Reconsideration of Statistical Hadronization in Light of LHC Results

Presented by: Johann Rafelski, Tucson, UArizona

with contributions from: (alphabetically)

Inga Kuznetsova, Jean Letessier, Vojtech Petracek,
Michal Petran, Gorgio Torrieri

March 20, 2014 CERN Heavy Ion Forum

ABSTRACT: I address hadronization process of a QGP fireball formed in relativistic heavy-ion collisions in the entire range of past and present reaction energies. A precise method of analysis of hadron multiplicities has evolved into “SHARE with CHARM” statistical hadronization model. We describe for the full range of reaction energies and centralities – exceptions are low SPS energies and very peripheral collisions – all hadron produced over many orders of magnitude in yield. The properties of the fireball final state can therefore be evaluated 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. The universal hadronization pressure $P = 80 \pm 3\,\mathrm{MeV/fm}^3$ is found. Strangeness content of a large fireball as compared to entropy shows presence of the quark-gluon plasma degrees of freedom near the chemical QGP equilibrium. "Universal Hadronization" condition common to SPS, RHIC, and LHC agrees with the proposed direct QGP fireball evaporation into free-streaming hadrons. Looking forward I discuss qualitatively how heavy flavor production contributes to energy stopping in central rapidity region as function of reaction energy: the cases of LHC at full energy and future super-LHC .

OUTLINE:

1. SHM Description of particle production in HI experiments
2. From LHC to RHIC to SPS
   2.1 QGP fireball physical properties at break-up
   2.2 Universal Hadronization Conditions
3. Synthesis: Comparison across energy and centrality of hadron source
4. Energy Stopping: Role of Massive Quarks

FOCUS ON PARTICLE ABUNDANCES: INTEGRATED $p_\perp$ SPECTRA

Particle yields allow exploration of the source properties in particle co-moving frame – collective transverse matter dynamics integrated out. Our interest in properties of the source evaluated independent from complex transverse dynamics is the reason to analyze integrated $p_\perp$ spectra. We describe particle yields within:

FERMI STATISTICAL HADRONIZATION MODEL (SHM)

Assuming equal hadron production strength irrespective of produced hadron type particle yields depend 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 $E \rightarrow T$ temperature
  T may be, but needs not be, a kinetic process temperature
- Grand-canonical – ensemble average energy and number of particles: $N \rightarrow \mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$

TO DESCRIBE PRODUCED HADRON YIELDS

- Average per collision yield of hadron *i* is calculated from integral of the distribution over phase space

$$\langle N_i \rangle \to \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3}\, n_i; \quad n_i\left(\varepsilon_i; T, \Upsilon_i\right) = \frac{1}{{\Upsilon_i}^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{n m_i}{T}\right)^2 K_2\left(\frac{n m_i}{T}\right)$$

- Hadron mass — PDG Tables
- Degeneracy (spin), $g_i = (2J+1)$ — PDG Tables

- Overall normalization — outcome of SHM fit
- Hadronization temperature — outcome of SHM fit
- Fugacity Υ_i for each hadron — – see next slide outcome of SHM fit

TO DESCRIBE PRODUCED HADRON YIELDS

- Average per collision yield of hadron i is calculated from integral of the distribution over phase space

$$\langle N_i \rangle \to \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_i; \quad n_i(\varepsilon_i; T, \Upsilon_i) = \frac{1}{\Upsilon_i^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{n m_i}{T}\right)^2 K_2\left(\frac{n m_i}{T}\right)$$

- Hadron mass — PDG Tables
- Degeneracy (spin), $g_i = (2J+1)$ — PDG Tables

- Overall normalization — outcome of SHM fit
- Hadronization temperature — outcome of SHM fit
- Fugacity Υ_i for each hadron — – see next slide outcome of SHM fit

To describe produced hadron yields

- Average per collision yield of hadron i is calculated from integral of the distribution over phase space

$$\langle N_i \rangle \to \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_i; \quad n_i(\varepsilon_i; T, \Upsilon_i) = \frac{1}{\Upsilon_i^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{n m_i}{T}\right)^2 K_2\left(\frac{n m_i}{T}\right)$$

- Hadron mass — PDG Tables
- Degeneracy (spin), $g_i = (2J + 1)$ — PDG Tables

- Overall normalization — outcome of SHM fit
- Hadronization temperature — outcome of SHM fit
- Fugacity Υ_i for each hadron — – see next slide outcome of SHM fit

TO DESCRIBE PRODUCED HADRON YIELDS

- Average per collision yield of hadron i is calculated from integral of the distribution over phase space

$$\langle N_i \rangle \to \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_i; \quad n_i(\varepsilon_i; T, \Upsilon_i) = \frac{1}{\Upsilon_i^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{nm_i}{T}\right)^2 K_2\left(\frac{nm_i}{T}\right)$$

- Hadron mass — PDG Tables
- Degeneracy (spin), $g_i = (2J+1)$ — PDG Tables

- Overall normalization — outcome of SHM fit
- Hadronization temperature — outcome of SHM fit
- Fugacity Υ_i for each hadron — see next slide; outcome of SHM fit

TO DESCRIBE PRODUCED HADRON YIELDS

- Average per collision yield of hadron i is calculated from integral of the distribution over phase space

$$\langle N_i \rangle \rightarrow \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_i; \quad n_i(\varepsilon_i; T, \Upsilon_i) = \frac{1}{\Upsilon_i^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{n m_i}{T}\right)^2 K_2\left(\frac{n m_i}{T}\right)$$

- Hadron mass — PDG Tables
- Degeneracy (spin), $g_i = (2J + 1)$ — PDG Tables

- Overall normalization — outcome of SHM fit
- Hadronization temperature — outcome of SHM fit
- Fugacity Υ_i for each hadron — – see next slide outcome of SHM fit

TO DESCRIBE PRODUCED HADRON YIELDS

- Average per collision yield of hadron i is calculated from integral of the distribution over phase space

$$\langle N_i \rangle \to \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_i; \quad n_i\left(\varepsilon_i; T, \Upsilon_i\right) = \frac{1}{\Upsilon_i^{-1} e^{\varepsilon_i/T} \pm 1}$$

$$= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{nm_i}{T}\right)^2 K_2\left(\frac{nm_i}{T}\right)$$

• Hadron mass	PDG Tables
• Degeneracy (spin), $g_i = (2J + 1)$	PDG Tables
• Overall normalization	outcome of SHM fit
• Hadronization temperature	outcome of SHM fit
• Fugacity Υ_i for each hadron	– see next slide outcome of SHM fit

FUGACITY AND QUARK FLAVOR CHEMISTRY

FLAVOR CONSERVATION FACTOR $\lambda_q = e^{\mu/T}$

- controls difference between quarks and antiquark of same flavor $q - \bar{q}$
- "Relative" chemical equilibrium

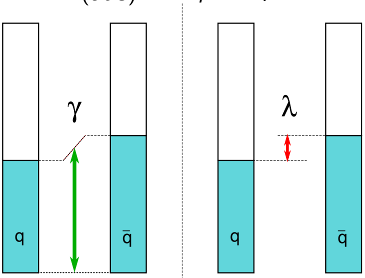
FLAVOR YIELD FACTOR γ_q

- phase spaces occupancy: absolute abundance of flavor q
- controls number of $q + \bar{q}$ pairs
- "Absolute" chemical equilibrium

P. Koch, B. Müller, JR, *Strangeness in Relativistic Heavy Ion Collisions*
Phys. Reports 142 (1986) 167-262

OVERALL FUGACITY $\Upsilon = \gamma\lambda$

- product of constituent quark flavor Υ_i
- example: $\Lambda(uds)$ $(q = u, d)$
  $\Upsilon_{\Lambda(uds)} = \gamma_q^2\gamma_s\,\lambda_q^2\lambda_s$
  $\Upsilon_{\overline{\Lambda}(\bar{u}\bar{d}\bar{s})} = \gamma_q^2\gamma_s\,\lambda_q^{-2}\lambda_s^{-1}$



$q = u, d, s, c, ..\bar{q} = \bar{u}, \bar{d}, \bar{s}, \bar{c}, ..$

HADRON RATIOS — CONCEPTUAL TEST OF SHM

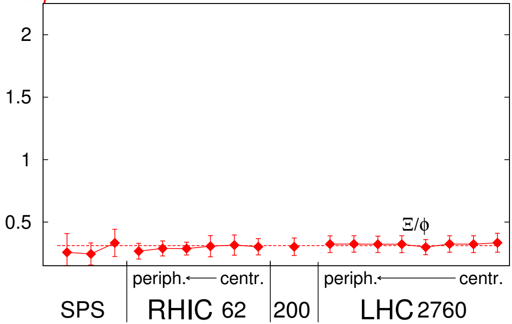
few(er)SHM parameters, easy to compare with data:

$$\frac{\Xi}{\phi} \equiv \sqrt{\frac{\Xi^-(ssd)\,\overline{\Xi}^+(\bar{s}\bar{s}\bar{d})}{\phi(s\bar{s})\,\phi(s\bar{s})}} = \sqrt{\frac{\gamma_s^4\gamma_q^2}{\gamma_s^4}\frac{\lambda_s^2\lambda_q\lambda_s^{-2}\lambda_q^{-1}}{\lambda_s^2\lambda_s^{-2}}}\,\frac{V_\Xi}{V_\phi}\,f(T, m_\Xi, m_\phi)$$

$$= \gamma_q\, f(T, m_\Xi, m_\phi).$$

$\gamma_q = 1$ **and system dependent T Impossible**

$\gamma_q \simeq 1.6$ **and system Independent T** $\simeq 140$ **perfect**



OTHER RATIOS

$$\frac{\phi}{\pi} \propto \frac{\gamma_s^2}{\gamma_q^2} \qquad \frac{\Xi}{\pi} \propto \frac{\gamma_s^2}{\gamma_q}$$

$$\frac{\phi}{K} \propto \frac{\gamma_s}{\gamma_q} \qquad \frac{\Xi}{K} \propto \gamma_s$$

- Ratios $\propto \gamma_s$ change $\Rightarrow \gamma_s$ change

Michal Petran, JR, Phys.Rev.C **82** (2010), 011901

HADRON RATIOS — CONCEPTUAL TEST OF SHM

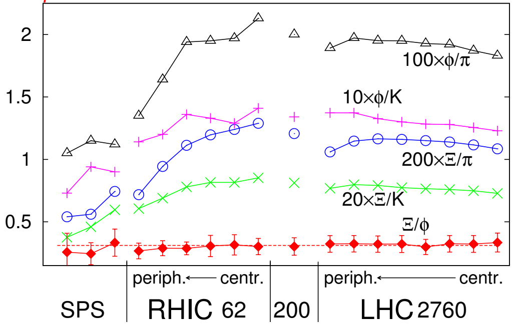
few(er)SHM parameters, easy to compare with data:

$$\frac{\Xi}{\phi} \equiv \sqrt{\frac{\Xi^-(ssd)\,\overline{\Xi}^+(\bar s\bar s\bar d)}{\phi(s\bar s)\;\phi(s\bar s)}} = \sqrt{\frac{\gamma_s^4\gamma_q^2}{\gamma_s^4}\,\frac{\lambda_s^2\lambda_q\lambda_s^{-2}\lambda_q^{-1}}{\lambda_s^2\lambda_s^{-2}}}\,\frac{V_\Xi}{V_\phi}\,f(T, m_\Xi, m_\phi)$$

$$= \gamma_q\, f(T, m_\Xi, m_\phi).$$

$\gamma_q = 1$ **and system dependent T Impossible**

$\gamma_q \simeq 1.6$ **and system Independent T** $\simeq 140$ **perfect**



Michal Petran, JR, Phys.Rev.C **82** (2010), 011901

OTHER RATIOS

$$\frac{\phi}{\pi} \propto \frac{\gamma_s^2}{\gamma_q^2} \qquad \frac{\Xi}{\pi} \propto \frac{\gamma_s^2}{\gamma_q}$$

$$\frac{\phi}{K} \propto \frac{\gamma_s}{\gamma_q} \qquad \frac{\Xi}{K} \propto \gamma_s$$

- Ratios $\propto \gamma_s$ change

  $\Rightarrow \gamma_s$ change

Statistical HAdronization with REsonances: (SHARE)

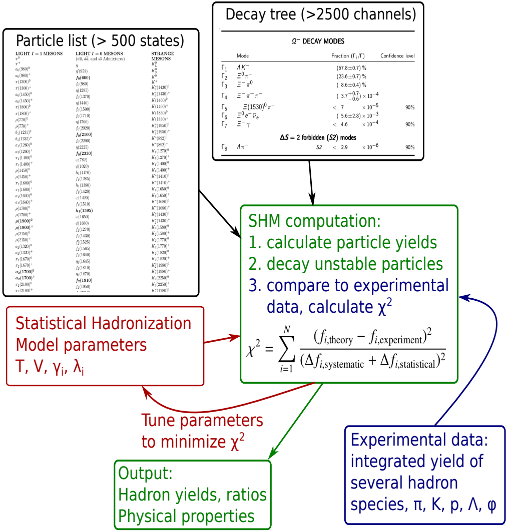
- SHM implementation in publicly available program
  Giorgio Torrieri et al, Arizona + Krakow; SHAREv1 (2004), SHAREv2 + Montreal, added fluctuations (2006)
  Michal Petran SHARE with CHARM: (2013)

SHARE INCORPORATES MANY THOUSANDS LINES OF CODE

- Hadron mass spectrum $>$ 500 hadrons (PDG 2012)
- Hadron decays $>$ 2500 channels (PDG 2012)
- Integrated hadron yields, ratios and decay cascades
- OUT:Experimentally observable $\lesssim$ 30 hadron species
- AND: Physical properties of the source at hadronization
  – also as input in fit e.g. constraints: $Q/B \simeq 0.39$, $\langle s - \bar{s} \rangle = 0$

PROCEDURE – FITTING SHM PARAMETERS TO DATA

1. Input: T, V, γ_q, γ_s, λ_q, λ_s.λ_3
2. Compute yields of all hadrons
3. Decay feeds – particles experiment observes
4. Compare to exp. data (χ^2)
5. Including bulk properties, constraints
6. Tune parameters to match data (minimize χ^2)

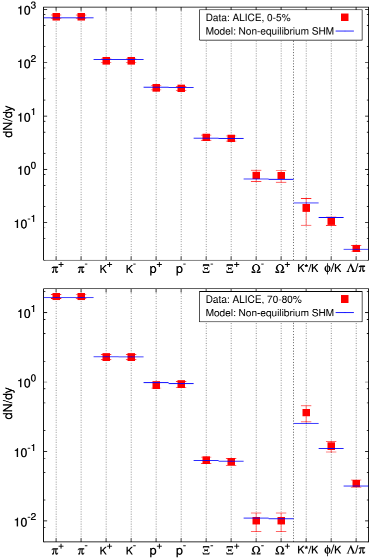


DOES SHM DESCRIBE PARTICLE PRODUCTION AT LHC?

HOW DOES THE QGP FIREBALL HADRONIZE?

COMPARISON BENCHMARK

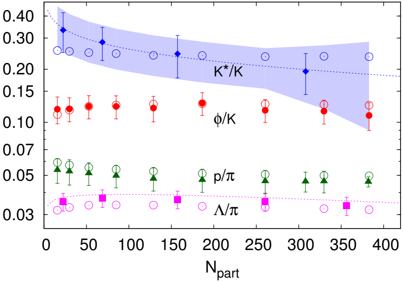
Fit to LHC hadron yields WORKS PERFECTLY



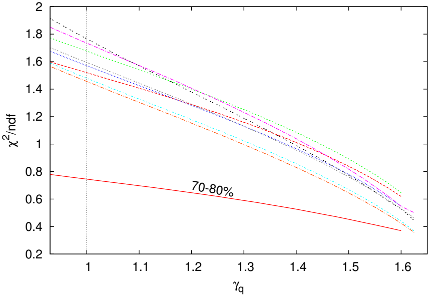
- Data from:
  Pb–Pb at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$
- Non-equilibrium SHM describes data across centrality
- Hadron yield range spans 5 orders of magnitude from central to peripheral

M.Petran et al., Phys. Rev. C 88, 034907 (2013)

PRECISE DATE DEMANDS CHEMICAL NON-EQUILIBRIUM OF LIGHT u, d AND STRANGE s QUARKS, $\gamma_i \neq 1$



M.Petran et al., Phys. Rev. C 88, 034907 (2013)



M.Petran et al., Phys. Rev. C 88, 034907 (2013)

- $\frac{p(uud)}{\pi(ud)} \propto \gamma_q$
- $\frac{p(uud)}{\pi(ud)} \simeq 0.05 \Rightarrow \gamma_q \simeq 1.6$

- $\gamma_q = 1$ no special importance
- $4\times$ smaller χ^2 for $\gamma_q = 1.6$

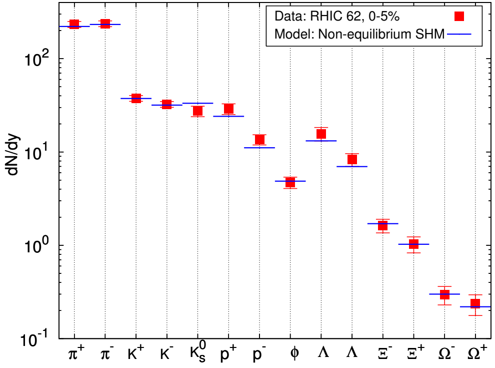
Only non-equilibrium describes all LHC data
afterburners ruin centrality systematics

RHIC-62 AS FUNCTION OF CENTRALITY

Does SHM describe particle production for all/most centralities?

For how small a system is the hadronization universal?

SHM AT RHIC 62 WORKS FOR US



SHM results: Petran et al., Acta Phys.Polon.Supp. 5 (2012) 255-262
Data from: [STAR Collaboration], Phys.Rev.C79, 034909 (2009)
[STAR Collaboration], Phys.Rev.C79, 064903 (2009).

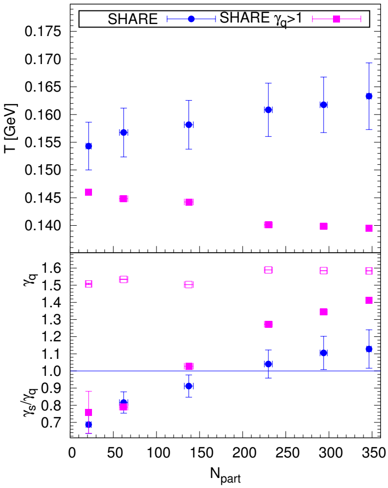
MODEL PARAMETERS

- $T = 140\,\mathrm{MeV}$
- $dV/dy = 850\,\mathrm{fm}^3$
- $\gamma_q = 1.6$
- $\gamma_s = 2.2$
- $\lambda_q = 1.16$
- $\lambda_s = 1.05$
- $\Rightarrow \mu_B = 62.8\,\mathrm{MeV}$
- $\chi^2/ndf = 0.38$

PHYS. PROPERTIES

- $\varepsilon = 0.5\,\mathrm{GeV}/\mathrm{fm}^3$
- $P = 82\,\mathrm{MeV}/\mathrm{fm}^3$
- $\sigma = 3.3\,\mathrm{fm}^{-3}$

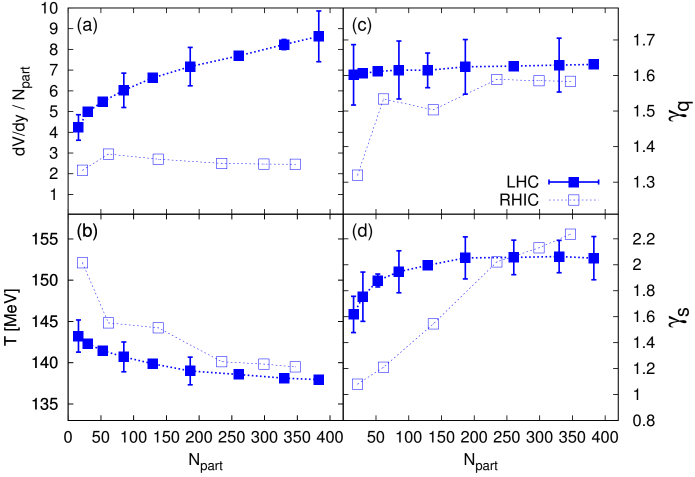
RHIC 62 GeV across centrality: two approaches (semi)equilibrium $\gamma_q = 1$ and 'nonequilibrium' $\gamma_q \neq 1$ QGP breakup



Petran et al.,Acta Phys.Pol.Supp. 5 (2012) 255-262

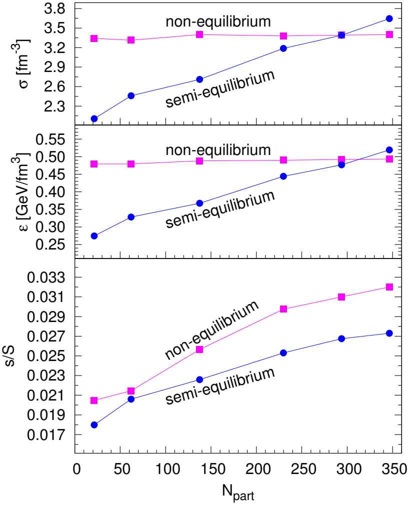
- Au–Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV at RHIC
- π,K,p,ϕ,Λ,Ξ and Ω fitted across centrality
- $\gamma_s \neq 1$ necessary to describe multistrange particles $\Rightarrow$ excludes chemical equilibrium
- $\gamma_s > 1$ in central collisions – strangeness overpopulation

SHM parameters as function of centrality LHC compared to RHIC



M.Petran et al., Phys. Rev. C 88, 034907 (2013)

Physical properties at RHIC 62 GeV



M.Petran et al.,Acta Phys.Polon.Supp. 5 (2012) 255-262

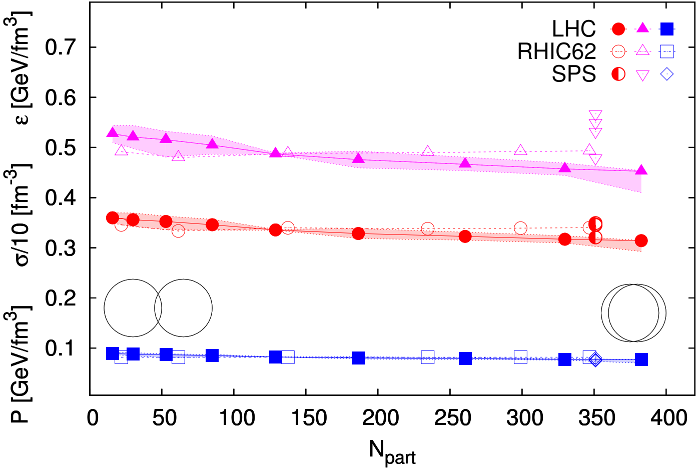
$dV/dy|_{central} = 17 \times dV/dy|_{peripheral}$

Non-equilibrium result $\gamma_q \neq 1$: universal hadronization

AND: Same physical conditions as at SPS for all RHIC-62 centralities

- Entropy density $\sigma = 3.3\,\mathrm{fm}^{-3}$
- Energy density $\varepsilon = 0.5\,\mathrm{GeV/fm}^3$
- Critical pressure $P = 82\,\mathrm{MeV/fm}^3$
- s/S near chemical equilibrium QGP $s/S \simeq 0.03$

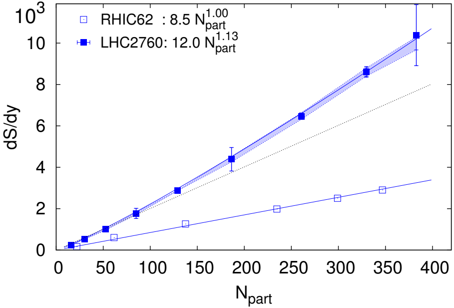
WHICH RHIC CASE IS MORE INTERESTING? A constant ϵ, σ, P as function of centrality at same value as at LHC, or a variable function without relation to LHC results?



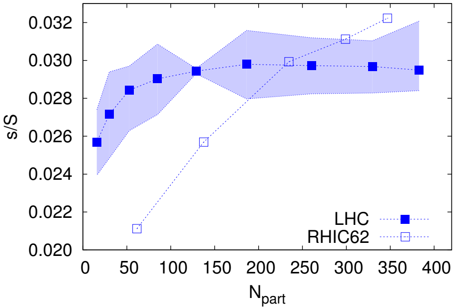
M.Petran et al., Phys. Rev. C 88, 021901(R) (2013)

M.Petran et al., Phys. Rev. C 88, 034907 (2013)

Important LHC-RHIC differences: Total entropy (final volume), strangeness vs. centrality



M.Petran et al., Phys. Rev. C 88, 034907 (2013)



M.Petran et al., Phys. Rev. C 88, 034907 (2013)

- LHC – steeper than linear
- Additional centrality dependent entropy production

- For small N_{part} rapid increase of strangeness
- For large N_{part} steady level of strangeness

Importance of Strangeness/Entropy=Particle Multiplicity

s/S: ratio of number of active degrees of freedom in QGP

For chemical equilibrium:

$$\frac{s}{S} \simeq \frac{1}{4}\frac{n_s}{n_s + n_{\bar{s}} + n_q + n_{\bar{q}} + n_G} = \frac{\frac{g_s}{2\pi^2} T^3 (m_s/T)^2 K_2(m_s/T)}{(g2\pi^2/45)T^3 + (g_s n_{\rm f}/6)\mu_q^2 T} \simeq$$

$$\simeq \frac{1}{35} = 0.0286$$

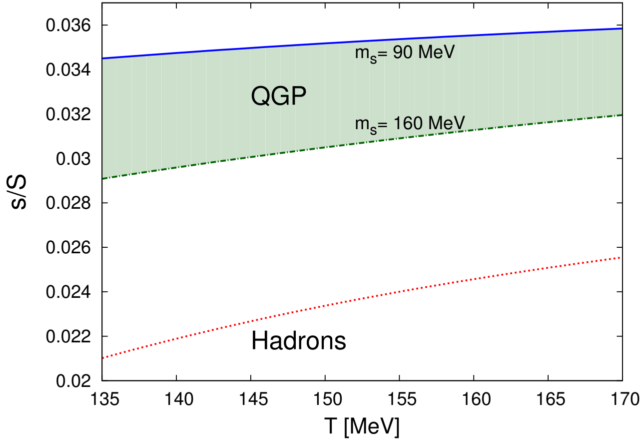
with $\mathcal{O}(\alpha_s)$ interaction $s/S \to 1/31 = 0.0323$

CENTRALITY A, and/or ENERGY DEPENDENCE:

Chemical non-equilibrium QGP occupancy of strangeness $\gamma_s^{\rm Q}$

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

WHAT DO WE EXPECT FOR s/S?



It is impossible to justify by hadron dynamics s/S at QGP level – this is one way of saying strangeness production is enhanced in QGP.

$_{\text{(AGS)}}$SPS – FIXED TARGET

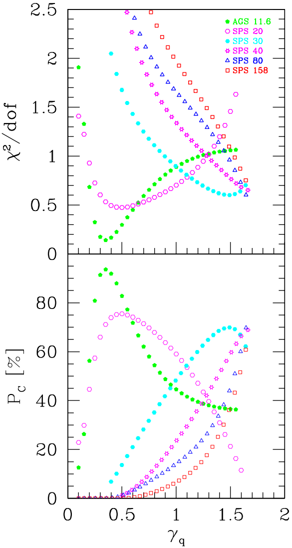
Does SHM describe particle production at SPS?

Is there any characteristic physical property of the hadronizing QGP fireball?

Table 1: AGS (on left) and SPS energy range particle multiplicity data sets used in fits (see text). In bottom of table, we show the fitted statistical parameters and the corresponding chemical potentials.

E[AGeV]	11.6	20	30	40	80	158
$\sqrt{s_{\rm NN}}$ [GeV]	4.84	6.26	7.61	8.76	12.32	17.27
$y_{\rm CM}$	1.6	1.88	2.08	2.22	2.57	2.91
$N_{4\pi}$ centrality	most central	7%	7%	7%	7%	5%
N_W, AGS: p/π^+	1.23 ± 0.13	349±6	349±6	349±6	349±6	362±6
Q/b	0.39±0.02	0.394±0.02	0.394±0.02	0.394±0.02	0.394±0.02	0.39±0.02
$(s-\bar{s})/(s+\bar{s})$	0 ± 0.05	0 ± 0.05	0 ± 0.05	0 ± 0.05	0 ± 0.05	0 ± 0.05
π^+	133.7±9.9	190.0±10.0	241±13	293±18	446±27	619±48
π^-, AGS: π^-/π^+	1.23 ± 0.07	221.0±12.0	274±15	322±19	474±28	639±48
K^+, AGS: K^+/K^-	5.23 ± 0.5	40.7±2.9	52.9±4.2	56.1±4.9	73.4±6	103±10
K^-	3.76±0.47	10.3±0.3	16±0.6	19.2±1.5	32.4±2.2	51.9±4.9
ϕ, AGS: ϕ/K^+	0.025 ± 0.006	1.89±0.53	1.84±0.51	2.55±0.36	4.04±0.5	8.46±0.71
Λ	18.1±1.9	27.1±2.4	36.9±3.6	43.1±4.7	50.1± 10	44.9±8.9
$\overline{\Lambda}$	0.017±0.005	0.16±0.05	0.39±0.06	0.68±0.1	1.82±0.36	3.68±0.55
Ξ^-		1.5±0.3	2.42±0.48	2.96±0.56	3.8±0.87	4.5±0.20
$\overline{\Xi}^+$			0.12±0.05	0.13±0.03	0.58 ±0.19	0.83±0.04
$\Omega+\overline{\Omega}$, or K_S				0.14±0.07		81±4
V[fm^3]	3649±331	4775±261	2229±340	1595±383	2135±235	3055±454
T [MeV]	153.5±0.8	151.7±2.8	123.8±3	130.9±4.4	135.2±0.01	136.0±0.01
$\lambda_q^{\rm HP}$	5.21±0.07	3.53±0.09	2.86±0.09	2.42±0.09	1.98±0.07	1.744±0.02
$\lambda_s^{\rm HP}$	1.565*	1.39±0.05	1.45±0.05	1.34±0.06	1.25±0.18	1.155±0.03
$\gamma_q^{\rm HP}$	0.366±0.008	0.49±0.03	1.54±0.37	1.66±0.14	1.65±0.01	1.64±0.01
$\gamma_s^{\rm HP}$	0.216±0.009	0.40±0.03	1.61±0.07	1.62±0.25	1.52±0.06	1.63±0.02
$\lambda_{I3}^{\rm HP}$	0.875±0.166	0.877±0.05	0.935±0.013	0.960±0.027	0.973±0.014	0.975±0.005
μ_B [MeV]	759	574	390	347	276	227
μ_S [MeV]	180	141	83.7	77.6	62.0	56.0

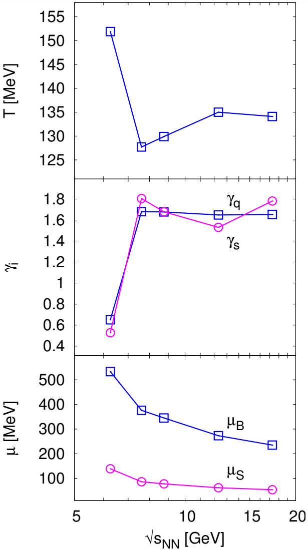
FIT RESULT χ^2 AT SPS (+ TOP AGS)



- Top AGS and lowest SPS energy: χ^2-minimum at $\gamma_q < 1$, change to $\gamma_q = 1.6$ between $\sqrt{s_{NN}} = 6.26$ and 7.61 GeV

- P[%] – confidence level satisfactory for best fit, while $\gamma_q = 1$ often not accaptable.

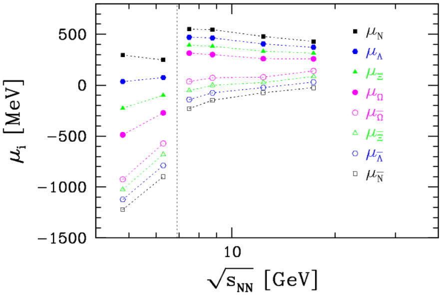
SHM PARAMETERS SPS



LOWEST $\sqrt{s_{NN}} = 6.26$ GEV OFTEN STANDS OUT

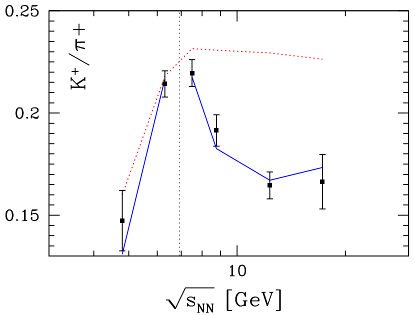
beginning at $\sqrt{s_{NN}} = 7.61$ features different

- T increases with $\sqrt{s_{NN}}$
- $\gamma_q \to$ condensation limit $\simeq 1.6$
- Chemical potentials:

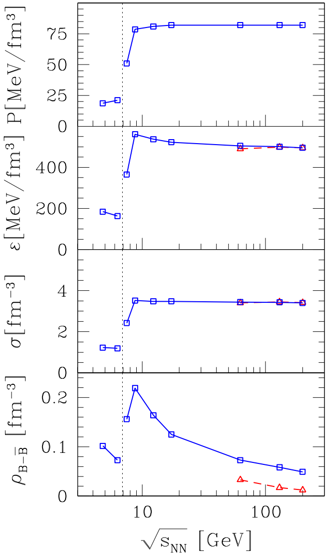


JR, J.Letessier, *Critical Hadronization Pressure*, J.Phys. G36 (2009) 064017 JR, J.Letessier, *Particle Production and Deconfinement Threshold*, arXiv 0901.2406

Particle Yields Described, Horn Tracked Perfectly



HADRONIZATION CONSISTENCY SPS – RHIC



AGS – SPS – RHIC

red RHIC central *y*

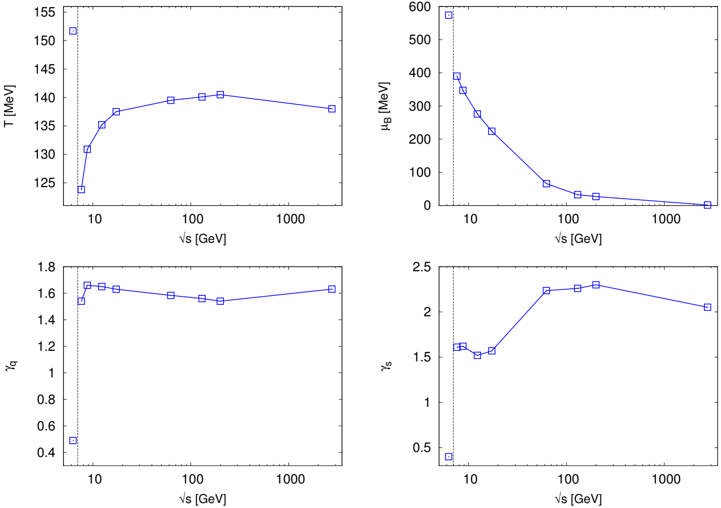
- P, ϵ, σ all show clearly common hadronization condition
- Baryon density peaks beyond the reaction mechanism change between $\sqrt{s_{NN}} = 6.26,\ 7.61$ GeV.

JR, J.Letessier, *Critical Hadronization Pressure*, J.Phys. G36 (2009) 064017

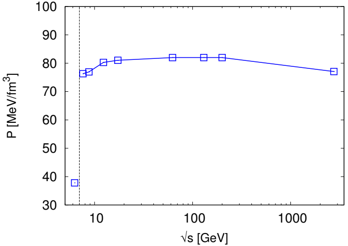
SYNTHESIS: LHC+RHIC+SPS

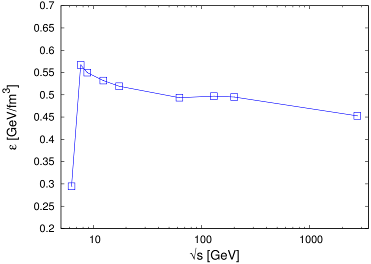
J. Rafelski and M. Petran, “Strangeness in QGP: Hadronization Pressure,” arXiv:1403.4036 [nucl-th].

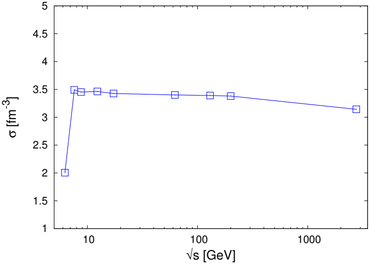
Comparison Across Energy SPS-RHIC-LHC: SHM parameters



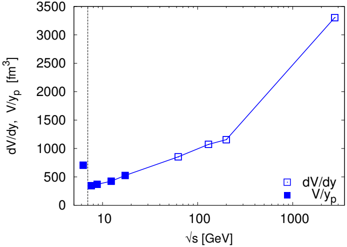
Comparison Across SPS-RHIC-LHC: Stable properties

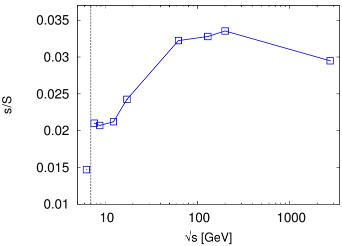




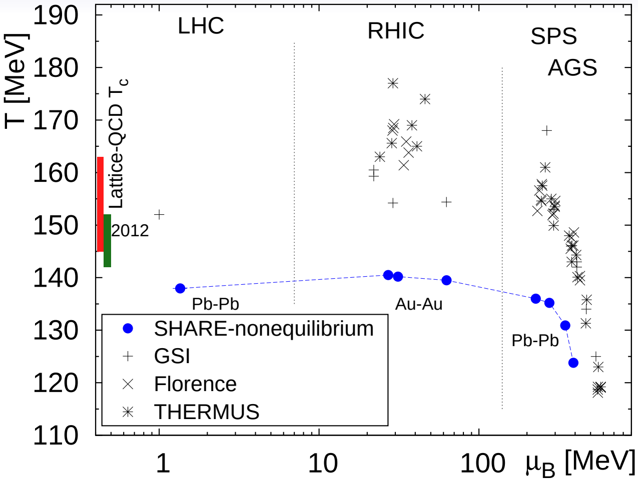


Comparison Across Energy
SPS-RHIC-LHC: Changing properties





CONSISTENCY WITH LATTICE-QCD



The observed chemical freeze-out MUST be below lattice results. Keep in mind, even if direct free-streaming emission from QGP no need for *T*-SHM parameter (there is no hadron temperature) to be the same as the QGP source temperature.

ANYTHING NEW ON THE HORIZON?

BJORKEN SCALING & TOP QUARK PRODUCTION

At 'infinite' energy density and absence of a recognizable reference frame the Lorentz-invariance of the vacuum requires that as function of rapidity there is exact y-scaling. Without a relevant time scales also exact transparency arises $dE/dy \rightarrow 0$. At LHC we find $dE/dy|_{y=0} = 1.5$ TeV out of 1400 TeV collision energy available. The energy stopping fraction is larger at lower energies – at RHIC-62 for example $dE/dy|_{y=0} = 0.6$ TeV out of 24 TeV.

When we increase HI reaction energy the scaling argument runs into heavy top t quarks.

Top has 'long' life span, $\Gamma_{\rm SM}^{t\rightarrow W^\pm b} = 1.3$ GeV corresponding to 1/7 fm. However, in CM $y = 0$ frame 'hard' partons in nuclei are within 1/1000 fm thick pancake so top is for collision physics stable.

Because the threshold energy requirement, the top pair production occurs in central rapidity region. With increasing number of produced tops a 'wall' of strongly interacting $y \simeq 0$ particles is creating. This piles up energy stopping opening up new physics opportunity for Heavy Ions.

Need: $W^\pm$ trigger detectors for selection of events. Evaluate of dE/dy in the accessible range – Where is the minimum?

MESSAGES OF THIS TALK

1. 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.

2. Irrespective of how a common QCD phase - the QGP state was created at 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 V and s.

3. Given universal hadronization conditions we believe that when QGP hadronizes it evaporates into free-streaming hadrons. There is no interlaced 'phase' of hadrons, no afterburners in general needed, nor are these in any way consistent with experimental results at LHC.

4. Heavy (c,b,t) quark production increases with increasing energy rapidly seeding energy stopping at sufficiently high collision energy.