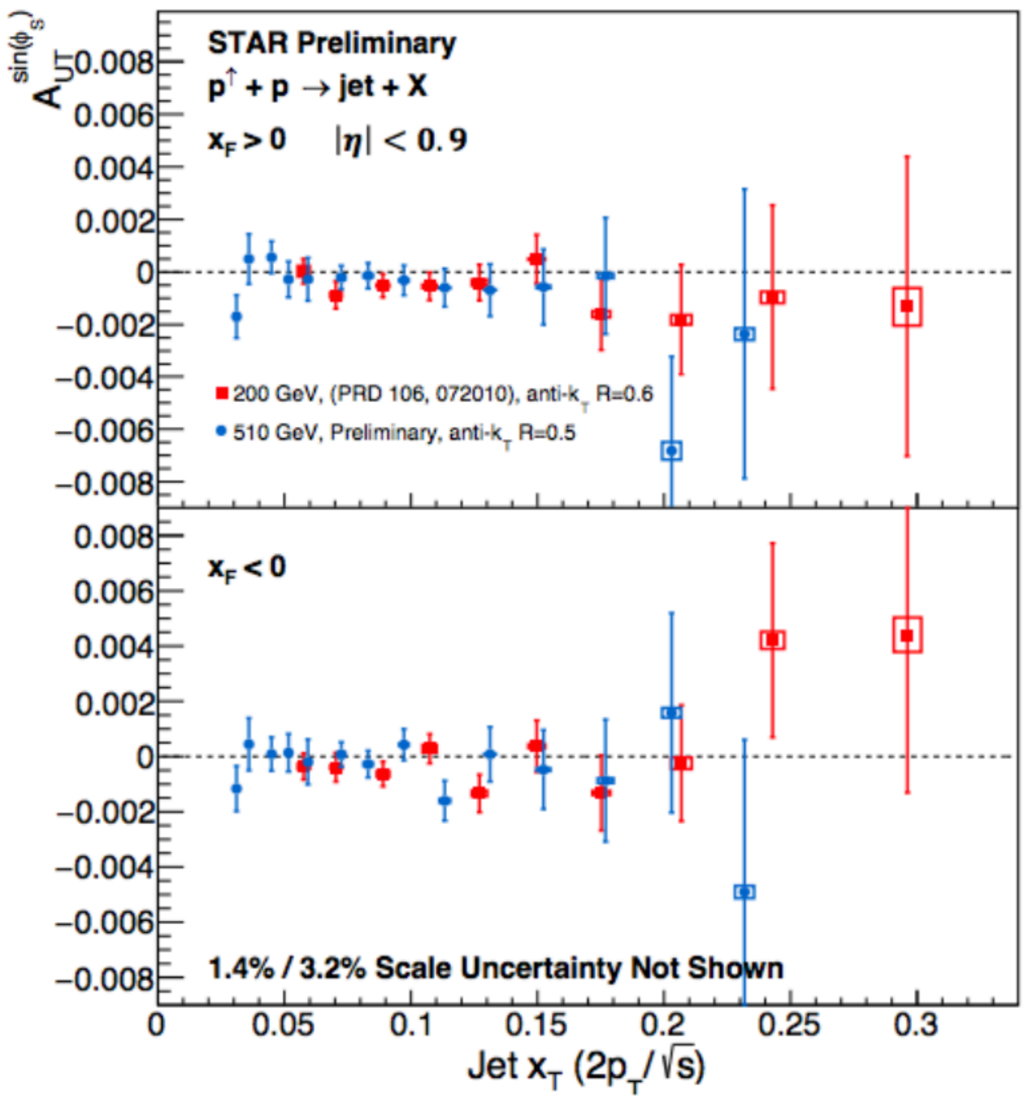


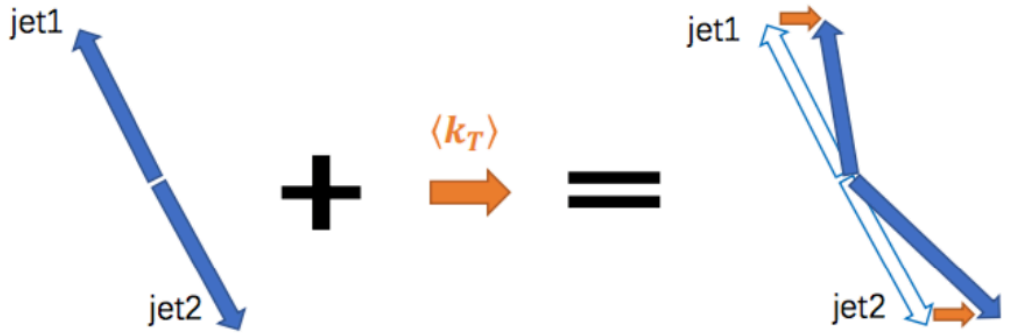
Measurements of A_N with jets

J. Nam, Tue. 11:25am

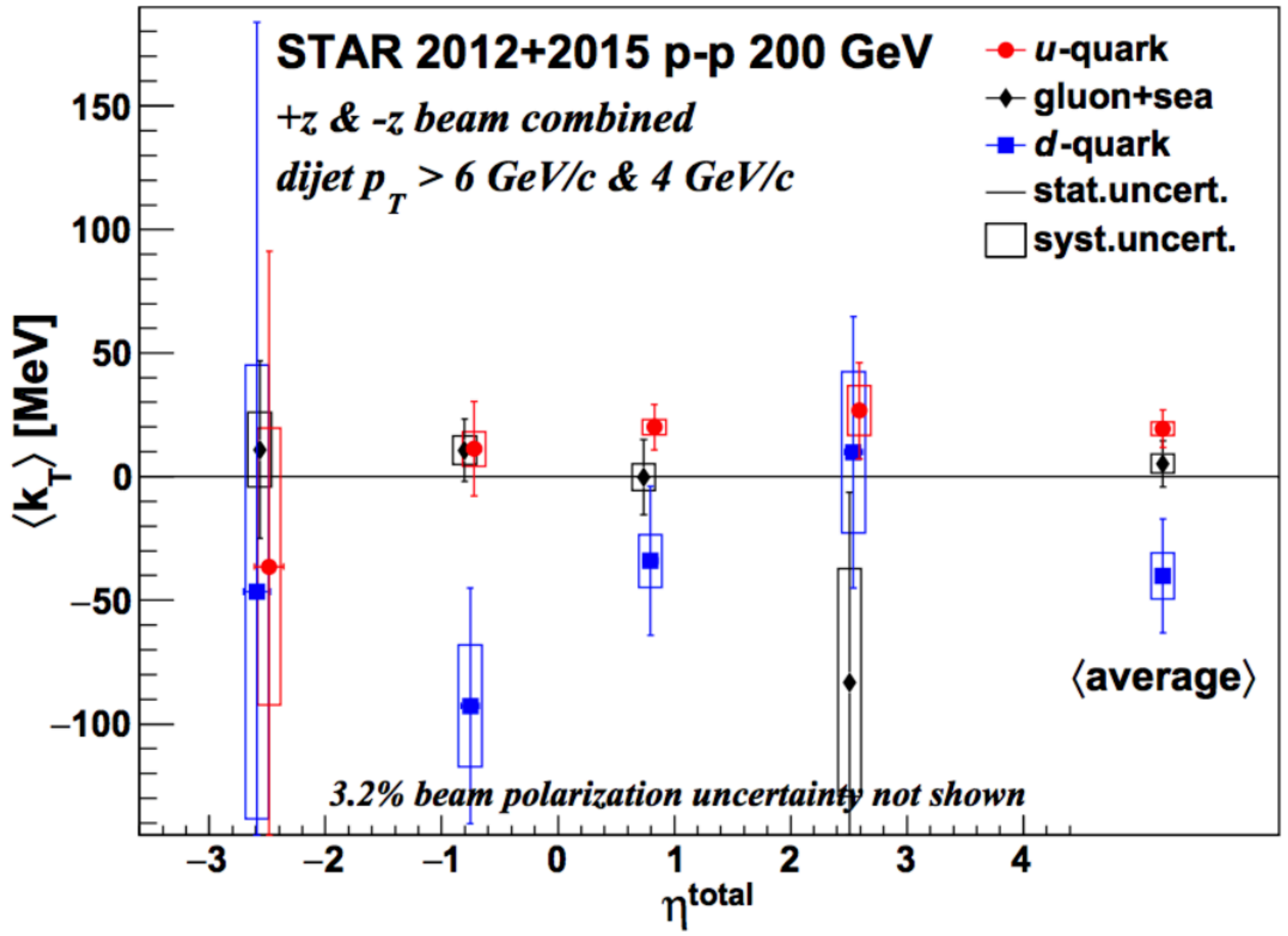
STAR, arXiv:2305.10359

Inclusive Jet A_N





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

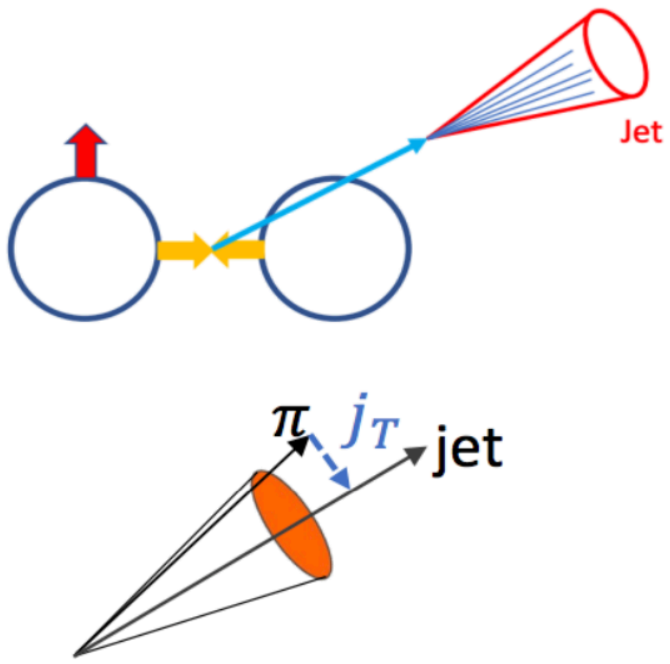


- Inclusive jet A_N consistent with 0, unlike in SIDIS: pQCD suggests cancellations of $\boldsymbol{u}$ and $\boldsymbol{d}$ quarks at initial and final states.
- First hint of non-zero Sivers effect in dijet at pp collisions.

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

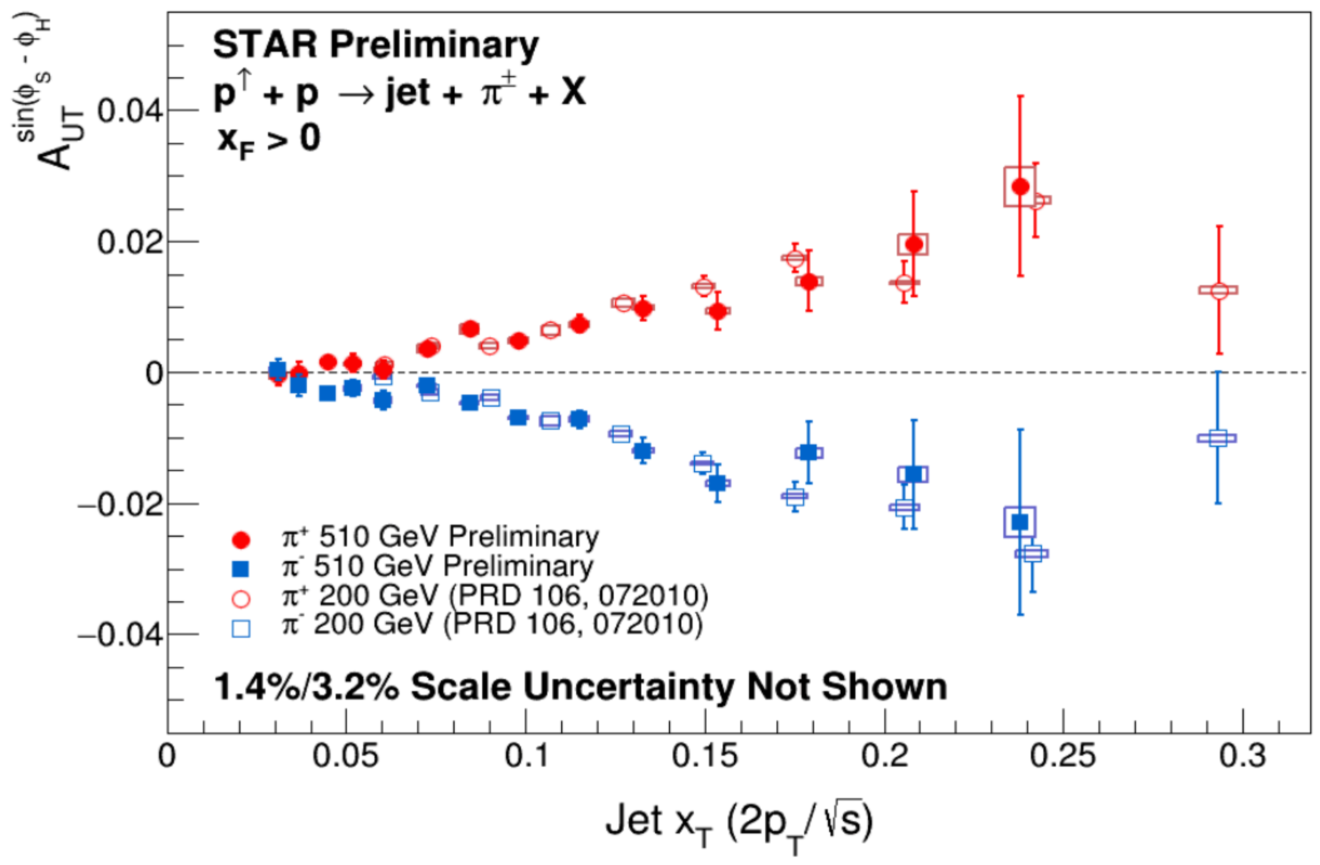
Investigation of Collins effect

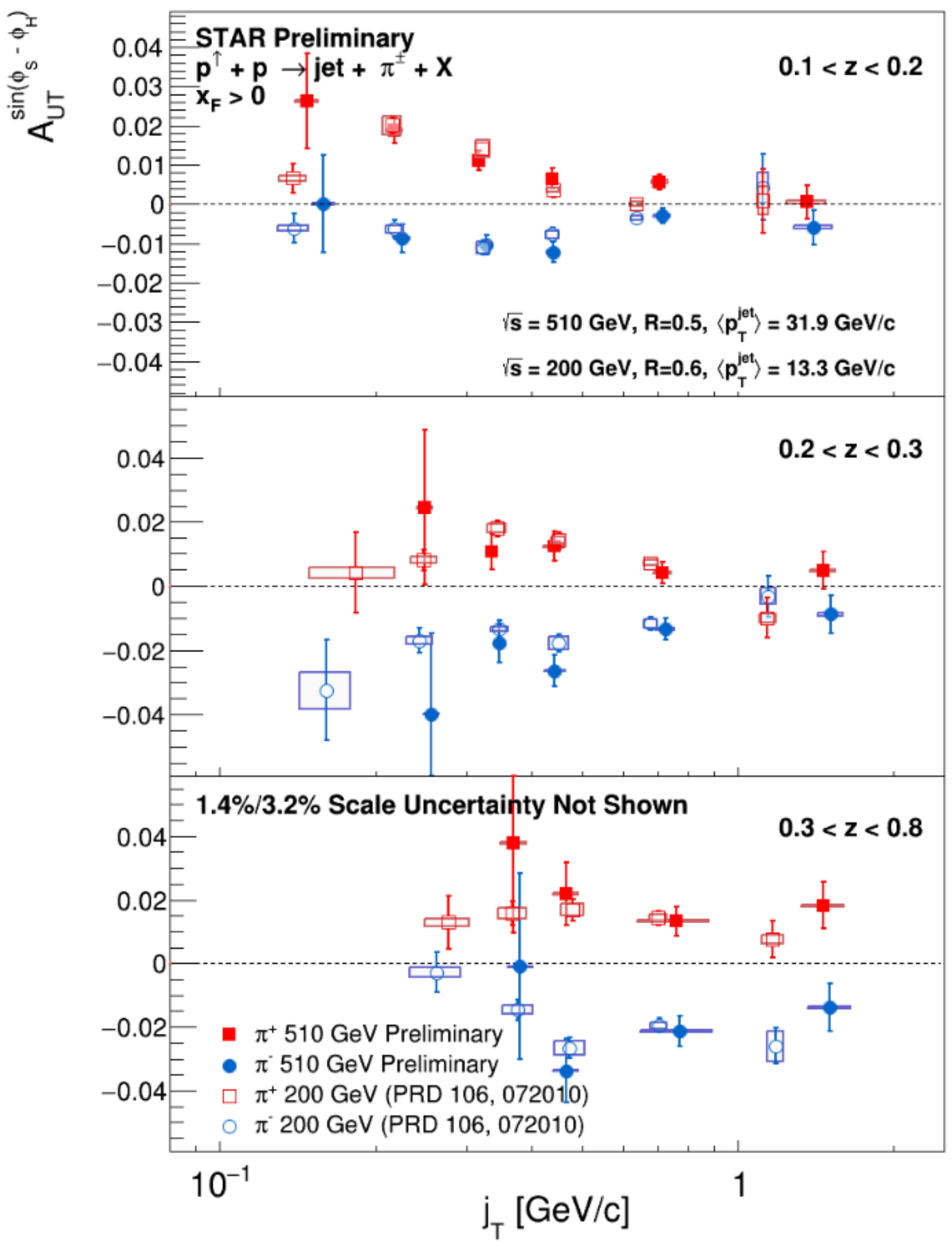
J. Nam, Tue. 11:25am



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

Transversity ⊗ Collins FF

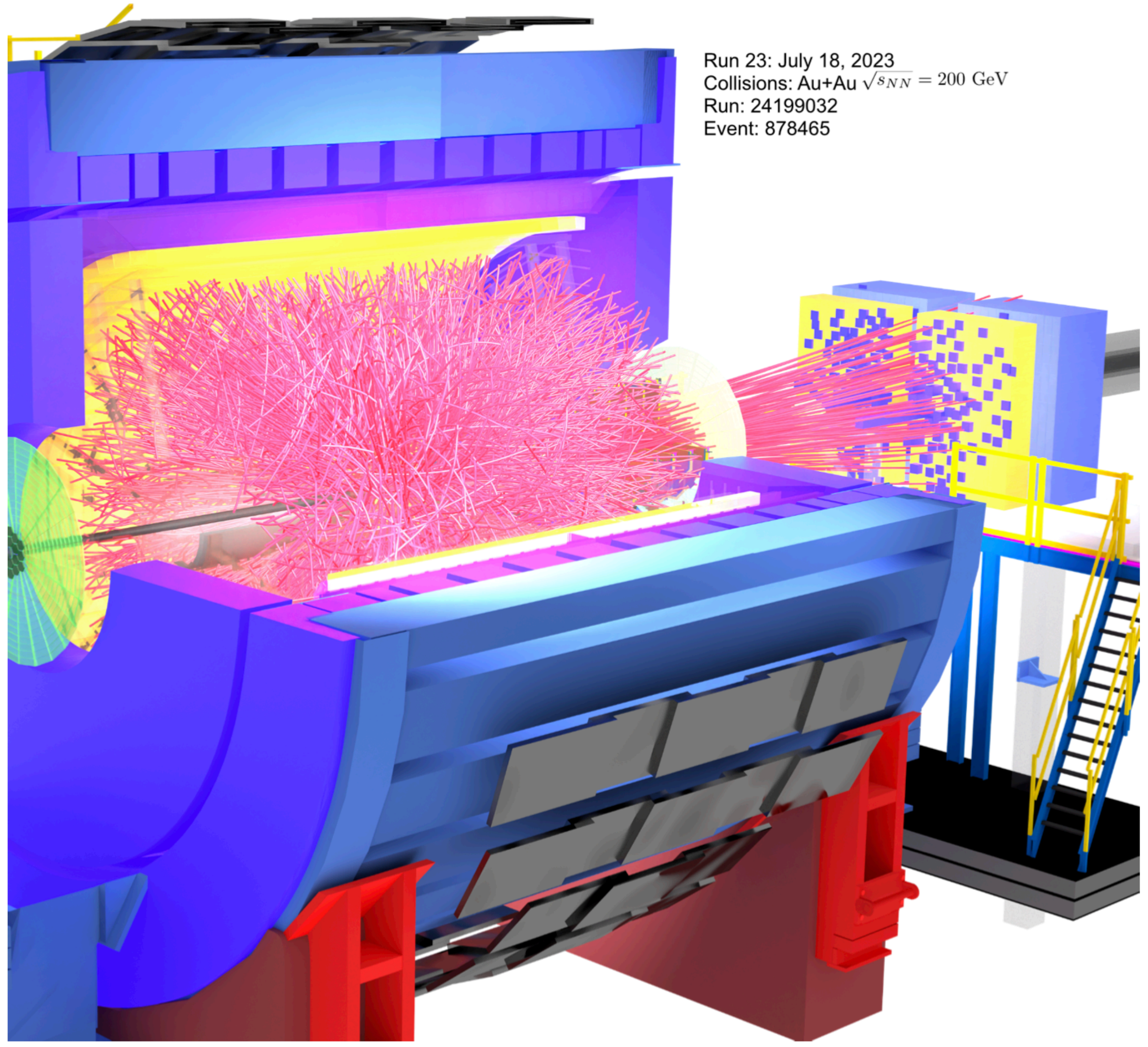




- Hadron-jet correlation measurements: a more direct probe of transversity than SIDIS: ***Collinear*** (pp, $h_1(x)$) vs. ***TMD*** (SIDIS, $h_1(x, k_T)$)
- By varying z and j_T, STAR simultaneously explores both the transversity distribution and the Collins FF.

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.

STAR Collaboration Meeting, 03/27/2025

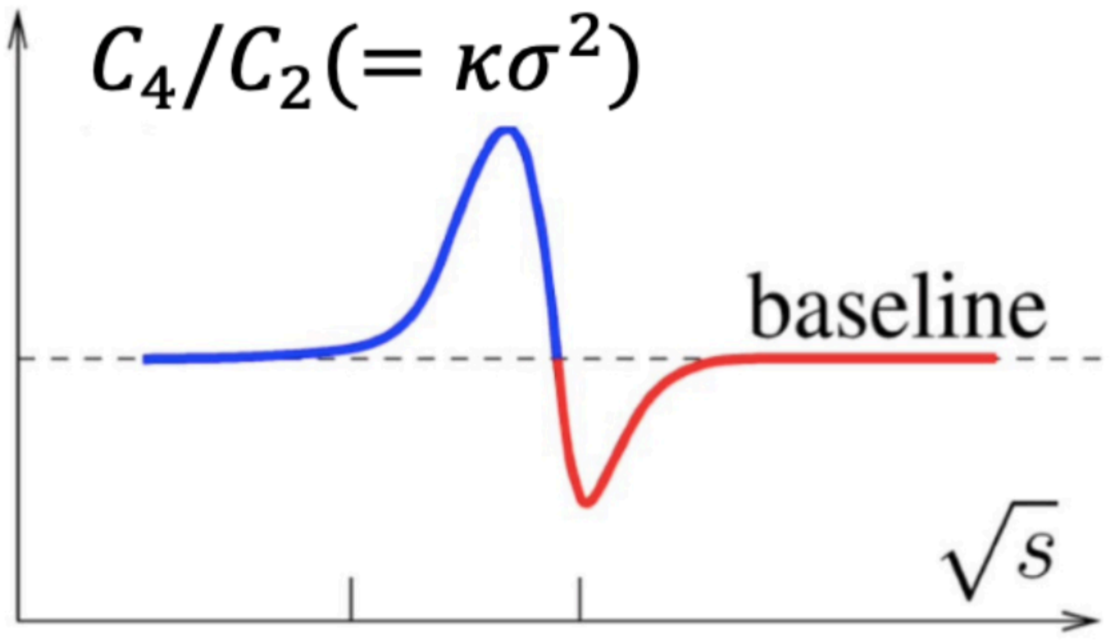
Thank you for your attention

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.

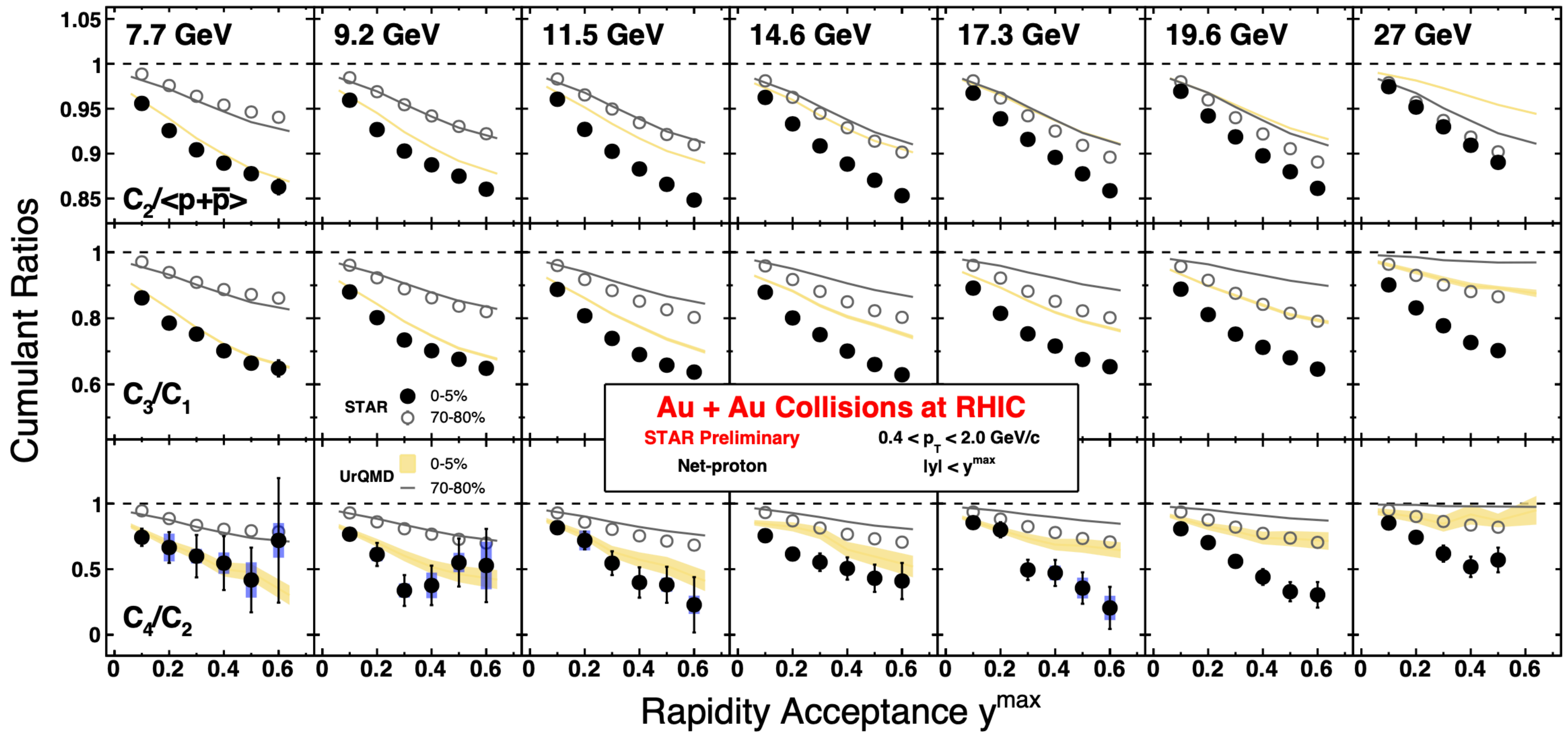


$$C_2 \sim \xi^2,\ C_4 \sim \xi^7$$

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

M.A. Stephanov: Phys. Rev. Lett. **107**, 052301 (2011)

Net-proton cumulant ratios: rapidity scan

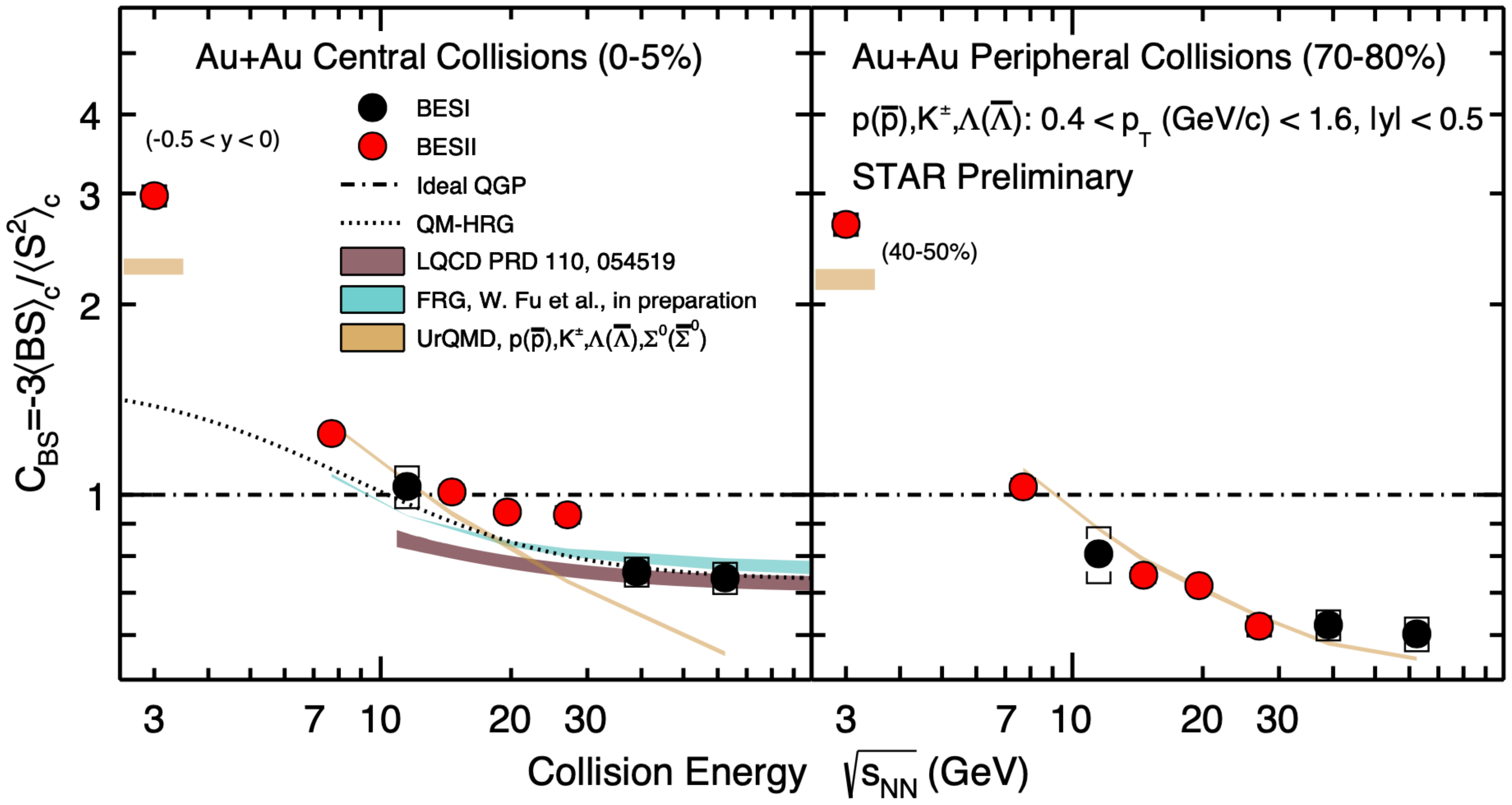


Widening y(pT) windows of measurement enhances potential critical contributions

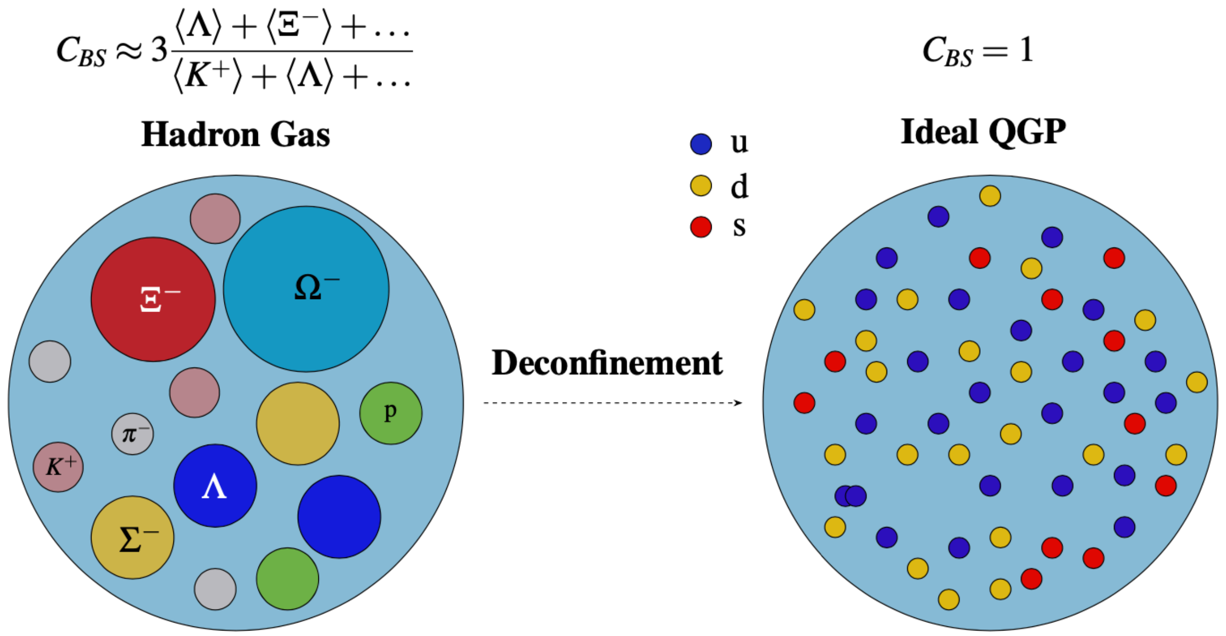
- Cumulant ratios decrease smoothly along rapidity window
- Deviation from UrQMD increases with y acceptance.

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.



M. Asakawa, U. W. Heinz and B. Muller, Phys. Rev. Lett. 85 (2000)

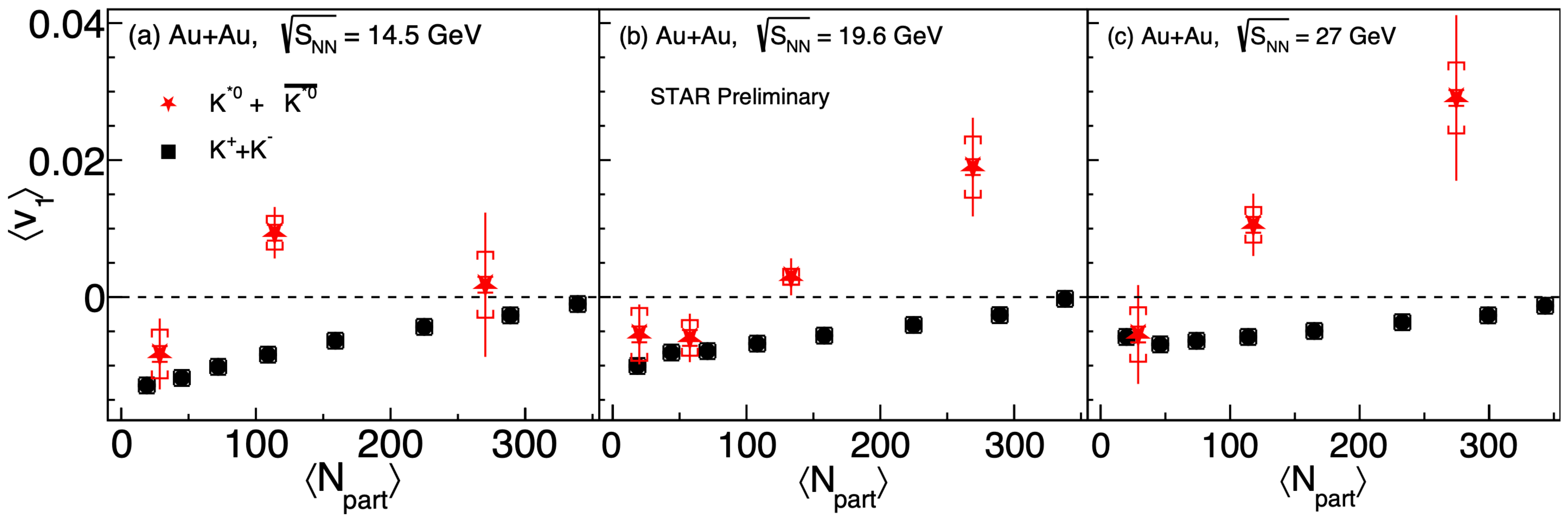


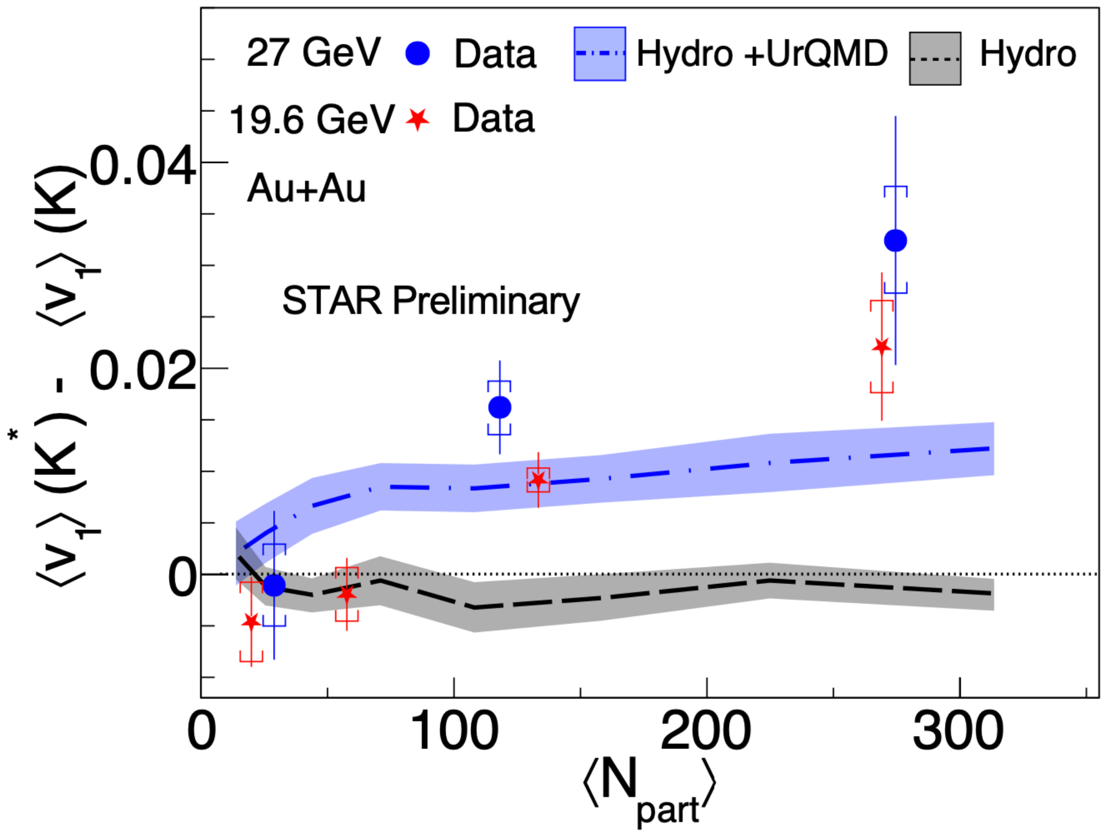
$$C_{BS} = -3\frac{\langle BS\rangle_c}{\langle S^2\rangle_c} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}$$

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

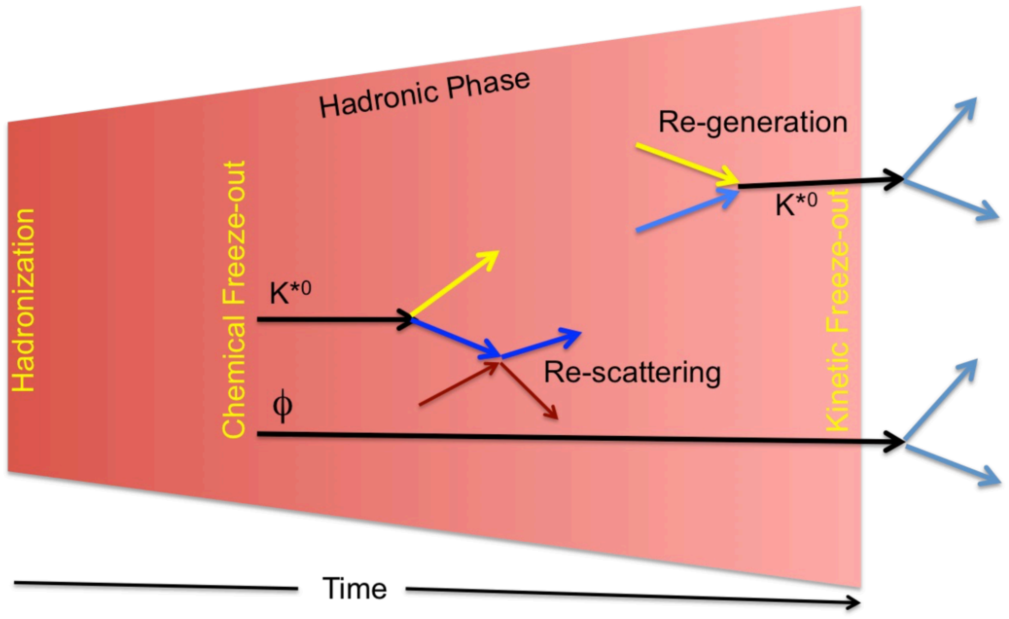
Directed flow of K^{*0}

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

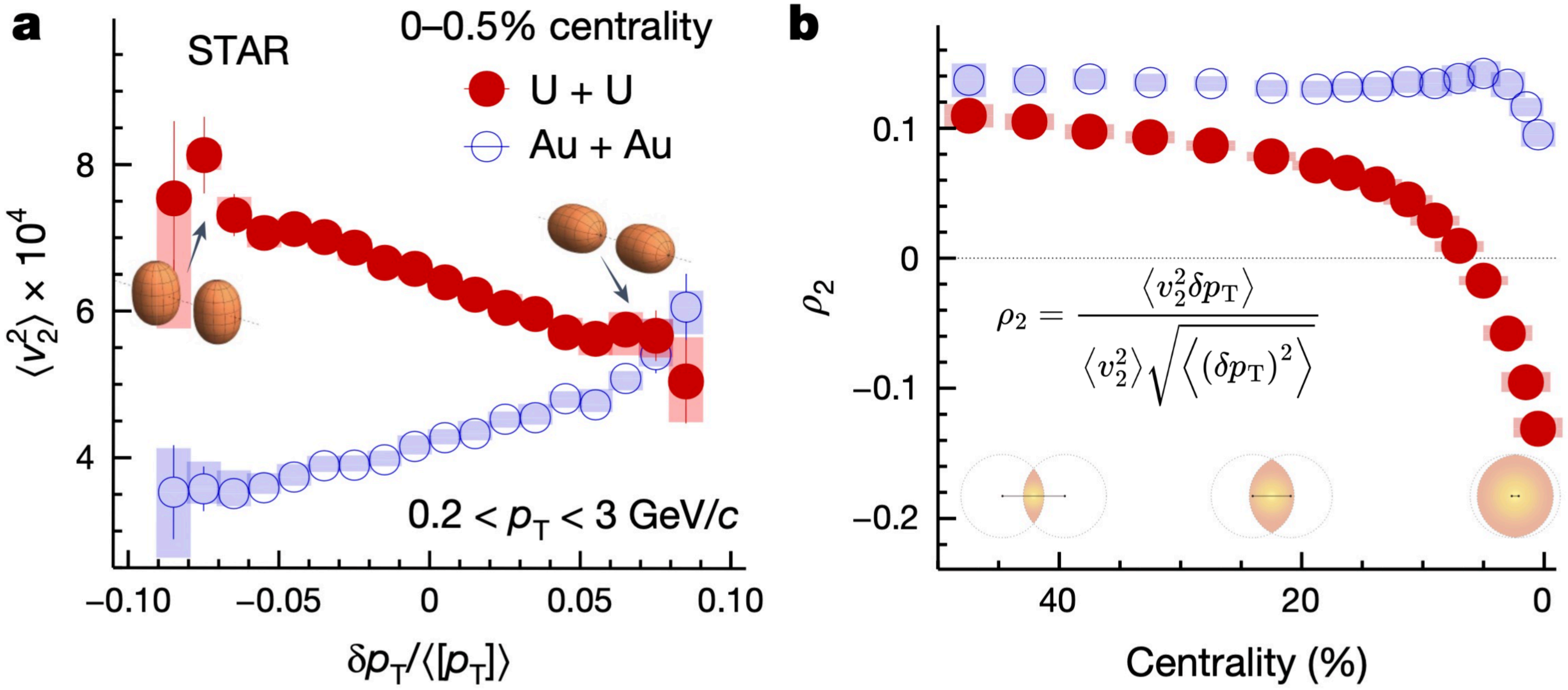
$\beta_3 \rightarrow$ octupole deformation

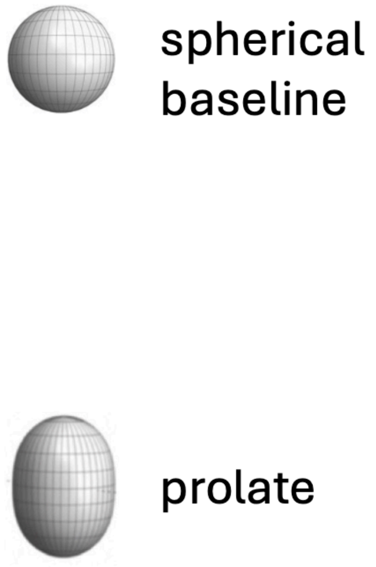
$\gamma \rightarrow$ triaxiality

$a_0 \rightarrow$ surface diffuseness

$R_0 \rightarrow$ nuclear size

STAR, Nature 635, 67-72 (2024)



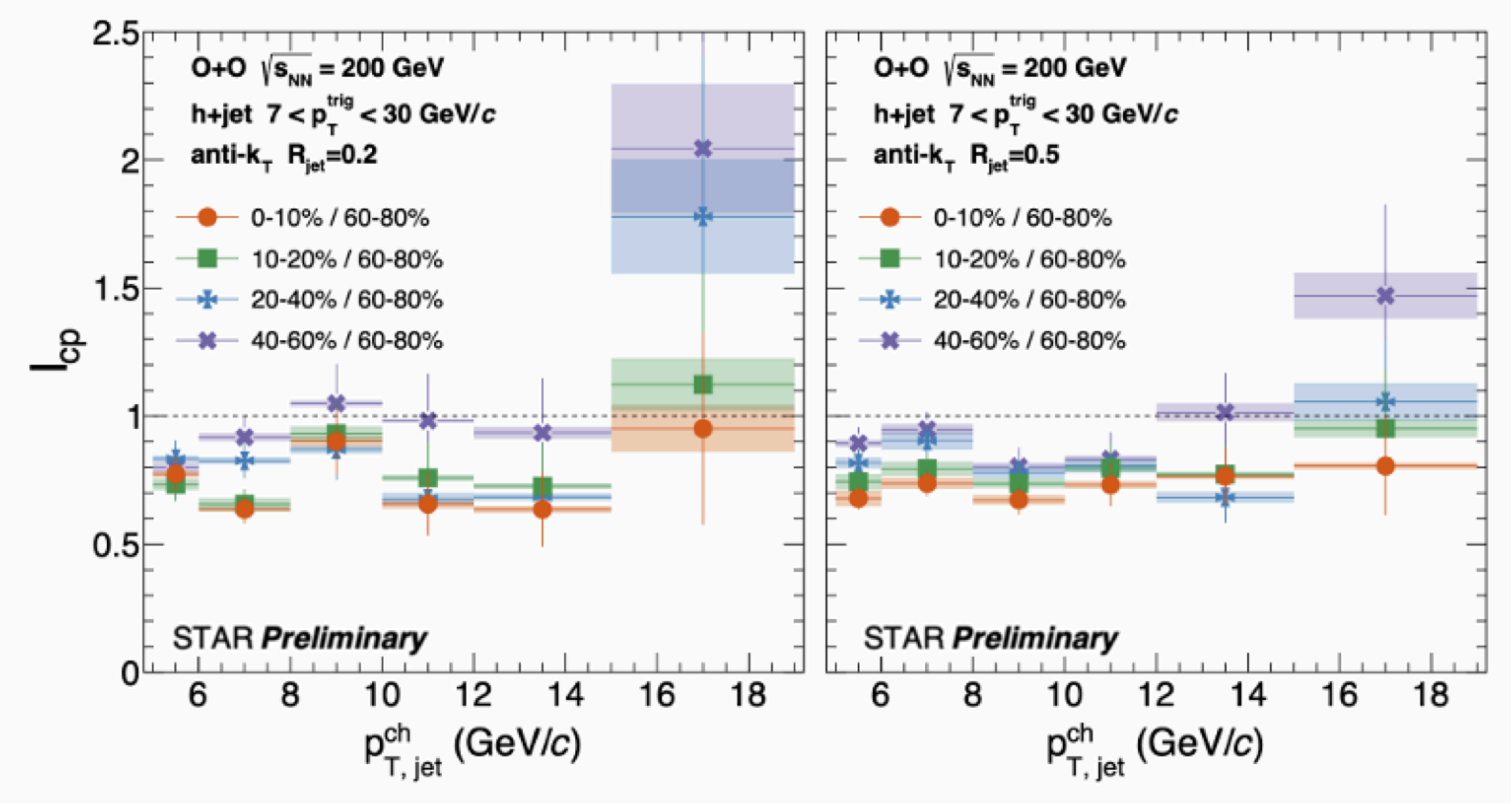


$$\langle v_2^2 \rangle = a_1 + b_1\beta_2^2$$
$$\left\langle (\delta p_T)^2 \right\rangle = a_2 + b_2\beta_2^2$$
$$\langle v_2^2 \delta p_T \rangle = a_3 - b_3\beta_2^3\cos(3\gamma)$$

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-pT jet suppression in O+O collisions.