Quark-Gluon Plasma: Universal Hadronization

Michal Petran and Johann Rafelski

Department of Physics,
The University of Arizona

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Wigner111, 11/11/13 Budapest; Session: Nuclear Physics

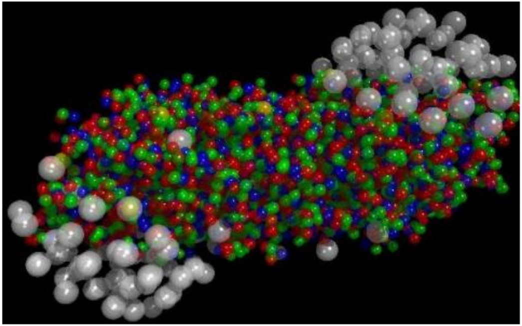
Part of: Ph.D. Defense Presentation by
Michal Petran, Tucson, November 5, 2013

OUTLINE

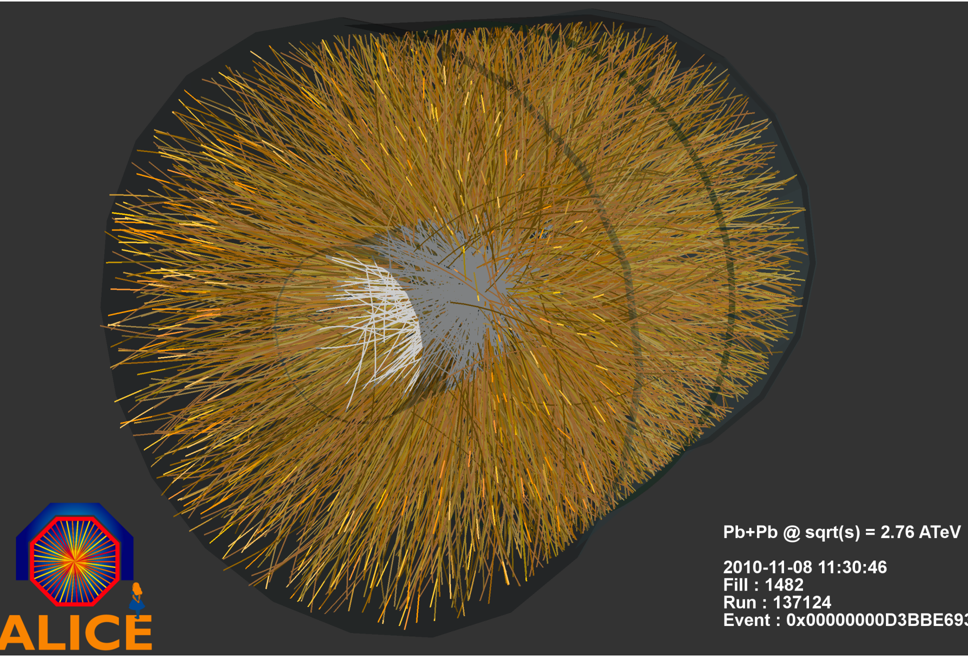
1. Quark-gluon plasma (QGP) – new state of matter
2. Description of particle production in HI experiments
3. QGP fireball physical properties at break-up
4. Universal Hadronization Conditions
5. Summary and Outlook

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.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QUARK-GLUON PLASMA – QGP

– NEW STATE OF MATTER

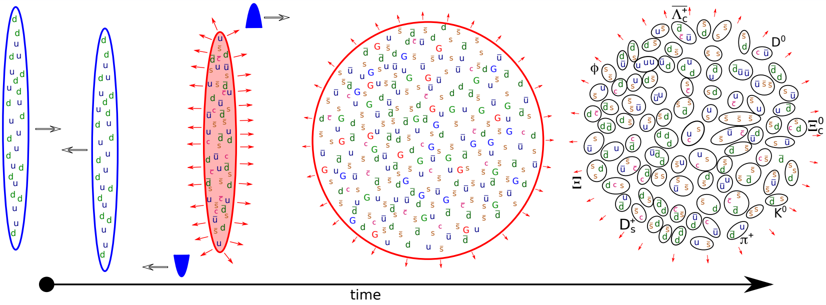
WHAT IS QGP?

- Hot soup of quarks and gluons
- Extremely hot and dense matter
  $T > 150\mathrm{MeV} \simeq 1.710^{12}\,K, 10^5 \times T_{sun})$
- Strongly interacting medium – color charge propagating
  – new state and a new form of matter

WHERE TO FIND QGP?

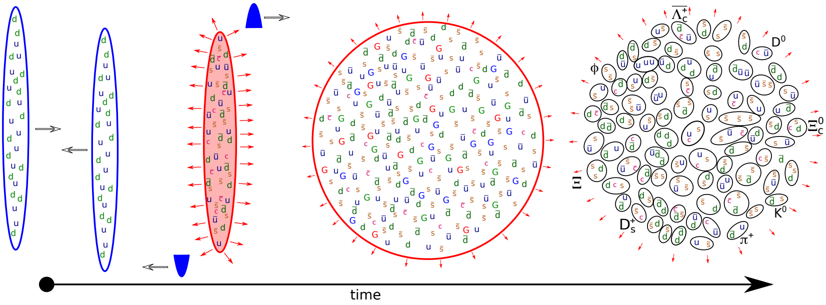
- Early Universe made of QGP, until $\mathcal{O}(15)\,\mu s$
- In laboratory, QGP created in
  relativistic heavy-ion collisions

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 $GG \to q\bar{q}$; surviving charm primordial
4. Hadronization, quarks bind into colorless hadrons – QGP properties imprinted on produced hadrons, at LHC $\mathcal{O}(10^5)$

QGP in laboratory – Heavy-Ion collision



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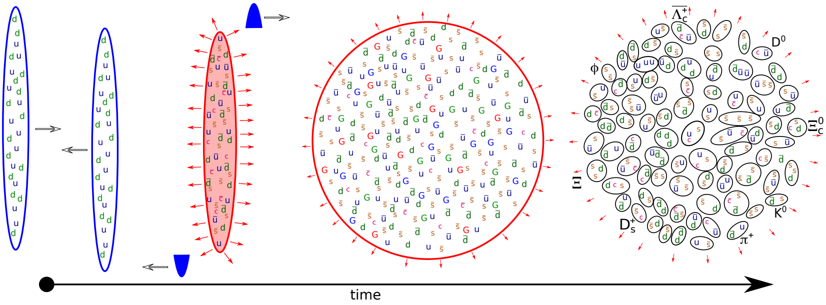

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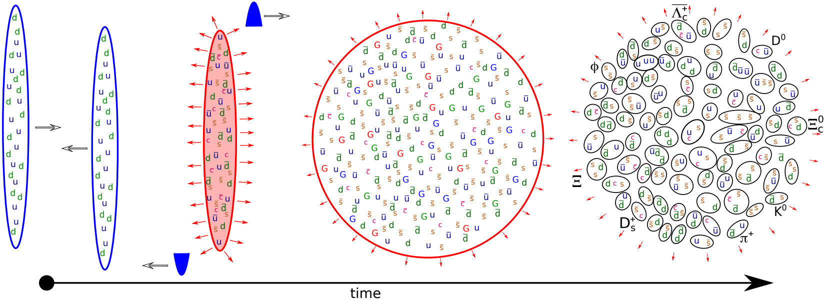
QGP IN LABORATORY – HEAVY-ION COLLISION



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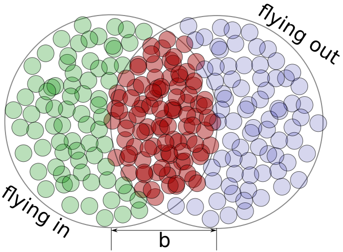
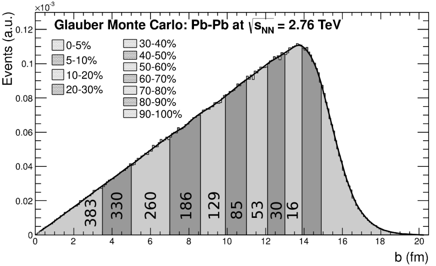
CENTRALITY OF HEAVY-ION COLLISION



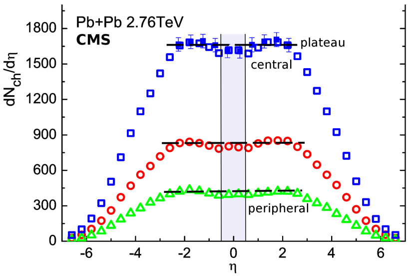


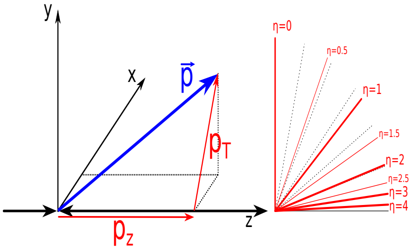
ALICE collaboration, Phys.Rev. C88 (2013) 044909

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: $b \to 0 \Leftrightarrow N_{part} \to 400$, $N_{bin} \to 1900$

(PSEUDO)RAPIDITY AND SPATIAL DISTRIBUTION OF PARTICLES





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

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 $\frac{dN_{ch}}{dy} \simeq 1601 \pm 60 << 15\,000$ (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

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

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

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

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

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FUGACITY AND QUARK FLAVOR CHEMISTRY

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

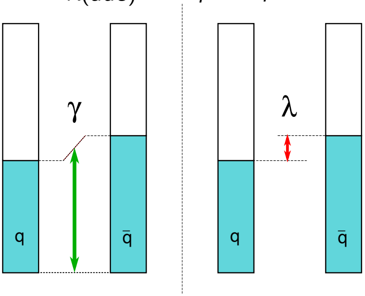
- controls difference between quarks and antiquark of same flavor $q - \bar{q}$
- "Relative" chemical equilibrium

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: $\Lambda(uds)$ $(q = u, d)$
  $\Upsilon_{\Lambda(uds)} = \gamma_q^2\gamma_s\,\lambda_q^2\lambda_s$
  $\Upsilon_{\overline{\Lambda}(\bar{u}\bar{d}\bar{s})} = \gamma_q^2\gamma_s\,\lambda_q^{-2}\lambda_s^{-1}$



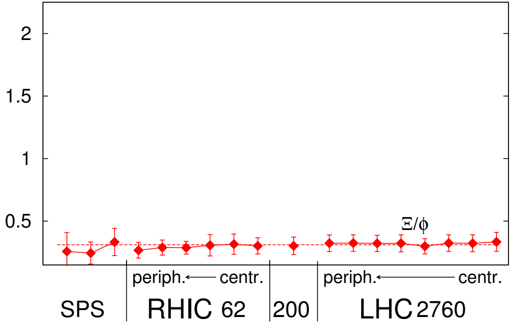
HADRON RATIOS — CONCEPTUAL TEST OF SHM

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

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

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

OTHER RATIOS



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

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

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

Petran et al, Phys.Rev.C 82 (2010),

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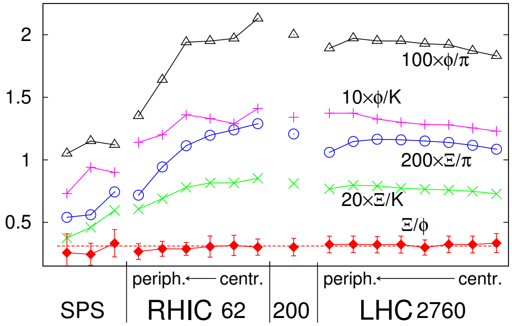

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Statistical HAdronization with REsonances: (SHARE)

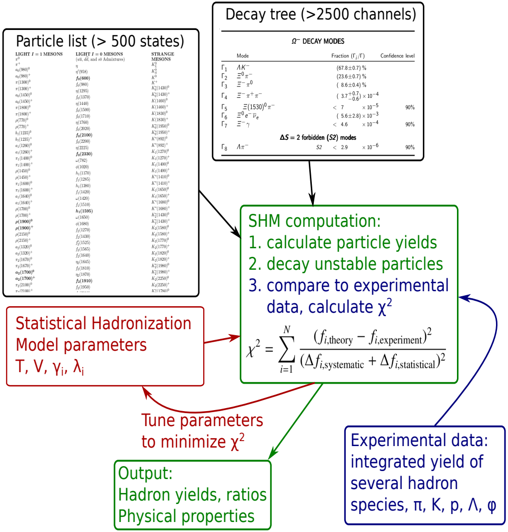
- SHM implementation in publicly available program
  G. Torrieri et al, Arizona + Krakow; SHAREv1 (2004), SHAREv2 (2006, added fluctuations, + Montreal)
  M. Petran SHARE(s) with CHARM: (2007–present)

SHARE INCORPORATES

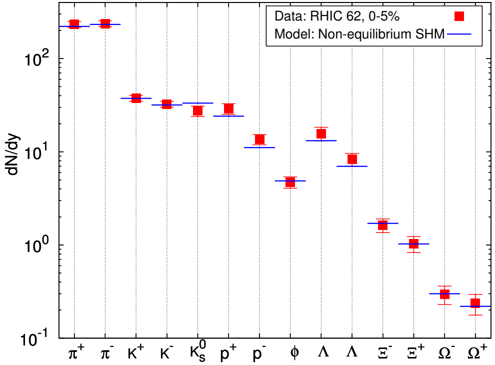
- Hadron mass spectrum $>$ 500 hadrons (PDG 2012)
- Hadron decays $>$ 2500 channels (PDG 2012)
- Integrated hadron yields, ratios and decay cascades
- OUT:Experimentally observable $\lesssim$ 30 hadron species
- AND: Physical properties of the source at hadronization – also as input in fit e.g. constraints: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

PROCEDURE – FITTING SHM PARAMETERS TO DATA

1. Input: T, V, 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 and constraints
6. Tune parameters to match data (minimize χ^2)



SHM description of central RHIC 62



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).

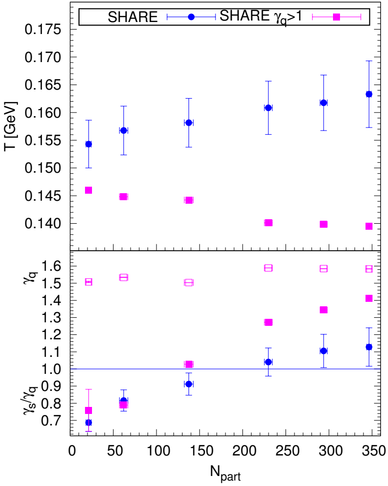
Model parameters

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

Phys. properties

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

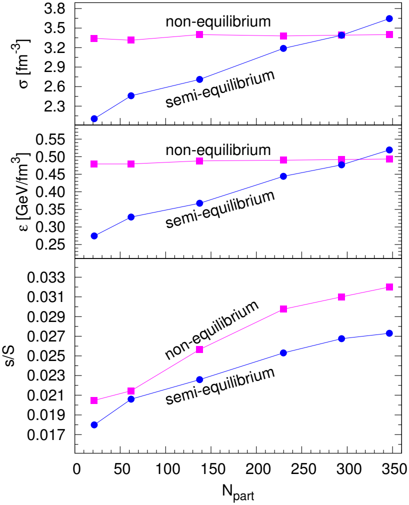
Describing RHIC 62 GeV across centrality: two approaches (semi)equilibrium $\gamma_q = 1$ and 'nonequilibrium' $\gamma_q \neq 1$ QGP breakup



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

Physical properties at RHIC 62 GeV



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

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

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

Same Universal Hadronization Conditions as at SPS

J.Phys. G36 (2009) 064017

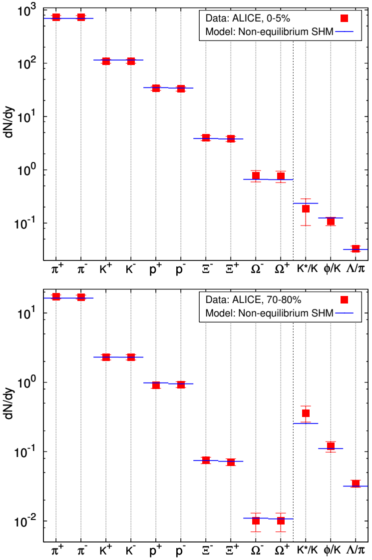
- Entropy density $\sigma = 3.3\,\mathrm{fm}^{-3}$
- Energy density $\varepsilon = 0.5\,\mathrm{GeV/fm}^3$
- Critical pressure $P = 82\,\mathrm{MeV/fm}^3$
- s/S near QGP value $s/S \simeq 0.03$

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?

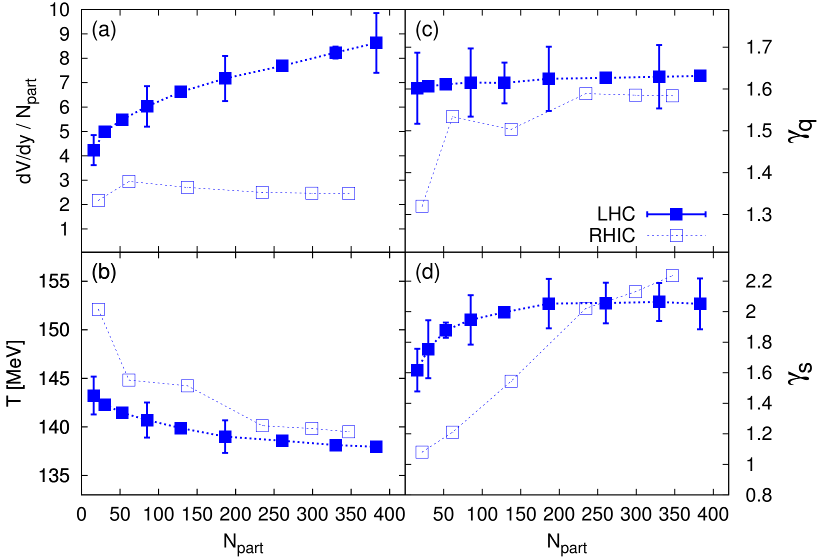
Fit to LHC hadron yields WORKS PERFECTLY and nearly same parameters as RHIC 62



- 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

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

Model parameters at LHC compared to RHIC



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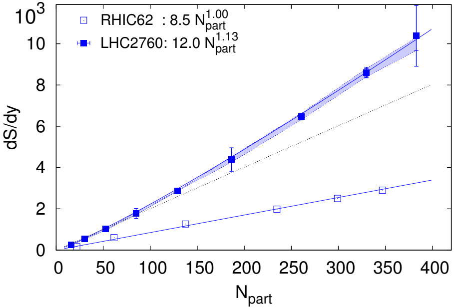
Important differences: Entropy, strangeness vs. centrality



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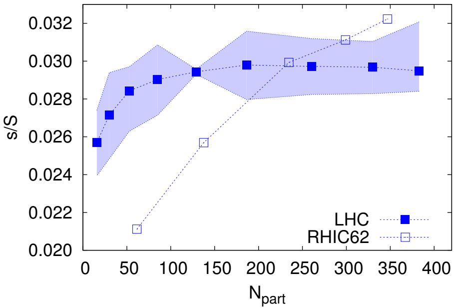
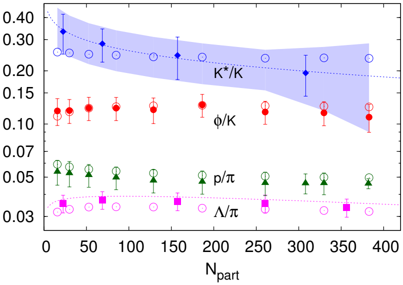


Petran et al., Phys. Rev. C 88, 034907 (2013)

- 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

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



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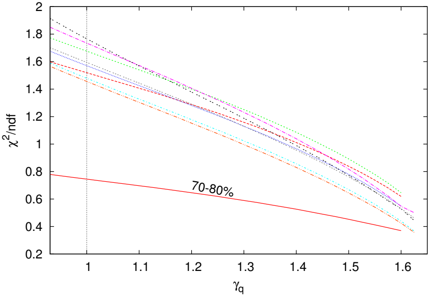


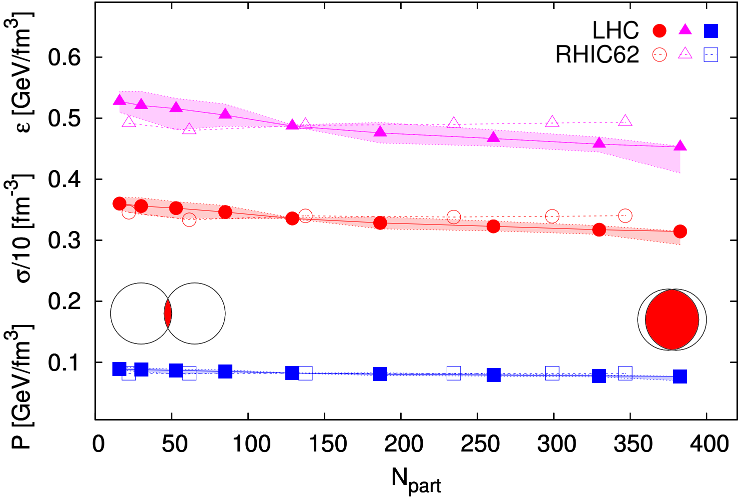
Petran et al., Phys. Rev. C 88, 034907 (2013)

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

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

Only non-equilibrium describes all LHC data

UNIVERSAL HADRONIZATION CONDITIONS: RHIC VS LHC



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

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.