Event-by-event determination of thermodynamic quantities at NICA energies

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Fundamental problems and applications

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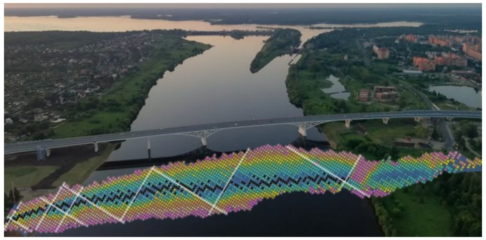
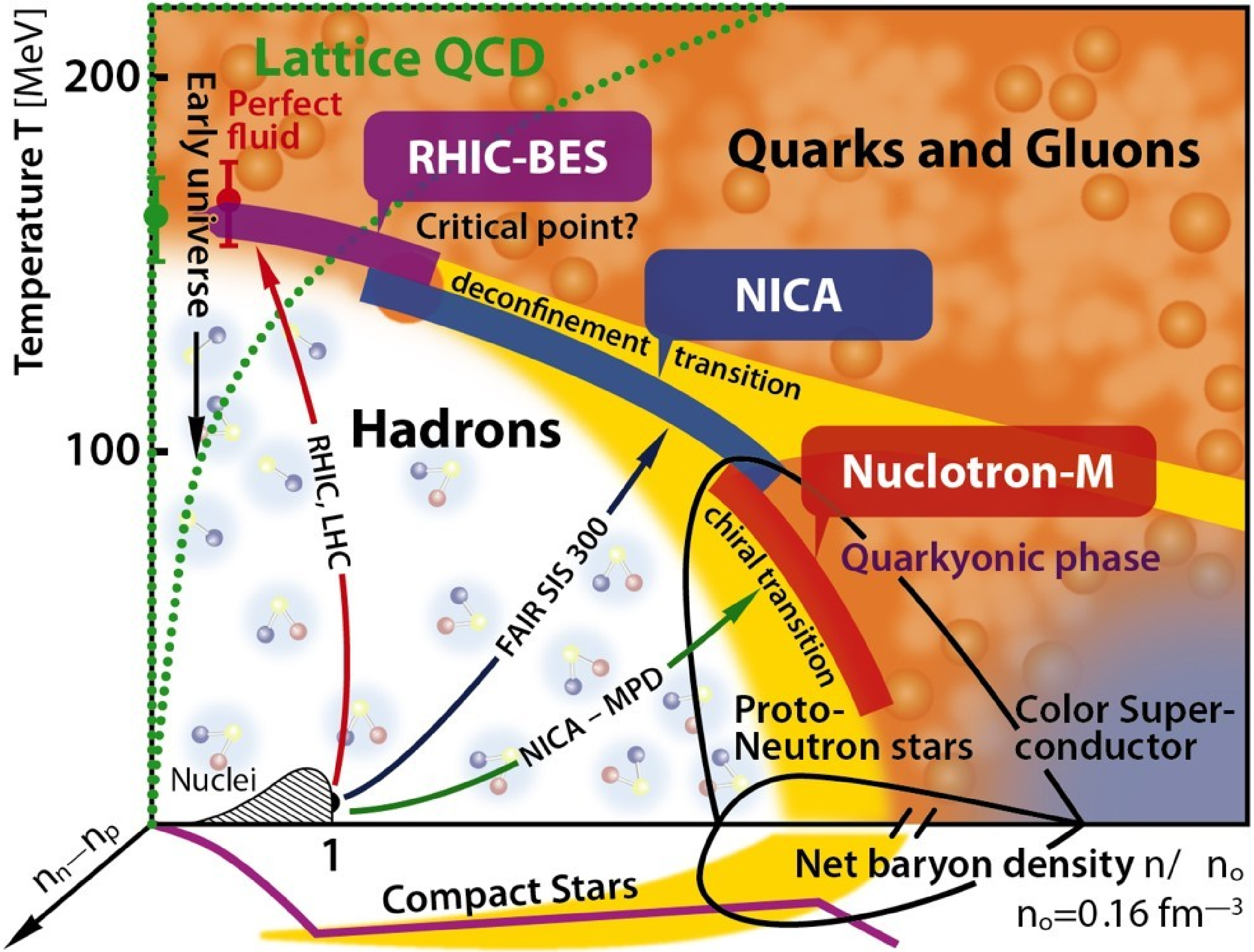


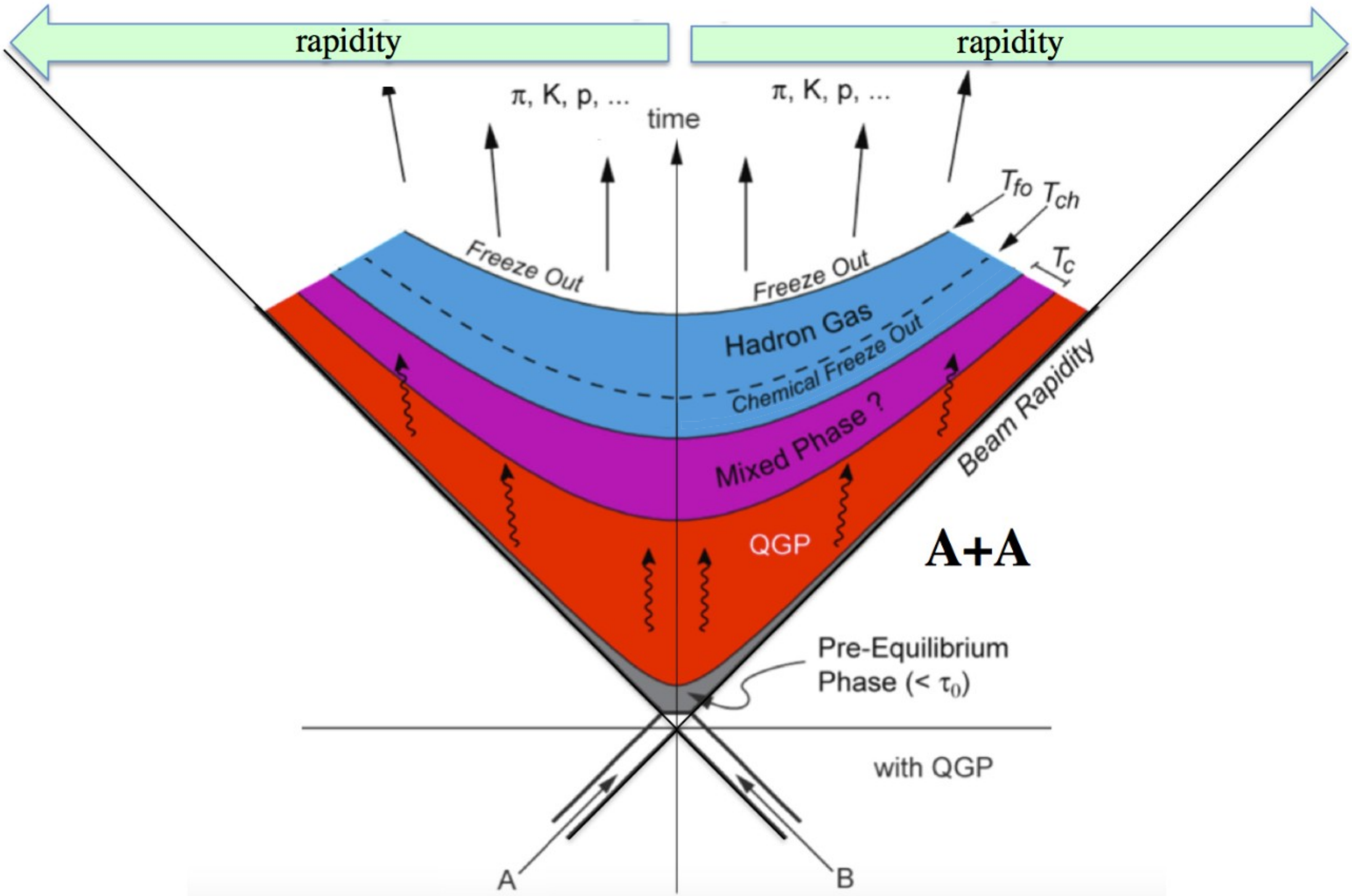
The study was funded by the Russian Science Foundation grant No.23-12-00042, https://rscf.ru/en/project/23-12-00042/.

Study of the Phase diagram of the QCD matter



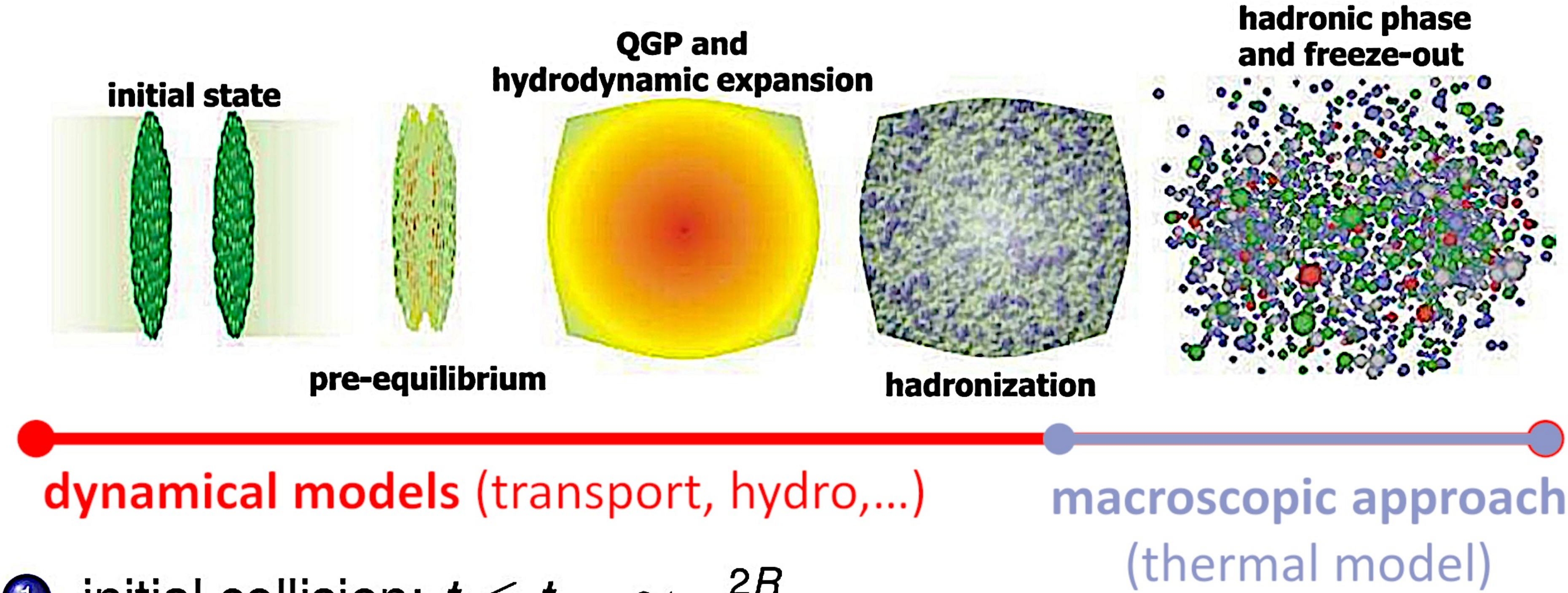
https://nica.jinr.ru/physics.php

Evolution stages of nucleus-nucleus collision



Adopted from Wei Li. An experimentalist's view on collectivity in small systems. XII QCHS Aug. 29 – Sep. 3, 2016

Evolution stages of nucleus-nucleus collision

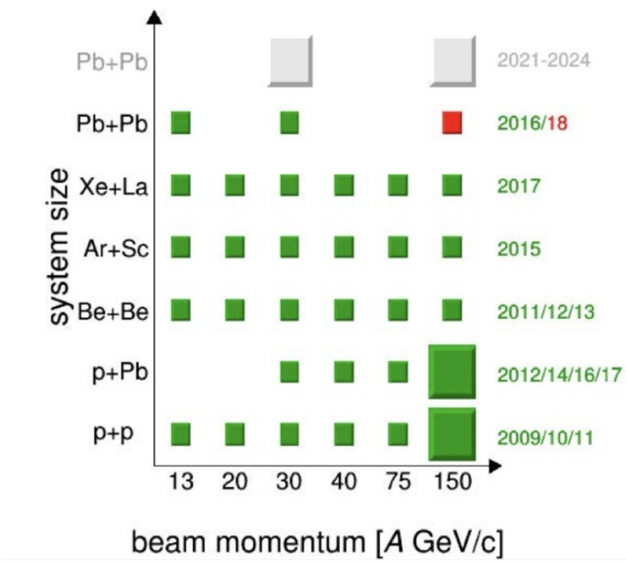


1. initial collision: $t \leq t_{coll} \simeq \frac{2R}{\gamma_{\text{cms}}^{\text{boost}} c}$
2. thermalisation: equilibrium is reached : $t \leq$ 1fm/c
3. expansion and cooling : $t \leq 10 - 15$fm/c
4. hadronisation
5. Chemical freeze-out: the inelastic collisions stop
   $\rightarrow$ the yields are fixed
6. Kinetic freeze-out : the elastic collisions stop
   $\rightarrow$ the spectra are fixed : $t \leq$ 30-50 fm/c

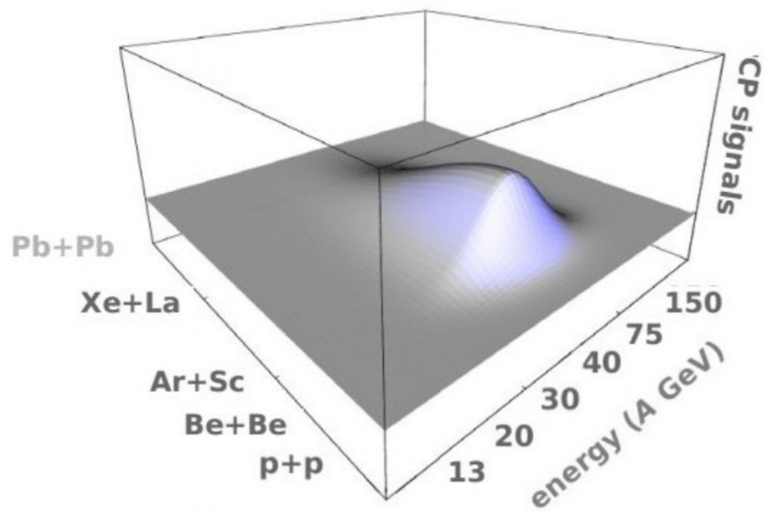
from lectures by D. Oliinychenko, E. Bratkovskaya
V. Vovchenko, Statistical thermal model https://vovchenko.net/files/pdf/lectures/vovchenko_lund2019_lect.pdf

Experimental search of the Critical point

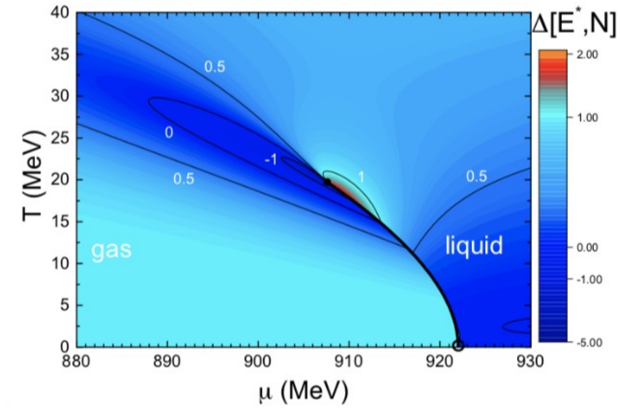
- study the properties of the onset of deconfinement
- search for the critical point (CP) of strongly interacting matter

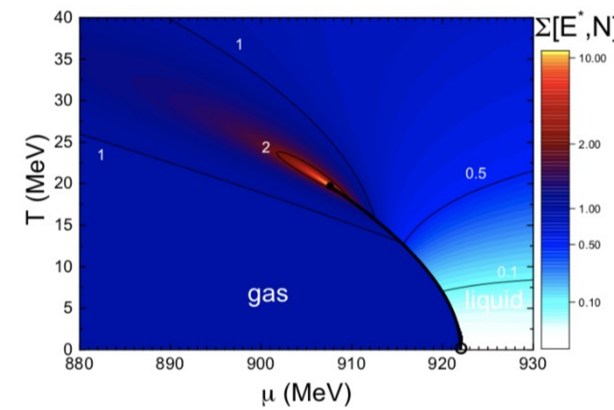


Data taking schedule



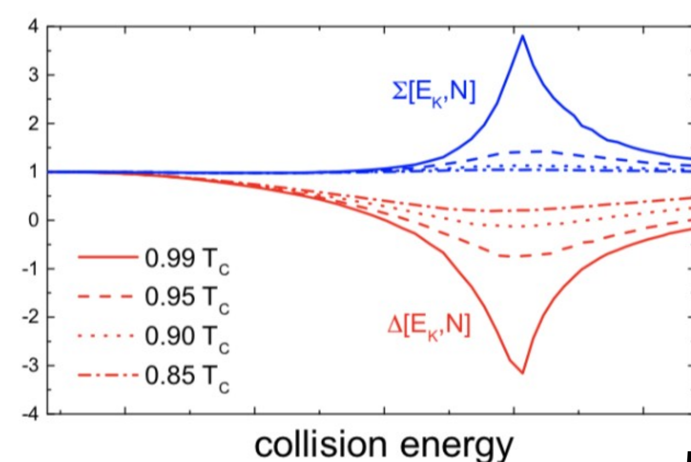
Sketch of the expected «critical hill»





What is the CP signal amplitude?
What if it is shadowed by volume fluctuations?

STAR at RHIC (BES+BES-FXT)
NA61/SHINE at SPS
MPD at NICA
CBM FAIR SIS-100



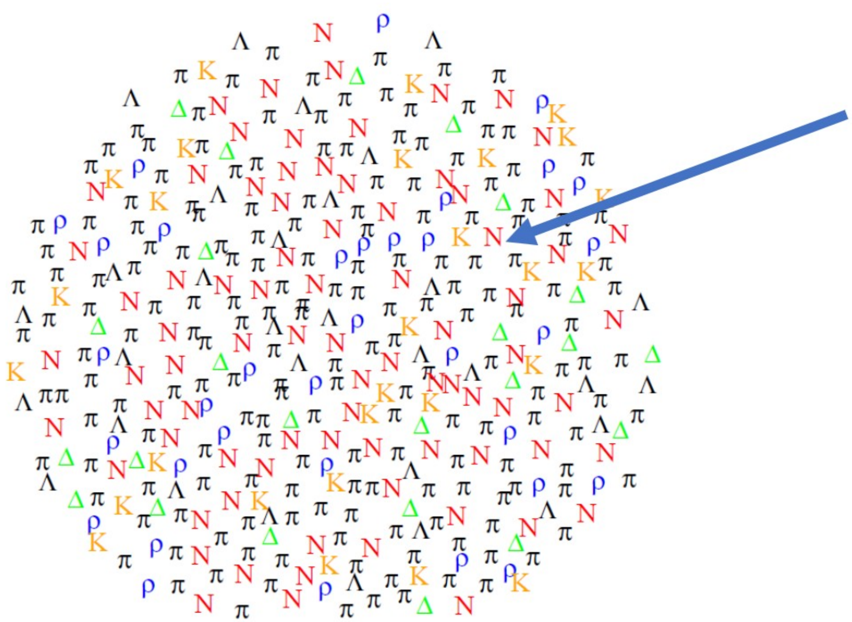
Daria Prokhorova for NA61/SHINE Collaboration, ICPPA 2018
Vovchenko, Gorenstein, Stoecker, PRL 118: 182301, Vovchenko, et al., JPA 48: 305001

Thermal model of the hadron resonance gas

HRG: Equation of state of hadronic matter as a multi-component non-interacting gas of known hadrons and resonances

$$\ln Z \approx \sum_{i\in M,B} \ln Z_i^{id} = \sum_{i\in M,B} \frac{d_i V}{2\pi^2} \int_0^\infty \pm p^2 dp \ln\left[1 \pm \exp\left(\frac{\mu_i - E_i}{T}\right)\right]$$

Grand-canonical ensemble: $\mu_i = b_i\mu_B + q_i\mu_Q + s_i\mu_S$ ***chemical equilibrium***



Thermal model:
Equilibrated hadron resonance gas at the chemical freeze-out stage of high-energy collisions

Model parameters:
T – temperature
μ_B, μ_Q, μ_S – chemical potentials
V – system volume

Include all resonances as free, point-like particles (~400 species) established in the PDG listing

Thermal model of the hadron resonance gas

$$N_i^{hrg} = \frac{d_i V}{2\pi^2}\int_0^\infty p^2 dp \left[\exp\left(\frac{E_i-\mu_i}{T}\right) \pm 1\right]^{-1} \quad \propto \quad e^{-m_i/T}$$

Particle decays: Unstable resonances decay before being detected

$\Delta \to N, \pi$ $\qquad K^* \to K, \pi$ $\qquad \rho \to \pi, \pi$ $\qquad$ etc.

Take into account feeddown: $N_i^{\text{fin}} = N_i^{\text{hrg}} + \sum_j BR(j \to i) N_j^{\text{hrg}}$

60-70% of π, p, etc. are from feeddown

Conservation laws:

Zero net strangeness $\to$ $\boldsymbol{\mu_S}$

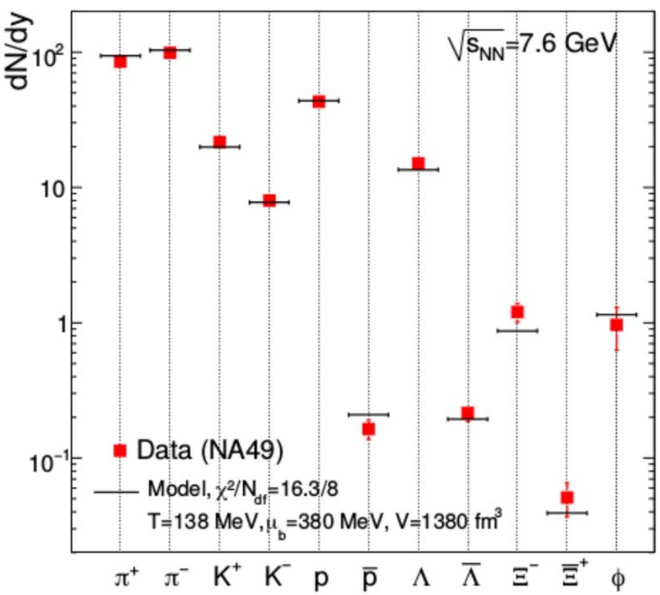
Electric-to-baryon ratio Q/B = 0.4-0.5 $\to$ $\boldsymbol{\mu_Q}$

Freeze-out parameters T, μ_B, V extracted through **χ^2 minimization**

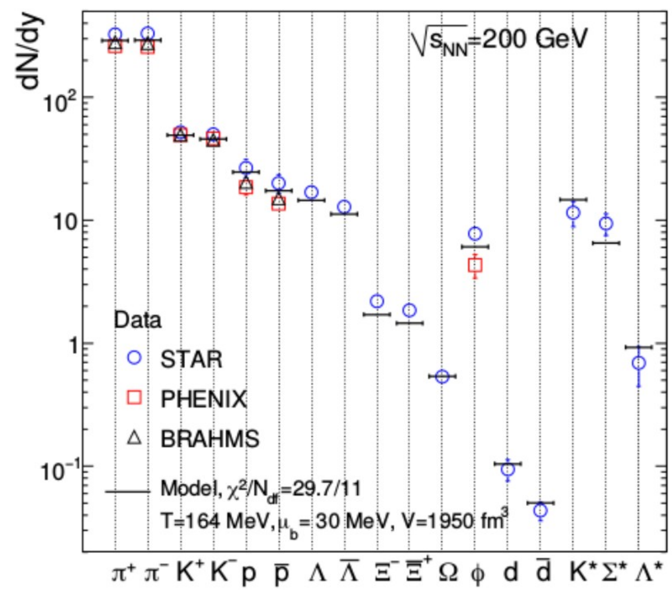
$$\chi^2 = \sum_i \frac{(N_i^{\text{fin}} - N_i^{\text{exp}})^2}{(\sigma_i^{\text{exp}})^2}, \qquad i = \pi, K, p, \Lambda, \ldots$$

V. Vovchenko, Statistical thermal model https://vovchenko.net/files/pdf/lectures/vovchenko_lund2019_lect.pdf

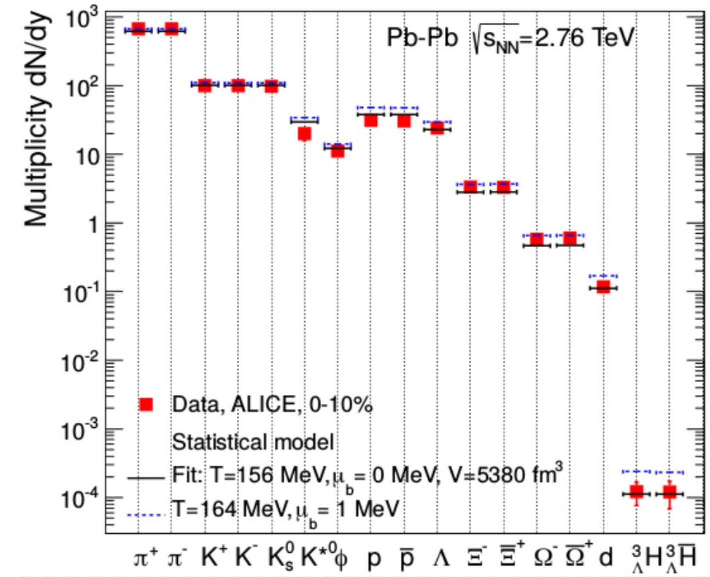
Determination of the chemical freeze-out parameters



NA49



RHIC



ALICE

$$\chi^2 = \sum_i \frac{(N_i^{\mathrm{fin}} - N_i^{\mathrm{exp}})^2}{(\sigma_i^{\mathrm{exp}})^2}, \qquad i = \pi, K, p, \Lambda, \ldots$$

Model

THERMUS 2.3

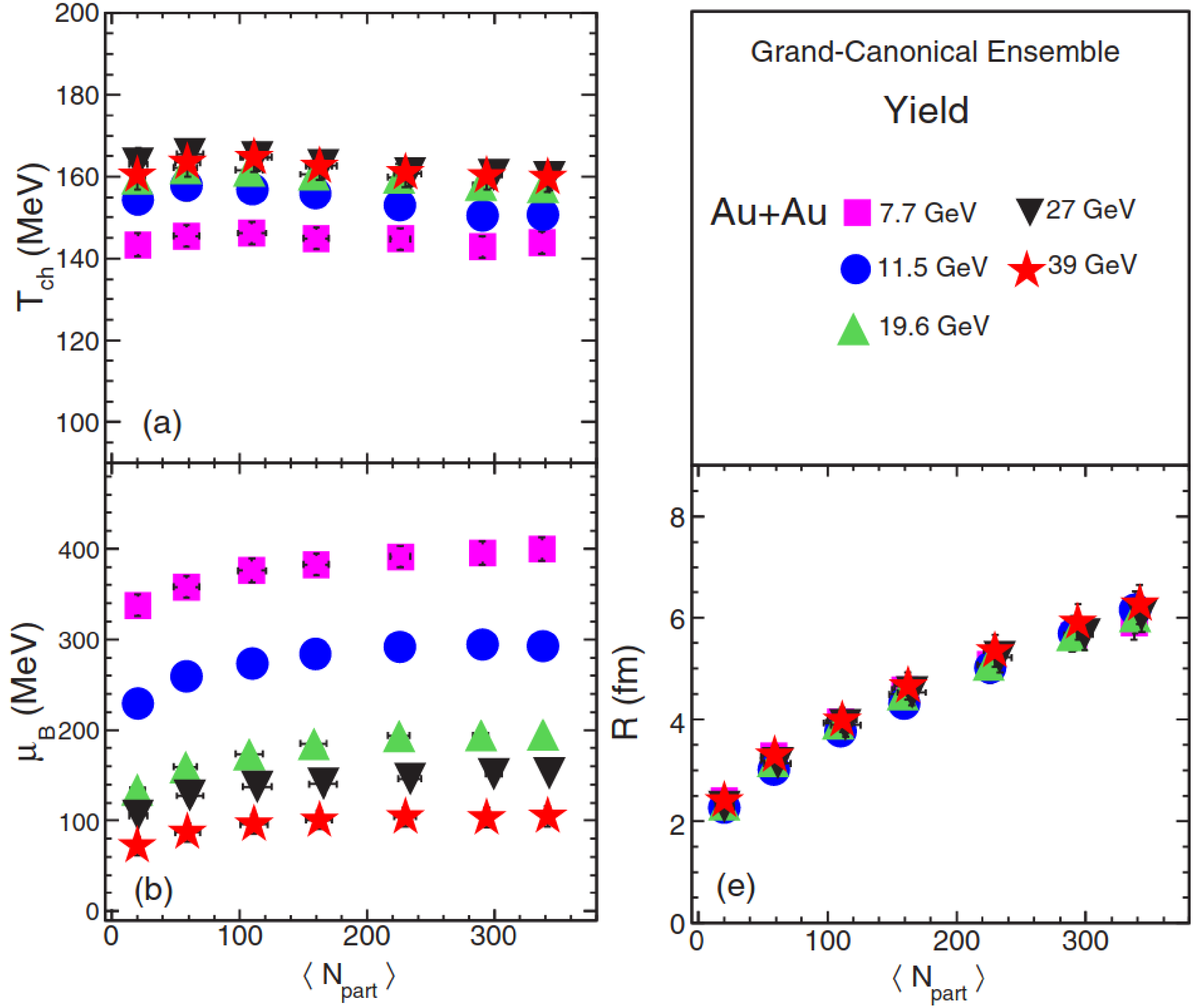
GSI-Heidelberg

SHARE 3

-> Thermal-FIST

V. Vovchenko. H. Stoecker, Thermal-FIST: A package for heavy-ion collisions and hadronic equation of state
Comput.Phys.Commun. 244 (2019), 295-310, arXiv 1901.05249 [nucl-th]

Chemical freeze-out parameters at RHIC energies



[1] L. Adamczyk et al (STAR Collaboration) Phys Rev C 96, 044904 (2017)

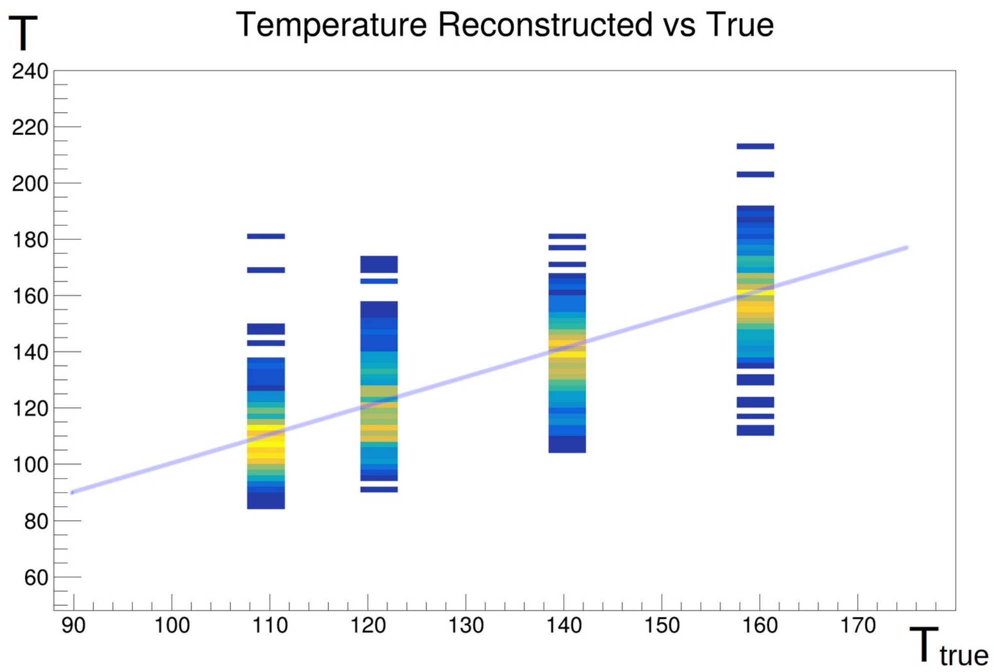
Event-by-event determination of μ_B and T

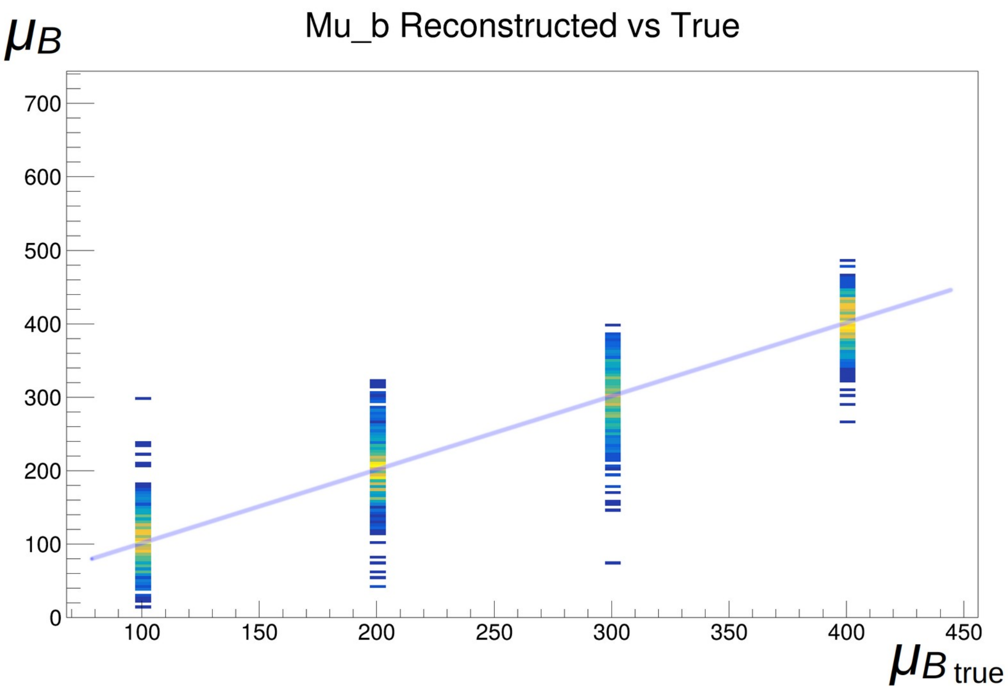
- Define μ_B and T (true values)
- Generate one event
- Select particles: $K^{\pm}$, $\pi^{\pm}$, p, $\bar{p}$, (optionally K_0^s, Λ, $\bar{\Lambda}$...)
- Count number of particles within the acceptance
- Fit per-event spectra with Thermal model (set error=√mean)
- Obtain $\mu_B \pm \Delta\mu_B$, $T \pm \Delta T$, $R \pm \Delta R$ (volume $V=4/3\ \pi R^3$)
- Repeat, average over event. Compare averages with true values.
- Check: fraction of events where $T_{true} - \Delta T_i < T_i < T_{true} + \Delta T_i$ (should be ≈68%)
- Calculate the method resolution as $R_T = \sqrt{(<T - T_{true}>^2)} / T_{true}$, etc

Event-by-event determination of μ_B and T

Au-Au collisions at 11 GeV, central class (0-5%)

We set in mid-rapidity $N_{ch} \approx 500$ (for $dN_{ch}/dy \approx 336$ [1])





Fraction of events where $T_{true} - \Delta T_i < T_i < T_{true} + \Delta T_i$: **70%**

Fraction of events where $\mu_{Btrue} - \Delta\mu_{Bi} < \mu_{Bi} < \mu_{Btrue} + \Delta\mu_{Bi}$: **69%**

[1] L. Adamczyk et al (STAR Collaboration) Phys Rev C 96, 044904 (2017)

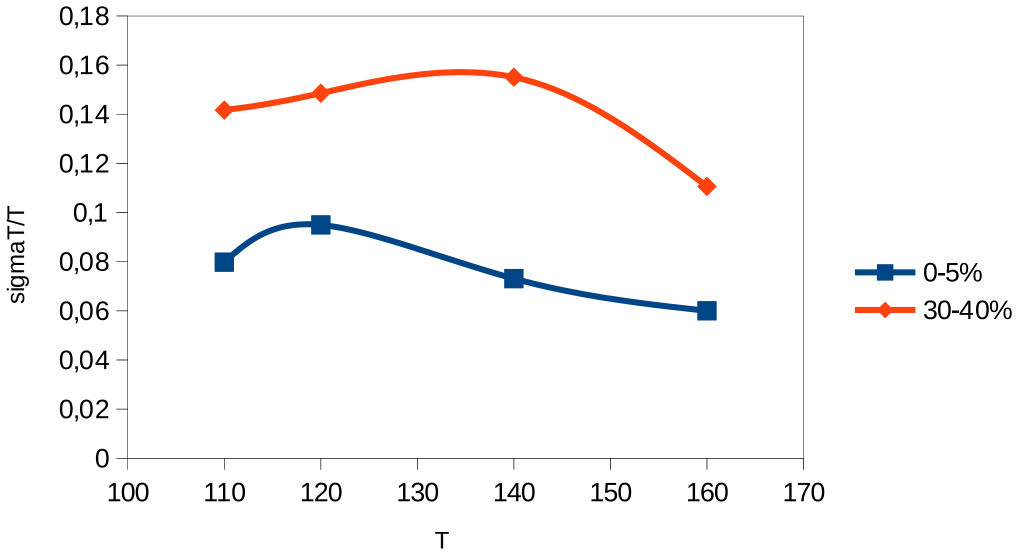
Determination of the method resolution

Au-Au collisions at 11 GeV

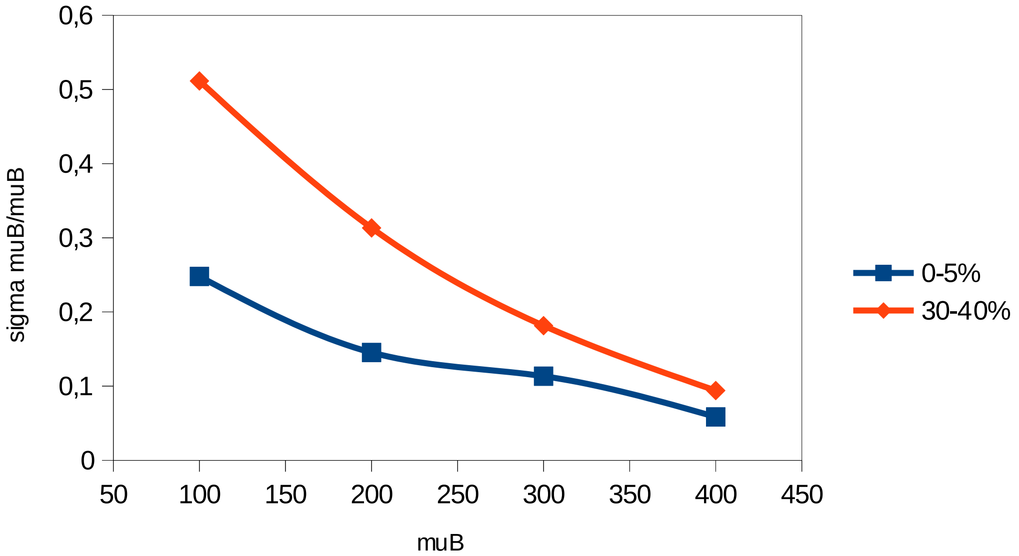
We set in mid-rapidity $N_{ch} \approx 500$ *(for* $dN_{ch}/dy \approx 336$ [1]*), central (0-5%)*

We set in mid-rapidity $N_{ch} \approx 168$ *(for* $dN_{ch}/dy \approx 113$ [1]*), non-central (30-40%)*

Temperature resolution



Baryochemical potential resolution



So, in Au-Au collisions at 11 GeV ($\mu_B \approx 300$ *MeV and* $T \approx 150$ *MeV)*
we expect resolution about 15% (without accounting detector effects)

[1] L. Adamczyk et al (STAR Collaboration) Phys Rev C 96, 044904 (2017)

Application to Monte Carlo generators: SMASH and EPOS4

***SMASH**, Au-Au collisions at 11 GeV, central (0-5%)*

*T=98.5MeV, σ_T=13.4MeV, R_T=14%, Fraction of events within ΔT **47%***

*μ_B=430MeV, $\sigma_{\mu B}$=25MeV, $R_{\mu B}$=6%, Fraction of events within $\Delta\mu_B$ **64%***

***SMASH**, Au-Au collisions at 11 GeV, non-central (30-40%)*

*T=93.1MeV, σ_T=18.0MeV, R_T=19%, Fraction of events within ΔT **55%***

*μ_B=447MeV, $\sigma_{\mu B}$=43MeV, $R_{\mu B}$=9.6%, Fraction of events within $\Delta\mu_B$ **68%***

***EPOS4**, Au-Au collisions at 11 GeV, central (0-5%)*

*T=139.1MeV, σ_T=12.1MeV, R_T=8.7%, Fraction of events within ΔT **64%***

*μ_B=337MeV, $\sigma_{\mu B}$=20MeV, $R_{\mu B}$=6.0%, Fraction of events within $\Delta\mu_B$ **69%***

J. Weil et al (SMASH Collaboration), Phys.Rev.C 94 (2016) 5, 054905, arXiv: 1606.06642 [nucl-th]
K. Werner, Phys. Rev. C 108, 064903 (2023), arXiv:2301.12517

Application for search for μ_B and T fluctuations in the real experimental data

- Fit experimental data and obtain average μ_B and T
- Set μ_B and T as true in Thermal Monte Carlo generator (for ex. Thermal-FIST).
  Set R to fit the multiplicity.
- Generate events and transfer data through Geant to get detector response, reconstruct events
- Obtain per-event μ_B and T
- Make sure that the estimate in reconstructed data is still correct, note the resolution.
- Apply the setup to experimental data, check if the fluctuations in μ_B and T are higher than the estimated resolution. The difference is accounted for real fluctuations in μ_B and T
- Check the estimate of fraction of events within sigma,
  it is expected to be ~68% at no fluctuations, and it is lower in presence of fluctuations (this also can reflect non-thermal behaviour in general)
- Each event can be assigned a probability density of the thermodynamical parameters, to use it together with other analysis sensitive to fluctuations.

Conclusions

- A method for estimating the temperature and baryon chemical potential in each event is developed
- Self-consistency of the method is demonstrated using Thermal-FIST package with its own Monte Carlo generator
- The approach was applied to event generators SMASH and EPOS4
- The resolution of the estimation at the level of 15% was obtained.
- The results showed the fundamental applicability of this method in a wide range of (T, μ_B)

Thank you

The reported study was supported by the Russian Science Foundation, project no. 23-12-00042, https://rscf.ru/en/project/23-12-00042/