INSTITUTO DE ALTA INVESTIGACIÓN

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STAR

Recent highlights from the STAR experiment at RHIC

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PHYSICS IN COLLISION

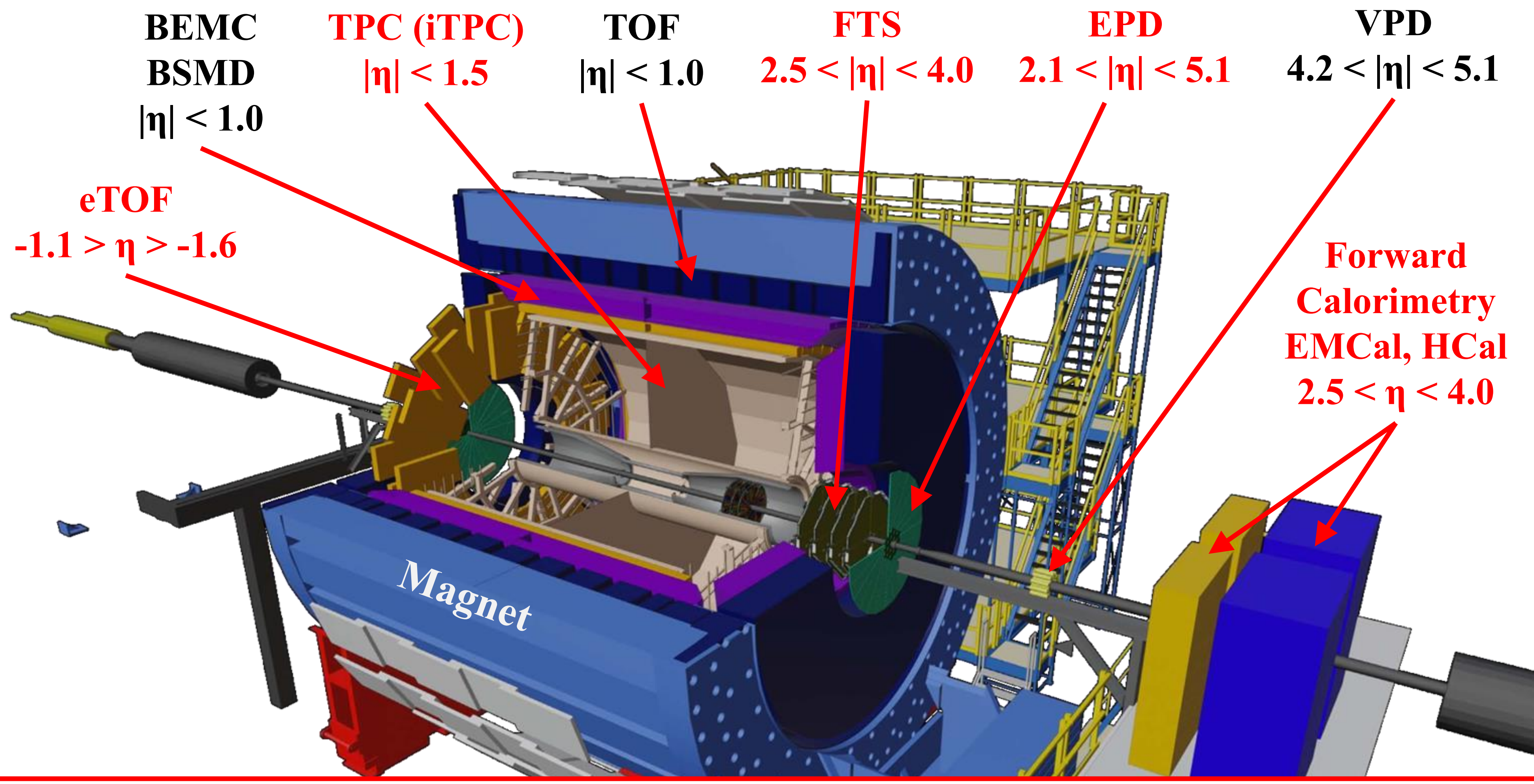
42nd International Conference on Physics in Collision

October 10 – 13, 2023 | Universidad de Tarapacá, Arica, Chile

Outline

- Introduction: STAR Experiment at RHIC
- Motivation
- Collective flow
- Nuclear size and deformation
- Search for the QCD critical point
- Particle Production and Freeze-out properties
- Summary and Outlook

STAR Experiment at RHIC

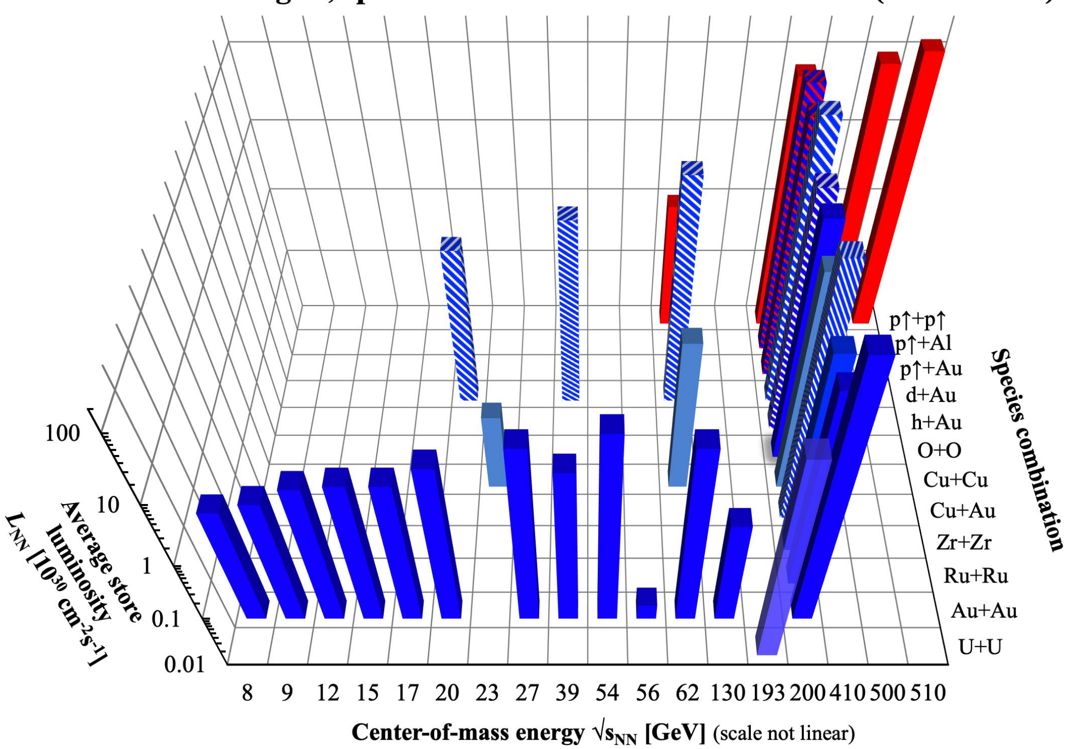


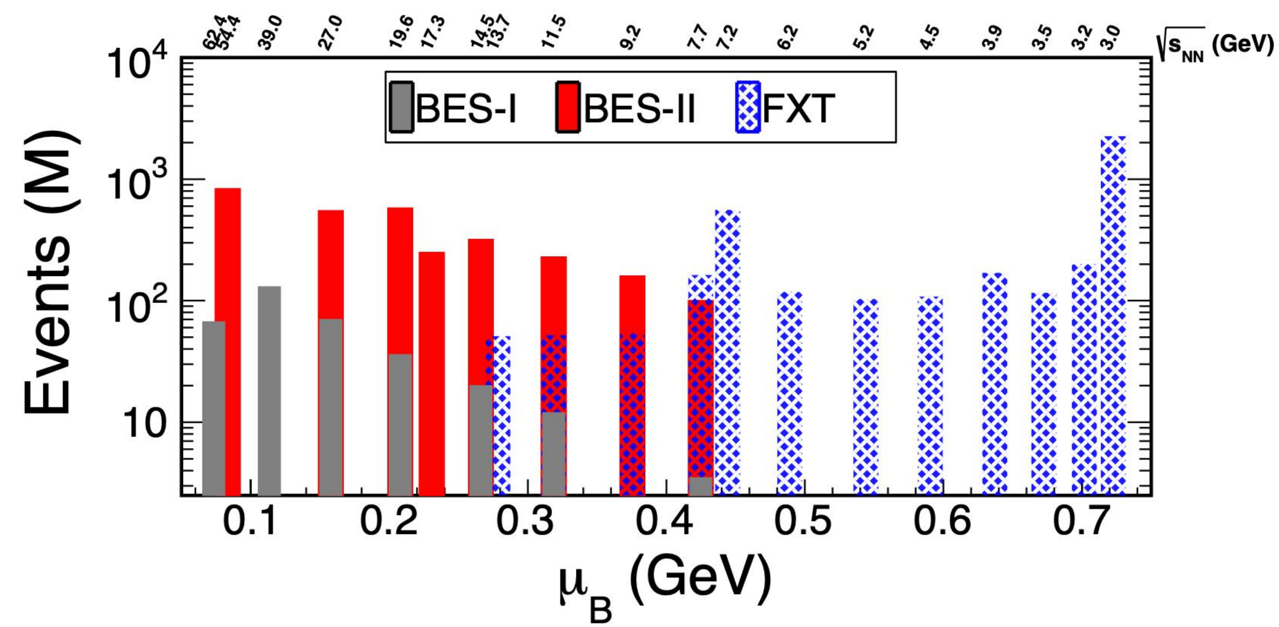
- iTPC: Improved tracking, extended acceptance to $|\eta| < 1.5$, better dE/dx and momentum resolution
- eTOF: Extended PID in the forward region
- EPD: Independent centrality detector, Improved EP resolution, Trigger
- Recent forward upgrades: FCS, FTS, EMcal & HCal

Beam Energies and Colliding Systems at STAR

- Wide range of collision beam energies to explore QCD phase diagram
  - Beam Energy Scan Phase II (BES-II): $\sqrt{s_{NN}}$ = 7.7 – 54.4 GeV
  - Fixed Target (FXT): $\sqrt{s_{NN}}$ = 3.0 – 7.7 GeV
- Different collision species to study the QCD medium at top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV
  - U+U, Au+Au, Ru+Ru, Zr+Zr, Cu+Cu, O+O, Cu+Au, *He*^{3}+Au, *d*+Au, *p*+Au etc
- Increase in statistics over the years for precision measurement

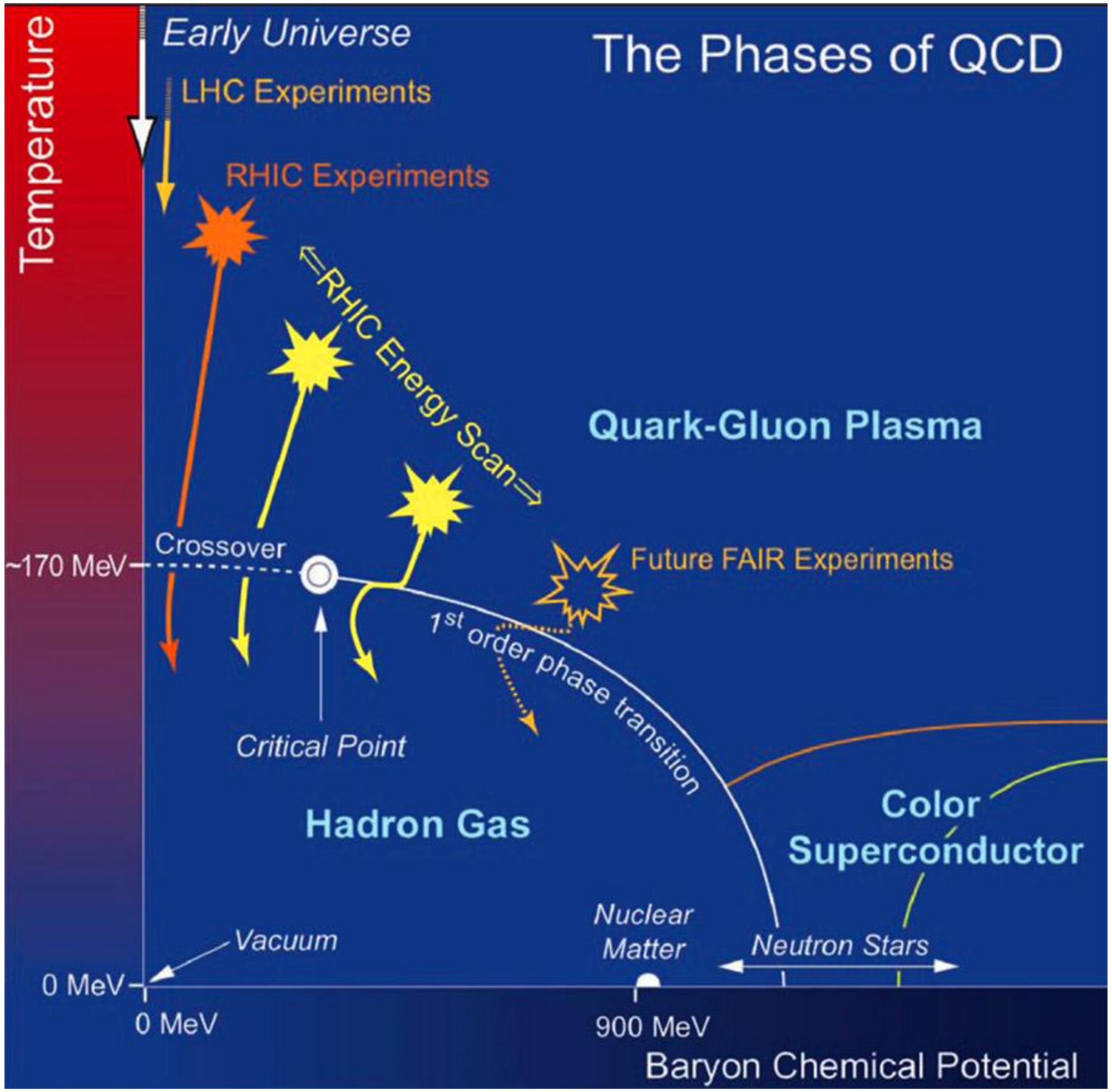
RHIC energies, species combinations and luminosities (Run-1 to 22)





https://www.agsrhichome.bnl.gov/RHIC/Runs/

Exploring phase structure of QCD matter



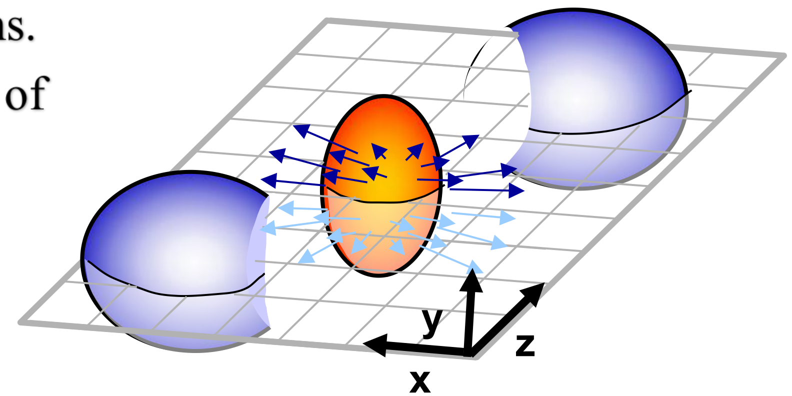
Conjectured QCD Phase diagram

- Explore QCD phase diagram by varying baryon chemical potential and temperature via beam energy scan.
- BES program at RHIC provide an experimental way to study nuclear matter at finite μ_B.
- Properties of the QCD matter can be probed through bulk observables such as collective flow.
- Provide a chance to study phase transition and to locate the critical point by studying fluctuation of conserved quantities.

STAR White Paper II
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Collective Flow

- Collective flow describe the response of the medium produced in heavy-ion collisions.
- Useful to study various characteristics such as the initial state, viscosity, equation of state, fluctuations, and particle production.

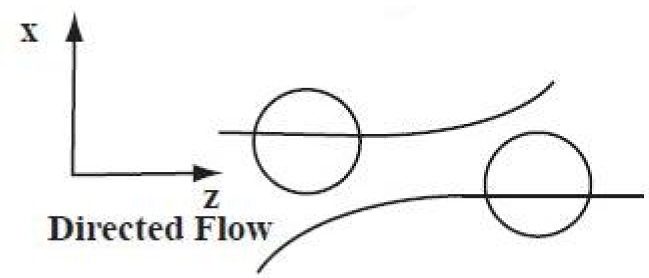


Reaction plane: xz plane

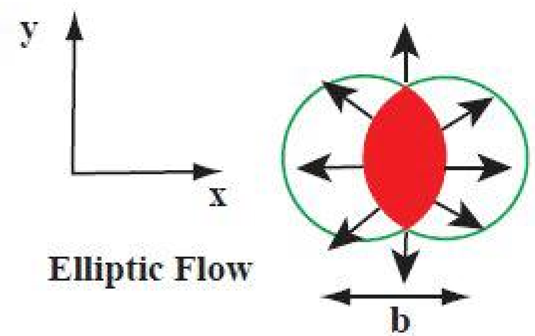
- Collective flow can be measured from the Fourier expansion:

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum 2v_n \cos n(\phi - \Psi_n^{EP})\right)$$

Different flow coefficients are sensitive to the initial state and properties of the medium.



- Directed Flow (v_1): Sideward deflection of produced particles in the reaction plane.
  - → Minimum in v_1 slpoe (dv_1/dy) predicted to be related to softening of EoS.
- Elliptic Flow (v_2): Result of pressure gradients caused by the initial overlap geometry.
  - → Sensitive to viscosity, EoS and initial state.
- Triangular Flow (v_3): Produced by event-by-event fluctuations in the initial shape.
  - → Sensitive to initial state fluctuations.

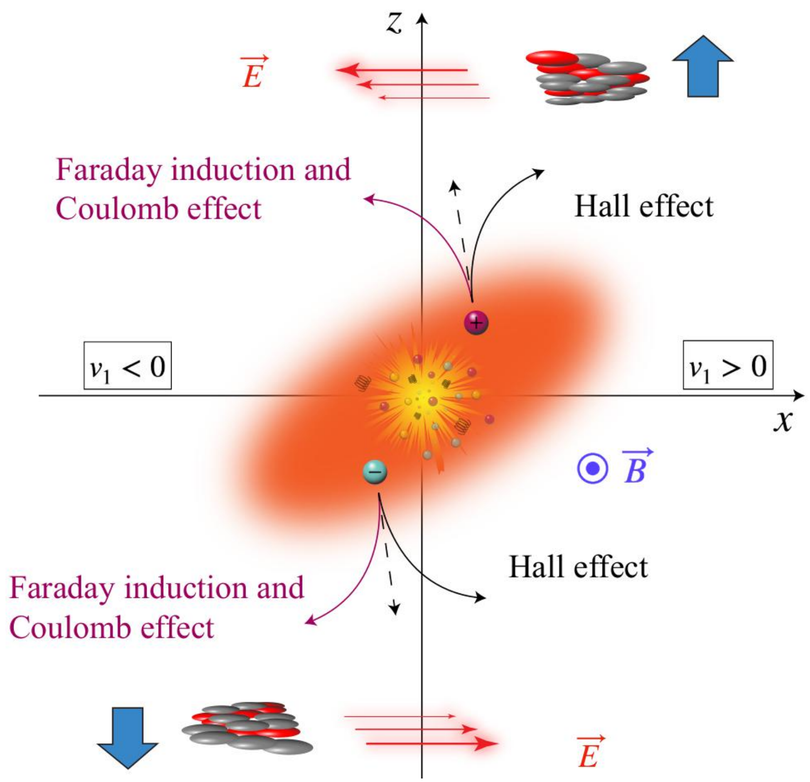


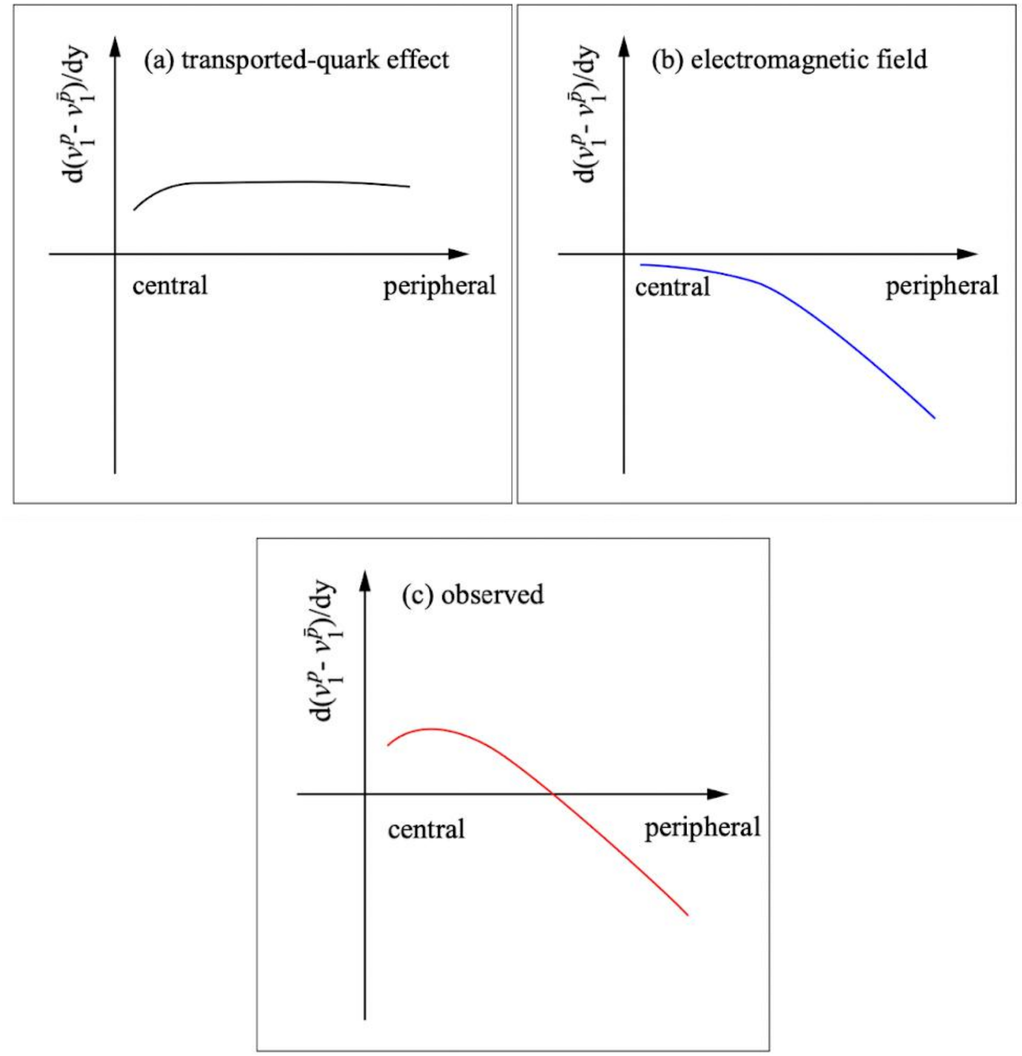
A. M. Poskanzer & S.A. Voloshin, Phys. Rev. C 58 (1998) 1671
S. A. Voloshin, A. M. Poskanzer & R. Snellings, Landolt-Bornstein 23 (2010) 293-333

Directed Flow and EM-Field effects

Quarks experience forces in the medium due to:

- **Hall Effect:** $\vec{F} = q(\vec{v} \times \vec{B})$
- **Coulomb Effect** ($\vec{E}$ generated by spectators) and
- **Faraday Induction** ($\vec{E}$ generated by decreasing magnetic field)



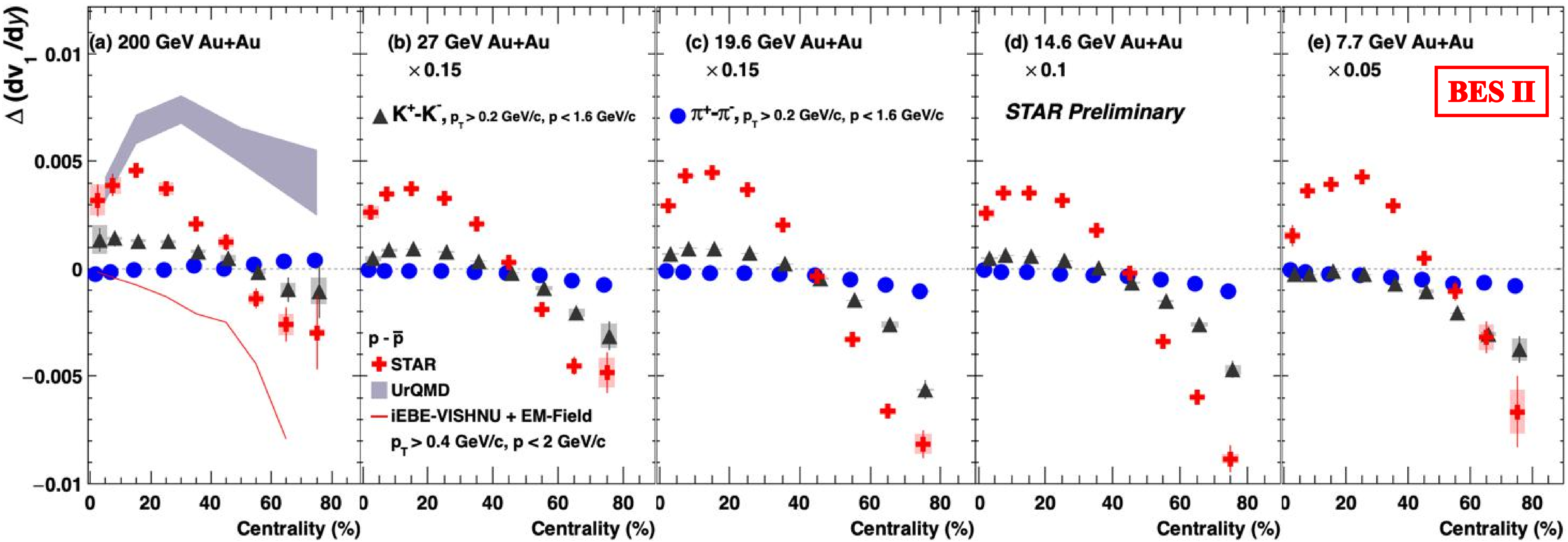


- Theory predict positive $\Delta dv_1/dy$ from transported quarks and negative $\Delta dv_1/dy$ from electromagnetic fields in QGP.

U. Gursoy el. al. Phys. Rev. C 98, 055201 (2018); Phys. Rev. C 89, 054905 (2014)

STAR, arXiv:2304.03430

Directed Flow and EM-Field effects

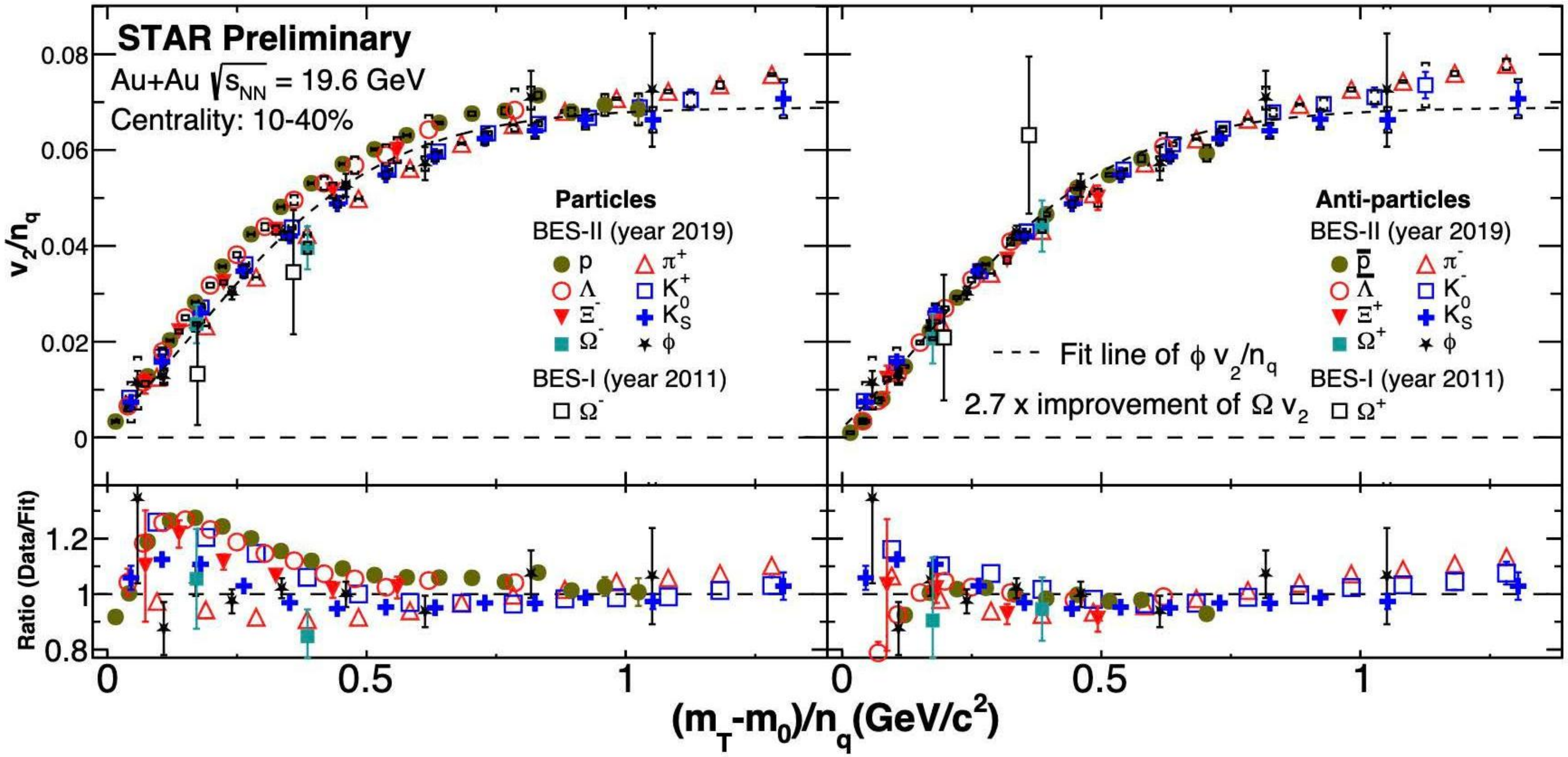


- Negative $\Delta(dv1/dy)$ in peripheral collisions consistent with expectation from electromagnetic field effects.
  → Dominance of Faraday + Coulomb effect in peripheral collisions
- Other explanations, e.g. contributions from hadronic meanfield interactions, are being investigated.
- Positive $\Delta(dv1/dy)$ for protons in (mid)central collisions shows transported quark effect.

STAR, arXiv:2304.03430

Elliptic Flow and Partonic Collectivity

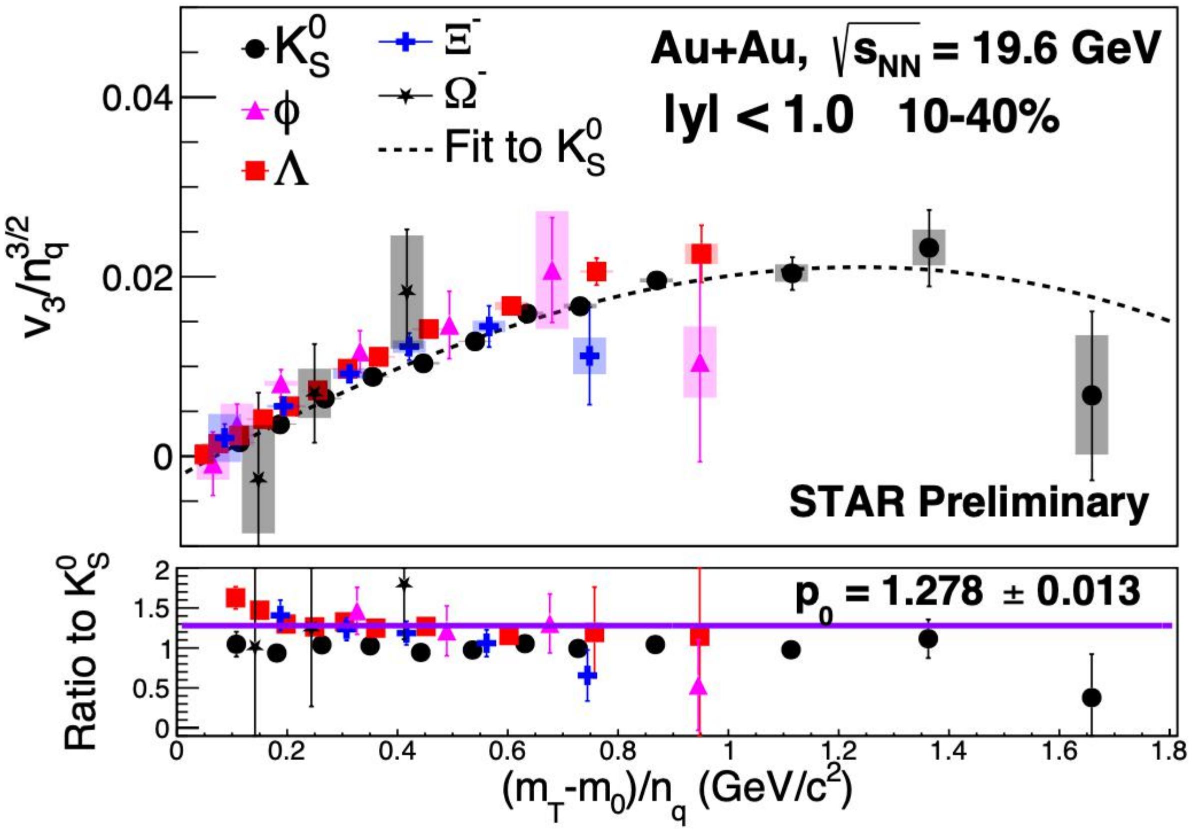
BES II

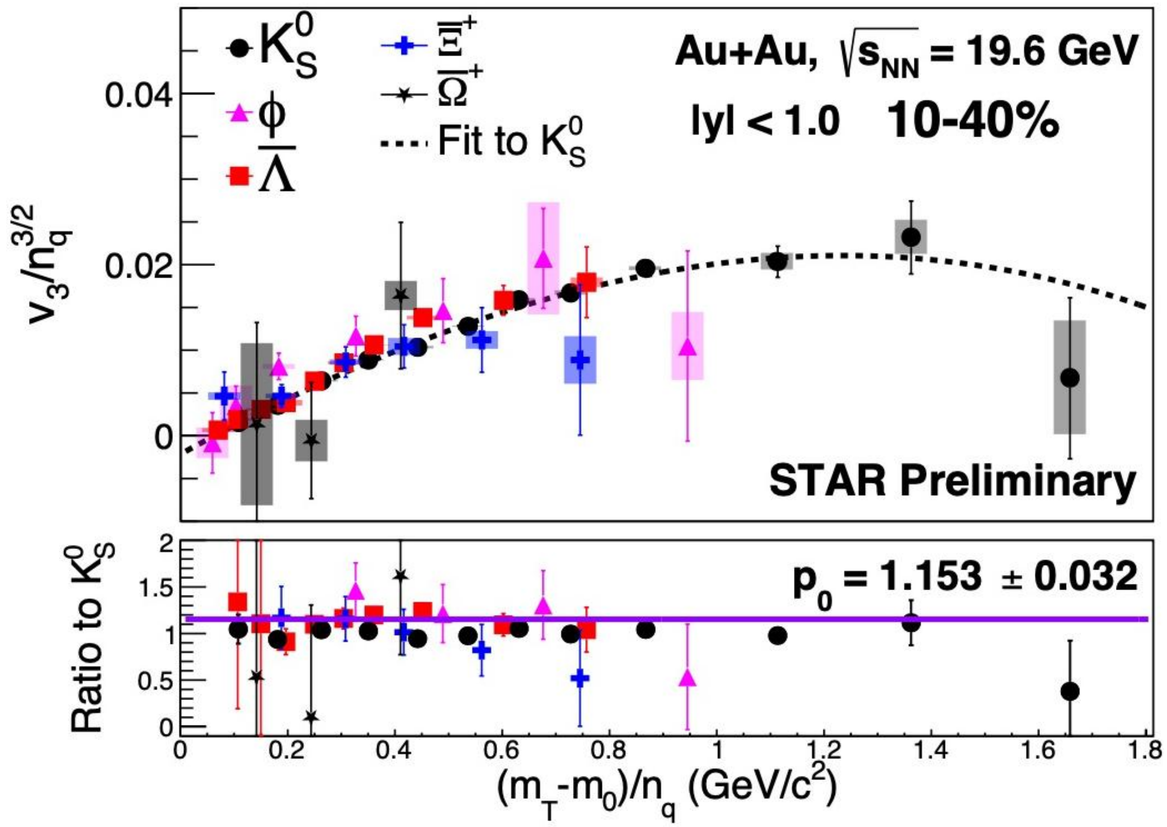


- BES-II improved statistical significance of flow measurements by a factor of ~3.
- NCQ scaling of v_2 holds better for anti-particles (~10%) than the particles (~20%).
- Observation of NCQ scaling of identified hadron v_2
  → Indicate partontic collecitivity

Triangular Flow (v_3)

BES II



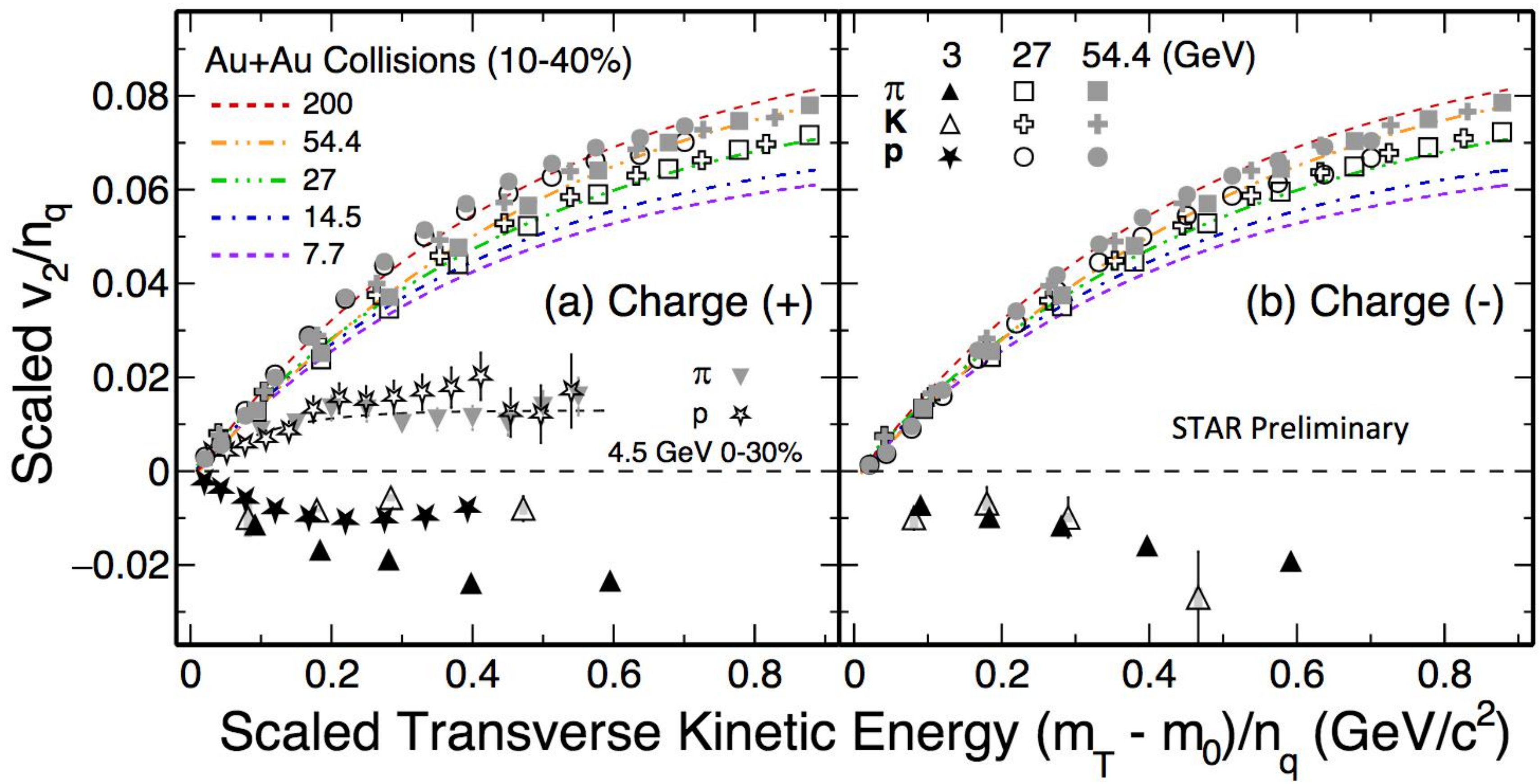


- Strange and multi-strange v_3 studied systematically in Au+Au collisions at BES-II energy $\sqrt{s_{NN}}$ = 19.6 GeV.
- NCQ scaling of v_3 holds better for anti-particles (~15%) than the particles (~30%).
- Observation of NCQ scaling of identified hadron v_2

  → Indicate partontic collecitivity

Disappearance of Partonic Collectivity

FXT & BES II

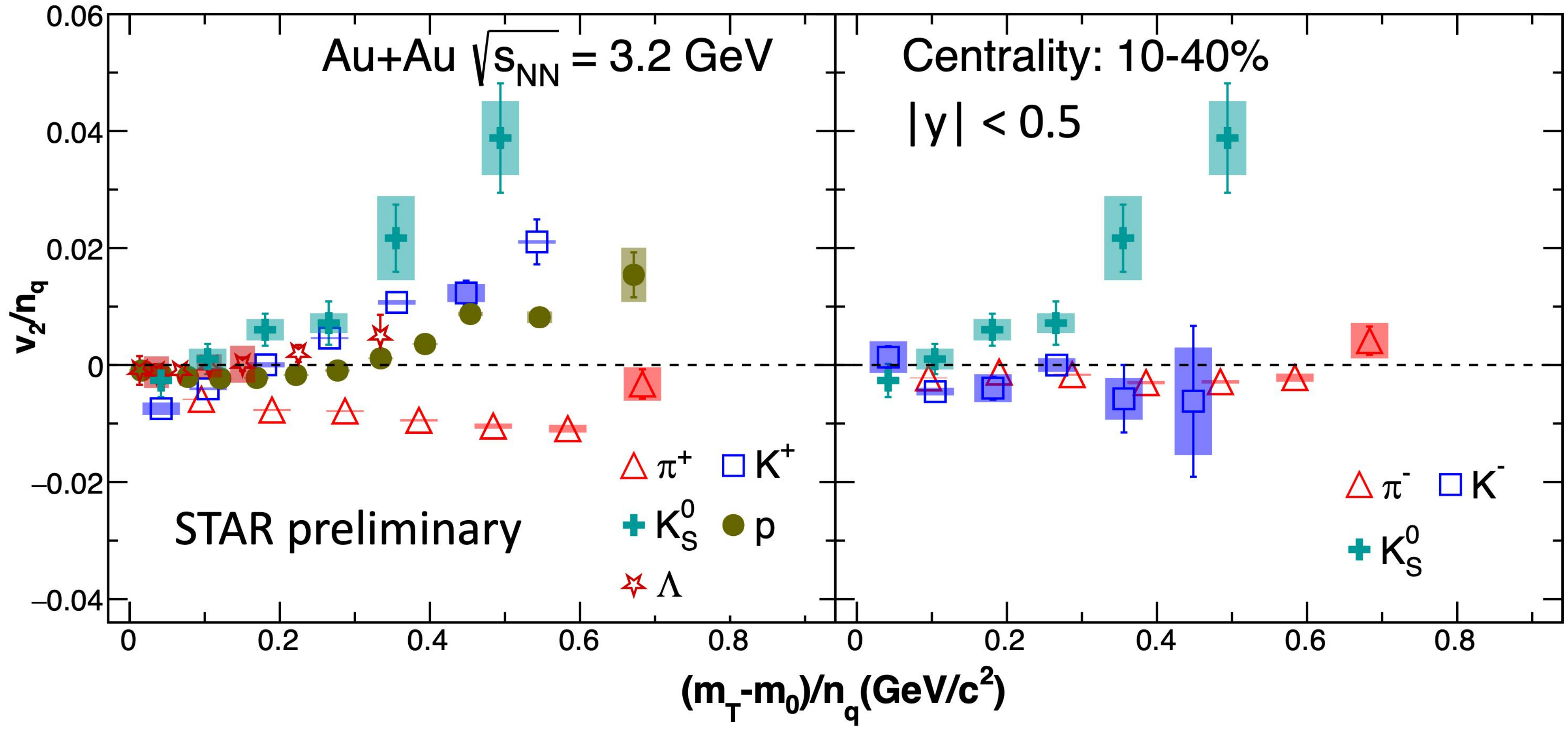


STAR: Phys. Rev. C 88, 014902 (2013)
STAR: Phys. Rev. C.103, 034908 (2021)
STAR: Phys. Lett. B 827, 137003, (2021)

- NCQ scaling holds in Au+Au collisions from top RHIC energy $\sqrt{s_{NN}}$ = 200 to 4.5 GeV
  → Partonic collectivity
- Negative v_2 values and breaking of NCQ scaling at $\sqrt{s_{NN}}$ = 3 and 3.2 GeV.
  → Indicative of medium dominated by hadronic interactions

Disappearance of Partonic Collectivity

FXT & BES II



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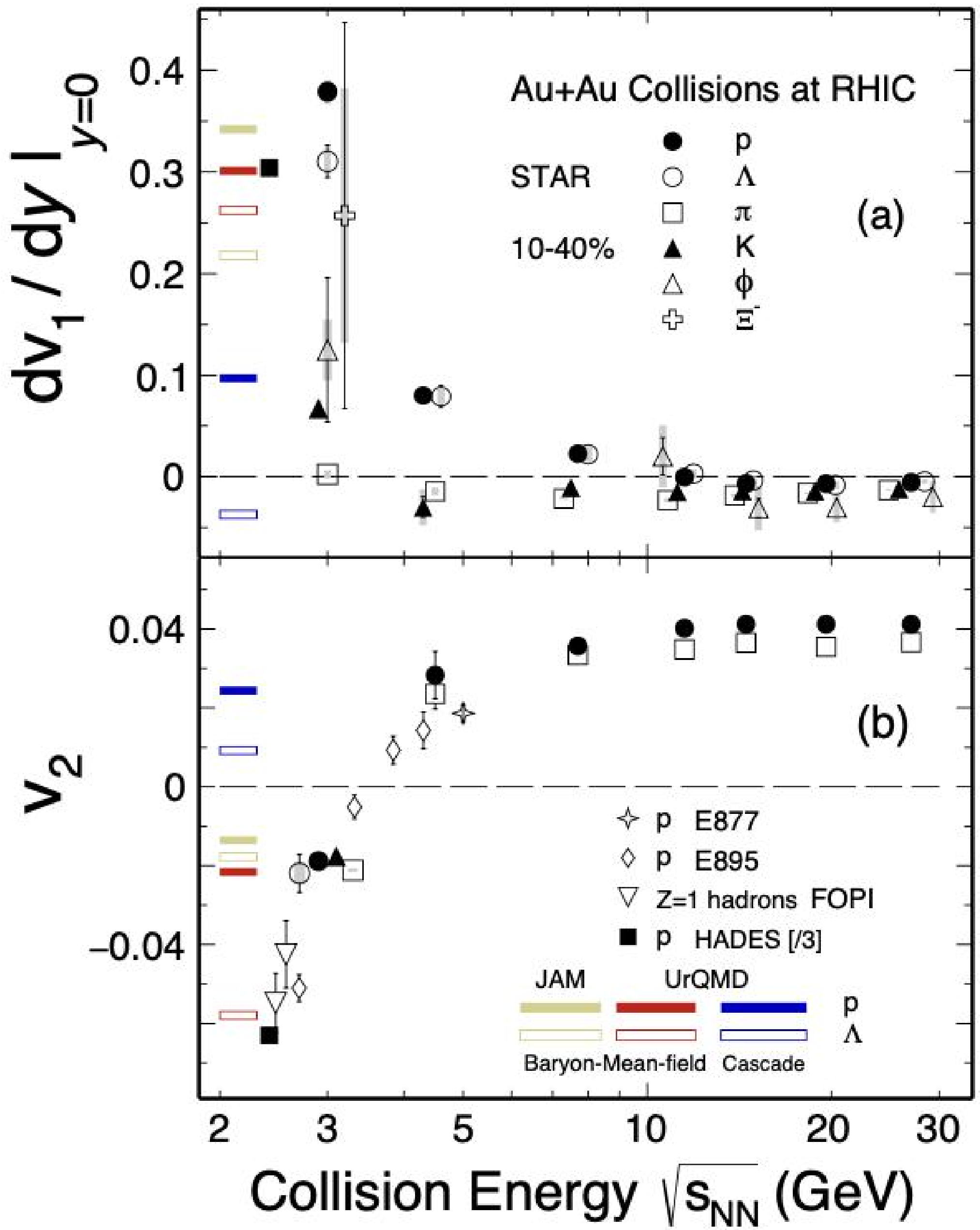
Beam Energy Dependence



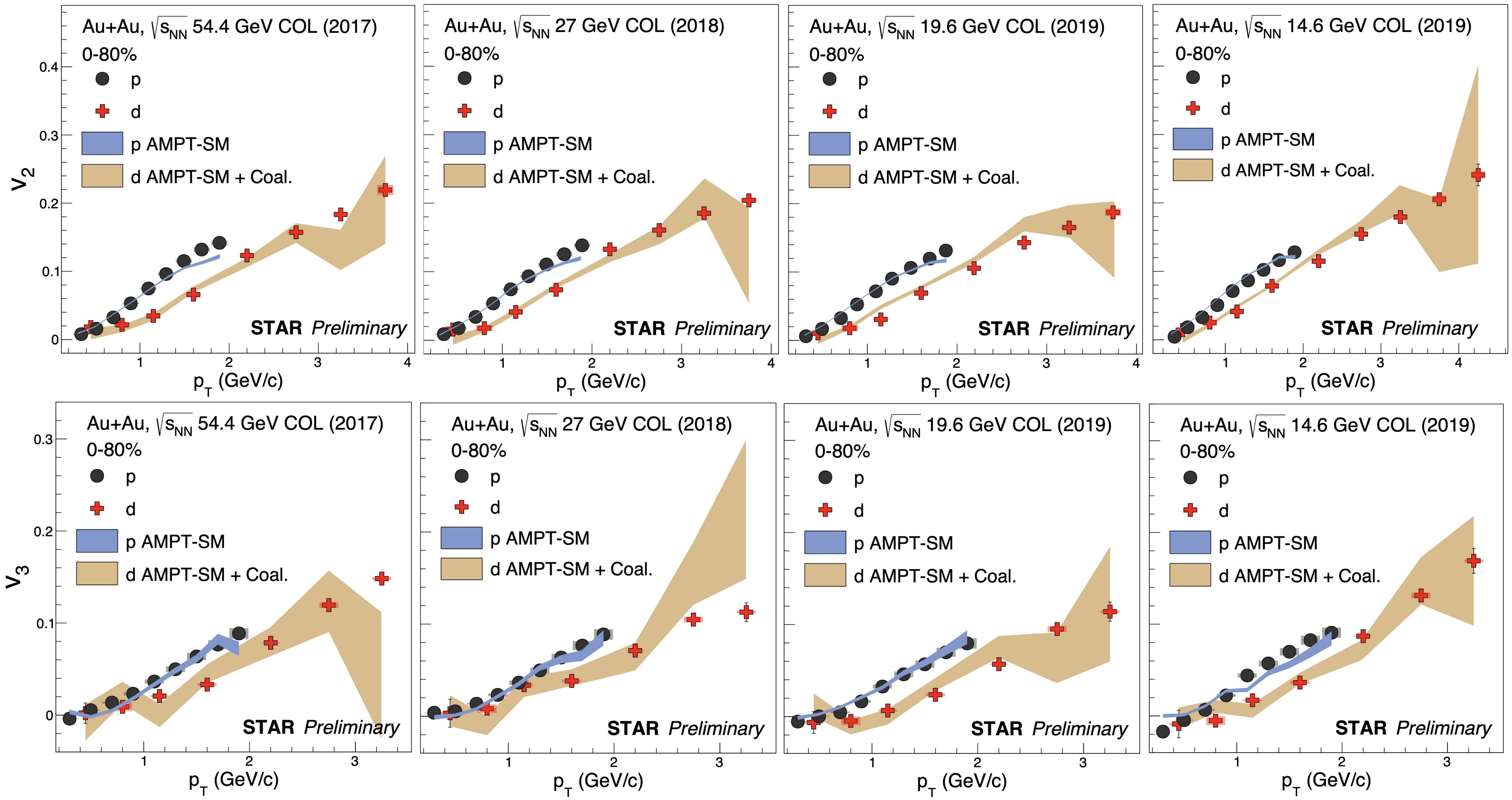
- Negative v_1 slope and large positive v_2 in Au+Au collisions at high beam energies.
- Positive v_1 slope and negative v_2 for all measured particles in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV.
- hadronic transport model JAM and UrQMD with baryonic mean-field interactions qualitatively describe the data.

  → EoS dominated by baryonic interactions at 3 GeV

E877: Phys. Rev. C 56, 3254-3264
E895: Phys. Rev. Lett.85, 940
FOPI: Phys. Lett. B 612, 173
STAR: Phys. Lett. B 827, 137003, (2021)

Light nuclei collectivity

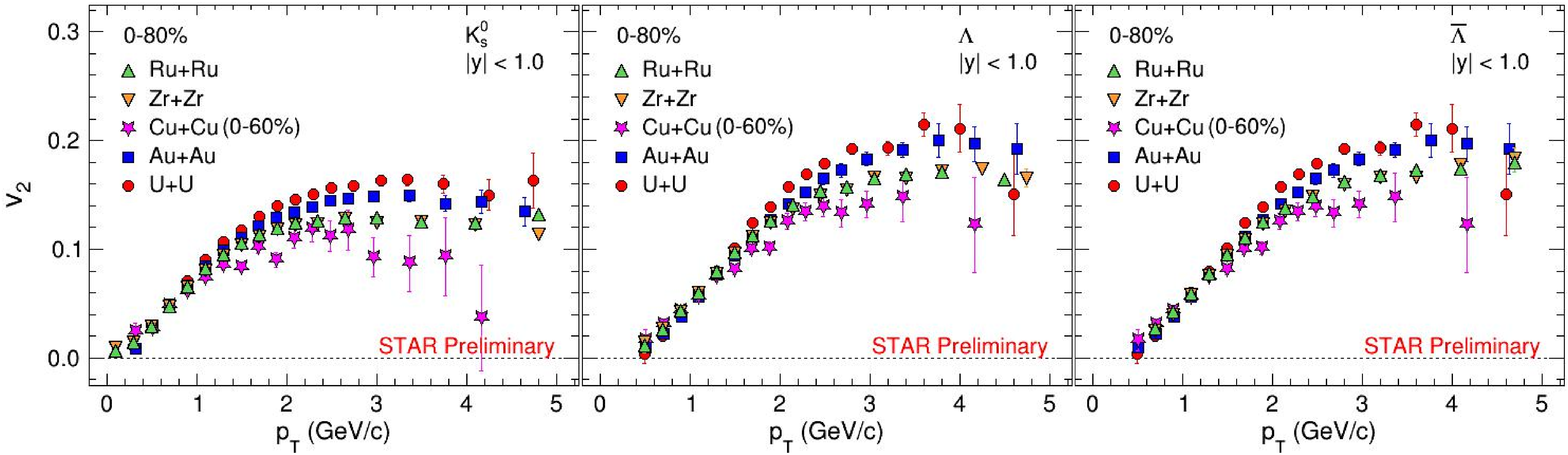
BES II



- AMPT(SM) model with coalescence describes deuteron v_2 and v_3
  → Insights to light nuclei production mechanism in heavy-ion collisions

Phys. Rev. C 72, 064901 (2005); Phys. Rev. C 93, 014907 (2016); Phys. Rev. C 88, 014902 (2013); Phys. Lett. B 827, 137003 (2022)

Nuclear Size and Deformation

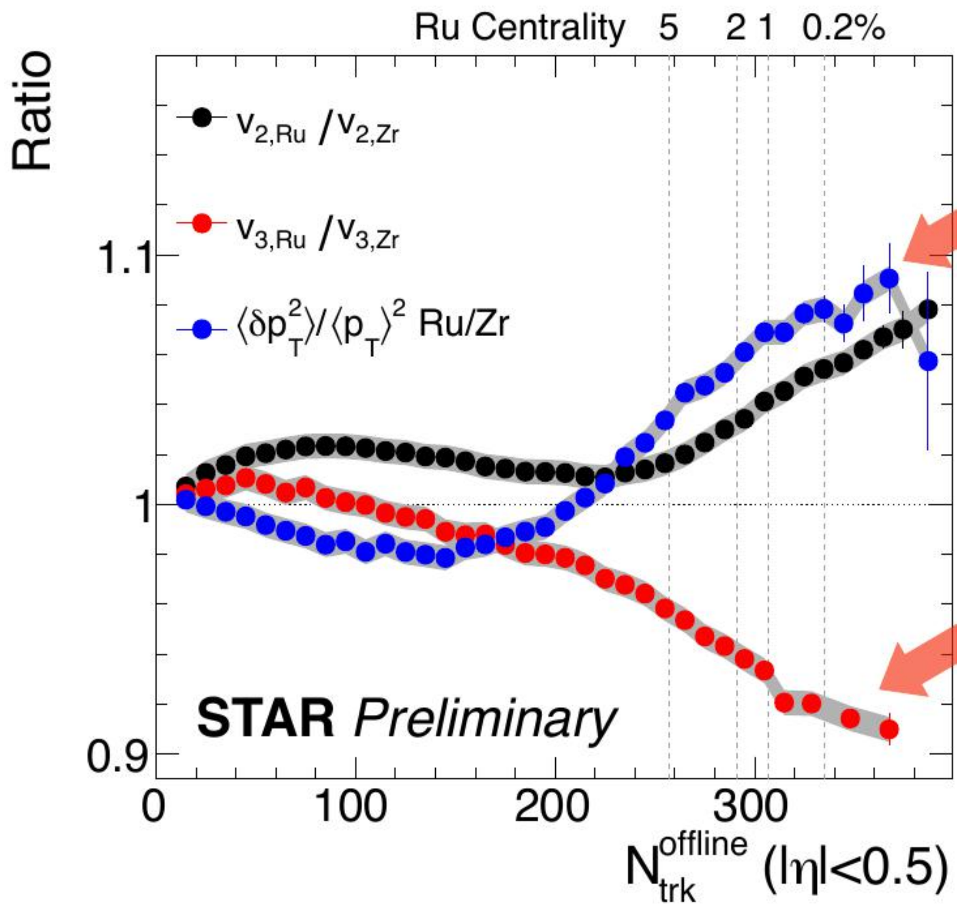


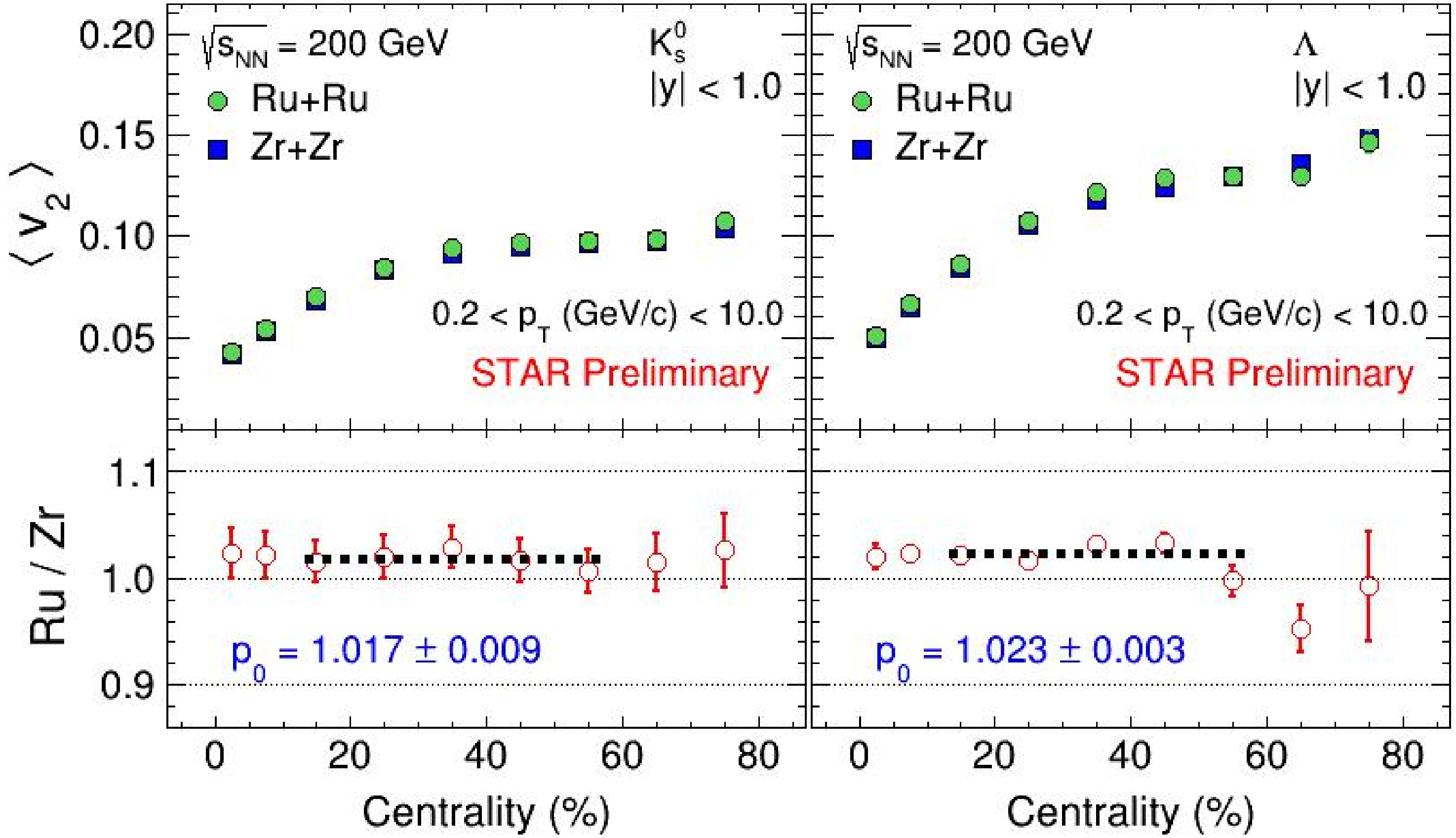
- Elliptic flow at high p_T increasases with atomic mass number of nuclei.

→ Indicating a nuclear size dependence

STAR: Phys. Rev. C 77 (2008) 054901
STAR: Phys. Rev. C 81 (2010) 044902
STAR: Phys. Rev. C 103 (2021) 064907

Nuclear Size and Deformation

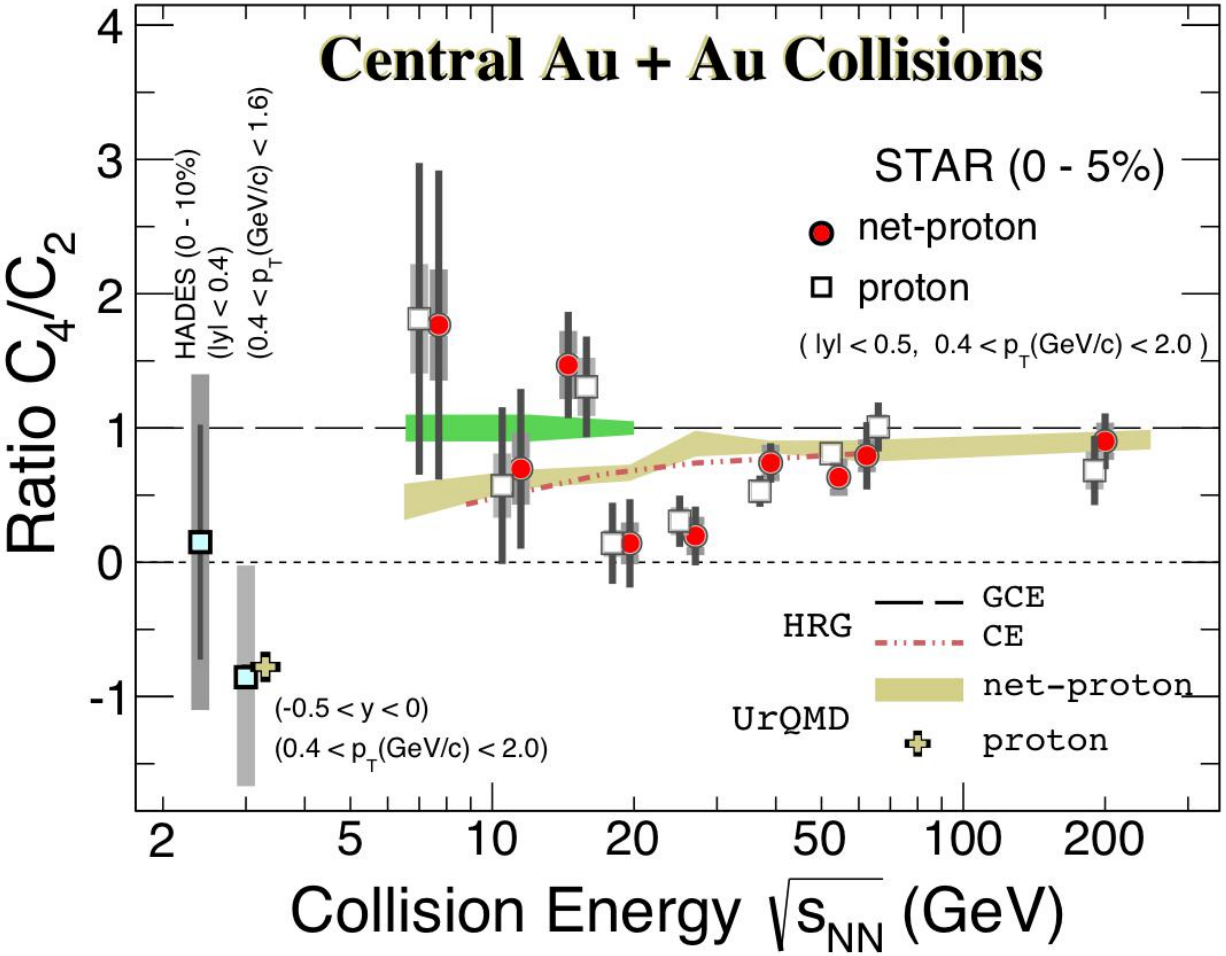




- Ratio of integrated v_2 between Ru+Ru and Zr+Zr collisions differs from unity

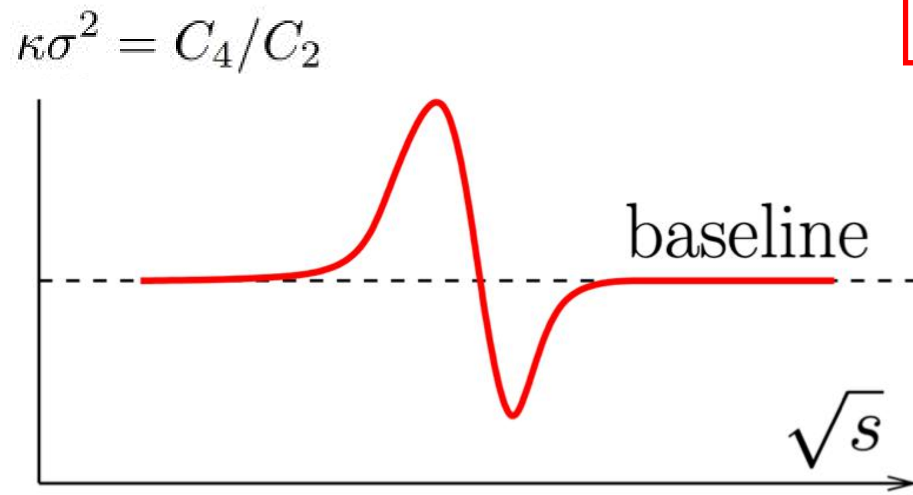
  → Indication of larger quadruple deformity in Ru nuclei than in the Zr nuclei

Search for QCD Critical Point



Projected BES-II statistical uncertainty

BES II

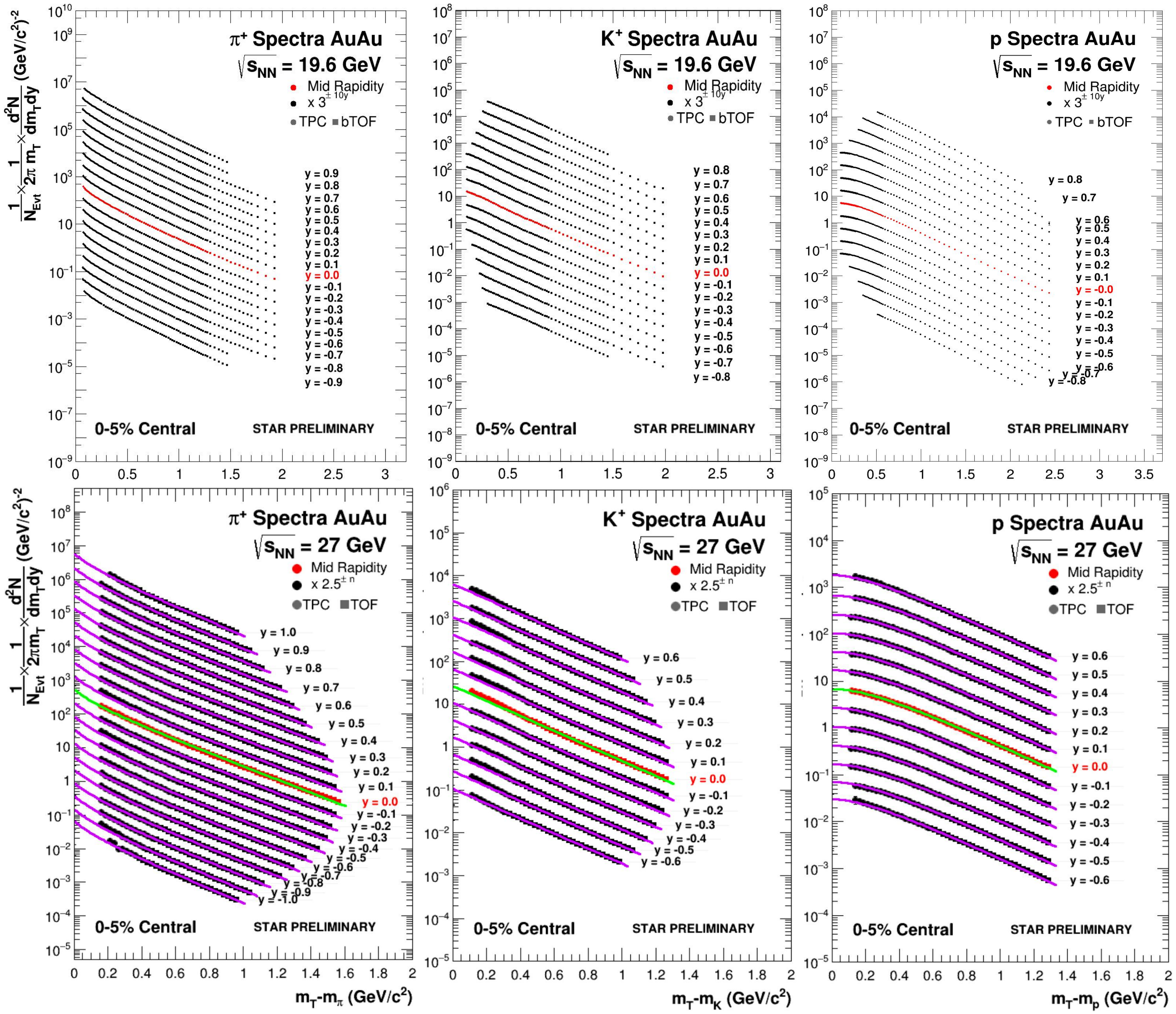


- Non-monotonic behavior of C_4/C_2 for proton and net-proton with $\sqrt{s_{NN}}$ with 3.1σ significance.
  → BES-II will significantly improve the precision
- BES-II: negative C_4/C_2 at $\sqrt{s_{NN}}$ = 3 GeV, consistent with UrQMD model calculation
  → Hadronic interaction dominates

STAR: Phys. Rev. Lett. 128, 202303 (2022)

M. Stephanov, J. Phys. G: Nucl. Part. Phys. 38, 124147 (2011)

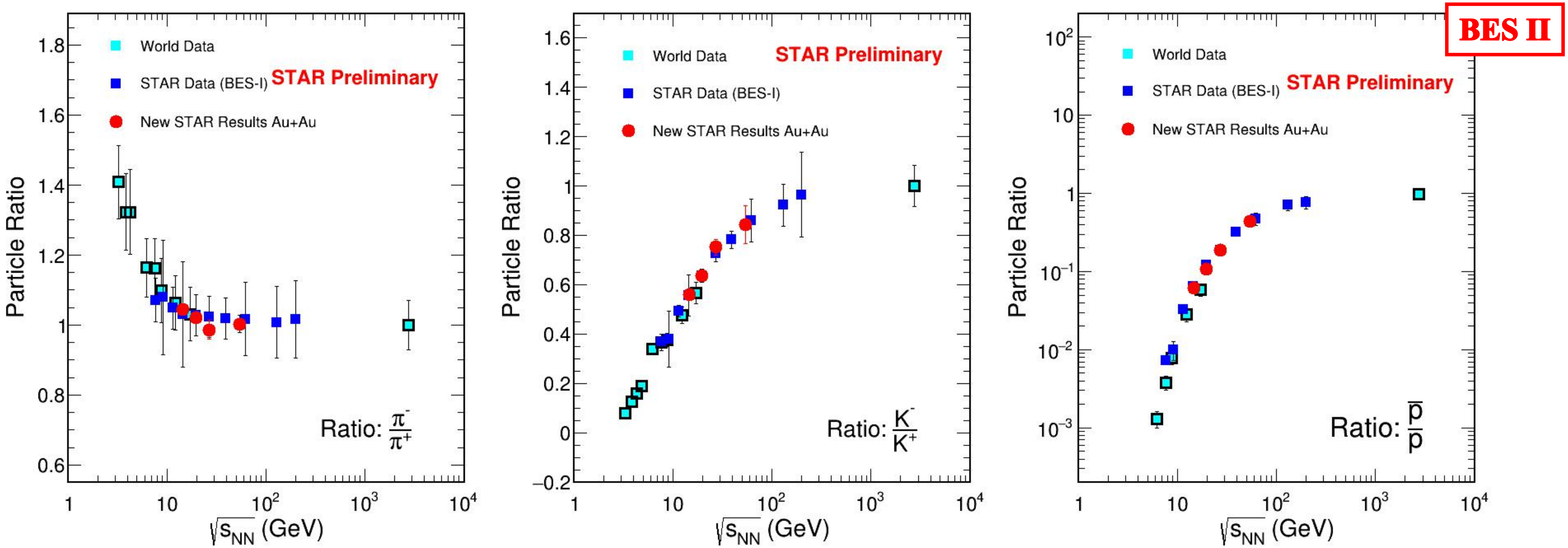
Particle Production



BES II

- Measured π, K, and p spectra across p_T and rapidity at BES-II energies.

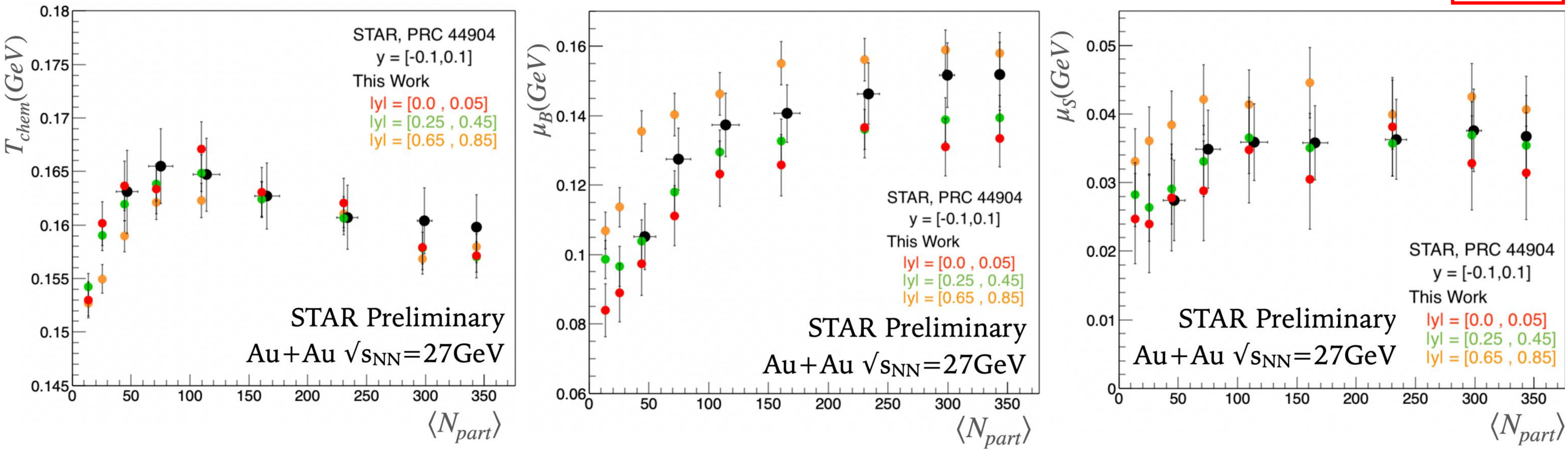
Particle Ratios



- π^-/π^+ ratio more than one shows π- excess at low energies, could due to delta resonance
  → Indicate neutron rich initial condition
- K^-/K^+ below one at lower energies shows associated K+ production dominates over pair production
  → Indicates non-zero μ_S
- p-bar/p ratio lower than one at low beam energies relates to baryon chemical potential μ_B
  → Indicates increase in baryon stopping towards low beam energies

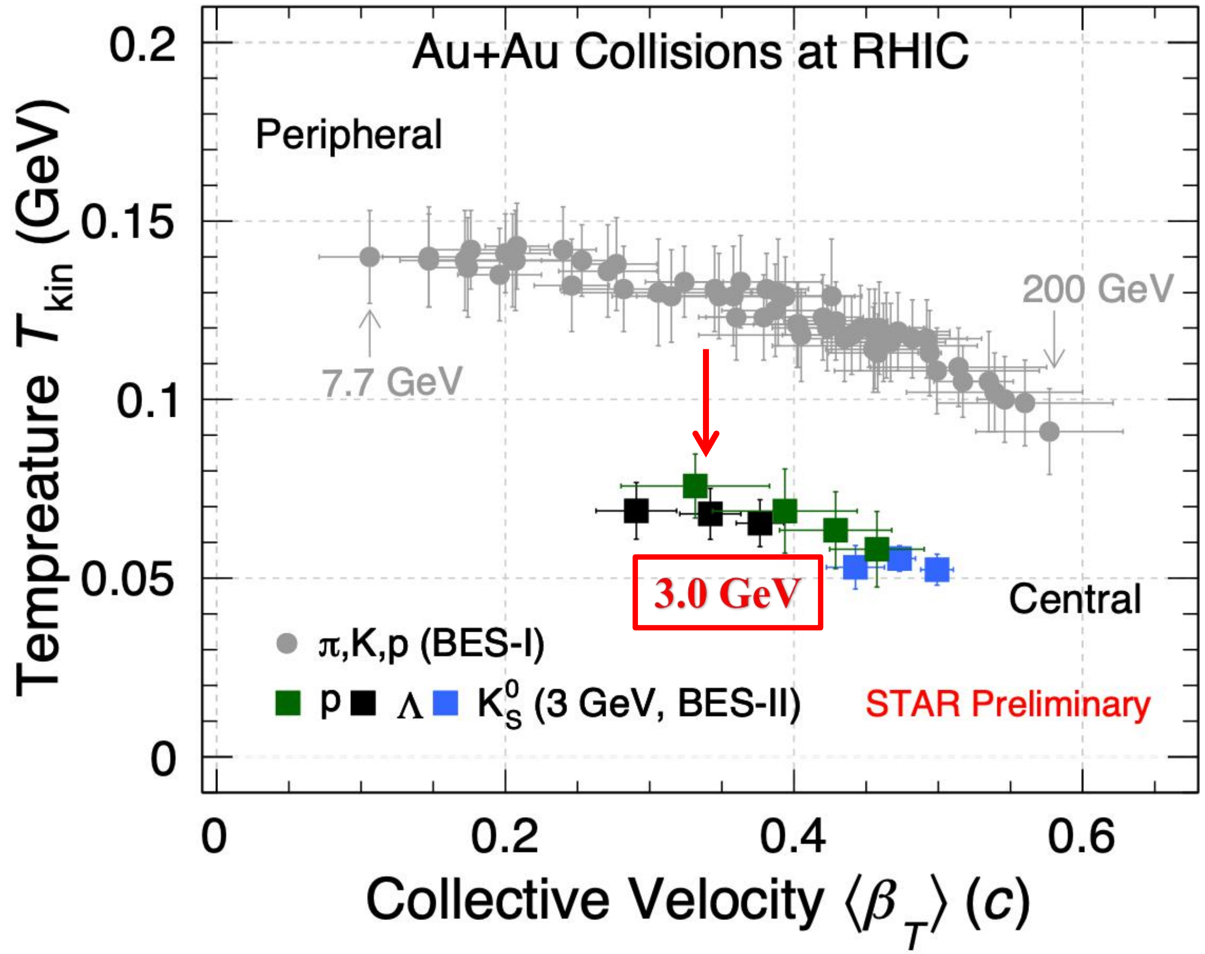
Freeze-out Properties

BES II



- Chemical freeze-out temperature (T_{chem}), baryon chemical potential (μ_B) and strangeness chemical potential (μ_s) from THERMUS chemical equilibrium model at $\sqrt{s_{NN}}$ = 27 GeV.

Freeze-out Properties



- Different kinetic freeze-out temperature and collective velocity at $\sqrt{s_{NN}}$ = 3 GeV
  → Indicate different EoS, dominated by baryonic interactions

STAR: Phys. Rev. C 96, 044904 (2017)

Summary & Outlook

Electromagnetic field effects in HIC

- Charge dependent v_1 results indicate dominance of Faraday + Coulomb effect in peripheral collisions.

Partonic collectivity

- NCQ scaling indicates partontic collecitivity at energies $\sqrt{s_{NN}}$ >= 4.5 GeV.
- Absence of NCQ scaling at $\sqrt{s_{NN}}$ = 3 and 3.2 GeV indicate baryonic interactions dominating nulcear EoS.

Light nuclei collectivity

- Indiacates coalescence to be the dominant mechanism of light nuclei production in heavy-ion collisions.

Nuclear size and deformation

- Elliptic flow at high p_T incresases with atomic mass number of nuclei indicating nuclear size dependence.
- Ratio of v_2 between isobar collisions provide access to nuclei deformation.

QCD critical point

- Non-monotonic behavior in higher order susceptibilities ratios could be a possible QCD critical point signature. BES-II will significantly improve results.

Particle production

- Measured identified hadron spectra across p_T and rapidity at BES-II energies with improved statistics and precision.
- Different kinetic freeze-out temperature and collective velocity at $\sqrt{s_{NN}}$ = 3 GeV compared to higher beam energies.

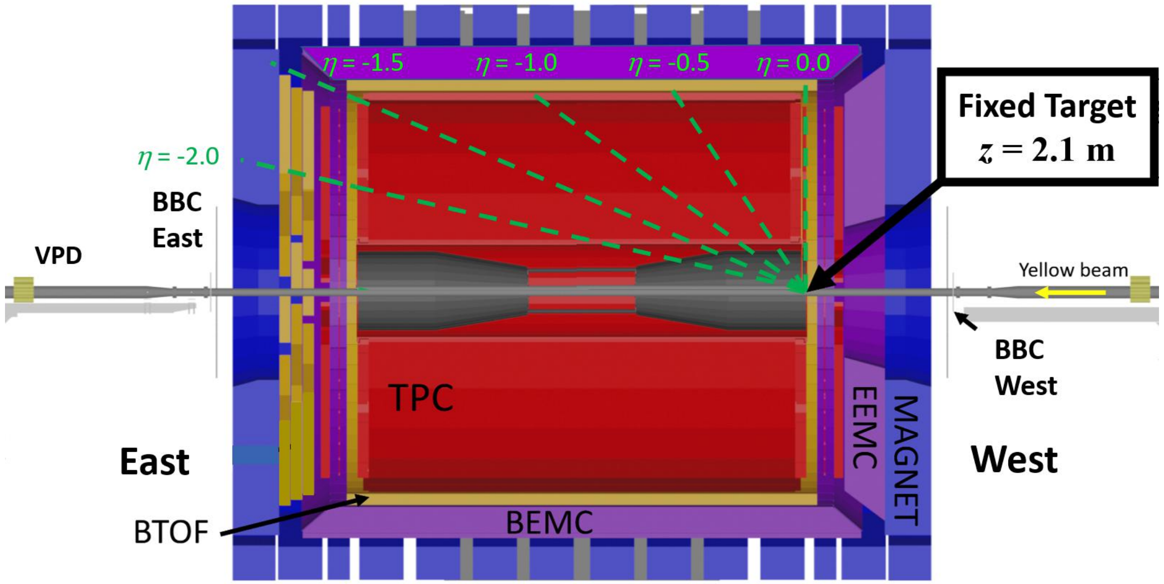
BES-II and FXT measurements on critical fluctuations, femtoscopy, flow are ongoing.

More exciting results to come from the high statistics data at STAR....

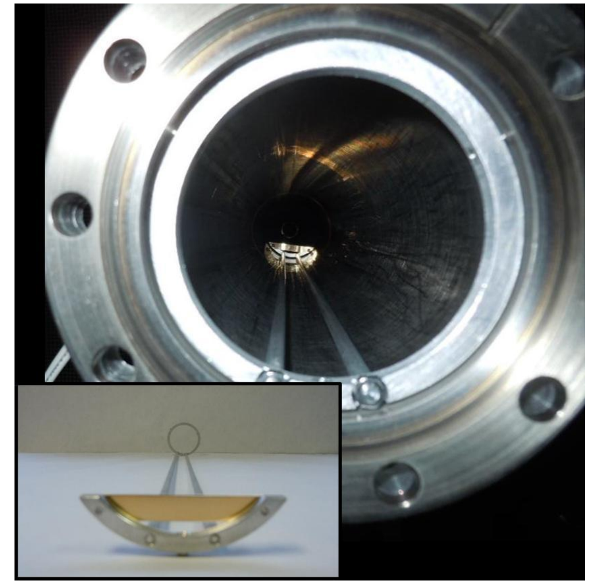
Thank you for your attention!

Backup

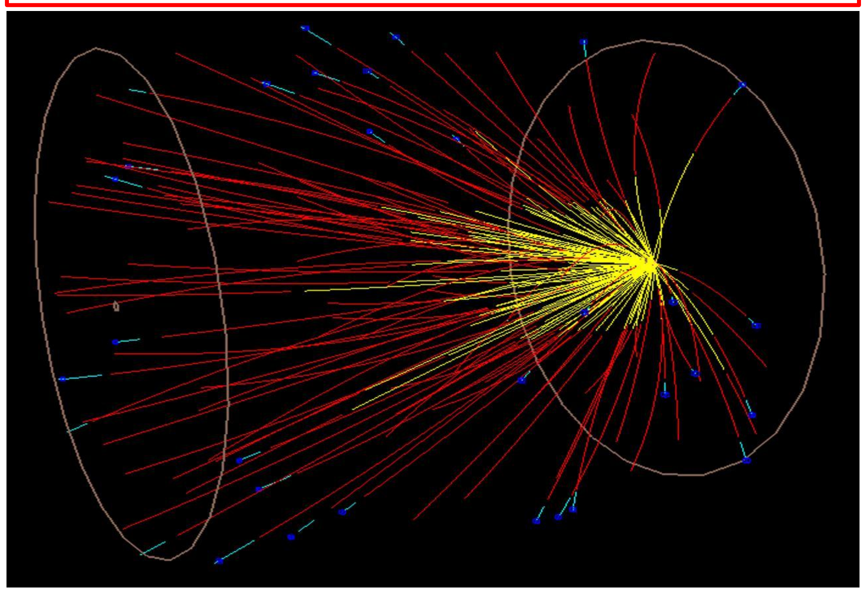
STAR Fixed Target (FXT) Setup



Gold target:
- **2 cm below nominal beam axis**
- **2.1 m from center of STAR**
- **0.25 mm foil**



Au+Au at $\sqrt{s_{NN}}$ = 4.5 GeV event

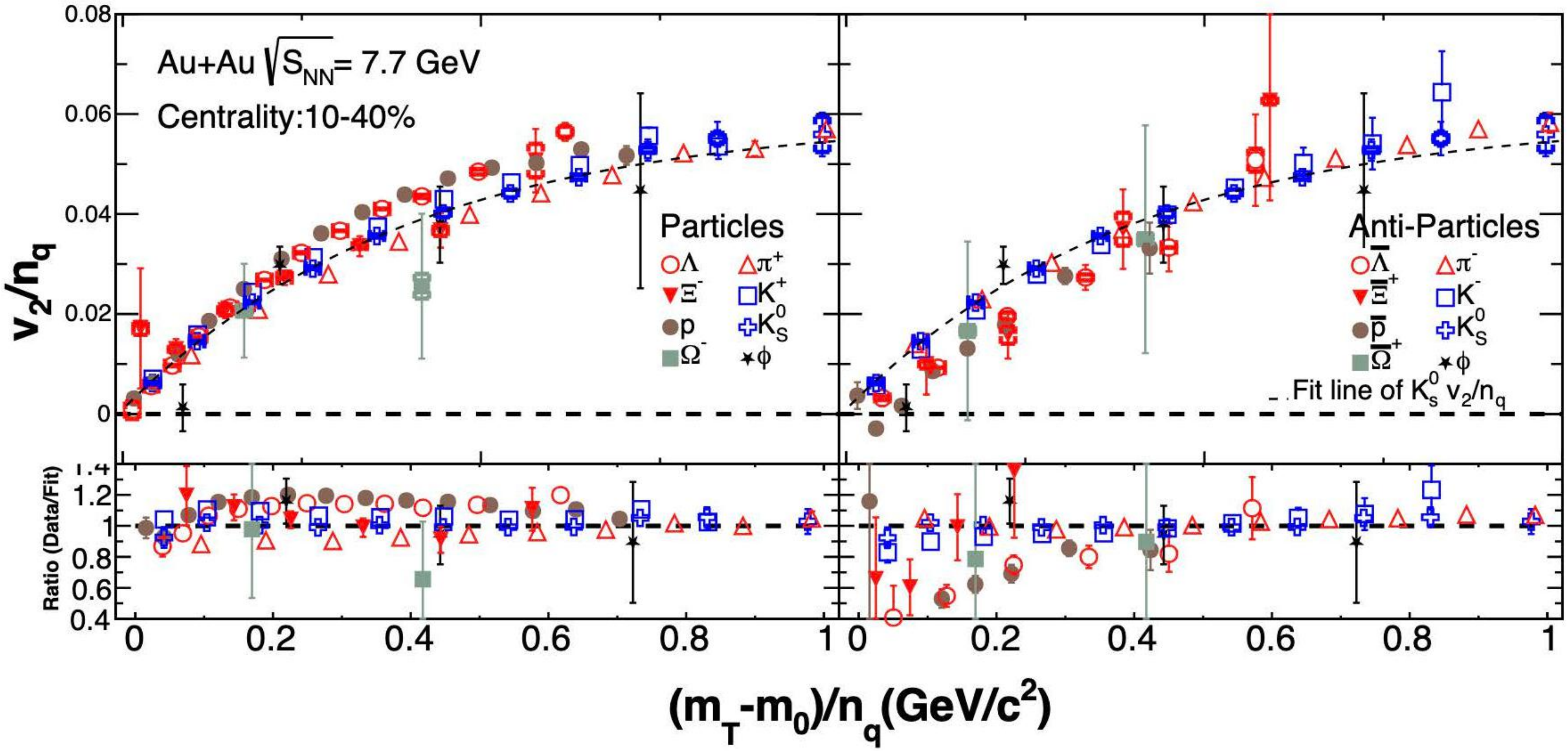


Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18
3.85	**3.0 (FXT)**	**721**	**13.7 days**	**(1.7 B)**	**Run-21**

STAR: Phys. Rev. C 103, 034908 (2021)

Elliptic Flow and Partonic Collectivity

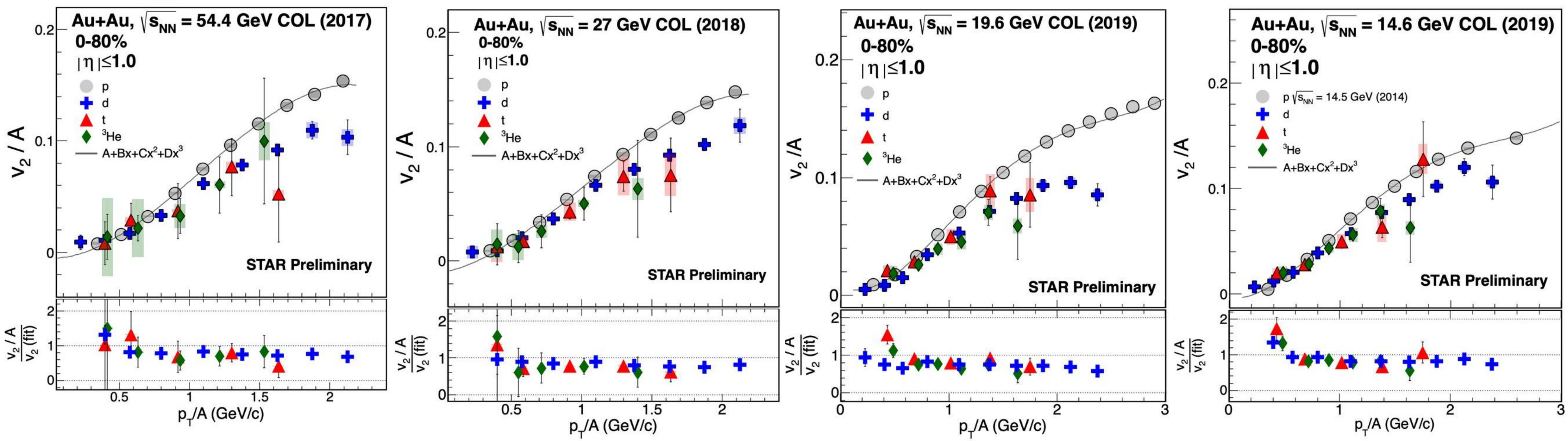
BES II



- Strange and multi-strange v_2 studied systematically in Au+Au collisions at lowest BES-II energy $\sqrt{s_{NN}} = 7.7$ GeV.
- NCQ scaling of v_2 holds better for anti-particles (~10%) than the particles (~20%).
- Observation of NCQ scaling of identified hadron v_2
  → Indicate partontic collecitivity

Light nuclei collectivity

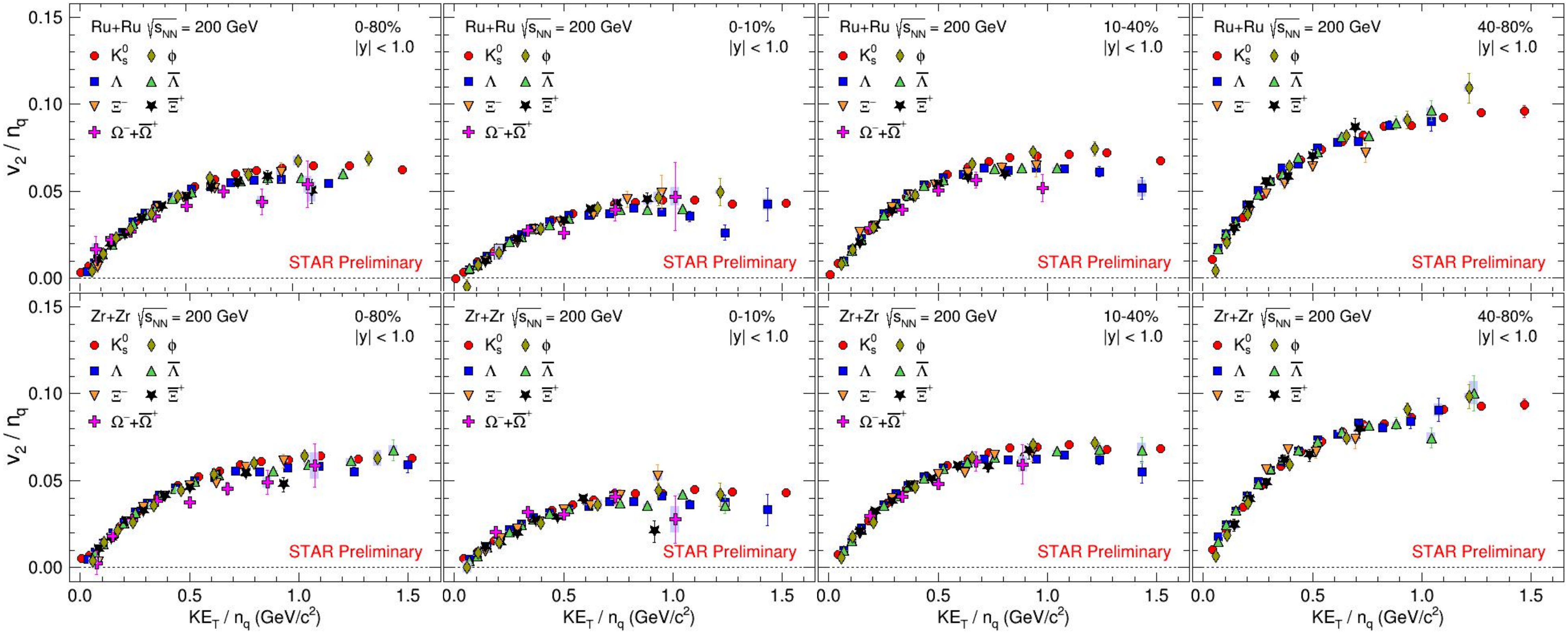
BES II



- Light nuclei v_2 obey mass number scaling at ~30% level in BES energies

Phys. Rev. C 72, 064901 (2005); Phys. Rev. C 93, 014907 (2016); Phys. Rev. C 88, 014902 (2013); Phys. Lett. B 827, 137003 (2022)
Nucl. Phys. A 729 (2003) 809–834

NCQ Scaling in Isobar Collisions



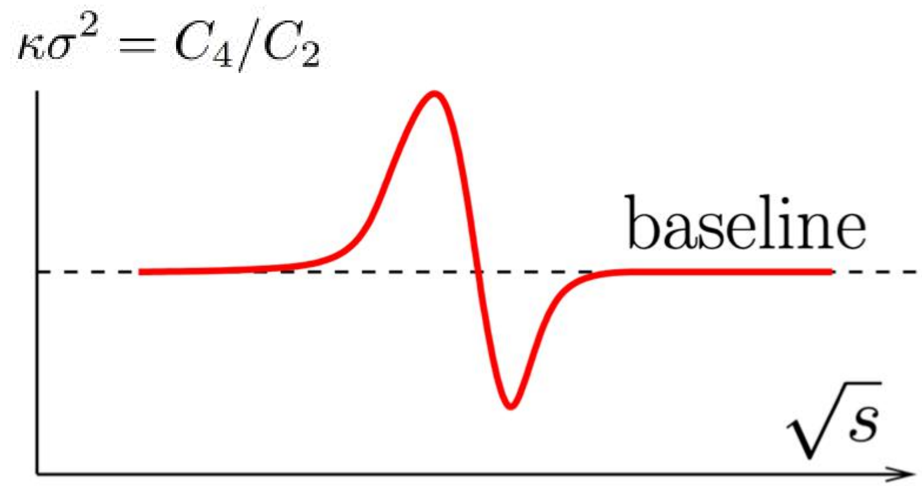
n_q = Number of constituent quarks (3 for baryons and 2 for mesons); Transverse kinetic energy (KE_T) = $m_T - m_0$

- NCQ scaling hold good to ±10% within uncertainties in both Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV.
- Elliptic flow (v_2) scaled by number of constituent quarks falling on a universal curve, indicating partonic collectivity.

Cumulants and Central Moments

Cumulants C_n and the central moments are defined as:

$$\begin{aligned}
\text{mean} : \mathrm{M} = \langle N \rangle &= C_1, \\
\text{variance} : \sigma^2 = \langle (\delta N)^2 \rangle &= C_2, \\
\text{skewness} : \mathrm{S} = \langle (\delta N)^3 \rangle / \sigma^3 &= C_3 / C_2^{3/2}, \\
\text{kurtosis} : \kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 &= C_4 / C_2^2.
\end{aligned}$$



Ratios of the Cumulants and their relation with susceptibility:

- $C_2/C_1 = \sigma^2/M = \chi2/\chi1$
- $C_3/C_2 = S\sigma = \chi3/\chi2$
- $C_4/C_2 = \kappa\sigma^2 = \chi4/\chi2$