

## QCD PHASE TRANSITION STUDIED BY MEANS OF HADRON PRODUCTION

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We address the hadronization process of a QGP fireball formed in relativistic heavy-ion collisions in the entire range of past and present heavy-ion collision reaction energies. A precise method of analysis of hadron multiplicities has evolved into the “SHARE with CHARM” statistical hadronization model. Using this tool, we successfully describe — over many orders of magnitude — the yield of all hadrons produced in the full range of reaction energies and centralities; exceptions are peripheral and more central collisions at low energies. The properties of the fireball final state can be understood by considering all primary hadronic particles. The dense hadron fireball created at SPS, RHIC, and LHC shows the final state differentiated solely by: i) volume changes; and ii) strangeness, (charm) flavor content. A universal hadronization pressure  $P = (80 \pm 3) \text{ MeV/fm}^3$  is found. The strangeness content of a large fireball, as compared to entropy, shows the presence of quark–gluon plasma degrees of freedom near the chemical QGP equilibrium. The “Universal Hadronization” condition common to SPS, RHIC, and LHC agrees with the proposed direct QGP fireball evaporation into free-streaming hadrons. Looking ahead, we discuss qualitatively how heavy-flavor production contributes to energy stopping in the central rapidity region as function of reaction energy: the cases of LHC at full energy and future super-LHC.

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### 1. STATISTICAL HADRONIZATION WITH RESONANCES

The focus of the statistical hadronization model is on particle abundances, i.e., the integrated  $p_{\perp}$  spectra as measured in heavy-ion collision experiments. Our interest is mainly in properties of the source which are evaluated independently of the complex transverse dynamics. This is the reason to analyze the integrated  $p_{\perp}$  spectra. Particle yields allow the exploration of the source properties in the frame comoving with the particles; the collective transverse matter dynamics gets integrated out.

We describe particle yields within Fermi’s statistical approach using Hagedorn’s canonical reformulation which we call statistical hadronization model

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(SHM). That if, by assuming equal hadron production strength irrespective of produced hadron type, the particle yields depend only on the available phase space:

- Fermi microcanonical phase space has sharp energy and a sharp number of particles [1]. However, since experiments report event-averaged rapidity particle abundances, the model should describe an average event.

- Canonical phase space has a sharp number of particles, but an ensemble of average energy  $E$  which is adjusted by the (inverse) temperature  $T$  as a Lagrange multiplier which may be, but needs not be, a kinetic process temperature.

- Grand-canonical ensemble phase space fixes both energy  $E$  and number of particles  $N$  on average.  $N$  is a constraint implemented by the Lagrange multiplier  $\mu$ , the chemical potential, which is equivalent to the use of the fugacity  $\Upsilon = e^{\mu/T}$ .

We have implemented the SHM in a publicly available program to fit the SHM parameters. The program is called SHARE (Statistical HAdronization with REsonances) and was released in its first version by Torrieri et al. [2], then augmented in its second version by fluctuations [3], and in its recently updated version charm was also included [4].

SHARE incorporates in its many thousand lines of code the mass spectrum of more than 500 hadrons according to the particle data group (PDG 2012) [5]; hadron decays in more than 2500 channels (PDG 2012); integrated hadron yields, ratios, and decay cascades. Its output provides the yields of all (presently  $\sim 30$ ) experimentally observed hadron species and the physical properties of the particle source at hadronization. Bulk matter constraints such as charge per baryon (for heaviest ions  $Q/B \sim 0.39$ ) and that the net strangeness vanishes  $\langle s - \bar{s} \rangle = 0$  are implemented.

In Fig. 1, we show the scheme of the SHARE program structure. The fitting of the SHM parameters to observational data proceeds according to the following steps:

1. Input by hypothesis:  $T, V, \gamma_q, \gamma_s, \lambda_q, \lambda_s, \lambda_3$ .
2. Compute the yields of all primary hadrons.
3. Account for decay feed-down to observed particles.
4. Evaluate bulk properties and bulk constraints.
5. Compare to experimental data and evaluate  $\chi^2$  including bulk constraints.
6. Use  $\chi^2$  minimization strategies to tune parameters to match data and constraints — with new parameters go back to item 1.

SHARE iterates these steps till CERN provided programs for parameter optimization terminate. Several initial input parameter sets can be tried to assure that the same best, stable parameter fit is found. If such a solution is not achieved, it is advisable to evolve a better initial input parameter set from fits that worked nearby either in energy or centrality. In order to account for the quark flavor chemistry, we introduce the following quantities which go back to the initial model of QGP hadronization of 30 years ago [6], for illustration see also Fig. 2:

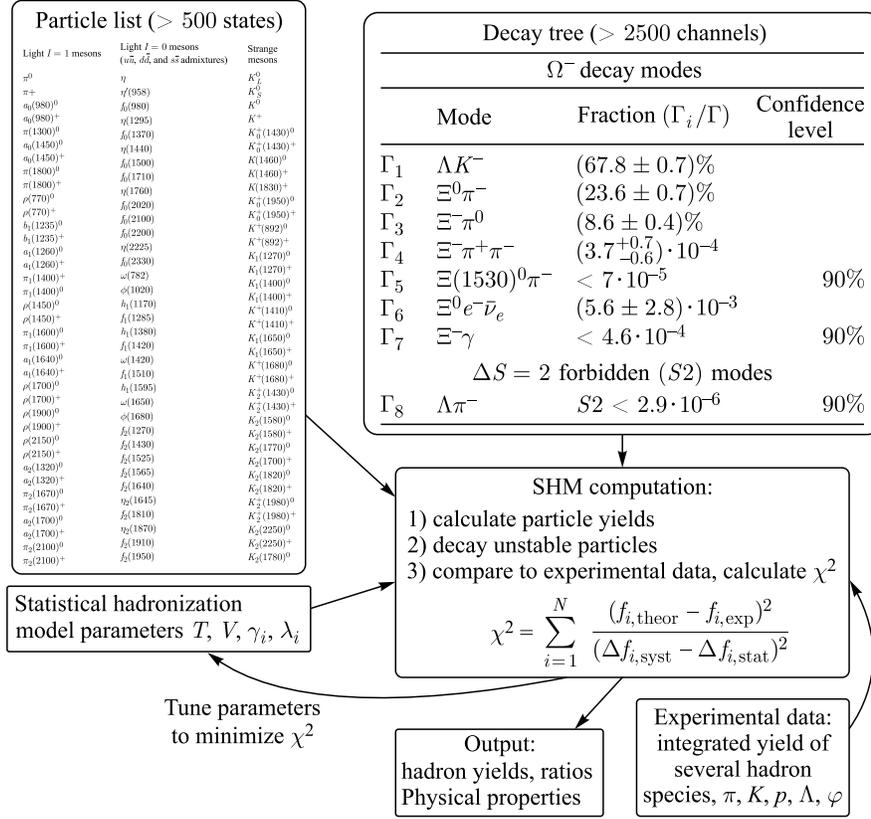
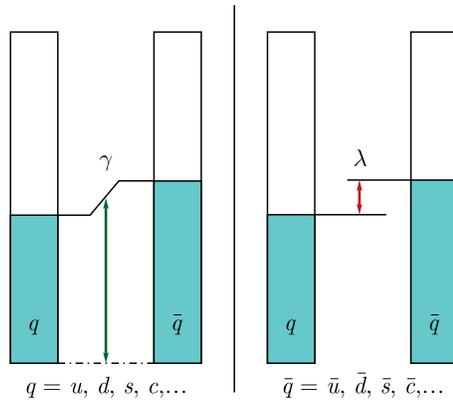


Fig. 1. Scheme of the SHARE program structure

Fig. 2. Illustration of the difference in action of quantities required in the SHM for describing chemical conditions: the flavor conservation factor  $\lambda$  and the flavor yield factor  $\gamma$

- Flavor conservation factor  $\lambda_q = e^{\mu/T}$ : it controls the difference between quarks and antiquarks of the same flavor  $q - \bar{q}$  and describes “relative” chemical equilibrium.

- Flavor yield factor  $\gamma_q$ : it measures the phase space occupancy, the absolute abundance of flavor  $q$ , controls the number of quark–antiquark pairs  $q + \bar{q}$ , and describes “absolute” chemical equilibrium.

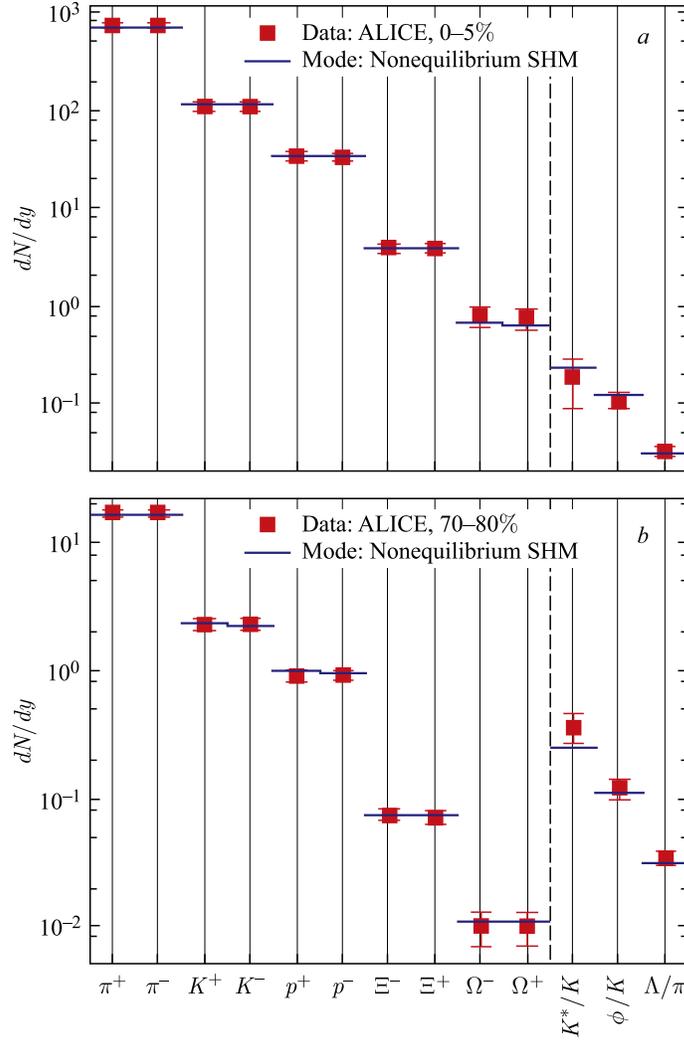


Fig. 3. Comparison of LHC–ALICE Collaboration results with the SHM: for both central (a) and peripheral (b) Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV

- Overall fugacity  $\Upsilon = \gamma\lambda$ : it is a product of the contributions from the constituent quark flavors contained in hadron  $i$ . For example,  $\Lambda(uds)$  is described with ( $q = u, d$ ):  $\Upsilon_{\Lambda(uds)} = \gamma_q^2 \gamma_s \lambda_q^2 \lambda_s$  and for the antilambda holds  $\Upsilon_{\bar{\Lambda}(\bar{u}\bar{d}\bar{s})} = \gamma_q^2 \gamma_s \lambda_q^{-2} \lambda_s^{-1}$ .

- As noted above, strangeness (and charm) has similar fugacity factors as light quarks  $q = u, d$  with flavor indicated by lower index.

The questions and topic we address in the following are:

1. Does the SHM describe particle production at LHC, see Fig. 3?
2. How does the QGP fireball hadronize?
3. What is the same and what is different comparing to RHIC?
4. Universality across all collision energies: SPS, RHIC, LHC.

## 2. SHM DESCRIPTION OF LHC RESULTS

We test the SHM by applying it to the LHC data of the ALICE Collaboration obtained in the Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, where the hadron yields span 5 orders of magnitude from central to peripheral collisions. The fit works perfectly, see Fig. 3, in the entire range of centralities. The salient element that makes the SHM work is the allowance for chemical nonequilibrium of light quarks  $\gamma_q \simeq 1.6$ , a result motivated by the entropy content of the QGP and fast hadronization. The preference for this nonequilibrium value is seen for all centralities in Fig. 4 in the study of the profile of  $\chi^2$  as the function of  $\gamma_q$ .

In Fig. 5, we see the centrality dependence of some of the particle yield ratios which play an important role in recognizing the chemical properties of the

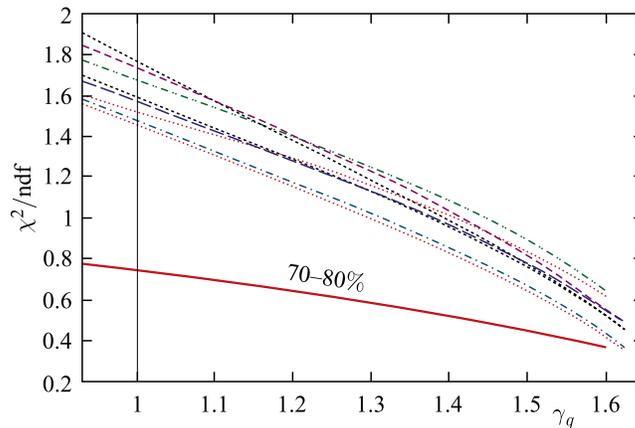


Fig. 4. The dependence of the  $\chi^2$  for the fit on the flavor yield factor justifies the choice of  $\gamma_q = 1.6$  for best fit, see [7]

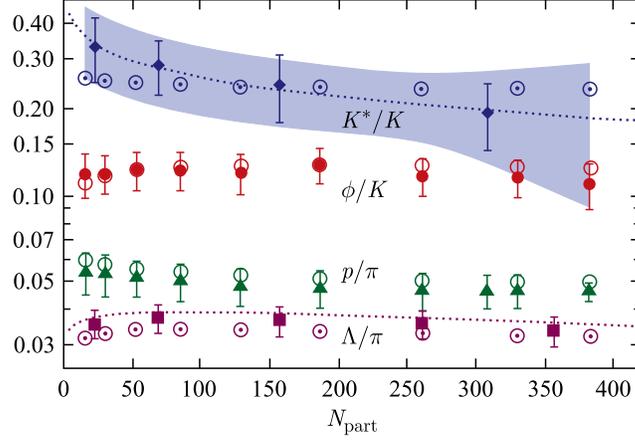


Fig. 5. Comparison of selected ratios in the ALICE experiment (full symbols) to the nonequilibrium SHM (open symbols) for the Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, see [7]

hadron source. Only with chemical nonequilibrium of light quarks,  $\gamma_q = 1.6$ , we can describe all LHC data. No other approach works; the so-called “afterburners” which can fix one particle yield, ruin the centrality systematics of other particles.

### 3. SHM DESCRIPTION OF RHIC-62

With the success of our approach at LHC, we turn now to the question, whether the SHM approach also describes particle production at RHIC. Clearly, this question is a very large one and we focus here on one of the collision energies that we were able to look at comprehensively. This is the case of Au–Au results obtained at  $\sqrt{s_{NN}} = 62$  GeV. As the energy is lower, one expects that more peripheral collisions are less likely to reach a thermally equilibrated QGP stage. Thus, another question arises: for how small a system is the hadronization at RHIC of the same universal character we see it at LHC?

We performed the analysis with SHARE for Au–Au collisions at RHIC  $\sqrt{s_{NN}} = 62$  GeV and have compared the results for the fireball properties with the LHC fits. The results are shown in Fig. 6, where an excellent fit ( $\chi^2 = 0.38$ ) of STAR data [8, 9] is obtained with the model parameters:  $T = 140$  MeV,  $dV/dy = 850$  fm<sup>3</sup>,  $\gamma_q = 1.6$ ,  $\gamma_s = 2.2$ ,  $\lambda_q = 1.16$ ,  $\lambda_s = 1.05$ , corresponding to  $\mu_B = 62.8$  MeV [10].

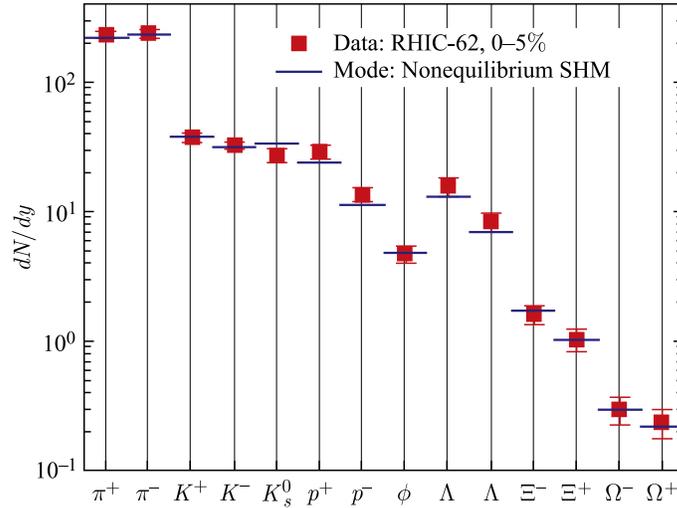


Fig. 6 (color online). The SHM analysis with SHARE (blue lines) of hadron yields from Au–Au collisions at RHIC for  $\sqrt{s_{NN}} = 62$  GeV (red symbols with error bars) results in a fit of freeze-out parameters  $T = 140$  MeV and  $\mu_B = 62.8$  MeV

Having demonstrated that SHARE works very well in explaining hadron yields over the whole energy range between RHIC and LHC, we are well equipped for a discussion of similarities and differences. We are particularly interested in strangeness as a signature of the QGP.

#### 4. SYNTHESIS: LHC + RHIC + SPS

The topic of a unified description of hadron production from SPS over RHIC to LHC is discussed in [12–14]. For the physical properties of the fireball at freeze-out, we find the energy density  $\varepsilon = 0.5$  GeV/fm<sup>3</sup>, the pressure  $P = 82$  MeV/fm<sup>3</sup>, and the entropy density of  $\sigma = 3.3$  fm<sup>-3</sup>. In Fig. 7, we show a synopsis of the results for physical properties as a function of collision centrality which impressively demonstrates their universality at freeze-out [11], i.e., independence of collision energy and centrality.

In Fig. 8, we highlight the differences we found between LHC and RHIC that arise in the SHM interpretation of the particle yields. The centrality dependence of the total entropy (plot *a*) shows at LHC a steeper than linear behavior and an additional centrality-dependent entropy production. The strangeness per entropy (plot *b*) shows a steeper increase at low  $N_{\text{part}}$  and a quick saturation at a steady level for  $N_{\text{part}} > 100$ .

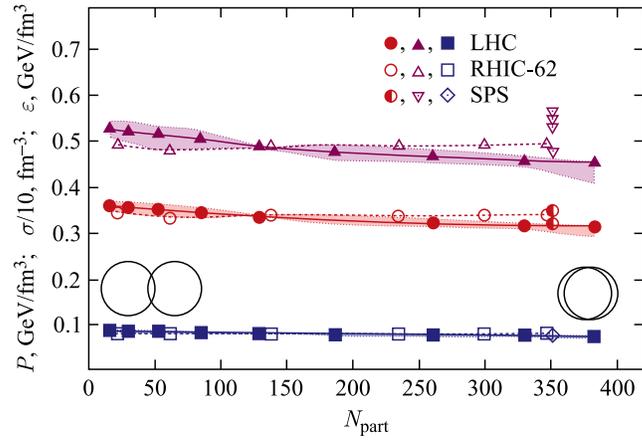


Fig. 7. Thermodynamic properties (pressure  $P$ , entropy density  $\sigma$ , and energy density  $\epsilon$ ) at freeze-out are universal [11], nearly independent of collision energy and centrality

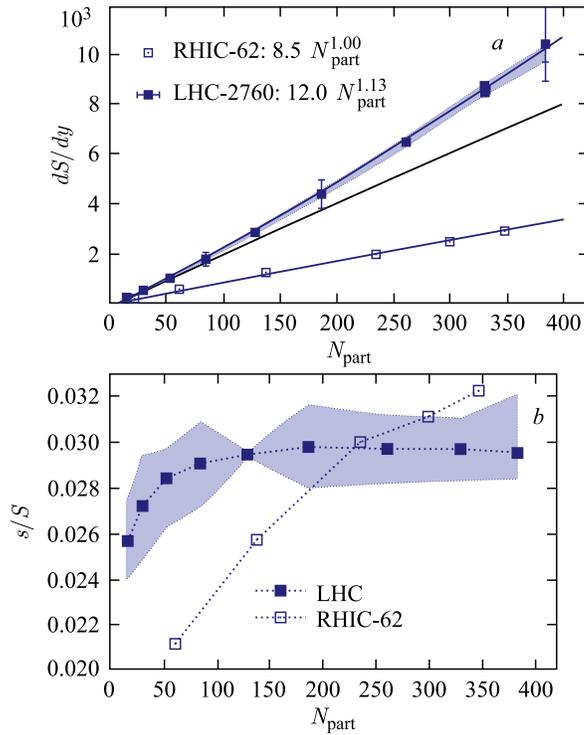


Fig. 8. The LHC–RHIC difference as a function of centrality: total entropy ( $a$ ) and strangeness production per entropy  $s/S$  ( $b$ ), from [7]

In Fig. 9, we demonstrate that it is impossible to justify by hadron dynamics the strangeness per entropy ratio which we obtained in our analysis that is in fact extracted in our analysis (see Fig. 8, *b*) at the QGP level. This is one way of saying that strangeness production is enhanced in the QGP, and in fact in QGP we have for most central collisions a nearly fully chemically equilibrated  $u, d, s, \bar{u}, \bar{d}, \bar{s}$  soup of quarks.

In Fig. 10, it is shown that the peak in the beam energy dependence of the  $K^+/\pi^+$  ratio (“Marek’s horn”) is tracked well as a function of energy with the nonequilibrium SHM fit provided by SHARE. The beam energy dependence of the SHM parameters is shown in Fig. 11, while Fig. 12 summarizes the result of the

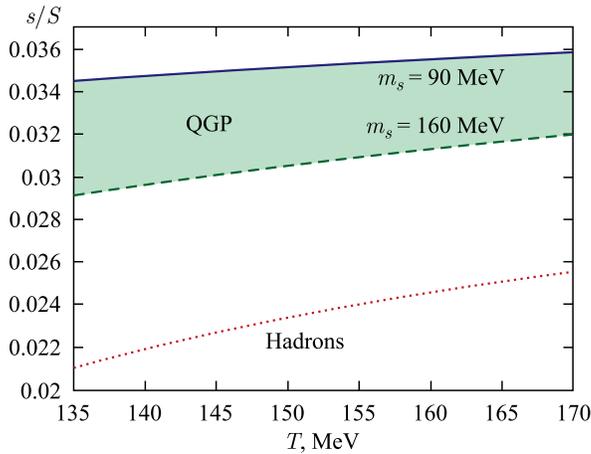


Fig. 9. Strangeness per entropy as a function of temperature in the hadron resonance gas and in the QGP

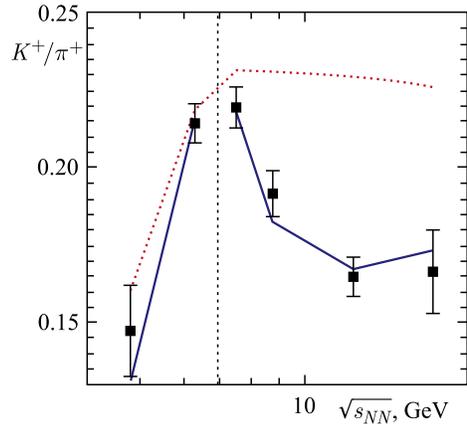


Fig. 10. The energy dependence of the  $K^+/\pi^+$  ratio (“Marek’s horn”) is tracked perfectly with SHARE

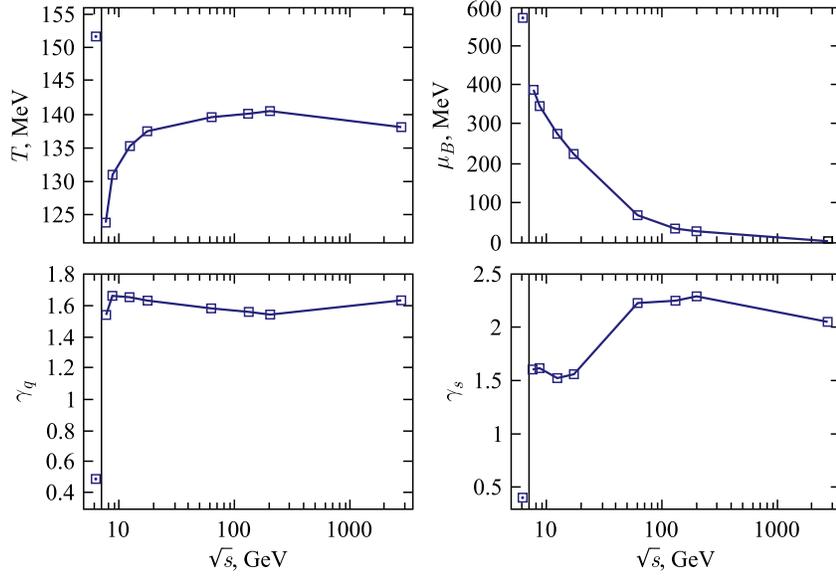


Fig. 11. Comparison of SHM parameters across the energies from SPS over RHIC to LHC

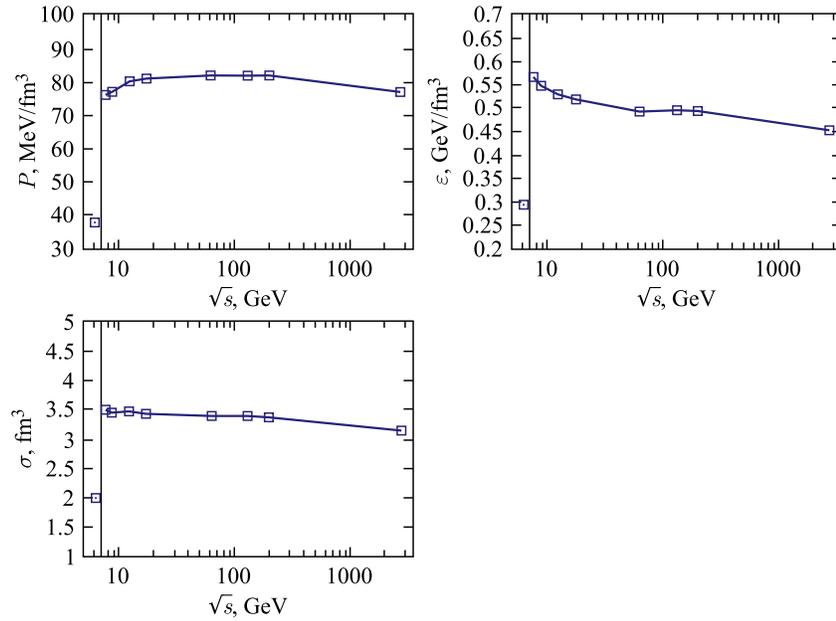


Fig. 12. Comparison of the fireball properties at freeze-out across the energies from SPS over RHIC to LHC

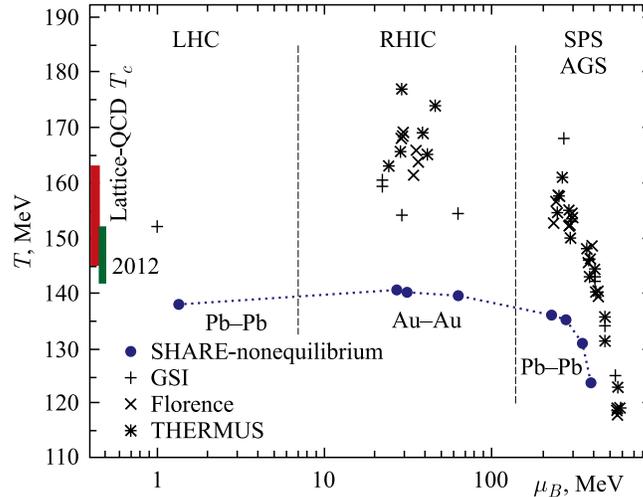


Fig. 13. Comparison of freeze-out parameters for different models with the pseudocritical temperature from Lattice QCD [15]. Figure from [7]

approximate universality of intense thermodynamic properties (pressure, energy density, and entropy density) of the fireball at freeze-out across all accessible energies.

In Fig. 13, we show a comparison of freeze-out parameters for different models with the pseudocritical temperature from Lattice QCD [15]. For consistency reasons, the observed chemical freeze-out must be in the hadron resonance domain, i.e., below the lattice results for the pseudocritical temperature of the chiral/deconfinement crossover transition. Clearly, the recent lattice results rule out most hadronization models. We are proud that since 1998 [16] we have proposed and defended a view of hadronization that produces results fully consistent with present-day lattice results.

## CONCLUSIONS

Our exploration of phases of QCD matter relies on a precise method of hadron abundance analysis within the SHARE statistical hadronization model. Properties of the QGP fireball are derived from what we see in all emitted hadronic particles.

Irrespective of how a common QCD phase — the QGP state — was created at LHC, RHIC, and SPS and how it evolves to hadronization, we observe in the final state the same physical conditions of the fireball particle source — with varying hadronization volume  $V$  or equivalently, entropy content  $S$  and strange-

ness  $s$ . At most central high-energy LHC collisions we also see relatively stable ratio  $s/S$  indicating a QGP fireball of consistent physical thermal equilibrium condition.

Under the given universal hadronization conditions that we have obtained we believe that when the QGP hadronizes it evaporates into free-streaming hadrons. There is no interlaced “phase” of hadrons, no afterburners needed. In fact, in further discussion not presented here we find that these would be inconsistent with experimental results at LHC in regard to multistrange baryon and antibaryon production as function of centrality.

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