LIGHT FLAVOR HADRONS & NUCLEI IN HEAVY-ION COLLISIONS

Vadim Kolesnikov

Joint Institute for Nuclear Research, Dubna, Russia

NICA days 2023

Belgrade, Serbia, October 02-03, 2023

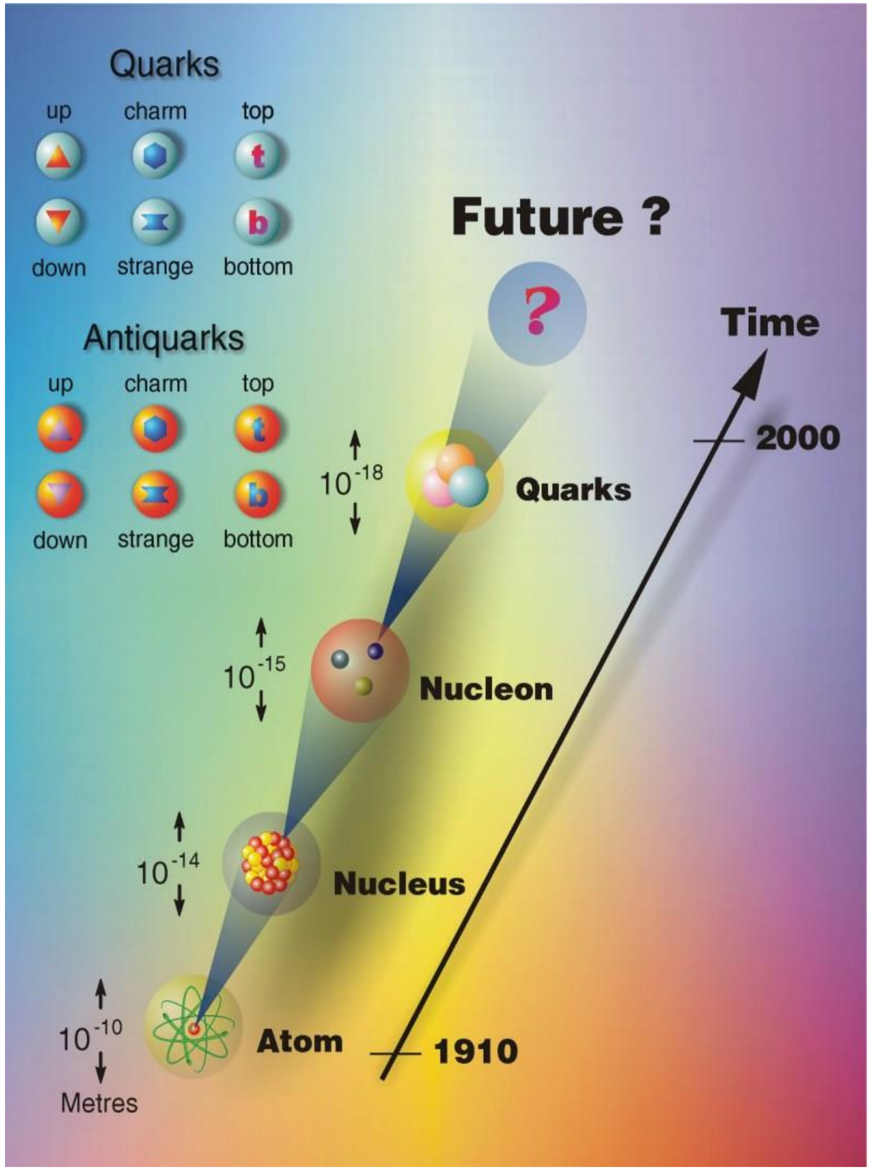
OUTLINE

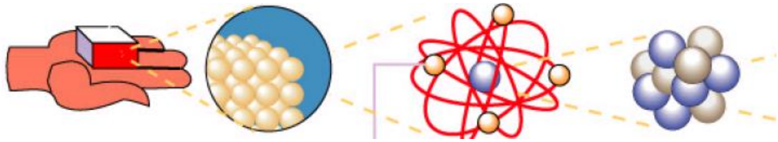
- Introduction about heavy-ion collisions and strongly interacting QCD matter
- The role of light flavor hadrons in the study of strongly interacting matter
  - Initial conditions estimates
  - QCD phase diagram mapping
  - Signals about phase transition and critical phenomena
- Light nuclei and hypernuclei from strongly interacting QCD medium
- Summary

NICA/MPD prospects for some selected probes will be discussed

I. Introduction

Heavy Ion Collision (HIC) – interaction between accelerated to high energies (relativistic) nuclei to study in the laboratory the structure of Matter, constituents, and forces between them





Typical scales and units in this study:

[L] : 0.1-10 fm, 1 fm = 10^{-15} m

[E] : 0.1-2000 GeV, 1eV = $1.6 \cdot 10^{-19}$ J

[β] : fractional velocity up to the speed of light ***c***

[t] : 1-100 fm/c, 1 fm/*c* = $3 \cdot 10^{-24}$ s

[ρ] = *M/V:* $A/(4/3\pi R^3)$ = **$2.3\ 10^{17}$** kg/m^3 for Au

[T] Temperature ~100 MeV = 10^{12} K

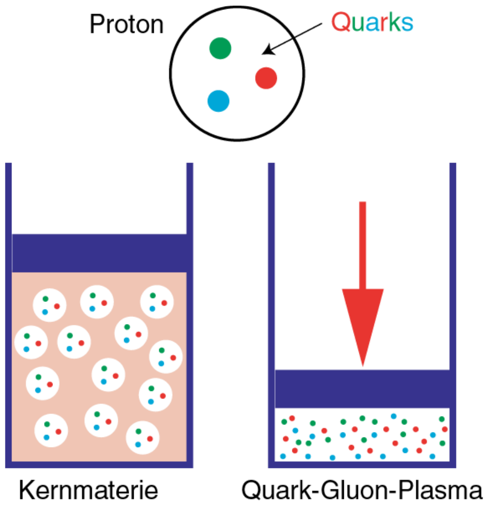
Matter under extreme conditions

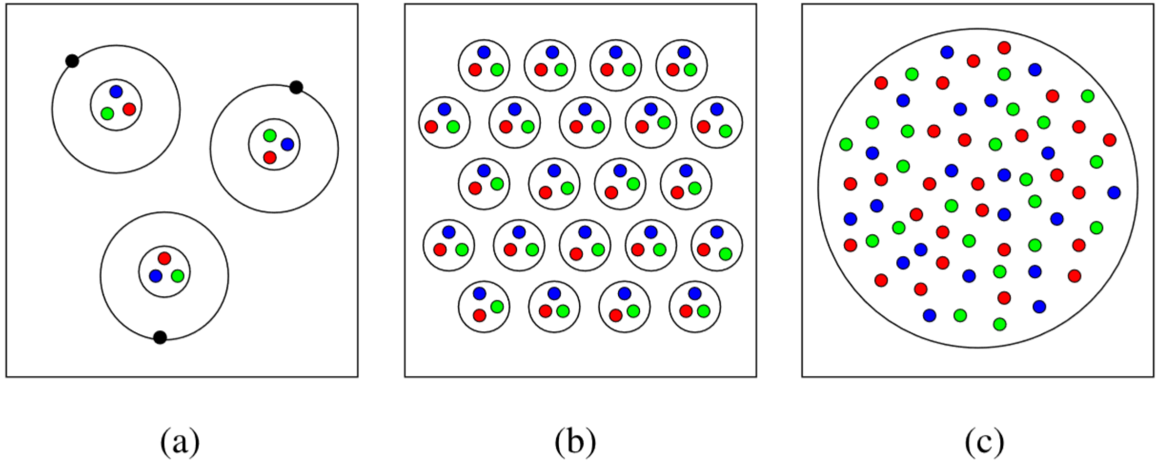
Main question : ***what are degrees of freedom in the state of Matter at exceedingly high density and temperature?***

solid → liquid → gas → plasma → nuclear matter (hadron gas) → QGP

NICA

Can we "melt" hadrons by compression or/and increasing energy density?





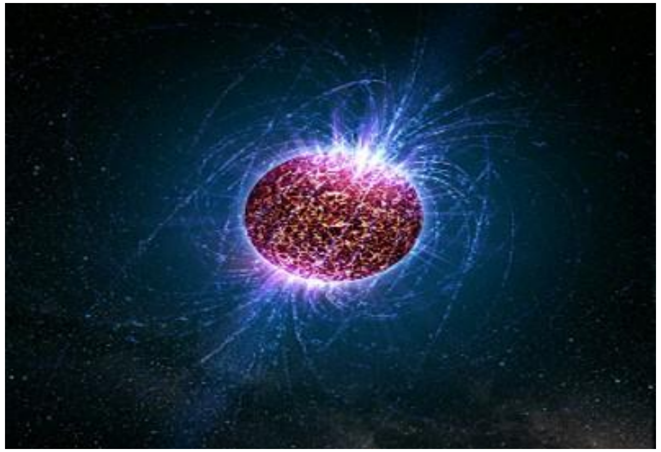
a) Ordinary matter (proton+electron=hydrogen); b) Nuclear natter – nucleus;
b) c) Quark-gluon matter

Bulk medium properties and its EOS are defined by interactions among degrees of freedom

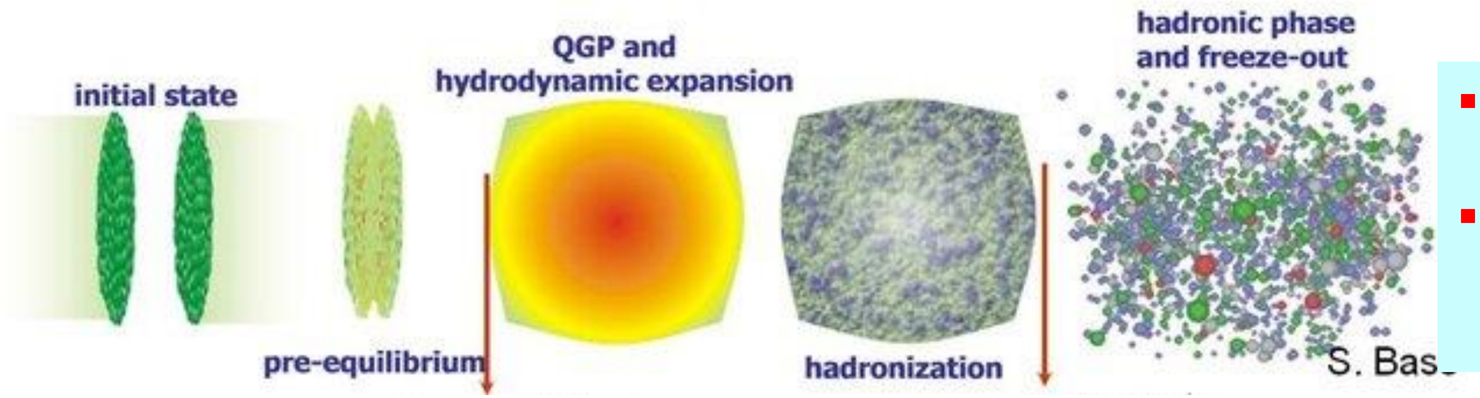
Where such extreme conditions of density and temperature can be achieved?

In the Early Universe

In Neutron Stars (NS)



In Heavy-Ion collisions (HIC)

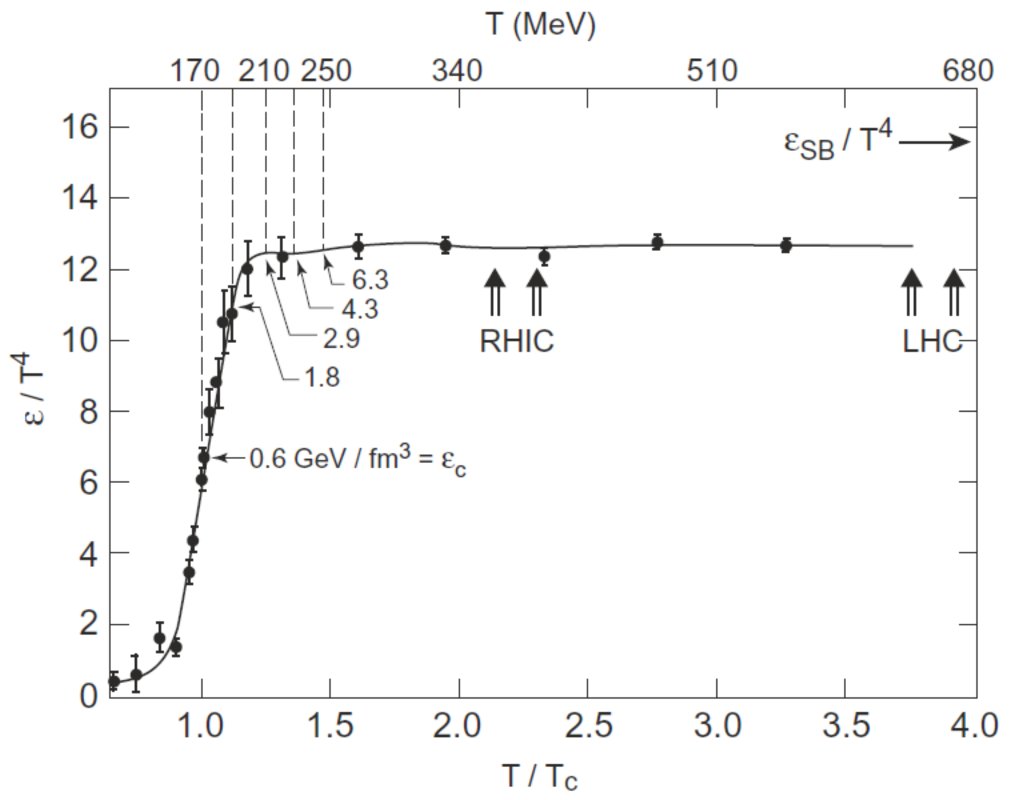


- *Huge amount of energy in a small volume!*
- *HIC not only address fundamental properties of Nature, but also has become a bridge between nuclear physics and astrophysics*

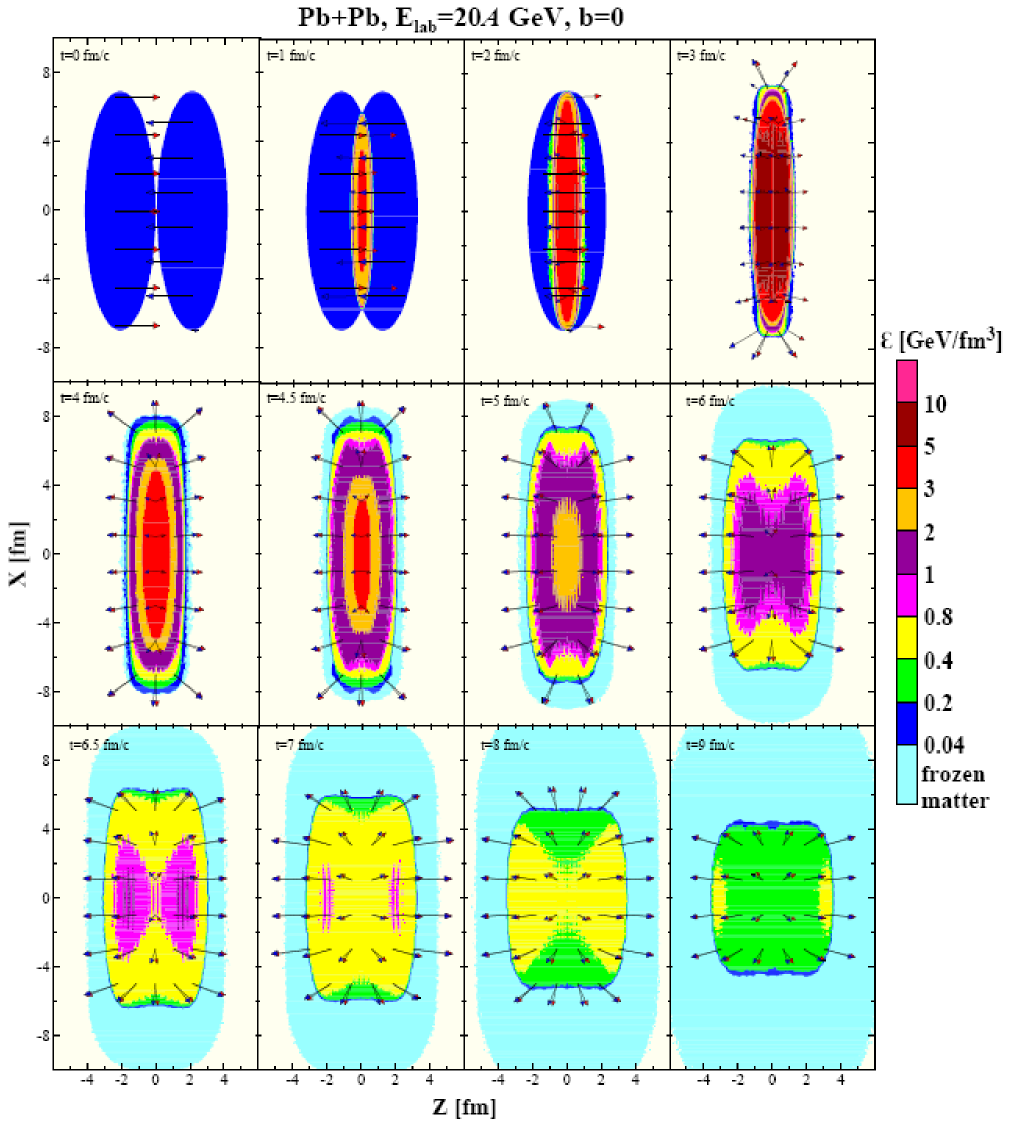
Deconfinement phase transition from hadron to quark-gluon *dof*

Theory predictions:

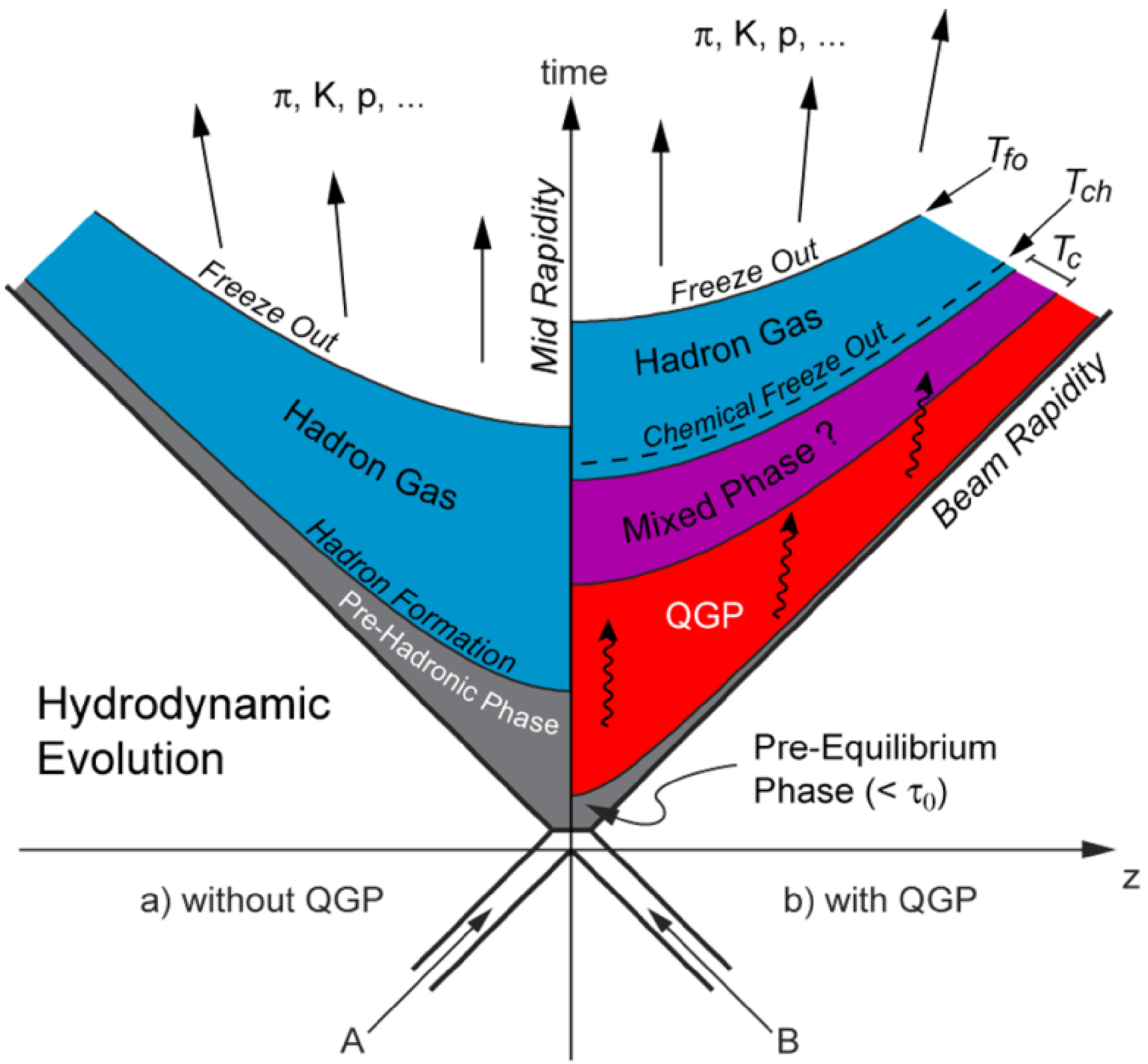
- Rapid increase of the degrees of freedom at:
  Tc = 160-170 MeV (can be higher in a finite size system)
  $\varepsilon \sim$ 0.6-1.0 GeV/fm^3
- Stefan-Boltzmann limit (for a non-interacting gas) is not reached by 20% for ε : QGP as a weak interacting gas?!

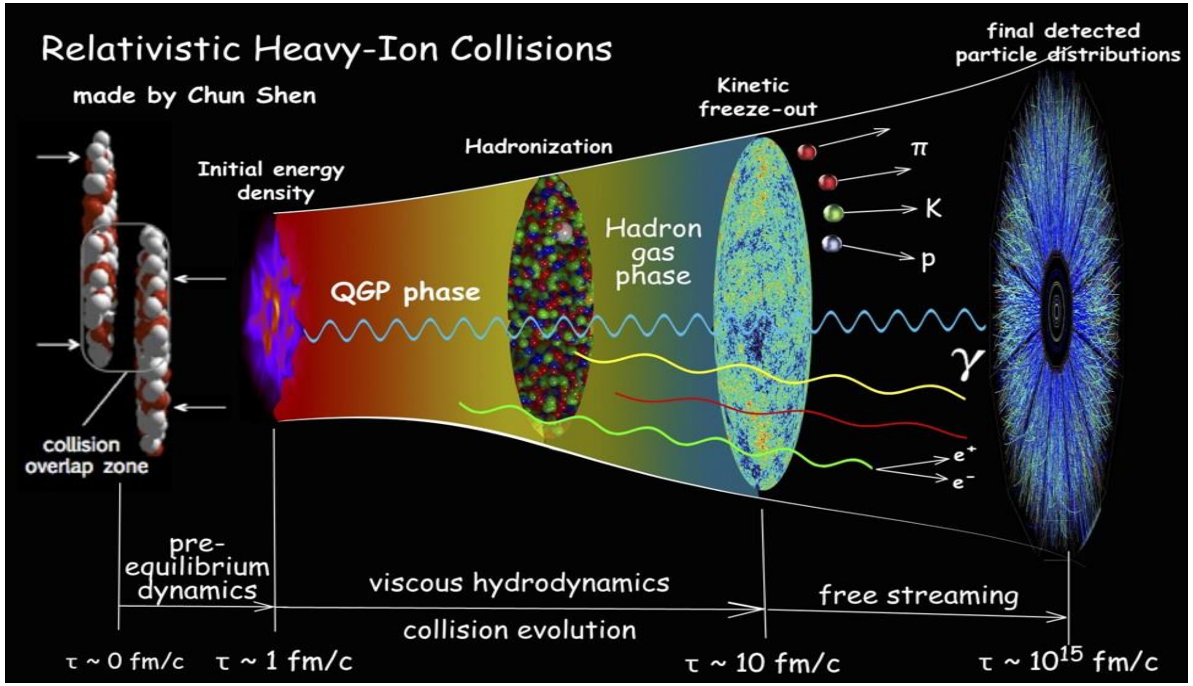


Model simulations : high energy density in the center of the interaction zone



Time evolution of an A+A collision





- A moment when particle abundances are fixed - ***chemical freezeout*** **(CFO)**

- A moment when particle's momentum distributions are fixed - ***kinetic freezeout t (FO)***

Hadrons, strongly interacting particles (mesons & baryons)

Specie for normal conditions

Particle	Mass (Gev/c2)	Quark composition	Q (units of e)	S	C	$\tilde{B}$
p	0.938	uud	1	0	0	0
n	0.940	udd	0	0	0	0
Λ	1.116	uds	0	-1	0	0
Λ_c	2.285	udc	1	0	1	0

Produced in collisions of particles or cosmic rays

Particle	Mass (Gev/c2)	Quark composition	Q (units of e)	S	C	$\tilde{B}$
π^+	0.140	$u\bar{d}$	1	0	0	0
K^-	0.494	$s\bar{u}$	-1	-1	0	0
D^-	1.869	$d\bar{c}$	-1	0	-1	0
D_s^+	1.969	$c\bar{s}$	1	1	1	0
B^-	5.279	$b\bar{u}$	-1	0	0	-1
Υ	9.460	$b\bar{b}$	0	0	0	0

Strange hadrons contain at least one strange (anti)quark s(sbar)

Strange particles produced in relativistic collisions

Example: $\pi^- + p \rightarrow K^0 + \Lambda$

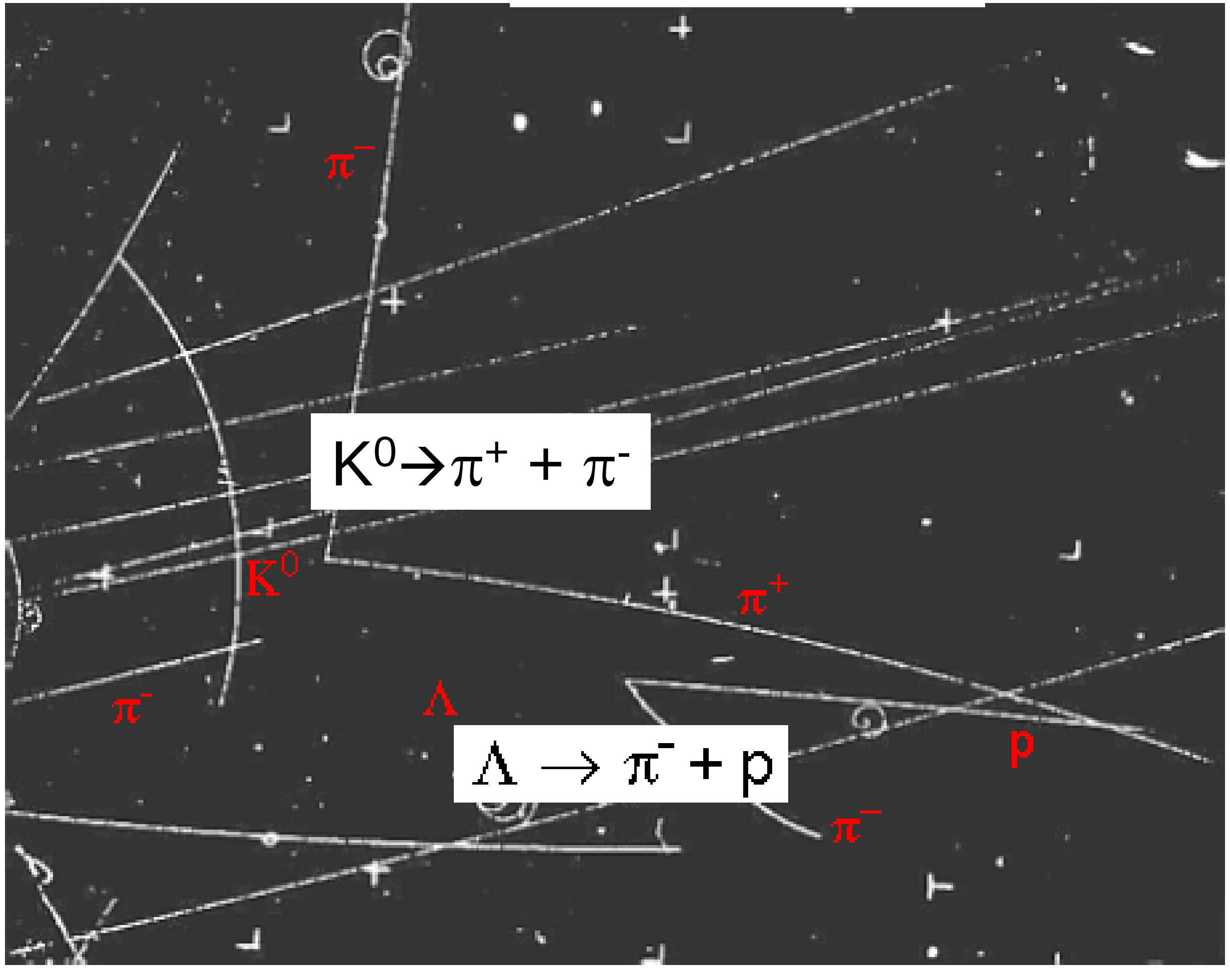


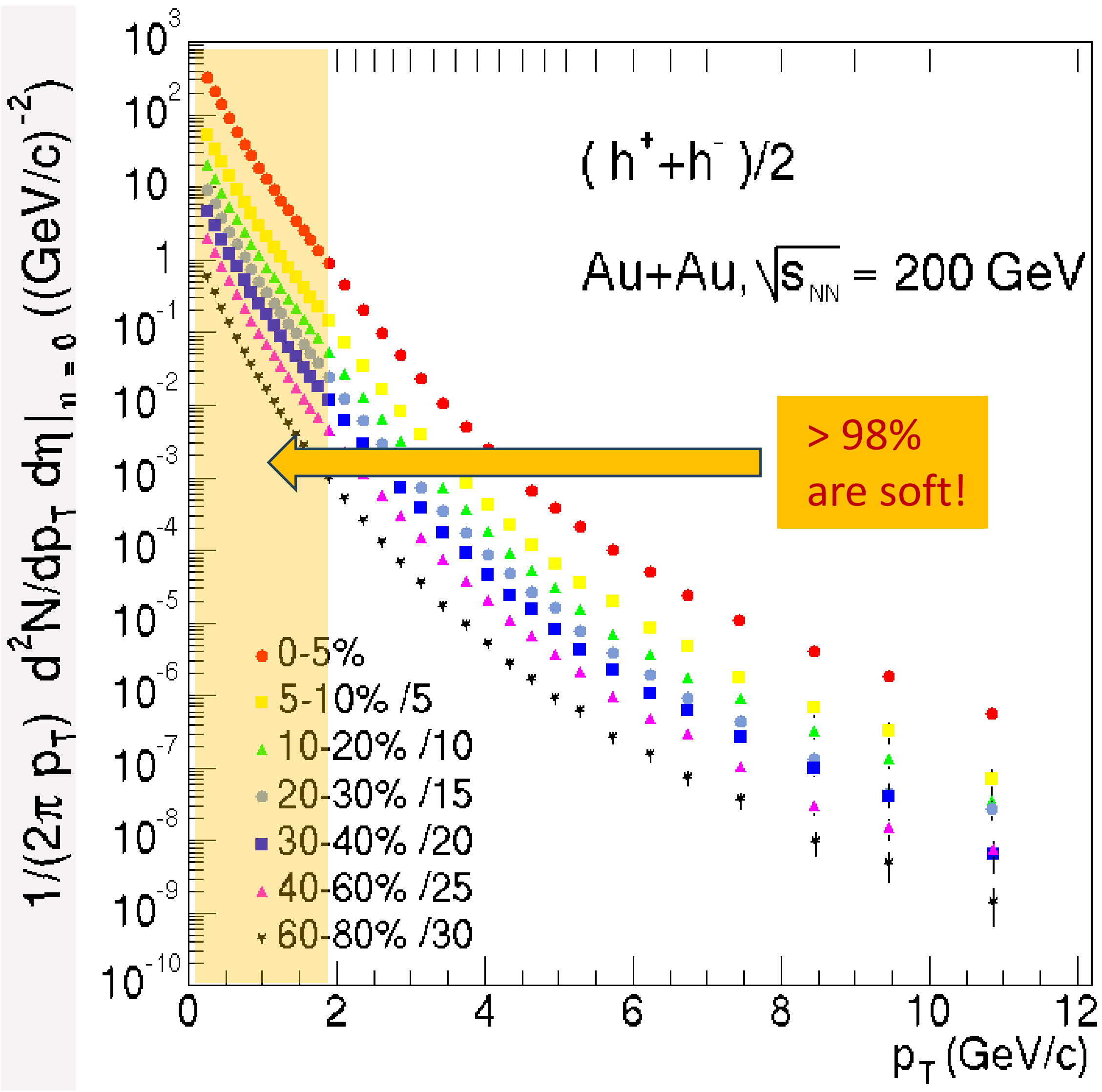
Photo from a bubble chamber

II. Heavy-ion collisions and soft hadrons

- QCD phase diagram and its mapping
- The role of soft hadrons

Bulk particle production in A+A collisions

Soft (thermal) particles (pT < 2 GeV/c) are copiously produced in HIC – bulk of the produced matter



Hadrons from bulk: particles containing most abundant quark specie (*u, d, s* + their anti-partners):

π, K, p, Λ, Ξ, K*, d, t, ^{3}He, ^{3}H$_\Lambda$

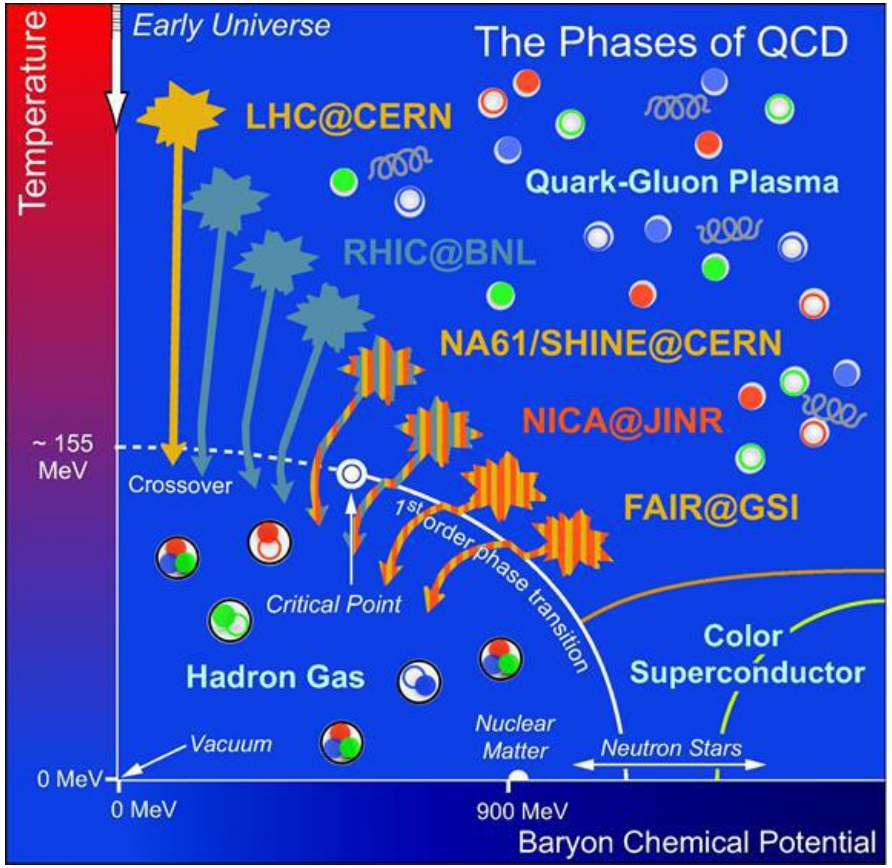
Thermal (soft) part of spectra contains most of the yield. Measurements of soft particles allow to address reaction dynamics and medium properties:

- Important geometrical quantities of the reaction
- Initial energy and entropy density
- Phases and their transformations
- Chemical composition and thermalization
- Space-time extent and collective effects
- Equation Of State (EOS)
- Constrains for the extraction of transport coefficients

Data on particle multiplicities, spectra and ratios are crucial for QCD phase diagram mapping!

Strongly interacting matter phase diagram

Important note: we do not investigate individual degrees of freedom (isolated quarks and gluons), instead, we study a medium (particle ensemble). Thus, thermodynamical (statistical, hydrodynamical) approaches and all the appropriate concepts (i.e., temperature, chemical potentials, equation of state, phase diagram and phase transitions etc.). Establishment of thermodynamical equilibrium in the system is crucial!



- Rich structure and variety of conditions (from Early Universe to Neutron Stars), but little confirmation about characteristic lines and points.
- Several running and future experimental programs worldwide. Each accelerator has its own range of collision energies and region on the phase diagram. Ultimate goal for all heavy-ion programs – cover the entire QCD phase diagram by measurements. Overlapping between different programs is appreciated!

Coordinates of the reaction final-state in the phase diagram are temperature *T* and baryochemical potential μ

How T and μ can be deduced?

A number of related questions should be answered:

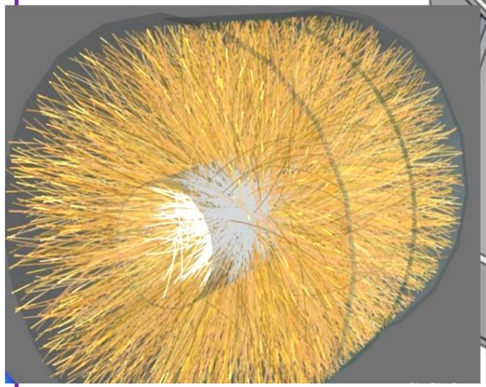
- Was local chemical and thermal equilibrium achieved?
- Are the yields and ratios of produced particles consistent with emission from an equilibrated medium?

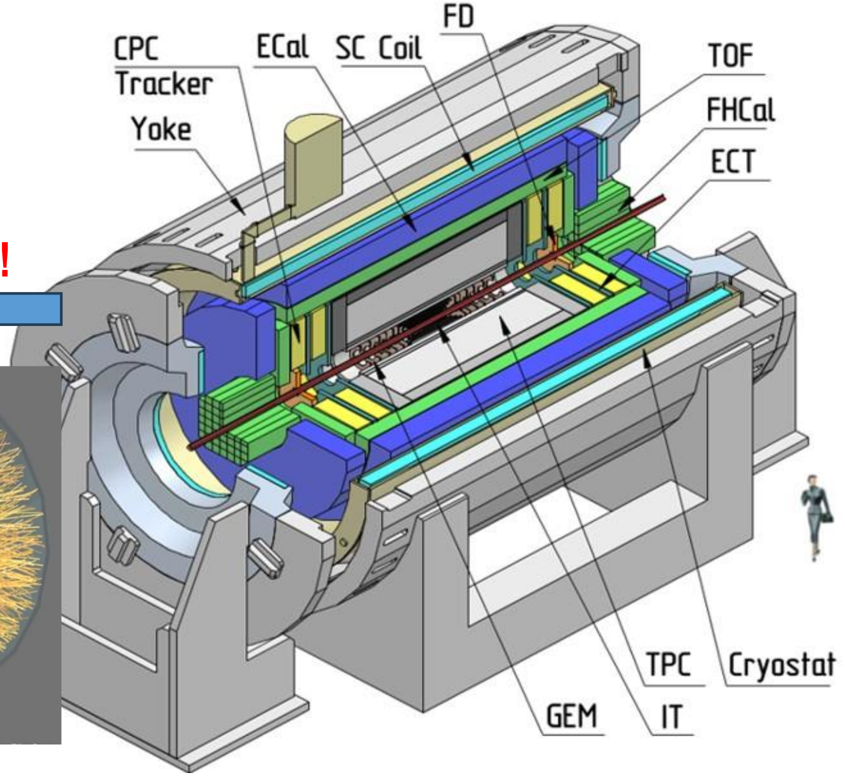
How hadrons from HIC are detected

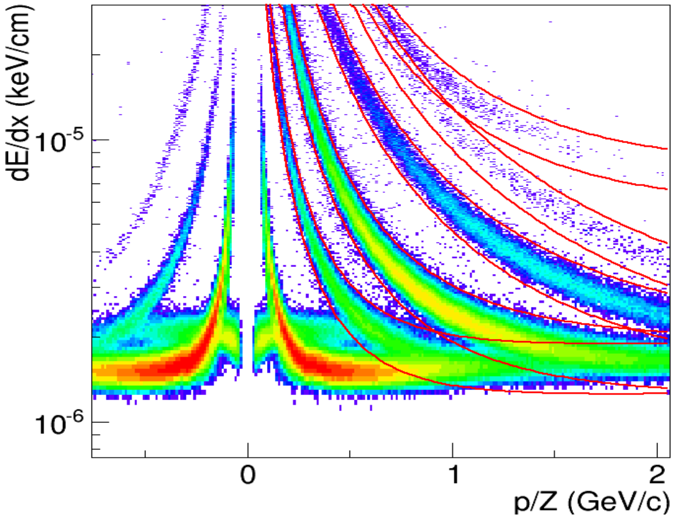
Actions taken in every nucleus-nucleus interaction:

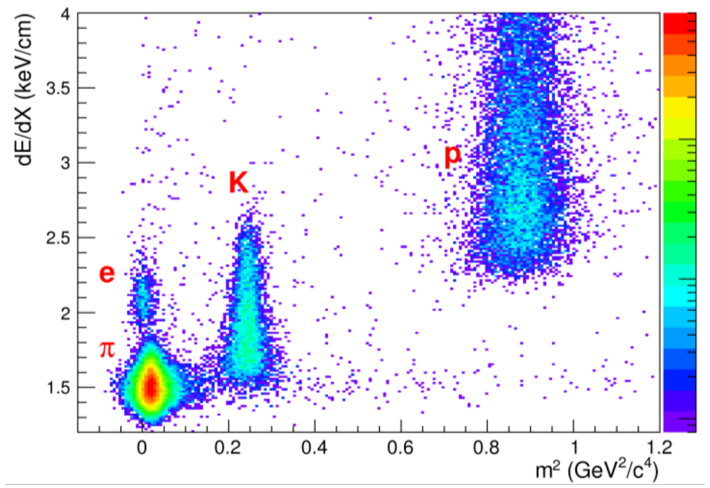
- Register all produced particles (charged and neutral). Reaction products emitted at any angle, thus, close to 4π coverage of the detector is required.
- Reconstruct the full collision geometry of collision:
  - main vertex,
  - secondary decay vertices,
  - estimate impact parameter, i.e., its value (centrality) and direction (event plane).
- Identify reaction products : masses, charges, etc.
- Determine kinematic characteristics (p_x, p_y, p_z).

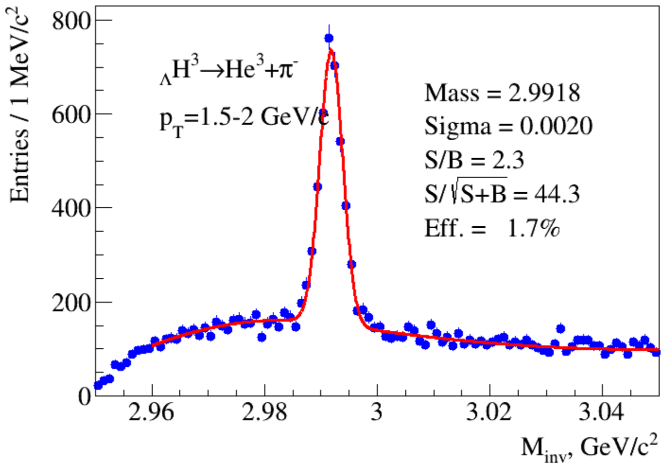
Detector mission!









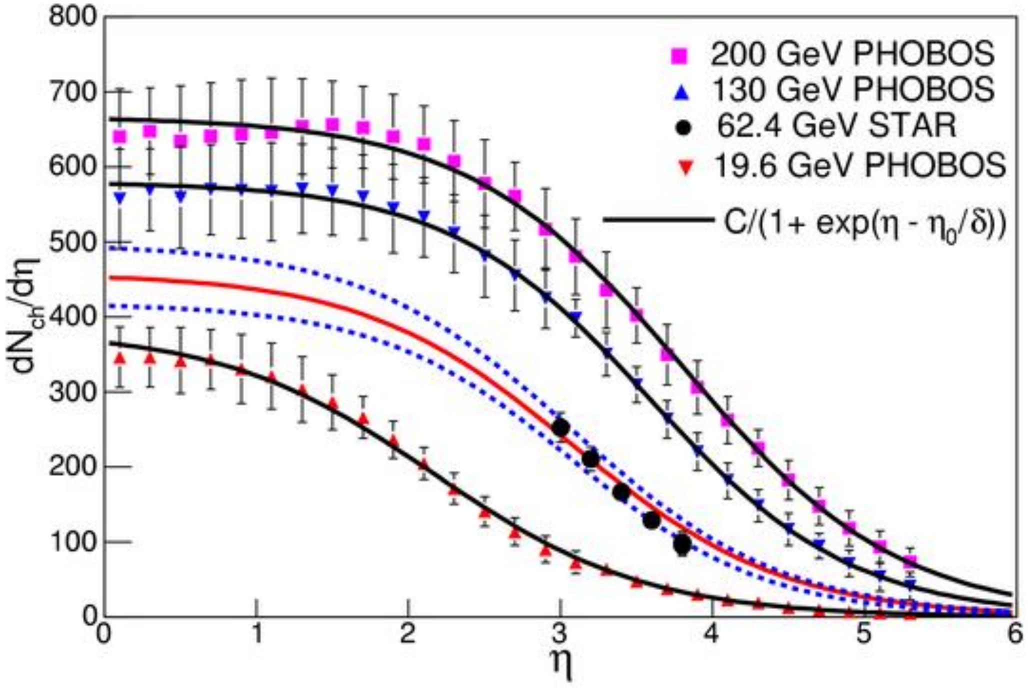


Starting point: estimates of initial conditions (energy density) in A+A collisions

- Rapidity density of charged multiplicity can be used in estimates of initial energy density

$$\epsilon_{\mathrm{Bj}} = \frac{\langle E \rangle}{R^2 \pi \tau_0} \frac{dN}{d\eta}$$

PHYSICAL REVIEW C **73**, 034906 (2006)

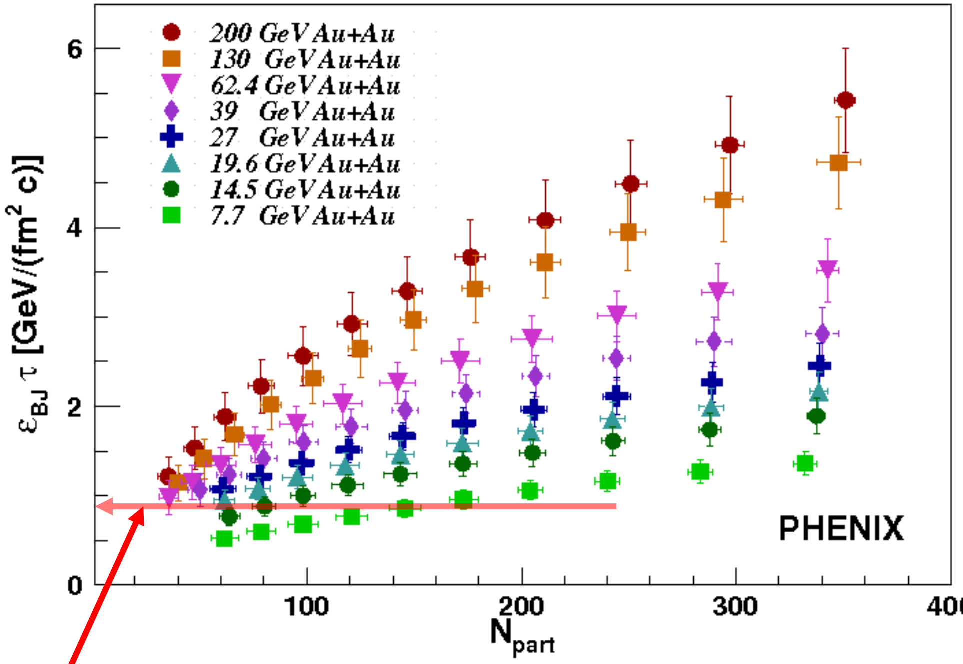


$\sqrt{s}$ = 5 GeV (AGS), ε = 1.4 GeV/fm^3
17 GeV (SPS), ε = 3.0 GeV/fm^3
200 GeV (RHIC), ε = 5.0 GeV/fm^3
2000 GeV (LHC), ε = 14 GeV/fm^3

- Can be complemented by measuring the total transverse energy in the reaction

$$\varepsilon_{BJ} = \frac{1}{A_\perp \tau} J(y,\eta) \frac{dE_T}{d\eta}$$

PHYSICAL REVIEW C **93**, 024901 (2016)



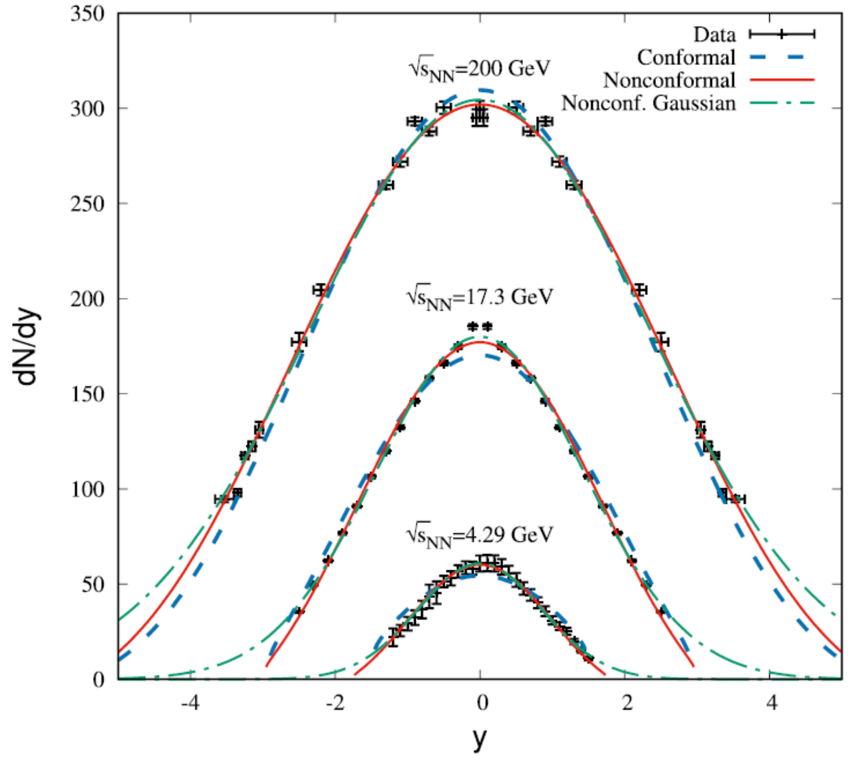
At NICA energies the estimated energy density exceeds the theoretical threshold value for deconfinement!

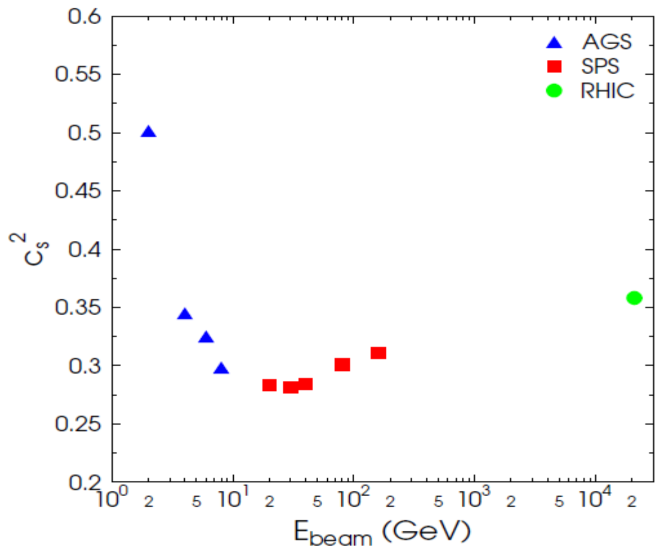
Rapidity spectra of soft hadrons from HIC: softest point?

If during the space-time evolution the newly formed in HIC matter can undergo phase transformations, the speed of sound is one of the crucial physical quantities to describe the variation of EOS.

Landau picture: fully stopped and thermalized source with EOS of $p = 1/3\,\varepsilon$ (μ is vanishing) and speed of sound (c_s) linked to the width of rapidity spectra

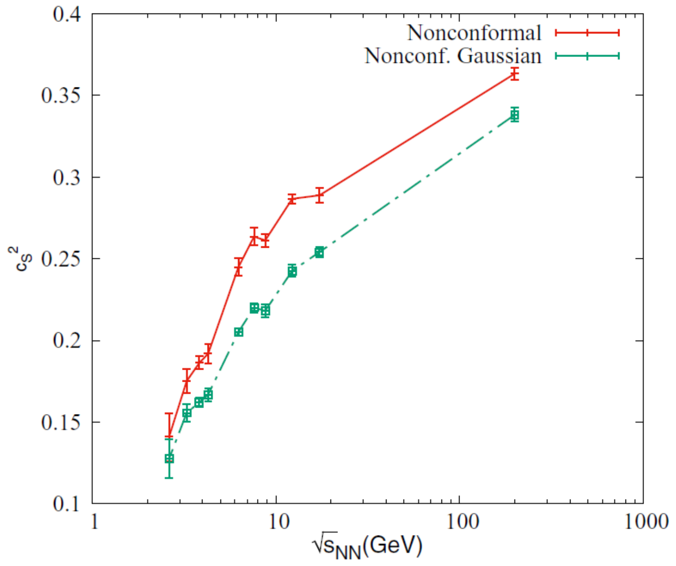
$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln(\sqrt{s_{NN}}/2m_p)$$





Vol. 42 (2011) ACTA PHYSICA POLONICA B

Softest point at NICA energies (signal about the mixed phase?) for the ideal (Landau) pictures



Phys. Rev. C102, 014912 (2020)

Inclusion of nonequilibrium effects and violation of boost invariant indicates a linear rise of speed of sound (no signal about the mixed phase)

Contradicting theory predictions!

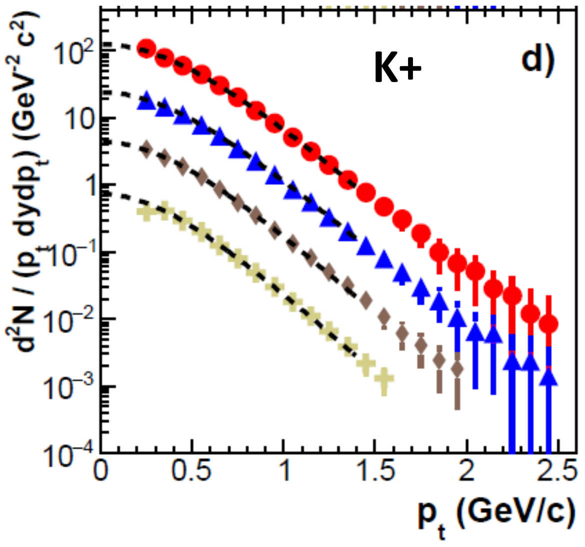
Hadron yields and ratios: bulk properties and phase diagram mapping

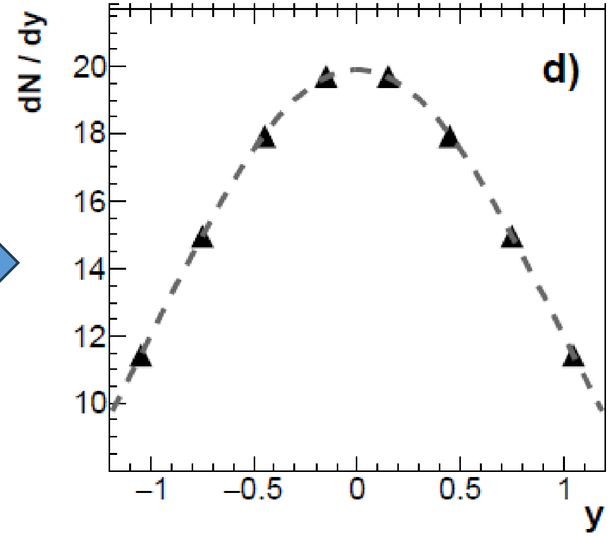
In the framework of statistical thermal models, the multiplicity N_C of a hadron with mass m, charge q, baryon number B and spin factor $g=2s+1$

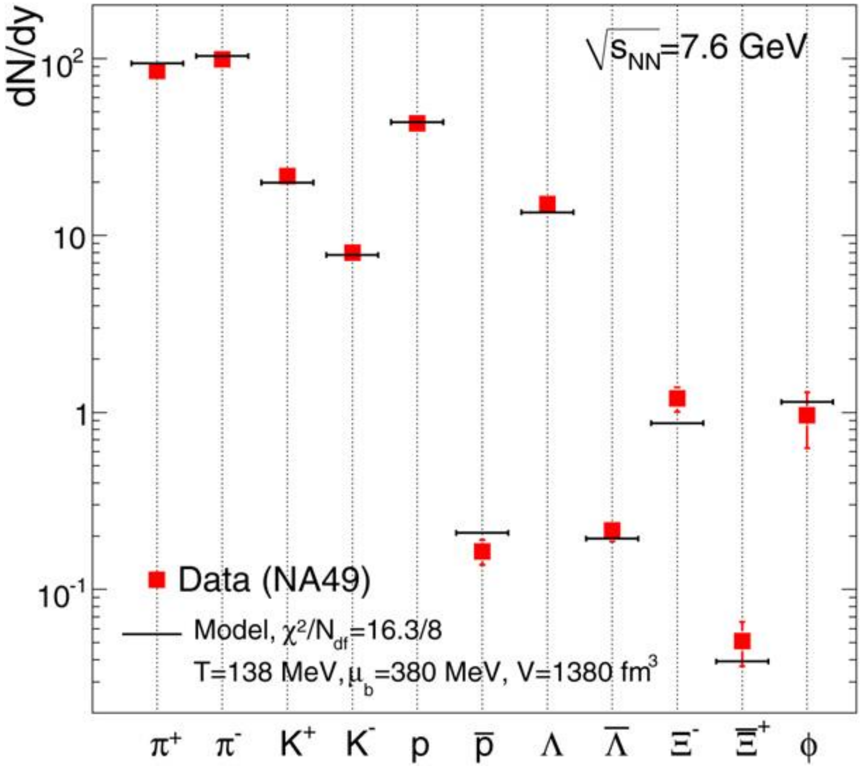
$$N_C = \frac{gV}{\pi^2} m^2 T K_2\left({}^{m}/_{T}\right) \exp\left(\frac{B\mu_B + q\mu_q}{T}\right) \qquad {}^{\mu_q}/_{T} = \frac{1}{2} \ln\frac{\pi^+}{\pi^-}$$

We solve the inverse problem – determination of the particle emitting source parameters from data on hadron multiplicities

In the experiment, we measure phase-space distributions of identified hadrons







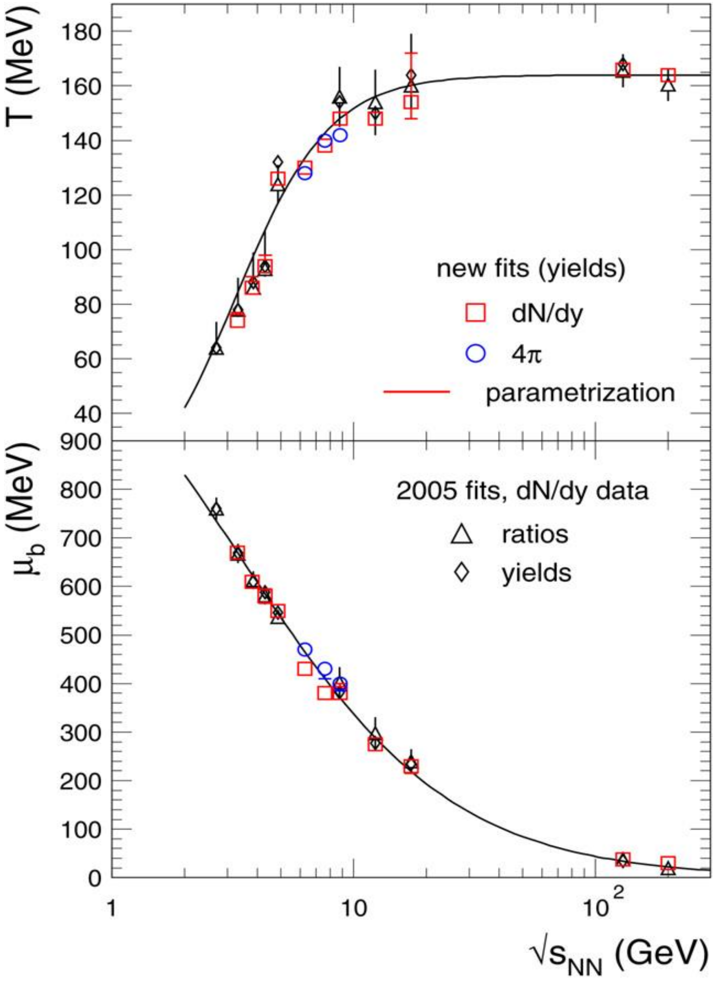
- Natural task for the First Day measurements → study of the medium bulk properties
- Thermodynamical source parameters (T and chemical potentials) are deduced by means of the study of the hadron production
- Large and uniform acceptance of the apparatus is of importance

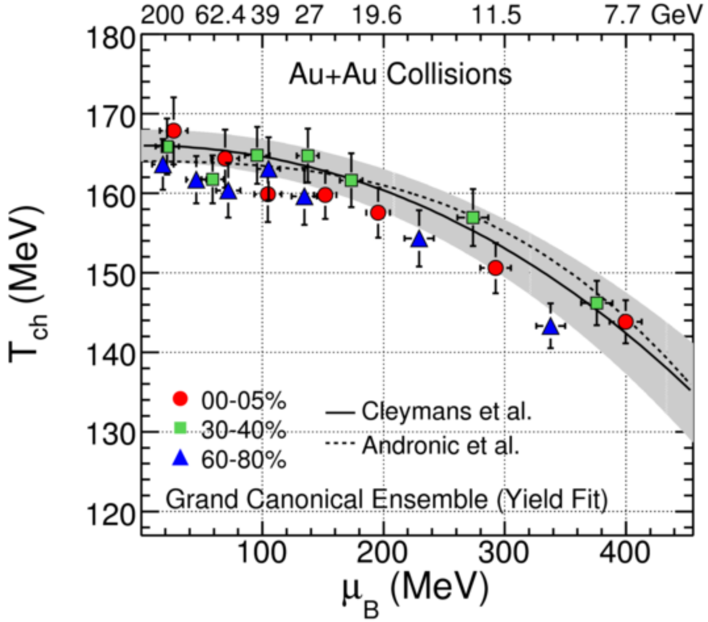
Soft particle production and hadrochemistry

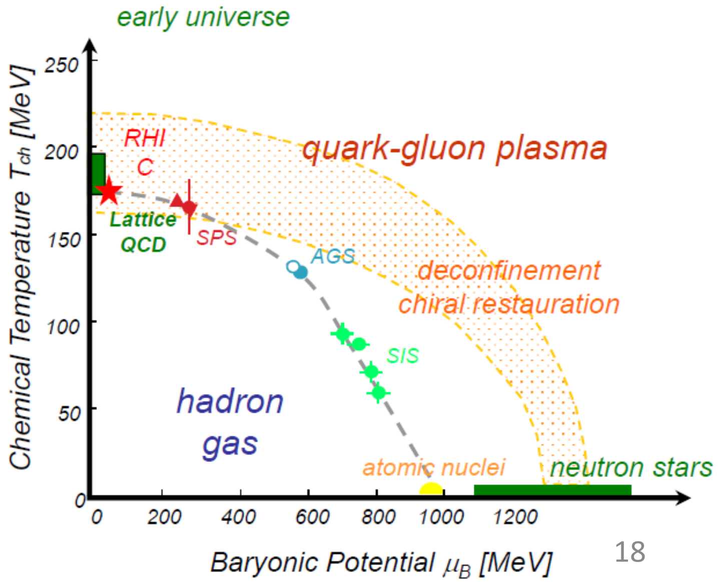
Actually, we analyze the property of the particle source in the form of hadronic matter.
Can we get insight into the phase boundary from that?

- Hadron yields over the entire accessible range of phase diagram (from AGS up to LHC) can be described in statistical thermal model.
- Therefore, particle yields and ratios can be predicted at any collision energy
- One observes a limiting temperature of hadron production around T≈160MeV
- For √s >≈ 10 GeV chemical freezeout very close to phase boundary

Phys. Lett. B 673 (2009) 142–145 143

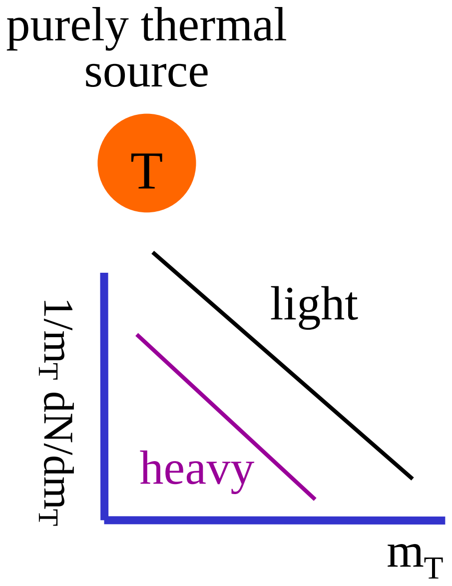




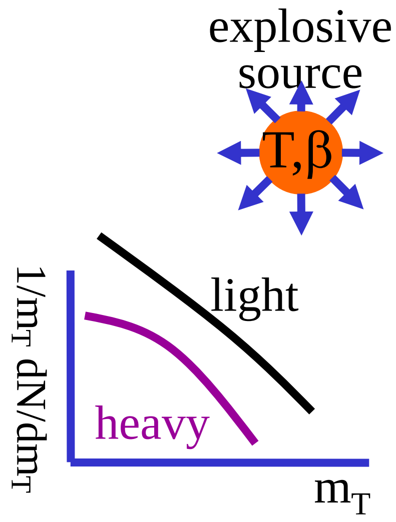


Hadron spectra and fireball *kinetic freezeout*

Blast-wave analysis

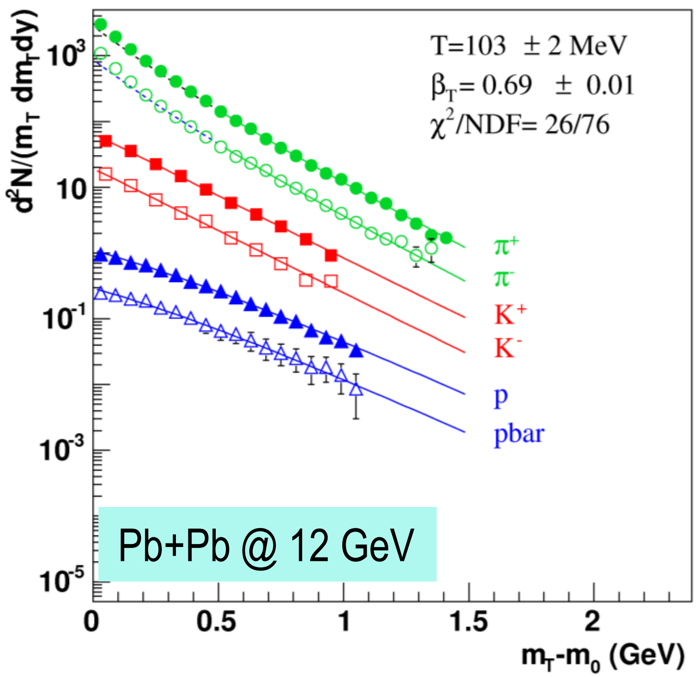


In the source with strong collective behavior the spectral shape is determined by more than a simple **T** but also by a radial velocity β_T



$$\frac{dN}{m_t dm_t} = A\int_0^1 m_t f(\xi) K_1\left(\frac{m_t \cosh(\rho)}{T}\right) I_0\left(\frac{p_t \sinh(\rho)}{T}\right)\xi d\xi$$

$$m_t = \sqrt{p_t^2 + m^2}, \quad \rho = \mathrm{atan}(\beta_t(\xi)), \quad \xi = \frac{r}{R}$$



Simultaneous fit to all particle species.
Fit parameters:

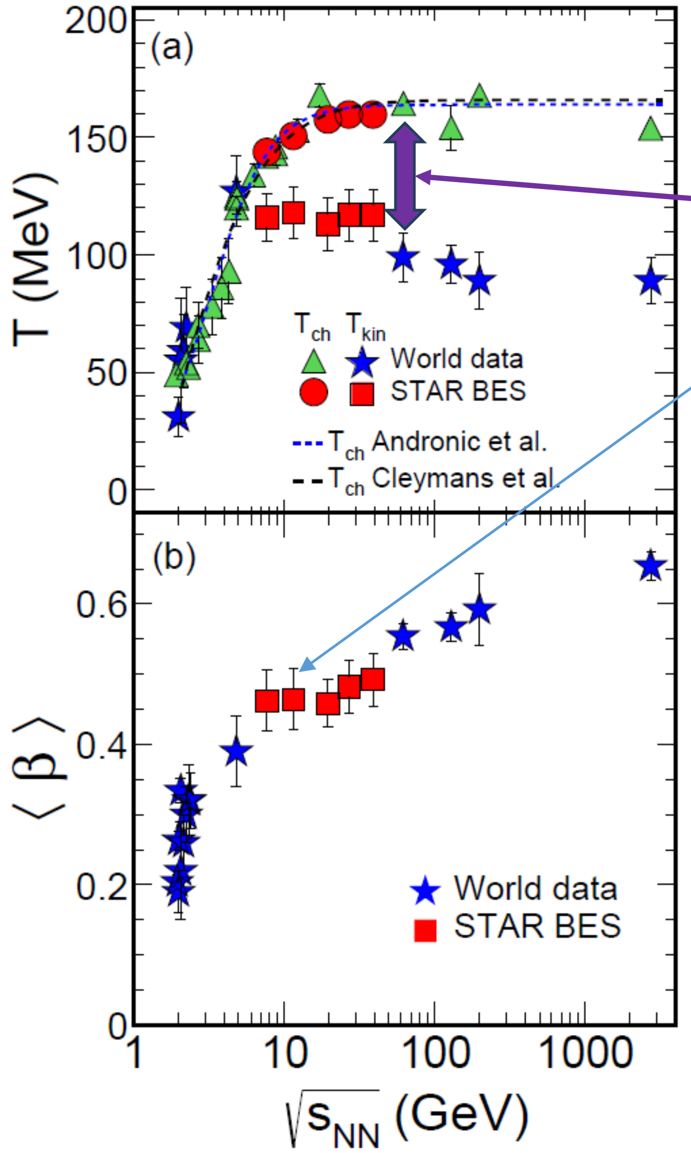
T – thermal freezeout temperature
β_T – max. transverse flow velocity

- The larger the temperature, the flatter the spectra
- The larger the velocity, the flatter the spectra ⇒ blueshift
- The heavier the particle, the more sensitive it is to flow (shape and slope)

Analysis results are correct if spectra of many hadrons are used!

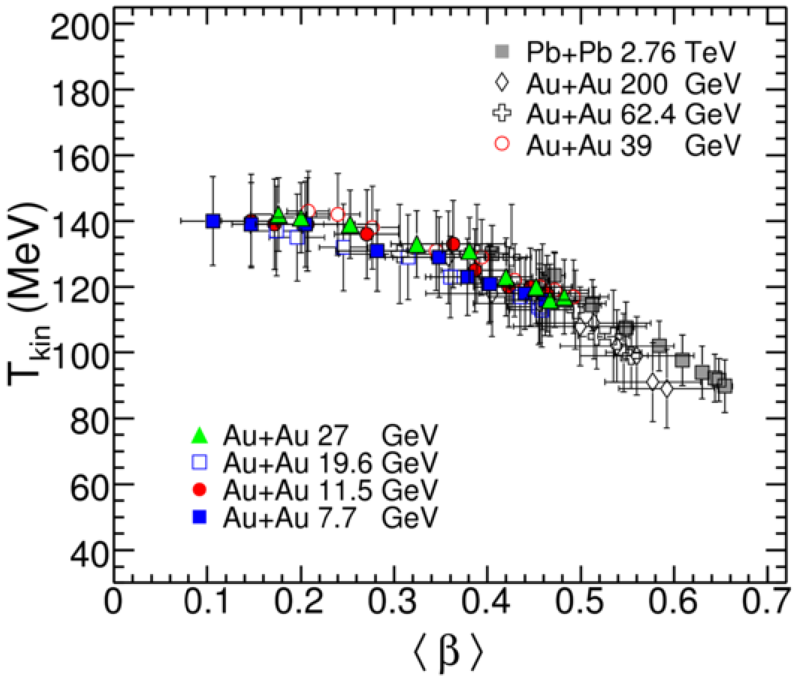
Analysis of soft hadron spectra: collection of results

Phys. Rev. C 96, 044904 (2017)



- T_{ch} approaches limiting temperature for HG phase of 160 MeV
- <β> rises with increasing energy suggesting stronger expansion. The plateau indicates mixed phase (HG+QGP)?
- The separation between T_{ch} and T_{kin} increases with increasing energy suggesting the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies.

Probes with small interaction probability in the hadronic phase are of interest!



Kinetic Freeze-out:

- Explosive collective expansion
- Higher radial flow for more central and higher energy collisions

So far, we spoke about the hadron cocktail in the reaction.

Is every single particle specie from the light sector equally valuable for physics?

In principle, Yes. Still, there exist more excited among them (IMHO):

1) Strange hadrons.

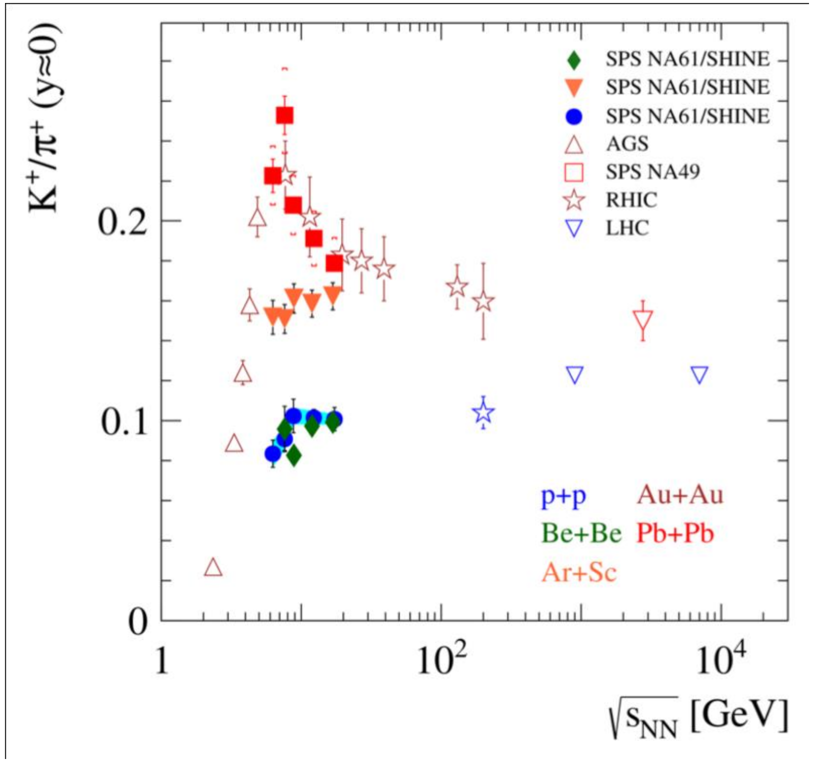
2) Light nuclei

1)+2) Hypernuclei

NICA/MPD physics cases: strange hadrons

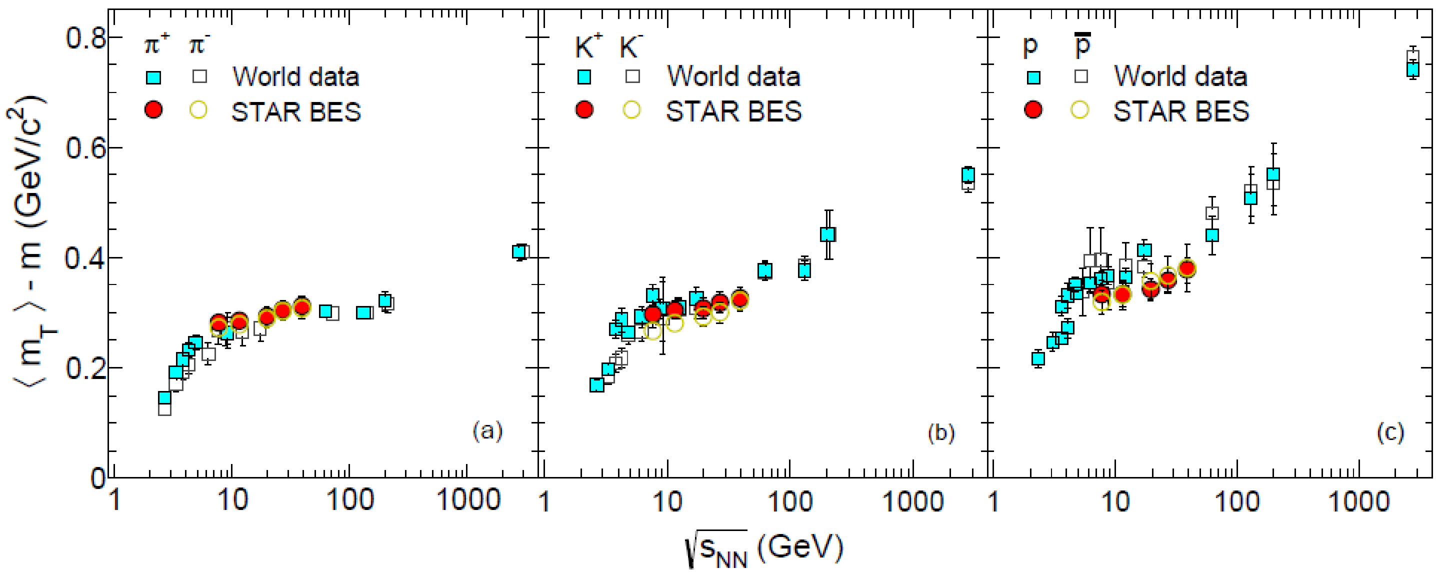
- Excitation function of hadrons, including strangeness (yields, spectra, and ratios)
- Nuclear matter EOS, phase transformations, in-medium effects, and chemical equilibration can be probed

- Non-monotonic strangeness-to-entropy can indicate phase transformation (abrupt change of strangeness carrier from hadrons to quarks). But system size of the energy dependence is not fully understood



- The energy dependence of <mt>-m could reflect the characteristic signature of a first order phase transition. The constant value of <mt>-m around BES energies could be interpreted as reflecting **the formation of a mixed phase of a QGP and hadrons** during the evolution of the heavy-ion system.

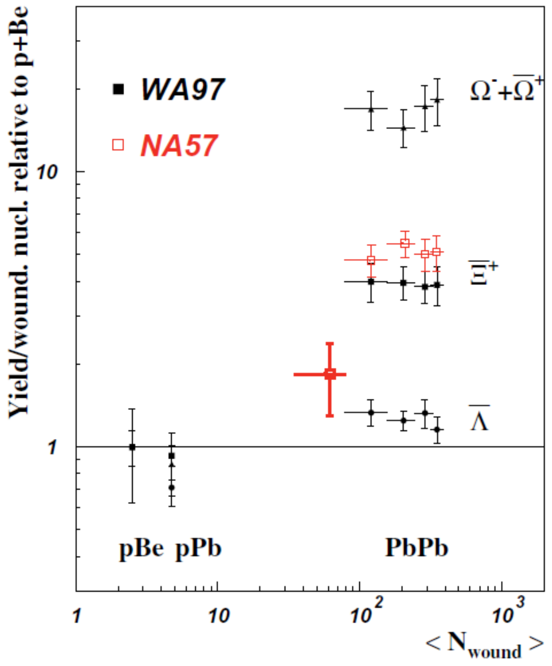
Phys. Rev. C 96, 044904 (2017)

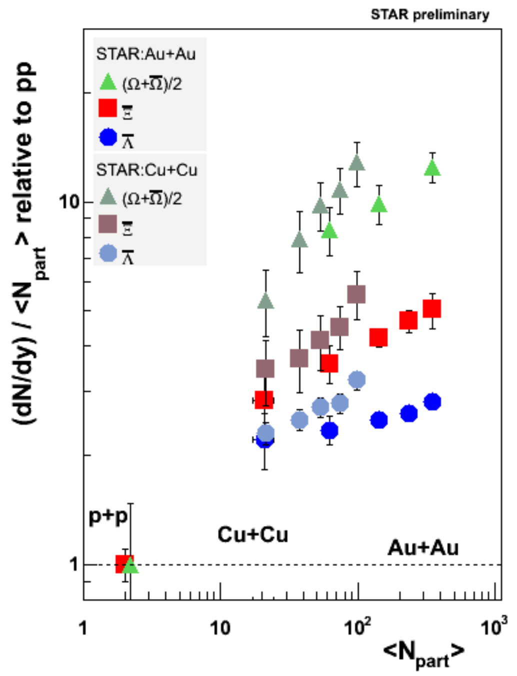


Strangeness enhancement in HIC

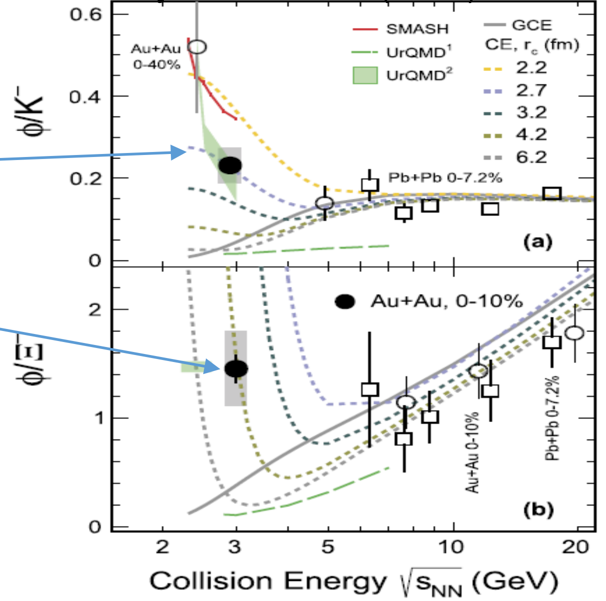
Enhancement in A+A is relative to (p+p) and normalized by (p+p)!

- Production of multistrange hadrons from statistical hadronization of a strangeness-enhanced phase (QGP?!) can explain hierarchy of strangeness enhancement pattern
- Canonical suppression of strangeness in small systems, which are used for normalization, can also explain the observed effect (QGP is not required!)
- Observed a significant change of strangeness production mechanism at low collision energies (Canonical ensemble in A+A describes the trend!)



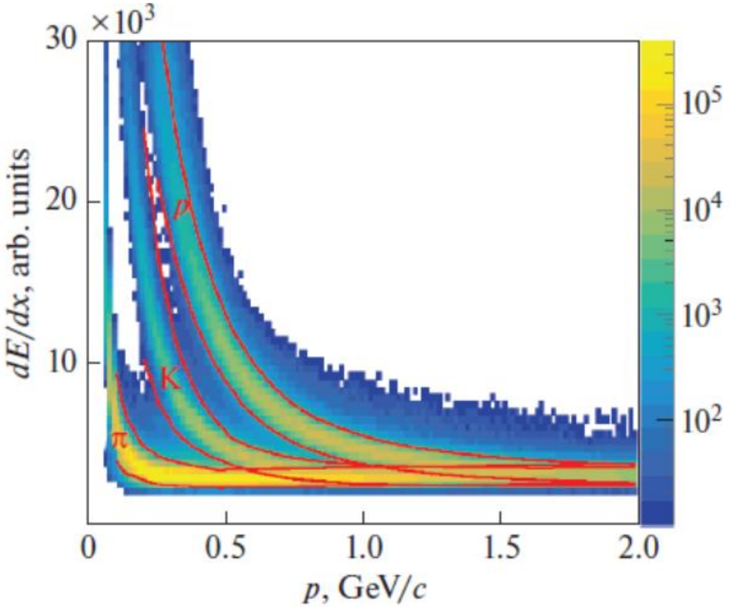


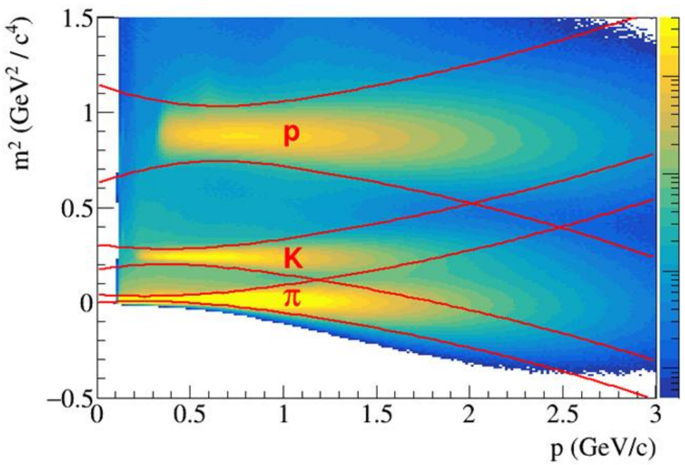
Phys. Lett. B831 (2022) 137152



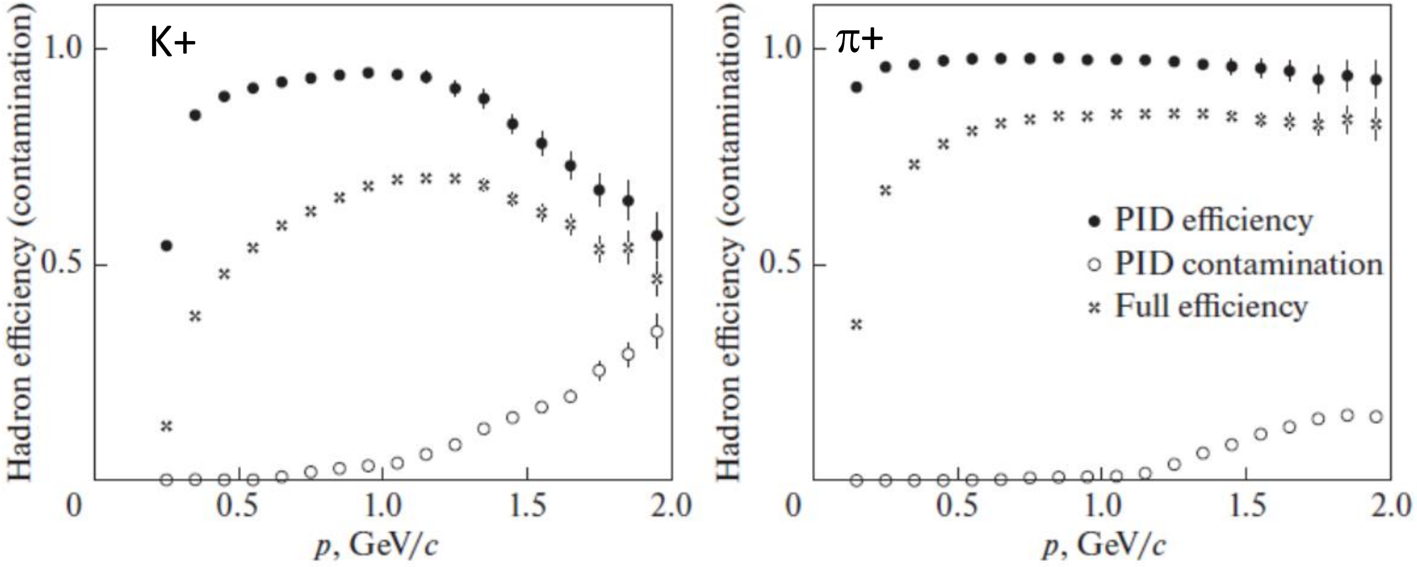
Data on (multi)strange hadrons provide new insights into the property od QCD matter at high baryon density. NICA/MPD can play a role!

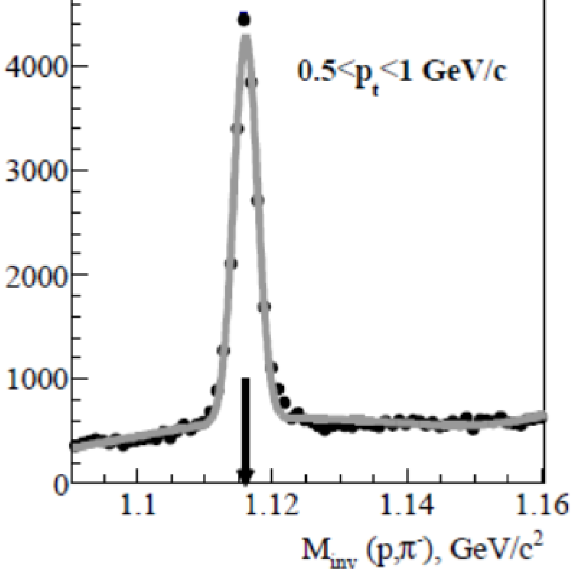
MPD: hadron spectra and yields from central Au+Au collisions



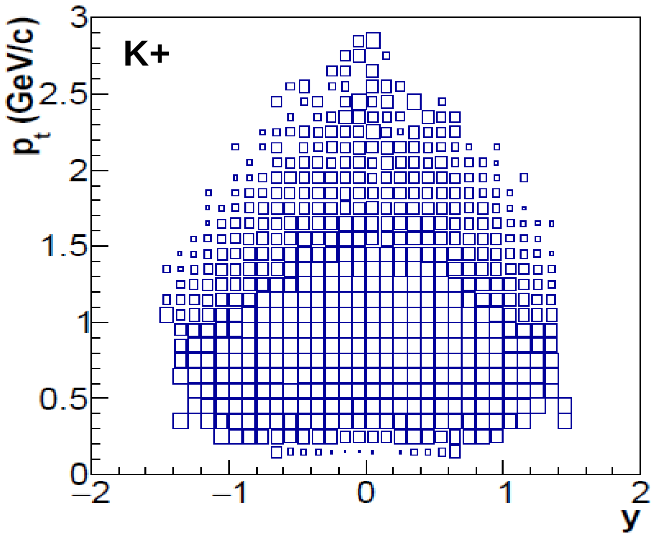


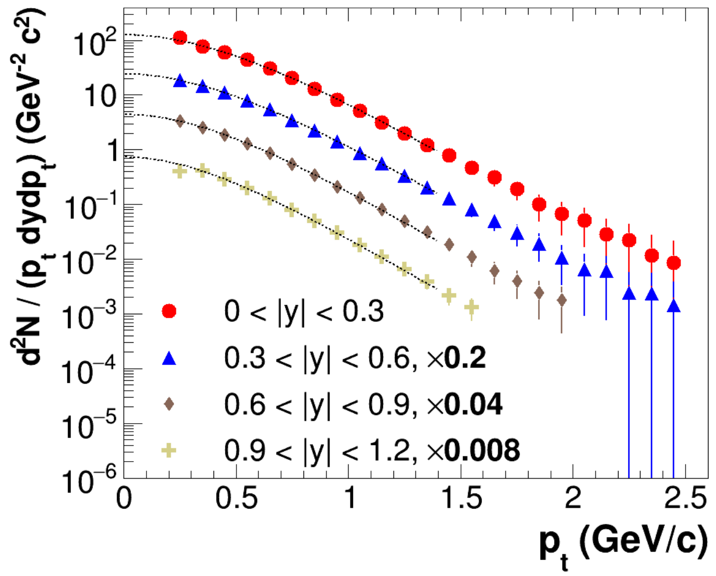
Analysis procedure for hadron yields:
- Event reconstruction
- Particle identification
- Corrections (efficiency, acceptance, etc.)
- Estimation of errors

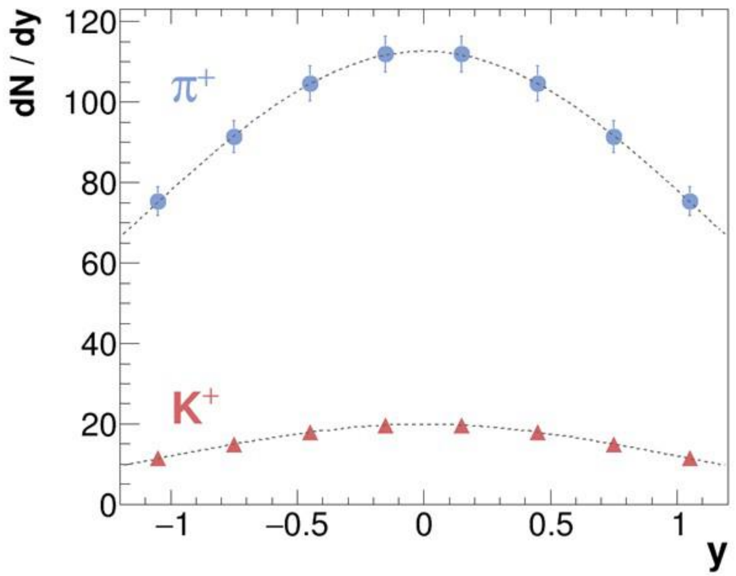


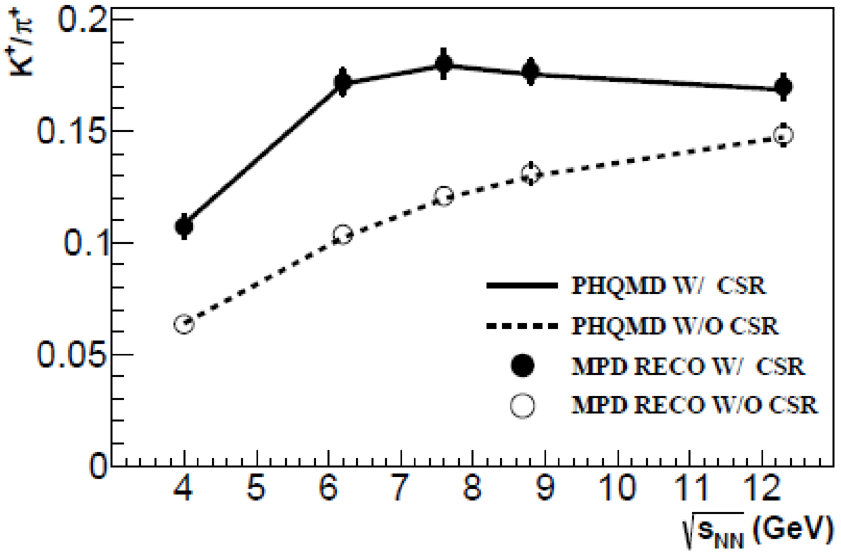


MPD: hadron spectra and yields from central Au+Au collisions



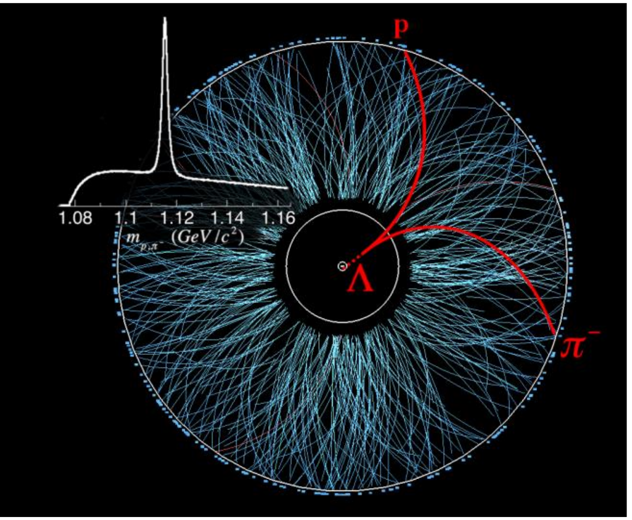




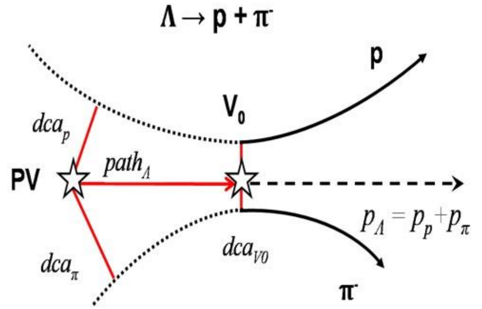


- MPD provides large phase-space coverage for identified pions and kaons
- Hadron spectra can be measured from pT=0.2 to 2.5 GeV/c
- Extrapolation to full pT-range and to the full phase space can be performed exploiting the spectra shapes (see BW fits for pT-spectra and Gaussian for rapidity distributions)

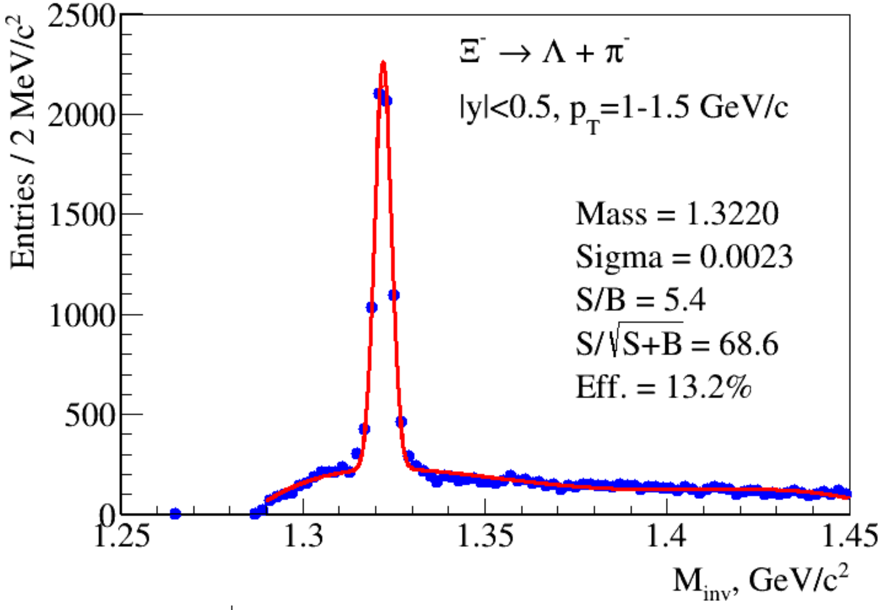
Λ-hyperon reconstruction in MPD

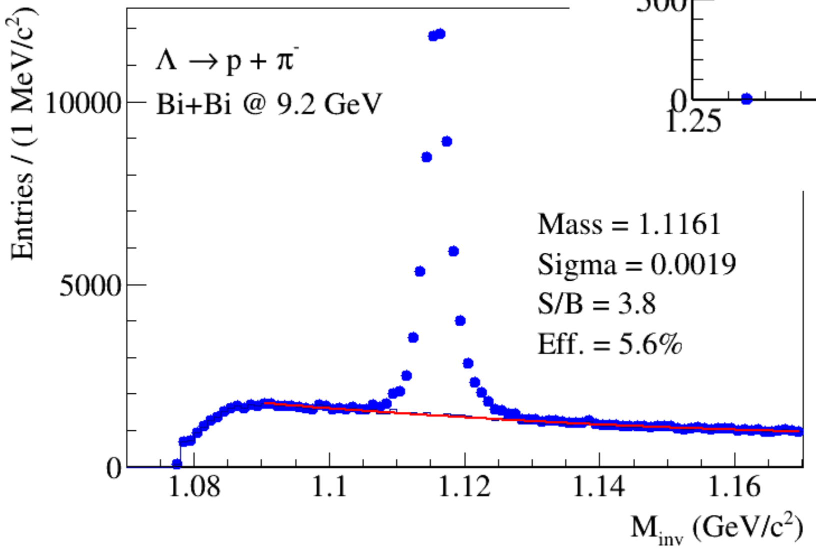


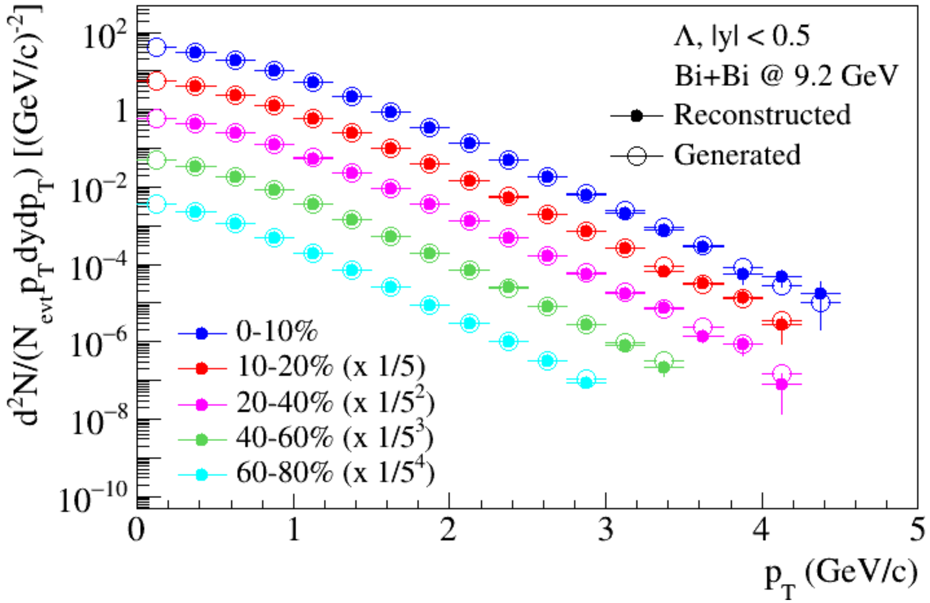
- ✓ **Model:** Bi+Bi @ 9.2 GeV UrQMD
- ✓ **PID:** dE/dx+TOF
- ✓ **Hyperon reco**: Secondary vertex finding technique with a set of topological cuts



PV *- primary vertex*
V0 *- vertex of decay*
dca- *distance of closest approach*
path *– decay length*

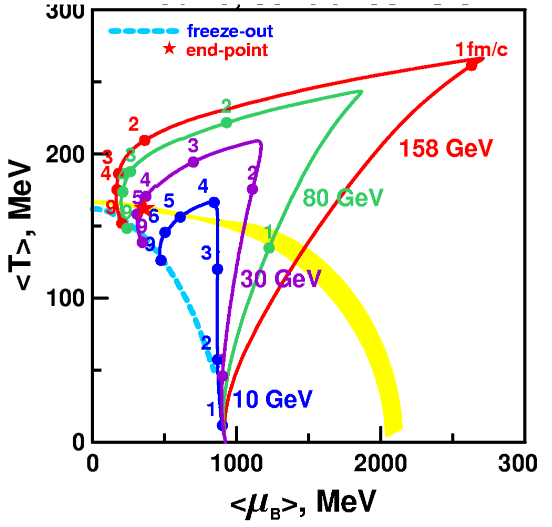


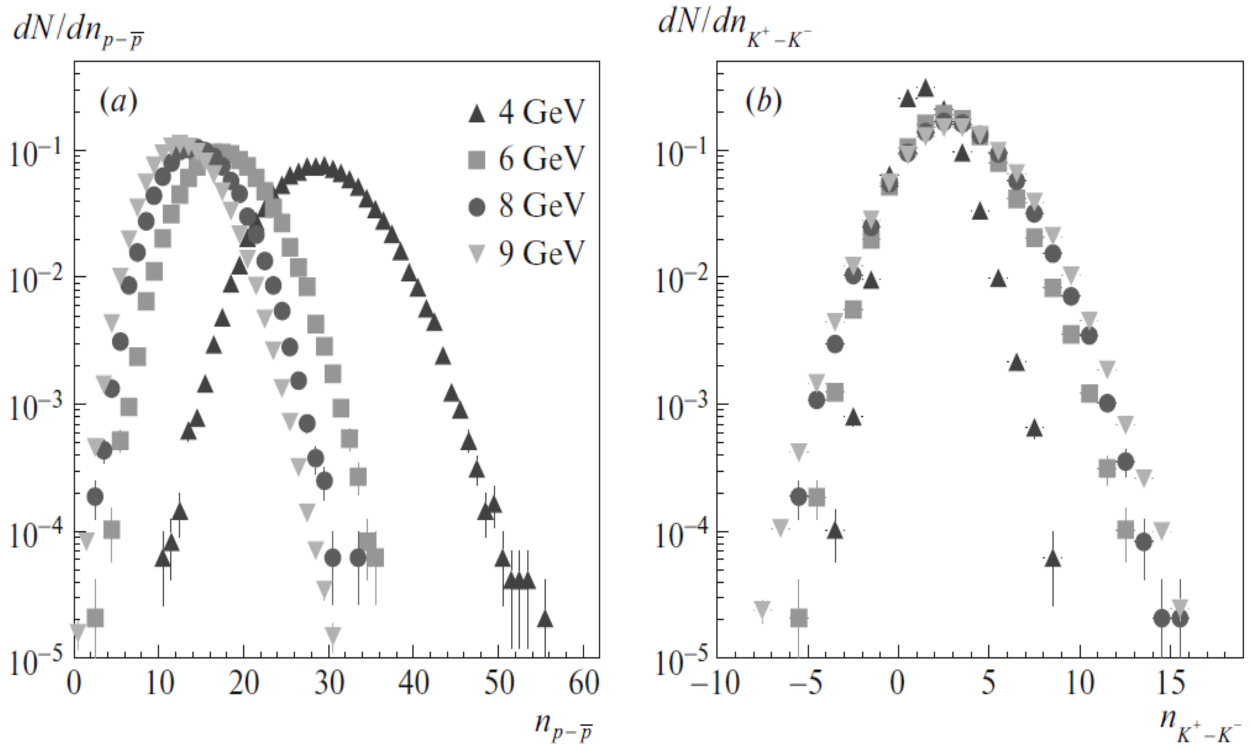




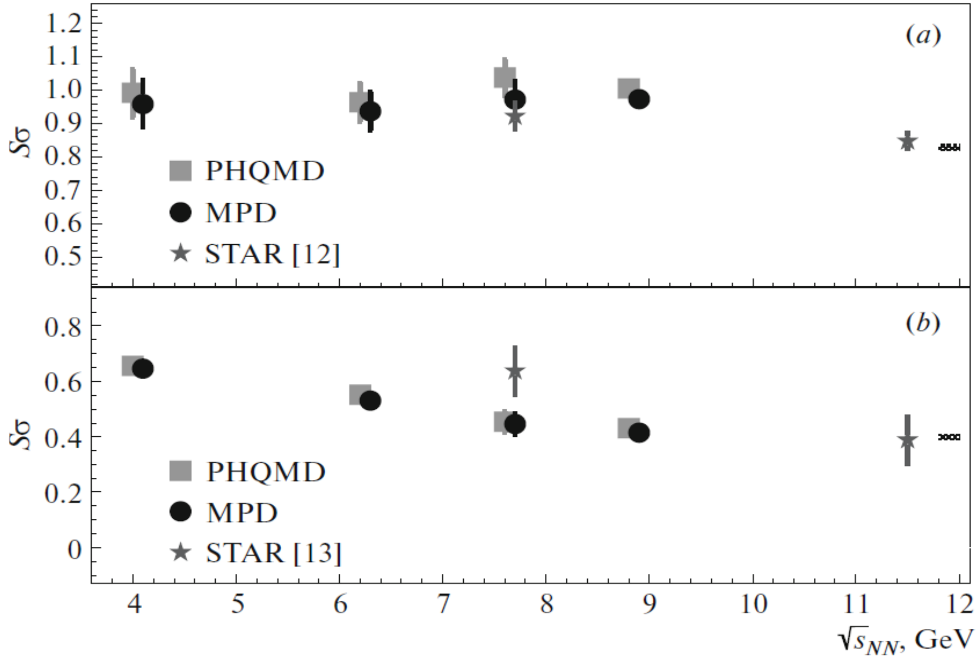
Critical end point (CEP) on the QCD phase diagram and soft hadrons

- If the trajectory is in the vicinity of the critical endpoint – abnormal fluctuations can be observed
- Moments of event-by-event multiplicity distributions or cumulant ratios are directly compared to susceptibilities, which diverge in the proximity of CEP
- MPD has a large uniform acceptance for hadrons and good per-event PID capability → good prospects for the study strangeness and baryon number fluctuations





effective skewness Sσ for net-protons (a) and net-kaons (б)



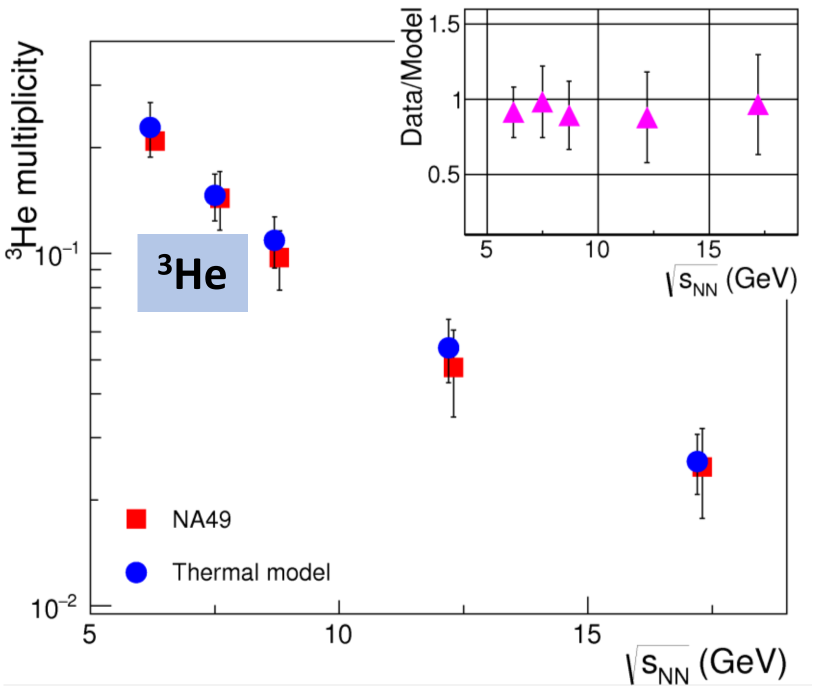
III. (Hyper)nuclei in heavy-ion collisions

Measurements at NICA/MPD: light (hyper)nuclei

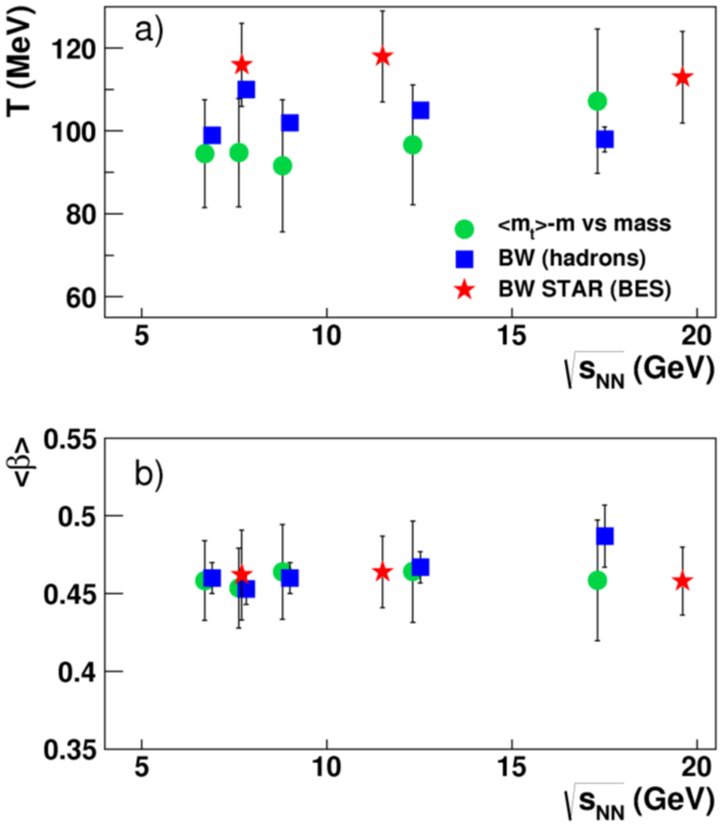
- Allow to probe the space-time structure of the source, production mechanism (coalescence, statistical model) and collective effects
- Production of nuclei is sensitive to nucleon phase-space density fluctuations, which are sensitive to spinodal instability (1st-order QGP-HG phase transition) or to 2nd-order transition (CEP)

CFO for hadrons and nuclei coincides?!

Phys. Rev. C 94, 044906 (2016)



..Kinetic freezout as well?

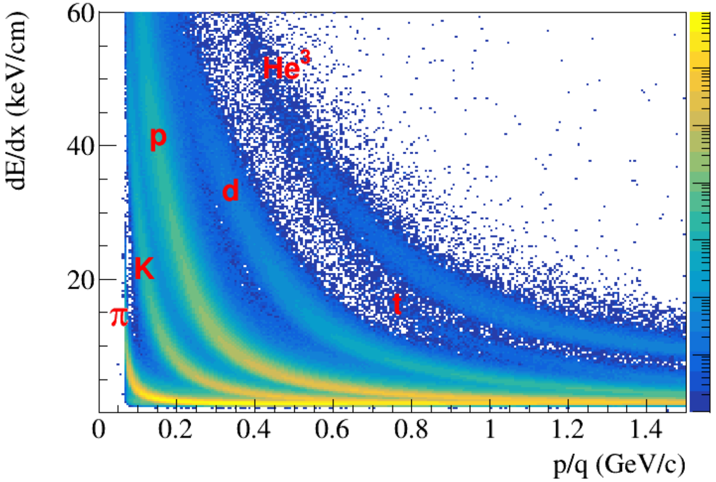


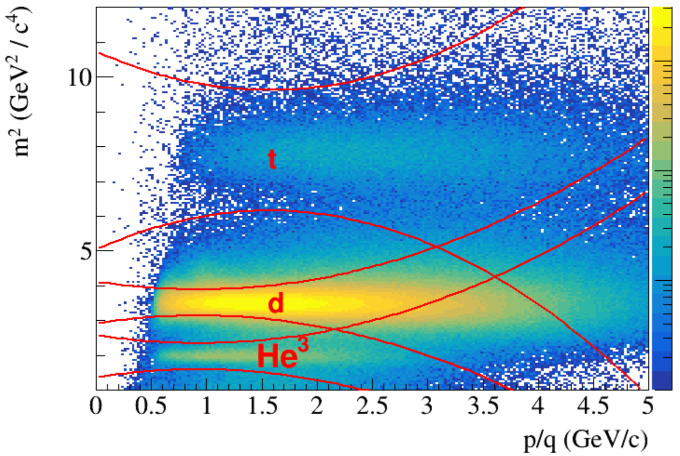
- Light nuclei are copiously produced in heavy-ion collisions at NICA energies
- *"Ice in the fire" puzzle* – weekly bound objects are formed in hot thermalized medium
- More experimental data are needed to shed light on the production mechanism

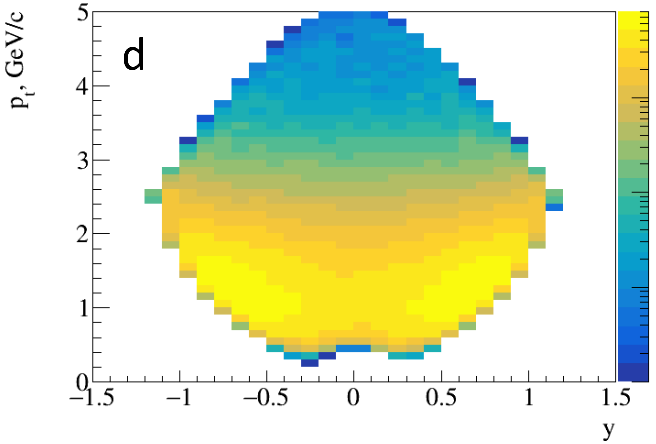
Light nuclei in MPD: spectra & yields and analysis of density fluctuations

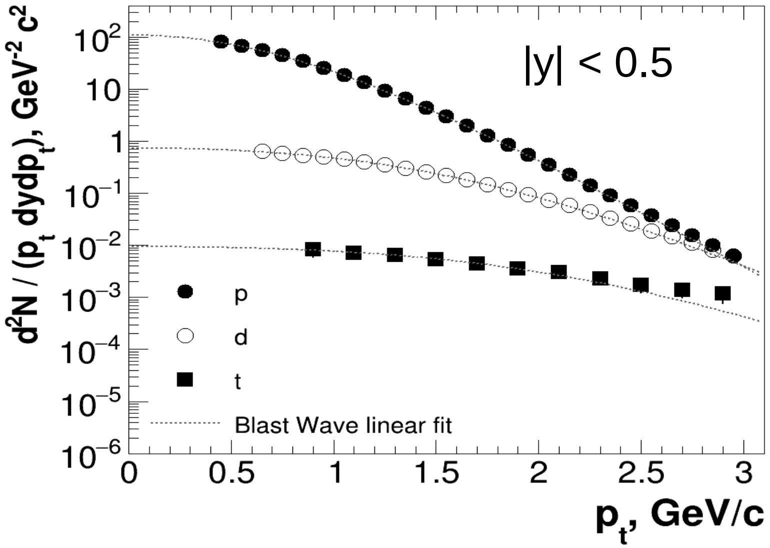
- A peak structure in the excitation function of relative neutron density fluctuations as a probe of the QCD phase diagram structure *K.J. Sun, et al, Phys. Lett. B 781, 499 (2018)*

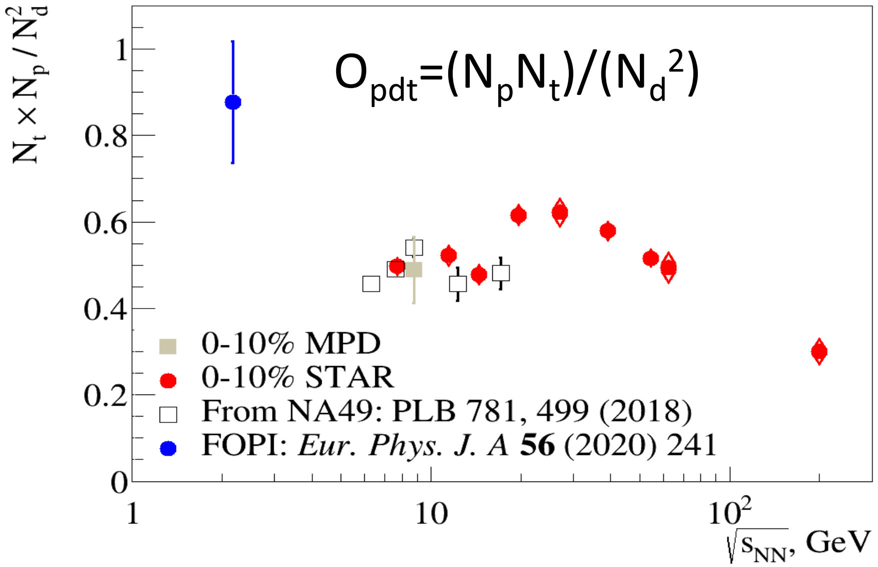
MPD simulation for nucleon cluster measurements in Bi+Bi collisions







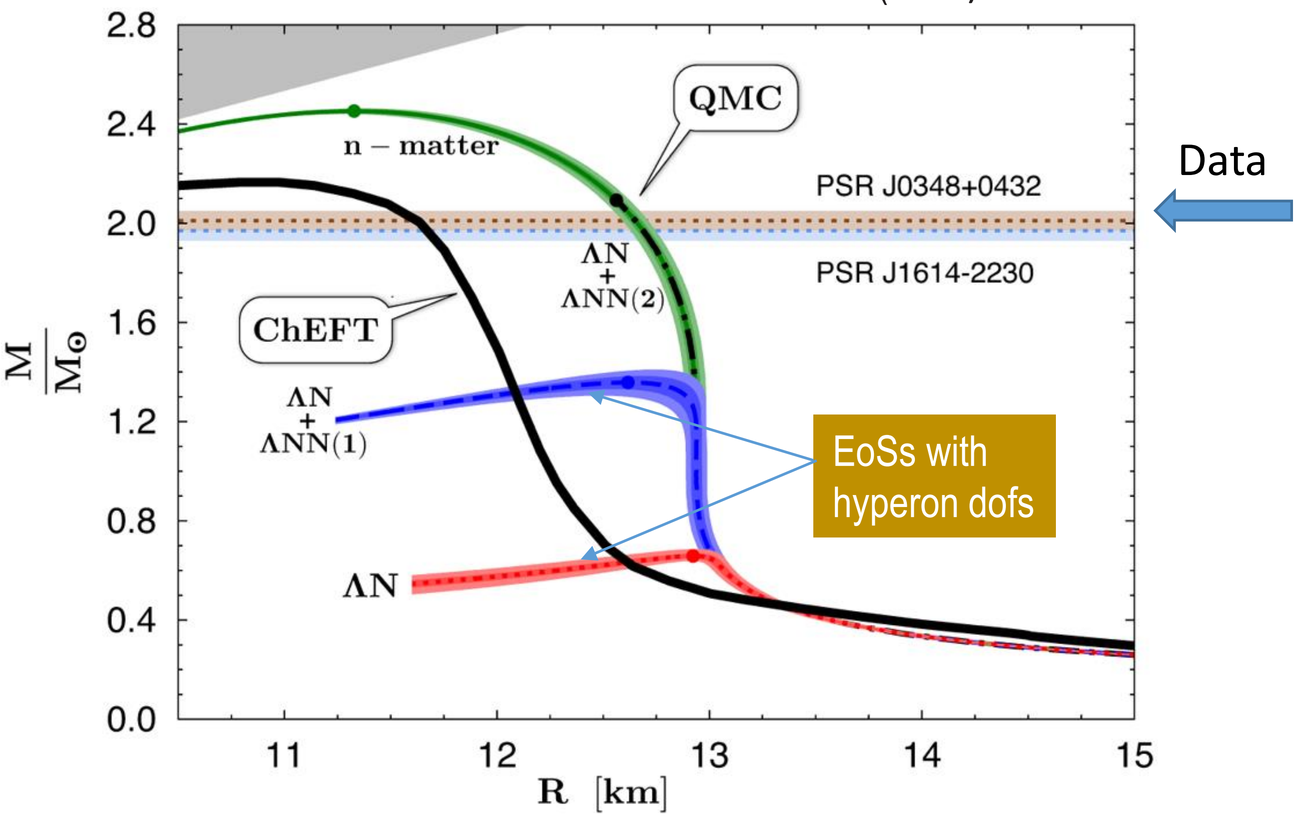




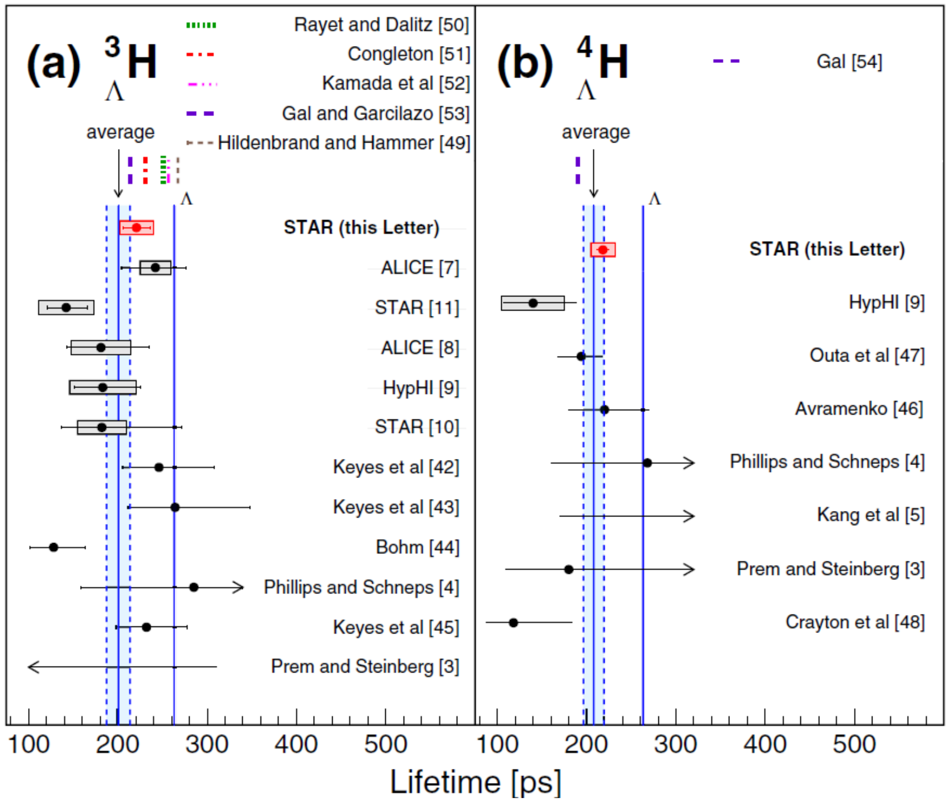
Strangeness in dense nuclear matter : puzzling behavior

- Hyperons appear in the core of neutron stars (NS) at ~ (2-3)n_0 leading to softening EoS and reducing the max. mass for NSs, but the latter is in contradiction with observations (NS hyperon puzzle)
- Averaged lifetimes of hypernuclei from A+A are shorter than expected from theory (lifetime puzzle)

REVIEWS OF MODERN PHYSICS 88 (2016)



PRL 128, 202301 (2022)



Many open questions on YN (YY, YNN) potentials in dense matter, new data on B_Λ, lifetimes, branching ratios are needed to provide tighter constrains

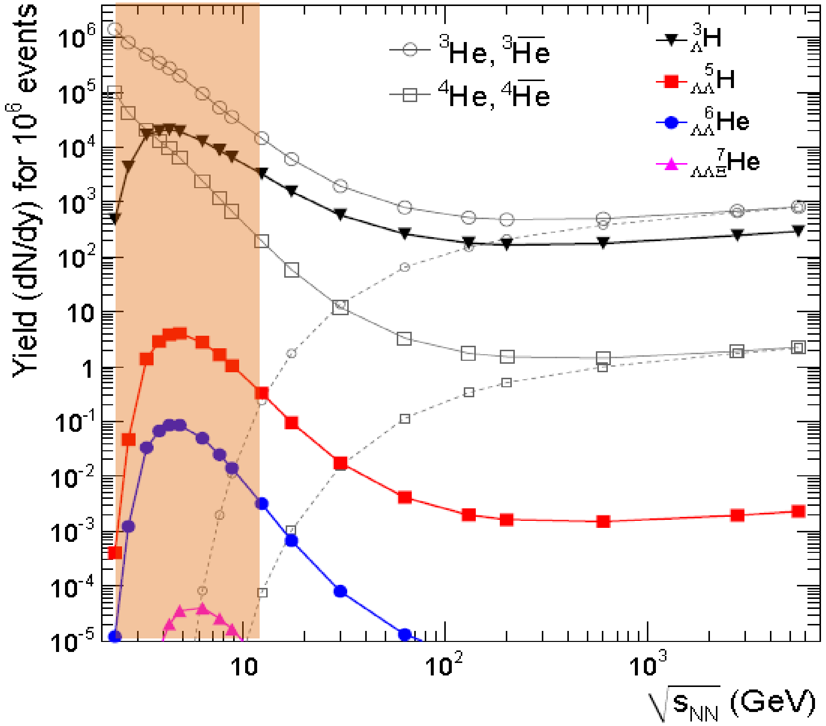
More data are required to reduce current uncertainty (NICA/MPD)

Hypernuclei at NICA energies: expectations & data

Hypernuclei are nuclei containing at least one hyperon

- Nuclear matter EOS is of importance for QCD, nuclear physics and astrophysics
- Only NN potential are very well determined from scattering experiments
- But YN or YY potentials are rather uncertain since such experiments difficult to perform
- High multiplicity heavy-ion collisions provide several methods to do the job: two-particle correlations and hypernuclei

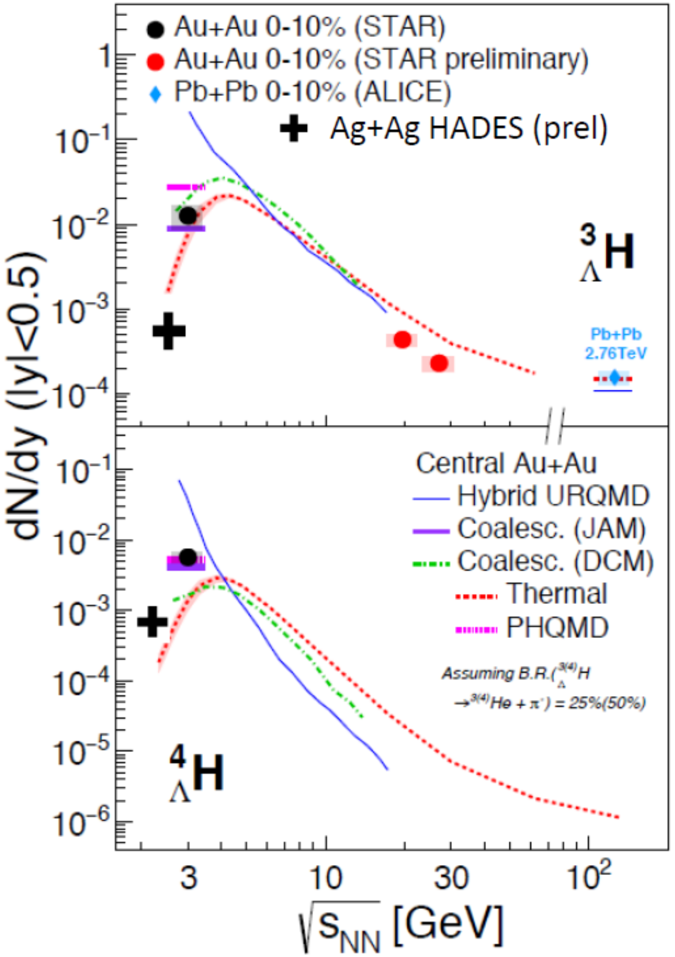
A. Andronic et al, PLB 697 (2011) 203



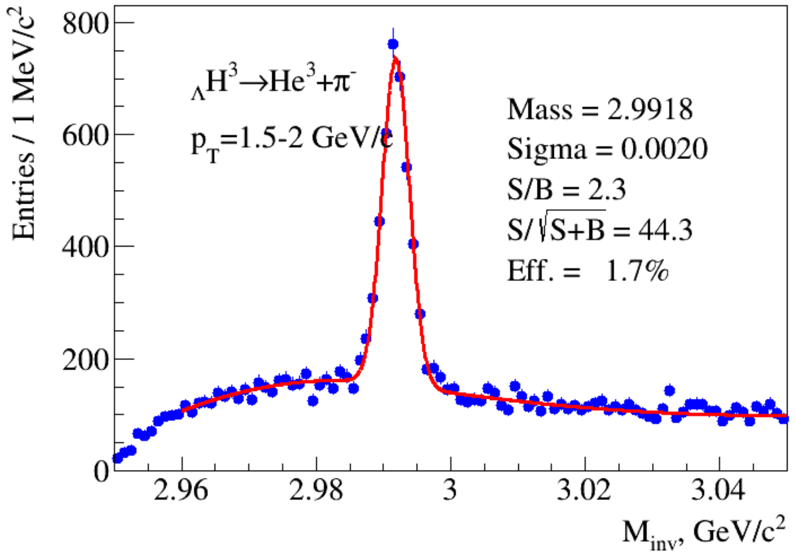
Thermal model predicts an enhanced production of (hyper)nuclei within the NICA energy range

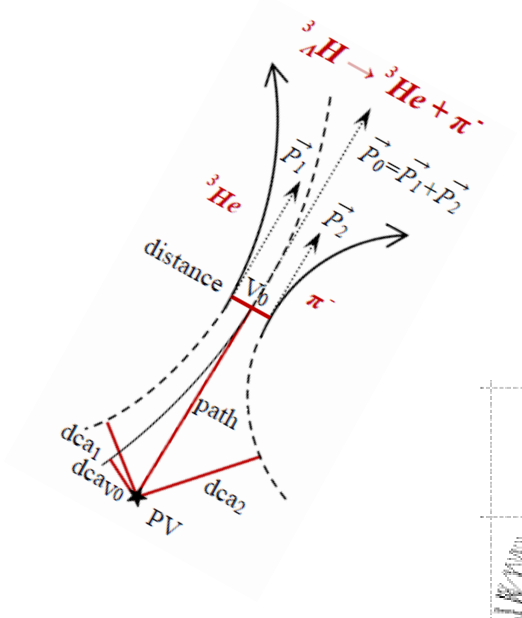
- Few data on the production of hypernuclei in HIC
- Available data leave space for various model predictions (thermal, coalesce, hybrid)
- Further and deeper investigations of the hypernuclear formation mechanisms require additional measurements at different energies and collision systems (**NICA**)

QM'2022

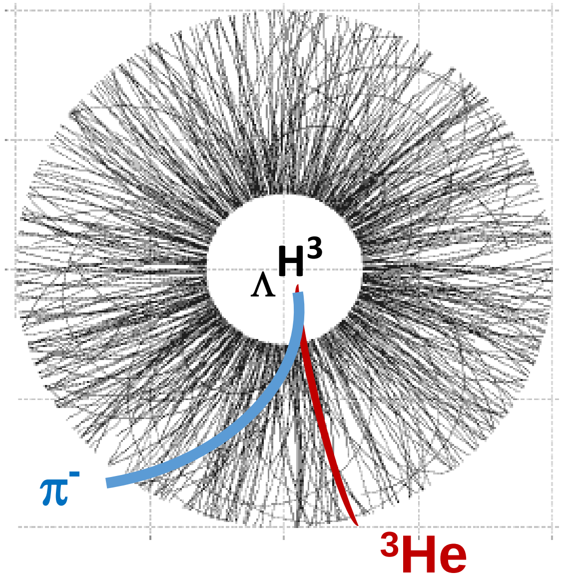


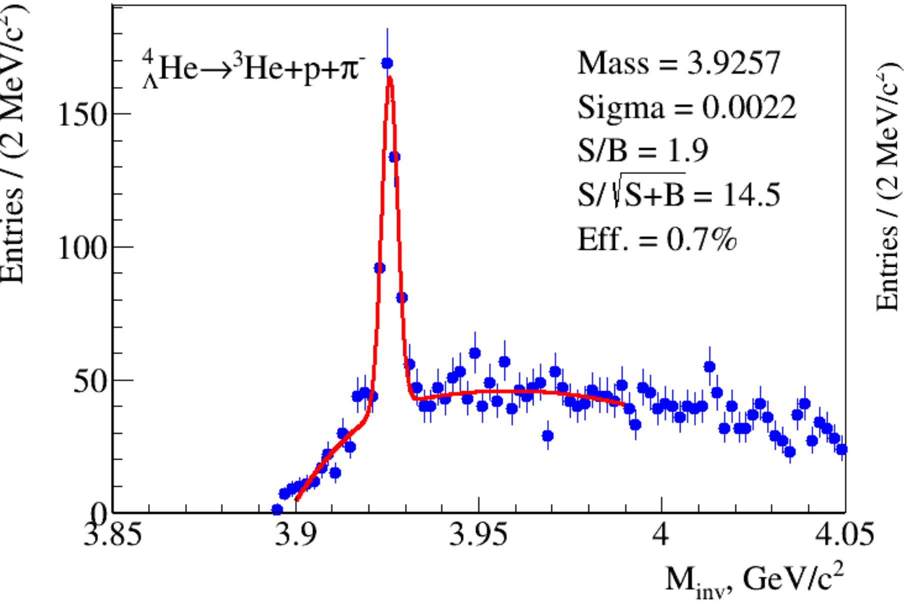
Reconstruction of hypertritons in MPD

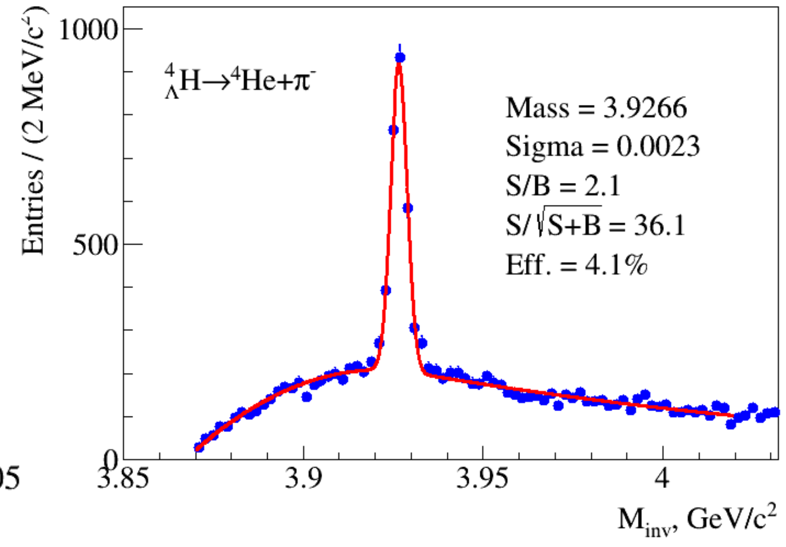




- PV – primary vertex
- V_0 – vertex of hyperon decay
- dca – distance of the closest approach
- path – decay length

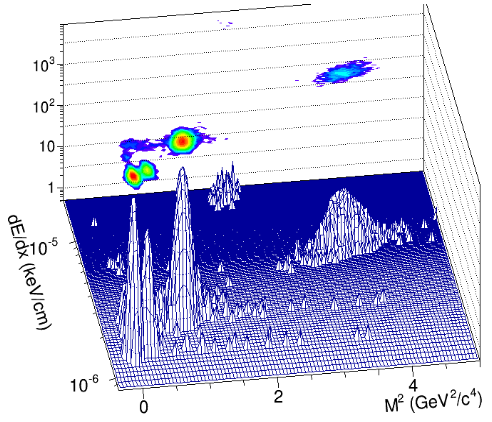


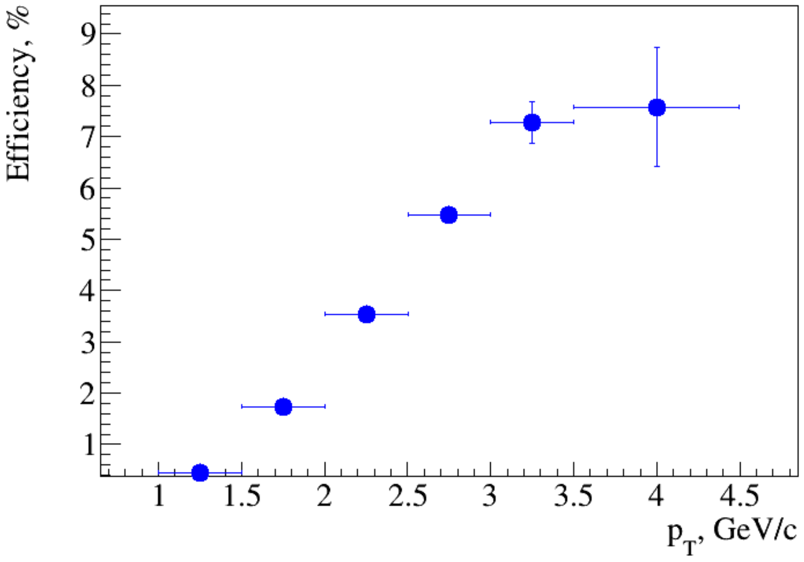


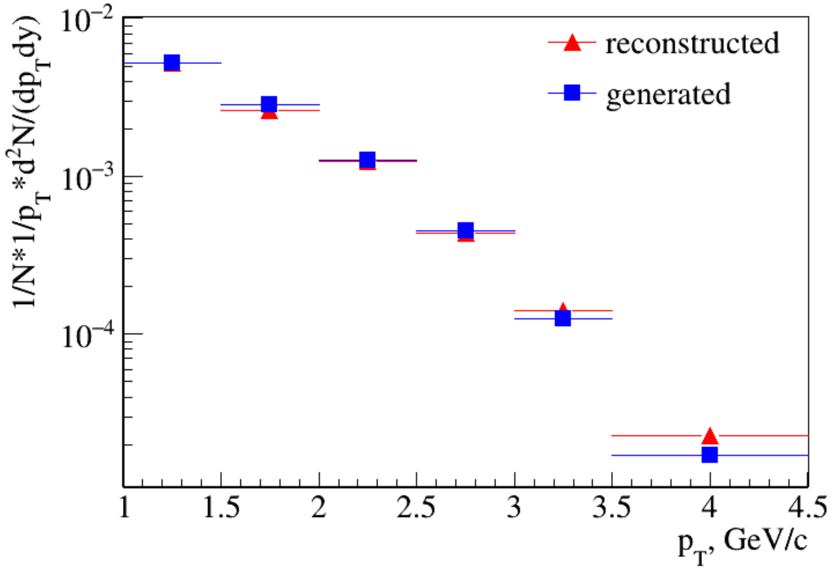


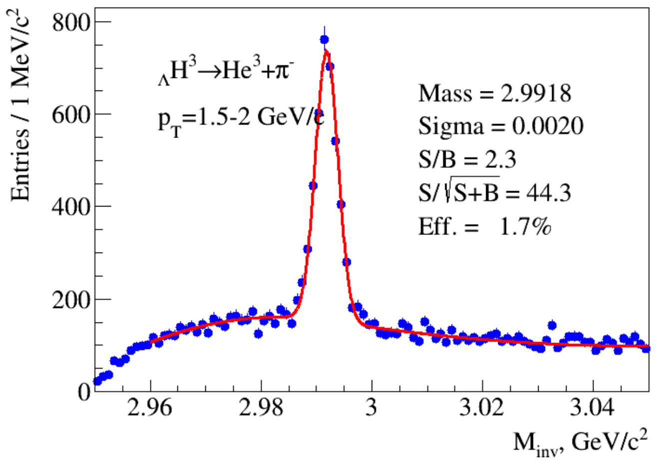
Hypertritons in MPD: invariant spectra

- 40M Events Bi+Bi at 9.2 GeV, |y|<1 (PHQMD model)
- Full event simulation and reconstruction
- A set of topological cuts aimed at maximizing significance





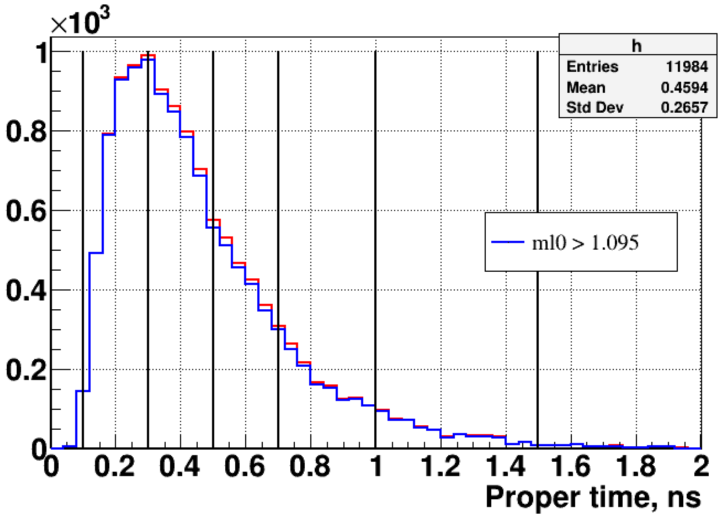


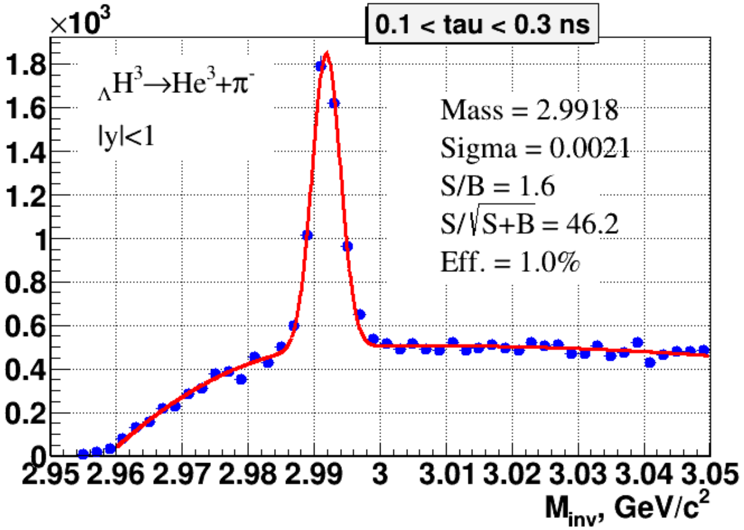


- Invariant spectrum of hypertritons is reconstructed up pT=4.5 GeV/c
- With a larger data sets, pT-spectra and rapidity densities can be obtained in centrality selected Bi+Bi collisions over a large phase space shedding light to the formation details and collective behavior of hypernuclei

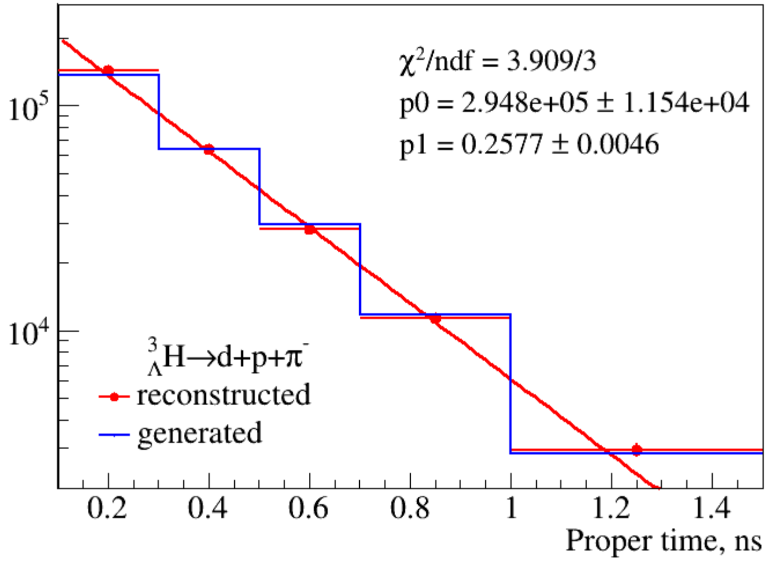
Hypertritons in MPD: lifetime analysis

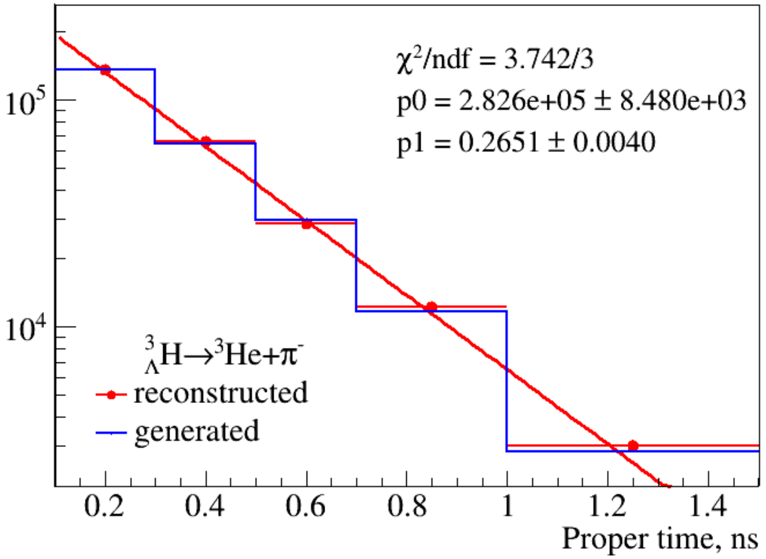
- Hypertritons are reconstructed in several \tau bins
- 2- and 3-prong decay modes were studied separately to estimate systematics





$\tau = ML/p$ (p – momentum, M-hypertriton mass, L-track length)





$$N(\tau) = N(0)\exp\left(-\frac{\tau}{\tau_0}\right) = N(0)\exp\left(-\frac{ML}{cp\tau_0}\right),$$

Results for different decay modes are consistent

Summary

- NICA complex has a potential for competitive research in the fields of dense baryonic matter

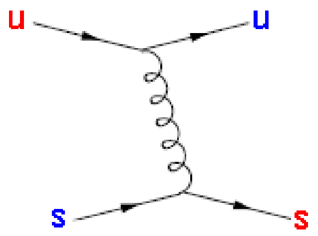
- With high statistics data on light hadrons and (hyper)nuclei from NICA we aim to understand better the structure of the QCD phase diagram, nuclear matter EOS, phase transformations and critical phenomena in strongly interacting matter.

Thanks for listening!

Spares

Standard Model (SM) of Particle Physics

SM postulates:

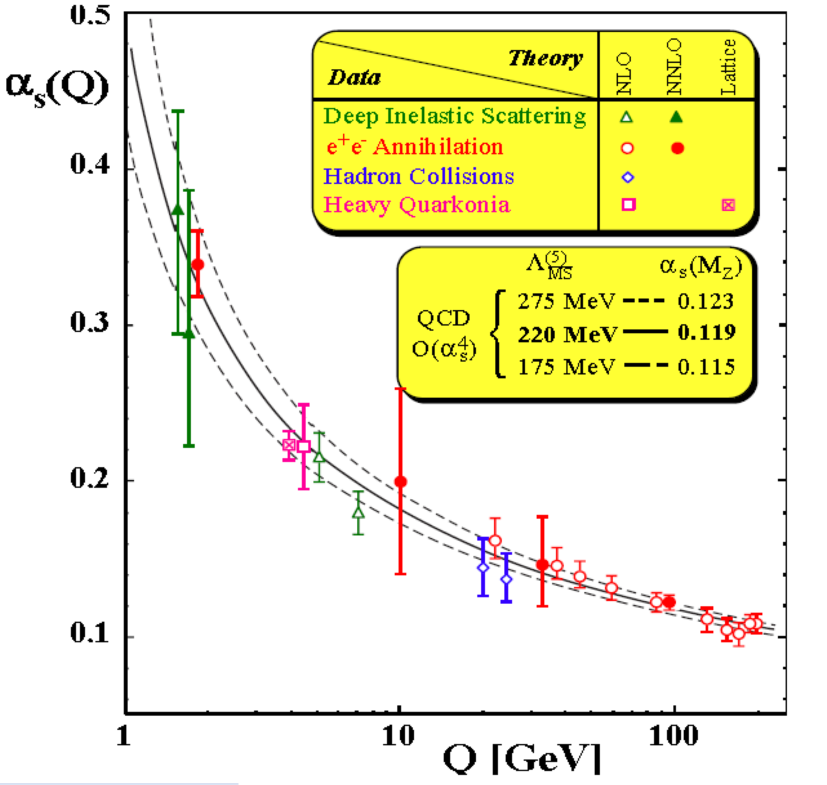


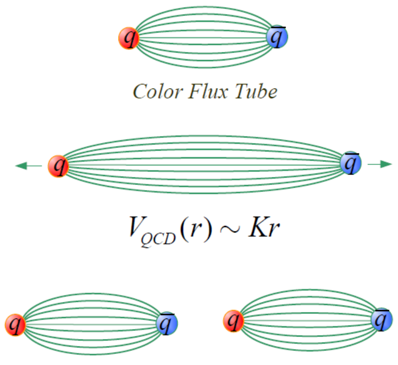
- Building blocks (fundamental particles) of Matter are quarks, leptons and gauge bosons (+ Higgs)

- Every quark possesses a new quantum number (degree of freedom): the color. There are 3 different colors, thus each quark can have three distinct color states (read, green, blue). Quarks interact via gluon exchange. There are 8 kinds of gluons, they are also colored and can interact with each other

- Distinctive features of strong interactions are **confinement** and **asymptotic freedom**.

Confinement Asymptotic freedom





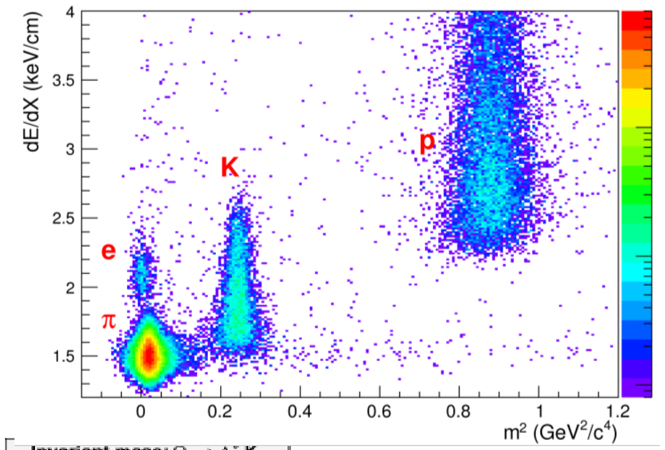
Quark-antiquark potential:

$$V(r) = -\frac{a}{r} + br$$

Theory of strong interactions Quantum Chromo-Dynamics (QCD)

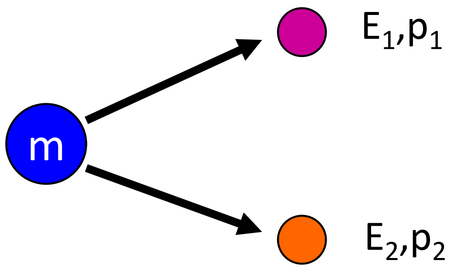
Particle ID in MPD

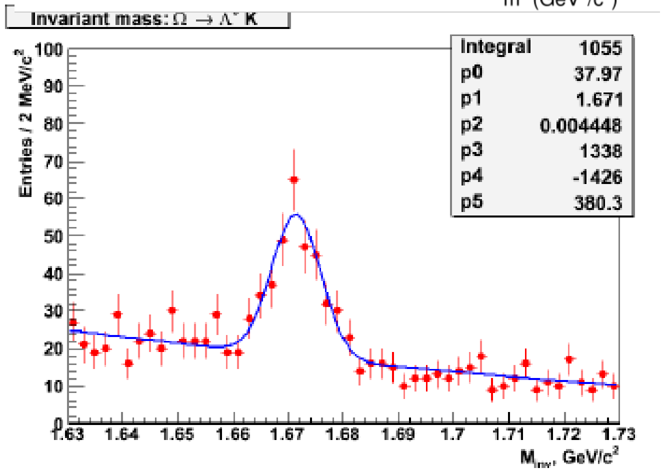
Measuring momentum and velocity $p = m\,v / \sqrt{1 - \beta^2}$



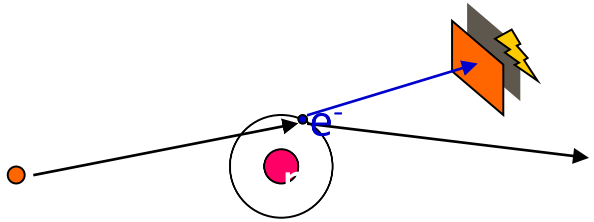
Measuring E and p of decay products:

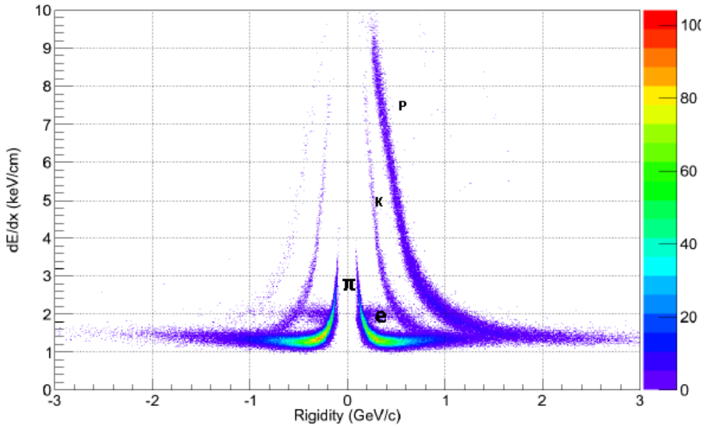
$$m^2 c^4 = (E_1+E_2)^2 - (cp_1+ cp_2)^2$$





Measuring ionization loss in the TPC gas





Kinematics in HIC

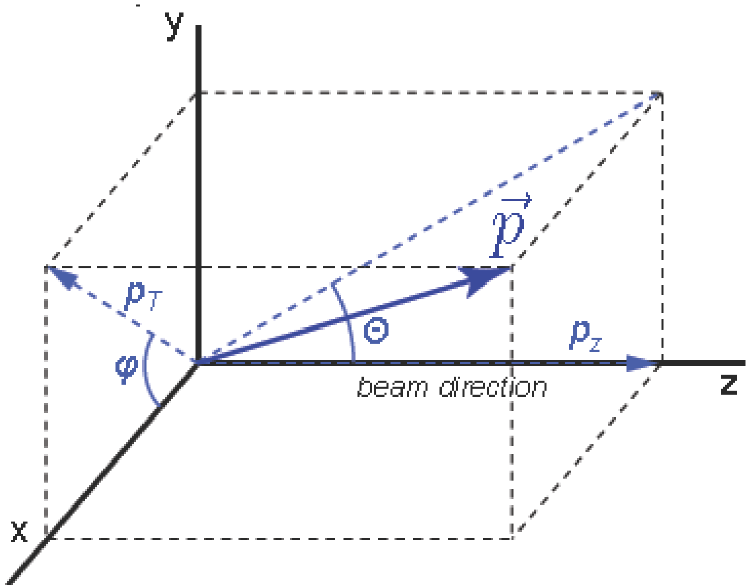
transverse momentum $$p_T = \sqrt{p_x^2 + p_y^2}$$

transverse mass $$m_T = \sqrt{p_T^2 + m^2}$$

rapidity $$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \tanh^{-1}\frac{p_z}{E}$$

pseudorapidity $$\eta = -\ln\tan\frac{\theta}{2}$$

$$y \approx \eta \text{ for } p \gg m$$



$$E = m_T \cosh y$$
$$p_z = m_T \sinh y$$

Invariant cross-section: $$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi}\frac{d^2\sigma}{p_T dp_T dy} = f(y)g(p_t)h(\phi)$$