STAR highlights with focus on BES results

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Road map

- Beam Energy Scan program
- QCD Phase Diagram
- STAR experiment
- Main questions
- Summary and perspectives

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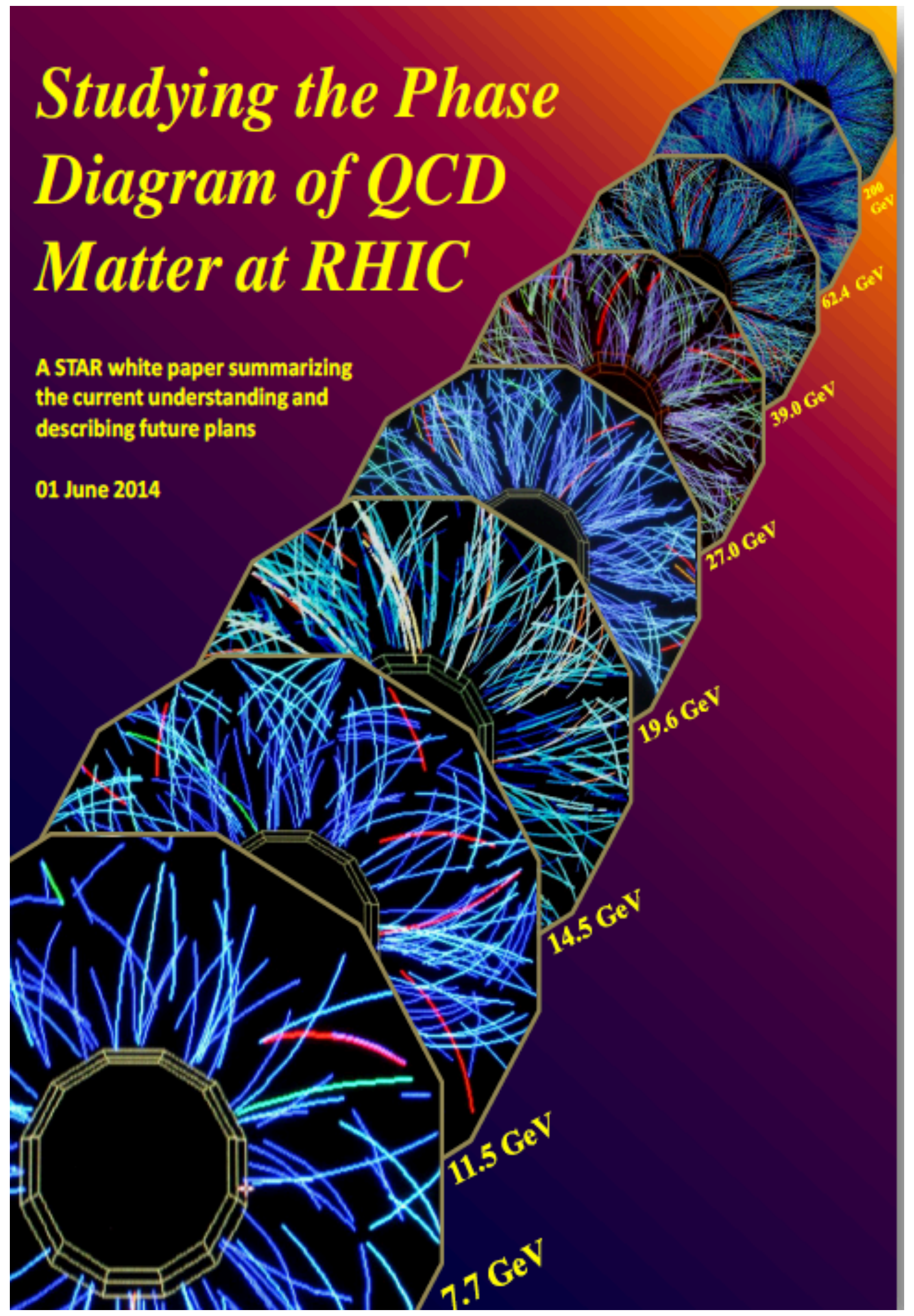
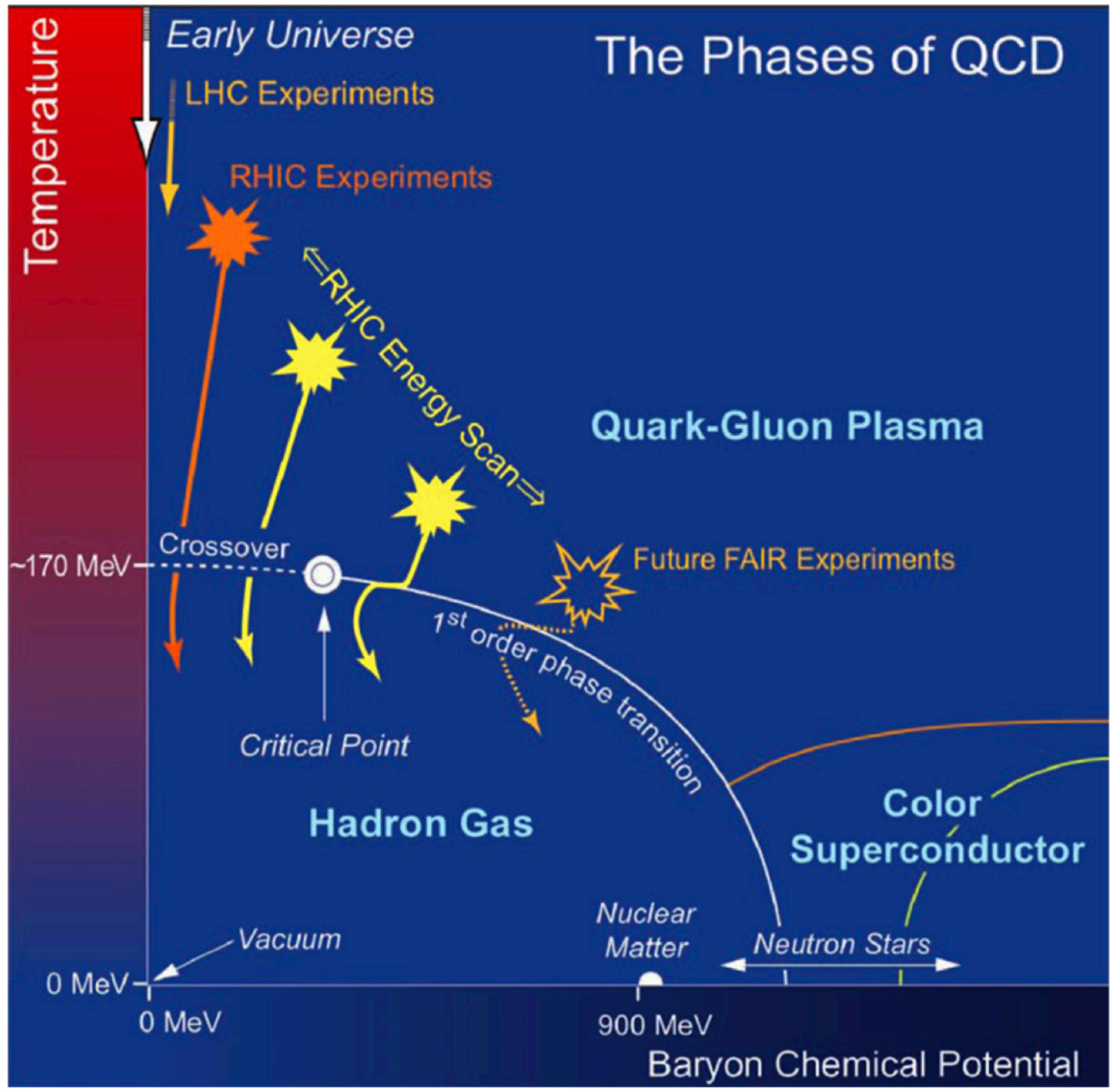
Beam Energy Scan program

Goals of the Beam Energy Scan Program:

1. Search for **turn-off** of **QGP** signatures
2. Search for signals of the **first-order phase transition**
3. Search for QCD **critical point**



http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598



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Probing QCD Phase Diagram

Heavy-ion collision used as a tool to probe QCD phase diagram

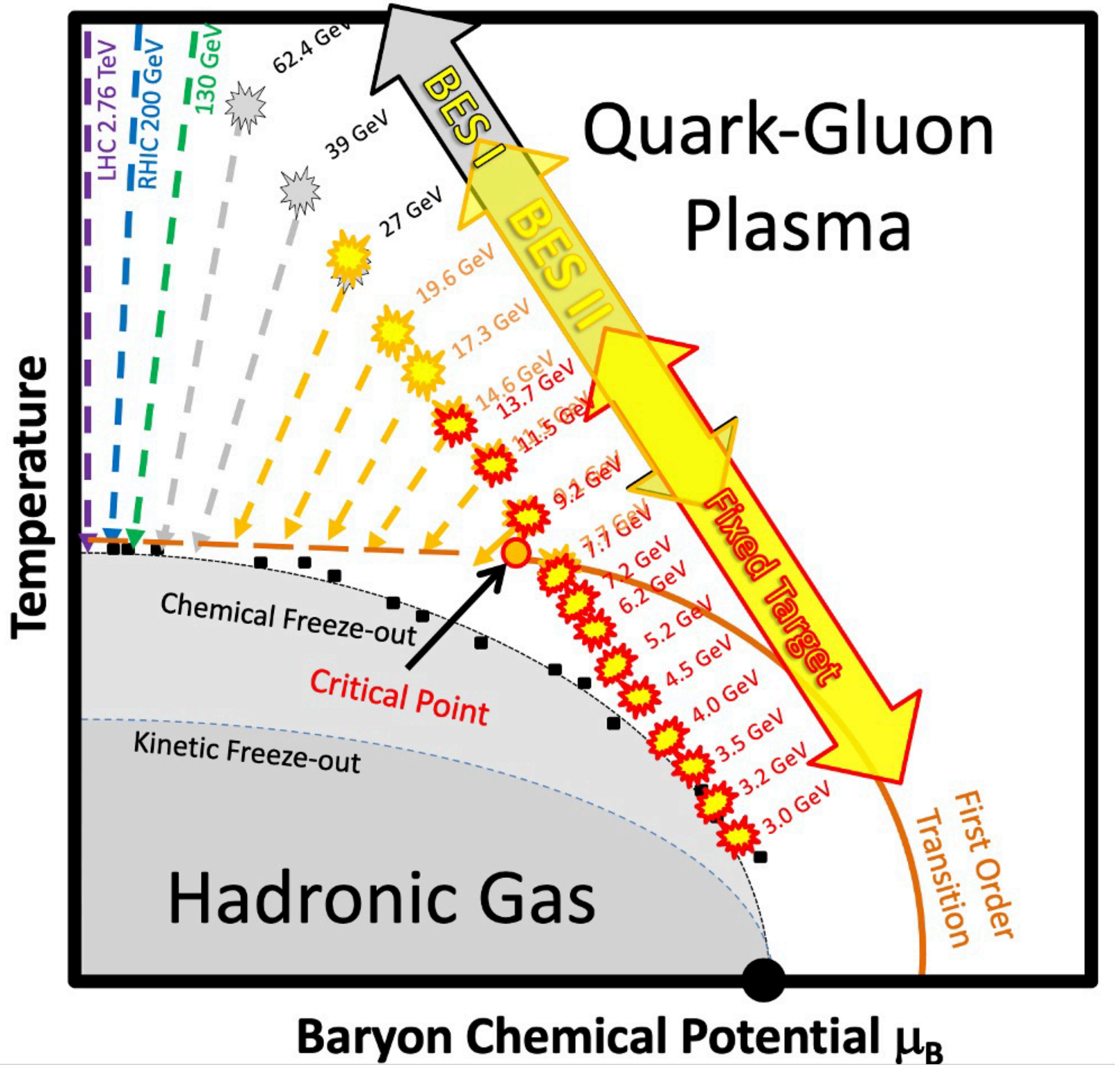
Believed to be understood:

Lattice QCD predicts a smooth **cross-over** transition at large T and $\mu_B \sim 0$

Various models predict **first-order phase transition** at large μ_B

Critical point is believed to exist, but.. where?

Strategy: to map the phase diagram (μ_B ,T) using heavy-ion collisions changing their collision energy: BES-I, BES-II (+FXT)



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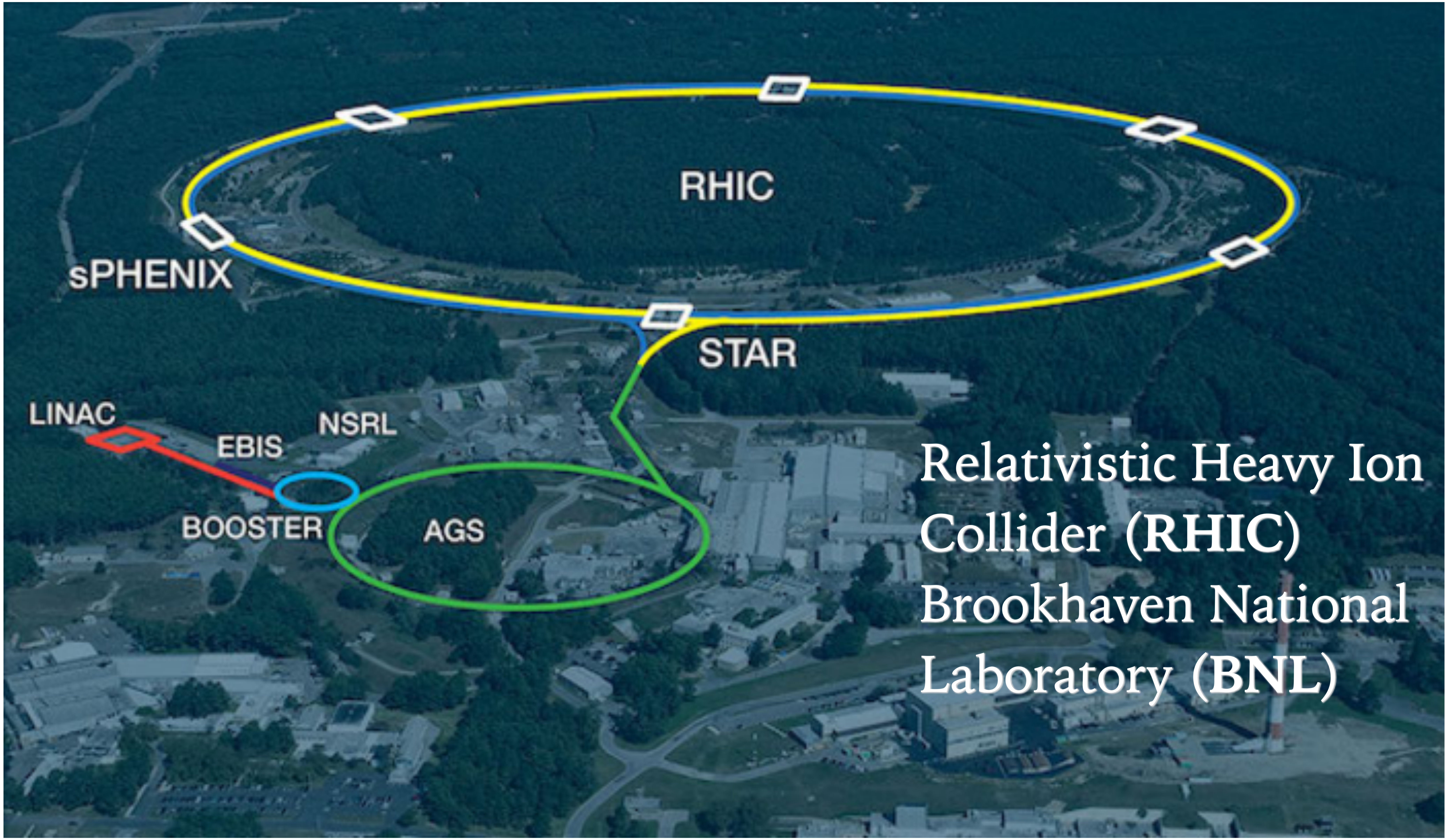
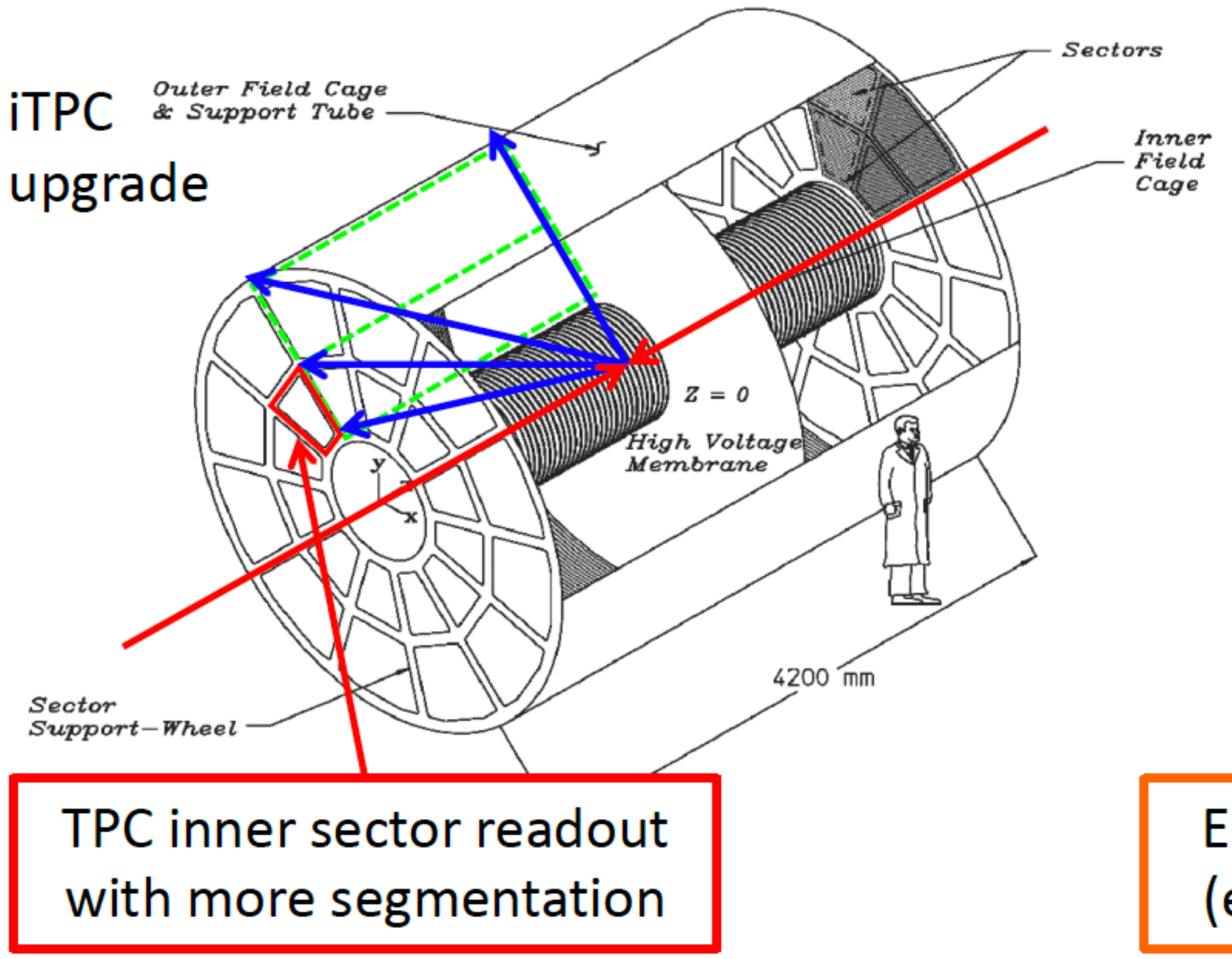
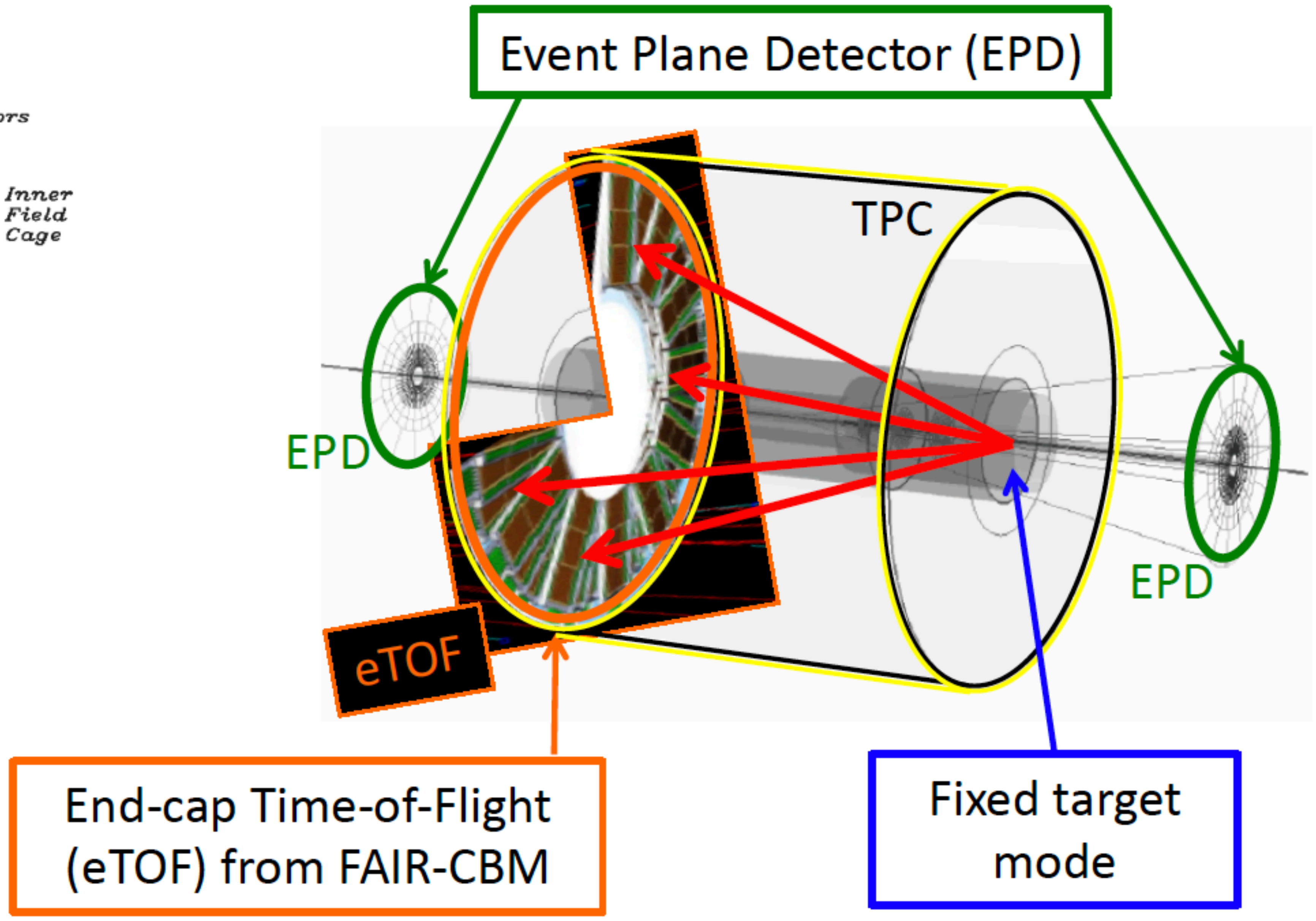
Relativistic Heavy Ion Collider

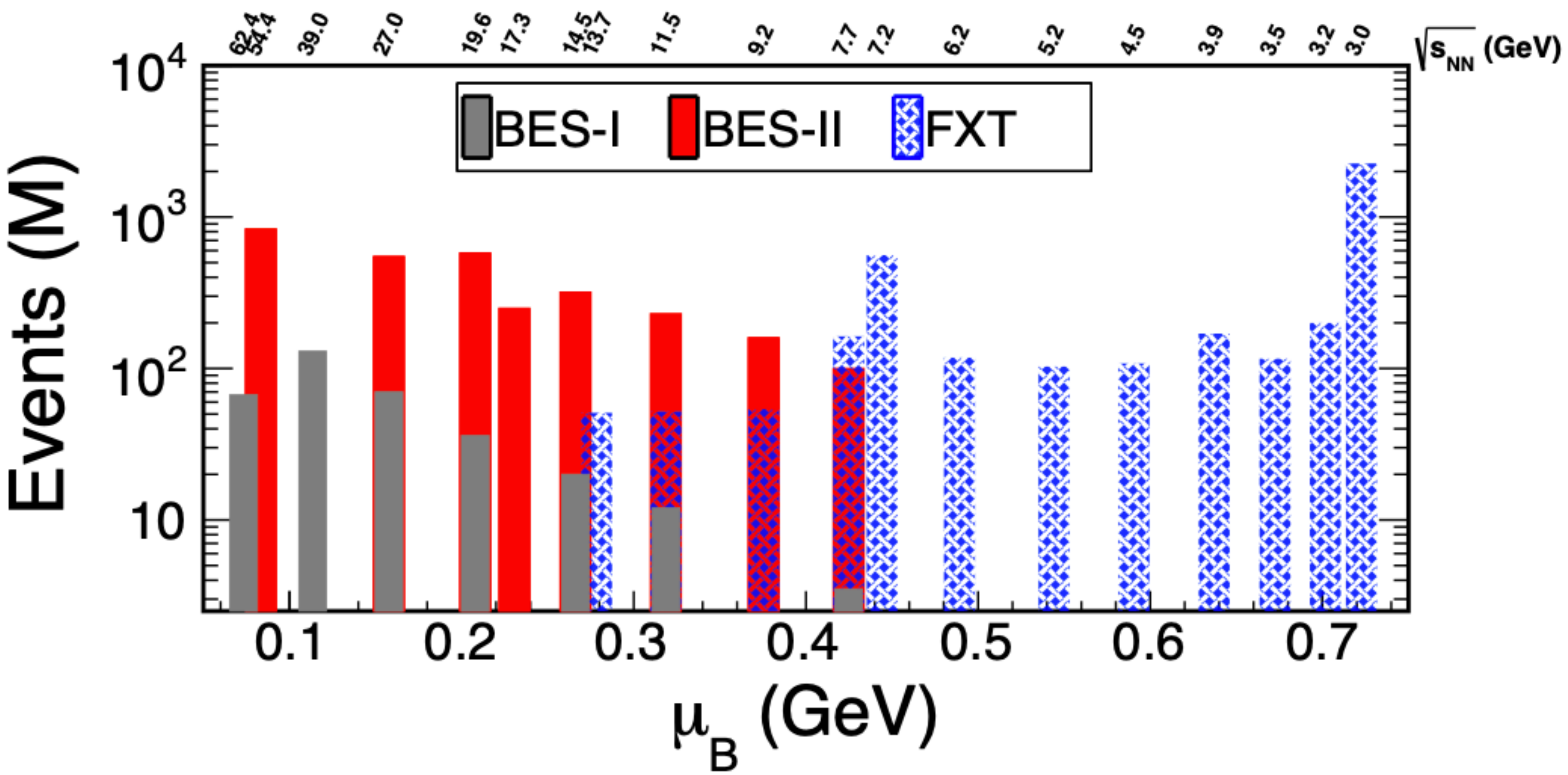
- 3.83 km circumference
- Two independent rings
- Collides so far:
  - Au+Au, p+p, d+Au, Cu+Cu, U+U, Cu+Au, ^{3}He+Au, p+Au Zr+Zr, Ru+Ru
- Top Center-of-Mass Energy
  - 510 GeV for p-p
  - 200 GeV/nucl. for Au-Au



STAR detector system







Solenoidal **T**racker **A**t **R**HIC originally designed to search for **Quark Gluon Plasma**.

BES program started at 2010.

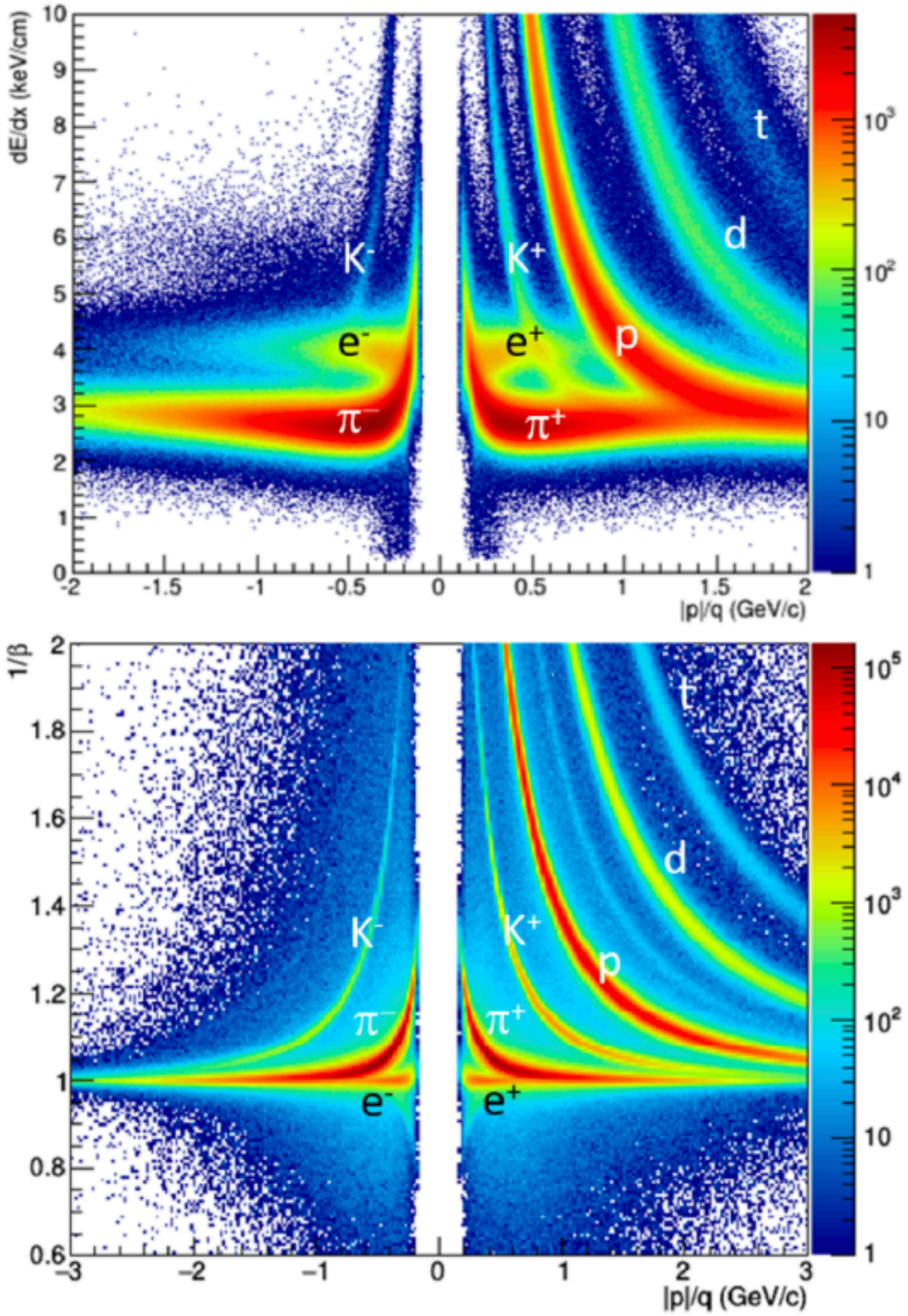
Luminosity of the RHIC collider-mode is unusable for $\sqrt{s_{NN}} < 7.7$ GeV.

Fixed-target (FXT) program extends the collision energy and μ_B coverage.

Particle identification

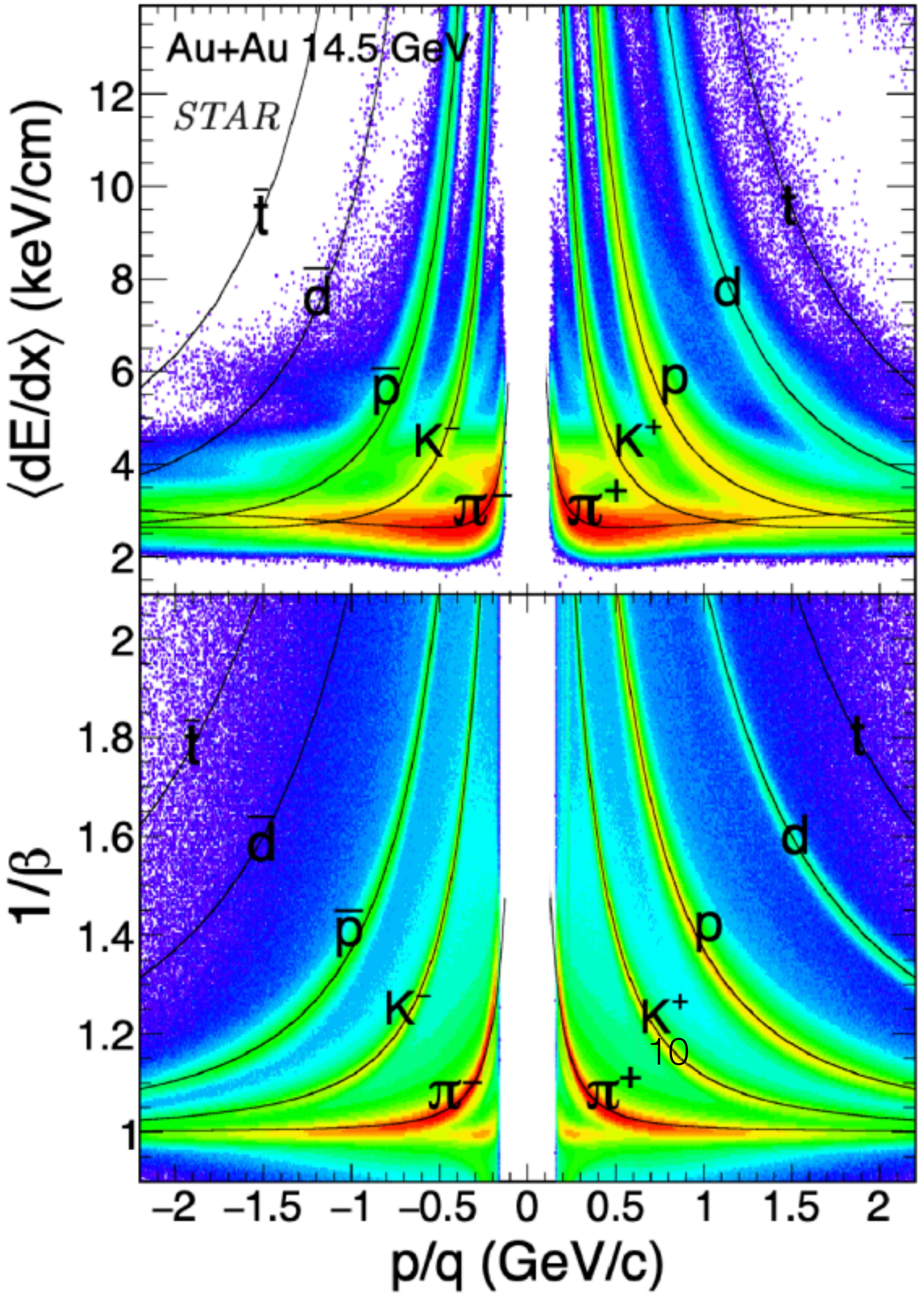
arXiv:2007.14005 (STAR)

$\sqrt{s_{NN}}$=4.5GeV Fixed Target



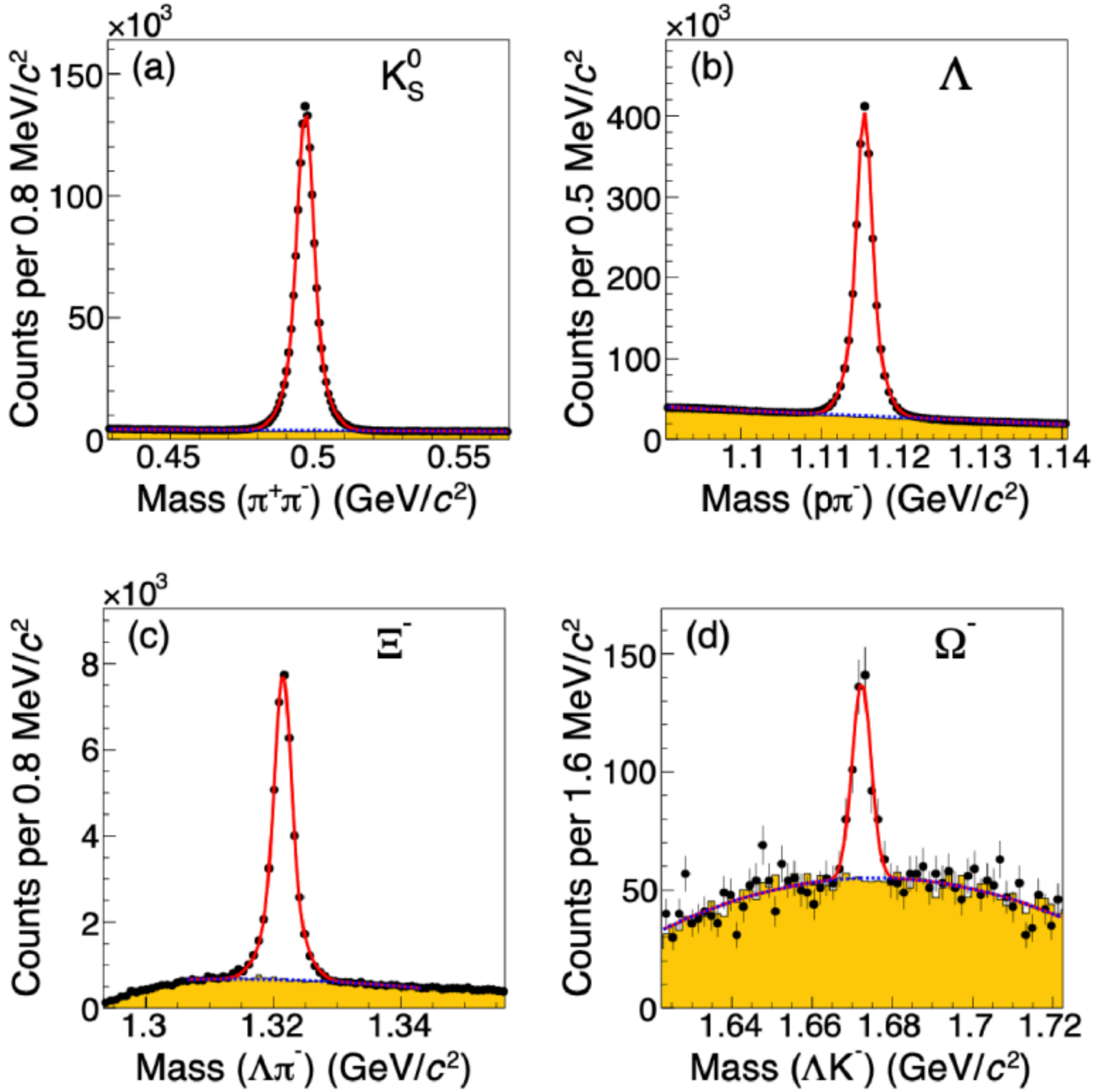
PRC 101 (2020) 24905 (STAR)

$\sqrt{s_{NN}}$=14.5GeV Collider

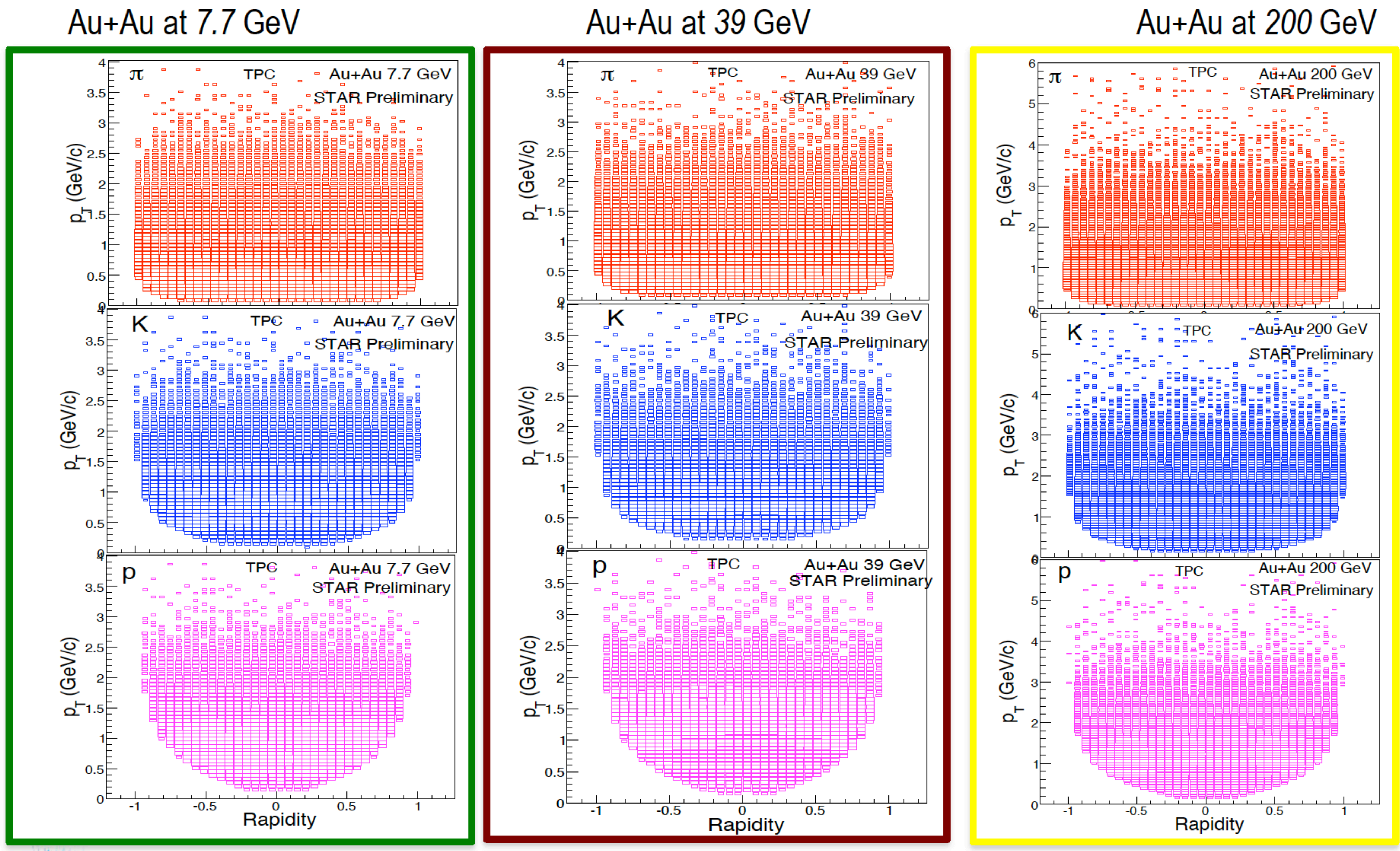


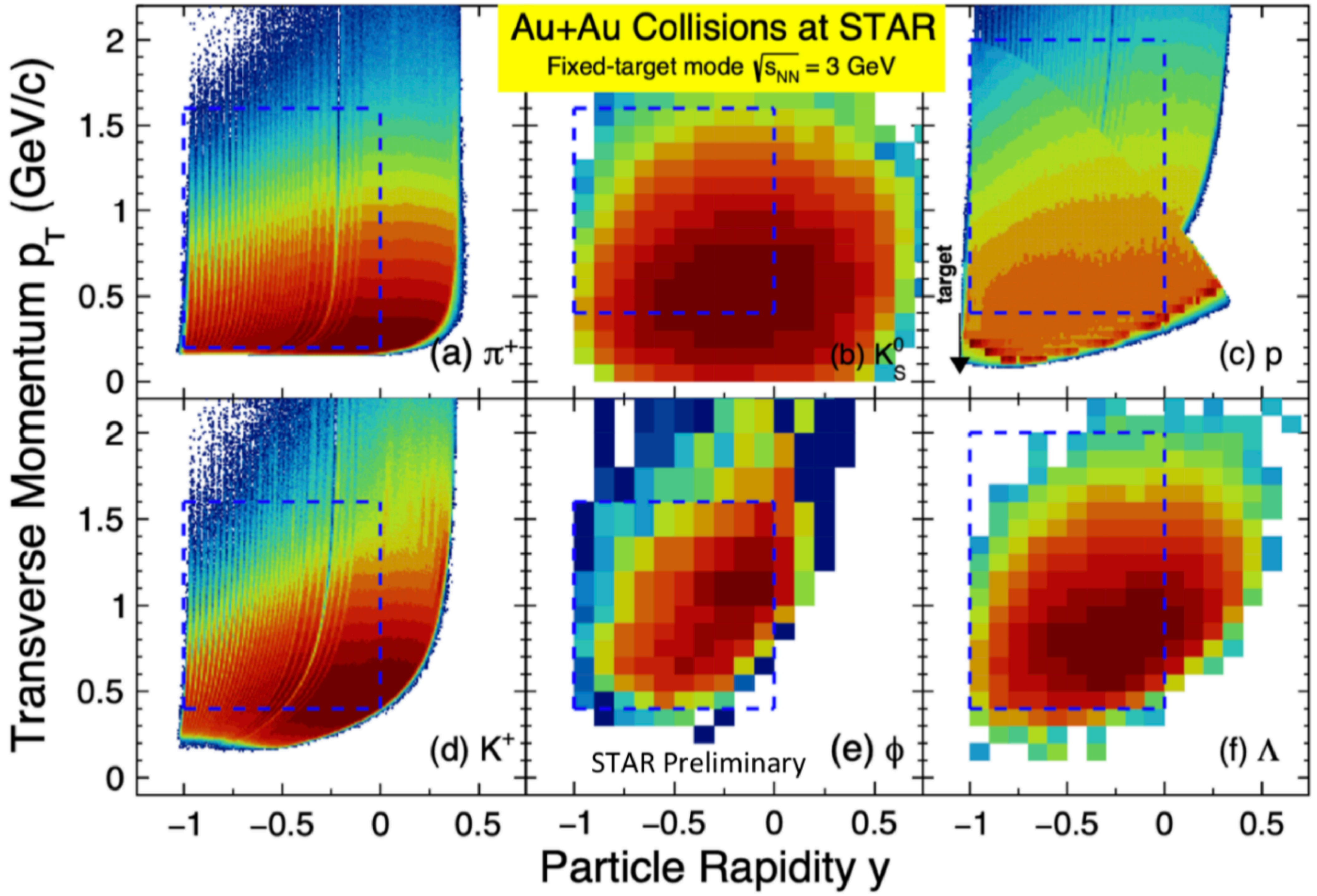
PRC 102 (2020) 34909 (STAR)

$\sqrt{s_{NN}}$=7.7GeV Collider



Collider and fixed-target acceptance

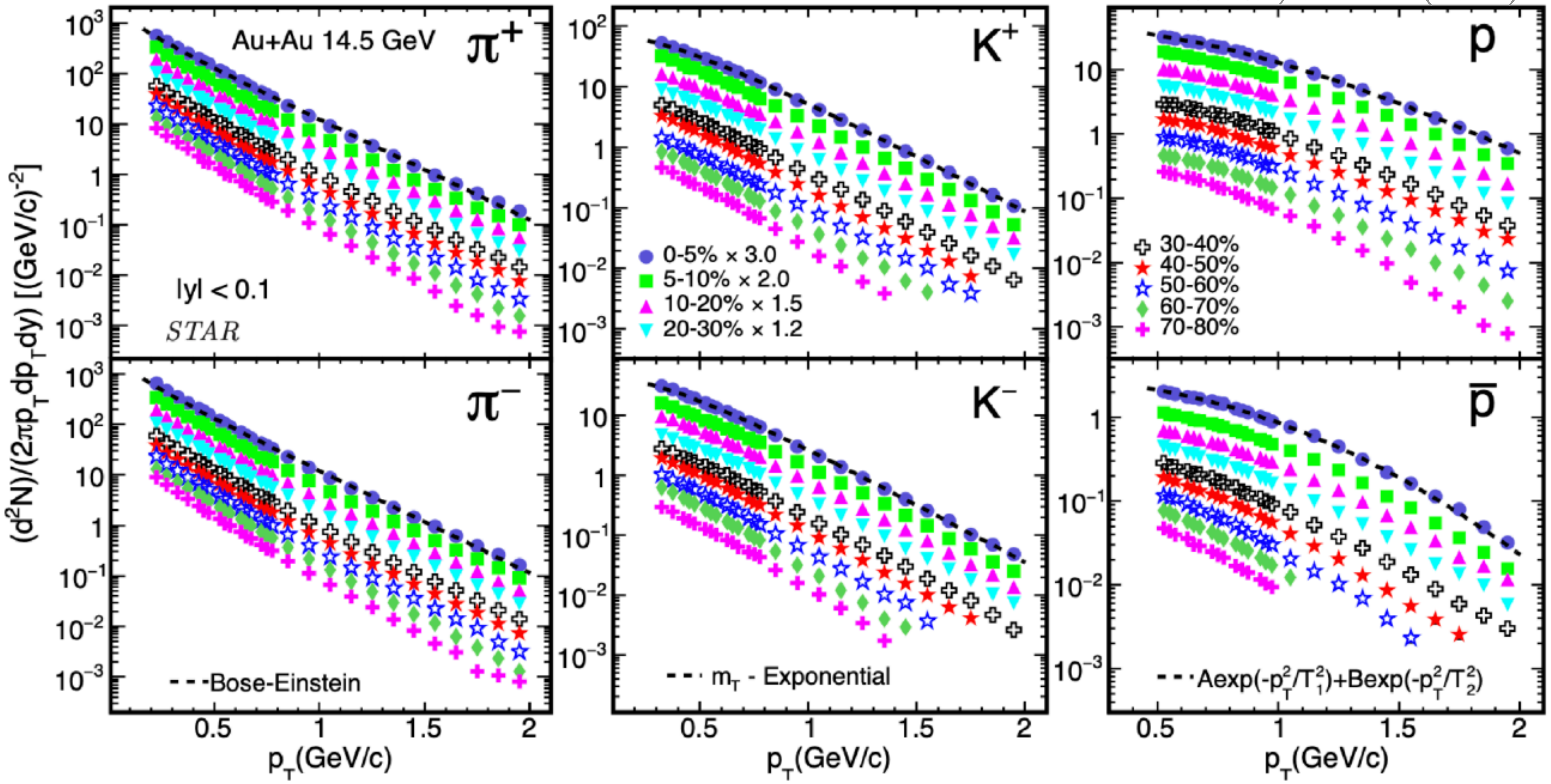




Similar acceptance for all particles and energies

Particle spectra

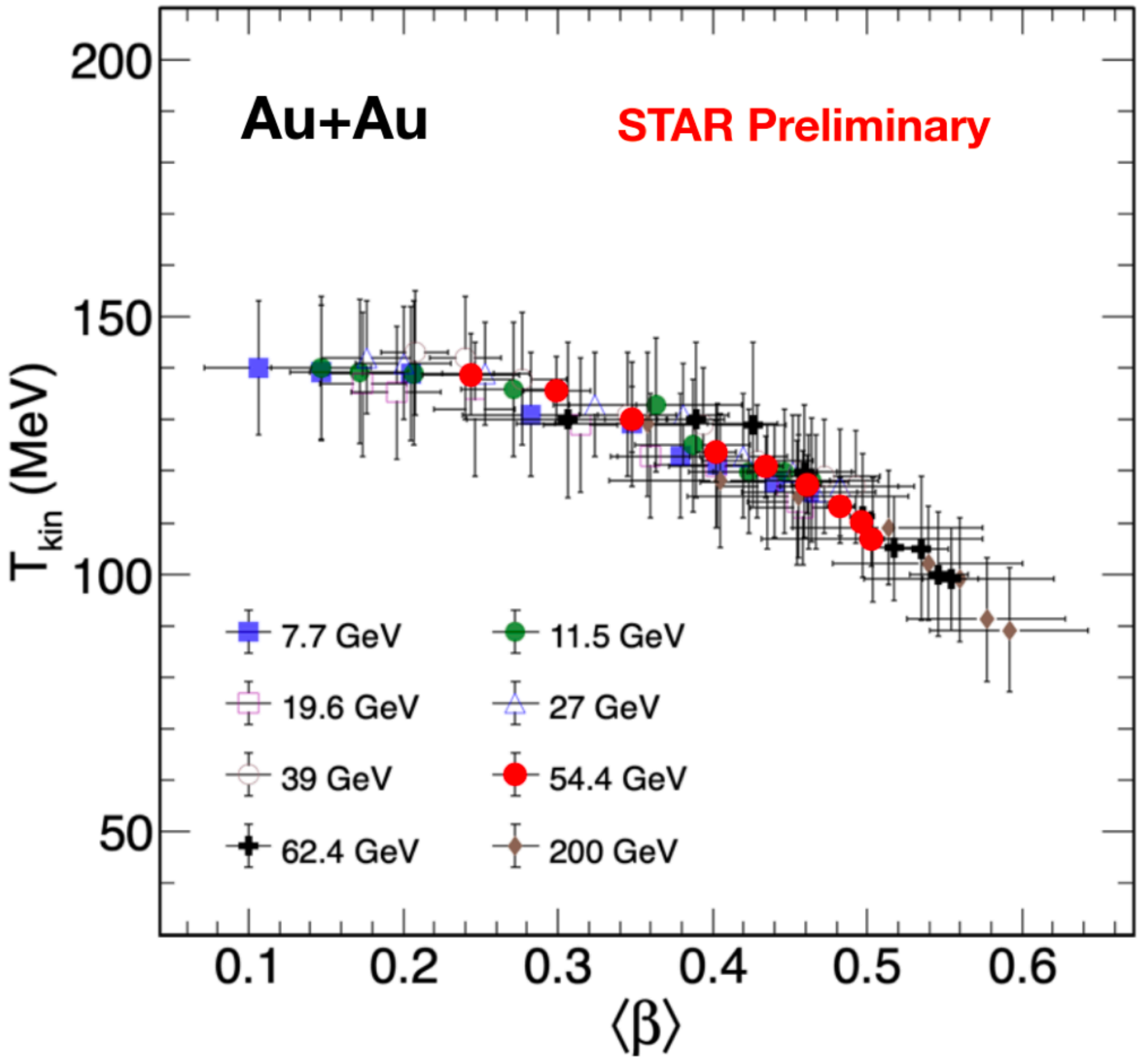
PRC **101**, 024905 (2020)



Inverse slopes of the identified hadron spectra follow the order π < K < p

$$\frac{dN}{m_T dm_T dy} = f(y) exp(\frac{-m_T}{T}); \; m_T = \sqrt{m^2 + p_T^2}$$

Chemical and kinetic freeze-out parameters

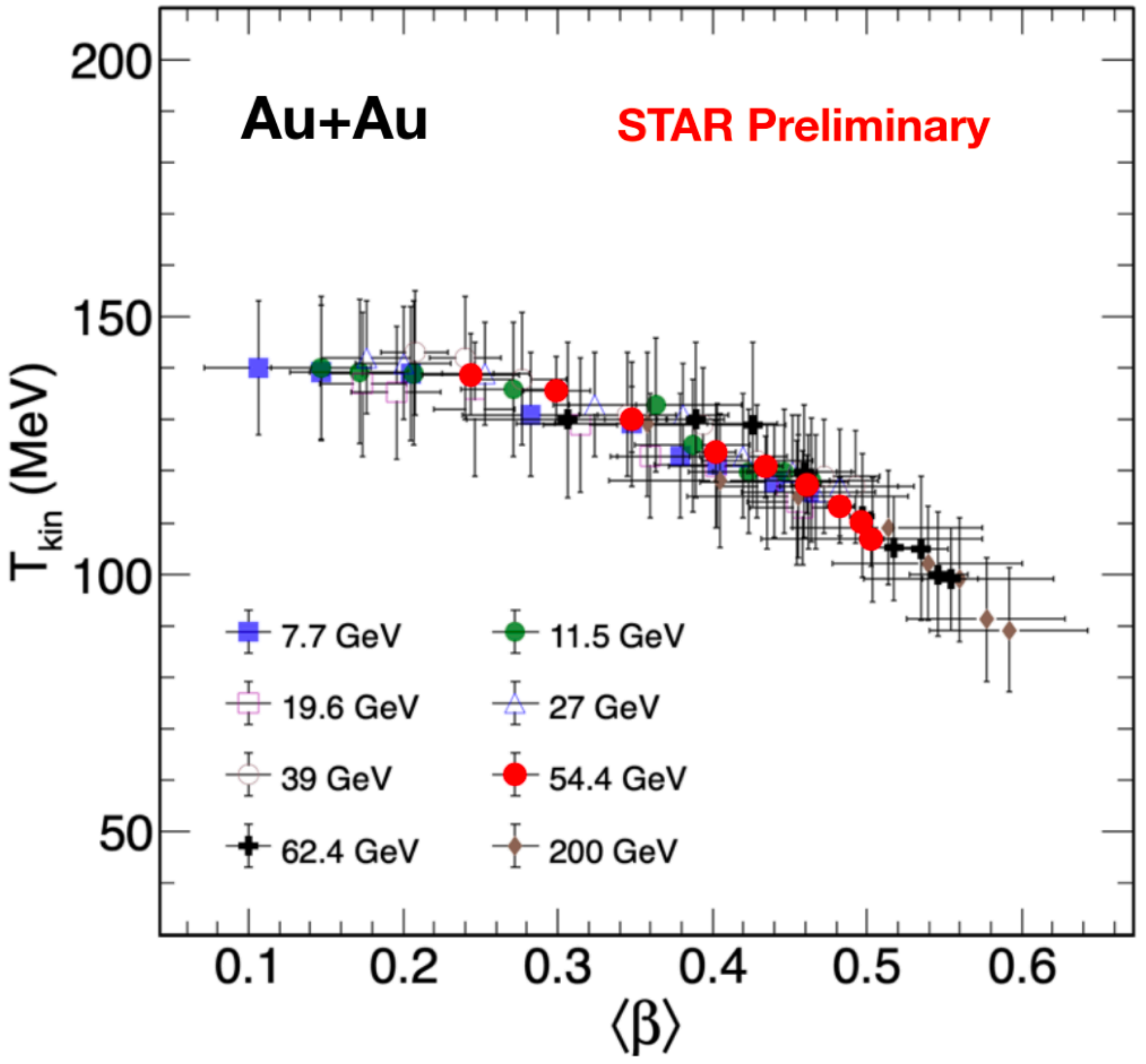


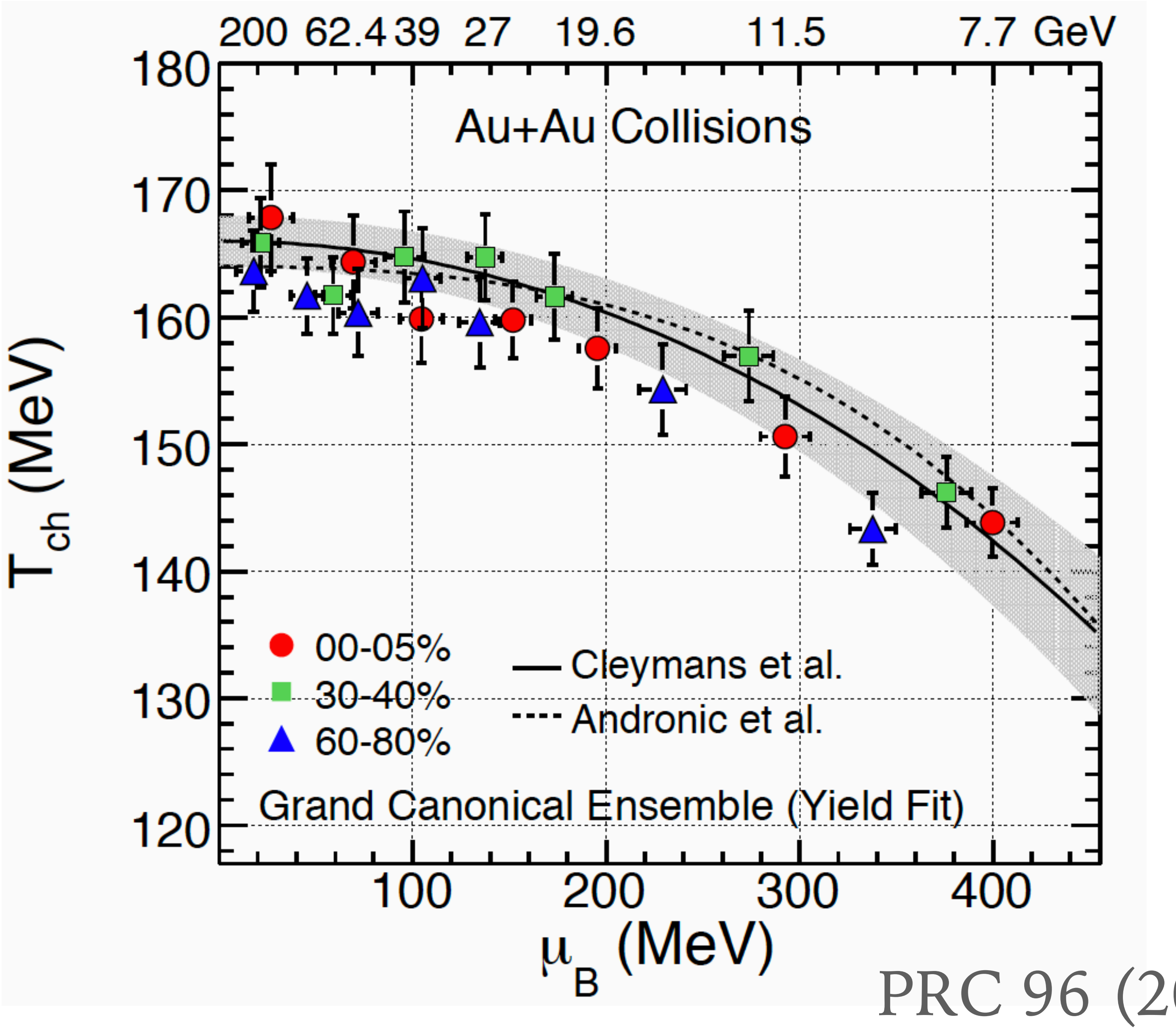
Extracted from spectra:

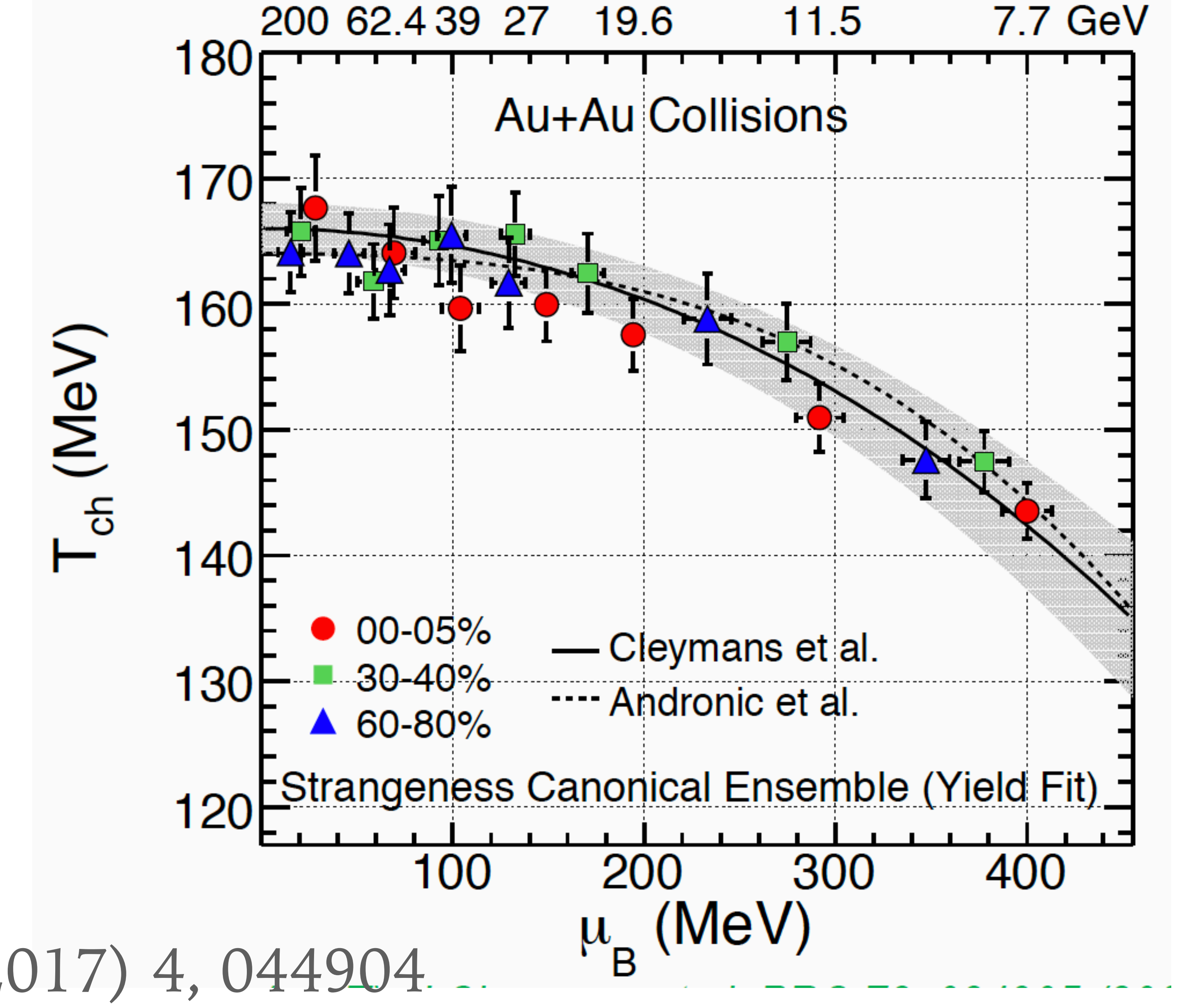
$m_T - m$ of π, K, p

Chemical and kinetic freeze-out parameters

Extracted from particle yields with THERMUS model







PRC 96 (2017) 4, 044904

Extracted from spectra (from Blast Wave model):

$m_T - m$ of π, K, p

Extracted from particle yields with THERMUS model assuming Grand (Strangeness) Canonical ensemble.

BES-I: $\mu_B \sim$ 20 MeV - 420 MeV

BES-II: $\mu_B \sim$ 205 MeV - 720 MeV

Road map

Beam Energy Scan program

QCD Phase Diagram

STAR experiment

Main questions

Summary and perspectives

Observables

1. **Onset of QGP** (disappearance of signals of partonic degrees of freedom)

Charge separation w.r.t. EP

NCQ scaling of elliptic flow

2. Search for signatures of first order **phase transition** (softening of EOS at lower collision energy)

Directed flow v_1

Femtoscopy

3. Existence of **Critical Point** (CP)

Fluctuation analyses

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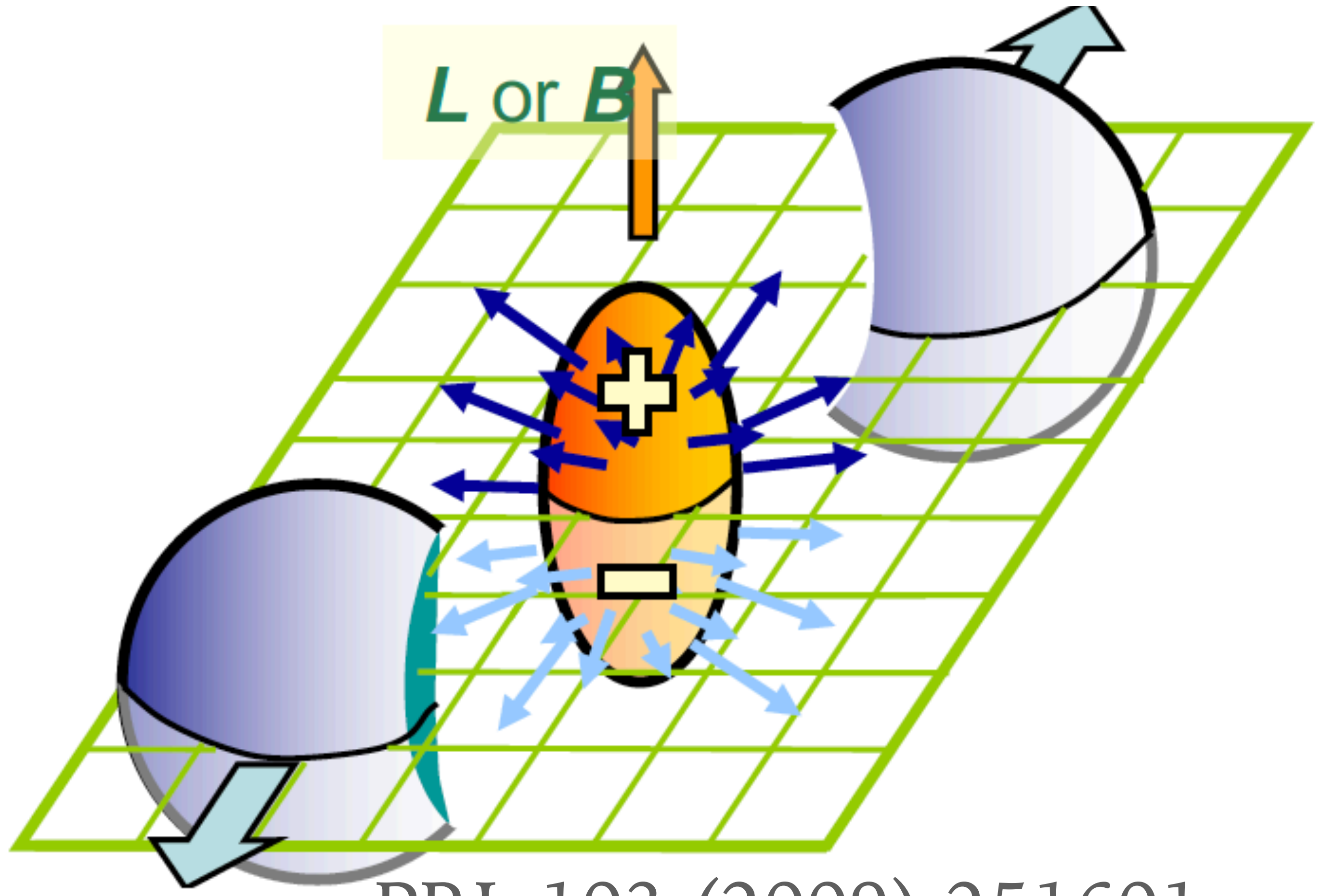
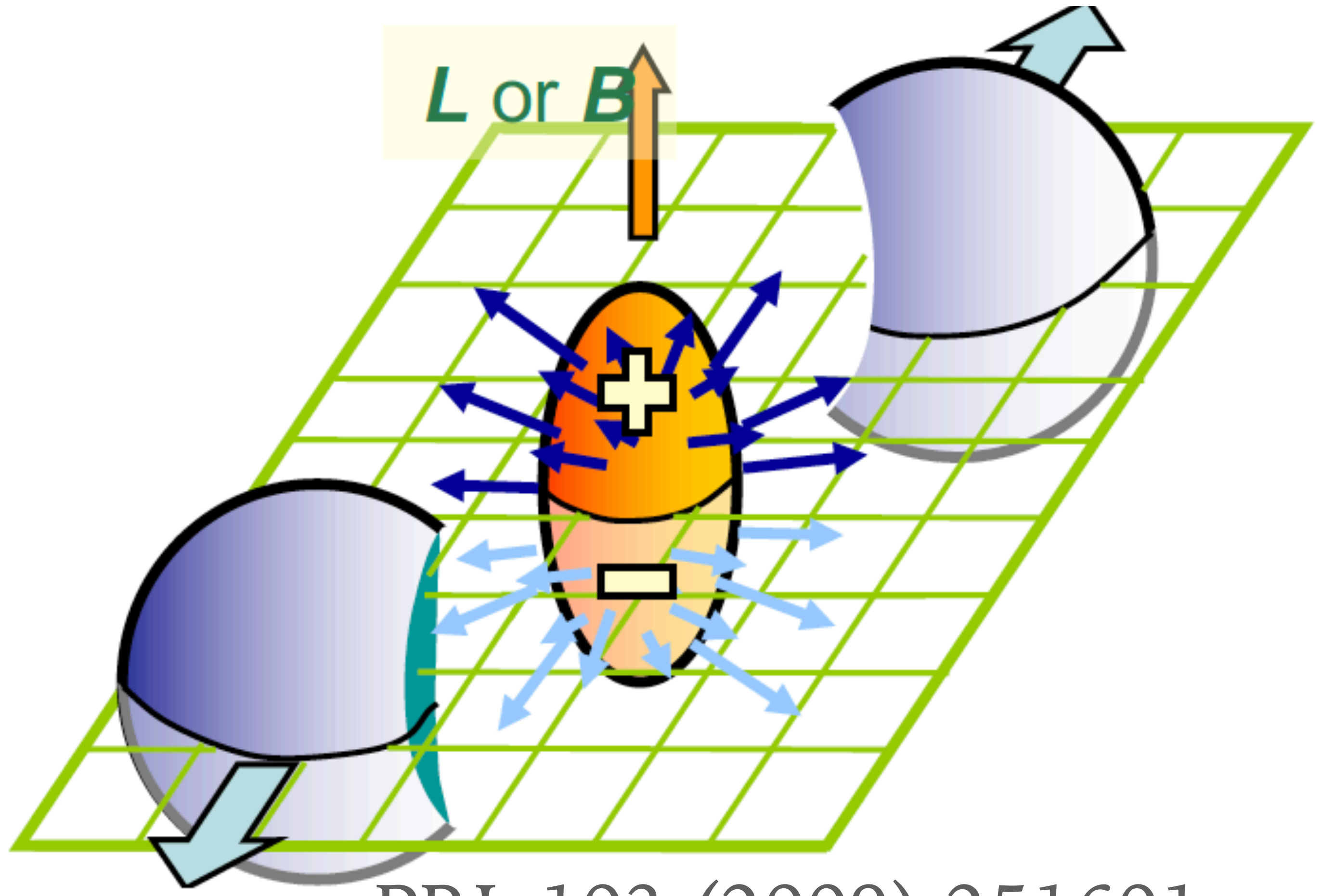


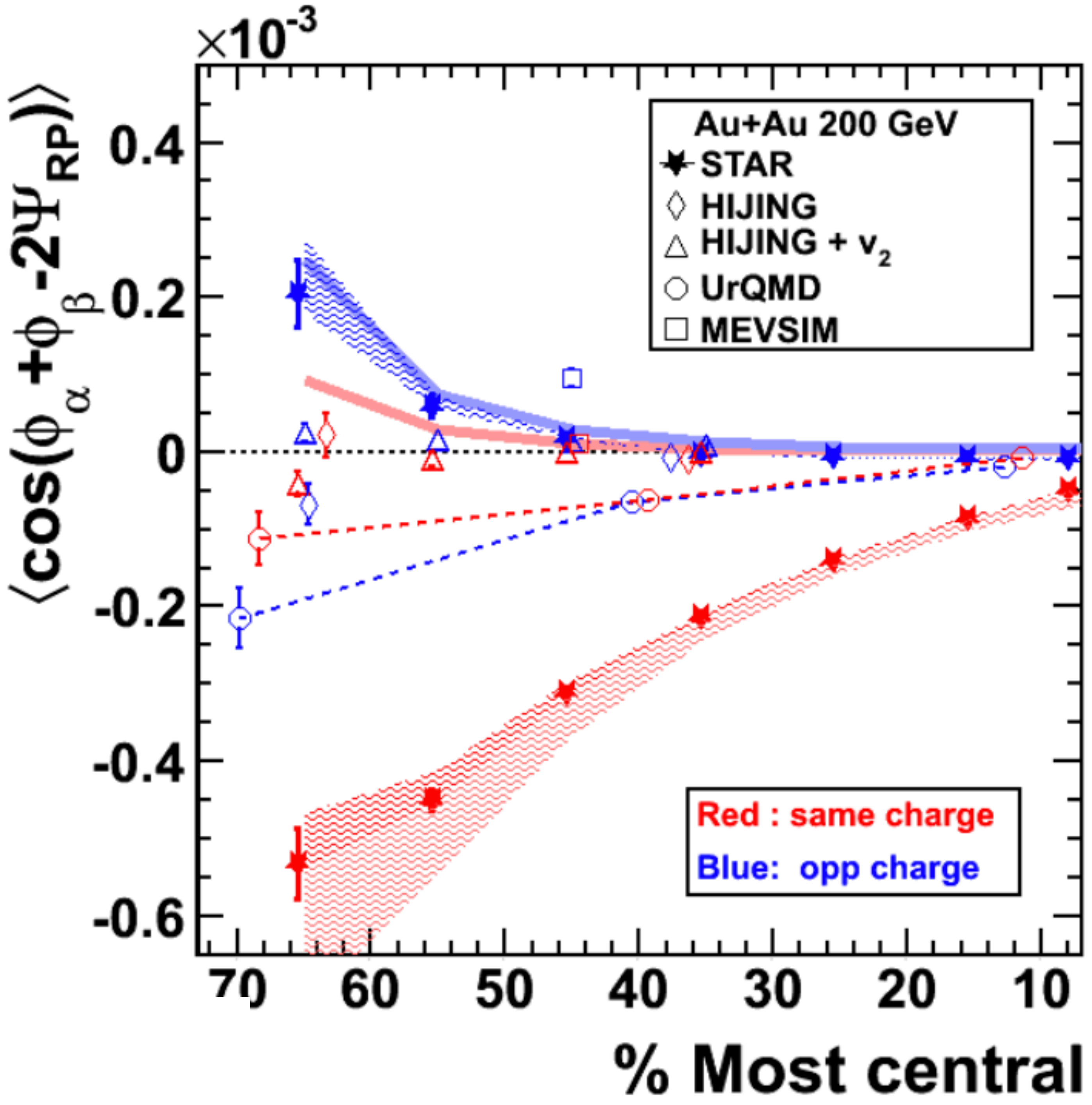
PRL 103 (2009) 251601

- Strong **B**, system is **deconfined**, chiral symmetry restoration is reached.
- Chiral symmetry breaking and the origin of hadrons masses related to the existence of gluons field.
- Quarks interactions with gluons fields can change quarks chirality, and may lead to **L**ocal **P**arity **V**iolation.
- **C**hiral **M**agnetic **E**ffect: separation of the charges along the **B** axis (or **L**).

Charge separation



PRL 103 (2009) 251601



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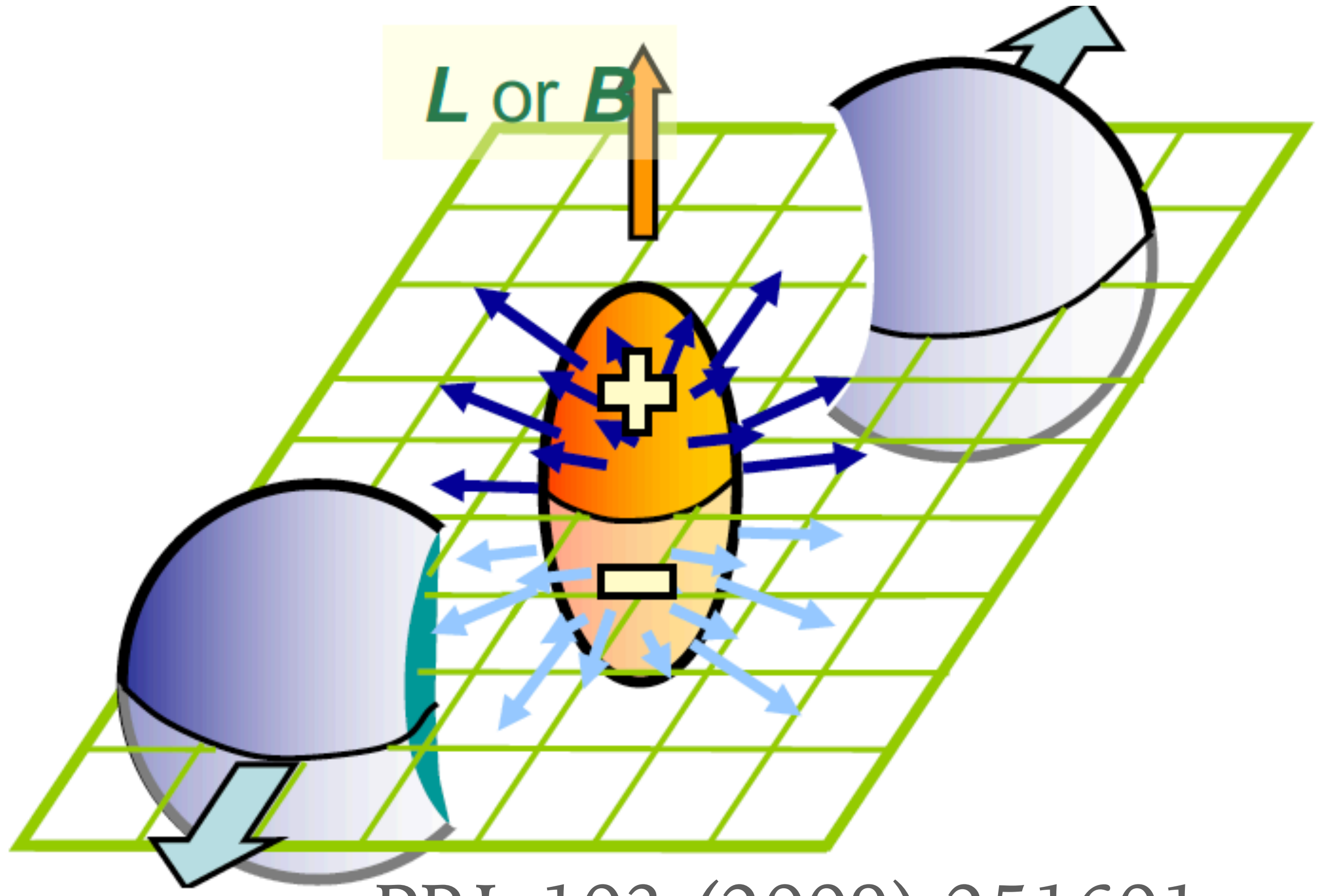
- Au+Au, U+U and Cu+Cu at top RHIC energies show charge separation measures as $\gamma = < cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) >$

Charge separation



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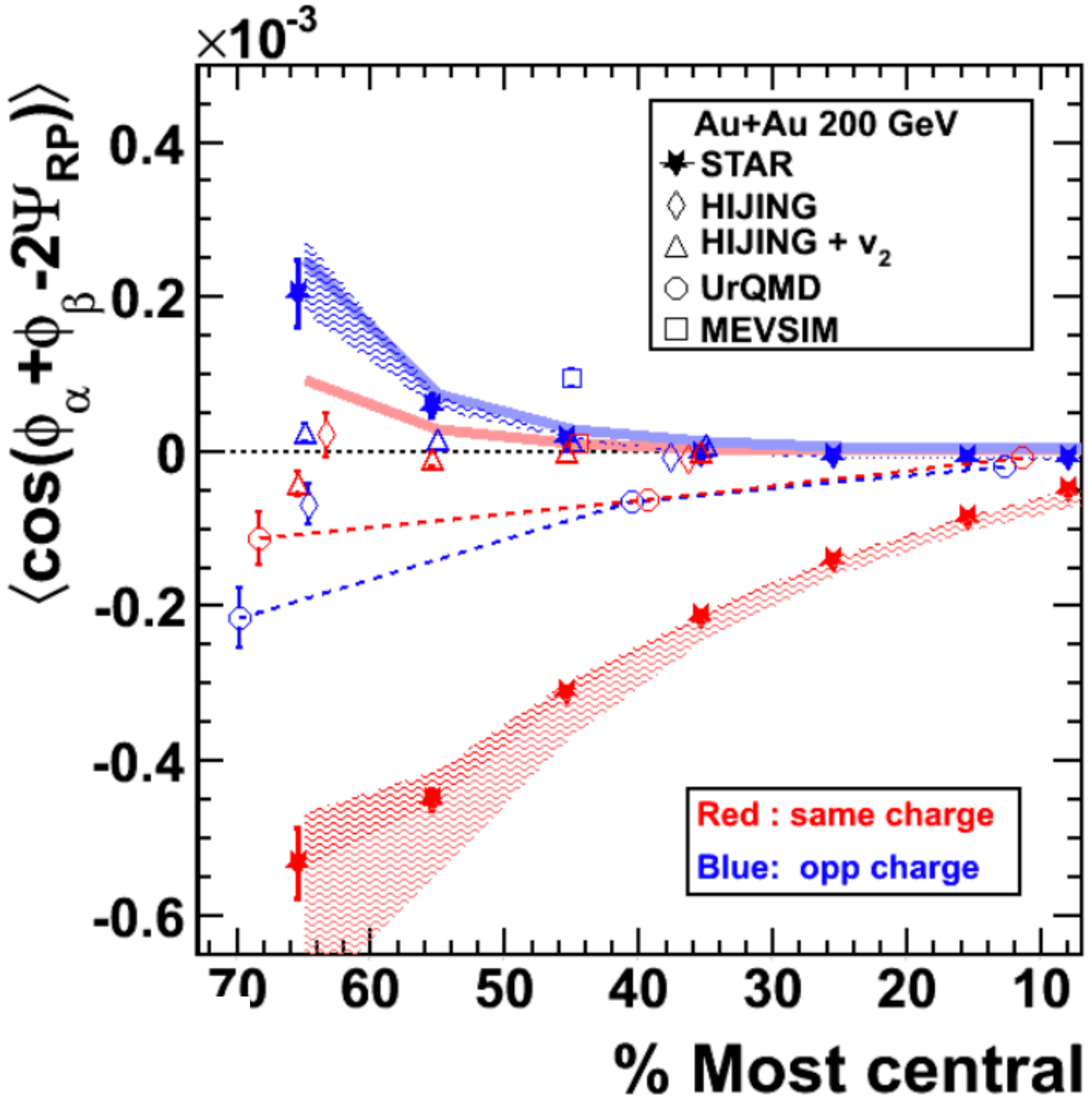

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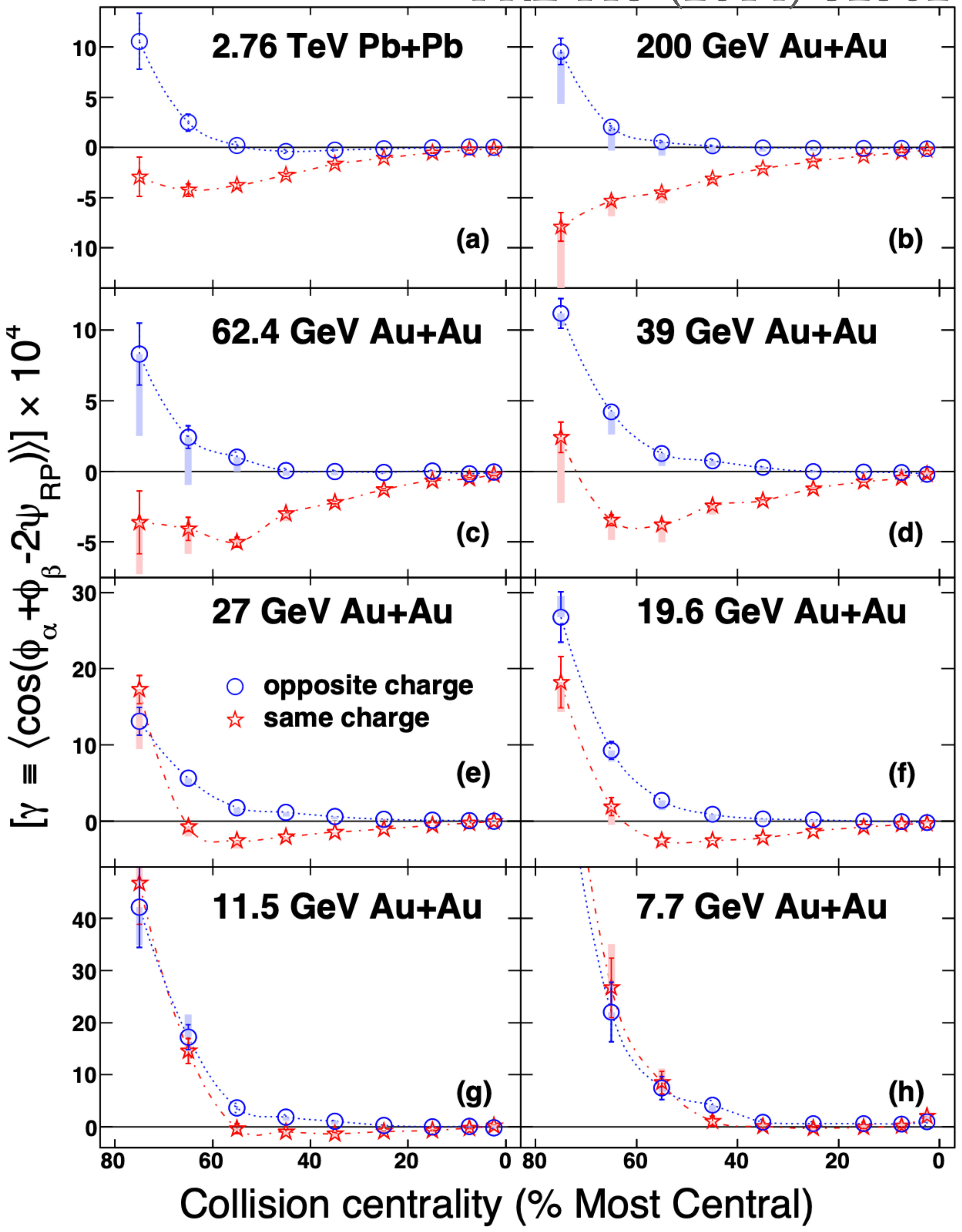
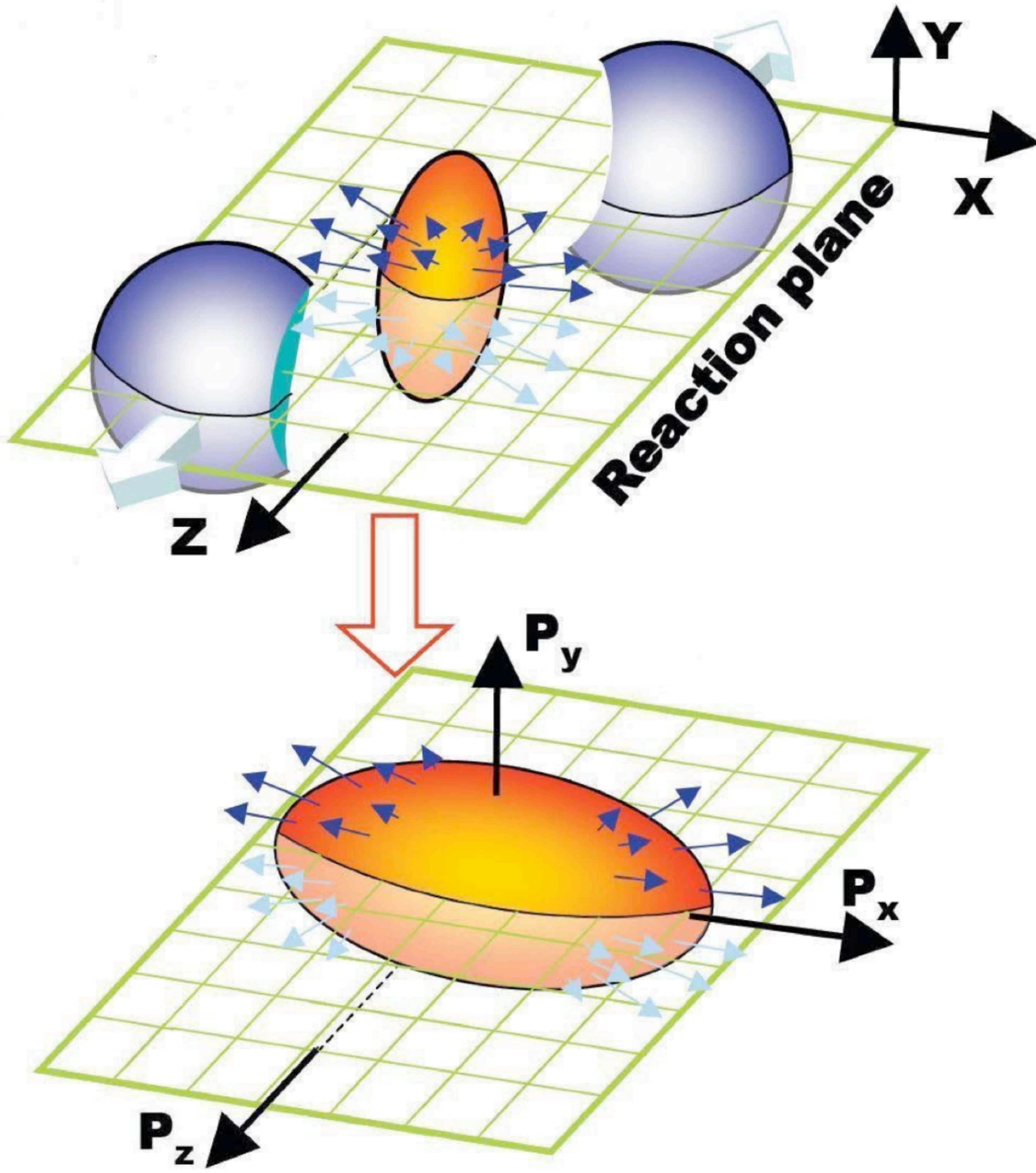
- Is reduction of signal with decreasing collision energy the signal of turn-off of deconfinement?

PRL 113 (2014) 52302

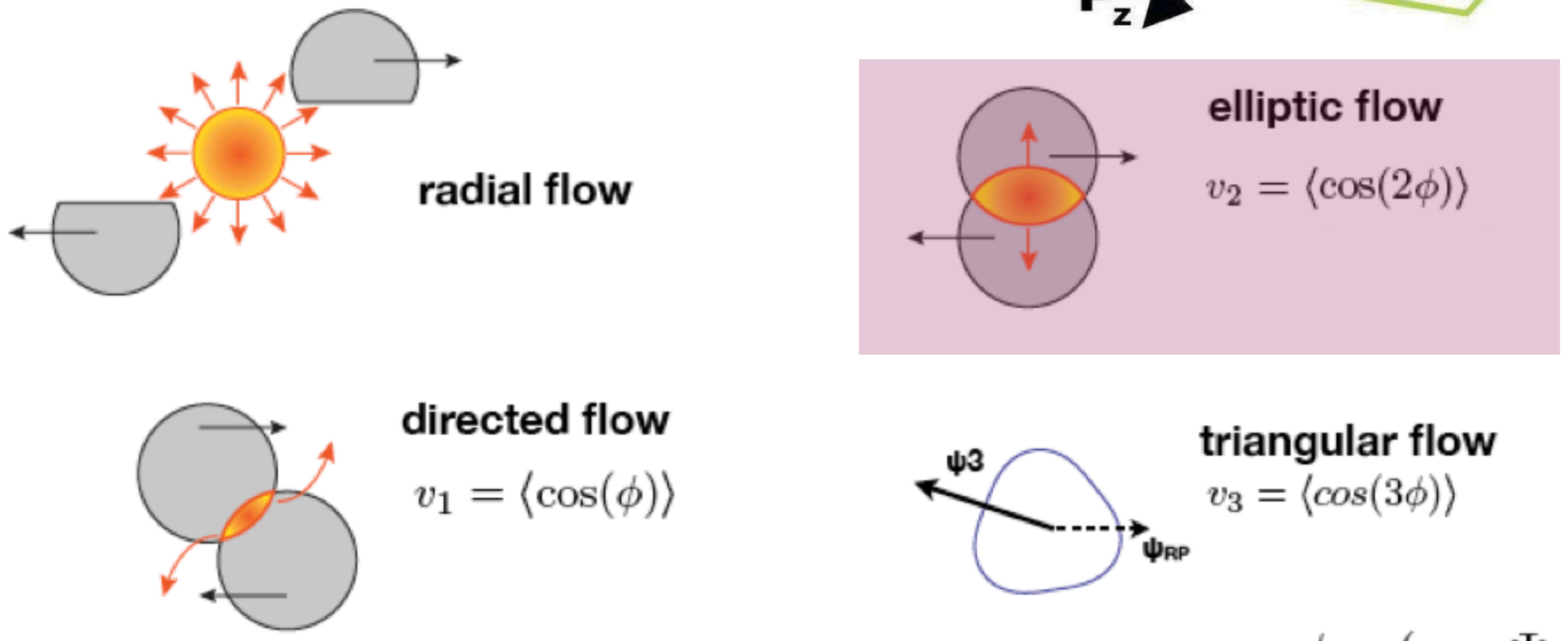


Splitting between same- and opposite-sign charges decreases with decreasing collision energy and disappears below $\sqrt{s_{NN}} = 11.5$ GeV

Elliptic flow



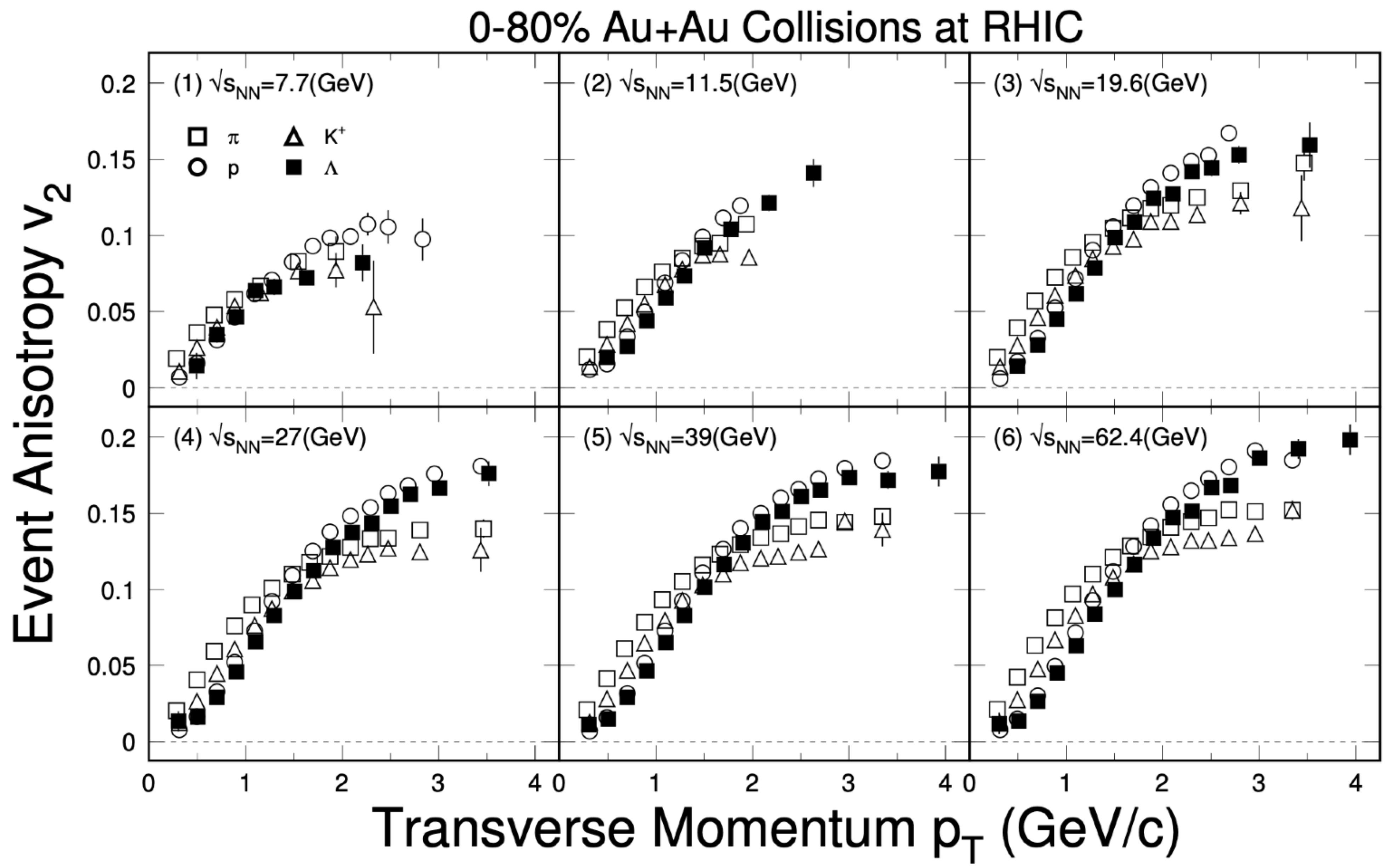
Initial spatial anisotropy leads to the final momentum anisotropy

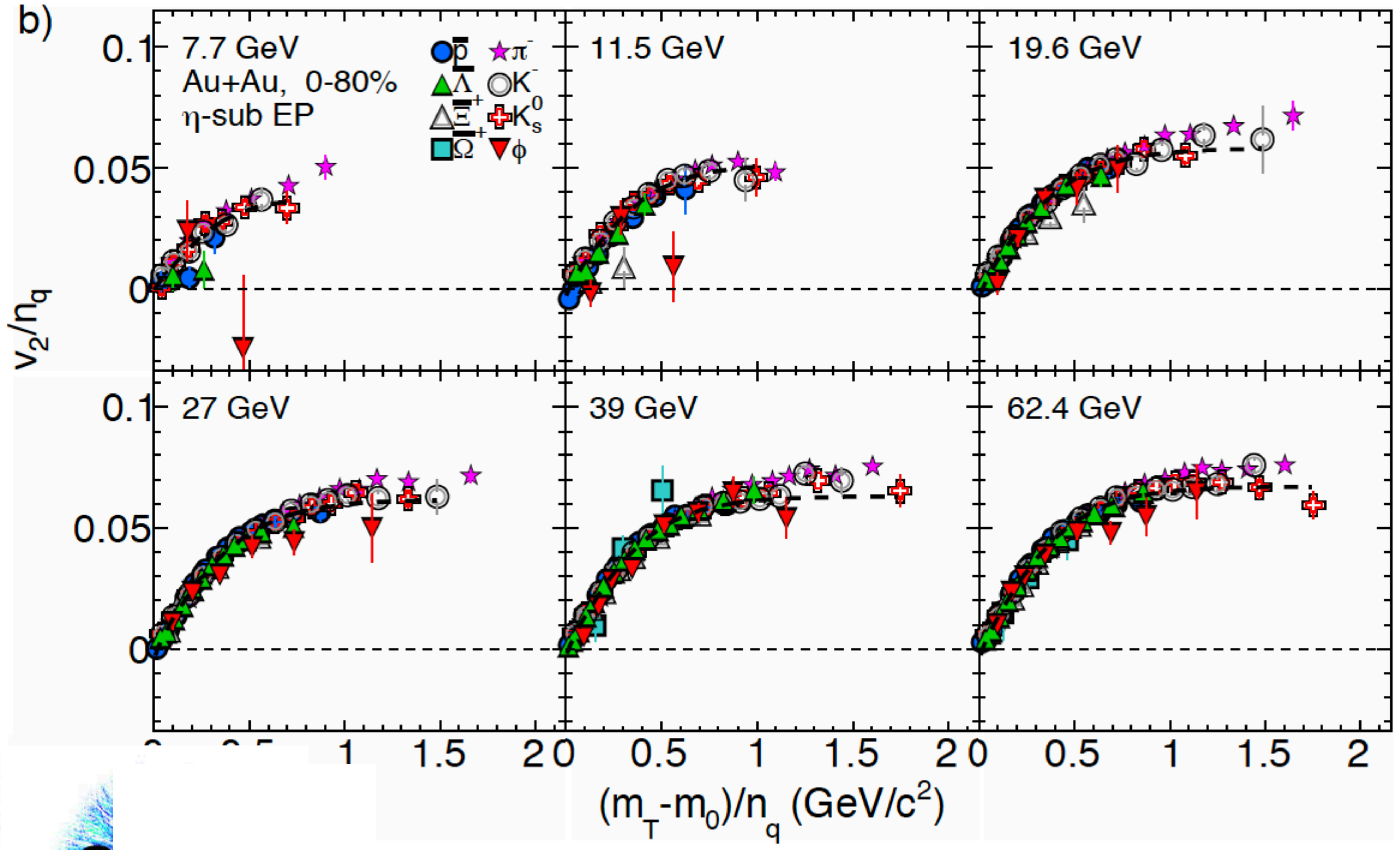


$$\phi = (\varphi - \Psi_{RP})$$

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

Elliptic flow





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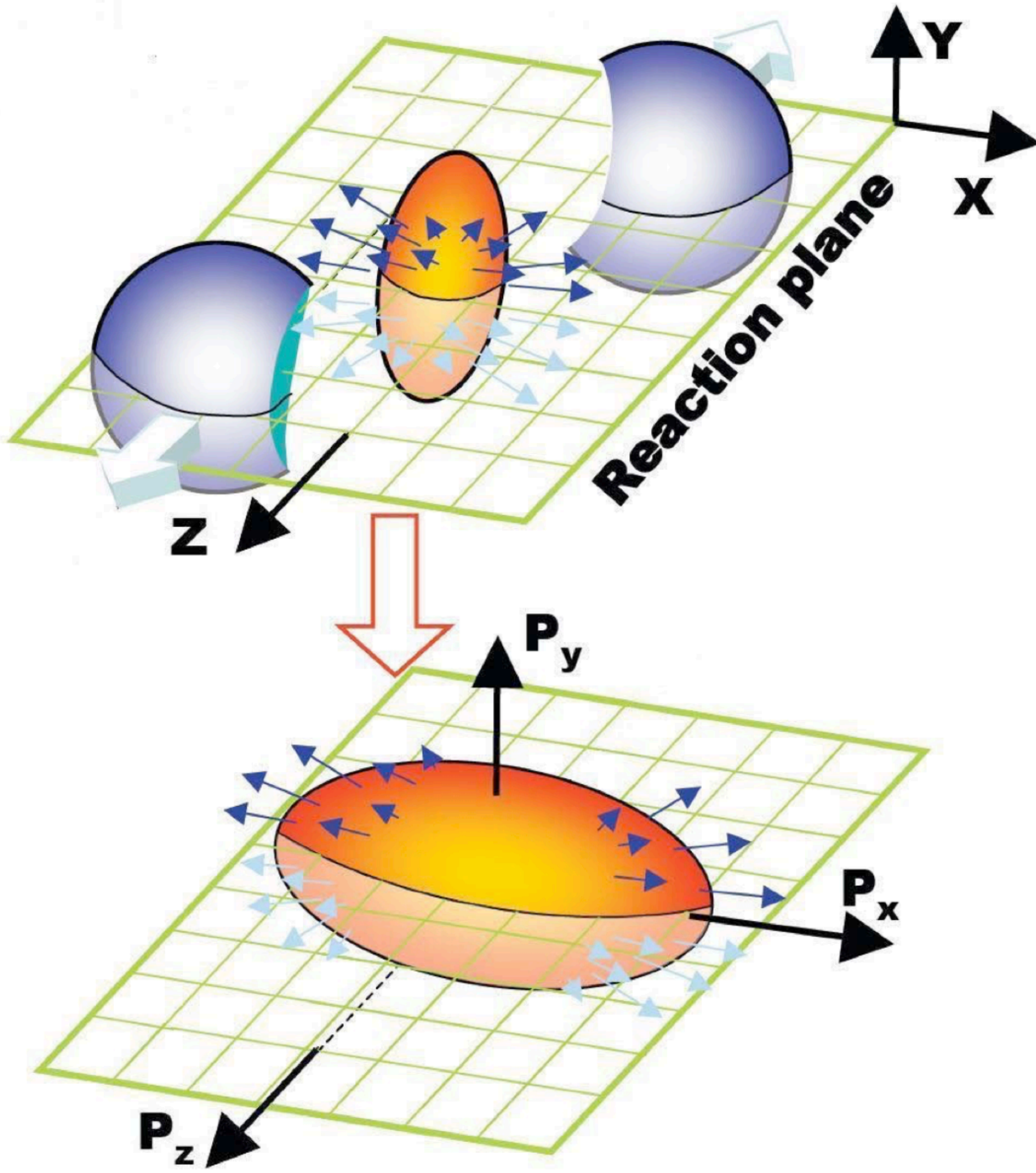

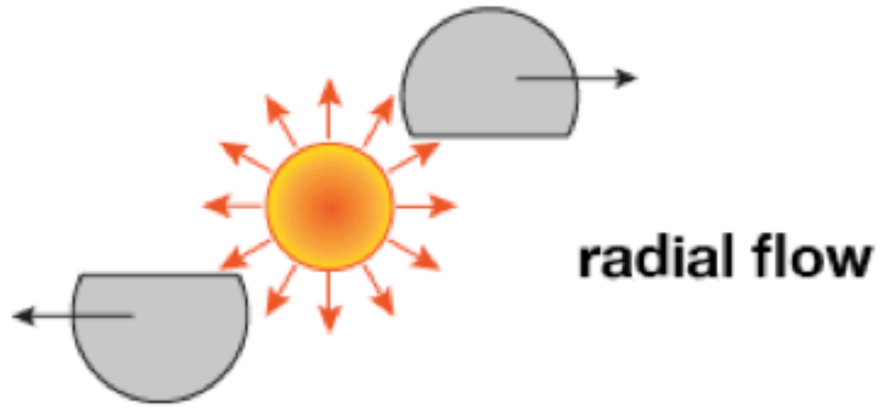

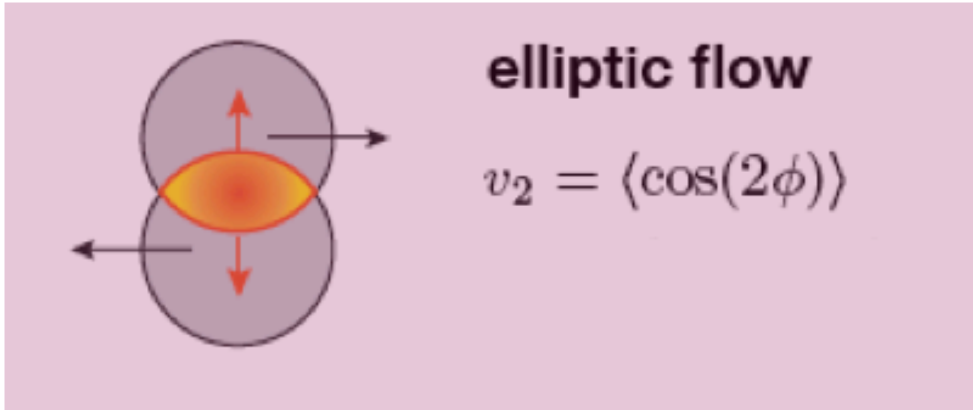

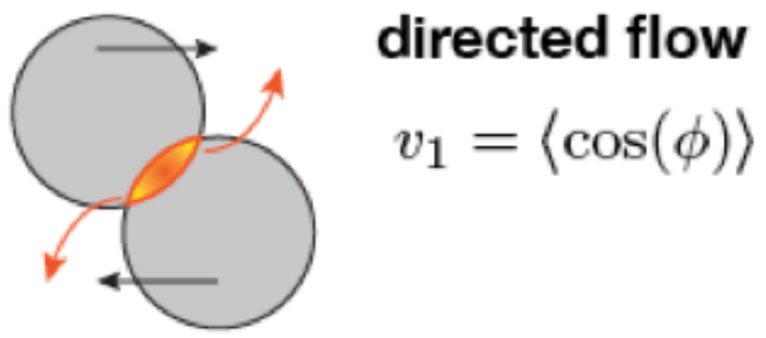

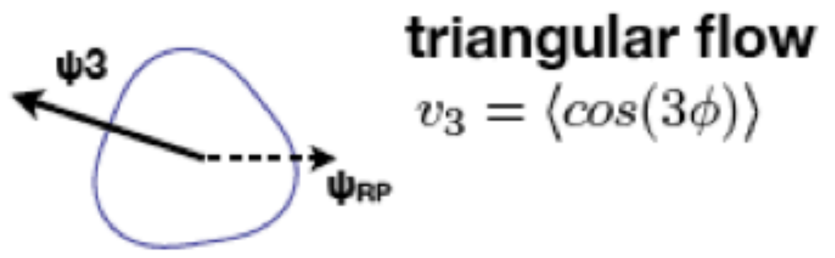

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STAR: PRC 88 (2013) 14902
Phys. Rev. C 93, 014907 (2016)
Phys. Rev. Lett. 116, 062301 (2016)

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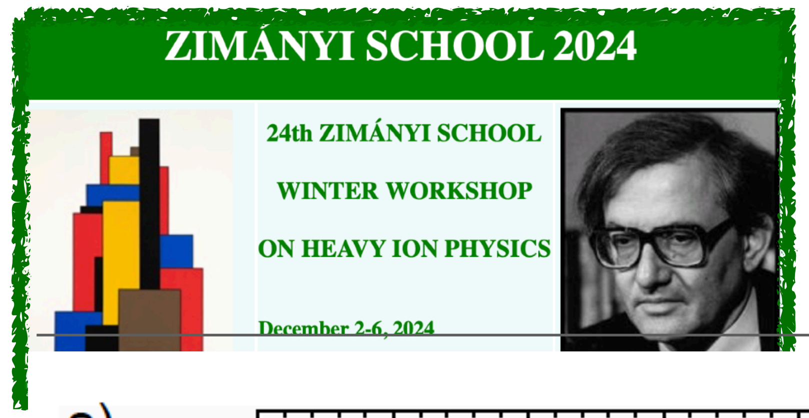
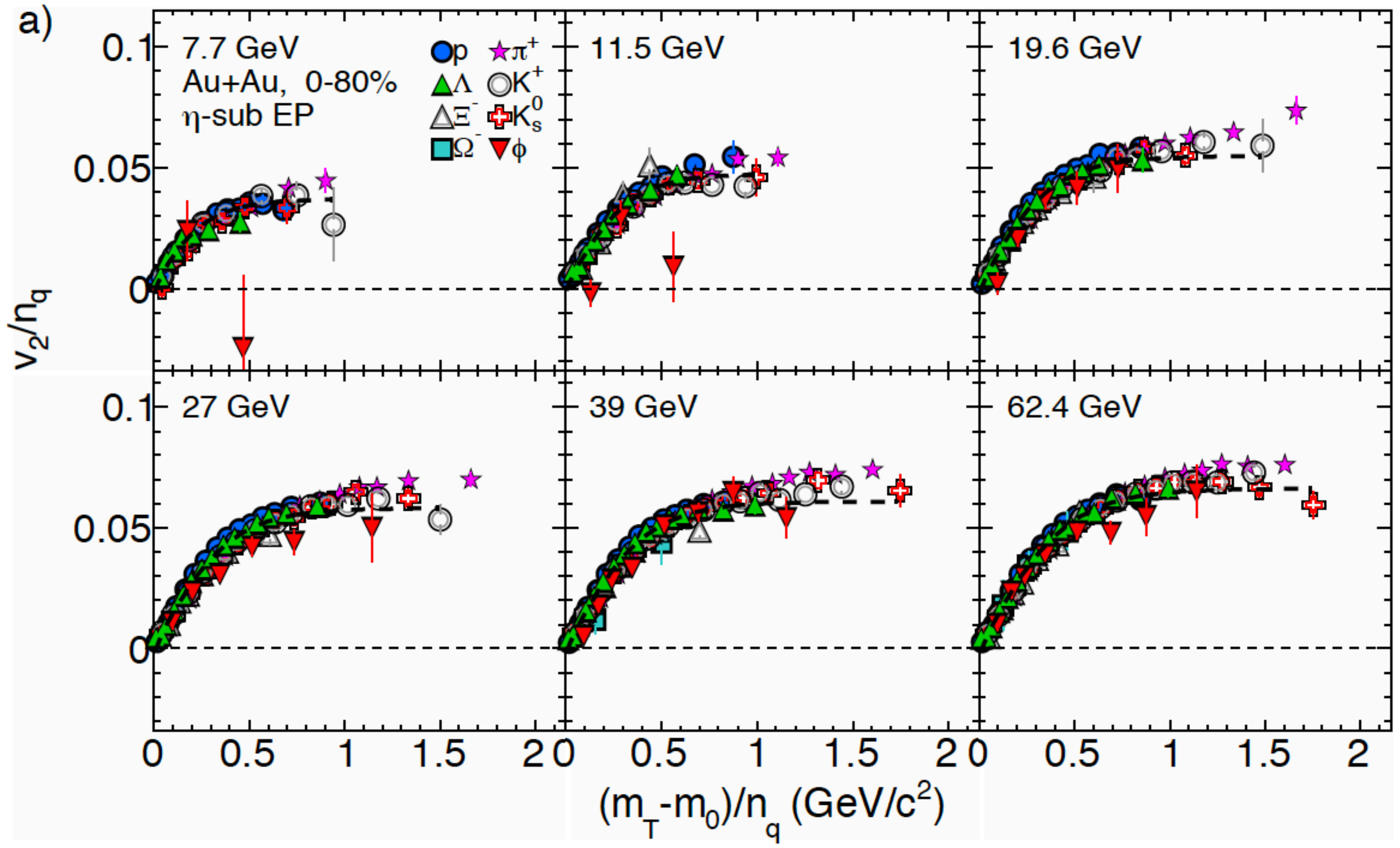
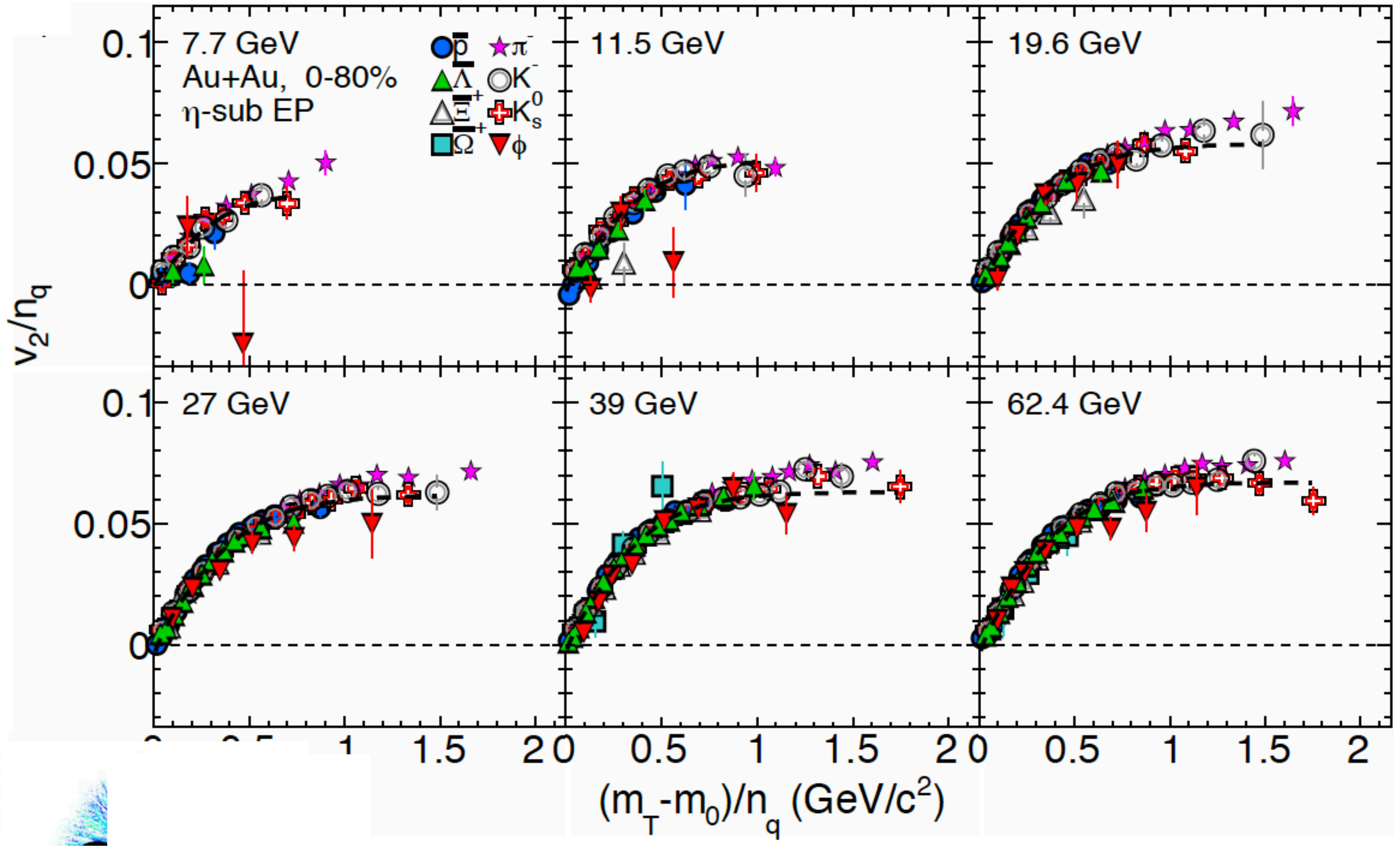


Elliptic flow





$v_2(p_T)$ are mass ordered

- ϕ meson v_2 fails the trend from other hadrons at $\sqrt{s_{NN}}$ = 11.5 GeV, (low statistics)
- The NCQ scaling holds within uncertainties for these BES-I energies

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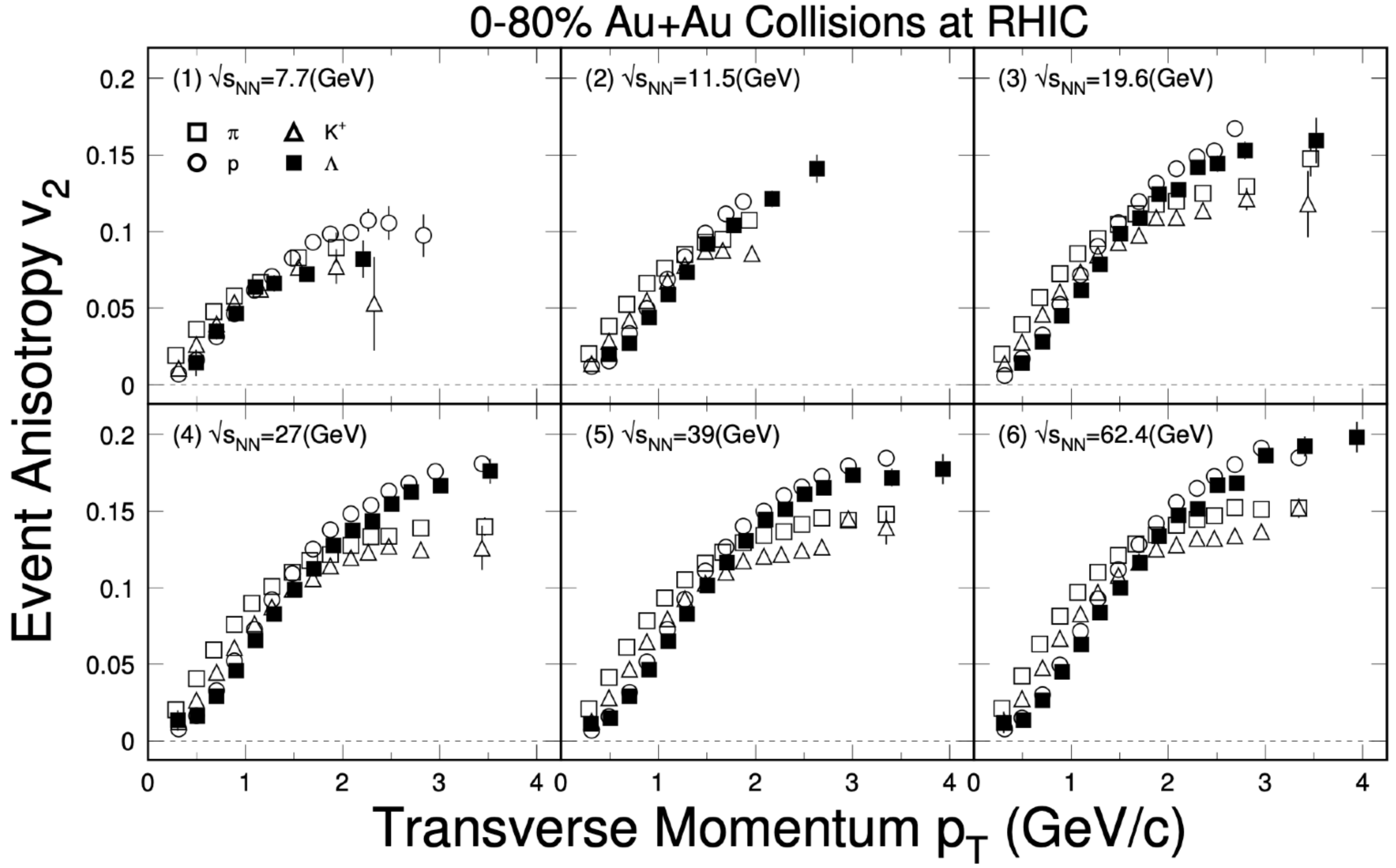

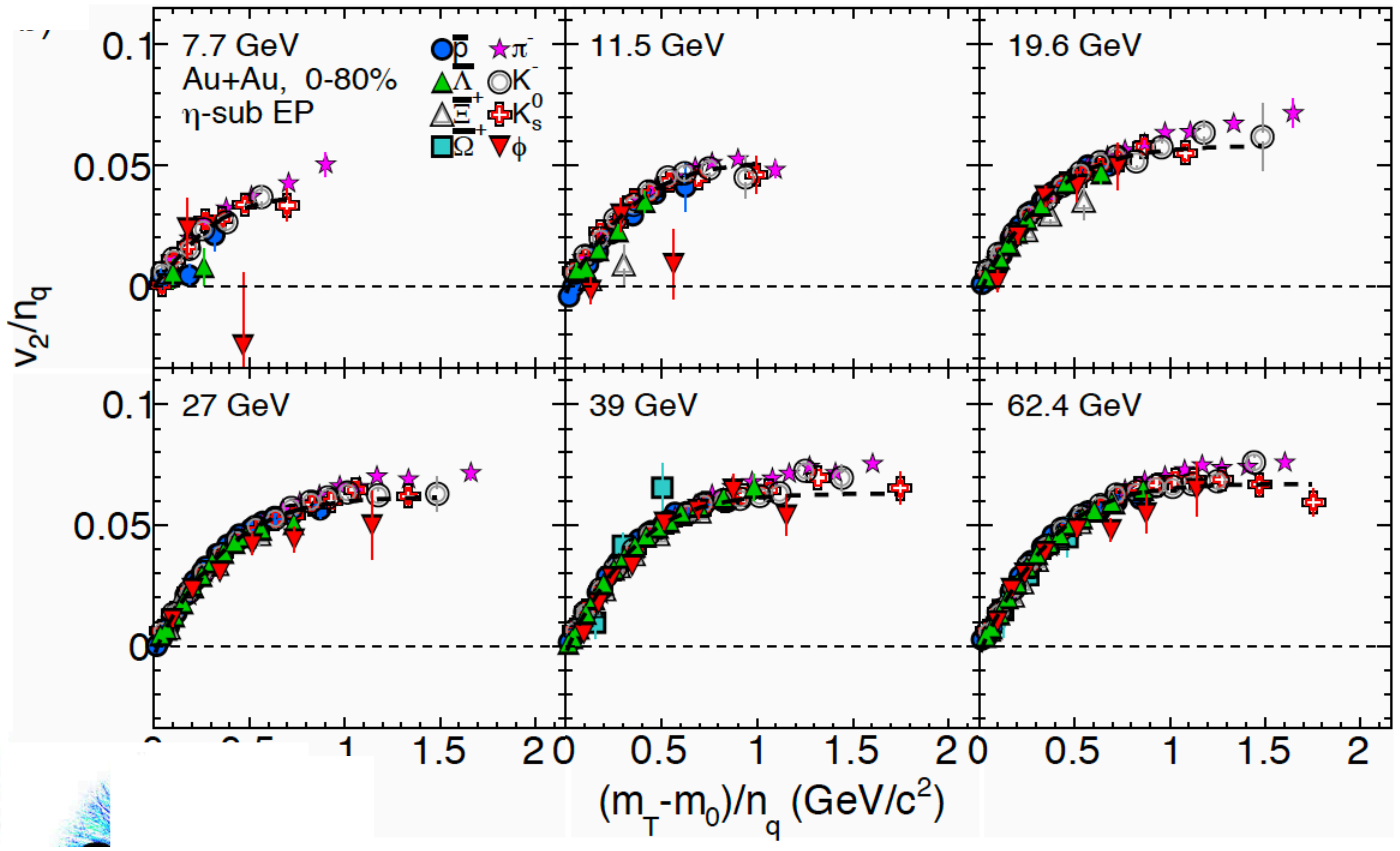

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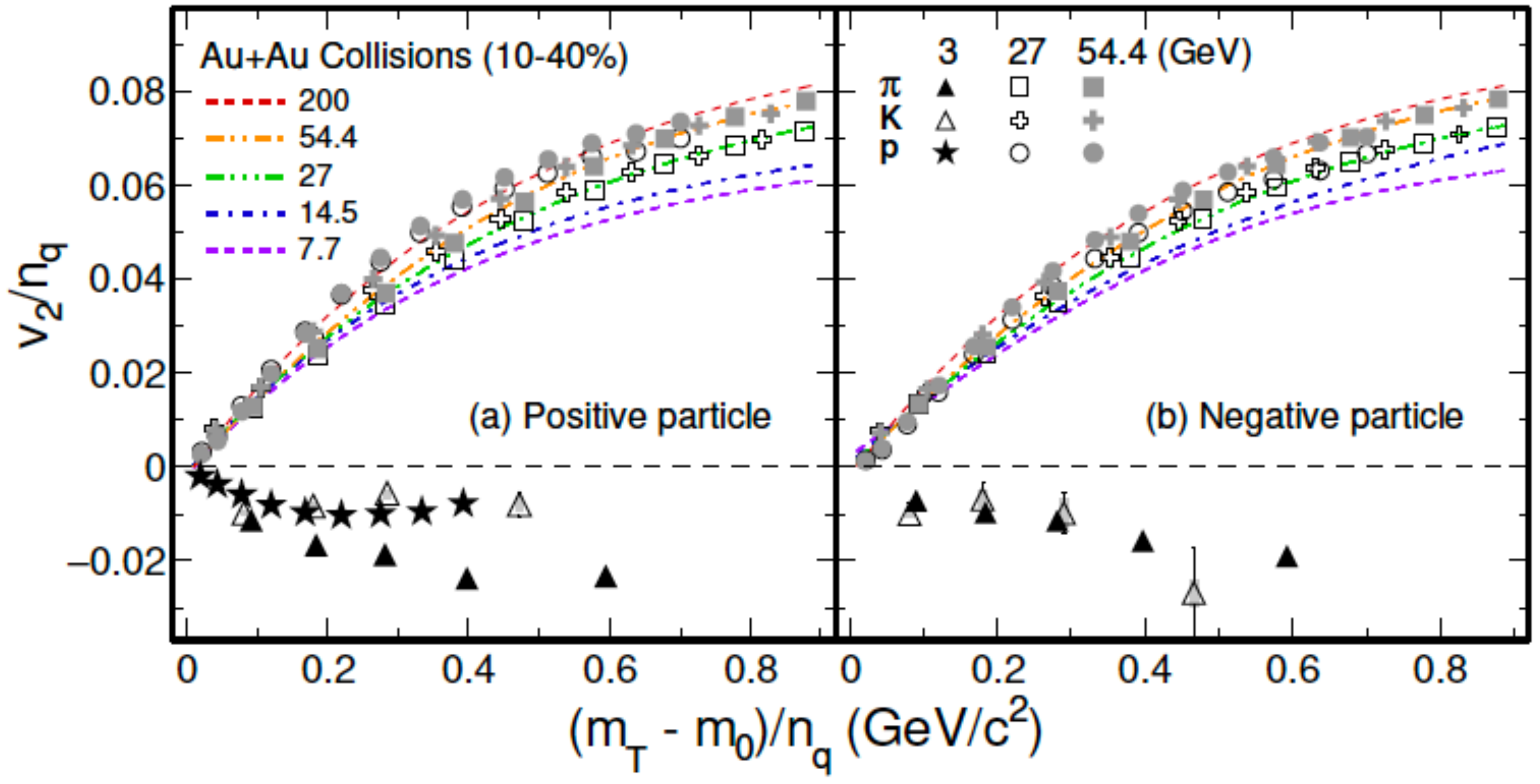

- $v_2 > 0 \rightarrow$ formation of the QGP, scaling of NCQ
- $v_2 < 0$, slope of the $v_1 < 0$ ($\sqrt{s_{NN}} = 3$ GeV) $\rightarrow$ NCQ scaling absent

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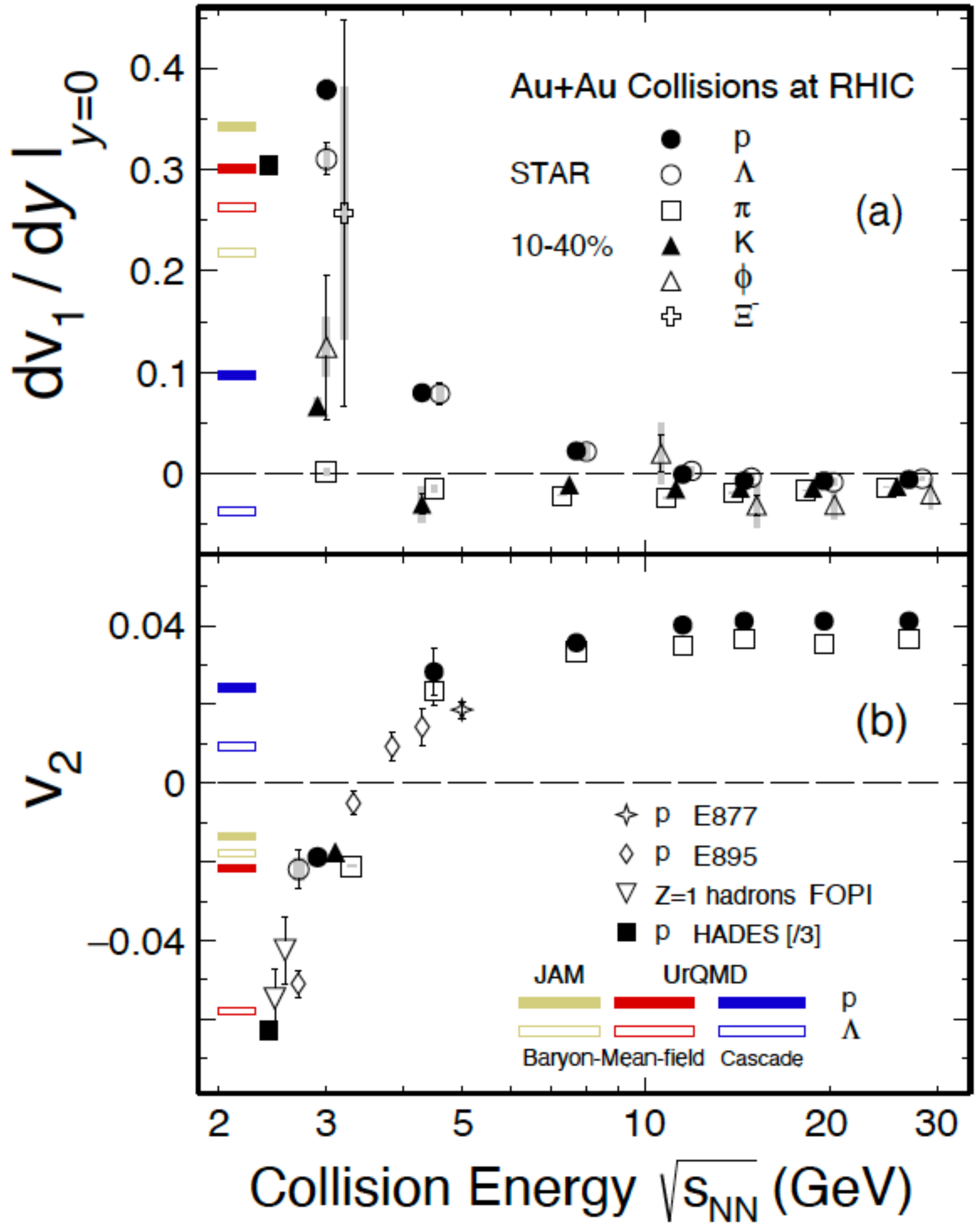

- $v_2 > 0 \rightarrow$ partonic collectivity $\rightarrow$ formation of QGP $\rightarrow$ scaling of NCQ
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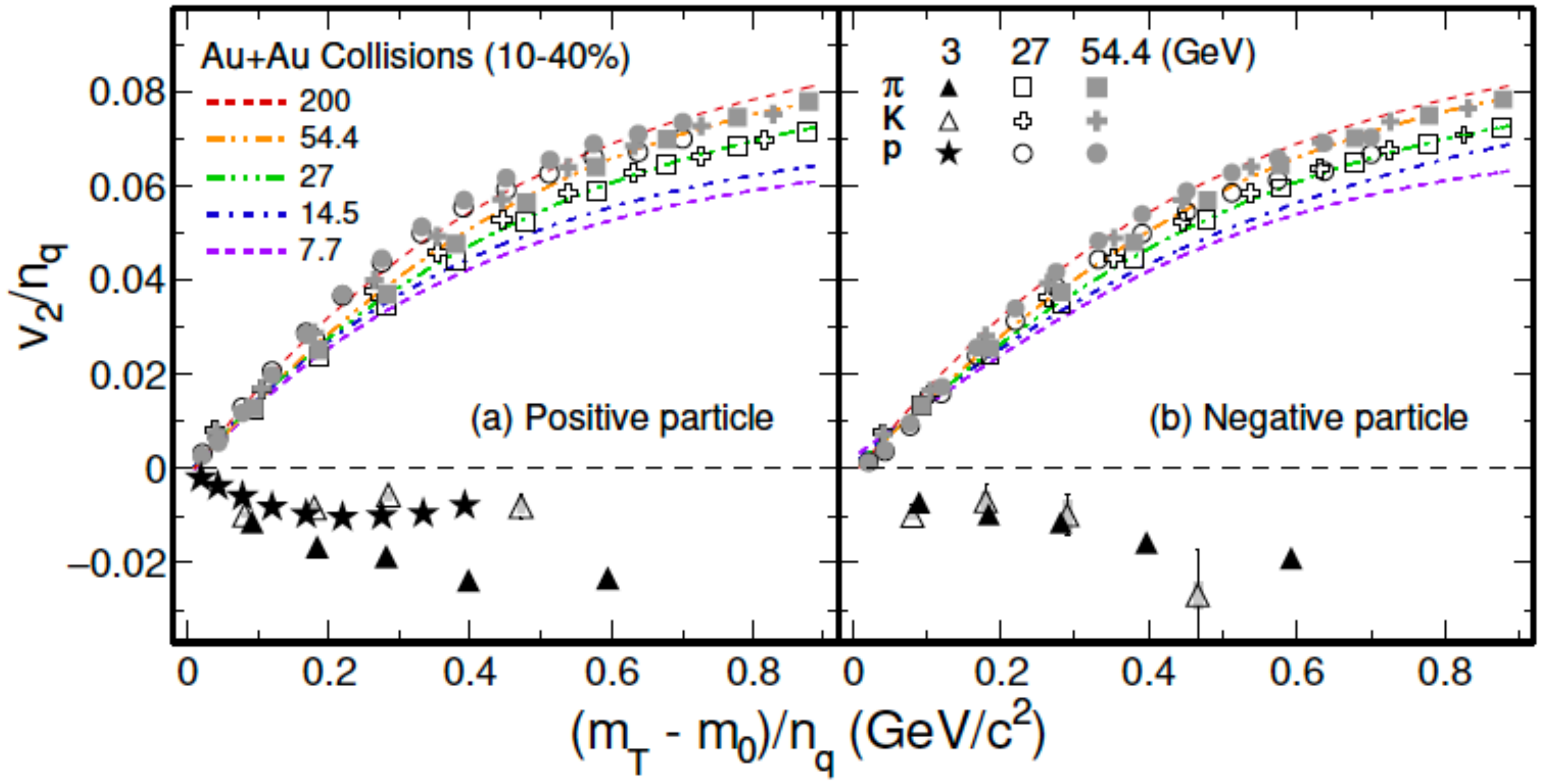

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- JAM, UrQMD mean field reproduced results.
- Vanishing of partonic collectivity and a new EOS, dominated by baryonic interactions in the high baryon density region.

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Observables

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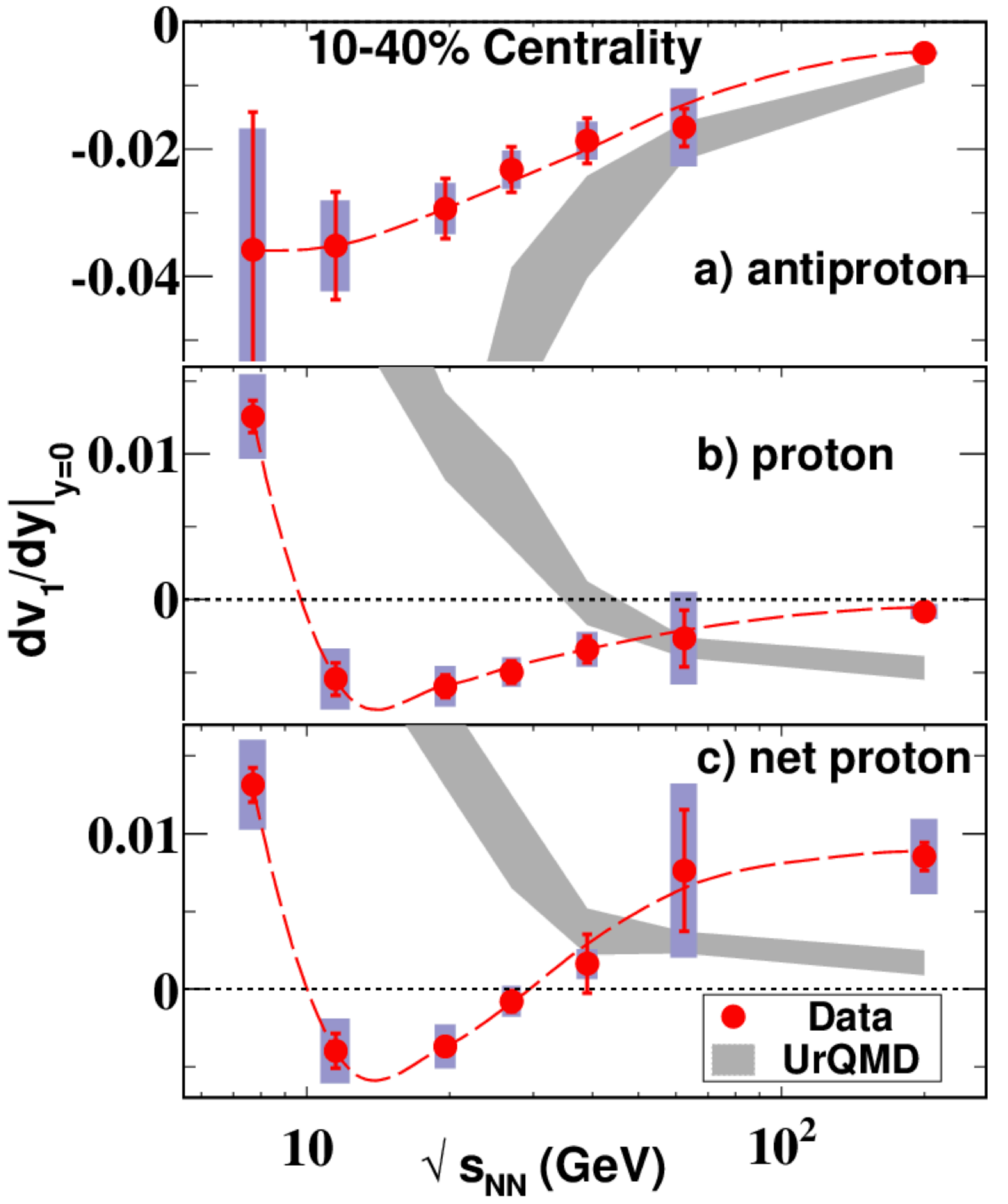
   Charge separation w.r.t. EP
   NCQ scaling of elliptic flow

2. Search for signatures of first order **phase transition** (softening of EOS at lower collision energy)
   Directed flow v_1
   Femtoscopy

3. Existence of **Critical Point** (CP)
   Fluctuation analyses

Directed flow and $< m_T > - m$ dependence

- v_1 probes early stage of collision;
- v_1 sensitive to compression;
- v_1 should be sensitive to the first-order phase transition;
- change of sign in the slope of $\frac{dv_1}{dy}$ (for baryons, or net-baryons) predicted as a probe to the softening of EOS and/or the first-order phase transition;
- If a system undergoes a first-order phase transition, due to formation of mixed phase, pressure gradient is small (minimum in the v_1 slope parameter);



STAR, PRL 112, 162301 (2014)

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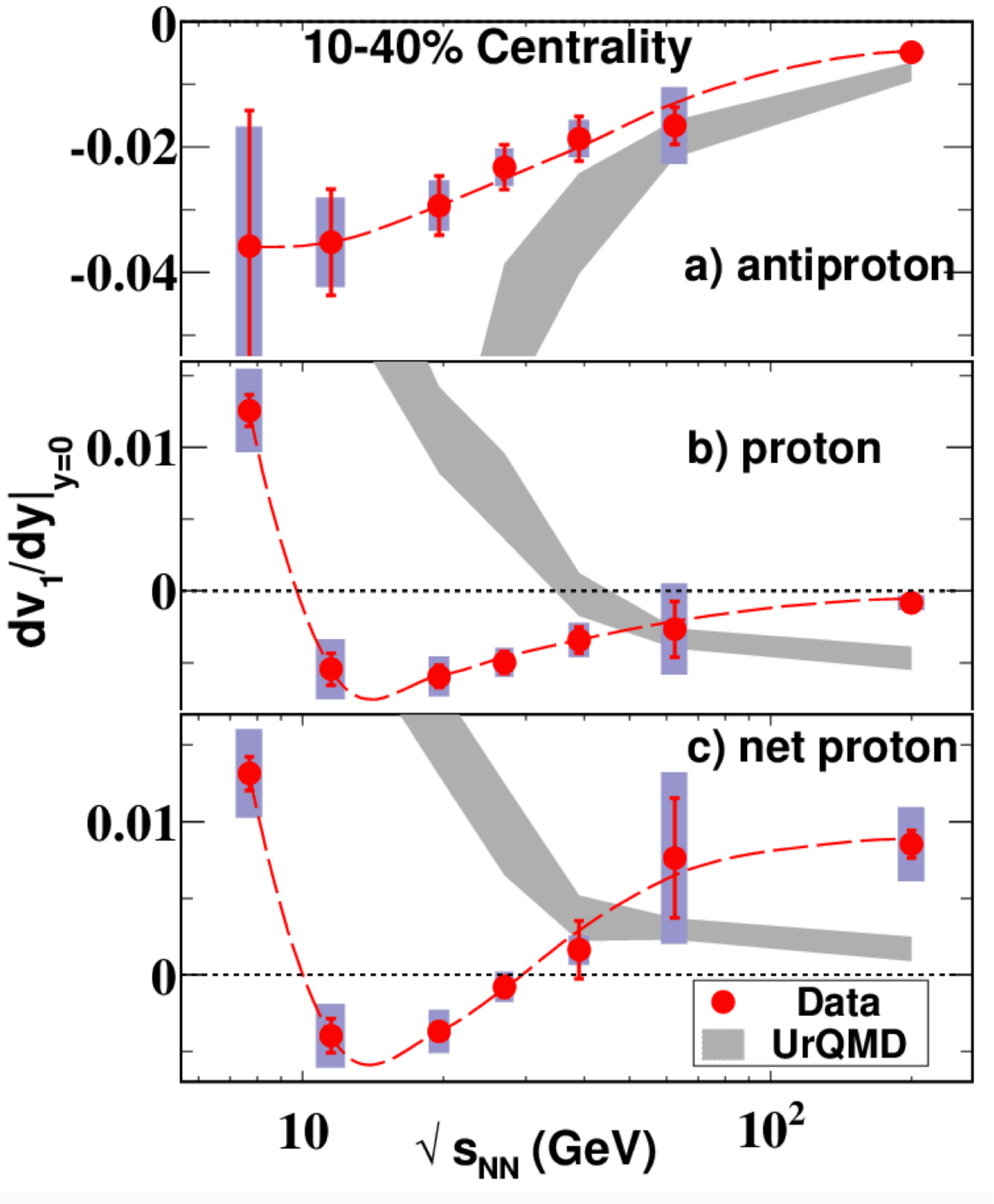
- $< m_T > - m$ measures thermal excitation in the transverse direction



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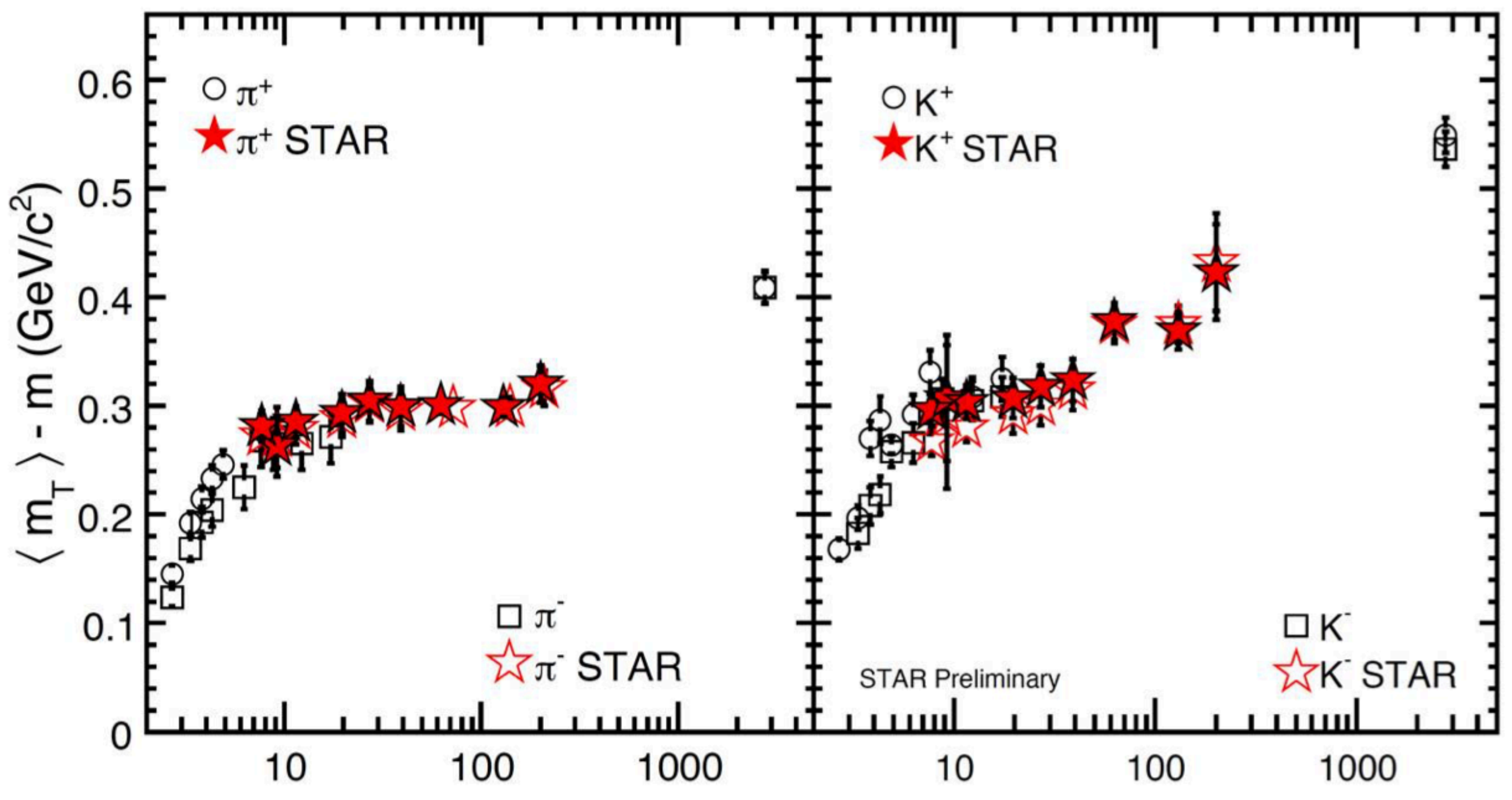
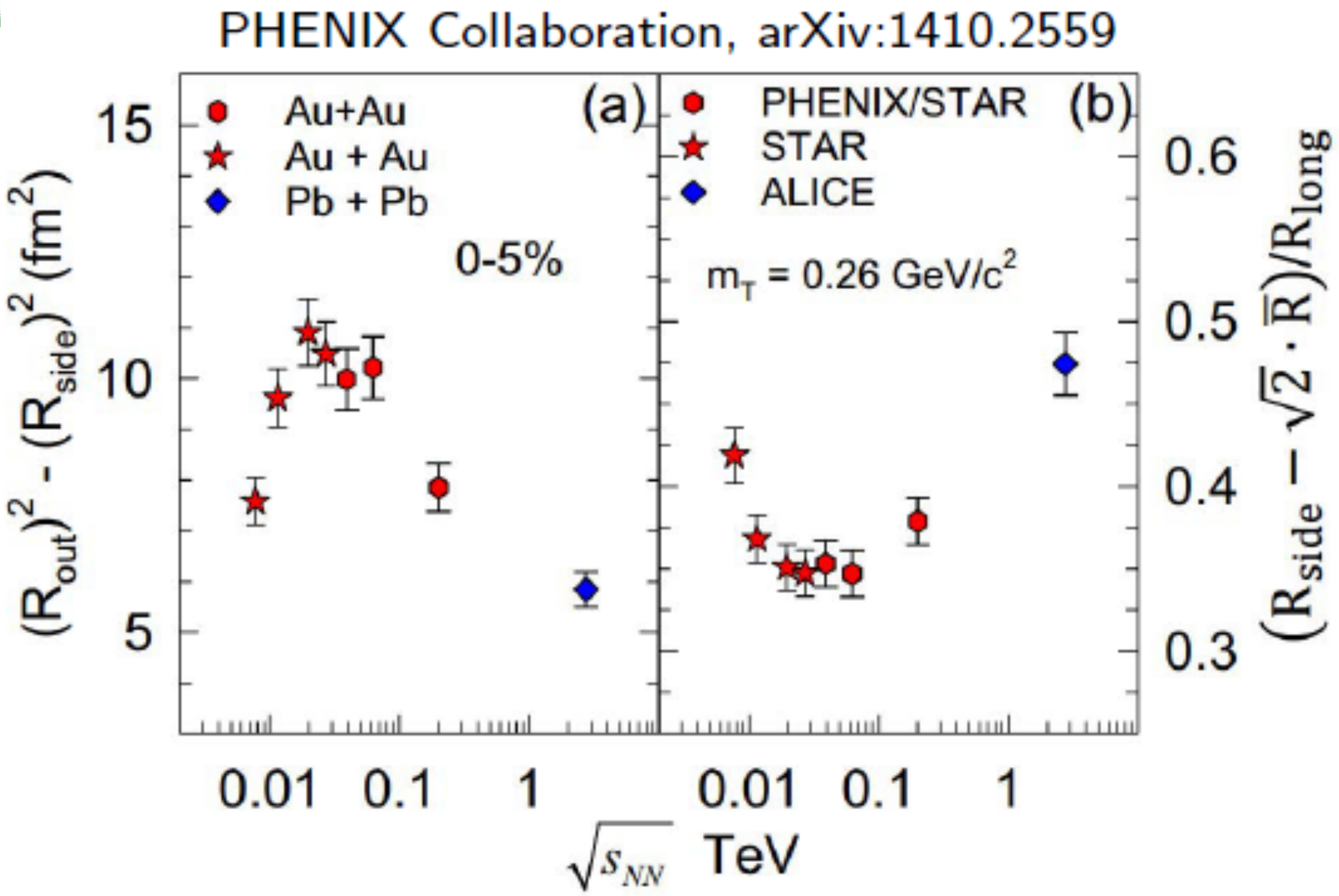
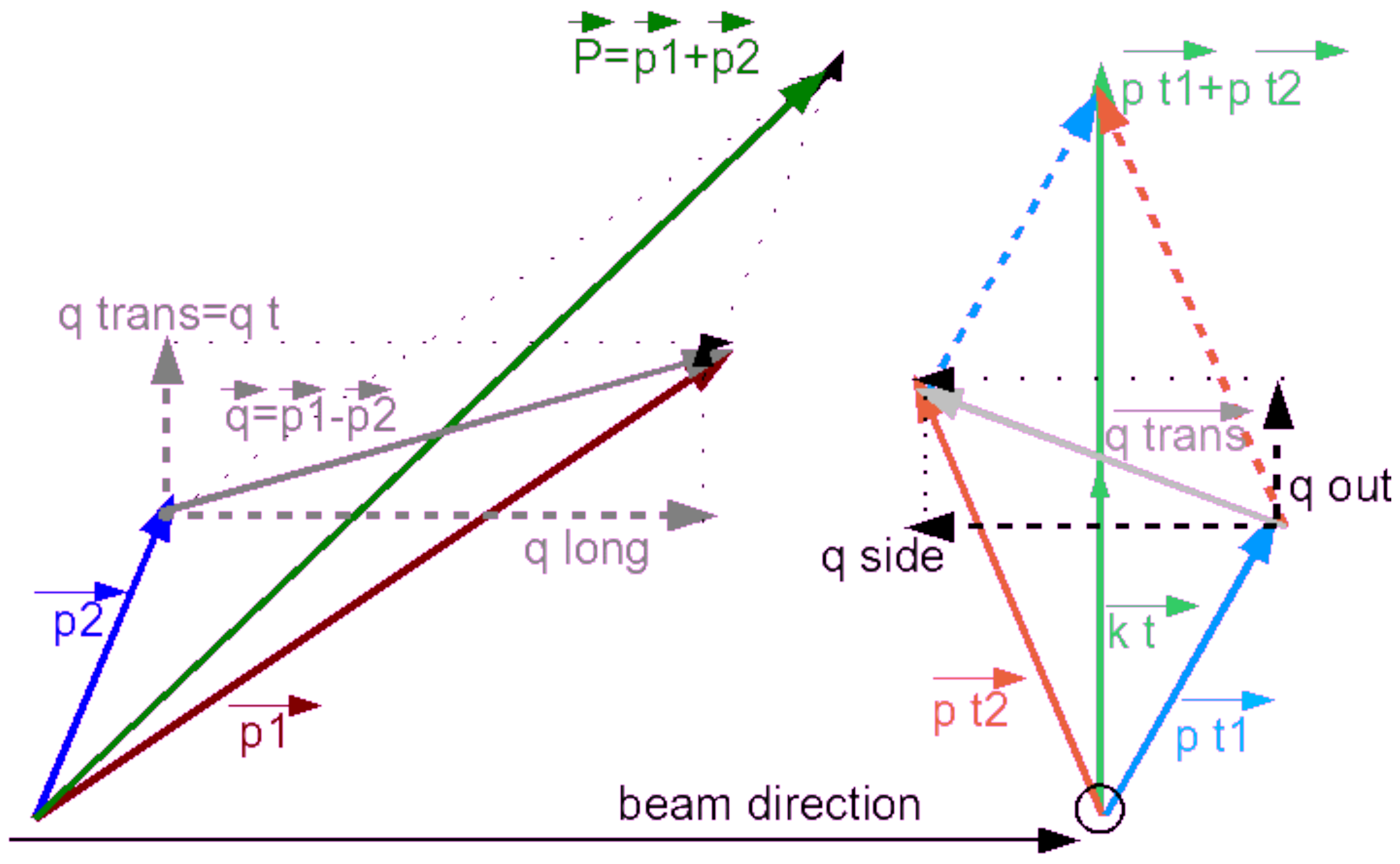


Center of Mass Collision Energy $\sqrt{s_{NN}}$ (GeV)

Femtoscopy



- $R_{out}^2 - R_{side}^2 = \beta_t^2 \Delta\tau^2$: related to emission duration
- $(R_{\rm side} - \sqrt{2}\bar{R})/R_{\rm long}$: related to expansion velocity, $\bar{R}$: initial transverse size
- Indication of the critical behavior?



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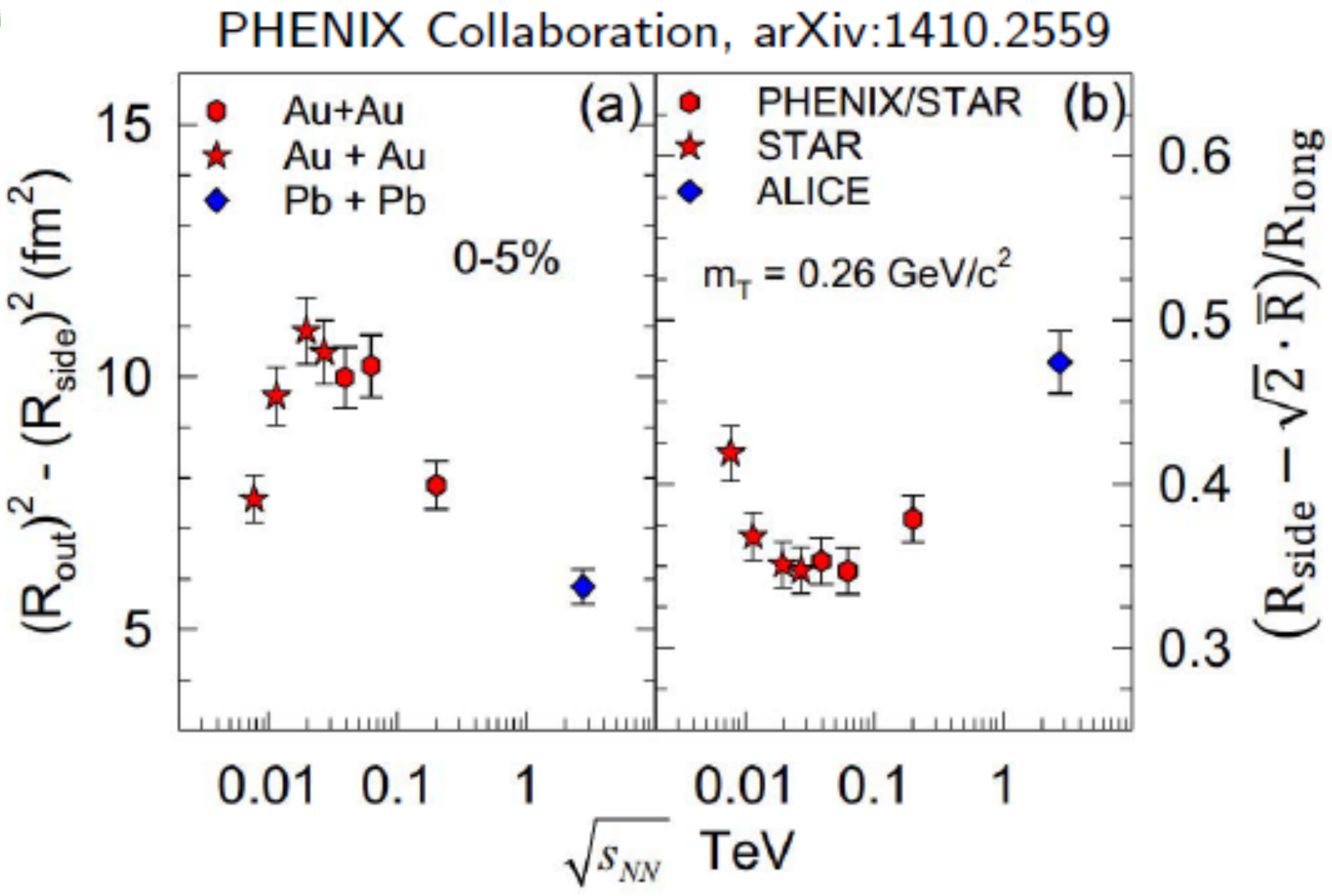

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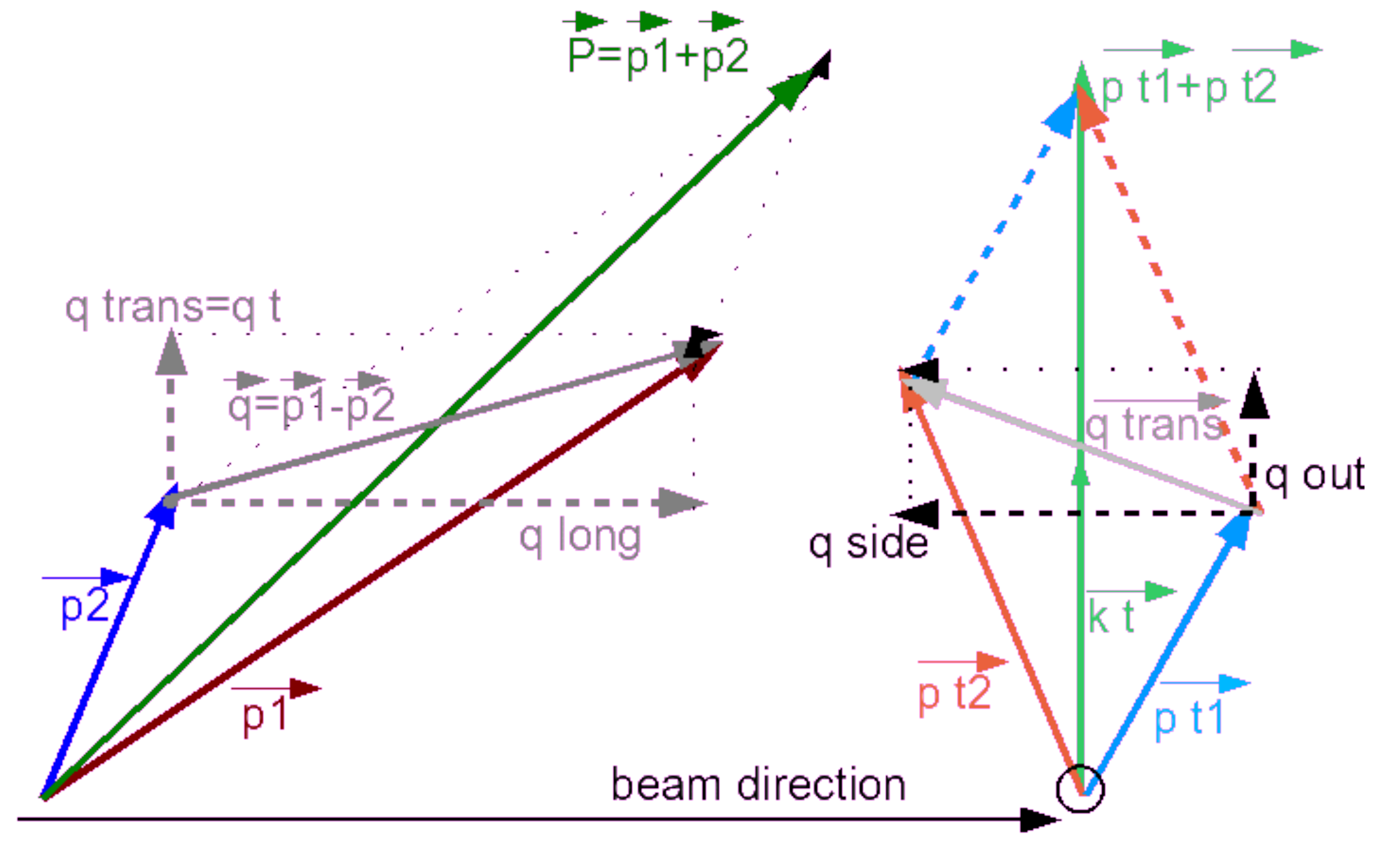
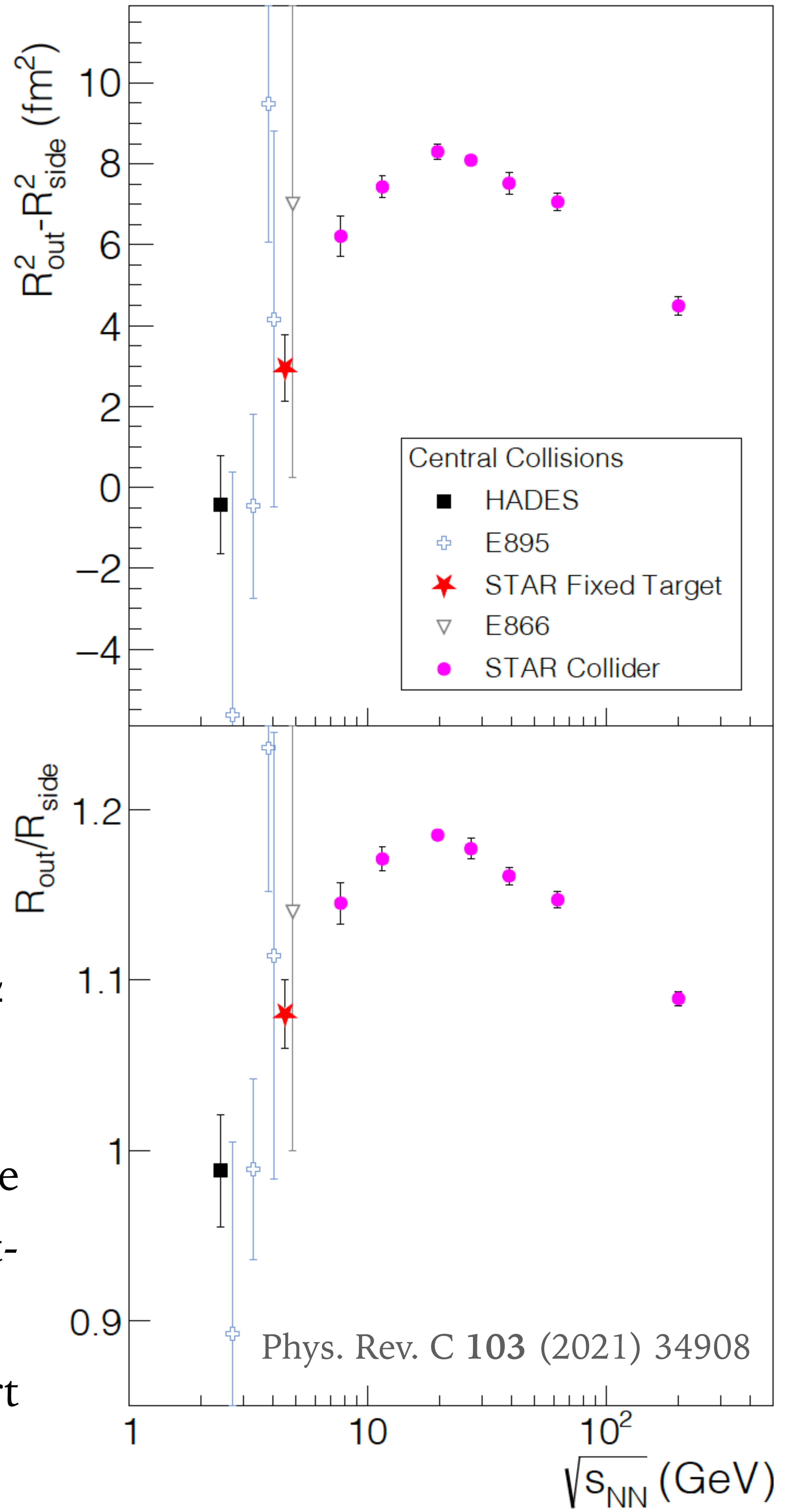
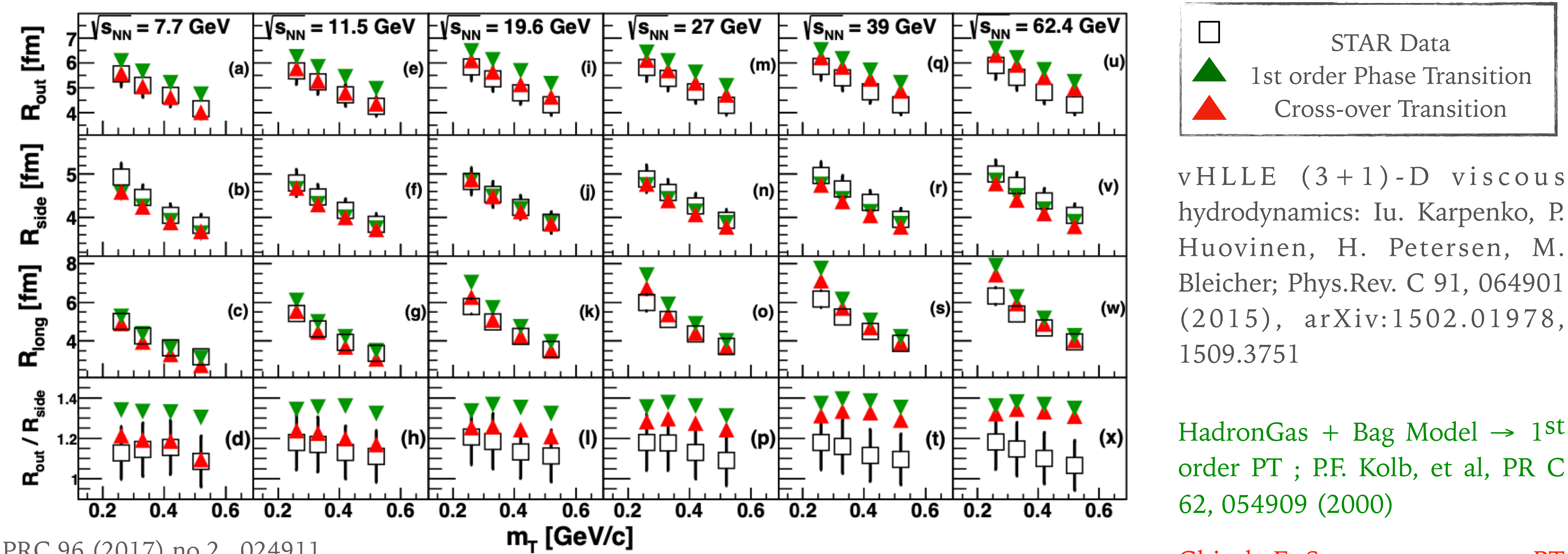


- Visible **peak** in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near the $\sqrt{s_{NN}} \simeq$ 20 GeV
- QCD calculations predict a peak near to the QGP transition threshold - signature of first-order phase transition?
- Theoretical attention from hydro and transport models needed



How to measure phase transition?



PRC 96 (2017) no.2, 024911

vHLLE (3+1)-D viscous hydrodynamics: Iu. Karpenko, P. Huovinen, H. Petersen, M. Bleicher; Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978, 1509.3751

HadronGas + Bag Model → 1st order PT ; P.F. Kolb, et al, PR C 62, 054909 (2000)

Chiral EoS → crossover PT (XPT); J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

Pre-thermal → Hydrodynamical phase → Hydronic cascades

UrQMD vHLEE UrQMD

vHLEE+UrQMD model verify **sensitivity of HBT measurements to the first-order phase transition**

Observables

1. **Onset of QGP** (disappearance of signals of partonic degrees of freedom)

Charge separation w.r.t. EP

NCQ scaling of elliptic flow

2. Search for signatures of first order **phase transition** (softening of EOS at lower collision energy)

Directed flow v_1

Femtoscopy

3. Existence of **Critical Point** (CP)

Fluctuation analyses

Fluctuations and correlations

$$\delta N = N - \langle N \rangle$$

$$C_1 = \langle N \rangle$$

$$C_2 = \langle (\delta N)^2 \rangle = \sigma^2$$

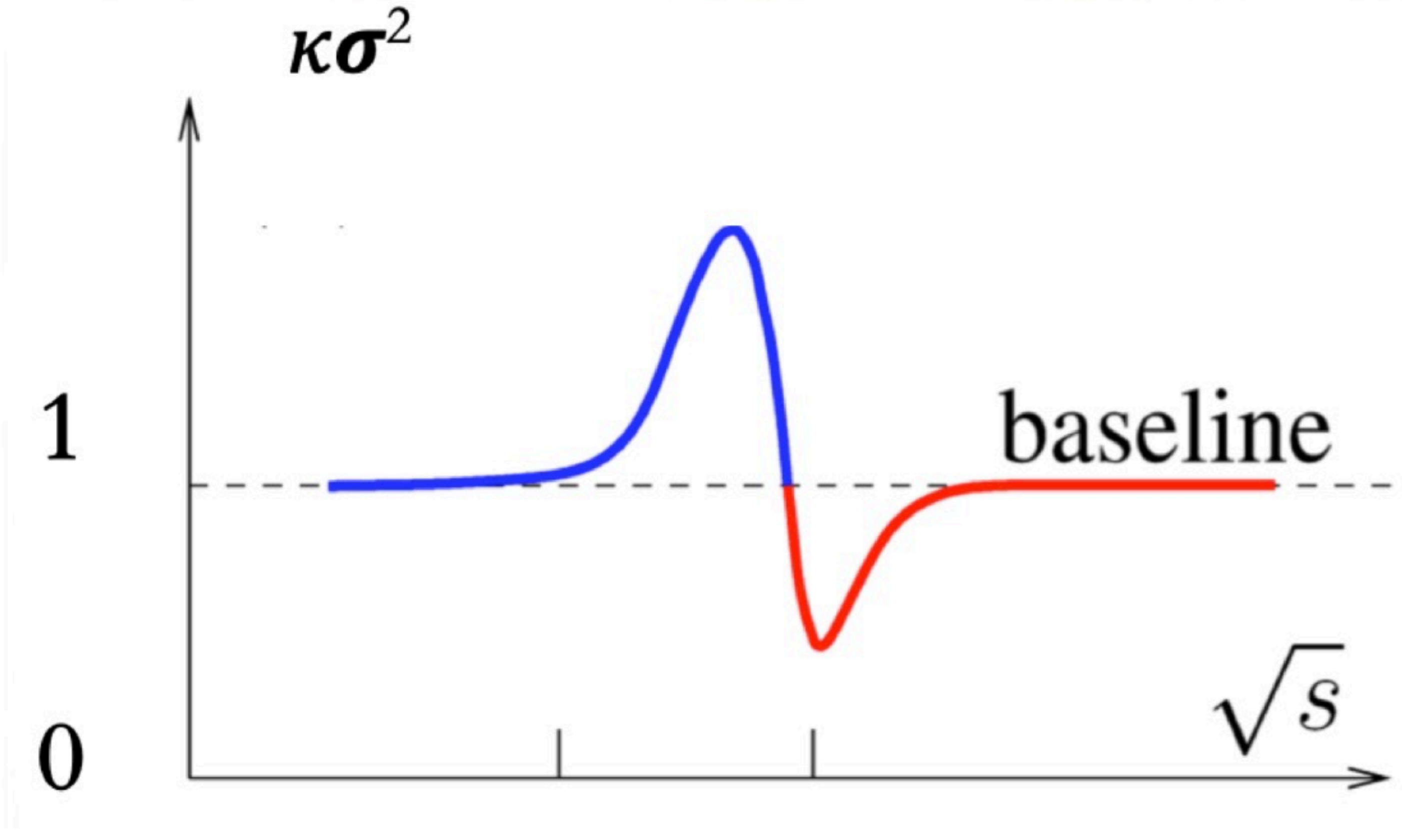
$$C_3 = \langle (\delta N)^3 \rangle$$

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

$$S\sigma = \frac{C_3}{C_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2}$$

$$C_2 \sim \xi^2 \quad C_3 \sim \xi^{4.5} \quad C_4 \sim \xi^7$$

The higher cumulant order, the more sensitive to the correlation length



4th order: predicts a non-monotonic energy dependence due to contribution from QCD critical point

- Near the QCD CP the divergence of the correlation length expected
- Non-monotonic correlations and fluctuations related to conserved quantities (B, Q, S) could indicate CP

- Higher moments of conserved quantities measure non-Gaussian nature of fluctuations, and are more sensitive (than e.g. variance) to CP fluctuations (leads to correlation length)

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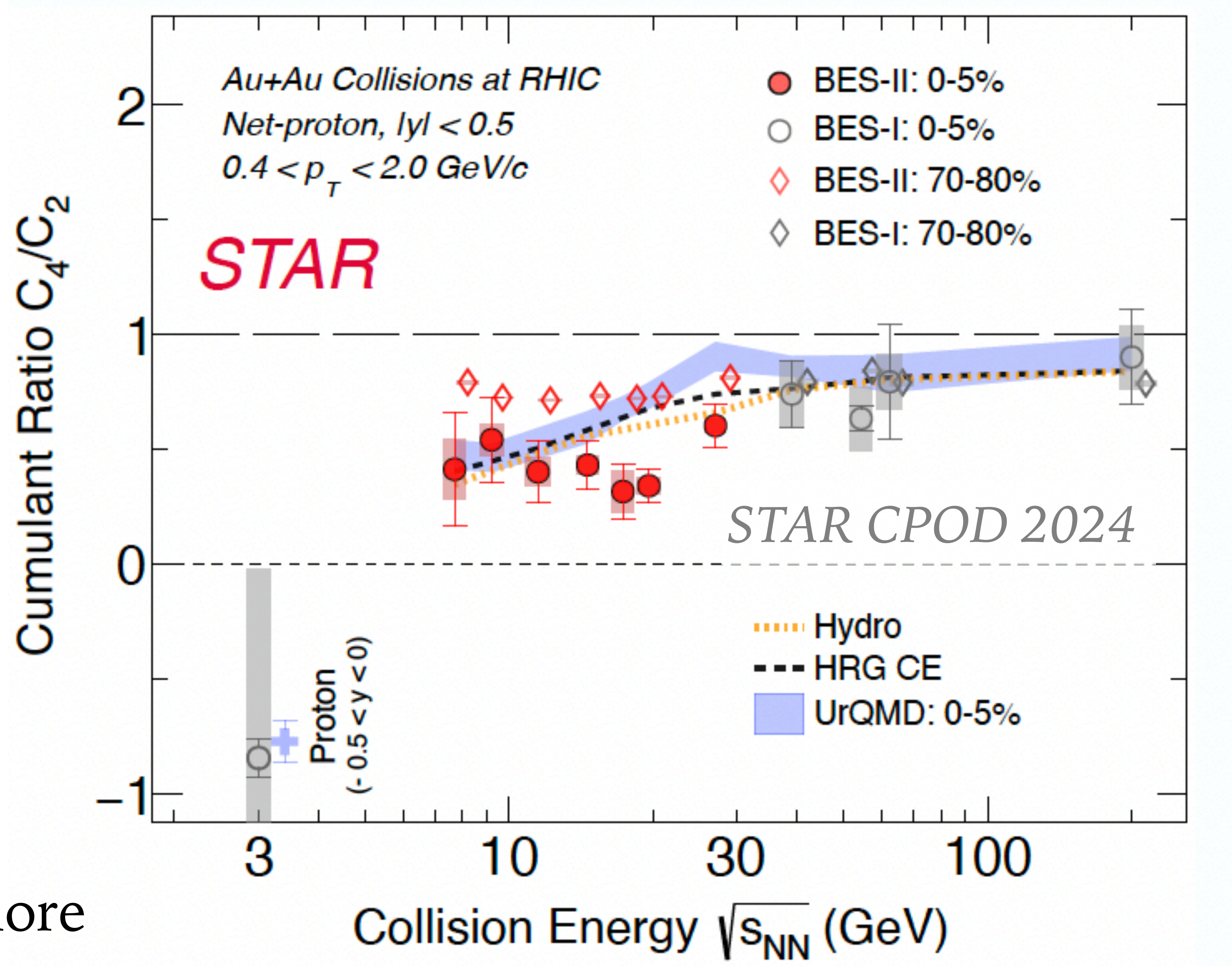

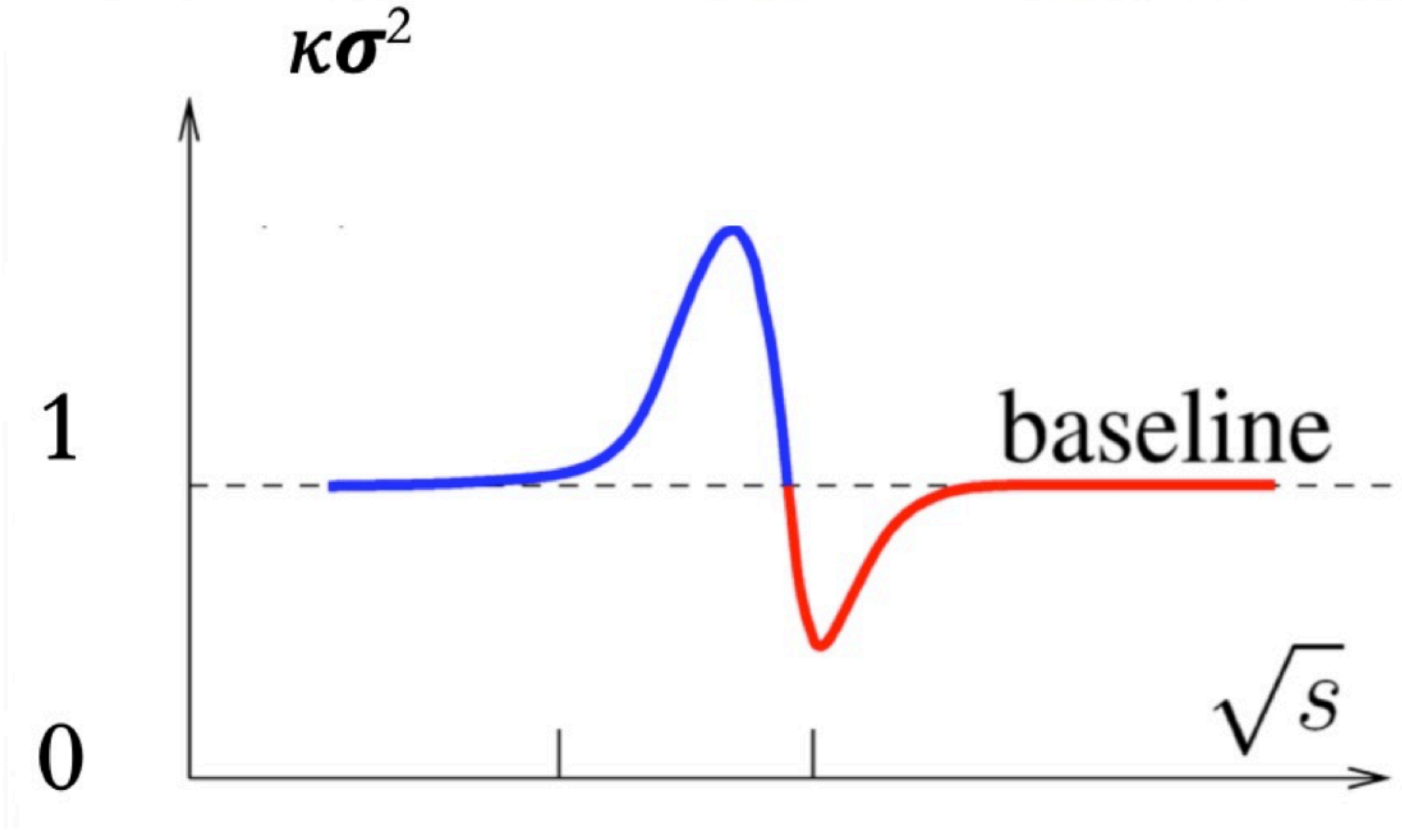

C_4/C_2: predicts a non-monotonic energy dependence due to contribution from QCD critical point

- Near the QCD CP the divergence of the correlation length expected
- Non-monotonic correlations and fluctuations related to conserved quantities (B, Q, S) could indicate CP
- Higher moments of conserved quantities measure non-Gaussian nature of fluctuations, and are more sensitive (than e.g. variance) to CP fluctuations (leads to correlation length)
- Non-monotonic energy dependence of net-proton seen as deviation w.r.t to model calculations without CP.
- The suppression of C4/C2 consistent with fluctuations driven by baryon number conservation indicating a hadronic interaction dominated region at $\sqrt{s_{NN}} = 3$ GeV
- The QCD critical point, (if exists in heavy ion collisions), could be located at $\sqrt{s_{NN}} > 3$ GeV; STAR, PRL 126, 092301 (2021), PRC 104.024902 (2021), PRL 128.202303 (2022)

Road map

Beam Energy Scan program

QCD Phase Diagram

STAR experiment

Main questions

Summary and perspectives

Summary from BES

Continue to look for the **Critical Point** and
the **first-order phase transition**.

High statistics exploration of QCD phase diagram and its key features has already begun

More coming soon (BES-II, SPS, FAIR)

Turn trends and features into definite conclusions

More interesting questions appeared..

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Thank You for your attention!