STAR highlights with focus on BES results

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EXCELLENCE INITIATIVE RESEARCH UNIVERSITY

Road map

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

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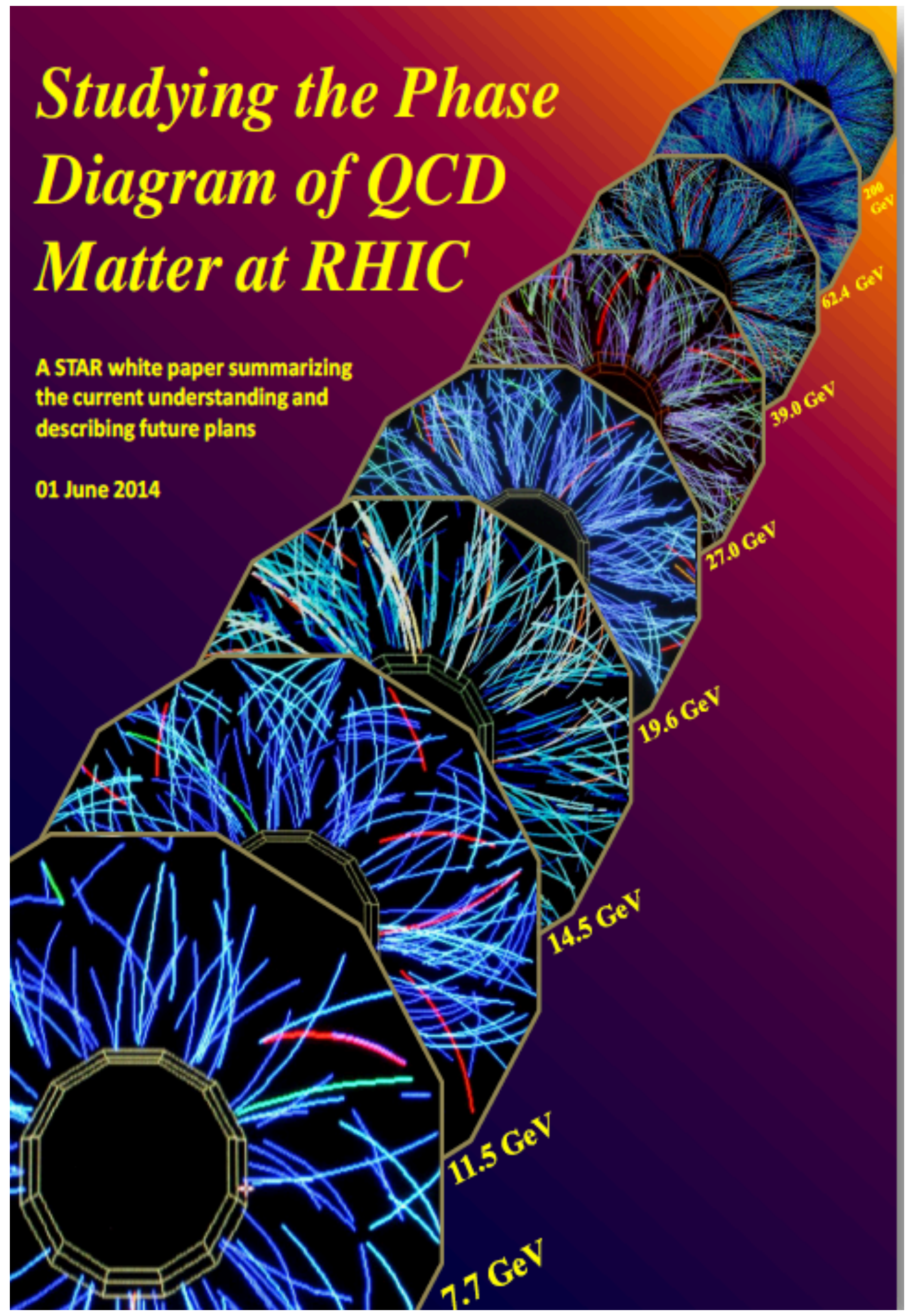
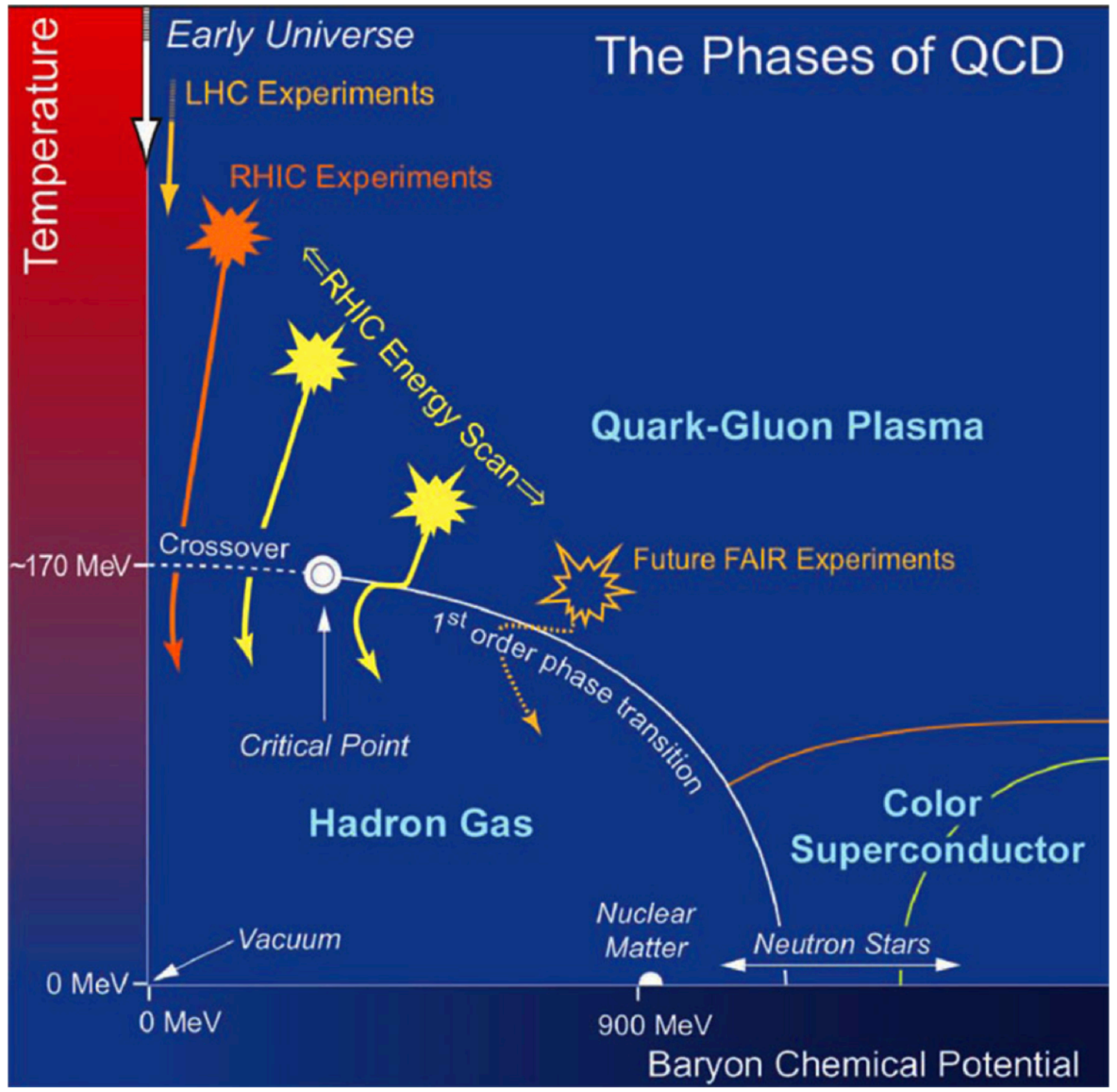
Beam Energy Scan program

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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- **QCD Phase Diagram**
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Probing QCD Phase Diagram

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

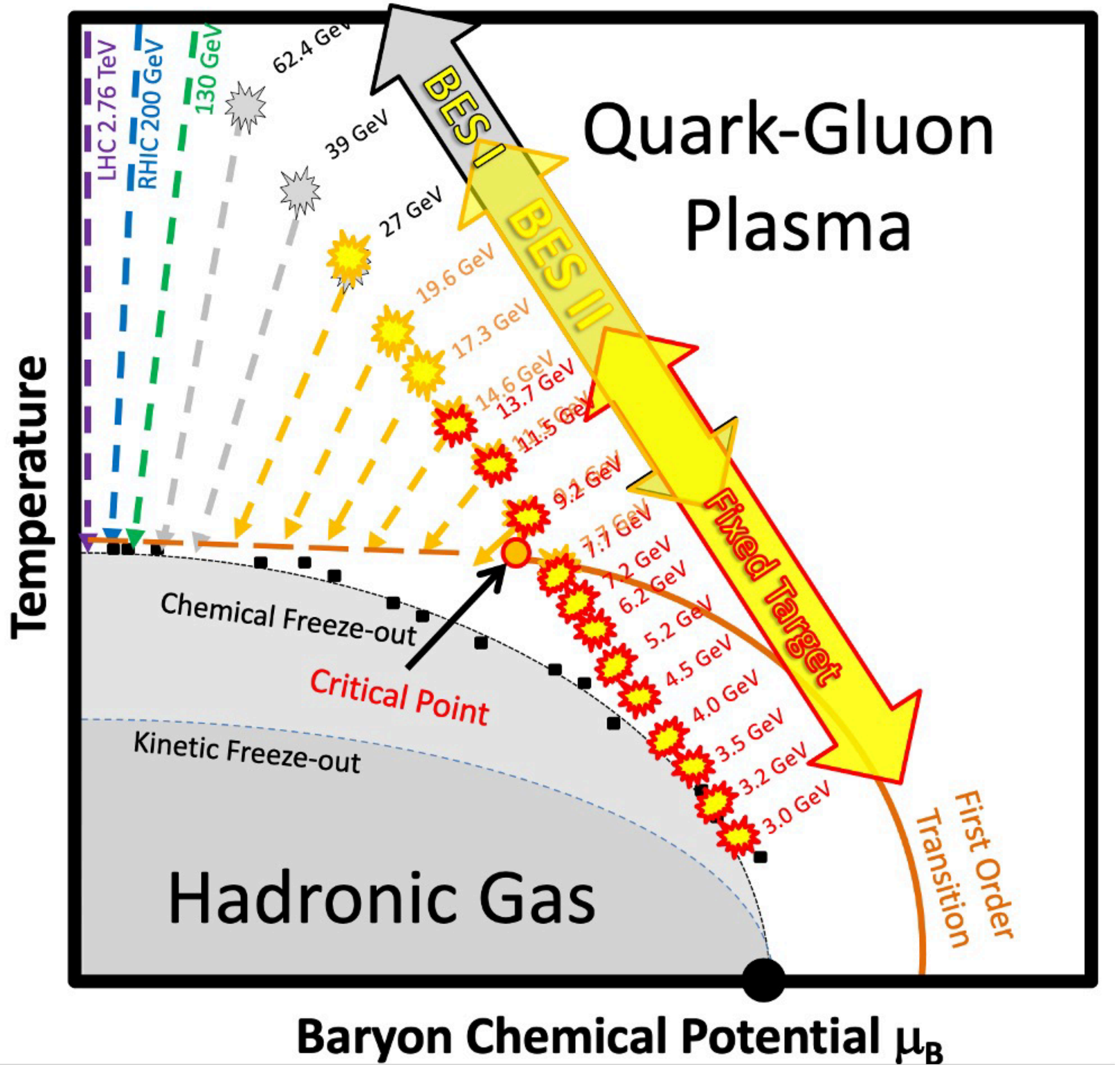
Believed to be understood:

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)



Road map

Beam Energy Scan program

QCD Phase Diagram

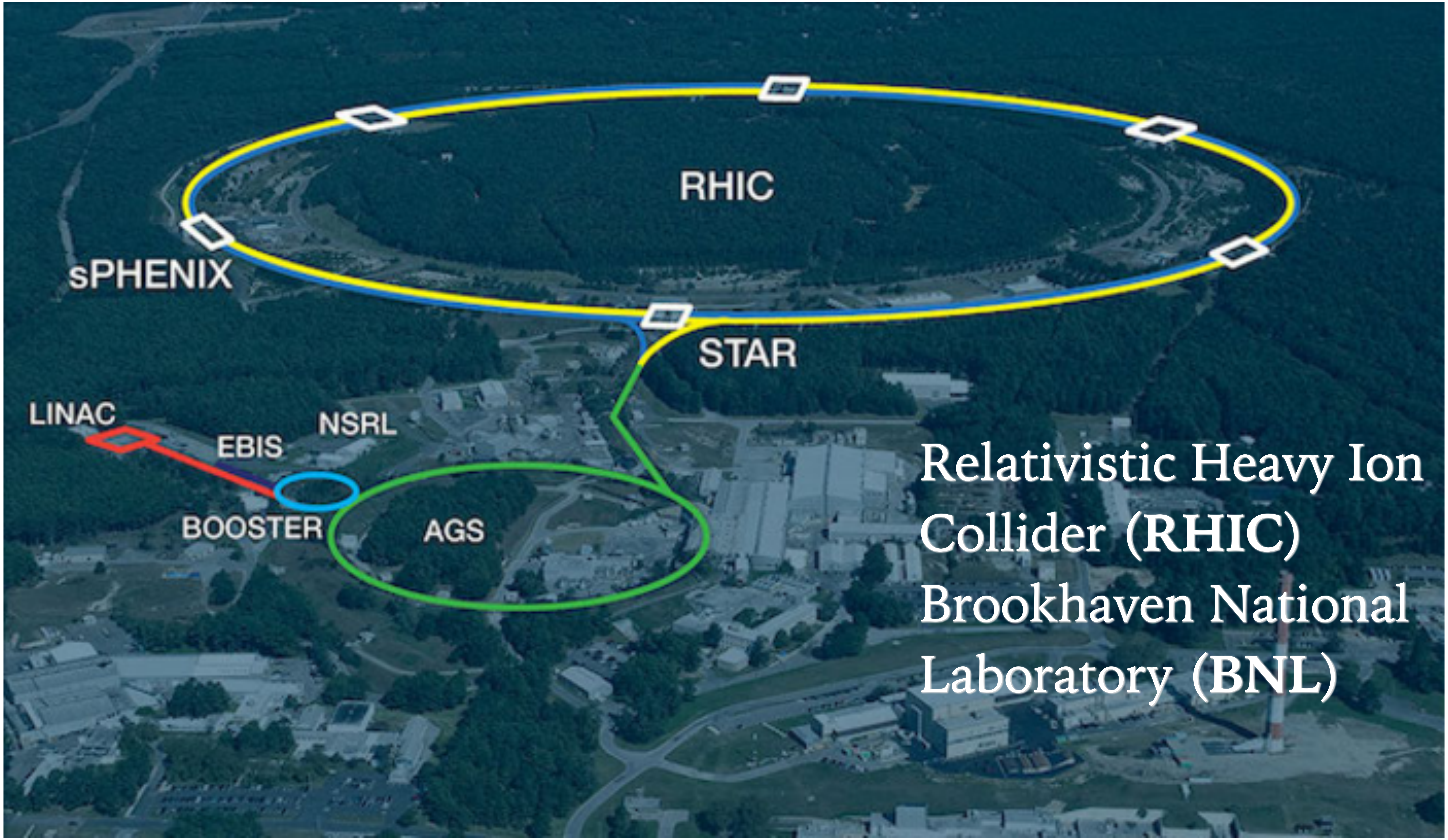
STAR experiment

Main questions

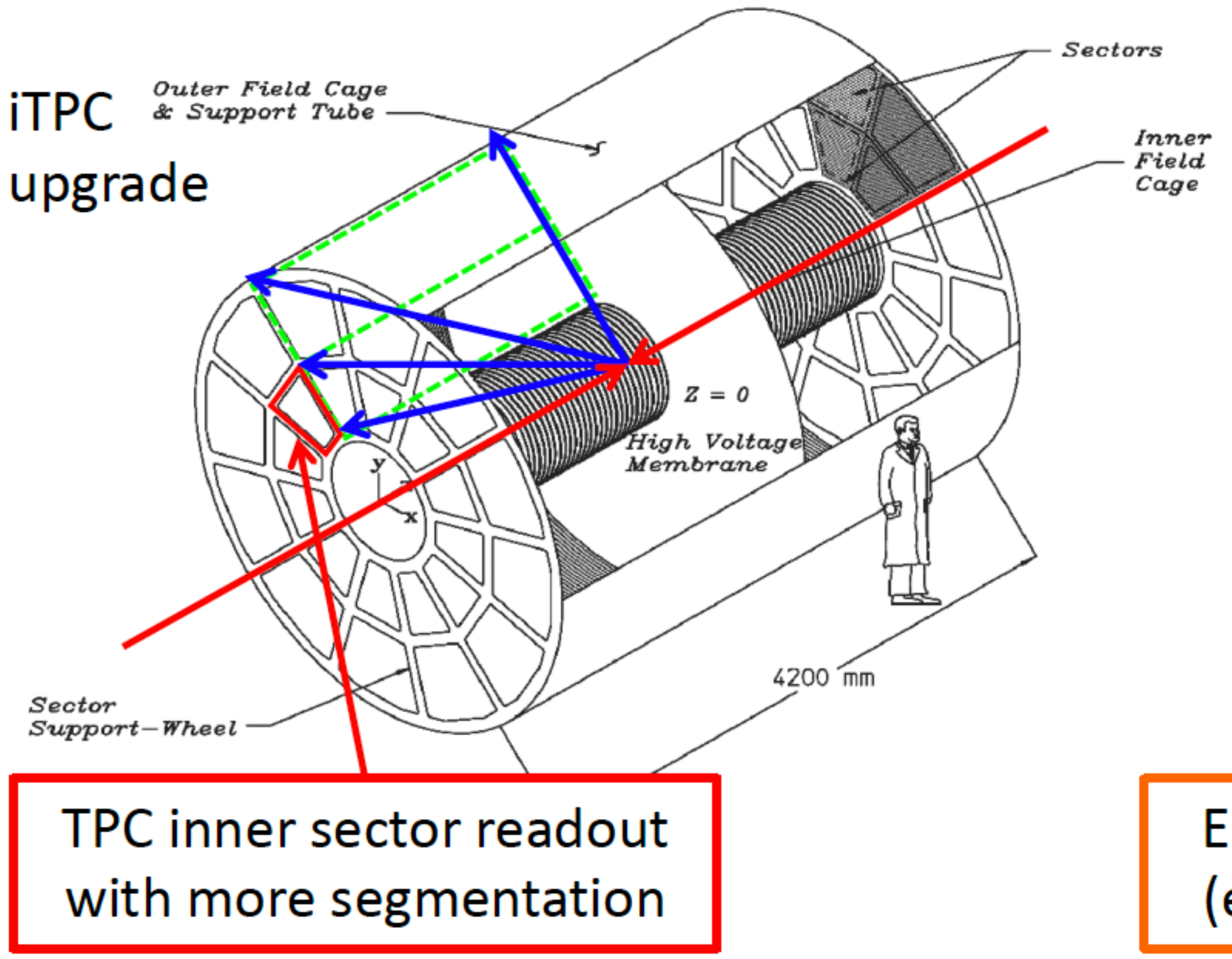
Summary and perspectives

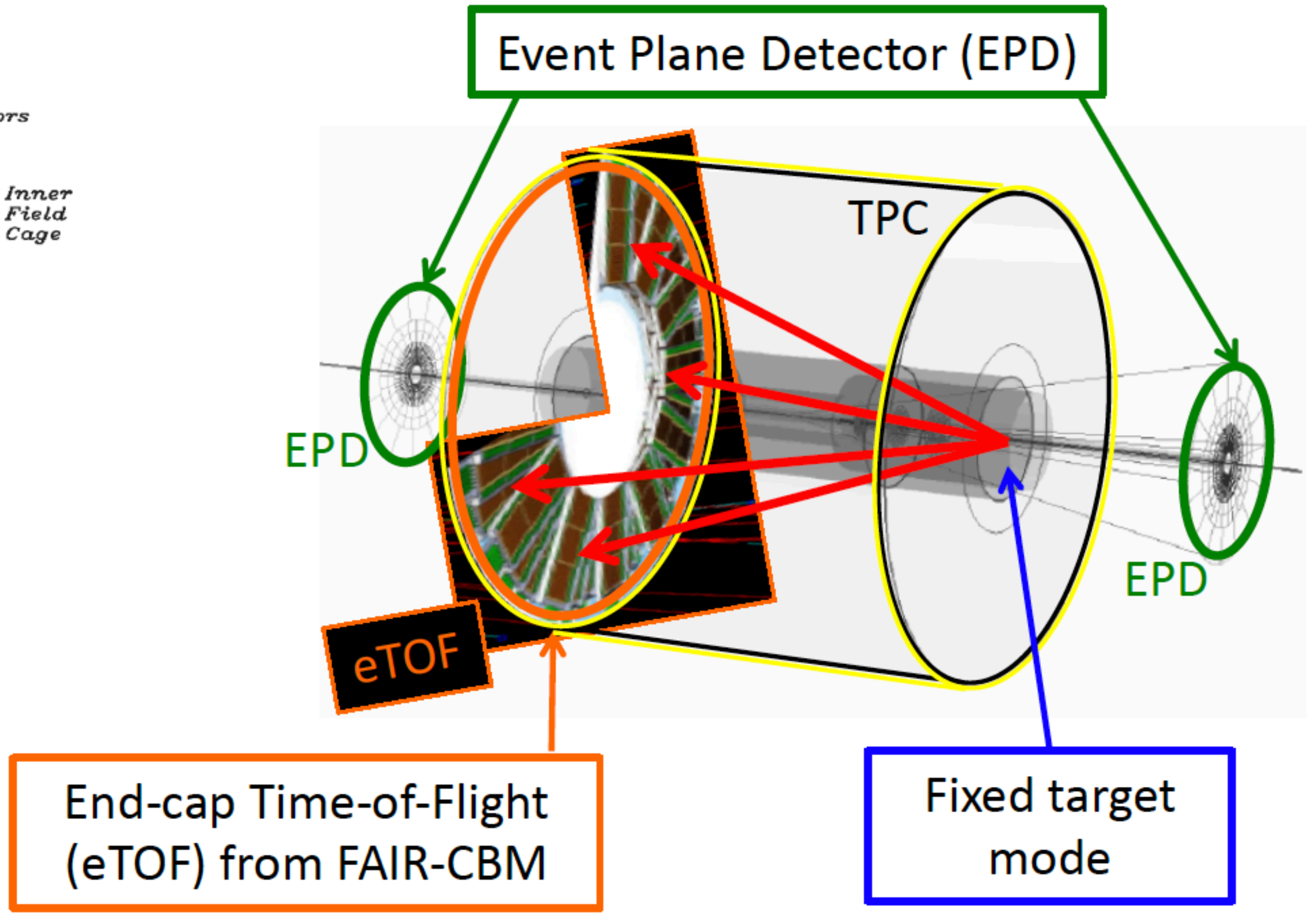
Relativistic Heavy Ion Collider

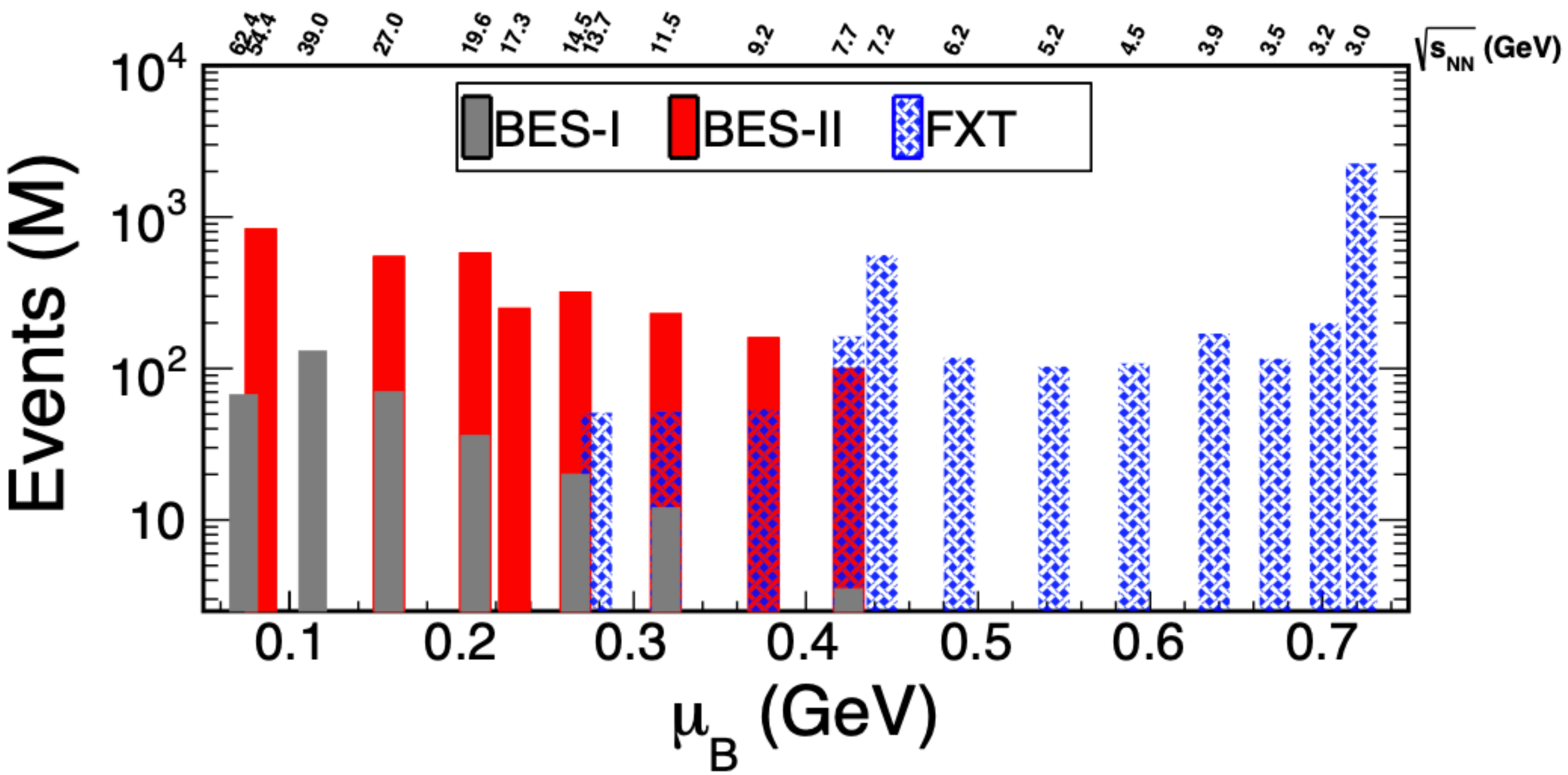
- 3.83 km circumference
- Two independent rings
- Collides so far:
  - Au+Au, p+p, d+Au, Cu+Cu, U+U, Cu+Au, ^{3}He+Au, p+Au Zr+Zr, Ru+Ru
- Top Center-of-Mass Energy
  - 510 GeV for p-p
  - 200 GeV/nucl. for Au-Au



STAR detector system







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

BES program started at 2010.

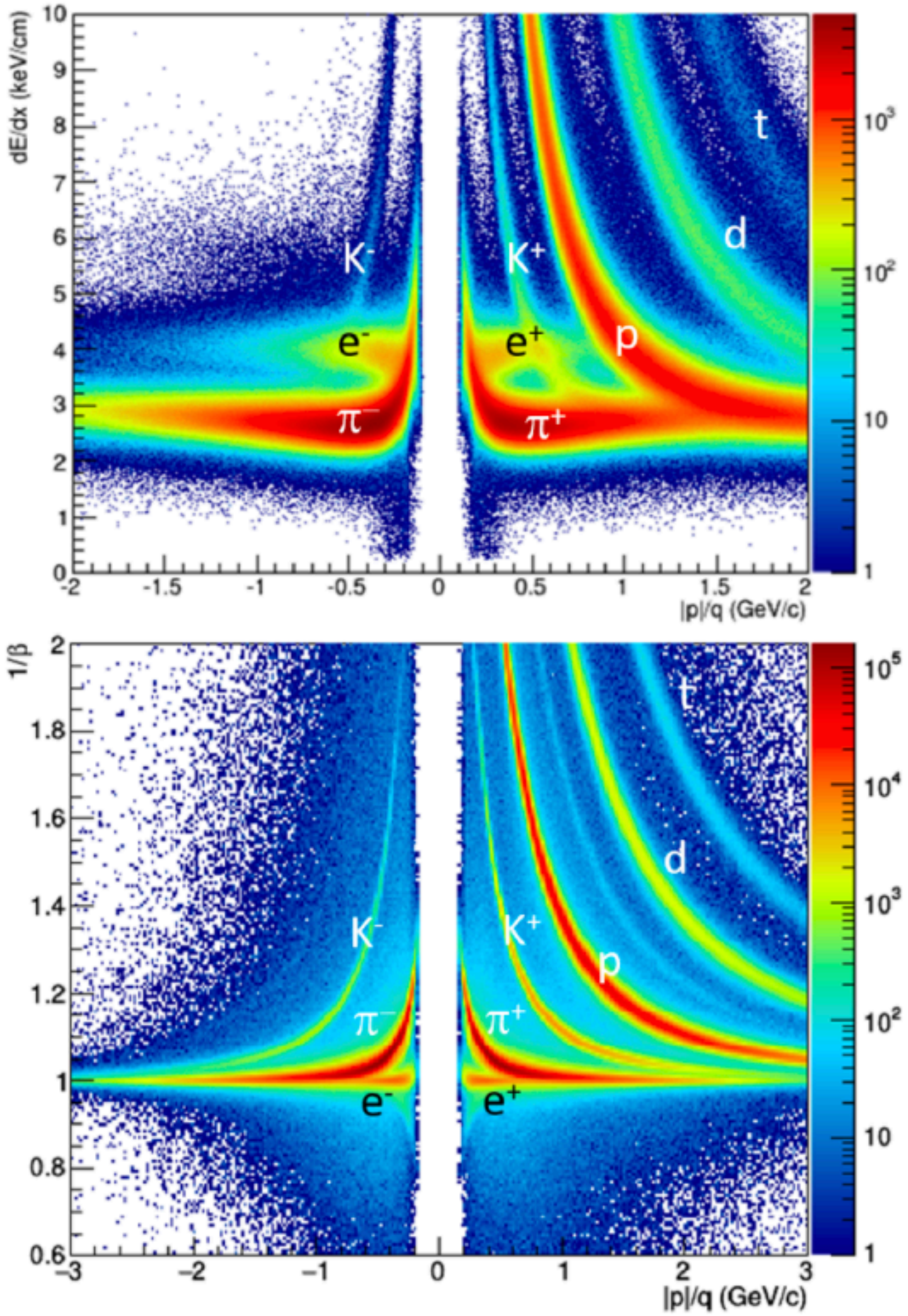
Luminosity of the RHIC collider-mode is unusable for $\sqrt{s_{NN}} < 7.7$ GeV.

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

Particle identification

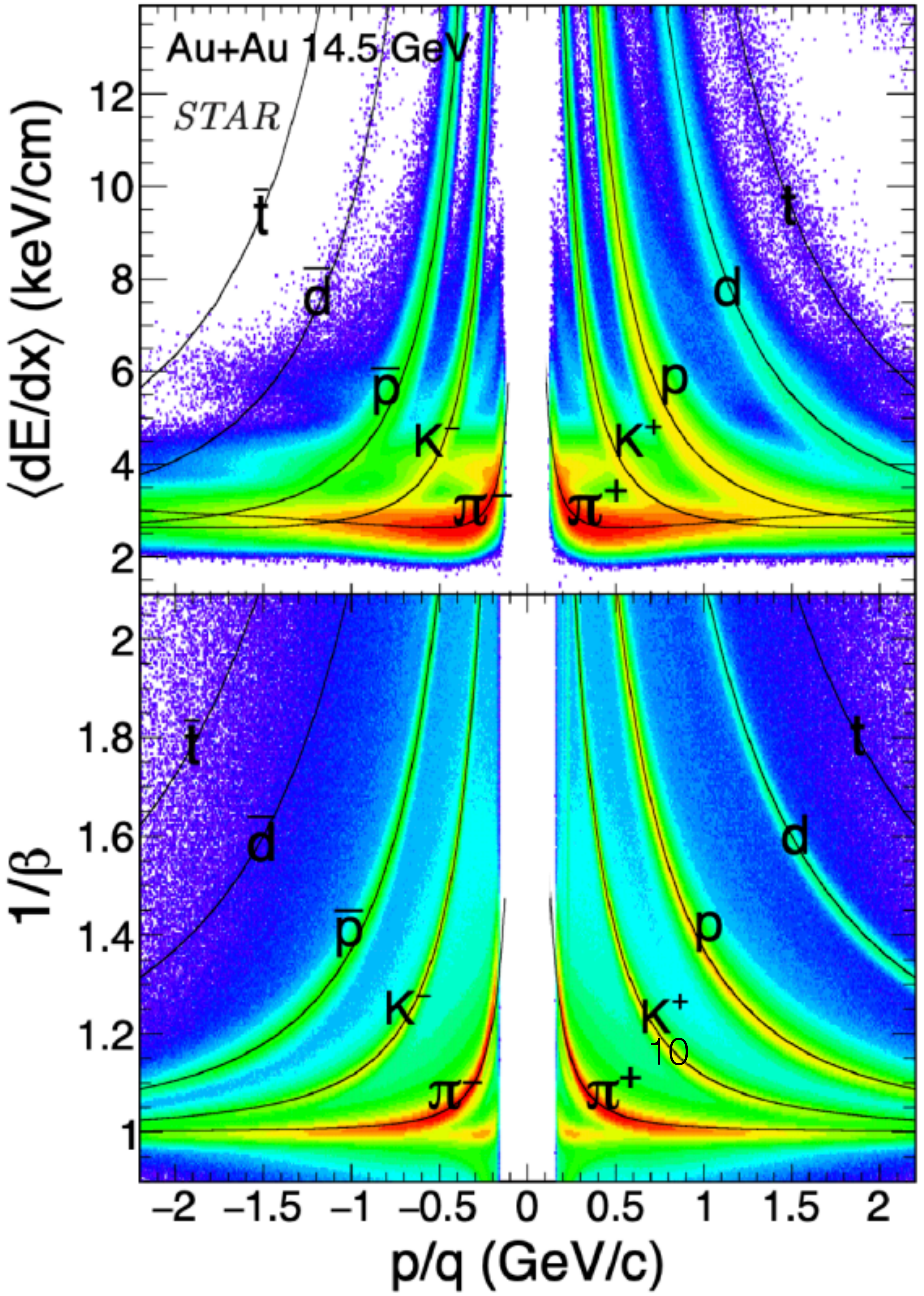
arXiv:2007.14005 (STAR)

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



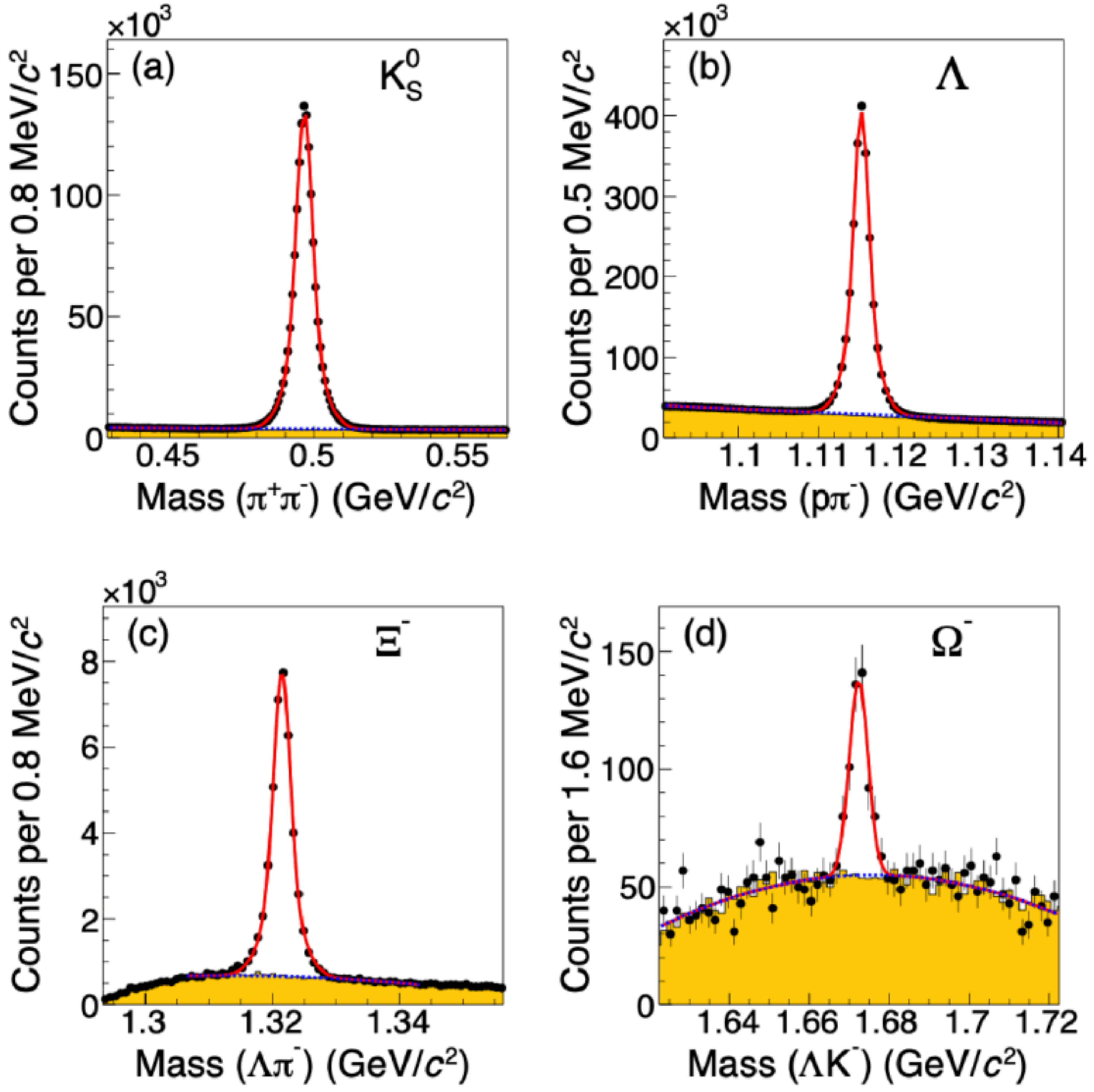
PRC 101 (2020) 24905 (STAR)

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



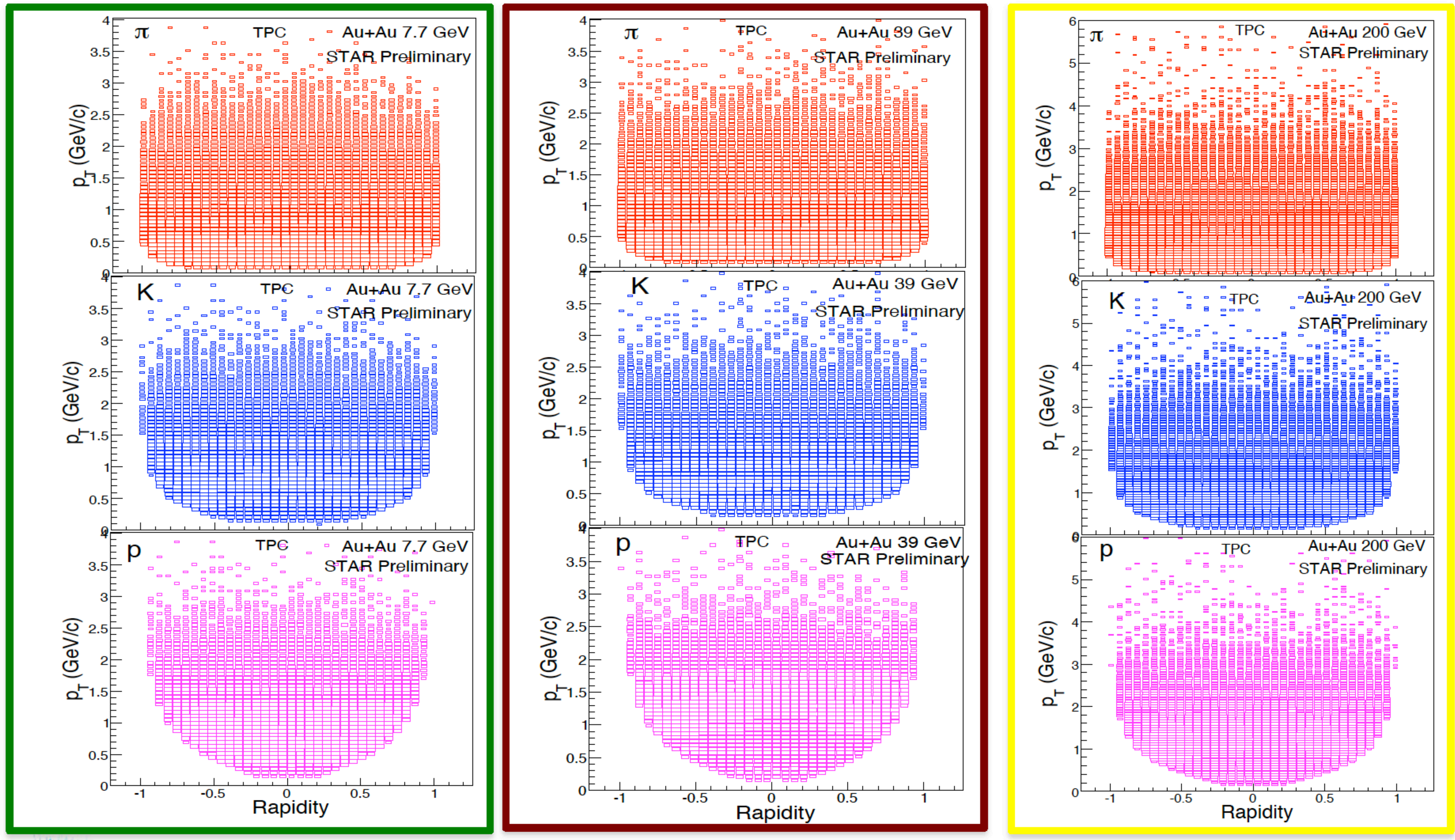
PRC 102 (2020) 34909 (STAR)

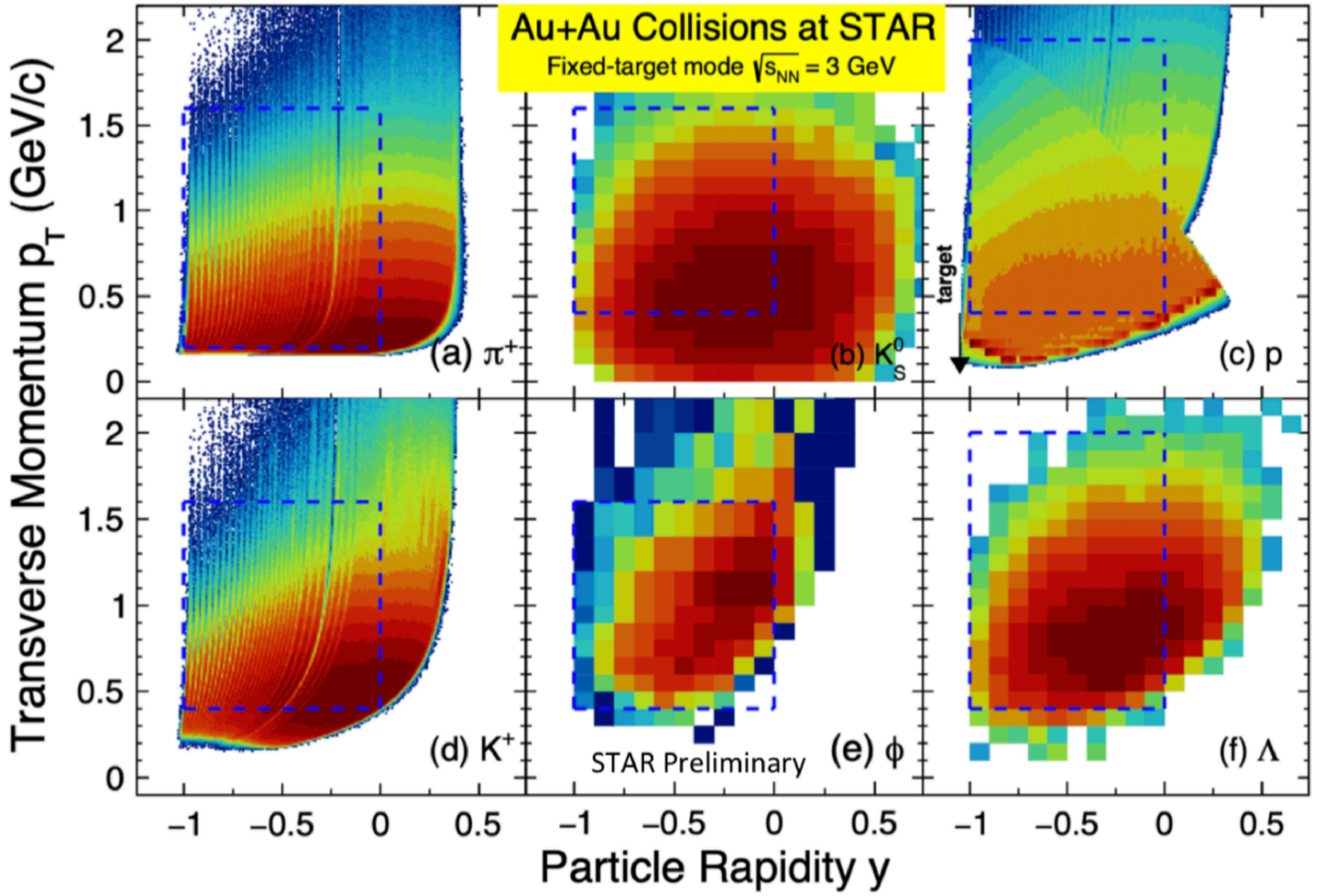
$\sqrt{s_{NN}}$=7.7GeV Collider



Collider and fixed-target acceptance

Au+Au at 7.7 GeV | Au+Au at 39 GeV | Au+Au at 200 GeV

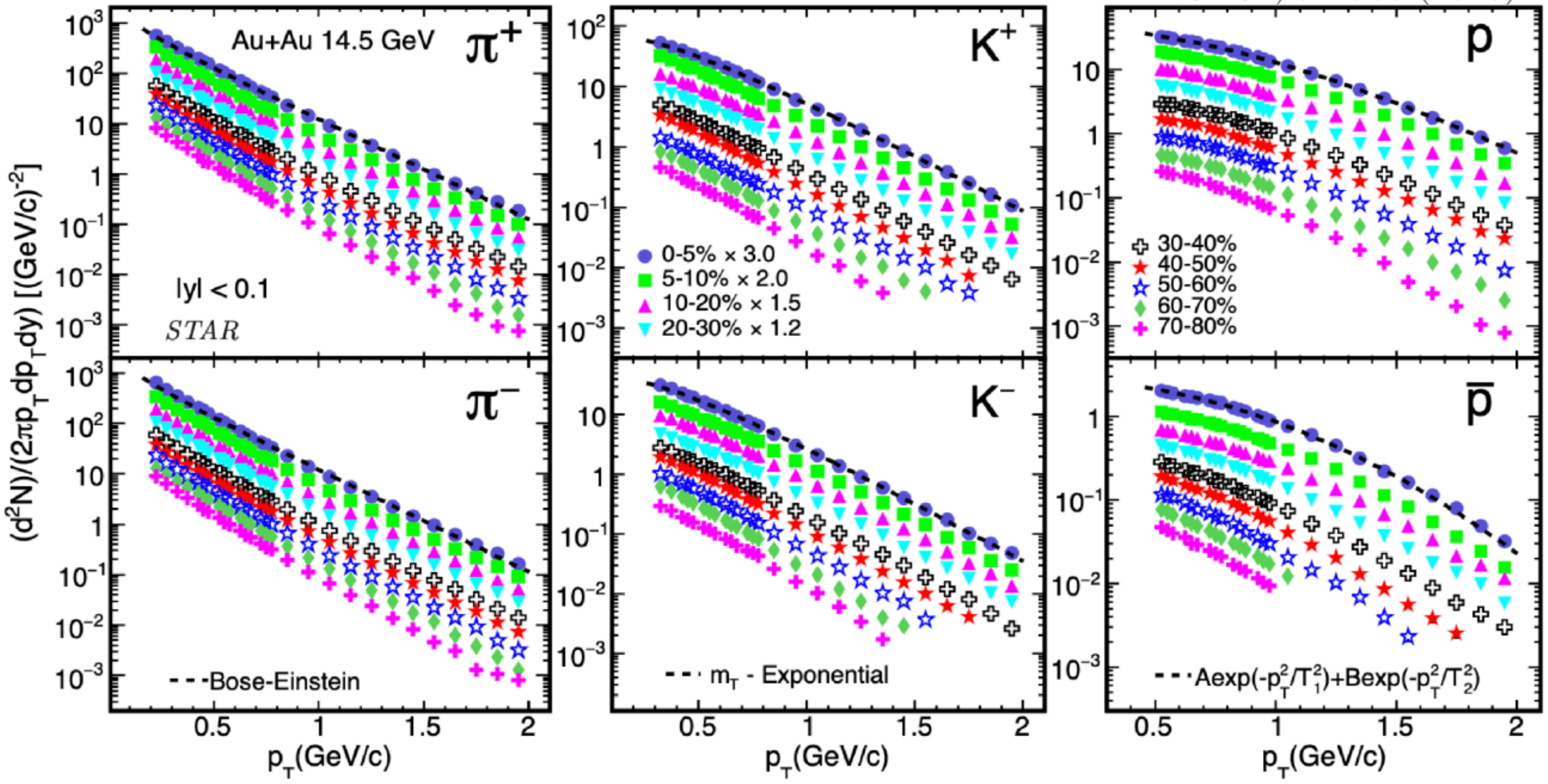




Similar acceptance for all particles and energies

Particle spectra

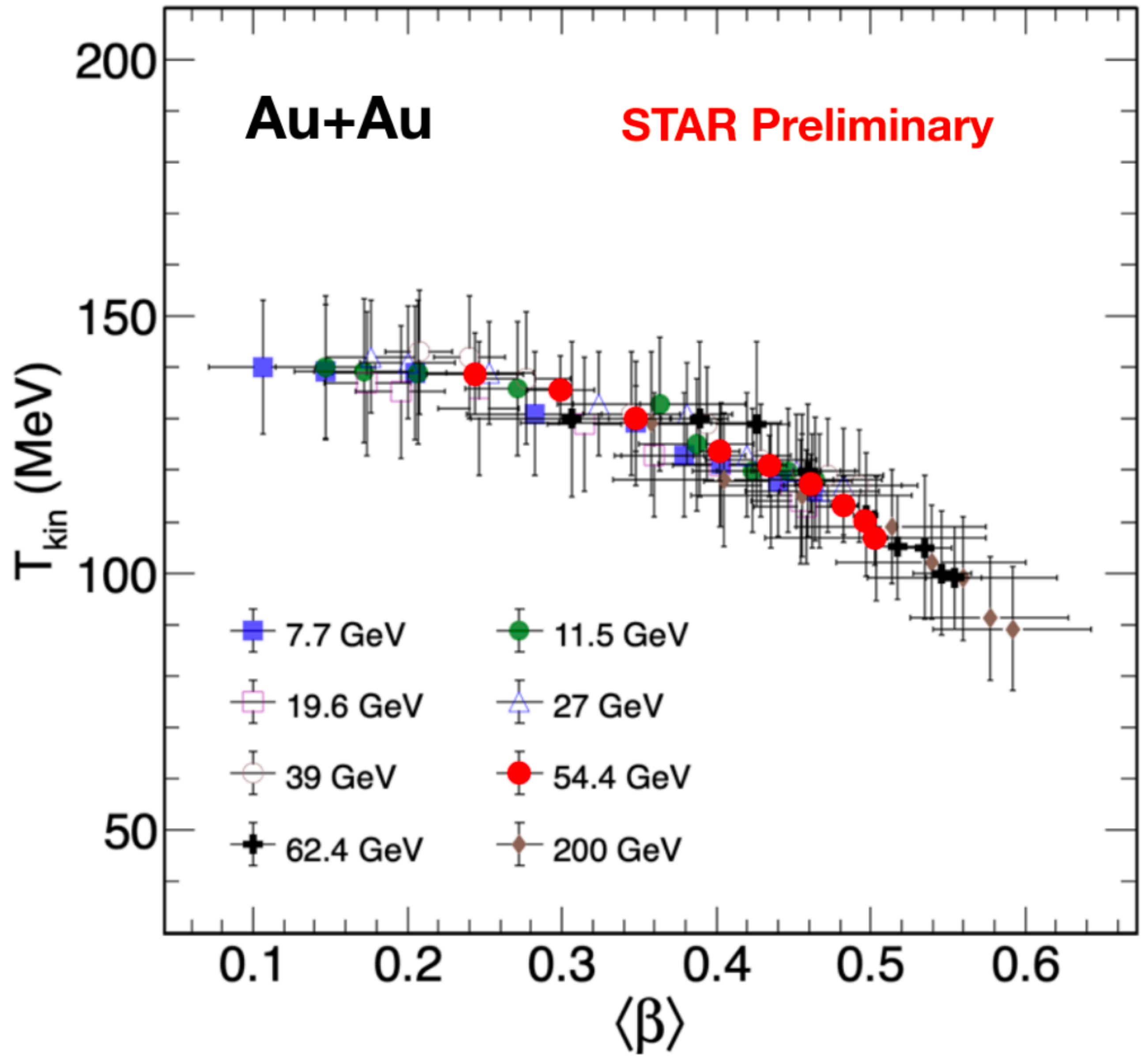
PRC **101**, 024905 (2020)



Inverse slopes of the identified hadron spectra follow the order $\pi < \mathrm{K} < \mathrm{p}$

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

Chemical and kinetic freeze-out parameters

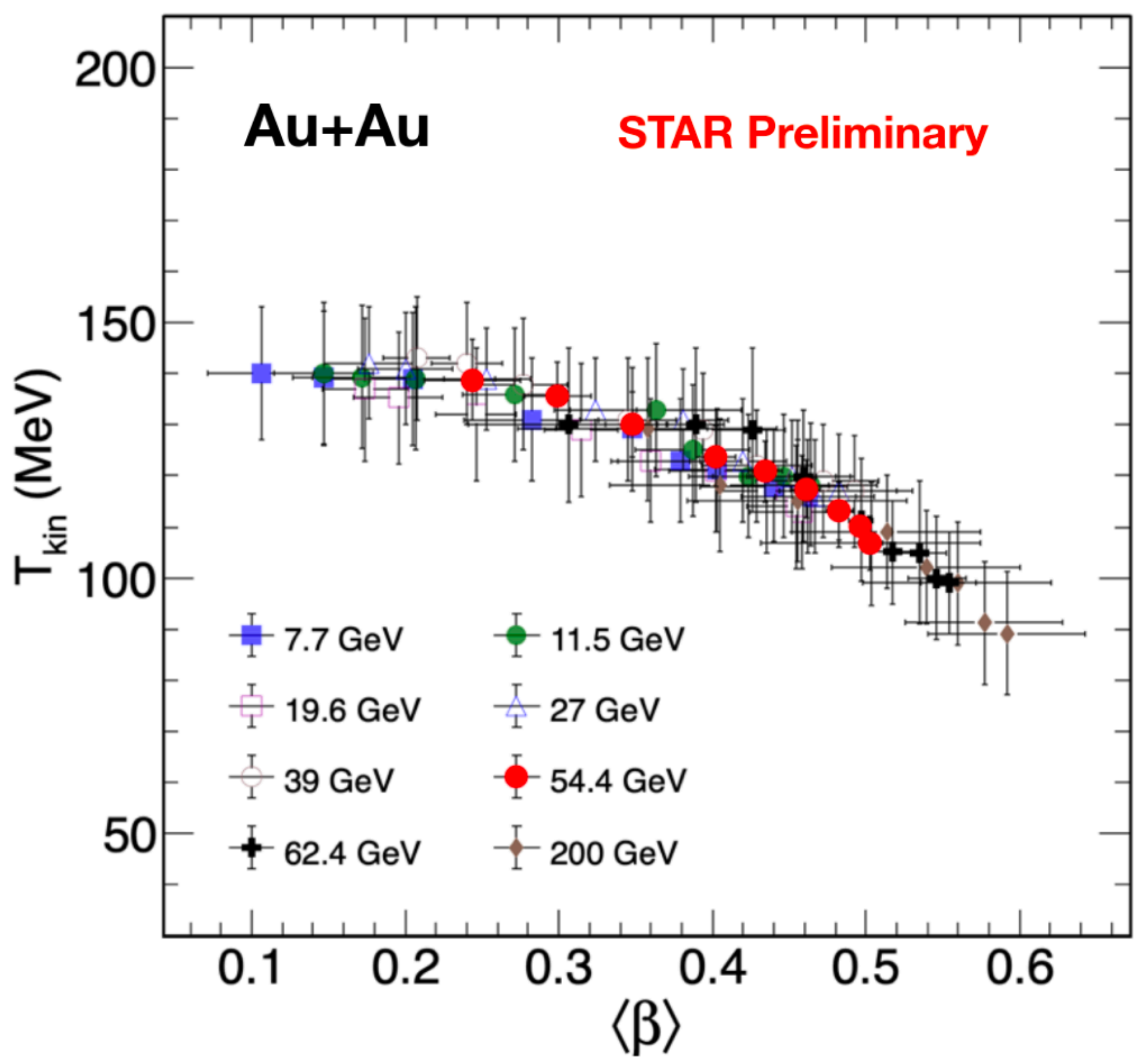


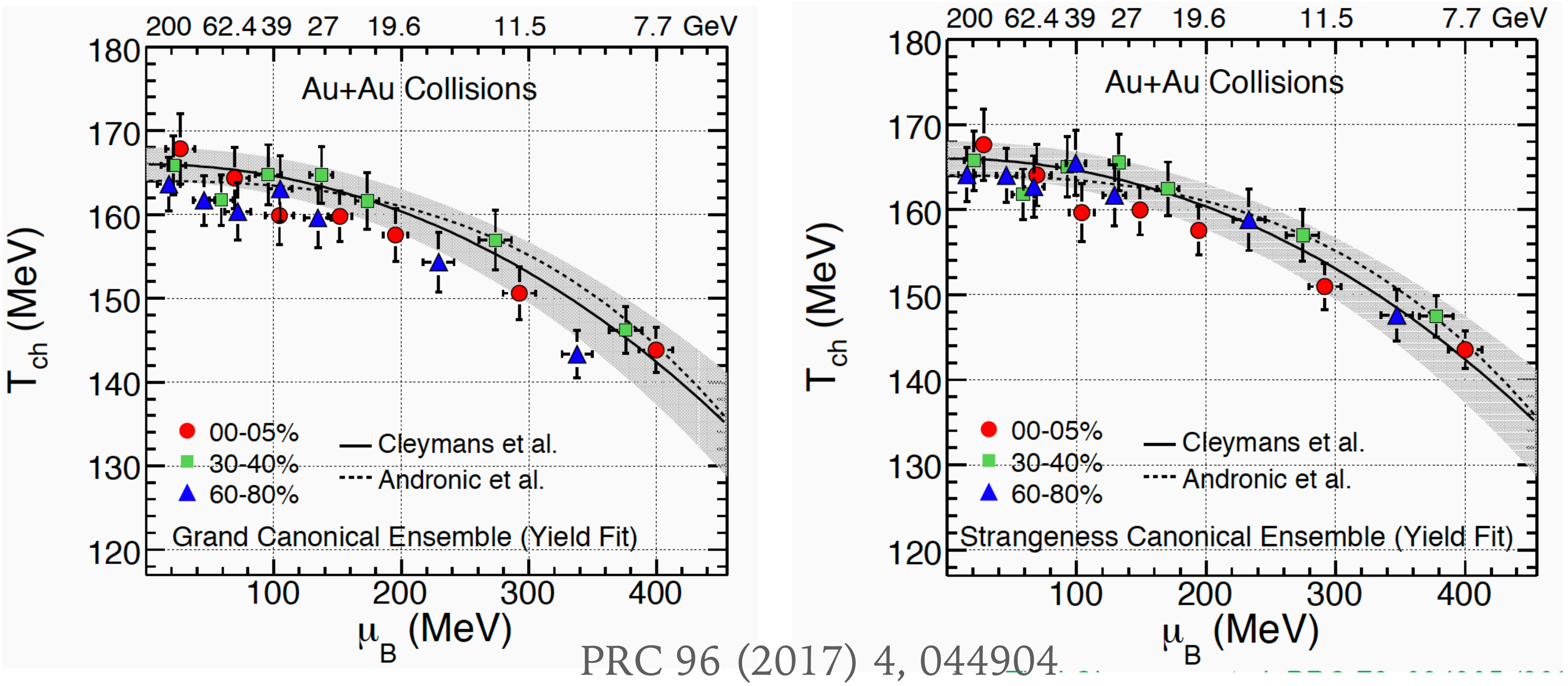
Extracted from spectra:

$m_T - m$ 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

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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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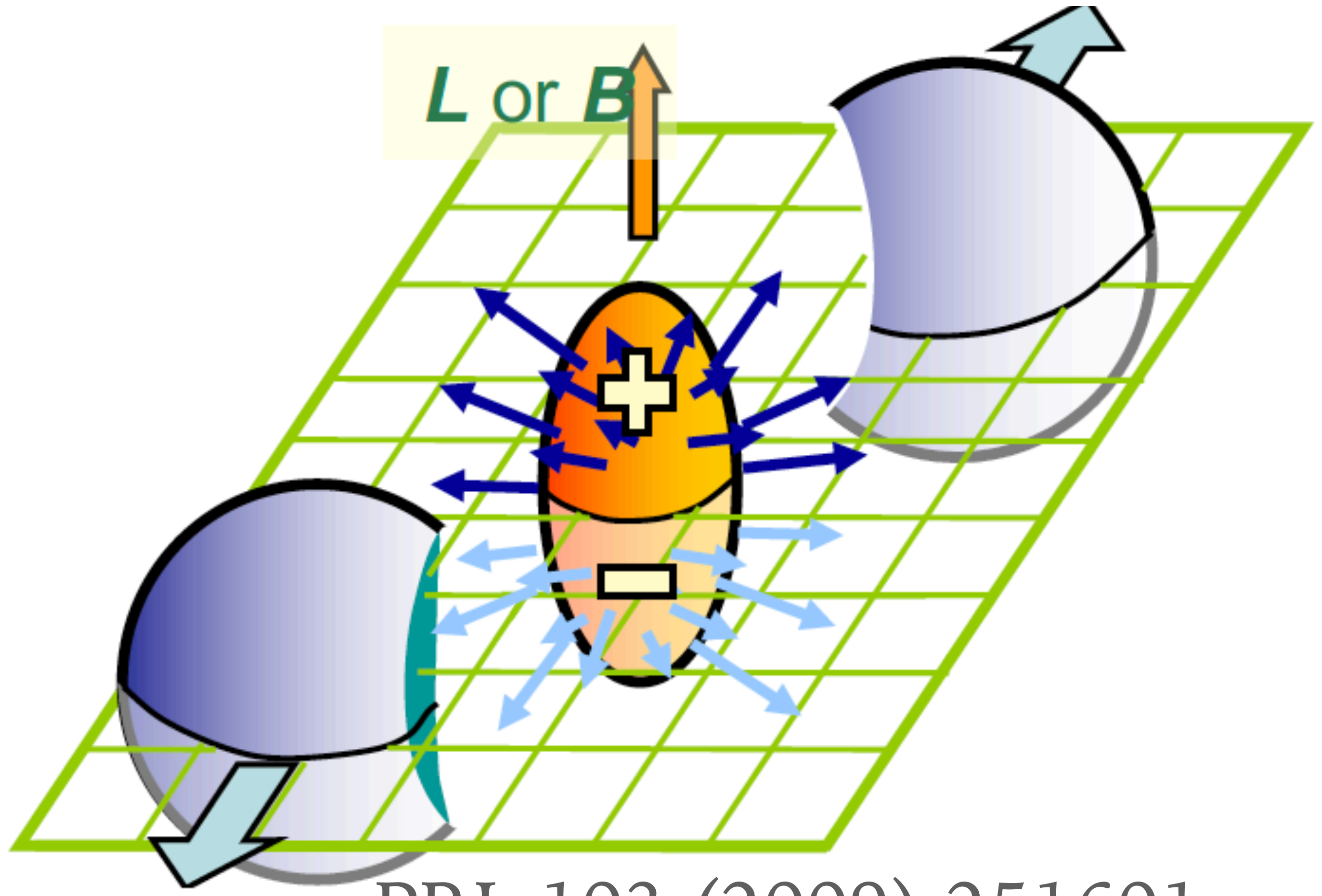
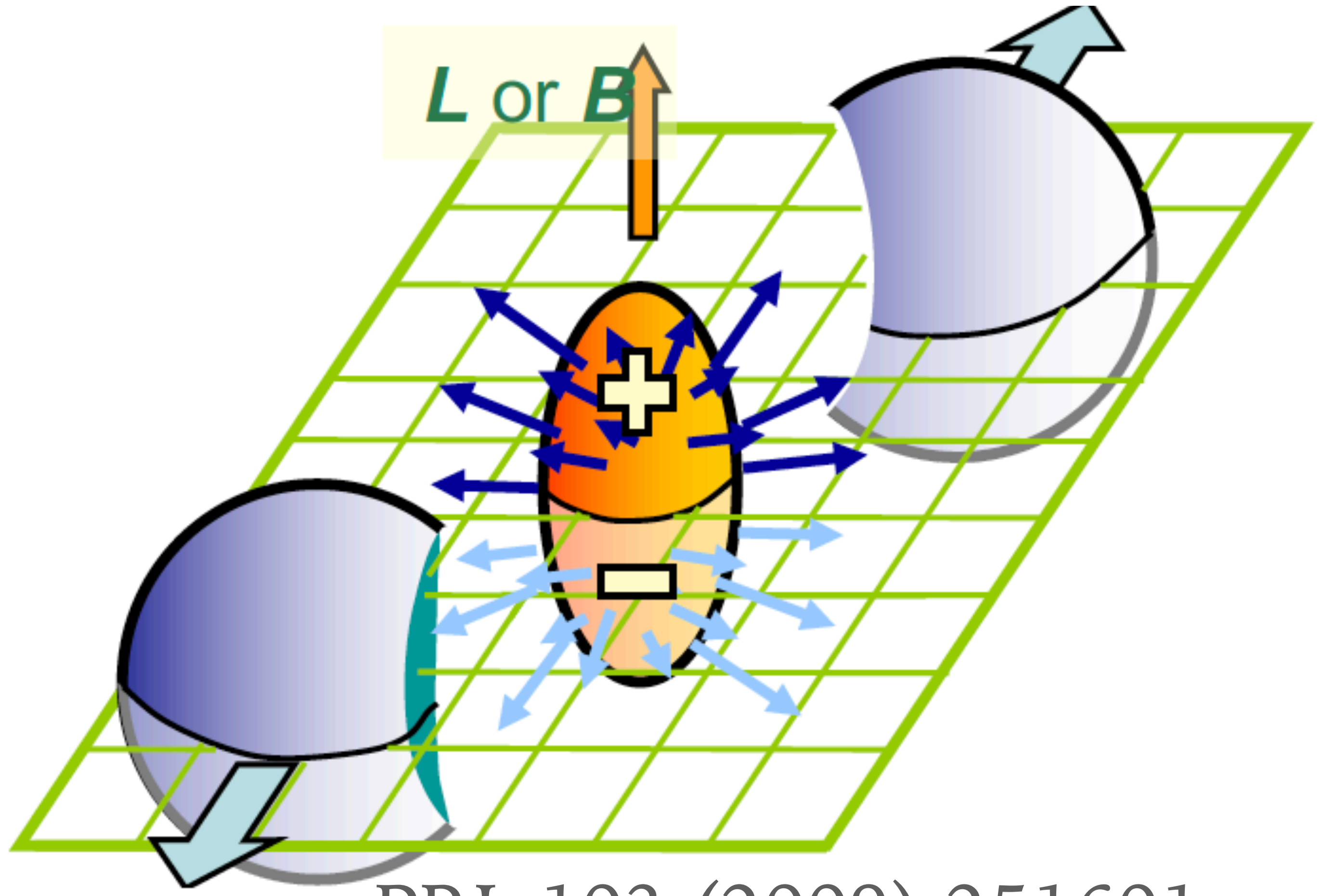
Charge separation



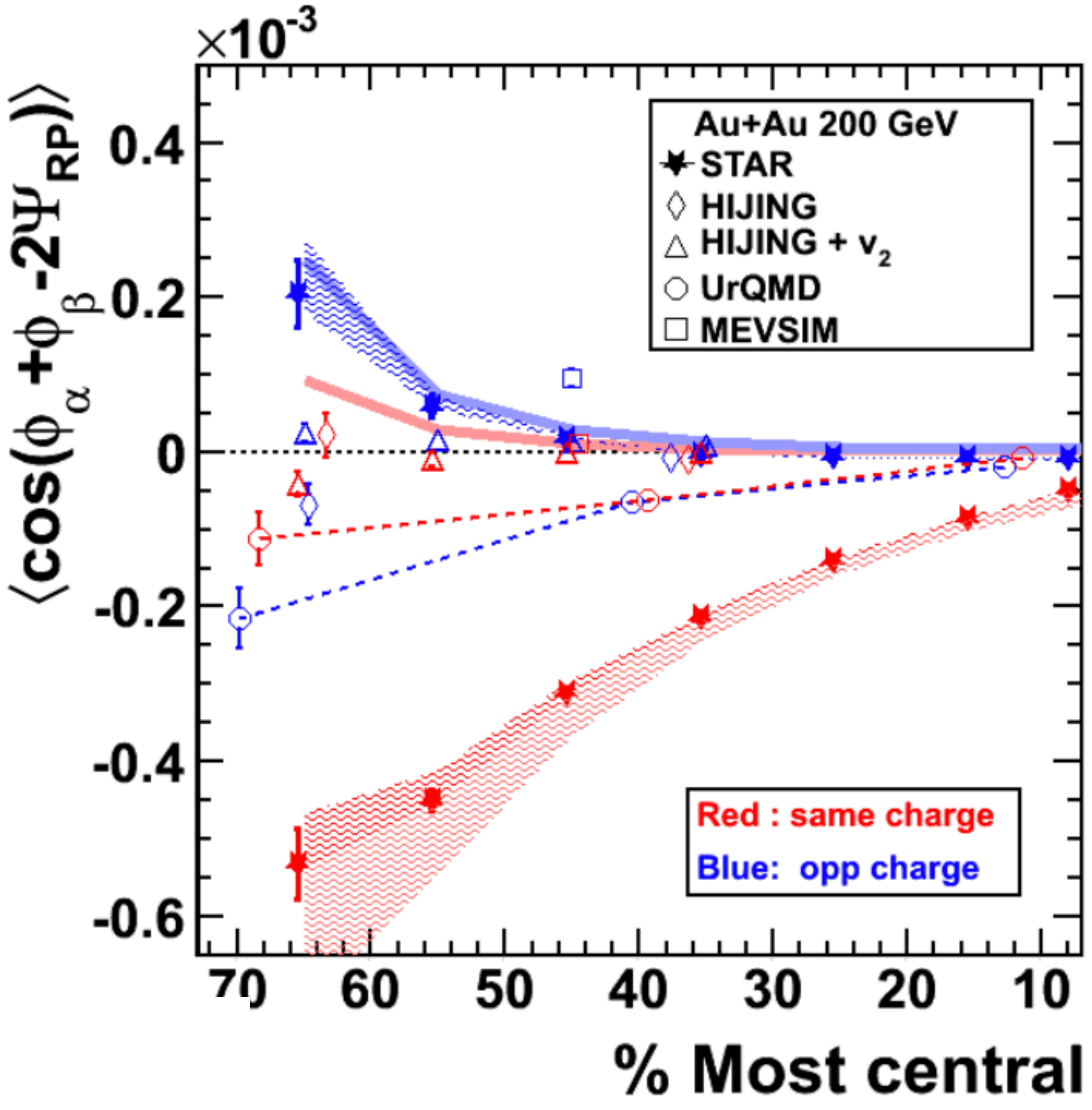
PRL 103 (2009) 251601

- 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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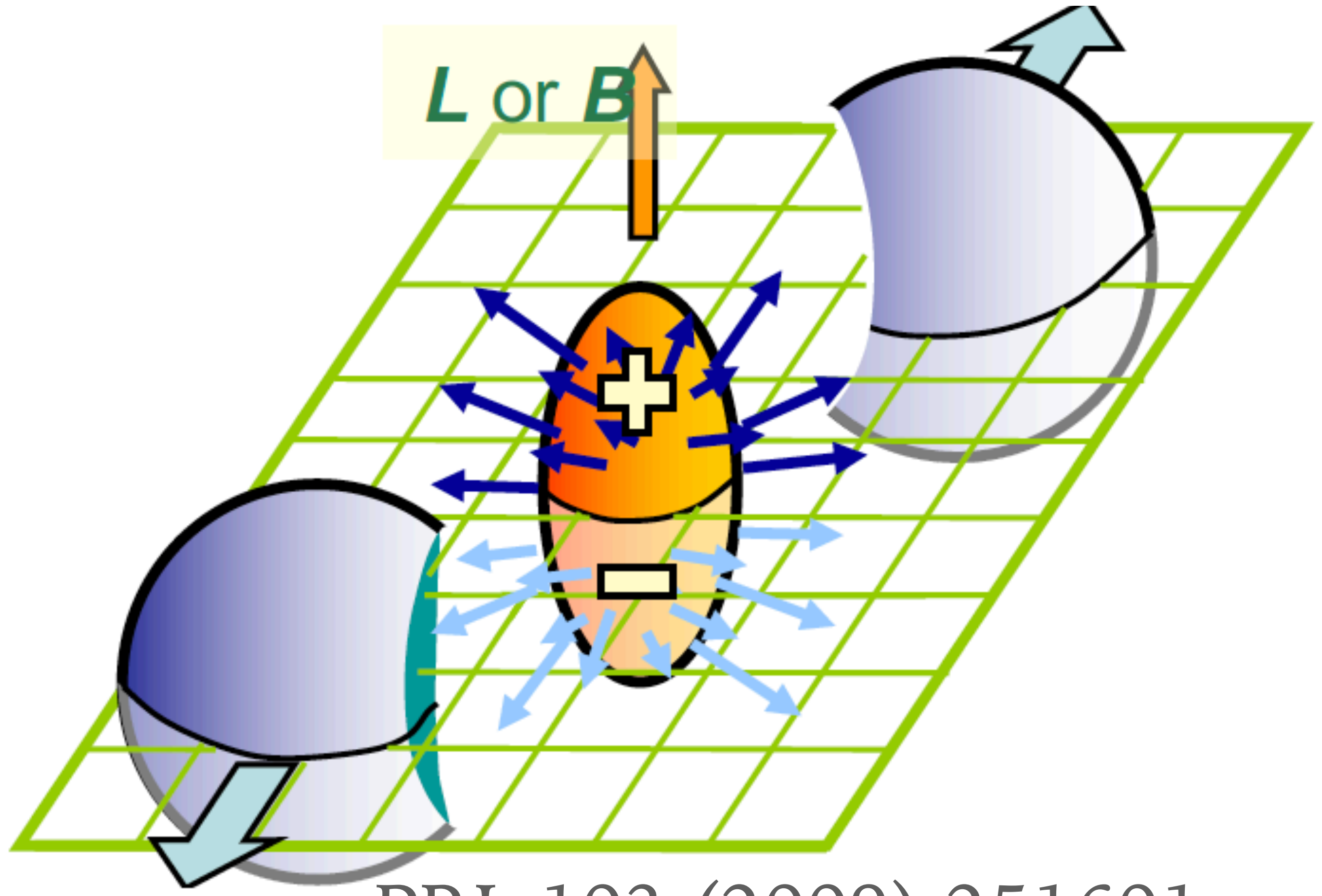
Charge separation



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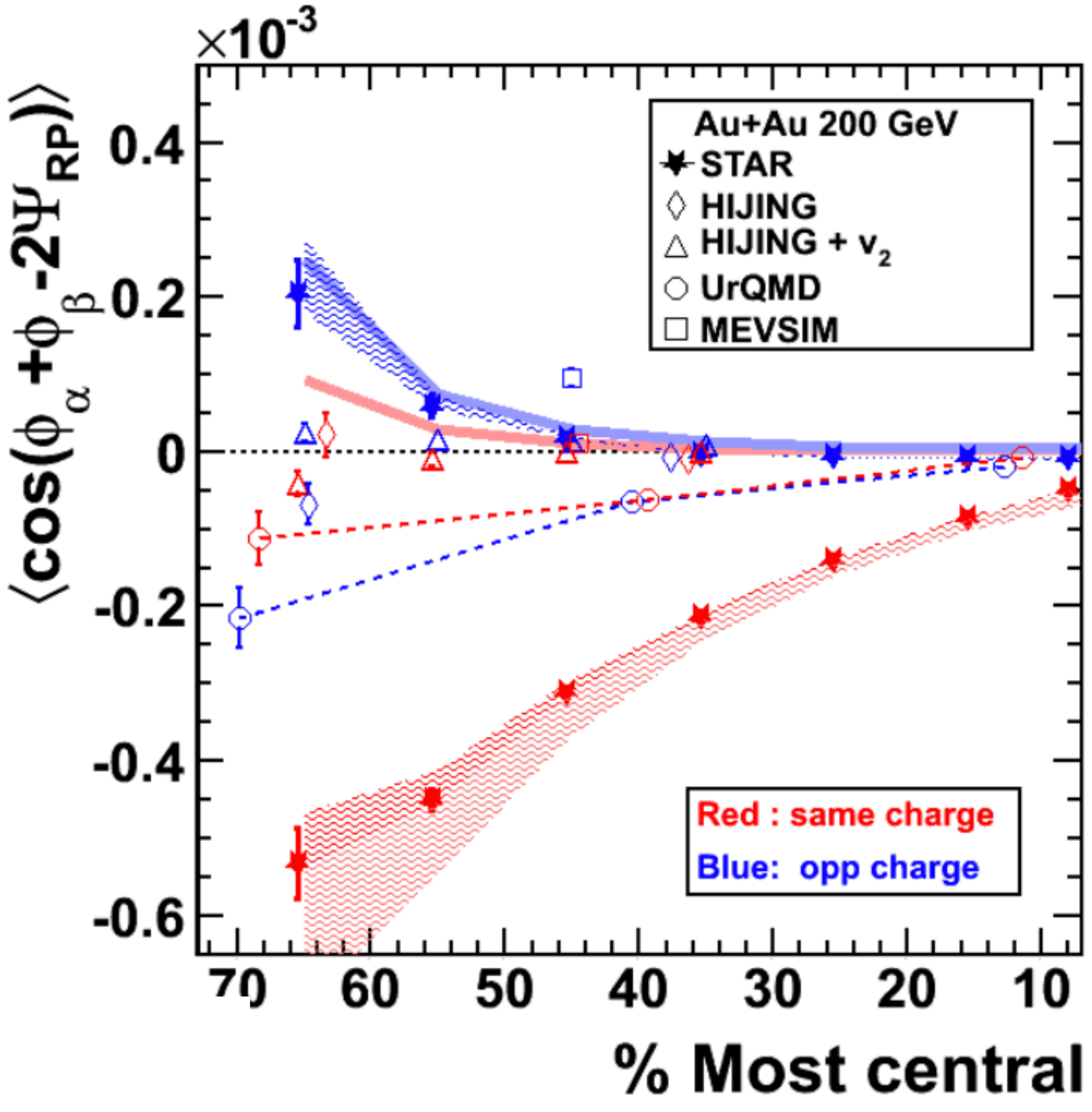

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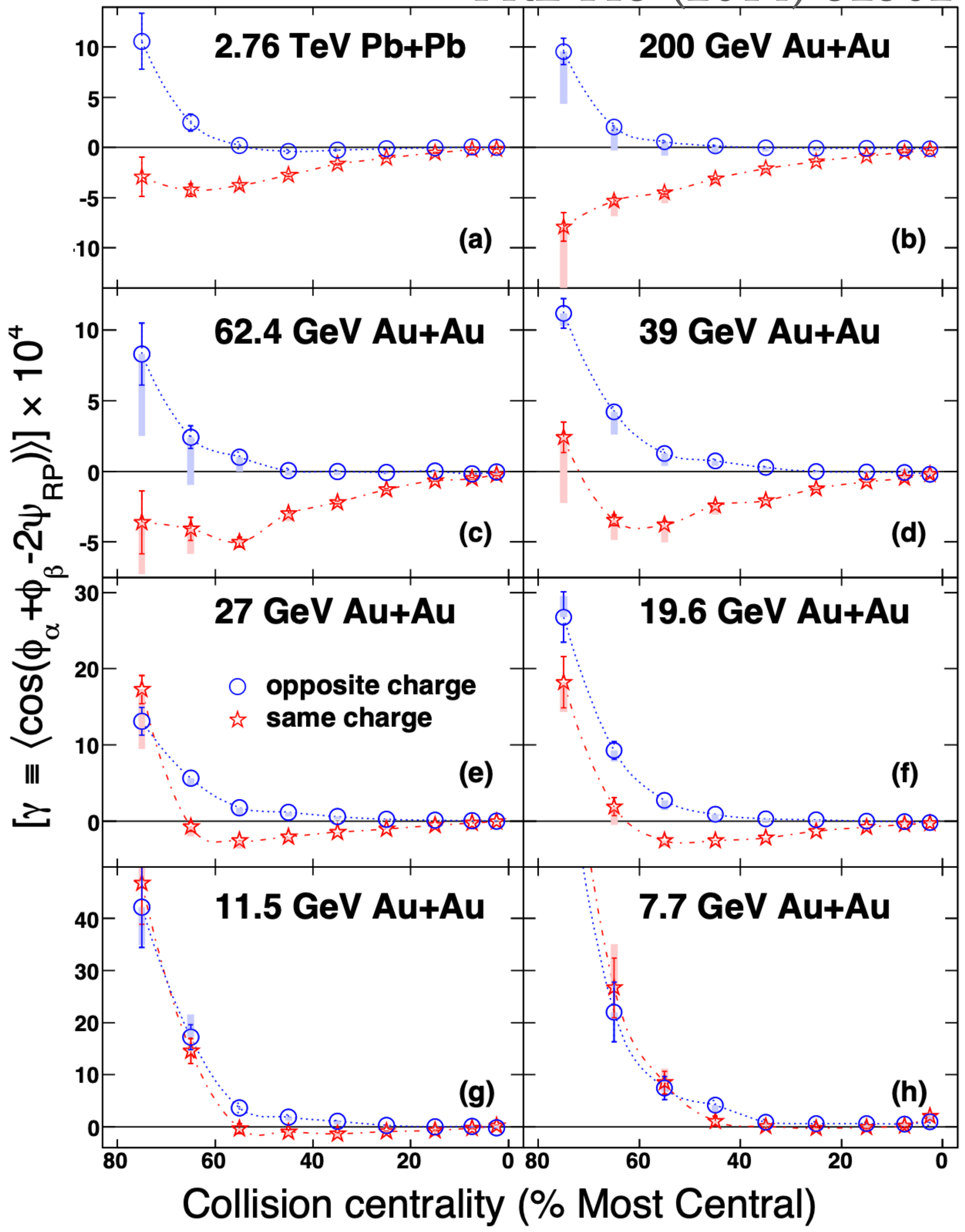
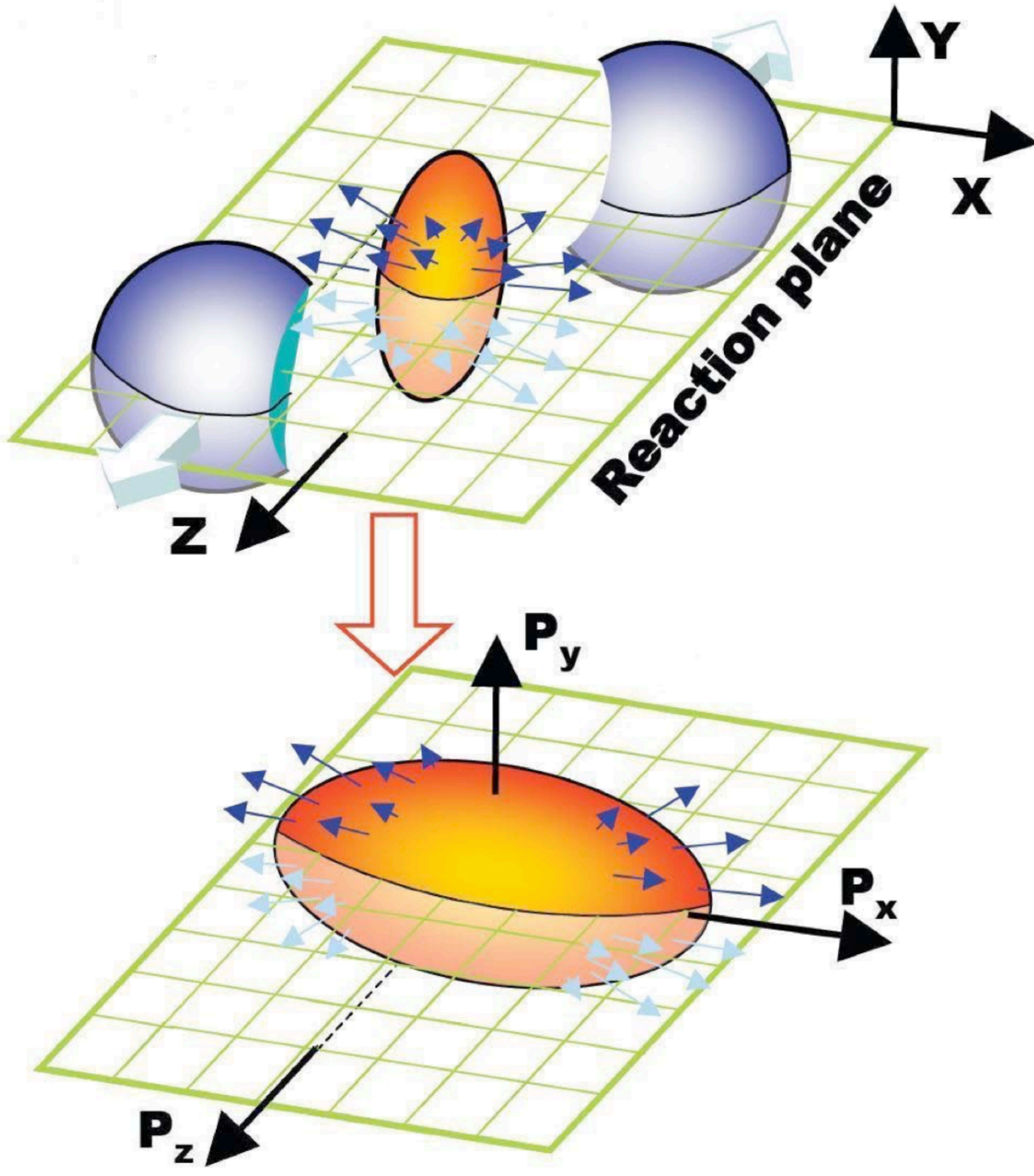
- Is reduction of signal with decreasing collision energy the signal of turn-off of deconfinement?

PRL 113 (2014) 52302

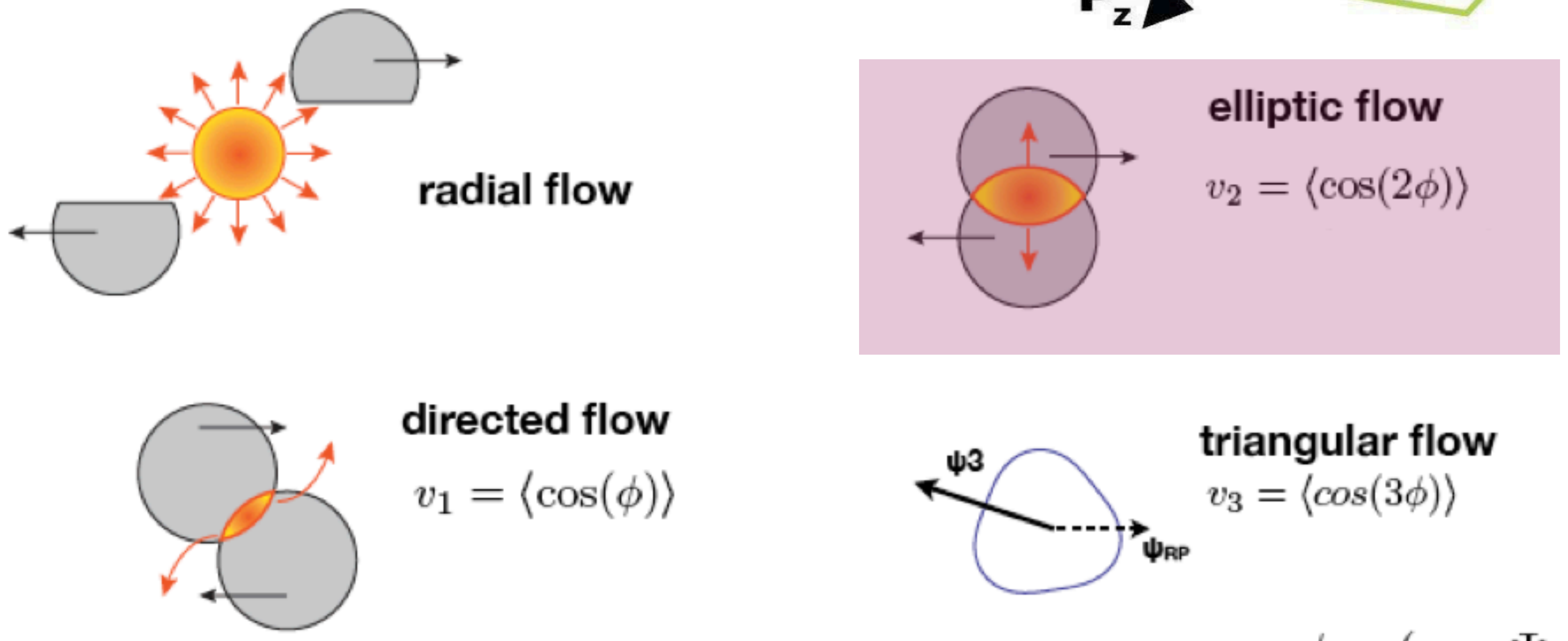


Splitting between same- and opposite-sign charges decreases with decreasing collision energy and disappears below $\sqrt{s_{NN}} = 11.5$ GeV

Elliptic flow



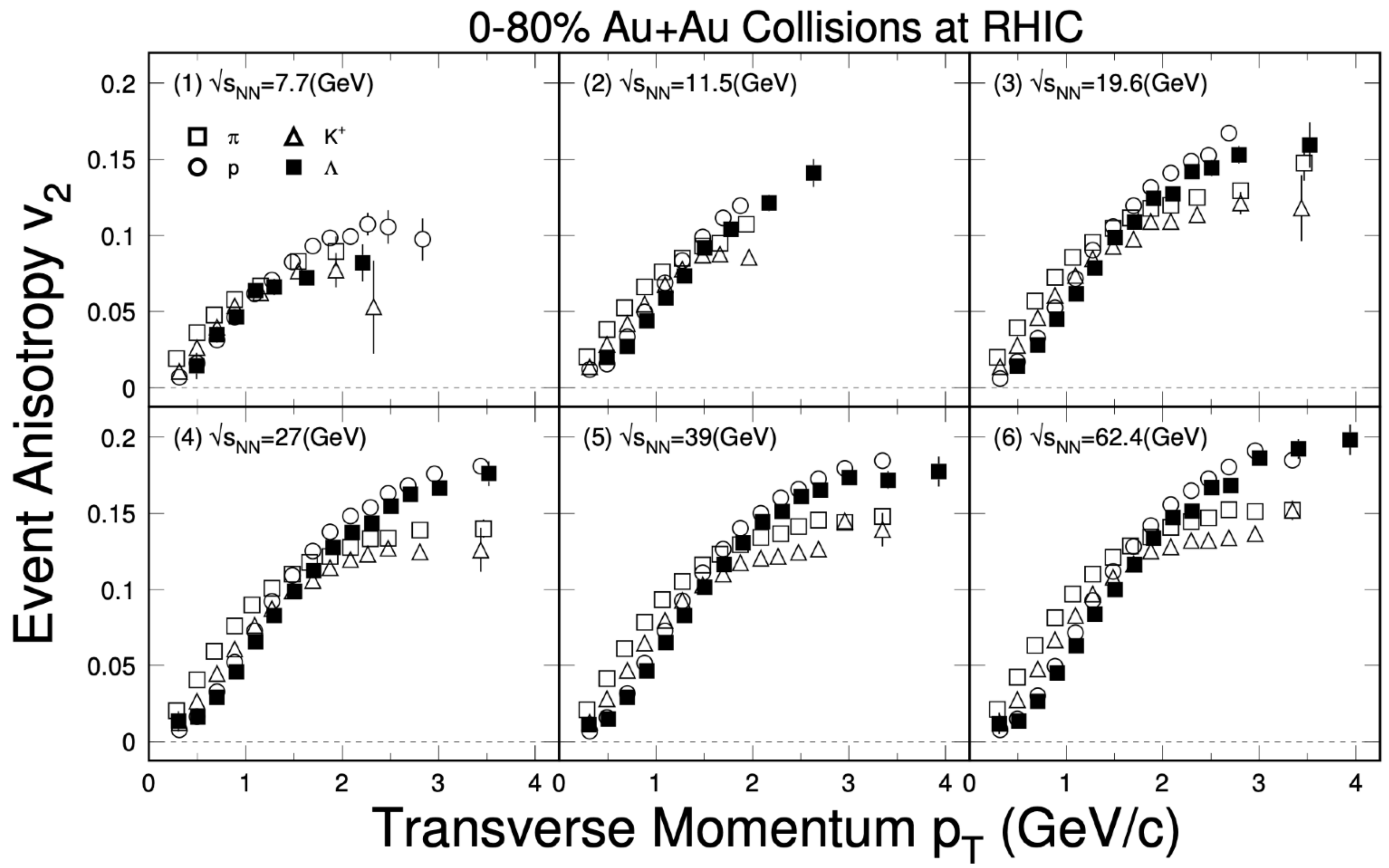
Initial spatial anisotropy leads to the final momentum anisotropy

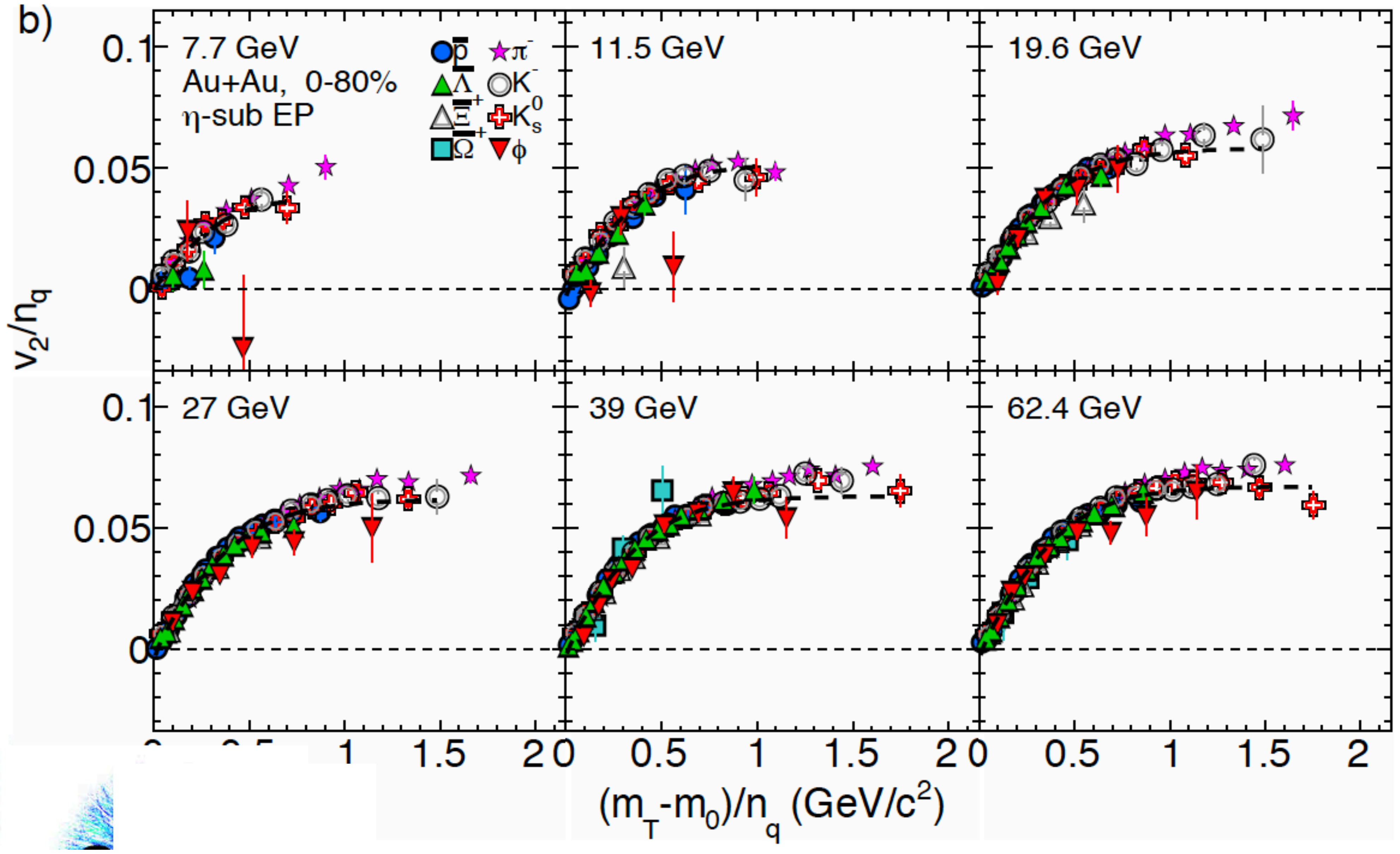


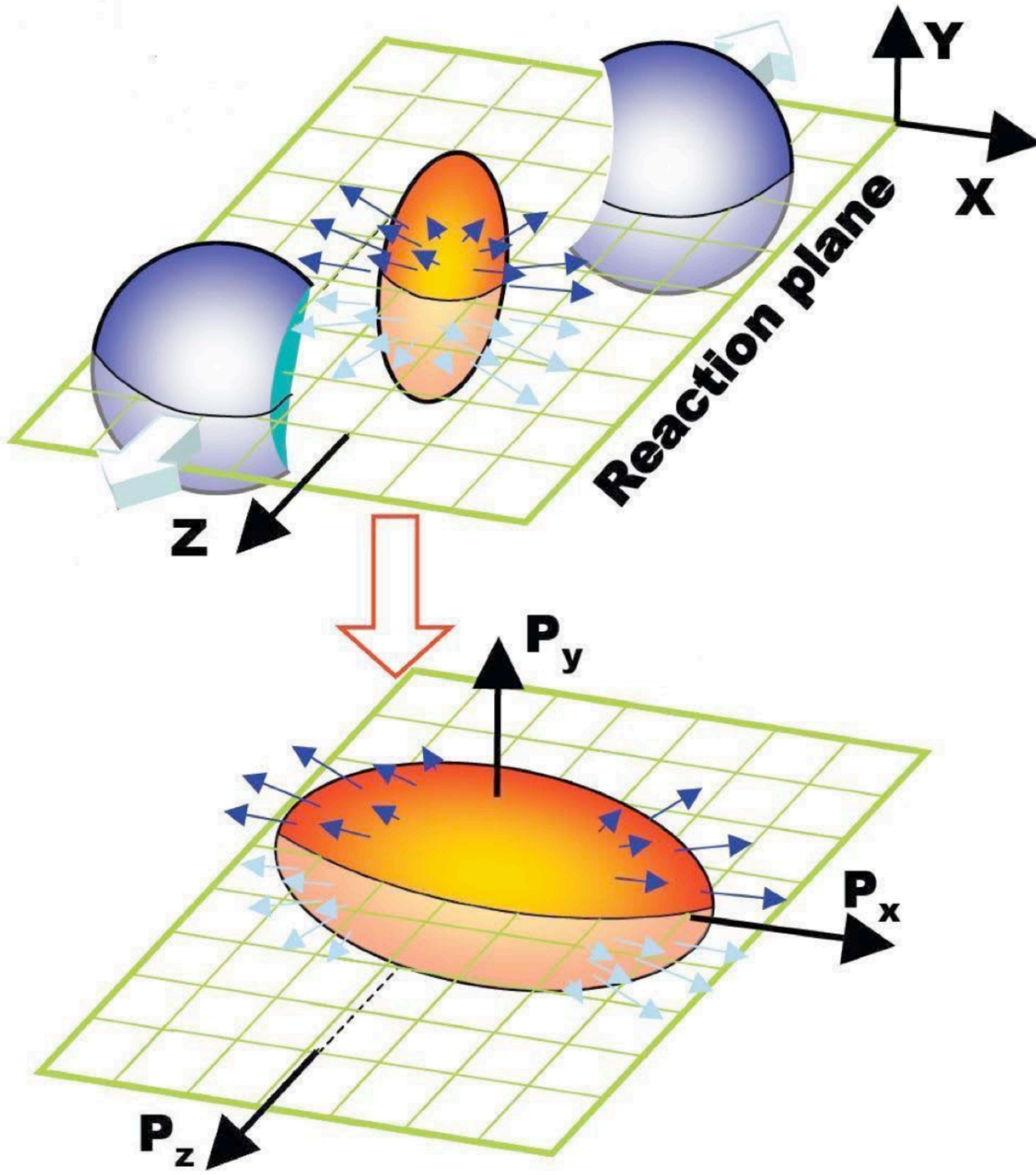
$\phi = (\varphi - \Psi_{RP})$

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

Elliptic flow







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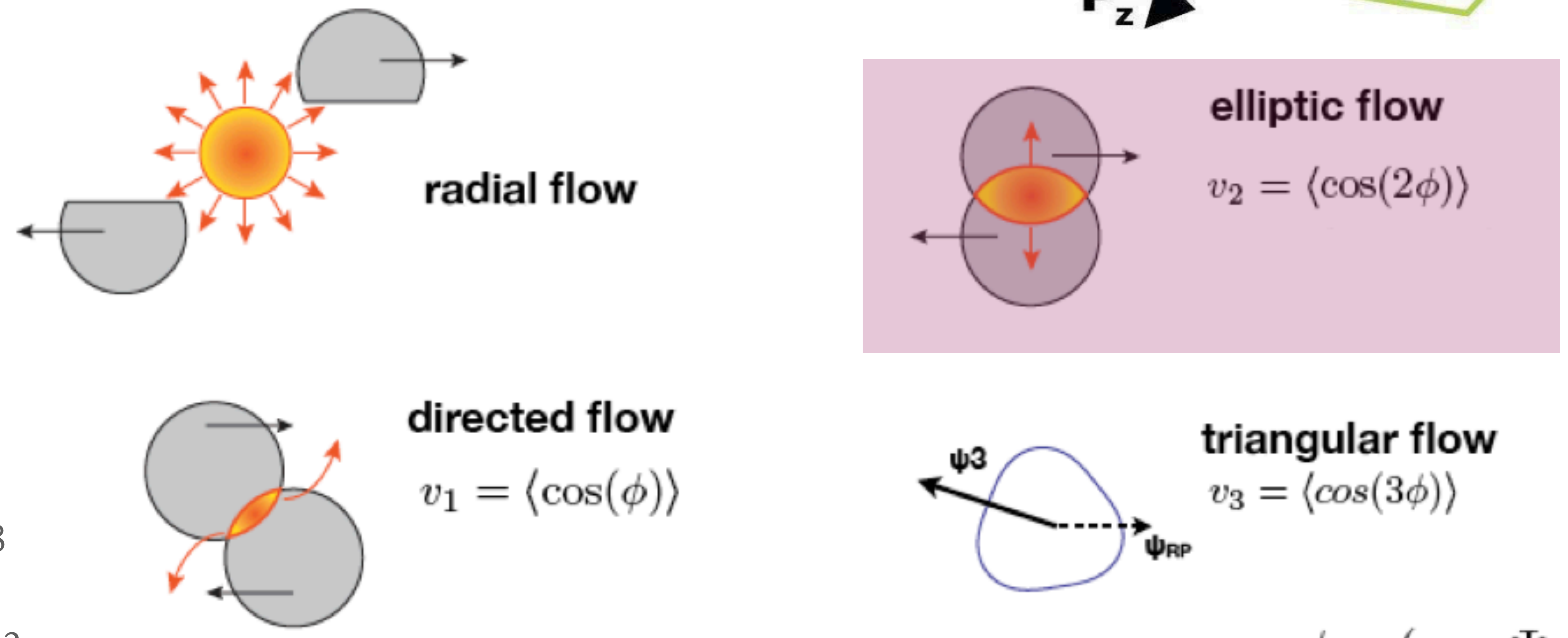

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STAR: PRC 88 (2013) 14902
Phys. Rev. C 93, 014907 (2016)
Phys. Rev. Lett. 116, 062301 (2016)

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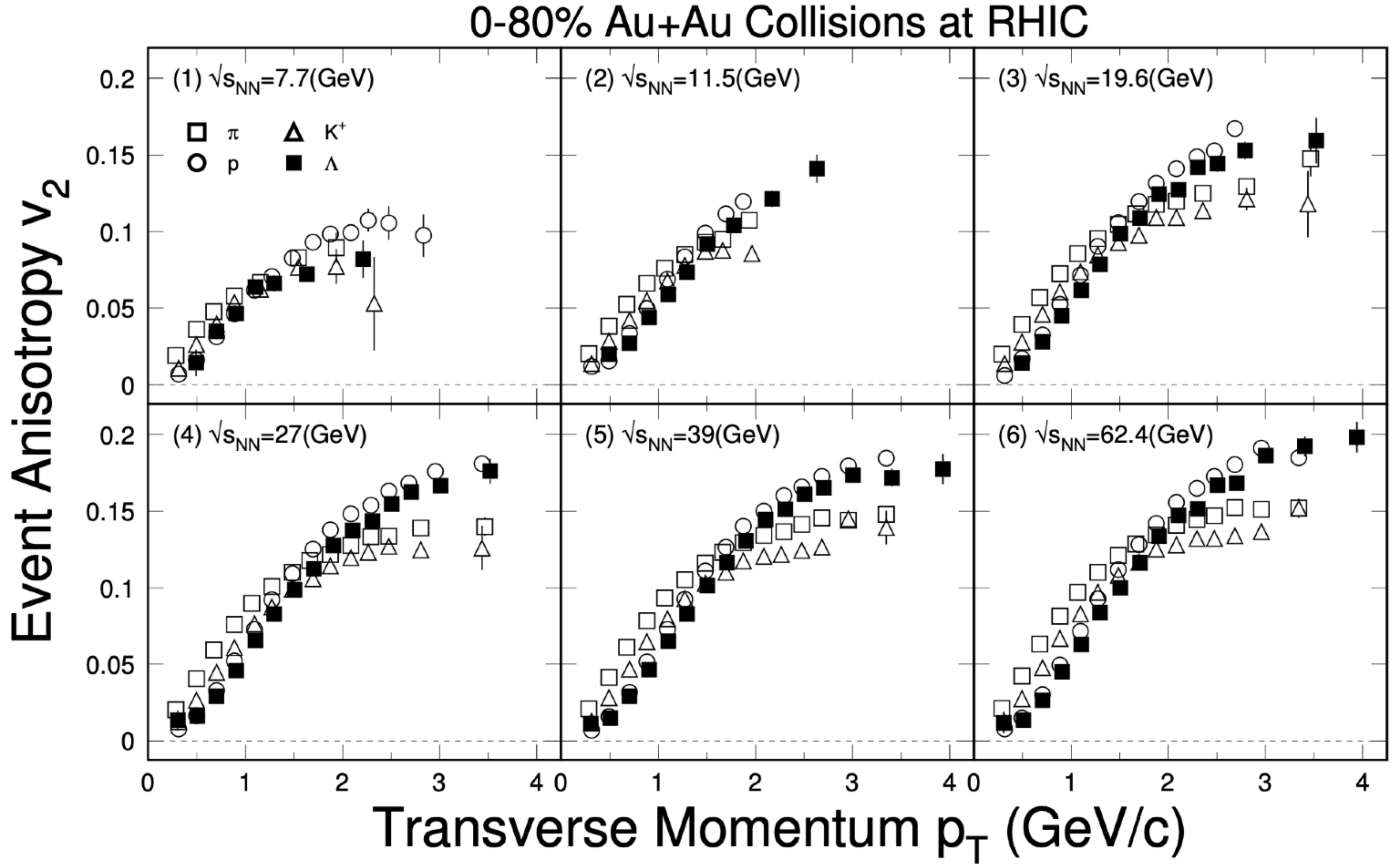
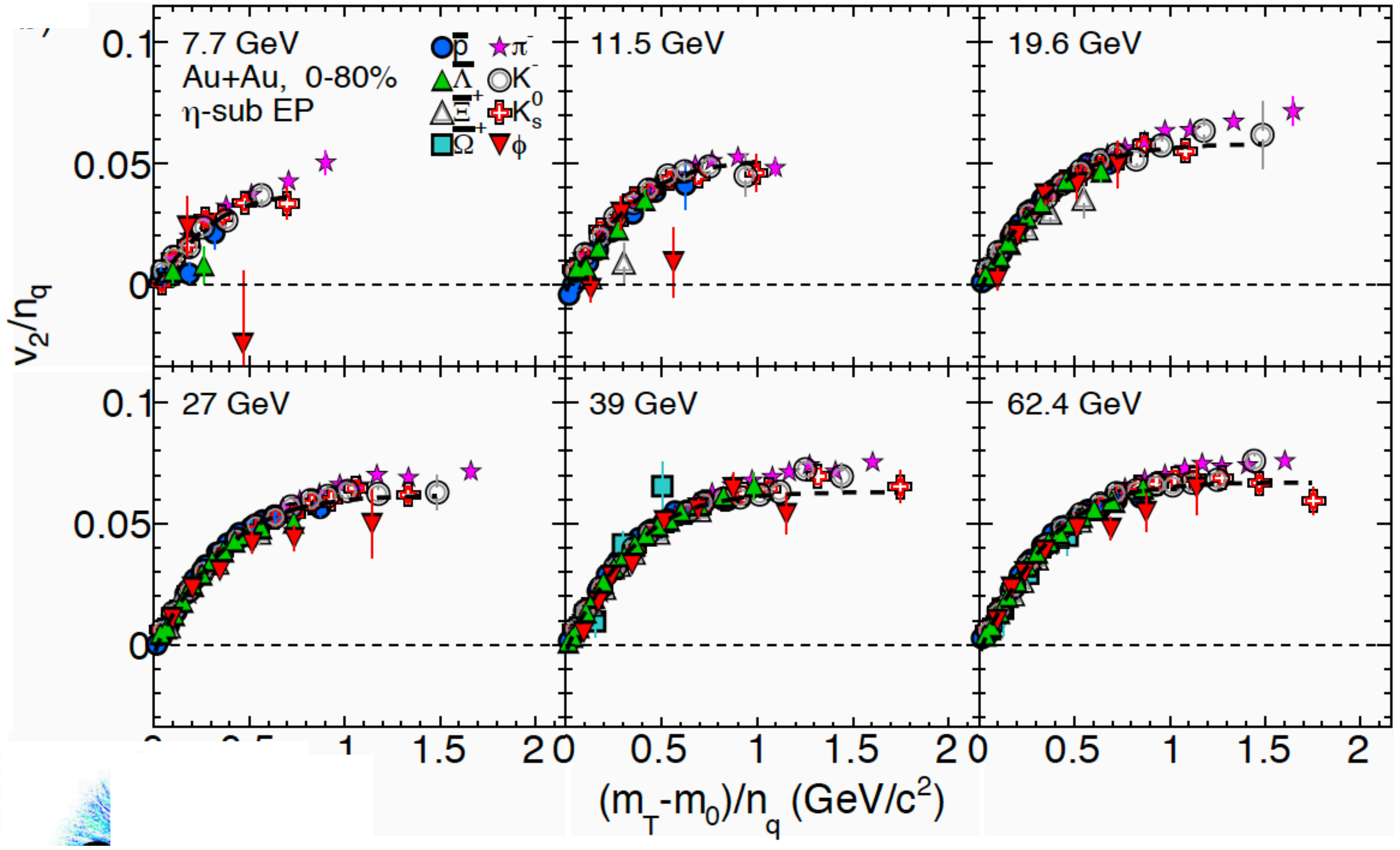
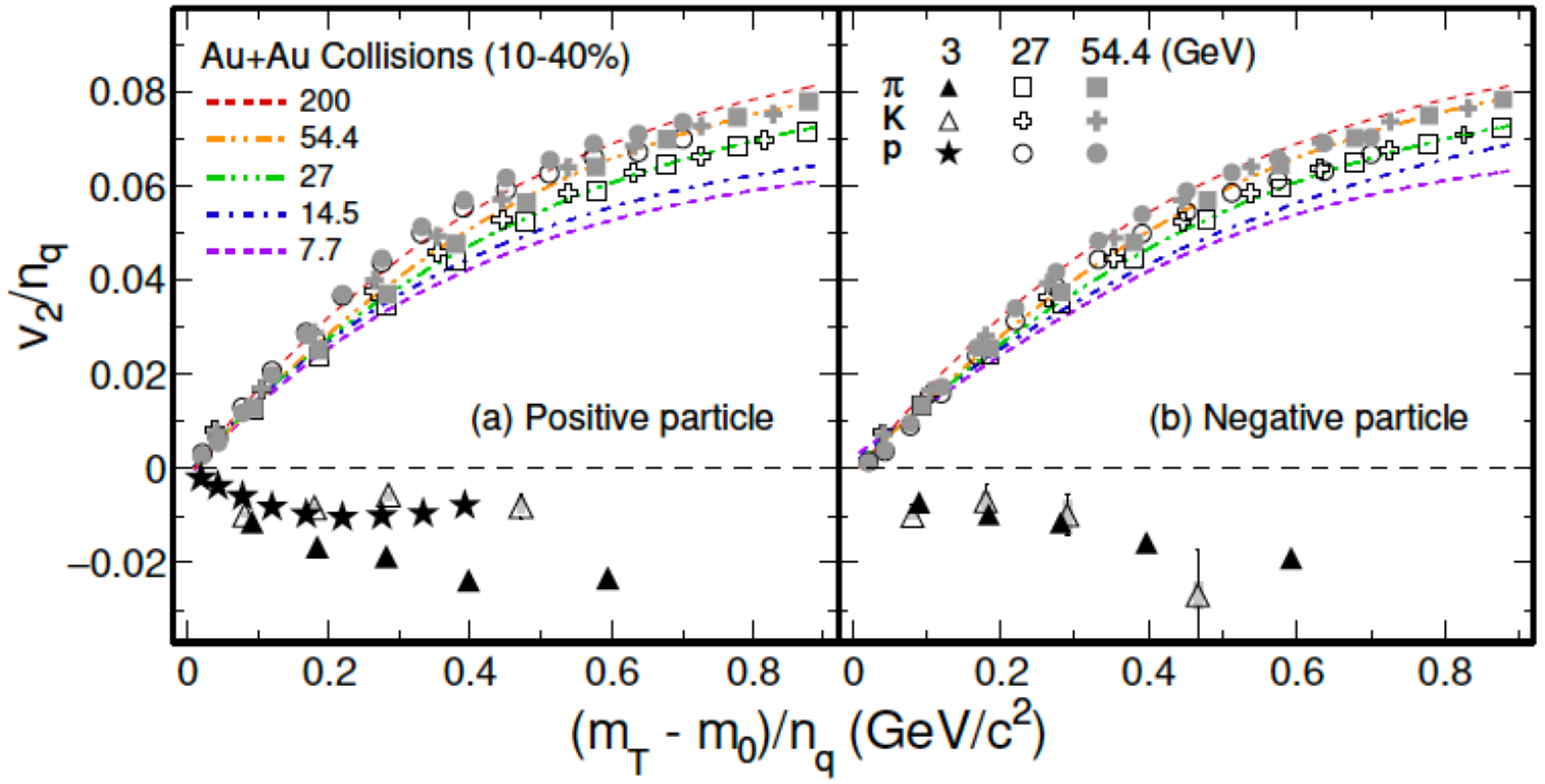


$v_2(p_T)$ are mass ordered

- ϕ meson v_2 falls 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





- $v_2 > 0 \rightarrow$ 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

STAR: PRC 88 (2013) 14902
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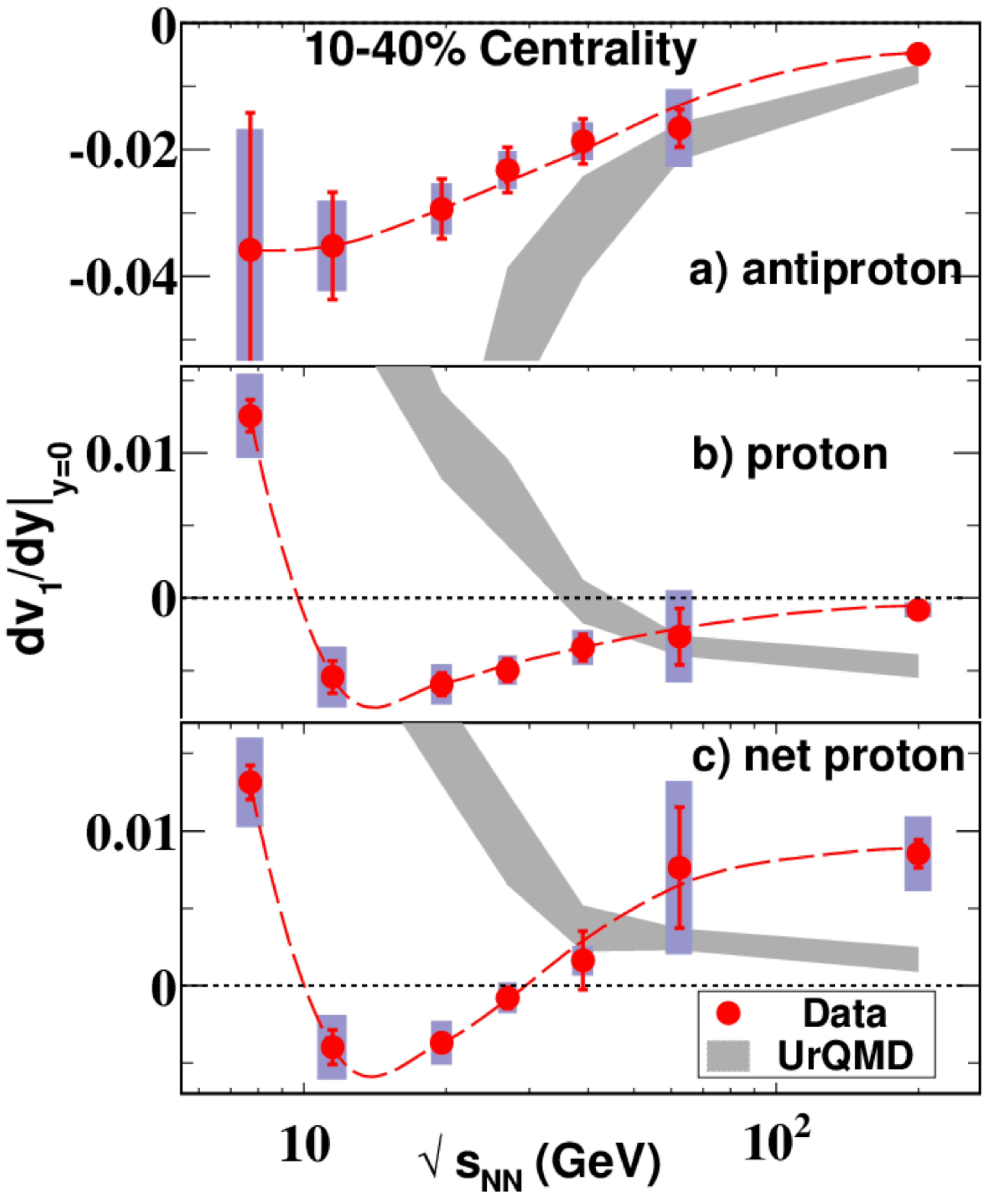
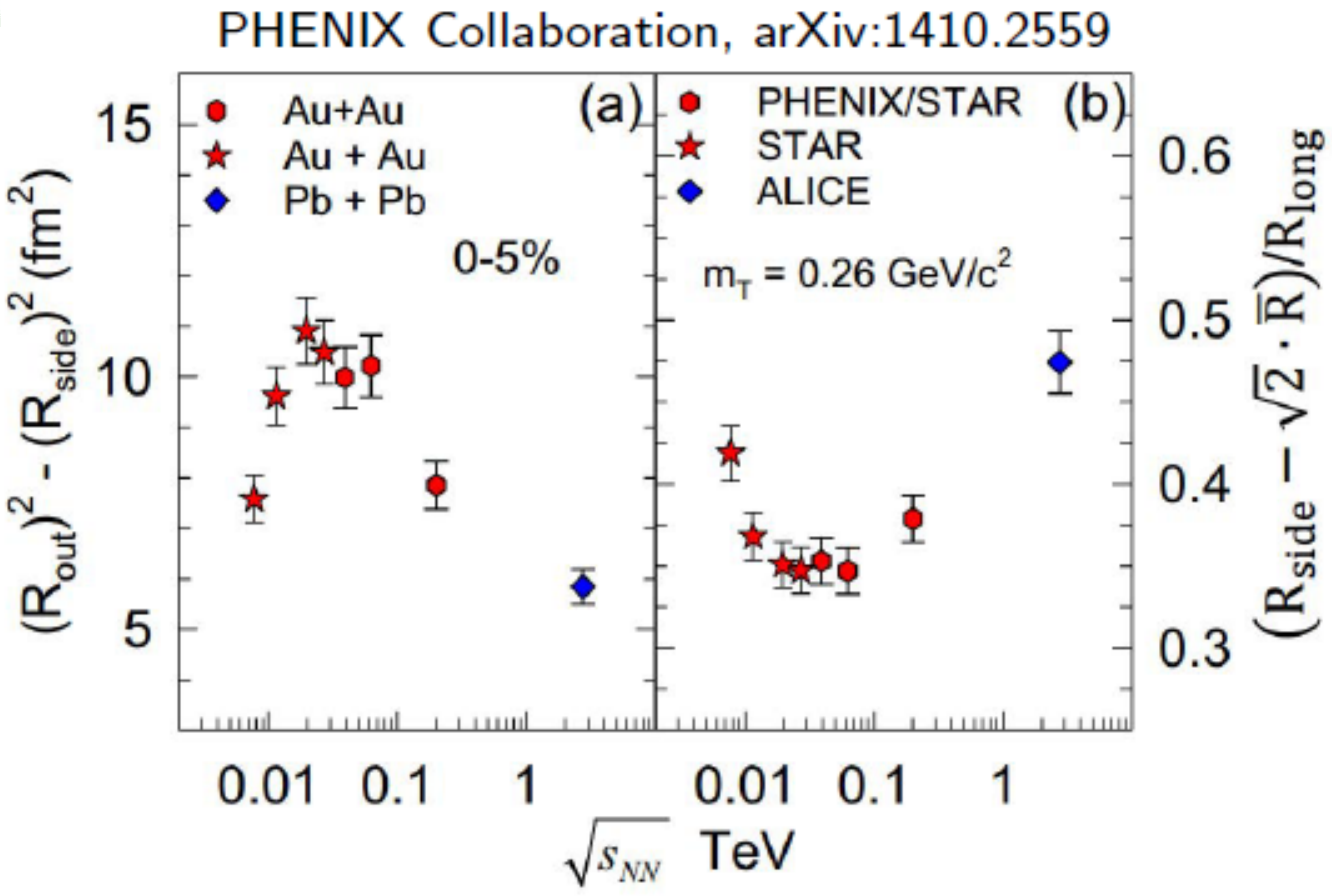
Directed flow and $< m_T > - m$ dependence

- 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);

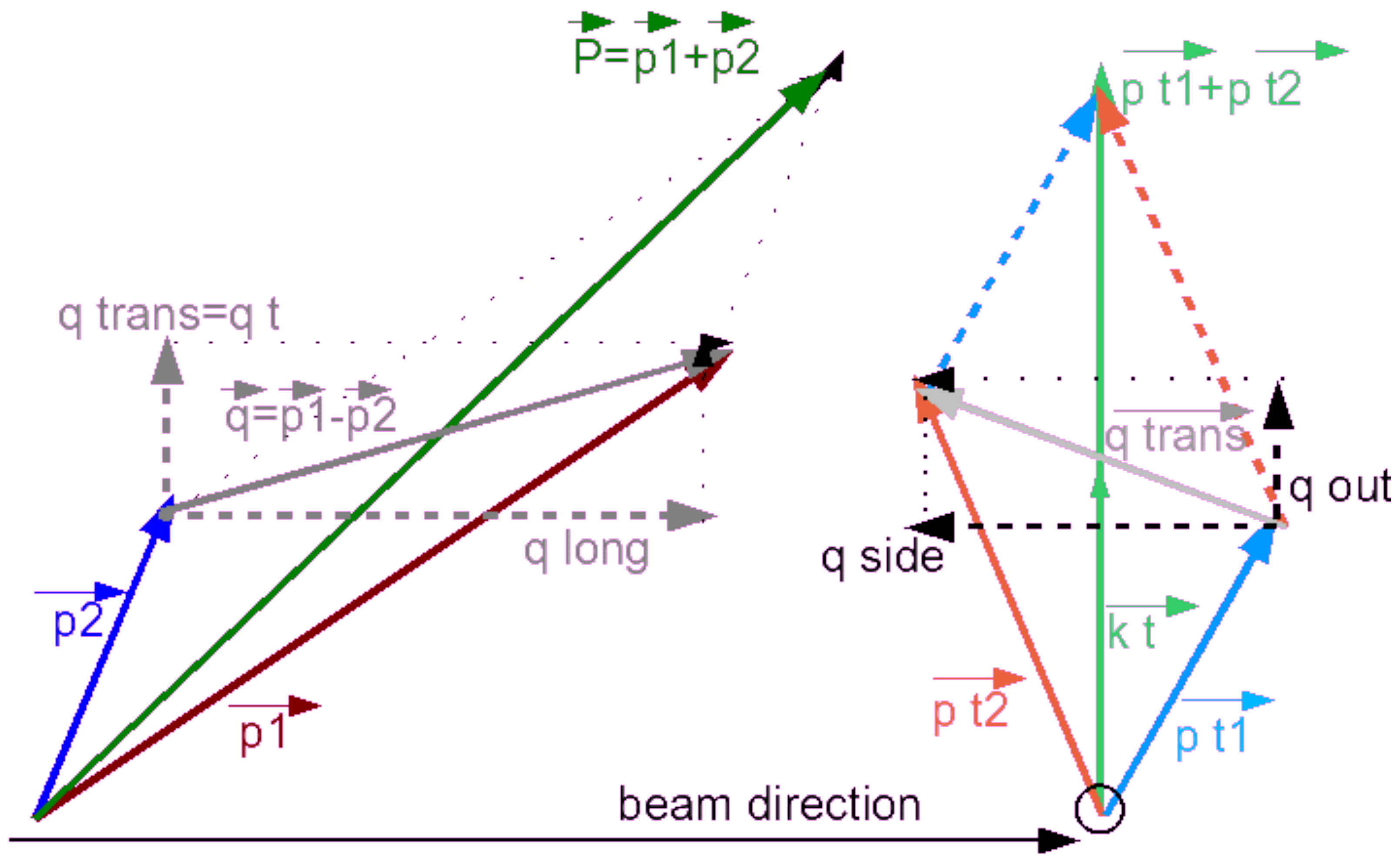


STAR, PRL 112, 162301 (2014)

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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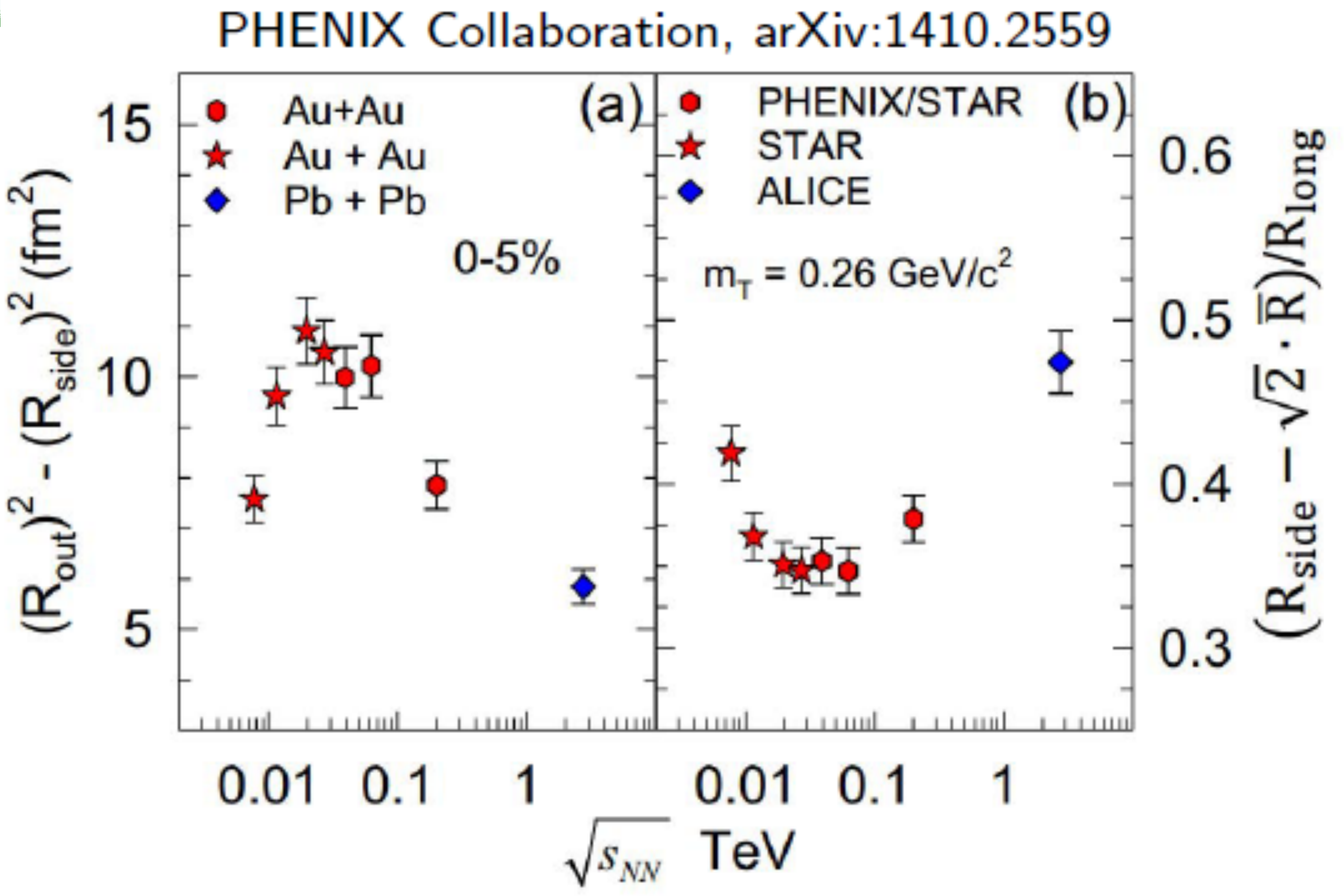

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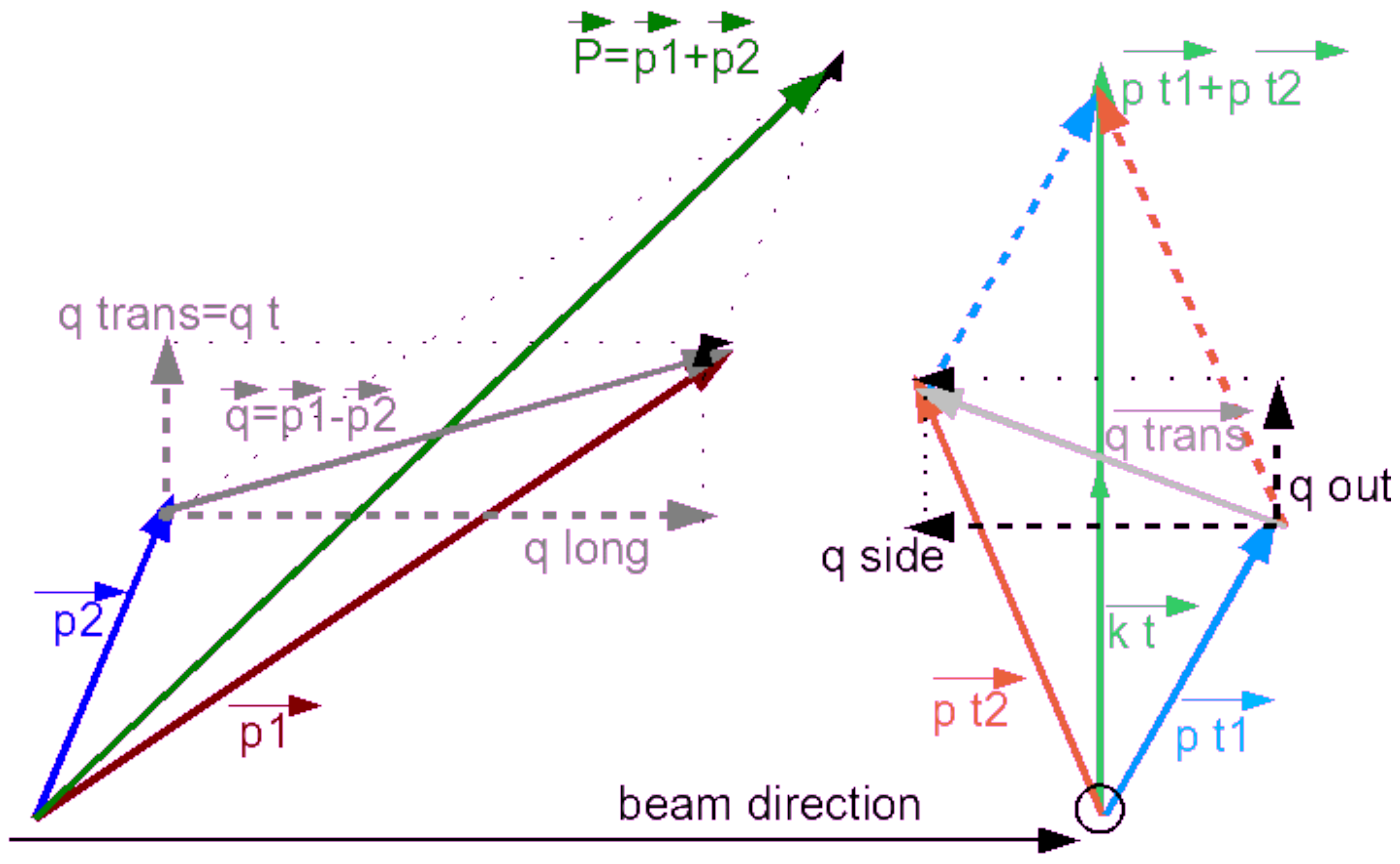
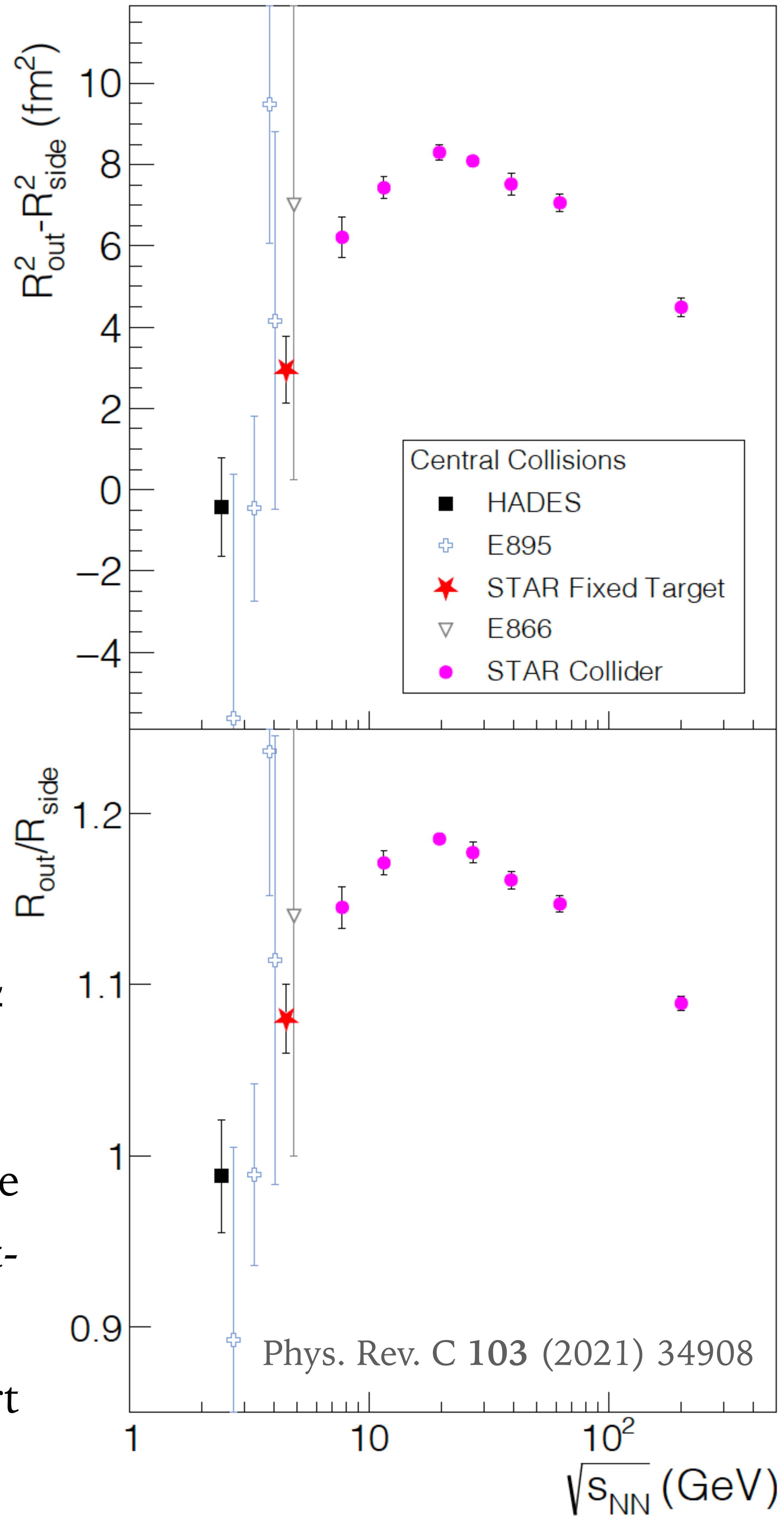
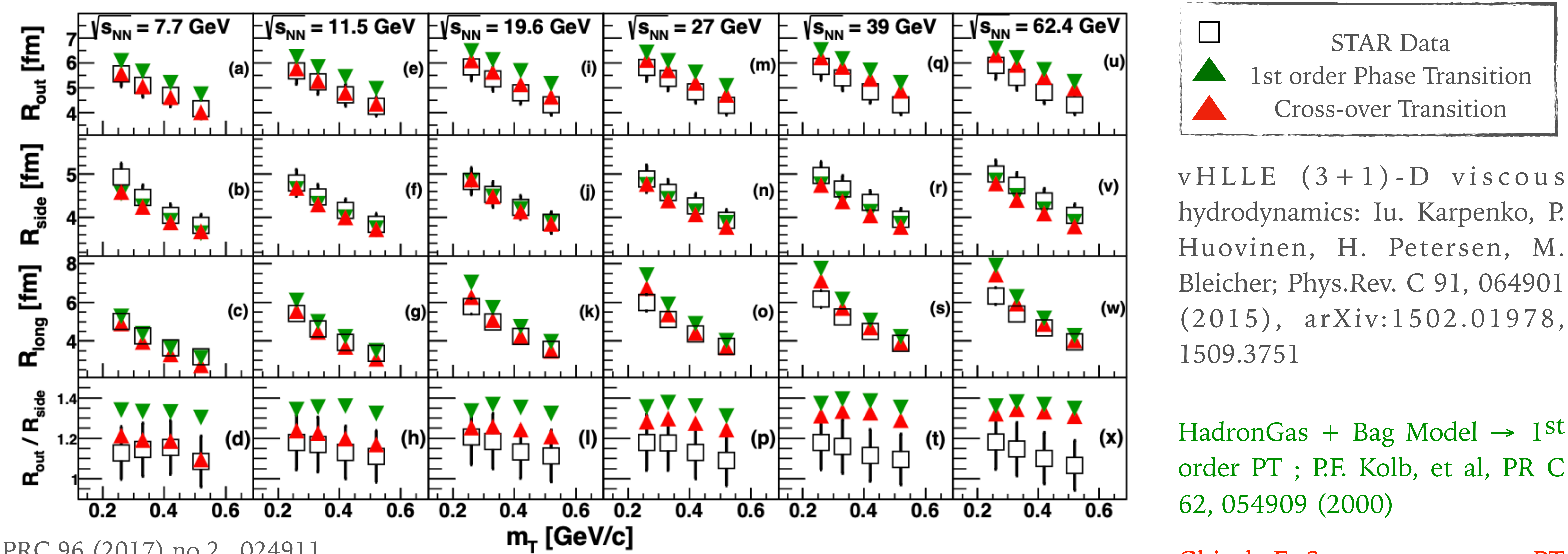


- Visible **peak** in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near the $\sqrt{s_{NN}} \simeq$ 20 GeV
- QCD calculations predict a peak near to the QGP transition threshold - signature of first-order phase transition?
- Theoretical attention from hydro and transport models needed



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)

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

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Fluctuation analyses

Fluctuations and correlations

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

$$C_1 = \langle N \rangle$$

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

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

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

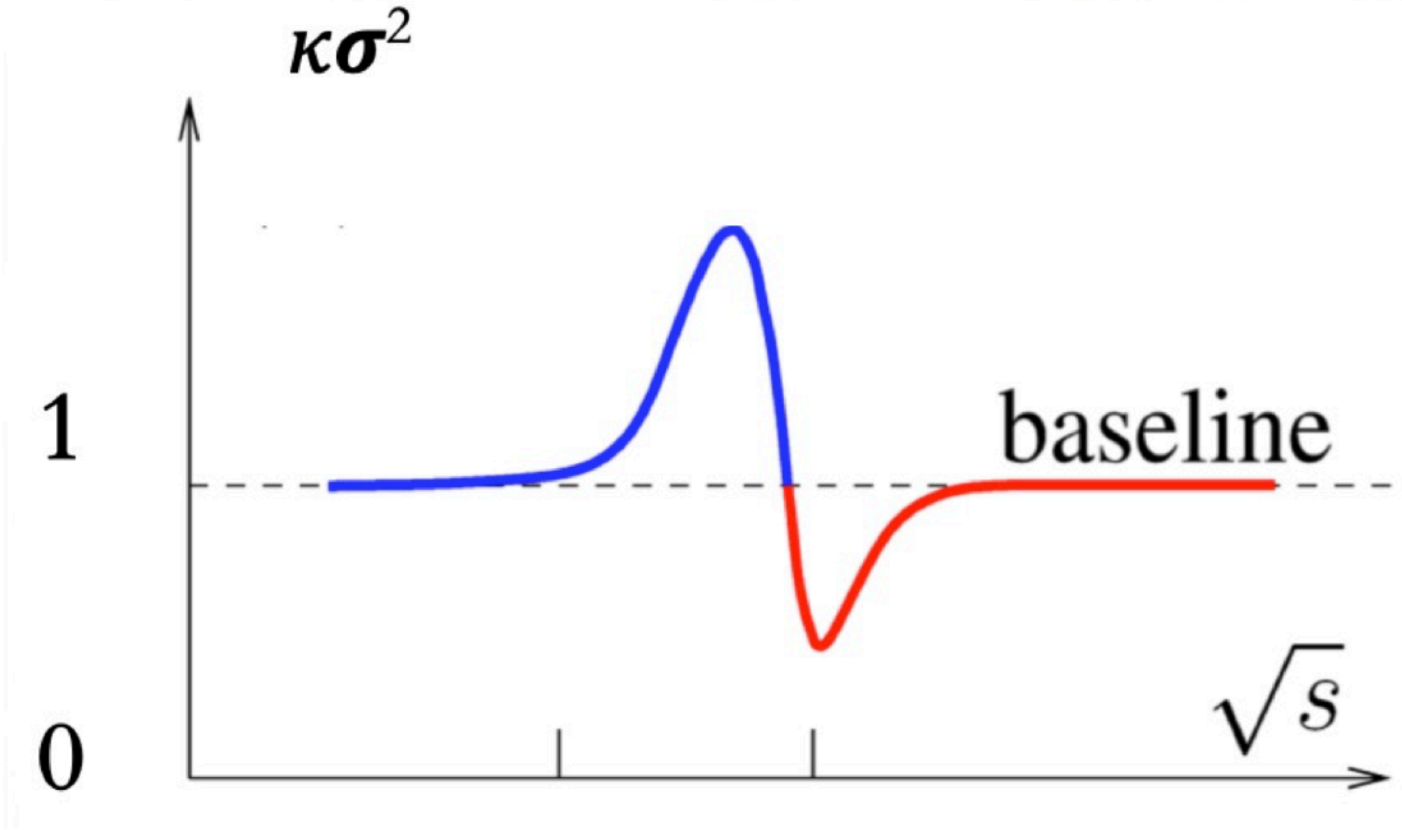
$$S\sigma = \frac{C_3}{C_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2}$$

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

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

- 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)



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

Fluctuations and correlations

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

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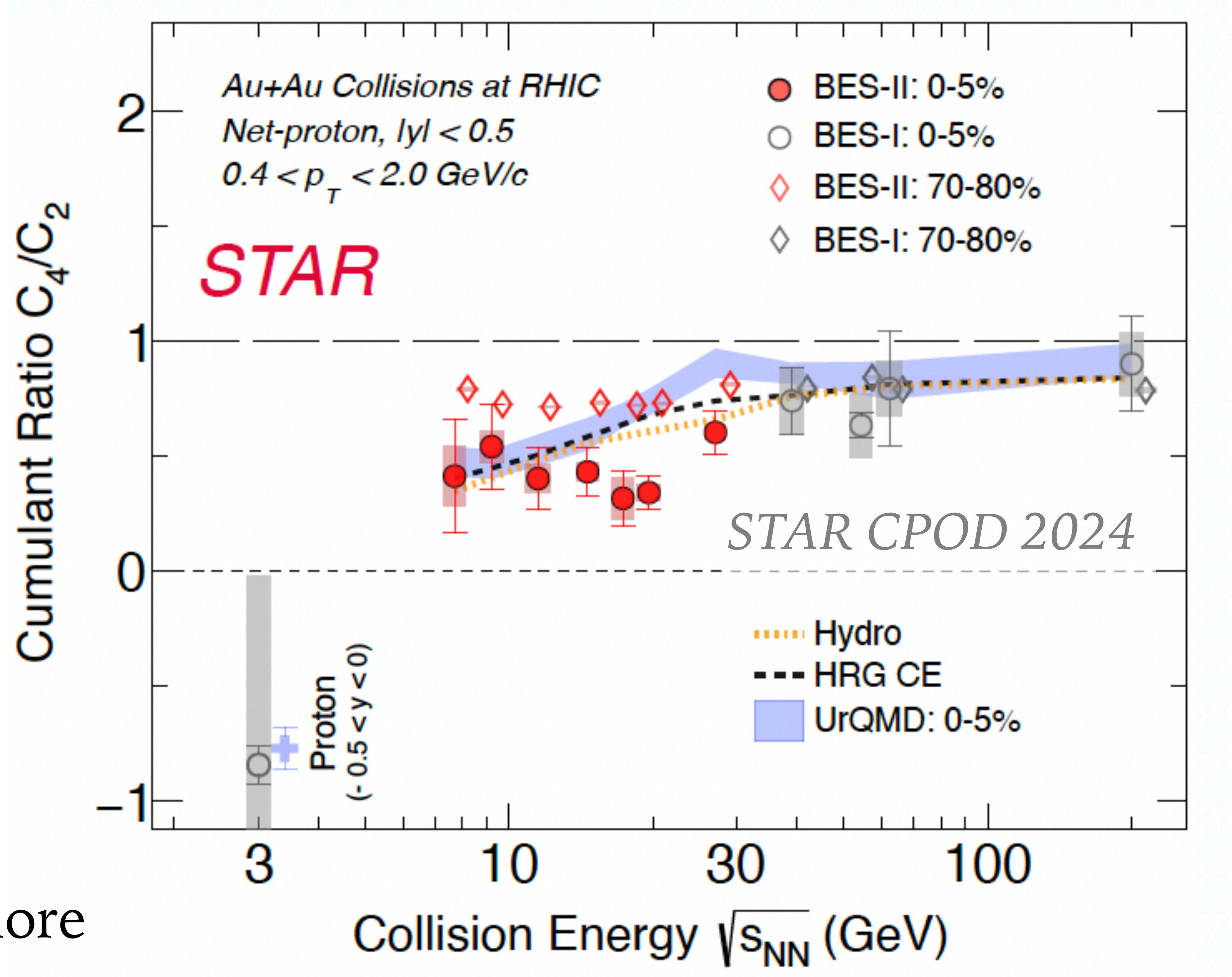

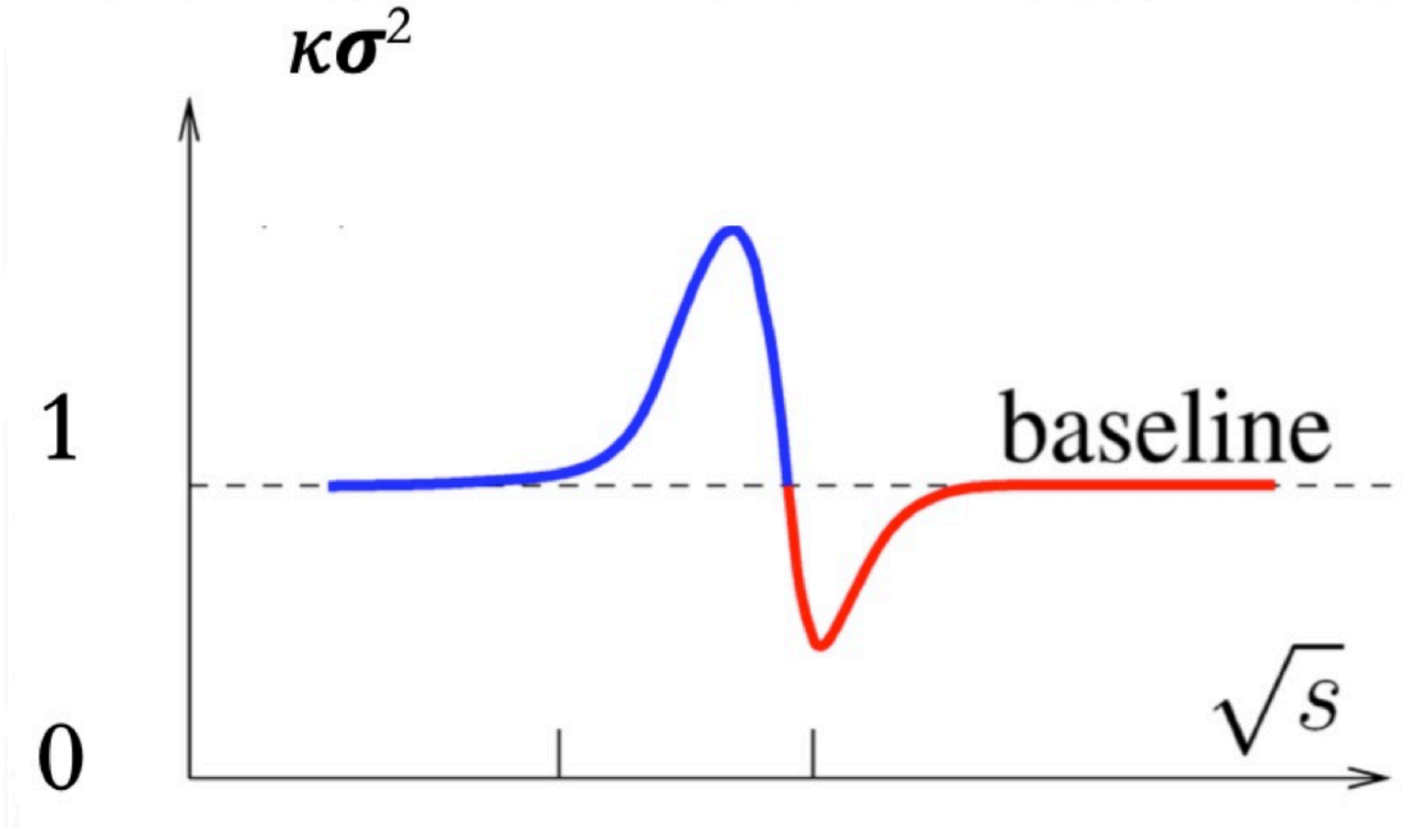

C_4/C_2: predicts a non-monotonic energy dependence due to contribution from QCD critical point

- 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)

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- 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..

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..

Thank You for your attention!