The statistical model in Pb-Pb collisions at the LHC

- Introductory remarks – is quark matter at LHC in equilibrium?
- Energy dependence of hadron production and statistical model
- Is there anything special at LHC energy?
- The case of heavy quarks and quarkonia

work based on collaboration with

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Equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: a test of equilibration of quark matter near the phase boundary

- No (strangeness) equilibration in hadronic phase

- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis
  
  pbm, Stachel, Wetterich, Phys.Lett. B596 (2004) 61-69

- This implies little energy dependence above RHIC energy

- Analysis of hadron production $\rightarrow$ determination of $T_c$

Is this picture also supported by LHC data?
Parameterization of all freeze-out points before LHC data

note: establishment of limiting temperature

\[ T_{\text{lim}} = 164 \pm 4 \text{ MeV} \]

get \( T \) and \( \mu_B \) for all energies

for LHC predictions we picked \( T = 164 \text{ MeV} \)

A. Andronic, pbm, J. Stachel, Nucl. Phys. A772 (2006) 167 nucl-th/0511071
Important note: corrections for weak decays

All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker.

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

In light of high precision LHC data the corrections done at RHIC need to be revisited.
Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

In the following, corrections were applied as specified by the different RHIC experiments
Au+Au central at 200 GeV, all experiments combined

\[ T = 162 \text{ MeV} \]
RHIC lower energies, STAR data alone

Reasonable fits, $T = 160 - 164$ MeV
now new ALICE data at LHC energy
arXiv:1208.1974 [hep-ex]

rather poor fit,
low $T = 152$ MeV,
all hyperons underestimated

is there no equilibrium near $T_c$?
fitting the data without protons and antiprotons

good fit, $T = 164$ MeV

is there a proton anomaly?
analyzing the deviations

Au-Au 62.4 GeV

Au-Au 130 GeV

Au-Au 200 GeV

Pb-Pb 2.76 TeV incl. protons

Peter Braun-Munzinger
analyzing the deviations – LHC energy

Pb-Pb 2.76 TeV
fit without protons

protons are 6 sigma off, but note 6% overall error, about a factor 2.5 smaller than all previous measurements
could it be weak decays from charm?

weak decays from charmed hadrons are included in the ALICE data sample

at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

first results including charm and beauty hadrons indicate changes of less than 3%, mostly for kaons

not likely an explanation
overall systematics, including ALICE data, on proton/pion and kaon/pion ratios
Summary, light flavors (i)

- with more precision data, differences to thermal model 'predictions begin to appear, especially for protons and hyperons. Note that data precision at LHC is about 6% including systematic and statistical errors.

- at RHIC energies, differences of data for different experiments are of the order of the observed deviations, fits including weak decay corrections yield T close to 160 MeV and good chi2.

- all thermal model fits at RHIC energies closely follow the systematics established previously.

- fits to ALICE data are poor and yield anomalously low T (152 MeV).

- fits to ALICE data excluding protons are excellent and yield T ≈164 MeV.
Summary, light flavors (ii)

- one scenario: flavor chemistry of QGP matter at LHC is established close to $T_c$ as at RHIC but protons and anti-protons are anomalous.

- maybe result of annihilation in hadronic phase close to $T_c$.

- modelling annihilation in hadronic phase needs detailed balance (Rapp and Shuryak, Phys.Rev.Lett. 86 (2001) 2980-2983).

- what is the role of the 'quasi-mixed phase' and the asymmetry between protons and hyperons?

- what is the role of the 2x longer QGP lifetime at LHC energy compared to that at RHIC?

- simultaneous description of protons and all hyperons is required to settle the issue - a challenge to theory.
On to hadrons with heavy quarks

specifically, charmonium

can charmonium production be understood in the framework of the statistical hadronization model?
Charmonium (re)generation models

- statistical hadronization model
  original proposal: pbm, J. Stachel, Phys. Lett. B490 (2000) 196
  assumptions:
  - all charm quarks are produced in hard collisions, \( N_c \) const. in QGP
  - all charmonia are dissolved in QGP or not produced before QGP
  - charmonium production takes place at the phase boundary with statistical weights
    \[ \rightarrow \text{yield} \sim N_c^2 \] -- quarkonium enhancement at high energies
    \[ \text{-- no feeding from higher charmonia} \]

- charm quark coalescence model
  original proposal: R.L. Thews, M. Schroedter, J. Rafelski, Phys. Rev. C63 (2001) 054905
  assumptions:
  - all charm quarks are produced in hard collisions
  - all charmonia are produced in the QGP via charm quark recombination
    \[ \rightarrow \text{yield} \sim N_c^2 \] -- quarkonium enhancement at high energies
Quarkonium as a probe for deconfinement at the LHC

charmonium enhancement as fingerprint of deconfinement at LHC energy

pbm, J. Stachel
Nature 448 (2007) 302-309
Comparison of model predictions to RHIC data: rapidity dependence

suppression is smallest at mid-rapidity (90 deg. emission) a clear indication for regeneration at the phase boundary
newest ALICE data at central and forward rapidity

![Graph showing $R_{AA}$ vs. $\langle N_{\text{part}} \rangle$ for different ALICE experiments with $\sqrt{s_{\text{NN}}} = 2.76$ TeV and various $L$ values.](image-url)
Comparison to PHENIX data

J/psi is the only particle for which $R_{AA}$ increases when going from RHIC to LHC energy.
less suppression when increasing the energy density

from here to here, more than factor of 2 increase in energy density, but $R_{AA}$ increases by more than a factor of 3
Rapidity dependence

- ALICE Preliminary, Pb-Pb: $s_{NN} = 2.76$ TeV, $L = 70 \mu$b$^{-1}$
  - Inclusive $J/\psi$, centrality 0%-90%, $0<p_t<8$ GeV/c, global sys. = $\pm 6\%$

- ALICE Preliminary, Pb-Pb: $s_{NN} = 2.76$ TeV, $L = 1.7 \mu$b$^{-1}$
  - Inclusive $J/\psi$, centrality 0%-80%, $|y|<0.9$

note: energy density largest at $y = 0$
statistical hadronization model

ALICE data and evolution from RHIC to LHC energy described quantitatively
Summary

- charmonium production – a fingerprint for deconfined quarks and gluons

- evidence for energy loss and flow of charm quarks --> thermalization

- charmonium generation at the phase boundary – a new process

- first indications for this from psi'/(J/psi) SPS and J/psi RHIC data

- evolution from RHIC to LHC described quantitatively

- charmonium enhancement at LHC – deconfined QGP

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cartoon Helmut Satz, 2009

SPS RHIC LHC
back-up
Rapidity dependence of J/psi in statistical hadronization model
Grand Canonical Ensemble

\[
\ln Z_i = \frac{V g_i}{2 \pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))
\]

\[
n_i = \frac{N}{V} = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu_i} = \frac{g_i}{2 \pi^2} \int_0^\infty \frac{p^2 dp}{\exp((E_i - \mu_i)/T) \pm 1}
\]

\[
\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3
\]

for every conserved quantum number there is a chemical potential \(\mu\) but can use conservation laws to constrain:

- Baryon number: \(V \sum_i n_i B_i = Z + N\) \(\rightarrow V\)
- Strangeness: \(V \sum_i n_i S_i = 0\) \(\rightarrow \mu_S\)
- Charge: \(V \sum_i n_i I_i^3 = \frac{Z - N}{2}\) \(\rightarrow \mu_{I_3}\)

This leaves only \(\mu_b\) and \(T\) as free parameter when \(4\pi\) considered for rapidity slice fix volume e.g. by \(dN_{ch}/dy\)
Method and inputs

Thermal model calculation (grand canonical) $T, \mu_B : \rightarrow n_X^{th}$

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$$

$N_{c\bar{c}} \ll 1 \rightarrow \textbf{Canonical:}$ J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137

charm balance equation

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{occ}^{th} \frac{I_1(g_c N_{occ}^{th})}{I_0(g_c N_{occ}^{th})} + g_c^2 N_{c\bar{c}}^{th} \rightarrow g_c$$

Outcome: $N_D = g_c V n_D^{th} I_1 / I_0$ \hspace{1cm} $N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

Inputs: $T, \mu_B, \hspace{1cm} V = N_{ch}^{exp} / n_{ch}^{th}, \hspace{1cm} N_{c\bar{c}}^{dir} \hspace{1cm} \text{(pQCD)}$