The Mar(e)k of QGP: Strangeness and Entropy

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CPOD, WROCLAW, June 2, 2016

Presented in celebration of Marek Gaździcki contributions to the study of quark-gluon plasma phase of matter, and its strangeness and entropy signature, on occasion of his 60th birthday.

1964/65: Two new fundamental ideas

- Quarks → Standard Model of Particle Physics
- Hagedorn Temperature → New State of Elementary Matter

Merging in 1979/80 into Quark-Gluon Plasma

Topics today:

1. From Hagedorn temperature to heavy ion collisions
2. Strangeness and how Marek found his destiny
3. Cooking plasma and the horn

Hagedorn exponential mass spectrum: boundary of a new phase of matter

65/166/5 – TH. 520
25 January 1965

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

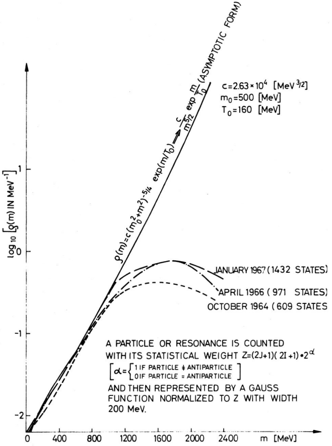
R. Hagedorn
CERN – Geneva

A B S T R A C T

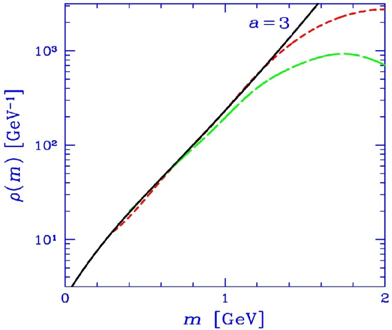
In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

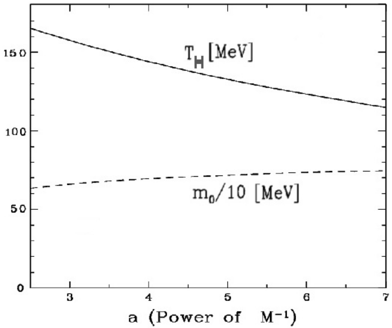
$$\rho(m) \xrightarrow[m \to \infty]{} \mathrm{const.}\, m^{-5/2} \exp\left(\frac{m}{T_0}\right).$$

T_0 is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_0^-$. T_0 is therefore the highest possible temperature for strong interactions. It should – via a Maxwell-Boltzmann law – govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then T_0 is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_0 the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.



Experimental mass spectrum defines T_H





To fix T_H in a limited range of mass need prescribe value of a obtained from SBM. In 1978 we noted that at T_H sound velocity vanishes. This creates another way of fixing T_H both in experiment and in lattice QCD and when this is done, the critical power a is also determined.

Hagedorn Temperature $T_{\rm H}$
Singular point of partition function

$$Z_1(\beta,V) = \int \frac{2V^{\rm ex}_\mu p^\mu}{(2\pi)^3}\tau(p^2)e^{-\beta_\mu p^\mu}d^4p\,.$$

Inserting $1 = \int \delta_0(m^2-p^2)dm^2$

l replacing $\tau(m^2)dm^2$ by $\rho(m)dm$

$$Z_1(\beta,V) = \frac{V^{\rm ex}T}{2\pi^2}\int m^2\rho(m)K_2(m\beta)dm\,.$$

$$Z_1(\beta,V) \underset{T\to T_0}{\sim} C\int_M^\infty m^{3/2-a}e^{-(\beta-\beta_0)m}dm + C\,.$$

$$Z_1(\beta,V) \underset{T\to T_0}{\sim} \begin{cases} C + C\Delta T^{a-5/2}\,, & a \neq 5/2 \\ C - \ln\frac{\Delta T}{T_0}\,, & a = 5/2 \end{cases}$$

a	P	n	ε	$\delta\varepsilon/\varepsilon$	$C_V = d\varepsilon/dT$
1/2	$C/\Delta T^2$	$C/\Delta T^2$	$C/\Delta T^3$	$C+C\Delta T$	$C/\Delta T^4$
1	$C/\Delta T^{3/2}$	$C/\Delta T^{3/2}$	$C/\Delta T^{5/2}$	$C+C\Delta T^{3/4}$	$C/\Delta T^{7/2}$
3/2	$C/\Delta T$	$C/\Delta T$	$C/\Delta T^2$	$C+C\Delta T^{1/2}$	$C/\Delta T^3$
2	$C/\Delta T^{1/2}$	$C/\Delta T^{1/2}$	$C/\Delta T^{3/2}$	$C+C\Delta T^{1/4}$	$C/\Delta T^{5/2}$
5/2	$C\ln(T_0/\Delta T)$	$C\ln(T_0/\Delta T)$	$C/\Delta T$	C	$C/\Delta T^2$
3	$P_0 - C\Delta T^{1/2}$	$n_0 - C\Delta T^{1/2}$	$C/\Delta T^{1/2}$	$C/\Delta T^{1/4}$	$C/\Delta T^{3/2}$
7/2	$P_0 - C\Delta T$	$n_0 - C\Delta T$	ε_0	$C/\Delta T^{1/2}$	$C/\Delta T$
4	$P_0 - C\Delta T^{3/2}$	$n_0 - C\Delta T^{3/2}$	$\varepsilon_0 - C\Delta T^{1/2}$	$C/\Delta T^{3/4}$	$C/\Delta T^{1/2}$

energy density diverges for $a < 7/2$. Thus only for $a < 7/2$ can we expect T_0 a maximum temperature.

From J.R. and R. Hagedorn: Thermodynamics of Hot Nuclear Matter in the Statistical Bootstrap Model 1979, in memorial volume.

CERN Courier June 2016

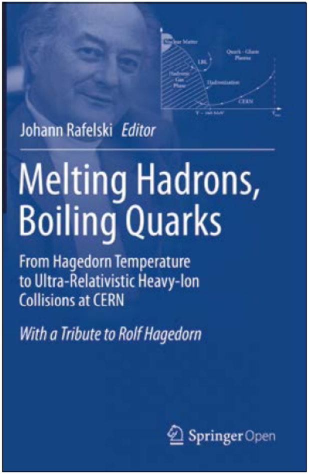
Melting Hadrons, Boiling Quarks: From Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN. With a Tribute to Rolf Hagedorn

By Johann Rafelski (ed.)

Springer

The statistical bootstrap model (SBM), the exponential rise of the hadron spectrum, and the existence of a limiting temperature as the ultimate indicator for the end of ordinary hadron physics, will always be associated with the name of Rolf Hagedorn. He showed that hadron physics contains its own limit, and we know today that this limit signals quark deconfinement and the start of a new regime of strong-interaction physics.

This book is edited by Johann Rafelski, who was a long-time collaborator with Hagedorn and took part in many of the early conceptual developments of the SBM. It may perhaps be best characterised by pointing out what it is not. It is not a collection of review articles on the physics of the SBM and related topics, which could be given to newcomers as an introduction to the field. It is not a collection of reprints



relativistic heavy-ion programme at CERN that took place in the early 1980s. It starts with his thoughts about a possible programme of this kind, presented at the workshop on future relativistic heavy-ion experiments, held at the Gesellschaft fuer Schwerionenforschung (GSI). It also includes the draft minutes of the 1982 CERN SPC meeting, and some early works on strangeness production as an indicator for quark–gluon plasma formation, as put forward after many years by Rafelski.

The book is undoubtedly an ideal companion to all those who wish to recall the birth of one of the main areas of today's concepts in high-energy physics, and it is definitely a well-deserved credit to one of the great pioneers in their development.

● *Frithjof Karsch, Bielefeld University, Germany.*

Bookshelf

First strangeness signature 1980: ratio of $\bar{s}/\bar{q}$ in $\overline{\Lambda}/\bar{p}$ triggers Marek's strange interest!

What we intend to show is that there are many more $\bar{s}$ quarks than antiquarks of each light flavour. Indeed:

$$\frac{\bar{s}}{\bar{q}} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\left(\frac{m_s}{T}\right) e^{\mu/3T} \qquad (28)$$

The function $x^2K^2(x)$ is, for example, tabulated in Ref. 15). For $x = m_s/T$ between 1.5 and 2, it varies between 1.3 and 1. Thus, we almost always have more $\bar{s}$ than $\bar{q}$ quarks and, in many cases of interest, $\bar{s}/\bar{q} \sim 5$. As $\mu \to 0$ there are about as many $\bar{u}$ and $\bar{q}$ quarks as there are $\bar{s}$ quarks.

FROM HADRON GAS TO QUARK MATTER II

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and

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CERN--Geneva

Ref.TH.2969-CERN
13 October 1980

ABSTRACT

We describe a quark-gluon plasma in terms of an many questions remain open. A signature of the quark-gluon phase surviving hadronization is suggested.

In *Statistical mechanics of quarks and hadrons* proceedings of Bielefeld, August 24-31, 1980 / edited by **Helmut Satz** picked up by Marek in Dubna . . .

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on July, 20, 1983.

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Anikina M. et al. E1-83-521

A Study of Λ-Production in Central Nucleus-Nucleus Interactions at a Momentum of 4.5 GeV/c Per Incident Nucleon

Transverse momenta and rapidities of Λ's produced in central nucleus-nucleus collisions at 4.5 GeV/c per nucleon /CC, CNe, ONe, CCu, CZr, CPb, OPb/ have been studied and compared with those from inelastic He-Li interactions at the same incident momentum. Polarization of Λ hyperons was found to be consistent /within the errors/ with zero (αP_z = -0.06 ± 0.11) for 224 Λ's from central collisions. The upper limit of $\bar{\Lambda}/\Lambda$ production ratio was estimated to be less than 10^{-2} at a 90% confidence level.

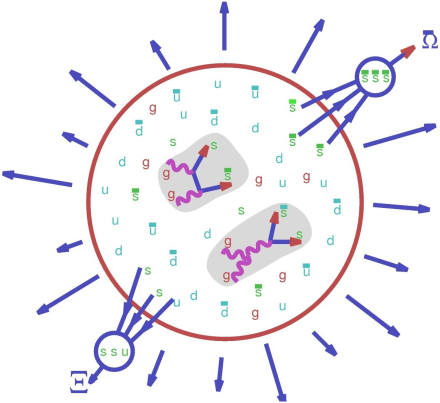
The analyzed experimental data were obtained using the triggered 2 m streamer spectrometer SKM-200.

The investigation has been performed at the Laboratory of High Energies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1983

$\longrightarrow$JR 1980;1982 JR,Berndt Müller; 1986 P. Koch

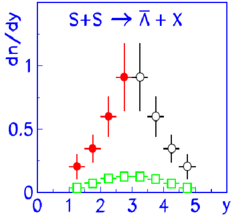
Cooking strange quarks → strange antibaryons

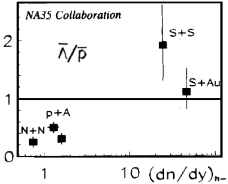


A first meeting September 1988 with RHI data

“Hadronic Matter in Collision,” Tucson, September 1988 – in the picture & in this room: Marek G., Mark G., Stanislaw M., Jan R.; also: Wit B., Roy G., Walter G., Hans G., Berndt M., Emanuele Q., Chris Q.,Gena Z. , and some who are in our memory: Leon VanH, Maurice J., Mike D., ...

Joint MG+JR S+S analysis paper 1994: features $\bar{\Lambda}/\bar{p}$





$\bar{\Lambda}/\bar{p}$-ratio near midrapidity in proton-proton, minimum bias proton-nucleus and central nucleus-nucleus collisions at 200 GeV per nucleon as a function of the rapidity density of negatively charged hadrons at midrapidity.

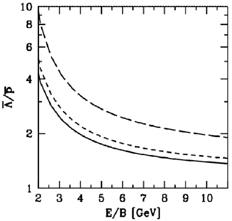
Physics Letters B 366 (1996) 56–62 Fig. 3. p61 inclusion of secondary processes at a partonic and/or hadronic level is needed to explain the data. The string-hadronic RQMD model including secondary collisions underestimates the $\bar{\Lambda}$ production in central S+S collisions at 200 GeV per nucleon by a factor of 5 and the $\bar{p}$ yield by a factor of about 3 [1].

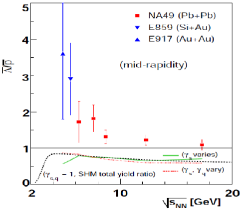
Attempts to describe the antibaryon yields within the RQMD model require the introduction of a new production mechanism beyond hadronic rescattering.

J. Rafelski, Arizona Quarks in the Universe December 7, 2006, MLL-München, page 11

Ratio anomaly predicted 1980, status 2006: $\bar{\Lambda}/p > 1$

$$\left.\frac{\bar{\Lambda}}{\bar{p}}\right|_{QGP} = \frac{N_{\bar{s}}N_{\bar{u}}N_{\bar{d}}}{N_u N_u N_{\bar{d}}} \simeq \frac{\gamma_s^{QGP}}{\gamma_q^{QGP}}\left[\frac{1}{2}\frac{m_s^2}{T_h^2}K_2(m_s/T)\right] e^{(\mu_u^{QGP}-\mu_s^{QGP})/T} \to 0.9\, e^{\mu_u^{QGP}/T}$$





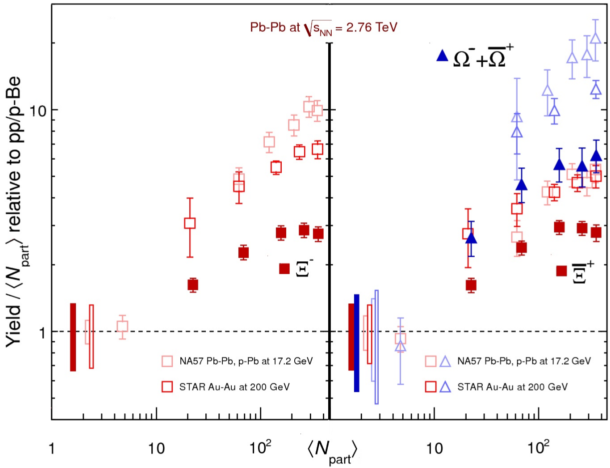
Chemical freeze-out conditions in central S-S collisions at 200 A GeV

Josef Sollfrank[1], Marek Gaździcki[2,*], Johann Rafelski[3]

Received 5 August 1993;
ZEITSCHRIFT FÜR PHYSIK C
Z. Phys. C 61, 659–665 (1994)

Abstract. We determine the chemical freeze-out parameters of hadronic matter formed in central S-S collisions at 200 A GeV, analyzing data from the NA35 collaboration at CERN. In particular we study the quark (baryon number) and strange quark fugacities, as well as the strange quark phase-space occupancy and the freeze-out temperature.

Largest medium effect: Strange antibaryons



(FERMI) STATISTICAL HADRONIZATION MODEL (SHM)

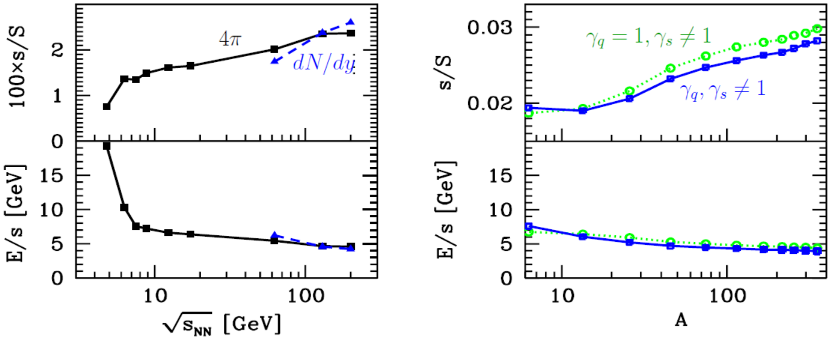
Very strong interactions: equal hadron production strength irrespective of produced hadron type particle yields depending only on the available phase space

- Fermi: Micro-canonical phase space
  sharp energy and sharp number of particles
  E. Fermi, Prog.Theor.Phys. 5 (1950) 570: HOWEVER

  Experiments report event-average rapidity particle abundances, model should describe an average event
- Canonical phase space: sharp number of particles
  ensemble average energy $E \to T$ temperature
  T could be, but needs not to be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles: $N \to \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

Our interest in the bulk thermal properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated spectra.

Fits 2003-2008 as a function of $\sqrt{s_{NN}}$ and A



Interest in energy cost of strangeness pair E/s as it may show change in reaction mechanism.

Why relative s/S

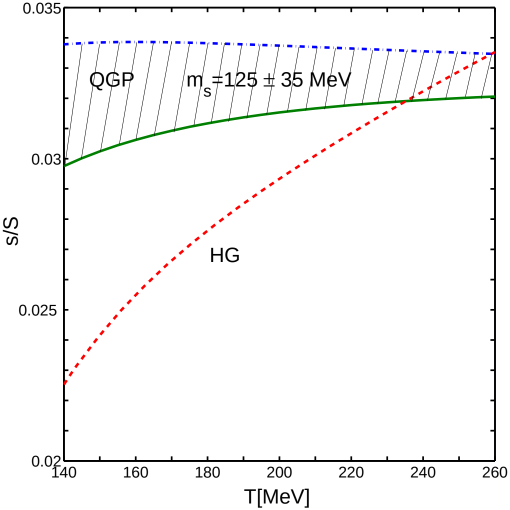
Relative s/S yield measures the number of active degrees of freedom and the degree of relaxation when strangeness production freezes-out. Perturbative expression in chemical equilibrium:

$$\frac{s}{S} = \frac{\frac{g_s}{2\pi^2} T^3 (m_s/T)^2 K_2(m_s/T)}{(g 2\pi^2/45) T^3 + (g_s n_{\mathrm{f}}/6)\mu_q^2 T} \simeq \frac{1}{35} = 0.0286$$

much of $\mathcal{O}(\alpha_s)$ interaction effect cancels out. When considered $s/S \to 1/31 = 0.0323$. Now introduce QGP nonequilibrium

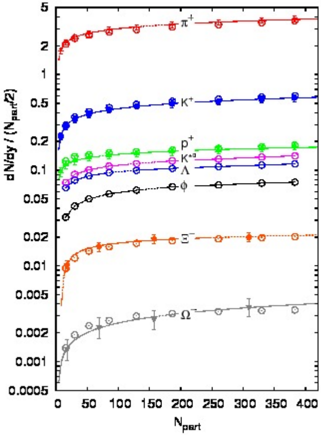
$$\frac{s}{S} = \frac{0.03\gamma_s^{\mathrm{QGP}}}{0.4\gamma_{\mathrm{G}} + 0.1\gamma_s^{\mathrm{QGP}} + 0.5\gamma_q^{\mathrm{QGP}} + 0.05\gamma_q^{\mathrm{QGP}}(\ln\lambda_q)^2} \to 0.03\gamma_s^{\mathrm{QGP}}.$$

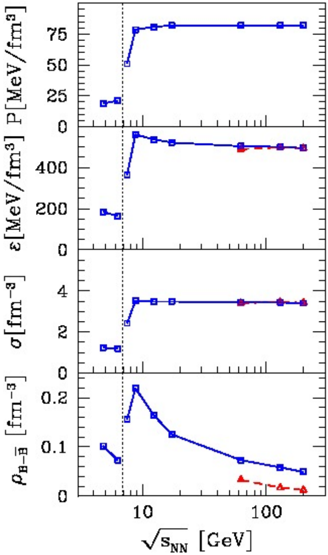
Two phases: Difference of equilibrium



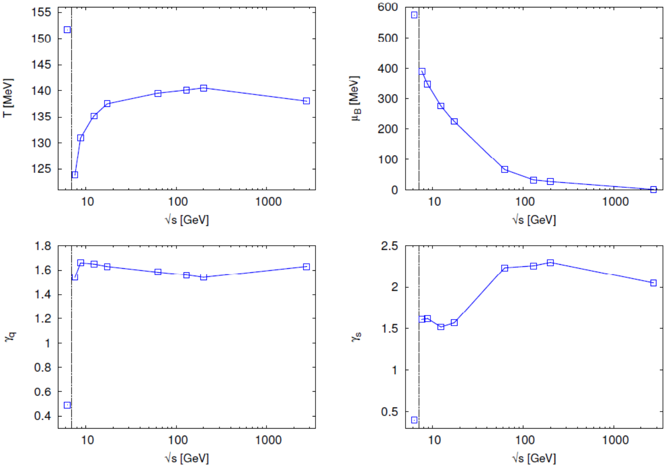
AGS,SPS,RHIC bulk properties⇒

⇓Fit to ALICE data⇓

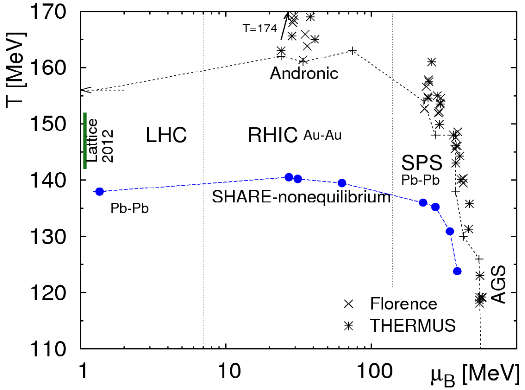




Comparison Across Energy SPS-RHIC-LHC: SHM parameters

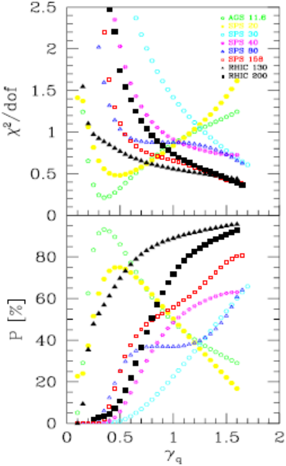


Consistency with Lattice-QCD



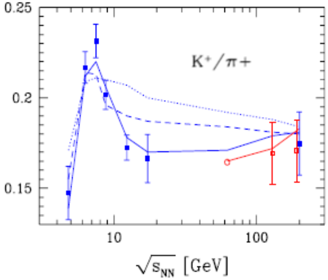
Chemical freeze-out MUST be below lattice results. For direct free-streaming hadron emission from QGP, T-SHM is the QGP source temperature, there cannot be full chemical equilibrium.

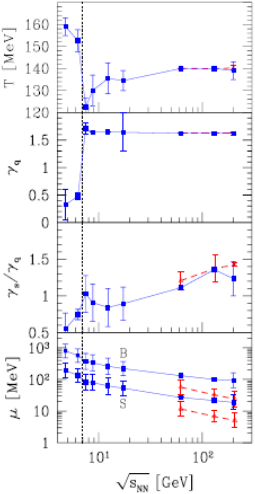
Use of nonequilibrium and the rôle of s/S= strangeness/multiplicity



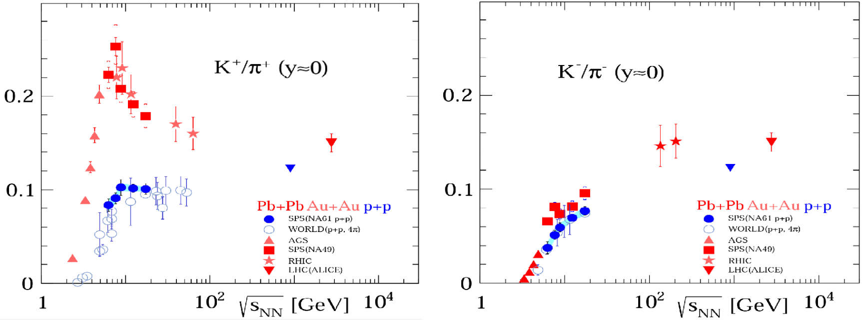
To describe the horn we need $\gamma_q \neq 1$

Looking a the fit χ^2 we see that between 20 and 30GeV results favor that γ_q jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The individual fits relevant to understanding how the horn is created have good quality - see $P\%$.





Marek's Discovery: The HORN is doing well today



Evidence of drastic change in matter properties – far from equilibrium hadrons turn at the peak into a quark-gluon plasma ball in near equilibrium. Use of non-equilibrium physics essential in understanding the Horn and understanding the threshold of QGP formation.

Summary

- 50 years ago particle production in pp reactions prompted introduction of Hagedorn Temperature T_{H}; soon after recognized as the critical temperature at which matter surrounding us dissolves into the fundamental phase of quarks and gluons – the QGP.
- Global effort to discover QGP - followed. Strangeness and Marek's lifespan of dedicated research played a pivotal role. The predicted signatures confirmed – not only strange antibaryons! New ideas emerge showing QGP consistency. While some people will keep arguing, ...
- ...overall there is little doubt that the totality of evidence is evidence for QGP phase of matter; each small item in the long list can be explained in some other way but all of the list emerges in a simple new paradigm.