SHARE: Statistical Hadronization with Resonances[†]

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Abstract

SHARE is a collection of programs designed for the statistical analysis of particle production in relativistic heavy-ion collisions. With the physical input of intensive statistical parameters, it generates the ratios of particle abundances. The program includes cascade decays of all confirmed resonances from the Particle Data Tables. The complete treatment of these resonances has been known to be a crucial factor behind the success of the statistical approach. An optional feature implemented is a Breit–Wigner type distribution for strong resonances. An interface for fitting the parameters of the model to the experimental data is provided.

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PROGRAM SUMMARY

Title of the program: SHARE, July 2004, version 1.1;

Computer:

PC, Pentium III, 512MB RAM not hardware dependent;

Operating system:

Linux: RedHat 6.1, 7.2, FEDORA etc. not system dependent;

Programming language: FORTRAN77: g77, f77

as well as Mathematica, with temperature-fixed particle yields and excluding option of finite width;

Size of the package: 645 KB directory including example programs (82KB compressed distribution archive), without libraries (see

http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/minmain.html

http://wwwasd.web.cern.ch/wwwasd/cernlib.html

for details on library requirements).

Distribution format: tar gzip file

Number of lines in distributed program, including test data, etc: 14893

Keywords: relativistic heavy-ion collisions, particle production, statistical models, decays of resonances

Computer: Any computer with an f77 compiler

Nature of the physical problem:

Statistical analysis of particle production in relativistic heavy-ion collisions involves the formation and the subsequent decays of a large number of resonances. With the physical input of thermal parameters, such as the temperature and fugacities, and considering cascading decays, along with weak interaction feed-down corrections, the observed hadron abundances are obtained. SHARE incorporates diverse physical approaches, with a flexibility of choice of the details of the statistical hadronization model, including the selection of a chemical (non)equilibrium condition. SHARE also offers evaluation of the extensive properties of the source of particles, such as energy, entropy, baryon number, strangeness, as well as the determination of the best intensive input parameters fitting a set of experimental yields. This allows exploration of a proposed physical hypothesis about hadron production

mechanisms and the determination of the properties of their source.

Method of solving the problem:

Distributions at freeze-out of both the stable particles and the hadronic resonances are set according to a statistical prescription, technically calculated via a series of Bessel functions, using CERN library programs. We also have the option of including finite particle widths of the resonances. While this is computationally expensive, it is necessary to fully implement the essence of the strong interaction dynamics within the statistical hadronization picture. In fact, including finite width has a considerable effect when modeling directly detectable short-lived resonances ($\Lambda(1520), K^*$, etc.), and is noticeable in fits to experimentally measured yields of stable particles. After production, all hadronic resonances decay. Resonance decays are accomplished by addition of the parent abundances to the daughter, normalized by the branching ratio. Weak interaction decays receive a special treatment, where we introduce daughter particle acceptance factors for both strongly interacting decay products. An interface for fitting to experimental particle ratios of the statistical model parameters with help of MINUIT [1] is provided.

The χ^2 function is defined in the standard way. For an investigated quantity f and experimental error Δf ,

$$\chi^2 = \frac{(f_{\text{experiment}} - f_{\text{theory}})^2}{(\Delta f_{\text{statistical}} + \Delta f_{\text{systematic}})^2} \tag{1}$$

$$N_{DoF} = N_{data points} - N_{free parameters}.$$
 (2)

(note that systematic and statistical errors are independent, since the systematic error is not a random variable).

Aside of χ^2 the program also calculates the statistical significance [2], defined as the probability that, given a "true" theory and a statistical (Gaussian) experimental error, the fitted χ^2 arises at or above the considered value. In the case that the best fit has statistical significance significantly below unity, the model under consideration is very likely inappropriate. In the limit of many degrees of freedom (N_{DoF}), the statistical significance function depends only on χ^2/N_{DoF} , with 90% statistical significance at $\chi^2/N_{DoF} \sim 1$, and falling steeply at $\chi^2/N_{DoF} > 1$. However, the degrees of freedom in fits involving ratios are generally not sufficient to reach the asymptotic limit. Hence, statistical significance depends strongly on χ^2 and N_{DoF} separately.

In particular, if $N_{DoF} < 20$, often for a fit to have an acceptable statistical significance, a χ^2/N_{DoF} significantly less than 1 is required.

The fit routine does not always find the true lowest χ^2 minimum. Specifically, multi-parameter fits with too few degrees of freedom generally exhibit a non-trivial structure in parameter space, with several secondary minima, saddle points, valleys, etc. To help the user perform the minimization effectively, we have added tools to compute the χ^2 contours and profiles. In addition, our program's flexibility allows for many strategies in performing the fit. It is therefore possible, by following the techniques described in Sect. 3.7, to scan the parameter space and ensure that the minimum found is the true one. Further systematic deviations between the model and experiment can

be recognized via the program's output, which includes a particle-by-particle comparison between experiment and theory.

Purpose:

In consideration of the wide stream of new data coming out from RHIC, there is an on-going activity, with several groups performing analysis of particle yields. It is our hope that SHARE will allow to create an analysis standard within the community. It can be useful in analyzing the experimental data, verifying simple physical assumptions, evaluating expected yields, as well as allowing to compare various similar models and programs which are currently being used.

Computation time survey:

We encounter, in the Fortran version computation, times up to seconds for evaluation of particle yields. These rise by up to a factor of 300 in the process of minimization and a further factor of a few when χ^2/N_{DoF} profiles and contours with chemical non-equilibrium are requested.

Accessibility:

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http://www.ifj.edu.pl/Dept4/share.html
or http://www.physics.arizona/~torrieri/SHARE/share.html
as well as from the authors upon request
```

1 Introduction

In strong interaction reaction processes particle production is abundant. In his seminal 1950 article Fermi proposed a non-perturbative description of particle yields based on the assumption that the accessible phase space will be fully saturated [3]. Pomeranchuk extended the model by reconsidering the particle freeze-out condition [4]. He argued that the reaction volume should expand to the point where particles would decouple from each other, given their inelastic reaction cross sections. We call this stage the chemical freeze-out. In the ensuing decade another important feature of the strong interactions was discovered: the existence of numerous hadronic resonances. Hagedorn recognized that the large number of different hadronic states is an expression and characterization of their strong interactions. He has shown that the increase in the number of resonances with their mass has profound implications for the behavior of matter at high temperature [5]: hot hadronic matter could undergo a phase transition at Hagedorn temperature, $T_{\rm H} \approx$ 160 MeV. Hagedorn referred to this as the boiling point of hadronic matter beyond which the gas of quarks would prevail as a new form of matter. For an introduction into the literature and history of this subject see [6], and for recent developments also [7].

High energy relativistic heavy nuclei (RHI) collisions allow to create, in the laboratory environment, a fireball of matter at extreme density and temperature. The immediate objective of this experimental program is to identify formation of a relatively large volume of deconfined quark—gluon matter, the quark—gluon plasma (QGP), and to explore its properties. This form of matter has existed in the early Universe just before quarks and gluons evolved into the 'normal' hadronic particles which surround us today. Formation of a region of space in which quarks can roam freely would confirm that their confinement is a property of the structured strong interaction vacuum state. For a general introduction to these physics questions see [8].

Considering the short available lifetime of the fireball, it is difficult to develop probes capable of uniquely distinguishing a reaction involving formation of the deconfined QGP state from the one involving a cascade of reactions between individual confined baryons and mesons. The characteristic feature of the RHI reaction is the formation of a large number of hadronic particles. Irrespective if, or not, deconfinement has been achieved, this constitutes the final state of a RHI collision. Theoretical considerations suggest that features of the final hadron abundances are sensitive to the question if deconfined state has been formed [10].

Analysis of the final hadron state can thus lead to important insights regarding reaction mechanisms governing the last stage of the QGP evolution. We offer here a standardized version of the Statistical HAdronization with REsonances (SHARE) approach allowing to obtain final state hadron particle yields. We have at first prepared two platforms, developed in parallel in the form of Fortran and Mathematica shareware, and verified their input and logical structure by making sure they yield identical results using the same input file. However, in physics applications which require optimization of parameters, Mathematica turns out to be forbiddingly slow, and Fortran is preferred. For some other applications, the versatility of Mathematica is of clear advantage, e.g., one can track the feeding from resonances, make use of the integrated graphics, or modify the notebook to extend the model.

Several research groups beginning with P. Koch et al. [11] have developed statistical models of hadron production based on the seminal work by Fermi, Pomeranchuk and Hagedorn [3–5]. Hadron yields are computed assuming that hadron production can be obtained evaluating the accessible phase space size. Known hadron resonances are incorporated and their decay chain evaluated. One has to view this type of hadronization as providing a bottom line, there could be always additional microscopic production mechanisms which should be most clearly visible for most rarely produced particles. The experimental data coming from lower energy collisions of 2–11 GeV at AGS, through the CERN SPS energies of 8–17 GeV, to the highest presently available energies at RHIC, reaching 200 GeV, can be understood, sometimes to a surprising accuracy, with the help of such straightforward statistical ideas. There are many variants of statistical approaches, with the common feature that at some point of its evolution the hadronic system freezes, and the particle fill out the phase space according to statistical distribution. The particles form a 'soup' of both stable hadrons, as well as hadronic resonances, which later decay, increasing significantly the yields of stable particles. In addition, the system expands, i.e., undergoes longitudinal and transverse flow, which is an important phenomenon in heavy-ion collisions, distinguishing them from elementary hadronic collisions.

We note that statistical hadronization programs [12–18] require a very detailed input of the hadronic spectrum, and definitions of the subsequent cascading decays of hadron resonances. Tacit assumptions can make a difference of physical significance in the outcome of the analysis. In addition, some information is not available for relevant resonances and has to be assessed by using the current hadron structure knowledge, in particular regarding particle degeneracy and decay patterns. We have excluded from consideration all so called single-* resonances, and practically all double-** resonances seen in particle data book [2]. The double-** resonances we accept are those

where the discovery record is convincing, but a confirmation experiment not available. An example are Ω -resonances, see comment on $\Omega(2470)$ in [2].

The statistical hadronization approach to describe particle yields arises naturally when considering a pot of boiling quark–gluon soup: hadrons evaporate with an abundance corresponding to the accessible phase space. The quark-chemical equilibrium in the pot implies that the evaporated hadrons are near, but in general not at their chemical equilibrium. For the dynamically evolving fireball of quark–gluon plasma, a similar situation arises should the QGP fireball undergo sudden hadronization in the final stages of its evolution [19]. In this case QGP breaks rapidly into ever smaller drops of matter, ultimately consisting of individual elementary hadronic particle species. The statistical particle production model also applies in the opposite limit of a very slow hadronization process [20, 21], assuming that there is time for diverse hadronic particles to be produced and destroyed in a chemical (re)equilibration process.

2 Statistical models in a capsule

The statistical models we are concerned with have the following main physical ingredients:

- Particle abundances at chemical freeze-out,
- Resonance decays.

For the details of different statistical approaches the reader is referred to Refs. [22–37].

2.1 Statistical particle distributions

The densities of particle species i are given by the Fermi-Dirac or Bose-Einstein distribution functions

$$n(m_i, g_i; T, \Upsilon_i) \equiv n_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\Upsilon_i^{-1} \exp(\sqrt{p^2 + m_i^2}/T) \pm 1},$$
 (3)

$$= \frac{g_i}{2\pi^2} \sum_{n=1}^{\infty} (\mp)^{n-1} \Upsilon_i^n \frac{T m_i^2}{n} K_2 \left(\frac{nm_i}{T}\right). \tag{4}$$

The second form, Eq. (4), expresses the momentum integrals in terms of the modified Bessel function K_2 . This form is practical in the numerical

calculations and is used in the Fortran code. The series expansion (sum over n) converges when $\Upsilon_i e^{-m_i/T} < 1$. Consideration of this condition is required only for the pion case in the range of parameters of interest. In Eq. (4), the upper signs refer to fermions and the lower signs to bosons, respectively. Υ_i is the fugacity factor, and m_i is the particle mass. The quantity $g_i = (2J_i + 1)$ is the spin degeneracy factor as we distinguish all particles according to their electrical charge and mass. The index i labels different particle species, including hadrons which are stable under strong interactions (such as pions, kaons, nucleons or hyperons) and hadron which are unstable (ρ mesons, $\Delta(1232)$, etc.).

In the most general chemical condition ¹, the fugacity is defined through the parameters $\lambda_{I_3^i}$, λ_q , λ_s , λ_c (expressing, respectively, the isospin, light, strange and charm quark fugacity factors), and γ_q , γ_s , γ_c (expressing the light, strange and charm quark phase space occupancies, = 1 for absolute yield equilibrium). The fugacity Υ_i is then given by:

$$\Upsilon_{i} = \lambda_{I_{2}^{i}} \left(\lambda_{q} \gamma_{q} \right)^{N_{q}^{i}} \left(\lambda_{s} \gamma_{s} \right)^{N_{s}^{i}} \left(\lambda_{c} \gamma_{c} \right)^{N_{c}^{i}} \left(\lambda_{\bar{q}} \gamma_{\bar{q}} \right)^{N_{\bar{q}}^{i}} \left(\lambda_{\bar{s}} \gamma_{\bar{s}} \right)^{N_{\bar{s}}^{i}} \left(\lambda_{\bar{c}} \gamma_{\bar{c}} \right)^{N_{\bar{c}}^{i}}, \tag{5}$$

where

$$\lambda_q = \lambda_{\bar{q}}^{-1}, \qquad \lambda_s = \lambda_{\bar{s}}^{-1}, \qquad \lambda_c = \lambda_{\bar{c}}^{-1},$$
 (6)

and

$$\gamma_q = \gamma_{\bar{q}}, \qquad \gamma_s = \gamma_{\bar{s}}, \qquad \gamma_c = \gamma_{\bar{c}}.$$
(7)

Here, N_q^i , N_s^i and N_c^i are the numbers of light (u,d), strange (s) and charm (c) quarks in the ith hadron, and $N_{\bar{q}}^i$, $N_{\bar{s}}^i$ and $N_{\bar{c}}^i$ are the numbers of the corresponding antiquarks in the same hadron.

In the case of the models of Refs. [12, 13, 29], where the chemical potentials for the conserved quantum numbers are considered assuming chemical equilibrium ($\gamma_q = \gamma_s = 1$) and absence of charm ($N_c^i = N_{\bar{c}}^i = 0$) one has

$$\Upsilon_i^{\text{eq}} = \exp\left(\frac{B_i \mu_B + S_i \mu_S + I_3^i \mu_{I_3}}{T}\right),\tag{8}$$

where B_i , S_i , and I_3^i are the baryon number, strangeness, and the third component of the isospin of the *i*th particle, and μ 's are the corresponding chemical potentials. In this case, the two formulations are related by

¹This condition is commonly called chemical non-equilibrium. However, the conventional equilibrium in which existent particles are redistributed according to chemical potentials is maintained here. The non-equilibrium regarding particle production is, in precise terms, called absolute chemical (non)equilibrium.

equations:

$$\lambda_a^{\text{eq}} = e^{\mu_B/3T},\tag{9}$$

$$\lambda_s^{\text{eq}} = e^{(-3\mu_s + \mu_B)/3T},$$
 (10)

$$\lambda_{I_3^i}^{\text{eq}} = \lambda_{I_3^i} = e^{I_3^i \mu_{I_3}/T}.$$
 (11)

The user is free to input either format for all of the three chemical potentials $(\mu_B, \mu_S, \mu_{I_3})$ or fugacities $(\lambda_q, \lambda_s, \lambda_{I_3})$ (see section 3.1 for details). All quantities are automatically converted into fugacities for calculations and fits, however both chemical potentials and fugacities are presented in the output of the program.

2.2 Resonance decays

In the first instance, we consider hadronic resonances as if they were particles with a given well defined mass, e.g., their decay width is insignificant. All hadronic resonances decay rapidly after freeze-out, feeding the stable particle abundances. Moreover, heavy resonances may decay in cascades, which are implemented in the algorithm where all decays proceed sequentially from the heaviest to lightest particles. As a consequence, the light particles obtain contributions from the heavier particles, which have the form

$$n_1 = b_{2\to 1} \dots b_{N\to N-1} n_N,$$
 (12)

where $b_{k\to k-1}$ combines the branching ratio for the $k\to k-1$ decay (appearing in [2]) with the appropriate Clebsch–Gordan coefficient. The latter accounts for the isospin symmetry in strong decays and allows us to treat separately different charged states of isospin multiplets of particles such as nucleons, Deltas, pions, kaons, *etc.* For example, different isospin multiplet member states of Δ decay according to the following pattern:

$$\Delta^{++} \to \pi^+ + p, \tag{13}$$

$$\Delta^+ \to \frac{1}{3}(\pi^+ + n) + \frac{2}{3}(\pi^0 + p),$$
 (14)

$$\Delta^0 \to \frac{1}{3}(\pi^- + p) + \frac{2}{3}(\pi^0 + n),$$
 (15)

$$\Delta^- \to \pi^- + n. \tag{16}$$

Here, the branching ratio is 1 but the Clebsch–Gordan coefficients introduce another factor leading to the effective branching ratios of 1/3 or 2/3, where appropriate.

For two-body strong decays (such as the example shown above), the Clebsch–Gordan coefficients are automatically calculated by the program. In this case, the branching ratio taken from [2] is the only input in the program. For three-body decays, the products of the Clebsch–Gordan coefficients have been averaged, with equal weights, over all possible couplings between the three isospins. The result of this procedure has been used to rescale the branching ratio taken from [2], and the effective branching ratio has been obtained in this way, which is delivered as the input.

The case of $\Delta \longrightarrow \pi N$ is easy to deal with, since only one decay channel is present and the branching ratio is well known. However, in most of the cases, we take into account several decay channels appear. We note that the partial widths (product of branching ratio with total width) are not sufficiently well known. In our approach we disregard, as a rule, all decays with the branching ratios smaller than 1%. In addition, if the decay channels are classified as dominant, large, seen, or possibly seen, we always take into account the most important channel. If two or more channels are described as equally important, we take all of them with the same weight. For example $f_0(980)$ decays into $\pi\pi$ (according to [2] this is the dominant channel) and $K\overline{K}$ (according to [2] this is the seen channel). In our approach, according to the rules stated above, we include only the process $f_0(980) \longrightarrow \pi\pi$. Similarly, $a_0(1450)$ has three decay channels: $\eta\pi$ (seen), $\pi\eta'(958)$ (seen), and KK (again seen). In this case, we include all three decay channels with the weight (branching ratio) 1/3. Certainly this procedure is not unique and other methods of selection/treatment of the decays are conceivable.

Another difficulty is that the branching ratios are not given exactly (instead of one value, the whole range of acceptable values is given) and the sum of the branching ratios may differ significantly from 1. In this case we take the mean values of the branching ratios. Since we require that their sum is properly normalized, sometimes we are forced to rescale all the mean values in such a way that their sum is indeed 1. Of course, a different convention from ours can be implemented by the user through a different particle data input file.

Weak decays (identified by the fact that they break strangeness and isospin) are stored separately, and added to the ratios with a feed-down correction set by the user. However, electromagnetic decays such as $\Sigma^0 \to \Lambda + \gamma$

are counted as if it were hadronic in the contribution to the yield of Λ (and the antiparticle).

2.3 Finite resonance width

If the particle i has a finite width Γ_i , the thermal yield of the particle is more appropriately obtained by weighting Eq. (3) over a range of masses to take the mass spread into account:

$$\tilde{n}_i^{\Gamma} = \int dM \, n(M, g_i; T, \Upsilon_i) \frac{1}{2\pi} \frac{\Gamma_i}{(M - m_i)^2 + \Gamma_i^2/4} \to n_i, \quad \text{for } \Gamma_i \to 0. \quad (17)$$

The use of the Breit-Wigner distribution with energy independent width means that there is a finite probability that the resonance would be formed at unrealistically small masses. Since the weight involves a thermal distribution $n(M, g_i; T, \Upsilon_i)$ which would contribute in this unphysical domain, one has to use, in Eq. (17), an energy dependent width.

The dominant energy dependence of the width is due to the decay threshold energy phase space factor, dependent on the angular momentum present in the decay. The explicit form can be seen in the corresponding reverse production cross sections [38,39]. The energy dependent partial width in the channel $i \to j$ is to a good approximation:

$$\Gamma_{i\to j}(M) = b_{i\to j}\Gamma_i \left[1 - \left(\frac{m_{ij}}{M}\right)^2 \right]^{l_{ij} + \frac{1}{2}}, \quad \text{for} \quad M > m_{ij}.$$
 (18)

Here, m_{ij} is the threshold of the decay reaction with branching ratio $b_{i\to j}$. For example for the decay of $i := \Delta^{++}$ into $j := p + \pi^+$, we have $m_{ij} = m_p + m_{\pi^+}$, while the branching ratio is unity and the angular momentum released in decay is $l_{ij} = 1$. From these partial widths the total energy dependent width arises,

$$\Gamma_i \to \Gamma_i(M) = \sum_j \Gamma_{i \to j}(M).$$
 (19)

For a resonance with width, we thus have replacing Eq. (17):

$$n_i^{\Gamma} = \frac{1}{N_i} \sum_{i} \int_{m_{ij}}^{\infty} dM \, n(M, g_i; T, \Upsilon_i) \frac{\Gamma_{i \to j}(M)}{(M - m_i)^2 + [\Gamma_i(M)]^2 / 4}, \tag{20}$$

and the factor N (replacing 2π) ensures the normalization:

$$N_{i} = \sum_{j} \int_{m_{ij}}^{\infty} dM \frac{\Gamma_{i \to j}(M)}{(M - m_{i})^{2} + [\Gamma_{i}(M)]^{2}/4}.$$
 (21)

In principle, Eq. (20) does not take into account the possibility that the state into which one is decaying is itself a unstable state in a thermal bath. Doing this would require a further average over the width distribution of receiving state. We will not implement here this refinement.

The evaluation of the Breit–Wigner integral requires additional attention. The presence of the thermal distribution limits the integral range in Eq. (17) and thus the integral is finite and well behaved. However, it involves in general diverse cases of both very narrow, $\Gamma \ll m$, and wide, $\Gamma \simeq m$, resonances. To perform the integral reliably and precisely in all of these cases we split it in two parts, $\int_{m_{ij}}^{\infty} = \int_{m_{ij}}^{m_0+2\Gamma} + \int_{m_0+2\Gamma}^{\infty}$. The first part can be securely done using, e.g., Gaussian integration. The second part, with a potentially slowly falling tail, can be computed through a variable change $z = \frac{(m_0+2\Gamma)}{M}$ before the numerical integration.

Calculating widths adds considerably to the computation time. It should be noted that Eq. 3 is in the form of K_2 functions depending on temperature and mass, weighted by coefficients representing chemical potentials. The expensive width integrals, therefore, only have to be recalculated when the temperature under consideration changes. The program takes advantage of this in its fitting algorithm, something which can dramatically increase fitting time. See section 3.7 for details.

3 SHARE structure

SHARE is a modular program, whose basic structure is illustrated in Fig. 1. Five input data files are required, containing model and experimental data. There is a calculational and a fitting block, piloted by instructions which the program reads from a running file (called sharerun.data). Each command will generally be performed independently from the others, and generate its own output in a separate file.

Any user defined file names of specified length can be used for all input files except sharerun.data, but the defaults are:

thermo.data (11 letter filename),

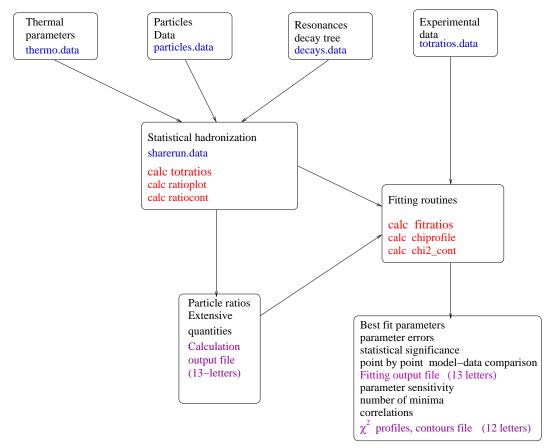


Figure 1: Structure of the SHARE package. Running commands which can be given are in red, default input filenames are in blue, while possible output files are in violet (color online). All output filenames are set by the user

```
particles.data (14 letter filename),
decays.data (11 letter filename),
totratios.data (14 letter filename),
ratioset.data (13 letter filename).
```

These deal, respectively, with initial thermal parameters defining the beginning of the fit procedure, particle properties, decay patterns, and the particle ratios (Math SHARE uses particles.data and decays.data only). These input files are described in detail in the next subsections. It is possible to insert comments into all of these files: any time the first character starts with '#', the subsequent input is disregarded (CAUTION: For Math SHARE a comment line must include at least one more word after '#', e.g., '# This is a comment').

3.1 Thermal parameter input (11 letter filename, default name: thermo.data)

The thermo.data file contains input temperature and chemical potentials. Where applicable, all units are GeV. A sample is given in Table 1.

ag	value	explanation (not part of file)
$_{\text{temp}}$	0.165	temperature
mu_b	0.028	light quark fugacity or chemical potential
mu_s	0.006	strange quark fugacity or chemical potential
gamq	1.	light quark phase space occupancy
gams	1.	strange quark phase space occupancy
lmi3	-0.001	I_3 fugacity or chemical potential
norm	1.	$absolute \ normalization$
lamc	1.	charm quark fugacity
gamc	0.001	charm quark phase space occupancy
accu	0.001	calculations accuracy

Table 1: A typical thermal input file

Chemical potentials can be input as $\lambda's$ and $\gamma's$, Eqs. (5)–(7), or as $\mu's$, Eqs. (8)–(10). If the tag is, respectively, 'mu_b', 'mu_s' or 'mui3' the program assumes input is given as in Eqs. (5)–(7) otherwise Eqs. (8)–(10) are assumed.

The 4-letter tags given in the file are used throughout the program to label the corresponding thermodynamic parameters (fitting variables, arguments for profiles and contour plots, *etc*).

3.2 Particle properties data file (14 letter filename, default name: particles.data)

This input file contains information about the properties of particles such as: mass, width, spin, isospin, the quark contents, and the Monte-Carlo identification number. The data file is written in the following format

name mass width spin I I3 $\mathbf q$ s $\mathbf a\mathbf q$ as $\mathbf c$ ac MC where:

```
name — a nine-letter character string identifying the particle,
```

 $\mathbf{mass} \quad -- \ \mathrm{mass} \ \mathrm{in} \ \mathrm{GeV},$

width — width in GeV,

 $\mathbf{spin} \quad -\mathrm{spin},$

 $\mathbf{I} \qquad \quad -\mathrm{isospin},$

I3 — 3rd component of isospin,

q, **s** — number of light/strange quarks,

aq, as — number of light/strange antiquarks,

c, ac — number of charm/anticharm quarks,

MC — particle's identification number, usually (where applicable) corresponding to the standard Monte-Carlo particle identification convention [2].

For example, the $\Delta(1232)^{++}$ will appear in the input file as

Dl1232plp 1.2320000 0.1200000 1.5 1.5 1.5 3 0 0 0 0 0 2224

The quark number can be a non-integer, to accommodate strong interaction flavor mixing such as that of the η . Note that SHARE calculations are relevant for a strongly interacting system, where the relevant states are K^0 and $\overline{K^0}$. $K^0 - \overline{K^0}$ mixing is an electroweak process, occurring on a longer timescale, and should be implemented at the end of the calculation.

Several versions of this input file are available, described in detail in section 6.1

Our particle naming convention is to form a 9-letter name through a lettersmass-ending combination (e.g., Lm1115zer for Λ), with the following usual three letter endings

```
for Zero
zer
zrb
          for Zerobar
plu
          for plus
plb
          for plusbar
          for minus
min
          for minusbar
mnb
plp
          for plusplus
ppb
          for plusplusbar
\mathbf{sht}
          for particle with this ending sht = \frac{1}{\sqrt{2}} (zer+zrb)
       e.g., K0492sht for K_S = \frac{1}{\sqrt{2}}(K_0 + \overline{K_0})
          tot = (zer + zrb)
tot
       e.g., Lm1115tot for \Lambda + \overline{\Lambda}
          mnt = (min + mnb)
       e.g., UM1321mnt for \Omega + \Omega
          pmb = (plu+plb)
       e.g., pr0938pmb for p + \overline{p}
          plm = (plu + min)
plm
       e.g., Xi1321plm for \Xi^+ + \Xi^-
```

These conventions will be assumed also when fitting particle ratios and/or yields (see section 3.4 for details)

3.3 Particle decay pattern data file (11 letter filename, default name: decays.data)

This input file contains the information on particle decays. The data file lines are here written in the format:

 $Name_{parent} \ Name_{daughter1} \ Name_{daughter2} \ Name_{daughter3}^2 \ BR \ C-G?(0/1)$

where **BR** refers to the branching ratio of this decay (without the Clebsch–Gordan factor, as it appears in the data book) and C–G refers to whether

²Where applicable.

the branching ratio should be completed by a Clebsch–Gordan coefficients (0: no, 1: yes). For instance, the decays $\Delta^+ \to \pi^+ + n$ and $\Delta^+ \to \pi^0 + p$ will be given as (compare Eqs. (13)–(16)):

```
Dl1232plu pi0139plu ne0939zer 1.0 1
Dl1232plu pi0135zer pr0938plu 1.0 1
```

while η decays will be (see discussion in Sect. 2.2):

```
eta547zer
           gam000zer
                        gam000zer
                                                  0.3943
                                                          0
eta547zer
           pi0135zer
                                     pi0135zer
                                                  0.3251
                        pi0135zer
                                                          0
eta547zer
           pi0139plu
                        pi0139min
                                     pi0135zer
                                                  0.226
                                                           0
eta547zer
           pi0139plu
                                                  0.0468
                                                          0
                        pi0139min
                                     gam000zer
```

3.4 (Experimental) Values to be calculated (14-letter filename, default file: totratios.data)

Experimental data values of interest are submitted in in the following format.

3.4.1 Particle ratios

When considering the particle ratio evaluation: name1 name2 data random systematic fit?(-1/0/1/2)

where

name1 The first particle in the ratio (numerator)

name2 The second particle in the ratio (denominator. Can also be a tag indicating the quantity is not a ratio but a yield or a density)

data The experimental value of the data point

random The random (statistical) error

systematic The systematic error

fit? This ratio contributes to the evaluation of χ^2/N_{DoF} if this parameter is set to 1 or 2. If the parameter is set to 0, the ratio is not fitted, but calculated and output to the graph file (see cards in section 4 for details). if fit = -1 or 2 means the ratio is not output to the graph file.

Exact					
etstrang Approxima	solvelams ate	0.	0.0001	0.	2
netstrang	totstrang	0.	0.0001	0.	2
Weak decay		K_S->pi		Y->pi,K	Y->N
weakdecay	•	0.0	0.00	0.0	1.00
reakdecay		0.0	0.00	0.0	1.00
ratio	 ratio		• • • • • • • • • •		
	denominator	yield	star. eri	s. sys. err.	Fit?
i1321min	pi0139min	0.0093	0.002	0.	1
	pi0139min	0.0080	0.0017	0.	1
	Xi1321min	0.8530	0.1000	0.	1
	Xi1321mnt	0.1438	0.035	0.	1
	Lm1115zer	0.1870	0.460	0.	1
	Lm1115zrb ph1020zer	0.2150 0.3400	0.5400 0.070	0. 0.	1 1
	Lm1115zer	0.74	0.05	0.	1
	pi0139min	0.181	0.025	0.	1
a0492plu	*	0.201	0.025	0.	1
Weak decay			K_L->pi	Y->pi,K	Y->N
reakdecay	top	0.5	0.00	0.5	1.00
eakdecay	bottom	0.5	0.00	0.5	1.00
	pr0938plu	2.4	0.5	0.	1
	pr0938plb	3.0	0.5	0.	1
r0938plb	pr0938plu	0.71	0.06	0.	1
STAR		- K+/K-	Both expe	riments	
a0492plu	Ka0492min	1.103	0.025	0.	1
PHENIX Ka0492plu					
maaaaptu	Ka0492min	1.153	0.040	0.	1
:			0.040	0. 	1
: :	RE	SONANCES -		0. 0.	1 0
 m1520zer	RE RE Lm1115zer	SONANCES -	0.01		
= =	RE Lm1115zer pi0139min	SONANCES -		0.	0
m1520zer ho770zer 00980zer	Lm1115zer pi0139min pi0139min Ka0492min	SONANCES - 0.022 0.1	0.01 0.02	0.	0 1
m1520zer cho770zer c00980zer (a0892zer	Lm1115zer pi0139min pi0139min Ka0492min	SONANCES - 0.022 0.1 0.02 0.24	0.01 0.02 0.01 0.01	0. 0. 0. 0.	0 1 1 1
m1520zer rho770zer 500980zer Ka0892zer Weak decay	Lm1115zer pi0139min pi0139min Ka0492min	SONANCES - 0.022 0.1 0.02 0.24 	0.01 0.02 0.01 0.01 K_L->pi	0. 0. 0. 0. V->pi,K	0 1 1 1 1 Y->N
m1520zer rho770zer 600980zer 620892zer 	Lm1115zer pi0139min pi0139min Ka0492min y scheme top	SONANCES - 0.022 0.1 0.02 0.24 K_S->pi 0.50	0.01 0.02 0.01 0.01 0.01 K_L->pi 0.00	0. 0. 0. 0. 0. Y->pi,K 1.00	0 1 1 1 1 Y->N 0.00
m1520zer rho770zer 600980zer 630892zer Weak decay weakdecay	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom	SONANCES - 0.022 0.1 0.02 0.24 	0.01 0.02 0.01 0.01 K_L->pi	0. 0. 0. 0. V->pi,K	0 1 1 1 1
m1520zer cho770zer co980zer ka0892zer Weak decay reakdecay	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom	SONANCES - 0.022 0.1 0.02 0.24 K_S->pi 0.50 0.50	0.01 0.02 0.01 0.01 0.01 K_L->pi 0.00	0. 0. 0. 0. 0. Y->pi,K 1.00	0 1 1 1 1
m1520zer cho770zer c00980zer ca0892zer dweak decay reakdecay reakdecay ch1020zer	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom Ka0892min	SONANCES - 0.022 0.1 0.02 0.24 K_S->pi 0.50 0.50	0.01 0.02 0.01 0.01 K_L->pi 0.00 0.00	0. 0. 0. 0. 0. Y->pi,K 1.00	0 1 1 1 1 Y->N 0.00 0.00
m1520zer cho770zer c00980zer sa0892zer weak decay reakdecay cakdecay cakdecay cakdecay cakdecay	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom Ka0892min pr0938plu	SONANCES - 0.022 0.1 0.02 0.24 K_S->pi 0.50 0.50	0.01 0.02 0.01 0.01 K_L->pi 0.00 0.00	0. 0. 0. 0. 0. Y->pi,K 1.00 1.00	0 1 1 1 1 Y->N 0.00 0.00
m1520zer rho770zer 600980zer 600980zer i Weak decay reakdecay reakdecay reakdecay reakdecay reakdecay reakdecay reakdecay reakdecay	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom Ka0892min pr0938plu ions (NOT fit	SONANCES - 0.022	0.01 0.02 0.01 0.01 K_L->pi 0.00 0.00 0.24 0.037	0. 0. 0. 0. V->pi,K 1.00 1.00	0 1 1 1 1 Y->N 0.00 0.00
m1520zer cho770zer congresses weak decay weakdecay weakdecay ch1020zer ch11232plp ch232plp ch232plp	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom Ka0892min pr0938plu ions (NOT fit	SONANCES - 0.022	0.01 0.02 0.01 0.01 0.01 K_L->pi 0.00 0.00 0.24 0.037	0. 0. 0. 0. 1.00 1.00	Y->N 0.00 0.00 0.00
Lm1520zer cho770zer conyenter conyen	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom Ka0892min pr0938plu ions (NOT fit Xi1321min Xi1321min	SONANCES - 0.022 0.1 0.02 0.24 K_S->pi 0.50 0.50 0.595 0.24 ted) 0.64403 0.1802	0.01 0.02 0.01 0.01 0.01 K_L->pi 0.00 0.00 0.24 0.037	0. 0. 0. 0. 0. Y->pi,K 1.00 1.00	Y->N 0.00 0.00 0.00 0.00
tm1520zer rho770zer rho770zer f200980zer ka0892zer t tWeak decay weakdecay the control of the control the contro	Lm1115zer pi0139min pi0139min Ka0492min y scheme top bottom Ka0892min pr0938plu ions (NOT fit	SONANCES - 0.022	0.01 0.02 0.01 0.01 0.01 K_L->pi 0.00 0.00 0.24 0.037	0. 0. 0. 0. 1.00 1.00	Y->N 0.00 0.00 0.00

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Figure 2: A typical totratios.data file

3.4.2 Particle yields and source properties

The entries in this files have a second use when name1 and name2 are not particle names but are as follows:

In case **name2** is:

prt_yield the yield of the first particle or collective quantity. **prdensity** the density of the first particle or collective quantity (in fm^{-3}). **solveXXXX** See section 3.6

In case **name1** is:

```
negatives All negative particles stable under the strong interaction totstrang strangeness^3 \langle s \rangle netstrang net strangeness \langle s - \bar{s} \rangle totenergy energy (in GeV) totbaryon sum of all baryons and antibaryons, B + \overline{B} netbaryon net baryon number, i.e., baryons minus antibaryons, B - \overline{B} totcharge charge Q netcharge net charge \langle Q - \overline{Q} \rangle entropy_t entropy S
```

We provide several data files as an example, described in section 6.1

3.4.3 Weak decay feed-downs

All weak decays are included with the provided SHARE decay tree input files. They are identified as weak by the program due to the violation of strangeness and isospin within the decay. Weak decays present additional complications, since their reconstruction acceptance is usually non-trivial and experiment-specific.

SHARE therefore, includes additional parameters, set by the user, to regulate the acceptance of these decays. These parameters are read in from the same file as the experimental data points, and have approximately the same format.

³For this and the subsequent quantities, volume normalization can be correct only when total particle yields are considered. The units of the calculated result vary according to whether the quantity is a density, a yield or a ratio

A statement specifying weak decay feed-downs has the form weak decay Tag F_1 F_2 F_3 F_4 Where:

Tag specifies weather the coefficients refer to the numerator or denominator of the ratio (note that they are often different, e.g. in a ratio such as Ξ/h^-). If the user is setting the numerator feed-down coefficients, tag is set to "top". In case of the denominator, tag is set to "bottom".

 F_{1-4} are four numbers, specifying the weak feed-down coefficients.

- F_1 refers to the acceptance of π from $K_S \to \pi\pi$ decays. It is by default set to 0.5
- F_2 refers to the acceptance of π from $K_L \to \pi\pi\pi$ decays. It is typically very small, so it is by default set to 0
- F_3 refers to the acceptance of mesons from weak hyperon decays. It is by default set to 0.25
- F_4 refers to the acceptance of baryons from weak hyperon decays. It is by default set to 1.

It is possible to specify a different feed-down for each data-point, by preceding a data line with "weakdecay" statements, eg:

```
weakdecay
             top
                        1.0
                             0.0
                                   0.3
                                        0.8
weakdecay
             bottom
                        0.0
                             0.0
                                   0.5
                                        0.8
            negatives 0.2 0.05
                                   0.
Xi1321mnt
                                         1
```

It is also possible to specify one weak feed-down for a series of data points, or all the datapoints analyzed; The program assumes all data points after a "weakdecay" statement to have the same value until a new "weakdecay" statement is encountered. For example,

```
weakdecay
                         1.0
                               0.0
                                      0.3
                                           0.8
             top
weakdecay
             bottom
                         0.0
                               0.0
                                      0.5
                                           0.8
Xi1321mnt
            negatives
                         0.2
                               0.05
                                     0.
                                           1
            pr0938plu 0.15
                               0.05
                                     0.1
Lm1115zer
```

fixes the feed-down for both Ξ/h^- and Λ/p ratios. (In this case, of course, three of the four feed-down coefficients will have no effect on the second data-point)

3.5 Fit parameters (13 letter filename, default name: ratioset.data)

The ratioset.data file defines the parameters which will be varied during the fit or kept constant. It further contains the limits to be used in the fit (for the use of MINUIT), as well as the initial step size. The typical format is:

tag	lower /	upper limit	step size	fit? $(0/1)$
temp	0.	1.	0.01	1
lamq	0.	10.	0.1	1
lams	0.	10.	0.1	1
gamq	0.	10.	0.01	1
gams	0.	10.	0.1	1
mui3	0.	10.	0.2	1
norm	0.	10000.	0.3	0
lamc	0.	10.	0.1	0
gamc	0.	10.	0.1	0

If the lower and upper limit are equal, MINUIT will fit with no limits. If the only fit parameters are particle ratios and densities, the normalization is automatically kept fixed. The parameters can be input in any order. We have found that the fit quality (speed, reliability) depends considerably on the order of parameter input which is retained calling the MINUIT package: firstly, the most significant fit parameters should be input first (temp, norm). Secondly, the highly correlated parameters should be placed next to each other.

Note that values of parameters also arise as result of conservation laws rather than from fits to particle yields. For example, λ_s can be computed in terms of the other parameters requiring overall strangeness conservation within the phase space domain covered by the results considered. λ_{I_3} is similarly determined via the participant matter proton-neutron ratio, however, here it is possible to use this only when the data is available in 4π acceptance, since other hadrons can buffer the balance of charge condition. For example, at RHIC in the central rapidity region the large number of pions implies in effect nearly symmetric $\lambda_{I_3} = 1$. Also, μ_B can be fixed through the participant number in the phase space region observed. The next section describes how SHARE allows the user to implement these constraints either by solving the constraints (numerically) or by a fit.

3.6 Implementing conservation laws

SHARE allows the user to solve for a fit parameter, rather than to find its value through a fit. For instance, it is possible to implement strangeness conservation by solving numerically the constraint equation

$$\langle s - \overline{s} \rangle = 0 \tag{22}$$

for λ_s . In this case, λ_s is not a fit parameter anymore, but rather an analytical function of the other fit parameters and experimental particle yields.

To solve for a fit parameter, **name2** in the totratios.data file should be of the form **solveXXXX** where XXXX corresponds to the parameter for which one wants to solve. The parameter limits are still used by the program, as a constraint solution outside the limits is rejected. This is useful for rejecting unphysical solutions of the constraint equation, such as $\lambda_s < 0$.

It is, in principle, possible to solve any data point for any thermal parameter. However, many such combinations do not have minima to which the equations converge nicely. If this is the case with a lot of MINUIT iterations, it is unlikely that the minimization procedure will work.

It is therefore recommended that the solving algorithm only be used to solve for chemical potentials from conservation laws. For instance, to ensure strangeness conservation through solving for λ_s the input file should contain the following line:

netstrang solvelams 0. 0. 0. 0. 0. 0

A line solving for λ_q from baryon conservation in case of Pb-Pb collisions might be

netbaryon solvelamq 362. 0. 0. 0. 0. 0

and the corresponding charge conservation statement will be

netcharge solvelmi3 142. 0. 0. 0. 0. 0

Note that it is also possible to implement conservation laws in terms of particle ratios. The two lines

netbaryon solvenorm 362. 0. 0. 0. 0. 0

netcharge solvelamq 142. 0. 0. 0. 0. 0

will fix λ_q in terms of the baryon/charge $(\frac{B}{Q} = \frac{p+n}{p} = 0.44$ for Pb-Pb) ratio even when the absolute normalization **norm** is a dummy variable which appears in no other data point and is not used in the fit.

The alternative to exact solving is to implement a conservation law by treating it as a data point. A line such as

netbaryon prt_yield 362. 10. 0. 0. 0. 1

will make sure that the baryon number is close to the one expected for Pb-Pb collisions at SPS. Similarly,

netstrang totstrang 0. 0.01 0. 0. 0. 1

will make conserve strangeness to one unit in $100 \, \overline{s}$ pairs, rather than solving the constraint exactly.

The choice of whether to implement the conservation law analytically or through a fit is therefore left to the user. It was found that both approaches are giving very similar results. However the most reliable approach is to use the exact constraint only.

solve statements should be put at the top of the experimental ratios file. If this is not done, the program returns with an error.

3.7 Fitting strategies

Multi-parameter fits can be very time-consuming, and occasionally give the wrong answer when a "false" (i.e., local rather than absolute) minimum is found. If these minima are close enough, MINUIT's error and contour calculations fail to converge convincingly. If this is the case, a warning message is printed in the minimization output file.

The user should make note of a few simple rules which can dramatically decrease the fitting time, and enhance the probability that the right minimum is found.

- Appropriate calibration of the step size and limits can:
 - dramatically decrease the running time for the case that the user already knows a good estimate of the minimum,
 - select the appropriate minimum if several minimal points are present in the parameter space. Certain datasets analyzed in the literature present three minimal points: at equilibrium, at $\gamma_q > 1$, and $\gamma_q < 1$ [18].
- Fitting absolute yields is more difficult (prone to converge to a false minimal points or spend very long time finding a minimum), as the yield normalization strongly correlates with other parameters of the fit. Especially with a limited experimental data set it is not always easy to distinguish a hot, dense and small fireball from a colder, more

- dilute larger one using yields alone. It is therefore advisable to convert all data points to ratios.
- Inclusion in the fit of extensive fireball properties, which require a sum over every hadron, considerably increase the running time. This is especially true for energy (density), pressure and entropy (density), which require the Bessel function evaluation to be redone for every hadron at each iteration step. It is therefore suggested that the experimental file used for the fit not contain these quantities: They can be calculated after the fit in a single pass evaluation, with the fitted parameters as input, using modified input files. The provided experimental input files (see section 6.1) contain the thermodynamic quantities used in a typical fit (total baryon number, strangeness and charge). We also provide an input file (totratext.data) devoted exclusively to thermodynamic quantities.
- The more variable parameters a fit has, the more minimal points are likely. In case of a particularly difficult fit, it is suggested it be completed in two stages: An initial fit with only temperature and normalization as varying parameters, followed by a subsequent fit, starting from the previously found minimum, where the remaining parameters are released (the sharerun.data provided with the program is based on this strategy). Alternatively, the conservation law constraints (for e.g., zero net strangeness, given charge and/or baryon number) can be tightened or relaxed. A χ^2 profile can also be helpful. Generally, a minimum with a χ^2 significantly above expectation signals that the true minimum has not been found.
- Fits with finite resonance widths are much more computationally expensive. However, as explained in section 2.3, the computationally expensive integrals and Bessel functions only have to be recalculated when the temperature is changed. For this reason, a temperature χ^2 profile (which finds the minimum at each value of the temperature parameter, kept fixed throughout each fit. Hence, the temperature only has to be calculated once per datapoint) can be computed much more quickly than a fit in which temperature is a free parameter.

4 Running program cards (sharerun.data)

This file contains the instructions which the program executes on running. Each line corresponds to a different operation, such as reading data files, assigning values to parameters, calculating ratios, minimizing, and plotting contours and χ^2/NDoF profiles. The program will read this file line by line, execute each command, and stop when it reaches the end of the file. Fig. 1 has an example of a typical sharerun data file.

Each command can be used more than once with different input and output files, one at a time. We shall proceed to give a detailed description of each command's meaning and syntax. Keep in mind that 2 spaces have to be maintained between each word or number. The lines have the general form:

PSET <4-letter tag> VALUE

This Parameter SET command sets the thermodynamic variable defined by the TAG (name) to its designated VALUE. The initial command shown in figure 3, READ THERM_INI, comprises a series of PSET-type commands which read from an input file, covering all allowed thermal parameters.

READ THERM_INI <11-letter filename>

Reads the file corresponding to thermo.data, containing the values for the thermal parameters, as described in section 3.1.

READ PARTICLES <14-letter filename> <11-letter filename>

Reads the file containing particle properties as well as the file containing the decay tree, as described in sections 3.2 and 3.3.

READ TOTALDATA <14-letter filename>

Reads the file containing experimental data and particle ratios to calculate, as described in section 3.4.

- **PFIX tag** Fixes the given thermodynamic Parameter to its current value. In a fit, that parameter will not be a variable.
- PREL tag <Lower limit> <Upper limit> <Step size> Releases the given thermodynamic Parameter, giving the limits and initial step size used in the fit. The next command, 'READ FIT_PARAM', can be

⁴The program, being written in FORTRAN, is very sensitive to the file's format. An extra space may cause the sharerun.data file to be unreadable. Hence, it is recommended that the user bases his modifications on the sharerun.data file shown in the Fig. 1.

```
# Reading experimental data
READ TOTALDATA totratios.data
#----- no width (file partnowdt.data), should not take that long
READ PARTICLES partnowdt.data decays.data
# Temperature initialization file (CAN ALSO USE PSET, as in width calculation)
READ THERM_INI thermo.data
READ FIT_PARAM rtonlnrm.data
CALC FITRATIOS fit_junkl.out READ FIT_PARAM ratioset.data
CALC FITRATIOS fit_nwrhi.out
CALC PLOT_DATA graph_nwd.fit graph_nwd.clc graph_nwd.exp
READ TOTALDATA totratext.data
CALC RATIODATA extrhicnw.out
READ TOTALDATA totratios.data
CALC SIGPROFIL prof_T_nowdt temp 0.12 0.18 100 CALC SIGPROFIL profgq_nowdt gamq 0.12 1.80 50
PSET gamq 1.
PSET gams 1.
PFIX gamq
PFIX gams
CALC FITRATIOS fit_nweqi.out
CALC PLOT_DATA graph_neq.fit graph_neq.clc graph_neq.exp
READ TOTALDATA totratext.data
CALC RATIODATA extrhicne.out
READ TOTALDATA totratios.data
CALC SIGPROFIL prof_T_noweq temp 0.12 0.18 100
PREL gams
            0.1 5. 0.02
CALC FITRATIOS fit_rhins.out
CALC PLOT_DATA grphrhins.fit grphrhins.clc grphrhins.exp
READ TOTALDATA totratext.data
CALC RATIODATA ext_rhins.out
READ TOTALDATA totratios.data
CALC SIGPROFIL prof_T_rhins temp 0.09 0.18 10 CALC SIGPROFIL profgs_rhins gams 0.03 1.80 50
                                       0.09 0.18 100
```

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Figure 3: A typical sharerun.data file

understood as a series of PFIX and PREL instructions read from an input file.

READ FIT_PARAM <14-letter filename>

Reads the file containing fit parameters, as described in section 3.5.

CALC RATIODATA <13-letter filename>

Calculates the value of the ratios read with the READ RATIODATA command and the current value of the thermal parameters (obtained either from READ THERM_INI or a previous fit). The output of the calculation is stored with the given filename, as a table in the following format:

RATIO NAM1/NAM2 < numerical value >

CALC RATIOPLOT Datapoint <12-letter Filename> tag L H P

Calculates the ratio of 2 particles, or a particle's yield, or a thermodynamic quantity, as a function of the variable represented by the 4-letter tag, in a parameter segment delimited by the limits (**L,H**) and number of points (**P**). The ratio to be calculated must be in the experimental ratios datafile; datapoint specifies which point to graph (for instance, if datapoint is 2, the second point from the to will be calculated). The output is saved as a 2-column table in the given output file, and can be plotted with packages such as PAW, Mongo or Xmgrace.

CALC RATIOCONT datapoint <12-letter Filename> tag1 L1 H1 P1 tag2 L2 H2 P2⁵

Calculates the ratio of 2 particles, or a particle's yield or density, or a thermodynamic quantity, as a function of two thermodynamic variables represented by the two 4-letter tags, in the parameter region delimited by the limits (**L1,2 H1,2**) and number of points. (**P1,2**. Note that an 100×100 grid has $10\,000$ points, and can take a long time to calculate). The ratio to be calculated is indicated in the same way as in **CALC RATIOPLOT**. The output is saved as a 3-column table in the given output file, and can be plotted with a program capable of 3D plots.

CALC FITRATIOS <13-letter filename>

Minimizes the χ^2/N_{DoF} of the set of experimental data obtained through READ RATIODATA according to the parameters in

READ FIT_PARAM and initial values in

READ THERM_INI. The output is written out to the given filename in the following format:

⁵one line in the file

First, the output parameters (+/- error if fitted).

Then the detailed fit results, as a table with the format:

Top Bottom Theory Experiment Tot. error. Chiterm

Where Top and Bottom refer to each ratio's numerator and denominator, and **Chiterm** for each ratio refers to χ as defined in Eq. 1

$$\chi = \frac{f_{\text{experiment}} - f_{\text{theory}}}{\Delta f_{\text{statistical}} + \Delta f_{\text{systematic}}} (= 0 \text{ if not fitted})$$
 (23)

Finally, the total χ^2/N_{DoF} is presented. A typical output file is shown in Fig. 2

CALC PLOT_DATA <3 13-letter filenames>

Generates three files which are optimized to be graphed by a package such as PAW, Mongo or Xmgrace. The first file has a numerical list of ratios which were fitted, the second, a numerical list of calculated, but not fitted, ratios. The third has the experimental data, including the error bars. See the discussion at the bottom of section 3.4 for details on which ratio gets fitted and which just gets calculated.

CALC CHIPROFIL <12-letter file> tag L H P

This computes a χ^2/N_{DoF} profile of the Parameter designated by tag <Parameter tag> (see the thermal input file for a list), from the L to the H limit (real numbers), with P specifying the number of computed points (integer). The given file will store the main result, as a 2 column table of the parameter value and χ^2/N_{DoF} . The minimum of each of the other parameters for each data point will also be stored in files in which the parameter is appended to the name. For instance, if the T, χ^2/N_{DoF} profile is stored in file 'profTforratio' the minimal points of γ_q across the χ^2/N_{DoF} profile are stored in file 'profTforratio_gamq'.

CALC SIGPROFIL This command is very similar to

CALC CHIPROFIL. However, instead of the χ^2 , the profile for the statistical significance is calculated. The command syntax is identical to CALC CHIPROFIL

CALC CHI2_CONT <9-letter filename> deviation tag1 tag2 Computes a χ^2/N_{DoF} contour of parameters denoted by tag1 and tag2, with a given deviation from the χ^2/DoF minimum (e.g., 1.1 for a $1.1 \times \chi^2_{min}$ contour). The contour is stored in an output file 9 characters long.

4.1 Run log (sharerun.out)

The complete 'log' for each run is saved in the file sharerun.out. This includes:

- The content of each input file (in the same format as read)
- A list of performed operations
- The output from MINUIT
- The content of each output file (in the same format as in the file)

If the program ends without a problem, the message 'PROGRAM TERMI-NATED SUCCESSFULLY' is printed, both on the screen and this file. If an error occurs, the program writes to the screen that an error has occurred, and outputs the details of the error to sharerun.log.

5 Installation

SHARE is distributed in a form of an archive containing source and data files. Running under the Linux operating system is supported presently. We have checked SHARE on FORTRAN in a few Linux installations. In order to run SHARE one needs:

- FORTRAN compiler e.g. g77, f77;
- CERN library
 SHARE needs the CERN Library, in particular MINUIT and the CERN
 mathematical routines library. These can be found on the CERN web site if not installed in current environment.

After unpacking, one needs to compile SHARE using the included shellscript 'fortrat' (which needs to be amended with the correct path to where the CERN libraries are)

6 Organization of the Fortran package

6.1 Directory tree

source code:

sharev1.1.f F77

share1.0.nb mathematica

Data files:

thermo.data Thermal inputs

particles.data Particle datafile — full width

partnowdt.data Particle datafile — no width

decays.data Full decays file

dec_no.data Empty decays file

ratioset.data Minimization settings

rtonlnrm.data Minimization settings with most parameters fixed (used in the course of an intermediate minimization, see section 3.7)

totratios.data Sample input drawn from RHIC data (2004).

totratext.data Sample input with extensive thermodynamic functions

chi2.data Sample input in Mathematica-readable format

sharerun.data running script optimized for RHIC

Shell-scripts:

fortrat Sample compiling shell-script

tarrat Sample archiving shell-script

7 SHARE webpage edition

A reduced version of SHARE is also accessible directly from the web, at the same website from which the program is downloaded. It is possible to submit thermal parameters, and calculate a select table of experimentally relevant ratios and thermodynamic quantities. The webpage can be used as a cross-check between statistical hadronization packages, and for a comparison with experimental data. For full input and calculational versatility, however, we recommend downloading the full version

8 Mathematica version of SHARE

The Mathematica notebook Math SHARE, included in the SHARE distribution, has a similar functionality as the Fortran program but greatly restricted physical scope. It uses the same universal input files as the Fortran, namely particles.data, decays.data, and in addition the file chi2.data. The notebook is designed to perform three types of calculations:

- 1. Run the thermal model for specific thermal parameters T, μ_B , μ_S , and μ_I (in the Mathematica code the γ factors of Sect. 2.1 are set to unity) and determine the particle ratios,
- 2. Fit the thermal parameters to the experimental ratios read from file chi2.data via the χ^2 method,
- 3. Track the feeding of a specified particle from decays of higher states. This shows the physical importance of high-lying states and allows to determine the amount of feeding for a given state.

The installation of Math SHARE requires only setting the path to the data files (the first cell of the notebook). The following modules are particularly useful when running the notebook:

- readpart[fn] reads the particle properties from the file fn and initializes the primordial yields to zero
- decay[fn1] performs the decays according to the file fn1 (CAUTION: these to modules should be always run in sequence, *i.e.*,

... readpart[fn] decay[fn1]

- prop[part] displays the properties of particle part
- prrat[part1,part2] gives the ratio of yields of particles part1 and part2 after the resonances have decayed
- prrat0[part1,part2] gives the ratio of 'primordial' (before the decays) yields of particles part1 and part2

The following flags are used throughout the notebook to control the output and decays:

- listp (False or True) when True, echos the properties of read particles in the readpart module
- describe (False or True) controls the output of the readpart and decay modules. It is recommended to set it to True when running for the first time
- debug (False or True) when True, tests of the input files are performed while running the readpart and decay modules. In particular, a check is made if the decays proceed from the heaviest to the lightest particle (otherwise the DECAY OUT OF SEQUENCE warning is printed), the conservation of the baryon number and the electric charge is checked, and finally, the sum of the branching ratios is printed (of course, it should be equal to 1 within the assumed accuracy). It is recommended to set debug to True when running after modification of the input files.
- yes3b (True or False) when True, three-body decays are included. This is the normal mode. Switching off the three-body decays allows to test their importance
- nomass (True or False) when True, decays into product whose total mass is heavier than the mass of the decaying particle are allowed (!). There are a few decays like this in the Particle Data Tables, where the decaying particle is sufficiently wide. To switch off such decays, set nomass to False
- threshmass (Infinity or number) when Infinity, all decays are included, when set to a number, only particle lighter than threshmass are decayed
- tracking (False or True) when True, tracking of feeding to particle tracklab is made

For convenience, particle labels **negatives** and **positives** are introduced. They include all negative or positive charge ground-state hadrons which are stable with respect to the strong interactions.

Furthermore, we include the weak-decays feeding corrections as done by the STAR collaboration at RHIC. The STAR procedure excludes the feeding of pions from the decays of $\Lambda(1115)$. We define labels of such pions as pi0139pluSTAR or pi0139minSTAR at the end of the decay module. Similar corrections can be defined for other ways of including the weak-decay corrections.

The format of the chi2.data file, containing the experimental information for the fitting, is

part1 part2 ratio stat.err syst.err

More information on how to run Math SHARE is included in comments in the notebook itself.

9 Conclusion

We hope that SHARE will be useful both as an auxiliary tool in the analysis of experimental data and as a benchmark to verify more detailed ideas about the statistical approach to particle production in relativistic heavy-ion collisions. Also, the modules with the particle data and the resonance decays may be useful in their own right and interfaced to other models of particle production. We hope that given the versatility and modular structure of SHARE it will become a useful widely applied tool in study of hadron production in heavy-ion physics.

Acknowledgments

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```
DATE: 20/07/04 TIME: 06.47.04
UNITS: ENERGY IN GeV, DENSITY IN 1/fm^3
                                               0.1000
                                                          0.1800
temp
           0.1373+/-
                          0.0102 limits:
           1.0591+/-
                          0.0439 limits:
                                               1.0000
                                                          10.0000
lamq
      1.02737723
lams
gamq
           1.4294+/-
                          0.6479 limits:
                                               0.1000
                                                          2.1000
gams
           1.8735+/-
                          1.1862 limits:
                                               0.1000
                                                           5.0000
           1.1014+/-
                          0.1457 limits:
                                                          1.2500
                                               0.7500
1mi3
lamc
     1.
gamc
      1.
norm 2481.0208
MU_B, MU_S
            0.0236606956 0.00417839215
        TOP
                 BOTTOM
                              THEORY
                                             EXP
                                                        ERROR
                                                                   CHITERM
   Xi1321min
                pi0139min
                                0.0089
                                             0.0093
                                                         0.0020
                                                                     -0.1954
   Xi1321mnb
                pi0139min
                                0.0074
                                             0.0080
                                                         0.0017
                                                                     -0.3426
   Xi1321mnb
                Xi1321min
                                0.8326
                                             0.8530
                                                         0.1000
                                                                     -0.2043
   UM1672mnt
                Xi1321mnt
                                0.1422
                                             0.1438
                                                         0.0350
                                                                     -0.0443
   Xi1321min
                Lm1115zer
                                0.1453
                                             0.1870
                                                         0.4600
                                                                     -0.0906
   Xi1321mnb
                Lm1115zrb
                                0.1572
                                             0.2150
                                                         0.5400
                                                                     -0.1070
   Xi1321min
                ph1020zer
                                0.3162
                                             0.3400
                                                         0.0700
                                                                     -0.3397
   Lm1115zrb
                Lm1115zer
                                0.7696
                                             0.7400
                                                         0.0500
                                                                      0.5929
   Ka0492min
                pi0139min
                                0.2073
                                             0.1810
                                                         0.0250
                                                                      1.0533
   Ka0492plu
                pi0139plu
                                0.1959
                                             0.2010
                                                         0.0250
                                                                     -0.2053
                pr0938plu
                                2.0164
                                             2.4000
   Ka0492plu
                                                         0.5000
                                                                     -0.7671
   Ka0492plu
                pr0938plb
                                2.9504
                                             3.0000
                                                         0.5000
                                                                     -0.0992
   pr0938plb
                pr0938plu
                                0.6834
                                             0.7100
                                                         0.0600
                                                                     -0.4426
   Ka0492plu
                Ka0492min
                                1.1185
                                             1.1030
                                                         0.0250
                                                                      0.6202
   Ka0492plu
                Ka0492min
                                1.1185
                                             1.1530
                                                         0.0400
                                                                     -0.8623
   Lm1520zer
                                                         0.0100
                                                                      0.0000
                Lm1115zer
                                0.0421
                                             0.0220
                                                         0.0200
                                0.0858
                                             0.1000
   rho770zer
                pi0139min
                                                                     -0.7076
                pi0139min
   f00980zer
                                0.0065
                                             0.0200
                                                         0.0100
                                                                     -1.3547
   Ka0892zer
                Ka0492min
                                0.2424
                                             0.2400
                                                         0.0100
                                                                      0.2413
   ph1020zer
                Ka0892min
                                0.5803
                                             0.5950
                                                         0.2400
                                                                     -0.0611
   D11232plp
                pr0938plu
                                0.2002
                                             0.2400
                                                         0.0370
                                                                     -1.0762
DATA POINTS: 21 PARAMETERS: 5 Dof: 16
TOTAL CHI**2/DEG. OF FREEDOM 0.457254927
SIGNIFICANCE OF FIT:
                        0.966676891
[ (S-SBAR) / (S+SBAR) ] -5.50687837E-17
```

Figure 4: A typical fitratios.out file