Hadronic Resonance Gas Model and high multiplicity in p-p, p-Pb, Pb-Pb collisions

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The II International Workshop on the
Theory of Hadronic Matter under Extreme Conditions

Outline

Based on

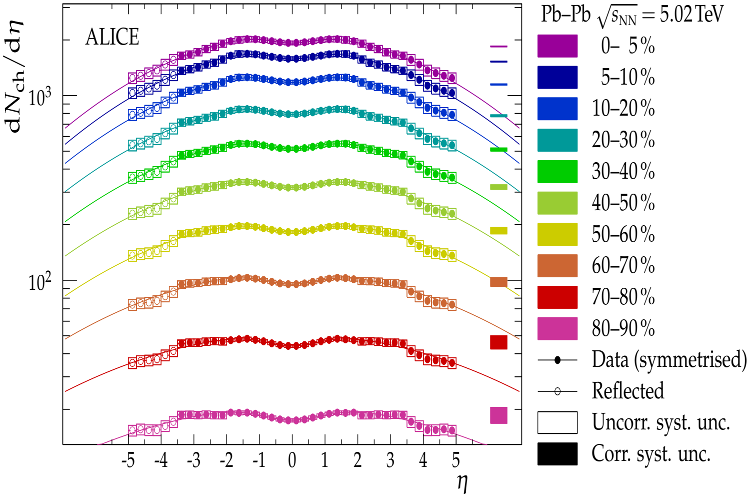
Natasha Sharma, J.C., Boris Hippolyte, Masimba Paradza,
Phys. Rev. C99 (2019) no.4, 044914

Natasha Sharma, J.C., Boris Hippolyte,
Adv. High Energy Phys. 2019 (2019) 5367349

High multiplicities may be more indicative of the quark-gluon plasma phase.

Learn about the validity of the Thermal Model.

Particle Multiplicity in Heavy Ion Collisions



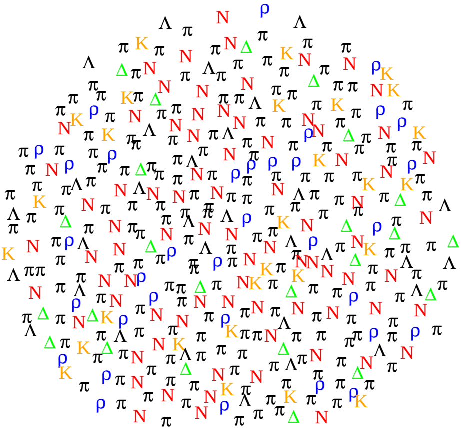
arXiv: 1612.08966 Phys. Lett. B772 (2017) 567-577

Particle Multiplicity in Heavy Ion Collisions

Maximum is about 2000, pseudo-rapidity interval is about 10, hence about 20 000 charged particles. About 30 000 particles are produced in a heavy ion collision at the LHC.

Hence: Use Concepts from Statistical Mechanics to analyze the final state
e.g. use Energy Density, Particle Density, Pressure, Temperature, Chemical Composition, ...
Question: when are they applicable?

Hadronic Gas before Chemical Freeze-Out



J.C. and H. Satz, Z. fuer Physik C57, 135, 1993.

The Theoretical Basis for the Thermal Model

The number of particles of type i is determined by:

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int d\sigma_\lambda p^\lambda \exp\left(-\frac{p^\mu u_\mu}{T} + \frac{\mu_i}{T}\right)$$

Integrating this over all momenta

$$N_i = \frac{g_i}{(2\pi)^3}\int d\sigma_\lambda \boxed{\int \frac{d^3p}{E} p^\lambda \exp\left(-\frac{p^\mu u_\mu}{T} + \frac{\mu_i}{T}\right)}$$

box must be a four-vector, only u^λ is available as a four-vector

$$\boxed{N_i = \int d\sigma_\lambda u^\lambda n_i^0(T,\mu)}$$

where n_i^0 is the density in a fireball at rest.

The Theoretical Basis for the Thermal Model

If the temperature and chemical potential are unique along the freeze-out curve

$$N_i = n_i^0(T, \mu) \int d\sigma_\lambda u^\lambda$$

i.e. integrated (4π) multiplicities are the same as for a single fireball at rest (apart from the volume).

The Theoretical Basis for the Thermal Model

In general

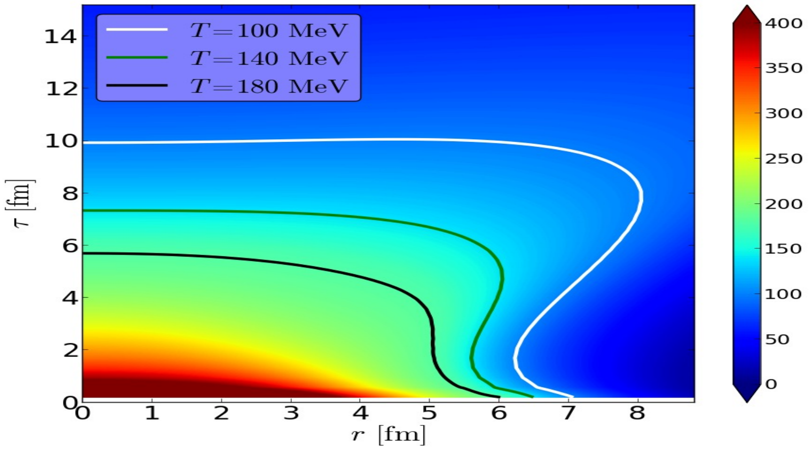
If hydrodynamics is the basic underlying mechanism, then, **after integration over p_T and y**

$$\frac{N_i}{N_j} = \frac{n_i^0}{n_j^0}$$

where n_i^0 is the particle yield as calculated in a fireball **AT REST!**

This is because N_i is a Lorentz invariant quantity unaffected by boosts and flows. This needs the freeze-out temperature to be the same for all particles which may not be the case always.

This does NOT mean that the freeze-out has to be instantaneous. The only requirement is that the freeze-out temperature has to be the same along the freeze-out curve.



H. Niemi and G.S. Denicol arxiv 1404.7327

The Theoretical Basis for the Thermal Model

Bjorken scaling + Transverse expansion

After integration over p_T (and ONLY! after integration over p_T)

$$\frac{dN_i/dy}{dN_j/dy} = \frac{N_i^0}{N_j^0}$$

where N_i^0 is the particle yield
as calculated in a fireball **AT REST!**

Effects of hydrodynamic flow cancel out in ratios.
The volume is given by $\pi R^2 \tau$!

Uncertainties in the Thermal Model

:w Uncertainties are related to our knowledge of hadron species and resonance properties as reflected in the Particle Data Booklet.
Particle yields are determined from:

$$N_i = \sum_j N_j Br(j \to i).$$

Hence one must know how hadronic resonances decay.

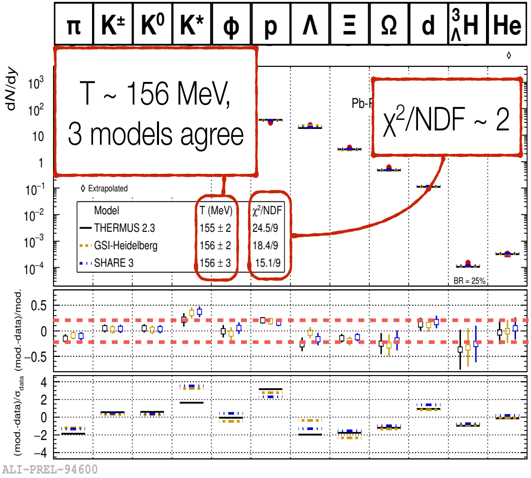
As an example, the final yield of π^+'s is given by

$$N_{\pi^+} = N_{\pi^+}(\text{thermal}) + N_{\pi^+}(\text{resonance decays})$$

depending on the temperature, over 80% of observed pions are due to resonance decays

Equilibrium SHM Fits in Central Pb-Pb

AL

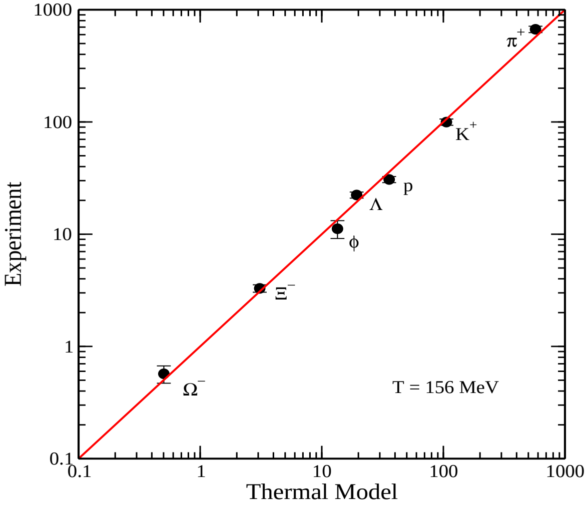


N.B.
RHIC (STAR)
$\sqrt{s}$ = 200 GeV
χ^2/NDF~1

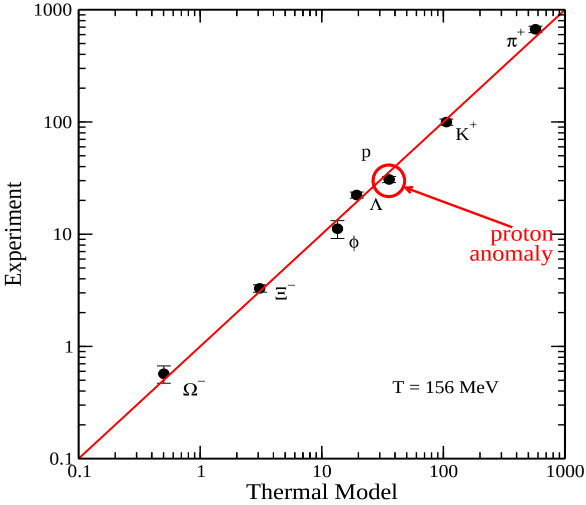
Better fit in
60-80%,

Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

ALICE


Experiment
Thermal Model
1000
100
10
1
0.1
0.1
1
10
100
1000
π+
K+
p
Λ
ϕ
Ξ−
Ω−
T = 156 MeV

ALICE


1000
100
10
1
0.1
0.1
1
10
100
1000
Experiment
Thermal Model
π+
K+
p
Λ
φ
Ξ−
Ω−
proton
anomaly
T = 156 MeV

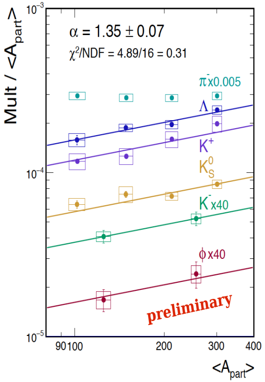
Proton Anomaly

Possible explanations:

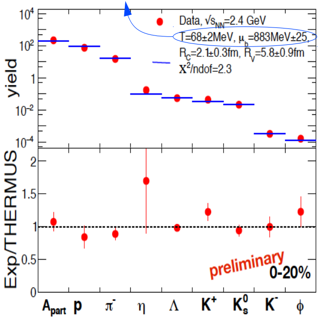
- incomplete hadron spectrum
- chemical non-equilibrium at freeze-out
- modification of hadron abundancies
- separate freeze-out temperatures for strange and non-strange hadrons
- excluded volume interactions
- energy dependent Breit-Wigner $T = 155 \pm 1.7$ MeV
- replace Breit-Wigner by phase shift analysis $T = 155.0$ MeV

Strangeness production: The complete picture

First comprehensive set of strange particles from AuAu @$\sqrt{S_{NN}}$=2.42 GeV!



Chemical freeze-out



- Universal centrality dependence *(not expected from different NN thresholds)*
- Hadron yields reflect matter properties

- All yields described by SHM with 4 global parameters: T, μ_B, R_V and R_C *(to suppress strangeness at low T)*
- Compatible with the assumption of reaching thermal equilibrium at high-μ_B

HADES: Celso Franco presented at Kruger2018.

References

ALICE Pb-Pb Collisions at 2.76 TeV

- Phys. Rev. C88 (2013) 044910
- Phys. Rev. Lett. 111 (2013) 222301
- Phys. Lett. B728 (2014) 216 - 227

ALICE p-Pb Collisions at 5.02 TeV

- Phys. Lett. B728 (2014) 25 - 38
- Phys. Lett. B758 (2016) 389 - 401

ALICE p-p Collisions at 7 TeV

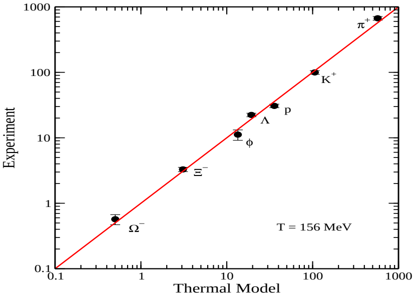
- NATURE Phys. 13 (2017) 535 - 539

THERMUS

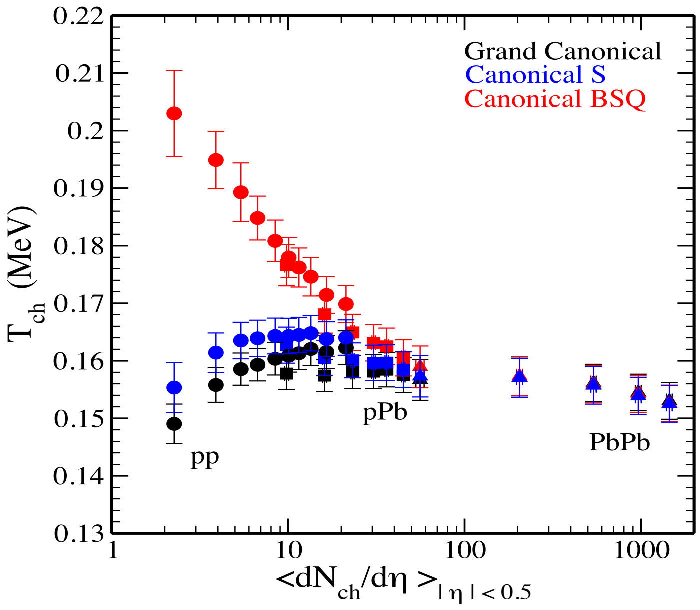
$$\mathrm{https://github.com/thermus-project/THERMUS}$$

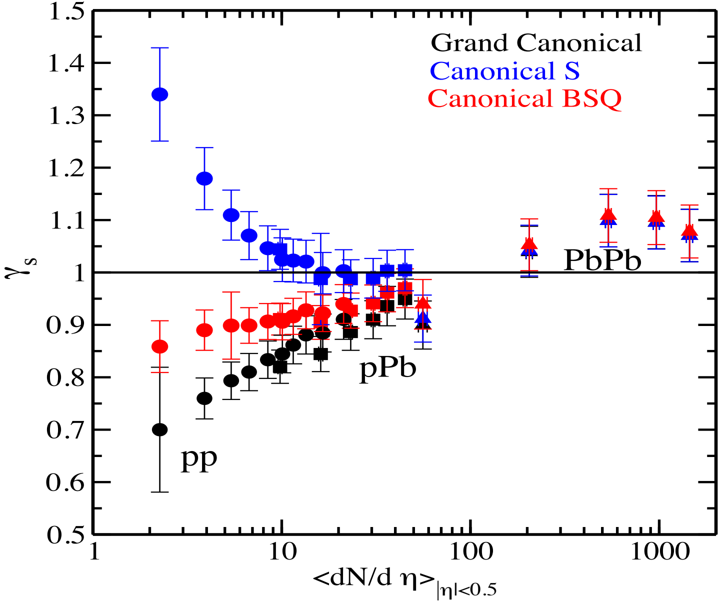
B. Hippolyte and Y. Schutz
S. Wheaton, J.C., M. Hauer,
Comput. Phys. Commun. 180 (2009) 84
Documentation is being updated.

Multiplicity Dependence



Repeat this analysis 63 times, namely, for each multiplicity bin, for p-p, p-Pb and Pb-Pb.

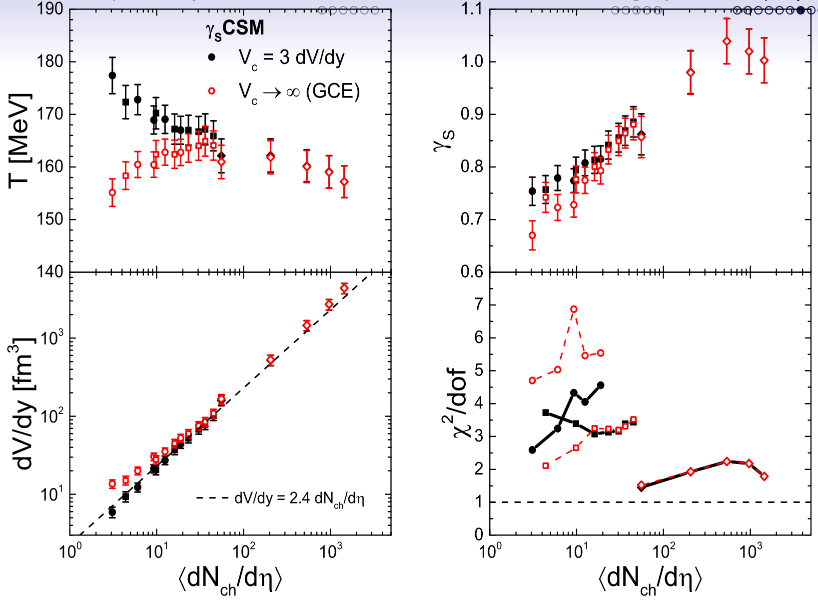

Grand Canonical
Canonical S
Canonical BSQ
0.22
0.21
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
T_{ch} (MeV)
pp
pPb
PbPb
1
10
100
1000
$<dN_{ch}/d\eta>_{|\eta|<0.5}$


Grand Canonical
Canonical S
Canonical BSQ
PbPb
pPb
pp
γ_s
$<dN/d\eta>_{|\eta|<0.5}$
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
1
10
100
1000

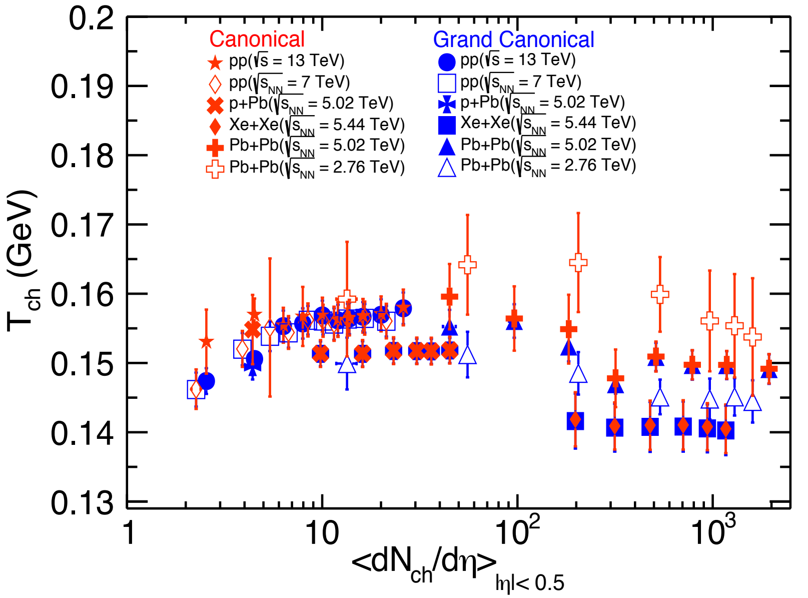
Thermodynamic Limit

$$
\begin{aligned}
N &\rightarrow \infty \\
V &\rightarrow \infty \\
N/V &\rightarrow \textbf{finite}
\end{aligned}
$$

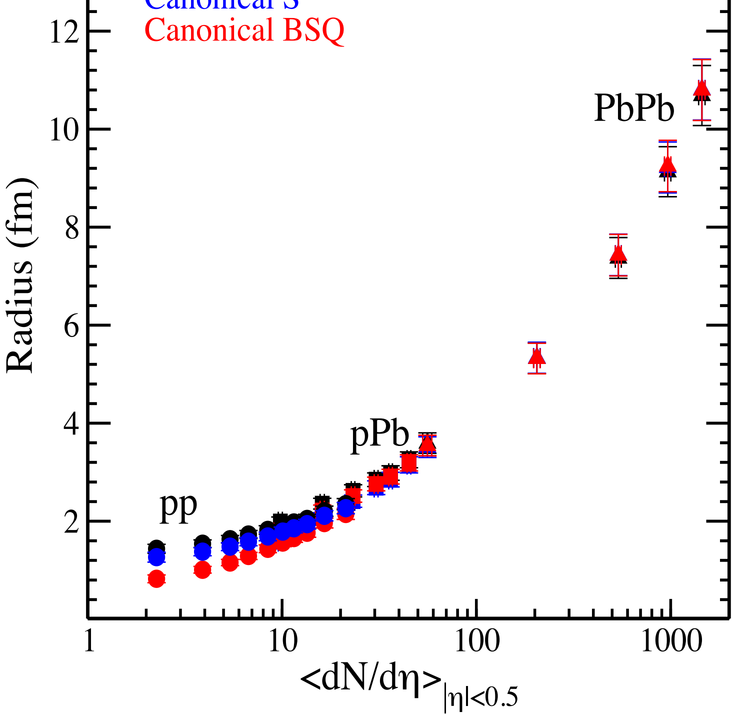
All ensembles (microcanonical, canonical and grand canonical) become identical.
Does this ever happen in high-energy collisions at the LHC?
Yes, in p-p collisions at high multiplicities, in Pb-Pb always.



V. Vovchenko, B. Dönigus, H. Stoecker, arXiv:1906.03145v1[hep-ph]



R. Rath, A. Khuntia, R. Sahoo, arXiv:1905.07959[hep-ph]


Canonical S
Canonical BSQ
Radius (fm)
12
10
8
6
4
2
PbPb
pPb
pp
1
10
100
1000
<dN/dη>|η|<0.5

Conclusions

Three different statistical ensembles have been used to analyze the variation of particle yields with the multiplicity of charged particles produced in p-p, p-Pb and Pb-Pb collisions.
All three ensembles lead to the same results when the multiplicity of charged particles $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ exceeds about 20. This could be interpreted as reaching the thermodynamic limit since the three ensembles lead to the same results.

$\langle dN_{ch}/d\eta \rangle \|_{\|\eta\|<0.5}$	Can S	Can B, S, Q	GC
2.89	6.04 / 3	24.29 / 3	29.05 / 3
6.06	16.02 / 3	25.89 / 3	32.28 / 3
9.039	21.53 / 3	25.44 / 3	34.58 / 3
12.53	23.83 / 3	25.08 / 3	27.45 / 3
17.47	23.73 / 3	15.93 / 3	11.81 / 3

Table: Values of χ^2/ndf for various fits.