Probing phase-transition boundary of nuclear matter based on heavy-ion collisions below 10 GeV

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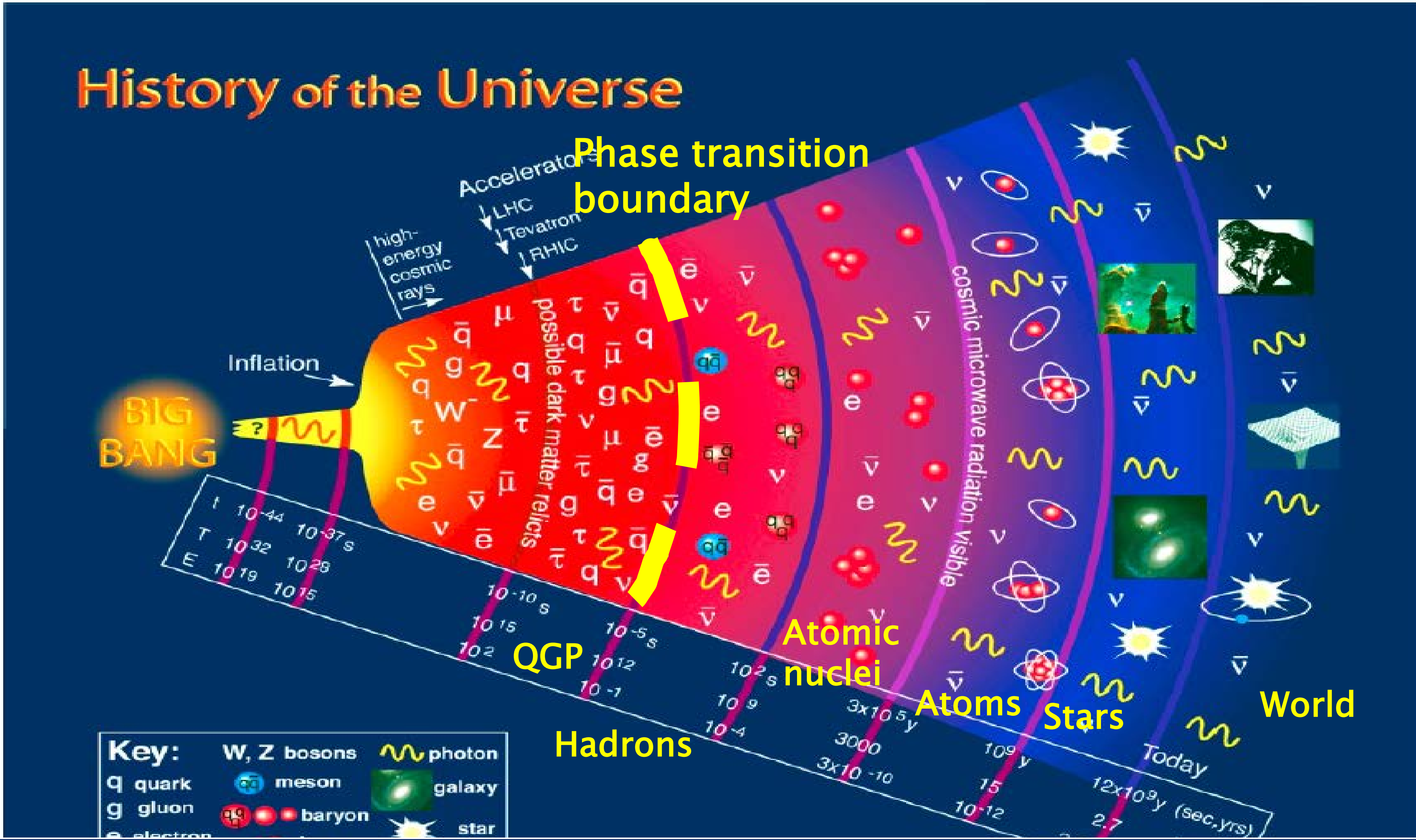
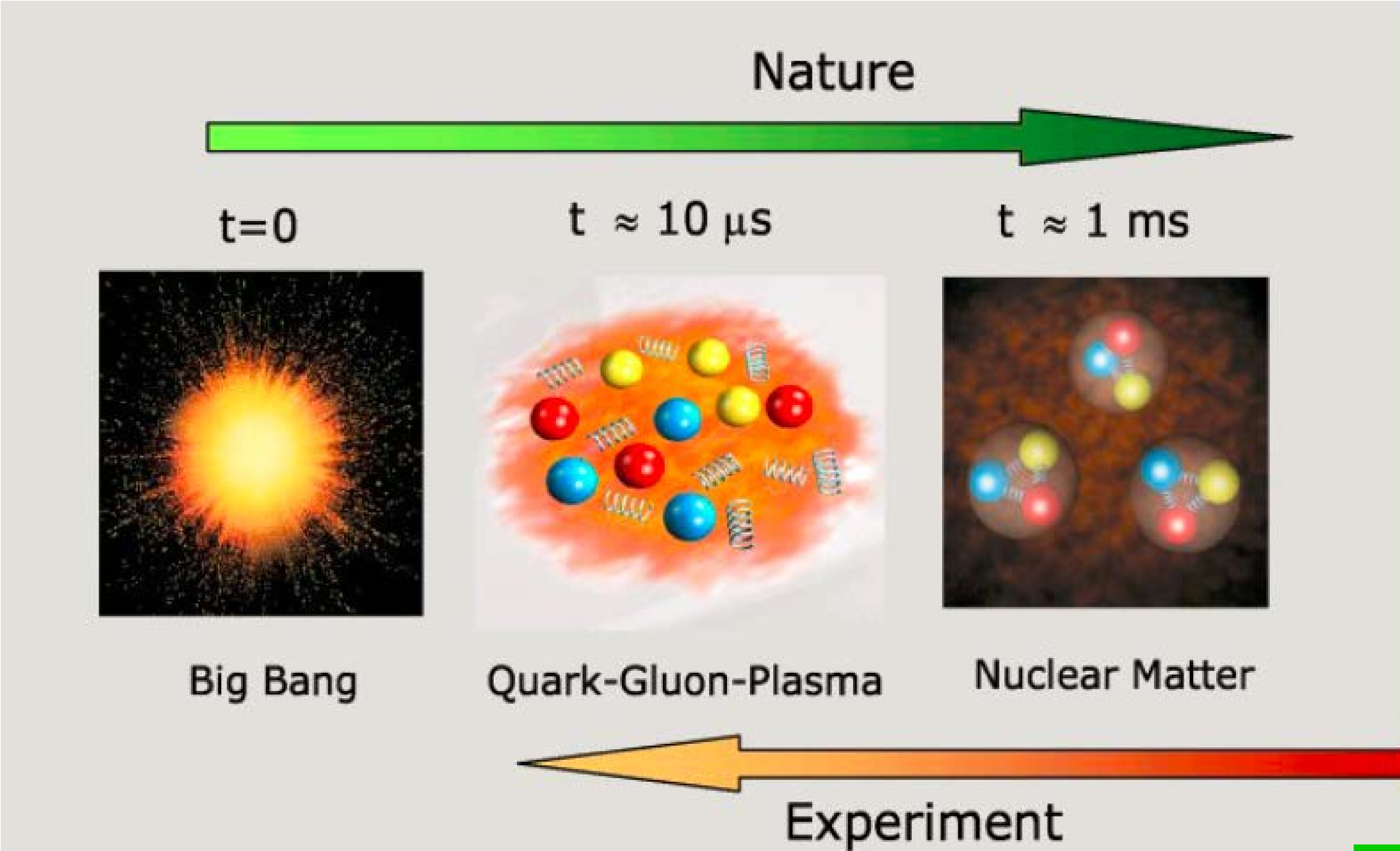
Why phase transition



PT boundary positions (specific energy density, temperature) affect **nuclear fusion**, influence the **synthesis of light elements** in the early universe, impact the **formation of stars** and **supernova explosions**, and subsequently the **formation of heavy elements** in the universe and the **development of human civilization** on Earth..

Universe evolution & Heavy-ion collisions



Number-of-constituent quark scaling of elliptic flow

Quark → hadron

Quark coalescence

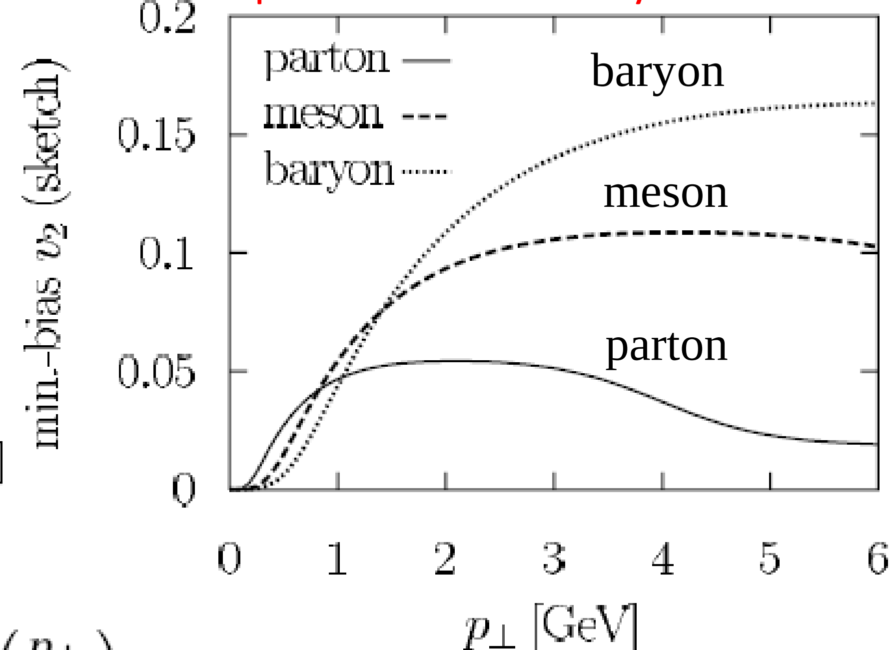
$$\frac{dN_B}{d^2p_\perp}(\vec{p}_\perp) = C_B(p_\perp)\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/3)\right]^3,$$

$$\frac{dN_M}{d^2p_\perp}(\vec{p}_\perp) = C_M(p_\perp)\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/2)\right]^2,$$

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

$$v_{2,M}(p_\perp) \approx 2v_{2,q}\left(\frac{p_\perp}{2}\right) \qquad v_{2,B}(p_\perp) \approx 3v_{2,q}\left(\frac{p_\perp}{3}\right)$$

parton: meson: baryon → 1:2:3

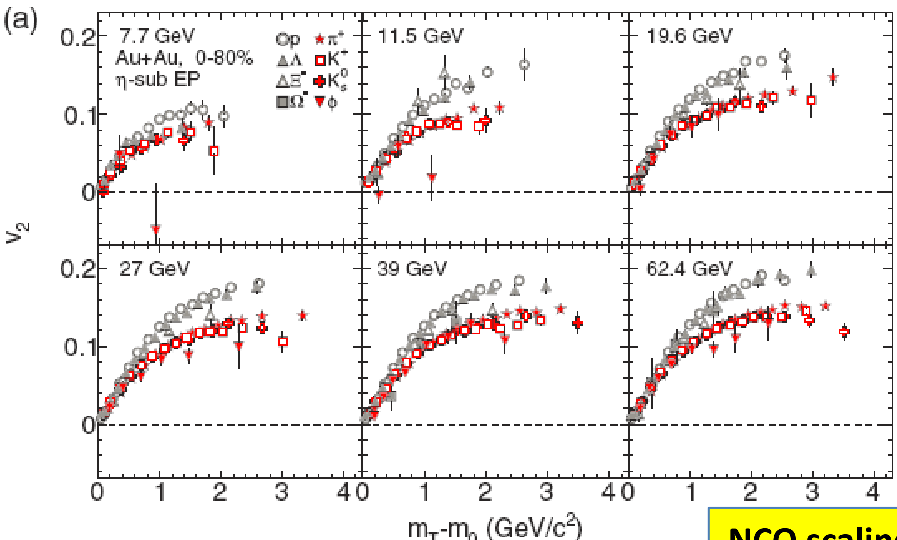


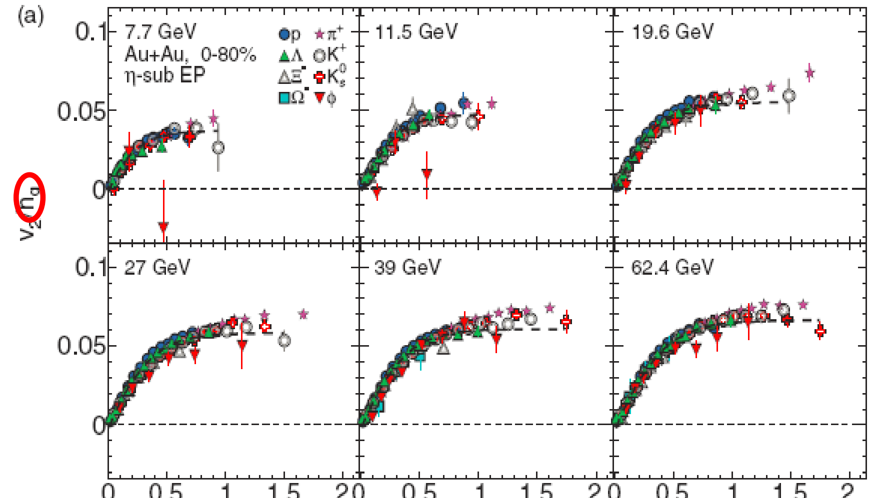
meson baryon

Dénes Molnár and Sergei A. Voloshin
Phys. Rev. Lett. 91, 092301 (2003).
H. Sato and K. Yazaki, Phys. Lett. B **98**, 153 (1981).

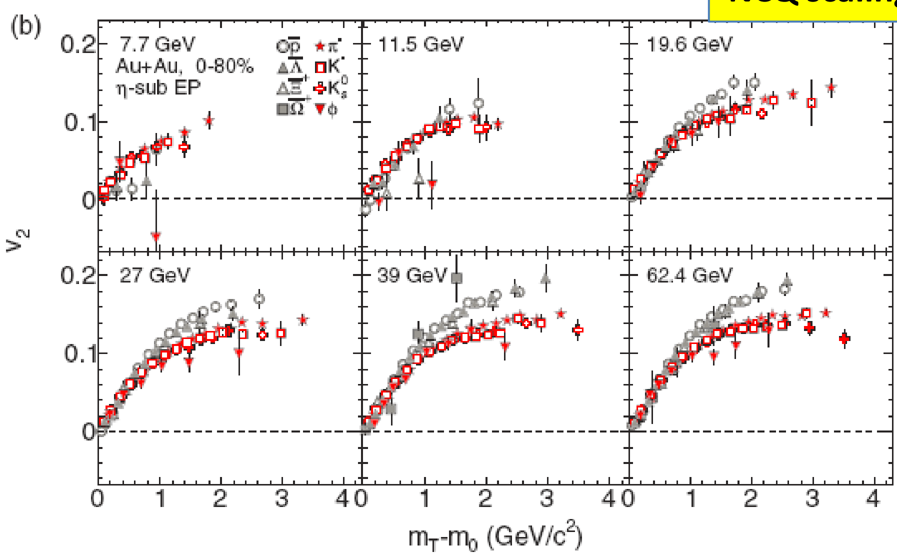
Number-of-constituent quark scaling law

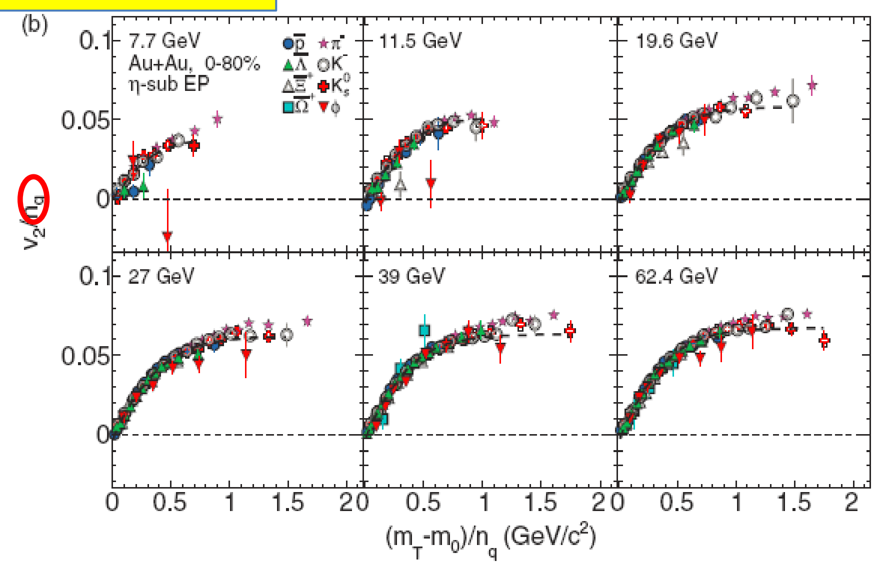
$\sqrt{s} > 7.7\ GeV$: Quark matter ?





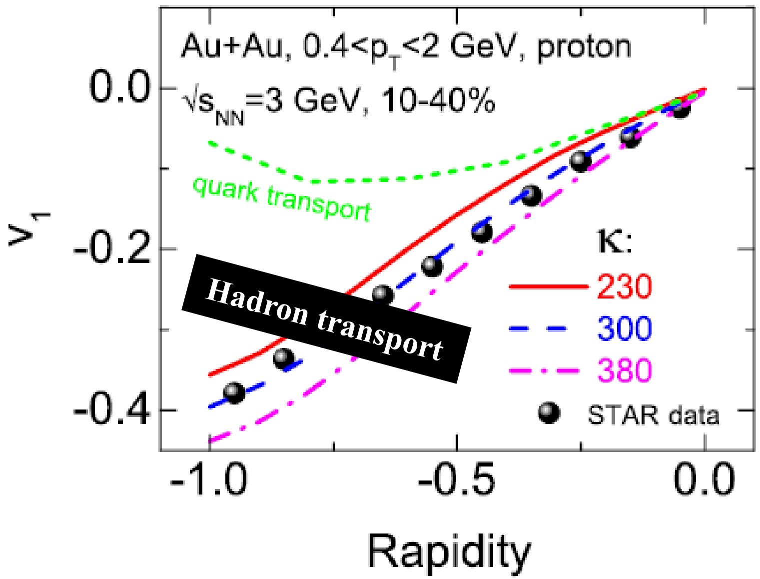
NCQ scaling = quark matter ?

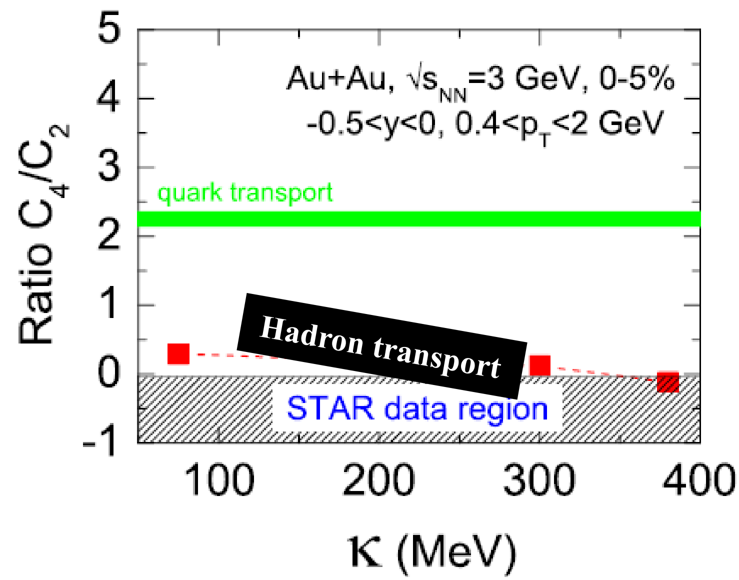


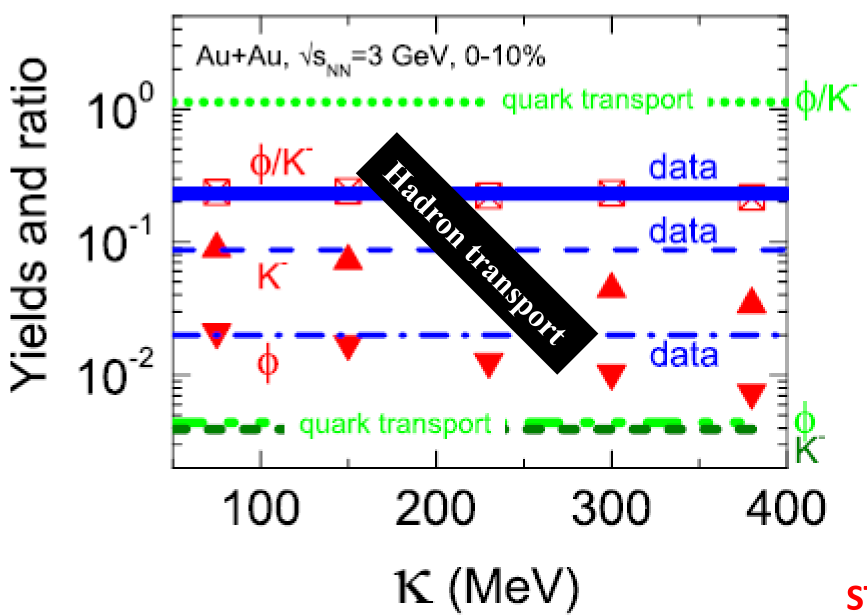


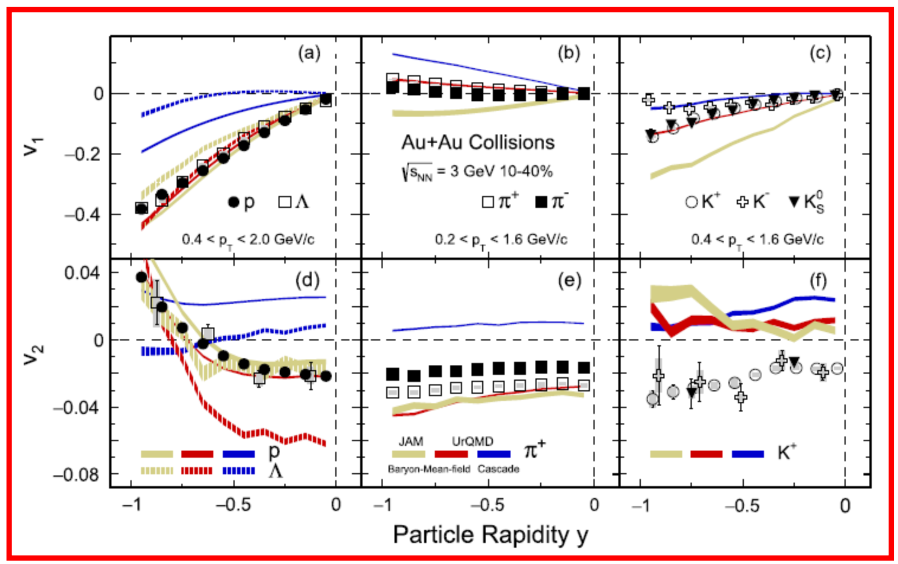
L. Adamczyk et al.(STAR Collaboration), PRC 88, 014902 (2013)

Hadronic matter at 3GeV: Hadron/quark transport comparison







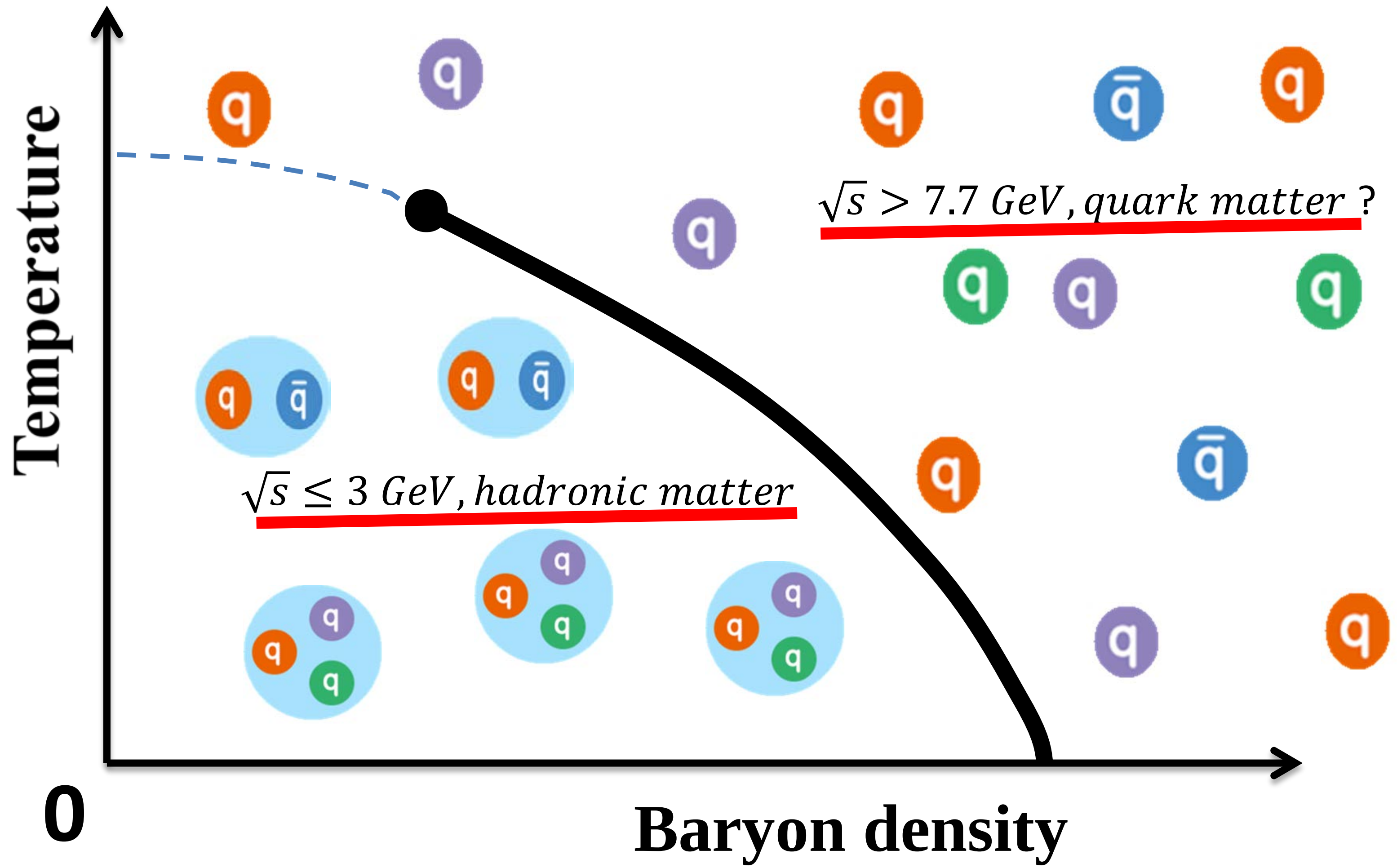


Zhi-Min Wu, Gao-Chan Yong, Phys. Rev. C 107, 034902 (2023)

STAR: baryonic mean field plays crucial role, so hadronic matter

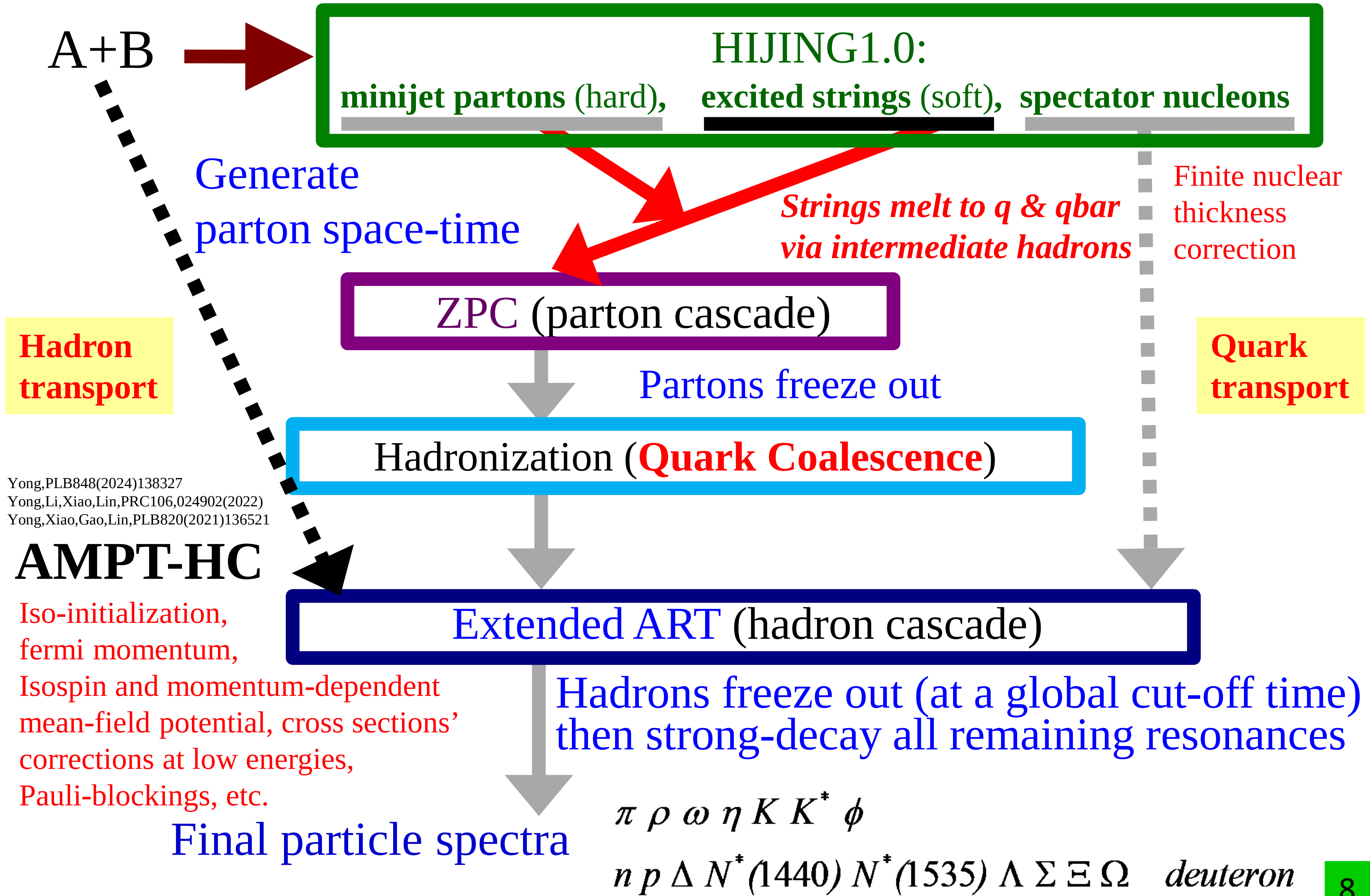
M.S. Abdallah et al.(STAR Collaboration), Physics Letters B 827 (2022) 137003

Energy range for Probing the Phase Boundary

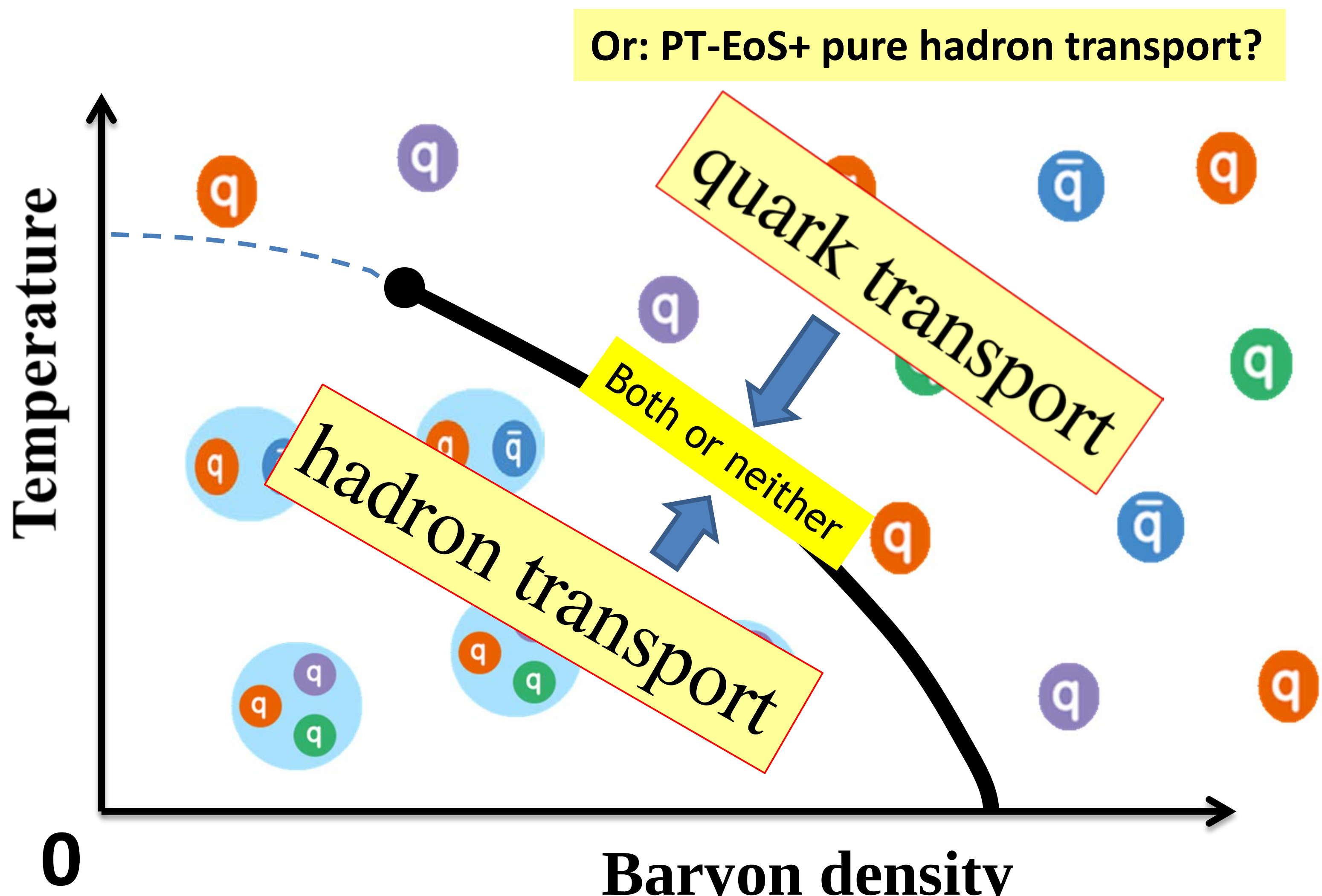


May be not accepted by all of you!

A Multi-Phase Transport (AMPT-SM)



Ways to probe the phase-transition boundary

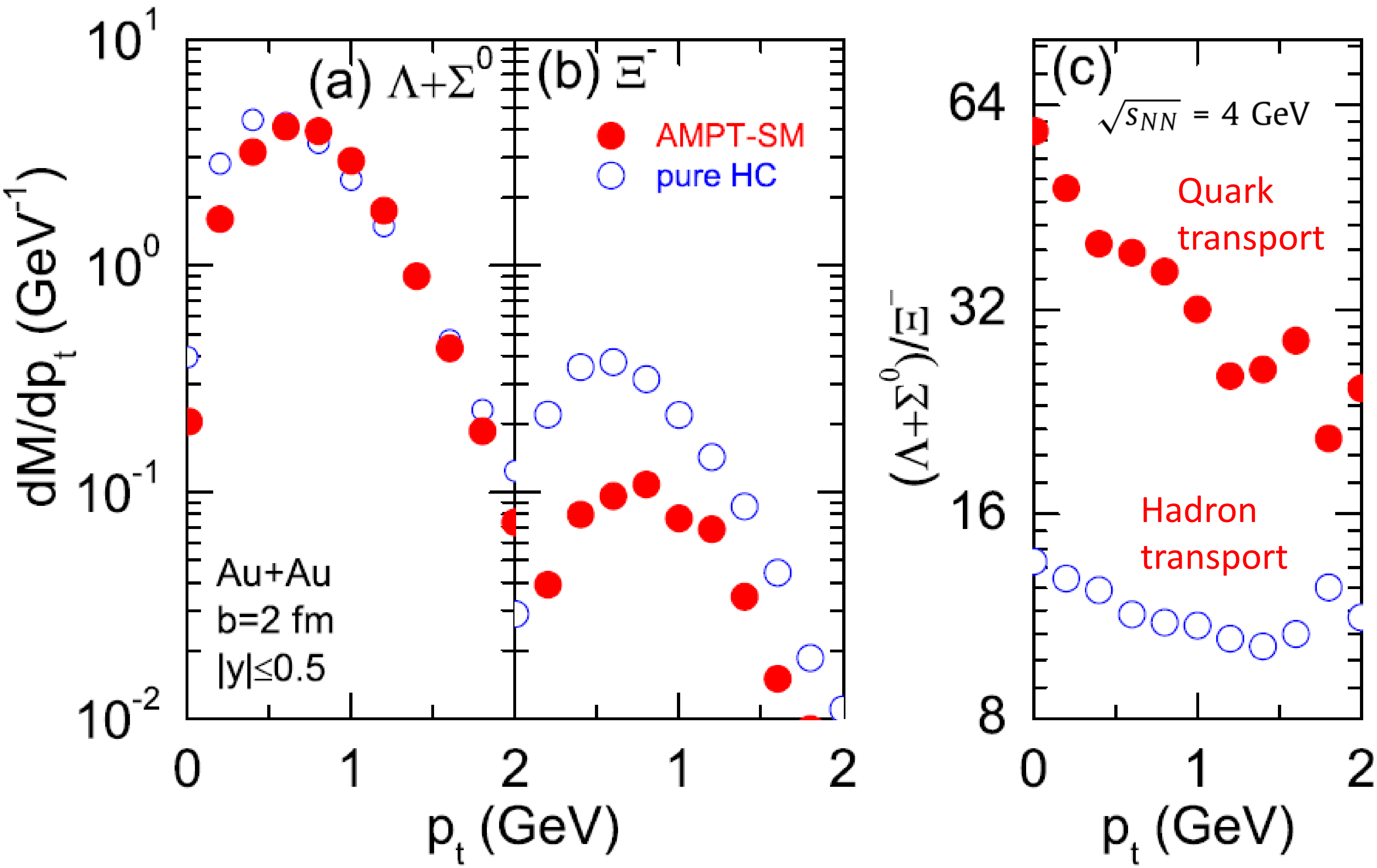


1). EoS softening

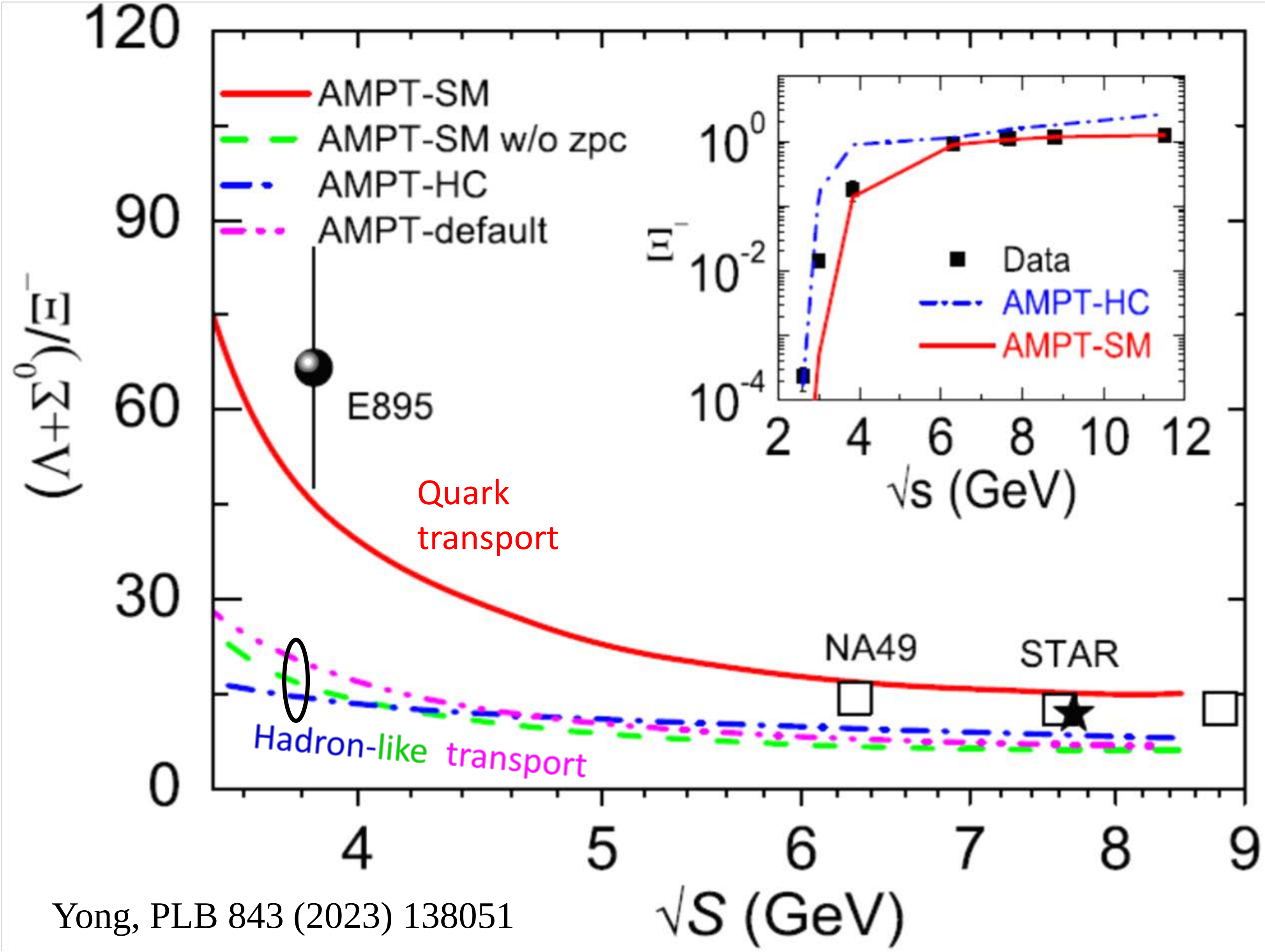
2). Hadron/quark transport comparison

3). Phase transition fluctuation-correlation dynamics

Strange singlet-to-doublet ratio:
Sensitive to hadron/quark transport



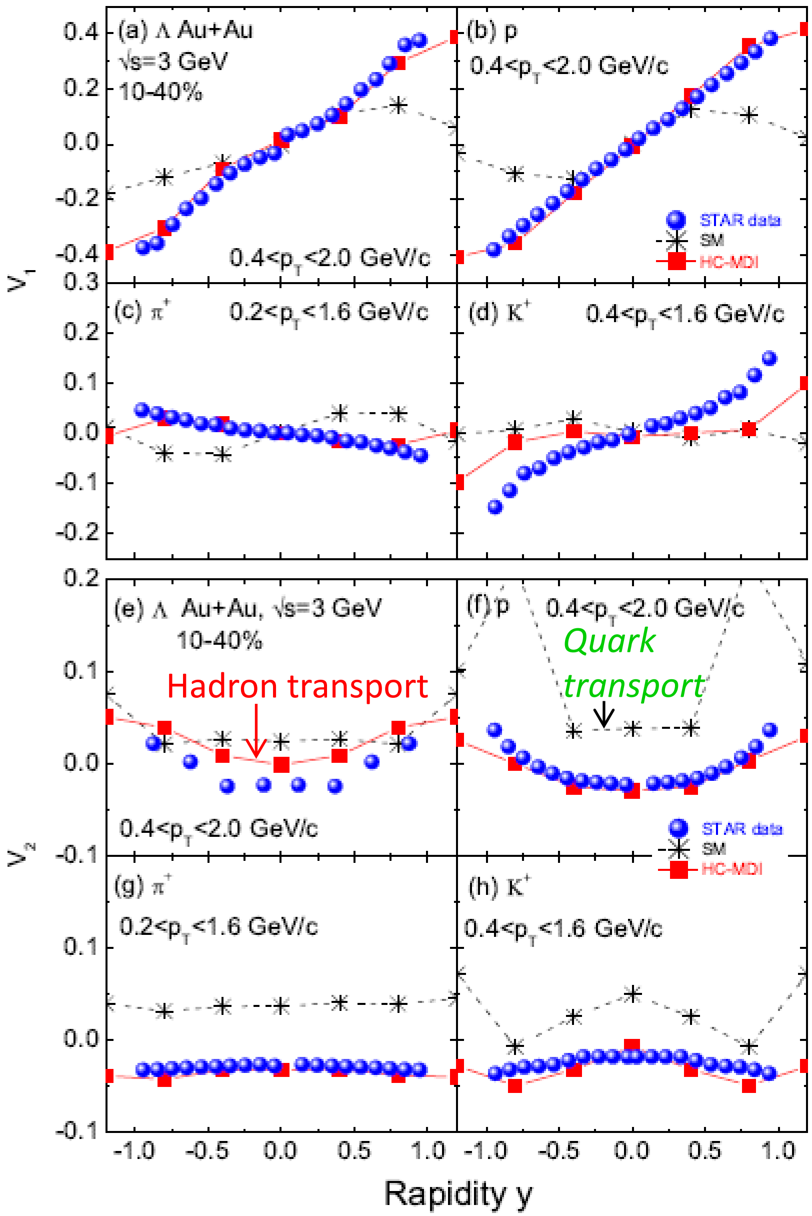
A phase transition occurrs at 4 GeV?



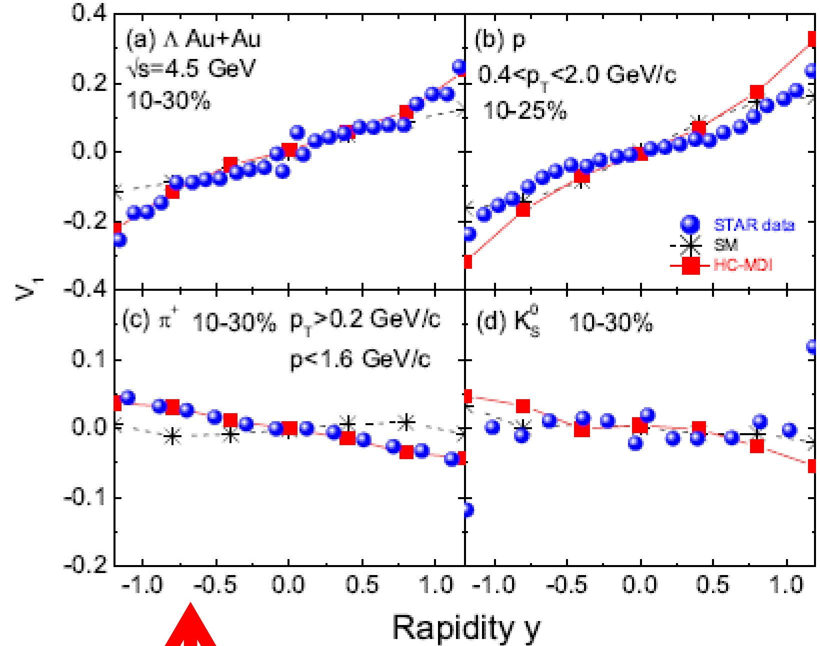
Yong, PLB 843 (2023) 138051

Multiple-observable v1 and v2 comparison

3 GeV: 8 kinds of data



4.5 GeV: 4 kinds of data



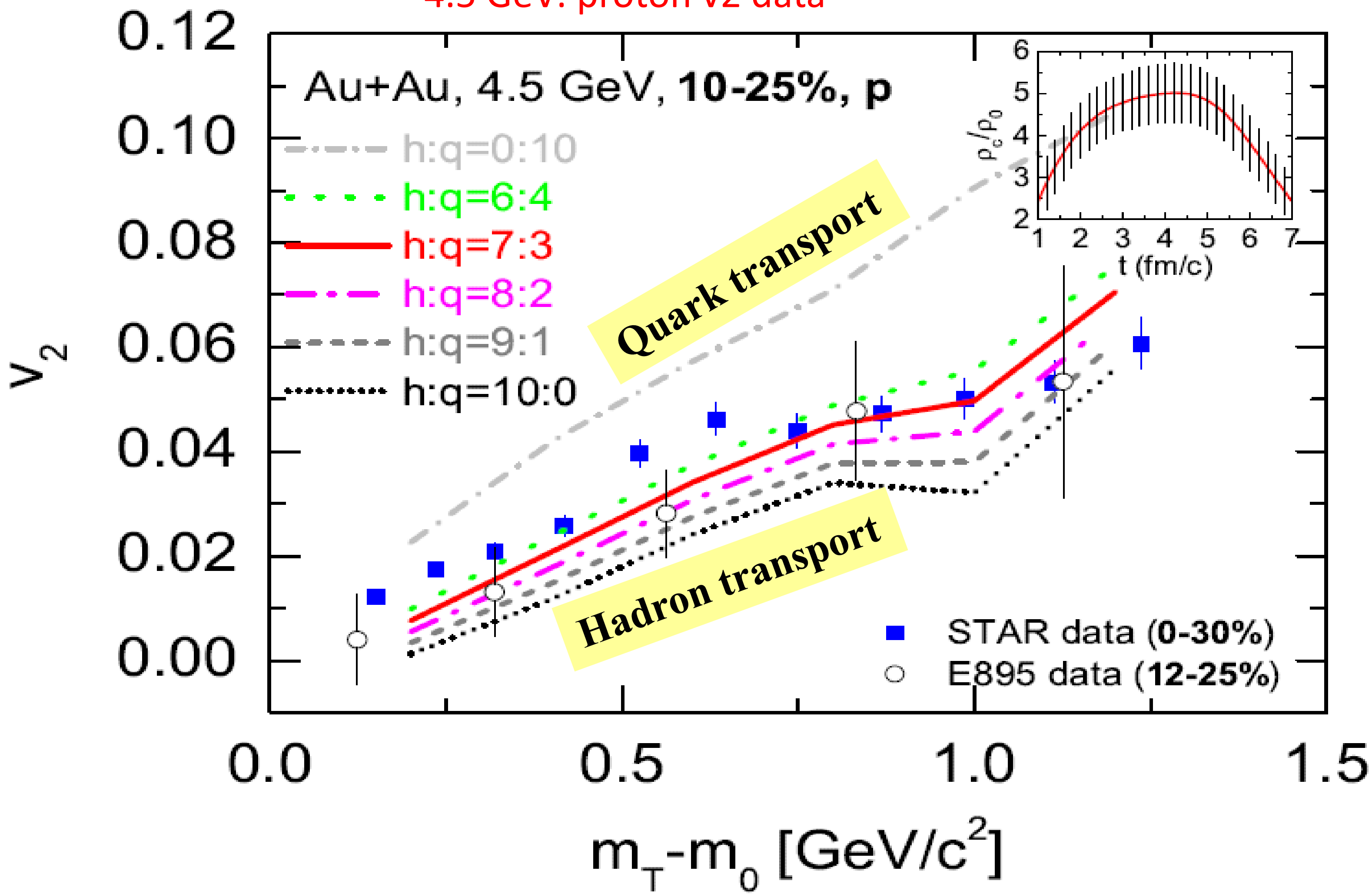
4.5GeV: Quark Transport/Hadron Transport. Both can essentially reproduce the transverse flow

3GeV: Au+Au collisions, transverse flow and elliptic flow. Only hadron transport can roughly reproduce both simultaneously

Yong, PLB 848 (2024) 138327

V2 at 4.5 GeV: a certain amount of parton is needed

4.5 GeV: proton v2 data



$5\,\rho_0$

Data taken from:
M. S. Abdallah et al.(STAR Collaboration),
Phys. Rev. C 103, 034908 (2021)

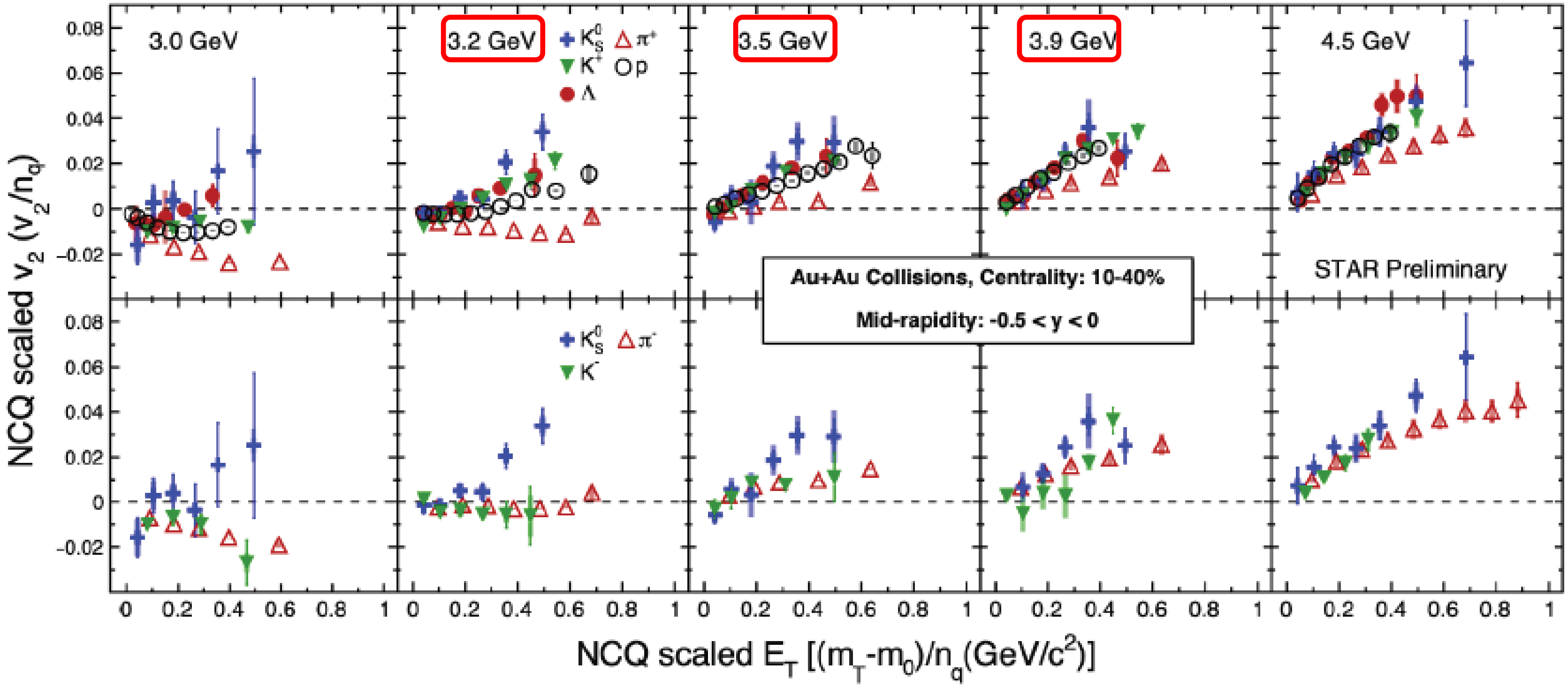
Yong, PLB 848 (2024) 138327

NCQ scaling of v_2 at 3 - 4.5 GeV

Hadronic interaction

From Shusu Shi's talk

Partonic collectivity

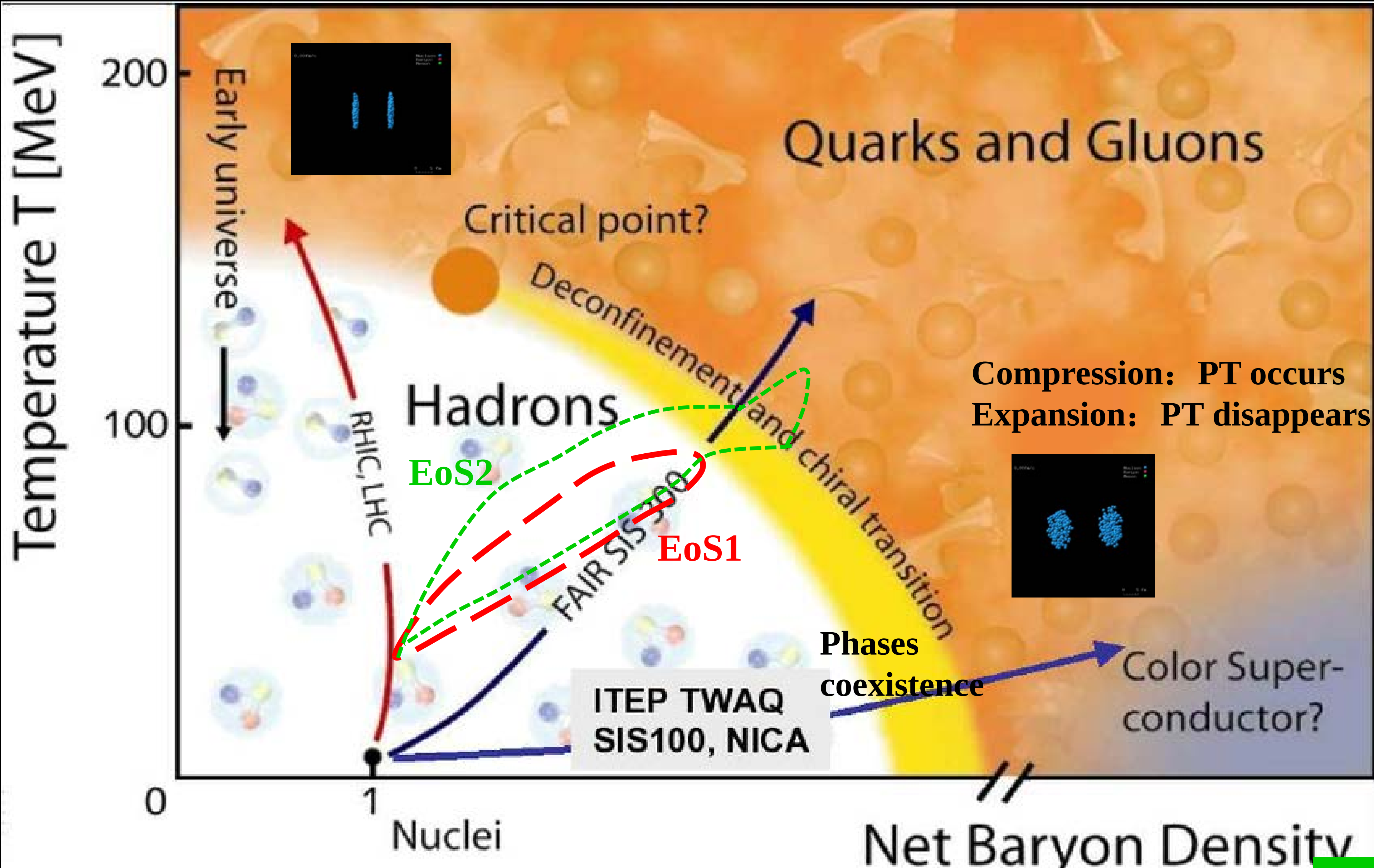


➢ NCQ scaling completely breaks below 3.2 GeV

➢ NCQ scaling becomes better gradually from 3.2 to 4.5 GeV

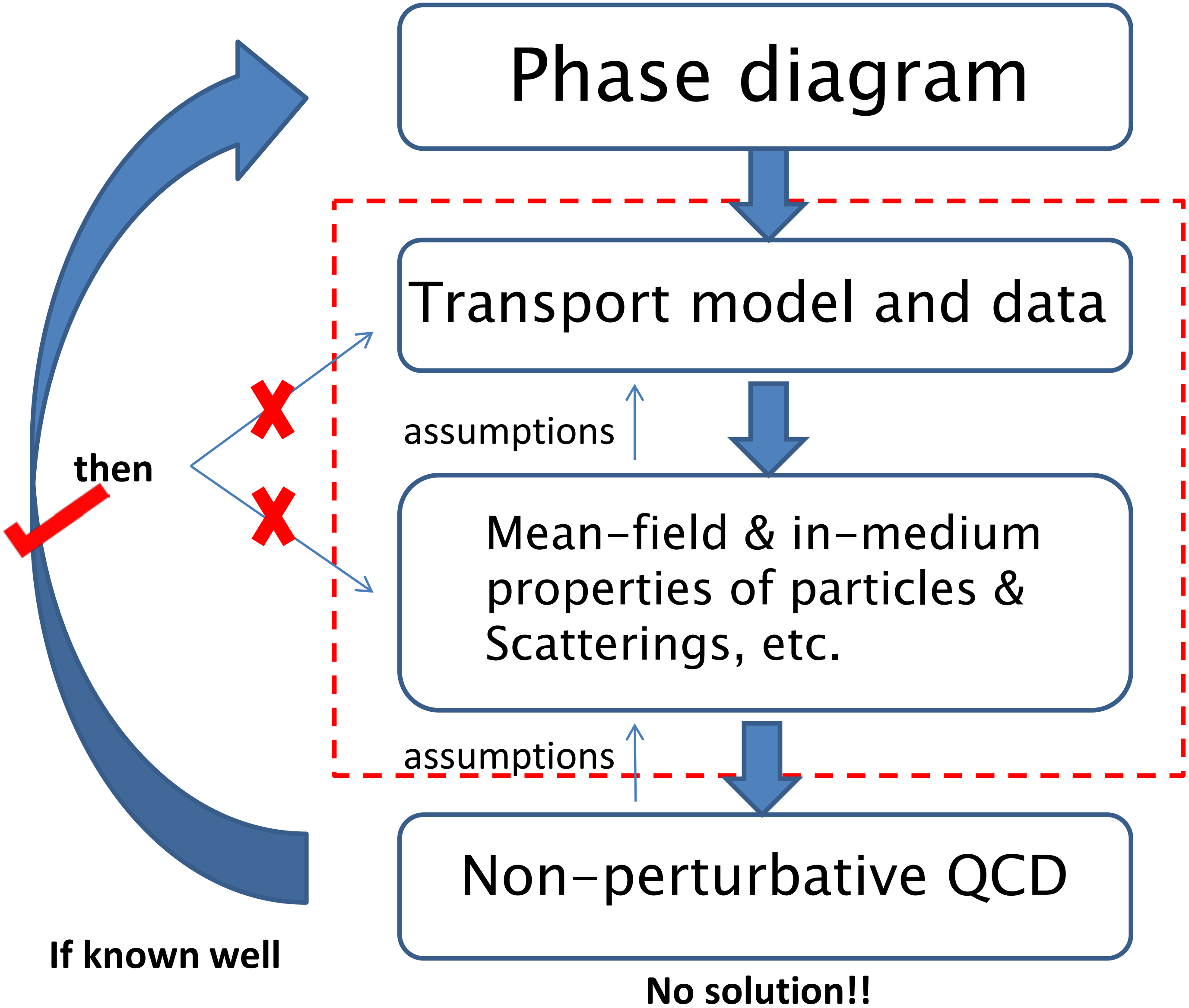
NCQ scaling = quark matter ?

Phase diagram



Discuss model dependence

one of the primary reason why the PT is not determined over 20 years!



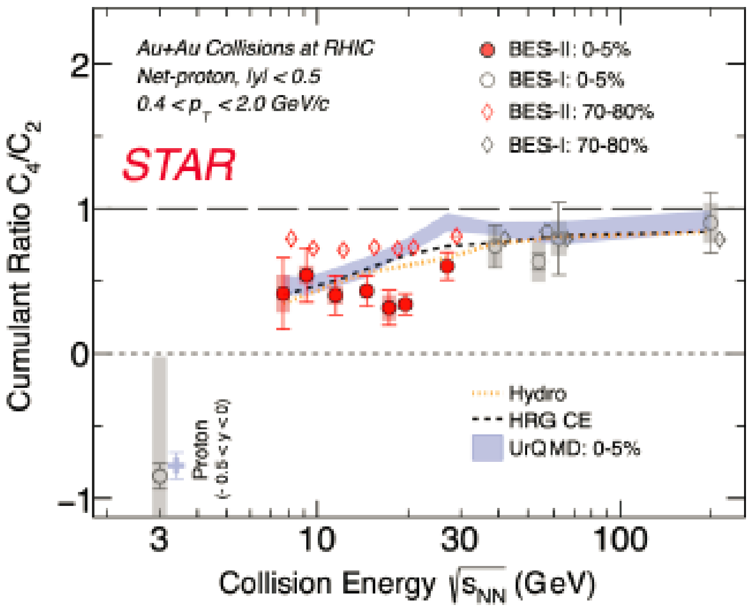
Theoretical uncertainties are inevitable.

Good model: able to provide **a unified description of as many observations as possible!**

Recent results in BES-II

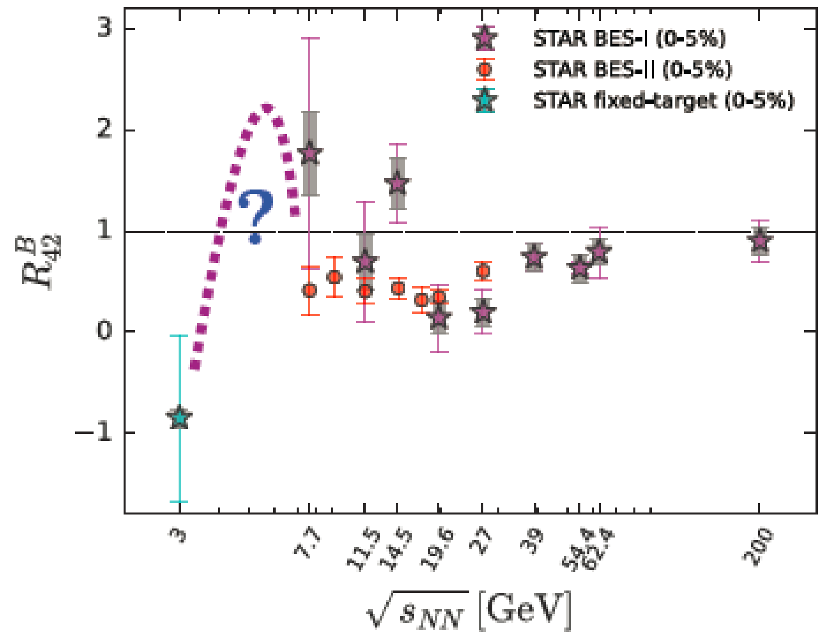
From Wei-Jie Fu's talk

Net proton kurtosis



Ashish Pandav for STAR Collaboration in CPOD2024

Results in BES-I and BES-II

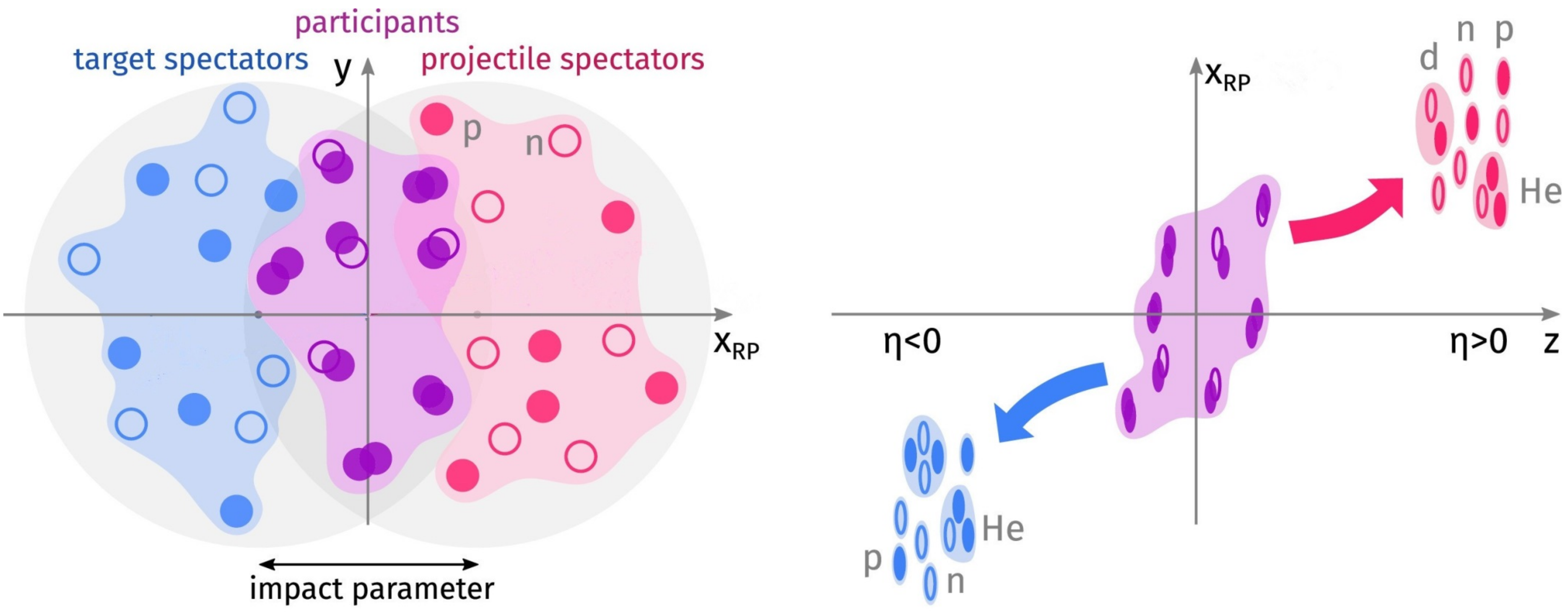


also cf. talk by Xiaofeng Luo

- The kurtosis in the energy regime of fixed-target experiments, i.e. 3 GeV $\lesssim \sqrt{s_{NN}} \lesssim$ 7.7 GeV, then become very pivotal.
- Is there a "peak" structure?

We hope: This qualitative probe works

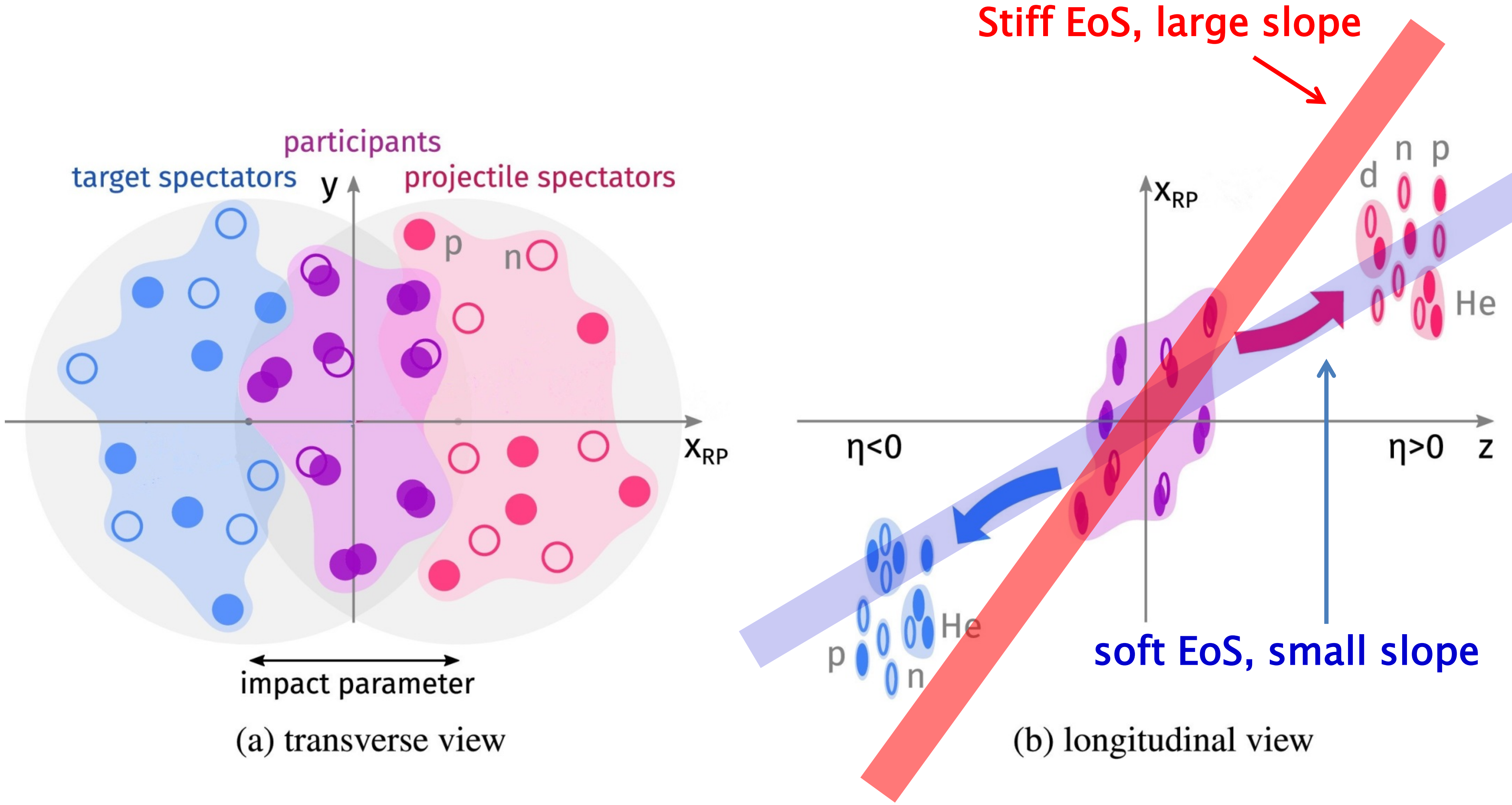
Directed flow probes dense EoS



(a) transverse view (b) longitudinal view

Physics Letters B 846 (2023) 137453

Directed flow probes dense EoS



(a) transverse view
(b) longitudinal view

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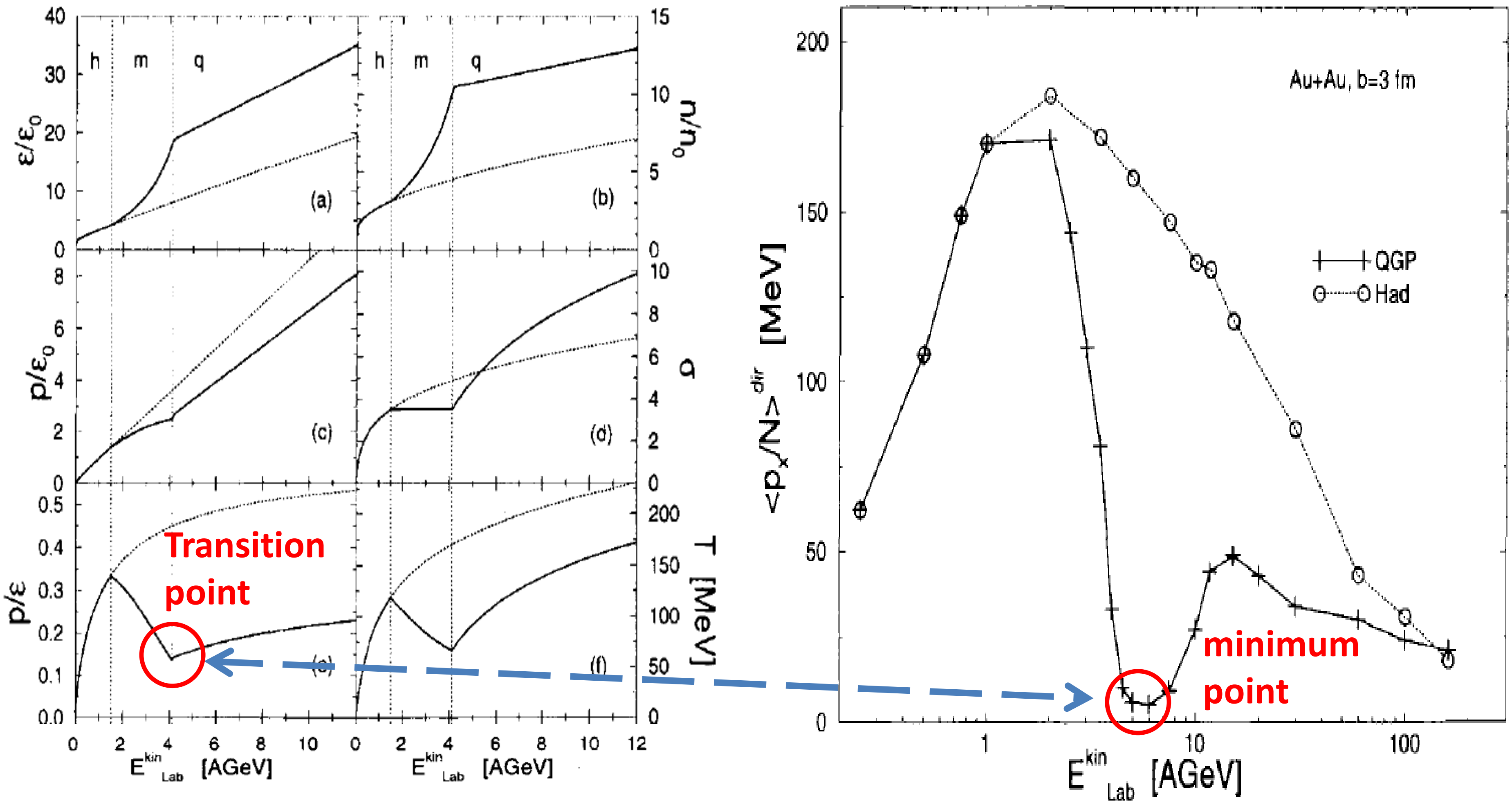
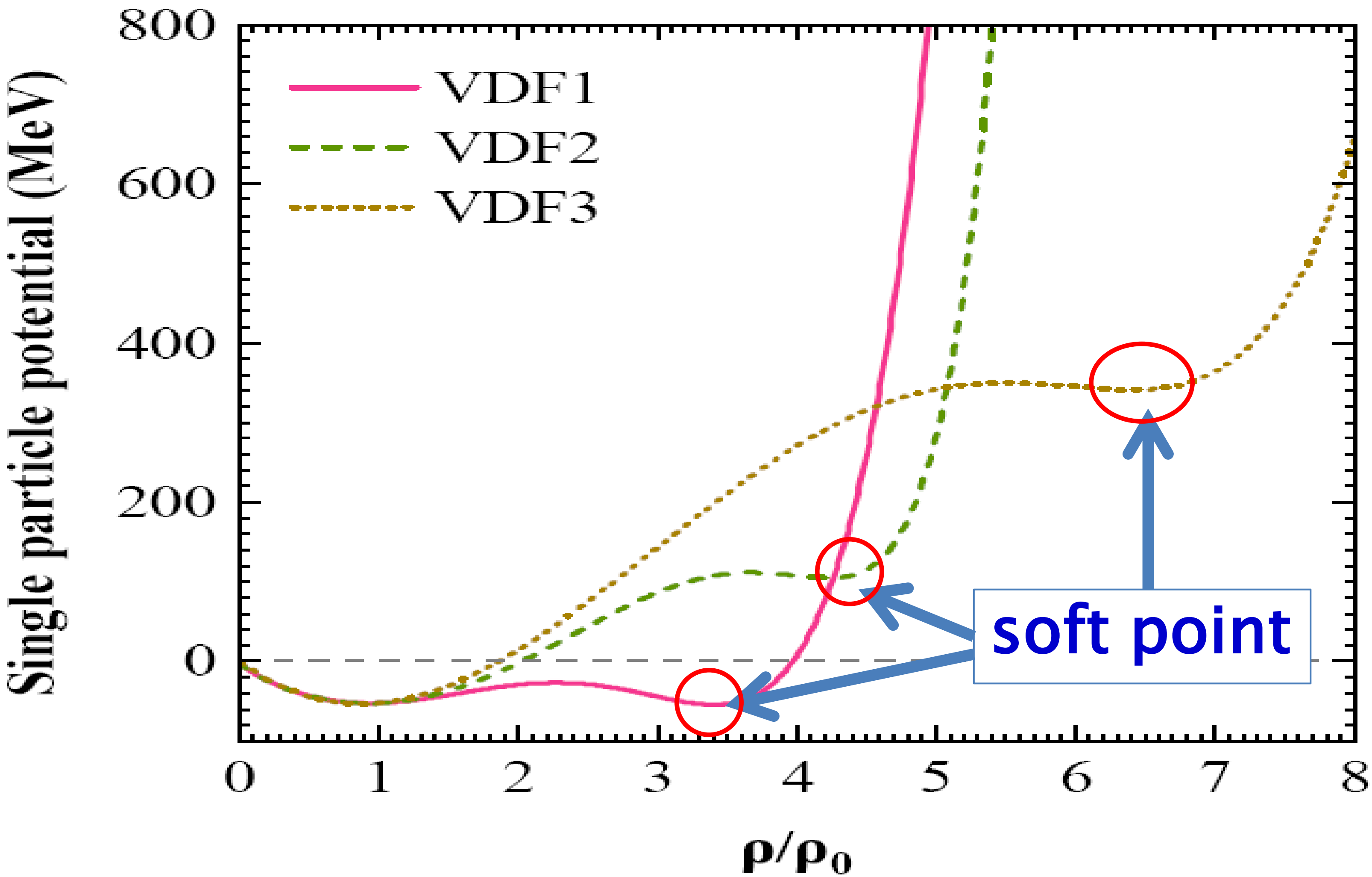
Phase-transition EoS and directed flow



D.H. Rischke, Y. Pursun, J. A. Maruhn, H. Stoecker, and W. Greiner, Acta Phys. Hung. A 1 (1995), 309-322

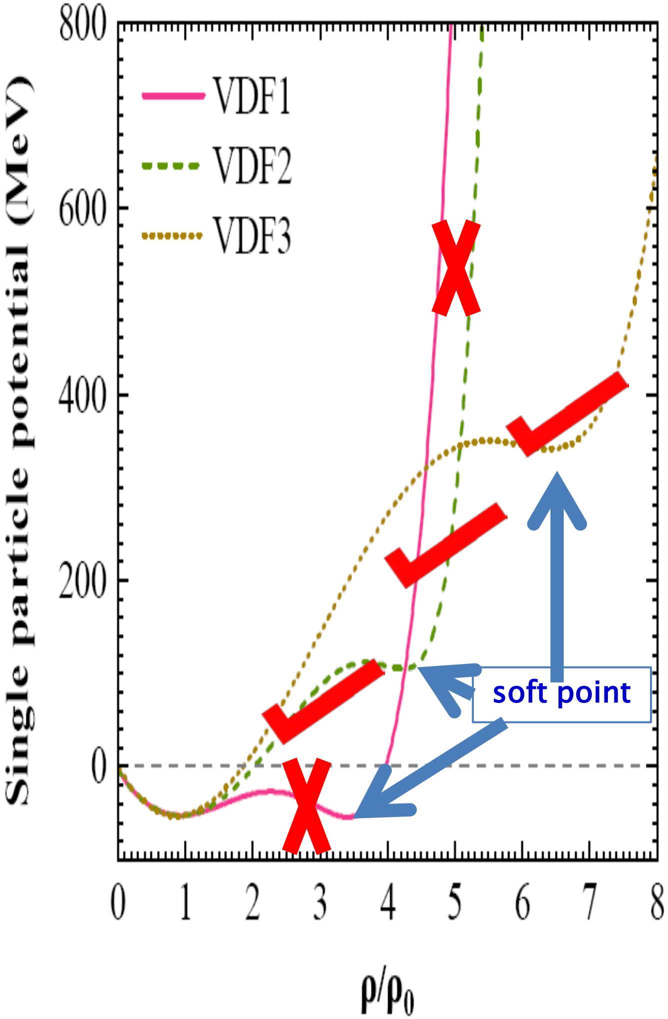
With 3 phase-transition EoSs

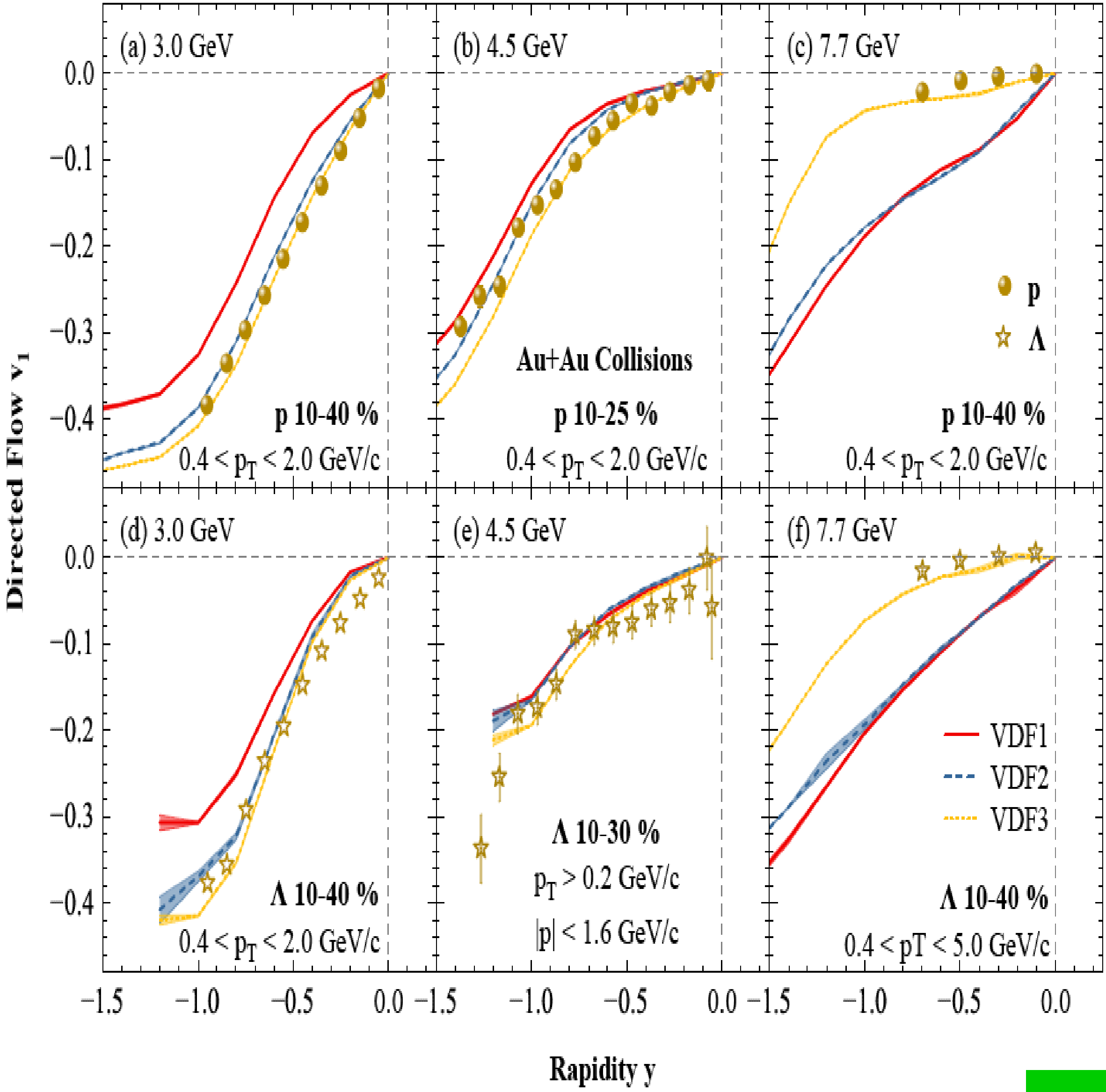


J. Steinheimer, A. Motornenko et al., Eur. Phys. J. C 82, 911 (2022).

relativistic vector density function (VDF) model based on Landau Fermi-Liquid theory

Directed flows and EoS

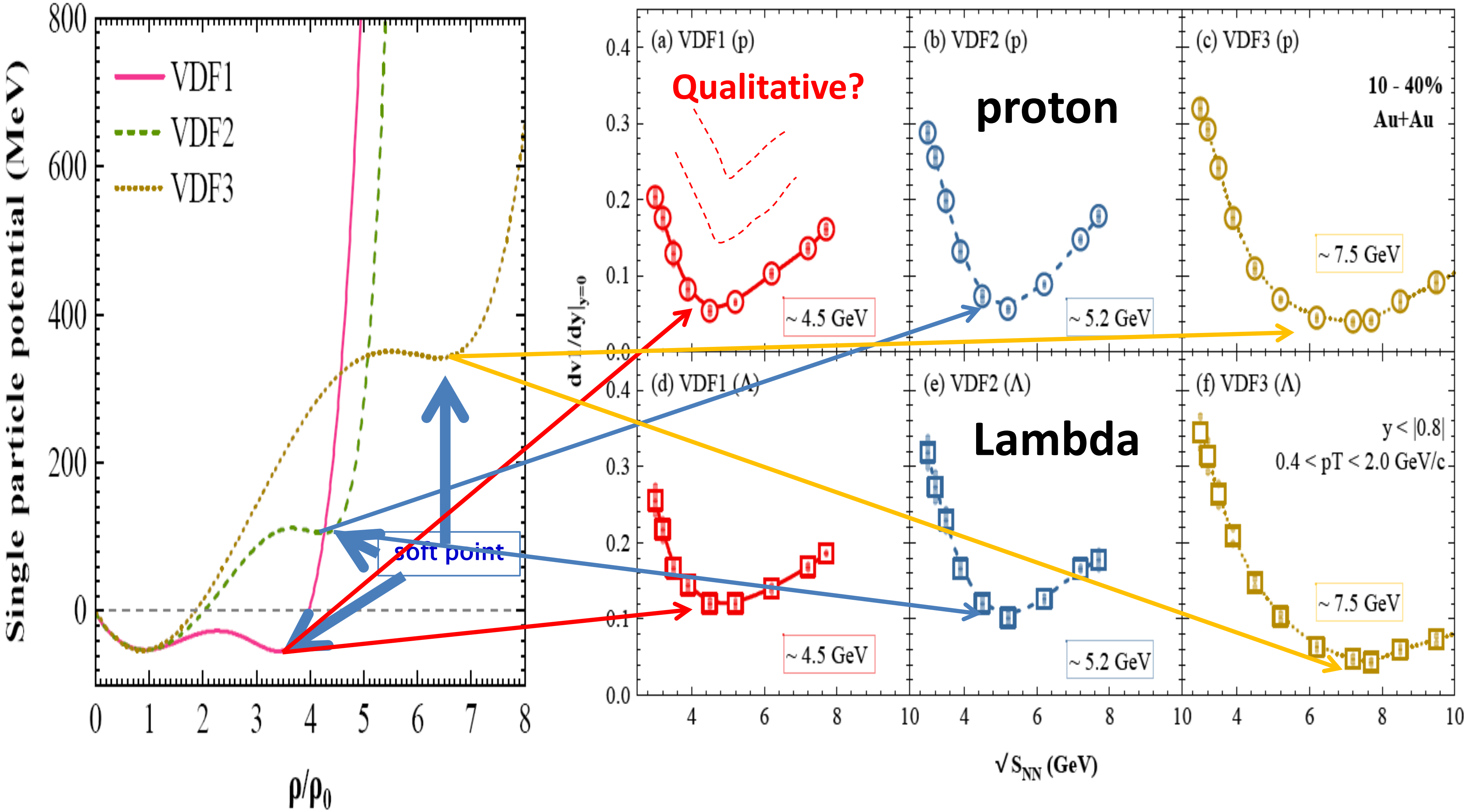




Minimum point suggests phase transition

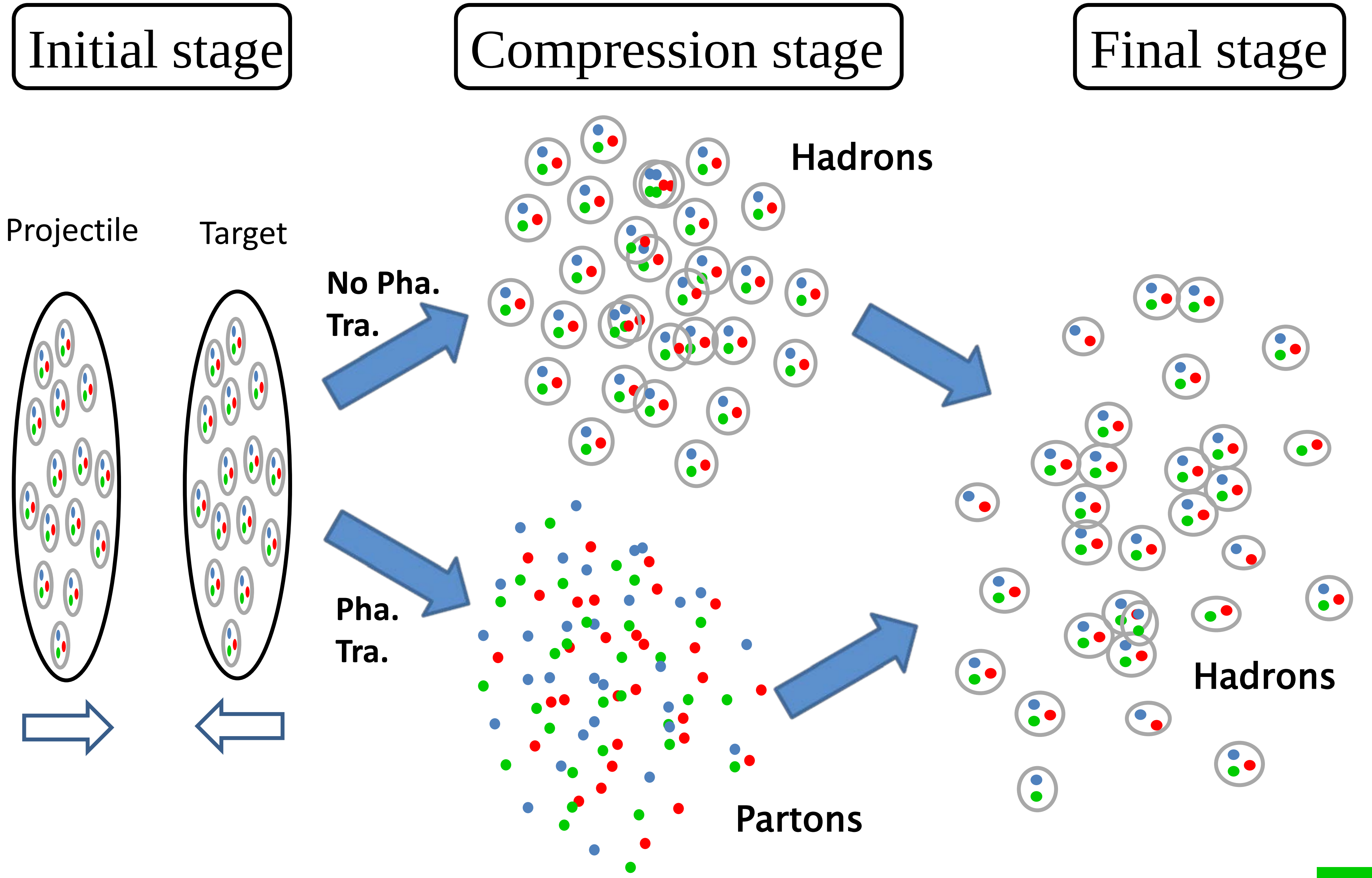
ZMW and GCY, submitted

Use proton and Lambda as Cross-check

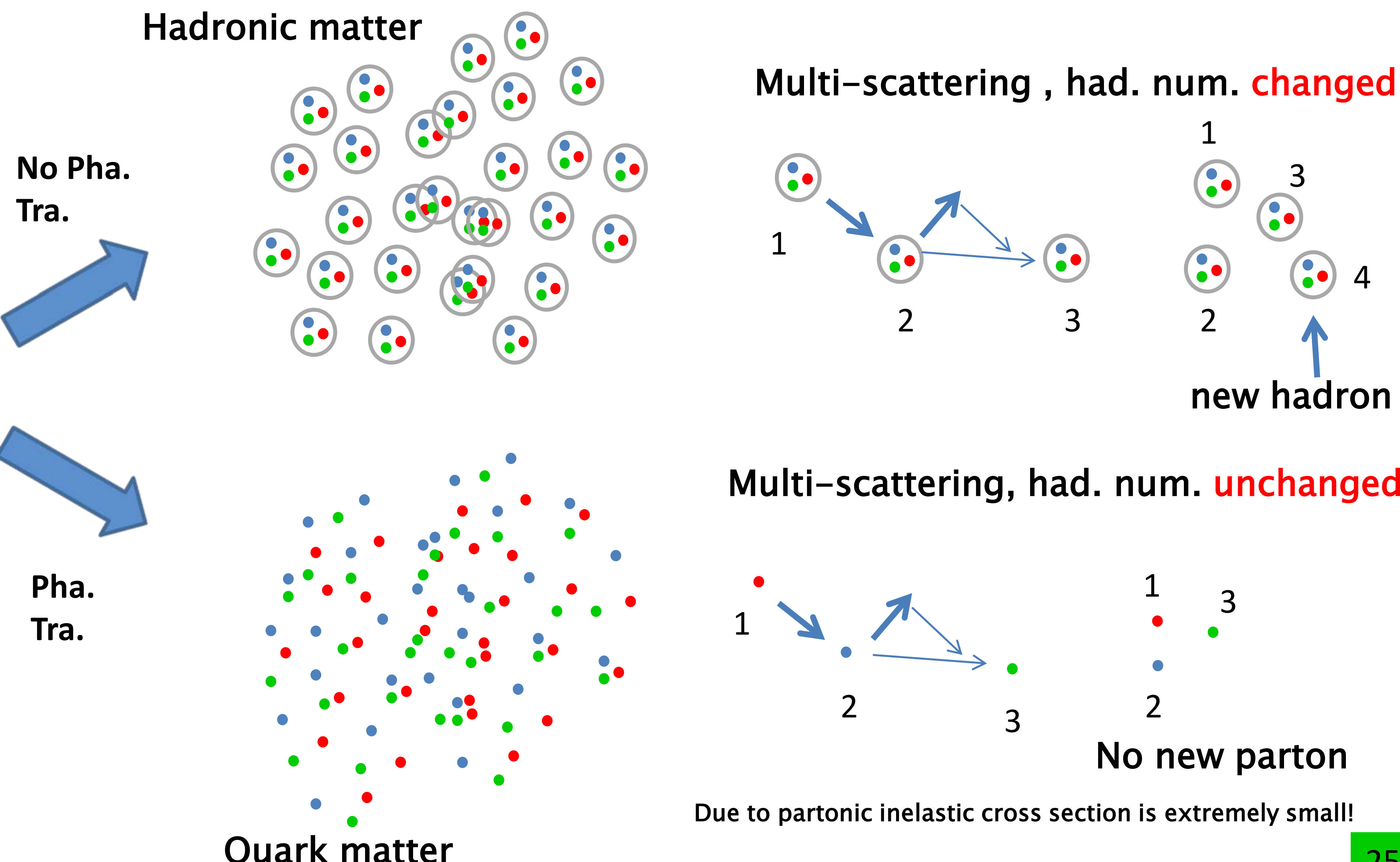


Locate minimum point, deduce phase transition point

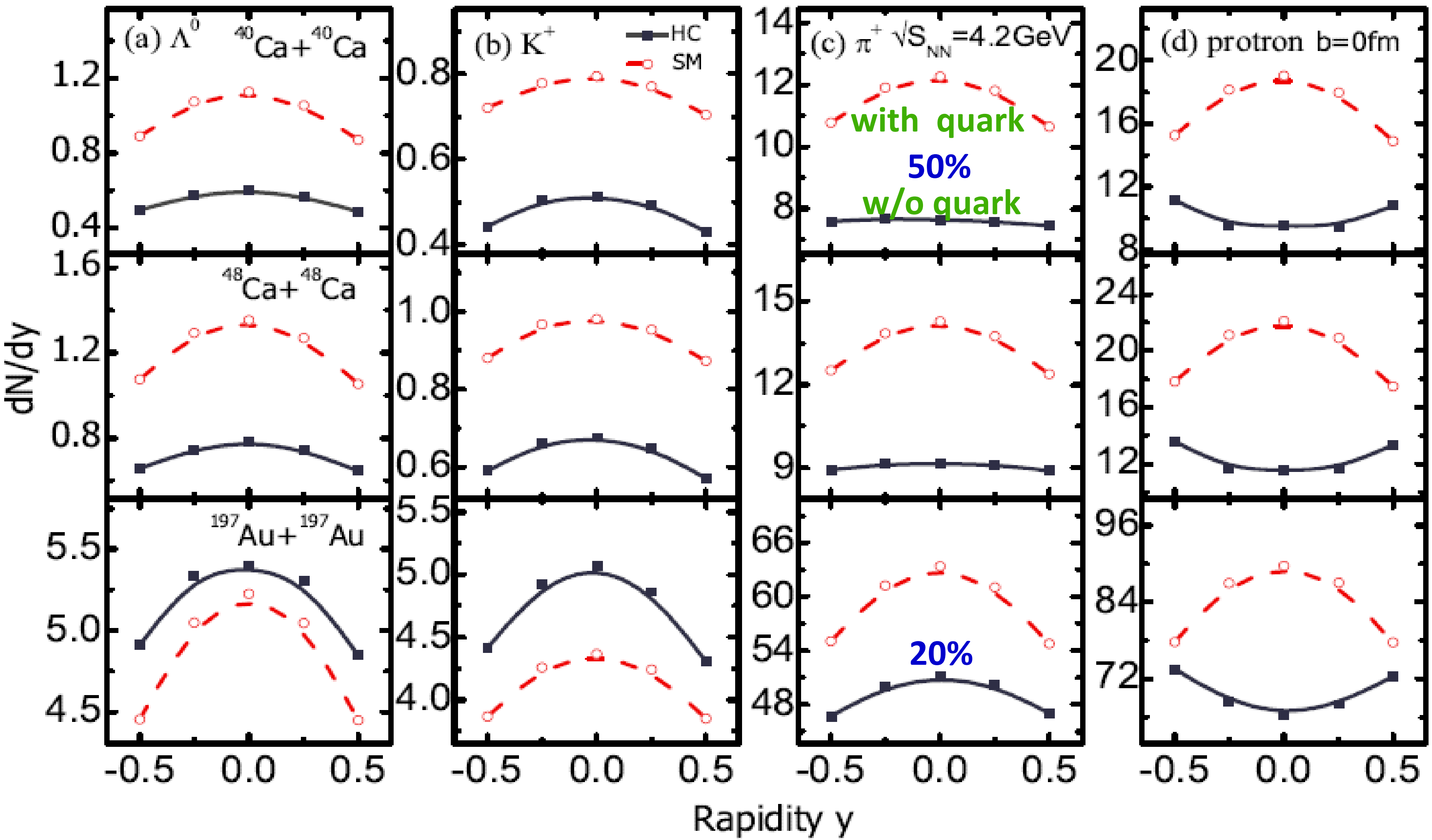
Evolution 3 stages of HICs



Compression stage



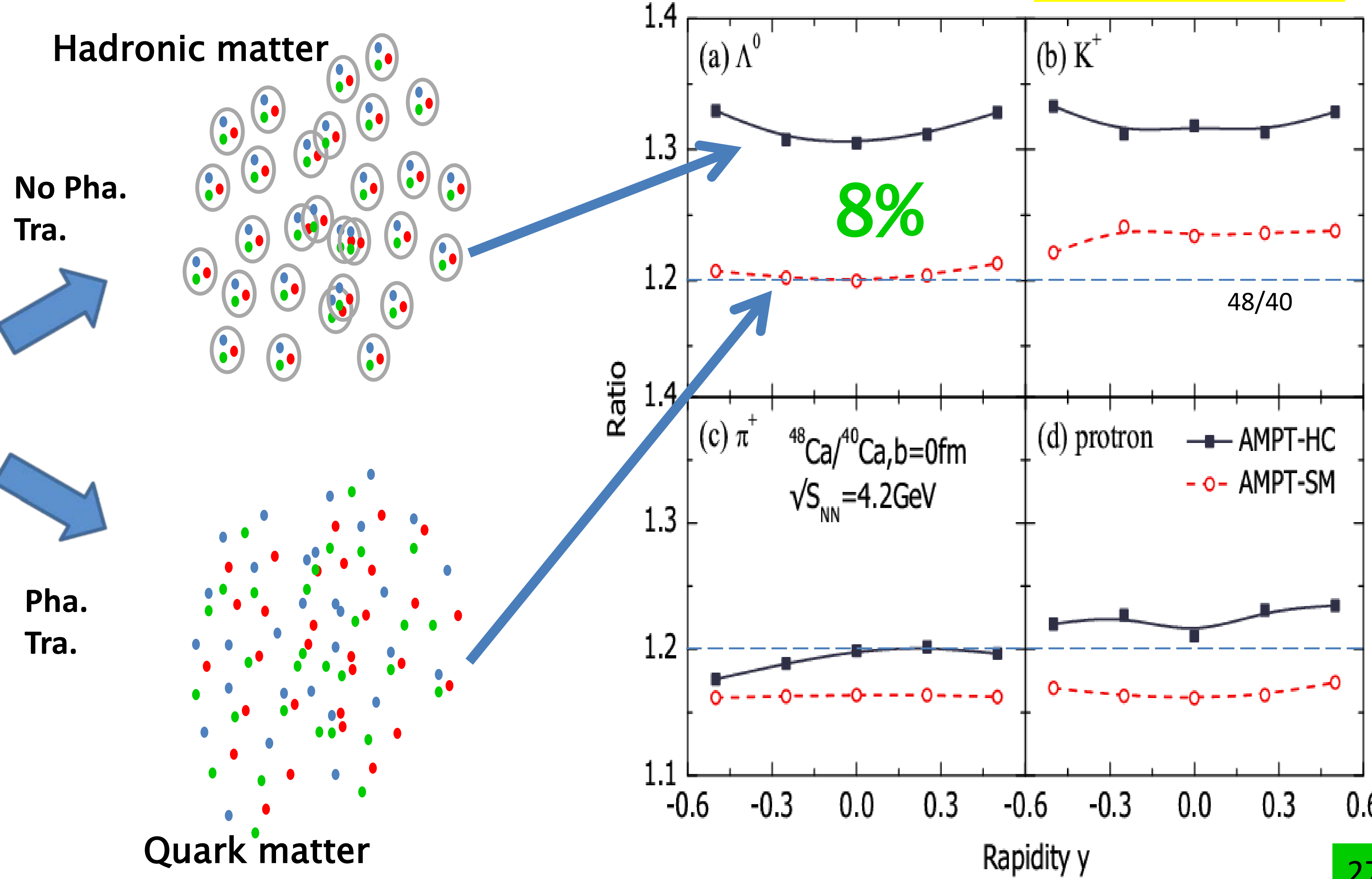
Particles from 3 reaction systems



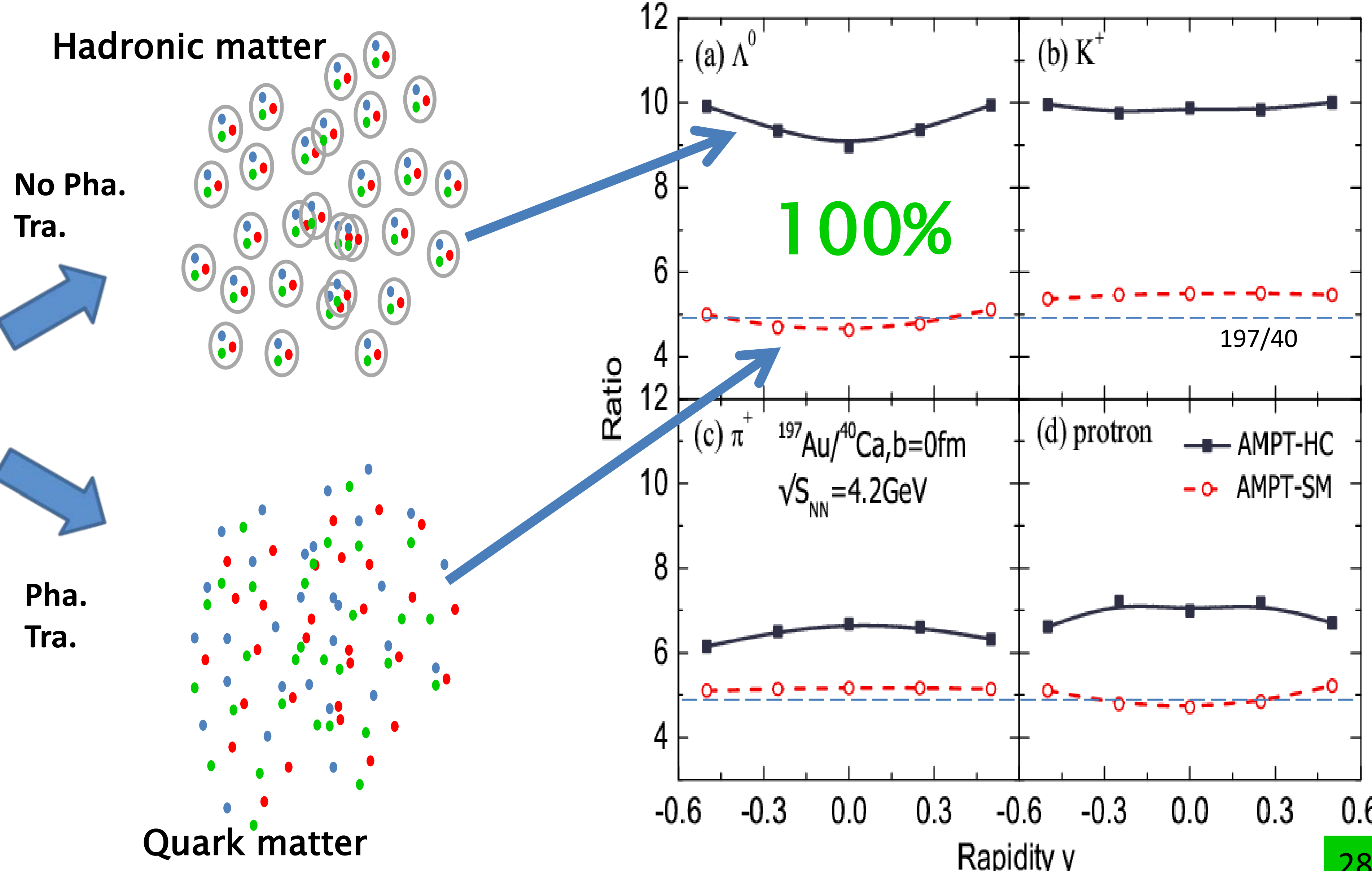
HC: there is an even faster increase than SM

Ratios from Ca48Ca48/Ca40Ca40

Ratio: less model dependent?



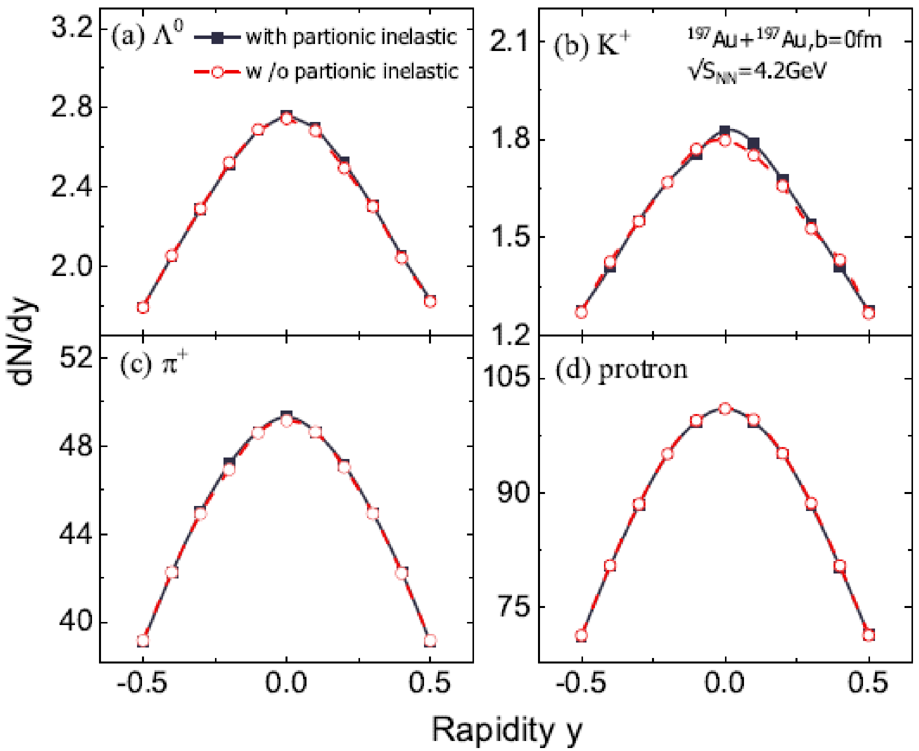
Ratios from Au197Au197/Ca40Ca40

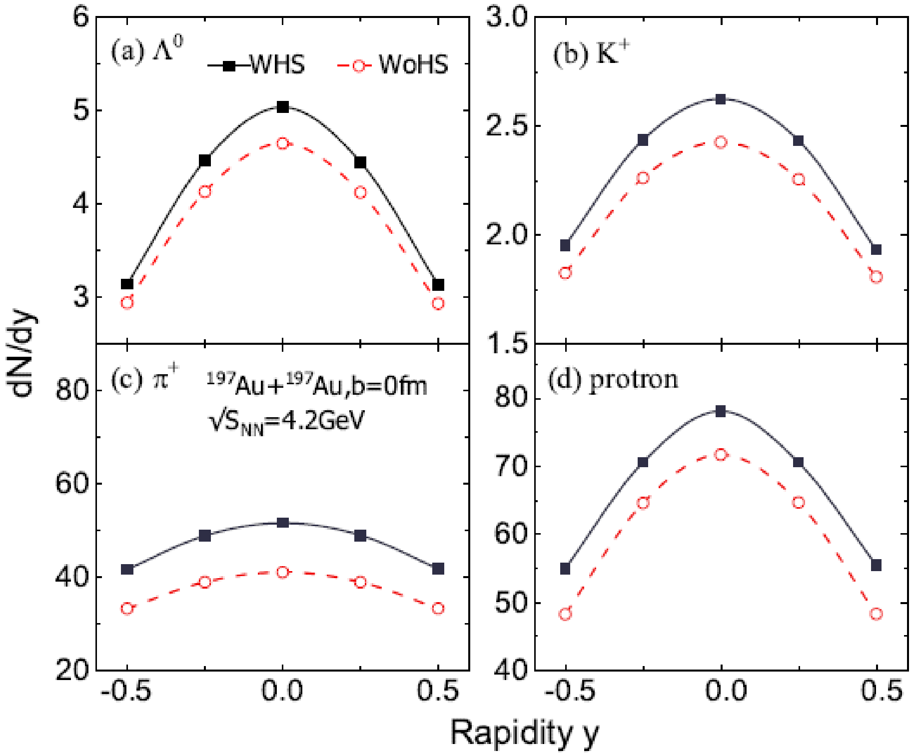


PACIAE3.0 check

XZ and GCY, submitted

PACIAE model: see
*An-Ke Lei et al., PRC **108**, 064909 (2023)*





Parton rescatterings do not increase hadron yields !

Hadron rescatterings really increase hadron yields !

Summary

1). Our previous research suggests that a phase-transition may occur around sqrt(s) ~ 4 GeV.

2). Ratio of strangeness productions from heavy-light systems and minimum point of proton or hyperon directed flow slope are potential probes of phase transition.

3). **A variety of models/observables is needed.**