Hadronic Resonance Gas Model and Multiplicity Dependence in p-p, p-Pb, Pb-Pb collisions: Strangeness Enhancement

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in collaboration with
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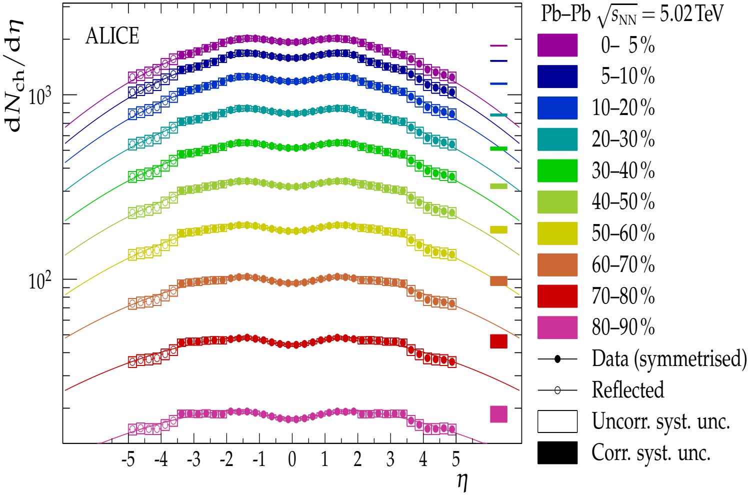
Criticality in QCD and the Hadron Resonance Gas,
29 - 31 July, 2020

Outline

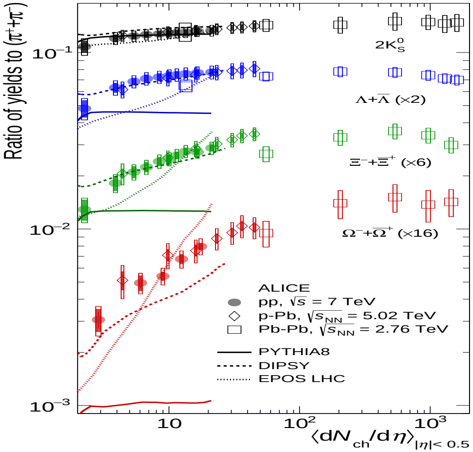
Motivation:

- High multiplicities may be more indicative of the quark-gluon plasma phase.
- Learn about the validity of the Thermal Model.



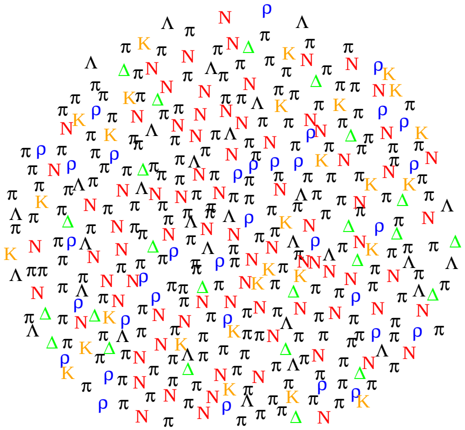
arXiv: 1612.08966 Phys. Lett. B772 (2017) 567-577

Focus of talk will be on the multiplicity dependence



ALICE collaboration, J. Adam et al. Nature Phys. 13 (2017) 535-539.

Hadronic Gas before Chemical Freeze-Out



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

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.

The Theoretical Basis for the Thermal Model

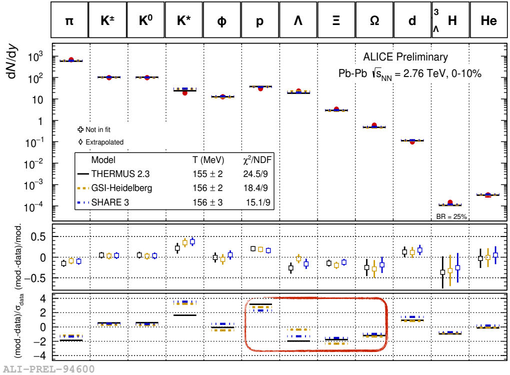
Bjorken scaling + Transverse expansion

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

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

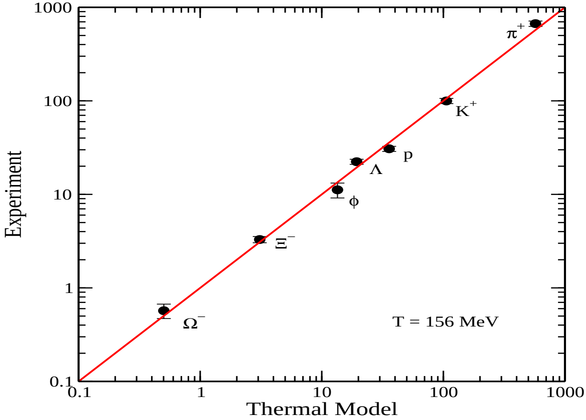
where N_i^0 is the particle yield
as calculated in a fireball **AT REST!**

Effects of hydrodynamic flow cancel out in ratios.

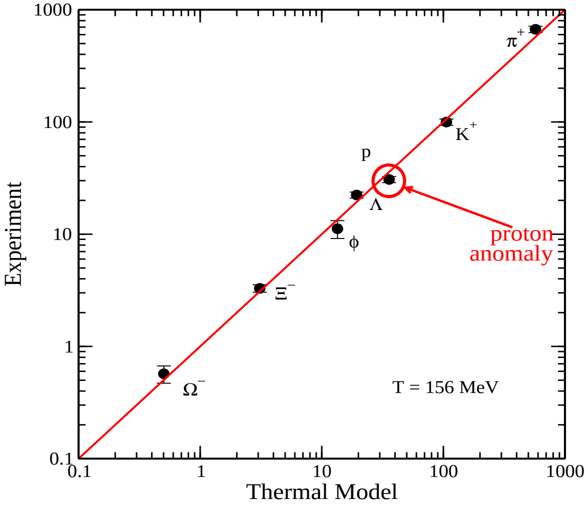


M. Floris EPS-HEP, Venice, July 2017

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
- include interactions using the K-matrix formalism

Taking into account interactions using phase shifts

$$N^{int}(T, M_R) = \int_{m_{th}}^{\infty} \frac{dM}{2\pi} B(M) N^0(T, M)$$

where N^0 is the particle density given by the ideal gas formula and the function B is related to the phase shift as follows:

$$\begin{aligned} B(M) &= 2\frac{d}{dM}\delta(M) \\ &\to 4\frac{M^2\Gamma_R}{(M^2 - M_R^2)^2 + M^2\Gamma_R^2} \\ &\to 4\pi M\delta(M^2 - M_R^2) \end{aligned}$$

Including interactions using phase shifts

An analysis using the available phase shifts has been performed in

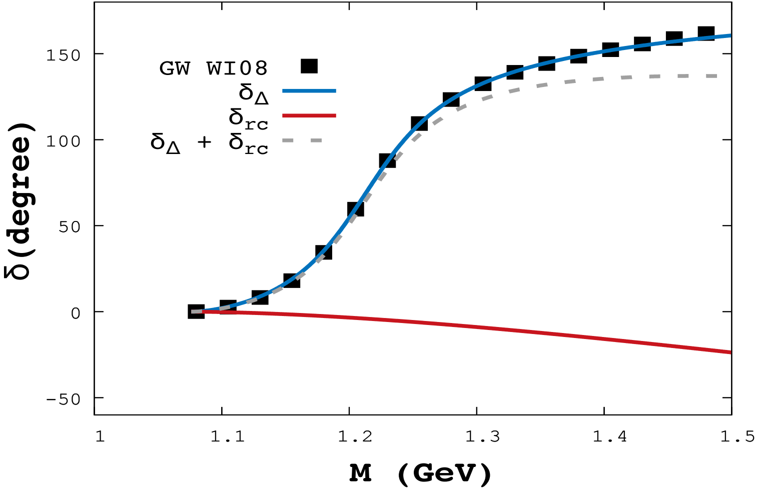
B. Friman, P.M. Lo, M. Marczenko, K. Redlich, C. Sasaki, Phys. Rev. D92 (2015) 074003

P.M. Lo, B. Friman, M. Marczenko, K. Redlich, C. Sasaki, Phys. Rev. C96 (2017) 015207

A. Dash, S. Samanta, B. Mohanty, Phys. Rev. C99 (2019) 044919

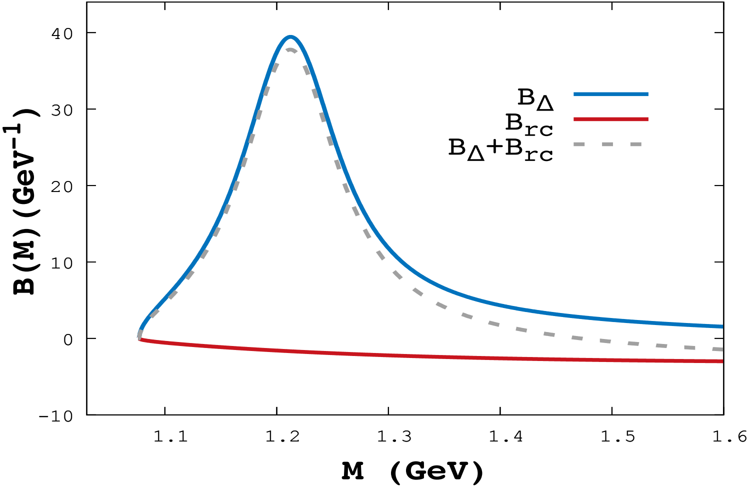
J. Goswami presentation at this workshop

Including interactions using phase shifts



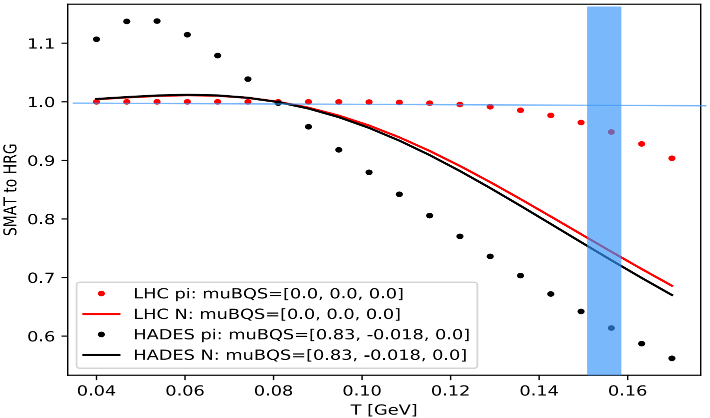
P.M. Lo, B. Friman, M. Marczenko, K. Redlich, C. Sasaki PRC 96 015207 (2017)

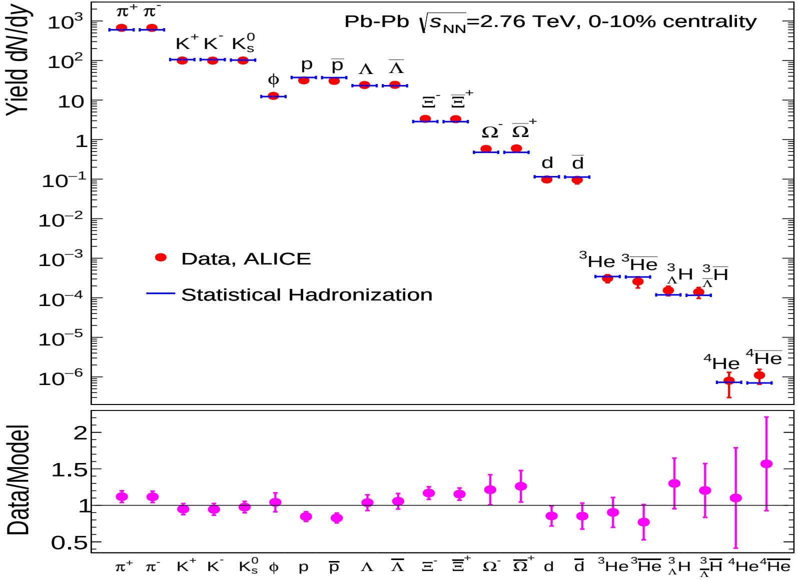
Phase Shifts



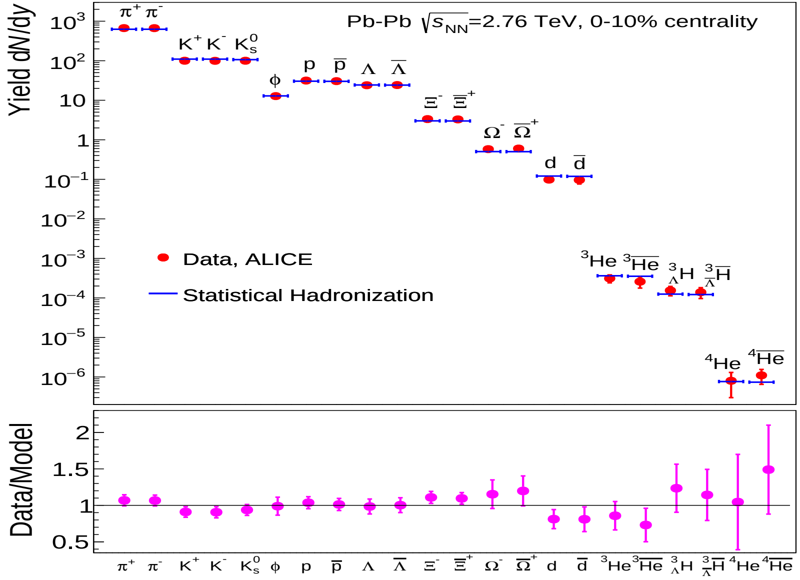
P.M. Lo, B. Friman, M. Marczenko, K. Redlich, C. Sasaki PRC 96 015207 (2017)

Phase Shifts: correction factor of about 25% for protons





A. Andronic, P. Braun-Munzinger, B. Friman, P. M. Lo, K. Redlich and J. Stachel, Phys. Lett. B **792** (2019), 304-309



A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature **561** (2018) no.7723, 321-330

Multiplicity Dependence and Strangeness Canonical Ensemble

Focus on the multiplicity dependence using the strangeness canonical ensemble.

$$Z_{S=0} = \mathrm{Tr}\left(e^{-(E-\mu)/T}\delta_{S,0}\right)$$

Ph. D. Thesis of Krzysztof Redlich
K. Redlich and L. Turko, Z. Phys. C5 (1980) 201

Strangeness Canonical Ensemble

This leads to replacing the standard expression, e.g. for kaons

$$N_K = Ve^{\frac{\mu}{T}} \int \frac{d^3p}{(2\pi)^3} e^{-\frac{E}{T}}$$

by the following

$$N_K = VS \int \frac{d^3p}{(2\pi)^3} e^{-\frac{E}{T}}$$

where

$$S = \frac{I_1(x)}{I_0(x)} \frac{S_1}{\sqrt{S_1 S_{-1}}}$$

and $x \equiv 2\sqrt{S_1 S_{-1}}$ and $S_1 = Z_{\bar{K}} + Z_\Lambda + \ldots$

Strangeness Canonical Ensemble

$$N_K = VS\int \frac{d^3p}{(2\pi)^3} e^{-\frac{E}{T}}$$

The correction factor S depends on the volume V which is not necessarily the same, it will be referred to as the canonical volume V_C and correspondingly a canonical radius R_C.

Strangeness Canonical Ensemble

For $\mu_B = 0$ replace

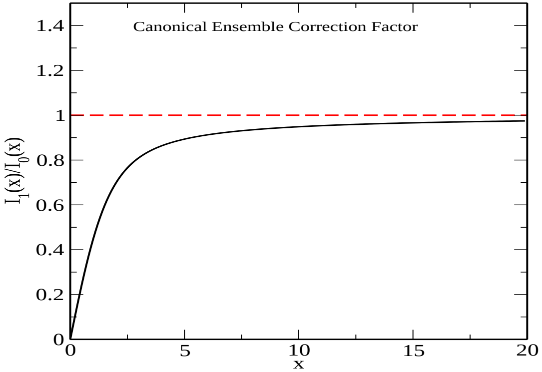
$$N_K = V \int \frac{d^3p}{(2\pi)^3} e^{-\frac{E}{T}}$$

by

$$N_K = V \frac{I_1(x)}{I_0(x)} \int \frac{d^3p}{(2\pi)^3} e^{-\frac{E}{T}}$$

and $x \equiv Z_{\bar{K}} + Z_{\Lambda} + \ldots$

Strangeness Canonical Ensemble

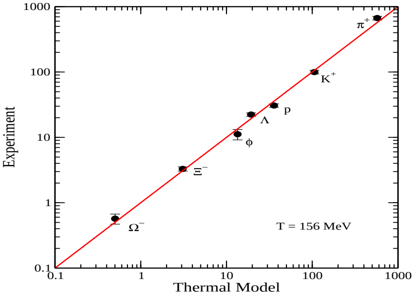


THERMUS

The case where strangenes 2 and 3 are included is more complicated and has been fully implemented in THERMUS.
S. Wheaton, J.C., M. Hauer,
Comput. Phys. Commun. 180 (2009) 84
Latest update: B. Hippolyte and Y. Schutz in:

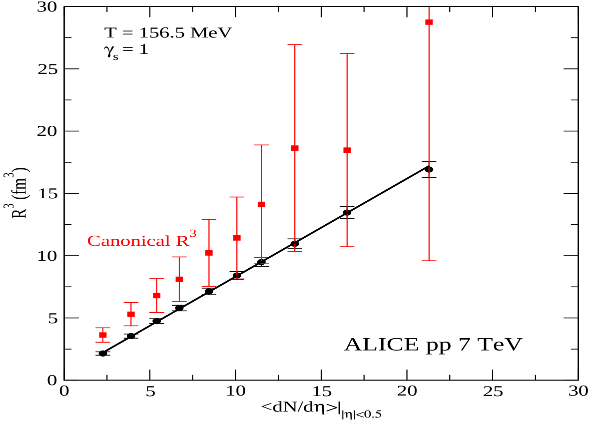
$$\mathrm{https://github.com/thermus-project/THERMUS}$$

Multiplicity Dependence



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

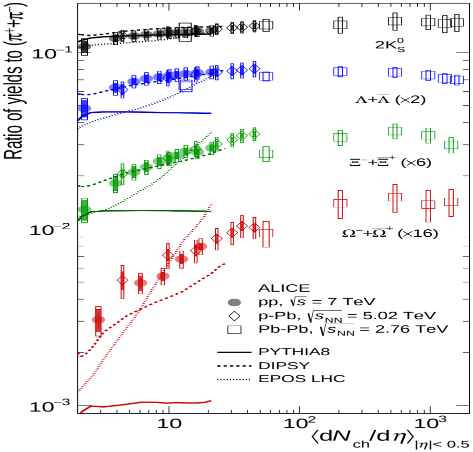
Find the Volume



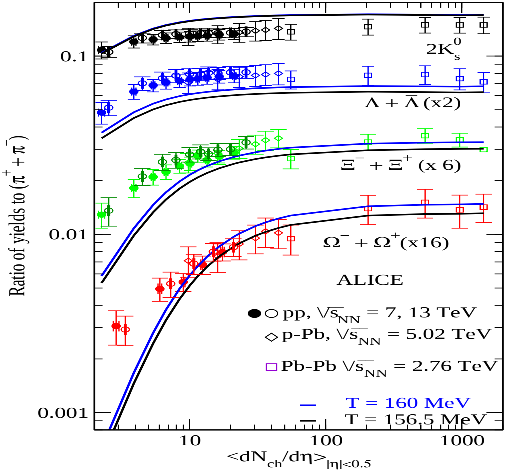
Fitting the Volume

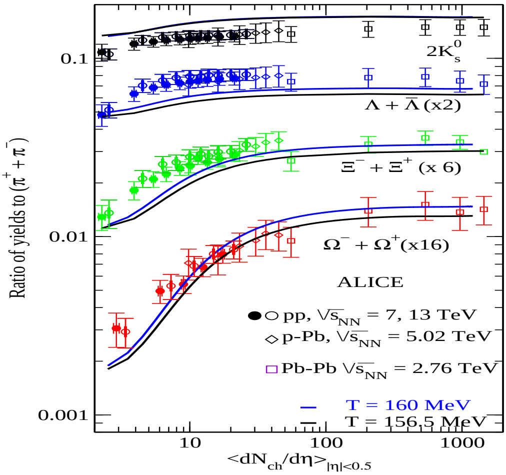
Canonical volume cannot be determined precisely.
Only for low multiplicities is there a clear difference.
At high multiplicities only one radius is needed, this is confirmed by Pb-Pb fits.
Try first to fit with a single volume.

Multiplicity Dependence



ALICE collaboration, J. Adam et al. Nature Phys. 13 (2017) 535-539.


0.1
0.01
0.001
10
100
1000
Ratio of yields to (π⁺ + π⁻)
<dN_ch/dη>_|η|<0.5
2K⁰_s
Λ + Λ̄ (x2)
Ξ⁻ + Ξ⁺ (x 6)
Ω⁻ + Ω⁺(x16)
ALICE
pp, √s_NN = 7, 13 TeV
p-Pb, √s_NN = 5.02 TeV
Pb-Pb √s_NN = 2.76 TeV
T = 160 MeV
T = 156.5 MeV


Ratio of yields to $(\pi^+ + \pi^-)$
$2K_s^0$
$\Lambda + \bar{\Lambda}$ (x2)
$\Xi^- + \Xi^+$ (x 6)
$\Omega^- + \Omega^+$(x16)
ALICE
pp, $\sqrt{s_{NN}}$ = 7, 13 TeV
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
T = 160 MeV
T = 156.5 MeV
$<dN_{ch}/d\eta>_{|\eta|<0.5}$
0.1
0.01
0.001
10
100
1000

Fitting the Volume

Using a canonical volume considerably improves the fits at small multiplicity.
For large multiplicities the canonical corrections are negligible (as expected).

Conclusions

Our results show some interesting new features:

- The thermal model with chemical equilibrium provides an excellent description of hadronic yields.
- It is possible to take into account repulsive **and** attractive interactions using phase shifts for a few channels.
- The strangeness increase might be described by imposing exact strangeness conservation for low multiplicities.
- High multiplicities at high energies can be described by the grand canonical ensemble.

THANKS.

Thermal Model

The number of particles of type *i* is determined by:

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

Integrating this over all momenta

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

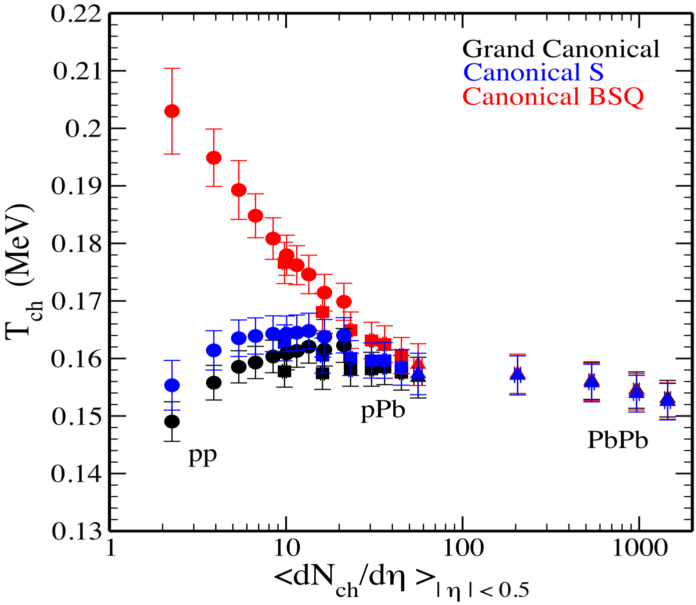
or

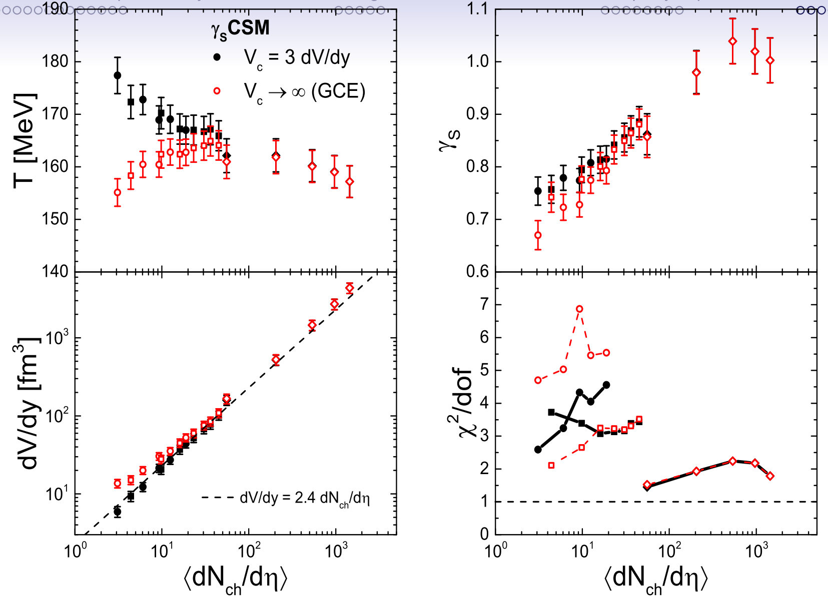
$$N_i = \int d\sigma_\mu u^\mu n_i(T,\mu)$$

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

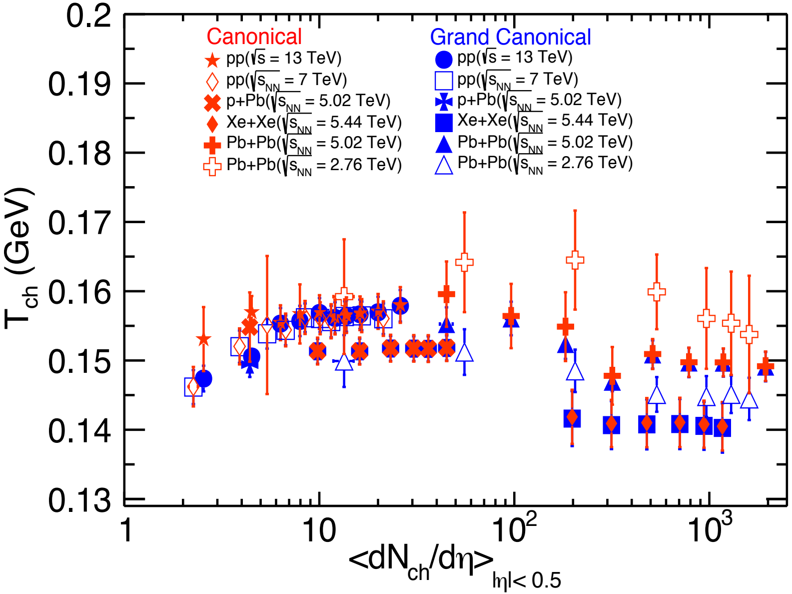
$$N_i = n_i(T,\mu)\int d\sigma_\mu u^\mu$$

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


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



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



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