Thermal properties of the medium created in heavy-ion collisions

For Au-Au collisions at $\sqrt{s_{NN}}$= 62.4, 130 and 200 GeV

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Thermal models for particle production

Hadronic reactions involving copious production of secondary particles have been associated with an underlying thermodynamic behaviour since the earliest observations in cosmic rays e.g. [1]

Thermodynamic models are widely and successfully used to describe identified particle yields and particle ratios produced in hadronic and especially heavy ion collisions e.g. [2].

We use the grand canonical ensemble; we assume that particles produced out of collision of particles and/or nuclei (p+p, p+A, A+A) at colliders are emerging from a thermal source and we calculate the expected particle ratios, for various assumed Temperatures and chemical potentials. We compare the experimental data to these predictions to assess the degree of agreement of this hypothesis with experimental data. If the agreement is good, (as evidenced by the Chi-Squared/DOF characterizing the fit) this comparison is used to estimate the temperature and chemical potentials of the hypothetic thermal particle source.

References:

1. Y. Fujimoto and S. Hayakawa, in Encylopedia of physics, vol. 46, no. 2) 4, 044904
2. F. Becattini et al, Phys.Rev.C 64 (2001) 024901 • e-Print: hep-ph/0002267 [hep-ph]

- *S. Kabana, The European Physical Journal C, Volume 21, Issue 3, pp. 545-555 (2001)*
- *S. Kabana, P. Minkowski, New J.Phys. 3 (2001) 4*
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*
- *J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton Phys. Rev. C 73, 034905 (2006)*
- *G. Torrieri, J. Rafelski, New J.Phys. 3 (2001) 12 • e-Print: hep-ph/0012102 [hep-ph]*
- O.V. Vityuk et al, Eur.Phys.J.A 57 (2021) 2, 74 • e-Print: 2007.07376 [hep-ph]
- *K.A. Bugaev et al, Eur.Phys.J.A 56 (2020) 11, 293 • e-Print: 2005.01555 [nucl-th]*
- *S. Chatterjee et al, Advances in High Energy Physics, vol. 2015, Article ID 349013, 20 pages, 2015.*

Particle Ratios for Au-Au collisions at 62.4 GeV

Preliminary

Particles	Exp Ratio	Error in Ratio	Th. Ratio
$\frac{K^-}{K^+}$	0.862	0.087	0.872
$\frac{\bar{p}}{p}$	0.469	0.0849	0.467
$\frac{K^-}{\pi^-}$	0.137	0.0138	0.170
$\frac{\bar{p}}{\pi^-}$	0.057	0.0083	0.058
$\frac{K^+}{\pi^+}$	0.1614	0.0165	0.1951
$\frac{p}{\pi^+}$	0.124	0.0187	0.124

- Exp. Ratios and Error in Ratio correspond to the ratios calculated and the error in the them respectively, from the STAR results
- Th. Ratios corresponds to the ratios from this Thermal Model and are compared to the STAR results for 62.4 GeV

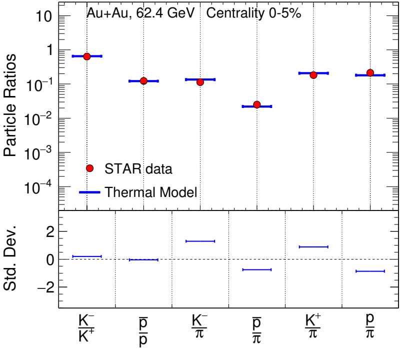
References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

Particle Ratios for Au-Au collisions at 62.4 GeV

Preliminary

- The comparison of experimental particle ratios and ratios from the thermal model is plotted corresponding to the data from previous slide



- Thermal model is successfully predicting the experimental particle ratios within $\pm 2\sigma$ deviation where, σ is represented by:

$$\sigma = \frac{Ratio_{Th.} - Ratio_{Exp}}{\sigma_{Exp}}$$

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

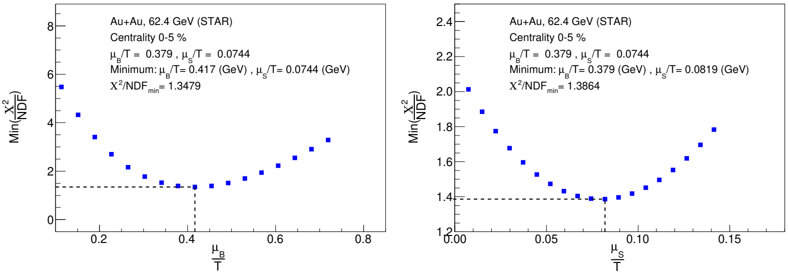
Variation of Input parameters ($\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$)

Preliminary

$$\frac{\overline{p}}{p} = \exp\left(\frac{-2\mu_B}{T}\right) \text{ and } \frac{K^-}{K^+} = \exp\left(\frac{-2\mu_S}{T}\right)$$

$\frac{ap}{p} = 0.469$, $\ln\frac{ap}{p} = -0.7572$, $\frac{\mu_B}{T} = -\frac{\ln\frac{ap}{p}}{2} = 0.3786$

$\frac{K-}{K+} = 0.8617$, $\ln\frac{K-}{K+} = -0.14884$, $\frac{\mu_S}{T} = -\frac{\ln\frac{K-}{K+}}{2} = 0.07442$

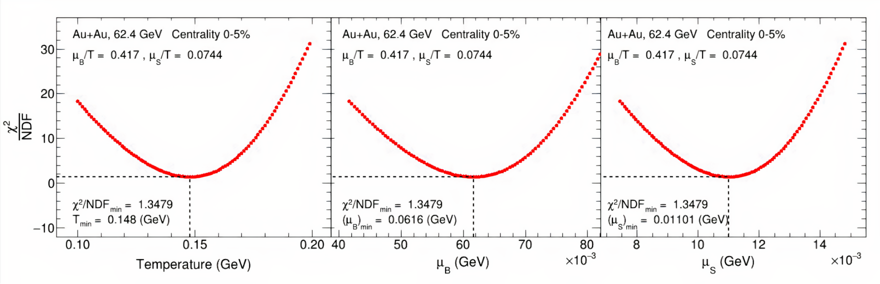


- $\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$ are varied in steps upto $\pm$ 90% of the initial value, as a function of $\frac{\chi^2}{NDF}$. A minimum $\frac{\chi^2}{NDF}$ is found for the variation
- $\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$ corresponding to the minimum $\frac{\chi^2}{NDF}$ is chosen as the input parameter

Thermal parameters for Au-Au collisions at 62.4 GeV

Preliminary

- Fit results from thermal model is plotted to extract the thermal parameters from Au-Au collisions at 62.4 GeV for 0-5% centrality



- At the minimum of $\frac{\chi^2}{NDF}$, i.e. $\frac{\chi^2}{NDF} = 1.3479$, we get $T = 0.148 \pm 0.009\ GeV, \mu_B = 0.0616 \pm 0.0036\ GeV, \mu_S = 0.01101 \pm 0.0007\ GeV$

Thermal parameters for Au-Au collision at 62.4 GeV

Preliminary

- Table for the results from Au-Au at 62.4 GeV for 0-5% centrality
- Only π, p, and K are used for the particle ratios
- π is corrected for weak decays
- p and K are inclusive.

	STAR results	Thermal Model	Thermal Model (Strangeness Conservation)
χ^2/NDF	0.48	1.3479	2.204
T (GeV)	0.154+0.010-0.007	0.148 $\pm$0.009	0.157 $\pm$0.013
μ_B (GeV)	0.0627 $\pm$0.006	0.0616 $\pm$0.0036	0.0655 $\pm$0.0053
μ_S (GeV)	0.0071 $\pm$0.0035	0.01101 $\pm$0.0007	0.01168 $\pm$0.0010

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

Error on Thermal Parameters

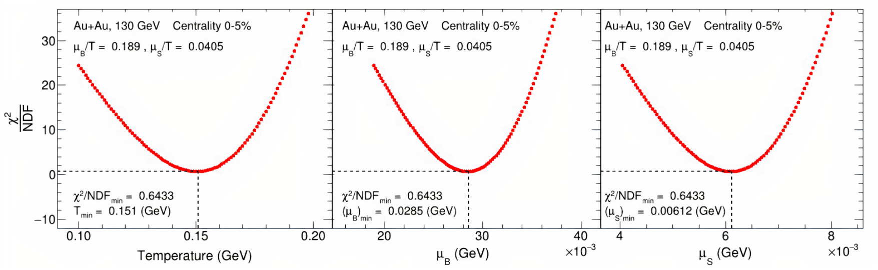
Preliminary

- Default Case
  - Systematic error is taken to be the average of deviation of the results from 100% and 0% of weak decay correction
  - Statistical error is taken to be the maximum deviation of the two cases, i.e. by adding and subtracting the experimental errors from the experimental ratios
  - Total error on the results is calculated as the square root of quadratic sum of Statistical and Systematic Errors
- Strangeness Conservation Case
  - The error is taken for the strangeness conservation case to be the deviation from the default case.
  - The total error is the square root of the quadratic sum of the error in the default case and the strangeness conservation case

Thermal parameters for Au-Au collisions at 130 GeV

Preliminary

- Fit results from thermal model is plotted to extract the thermal parameters at Au-Au collisions at 130 GeV for 0-5% centrality



- At the minimum of $\frac{\chi^2}{NDF}$, i.e. $\frac{\chi^2}{NDF} = 0.6433$, we get $T = 0.151 \pm 0.0156\, GeV, \mu_B = 0.0285 \pm 0.0029\, GeV, \mu_S = 0.00612 \pm 0.00063\, GeV$

Thermal parameters for Au-Au collision at 130 GeV

Preliminary

- Table for the results from Au-Au at 130 GeV for centrality 0-5%
- Only π, p, and K are used for the particle ratios
- π is corrected for weak decays
- p and K are inclusive.

	STAR results	Thermal Model	Thermal Model (Strangeness Conservation)
χ^2/NDF	0.136	0.6433	5.252
T (GeV)	0.154+0.010-0.006	0.151 $\pm$0.0156	0.168 $\pm$0.023
μ_B (GeV)	0.029 $\pm$0.0046	0.0285 $\pm$0.0029	0.0318 $\pm$0.0044
μ_S (GeV)	0.0024 0.0033	0.00612 $\pm$0.00063	0.0068 $\pm$0.00093

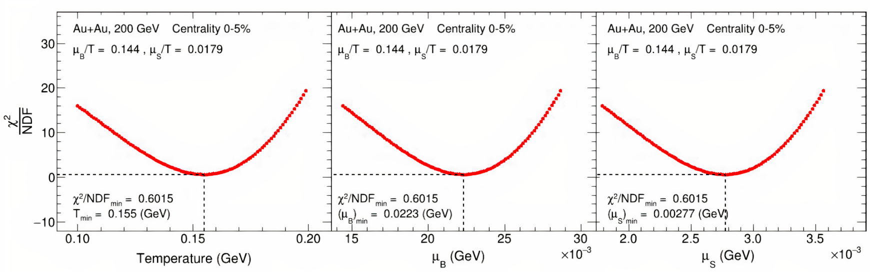
References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

Thermal parameters for Au-Au collisions at 200 GeV

Preliminary

- Fit results from thermal model is plotted to extract the thermal parameters from Au-Au collisions at 200 GeV for 0-5% centrality



- At the minimum of $\frac{\chi^2}{NDF}$, i.e. $\frac{\chi^2}{NDF} = 0.6015$, we get $T = 155 \pm 0.012\ GeV, \mu_B = 0.0223 \pm 0.004\ GeV, \mu_S = 0.00277 \pm 0.00022\ GeV$

Thermal parameters for Au-Au collisions for 200 GeV

Preliminary

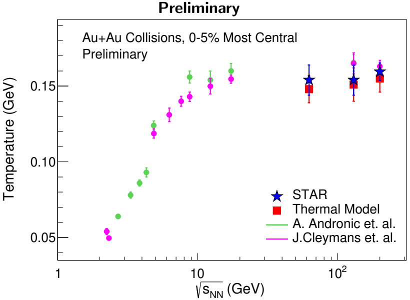
- Table for the results from Au-Au, at 200 GeV, for 0-5% centrality
- Only π, p, and K are used for the particle ratios
- π is corrected for weak decays
- p and K are inclusive.

	STAR results	Thermal Model	Thermal Model (Strangeness Conservation)
χ^2/NDF	0.03	0.004	1.926
T (GeV)	0.1593 $\pm$0.0058	0.155 $\pm$0.012	0.142 $\pm$0.0177
μ_B (GeV)	0.0219 $\pm$0.0045	0.0223 $\pm$0.004	0.020448 $\pm$0.0044
μ_S (GeV)	0.0039 $\pm$0.0021	0.00212 $\pm$0.00022	0.00254 $\pm$0.0003

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

Energy dependence of freezeout Temperature

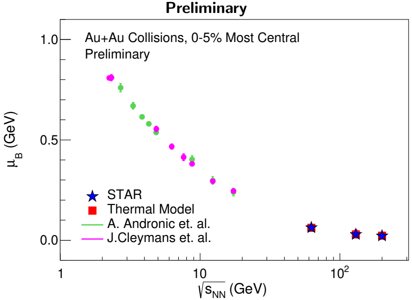


- Temperature as a function of beam energy is plotted for 62.4, 130 and 200 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The results from A. Andronic and J.Cleymans are shown by the green and magenta marker, respectively
- The chemical freezeout temperature increases with the beam energy
- The results of this Thermal model agrees with the results from the other model (STAR Thermus) at the same energy, within errors.
- All the models are showing consistently the same behaviour

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*
- *J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton Phys. Rev. C 73, 034905 (2006)*

Energy dependence of Baryon chemical potential

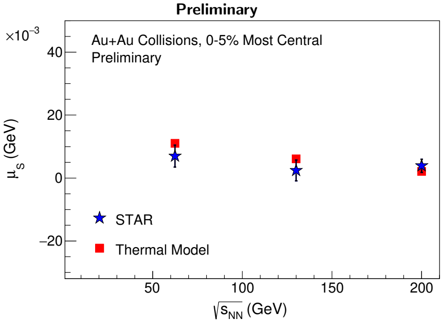


- Baryon chemical potential as a function of beam energy is plotted for 62.4, 130 and 200 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The results from A. Andronic and J.Cleymans are shown by the green and magenta marker, respectively
- The Baryon chemical potential decreases with increasing the beam energy
- The results of this Thermal model agrees with the results from the other model (STAR Thermus) at the same energy, within errors.
- All the models are showing consistently the same behaviour

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*
- *J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton Phys. Rev. C 73, 034905 (2006)*

Energy dependence of Strangeness chemical potential



- Strangeness chemical potential as a function of beam energy is plotted for 62.4, 130 and 200 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The Strangeness chemical potential decreases with increasing the beam energy
- The results of this Thermal model deviates from the other model (STAR Thermus)
- All the models are showing consistently the same behaviour

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

Summary

Preliminary

- We have shown Thermal model parameters (T, μ_B and μ_S) for different Beam energies of 62.4, 130 and 200 GeV
- The model successfully describes the value of different particle ratios within 2σ and χ^2/NDF by the order of 1-2
- Chemical freezeout temperature increases as we increase the Beam energy
- Baryon chemical potential decreases as we increase the Beam energy
- The results of thermal parameters and their energy dependence is consistent with the STAR results within uncertainties
- The results are comparable with other thermal model calculations from A. Andronic, J.Cleymans and S. Kabana.

Thank You

Backup

Preliminary

Au-Au Collisions at 62.4 GeV for 0-5% Centrality

Variation of $\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$

$$\frac{ap}{p} = 0.0071,\ \ln\frac{ap}{p} = -4.9471,\ \frac{\mu_B}{T} = -\frac{\ln\frac{ap}{p}}{2} = 2.4736$$

$$\frac{K-}{K+} = 0.3702,\ \ln\frac{K-}{K+} = -0.9937,\ \frac{\mu_S}{T} = -\frac{\ln\frac{K-}{K+}}{2} = 0.4968$$

Case	$\frac{\mu_B}{T}$	$\frac{\mu_S}{T}$	% change	Case	$\frac{\mu_B}{T}$	$\frac{\mu_S}{T}$
0	2.4736	0.4968	0			
1	0.2474	0.4968	-90	19	2.4736	0.0497
2	0.4947	0.4968	-80	20	2.4736	0.0994
3	0.7421	0.4968	-70	21	2.4736	0.1490
4	0.9894	0.4968	-60	22	2.4736	0.1987
5	1.2368	0.4968	-50	23	2.4736	0.2484
6	1.4841	0.4968	-40	24	2.4736	0.2981
7	1.7315	0.4968	-30	25	2.4736	0.3478
8	1.9788	0.4968	-20	26	2.4736	0.3975
9	2.2262	0.4968	-10	27	2.4736	0.4472
10	2.7209	0.4968	10	28	2.4736	0.5465
11	2.9683	0.4968	20	29	2.4736	0.5962
12	3.2156	0.4968	30	30	2.4736	0.6459
13	3.4630	0.4968	40	31	2.4736	0.6956
14	3.7103	0.4968	50	32	2.4736	0.7453
15	3.9577	0.4968	60	33	2.4736	0.7950
16	4.2051	0.4968	70	34	2.4736	0.8447
17	4.4524	0.4968	80	35	2.4736	0.8944
18	4.6998	0.4968	90	36	2.4736	0.9440

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Preliminary

Particle Ratios for Au-Au collisions at 130 GeV

Particles	Exp Ratio	Error in Ratio	Th. Ratio
$\frac{K^-}{K^+}$	0.922	0.085	0.913
$\frac{\bar{p}}{p}$	0.709	0.110	0.741
$\frac{K^-}{\pi^-}$	0.153	0.015	0.166
$\frac{\bar{p}}{\pi^-}$	0.071	0.009	0.0586
$\frac{K^+}{\pi^+}$	0.167	0.016	0.182
$\frac{p}{\pi^+}$	0.101	0.013	0.079

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

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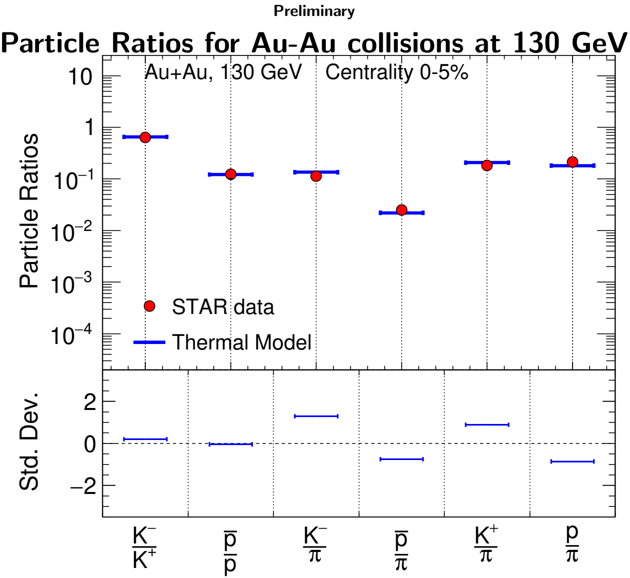
Preliminary
Particle Ratios for Au-Au collisions at 130 GeV
Au+Au, 130 GeV
Centrality 0-5%
Particle Ratios
STAR data
Thermal Model
Std. Dev.
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2
0
−2
$\frac{K^-}{K^+}$
$\frac{\bar{p}}{p}$
$\frac{K^-}{\pi}$
$\frac{\bar{p}}{\pi}$
$\frac{K^+}{\pi}$
$\frac{p}{\pi}$

Backup

Preliminary

Particle Ratios for Au-Au collisions at 200 GeV

Particles	Exp Ratio	Error in Ratio	Th. Ratio
$\frac{K^-}{K^+}$	0.965	0.172	0.958
$\frac{\bar{p}}{p}$	0.769	0.138	0.787
$\frac{K^-}{\pi^-}$	0.151	0.022	0.184
$\frac{\bar{p}}{\pi^-}$	0.082	0.012	0.086
$\frac{K^+}{\pi^+}$	0.159	0.024	0.192
$\frac{p}{\pi^+}$	0.108	0.016	0.109

References:

- B. I. Abelev et. al. (STAR Collaboration) Phys.Rev.C 79 (2009) 034909

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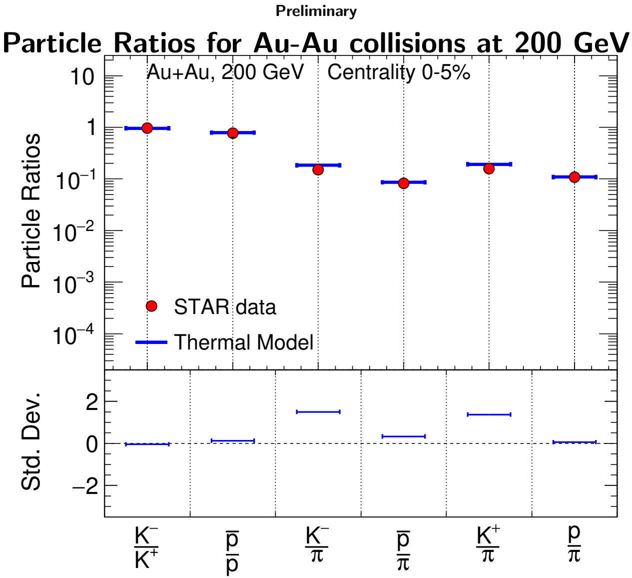

Preliminary
Particle Ratios for Au-Au collisions at 200 GeV
Au+Au, 200 GeV
Centrality 0-5%
Particle Ratios
STAR data
Thermal Model
Std. Dev.
K^-/K^+
$\bar{p}/p$
K^-/π
$\bar{p}/\pi$
K^+/π
p/π