Snapshots of fireballs at freeze-out from heavy-ion collisions at different energies

Ivan Melo (Žilina) & Boris Tomášik (Banská Bystrica)
Motivation

Phase diagram of strongly interacting matter can be explored with heavy-ion collisions at various energies.

Dependences of various variables on energy $E$ are studied for that purpose.

Here we reconstruct $T(E)$ and $v_t(E)$ of the fireball at the moment of the kinetic freeze-out from fits to $p_t$ spectra of $p, \text{anti-}p, \pi^+, \pi^-, K^+, K^-$ from the most central collisions.

Scenario with two freeze-outs, chemical and kinetic:

\[
\begin{align*}
\text{T}_{\text{critical}} & \\
\text{T}_{\text{chemical}} & \\
\text{T}_{\text{kinetic}} & \\
\end{align*}
\]

\{ Partial chemical equilibrium \}

Blast wave model kinetic freeze-out implemented in DRAGON MC tool.

$P_t$ spectra fits typically do not include resonance decays.

See, e.g., ALICE Collaboration ArXiv:1303.0737[hep-ex]: Centrality dependence of $p, K, p$ production in Pb-Pb at 2.76 TeV.
DRAGON is MC code based on Blast Wave model
+ decays of unstable resonances, 277 hadrons included + possible fragmentation of fireball is included

\[ E \frac{d^3N}{dp^3} = \int \Sigma S(x, p) \, d^4x \quad S(x, p) \, d^4x = g_i \frac{m_t \cosh(\eta - y)}{(2\pi)^3} \left( \exp \left( \frac{p_\mu u^\mu - \mu_i}{T} \right) \pm 1 \right) \left( 1 - \frac{r}{R} \right) \]

Energy of particle
Bose/Einstein – Fermi/Dirac

Boost invariant and cylindrically symmetric

Freeze-out at const proper time

\[
\sqrt{t^2 - z^2} = \tau_0 = \text{const}
\]

our freeze-out curve

\( R \) is radius of fireball at freeze-out

\[ T = T_{\text{kin}} \quad \text{freeze-out temperature}, \quad \eta_f \quad \text{transverse flow gradient}, \quad n \quad \text{profile of transverse velocity} \]
Partial chemical equilibrium

\[ T_{\text{critical}} \]
\[ T_{\text{chemical}} \]
\[ T_{\text{kinetic}} \]

Interactions maintain partial equilibrium between stable hadrons and resonances through which they interact, e.g.
\[ \rho \rightarrow \pi \pi \quad N_\pi + 2 N_\rho \text{ conserved} \]

Pions, kaons, protons and resonances develop chemical potentials below \( T_{\text{chemical}} \)

\[ \mu_\pi \text{[GeV]} \]
\[ \mu_K \text{[GeV]} \]
\[ \mu_p \text{[GeV]} \]

These values reproduce the ratios of hadron multiplicities we take them as input

<table>
<thead>
<tr>
<th>( \sqrt{s_{NN}} ) [GeV]</th>
<th>( T ) [MeV]</th>
<th>( \mu_B ) [MeV]</th>
<th>( \mu_S ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>144.3</td>
<td>389.2</td>
<td>89.5</td>
</tr>
<tr>
<td>11.5</td>
<td>149.4</td>
<td>287.3</td>
<td>64.4</td>
</tr>
<tr>
<td>19.6</td>
<td>153.9</td>
<td>187.9</td>
<td>45.3</td>
</tr>
<tr>
<td>27</td>
<td>155.0</td>
<td>144.4</td>
<td>33.5</td>
</tr>
<tr>
<td>39</td>
<td>156.4</td>
<td>103.2</td>
<td>24.5</td>
</tr>
<tr>
<td>62.4</td>
<td>160.3</td>
<td>69.8</td>
<td>16.7</td>
</tr>
<tr>
<td>130</td>
<td>154.0</td>
<td>29.0</td>
<td>2.4</td>
</tr>
<tr>
<td>200</td>
<td>164.3</td>
<td>28.4</td>
<td>5.6</td>
</tr>
<tr>
<td>2760</td>
<td>156.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Experimental data

We fitted $p_t$ spectra of $p$, anti-$p$, $\pi^+$, $\pi^-$, $K^+$, $K^-$ from the most central collisions at $\sqrt{s_{_{NN}}} = 7.7, 11.5, 19.6, 27, 39$ GeV, STAR [1], $p_t < 2$ GeV

$\sqrt{s_{_{NN}}} = 62.3, 130, 200$ GeV, STAR [2], $p_t < \sim 0.7 – 1.1$ GeV

and $\sqrt{s_{_{NN}}} = 2760$ GeV, ALICE [3], $p_t < 2$ GeV


MADAI fitting technique

- The best fit point \((T, \eta_f, n)\) was found using MADAI package [4], a Monte Carlo exploration of the 3-parameter space weighted by the posterior probability

- First, 400 training points are generated at random

- \(p_t\) spectra were generated in each training point with DRAGON (0.5 – 5 hours/point)
  - for each of 6 species, spectrum is normalized independently

- Posterior probability in points other than training points is estimated with Gaussian emulator trained on the training points

- Output of MADAI is the best fit point + uncertainties + correlation matrix among parameters (can be displayed as 2-dim projections of the posterior distribution)

MADAI: 2-dim projections of posterior probability

$\sqrt{s_{NN}} = 7.7 \text{ GeV}$

$\sqrt{s_{NN}} = 2760 \text{ GeV}$
Best fit parameters

χ² fit was performed as an independent check

\[ \sqrt{s_{NN}} \text{ [GeV]} \quad T \text{ [MeV]} \quad \eta_f \quad n \quad \chi^2_{N_{dof}} \quad <v_t> \]

<table>
<thead>
<tr>
<th>√s_{NN} [GeV]</th>
<th>T [MeV]</th>
<th>η_f</th>
<th>n</th>
<th>χ²_{N_{dof}}</th>
<th>&lt;v_t&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>102.0 ± 2.0</td>
<td>0.620 ± 0.016</td>
<td>0.726 ± 0.073</td>
<td>0.83</td>
<td>0.45</td>
</tr>
<tr>
<td>11.6</td>
<td>103.6 ± 1.5</td>
<td>0.632 ± 0.012</td>
<td>0.792 ± 0.069</td>
<td>0.66</td>
<td>0.45</td>
</tr>
<tr>
<td>19</td>
<td>98.1 ± 1.6</td>
<td>0.711 ± 0.009</td>
<td>1.122 ± 0.064</td>
<td>0.38</td>
<td>0.46</td>
</tr>
<tr>
<td>27</td>
<td>97.4 ± 1.4</td>
<td>0.715 ± 0.007</td>
<td>1.022 ± 0.048</td>
<td>0.68</td>
<td>0.47</td>
</tr>
<tr>
<td>39</td>
<td>98.5 ± 1.4</td>
<td>0.729 ± 0.007</td>
<td>1.006 ± 0.045</td>
<td>0.47</td>
<td>0.49</td>
</tr>
<tr>
<td>62</td>
<td>80.2 ± 0.8</td>
<td>0.756 ± 0.007</td>
<td>0.689 ± 0.020</td>
<td>0.93</td>
<td>0.56</td>
</tr>
<tr>
<td>130</td>
<td>75.0 ± 0.8</td>
<td>0.797 ± 0.006</td>
<td>0.760 ± 0.015</td>
<td>1.07</td>
<td>0.58</td>
</tr>
<tr>
<td>200</td>
<td>75.4 ± 1.8</td>
<td>0.841 ± 0.012</td>
<td>0.810 ± 0.020</td>
<td>0.25</td>
<td>0.60</td>
</tr>
<tr>
<td>2760</td>
<td>78.3 ± 1.6</td>
<td>0.903 ± 0.005</td>
<td>0.766 ± 0.018</td>
<td>0.32</td>
<td>0.65</td>
</tr>
</tbody>
</table>

\[ v_t = \tanh \eta_t = \eta_f \left( \frac{r}{R} \right)^n \quad \Rightarrow \quad \langle v_t \rangle = \frac{2}{n + 2\eta_f} \]
Energy dependence of the freeze-out parameters
Transverse momentum spectra at different energies + ratio data/MC

- \( R = \frac{\text{data}}{\text{MC}} + k \) (\( k = 0, 1, 2, \ldots, 8 \)) to display all ratios in one Fig.
Anatomy of spectra

Fraction of $\pi^-$, $K^-$, p coming either from a given resonance or direct production

- Other resonances
- $K_0^*$
- $K_0^0$
- $\Lambda_0^0$
- $\bar{\Lambda}_0$
- $\phi$
- Direct

![Graphs showing the fraction of pions, kaons, and protons coming from different resonances or direct production at various energies.](image)

- $T_{\text{ch}} = 144.3$ MeV
- $T_{\text{kin}} = 102.0$ MeV
- $T_{\text{ch}} = 164.3$ MeV
- $T_{\text{kin}} = 75.4$ MeV

- Fraction of $\pi^-$, $K^-$, p coming either from a given resonance or direct production

11/13
Anatomy of spectra cont‘d

• Fraction of resonance-produced hadrons goes down as energy goes up

  \[ E = 7.7 \text{ GeV: } T_{ch} = 144.3 \text{ MeV} \quad T_{kin} = 102.0 \text{ MeV} \]
  \[ E = 200 \text{ GeV: } T_{ch} = 164.3 \text{ MeV} \quad T_{kin} = 75.4 \text{ MeV} \]

• Fraction of resonance-produced hadrons becomes flat at high energy unlike at low energy

  \[ \Delta^- \rightarrow n + \pi^-, \quad m_\Delta = 1232 \text{ MeV} \]

\[ \Delta^- \text{ decay happens closely above the threshold, so that daughter particles do not acquire high momentum,} \]
\[ p_t = 227.7 \text{ MeV} \]

In combination with small transverse expansion velocity this causes that pions from such decays stay at low pt
\[ p_t = 500 \text{ MeV for } 7.7 \text{ GeV} \quad p_t = 1090 \text{ MeV for } 200 \text{ GeV} \]

The same applies for kaons from the decay of \( \Phi \).
Summary

- With increase of collision energy the fireball cools down more and develops stronger transverse expansion

- Although the freeze-out temperature seems to show a sharp step between 39 and 62.4 GeV, it may be connected with different coverage of $p_t$ intervals

- Full results with resonances coincide with those with only directly produced hadrons, i.e. no resonances, except for the two lowest collision energies.

- Lowest $p_t$ pions at LHC are underestimated by the fits (unlike in nonequilibrium Cracow freeze-out model)

- A more comprehensive study which will include the centrality dependence is being elaborated