Statistical hadronization in ultra-relativistic heavy-ion collisions using THERMINATOR 2 package - "Hands-on" session

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1 Compiling the code

- Hit the keyboard shortcut Ctrl + Alt + T to open a new Terminal window.
- Change the directory to the THERMINATOR 2 main directory

```
cd /media/lubuntu/Data/therminator2/
```

and compile the package typing

```
make
```

After a successful compilation, the binary files are present in the main directory. To inspect the directory content type

```
ls
```

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- The main code of THERMINATOR 2 [1] is *therm2_events*, which generates the events. Single event is an equivalent to the single experimental event (collision) measured in the detector. The program *therm2_events* uses configuration file *events.ini* and one of the **.ini* files from the `./fomodel/` subdirectory. Selection of certain configuration file from `./fomodel/` subdirectory depends on the choice of the freeze-out model in the *events.ini* file (see `FreezeOutModel` parameter in the *events.ini* file and the respective table above it).

2 Default run

- In order to perform the default run of the *therm2_events* program evaluate the script

```
./runevents.sh
```

The run with the default setup corresponds to Au+Au collisions at the RHIC energy of $\sqrt{s_{NN}} = 200$ GeV and centrality $c = 20 - 30\%$. As an input the code uses the hypersurface extracted from (2+1)D boost-invariant perfect-fluid hydrodynamics simulation (see `FreezeOutModel = Lhyquid2DBI` setting in *events.ini* file). The hypersurface is contained in the THERMINATOR 2 package in the form of **.xml* file in `./fomodel/lhyquid2dbi/` subdirectory (see `FreezeFile = lhyquid2dbi/RHICAuAu200c2030Ti455ti025Tf145.xml` setting in *lhyquid2dbi.ini* file). It is a part of a set of exemplar hypersurfaces in `./fomodel/lhyquid2dbi/` subdirectory.

The code evaluation starts (1 stage) with calculation of the **average multiplicity** and **maximal value of the integrand** of Cooper-Frye integral [1] of primordial particles corresponding to a selected freeze-out model and parameters (this is done for each of ~ 400 hadronic states). Subsequently the code proceeds with **generating events** (2 stage). On the Intel Core i7-4930MX CPU @ 3.00GHz the run takes 20 min (1 stage) + 0.5 min (2 stage).

- The output of the run is stored in the `./events/lhyquid2dbi-RHICAuAu200c2030Ti455ti025Tf145/` subdirectory and contains:
  - a sequence of *eventNNN.root* ROOT files (containing information on all generated events; single *eventNNN.root* file may contain up to 500 events; the number identifier NNN equals 000 if no event files are present in the directory, whereas it is one unit larger from identifier of the file with highest identifier if there are any files already present)
  - text file *fmultiplicity_*.txt* (that stores maximal values of the integrand and the primordial particle multiplicities)
  - **.ini* files (containing the configuration used for the run – just for the record)

By default, 100 events are generated (see `NumberOfEvents = 100` setting in *events.ini* file).

3 Performing the analysis

- Once the output of the run is stored in *event*.root* files one can use the ROOT interface to perform the physical analysis. This is done through the ROOT **macros** which are prepared in C programming language and use ROOT libraries. A set of exemplar ROOT macros is provided with the THERMINATOR 2 code and may be found in the `./macro/` subdirectory.

- For instance, to generate the figure showing the p_T spectra of π^+, K^+, and p produced at midrapidity one may use *figure_distpt.C* macro. For this purpose one has to issue the command

```
root -x './macro/figure_distpt.C("./events/
                    lhyquid2dbi-RHICAuAu200c2030Ti455ti025Tf145/",1)'
```

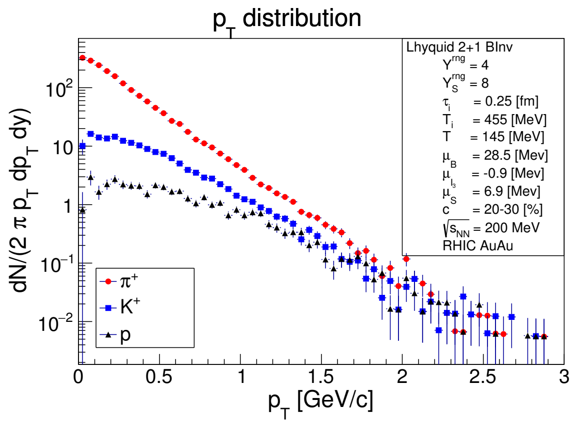

Figure 1: Transverse-momentum spectra of π^+, K^+, and p for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and the centrality class 20-30% for **100** events (protons from Λ weak decays are excluded).

The single and double quotation marks are necessary to pass the parameters to the macro. One of the parameters is a string of characters defining the path to the *event*.root* files, the other one is integer number (equal 1 in this case), which denotes the number of *event*.root* files which one wants to use for the analysis (plotting). The macro creates two files in the `./events/lhyquid2dbi-RHICAuAu200c2030Ti455ti025Tf145/` subdirectory: *fig_distpt.eps* and *fig_distpt.xml*. The first one is the EPS graphics file, the second one contains the data from the histogram in a form of the XML file.

- The resulting plot should be similar to Fig.1.
- To exit `ROOT` interface issue the command

```
.q
```

4 Improving statistics

- To increase the statistics (number of events) to 1000 in total one should edit the configuration file *events.ini* in the main directory

```
gedit events.ini
```

set the parameter `NumberOfEvents = 900`, save the *events.ini* file hitting Ctr+S, and repeat the command

```
./runevents.sh
```

This time the code skips 1 stage and starts immediately with the generation of events using the data stored in *fmultiplicity_*.txt* file. The code will generate additional *event*.root* files in the previously created output directory (two files with 500 and 400 events, respectively).

- Repeating the generation of the figure with the p_T spectra with all 3 *event*.root* files

```
root -x './macro/figure_distpt.C("./events/
                    lhyquid2dbi-RHICAuAu200c2030Ti455ti025Tf145/",3)'
```

will improve the plot, see Fig.2, and compare with Fig.1.

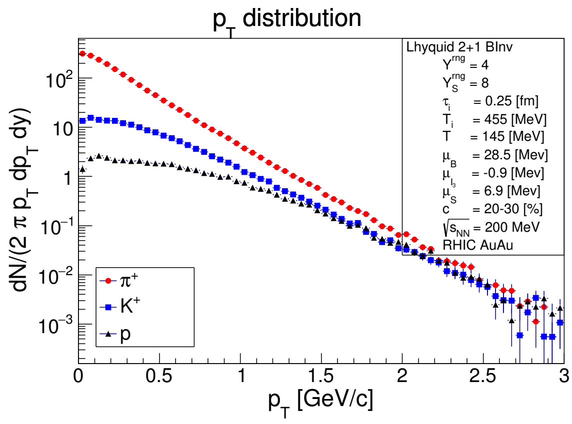

Figure 2: Transverse-momentum spectra of π^+, K^+, and p for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and the centrality class 20-30% for **1000** events (protons from Λ weak decays are excluded).

5 Studying the impact of resonance decays

- The key ingredient in the **thermal model** [2, 3, 4] approach are the hadronic resonances, which must be included in a complete way, together with their decay channels and branching ratios. For that purpose `THERMINATOR 2` uses the universal input files with the information from the Particle Data Tables [5].
- Apart from the generation of primordial hadrons (directly at the freeze-out hypersurface), for the unstable resonances the `THERMINATOR 2` program also performs their free streaming (according to the momenta assigned to them)

$$x^\mu_{\text{decay}} = x^\mu_{\text{origin}} + \frac{p^\mu}{M}\Delta\tau$$

and takes care of their decays (which may proceed in cascades) until all unstable particles decay. The lifetime $\Delta\tau$ of the decaying particle of mass M, mowing with the four-momentum p^μ, is generated randomly according to the exponential decay law, $\exp(-\Gamma\Delta\tau)$. The stable particles coming from decays are feeding the spectra of primordial ones giving effective result of cooler (steeper) total spectrum. This effect may be clearly seen by creating the following plot

```
root -x './macro/figure_distpt_pion.C("./events/
                     lhyquid2dbi-RHICAuAu200c2030Ti455ti025Tf145/",3)'
```

which presents contributions of pions coming from various decays to the total pion spectrum, see Fig.3. One can see that primordial pions form only $\sim 1/3$ of the total measured pions.

6 Applying the experimental feed-down corrections

- The experimental proton spectra are usually feed-down corrected for $\Lambda^0 \to p^+ + \pi^-$ weak decays, see Fig.5 from [6]. WHY? Such corrections were also applied in Fig.2.

  Exercise: Create a new macro by copying the file *figure_distpt.C* used previously

```
cp macro/figure_distpt.C macro/figure_distpt_feed.C
```

  and edit it

```
gedit macro/figure_distpt_feed.C
```

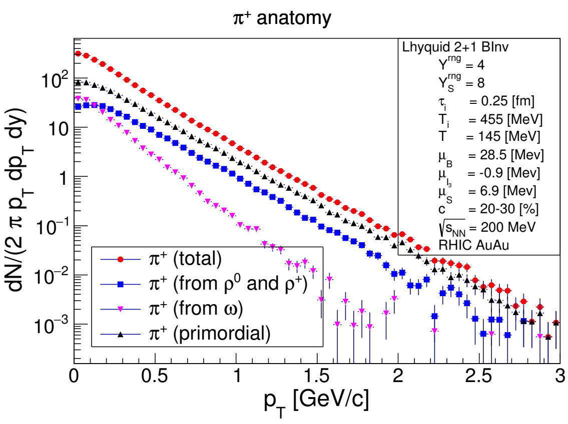

Figure 3: Transverse-momentum spectra of π^+ for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and the centrality class 20-30% for **1000** events. The contributions from decays of ρ^0 and ρ^+, ω , and primordial ones to the total π^+ spectrum are presented.

to prepare the plot of the comparison of the p_T spectrum of protons **with** and **without** the feed-down correction for Λ^0.

Prerequisites: For each particle stored in the *event*.root* files the **particle PDG (Particle Data Group) number** of its parent particle is stored in the `fatherpid` property and the particle PDG number of the particle itself is stored in `pid` variable respectively. The particle PDG numbers of all particles may be found in *particles.data* file in the `./share/` subdirectory in the last (`MC`) column. In this respect `THERMINATOR 2` uses the same input files as the `SHARE` package [7]. The particle PDG number for Λ^0 is `3122` and its name is `Lm1115zer` (see the first column of the same file). The particle PDG number for p is `2212` and its name is `pr0938plu`.

The result should look similar to Fig.4.

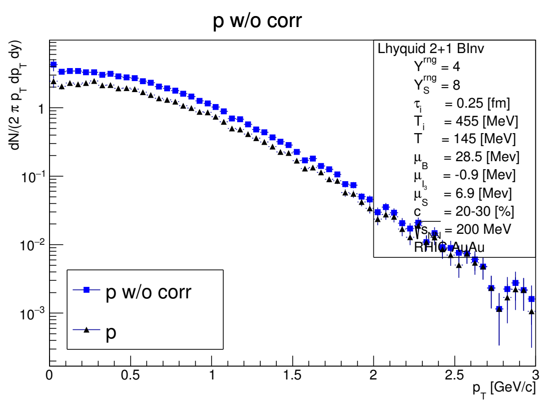

Figure 4: Transverse-momentum spectra of p with and without feed-down correction for Λ^0 weak decays.

7 Calculating particle yields

- Sometimes it is useful and easier to **parametrize** the freeze-out (shape of the hypersurface and the flow profile on it) generated in relativistic heavy-ion collisions instead of performing complicated hydrodynamic evolution of the QCD medium. Approaches based on such parametrizations are often called **hydro-inspired models** due to the hints coming from realistic hydrodynamic simulations which are often used to formulate them. It was shown that one of such models, the so called **Cracow single freeze-out model** [3], describes both the spectra and particle ratios reasonably well. We may use it also within THERMINATOR 2 to study the impact of the change of the freeze-out temperature.

- In order to perform the run using the Cracow model first one has to use `FreezeOutModel = KrakowSFO` setting in the *events.ini* file. Moreover we will use `NumberOfEvents = 1000`. Subsequently, following the table in the *events.ini* file, we need to modify the *krakow.ini* file in the `./fomodel/` subdirectory accordingly: `TauC = 9.74` and `RhoMax = 7.74` to set the shape of the hypersurface. The latter values were extracted from the central (0-5% centrality) RHIC top energy data on particle ratios and spectra [8]. In the latter analysis also the default values of chemical potentials `MuB = 28.5, MuI = -0.9, MuS = 6.9, MuC = 0.0` and freeze-out temperature `Temperature = 165.6` were extracted. Finally we need to set `EventSubDir = krakow/highT/` to set the separate output storage, and run the code. On the Intel Core i7-4930MX CPU @ 3.00GHz the run takes 12 min (1 stage) + 6.5 min (2 stage).

Once the run is finished we shall evaluate the macro *figure_distpt_bar.C*

```
root -x './macro/figure_distpt_bar.C("./events/
                    lhyquid2dbi-RHICAuAu200c2030Ti455ti025Tf145/",3)'
```

The output of the macro returns the p_T spectra of π^-, K^-, and $\bar{p}$. The *fig_distpt_bar.xml* file contains the respective data from the histogram used for plotting. The latter file may be used directly to calculate the ratios of particle multiplicities. For instance, one may calculate them by reading off the total number of pions from the
`<PARTICLE entries="243989">#pi^{-} (total)</PARTICLE>`
markup of the *fig_distpt_bar.xml* file and dividing by the total number of events
`<EVENTS>1000</EVENTS>`. Repeating the procedure for K^-, and $\bar{p}$ one may subsequently generate the ratios $\bar{p}/\pi^-$ and K^-/π^- and compare it with STAR experiment [9]. The results should be similar to the ones obtained in Ref.[8]. The exact numbers should be approximately $\bar{p}/\pi^- = 0.058$ and $K^-/\pi^- = 0.152$ (compare to experimental results in Table 1 from [8]).

Exercise: Following some recent studies [10] the freeze-out temperatures extracted from the data can be as low as 150 MeV. One may repeat the Exercise 7 with the only change in the `Temperature = 150` setting in *krakow.ini* file and in the `EventSubDir = krakow/lowT/` parameter to avoid loosing previous results. One may check whether ratios $\bar{p}/\pi^-$ and K^-/π^- are in agreement with the data at such low temperatures.

8 Including heavy states

- In its default configuration THERMINATOR 2 uses the SHARE tables which include all the **** and *** resonances listed in Particle Data Tables up to 2.6 GeV. In the heavy-ion collisions pions, kaons and protons form most of the measured particles, thus reproducing their spectra is crucial. The heavy resonances populate strongly the spectra of light particles, however their production is suppressed due to their large masses.

Exercise: By commenting out lines (or blocks of lines) in the *particles.data* file in the `./share/` subdirectory with the # sign and subsequently running the code figure out a mass cut which minimizes the number of resonances required for the simulations and at the same time provides reasonable description of the pion, kaon and proton spectra. Assume that the full resonance table provides the exact result.

Prerequisites: To comment out the block of lines in the *particles.data* file using gedit editor, mark the block of lines and hit the Ctrl+M shortcut. The opposite result may be obtained using Ctrl+Shift+M shortcut. To compare the resulting spectra for any two cases (runs) evaluate the command

```
root -x './macro/figure_distpt_compare.C("./events/krakow/highT-2GeVcut/",
"./events/krakow/highT/",4,4)'
```

where `./events/krakow/highT-2GeVcut/` and `./events/krakow/highT/` denote the directories of the two sets of data and the last two arguments denote numbers of *events*.root* files used for the plotting in the two cases.

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