SHAREv2: fluctuations and a comprehensive treatment of decay feed-down †

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Abstract

This the user's manual for SHARE version 2. SHARE [1] (Statistical Hadronization with Resonances) is a collection of programs designed for the statistical analysis of particle production in relativistic heavy-ion collisions. While the structure of the program remains similar to v1.X, v2 provides several new features such as evaluation of statistical fluctuations of particle yields, and a greater versatility, in particular regarding decay feed-down and input/output structure. This article describes all the new features, with emphasis on statistical fluctuations.

Keywords: Heavy ion collisions, Statistical models, Fluctuations
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Updates available from: `http://www.physics.arizona.edu/~torrieri/SHARE/share.html` and the authors upon request

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1 Program Summary

Title of the program: `SHAREv2`, April 2006

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`

Size of the package: 167 KB directory, 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.: 25879

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

Computer: Any computer with an f77 compiler

Nature of the physical problem:

For a proper falsification and constraing of models based on statistical mechanics, both particle yields and event-by-event fluctuations have to be taken into account.

Event-by-event Fluctuations have been shown to be both an observable with considerable power both to constrain particle production models and as an indicator of new physics.

As in the case of yields, to properly compare model calculations to data it is necessary to consistently take into account resonance decays.

Event-by-event fluctuations are more sensitive than yields to experimental acceptance issues, and a range of techniques need to be implemented to extract "physical" fluctuations from an experimental event-by-event measurement. Model calculations have to take these experimental techniques into account.

Method of solving the problem:
The techniques used within the SHARE suite of programs [1] are updated and extended to fluctuations. A full particle data-table, decay tree, and set of experimental feed-down coefficients are provided. Unlike SHAREv1.X, experimental acceptance feed-down coefficients can be entered for *any* resonance decay.

SHAREv2 can calculate yields, fluctuations, and bulk properties of the fireball from provided thermal parameters; Alternatively, parameters can be obtained from fits to experimental data.

Averages and fluctuations 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. A χ^2 minimization algorithm, also from the CERN library programs, is used to perform and analyze the fit. Please see [1] for more details on these.

Purpose:
Aside from the fundamental necessity of using both fluctuations and yields in a statistical model analysis, it has long been noted that fluctuations posses a considerable phenomenological power [19–21]. In particular, they can be used to experimentally distinguish between equilibrium and non-equilibrium freeze-out, as well as to determine which statistical ensemble (if any) is more *physically* appropriate for analyzing a given system. Together with resonances, fluctuations can also be used for a direct estimate of the extent the system re-interacts between chemical and thermal freeze-out.

Statistical hadronization models are believed to be very successful at describing soft particle abundances in heavy ion collisions for a range of energies. However, the variety of models currently on the market make it impossibleto make a direct link between the statistical *model* and *physical conditions* at freeze-out, and hence to unambiguisly explore any features in thermal parameters that might indicate a phase transition.

The vast amount of high quality soft data coming out of SPS and RHIC In consideration of the wide stream of yield, fluctuation and resonance data coming out from SPS and RHIC, offers a way to go from model *development* to model *falsification*. We hope SHAREv2 will contribute to find out which statistical model (if any), has a genuine physical connection to the physics at freeze-out.

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 $\chi^2/\mathrm{N}_{\mathrm{DoF}}$ profiles and contours with chemical non-equilibrium are requested.

Accessibility:

The program is available from:

- The CPC program library
- The following websites:
  `http://www.ifj.edu.pl/Dept4/share.html`
  or `http://www.physics.arizona.edu/~torrieri/SHARE/share.html`
- from the authors upon request

SUMMARY OF NEW FEATURES (w.r.t. SHAREv1.X)

Fluctuations: In addition to particle yields, ratios and bulk quantities SHARE v2 can calculate, fit and analyze statistical fluctuations of particles and particle ratios;

Decays: SHARE v2 has the flexibility to account for any experimental method of allowing for decay feed-downs to the particle yields;

Charm flavor: Charmed particles have been added to the decay tree, allowing as an option study of statistical hadronization of J/ψ, χ_c, D_c, etc.;

Quark chemistry: Chemical non-equilibrium yields for both u and d flavors, as opposed to generically light quarks q, are considered; η–η' etc. mixing is properly dealt with, and chemical non-equilibrium can be studied for each flavor separately.

Misc: Many new commands and features have been introduced and added to the basic *simplified* user interface. For example it is possible to study combination of particles and their ratios.

2 Particle yield fluctuations

2.1 Introduction

The statistical hadronization model [2–5] (SHM) assumes particles are created according to their phase space weight, given the locally available energy and quantum numbers. Such a reaction model implies that the underlying dynamics of strong interactions saturates the strength of each particle production quantum matrix element.

This approach can be used to calculate the event-by-event average, as well as fluctuation (distribution width) and higher cumulants of any "soft" observable. Event-by-event particle fluctuations have been subject to intense current theoretical [6–14], and experimental interest [15–18]. SHARE v2 will offer a standardized framework to evaluate these.

While *qualitative* study of fluctuations is useful as a test of new physics, we have further argued [19–22] that an analysis of particle fluctuations, together with yields, constitute a powerful probe of hadronization conditions. In particular, the following questions can be addressed when both yields and fluctuations are considered in the same model framework:

- SHM can be falsified if and when fluctuations do not scale w.r.t. averages as expected in statistical physics. Moreover, only if the same set of thermal parameters gives good description of experimentally measured yields *and* fluctuations, can we claim the validity of the SHM fit.

- As has recently been shown [23–27], the value to which the scaled variance σ_N (see Eq. (3)) for a single particle converges in the thermodynamic limit varies by as much as an order of magnitude when different statistical ensembles are considered. Thus fluctuations can help decide if and when certain particle yields should be studied in grand canonical or canonical ensembles.

- SHM fits containing both the average particle multiplicity and the fluctuation break the correlation between hadronization temperature T and light quark phase space occupancy γ_q (see, e.g., Eq. 7 in [1]) typical of fits when only the average multiplicities are fitted [19].

  Therefore, the study of both fluctuations and yields can help to experimentally distinguish between the chemical equilibrium freeze-out model ($T \simeq 170$ MeV, $\gamma_q = 1$ [28]), or the best fit with chemical non-equilibrium at typically lower T [29].

- Considering the directly detectable resonance decays, fluctuations of particle yield ratios offer a way to quantitatively gauge the effect of hadronic re-interactions between formation and thermal freeze-out [20].

To investigate these questions, it is necessary in evaluation of both particle yields and fluctuations to:

- Incorporate all particles resonance decay trees [30] in the program structure;

- Obtain particle yields and fluctuations for a given set of thermodynamic parameters;

- i) Check if the parameters obtained by fitting particle yields are consistent with observed fluctuations;
  ii) Once all corrections to fluctuations due to experimental setup are understood, incorporate the fluctuations along with yields into the chemical freeze-out fitting procedure.

SHARE v2 comprises a framework that addresses these challenges.

As implied above, event particle yield fluctuations are subject to many subtle experimental effects which need to be understood and kept under control for a joint yield-fluctuation analysis to proceed. Further, there is the choice of statistical model ensemble in computation of the phase space volume:
1) Evaluation with exact energy and discrete quantum number conservation (micro-canonical ensemble — MCE),
2) In the canonical ensemble (CE), statistical energy fluctuations are allowed, conserving discrete quantum number(s) exactly.
3) In the grand-canonical ensemble (GCE), statistical fluctuations of all conserved quantities occur — there are also mixed CE-GCE ensembles where some particle yields are conserved and other fluctuate.

Clearly, the fluctuations of particle yields are most constrained in MCE and least constrained in GCE. Thus, although in the three ensembles, the first moments of any observable distribution, i.e., expectation values, coincide in the 'thermodynamic limit' (TL), this will not be the case for the fluctuations [23–25]. The choice of appropriate ensemble in the situation considered has to be made based on evaluation of prevailing *physical* conditions.

In study of total particle yields in the physical context of heavy ion collisions, the electrical charge and baryon number are fixed and, in these variables, we have to consider the CE if and when we are observing all particles. On the other hand, if we only observe a sub-volume of the system, which is exchanging energy and particles with an unobserved 'bath' consisting of the remainder of the reaction system, then, also *conserved* quantum numbers must be allowed to fluctuate, which implies use of the GCE for all observables.

Within the context of heavy ion physics, with reactions occurring at large energy, a study of fluctuations within a narrow momentum rapidity[1] acceptance window provides for the division between 'system' and 'bath', with the bath being the unobserved rapidity domain. In all experiments currently capable to measure fluctuations, detector acceptance is limited typically to the central rapidity *phase space* coverage. Such an acceptance domain in the boost invariant (denoted below as subscript b.i.) limit is equivalent to a *configuration space* sub-volume [31] and thus for both particle ratios, and particle yield width (fluctuation) [22], we have:

$$\frac{\langle N_i \rangle_{\rm GC}}{\langle N_j \rangle_{\rm GC}} = \frac{(dN_i/dy)_{\rm b.i.}}{(dN_j/dy)_{\rm b.i.}}, \tag{1}$$

$$\sigma^2_{N_i} = \left(\frac{d\sigma^2_{N_i}}{dy} \right)_{\rm b.i.}. \tag{2}$$

[1] $y = \tanh(m/E)$, where m is the mass and E is the energy

Here, $\langle N_i \rangle$ is the event-by-event average of particle i, dN_i/dy is the number of particles in an element of rapidity at central rapidity, and the scaled variance of any quantity X is defined as

$$\sigma_X^2 = \frac{\langle (\Delta X)^2 \rangle}{\langle X \rangle} = \frac{\langle X^2 \rangle - \langle X \rangle^2}{\langle X \rangle}. \tag{3}$$

We conclude that, in experiments with limited central rapidity acceptance, both yields and fluctuations should be evaluated in the GCE with respect to the conserved quantum numbers (charge Q , baryon number b, strangeness $s - \bar{s}$.).

For example, considering the RHIC mid-rapidity electromagnetic charge fluctuation results [15–17], the non-zero result suggests that use of GCE is *required.* That is supported by the observation that the fluctuations observed are compatible with Poisson scaling,

$$\left\langle (\Delta N)^2 \right\rangle \sim \langle N \rangle \,, \tag{4}$$

which is approximately followed by the GCE fluctuations. This is not the only scaling known to be present in this area of physics. Elementary reaction systems have been observed to follow a non-Poissonian scaling [32, 33] w.r.t. multiplicity averages,

$$\left\langle (\Delta N)^2 \right\rangle \sim \langle N \rangle + c \langle N \rangle^2 \,, \tag{5}$$

where c is a constant. As has been argued previously, [34–36], it is possible to describe this scaling by considering an extension of the Grand Canonical ensemble (variously referred to as Isobaric or Pressure ensemble) where system volume is also allowed to fluctuate.

In SHARE v2, we consider only GCE yields and fluctuations and search to explore weather the grand canonical statistical hadronization model can quantitatively reproduce fluctuations in the same way as it was shown to reproduce particle yields in heavy ion A–A reactions.

2.2 Evaluation of fluctuations

In GCE, particle yields and fluctuations can be calculated by a textbook method. For a hadron with an energy $E_p = \sqrt{p^2 + m^2}$, the energy state occupancy is,

$$n_i(E_p) = \frac{1}{\Upsilon_i^{-1} e^{E_p/T} \pm 1}, \tag{6}$$

where the upper sign is for fermions and the lower sign is for bosons. Here, T is the temperature, while Υ_i is the fugacity, described in detail in [1], section 2.1.

The yield average are obtained by multiplying the density of states by the occupancy number:

$$\langle N_i \rangle \quad = \quad gV \int \frac{d^3p}{(2\pi)^3} \, n_i(E_p). \tag{7}$$

The fluctuation in this number is well known, found in elementary statistical physics books:

$$\left\langle (\Delta N_i)^2 \right\rangle = \Upsilon \left. \frac{\partial N_i}{\partial \Upsilon} \right|_{T,V} = gV \int \frac{d^3p}{(2\pi)^3} \, n_i(E_p) \left(1 \mp n_i(E_p)\right). \tag{8}$$

Eqs. (7–8) can be evaluated to any desired accuracy through converting them into an expansion of Bessel function terms [4]:

$$\langle N_i \rangle = \frac{\pm g V T^3}{2\pi^2} \sum_{n=1}^{\infty} \frac{(\pm\lambda)^n}{n^3} W\left(\frac{nm}{T}\right), \tag{9}$$

$$(\Delta N_i)^2 = \frac{\pm g V T^3}{2\pi^2} \sum_{n=1}^{\infty} \frac{(\pm\lambda)^n}{n^3} \left(\begin{array}{c} 2+n-1 \\ n \end{array}\right) W\left(\frac{nm}{T}\right), \tag{10}$$

where $W(x) = x^2 K_2(x)$ (see [1] section 2 for the technical details required in doing these calculations, as well as a discussion of particles with finite width).

Eq. 7 and 8 can be used to calculate the event-by-event averages and fluctuations of all hadrons *at hadronization*. This, however, is quite different from the *observed* averages and fluctuations, since most hadrons are strong resonances (unstable states), which decay after freeze-out, either to stable particles or to other resonances. The final state particle yields can be computed by taking the effect of these feed-downs into account [5].

The ensemble average of the total yield $\langle N_i \rangle$ is:

$$\langle N_i \rangle_{\text{total}} = \langle N_i \rangle + \sum_{j \neq i} B_{j\to i} \langle N_j \rangle. \tag{11}$$

$B_{j\to i}$ is the probability (branching ratio) for the decay products of j to include i.

The fluctuation after resonance feed-down is given by

$$\left\langle (\Delta N_{j\to i})^2 \right\rangle = B_{j\to i}(\mathcal{N}_{j\to i} - B_{j\to i}) \langle N_j \rangle + B_{j\to i}^2 \left\langle (\Delta N_j)^2 \right\rangle. \tag{12}$$

The second term corresponds to the fluctuation in *the yield of resonances*. The first term, in the *number of* $j \to i$ decays given the branching ratio $b_{j\to i}$. $\mathcal{N}_{j\to i}$ is the number of particles type i produced in the decay, so that $\sum_i B_{j\to i} = \mathcal{N}_{j\to i}$ ($\mathcal{N}_{j\to i} = 1$ for nearly all decays of nearly all resonances)

The above expressions neglect volume fluctuations, coming from centrality cuts and dynamics of system expansion. These are accounted for by dividing the observed fluctuation into an extensive and an intensive part,

$$\left\langle (\Delta X)^2 \right\rangle \approx \left\langle (\Delta x)^2 \right\rangle \langle V \rangle^2 + \langle x \rangle^2 \left\langle (\Delta V)^2 \right\rangle, \tag{13}$$

$\langle x \rangle$, $\langle x^2 \rangle$ can be calculated by the statistical methods described in this section.

It is difficult to describe the volume fluctuation coefficient $\langle (\Delta V)^2 \rangle$ in a model-independent way. The most straight forward way to deal with this problem is to choose observables insensitive to $\langle (\Delta V)^2 \rangle$.

Any observable where $\langle x \rangle^2 \ll \langle \Delta x)^2 \rangle$ would be a good candidate. This is why the fluctuation in electromagnetic charge has long been considered to be a promising observable [9].

A more general approach is to consider the event-by-event fluctuation of particle ratios [8], where the volume fluctuation $\langle (\Delta V)^2 \rangle$ is zero by construction. Fluctuation of particles ratios can be calculated from the denominator and numerator's fluctuation once the full resonance decay tree is known [8]. Note that, unlike in the case of particle yields, resonance decays produce both fluctuations and *correlations*, since a resonance can decay both into a numerator and a denominator particle. If this is the case, a high resonance admixture can considerably reduce the fluctuation of a ratio w.r.t. Poisson expectation.

The formulas to be used are [8] (note absence of $\langle(\Delta V)^2\rangle$ and the negative sign on the correlation term D_{12}):

$$\sigma^2_{N_1/N_2} = \frac{1}{\langle N_2\rangle}\left(D_{11} + D_{22} - 2D_{12}\right), \tag{14}$$

with

$$D_{11} = \frac{\langle N_2\rangle}{\langle N_1\rangle} F_1, \tag{15}$$

$$D_{22} = F_2, \tag{16}$$

$$D_{12} = \sum_{j\to 1,2} \langle b\rangle_{j\to 1,2} \frac{\langle N\rangle_j}{\langle N_1\rangle}, \tag{17}$$

where

$$F_i = \left(\frac{\left\langle(\Delta N_i^{\mathrm{direct}})^2\right\rangle}{\langle N_i\rangle} + \sum_{j\to i} \left\langle n_i^2\right\rangle_j \frac{\langle N\rangle_{j\to i}}{\langle N_i\rangle}\right). \tag{18}$$

in the last expression, $\left\langle(\Delta N_i^{\mathrm{direct}})^2\right\rangle$ refers to the fluctuation before the resonance decay, as given by Eq. 8.

Note that σ_N does not depend on system volume, since it cancels between the numerator and the denominator. $\sigma_{N1/N2}$, however, do acquire a volume dependence since they scale as $\langle N\rangle^{-1}$. Hence, an analysis incorporating fluctuations of particle ratios should also consistently account for particle yields, and the system normalization (thermodynamic parameter **norm**, [1] section 3.1) should be considered as a fit parameter.

2.2.1 Finite acceptance effects affecting fluctuations

One way to separate detector acceptance effects from physics is to eliminate the former via mixed event techniques; A "static" fluctuation σ_{stat} is measured in a sample of fake events, constructed by using tracks from different events [15]. Since tracks from different events have no correlations or quantum corrections, σ_{stat} is determined solely by a trivial Poisson constribution as well as detctor acceptance effects.

Within the statistical hadronization model

$$\sigma^{stat}_{N_i} = 1\,. \tag{19}$$

For particle ratios in mixed events, the correlation term D_{12} (Eq. 17) vanishes, while particle the fluctuations of denominator and numerator again follow Poisson scaling (F_i in Eq. 18 is unity).

Hence (Eq. 14)

$$\sigma^{stat}_{N_i/N_j} = \frac{1}{\langle N_i \rangle} + \frac{1}{\langle N_j \rangle}. \tag{20}$$

The 'dynamical fluctuation' σ_{dyn} [8, 37–39] corresponds to the difference between the "raw" total fluctuation σ and the fake event fluctuation. In certain limits, it

$$\sigma^{dyn} \equiv \sqrt{\sigma^2 - (\sigma^{stat})^2}, \tag{21}$$

can be shown [37] to be independent of detector acceptance.

2.2.2 Finite acceptance effects affecting correlations

Because mixed event tracks are uncorrelated, mixed event techniques can not account for detector acceptance effects within *particle correlations*. Thus, Eq. 14 needs to be updated to

$$\sigma^2_{N_1/N_2} = \frac{1}{\langle N_2 \rangle} \left(\alpha_1 D_{11} + \alpha_2 D_{22} - 2\alpha_{12} D_{12} \right), \tag{22}$$

where α_1 and α_2 refer to the probability that, respectively, particles 1 and 2 will end up in the detector's acceptance region, while α_{12} measures the probability that *both* decay products will be inside this region.

For a boost invariant azimuthally complete system, $\alpha_1 = \alpha_2 = 1$ since particles leaving the detector acceptance region will be balanced by particles coming in. However, in general $\alpha_{12} < 1$, since if a resonance is outside the detector acceptance region *both* particles can *not be* inside it, and the intrinsic particle decay momentum adds a rapidity scale to the system, breaking boost invariance [19].

See [19] for an illustration of how to alculate α_{12}. While such a comprehensive calculation is outside the scope of the current version of the program, we offer the user the possibility of entering an α_{12} for any resonance decay as an input parameter, see section 3. In practice, this should only be necessary for a few most frequent and energetic resonance decays, such as $\rho \to \pi\pi$ and $K^* \to K\pi$.

2.3 Implementation of GCE fluctuations in SHARE v2

Fluctuation experimental data-points were implemented in the SHARE interface in a similar manner as described in for yield and ratio data points ([1] section 3.4). The tag which denotes that a fluctuation is being calculated is **fluct_yld**. A statement such as

particle1 fluct_yld data $\Delta_{\rm stat}$ $\Delta_{\rm syst}$ **fit?**

will calculate σ_N of **particle1** (defined in Eq. 3), and, if **fit?** is set to 1, use it within a fit together with the experimentally measured value **data** and the statistical ($\Delta_{\rm stat}$) and systematic ($\Delta_{\rm syst}$) error . The format of the data-line is exactly the same as in SHARE v1.x ([1] section 3.4).

To calculate the fluctuation of a ratio, **particle1** should be substituted by the data point number where the ratio is defined. For instance, if the 5th data-point (from the top) is a K^-/π^- ratio, than it's fluctuation is given by:

05 **fluct_yld** **data** $\Delta_{\rm stat}$ $\Delta_{\rm syst}$ **fit?** SHARE implements most definitions of dynamical fluctuations used to date by experimental collaborations. These are implemented as additional tags of **fluct_xxx** type, where **xxx** refers to different ways the experimental measurement is presented

The possible types of data-points are:

fluct_dyn To calculate $\sigma_1^{dyn} = \sqrt{\sigma^2 - (\sigma^{stat})^2}$, as measured in [39],

fluct_dns To calculate $\sigma_2^{dyn} = \sqrt{\sigma^2} - \sqrt{(\sigma^{stat})^2}$ as given in [37],

fluct_dnr To calculate $\sigma_3^{dyn} = \frac{\sigma^2}{\sigma^2_{stat}}$ as suggested in [8].

3 Decay feed-down and particle yields

3.1 Particle decay acceptance data files

As explained in the previous section, decay feed-down is a fundamental component of the statistical hadronization model. However, the limited coverage of most detectors means that the feed-down coefficients will aquire an *experimental* correction, corresponding to the probability that the decay products of a given resonance formed within the detector acceptance region will also be in that region.

Weak decays, such as $\Lambda \to p$ (most protons are in fact given by feed-down from hyperons), are particularly susceptible to experimental acceptance, as they occur at a *macroscopic* distance from the primary vertex. Hence, weak experimental feed-down corrections include a geometrical as well as a momentum space component.

Since the "parent" particles are not always directly observed, SHARE must be able to compute final hadron multiplicities including experimental feed-down coefficients for all decays where this effect is non-negligible.

SHARE v1.x allowed the user to input experimental (weak) feed-down contributions to produced particle yields via four acceptance coefficients:
$K_S \to$ anything, $K_L \to$ anything, $Y \to$ **Mesons**, $Y \to$ **baryons** (see [1], section 3.4.1).

It turns out this approach was not sufficiently flexible: for instance, $\Sigma \to p$ contamination can be very different from $\Lambda \to p$ corrections, considering the difference in lifespan, and (vertex) acceptance cuts applied. Moreover, the experimental acceptance of different **hyperon** $\to$ **nucleon** weak decays, such as $\Xi \to \Lambda$ as compared to $\Lambda \to p$ is likely to be considerably different. Finally, different weak decays of the same hadron can have varying acceptances, compare $K_L \to 3\pi$, with $K_L \to \pi e \nu$, and with $K_L \to \pi \mu \nu$. Aside of weak decays, a similar acceptance problem may arise in special cases involving strong decay chains.

A more flexible way of treating weak decay contributions to particle yields is therefore necessary. Specifically, there should be an easy way to allow for any *arbitrary* decay/reaction contributing to *any* data-point. SHARE v2 provides such a possibility through user defined decay feed-down files.

```
Example of Experimental data file:

#STAR data-points
#--------------------------------
weakdecay  star.feed
#--------------------------------
Ka0492plu  pi0139plu    0.156    0.0208     0.          0
Ka0492min  pi0139min    0.15     0.02       0.          1
#PHENIX data-points
#--------------------------------
weakdecay  phen.feed
#--------------------------------

Example of weak feed-down file:

#------------------------------K_L corrections -----------------
#K_L-> pi lepton
Ka0492lng   pi0139min   el0000plu   nue000zer   all   0.
Ka0492lng   pi0139plu   el0000min   nue000zer   all   0.
Ka0492lng   pi0139min   mu0000plu   num000zer   all   0.
Ka0492lng   pi0139plu   mu0000min   num000zer   all   0.
#K_L-> 3pi
Ka0492lng   pi0139plu   pi0139min   pi0135zer   all   0.
#----------------------------- K_S corrections ------------------
Ka0492sht   pi0139plu   pi0139min   all  0.
#--------------------------------- Hyperon corrections
Lm1115zer   pr0938plu   pi0139min   2nd  0.
#Lm1115zer   ne0939zer   pi0135zer   2nd  0.
#
Lm1115zrb   pr0938plb   pi0139plu   2nd  0.
#Lm1115zrb   ne0939zrb   pi0135zer   2nd  0.
#-------------------------Strong correction---------------
Ka0892zer   pi0139min   Ka0492plu   all  0.6
```

Figure 1: An example of the SHARE v2 weak feed-down acceptance coefficient implementation.

In data file containing the experimental results to be fitted (see [1] section 3.4.3), a weak decay control file is now signaled by a statement of the type:
Weakdecay File.feed
where **File.feed** is a 9-letter filename. The program then obtains the decay acceptance weights from **File.feed**, an ASCII file in a format similar to the decay tree files (described in [1] section 3).

Fig. 1, and the attached input files provided with the SHARE package, show how to implement the weak decay acceptance coefficients. While many weak feed-down files might be involved in the same analysis, generally, they are experiment-specific, and hence can be kept track of in a systematic way. Alternatively, all weak feed-down files and experimental data-files can be combined in a single large file, using the methods described in section 5.1.

In more detail, a typical line in a feed-down file will be:

Parent Daughter$_1$ Daughter$_2$ all/1st/2nd/cor Coeff.
or, for 3-body decays,
Parent Daughter$_1$ Daughter$_2$ Daughter$_3$ all/1st/2nd/3rd/cor Coeff.
The switch **all/1st/2nd/3rd** refers to the daughter to which the decay coefficient applies.

all means that the decay coefficient is the same for all daughters, while **1st/2nd/3rd** means only the 1st/2nd/3rd daughter will be removed from the experimental yield. For example, in the $\Lambda \to \pi p$ decay in STAR [40, 41], STAR accepts the nucleon from the Λ decay but not the π, and this fine tuning of the decay is clearly quite important as a relatively large fraction of all nucleons comes from weak Λ decays.

cor refers to the fractional contribution of the decay to the two particle correlation $\langle Daughter_1$ $Daughter_2\rangle$ induced by a common resonance decay from parent, denoted as α_{12} in Eq. 22 (section 2.2.2).

SHARE will assume that the probability for the decay
Parent $\to$ **all/1st/2nd/3rd/cor**
to impact the observed particle multiplicities, fluctuations and correlations to be given by the number **coeff.** (between 0 for no acceptance and 1, assumed by default, for full acceptance). This probability will be included in the decay tree calculation for each data-point separately.

It is possible to assign different weak decay contributions to each data-point, or assume that a group of data-points are subject to the same set of weak decay yield contribution, (e.g., many experimental results considered have the same weak decay contributions). The way to do this is the same as in v1.x ([1] section 3.4.3): when the program reads a **weakdecay** statement, it assigns the current decay pattern to *each* data point encountered until a *new* weak decay feed-down file is met.

Two special case exist, for which no **File.feed** file is needed:
weakdecay UNCORRECT 'uncorrected' (from perspective of experimental data set) means that all weak decays contributions to particle yields are fully accepted by SHARE v2.
weakdecay NOWK_FEED means that *all* particle yields are computed **without** contributions from weak decays, from perspective of experimental data this means that either all weak decay products are *not* accepted and/or have been all corrected for in experimental yields, as, e.g., applies to some NA49 results.

When fluctuations are considered, it is important to deal carefully with experimental corrections, which are neither close to total (close 100 % accepted) nor null (close to 0 % accepted). Weak decay corrections of the daughter particles are usually correlated with each-other in momentum space, so the straight-forward application of Eq. 8 will not be a good description of fluctuations with a non-trivial detector acceptance function. In this case, it's better to use dynamical, rather than total, fluctuations as we discussed in section 2.2.1.

3.2 Compatibility with SHARE v1.x experimental data files

The improved weak decay treatment does not impair compatibility of experimental input files between SHARE v2 and SHARE v1.x. SHARE v2 will read a SHARE v1.x experimental data-file, and automatically calculate applicable contributions for each weak decay based on the information contained in the SHARE v1.x **weakdecay** statement. A line will be printed within the **share-run.out** output file that signals a SHARE v1.x format **weakdecay** statement was encountered.

In addition, an output v2 weakdecay file called **weak#v1.x** (where # refers to the data-point number) is automatically generated translating the v1.x weak decay information into v2 format. The user is advised to eventually change all **weakdecay** lines to
weakdecay weak#v1.x
as the v2 format is considerably more powerful and less amenable to systematic error stemming from an incomplete understanding of weak decays.

4 Complete light quark chemistry and charm flavor

SHAREv1.X input files listed particle chemical content by total isospin I and it's third component, I_3, as well as the number of light, strange and charm quarks. As we will show, such an input can be inadequate to describe states, such as the η, which are given by an admixture of u, d and s quarks within chemical conditions where *no* flavors are in relative chemical equilibrium.

Thus, in SHARE v2, u and d quarks are now separately accounted for. The particle listing format is:
name mass width spin I I3 u d s au ad as c ac MC
where **name** is the particle's 9-character name, I and I_3 are the total and third component of the isospin, **u,d,s,c** are the numbers of up,down, strange and charm quark numbers, while **au,ad,as,ac** are the respective antiquark numbers. The format of the table is otherwise identical to that discussed in [1], section 3.2.

To check for the possibility that phase space occupancy differs for the up and down quarks, a statistical model fit parameter (see [1],section 3.1) **gam3** (γ_3) has been introduced, such that:

$$\gamma_u = \gamma_q \gamma_3, \qquad\qquad \gamma_d = \gamma_q / \gamma_3. \tag{23}$$

The quark/antiquark numbers can be fractional, to account for the fact that some mesons, such as the π^0 and the η are flavor-composite states [30].

It should be noted that, for $\gamma_{u,d,s} \neq 1$, chemical non-equilibrium in the fractional flavor content considerably alters the hadron yield. For a meson h of fractional quark number structure,

$$|h>= \alpha_u |u\overline{u}> + \alpha_d |d\overline{d}> + \alpha_s |s\overline{s}>, \quad \alpha_u^2 + \alpha_d^2 + \alpha_s^2 = 1, \tag{24}$$

the fugacity for h comprises the chemical yield fugacities as follows:

$$\Upsilon_h = \lambda_h \left(\gamma_u^2 \alpha_u^2 + \gamma_d^2 \alpha_d^2 + \gamma_s^2 \alpha_s^2 \right). \tag{25}$$

Fractional flavor content has non-negligible influence on the abundances of η^0 and η' and their decay products in fits which allow for chemical non-equilibrium factor γ_s. The same remarks applies when $\gamma_3 \neq 1$ to π^0, ρ^0, etc. Thus, $\gamma_3 \neq 1$ can considerably enhance $\pi^0 \propto \gamma_3^2 + \gamma_3^{-2}$ yield, while making $\pi^\pm$ yields asymmetric, $\pi^+/\pi^- \propto \gamma_3^4$.

Importantly, the evolution of quark-coalesced hadrons into final quark-eigenstates hadrons (like the oscillation of neutral kaons into K_S and K_L) means that the 'source' QGP quark content will *not*, in general, be equal to the 'final' hadron quark content. Hence, to calculate (u, d, s) quark abundance in the statistically hadronizing QGP system, new bulk variables **tot_u_qgp**, **tot_d_qgp** and **tot_s_qgp** were introduced. These can be used in the same way as other bulk variables (see [1] section 3.4.2).

Charmed particles have now been added in the files **particles.data** and **partnowdt.data**. Their nomenclature follows the general structure as described in [1], section 3.2. **Dcxxxxxxx** refer to D_c mesons, **Dsxxxxxxx**, **chixxxxcc** to χ_c states and **psixxxxcc** to J/ψ states.

Their abundance is regulated by the chemical potential λ_c and the phase space occupancy γ_c, described in [1] (section 3.1).

5 User Interface files and new commands

5.1 New single file control

SHAREv2 relies on several distinct input files:

- The run-file **sharerun.data**
- The particles list
- The particles decay tree
- The initial values of the thermodynamic parameters
- The experimental data-points
- Initialization for each fit parameter

(See section 3 of [1] for a detailed description of the role and format of each of these files).

This structure makes it easy to quickly explore regions of parameter space within an analysis *in progress*. However, this system makes it easy to mistakenly lose a successfully completed and saved analysis, since a change in each of the files could considerably alter the end-result. The introduction of weak decay correction file (see section 3) aggravates this problem.

SHARE v2, therefore, makes it possible to combine some, or all, input files into a single file. Once the user found an optimum analysis, all input files involved in it can be combined into one large **sharerun.data** file, which can be easily kept for future reproduction and modification.

This is done by changing the extension (**.data** or **.feed**) of the filename into **.HERE**. If the program encounters a filename ending in **.HERE**, it assumes the relevant input is immediately following the given line within the currently read file. The subsequent format is assumed to be *unchanged* from what it would have been had a separate file been opened (comments, etc.). The only difference is that a * symbol on a new line has to be present at the point where the separate

```
#Many-files format                         #One-file format
#----------------------                    #--------------------
READ  THERM_INI  th_neq.data               READ  THERM_INI  th_neq.HERE
                                           #---- content of thermal file starts
                                           temp    0.14
                                            ...
                                            accu    0.01
                                            *
                                            #--- content of thermal file ends
READ  TOTALDATA  tot200mix.data            READ  TOTALDATA  tot200mix.HERE
                                            #--- content of experiment file starts
                                            pi0139plu  prt_yield   286.4  24.2   0.   1
<within the tot200mix.data file>            ...
 weakdecay  star.feed                        weakdecay  star.HERE
                                            #---- content of weak decay file starts
                                            ...
                                            Ka492sht  pi0139plu   pi0139min all  0.7
                                            ...
                                            *
                                            #---- content of weak decay file ends
                                            *
                                            #--- content of experimental file ends
#--------------------------------------------  #--------------------------------------------
CALC  FITRATIOS  fitnw20M._neq              CALC  FITRATIOS  fitnw20M._neq
```

Figure 2: Left: sharerun.data calling other input files. Right: One-file format.

file would have *ended*. When the program encounters the * symbol, it switches back to reading the 'earlier' file, that is prior to the insert **.HERE**.

See Fig 2, and the provided file **sharerun.data_onefile**, for an example of how this works.

5.2 Combining data-points

It is possible, in SHARE v2, to refer to a different data-point for a fit, and/or combine two data-points, in order to fit the sum or a product of two particles. The referring data-point consists of one or two (for a combination) numbers, corresponding to the position, in the input file, of the point(s) being referred to.

Two numbers united by an operation sign (+, −, X, /) will add, subtract, multiply and divide two data-points. For instance, if the first data-points from the top of the file (see [1] section 3.4, for a detailed explanation of the format) are:

Lm1115zer	**pi0139min**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**Fit?**
Lm1115zrb	**pi0139plu**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**Fit?**

then,

01X02	**prt_yield**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**Fit?**

will fit $(\Lambda\overline{\Lambda})/(\pi^+\pi^-)$, while

01	**fluct_dyn**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**Fit?**

will fit the dynamical Λ/π^- fluctuation, as described in the first section.
To fit $(\Lambda + \overline{\Lambda})/(\pi^+ + \pi^-)$ (but NOT the separate yields), the input file will read:

Lm1115zer	**prt_yield**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**0**
Lm1115zrb	**prt_yield**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**0**
pi0139plu	**prt_yield**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**0**
pi0139min	**prt_yield**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**0**
01+02	**03+04**	**Data**	$\Delta_{\rm stat}$	$\Delta_{\rm syst}$	**1**

NOTE: SHARE was written in FORTRAN77. Feature mentioned in this subsection use implicitly recursive code. SHARE v2 has been tested on several compilers and platforms, and found to work. However, compilers and operating systems vary — we would like to know if and when you experience problems.

5.3 Miscellaneous

The following (small) modifications were made in SHARE v2 compared to SHARE v1:

5.3.1 Expanded parameter set

The expanded parameter set includes as noted before, Eq. (23), **gam3** which allows to incorporate a different u, d-flavor phase space occupancy. A further new variable **dvol** describes statistical pressure ensemble fluctuations in volume (Section 1,Eq. (13)). The provided input file sets and fixes **dvol** to zero and **gam3** to unity , since experimental measurements sensitive to these parameters have not as yet been published.

All details about how to configure these parameters, and fix or relax them in the context of fits to experimental data, are unchanged w.r.t. v1.X, described in [1] sections 3.1,3.6 and 3.7

5.3.2 Data-point sensitivity analysis

Command **DFIT**, within the file **sharerun.data** can turn on and off the given data-point as a point to be fitted.
The syntax for this command is
DFIT [Datapoint n.] [Fit(0/1)]
where **Datapoint n.** refers to the datapoint's position in the experimental data-file from the top, while **Fit(0/1)** turns this point on (1) or off (0) as a point to be fitted. For instance, the following input in **sharerun.data**:

READ TOTALDATA tot200mix.data
DFIT 5 1
CALC FITRATIOS fitnw20M-kpi
DFIT 5 0
CALC FITRATIOS fitnw20M-nkpi
performs two fits:
The first, saved in file **fitnw20M-kpi** uses the 5th data-point in **tot200mix.data** when calculating the χ^2 (to be minimized).
The second one, saved in file **fitnw20M-nkpi**,does not.

5.3.3 Data-point sensitivity profiles

Command **SNSPROFIL** calculates the datapoint *sensitivity*. The sensitivity is defined as the ratio between the data point's SHM prediction for a given statistical parameter, and SHM prediction at the *best fit* value for that parameter.

The syntax of **SNSPROFIL** is the same as **DATPROFIL** in [1], section 4. The two commands operate in the same way: All parameters, except the one on the abscissa, are minimized at each point in the profile.
Thus, the command
CALC SNSPROFIL temp 0.1 0.2 100 5
will calculate a sensitivity profile for the temperature, going from 0.1 to 0.2 GeV, with 100 points, of the fifth data-point within the experimental data-file.

5.3.4 Additional output in χ^2 and statistical significance profiles

χ^2 profile commands now output the following files:

name.log A fit output for each point in the χ^2 profile, in the same format as the usual fit output file ([1], Fig. 4).

name.chi2, name.stsg Commands **SNSPROFIL** and **DATPROFIL** also output the χ^2 profile (extension *.chi2) and P_{true} profile (extension *.stsg).

6 Comparison with previous versions

6.1 Testing SHARE v2

SHARE v2 was extensively tested for programming and physics errors:

- SHM Calculations and fit results for SPS and RHIC energies were verified to be equal between SHARE v2 and SHARE v1.X reference results;

- SHARE v2 reads SHARE v1.X weak decay input. The equivalence between the two treatments, when weak decay files are designed to reproduce SHARE v1.X format, was shown to all decimal places;

- Fluctuations of conserved quantities (such as $\langle(\Delta Q)^2\rangle$) were compared before and after resonance decays. The conservation of this quantity implies that the enhanced fluctuations after all resonances decayed are exactly balanced by multiplicity correlations between the resonance decay products. This holds true to two decimal places (up to three body correlations arising from decays such as $K(1600) \to K(892)\pi \to K\pi\pi$. These correlations are not tracked by SHARE, but their contribution is below 1%).

6.2 SHARE v1.X bugs found

While developing and testing SHARE v2, several minor bugs and choice issues were found in the previous version SHARE v1.X, The most noteworthy issues which lead to sometimes noticeable (beyond line width) changes in the results are:

SHARE v1.1, v1.2 The Bessel function series was incorrectly truncated for large γ_q (close to pion B–E condensation);

SHARE v1.3 Quark flavor mixing error in calculation of mesons such as η and ϕ for $\gamma_q \neq \gamma_s$;

SHARE v1.1–v1.3 The most relevant issue is actually not an error but lack of versatility in the handling of $\Sigma \to p\pi$ decays: Σ-particles decay weakly, like the Λs and the Ξs. However, unlike Λ and Ξ, Σ-decays are not experimentally reconstructible since at least one of Σ-decay products is neutral. In general, release SHARE v1.X particles from these decays were included in the yield count. However, it turned out that while some experiments had much less than full acceptance for these decays, other experiments, e.g., NA49, have removed $\Sigma \to p$ feed-down via Monte-Carlo simulations accounting for the experimental acceptance of the decay products, with Σ yields obtained from the observed Λ-yields.

Working with patched SHARE v1.X, we realized that Σ-decay issue mattered in that some fits got better allowing for a modified Σ weak decay pattern. Issues such as this one prompted us to introduce a more general treatment of weak decay particle yield contributions in SHARE v2.

7 Installation

The SHARE v. 2.0 program code and input files are contained in a tar.gz archive (filename sharev2.0.tar.gz). To unpack it, create a SHARE directory, put the archive in it, and execute the following commands:

gunzip sharev2.0.tar
tar -xf sharev2.0.tar

The following files will then be created, enough for a complete "representative" run of SHARE. It should be noted that this run explores all of the calculational potential of SHARE, including computations incorporating particle widths. Some of these, highlighted in the comments in the sharerun.data file, are very long (profiles with particle widths could take hours).

The SHAREv1.0 manual is available at [1]

List of the files:

decays.data The complete Particle Data Group decay tree (section 3.3 in [1])

dec_no.data An empty decays file, useful for testing the program calculations (abundancies reduce to modified Bessel functions) as well as studying the role of resonances in stable particle ratios

fortrat A shell script compiling (in f77) the FORTRAN code which should be modified depending on location of FORTRAN (g77 or f77) and CERN library of programs

particles.data Particle properties, with full widths (section 3.2 in [1]))

partnowdt.data Particle properties, with no widths. Calculations with this input file require considerably less computational time, and it suffices when there are no resonances in the fit.

ratioset.data The FORTRAN fit input file (section 3.5 in [1])

sharerun.data A "representative" run input file (section 4 in [1]) including an analysis of fluctuations and yields similar to what was presented in QM2005, [20]

sharerun.data_onefile The same file in the single file format, as explained in section 5.1

samplefit200 A directory containing the output files generated by running the provided "sharerun.data", as a debugging/comparison standard

sharev2.0.f SHARE v1.1 FORTRAN code. The header contains information about bug fixes

thermo.data A representative thermal parameter input file (section 3.1 in [1]) It is set to reasonable non-equilibrium fit values

totbar200.data A representative data input file (section 3.4 in [1]) Containing ratios, yields and fluctuations drawn from RHIC experiments, as of July 2004 (see references in [20])

star.feed An example of a decay feed-down coefficients file. See section 3

fotrat A shell-script that compiles sharev2.0

Note that SHARE requires CERN libraries, to be downloaded separately from *http://wwwasdoc.web.cern.c*
The compiler statement (in file "fortrat") is *f77 -L/usr/local/cern/pro/lib -o sharev2.0.exe sharev2.0.f -lmathlib -lkernlib -lpacklib -C* which assumes that the CERN libraries are in directory */usr/local/cern/pro/*
If this is not true on your system, fortrat should be changed accordingly.

Once the directory is unpacked, the program should be compiled with

./fortrat

After this, typing

./sharev2.0.exe

should produce a correct run with a detailed output which shows the program's capability. Several output files are produced, with the following names as default. The contents of each file are explained in detail in section 4 of the paper.

fit*.out Fit output files

graph* Fit output graphics (experiment, fitted values, calculated values)

prof* χ^2 profiles and correlation functions for the various fits

See [1] about more details about these files's contents

8 Status, conclusion, and future plans

One of the areas of current intense interest in the field of high energy heavy ion reactions is the understanding of the mechanisms of soft hadron production (chemical freeze-out), that is the study of how the energy confined in the central fireball turns into matter in a multi particle production process.

The SHARE suit of programs is an analysis tool of particle yields addressing the following questions:

- What is the chemical freeze-out temperature, potentials and volume?
- What are the physical properties of the fireball which hadronizes?
- Is the hadron system in chemical equilibrium at freeze-out?

The need for SHARE arises from recognition that the book keeping task involved in the correct application of the statistical hadronization model is considerable, often transcending the resources available to individual researchers. The current SHARE v2 program follows on SHARE v1.X [1] adding three significant novel features: a) flexible handling of particle decay feed-down, b) fluctuations, and c) complete u, d, s, c flavor content treatment. We note that, since SHARE v1.X was released, another analysis package appeared, THERMUS [42], which is, however, not handling many of the features SHARE offers, including chemical non-equilibrium.

Since analysis of experimental data cannot give results of greater precision than is inherent in the data it treats, no wide consensus has yet been reached about which is the most appropriate model version. This implies disagreement on what physics dynamics governs the systematic trends observed in soft hadron observables. The range of prevailing opinions is seen in the recent references [28, 29, 44, 44, 45]. SHARE v2 offers additional analysis features which should help to settle these issues with help of fluctuation observables, even if more precise particle yields experimental data were not available.

The development of phenomenological tools capable of falsifying statistical models is, of course, far from over. Possible extensions of chemical freeze-out model, in future version of SHARE, might include a canonical ensemble module, allowing to test SHM chemical non-equilibrium in small physical systems, and the introduction of an opacity parameter to correct the yields of observed resonances [46].

Another possible development would entail extending SHARE towards a detailed description of momentum distributions. This would be somewhat different from Ref. [47] which relies on scaling in rapidity, and thus, only applies to ultra high energy collisions. In either case, some questions SHAREv2 was designed to address are:

- Is there one common chemical and thermal (momentum spectrum) freeze-out?
- Are there hadronic interactions after chemical freeze-out, and if so, how do these influence soft hadron observables?
- Do some particles (such as multi-strange baryons and charm) freeze-out earlier than others?

Some of these questions are being presently answered indirectly by SHARE v2, but also in some approaches which are not always satisfactory. We refer to a recent review for discussion of the current status of the matter [48]. Here, we note that particle momentum distributions are dependent, in addition to the physics incorporated in SHARE v2 also on the dynamical evolution of the emitting source, and on degree of resonance rescattering after chemical freeze-out. Strategies how these two interwoven effects can be disentangled are being developed.

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