筑波大学
宇宙史研究センター
Tomonaga Center for the History of the Universe

Probing QCD phase structure and nuclear EOS in the RHIC Beam Energy Scan

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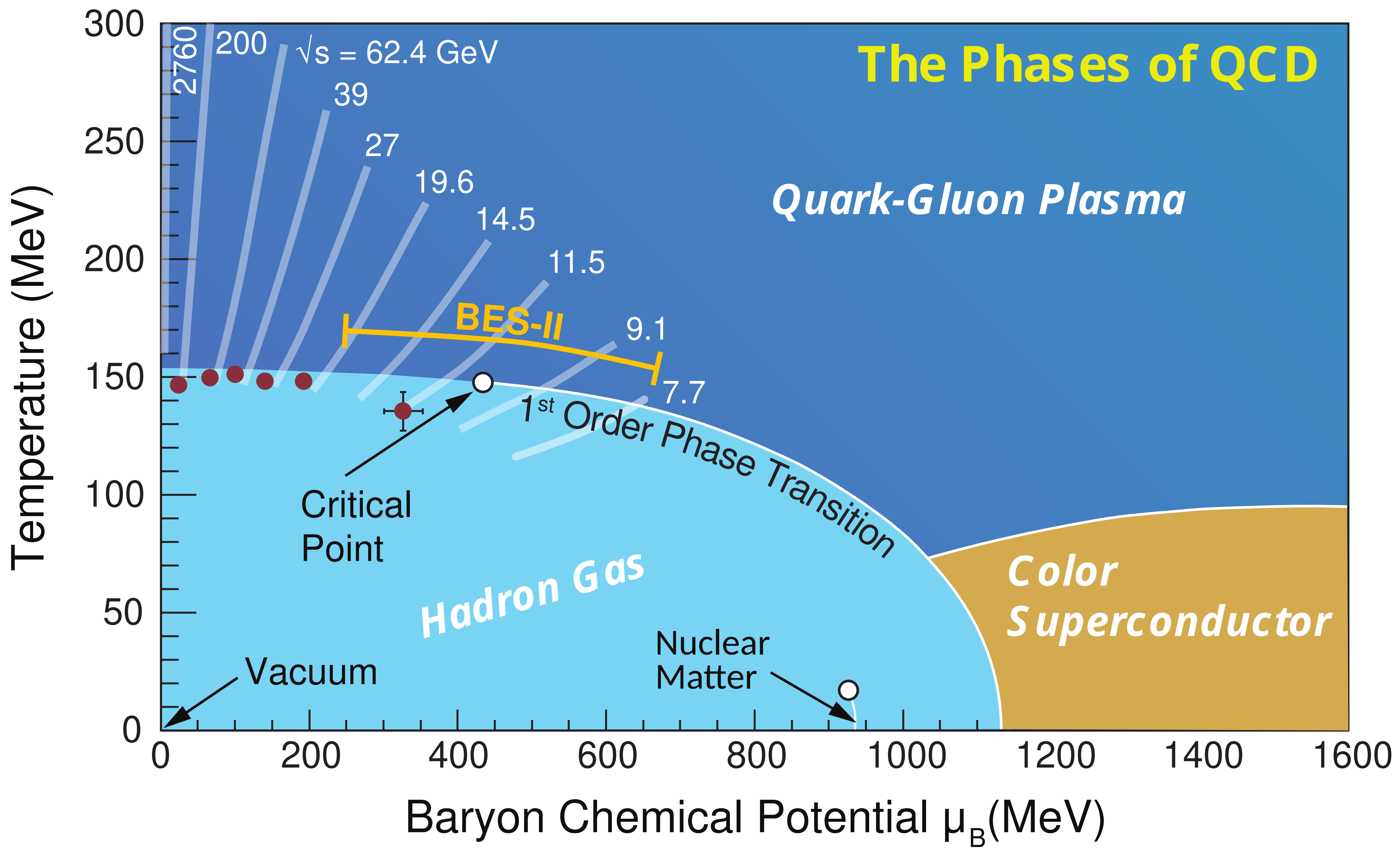
University of Tsukuba

"Equation of State of Dense Nuclear Matter at RIBF and FRIB", *May 23-36, 2023*

Heavy-ion collisions and QCD phase diagram

“Conjectured” QCD phase diagram



A. Bzdak et al., Phys. Rep. 853 (2020) 1-87

From Lattice QCD:

- a smooth crossover near μ_B~0 (<300 MeV)
- Pseudo-critical temperature T_{PC} = 156.5 MeV at μ_B=0

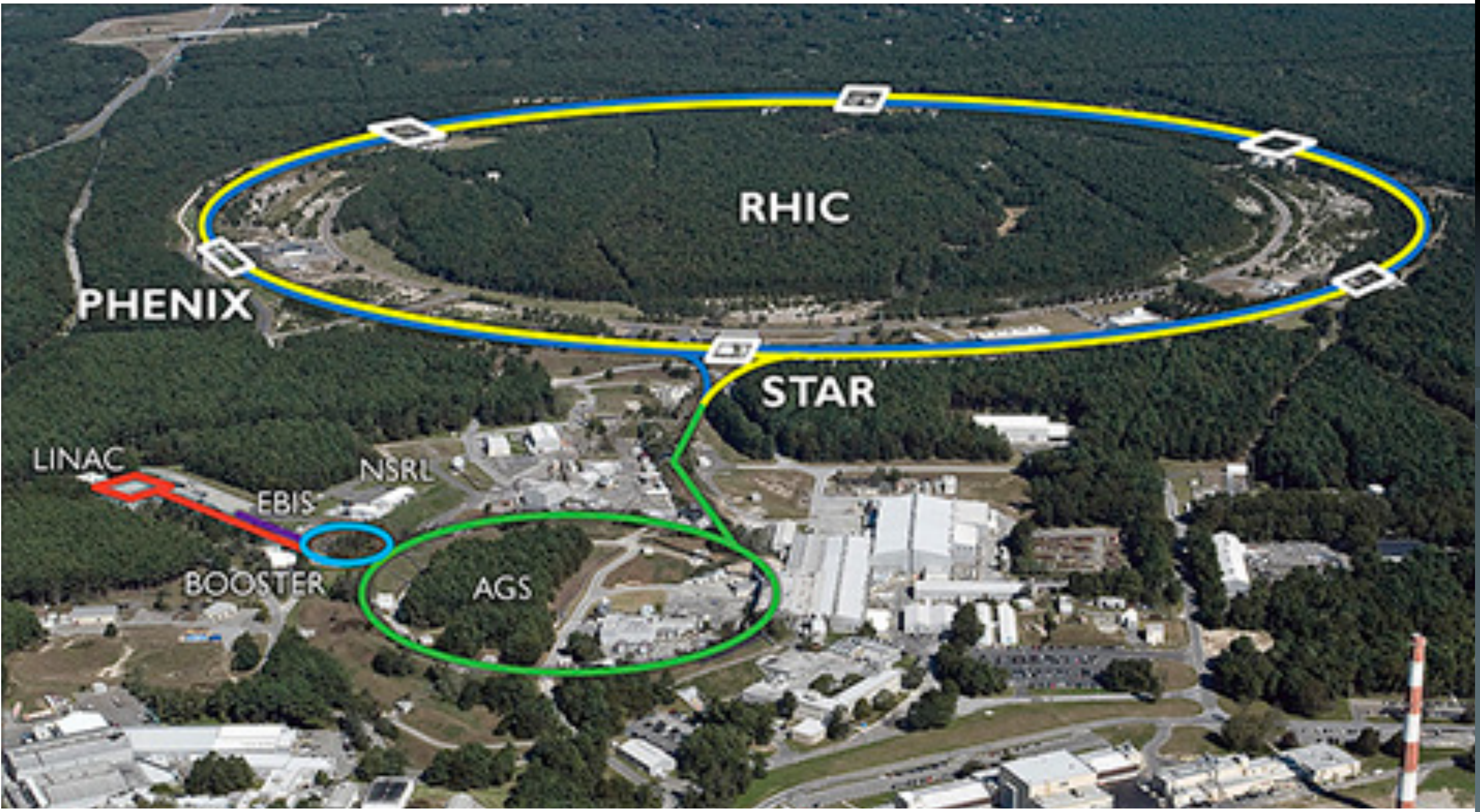
Y. Aoki et al., Nature 443, 675 (2006)
A. Bazavov et al., PLB795 (2019) 15

High energy heavy-ion collisions

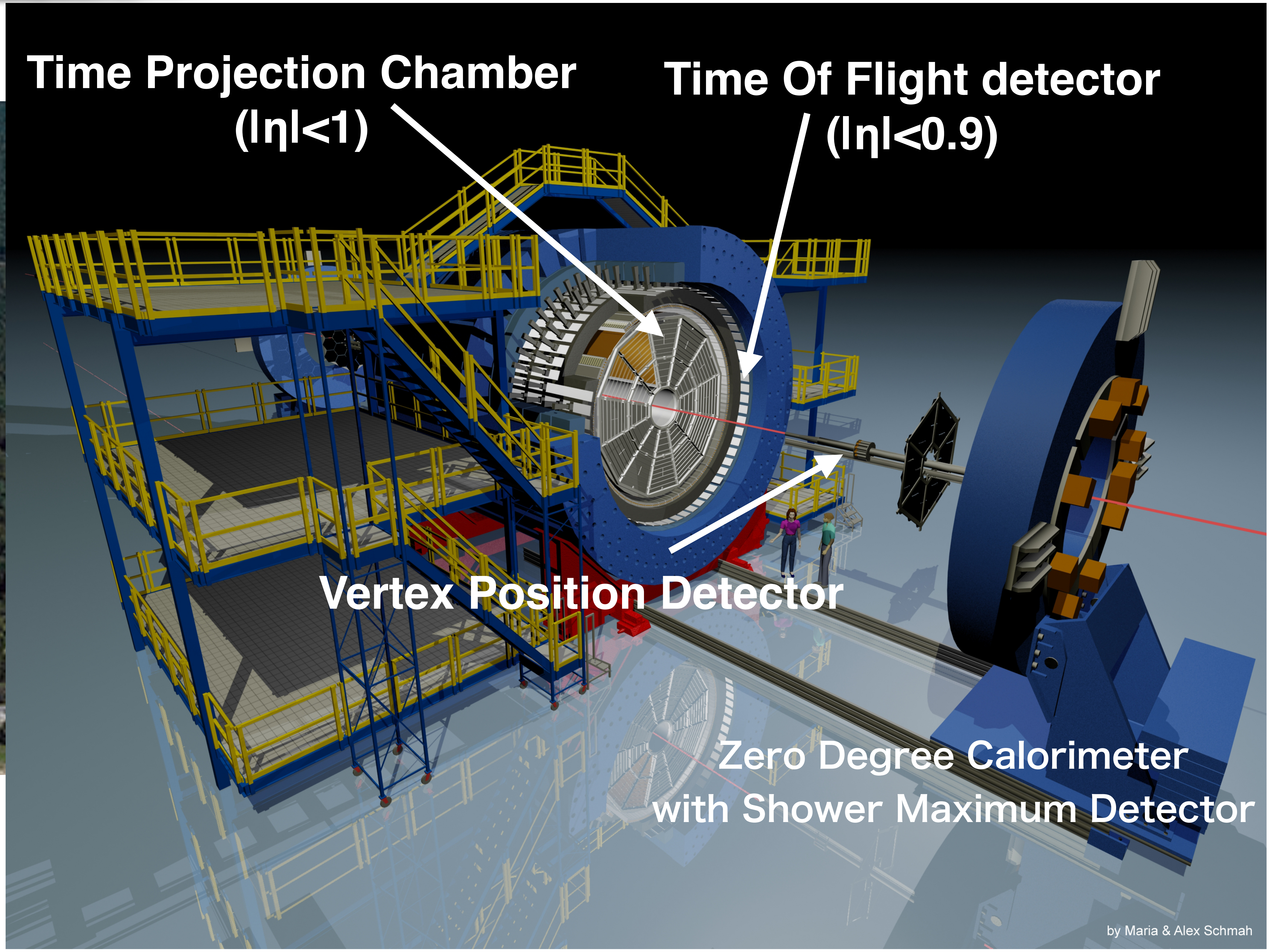
- Study properties of Quark-Gluon Plasma (QGP)
- Explore the QCD phase structure
  - Critical point, First-order phase transition, QGP turn-off

STAR experiment at RHIC

Relativistic Heavy Ion Collider @BNL

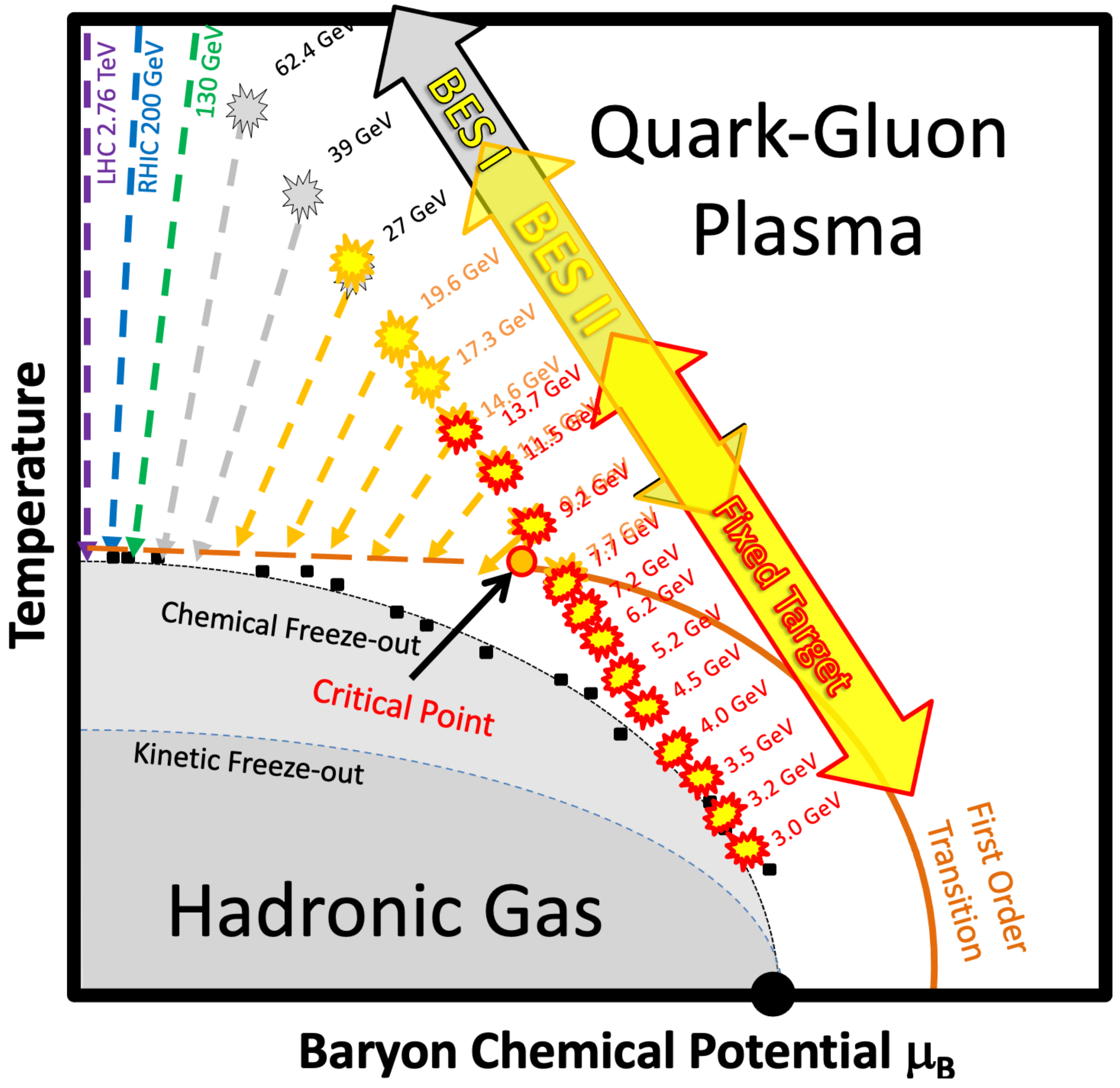


Location: BNL, Upton, NY
Circumference: 3.8 km
Energy: $\sqrt{s_{NN}}$ = 7.7-200 GeV for A+A
Species: p+p, p(d,He)+Au, Cu+Cu, Cu+Au, A+Au, U+U…



- Full azimuth and large rapidity coverage
- Excellent particle identification

RHIC Beam Energy Scan

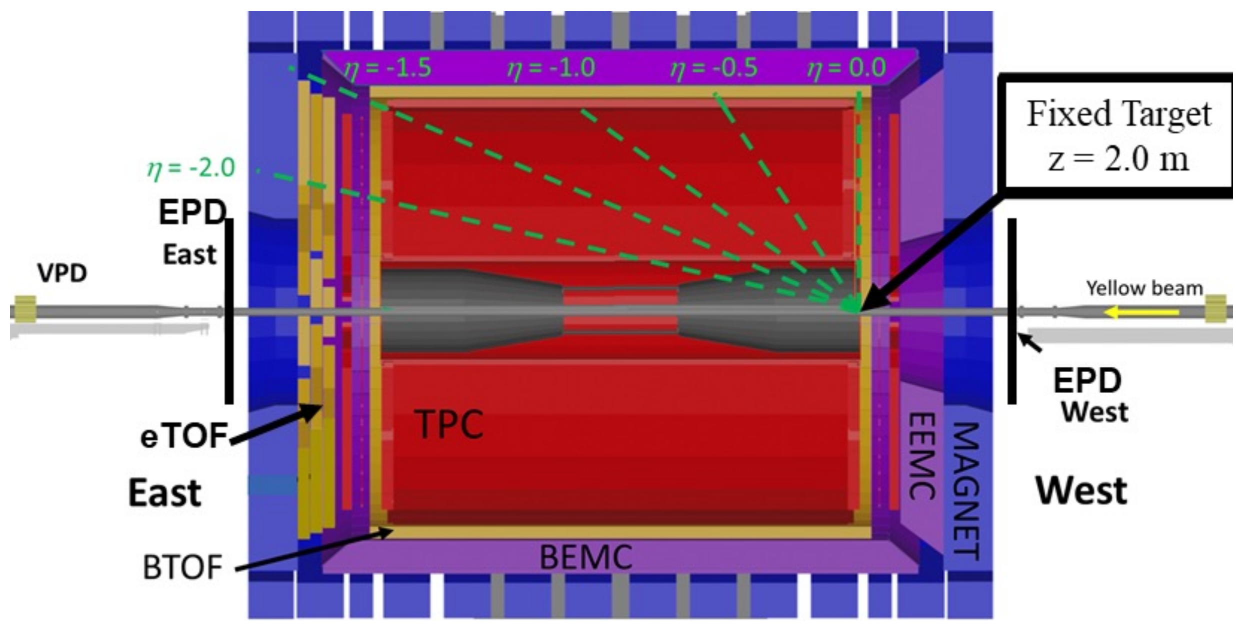


RHIC Beam Energy Scan (BES) program

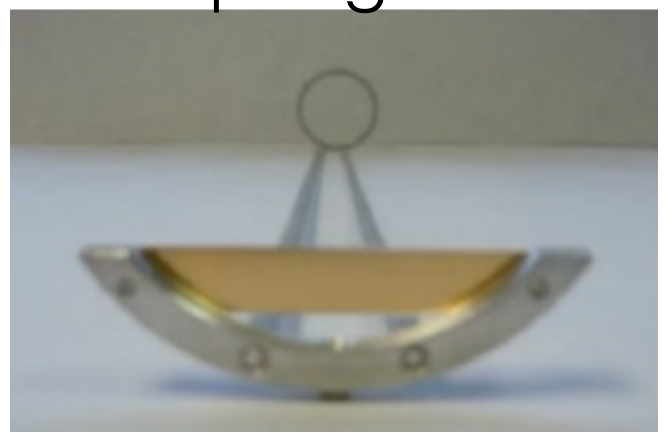
- Phase-I (BES-I) in 2010-2011 ($\sqrt{s_{NN}}$ = 7.7 - 39 GeV)
- Phase-II (BES-II) in 2019-2021 ($\sqrt{s_{NN}}$ = 3 - 27 GeV)
  Collider mode for 7.7-27 GeV and Fixed-target mode for 3-13.7 GeV

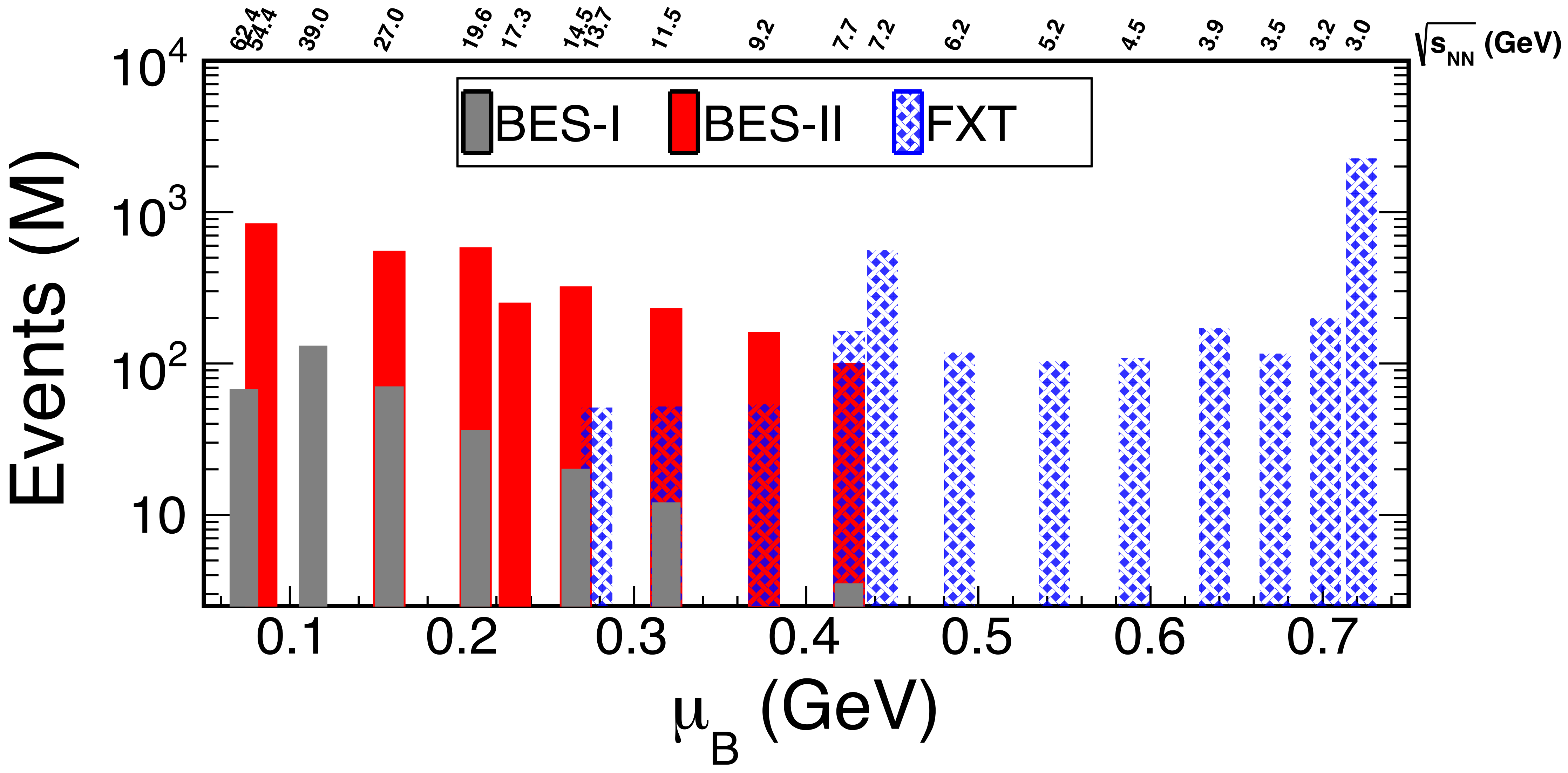
Main motivation

- Location of critical point
- Search for signatures of the 1st-order phase transition
- Onset of QGP formation

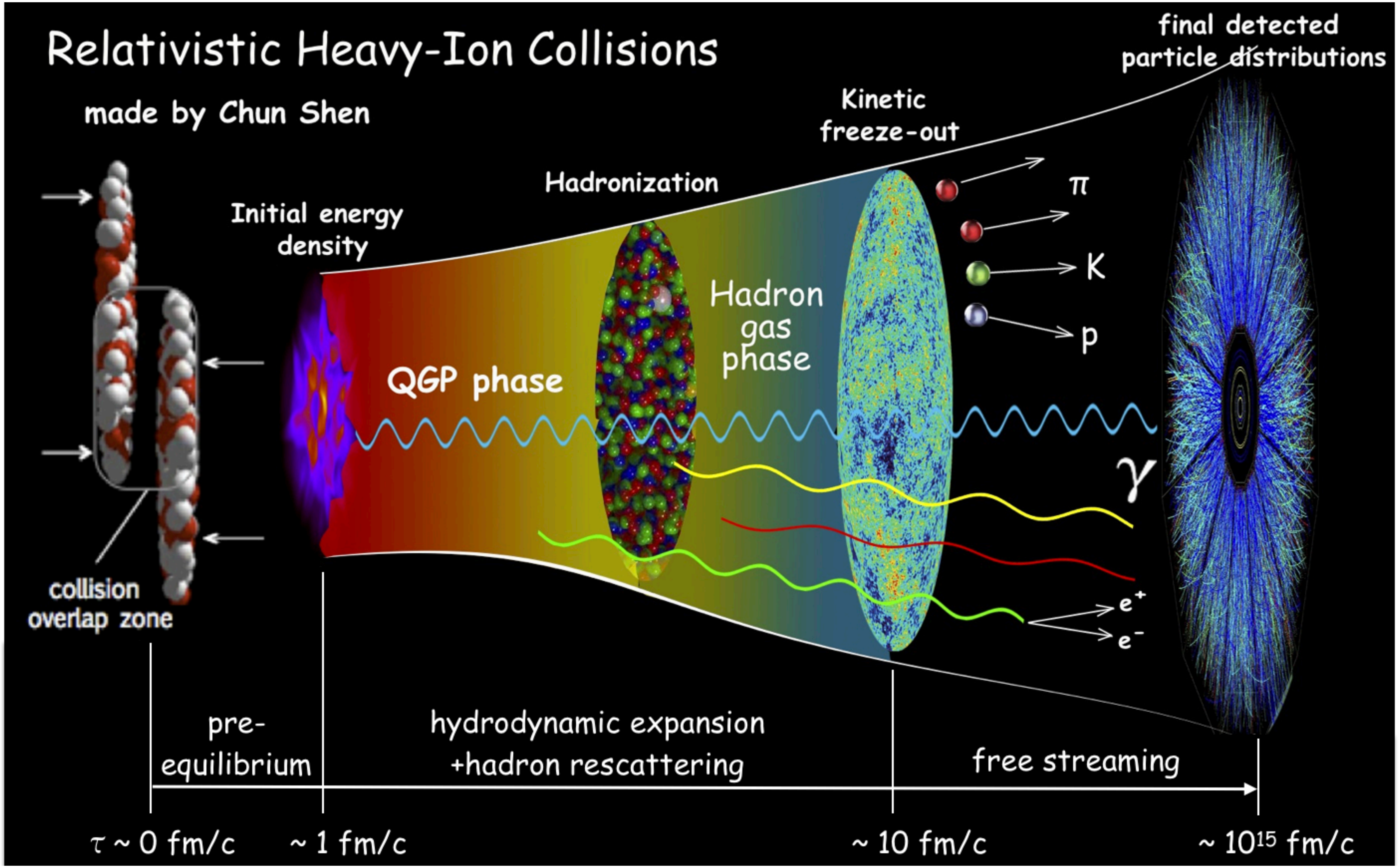


250 μm gold foil



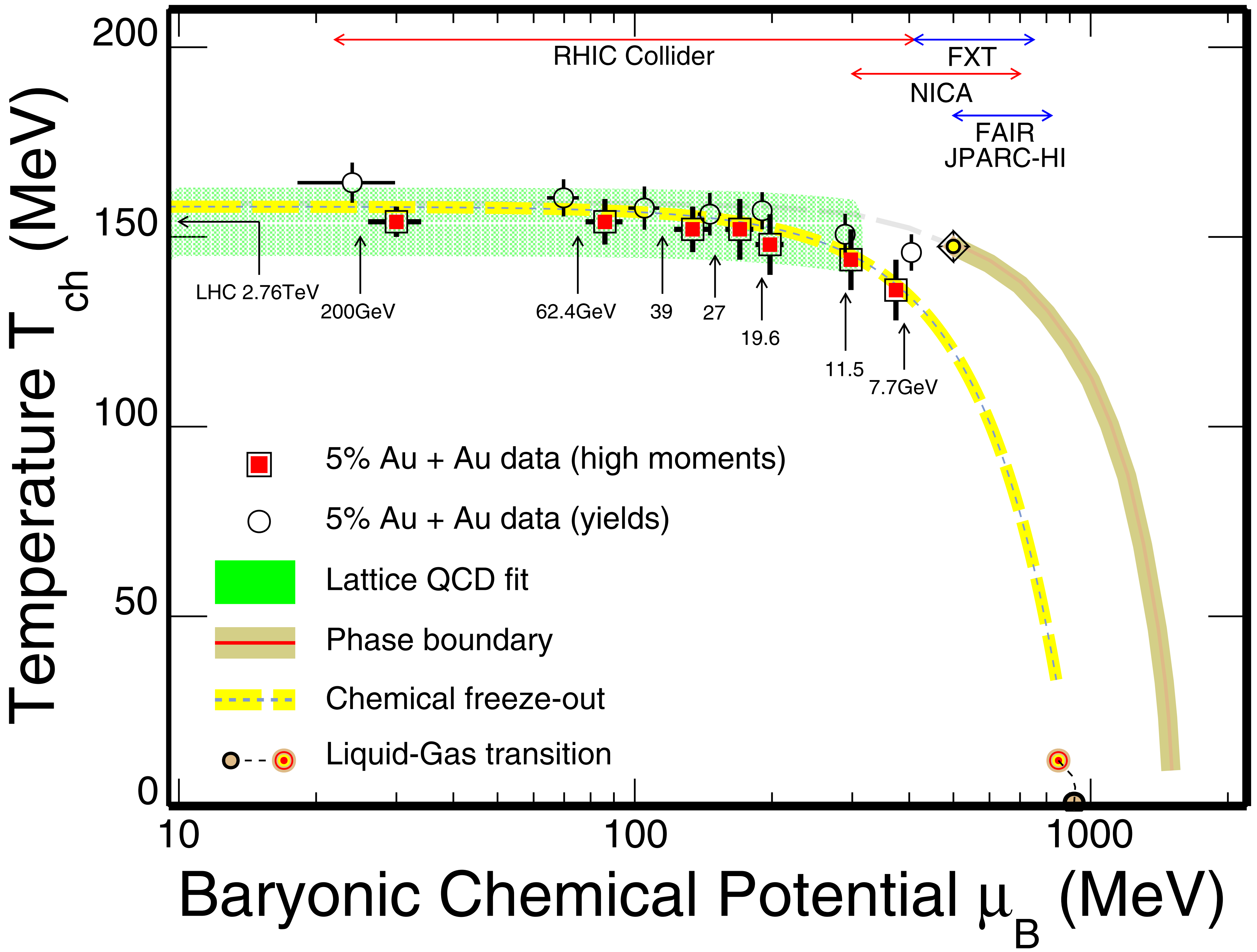


Time evolution of HIC

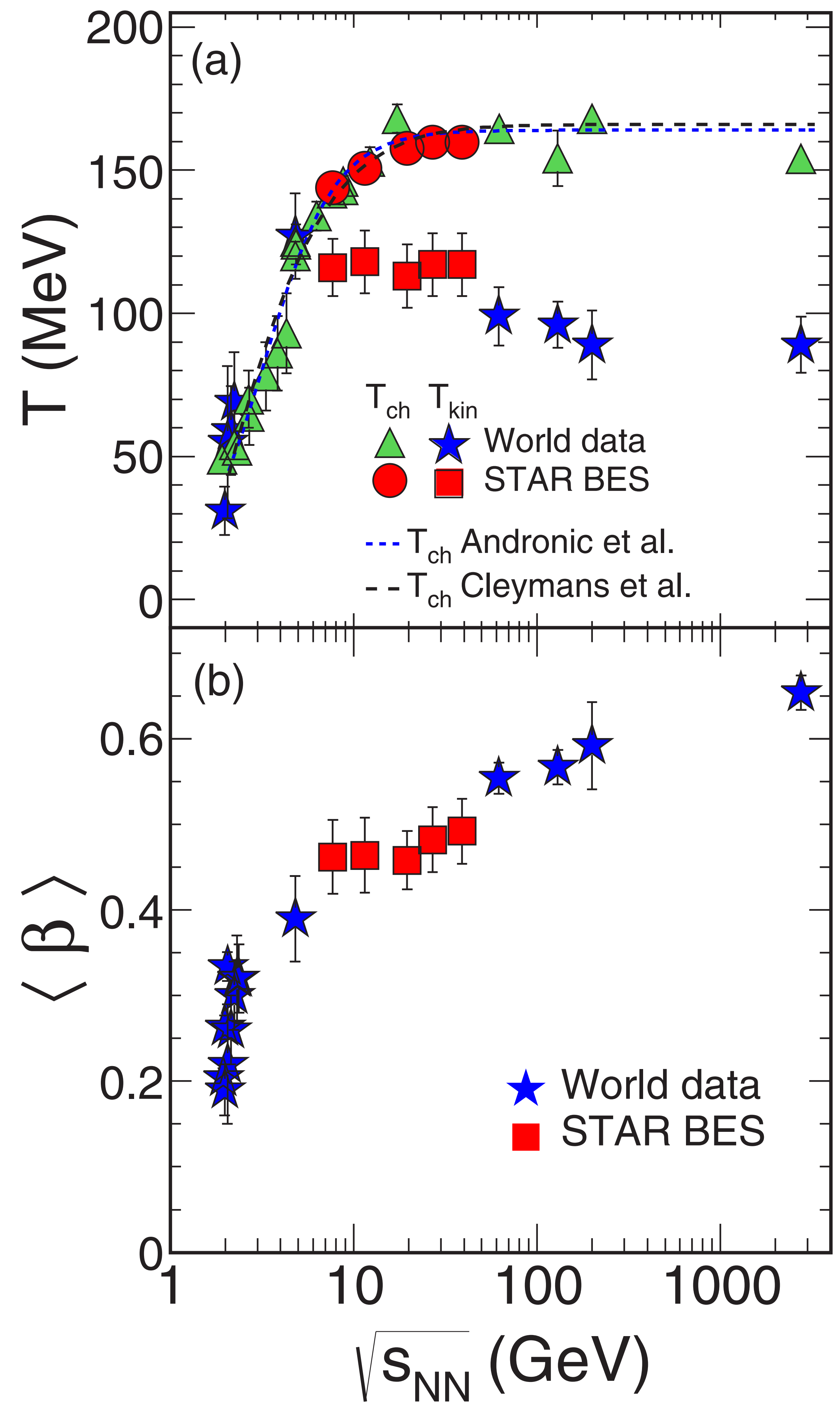


Chemical/Kinetic freeze-out temperatures

Fig. from N. Xu et al., AAPPS Bulletin (2021)31:1



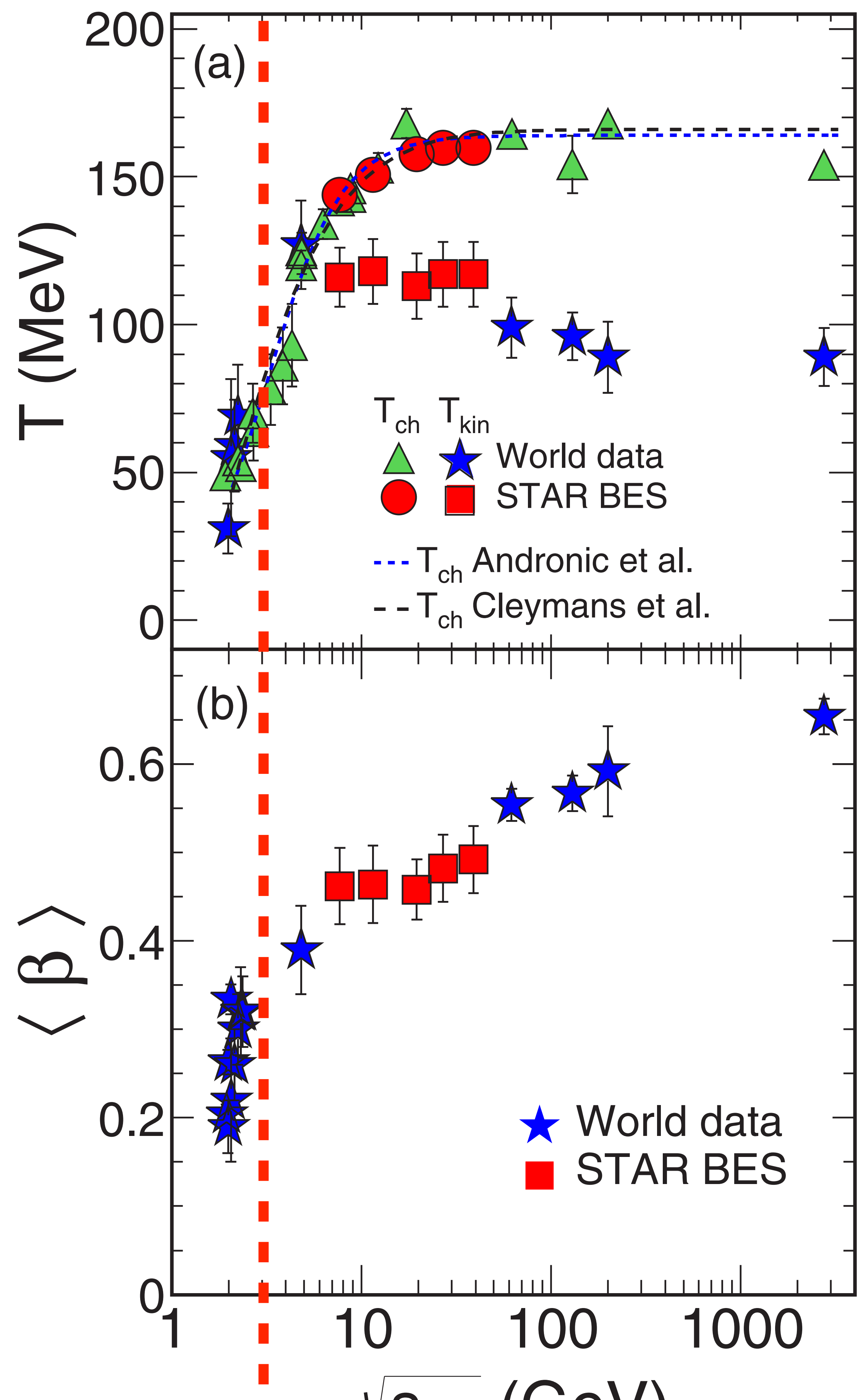
STAR, PRC96, 044904 (2017)

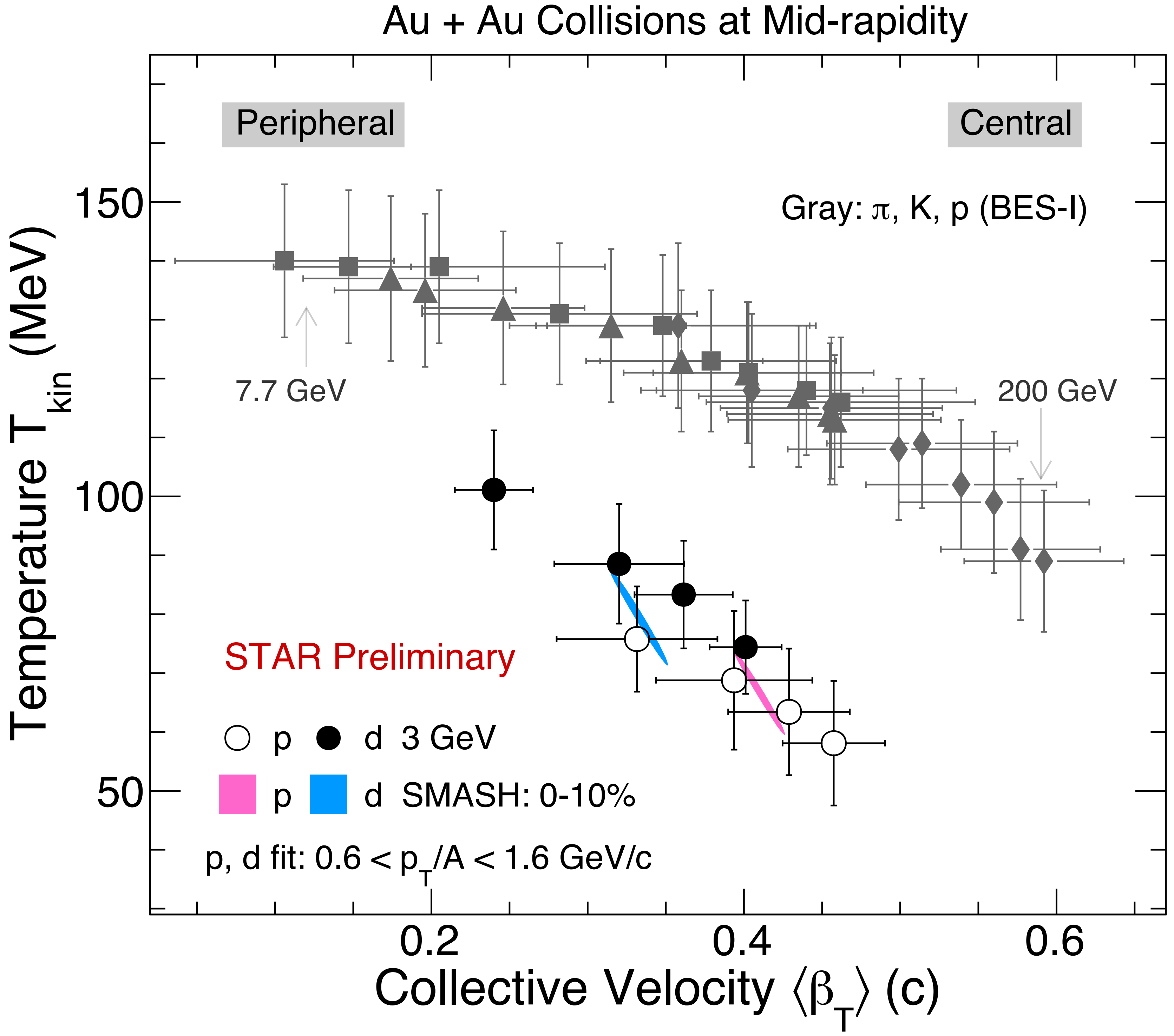


- T_{ch} is close to T_{PC} from LQCD and stays constant at $\sqrt{s_{NN}}$ >= 7.7 GeV
- Sudden change in T_{kin} around $\sqrt{s_{NN}}$ ~ 6-8 GeV, where T_{kin} coincides with T_{ch}

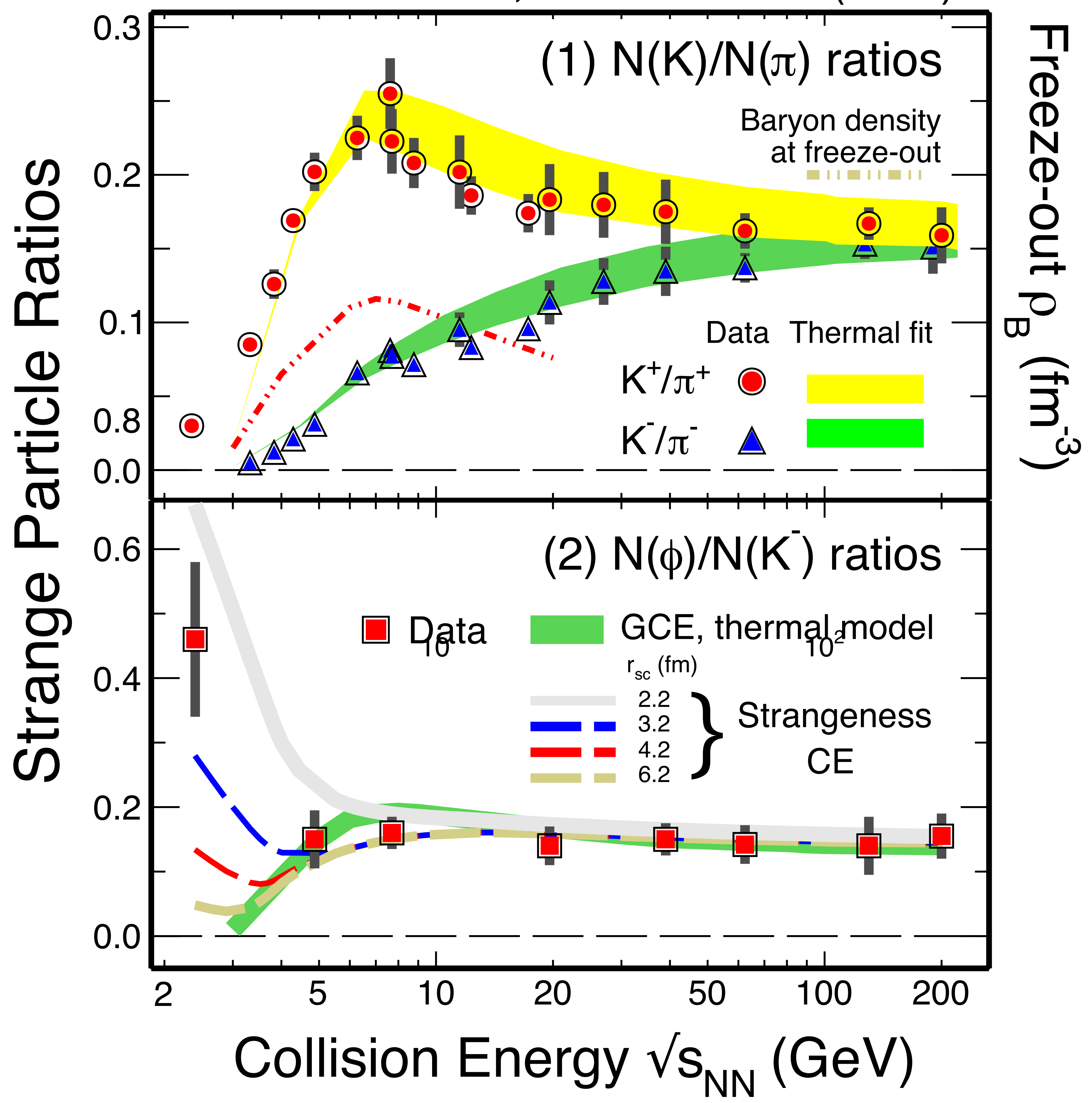
Chemical/Kinetic freeze-out temperatures

STAR, PRC96, 044904 (2017)





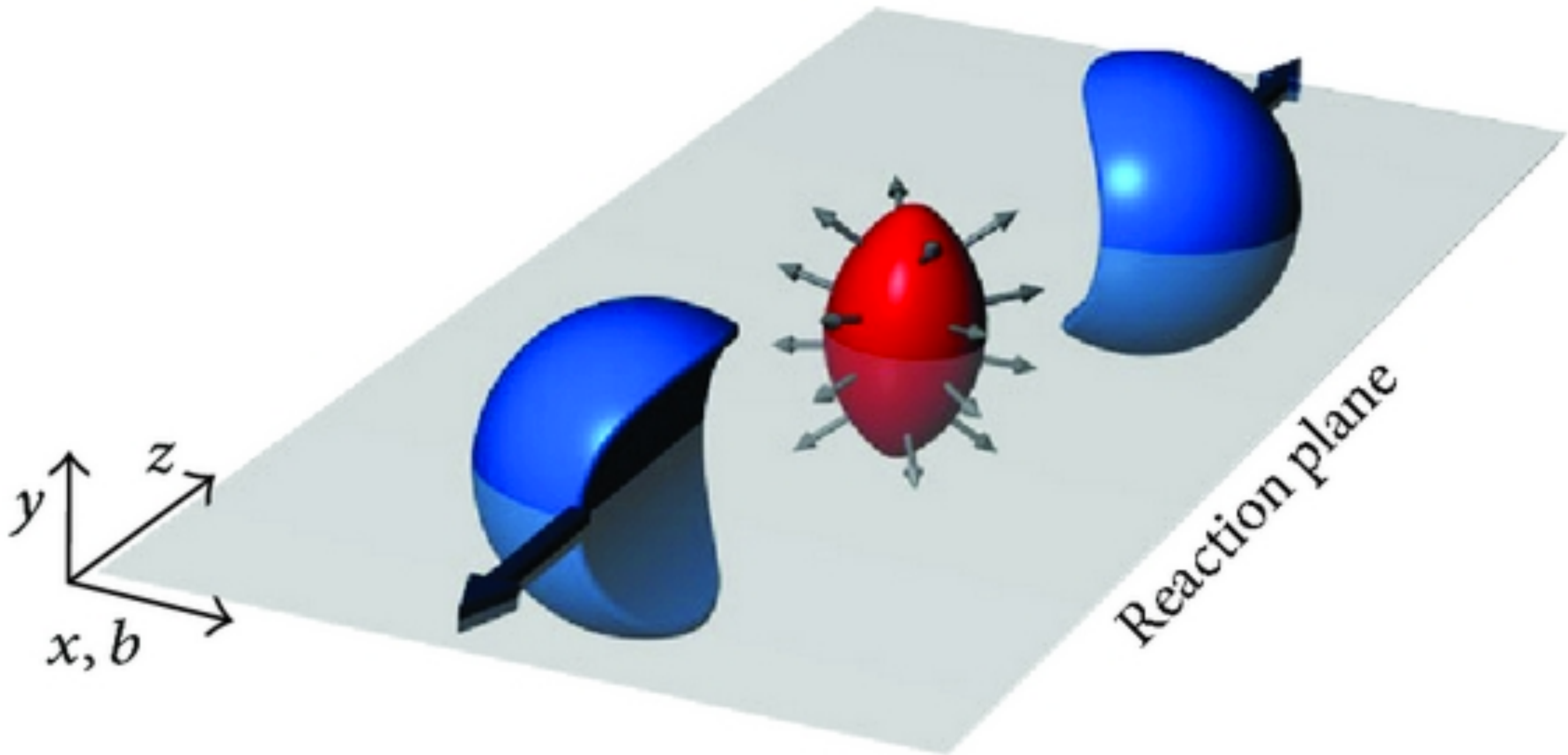
N. Xu et al., AAPPS Bull.31(2021)1



- Preliminary result from 3 GeV indeed shows such a trend
- Baryon density becomes maximum around $\sqrt{s_{NN}}$ = 7 GeV (associate production of K^+ and Λ: N + N → N + Λ + K^+)

Fixed-target mode can probe high baryon density region!

Collectivity (azimuthal anisotropy)



$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)\right)$$

ϕ: particle azimuthal angle relative to the nth-order event plane

- Extensive study of anisotropic flow for particle collectivity
  - Medium response to the initial geometry with fluctuations ($\varepsilon_n \propto v_n$).
- Anisotropic flow: Fourier coefficient v_n of azimuthal distributions of final state particles
  - v_1: directed flow
  - v_2: elliptic flow
  - v_3: triangular flow
  - v_4, v_5, v_6…

L. Yan, CPC42,042001(2018)

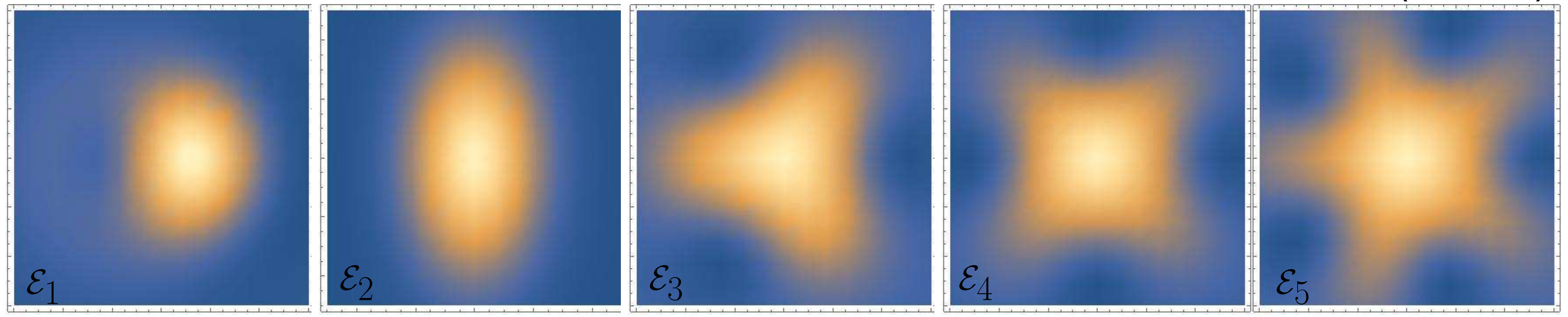
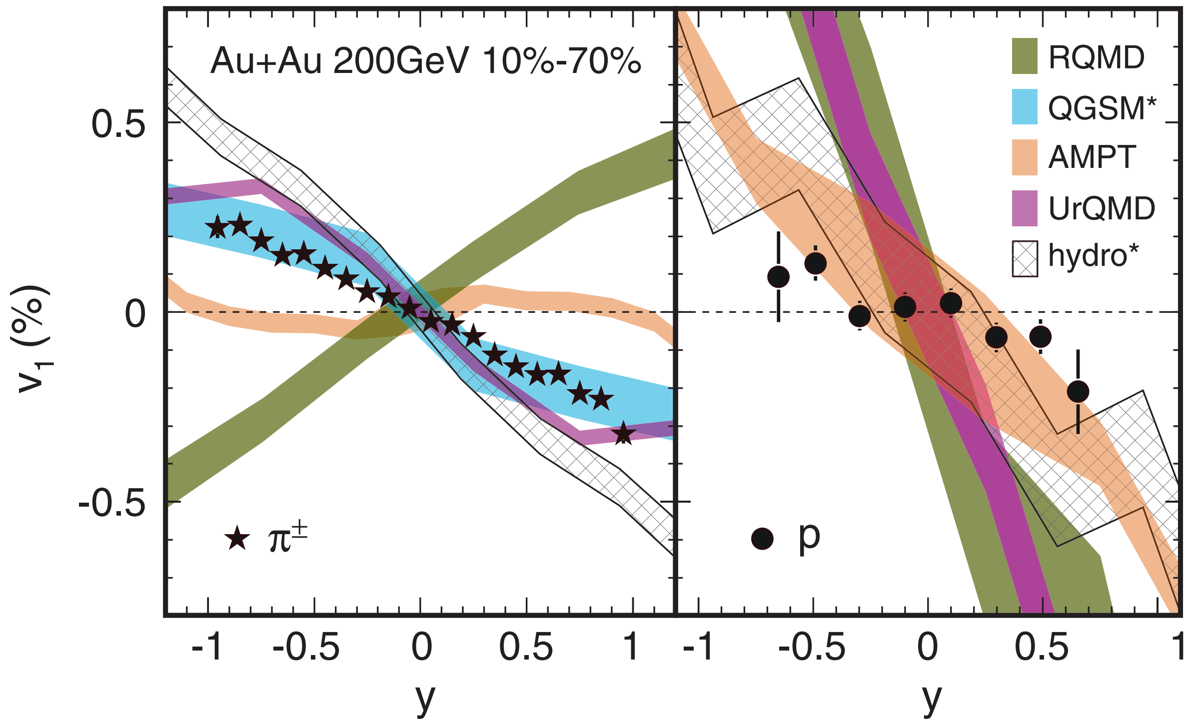


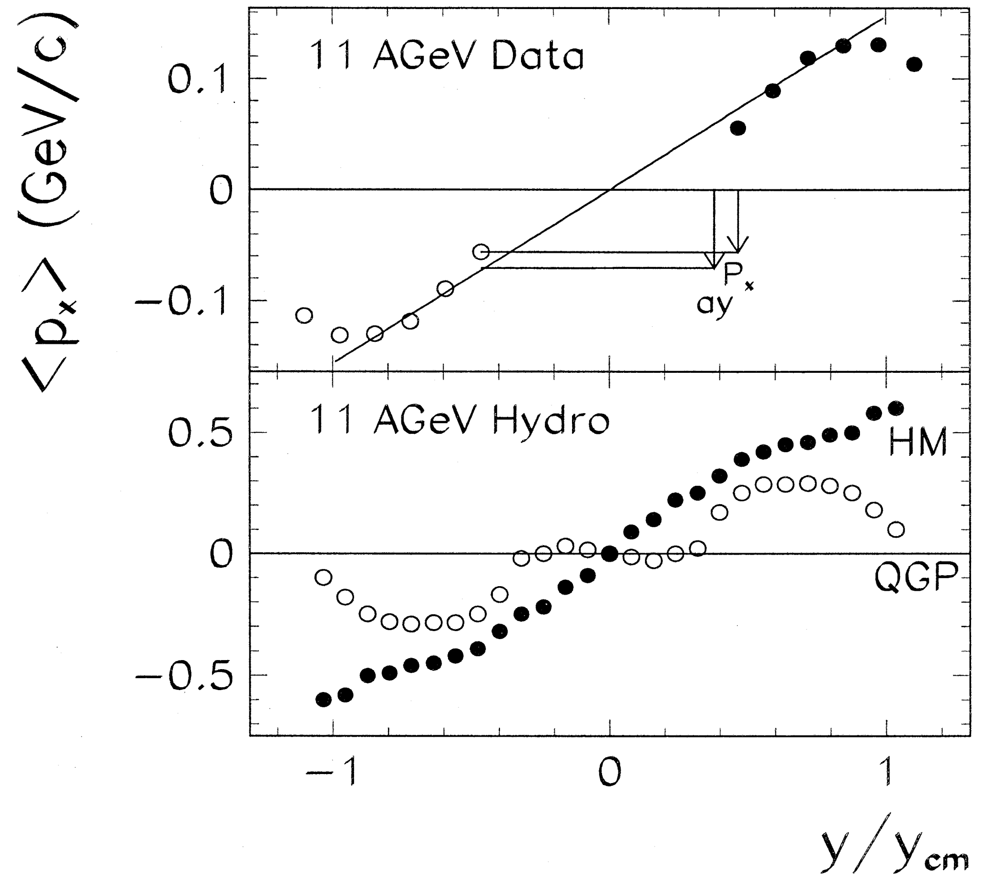
Fig. 2. Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right).

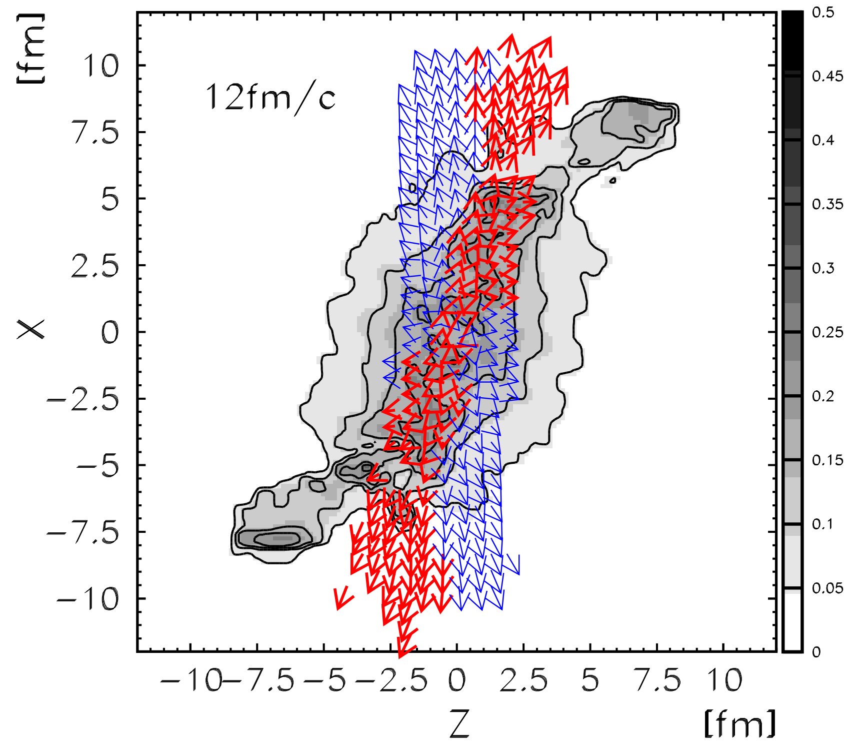
Directed flow v_1

- Directed flow: collective sideward motion of particles
  - Proposed as a sensitive probe to the 1st-order phase transition; "wiggle structure" or "anti-flow"
    L.P. Csernai and D. Rohrich, PLB458(1999)454
    J. Brachmann et al., PRC61, 024909 (2000)
  - Characteristic rapidity dependence ("~" shape) at mid-η due to: initial source tilt with expansion, density asymmetry, baryon stopping
    P. Bozek and I. Wyskiel, PRC81, 054902 (2010)
    U. Heinz and P. Kolb, J.Phys.G30;S1229 (2004)
    R. Snellings et al., PRL84, 2803 (2000)
  - Contribution from the tilt to v_1^{odd}: ~2/3 at RHIC, ~1/3 at the LHC
    STAR, PRC98, 014915 (2018)
  - Extensive study for various particle species and collision energy so far; none of models can describe the data simultaneously

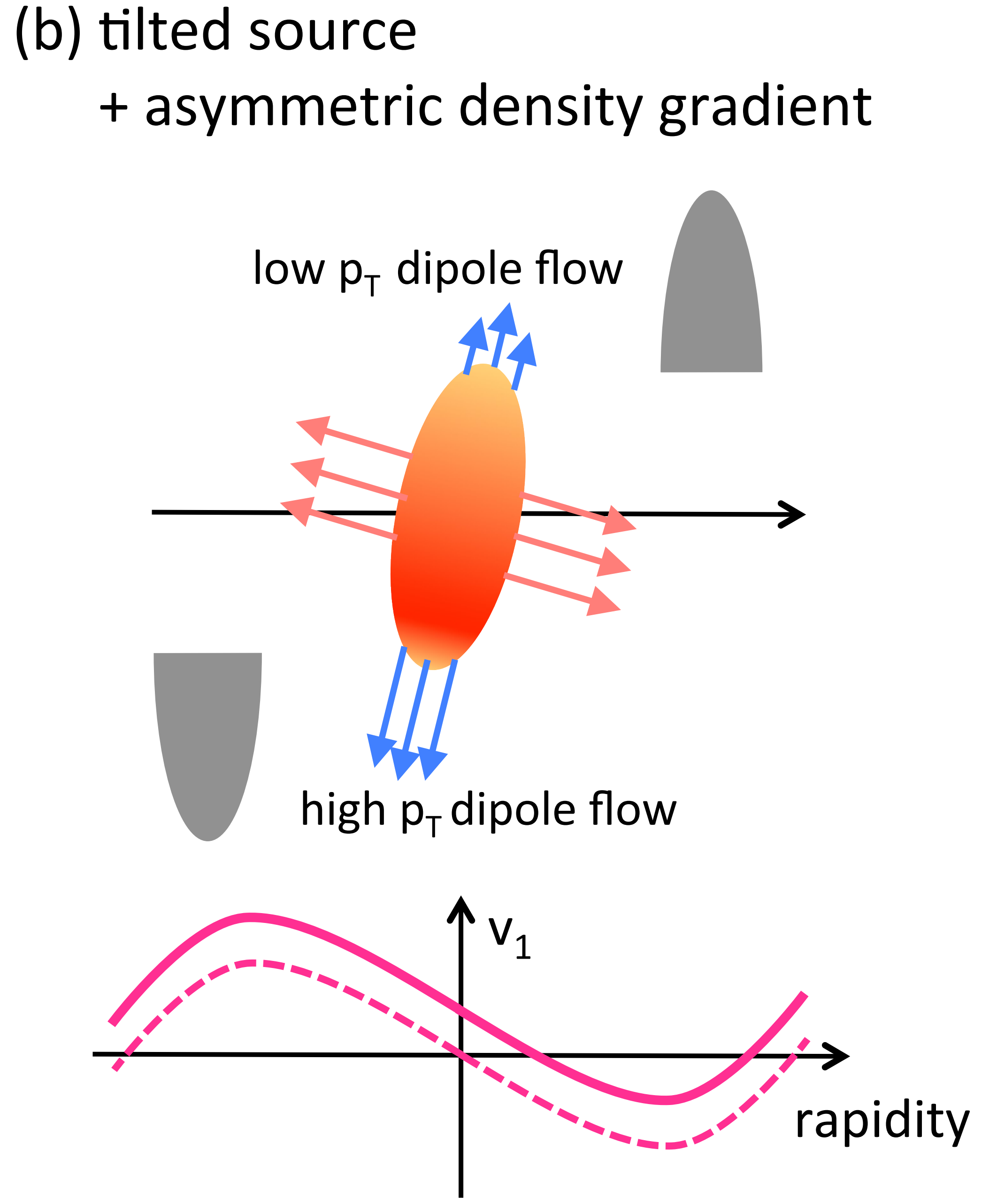
STAR, PRL108.202301 (2012)







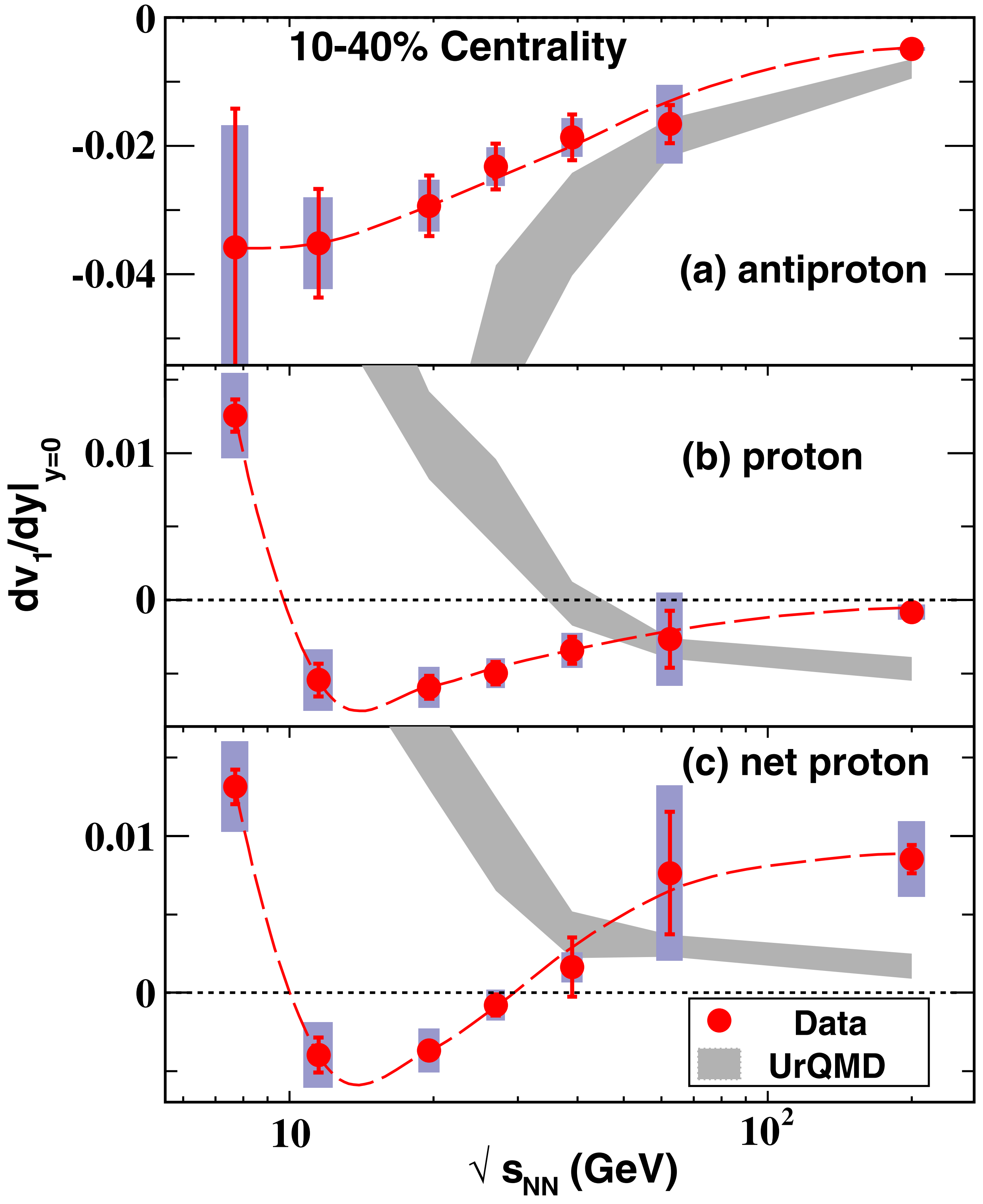
lower figure shows a typical example for fluid dynamical calculations with Hadronic and QGP EoS [3]. QGP leads to strong softening, ~100%.



Cartoon from "STAR, PRC98, 014915 (2018)"

Directed flow from BES

STAR, PRL112.162301 (2014)



Y. Nara et al., PLB769(2017)543

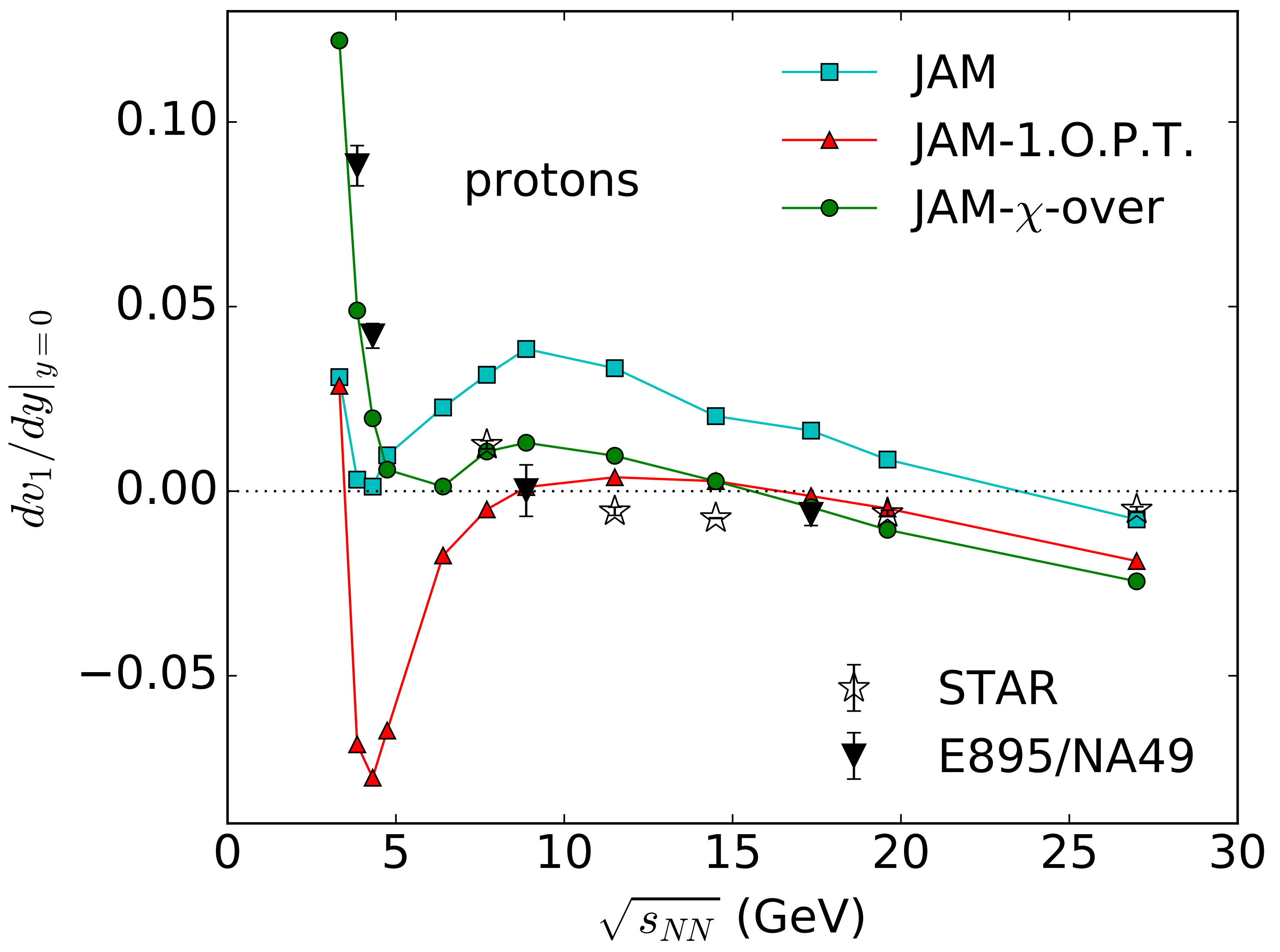
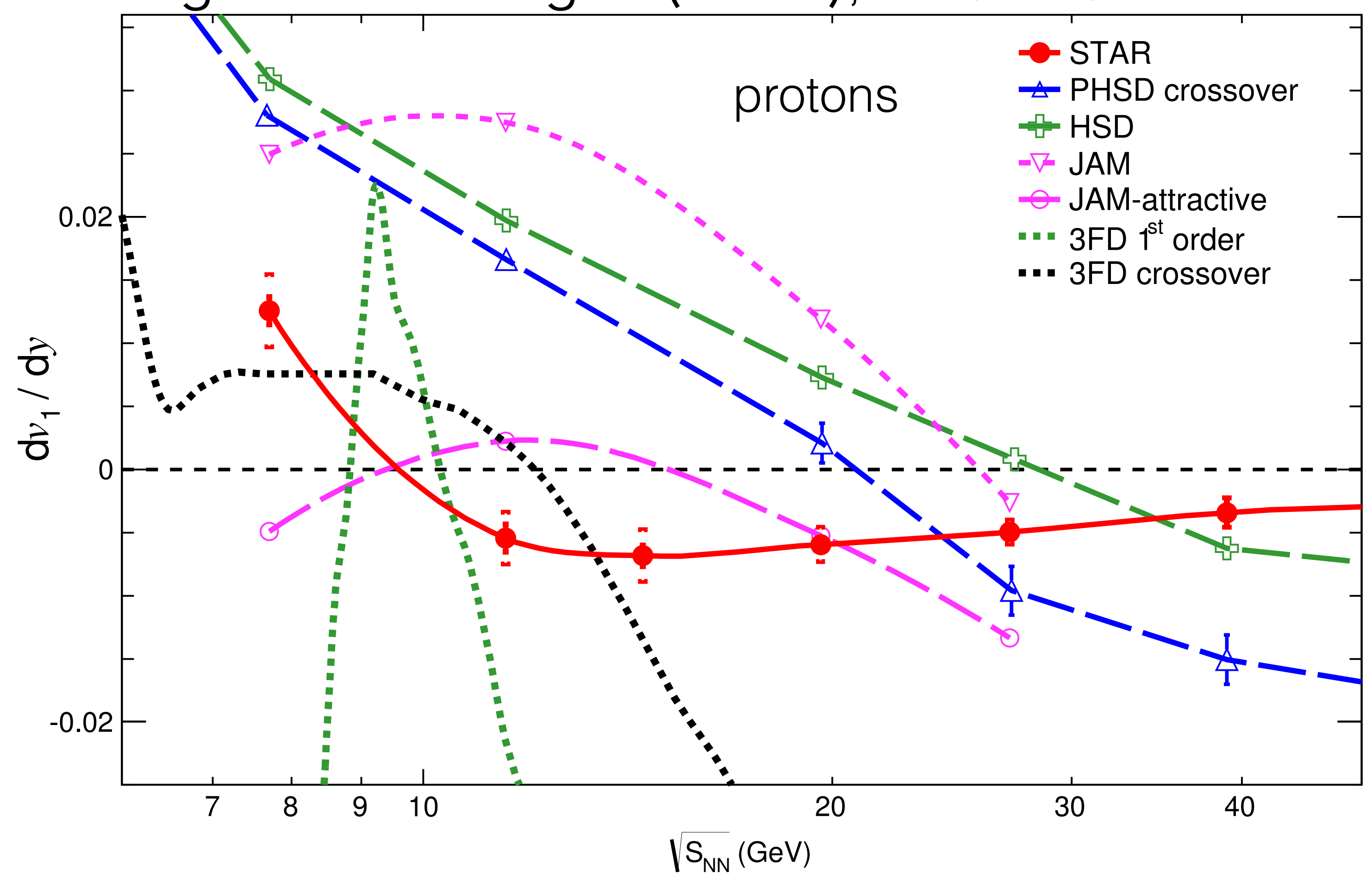


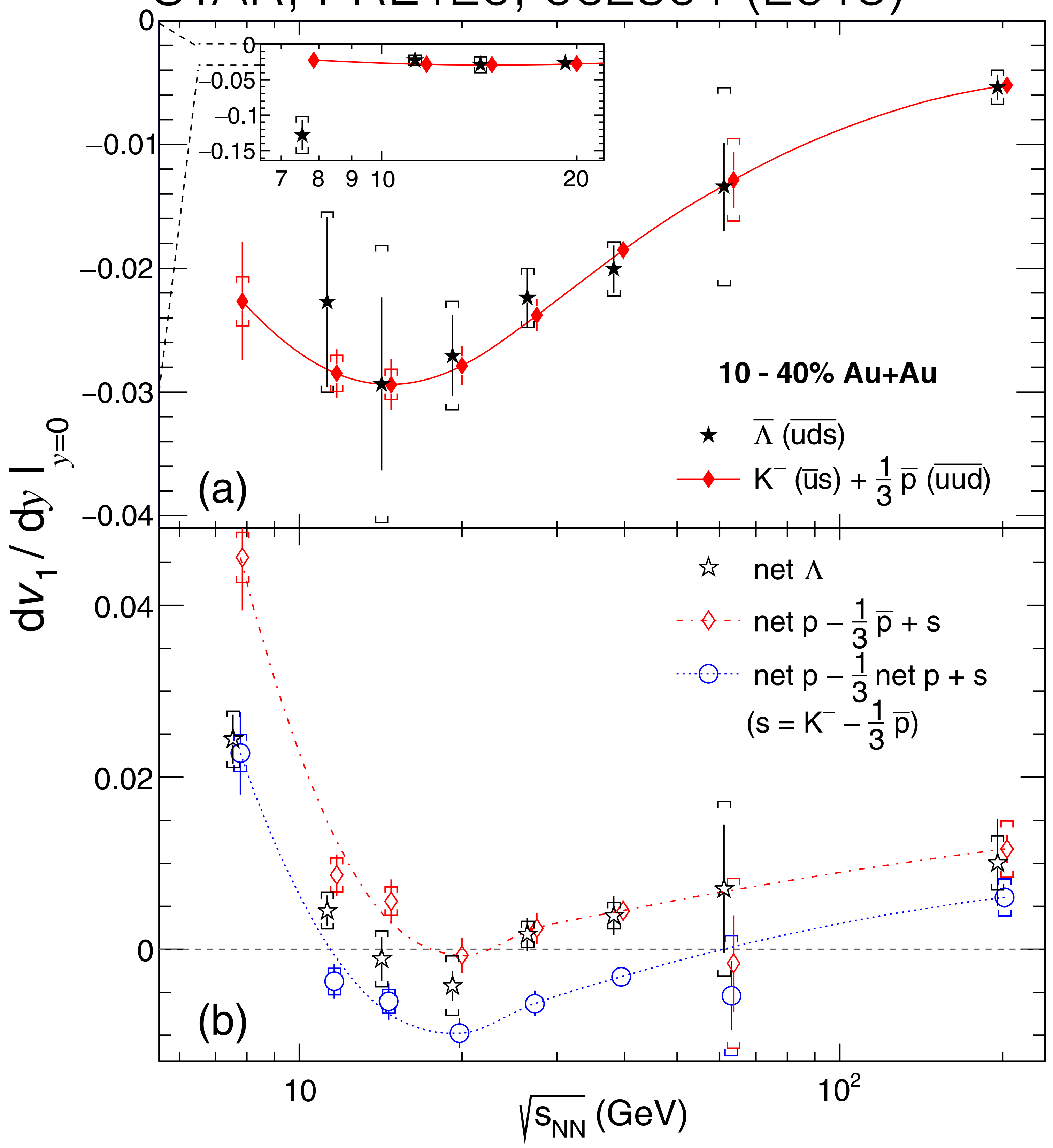
Fig. from S. Singha (STAR), CPOD2017



- Non-monotonic energy dependence of (net-)proton v_1 with a minimum at 10~20 GeV
  - Possibly related to the softening of EOS and 1st-order PT, but still many models cannot describe the data

Directed flow from BES

STAR, PRL120, 062301 (2018)



←Test for "produced" particles

←Test for "transported" particles (net-particles)

Assumption of coalescence sum rule

$$v_1^q = v_1^{\bar{q}}$$

$$v_1^h = \sum v_1^q$$

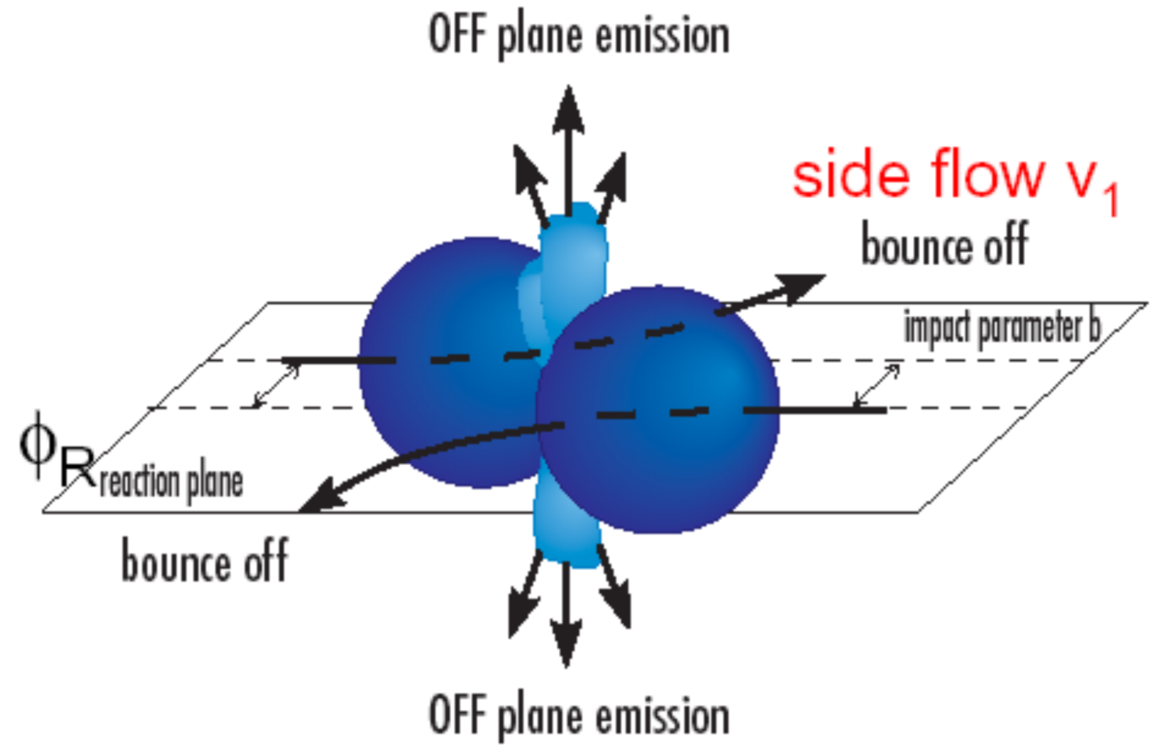
- Coalescence sum rule
  - "produced" : Holds at $\sqrt{s_{NN}}$ down to 11.5 GeV, with a minimum at 14.5 GeV
  - net-particles : dominated by "produced" quarks at high $\sqrt{s_{NN}}$, while by "transported" ones at low $\sqrt{s_{NN}}$

Energy dependence of elliptic flow v_2

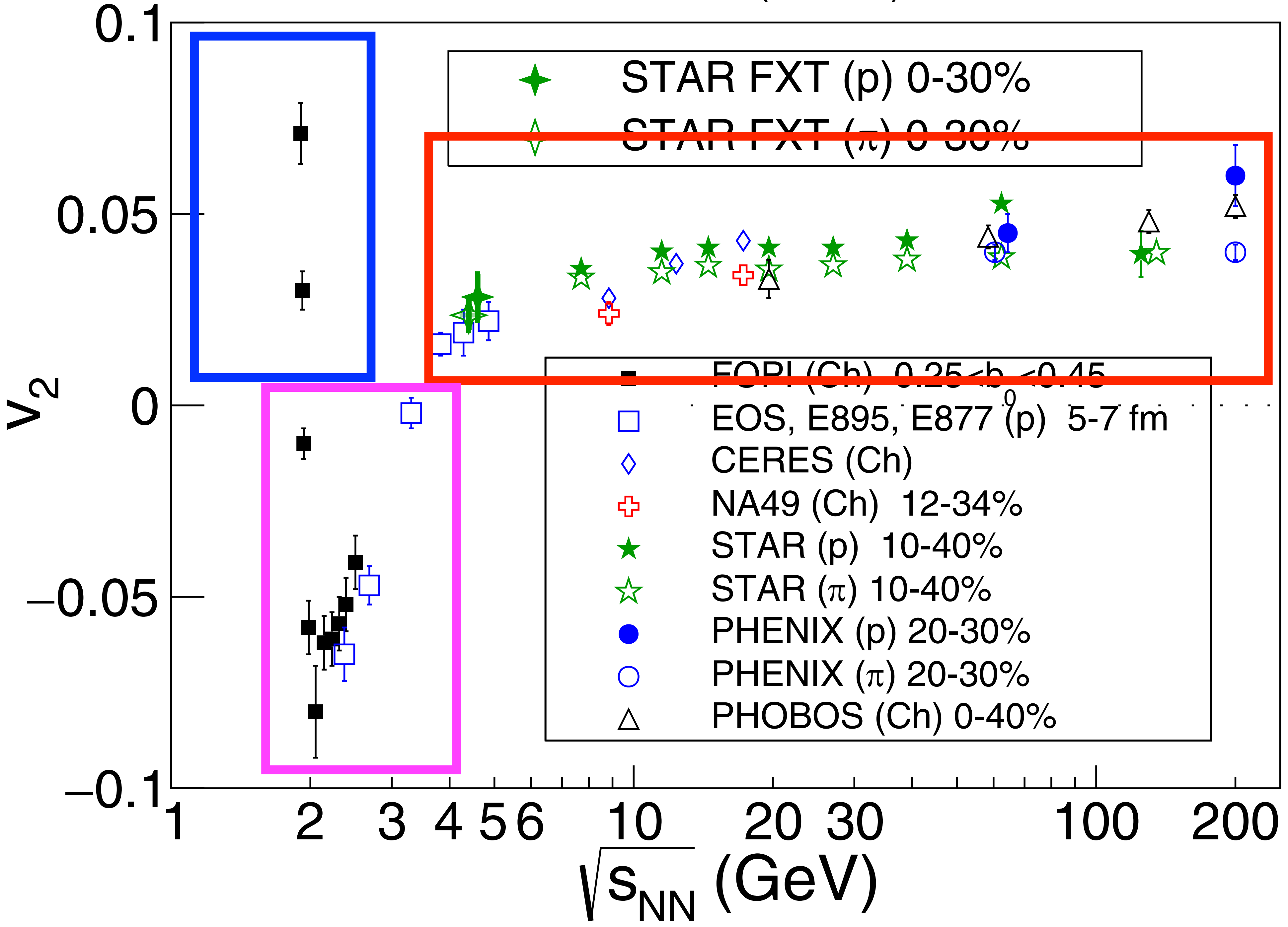
Rotating system of projectile-target

(v_2>0 at $\sqrt{s_{NN}}$ <1.4 GeV)

Squeeze-out emission (v_2<0)

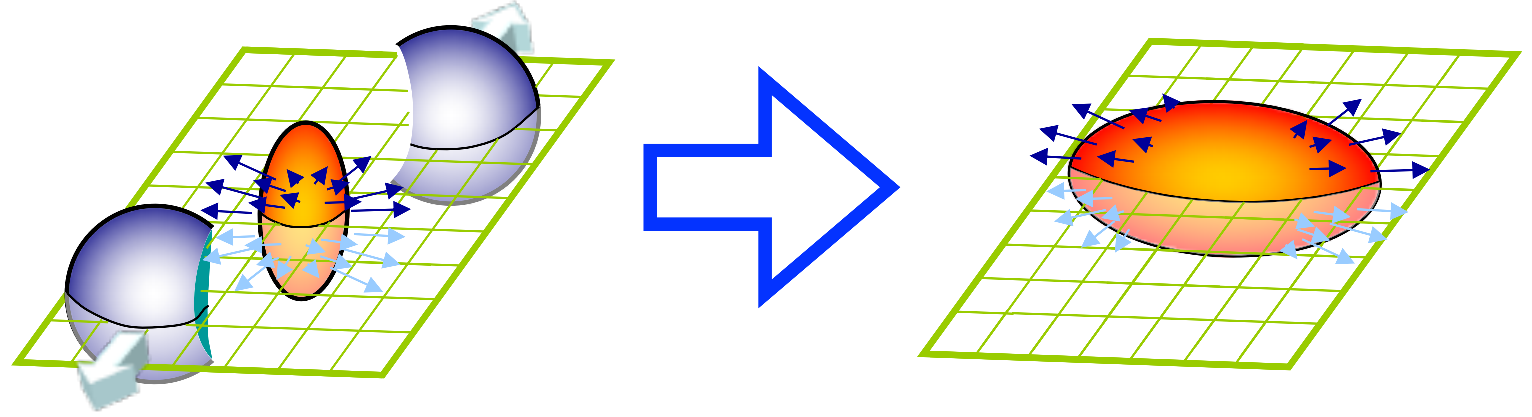


STAR, PRC103, 034908 (2021)



Pressure-gradient-driven expansion

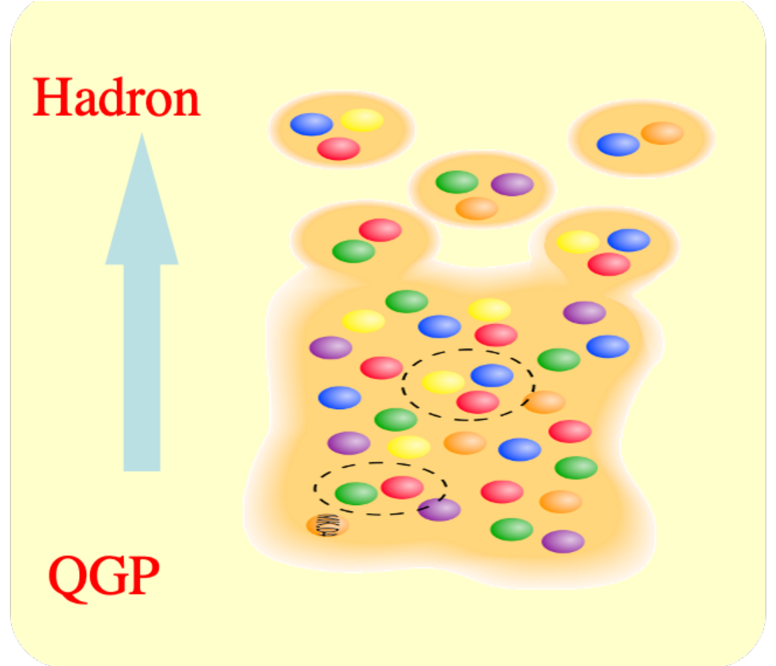
(v_2>0 at $\sqrt{s_{NN}}$ >4 GeV)



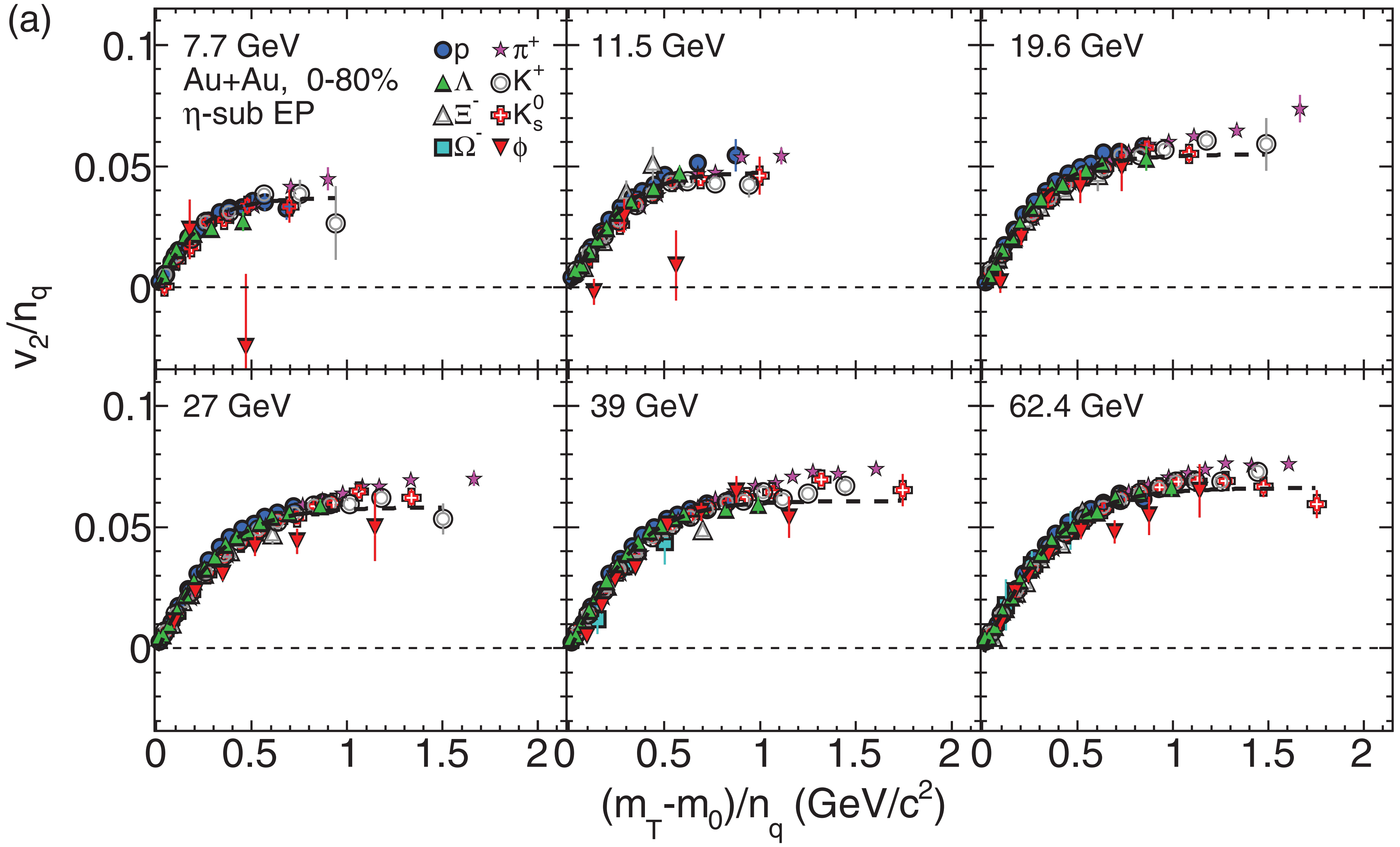
BES data follow the global trend.

The sign of v_2 changes twice with colliding beam energy.

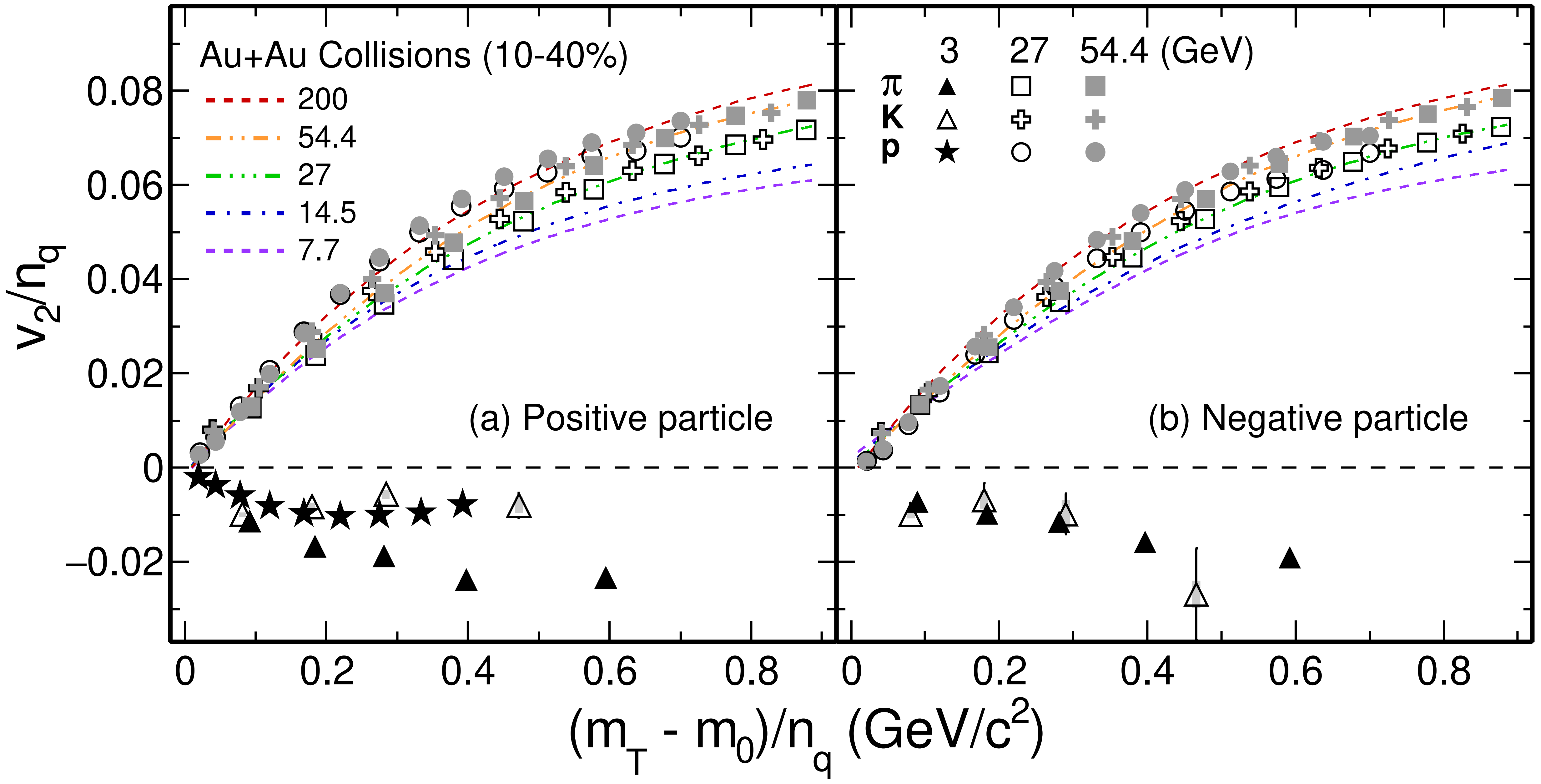
Number of Constituent Quark (NCQ) scaling



STAR, PRC88, 014902 (2013)



STAR, PLB827(2022)137003

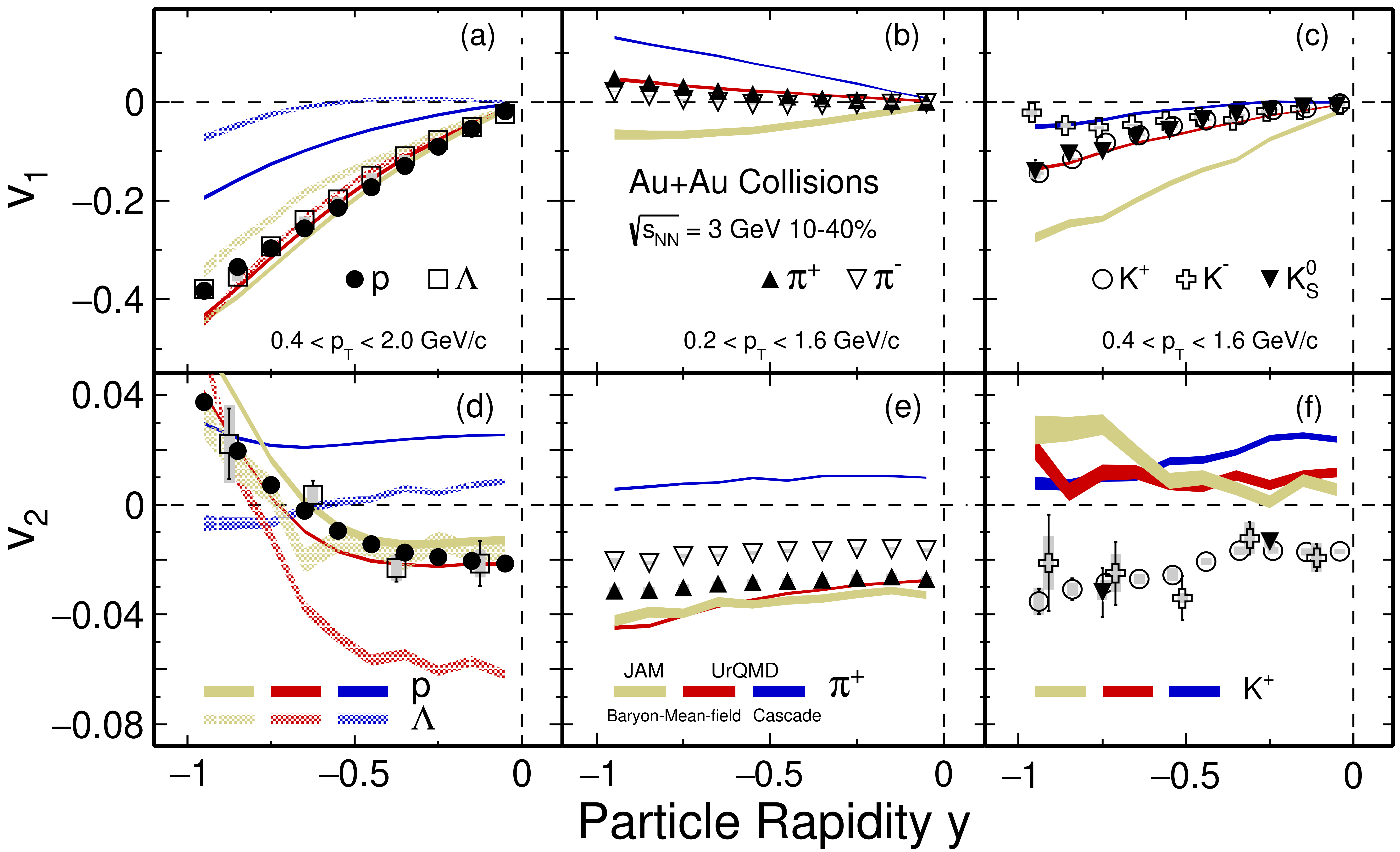


NCQ scaling holds well at $\sqrt{s_{NN}} \gtrsim 7.7$ GeV indicating partonic collectivity,
while the scaling doesn't work at 3 GeV where baryonic interaction is dominant.

π^+: Δ resonance
K^+: associated production of Λ
p: transported protons

Flow at 3 GeV, compared to models

STAR, PLB827(2022)137003



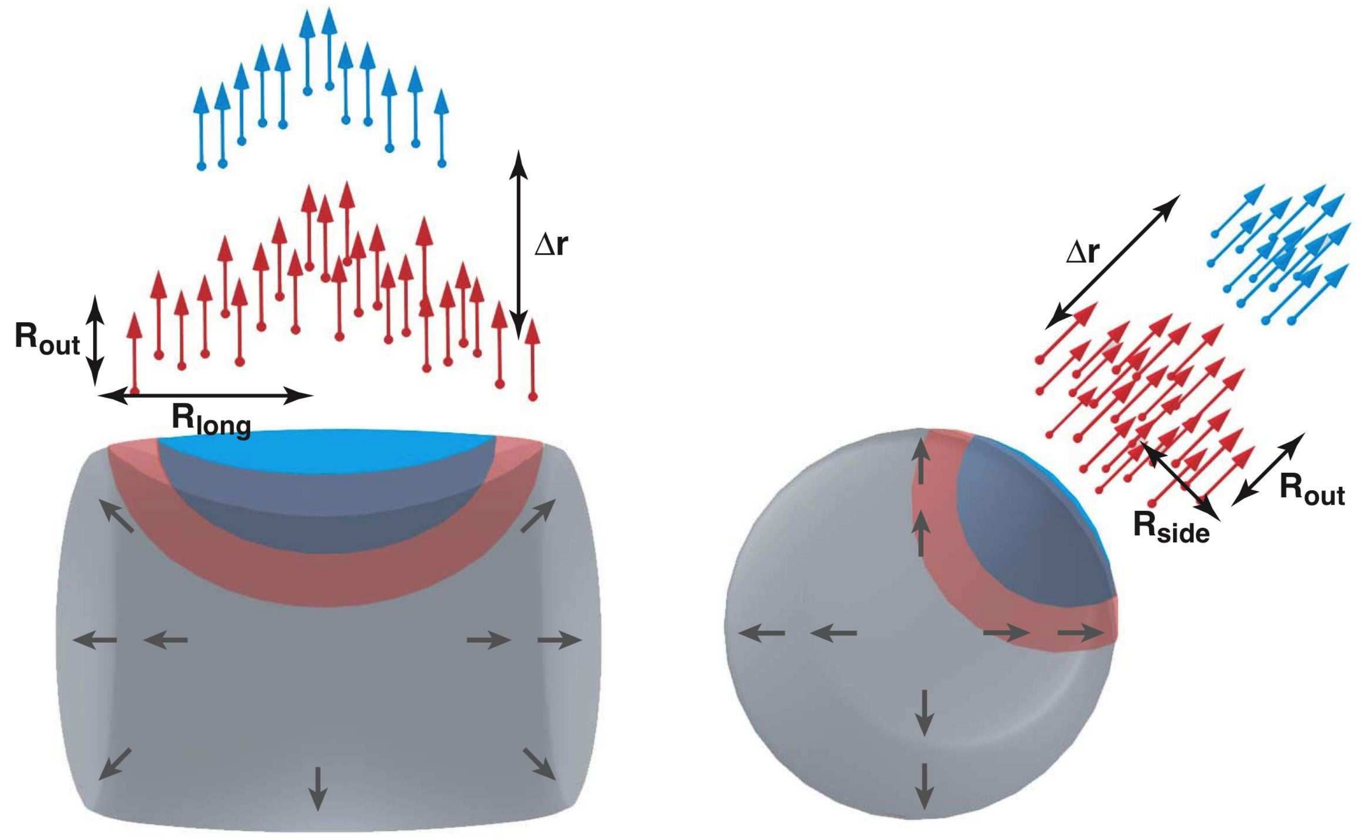
JAM: JET AA Microscopic Transportation Model
UrQMD: Ultra-relativistic Quantum Molecular Dynamics

Y. Nara et al., PRC61, 0249021 (1999)
S. Bass et al., Prog.Part.Nucl.Phys.41, 255 (1998)

Transport models with baryonic mean-field (JAM, UrQMD) qualitatively describes the data, except K^+ v_2 (and π v_1, Λ v_2).

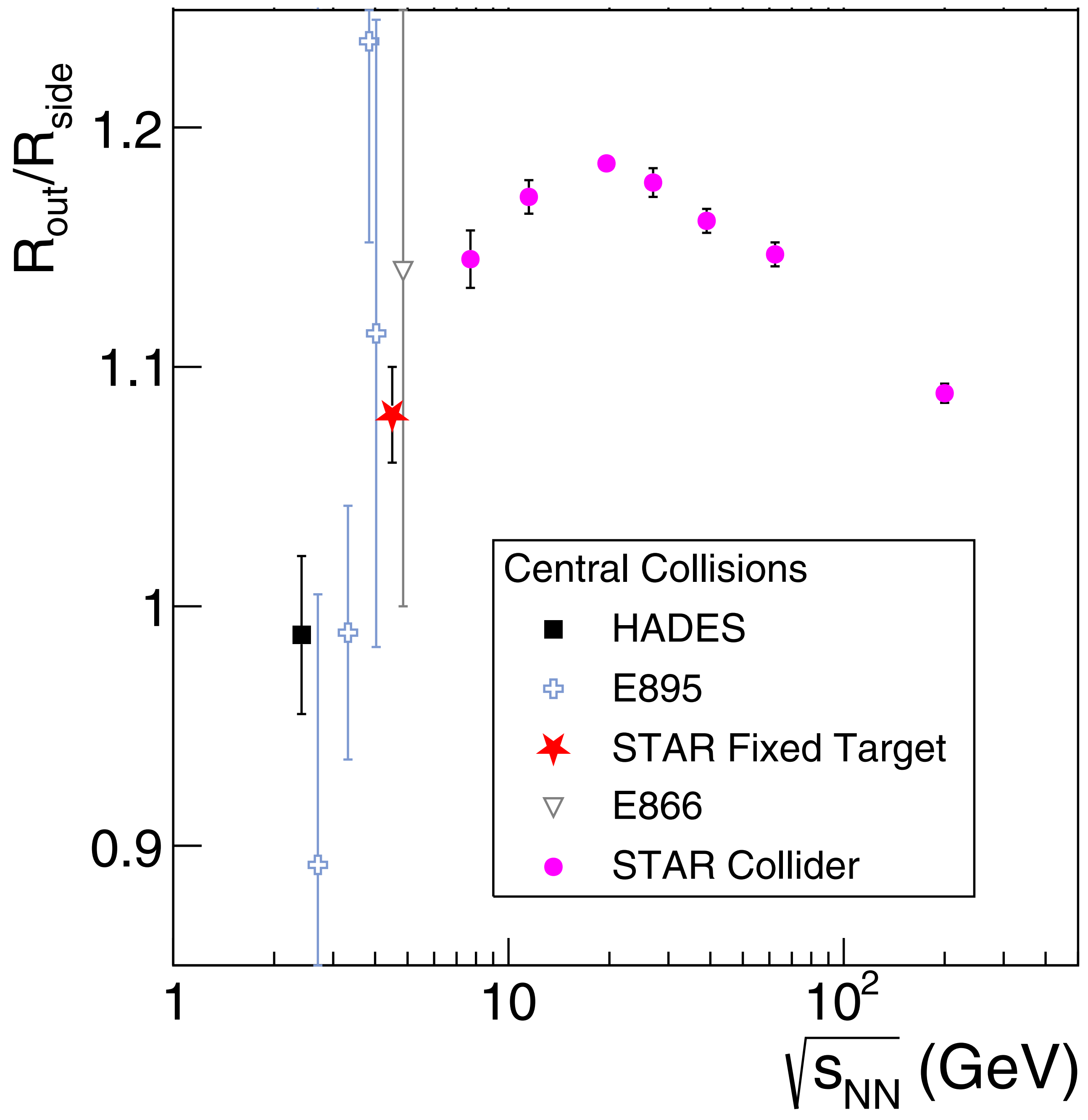
Femtoscopy

M. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357 (2005)

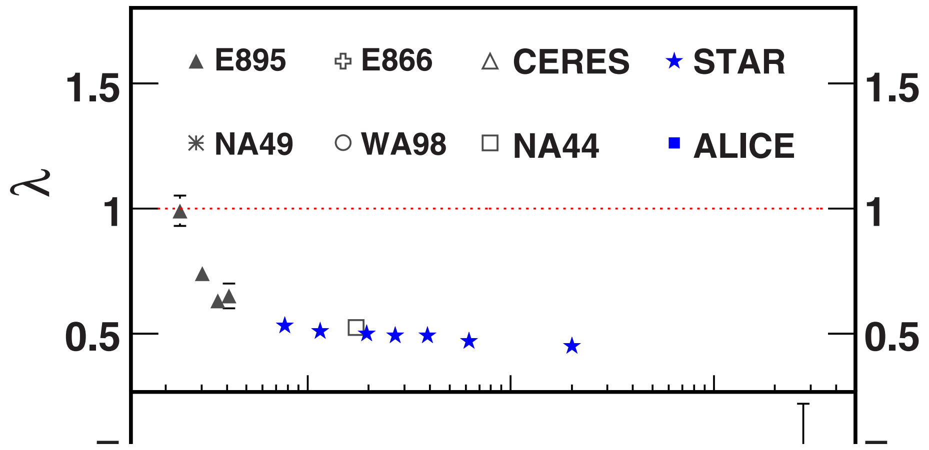


$$C(k^*) = \frac{P(\vec{p_1}, \vec{p_2})}{P(\vec{p_1})P(\vec{p_2})}$$
$$= \int S(\vec{r})\,|\Psi(k^*, \vec{r})|^2\, d\vec{r}$$

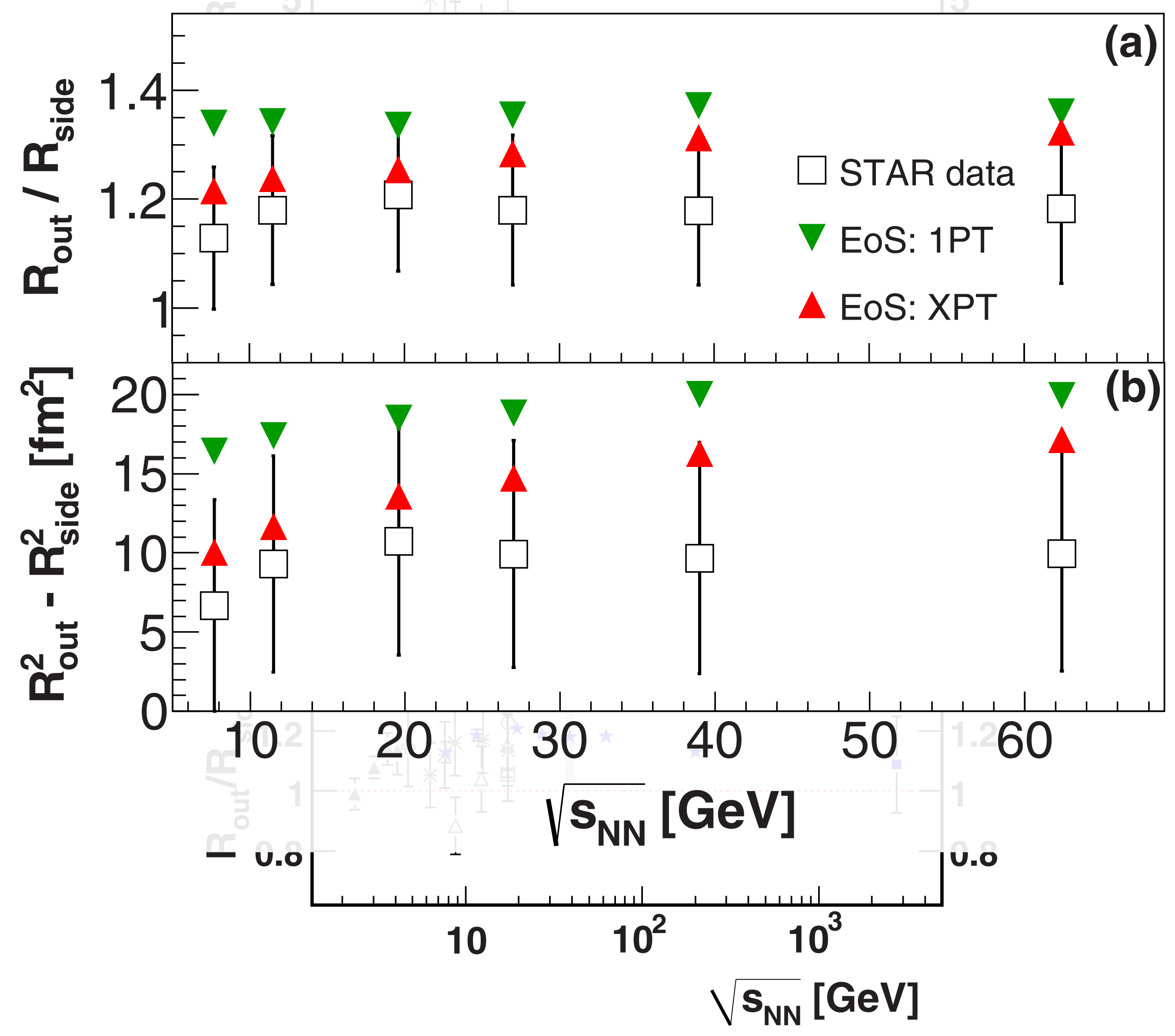
STAR, PRC103, 034908 (2021)



STAR, PRC92, 014904 (2015)



Viscous hydro+cascade (vHLLE+UrQMD)
P. Batyuk et al., PRC96, 024911 (2017)



"HBT" radii (Gaussian source size)

R_{long} : source radius along the beam axis

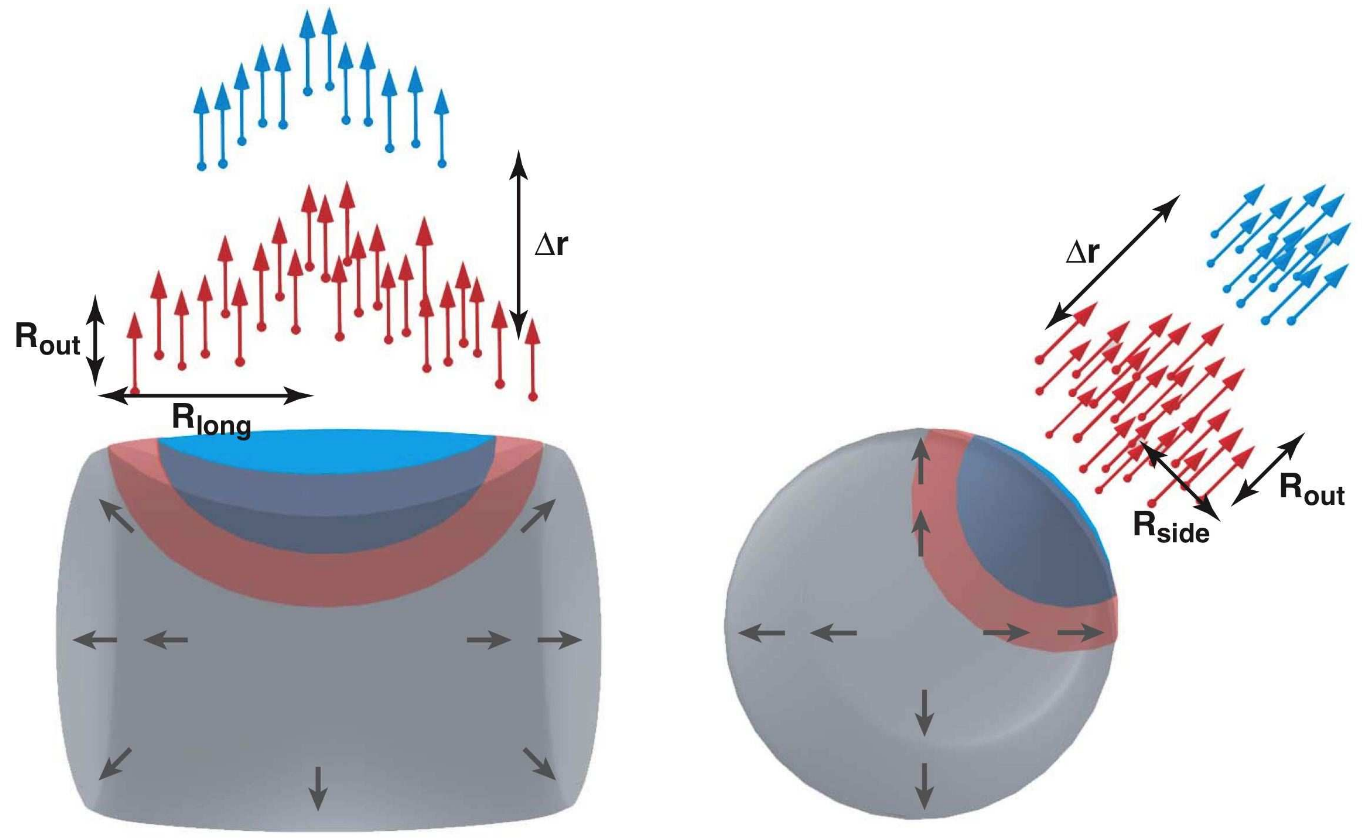
R_{out} : transverse radius + emission duration, parallel to pair momentum

R_{side} : transverse radius, orthogonal to R_{long} and R_{out}

- R_{out}/R_{side}, sensitive to the emission duration, peaks around 20 GeV. Indication of EOS softest point?
  - Model study shows sensitivity of HBT measurements to the EOS
- New data from BES-II+FXT will fill in 3-27 GeV with better precision

Femtoscopy

M. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357 (2005)



$$C(k^*) = \frac{P(\vec{p_1}, \vec{p_2})}{P(\vec{p_1})P(\vec{p_2})}$$
$$= \int S(\vec{r}) \left|\Psi(k^*, \vec{r})\right|^2 d\vec{r}$$

<u>"HBT" radii (Gaussian source size)</u>

R_{long} : source radius along the beam axis

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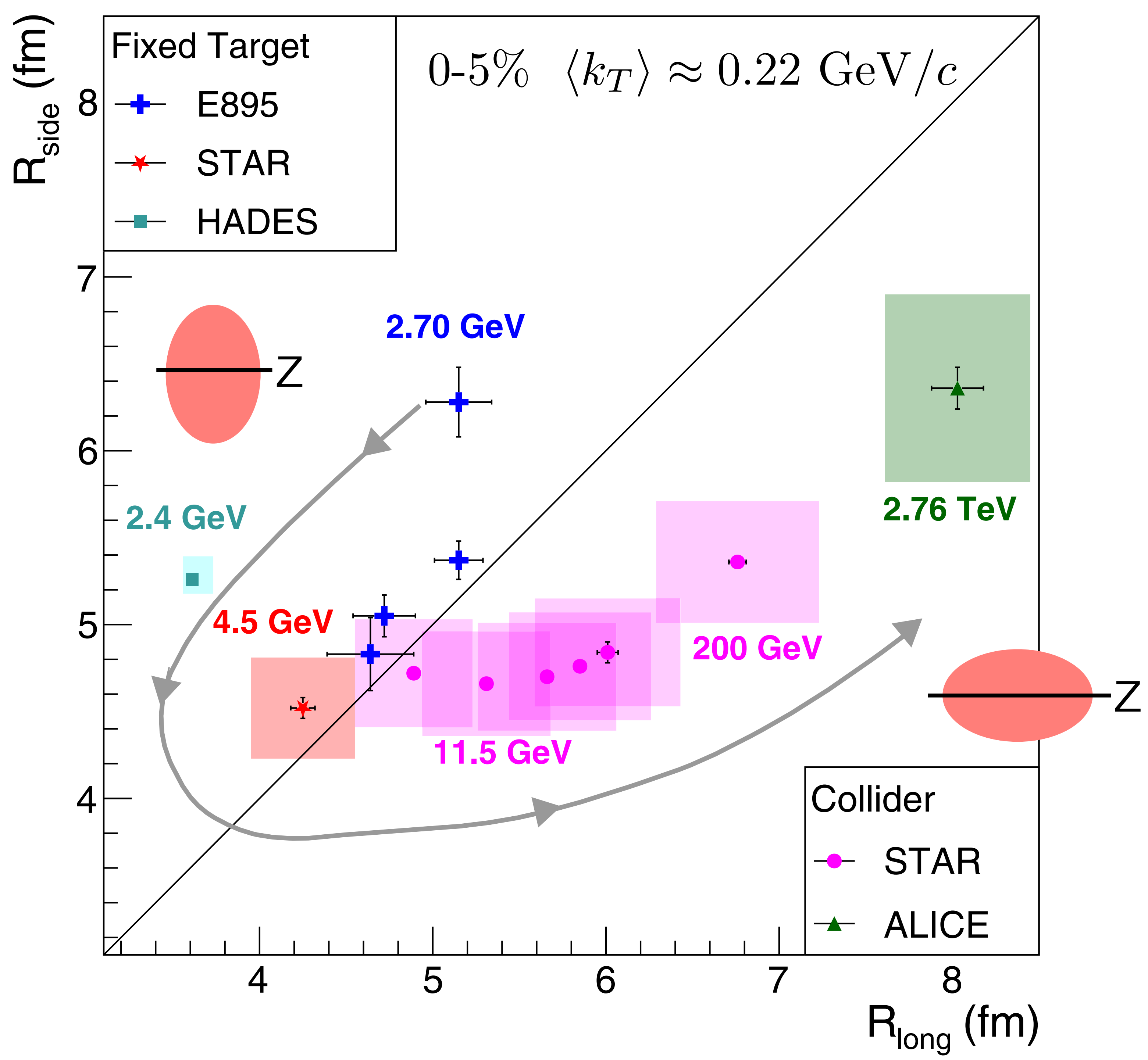
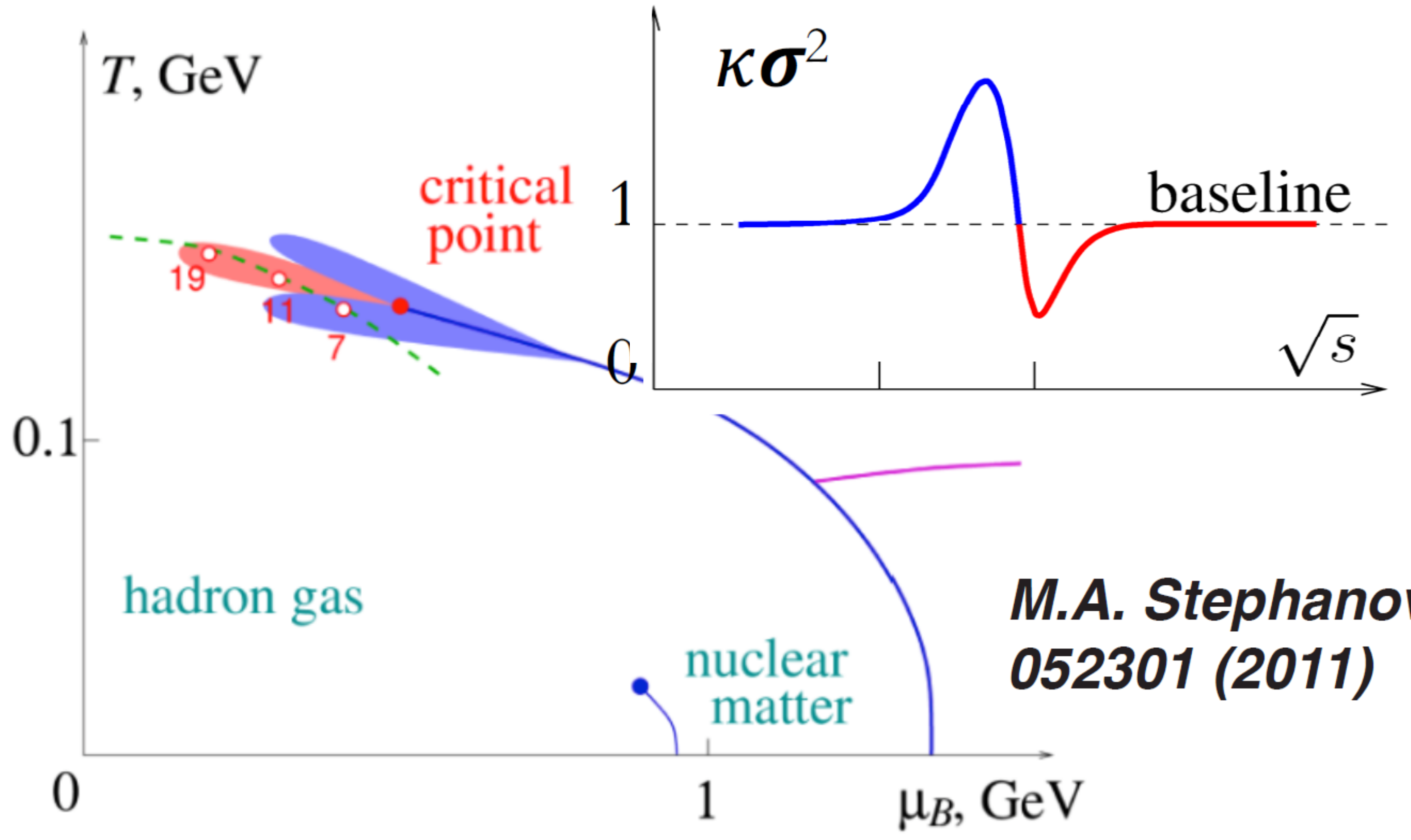


- Pion emission region turns from "oblate" to "prolate" shape around 4.5 GeV when increasing collision energy
  - Evolution from stopping at lower energies to longitudinally boost-invariance at higher energies

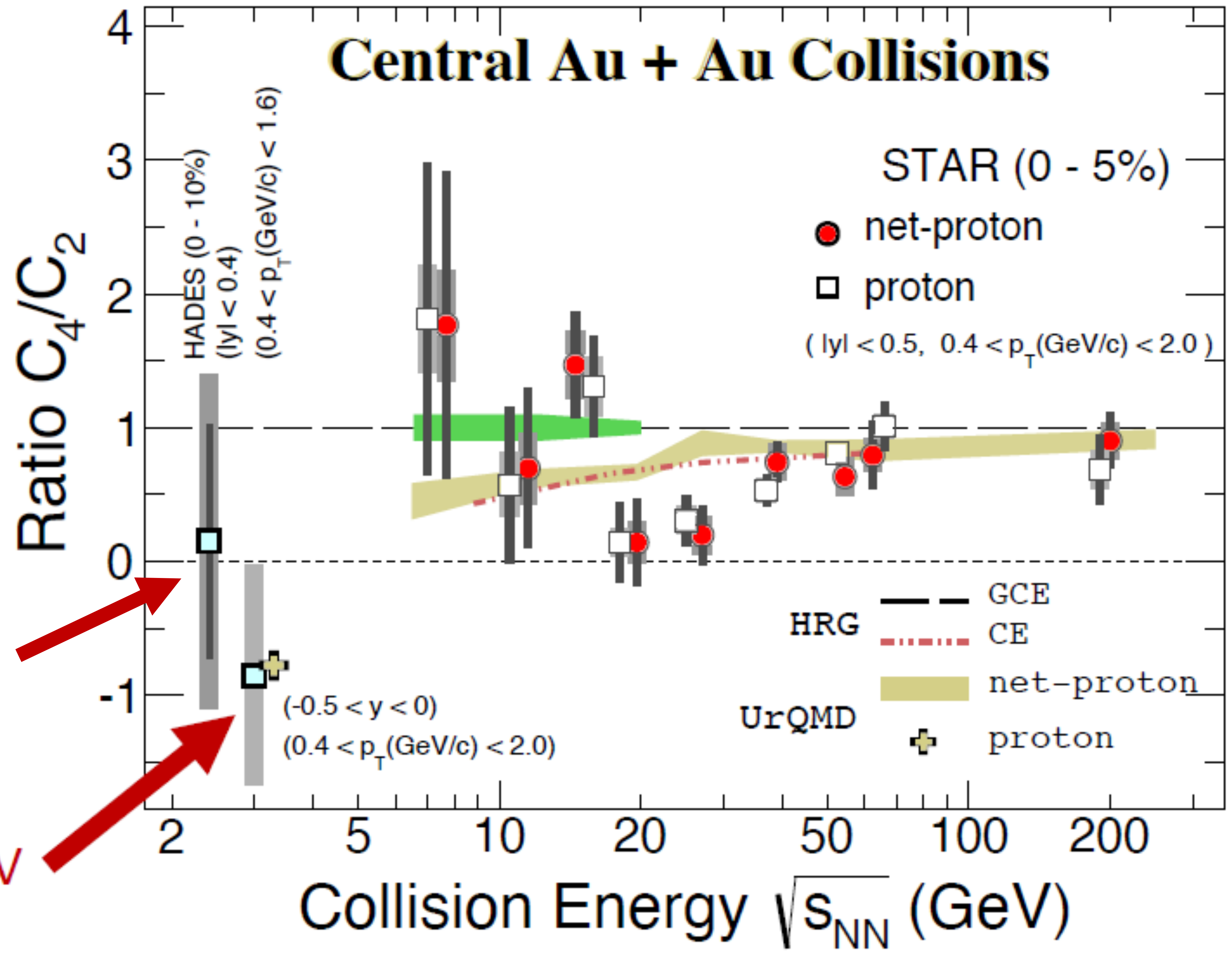
CP search with net-proton fluctuations

- Correlation length ξ diverges at CP (for infinite volume system)
- Fluctuations of conserved quantity sensitive to ξ
  - Net-proton is used as a proxy of net-baryon

M. Stephanov, PRL102.032301 (2009)
M. Asakawa et al., PRL103.262301(2009)
Y. Hatta and M. Stephanov, PRL91, 102003 (2003)



M.A. Stephanov, PRL107, 052301 (2011)



2.4 GeV

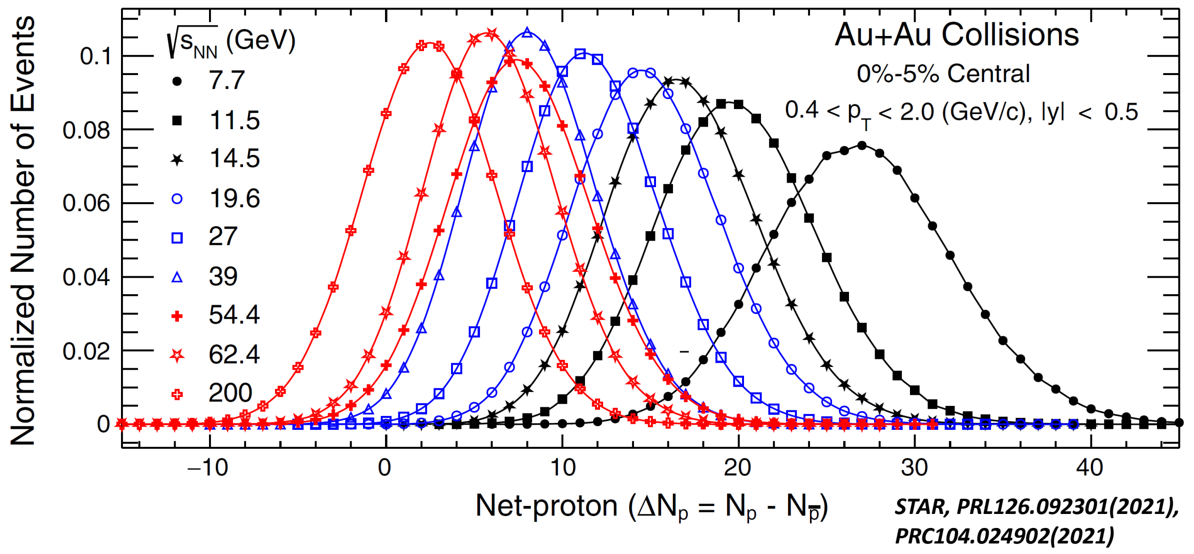
3 GeV

STAR, PRL128, 202303 (2022)
HADES, PRC102.024914 (2020)

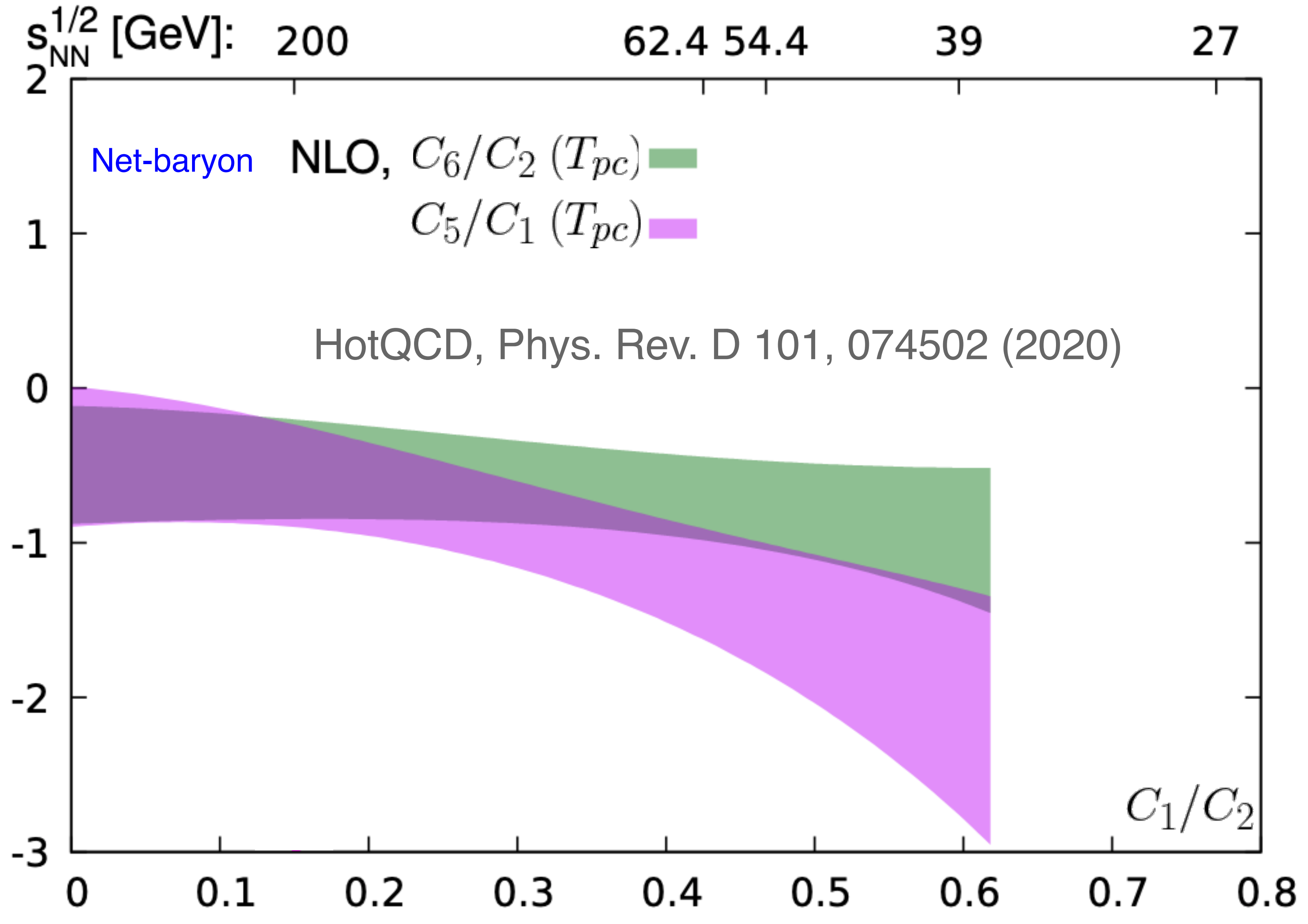
- Non-monotonic energy dependence of C_4/C_2. Qualitatively consistent with model expectation having a CP
- Suppression at 3 GeV, explained by baryon conservation (UrQMD)
- Need precise measurements around 3-20 GeV
  - Coming soon from BES-II

$$C_1 = \langle N \rangle,\ C_2 = \langle (\delta N)^2 \rangle \quad \delta N = N - \langle N \rangle$$

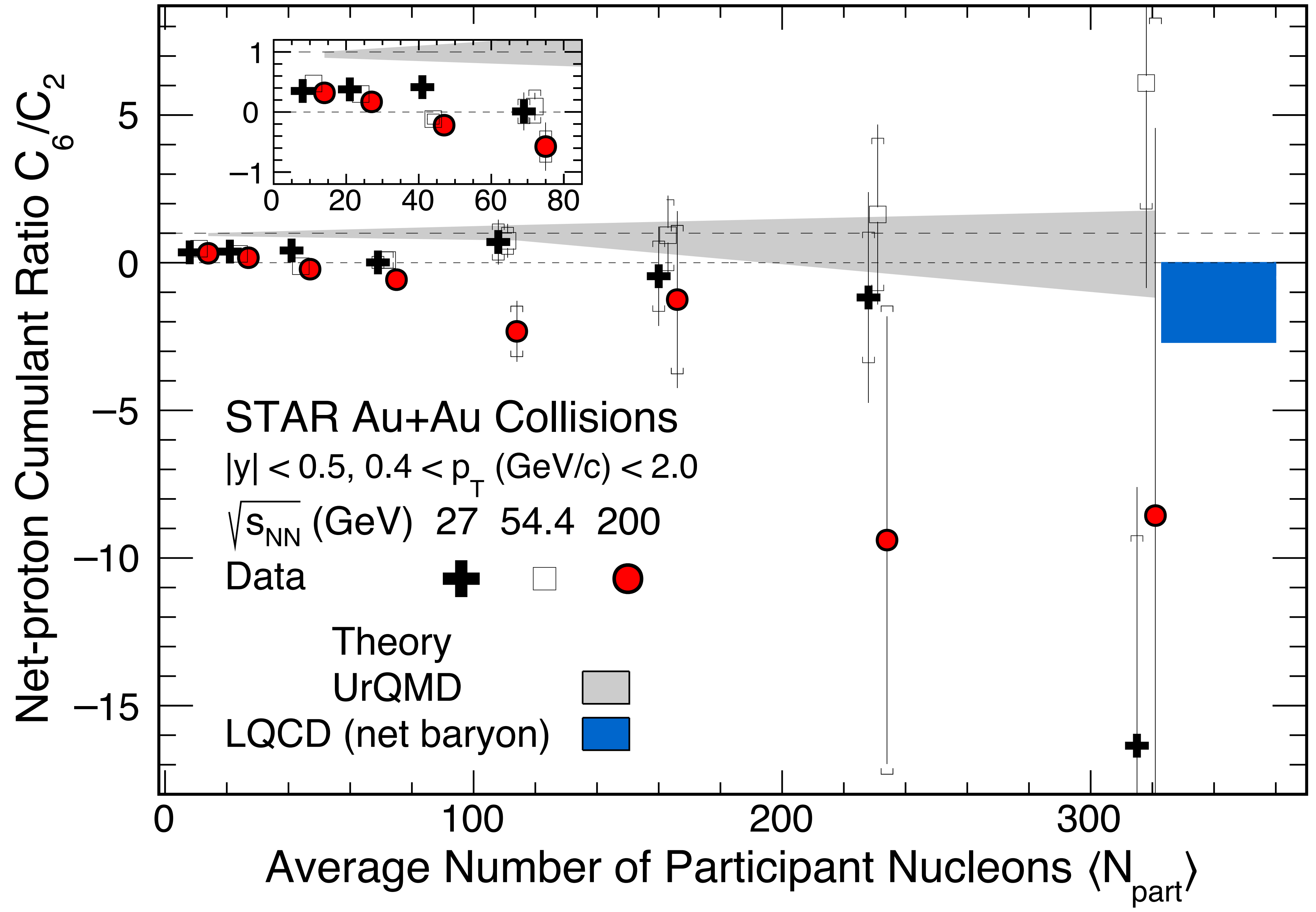
$$C_3 = \langle (\delta N)^3 \rangle \quad C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$



Search for the signal of crossover PT

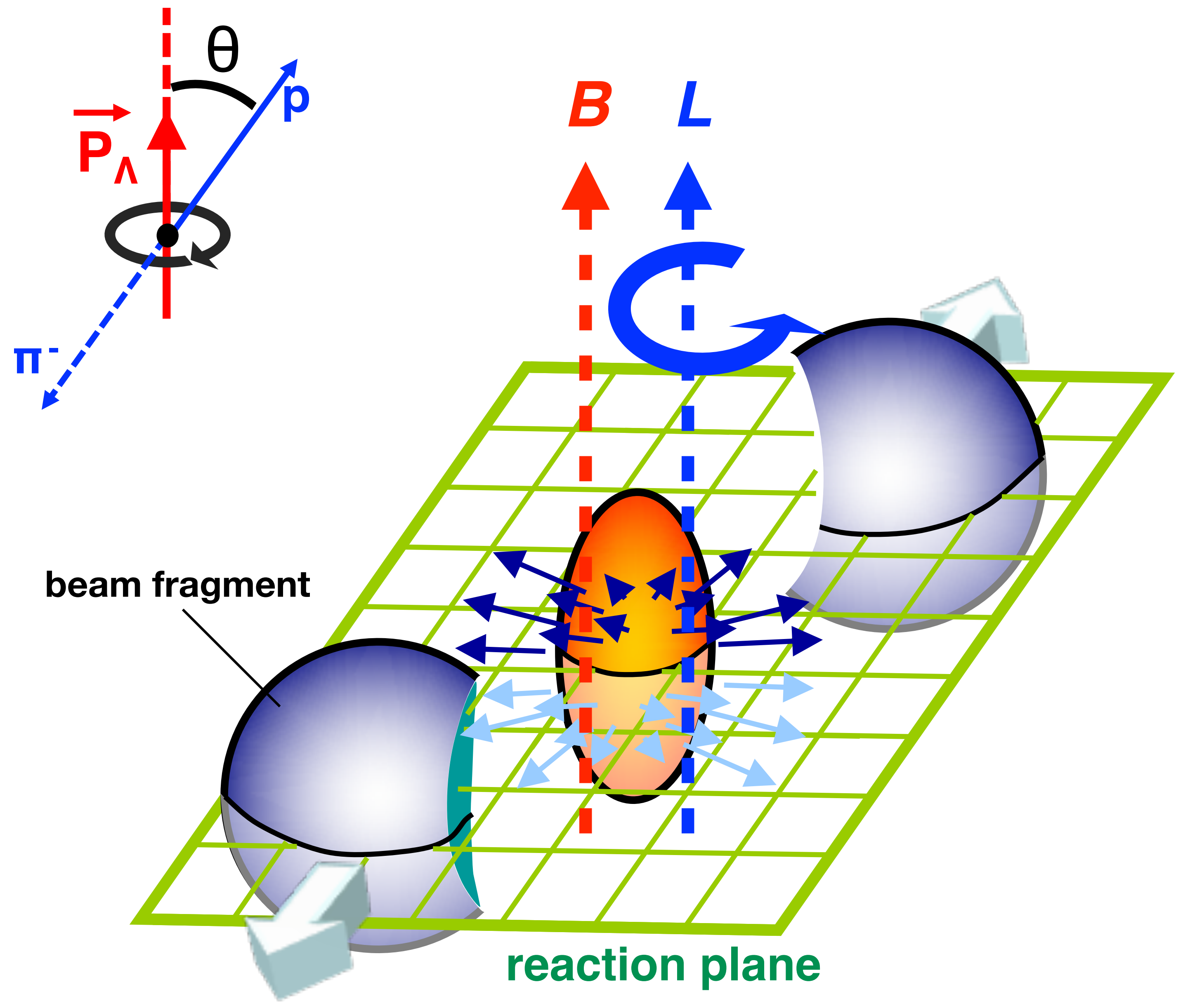


STAR, PRL127.262301 (2021)

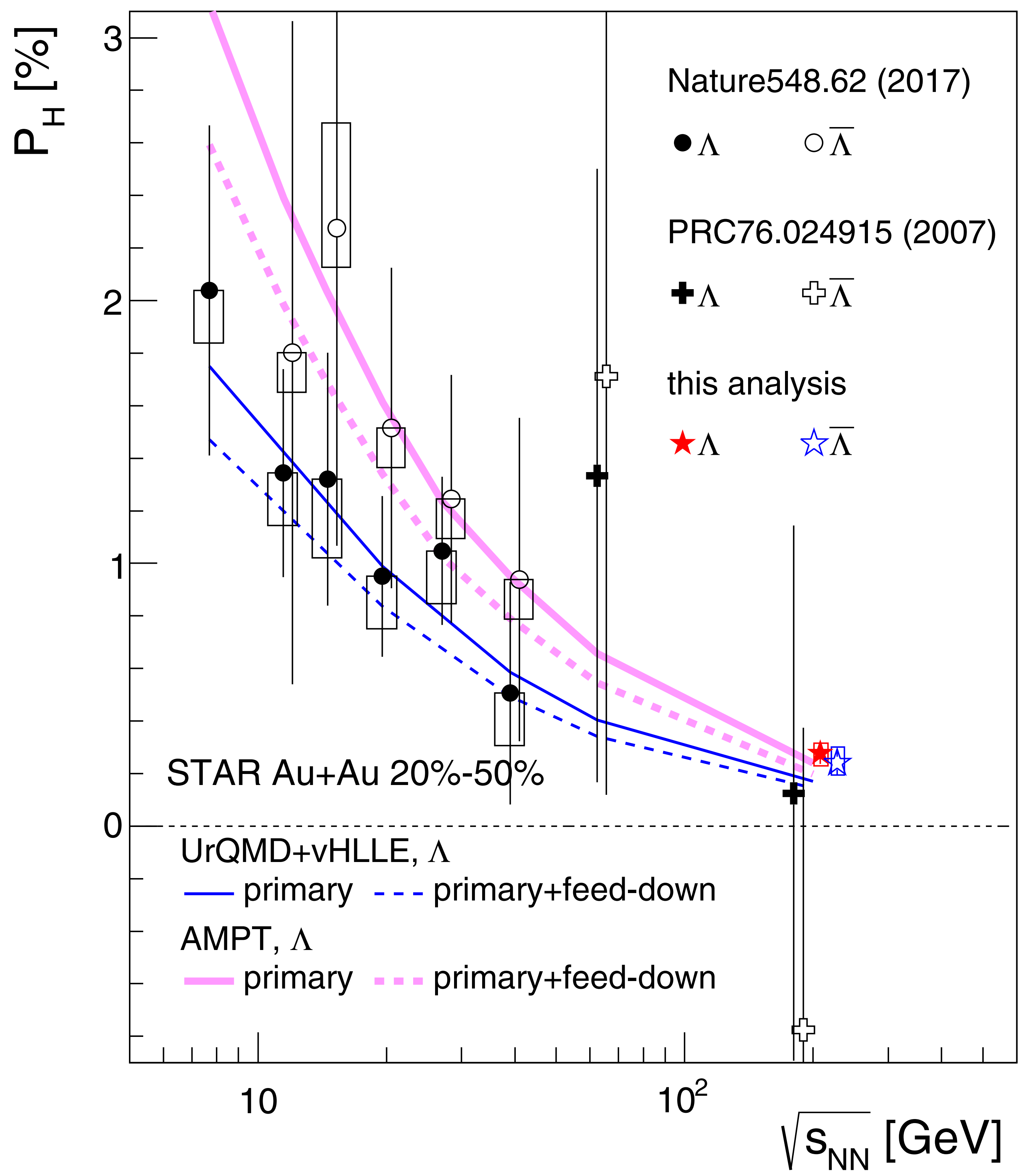


- Lattice QCD shows a smooth crossover at small μ_B but no experimental evidence so far
  - Lattice QCD predicts C5 and C6 to be negative for crossover PT
- At 200 GeV, the sign of C_6/C_2 seems to become negative when going to central collisions

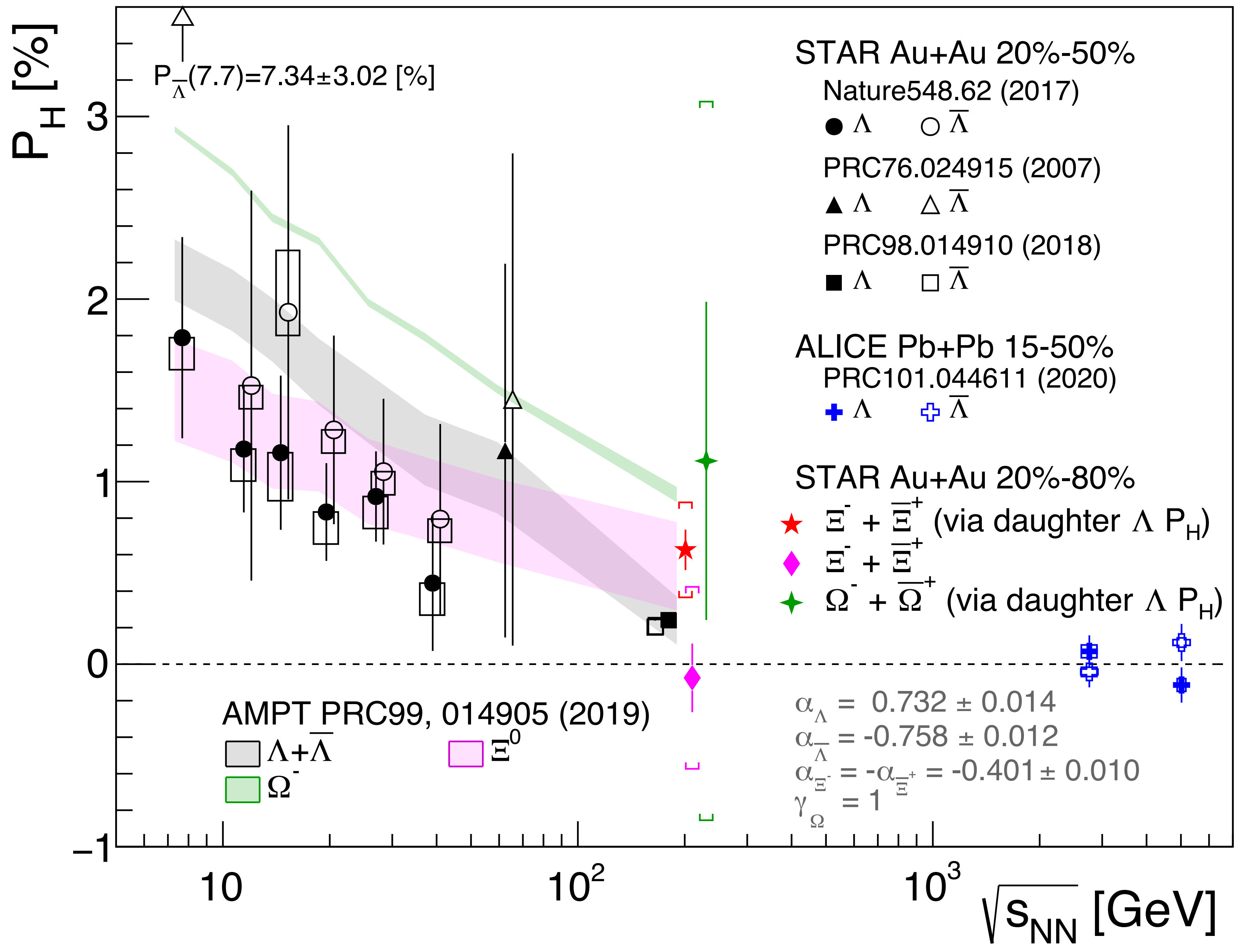
Global polarization of hyperons



STAR, Nature 548, 62 (2017)
STAR, PRC98, 014910 (2018)



STAR, PRL126, 162301 (2021)



"global polarization"

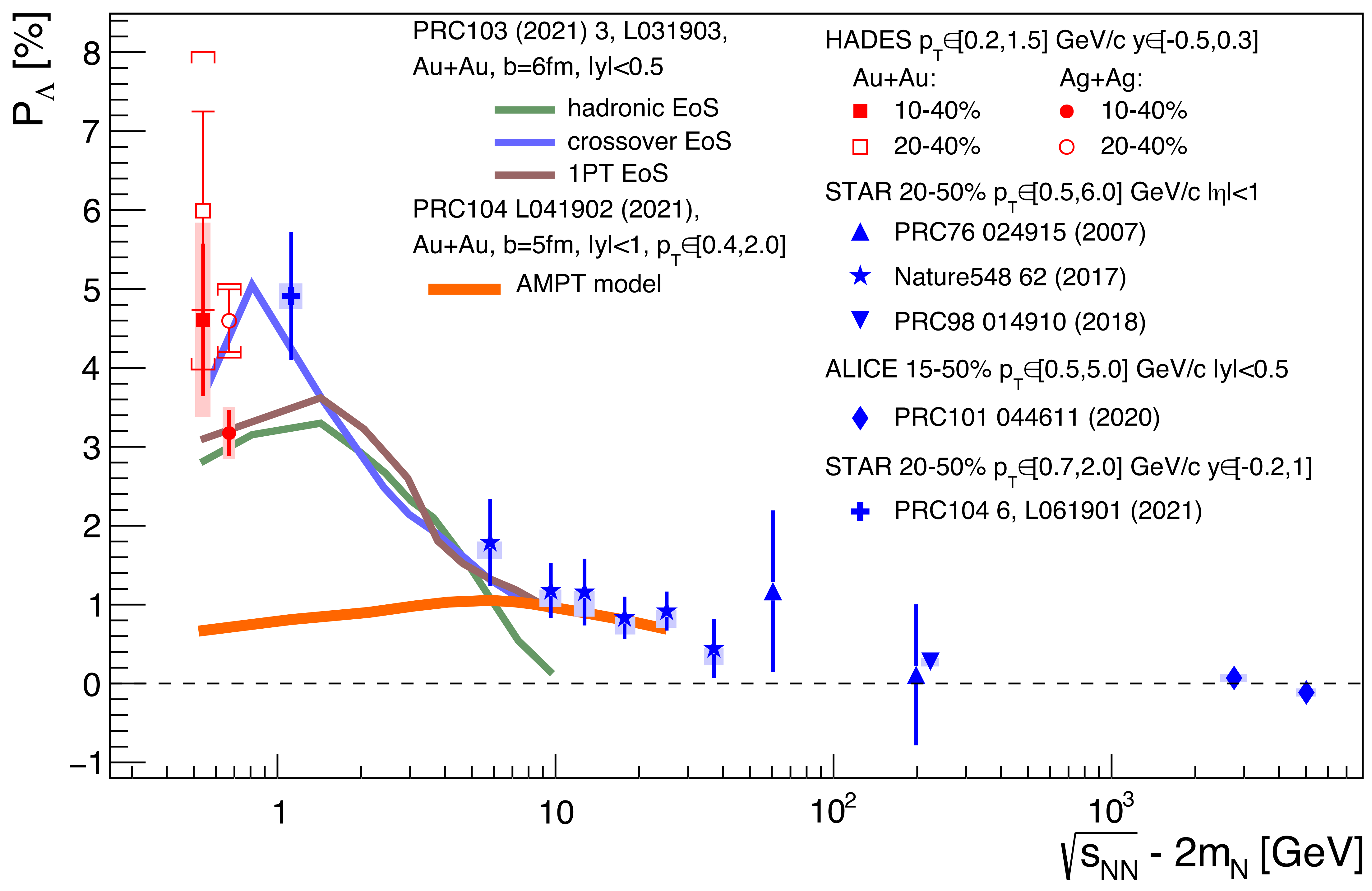
Initial orbital angular momentum L, partially transferred to the medium, polarize particles' spin globally.

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
S. Voloshin, nucl-th/0410089 (2004)
F. Becattini, F. Piccinini, and J. Rizzo, PRC77, 024906 (2008)

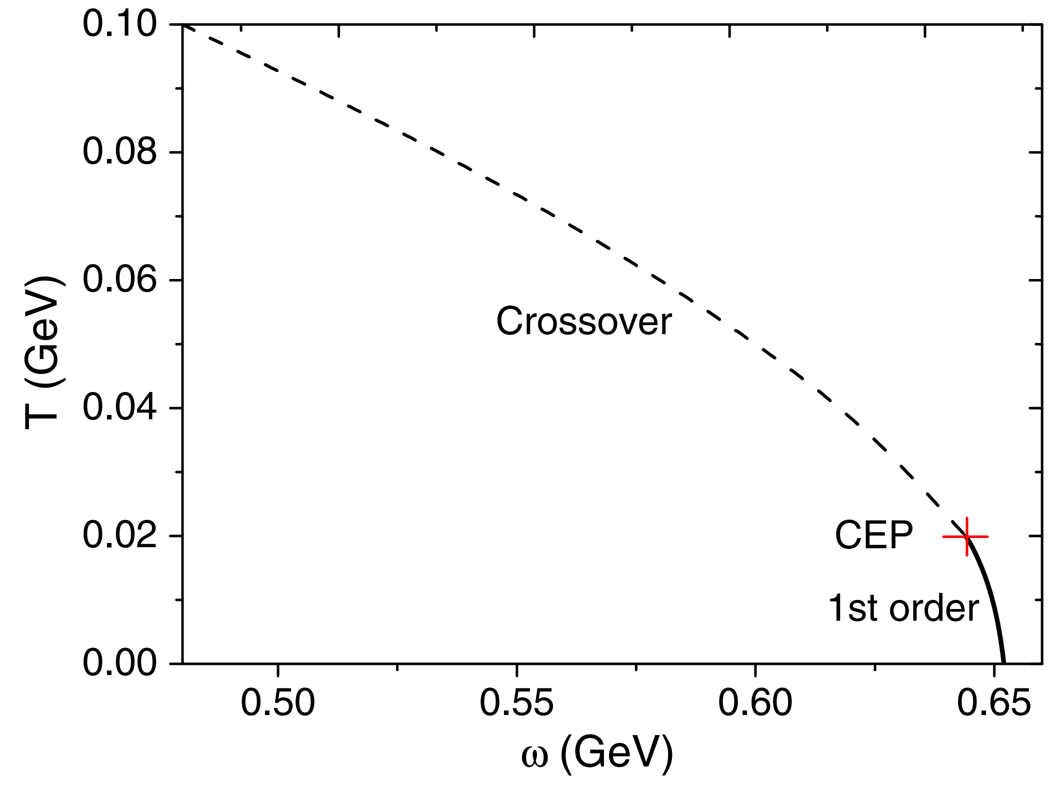
- Observation of Λ global polarization indicates the creation of the thermal vorticity, which is found to be the most vortical fluid ($\omega \sim 10^{21}$ 1/s)
- Recent measurements with Ξ(spin-1/2) and Ω(spin-3/2) supports the vorticity picture

Energy dependence of Λ global polarization

STAR, PRC104, L061901 (2021)
HADES, PLB835.2022.137506 (2022)



- Continuous increase down to $\sqrt{s_{NN}}$~2.5 GeV
  - Predicted to have the maximum around $\sqrt{s_{NN}}$ = 3 GeV
  - Slope seems to change around $\sqrt{s_{NN}}$ = 7-10 GeV, relying on model calculations (need data)
  - Little but slight dependence on EOS at low energy
- New data will come from STAR BES-II (3-27 GeV)



Y. Jiang and J. Liao, PRL117.192302(2016)
Y. Fujimoto, K. Fukushima, Y. Hidaka, PLB816(2021)136184

Summary

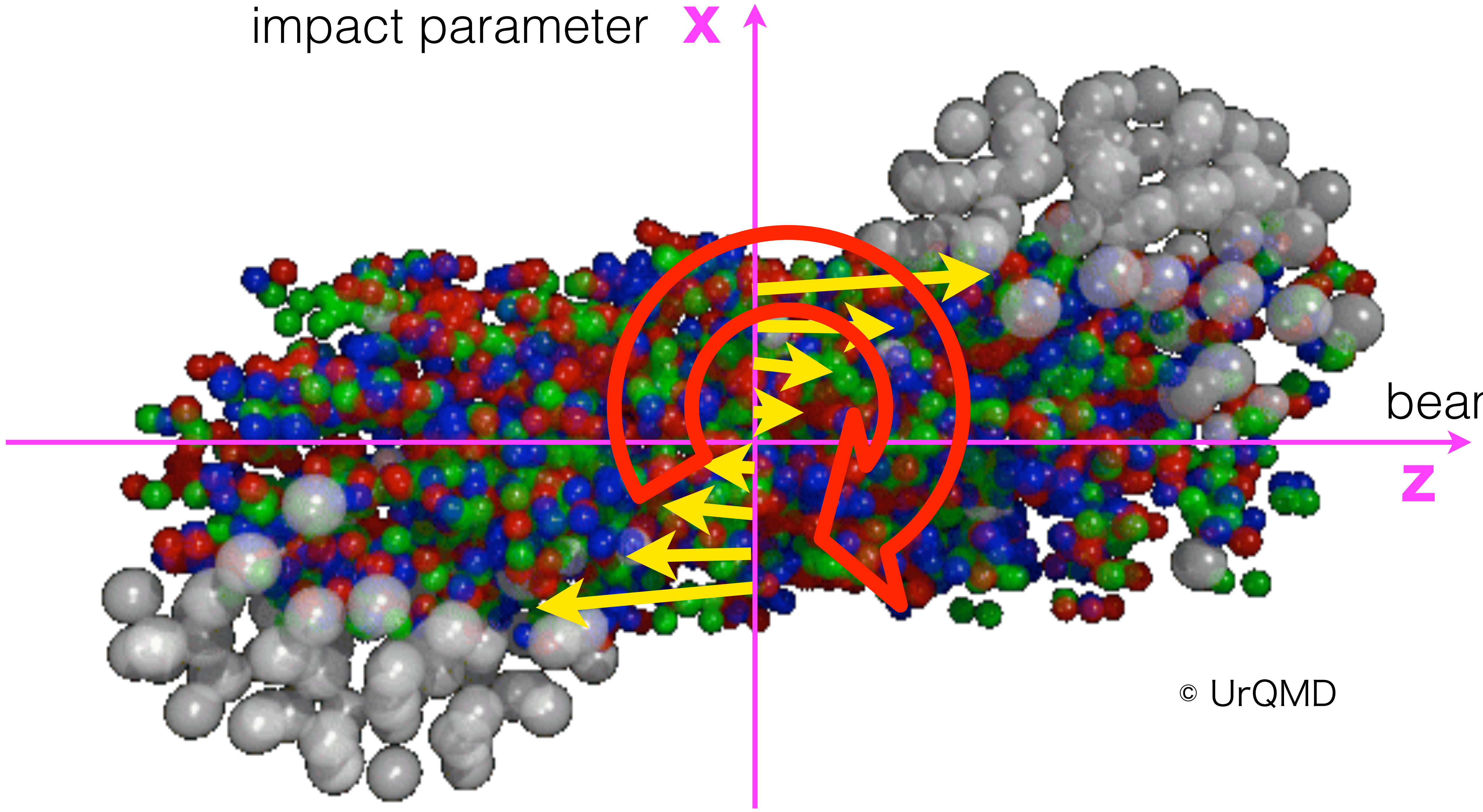
- Beam energy scan program at RHIC-STAR
  - Signatures of QGP formation observed at high energy are gone around $\sqrt{s_{NN}}$ = 3-10 GeV, e.g. breaking of NCQ scaling
  - Different observables such as flow, HBT, extracted temperatures show non-monotonic energy dependence, possibly related to the first-order phase transition. Some of the data are still not understood well by models.
  - Net-proton fluctuations show non-monotonic trend over the energy, qualitatively consistent with the expectation from CP but not conclusive yet

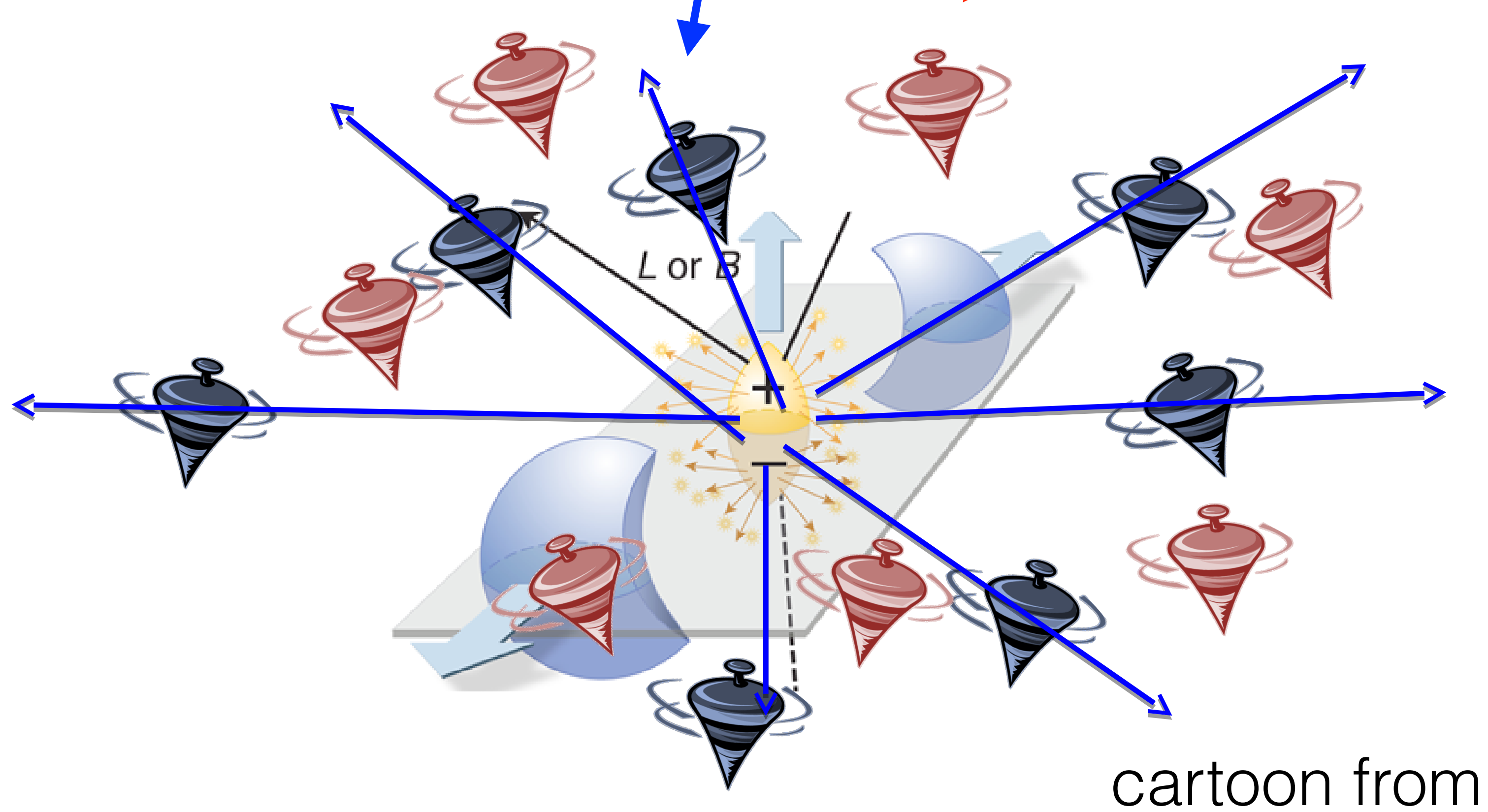
- BES-II data taking just finished and now data analyses have started.
  Stay tuned for more precise measurements!

Vorticity and polarization in HIC

Longitudinal shear flow is produced, where flow velocity v_z depends on x.

$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$





Particles are “globally" polarized along ***L***

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
S. Voloshin, nucl-th/0410089 (2004)
F. Becattini, F. Piccinini, and J. Rizzo, PRC77, 024906 (2008)