What could be measured at NICA energies

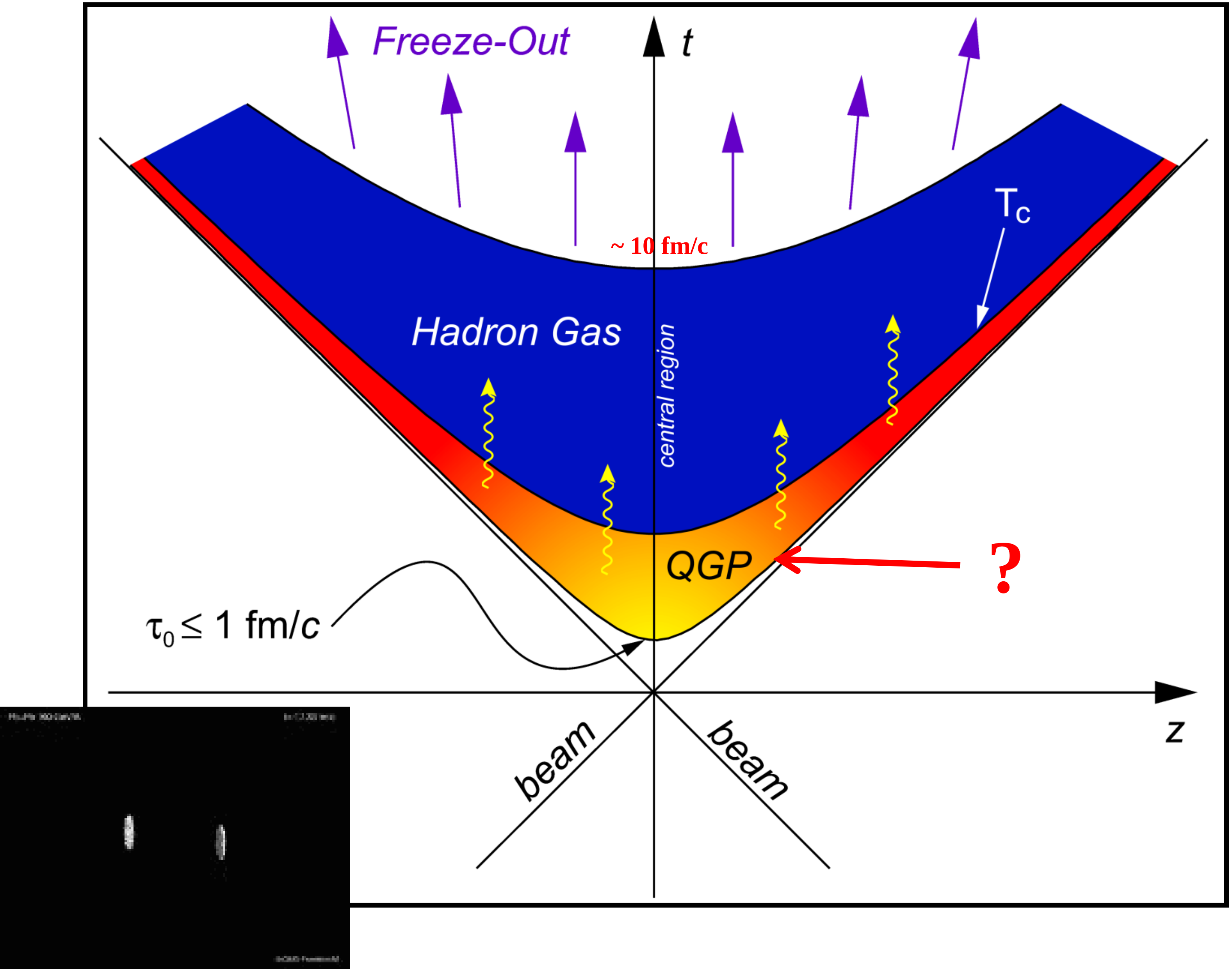
Private Viewpoint

G. Musulmanbekov

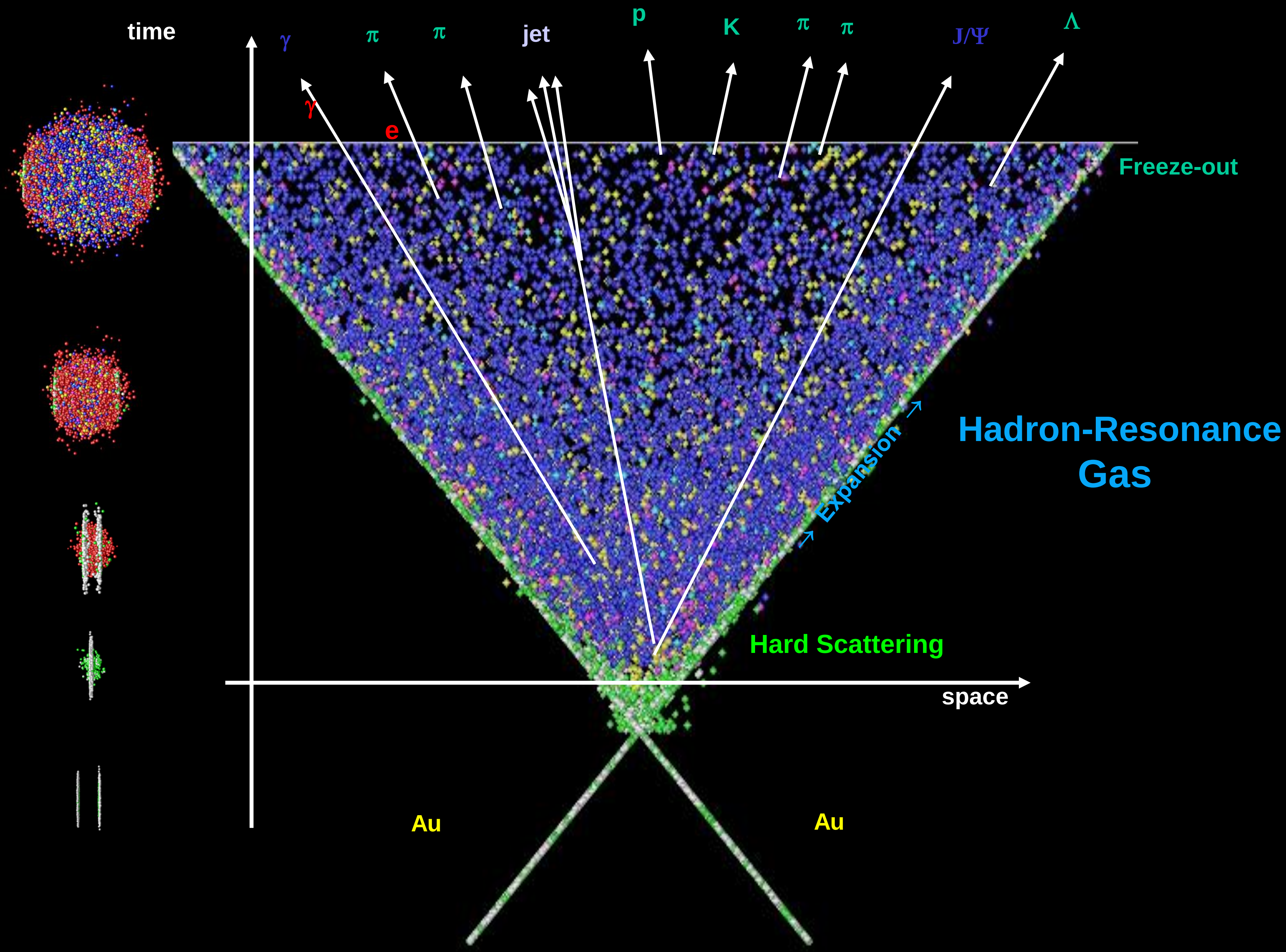
Does Phase Transition take place in central Heavy Ion Collisions?

Which one of the following scenario is realized?

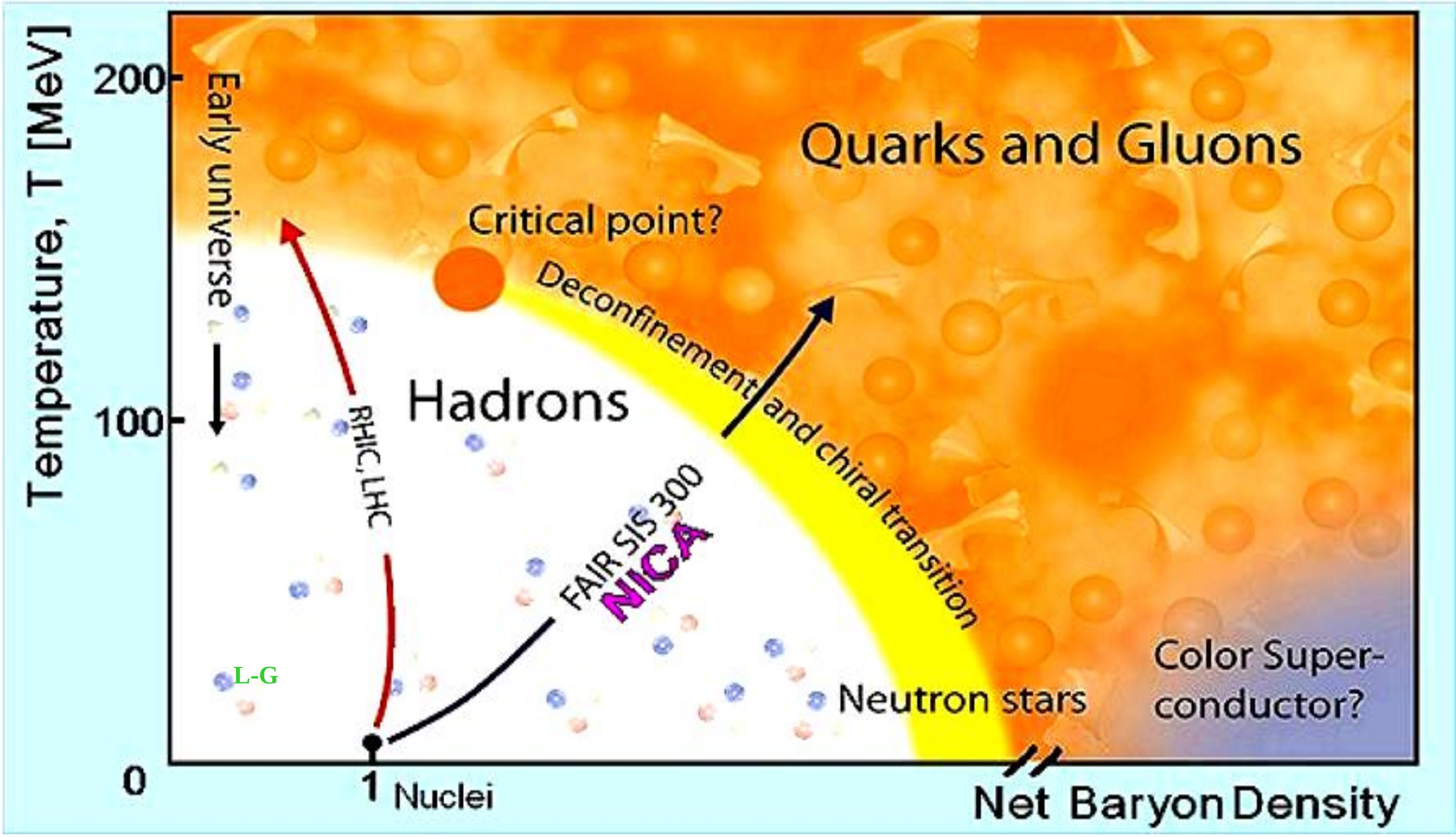
The ‘Little Bang’ in the Laboratory



Space-time Evolution of Collisions

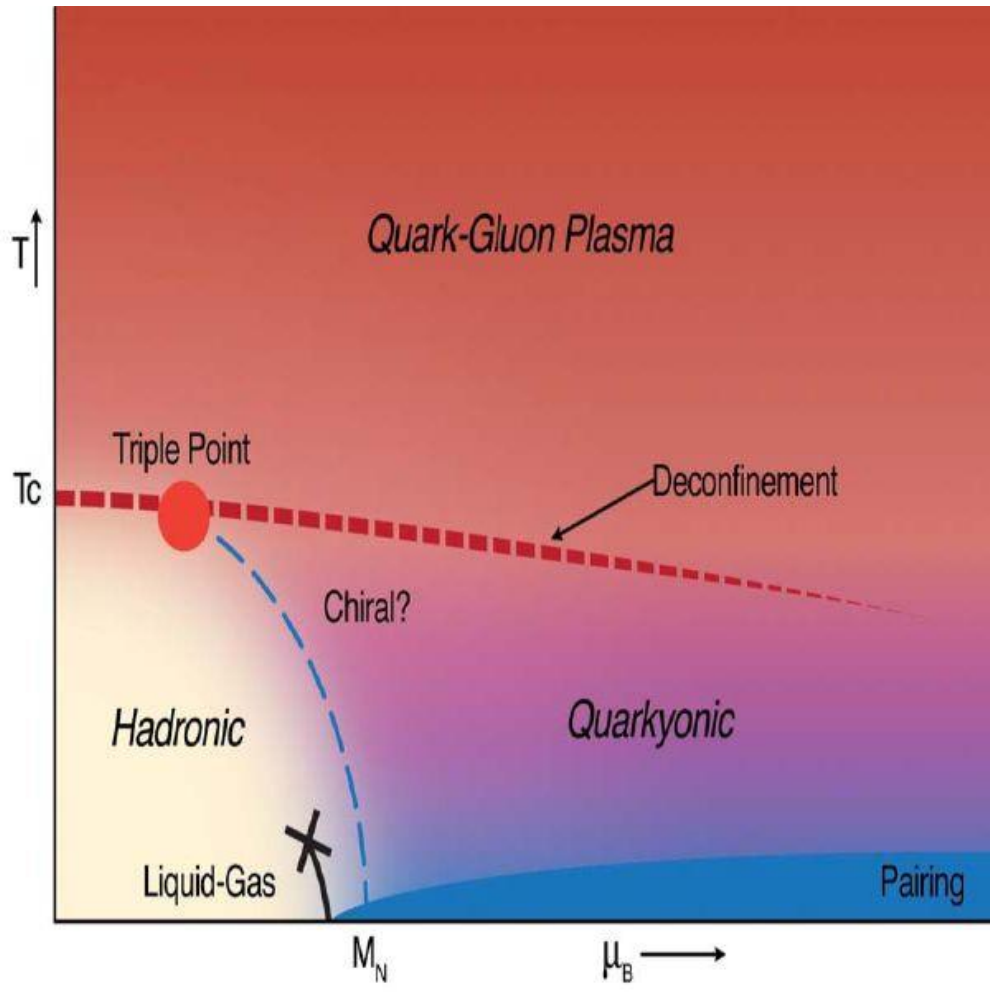


Phase diagram – artist's view



Phases of strongly interacting nuclear matter

Phase diagram with triple critical point



What are we searching for?

- Signatures of phase transition and/or mixed phase

- QCD critical (triple)endpoint

- Onset of chiral symmetry restoration at high ρ_B

- The equation-of-state at high ρ_B

Observables

Signatures of phase transition and/or mixed phase

- excitation function of particle yields and ratios (π, K, Λ, Σ, Ξ, Ω)
- transverse mass spectra of kaon
- particle correlations

QCD critical endpoint

- excitation function of event-by-event fluctuations (multiplicities, K/π, transverse momenta, …)

Onset of chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons (ρ, ω, $\varphi \rightarrow e^+e^-(\mu^+\mu^-)$)

The equation-of-state at high ρ_B

- collective flow of hadrons
- particle production at threshold

Available NICA energy range $\sqrt{s}$ = 4 – 11 GeV

What have been observed at AGS, SPS and BES RHIC ?

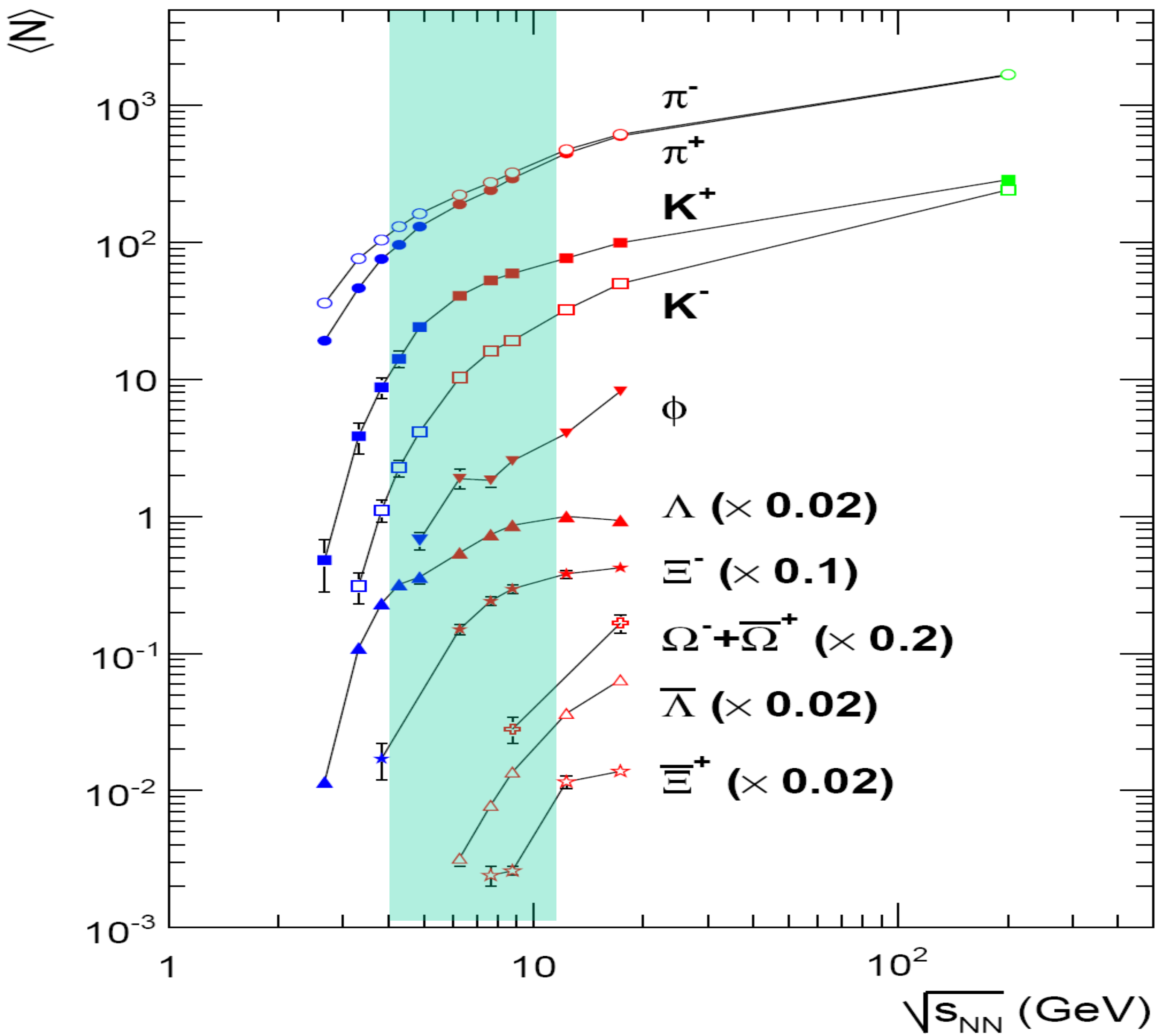
Signatures of phase transition and/or mixed phase?

- **excitation function of particle yields and ratios (π, K, Λ, Σ, Ξ, Ω)?**
- **transverse mass spectra of kaon**
- **fluctuations**
- **HBT correlations**

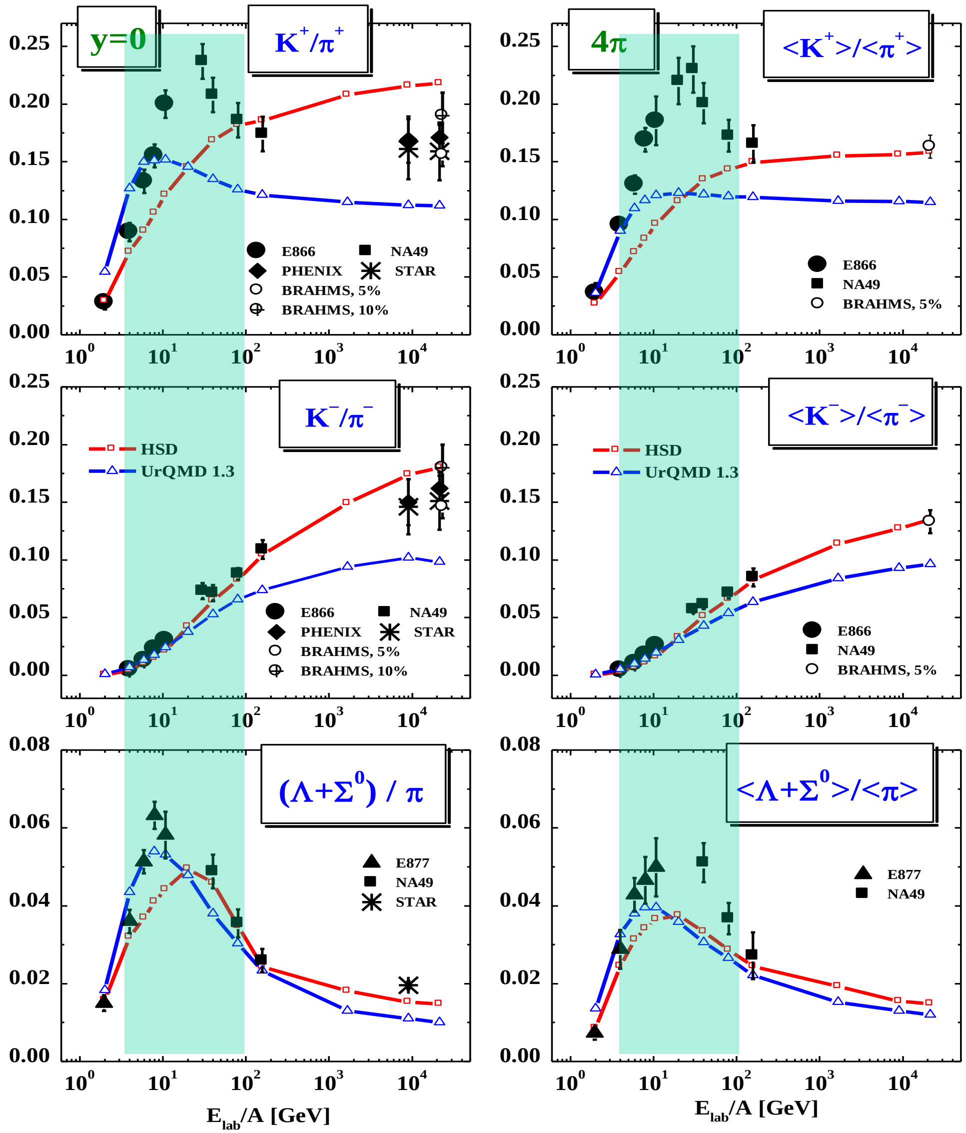
Onset of chiral symmetry restoration at high ρ_B ?

- **in-medium modifications of hadrons (ρ, ω, φ → e+e-(μ+μ-))**

Particle Yield



NA49 K/π and Λ/π ratio in central Pb-Pb collisions

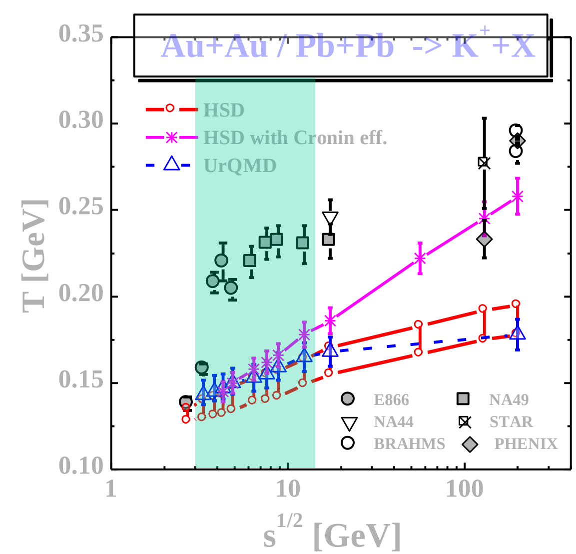


Clear evidence for horn structure in K+/pi+ and Lambda/pi+ ???

Non-horn structure in K-/pi-

Transport models fail to describe experimental data

Kink in Inverse Slope of Kaon Transverse Momentum Distributions



What do these effects tell about?

Particle Ratio Fluctuations

Theory expectations: Enhancement of fluctuations near CP

E-by-E Fluctuations, σ_{dyn}, ν_{dyn}, Ψ

- **NA49:** σ_{dyn}

$$\sigma_{\text{dyn}} = sign\left(\sigma^2_{\text{data}} - \sigma^2_{\text{mixed}}\right)\sqrt{\left|\sigma^2_{\text{data}} - \sigma^2_{\text{mixed}}\right|}$$

σ is relative width of K/π distribution

- **STAR:** ν_{dyn}

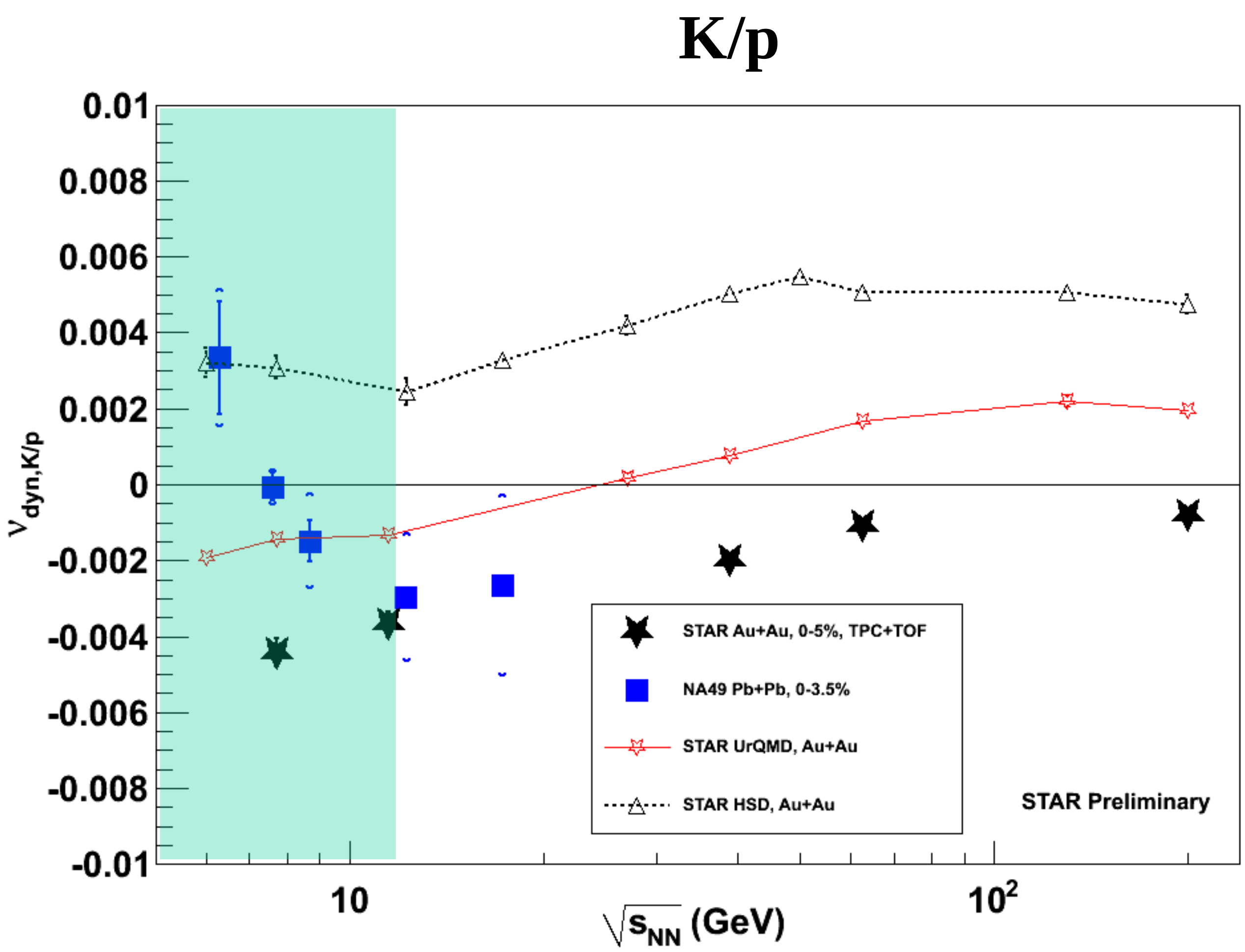
$$\nu_{\text{dyn},K\pi} = \frac{\left\langle N_K\left(N_K-1\right)\right\rangle}{\left\langle N_K\right\rangle^2} + \frac{\left\langle N_\pi\left(N_\pi-1\right)\right\rangle}{\left\langle N_\pi\right\rangle^2} - 2\frac{\left\langle N_K N_\pi\right\rangle}{\left\langle N_K\right\rangle\left\langle N_\pi\right\rangle}$$

$$\boxed{\sigma^2_{dyn} \approx \nu_{dyn}}$$

- **NA49/61: chemical 'identity'**

$$\boxed{\Psi_{w_h} = \frac{<Z^2>}{<N>} - \overline{z^2}} \qquad Z = \sum_{i=1}^{n}(w_{hi} - \overline{w_h}), \quad z = w_{hi} - \overline{w_h}, \quad \overline{w_h} = \frac{N_h}{N}$$

Excitation Function for σ_{dyn}, ν_{dyn}

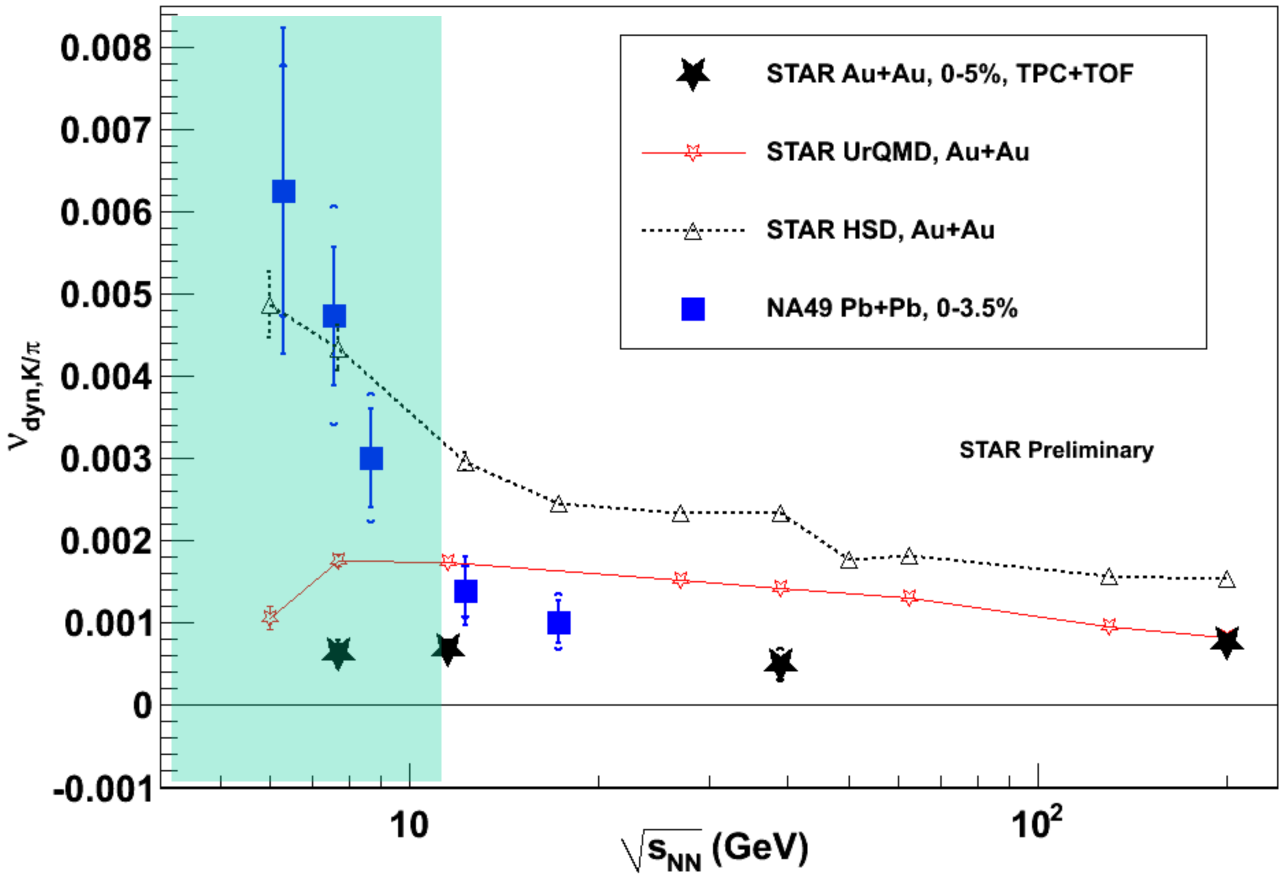


Large deviation between STAR and NA49 result at √sNN = 7.7 GeV.

No unusual enhancement of fluctuations are observed !

Excitation Function for σ_{dyn}, ν_{dyn}

K/π



Difference between STAR and NA49 result below $\sqrt{s_{NN}}$ = 11.5 GeV.

(NA49 data from C. Alt et al. [NA49 Collab.], Phys. Rev. C 79, 044910 (2009)

Both models show little acceptance effects.

UrQMD predicts little energy dependence.

HSD predicts an energy dependence.

Differences could be due to difference in acceptance and/or PID selections --- under discussion

No unusual enhancement of fluctuations are observed !

Higher Moments of Conserved Quantities

Theory: **Quark number density fluctuations will diverge at the critical end point**

Experimental observation:

- **Baryon number fluctuations**
- **Charge number fluctuations**

(Skewness and kurtosis of net-baryons, net-protons and net-charge)

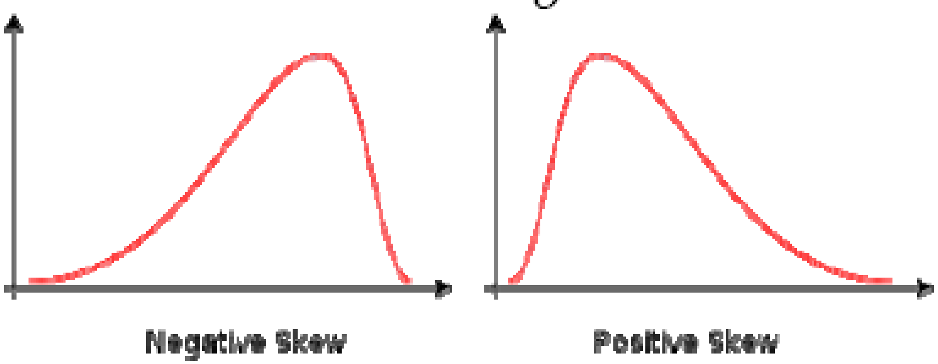
Skewness and Kurtosis

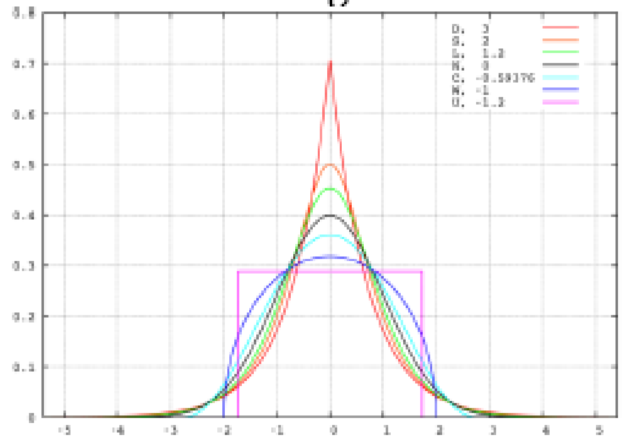
Mean: $Y = \langle N \rangle$

St. Deviation: $\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$

Skewness: $$S = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$$

Kurtosis: $$\kappa = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$$





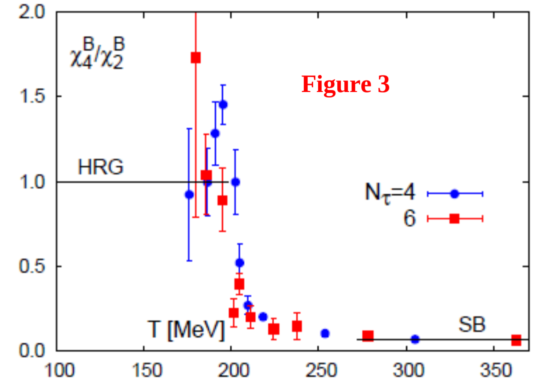
- Skewness describes the asymmetry of the distribution
- Kurtosis describes the peakness of the distribution
- Equal to zero for Gaussian distribution
- Ideal probes for non-Gaussian fluctuations

motivation

M.Cheng et al. arXiv: 0811.1006 v3 [hep-lat]
M.Cheng et al.Phys. Rev. D 79, 074505 (2009)

$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2\rangle$$

$$\chi_4^X = \frac{1}{VT^3}\left(\langle N_X^4\rangle - 3\langle N_X^2\rangle^2\right)$$



in all cases the quadratic(2nd order) fluctuations rise rapidly in the transition region and approach to SB limit where the quartic(4th order) fluctuations show a maximum.

This maximum is most pronounced for the baryon number fluctuations.

☞ ***The measurement of higher order cumulants of net-baryon distribution and its variations will provide the connection between experimental observable and Lattice Gauge Theory calculations.***

Higher moments of net-proton distribution are related to thermodynamic susceptibilities.

1st moment: **mean = M**

2nd moment: **variance = σ^2**

3rd standardized moment: **skewness = S**

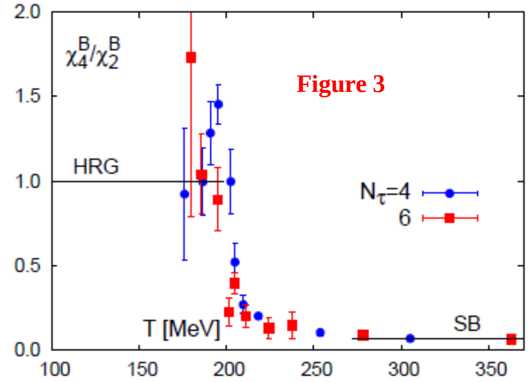
4th standardized moment: **kurtosis = κ**

– $(S\sigma)_B = \chi_B^3 / \chi_B^2$

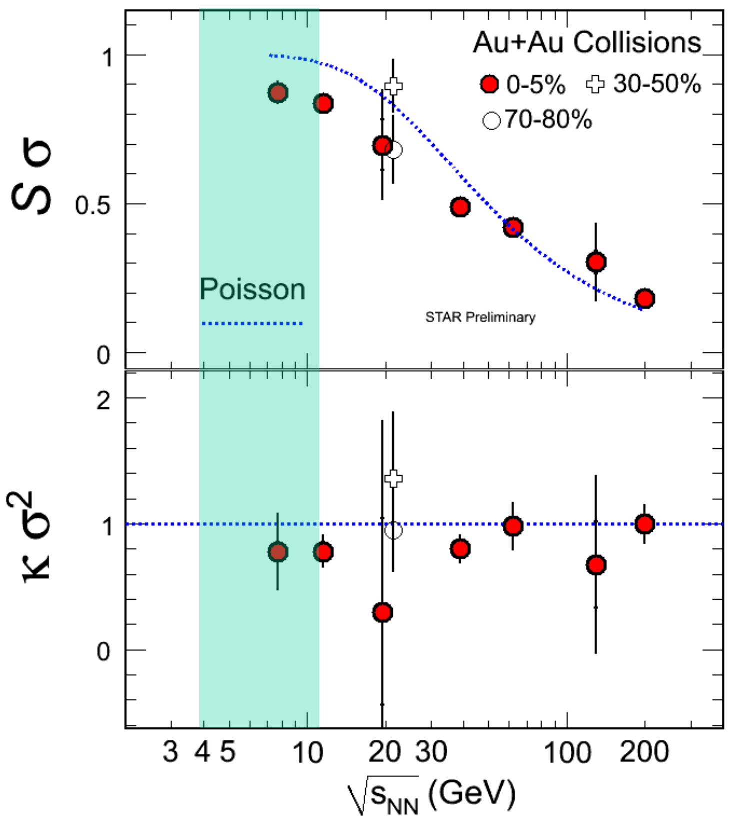
– $(\kappa\sigma^2)_B = \chi_B^4 / \chi_B^2$

No any irregularities was observed!

QCD Lattice predictions



Experiment

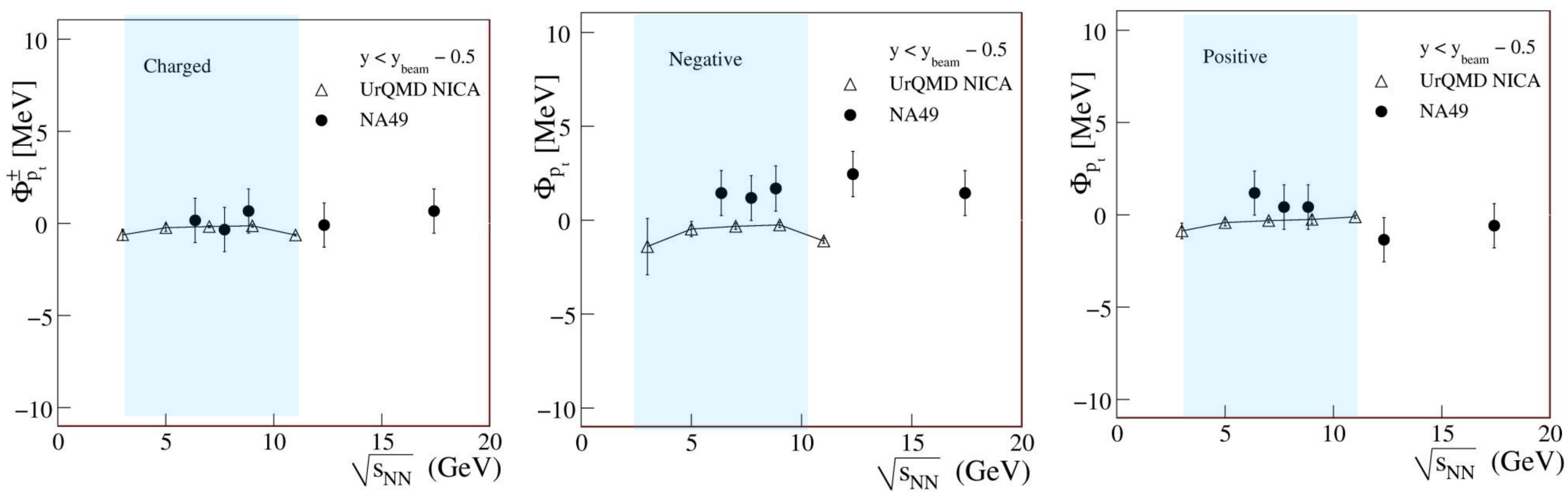


Event-by-event fluctuations

Transverse Momentum

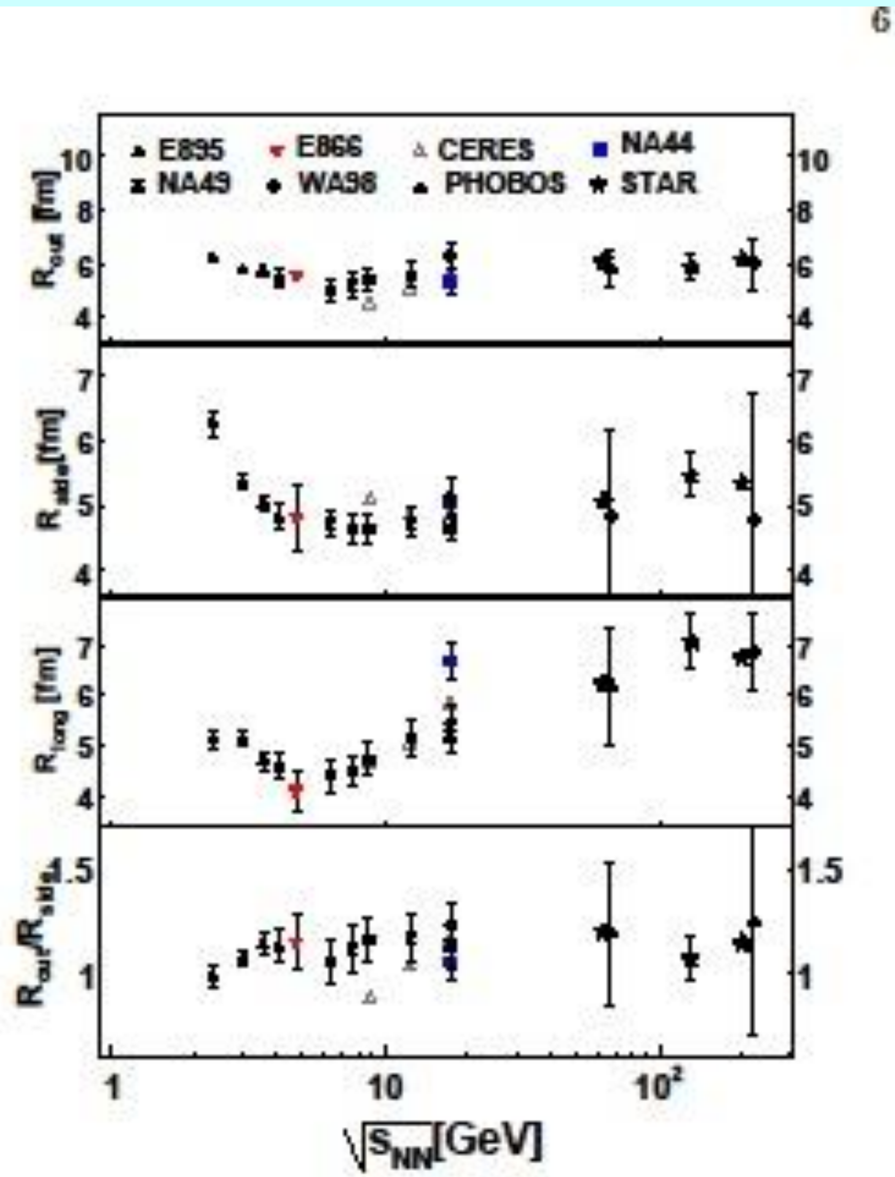
Event mixing for the statistical background estimation:

$$\Phi_{p_T} = \sqrt{\frac{< Z^2_{p_T} >}{< N >}} - \sqrt{\overline{z^2_{p_T}}}, \quad \textbf{where} \quad Z_{p_T} = \sum_{i=1}^{N} (p_{Ti} - \overline{p_T}), \quad z_{p_T} = p_T - \overline{p_T}$$



For the system of independently emitted particles fluctuation Φ_{pt} goes to zero (no particle correlations).

HBT identical particle correlations



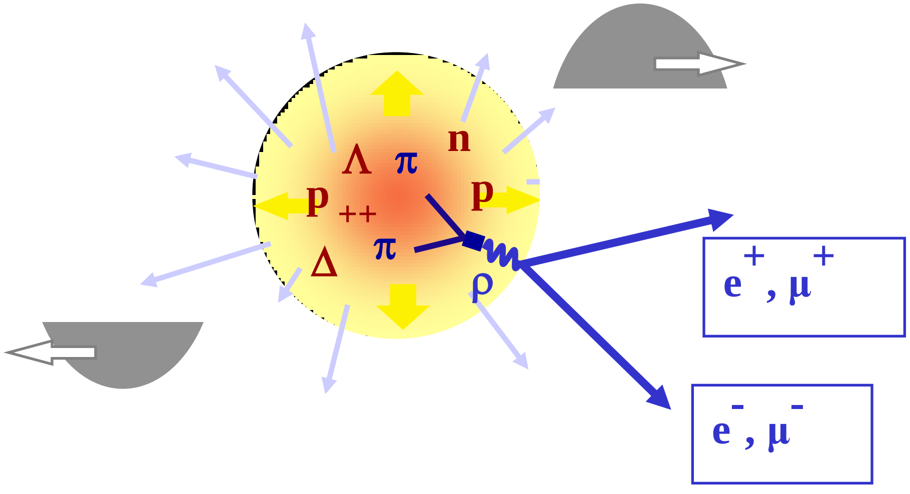
Increase of the lifetime ⇒ Softenning of the equation of state due to phase transition?!

but

$R_{out}/ R_{side} \approx 1$

Dileptons Yield

Dileptons are an ideal probe for vector meson spectroscopy in the nuclear medium and for the nuclear dynamics !

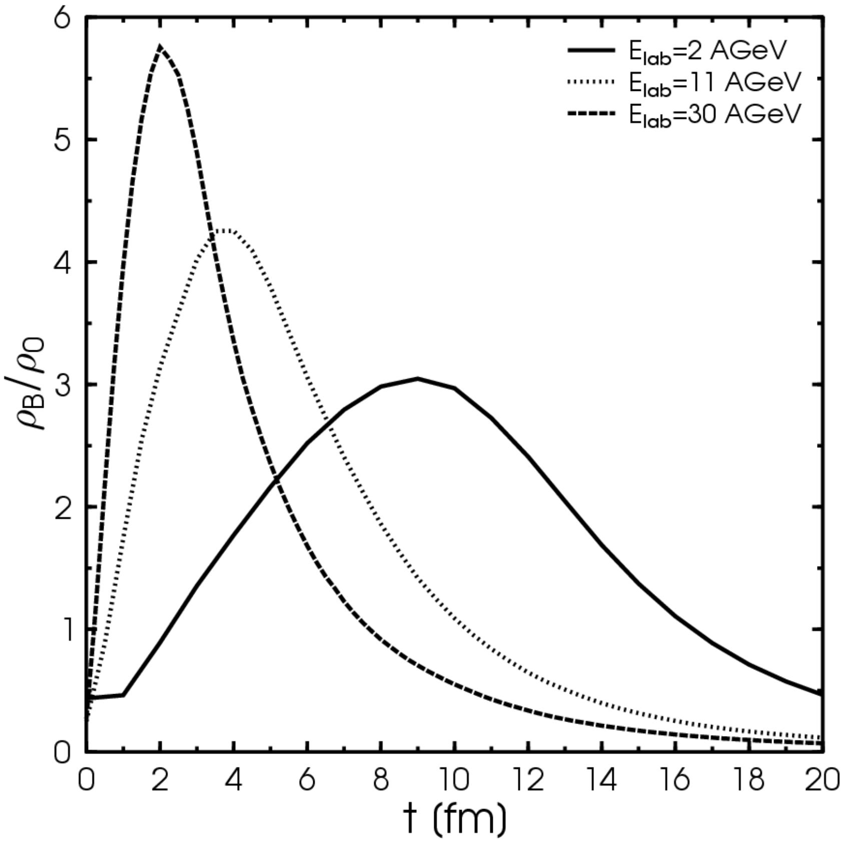


no measurements between
2-40 AGeV beam energy yet!

Physics Motivation

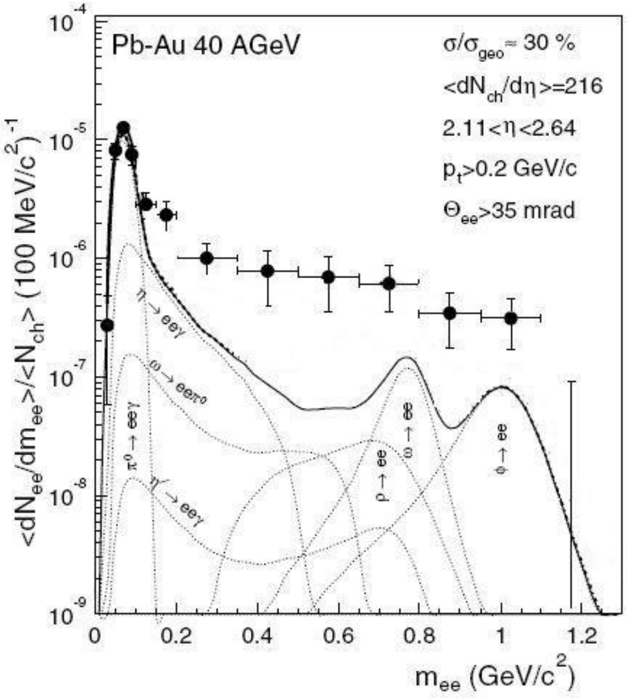
- Are we able to observe unambiguous signals from the most compressed region of the system?
- in-medium modifications of hadrons [$\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$]

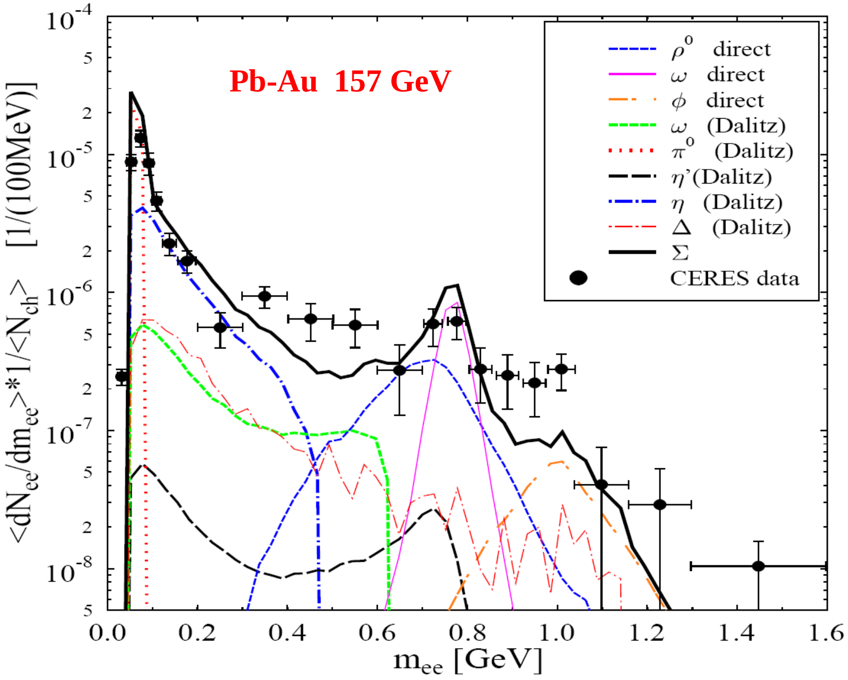
Central Au+Au/Pb+Pb collisions



CERES

Are resonances dissolved/broadened/shifted in dense hadronic matter ?





Two theory scenarios considered so far:

dropping ρ mass (Brown-Rho)

and

broadening of the ρ spectral function (Rapp-Wambach)

Modelling of in-medium spectral functions for vector mesons

In-medium scenarios:

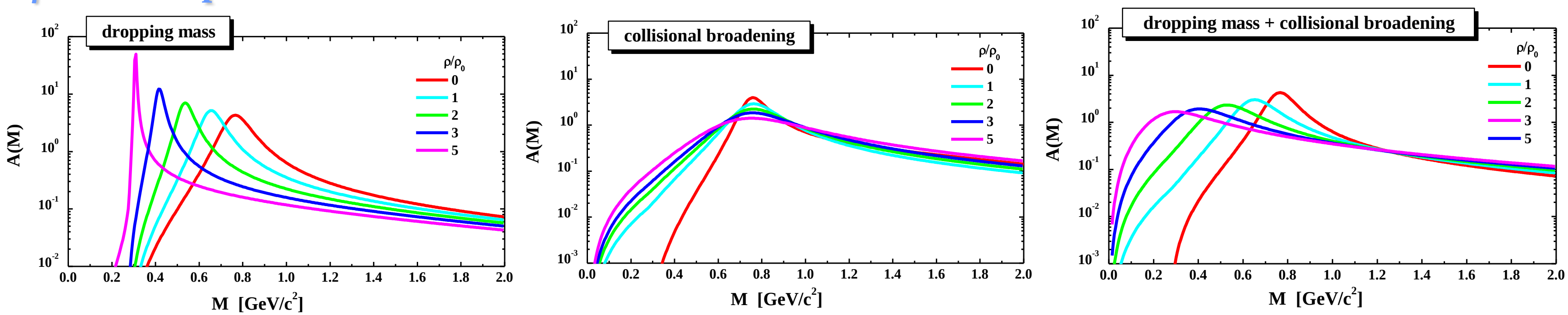
dropping mass — $m^* = m_0(1 - \alpha\, \rho/\rho_0)$

collisional broadening — $\Gamma(M,\rho) = \Gamma_{vac}(M) + \Gamma_{CB}(M,\rho)$

dropping mass + coll. broad. — m^* & $\Gamma_{CB}(M,\rho)$

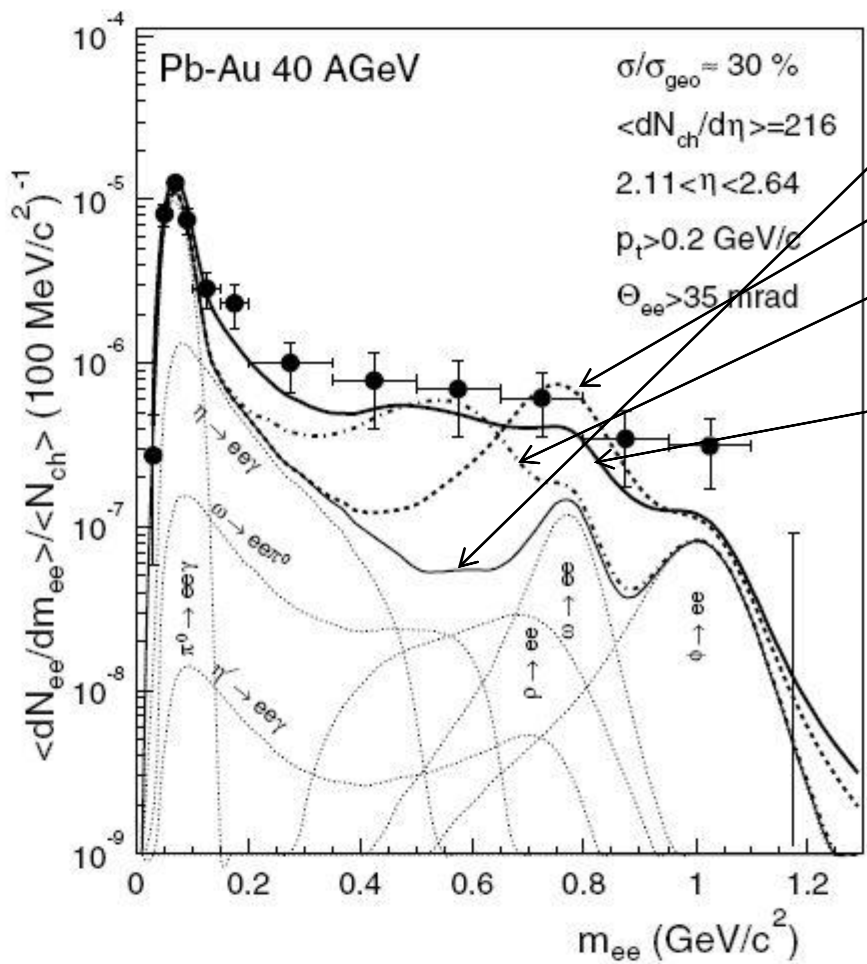
Collisional width $\Gamma_{CB}(M,\rho) \sim \gamma\, \rho\, \sigma_{VN}^{tot}$

ρ–meson spectral function:



- **Note:** for a consistent off-shell transport one needs not only in-medium spectral functions but also in-medium transition rates for all channels with vector mesons, i.e. the full knowledge of the in-medium off-shell cross sections $\sigma(s,\rho)$

E.L.B., NPA 686 (2001), E.L.B. &W. Cassing, NPA 807 (2008) 214



Hadronic Cocktail

+

$\pi+\pi \rightarrow \rho \rightarrow e^+ + e^-$

+

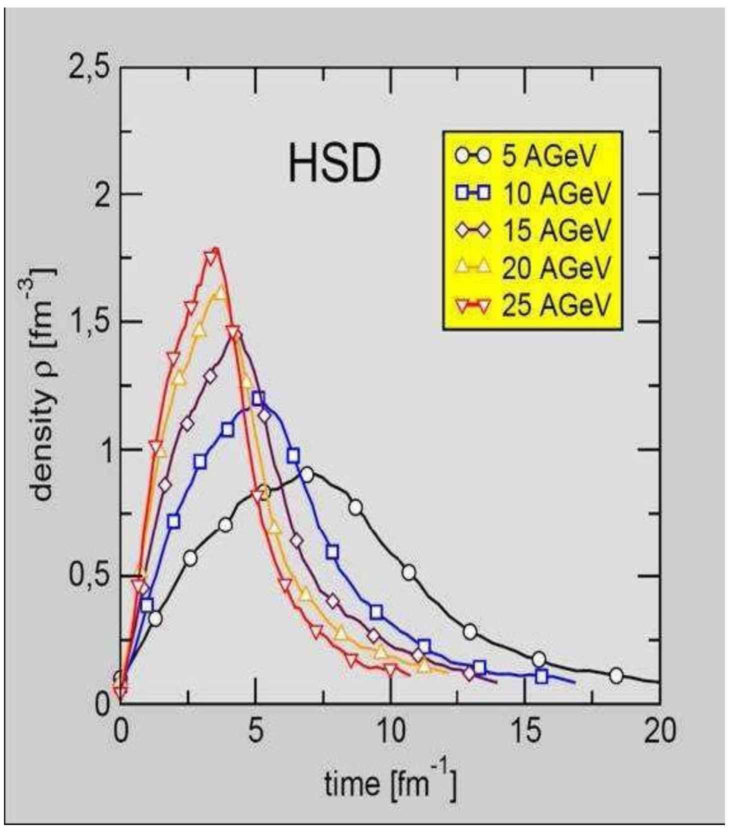
in-medium ρ – mass drop (B-R scaling)

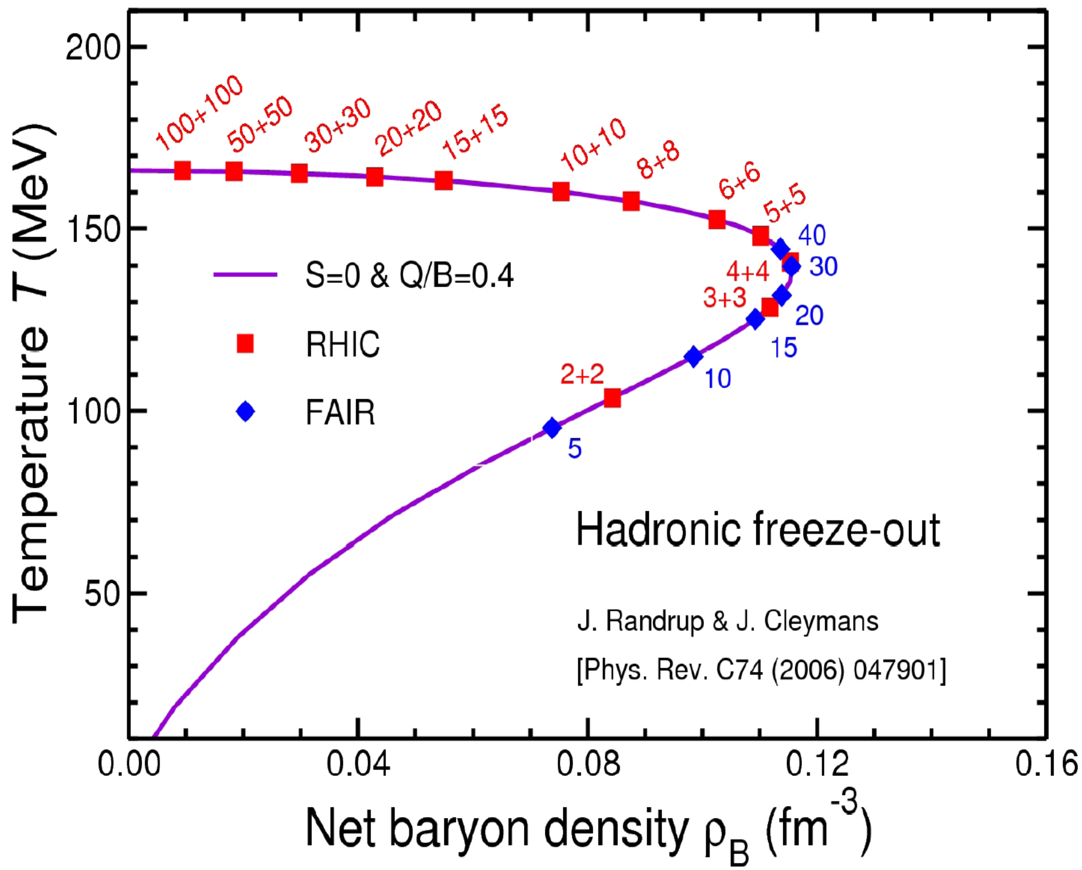
+

in-medium ρ – width spread

FAIR–NICA Energy Range

- the evolution time of the interacting system nearly coinsides with duration of colliding nuclei ovelapping → maximal net baryon density at freeze-out





FAIR–NICA Energy Range

Are there any unusual and evident effects measured in the experiments in this energy range?
Yes, – “Horn” and “Kink” effects!

Are them a manifestation of phase transition from HP to QGP?
Not likely!

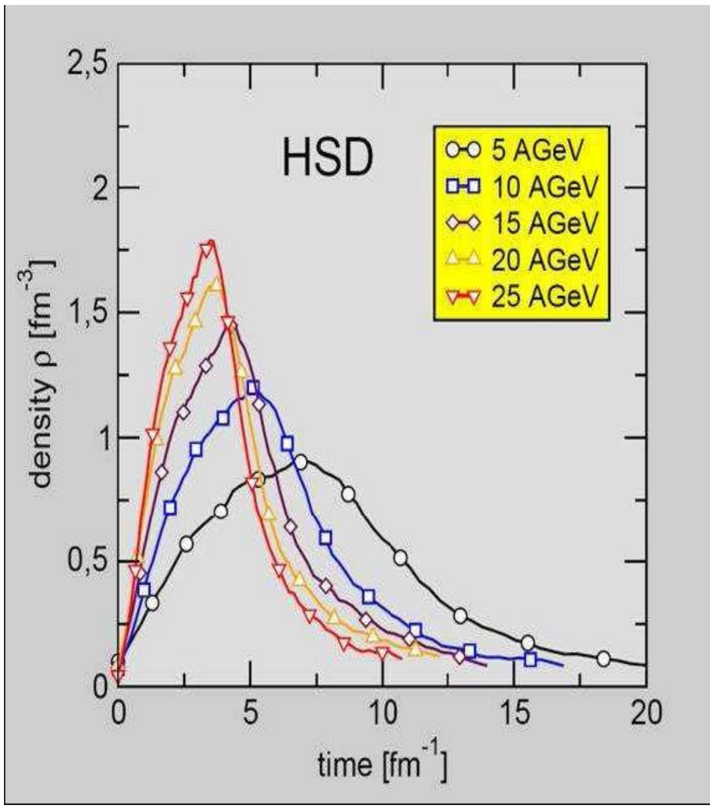
Then of what?

How nucleons behave under high compression and do they change their properties?
Nucleons transit to hypronic states!

Central HIC

Baryon density evolution

At NICA energies $\rho/\rho_0 \sim 5 - 10$

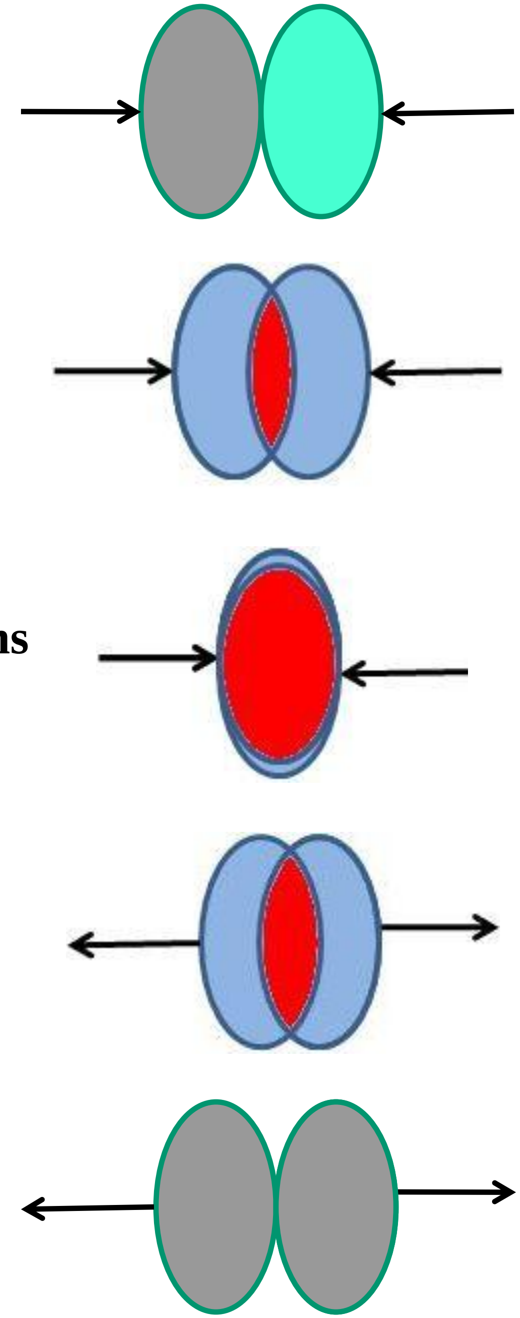


- **At NICA energies $\rho/\rho0 \sim 5 – 10$.**

- **In overlap region nucleons are suppressed and forced to occupy much less space volume.**

- **Overlap time:**

$$\tau_O = 2R_A/(\gamma v)$$



Nucleon Transformation into Hyperons

How do nucleons transform into hyperons?

If:

Under high suppression inside nuclear matter the strange quark-antiquark condensate is created.

And:

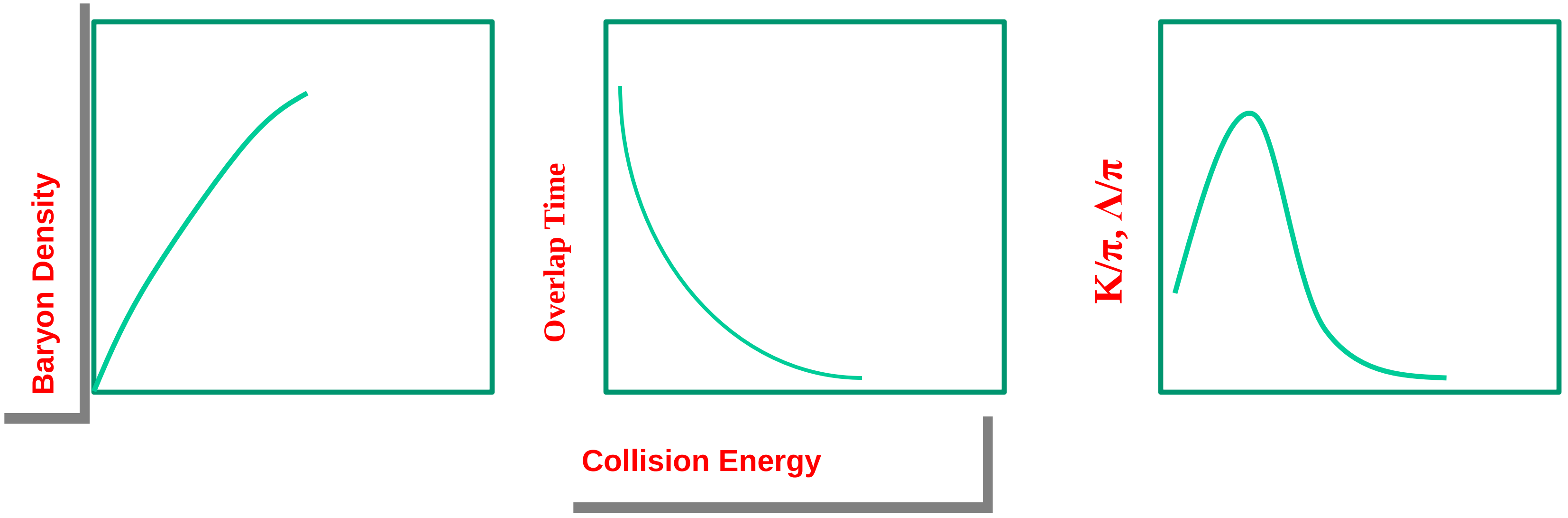
- ***u*** **and** ***d*** **quarks in nucleons are replaced by** ***s*** **quarks and antiquarks binding with the formes form kaons:**

  p, n → hyperons + kaons

- **the heavier quark content of a baryon, the less spatial dimensions it occupies**

Enchancment Mechanism in HIC

K/π and Λ/π ratio



Mechanisms of Strangeness Enchancment

- **Nucleons transformation to hyperons**

$$\sim (\tau_O / \tau_{re})\, f(\rho)$$

τ_O - overlap time

τ_{re} - rearrangement time

- **Non-equilibrium kinetic mechanism**

$$\sim 1/\lambda_{int} \sim \rho\sigma_{hN}$$

λ - mean free path

σ_{hB} - hadron-baryon cross section

Proton Transformations channels

$$p = (uud), \quad u, d \to s$$

$$\left.\begin{aligned} p(uud) &\to \Sigma^+(uus) + K^0(d\bar{s}) \\ &\to \Sigma^0(uds) + K^+(u\bar{s}) \end{aligned}\right\} S = -1, 1$$

$$\left.\begin{aligned} &\to \Xi^-(dss) + 2K^+(u\bar{s}) \\ &\to \Xi^0(uss) + K^0(d\bar{s}) + K^+(u\bar{s}) \end{aligned}\right\} S = -2, 2$$

$$\to \Omega^-(sss) + 2K^+(u\bar{s}) + K^0(d\bar{s}) \quad \} S = -3, 3$$

Only K^+ and K^0 are produced

No one K^- is created!

Neutron Transformations channels

$$n(udd), \quad u, d \rightarrow s$$

$$\left.\begin{aligned} n(ddu) &\rightarrow \Sigma^{-}(dds) + K^{+}(u\bar{s}) \\ &\rightarrow \Sigma^{0}(uds) + K^{0}(d\bar{s}) \end{aligned}\right\} S = -1, 1$$

$$\left.\begin{aligned} &\rightarrow \Xi^{0}(uss) + 2K^{0}(d\bar{s}) \\ &\rightarrow \Xi^{-}(dss) + K^{0}(d\bar{s}) + K^{+}(u\bar{s}) \end{aligned}\right\} S = -2, 2$$

$$\rightarrow \Omega^{-}(sss) + 2K^{0}(d\bar{s}) + K^{+}(u\bar{s}) \quad \} S = -3, 3$$

Only K^{+} and K^{0} are produced
No one K^{-} is created!

Higher Collision Energies

$$\left.\begin{aligned} p(uud) &\to \Sigma^{+*}(uus) + K^{0*}(d\bar{s}) \\ &\to \Sigma^{0*}(uds) + K^{+*}(u\bar{s}) \end{aligned}\right\} S = -1, 1$$

$$\left.\begin{aligned} &\to \Xi^{-*}(dss) + 2K^{+*}(u\bar{s}) \\ &\to \Xi^{0*}(uss) + K^{0*}(d\bar{s}) + K^{+*}(u\bar{s}) \end{aligned}\right\} S = -2, 2$$

$$\to \Omega^{-}(sss) + 2K^{+*}(u\bar{s}) + K^{0*}(d\bar{s}) \quad \} S = -3, 3$$

$$K^{+*} \to K^{0} + \pi^{+}$$

$$K^{0*} \to K^{+} + \pi^{-}$$

Only K^{+} and K^{0} are produced

No one K^{-} is created!

Higher Collision Energies

$$\left.\begin{aligned} n(ddu) &\rightarrow \Sigma^{-*}(dds) + K^{+*}(u\bar{s}) \\ &\rightarrow \Sigma^{0*}(uds) + K^{0*}(d\bar{s}) \end{aligned}\right\} S = -1, 1$$

$$\left.\begin{aligned} &\rightarrow \Xi^{0*}(uss) + 2K^{0*}(d\bar{s}) \\ &\rightarrow \Xi^{-*}(dss) + K^{0*}(d\bar{s}) + K^{+*}(u\bar{s}) \end{aligned}\right\} S = -2, 2$$

$$\rightarrow \Omega^{-}(sss) + 2K^{0*}(d\bar{s}) + K^{+*}(u\bar{s}) \quad \} S = -3, 3$$

$$K^{+*} \rightarrow K^{0} + \pi^{+}$$

$$K^{0*} \rightarrow K^{+} + \pi^{-}$$

Only K^+ and K^0 are produced

No one K^- is created!

Hyperon Resonances Decay

$$\Sigma^{0*} \rightarrow \Lambda + \pi^0 \quad 88\%$$

$$\rightarrow \Sigma^0 + \pi^0 \quad 12\%$$

$$\Sigma^{+*} \rightarrow \Lambda + \pi^+ \quad 88\%$$

$$\rightarrow \Sigma^+ + \pi^0 \quad 12\%$$

$$\Xi^{0*} \rightarrow \Xi^0 + \pi^0$$

$$\Xi^{-*} \rightarrow \Xi^{-0}$$

$$\Omega^- \rightarrow \Lambda + K^- \quad 68\%$$

$$\rightarrow \Xi^0 + \pi^- \quad 24\%$$

$$\rightarrow \Xi^- + \pi^0 \quad 8\%$$

Stangeness Production in central HIC

AGS: Kinetic + Transition mechanisms

- Nucleons transform to Δ- isobars and hyperons + kaons

$(\tau_o/\tau_{re}) \sim 1,$

NICA, CBM, low SPS: Kinetic + Transition mechanisms

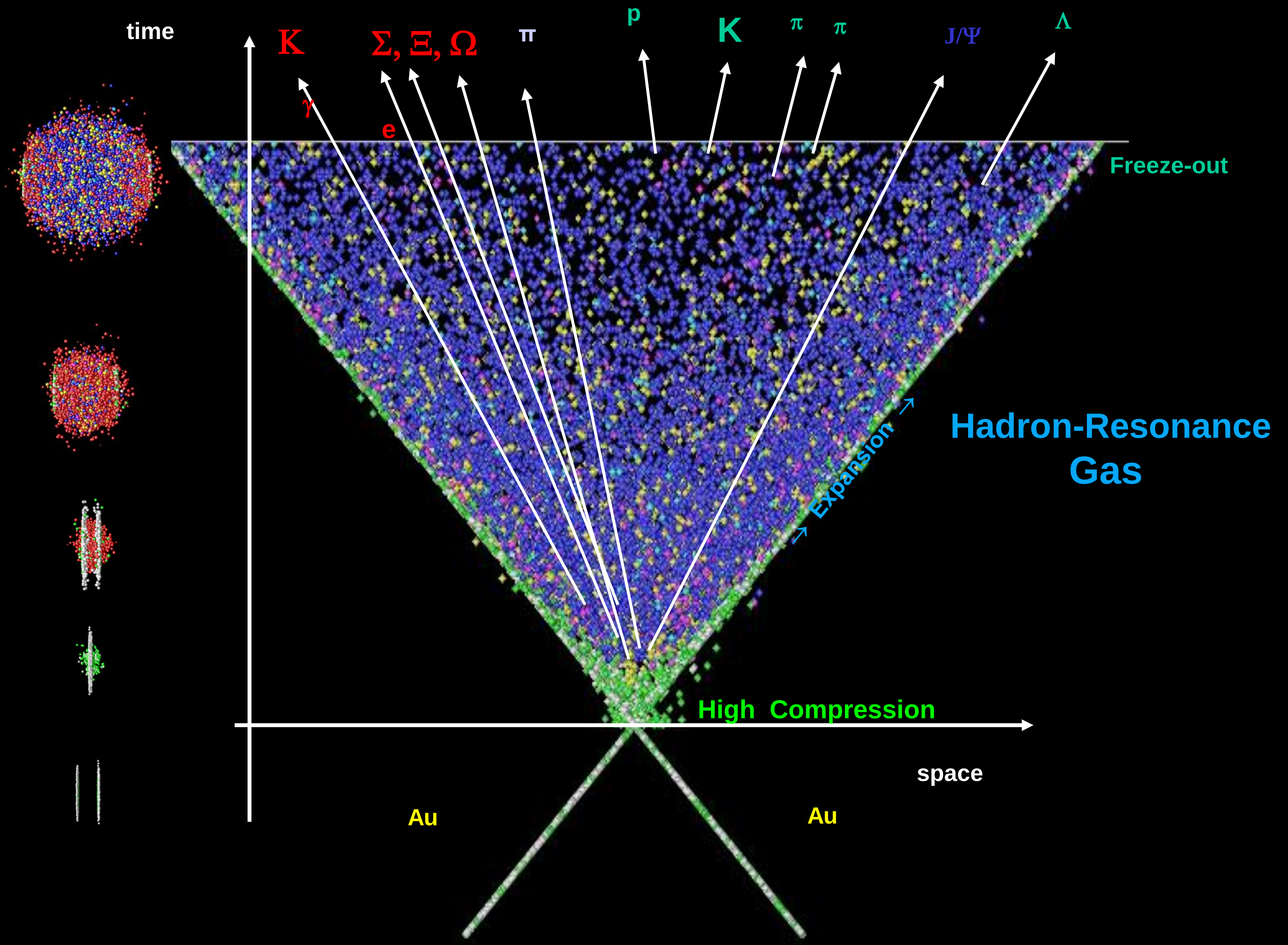
- Nucleons transform to (multi)strange hyperons + kaons

$(\tau_o/\tau_{re}) \leq 1$

RHIC, LHC: Kinetic mechanism

$(\tau_o/\tau_{re}) \ll 1$

Space-time Evolution of Collisions



What could be measured in FAIR-NICA energy region

- **Enhanced yield of positive and neutral kaons near threshold.**
- **Enhanced yield of one, double and triple strange baryons near threshould.**
- **Correlation of kaons with hyperons**
- **Elliptic and direct flows of hyperons**
- **Polarization of hyperons**

Neutron star

Gravitational suppression

…………

Nuclear matter

Δ- isobar matter

Hyperonic matter

Charmonic matter

Botonic matter

Toponic matter

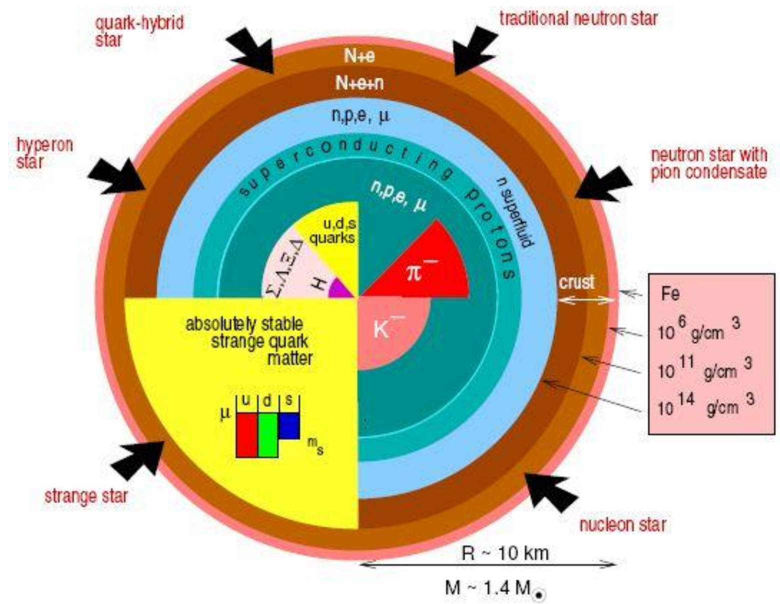
Gravitational suppression

…………

Nuclear matter

neutrons, hyperons ?

quarks?



Thank you for your attention!