Thermal properties of the medium created in heavy-ion collisions

For Au-Au collisions at $\sqrt{s_{NN}} = 19.6, 27$ and $39$ 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 Encyclopedia of physics, vol. 46, no. 2 ) 4, 044904

## Particle Ratios for Au-Au collisions at 19.6 GeV

<table>
<thead>
<tr>
<th>Particles</th>
<th>Exp. Ratio</th>
<th>Error in Ratio</th>
<th>Th. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{K^-}{K^+}$</td>
<td>0.635</td>
<td>0.089</td>
<td>0.656</td>
</tr>
<tr>
<td>$\frac{\bar{p}}{p}$</td>
<td>0.123</td>
<td>0.022</td>
<td>0.124</td>
</tr>
<tr>
<td>$\frac{\Lambda}{\bar{\Lambda}}$</td>
<td>0.148</td>
<td>0.010</td>
<td>0.157</td>
</tr>
<tr>
<td>$\frac{\Xi^+}{\Xi^-}$</td>
<td>0.260</td>
<td>0.025</td>
<td>0.250</td>
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<tr>
<td>$\frac{K^-}{\pi^-}$</td>
<td>0.113</td>
<td>0.017</td>
<td>0.142</td>
</tr>
<tr>
<td>$\frac{\bar{p}}{\pi^-}$</td>
<td>0.025</td>
<td>0.004</td>
<td>0.027</td>
</tr>
<tr>
<td>$\frac{\Lambda}{\pi^-}$</td>
<td>0.076</td>
<td>0.009</td>
<td>0.073</td>
</tr>
<tr>
<td>$\frac{\Xi^+}{\pi^-}$</td>
<td>0.0025</td>
<td>0.0003</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

- 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 19.6 GeV.

**References:**
The comparison of experimental particle ratios and ratios from the thermal model is plotted from Au-Au collision at 19.6 GeV for 0-5% centrality.

Thermal model is successfully predicting the experimental particle ratios within ±2σ deviation where, σ is represented by:

$$\sigma = \frac{\text{Ratio}_{\text{Th}} - \text{Ratio}_{\text{Exp}}}{\sigma_{\text{Exp}}}$$

References:

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

Preliminary

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

\[ \frac{ap}{p} = 0.123, \ln \frac{ap}{p} = -2.0971, \frac{\mu_B}{T} = -\frac{\ln \frac{ap}{p}}{2} = 1.049 \]

\[ \frac{K^-}{K^+} = 0.635, \ln \frac{K^-}{K^+} = -0.454, \frac{\mu_S}{T} = -\frac{\ln \frac{K^-}{K^+}}{2} = 0.2270 \]

\[ \chi^2_{\text{NDF}} = \min \] for $\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$ are varied in steps up to $\pm 90\%$ of the initial value, as a function of $\frac{\chi^2}{\text{NDF}}$. A minimum $\frac{\chi^2}{\text{NDF}}$ is found for the variation

\[ \frac{\mu_B}{T} \text{ and } \frac{\mu_S}{T} \text{ corresponding to the minimum } \frac{\chi^2}{\text{NDF}} \text{ is chosen as the input parameter} \]
Thermal parameters for Au-Au collisions at 19.6 GeV

Preliminary

Fit results from thermal model is plotted to extract the thermal parameters at Au-Au collisions at 19.6 GeV for 0-5% centrality.

At the minimum of $\frac{\chi^2}{NDF}$, i.e. $\frac{\chi^2}{NDF} = 0.5319$, we get $T = 0.150 \pm 0.006$ GeV, $\mu_B = 0.1730 \pm 0.007$ GeV, $\mu_S = 0.03405 \pm 0.0013$ GeV.
Thermal parameters for Au-Au collisions at 19.6 GeV

Table for the results from Au-Au at 19.6 GeV for 0-5% centrality

- $\pi$ and $\Lambda$ are corrected for weak decays
- $p$, $K$ and $\Xi$ are inclusive

<table>
<thead>
<tr>
<th></th>
<th>STAR results</th>
<th>Thermal Model</th>
<th>Thermal Model (Strangeness Conservation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2 / NDF$</td>
<td>1.3</td>
<td>0.5319</td>
<td>2.929</td>
</tr>
<tr>
<td>$T$ (GeV)</td>
<td>0.1539 ± 0.0052</td>
<td>0.150 ± 0.006</td>
<td>0.159 ± 0.0108</td>
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<tr>
<td>$\mu_B$ (GeV)</td>
<td>0.1879 ± 0.0086</td>
<td>0.173 ± 0.007</td>
<td>0.18333 ± 0.0125</td>
</tr>
<tr>
<td>$\mu_S$ (GeV)</td>
<td>0.0432 ± 0.0038</td>
<td>0.03405 ± 0.0013</td>
<td>0.036093 ± 0.0024</td>
</tr>
</tbody>
</table>

References:
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 27 GeV

Fit results from thermal model is plotted to extract the thermal parameters from Au-Au collisions at 27 GeV for 0-5% centrality

At the minimum of $\chi^2_{NDF}$, i.e. $\chi^2_{NDF} = 0.856$, we get $T = 0.152 \pm 0.0058$ GeV, $\mu_B = 0.1265 \pm 0.0049$ GeV, $\mu_S = 0.02426 \pm 0.00088$ GeV
Thermal parameters for Au-Au collisions at 27 GeV

Preliminary

Table for the results from Au-Au at 27 GeV for 0-5% centrality

- $\pi$ and $\Lambda$ are corrected for weak decays
- $p$, $K$ and $\Xi$ are inclusive

<table>
<thead>
<tr>
<th></th>
<th>STAR results</th>
<th>Thermal Model</th>
<th>Thermal Model (Strangeness Conservation)</th>
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</thead>
<tbody>
<tr>
<td>$\chi^2/NDF$</td>
<td>1.3</td>
<td>0.8956</td>
<td>2.17</td>
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<tr>
<td>$T$ (GeV)</td>
<td>$0.155 \pm 0.0051$</td>
<td>$0.152 \pm 0.0058$</td>
<td>$0.159 \pm 0.009$</td>
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<tr>
<td>$\mu_B$ (GeV)</td>
<td>$0.144 \pm 0.0072$</td>
<td>$0.1265 \pm 0.0049$</td>
<td>$0.13229 \pm 0.0076$</td>
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<tr>
<td>$\mu_S$ (GeV)</td>
<td>$0.0335 \pm 0.0036$</td>
<td>$0.02426 \pm 0.00088$</td>
<td>$0.025376 \pm 0.0014$</td>
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References:
Thermal parameters for Au-Au collisions at 39 GeV

Preliminary

Fit results from thermal model is plotted to extract the thermal parameters from Au-Au collisions at 39 GeV for 0-5% centrality

At the minimum of $\chi^2_{\text{NDF}}$, i.e. $\chi^2_{\text{NDF}} = 0.3743$, we get $T = 0.154 \pm 0.0072$ GeV, $\mu_B = 0.0963 \pm 0.0045$ GeV, $\mu_S = 0.0190 \pm 0.0008$ GeV
Thermal parameters for Au-Au collisions at 39 GeV

Preliminary

▶ Table for the results from Au-Au at 39 GeV for 0-5% centrality
▶ $\pi$ and $\Lambda$ are corrected for weak decays
▶ $p$, $K$ and $\Xi$ are inclusive

<table>
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<th>Thermal Model</th>
<th>Thermal Model (Strangeness Conservation)</th>
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<tr>
<td>$\chi^2 / NDF$</td>
<td>0.9</td>
<td>0.3743</td>
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<td>$T$ (GeV)</td>
<td>0.1564 ± 0.0054</td>
<td>0.154 ± 0.0072</td>
<td>0.162 ± 0.0086</td>
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<tr>
<td>$\mu_B$ (GeV)</td>
<td>0.1032 ± 0.0074</td>
<td>0.0963 ± 0.0045</td>
<td>0.10125 ± 0.0067</td>
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<tr>
<td>$\mu_S$ (GeV)</td>
<td>0.0245 ± 0.0038</td>
<td>0.019 ± 0.0008</td>
<td>0.019991 ± 0.0013</td>
</tr>
</tbody>
</table>

References:
Temperature as a function of beam energy is plotted for 19.6, 27 and 39 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:

Energy dependence of Baryon chemical potential

- Baryon chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 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:
Strangeness chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 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:
Energy dependence of freezeout Temperature
With the condition of Strangeness Conservation ($s - \bar{s} = 0$)

\[ \text{Au+Au Collisions, 0-5\% Most Central} \]

Preliminary

Temperature (GeV)

$\sqrt{s_{NN}}$ (GeV)

- Temperature as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results from 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 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:
Baryon chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 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 the increase in 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:
Energy dependence of Strangeness chemical potential

With the condition of Strangeness Conservation \((s - \bar{s} = 0)\)

Strangeness chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 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:

Energy dependence of Zero potential Temperature

With the condition of Strangeness Conservation \((s - \bar{s} = 0)\)

- Temperature for zero potential as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results from this Thermal model by red squares
- The results from S. Kabana are shown by the green marker
- The zero potential freezeout temperature saturates with the beam energy
- The results of this Thermal model agrees with the previously published results with different data
- Both the models (preliminary and previously published) are showing consistently the same behaviour

References:

Summary

Preliminary

- We have shown Thermal model parameters (T, $\mu_B$ and $\mu_S$) for different Beam energies from 19.6, 27 and 39 GeV
- The model successfully describes the value of different particle ratios within $2\sigma$ and $\chi^2/NDF$ 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
Preliminary

Au-Au Collisions at 19.6 GeV for 0-5% Centrality

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

\[
\frac{a_p}{p} = 0.123, \quad \ln \frac{a_p}{p} = -2.0971, \quad \frac{\mu_B}{T} = -\frac{\ln \frac{a_p}{p}}{2} = 1.049
\]

\[
\frac{K^-}{K^+} = 0.635, \quad \ln \frac{K^-}{K^+} = -0.454, \quad \frac{\mu_S}{T} = -\frac{\ln \frac{K^-}{K^+}}{2} = 0.2270
\]

<table>
<thead>
<tr>
<th>Case</th>
<th>( \frac{\mu_B}{T} )</th>
<th>( \frac{\mu_S}{T} )</th>
<th>% change</th>
<th>Case</th>
<th>( \frac{\mu_B}{T} )</th>
<th>( \frac{\mu_S}{T} )</th>
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<td>0</td>
<td>1.049</td>
<td>0.227</td>
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<td>12</td>
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<td>17</td>
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<td>36</td>
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### Preliminary Particle Ratios for Au-Au collisions at 27 GeV

<table>
<thead>
<tr>
<th>Particles</th>
<th>Exp. Ratio</th>
<th>Error in Ratio</th>
<th>Th. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-\over K^+$</td>
<td>0.727</td>
<td>0.092</td>
<td>0.744</td>
</tr>
<tr>
<td>$\overline{p}\over p$</td>
<td>0.189</td>
<td>0.032</td>
<td>0.221</td>
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<tr>
<td>$\Lambda\over \lambda$</td>
<td>0.236</td>
<td>0.0159</td>
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<tr>
<td>$\Xi^+\over \Xi^-$</td>
<td>0.381</td>
<td>0.036</td>
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</tr>
<tr>
<td>$K^-\over \pi^-$</td>
<td>0.128</td>
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<td>$\overline{p}\over \pi^-$</td>
<td>0.034</td>
<td>0.005</td>
<td>0.0386</td>
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<tr>
<td>$\Lambda\over \pi^-$</td>
<td>0.066</td>
<td>0.008</td>
<td>0.0613</td>
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<tr>
<td>$\Xi^+\over \pi^-$</td>
<td>0.0034</td>
<td>0.0004</td>
<td>0.0033</td>
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</tbody>
</table>

**References:**

Preliminary Particle Ratios for Au-Au collisions at 27 GeV

Particle Ratios for Au-Au, 27 GeV Centrality 0-5%

- STAR data
- Thermal Model

Plot showing particle ratios with error bars for different particle types: \( \frac{K^-}{K^+} \), \( \frac{\bar{p}}{p} \), \( \frac{\Lambda}{\bar{\Lambda}} \), \( \frac{\bar{K}^+}{\bar{K}^0} \), \( \frac{K^-}{\pi^-} \), \( \frac{\bar{p}}{\pi^-} \), \( \frac{\Lambda}{\pi^-} \), \( \frac{\bar{\Lambda}}{\pi^-} \).
## Preliminary Particle Ratios for Au-Au collisions at 39 GeV

<table>
<thead>
<tr>
<th>Particles</th>
<th>Exp. Ratio</th>
<th>Error in Ratio</th>
<th>Th. Ratio</th>
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</thead>
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<tr>
<td>$K^-/K^+$</td>
<td>0.781</td>
<td>0.101</td>
<td>0.796</td>
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<tr>
<td>$p/p$</td>
<td>0.321</td>
<td>0.052</td>
<td>0.323</td>
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<tr>
<td>$\Lambda/\bar{\lambda}$</td>
<td>0.347</td>
<td>0.042</td>
<td>0.366</td>
</tr>
<tr>
<td>$\Xi^+/\Xi^-$</td>
<td>0.506</td>
<td>0.095</td>
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<td>$K^-/\pi^-$</td>
<td>0.135</td>
<td>0.019</td>
<td>0.163</td>
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<tr>
<td>$p/\pi^-$</td>
<td>0.046</td>
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</tr>
<tr>
<td>$\Lambda/\pi^-$</td>
<td>0.059</td>
<td>0.008</td>
<td>0.055</td>
</tr>
<tr>
<td>$\Xi^+/\pi^-$</td>
<td>0.0041</td>
<td>0.0008</td>
<td>0.0040</td>
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References:
Preliminary

Particle Ratios for Au-Au collisions at 39 GeV

Au+Au, 39 GeV Centrality 0-5%

STAR data

Thermal Model

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