ON THE HISTORY OF MULTI-PARTICLE PRODUCTION IN HIGH ENERGY COLLISIONS*

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The 60th birthday of Johann Rafelski was celebrated during the Strangeness in Quark Matter 2011 conference in Kraków. Johann was born in Kraków and he initiated the series of the SQM conferences. This report, which briefly presents my personal view on the history of multi-particle production in high energy collisions, is dedicated to Johann.

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1. Introduction

The systematic study of particle production in collisions of high energy particles started about 60 years ago with the construction of first accelerators. Here, I will briefly present my personal view on the history of this era. Johann Rafelski, whose 60th birthday was celebrated at the Strangeness in Quark Matter conference in Krakow has been one of the key contributors since the mid-70s [1, 2]. Therefore, his impact on the development of the field will be emphasized.

2. Experimental and theoretical status quo

The experimental and theoretical *status quo* of multi-particle production in high energy collisions is summarized in Fig. 1, where a sketch of the transverse mass, m_{T}, spectra of hadrons produced in $p+p$ interactions at the center-of-mass energy $\sqrt{s} = 50\,\mathrm{GeV}$ is shown [3]. Clearly, there are three distinct domains:

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1. *the soft domain*, $m_{\rm T} \lesssim 2\,{\rm GeV}$, in which a predominant majority of all particles is produced, $m_{\rm T}$ spectra are exponential and produced particles are essentially uncorrelated; their production properties are well described by statistical and hydrodynamical models,
2. *the hard domain*, $2 \lesssim m_{\rm T} < \sqrt{s}/2\,{\rm GeV}$, in which only a small fraction of all produced particles is located, $m_{\rm T}$ spectra follow a power-law dependence and produced particles are strongly correlated (organized in so-called jets); in this domain particle production properties are best described by dynamical QCD-based approaches,
3. *the threshold domain*, $m_{\rm T} \approx \sqrt{s}/2$, the spectrum in this domain is not measured due to a very low particle yield, it is believed to steeply decrease to zero with $m_{\rm T}$ approaching its threshold value given by the energy–momentum conservation laws, $\sqrt{s}/2$.

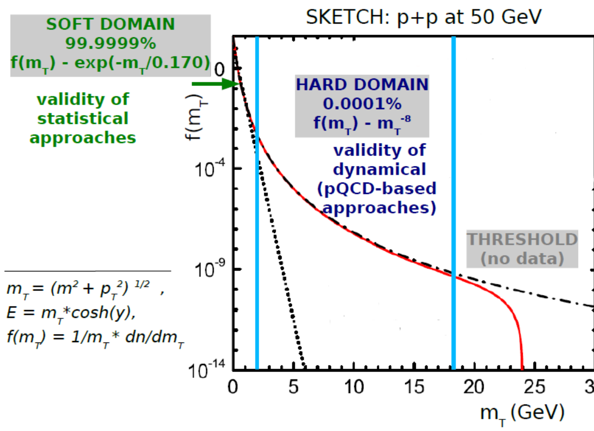

Fig. 1. Experimental and theoretical *status quo* of multi-particle production in high energy collisions.

3. History of multi-particle production in short

A brief history of multi-particle production is shown in Fig. 2. The field started in the 50s with discoveries of hadrons, first in cosmic-ray experiments and soon after in experiments using beams of particles produced in accelerators. Two classes of models were developed in this time, namely statistical and dynamical models of hadron production. The latter class was initiated by the scattering matrix approach. Systematic results on properties of hadrons and their interactions with electrons, accumulated in the 60–70s, led to discoveries of sub-hadronic particles, quarks and gluons. The idea of the quark-gluon plasma (QGP) was formulated. Subsequently, statistical approaches of quark and gluon hadronization and a statistical model of quark and gluon production were developed. In parallel, a dynamical theory of strong interactions (QCD) was established. Many QCD-based and QCD-inspired models of multi-particle production appeared. Finally, experimental studies of nucleus–nucleus collisions at high energies resulted in discoveries of strongly interacting matter and its phase transition between the hadron gas and quark-gluon plasma forms.

Johann Rafelski greatly contributed to the field by developing both statistical and QCD-inspired approaches to the quark-gluon plasma and its hadronization. For a long time his ideas inspired experimental developments and he was always devoted to the interpretation of new data.

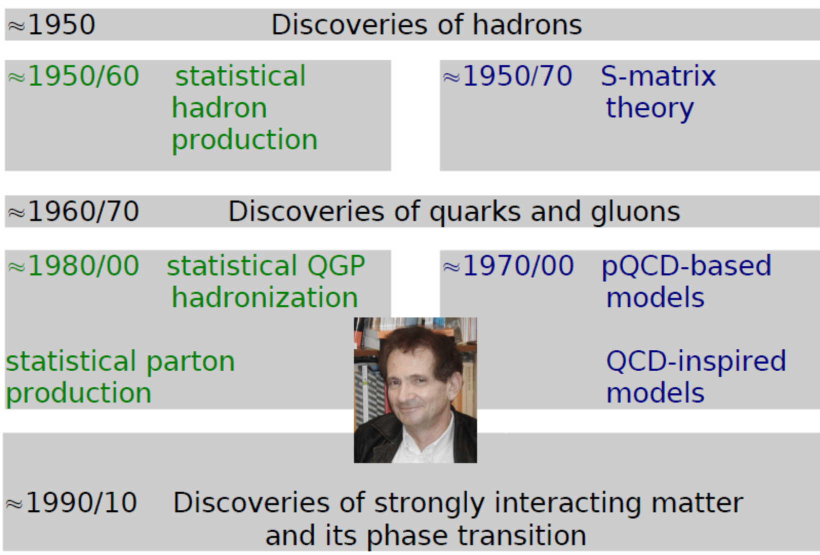

Fig. 2. History of multi-particle production in short. Johann Rafelski's contributions span between statistical and QCD-inspired approaches and are deeply rooted in experiment.

4. Discoveries of hadrons

Naturally, the first hadrons, discovered in collisions of cosmic-ray particles, were the lightest ones, pion, kaon and Λ. With the rapid advent of particle accelerators (see Fig. 3, for a brief history) new particles were discovered almost day-by-day. There are about 1000 hadronic states known at the moment. Their density in mass increases approximately exponentially [4] as predicted by Hagedorn's Statistical Bootstrap Model [5].

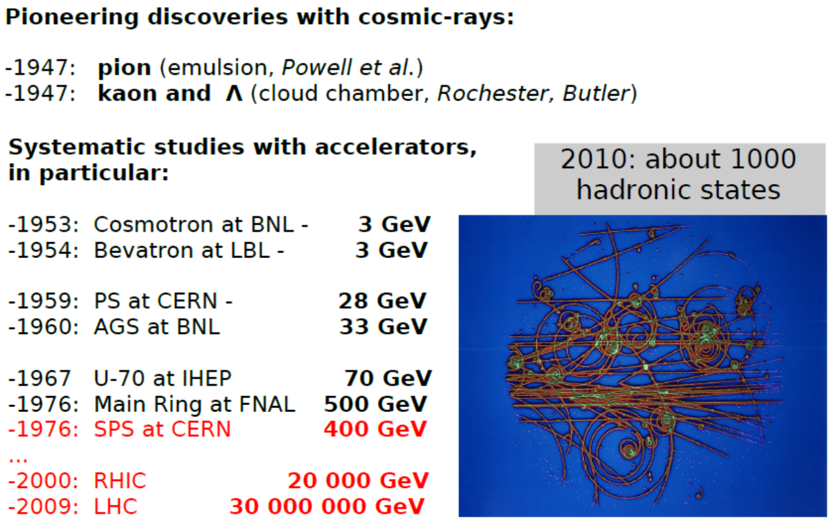

Fig. 3. Discoveries of hadrons and a brief history of particle accelerators. The maximum beam energy of accelerators is given in the fixed target system. Accelerators used so far in the study of multi-particle production are indicated in grey (red).

5. Statistical hadron production

The first statistical model of multi-hadron production was proposed by Fermi [6]. He assumed that hadrons produced in high energy collisions are in equilibrium and that the energy density of the created hadronic system increases with increasing collision energy. Soon after, Pomeranchuk [7] pointed out that hadrons cannot decouple (freeze-out) at high energy densities. They will rather continue to interact while expanding until the matter density is low enough for interactions to be neglected. He estimated the freeze-out temperature to be close to the pion mass, ≈ 150 MeV. Inspired by this idea, Landau [8] and his collaborators formulated a quantitative hydrodynamical model describing the expansion of strongly interacting hadronic matter between Fermi's equilibrium high density stage (the early stage) and Pomeranchuk's low density decoupling stage (the freeze-out). The Fermi–Pomeranchuk–Landau picture serves as a base for modeling high energy nuclear collisions up to now [9].

In the 60s Hagedorn made an important conjecture, namely that matter composed of hadrons has a maximum temperature, the so-called Hagedorn temperature $T_{\mathrm{H}} \approx 150$ MeV [16]. This conjecture was based on his Statistical Bootstrap Model. Note, that it was in contradiction to the Fermi's model in which the temperature of hadronic matter created at the early stage of collisions increases monotonically with collision energy and it is unlimited. Figure 4 sketches a brief history of pioneering ideas and models on statistical hadron production.

The statistical and hydrodynamical models predict an approximately exponential form of particle transverse mass spectra, provided collective flow of matter developed in the course of expansion is small.

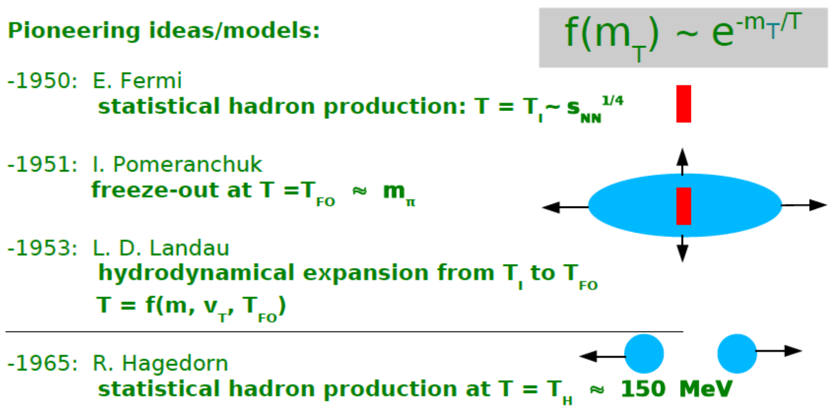

Fig. 4. Pioneering models and ideas on statistical hadron production.

6. S-matrix theory

The scattering (S-)matrix theory, which relates the initial state and the final state of a scattering process, was initiated by Wheeler and Heisenberg in the 30–40s. It led to the development of the Regge theory studying analytic properties of the scattering amplitude treated as a function of angular momentum, and it finally resulted in the string theory pioneered by Veneziano. These theories, formulated without specifying elementary particles, do not refer to a space-time structure of interaction processes. They assume that all particles are bound states lying on Regge trajectories and scatter self-consistently.

Within the spirit of these theories the Wounded Nucleon Model (WNM) was proposed by Bialas, Bleszynski and Czyz [10] in 1976. It assumes that particle production in nucleon–nucleus and nucleus–nucleus collisions is an incoherent superposition of particle production from wounded nucleons, *i.e.* nucleons which interacted inelastically and whose number is calculated using the Glauber approach. Up to now, predictions of the WNM model have remained an important baseline for interpretation of experimental data. In particular, in the case of mean hadron multiplicities the WNM predicts

$$\langle N_{AB} \rangle = \langle w_{AB} \rangle / 2 \langle N_{NN} \rangle \,, \qquad (1)$$

where $\langle N_{AB} \rangle$ and $\langle N_{NN} \rangle$ are mean hadron multiplicities in $A+B$ collisions and nucleon–nucleon interactions, respectively, whereas w_{AB} is a mean number of wounded nucleons in $A+B$ collisions. Note, that the above WNM prediction resembles the corresponding prediction of statistical models in the grand canonical approximation (thermodynamical models) providing the number of wounded nucleons is replaced by a system volume. This explains an approximate validity of the WNM for the yield of pions, the most popular hadrons. However, the model significantly fails already for yields of strange hadrons. Figure 5 presents milestones of the S-matrix era.

Pioneering ideas/models:

-1941: W. Heisenberg
S-matrix theory as a theory of particle interactions

≈1960: T. Regge + G. Chew, S. Frautschi, J. Collins
Regge theory

≈1970: G. Veneziano, S. Mandelstam
string model

-1976: A. Bialas, M. Bleszynski, W. Czyz
wounded nucleon model $<N_{AB}> = <w_{AB}>/2 \circ <N_{NN}>$

Fig. 5. Milestones of the S-matrix era.

7. Discoveries of quarks and gluons

The quark model of hadron classification proposed by Gell-Mann and Zweig in 1964 starts a 15 years-long term in which sub-hadronic particles, quarks and gluons, were discovered and a theory of their interactions, quantum chromodynamics was established. A brief history of this term is shown in Fig. 6. In parallel, conjectures were formulated concerning the existence and properties of matter consisting of sub-hadronic particles [11, 12], soon called a quark-gluon plasma and studied in detail within the QCD [13]. The first QCD-inspired estimate of the transition temperature to QGP gave $T_{\rm C} \approx 500$ MeV [14]. Figure 6 presents a brief history of discoveries of quarks and gluons.

Many physicists started to speculate that the QGP can be formed in nucleus–nucleus collisions at high energies and, thus, it may be discovered in laboratory experiments.

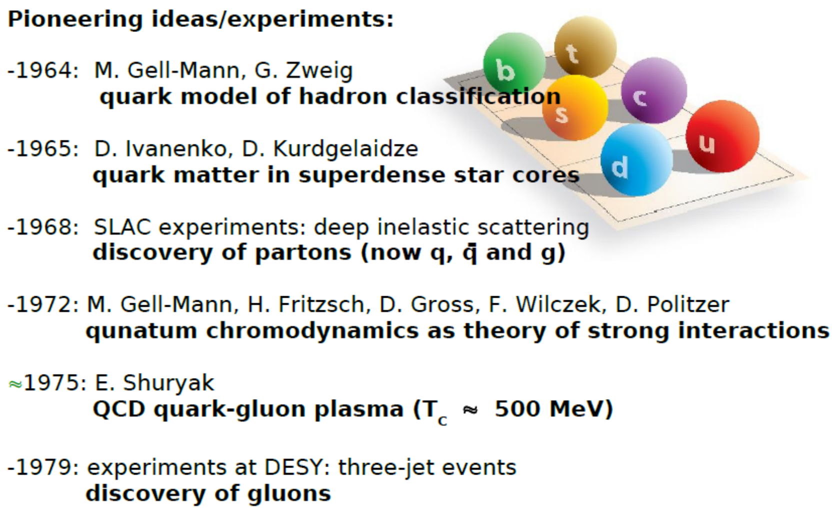

Fig. 6. A brief history of discoveries of quarks and gluons.

8. Statistical QGP hadronization and statistical parton production

Questions concerning QGP properties and properties of its transition to matter consisting of hadrons have been considered since the late 70s. *Cabibbo, Parisi [15], Hagedorn and Rafelski [16] suggested that the upper limit of the hadron temperature, the Hagedorn temperature, is the transition temperature to the QGP. Furthermore, Rafelski [17] and the collaborators introduced the statistical approach to the QGP hadronization. It predicted that the resulting system of hadrons is in incomplete equilibrium. The deviations from the equilibrium can be traced back to the QGP properties [18].*

In the mid-90s the Statistical Model of the Early Stage (SMES) was formulated [19] as an extension of Fermi's statistical model of hadron production. This model assumes a statistical production of confined matter at low collision energies (energy densities) and a statistical QGP creation at high collision energies (energy densities). SMES predicts a rapid change of the collision energy dependence of hadron production properties, that are sensitive to QGP, as a signal of a transition to quark-gluon plasma (the onset of deconfinement) in nucleus–nucleus collisions. The onset energy was estimated to be located in the CERN SPS energy range.

Clearly, the QGP hypothesis and the SMES model removed the contradiction between Fermi's and Hagedorn's statistical approaches (see Sect. 5). Namely, the early stage temperature of strongly interacting matter is unlimited and increases monotonically with collisions energy, whereas there is a maximum temperature of hadron gas, $T_{\mathrm{C}} = T_{\mathrm{H}} \approx 150\,\mathrm{MeV}$, above which strongly interacting matter is in a quark-gluon plasma phase. Figure 7 summarizes the developments discussed above.

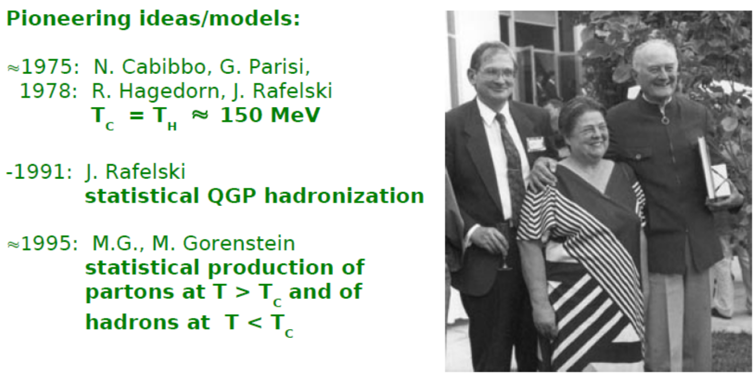

Fig. 7. Statistical QGP hadronization and statistical parton production. In photo from left to right: Johann Rafelski, Tatiana Faberge (the former CERN theory group secretary and the owner of the rights to Faberge eggs) and Rolf Hagedorn, Divonne-les-Bains, 1994.

9. QCD-based and QCD-inspired models

Attempts to derive from the QCD precise quantitative predictions for multi-particle production in high energy collisions have not been successful [20]. Predictions of QCD-based and QCD-inspired models suffer from large quantitative and large qualitative uncertainties, respectively.

The power-law dependence of transverse momentum spectra, $d\sigma/dp_{\mathrm{T}} \sim p_{\mathrm{T}}^{-4}$, at high p_{T} (in the perturbative domain) was predicted by Field and Feynman in 1977 based on the asymptotic freedom of the QCD. In fact, data at $p_{\mathrm{T}} > 2$–$3\,\mathrm{GeV}$ follow the power-law dependence, but with the p_{T}^{-8} [21] instead of p_{T}^{-4}. Parton cascade and hadronization models were developed [22], however their validity is in question due to statistical and hydrodynamical features of experimental data [9], which are difficult to explain within the dynamical, QCD-inspired approaches [23].

The most famous QCD-inspired models of QGP signals in nucleus–nucleus collisions, strangeness enhancement [24] and J/ψ suppression [25], were proposed in 1980s by Rafelski, Müller and Matsui, Satz, respectively. They motivated precision systematic measurements. Nevertheless, they did not lead to definite conclusions on the QGP creation, because alternative, QCD-inspired and/or statistical explanations of data were more successful. Figure 8 summarizes the developments discussed above.

Pioneering ideas/models:

$f(m_T) \sim m_T^{-P}$

-1977: R. Field, R. Feynman
pQCD-based model of high p_T phenomena

≈1980: J. Rafelski, B. Mueller, T. Matsui, H. Satz
QCD-inspired models of QGP signals,
strangeness enhancement and J/ψ suppression

-1991: K. Geiger, B. Mueller, J. Ellis
QCD-inspired parton cascade and hadronization model

Fig. 8. Pioneering QCD-based and QCD-inspired ideas and models.

10. Discoveries of strongly interacting matter and its phase transition

Systematic data from experiments at the CERN SPS and LHC and at the BNL AGS and RHIC clearly indicate that a system of strongly interacting particles created in heavy collisions at high energies is close to, at least, local equilibrium. At freeze-out the system occupies a volume which is much larger than the volume of individual hadrons. The latter conclusion is based on the failure of the WNM and the success of statistical [26] and hydrodynamical models [9]. Thus, one concludes that strongly interacting matter is created in heavy ion collisions.

Pioneering ideas/experiments:

-1980/00: AGS/SPS/RHIC experiments with heavy ions
discovery of strongly interacting matter
(large volume, in ≈ equilibrium)

≈2000: NA49 at the CERN SPS
discovery of phase transition of
strongly interacting matter

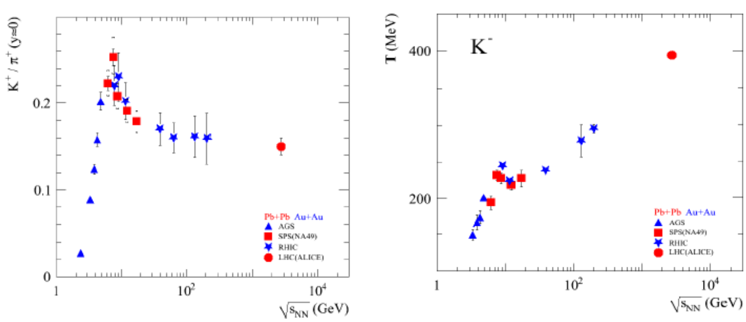

Fig. 9. Discoveries of strongly interacting matter and its phase transition. The horn (left) and step (right) structures in energy dependence of the K^+/π^+ ratio and the inverse slope parameter of K^- m_T spectra signal the onset of deconfinement located at the low CERN SPS energies.

The phase transition of strongly interacting matter to the QGP was discovered within the energy scan program of NA49 at the CERN SPS [27,28]. The program was motivated by the predictions of the SMES model. The discovery is based on the observation that several basic hadron production properties measured in heavy ion collisions rapidly change their dependence on collision energy in a common energy domain [29]. Figure 9 summarizes the developments discussed above.

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