

QUARK-GLUON PLASMA: UNIVERSAL HADRONIZATION

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The University of Arizona

November 12, 2013

Wigner 111, 11/11/13 Budapest; Session: Nuclear Physics

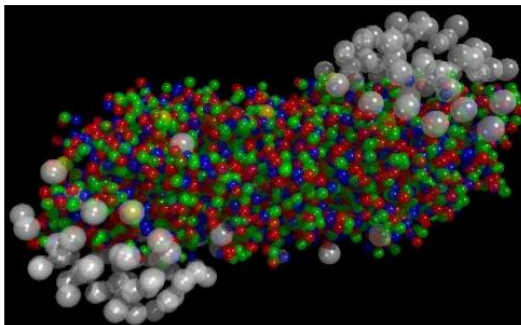
Part of: Ph.D. Defense Presentation by
Michal Petran, Tucson, November 5, 2013

OUTLINE

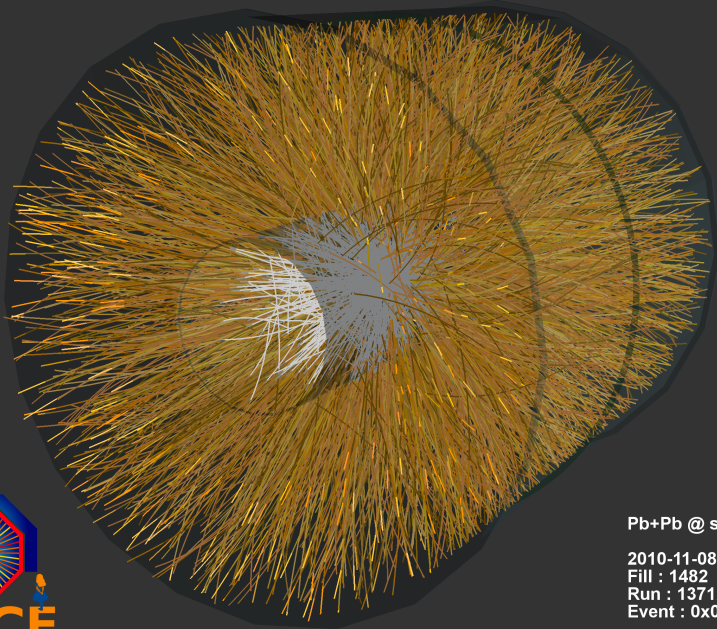
1. Quark-gluon plasma (QGP) – new state of matter
2. Description of particle production in HI experiments
3. QGP fireball physical properties at break-up
4. Universal Hadronization Conditions
5. Summary and Outlook

New State of Matter created at CERN

10 Feb 2000



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.



Pb+Pb @ $\sqrt{s} = 2.76$ ATeV

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QUARK-GLUON PLASMA – QGP

– NEW STATE OF MATTER

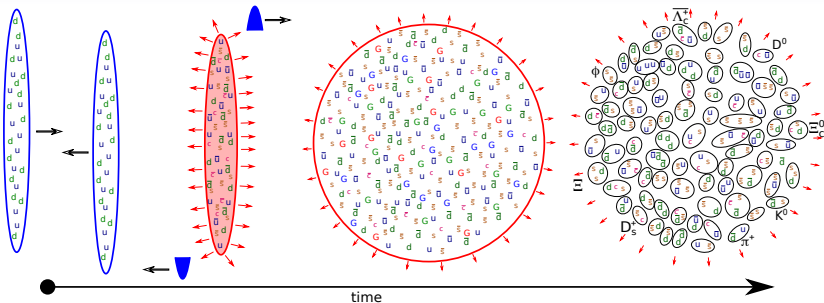
WHAT IS QGP?

- Hot soup of quarks and gluons
- Extremely hot and dense matter
 $T > 150\text{MeV} \simeq 1.7 \cdot 10^{12} \text{ K}, 10^5 \times T_{\text{sun}}$
- Strongly interacting medium – color charge propagating
– **new state and a new form of matter**

WHERE TO FIND QGP?

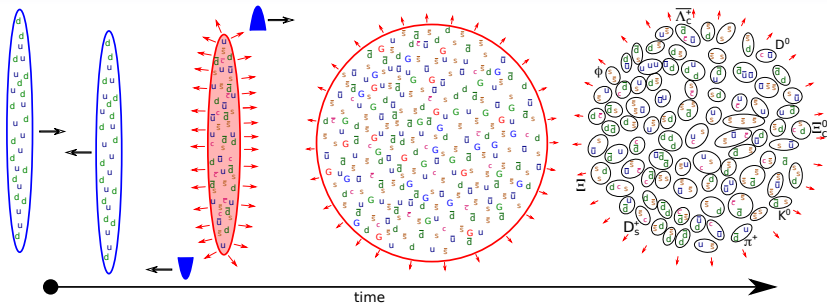
- Early Universe made of QGP, until $\mathcal{O}(15) \mu\text{s}$
- In laboratory, QGP created in
relativistic heavy-ion collisions

QGP IN LABORATORY – HEAVY-ION COLLISION



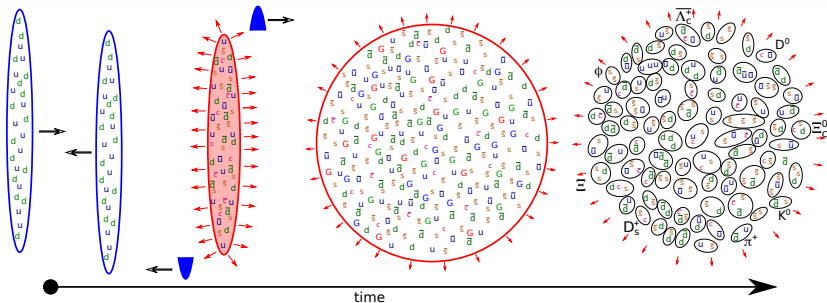
1. Nuclei collide – dominantly u, d quark content
2. parton scattering – rescattering, thermalization, formation of QGP, $m_s < T_{init} < m_c$
3. QGP fireball expands, cools down, thermal production of u, d, s -quarks by gluon fusion $GG \rightarrow q\bar{q}$; surviving charm primordial
4. Hadronization, quarks bind into colorless hadrons – QGP properties imprinted on produced hadrons, at LHC $\mathcal{O}(10^5)$

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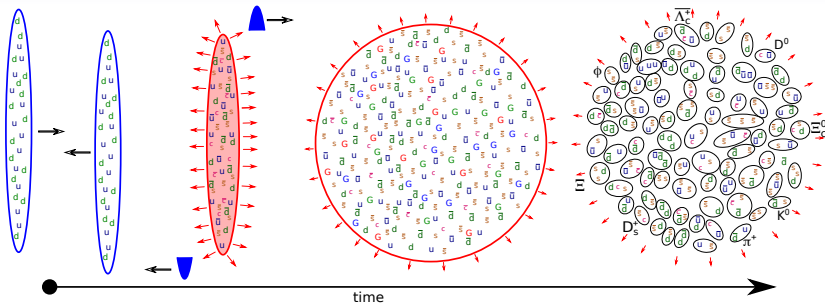
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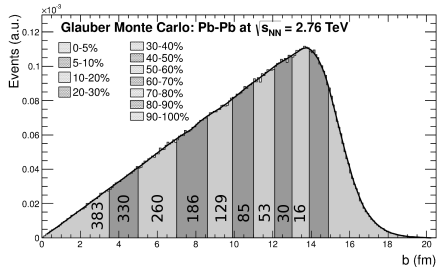
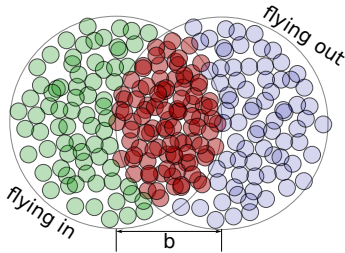
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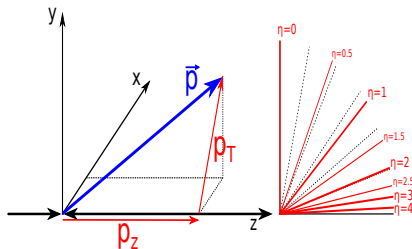
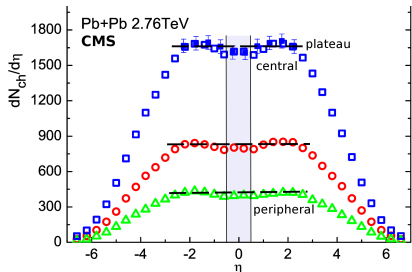
CENTRALITY OF HEAVY-ION COLLISION



IMPACT PARAMETER b analogue expressions

- N_{part} – number of participants
– number of nucleons that interact at least once
- N_{bin} – number of 1-on-1 nucleon reactions (Glauber model)
- Central collision: $b \rightarrow 0 \Leftrightarrow N_{part} \rightarrow 400, N_{bin} \rightarrow 1900$

(PSEUDO)RAPIDITY AND SPATIAL DISTRIBUTION OF PARTICLES



$$\eta \simeq y \in (-0.5, 0.5),$$

$$\text{rapidity } y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

REPRESENTATIVE CENTRAL (PSEUDO)RAPIDITY UNIT

- Corresponds to $\pm 27.5^\circ$ from transverse (xy) plane
- Represents a fraction of invariant particle yield $N \longrightarrow \frac{dN}{dy}$
- Fit produces normalization $V \longrightarrow \frac{dV}{dy}$
- # charged particles in study $\frac{dN_{ch}}{dy} \simeq 1601 \pm 60 \ll 15000$
(ALICE Pb–Pb at 2.76TeV 0-5%)

PARTICLE ABUNDANCES

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

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
 - 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

TO DESCRIBE PRODUCED HADRON YIELDS

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

$$\begin{aligned}\langle N_i \rangle &\rightarrow \frac{dN_i}{dy} = g_i \frac{dV}{dy} \int \frac{d^3p}{(2\pi)^3} n_i; & n_i(\varepsilon_i; T, \Upsilon_i) &= \frac{1}{\Upsilon_i^{-1} e^{\varepsilon_i/T} \pm 1} \\ &= \frac{g_i T^3}{2\pi^2} \frac{dV}{dy} \sum_{n=1}^{\infty} \frac{(\pm 1)^{n-1} (\Upsilon_i)^n}{n^3} \left(\frac{nm_i}{T}\right)^2 K_2\left(\frac{nm_i}{T}\right)\end{aligned}$$

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

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

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- **Hadron mass**

PDG Tables

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FUGACITY AND QUARK FLAVOR CHEMISTRY

FLAVOR CONSERVATION FACTOR

$$\lambda_q = e^{\mu/T}$$

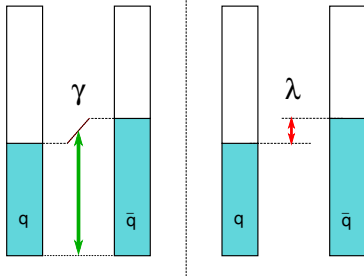
- controls difference between quarks and antiquark of same flavor $q - \bar{q}$
- “Relative”** chemical equilibrium

FLAVOR YIELD FACTOR γ_q

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

OVERALL FUGACITY $\Upsilon = \gamma\lambda$

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



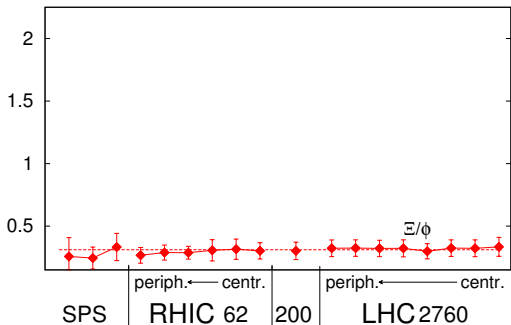
HADRON RATIOS — CONCEPTUAL TEST OF SHM

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

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

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

OTHER RATIOS



$$\frac{\Xi}{K} \propto \gamma_s$$

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

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

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

- Same T_{QGP}
 $\Xi/\phi \Rightarrow \gamma_q = \text{const.}$
- Ratios $\propto \gamma_s$ change
 $\Rightarrow \gamma_s$ change

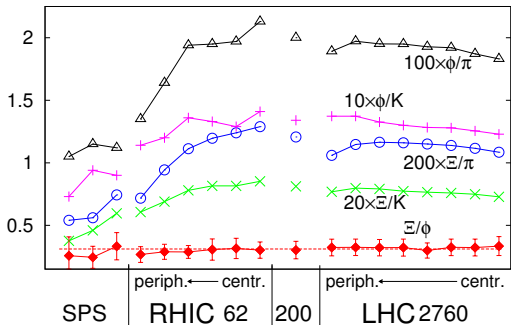
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$$= \gamma_q f(T, m_{\Xi}, m_{\phi}).$$

OTHER RATIOS



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 $\Rightarrow \gamma_s \text{ change}$

STANDARDIZED PROGRAM TO FIT SHM PARAMETERS

Statistical **HA**dronization with **RE**sonances: (**SHARE**)

- SHM implementation in publicly available program
G. Torrieri et al, Arizona + Krakow; SHAREv1 (2004),
SHAREv2 (2006, added fluctuations, + Montreal)
M. Petran SHARE(s) with CHARM: (2007–present)

SHARE INCORPORATES

- 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: $T, V, \gamma_q, \gamma_s, \lambda_q, \lambda_s, \lambda_3$
2. Compute yields of **all hadrons**
3. Decay feeds – particles experiment observes
4. Compare to exp. data (χ^2)
5. Including bulk properties and constraints
6. Tune parameters to match data (minimize χ^2)

Particle list (> 500 states)

LIBRI F = 1 HADRONS	LIBRI F = 0 HADRONS (ex. all set of Abundances)	LIBRI F = 0 HADRONS
*	0	A1
*2000P	0.0000	A2
2000P	0.0000	A3
2000P	0.0000	A4
2000P	0.0000	A5
2000P	0.0000	A6
2000P	0.0000	A7
2000P	0.0000	A8
2000P	0.0000	A9
2000P	0.0000	A10
2000P	0.0000	A11
2000P	0.0000	A12
2000P	0.0000	A13
2000P	0.0000	A14
2000P	0.0000	A15
2000P	0.0000	A16
2000P	0.0000	A17
2000P	0.0000	A18
2000P	0.0000	A19
2000P	0.0000	A20
2000P	0.0000	A21
2000P	0.0000	A22
2000P	0.0000	A23
2000P	0.0000	A24
2000P	0.0000	A25
2000P	0.0000	A26
2000P	0.0000	A27
2000P	0.0000	A28
2000P	0.0000	A29
2000P	0.0000	A30
2000P	0.0000	A31
2000P	0.0000	A32
2000P	0.0000	A33
2000P	0.0000	A34
2000P	0.0000	A35
2000P	0.0000	A36
2000P	0.0000	A37
2000P	0.0000	A38
2000P	0.0000	A39
2000P	0.0000	A40
2000P	0.0000	A41
2000P	0.0000	A42
2000P	0.0000	A43
2000P	0.0000	A44
2000P	0.0000	A45
2000P	0.0000	A46
2000P	0.0000	A47
2000P	0.0000	A48
2000P	0.0000	A49
2000P	0.0000	A50
2000P	0.0000	A51
2000P	0.0000	A52
2000P	0.0000	A53
2000P	0.0000	A54
2000P	0.0000	A55
2000P	0.0000	A56
2000P	0.0000	A57
2000P	0.0000	A58
2000P	0.0000	A59
2000P	0.0000	A60
2000P	0.0000	A61
2000P	0.0000	A62
2000P	0.0000	A63
2000P	0.0000	A64
2000P	0.0000	A65
2000P	0.0000	A66
2000P	0.0000	A67
2000P	0.0000	A68
2000P	0.0000	A69
2000P	0.0000	A70
2000P	0.0000	A71
2000P	0.0000	A72
2000P	0.0000	A73
2000P	0.0000	A74
2000P	0.0000	A75
2000P	0.0000	A76
2000P	0.0000	A77
2000P	0.0000	A78
2000P	0.0000	A79
2000P	0.0000	A80
2000P	0.0000	A81
2000P	0.0000	A82
2000P	0.0000	A83
2000P	0.0000	A84
2000P	0.0000	A85
2000P	0.0000	A86
2000P	0.0000	A87
2000P	0.0000	A88
2000P	0.0000	A89
2000P	0.0000	A90
2000P	0.0000	A91
2000P	0.0000	A92
2000P	0.0000	A93
2000P	0.0000	A94
2000P	0.0000	A95
2000P	0.0000	A96
2000P	0.0000	A97
2000P	0.0000	A98
2000P	0.0000	A99
2000P	0.0000	A100

Decay tree (>2500 channels)

Ω^- DECAY MODES		
Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1 AK^{*0}	$10.0 \pm 0.7\%$	
Γ_2 $2\pi^0\pi^+$	$13.6 \pm 0.7\%$	
Γ_3 $2\pi^+\pi^0$	$1.86 \pm 0.4\%$	
Γ_4 $2\pi^+\pi^+\pi^-$	$(3.7^{+0.7}_{-0.8}) \times 10^{-4}$	
Γ_5 $\Xi[1530]^0\pi^+$	$< 7 \times 10^{-5}$	90%
Γ_6 $\Xi^0\pi^+\pi^0$	$(5.6 \pm 2.0) \times 10^{-3}$	
Γ_7 $\Xi^0\pi^+\pi^+$	$< 4.6 \times 10^{-4}$	90%
$\Delta S = 2$ forbidden (SZ) modes		
Γ_8 $A\pi^+$	$SZ < 2.9 \times 10^{-6}$	90%

Statistical Hadronization Model parameters $T, V, \gamma_i, \lambda_i$

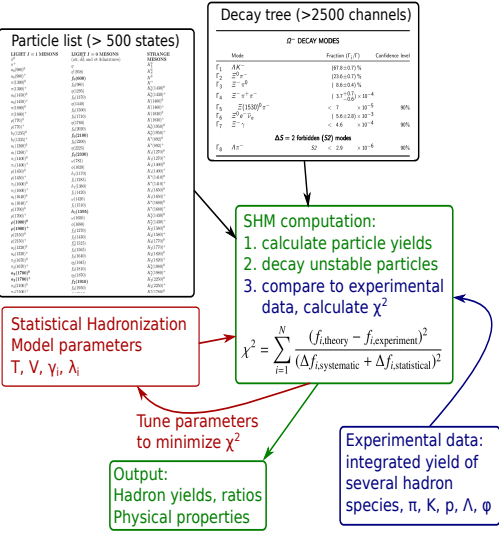
SHM computation:
 1. calculate particle yields
 2. decay unstable particles
 3. compare to experimental data, calculate χ^2

$$\chi^2 = \sum_{i=1}^N \frac{(f_{i,theory} - f_{i,experiment})^2}{(\Delta f_{i,systematic} + \Delta f_{i,statistical})^2}$$

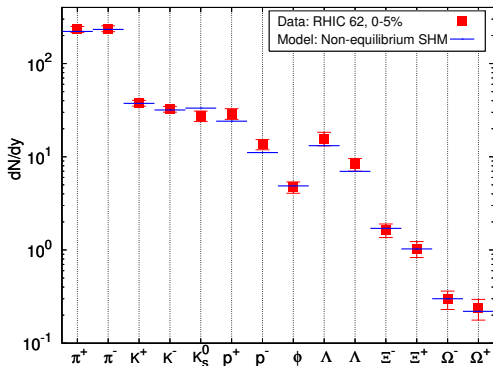
Output: Hadron yields, ratios Physical properties

Experimental data: integrated yield of several hadron species, π, K, p, Λ, ϕ

Tune parameters to minimize χ^2



SHM DESCRIPTION OF CENTRAL RHIC 62



MODEL PARAMETERS

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

PHYS. PROPERTIES

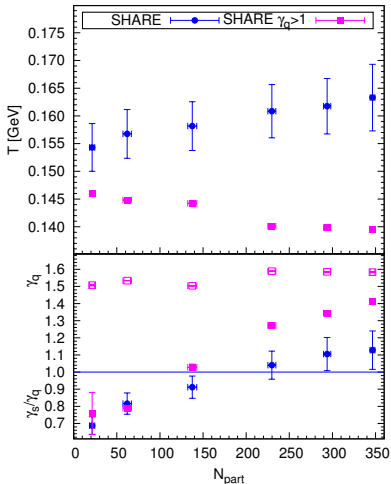
- $\varepsilon = 0.5 \text{ GeV}/\text{fm}^3$
- $P = 82 \text{ MeV}/\text{fm}^3$
- $\sigma = 3.3 \text{ fm}^{-3}$

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

Data from: [STAR Collaboration], Phys.Rev.C79, 034909 (2009)

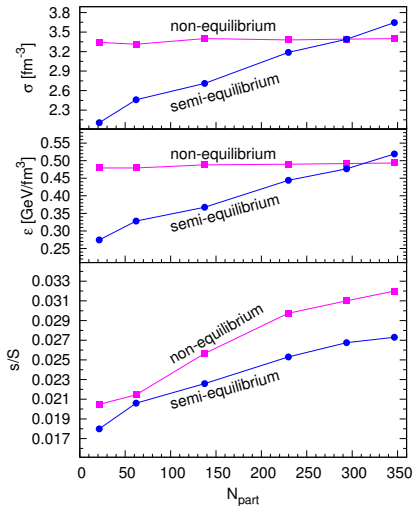
[STAR Collaboration], Phys.Rev.C79, 064903 (2009).

DESCRIBING RHIC 62 GeV ACROSS CENTRALITY:
 TWO APPROACHES (SEMI)EQUILIBRIUM $\gamma_q = 1$ AND
 'NONEQUILIBRIUM' $\gamma_q \neq 1$ QGP BREAKUP



- Au–Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV at RHIC
- $\pi, K, p, \phi, \Lambda, \Xi$ 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

PHYSICAL PROPERTIES AT RHIC 62 GEV



Non-equilibrium result $\gamma_q \neq 1$:
constant physical properties

SAME UNIVERSAL
HADRONIZATION
CONDITIONS AS AT SPS

J.Phys. G36 (2009) 064017

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

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

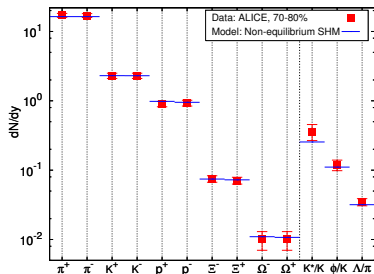
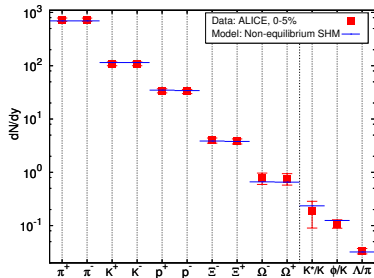
$dV/dy|_{central} = 17 \times dV/dy|_{peripheral}$

LHC – 45× HIGHER ENERGY (THAN RHIC 62)

Does SHM describe particle production at LHC?

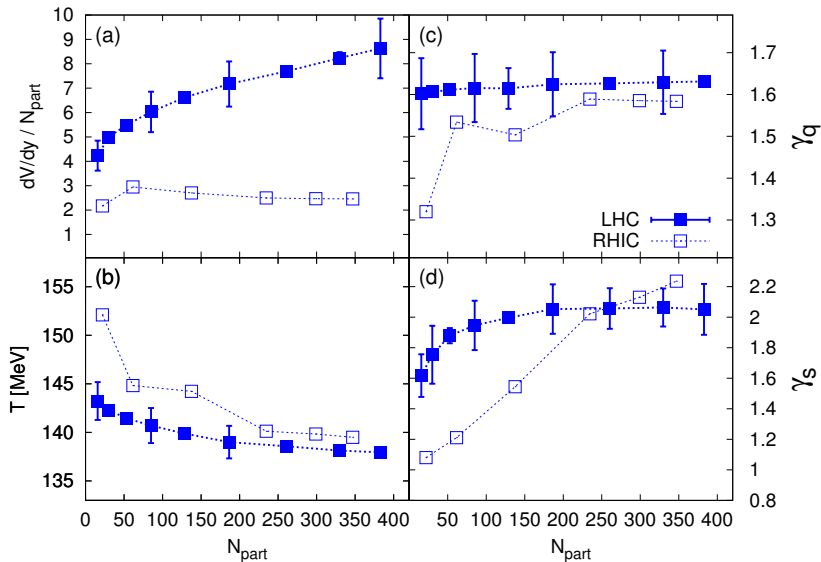
Does the QGP fireball hadronizes at the same ‘universal’
hadronization conditions as at SPS and RHIC 62?

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

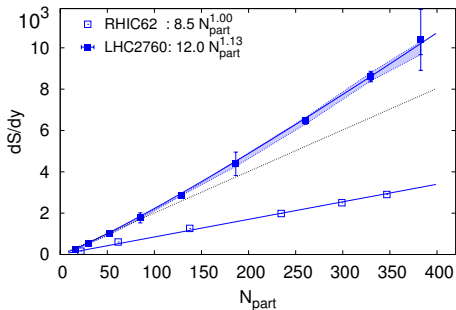


- Data from:
Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV
- Non-equilibrium SHM describes data across centrality
- Hadron yield range spans 5 orders of magnitude from central to peripheral

MODEL PARAMETERS AT LHC COMPARED TO RHIC

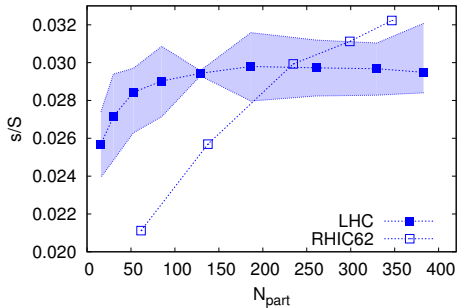


IMPORTANT DIFFERENCES: ENTROPY, STRANGENESS VS. CENTRALITY



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

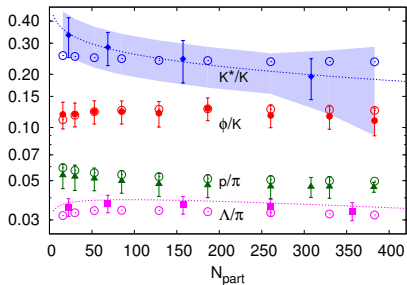
- LHC – steeper than linear
- Additional centrality dependent entropy production



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

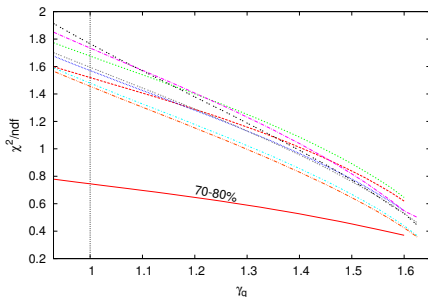
- For small N_{part} rapid increase of strangeness
- For large N_{part} steady level of strangeness

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



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

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

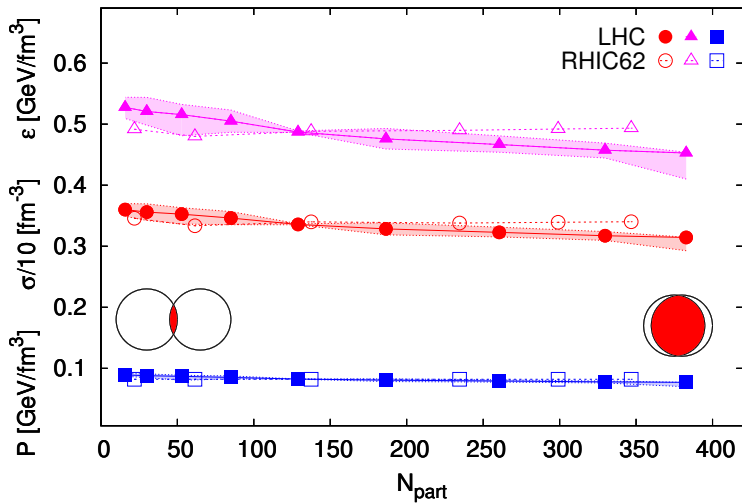


Petran et al., Phys. Rev. C 88, 034907 (2013)

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

Only non-equilibrium describes all LHC data

UNIVERSAL HADRONIZATION CONDITIONS: RHIC vs LHC



SUMMARY UP, DOWN, STRANGE

- Only non-equilibrium $\gamma_q \simeq 1.6$ SHM describes LHC data
- Universal hadronization conditions (ε, P, σ) of QGP at LHC, RHIC and SPS and at most centralities

NOT REPORTED

SHARE with CHARM shows consistency with charm decay feed to hadron yields

OUTLOOK

- Trace anomaly $\frac{\varepsilon-3P}{T^4}$ investigation in progress
- Isospin-3 iso-states (e.g. K^\pm vs K^0) not equally abundant seen hadron mass differences: given precise LHC data fit of γ_u, γ_d possible
 - required to measure μ_B^{LHC}
- Beam Energy Scan from RHIC, $\mathcal{O}(10)$ GeV,
 - look for onset of QGP creation,
 - test Universal Hadronization Conditions.