MESSAGE OF THIS TALK

Our study relies on a precise method of hadron abundance analysis within the statistical hadronization model (SHM) implemented within the SHARE approach. We describe very well all available comprehensively and correctly measured particle production yields at SPS, RHIC, *and* LHC.

Irrespective of how QGP state was formed and how it evolves to hadronization, we should observe in the laboratory the same physical conditions of the fireball particle source. The properties of the QGP fireball are derived from what we see in all emitted hadronic particles.

We find universal hadronization condition. This confirms that in most if not all cases QGP evaporates into free-streaming hadrons – without a 'phase' of hadrons, no afterburners needed, nor are these in any way consistent with experimental results at LHC. Many orders of magnitude of particle yields described solely by Volume changes and strangeness content change from system to system and as function of centrality.

Quark-Gluon Plasma: SPS, RHIC, LHC
Universality of Hadronization Condition

Michal Petran, Jean Letessier and Johann Rafelski

Presented by JR, Arizona

Contributed to NF-QCD Symposium @ Kyoto Yukawa Institute, Dec 2-6, 2013

Key References:

JR and Jean Letessier, *Critical hadronization pressure*,
J.Phys. G **36** (2009) 064017; arXiv:0902.0063 and 0901:2406

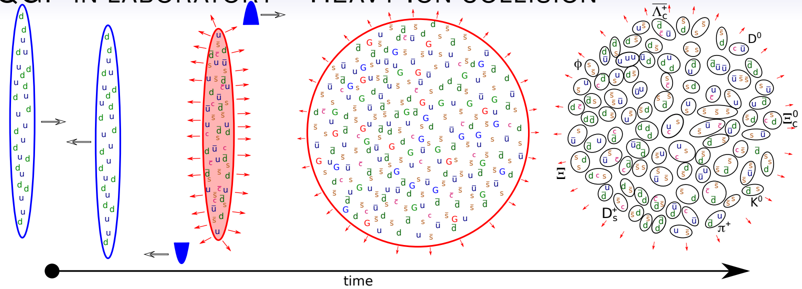
Michal Petran and JR, *Universal hadronization condition. . .*,
Phys. Rev C **88** 021901(R) (2013); arXiv:1303.0913

Michal Petran, Jean Letessier, Vojtech Petracek and JR *Hadron production and QGP hadronization . . .*, Phys. Rev. C **88**, 034907 (2013); arXiv:1303.2098

OUTLINE

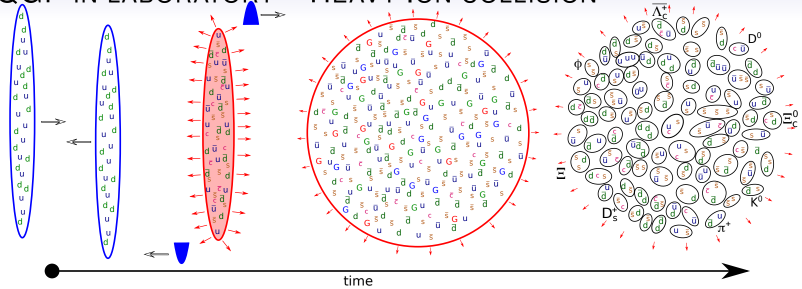
1. QGP in laboratory – heavy ion (HI) collisions
2. Description of particle production in HI experiments
3. QGP fireball physical properties at break-up
4. Universal Hadronization Conditions
5. Summary and Outlook

QGP IN LABORATORY – HEAVY-ION COLLISION



1. Nuclei collide – initial dominantly u, d quark content
2. parton (re)scattering, thermalization, formation of QGP, $m_s < T_{init} < m_c$, $\rightarrow$ different dominant s, c prod. mechanism
3. QGP fireball expands, cools down, thermal production of u, d, s-quarks by gluon fusion $GG \rightarrow q\bar{q}$; surviving charm primordial
4. Hadronization, quarks bind into colorless hadrons – QGP properties imprinted on produced hadrons

QGP in laboratory – Heavy-Ion collision



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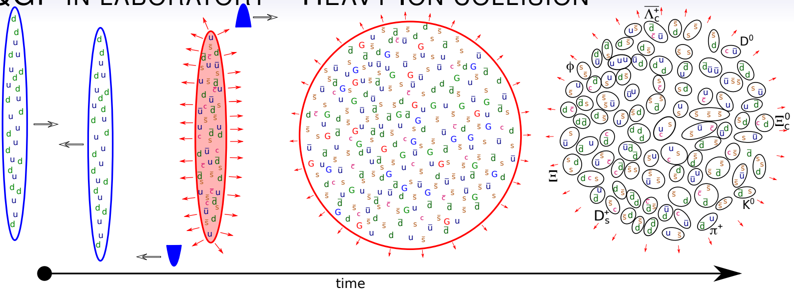

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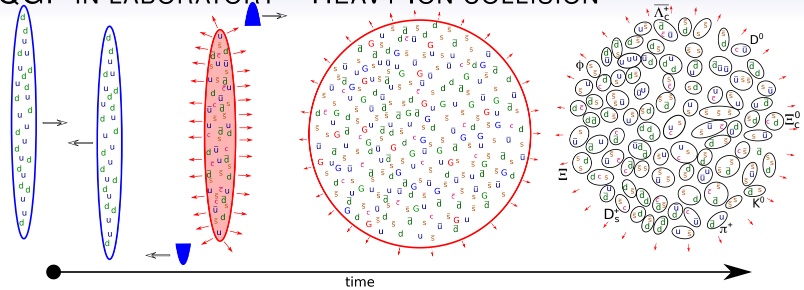

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STATISTICAL HADRONIZATION MODEL (SHM)

- Assuming equal hadron production strength irrespective of produced hadron type
- Particle yields depend only on available phase space
  - Micro-canonical – Fermi model
    fixed energy and number of particles
    E. Fermi, Prog.Theor.Phys. 5 (1950) 570
  - Canonical – fixed number of particles, average energy: T
  - Grand-canonical + average number of particles:
    $\mu \Leftrightarrow \Upsilon = e^{(\mu/T)}$
- Exploration of source properties in particle co-moving frame – collective matter flow irrelevant

PARTICLE ABUNDANCES

- Experiments report average particle abundances over many collision events
- Model calculations to describe an average event

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

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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

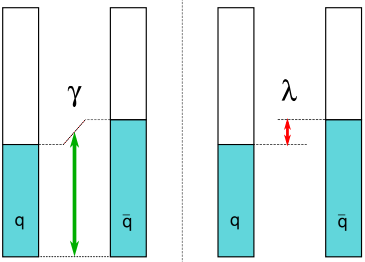
P. Koch, B. Müller, JR, *Strangeness in Relativistic Heavy Ion Collisions*
Phys. Reports 142 (1986) 167-262

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

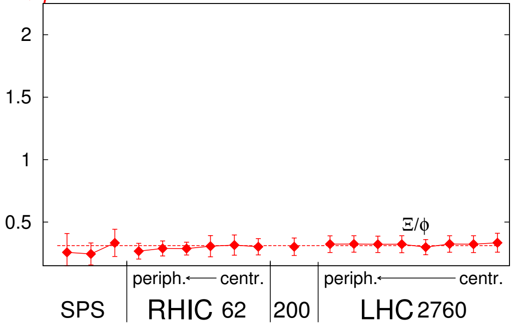
few(er)SHM parameters, easy to compare with data:

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

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

$\gamma_q = 1$ 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

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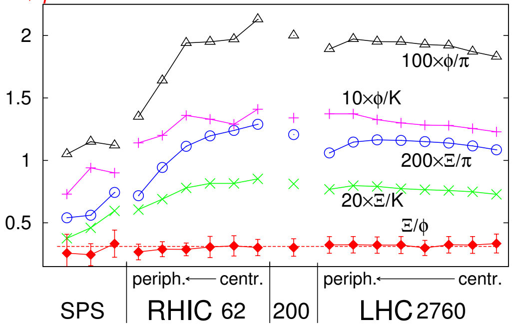

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Statistical HAdronization with REsonances: (SHARE)

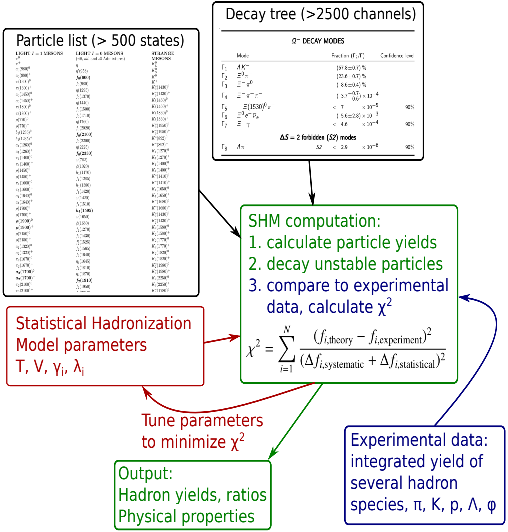
- SHM implementation in publicly available program
  Giorgio Torrieri et al, Arizona + Krakow; SHAREv1 (2004), SHAREv2 + Montreal, added fluctuations (2006)
  Michal Petran SHARE with CHARM: (2013)

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, $\lambda_s.\lambda_3$
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)



$_{\text{(AGS)}}$SPS – FIXED TARGET

Does SHM describe particle production at SPS?

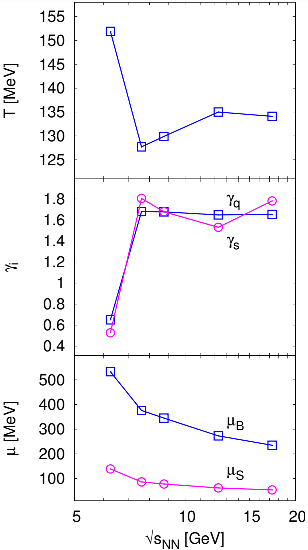
Is there any characteristic physical property of the hadronizing QGP fireball?

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
$\mu_{\rm B}$ [MeV]	759	574	390	347	276	227
$\mu_{\rm S}$ [MeV]	180	141	83.7	77.6	62.0	56.0

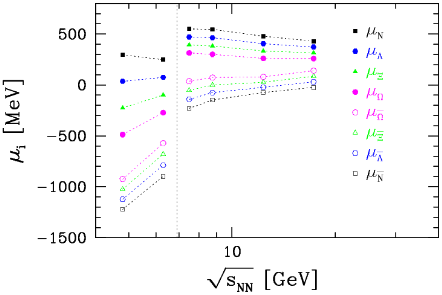
SHM PARAMETERS NA49-SPS

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



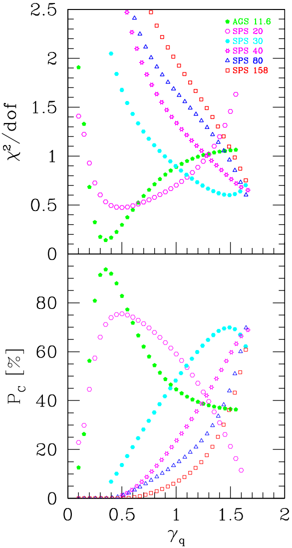
beginning at $\sqrt{s_{NN}} = 7.61$ features different

- 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

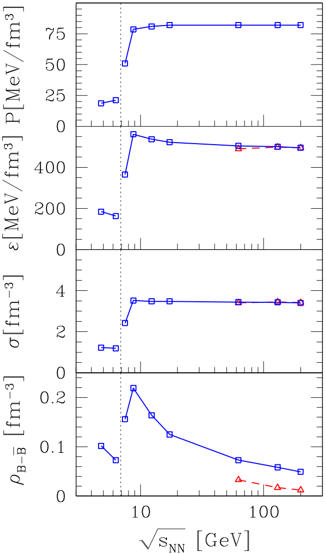
IS CHEMICAL NON-EQUILIBRIUM JUSTIFIED AT AGS/SPS?



- 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.

UNIVERSAL HADRONIZATION 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.

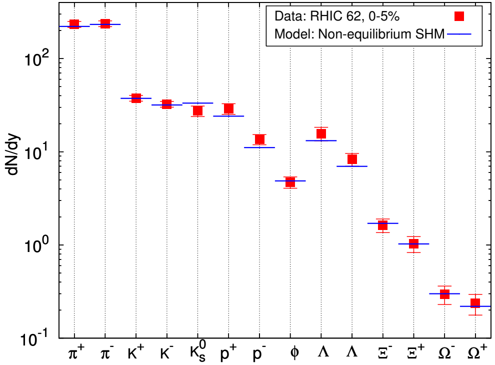
JR, J.Letessier, *Critical Hadronization Pressure*, J.Phys. G36 (2009) 064017

UNIVERSAL HADRONIZATION AT RHIC-62

AS FUNCTION OF CENTRALITY

For how small a system is the physical property of the hadronizing QGP fireball 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).

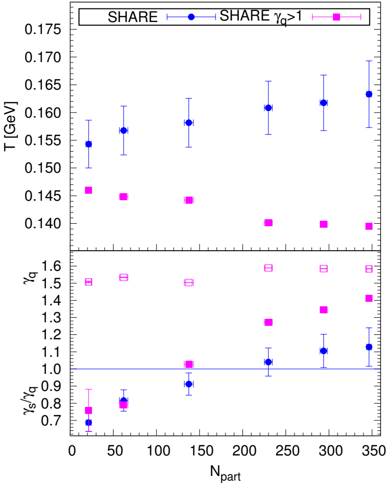
MODEL PARAMETERS

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

PHYS. PROPERTIES

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

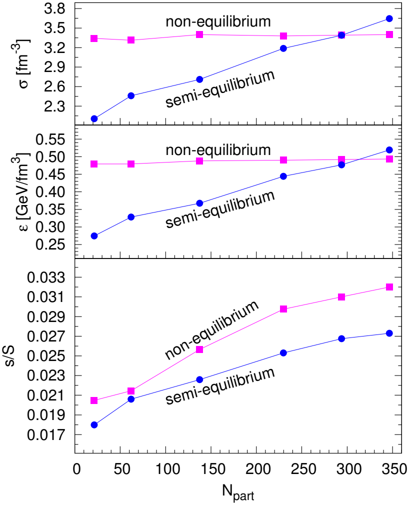
RHIC 62 GeV across centrality: two approaches (semi)equilibrium $\gamma_q = 1$ and 'nonequilibrium' $\gamma_q \neq 1$ QGP breakup



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 ⇒ excludes chemical equilibrium
- $\gamma_s > 1$ in central collisions – strangeness overpopulation

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 $s/S \simeq 0.03$

IMPORTANCE OF STRANGENESS/ENTROPY=PARTICLE MULTIPLICITY

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

For chemical equilibrium:

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

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

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 $\gamma_s^{\rm Q}$

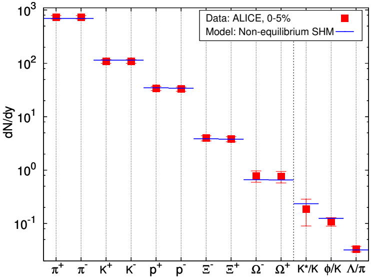
$$\frac{s}{S} = \frac{0.03\gamma_s^{\rm Q}}{0.4\gamma_{\rm G}+0.1\gamma_s^{\rm Q}+0.5\gamma_q^{\rm Q}+0.05\gamma_q^{\rm Q}(\ln\lambda_q)^2} \to 0.03\gamma_s^{\rm Q}.$$

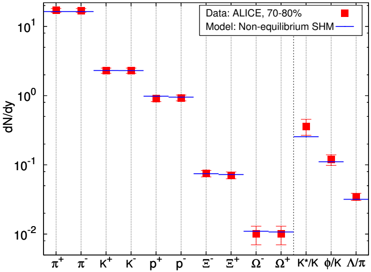
LHC – 45$\times$ HIGHER ENERGY (THAN RHIC 62)

Does SHM describe particle production at LHC?

Does the QGP fireball hadronizes at the same ‘universal’ hadronization conditions as at SPS and RHIC 62?

FIT TO LHC HADRON YIELDS WORKS PERFECTLY and nearly same parameters as RHIC 62

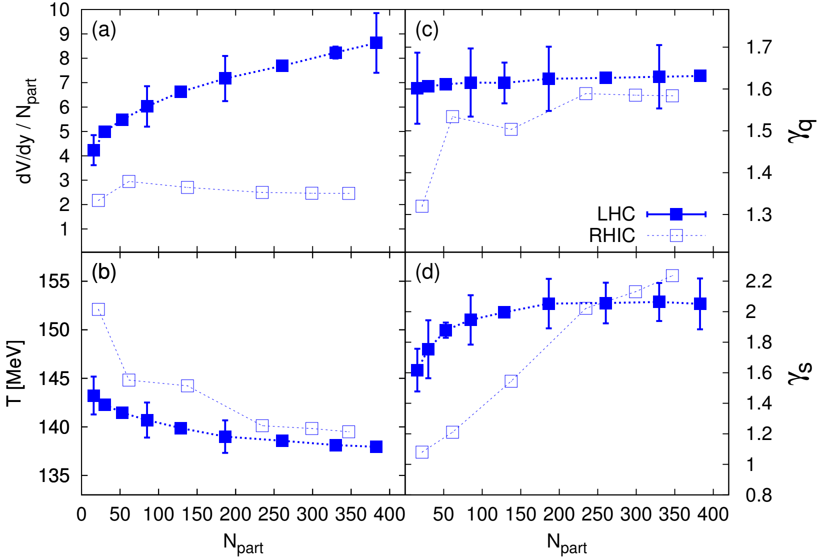




- Data from:
  Pb–Pb at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$
- Non-equilibrium SHM describes data across centrality
- Hadron yield range spans 5 orders of magnitude from central to peripheral

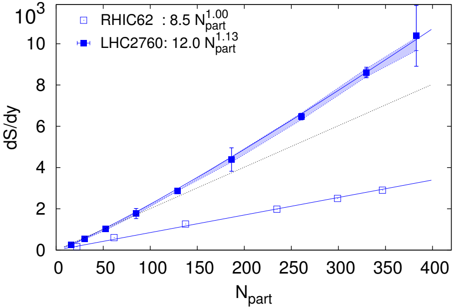
M.Petran et al., Phys. Rev. C 88, 034907 (2013)

Model parameters at LHC compared to RHIC



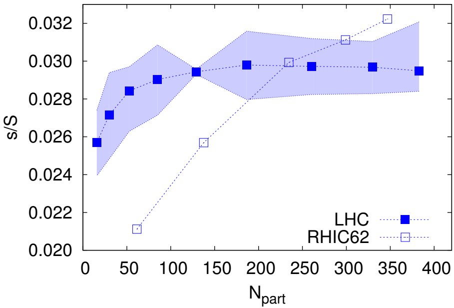
M.Petran et al., Phys. Rev. C 88, 034907 (2013)

IMPORTANT DIFFERENCES:
ENTROPY, STRANGENESS VS. CENTRALITY



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

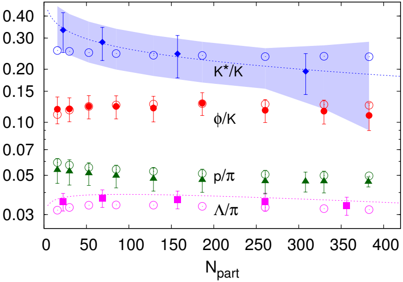
- LHC – steeper than linear
- Additional centrality dependent entropy production



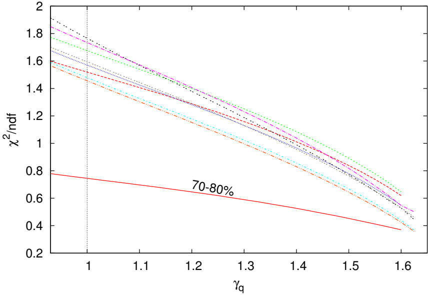
M.Petran et al., Phys. Rev. C 88, 034907 (2013)

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

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)



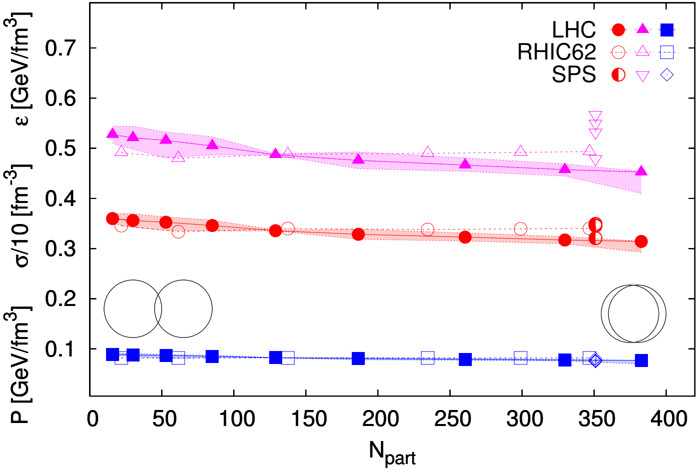
M.Petran et al., Phys. Rev. C 88, 034907 (2013)

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

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

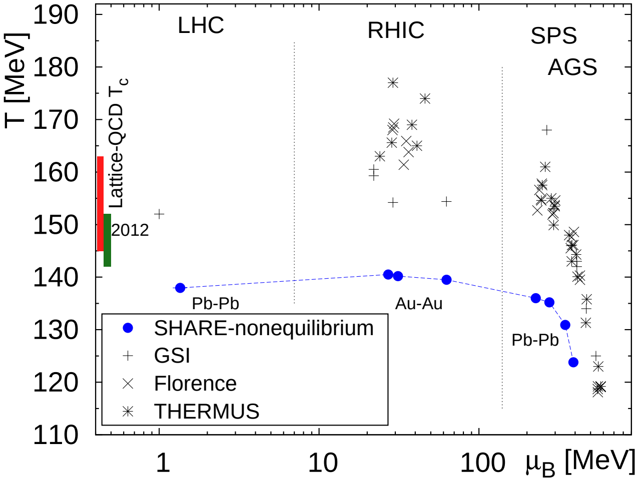
Only non-equilibrium describes all LHC data
afterburners ruin centrality systematics

UNIVERSAL HADRONIZATION CONDITIONS: RHIC VS LHC AS FUNCTION OF CENTRALITY + SPS POINTS



M.Petran et al., Phys. Rev. C 88, 021901(R) (2013)
M.Petran et al., Phys. Rev. C 88, 034907 (2013)

Consistency with Lattice-QCD



We need to remember that HI collisions are highly dynamic and observed phase boundary MUST be below lattice results.

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

SUMMARY UP, DOWN, STRANGE flavor contents

- Only non-equilibrium allowed $\gamma_q \simeq 1.6$, $\gamma_s \to 2+$
  SHM describes SPS,RHIC, *and*LHC data
- Universal hadronization conditions (ε, P, σ) of QGP
  at LHC, RHIC and SPS incl. most centralities available
- strangeness in QGP fireball near chemical equilibrium
  at LHC new entropy input for most central reactions
  (charm,jets?)

OUTLOOK

- Trace anomaly $\frac{\varepsilon - 3P}{T^4}$ investigation in progress
- given precise LHC data fit of both γ_u, γ_d in progress:
  impacts many yields e.g. $K^\pm$ vs K^0
  – prerequisite to measure $\mu_B^{\rm LHC}$
- Looking forward to results from RHIC
  – we established method to look for onset of QGP creation

MESSAGE OF THIS TALK

Our study relies on a precise method of hadron abundance analysis within the statistical hadronization model (SHM) implemented within the SHARE approach. We describe very well all available comprehensively and correctly measured particle production yields at SPS, RHIC, *and* LHC.

We find universal hadronization condition. This confirms that in most if not all cases QGP evaporates into free-streaming hadrons – without a 'phase' of hadrons, no afterburners needed, nor are these in any way consistent with experimental results at LHC. Many orders of magnitude of particle yields described solely by volume changes and strangeness content change from system to system and as function of centrality.