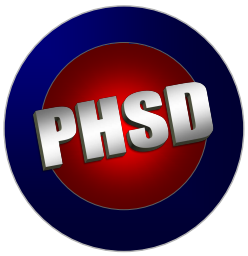

Parton-Hadron-String Dynamics
Transport approach

User Guide

v4.0 – February 19, 2019

The PHSD Team

The code is available from:
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Table of content

Table of content iii

Introduction 1

1 Technical information 3
- 1.1 Files description & code structure . . . 3
- 1.2 Compiling and running the code . . . 4
- 1.3 Particle identification . . . 4
  - 1.3.1 Baryons . . . 5
  - 1.3.2 Mesons . . . 6
- 1.4 Input/Output files . . . 6
  - 1.4.1 Input file and options . . . 6
  - 1.4.2 General output files . . . 12
  - 1.4.3 Single file output . . . 13

2 Initial conditions & dynamics 15
- 2.1 String models: FRITIOF & PYTHIA . . . 18
- 2.2 Low energies: from AGS to SPS . . . 19
- 2.3 High energies: from RHIC to LHC . . . 19
- 2.4 Hadrons dynamics . . . 19
- 2.5 Heavy flavors . . . 26
  - 2.5.1 Charm quark dynamics . . . 26
  - 2.5.2 Open/hidden heavy flavors . . . 26
  - 2.5.3 Perturbative charm . . . 30

3 Electromagnetic probes 33
- 3.1 Dileptons . . . 33
  - 3.1.1 Dalitz decays $A \to B\ l^+l^-$ . . . 33
  - 3.1.2 Direct decay of vector mesons $V \to\ l^+l^-$ . . . 36
  - 3.1.3 Input file . . . 37
  - 3.1.4 Output files . . . 38
  - 3.1.5 Analysis . . . 39
- 3.2 Photons . . . 39

4 List of output files 41

Bibliography 46

Introduction

The **Parton-Hadron-String Dynamics** (PHSD) transport approach is a microscopic covariant dynamical approach for strongly interacting systems in and out-of equilibrium [1, 2]. The PHSD incorporates both partonic and hadronic degrees-of-freedom as well as the transition from the hadronic to the partonic phase, the QGP phase in terms of strongly interacting quasiparticles with further dynamical hadronization and final hadronic interactions in the late stage; thus, PHSD covers the full time evolution of a relativistic heavy-ion collision on a microscopic level. The dynamical description of the strongly interacting system is realized by solving the generalised off-shell Cassing's transport equations which are obtained from the Kadanoff-Baym equations [3, 4, 5] in first-order gradient expansion and go beyond the mean-field and on-shell Boltzmann approximation for the collision terms.

The theoretical description of the partonic degrees-of-freedom (quarks and gluons) is realized in line with the Dynamical-Quasi-Particle Model (DQPM) [6, 5] and describes the properties of QCD in terms of resummed single-particle Green's functions. The three parameters of the DQPM are fitted to reproduce lQCD results in thermodynamical equilibrium [7, 8] such as energy density, pressure and entropy density; the real and imaginary parts of the parton self-energies are used to define the widths and pole positions of the spectral functions of quarks and gluons taken in relativistic Breit-Wigner form. The DQPM provides the properties of the partons, i.e. masses and widths in their spectral functions as well as the mean fields for gluons/quarks and their effective 2-body interactions that are implemented in the PHSD. For details about the DQPM model and the off-shell transport approach we refer the reader to the reviews in Refs. [9, 10]. We mention, that in equilibrium the PHSD reproduces the partonic transport coefficients such as shear and bulk viscosities or the electric conductivity from lattice QCD (lQCD) calculations as well [10, 11].

The hadronic part is governed by the **Hadron-String-Dynamics** (HSD) part of the transport approach [12, 13]; the hadronic degrees-of-freedom include the baryon octet and decouplet, the 0^- and 1^- meson nonets as well as higher resonances. In the beginning of relativistic heavy-ion collisions color-neutral strings (described by the LUND model [14] using FRITIOF 7.02 package (including PYTHIA and JETSET)) are produced in highly energetic scatterings of nucleons from the impinging nuclei, i.e. two strings can form through primary NN collisions. These strings are dissolved into 'pre-hadrons', i.e. unformed hadrons with a formation time of $\tau_F \sim 0.8$ fm/c in the rest frame of the corresponding string, except for the 'leading hadrons'. Those are the fastest residues of the string ends, which can re-interact (practically instantly) with hadrons with a reduced

cross sections in line with quark counting rules. If the energy density is below the critical value for the phase transition, which is taken to be $\mathcal{E}_C = 0.5\ GeV/fm^{-3}$ (e.g. in p+p reactions or in the hadronic corona), 'pre-hadrons' become real hadrons after the formation time $t_F = \tau_F\gamma$ (γ is the Lorentz gamma factor of the pre-hadron) in the calculational frame (center-of-mass system of A+A) and interact with hadronic cross sections. If the local energy density is larger than the critical value for the phase transition $\mathcal{E}_C$, the pre-hadrons melt into (colored) effective quarks and antiquarks in their self-generated repulsive mean-field as defined by the DQPM [9]. In the DQPM the quarks, antiquarks and gluons are dressed quasi-particles and have temperature-dependent effective masses and widths which have been fitted to lattice thermal quantities such as energy density, pressure and entropy density.

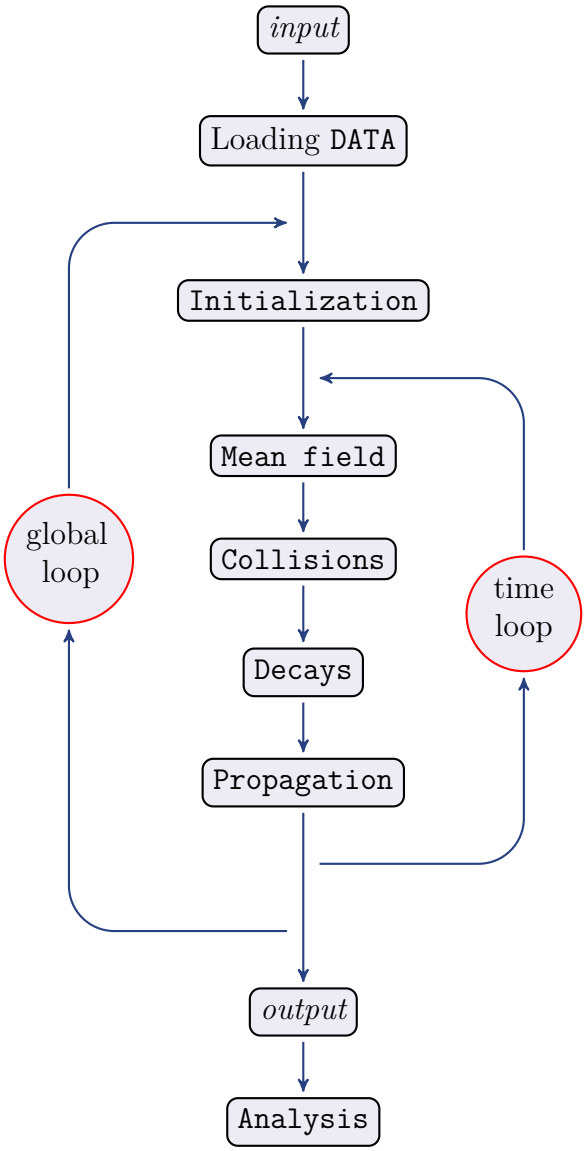
For the time evolution of the QGP phase off-shell transport equations with self-energies and cross-sections from the DQPM are used. With the expansion of the fireball the probability that the partons hadronize increases strongly close to the phase boundary. The hadronisation is carried out on the basis of covariant transition rates. The resulting hadronic system is then governed by the off-shell HSD dynamics with optionally incorporated self-energies for the hadronic degrees-of-freedom [15].

To summarise: the full evolution of a relativistic heavy-ion collision, from the initial hard NN collisions out-of equilibrium up to the hadronisation and final interactions of the resulting hadronic particles is fully realised in the PHSD approach. We recall that PHSD has been successfully employed for p+p, p+A and A+A reactions ranging from SIS to LHC energies (cf. Ref. [10] and references therein).

Chapter 1

Technical information

1.1 Files description & code structure



Global loop over:

- the impact parameter b (if one runs over different values),

- the subsequent runs ISUB,
- and the parallel events NUM (which describe the quantum aspect of the reaction).

The interaction between particles is allowed only inside a single event (but is allowed between parallel events for hadronization).

1.2 Compiling and running the code

The minimum requirement to compile PHSD is a Fortran 90 compiler running under Linux, Windows, or Mac OS platforms (32 or 64 bit). Currently the GFortran compiler is not supported, the produced executable is running endlessly without doing anything. The recommended compiler for compiling PHSD is the **Intel Fortran Compiler** (which is free for personal use and available for all platforms).

About random number generator:
The internal Fortran random number generator RAN(ISEED) (where ISEED is any integer number) is used in the PHSD code. However, the internal random number generator can be replaced by another routine which specifies a random number in the interval [0,1].

On Linux one can unzip the compressed source using the *unzip* command. Compilation is initiated by the *make* command (the makefile is already included in the package). After successful compilation the executable file has the name *phsd*. The following terminal display the full procedure:

```
$ unzip PHSD_linux64.zip -d phsd/
$ cd phsd/
$ make
$ ./phsd
```

For LHC energies,
the phsd code should be compiled in **double precision mode**. This can be easily performed by writing the command "make r8" instead of "make".

On Windows, makefiles are also included, by example "Makefile_Windows_ifort.BAT" which works with the **Intel Fortran Compiler**. This makefile will compile the code and then create an executable file (phsd.exe).

1.3 Particle identification

The baryons and mesons are stored in two different vectors:

Baryons:

ID(i,1) - type of baryon i
ID(i,2) - electric charge of baryon i

Antibaryons carry the ID(i,1) with negative sign.

Mesons:

IPI(j,1) - type of meson j

IPI(j,2) - electric charge of meson j

* For broad resonances the mass is indicated by the pole of the spectral function.

1.3.1 Baryons

The HSD approach incorporates nucleons, Δ's, N*(1440), N*(1535), Λ, Σ and Σ^* hyperons, Ξ's, Ξ^*'s and Ω's as well as their antiparticles on the baryonic side and the 0^- and 1^- octet states in the mesonic sector.

Higher baryonic resonances are discarded as explicit states (for propagation) in HSD; they are supposed to "melt" in the nuclear medium even at normal nuclear density (see e.g. [16, 17, 18]). The argument here is that the resonance structure (above the Δ-peak) is not seen experimentally even in photoabsorption on light nuclei [19, 20, 21].

Table 1.1: The **baryon** identification codes.

ID(j,1)	type	mass* [GeV]
1	p, n	0.938
2	$\Delta(1232)$	1.232
3	N(1440)	1.440
4	N(1535)	1.535
5	Λ	1.115
6	Σ	1.189
7	$\Sigma^\star$	1.385
8	Ξ	1.315
9	$\Xi^\star$	1.530
10	Ω^-	1.672
11	Λ_c	2.285
12	Σ_c	2.455
13	Ξ_c	2.467
14	$\Sigma_c^\star$	2.517
15	–	–
16	Ξ_c'	2.575
17	$\Xi_c^\star$	2.630
18	Ω_c^0	2.695
19	$\Omega_c^{\star 0}$	2.765
10	Λ_b^0	5.620
21	Σ_b	5.807
22	$\Sigma_b^\star$	5.829

Example: p : ID(j,1) = 1, ID(j,2) = +1 ; $\bar{p}$: ID(j,1) = -1, ID(j,2) = -1

1.3.2 Mesons

Table 1.2: The **meson** identification codes.

IPI(j,1)	type	mass* [GeV]
1	π	0.138
2	η	0.549
3	$K^{\pm}$	0.494
4	$K^{*\pm}$	0.892
5	ρ	0.775
6	ω	0.783
7	ϕ	1.020
8	η'	0.958
9	a_1	1.260
10	J/Ψ	3.097
11	K^0	0.498
12	$\bar{K}^0$	0.498
13	K^{0*}	0.892
14	$\bar{K}^{0*}$	0.892
15	$D^{\pm}$	1.870
16	D^0	1.865
17	$\bar{D}^0$	1.865
18	$D^{\star\pm}$	2.010
19	$D^{\star 0}$	2.007
20	$\bar{D}^{\star 0}$	2.007

IPI(j,1)	type	mass* [GeV]
21	–	–
22	Ψ'	3.686
23	D_s^+	1.968
24	D_s^-	1.968
25	$D_s^{\star +}$	2.112
26	$D_s^{\star -}$	2.112
27	η_c	2.980
28–30	–	–
31	$B^{\pm}$	5.279
32	B^0	5.279
33	$\bar{B}^0$	5.279
34	$B^{\star\pm}$	5.279
35	$B^{\star 0}$	5.325
36	$\bar{B}^{\star 0}$	5.325
37	B_s^0	5.366
38	$\bar{B}_s^0$	5.366
39	$B_s^{\star 0}$	5.415
40	$\bar{B}_s^{\star 0}$	5.415
41	$B_c^{\star\pm}$	6.602

Example: π^+ : IPI(j,1) = 1, IPI(j,2) = +1 ; π^- : IPI(j,1) = 1, IPI(j,2) = -1

1.4 Input/Output files

1.4.1 Input file and options

In order to run PHSD one has to specify the **initial parameters** in the input file - *inputPHSD*. There are a couple of examples for an 'input' file in the PHSD directory. Here we show how to initialize the code for low energy A+A, p+p and p+d collisions as well as for π^-+A and π^-+p reactions.

Input file (*inputPHSD*) for Au+Au @ 200 GeV - 30-40%

197,	MASSTA:	target mass
79,	MSTAPR:	protons in target
197,	MASSPR:	projectile mass
79,	MSPRPR:	protons in projectile
21300.,	ELAB:	lab energy per nucleon
8.7,	BMIN:	minimal impact parameter in fm
8.7,	BMAX:	maximal impact parameter in fm
1.,	DBIMP:	impact parameter step in fm
30,	NUM:	optimized number of parallel ensembles
1,	ISUBS:	number of subsequent runs
4567,	ISEED:	initial random seed [integer]
1,	IGLUE:	=1 with partons, =0 w/o partons (HSD)
150.,	FINALT:	final time of calculation in fm/c
10,	ILOW:	output level (default=10)
0,	IDILEPT:	=0 no dileptons; =1 electron pair; =2 muon pair
0,	ICQ:	=0 free,=1 drop. mass,=2 broad.,=3 drop.+broad.
0,	IHARD:	=1 hard collisions + direct charm/beauty, =0 no
0,	IBweight_MC:	=0 constant step in B =DBIMP; =1 B by MC
1,	IUSER:	=1 for general users; = 0 for PHSD team

Input file (*inputPHSD*) for p+p @ 1.5 AGeV

1,	MASSTA:	target mass
1,	MSTAPR:	protons in target
1,	MASSPR:	projectile mass
1,	MSPRPR:	protons in projectile
1.5,	ELAB:	lab energy per nucleon
0.,	BMIN:	minimal impact parameter in fm
0.,	BMAX:	maximal impact parameter in fm
1.,	DBIMP:	impact parameter step in fm
1000,	NUM:	optimized number of parallel ensembles
100,	ISUBS:	number of subsequent runs
4567,	ISEED:	initial random seed [integer]
0,	IGLUE:	=1 with partons, =0 w/o partons (HSD)
40.,	FINALT:	final time of calculation in fm/c
10,	ILOW:	output level (default=10)
1,	IDILEPT:	=0 no dileptons; =1 electron pair; =2 muon pair
0,	ICQ:	=0 free,=1 drop. mass,=2 broad.,=3 drop.+broad.
0,	IHARD:	=1 hard collisions + direct charm/beauty, =0 no
0,	IBweight_MC:	=0 constant step in B =DBIMP; =1 B by MC
1,	IUSER:	=1 for general users; = 0 for PHSD team

Input file (*inputPHSD*) for p+d @ 4.0 AGeV

2,	MASSTA:	target mass
1,	MSTAPR:	protons in target
1,	MASSPR:	projectile mass
1,	MSPRPR:	protons in projectile
4.,	ELAB:	lab energy per nucleon
0.,	BMIN:	minimal impact parameter in fm
0.,	BMAX:	maximal impact parameter in fm
1.,	DBIMP:	impact parameter step in fm
1000,	NUM:	optimized number of parallel ensembles
100,	ISUBS:	number of subsequent runs
4567,	ISEED:	initial random seed [integer]
0,	IGLUE:	=1 with partons, =0 w/o partons (HSD)
40.,	FINALT:	final time of calculation in fm/c
10,	ILOW:	output level (default=10)
1,	IDILEPT:	=0 no dileptons; =1 electron pair; =2 muon pair
0,	ICQ:	=0 free,=1 drop. mass,=2 broad.,=3 drop.+broad.
0,	IHARD:	=1 hard collisions + direct charm/beauty, =0 no
0,	IBweight_MC:	=0 constant step in B =DBIMP; =1 B by MC
1,	IUSER:	=1 for general users; = 0 for PHSD team

Input file (*inputPHSD*) for π^-+Pb @ 1.3 AGeV

208,	MASSTA:	target mass
82,	MSTAPR:	protons in target
0,	MASSPR:	projectile mass
0,	MSPRPR:	protons in projectile
1.3,	ELAB:	lab energy per nucleon
0.,	BMIN:	minimal impact parameter in fm
0.,	BMAX:	maximal impact parameter in fm
1.,	DBIMP:	impact parameter step in fm
100,	NUM:	optimized number of parallel ensembles
100,	ISUBS:	number of subsequent runs
4567,	ISEED:	initial random seed [integer]
0,	IGLUE:	=1 with partons, =0 w/o partons (HSD)
40.,	FINALT:	final time of calculation in fm/c
10,	ILOW:	output level (default=10)
1,	IDILEPT:	=0 no dileptons; =1 electron pair; =2 muon pair
1,	ICQ:	=0 free,=1 drop. mass,=2 broad.,=3 drop.+broad.
0,	IHARD:	=1 hard collisions + direct charm/beauty, =0 no
0,	IBweight_MC:	=0 constant step in B =DBIMP; =1 B by MC
1,	IUSER:	=1 for general users; = 0 for PHSD team

Input file (*inputPHSD*) for π^-+p @ 1.3 AGeV

1,	MASSTA:	target mass
1,	MSTAPR:	protons in target
0,	MASSPR:	projectile mass
0,	MSPRPR:	protons in projectile
1.3,	ELAB:	lab energy per nucleon
0.,	BMIN:	minimal impact parameter in fm
0.,	BMAX:	maximal impact parameter in fm
1.,	DBIMP:	impact parameter step in fm
1000,	NUM:	optimized number of parallel ensembles
100,	ISUBS:	number of subsequent runs
4567,	ISEED:	initial random seed [integer]
0,	IGLUE:	=1 with partons, =0 w/o partons (HSD)
40.,	FINALT:	final time of calculation in fm/c
10,	ILOW:	output level (default=10)
1,	IDILEPT:	=0 no dileptons; =1 electron pair; =2 muon pair
0,	ICQ:	=0 free,=1 drop. mass,=2 broad.,=3 drop.+broad.
0,	IHARD:	=1 hard collisions + direct charm/beauty, =0 no
0,	IBweight_MC:	=0 constant step in B =DBIMP; =1 B by MC
1,	IUSER:	=1 for general users; = 0 for PHSD team

MASSTA - mass of target nuclei
MSTAPR - number of protons in target nuclei
MASSPR - mass of projectile nuclei
MSPRPR - number of protons in projectile nuclei
ELAB - bombarding **'kinetic'** energy per nucleon in AGeV in laboratory frame (fixed target)
Center of mass energy: $s_{NN} = 2 \times m_N \times (\text{ELAB} + 2m_N)$ with $m_N = 0.938$ GeV.

AGS: $^{197}_{79}$Au

ELAB	$\sqrt{s_{NN}}$	NUM
2	2.70	250
4	3.32	250
6	3.84	250
8	4.30	250
10.7	4.86	240

SPS: $^{208}_{82}$Pb

ELAB	$\sqrt{s_{NN}}$	NUM
19.062	6.27	230
29.062	7.62	215
39.062	8.76	175
79.062	12.32	135
157.062	17.27	105

RHIC: $^{197}_{79}$Au

ELAB	$\sqrt{s_{NN}}$	NUM
29.728	7.7	225
43.241	9.2	175
68.620	11.5	145
110.198	14.5	120
202.900	19.6	95
386.717	27	80
808.892	39	65
2 073.689	62.4	50
9 006.653	130	40
21 320.086	200	30

BMIN - minimal impact parameter b in fm

BMAX - maximal impact parameter b in fm

DBIMP - step in impact parameter b in fm (Δb).

The code runs from BMIN to BMAX with the step DBIMP. For the calculation of final cross sections one has to perform the integration over impact parameter b with the weight $(2\pi b)$ from b_{min} to b_{max}.

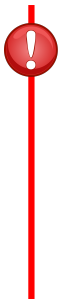
For example, the cross section for pion production in Au+Au collisions [in mb] in some centrality class from b_{min} to b_{max} is defined as

$$\sigma_\pi = 10 \int_{b_{min}}^{b_{max}} db\ 2\pi\ b\ A_\pi(b) \Rightarrow 10 \sum_{b_{min}}^{b_{max}} \Delta b\ 2\pi\ b\ A_\pi(b). \tag{1.4.1}$$

Here the factor 10 is to transform the result from fm^2 to mb. The function $A_\pi(b)$ is the pion multiplicity for given impact parameter b.

The multiplicity of particle type i (for given impact parameter b) is defined as the sum of all particles (type i) divided by the 'weight' factor (NUM·ISUBS):

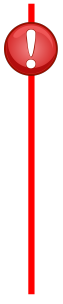
$$A_i(b) = \sum_{j=1}^{N_i} \frac{1}{\mathrm{NUM} \cdot \mathrm{ISUBS}}\ . \tag{1.4.2}$$



Please, even for p+p or p+d set DBIMP=1 (or some NON zero number!). This parameter is not used for p+p and p+d explicitly, however, enters in the organization of the main routine. The initialization for p+p is done by placing two protons in front of each other (i.e. b=0 fm). For the p+d collisions the deuteron target is initialized in momentum space using the Paris wave function with a high momentum tail – for the details see Ref. [22].

NUM - number of parallel events in each subsequent run ISUBS.

The HSD code is based on the parallel ensemble method (contrary to e.g. UrQMD, which is an event by event generator). In this way one can simulate simultaneously many (NUM) nucleus-nucleus collision - 'events'. The interaction between the particles is allowed *only* inside one event. However, such parallel ensemble algorithm allows to compute collective quantities (baryon or meson densities, temperature etc.) at a given time with good accuracy since the statistical fluctuations are much reduced by averaging over events. This is very important for the calculation of the hadron potentials (which depend on density etc.) as well as for the investigation of the in-medium properties of particles (since the spectral functions, self-energies also depend on density, temperature etc.).



Do not increase NUM too much! Remember - all produced particles are stored in the vectors, so, if NUM is too big, there is no storage left and the code will stop with the messages: *'Too many test particles'* if the number of initial baryons is beyond the limit or *'Too many mesons'* if the number of produced particles is out of dimension. In this case decrease NUM and alternatively increase ISUBS. Some 'optimal' NUM (for orientation) are given in the previous page.

ISUBS - number of subsequent runs
In order to improve statistics one can run the code many (ISUBS) times, but collect the output information in the same files (which simplifies the analysis). Equivalently: use ISUBS=1, but submit the job many times and store the output files.

ISEED - any integer number to initialize of random number generator

IDILEPT - flag to activate perturbative dileptons:
IDILEPT=0 - without dileptons,
IDILEPT=1 - electron pairs (e^+e^-),
IDILEPT=2 - muon pairs ($\mu^+\mu^-$)

ICQ - flag to activate the in-medium effects for vector mesons:
ICQ=0 - without in-medium effects (free spectral functions),
ICQ=1 - dropping mass scenario,
ICQ=2 - collisional broadening,
ICQ=3 - dropping mass + collisional broadening

IHARD - flag to activate hard collisions:
IHARD=0 - without
IHARD=1 - with charm and bottom production in primary hard collisions

IBweight_MC - impact parameter B chosen or not by Monte-Carlo
IBweight_MC=0 - B evaluated in the range [BMIN,BMAX] with a step DBIMP
IBweight_MC=1 - B evaluated in the range [BMIN,BMAX] by Monte-Carlo procedure (see chapter 2)

IUSER - default parameters for external users
IUSER=1 - parameters by default are used
IUSER=0 - parameters can be changed for the PHSD team

Note: p+A reactions
The proton initialization is done in form of a cylindrical beam profile perpendicular to the beam direction with transverse radius $R = R_T + 1$ fm, where R_T is the radius of the target nucleus. This implies that some 'distant' reactions will not show inelastic scattering. Such events can be excluded by (e.g.) looking at the final particles, e.g. the absence of newly produced particles indicates that this event is NOT inelastic. Also it is important to analyze the final events with respect to the experimental trigger conditions to obtain cross sections or multiplicities in accordance with the actual experimental setting.

The initialization of the pion beam in πA collisions is done in form of a cylindrical beam profile perpendicular to the beam direction with transverse radius $R = R_T + 1$ fm, where R_T is the radius of the target nucleus. This implies that some 'distant' reactions will not show inelastic scattering. Such events can be excluded by (e.g.) looking at the final particles: e.g. the absence of newly produced particles indicates that this event is NOT inelastic. Such events have to be excluded when calculating the total inelastic πA reaction cross section.

Note: $\pi^- A$ reactions
MASSPR and MSPRPR has to be set to zero for a pion beam! The parameters BMIN, BMAX, DBINP are NOT used for pion induced reactions. The initialization for $\pi - p$ is done by placing pion and proton in front of each other (i.e. b=0 fm).

Note: final propagation time t_{max}
The PHSD code is running with a dynamical time step up to the maximum time t_{max}. In order to simplify the initialization for the user we parametrized the time t_{max} as a function of the initial energy ($\sqrt{s}$):

$$t_{max} = 35 + \frac{170}{\sqrt{s}\ [\text{GeV}]} [\text{fm/c}] \tag{1.4.3}$$

This gives some 'optimal' computational time for the general tasks (particle multiplicities, spectra, rapidity distributions etc.) However, for some specific tasks (collective flow or some specific correlations) one needs to run the code longer (500 fm/c). Please, contact us for further explanations (or increase NTMAX in *main.f*).

1.4.2 General output files

The parameters for the output level (how much information are written out) is called `ILOW`. The default value is `ILOW = 10`, which provide the basic outputs:

- *fort.80* for complementary information,
- *fort.888* for general output and parameter settings,
- *fort.300* for baryons,
- *fort.301* for mesons,
- *phsd.dat* for all particles.

Please always keep the information files about the collision, i.e. *input* file and the parameter settings (*fort.888*) to know exactly which parameters were used in the simulation.

When one use `ILOW < 10`, there are more files written for more information. The main outputs *fort.15* and *fort.80* are written by a lot of different routines including the main routine. The output files for final particles *fort.300* and *fort.301* are written out by the routine `FINALOUT()` (in *pribig.f*).

The 'output' is written *after the decays* of all baryonic ($\Delta, N(1535), N(1440), \Sigma^*$) and mesonic ($\rho, \omega, \phi, a_1, \eta'$, all K^*) resonances, however, *before the weak decays* of strange particles (Λ and Σ). The momenta of final particles are given in the *nucleon-nucleon center-of-mass frame in GeV/c*.

Output file *fort.300* - final baryons

ID(j,1)	ID(j,2)	ISUB	IRUN	P_X	P_Y	P_Z	P_0	b
...	...	...	...	...	...	...	...	...

Output file *fort.301* - final mesons

IPI(j,1)	IPI(j,2)	ISUB	IRUN	P_X	P_Y	P_Z	P_0	b
...	...	...	...	...	...	...	...	...

- ID(j,1) or IPI(j,1) is the type of particle j (cf. Tables 1, 2)
- ID(j,2) or IPI(j,2) is the electric charge
- ISUB is the number of subsequent run, changes from 1 to ISUBS (maximum, defined in *input* file)
- IRUN is the number of current event, changes from 1 to NUM (maximum, defined in *input* file)
- P_X, P_Y, P_Z, P_0 are the 3-momentum and energy of particle j in the nucleon center-of-mass frame
- b is the current impact parameter in fm; it changes from b_{min} to b_{max} (defined in *input* file).

We provide an example of the **analysis routine** - file **analyse.f** - which shows how to calculate general observables such as multiplicities and rapidity distributions for p, π, K (as example) from **each A+A event individually** as well as averaged over all events.

1.4.3 Single file output

This output collect baryons, mesons and photons in one single file *phsd.dat*. It is convenient for event-by-event analysis and for MC simulations of detectors. Each stored event consists of header (2 lines) and particle list (number of lines defines in header).

Output file *phsd.dat* - all particles

N	ISUB	IRUN	b	IBweight_MC				
N_P	$\psi(2)$	$\varepsilon(2)$	$\psi(3)$	$\varepsilon(3)$	$\psi(4)$	$\varepsilon(4)$	$\psi(5)$	$\varepsilon(5)$
ID	Q	P_x	P_y	P_z	P_0	ID(J,5)/IPI(5,J)	$[X$	Y	Z	$T]$
...	...	...	...	...	...	...	...	...	...	...

For the header:

- N is the number of particles in event,
- `ISUB` is the current subsequent run,
- `IRUN` is the current parallel event,

- b is the current impact parameter in fm,
- `IBweight_MC` is the weight of the impact parameter in case of min bias,
- N_P is number of paticipants,
- $\psi(i)$ and $\varepsilon(i)$ are respectively the out-of-plane angle and the eccentricity of the i^{th} harmonic.

For the particle list:

- ID is type of particle in PDG notation,
- Q is electric charge,
- P_X, P_Y, P_Z, P_0 are the 3-momentum and energy of particle,
- `ID(J,5)`/`IPI(5,J)` is history of particle creation,
- $[X, Y, Z, T]$ are optional (if `IFemto`=1) coordinates of freeze-out.

Chapter 2

Initial conditions & dynamics

The PHSD code is based on the parallel ensemble method (simultaneous simulation of many events): this is important for the calculation of hadron potentials and in-medium properties of particles.

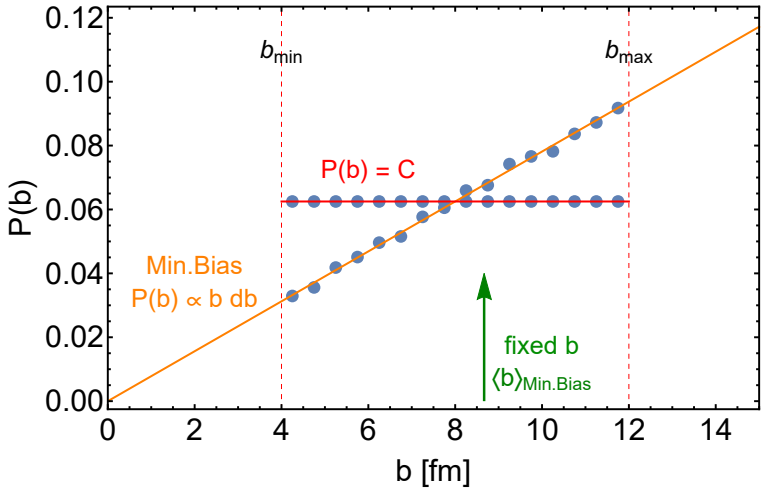


FIG. 2.1: Probability distribution $P(b)$ as a function of the impact parameter b in PHSD. One can use a fixed impact parameter, or a range (b_{min}, b_{max}), or the minimum bias distribution (see text for explanations).

For the initial impact parameter, the PHSD has several possibilities. For the minimum bias possibility, one can play with the distribution function using `IBweightMC=1` (in *main.f*). The minimum bias distribution is:

$$P(b) = \frac{2\pi\ b\ db}{\int_{b_{min}}^{b_{max}} 2\pi\ b\ db}, \tag{2.0.1}$$

In this case, the impact parameter would be chosen by Monte Carlo in the range (b_{min}, b_{max}) with the Min. Bias probability. One can also perform the calculation for a range (b_{min}, b_{max}) with a step DBIMP, with a constant probability (`IBweightMC=0`), or for a fixed value of the impact parameter, which would be the mean value of the Minimum Bias distribution on the range (b_{min}, b_{max}) : $\langle b \rangle_{Min.Bias} = \int_{b_{min}}^{b_{max}} b\ P(b)$

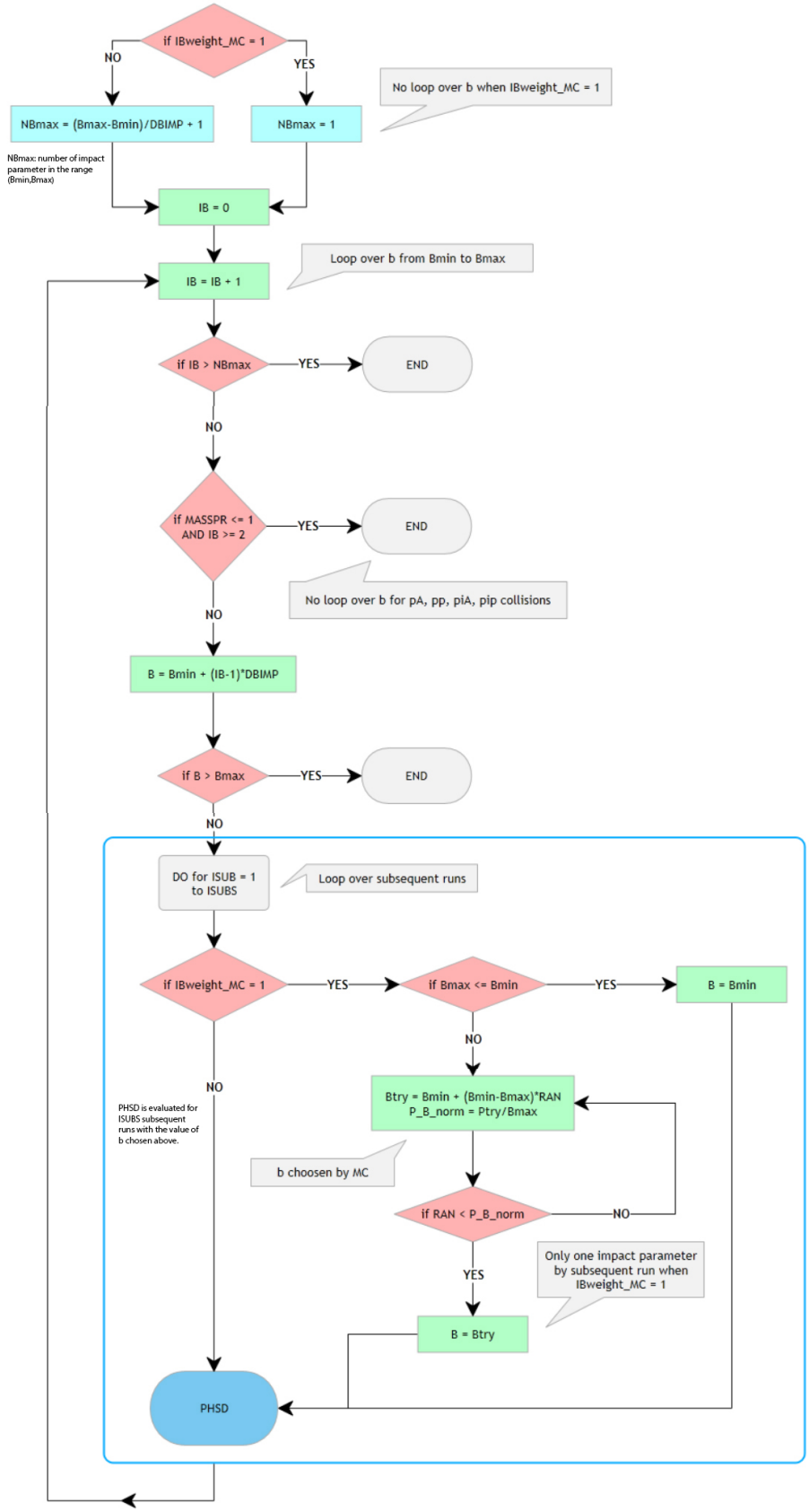


FIG. 2.2: Algorithm showing the two different options for the choose in impact parameter. For `IBweightMC=1` the impact parameter is chosen by Monte Carlo according to the Min. Bias probability. For `IBweightMC=0` it is simply chosen with a constant probability from a range (b_{min}, b_{max}) with a step DBIMP.

When you use IBweightMC=1 it means that the impact parameter b is chosen randomly (according to the Min.Bias probability $P(b)$), however for each selected b there will be NUM events simulated. The number of selected b correspond to ISUBS from *input*. Thus, when you set ISUBS=20, it means that you have **only** 20 values of impact parameter b. It is by example too small sampling for flow evaluation, in this case it is recommended to perform the calculation for a range (b_{min}, b_{max}) with a step DBIMP, and then weight the results with the Min. Bias probability.
Moreover, if you want to have all this NUM events at the same initial conditions (i.e. eccentricity), better to chose ISINGLE=1.

The total cross section of a reaction for a given range of impact parameter is :

$$\sigma_{tot} = \sum_{i=b_{min}}^{b_{max}} \sum_{j=events} N_i^j \times \sigma_{geom}, \tag{2.0.2}$$

with

$$\sigma_{geom} = \pi(b_{max}^2 - b_{min}^2). \tag{2.0.3}$$

Initial condition of PHSD [23]:

For example for a fixed impact parameter b, one use many parallel events NUM, and/or subsequent runs ISUB. For each event, we initialize the system in coordinate and momentum space.

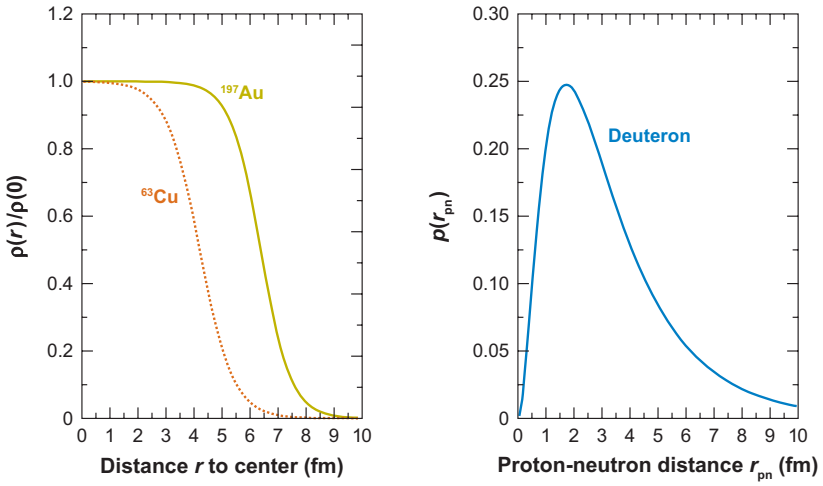


FIG. 2.3: (Left) Density distributions for nuclei used at RHIC. (Right) Distribution of the proton-neutron distance in the deuteron as given by the Hulthén wave function (from Ref. [23]).

The initial nucleon density is usually parameterized by a Fermi distribution with three parameters, known as the Wood-Saxon distribution:

$$\rho(r) = \rho_0 \frac{1 + \omega(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}, \tag{2.0.4}$$

where ρ_0 corresponds to the nucleon density in the center of the nucleus, $R = R_0 A^{1/3}$ corresponds to the nuclear radius (with A the atomic number and $R_0 = 1.096$ fm (in PHSD) being the volume occupancy of a nucleon), a to the skin depth, and ω characterizes deviations from a spherical shape. For ^{197}Au ($R = 6.38$ fm, $a = 0.535$ fm, $\omega = 0$) and ^{63}Cu ($R = 4.20641$ fm, $a = 0.5977$ fm, $\omega = 0$), the nuclei so far employed at RHIC, $\rho(r)/\rho_0$ is shown in Figure 2.3 (left). In the Monte Carlo procedure, the radius of a nucleon is drawn randomly from the distribution $4\pi r^2 \rho(r)$ (where the absolute normalization is of course irrelevant).

In momentum space, the initial energy for each nucleon is determined using Fermi motion

$$p_F = \hbar c \left(\frac{3}{2}\pi^2 \rho\right)^{1/3}, \tag{2.0.5}$$

with $\rho = \rho(r)$ given by the Wood-Saxon distribution in space. The initial momentum is given by Monte-Carlo as $0 < p < p_F$.

2.1 String models: FRITIOF & PYTHIA

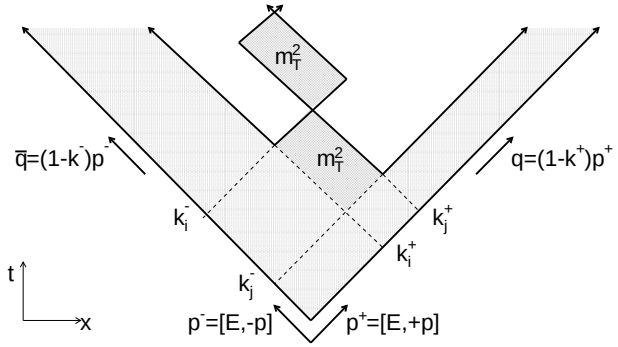


FIG. 2.4: Formation of hadrons from the Lund string picture.

$\sigma_{qq-N} = \frac{1}{3}\sigma_{N-N}$ leading.

σ_{m-m},σ_{m-B},σ_{q-B},$\sigma_{\bar{q}-B}$

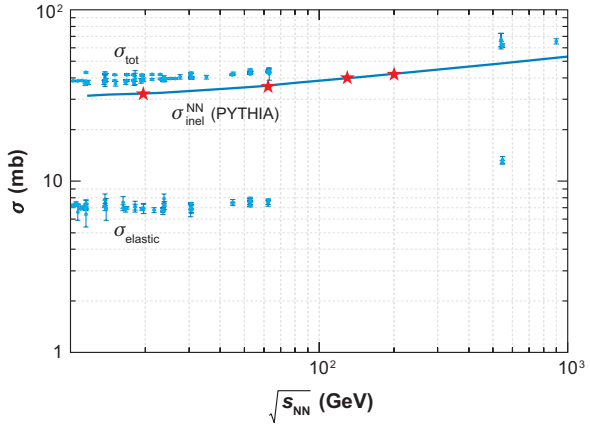


FIG. 2.5: The inelastic nucleon-nucleon cross section σ_{inel}^{NN} as parameterized by PYTHIA (*solid line*), in addition to data on total and elastic nucleon-nucleon cross sÂĄections as a function of $\sqrt{s}$ (from Ref. [23]).

2.2 Low energies: from AGS to SPS

2.3 High energies: from RHIC to LHC

2.4 Hadrons dynamics

`StatTimeOut(time)` (in *pribig.f*) called in `main` gives statistics in time for baryons and mesons in output files *fort.310* and *fort.311*.

The subroutine `MASS_SF_DELTA()` (in *sf_lib.f*) defines the masses of Δ-resonances through Breit-Wigner spectral functions.

The string formation is given through the routine `RELCOL` (in *collis.f*). For $B - B$, one call `FRITZI()`, and for $m - B$ one call `FRITZIPI()`.

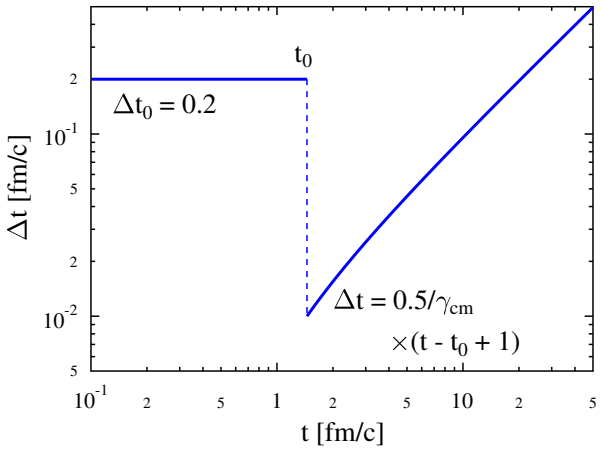


FIG. 2.6: Time step as a function of time evolution.

The calculations of mean fields, collisions, etc in PHSD are done using a 3D-grid of size $2 \times 28 = 56$ in each direction xyz. The size of the grid is 1 fm $\times$ 1 fm $\times 1/\gamma_{NN}$ fm $= 2\Delta t$ respectively in xyz direction. The size of the grid in the z-direction is linearly increasing in time, as well as the time step Δt. Then, the number of particle in each cells evolves smoothly in time.

For the calculation of macroscopic quantities such as the elliptic flow v_2, one must run the code up to $t_f = 500$ fm/c to be sure to reach the kinetic freeze-out.

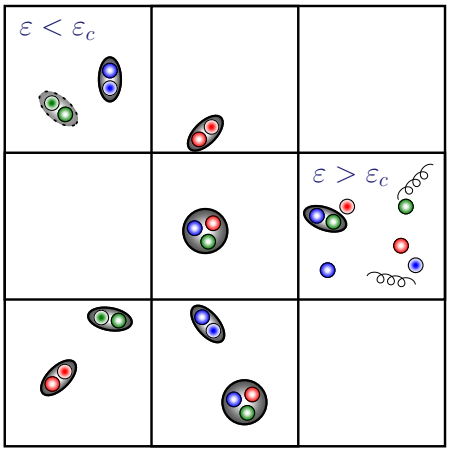


FIG. 2.7: Collisions and hadronization in cells depending on the local energy density ε, compared to the critical energy density $\varepsilon_c = 0.5$ GeV/fm^3.

For collisions of 2 particles, we use `COLLCRIT(P1,P2,s,t,Deltat,IFL)` which is a standard geometrical collision, according to the Kodama's prescription (in `GLUESCAT`).

The calculation of energy density which is used for mean field and cross sections, is done in two different routines for hadrons and for partons. For hadrons, the routine is `EnDensETRANS()` (in file *pribig.f*), and for partons, the routine is `PADENS()` (in file *partons.f*). For each case, the method is the same: for all cells, one compute the velocity of the cell from the velocity of the particles inside:

$$\vec{v}_{xyz} = \sum_i \frac{\vec{p}_i}{E_i}. \tag{2.4.1}$$

Then one extract the energy in local rest frame for hadrons and/or for partons.

Each time step, collisions are done with a loop over all parallel events inside collisions subroutines. First for BB collisions, we use the routine `RELCOL()` (in *collis.f*) for all baryonic channels (Monte-Carlo over all possible processes). All collisions are done in the BB cms frame. The *calculational frame* is the cms frame for NN. For high energy scattering $\sqrt{s} > \sqrt{s_0} = 2.6$ GeV, we call the Lund string routine fragmentation routine `FRITZI()`. For low energy scattering $\sqrt{s} < \sqrt{s_0}$, we are doing $BB \to BB + m$ or $BB \to BB' \to BB + m$ collisions (including resonances), we call the routine `CROSW()` (in *cbuu.f*)

for non-strange BB collision, or strangeness collision routines. Then for mesons scattering (mm or mB) we use the routine `PIONDI()`.

For the meson-baryon collisions, we use the routine `PIONAB()`. The test for collisions is done with two loops over mesons and baryons from the same parallel run (`NUM` and `ISUB`). As for BB collisions, we distinguish high energy scattering and low energy scattering. When $\sqrt{s} > \sqrt{s_0} = 2.6$ GeV, we call `FRITZIPI()` (in *fritzi.f*) for $mB \to X$. When $\sqrt{s} < \sqrt{s_0}$, we call low energy routines (including strangeness production), for $mB \to B'$ or $mB \to mB$ (elastic or inelastic).

For meson-meson collisions, we use the routine `PIONCO()` (no string excitation). This routine includes $mm \to m'$ (ex: $\pi\pi \to \rho$), and $mm \to mm$ (elastic or inelastic).

For all the hadronic decays (in *decays.f*), we use the decay width Γ taking into account the in-medium effect, and we compute the decay probability:

$$\omega = \exp\left(-\frac{\Delta t \times \Gamma(M)}{\gamma \hbar c}\right), \tag{2.4.2}$$

with $\Gamma(M) = \Gamma_{vac}(M) + \Gamma_{coll}(\rho)$ and $\Gamma_{coll}(\rho) = \alpha \frac{\rho_B}{\rho_0}$.

About the formation time, we use the routine `FORMA()` (in *collis.f*) for baryons and mesons. The normal "formed" hadrons have an identification number which is below 1000. For hadrons which are not yet formed, their identification number is increased by 1000. Hadrons are not formed if their formation time $\tau_f = 0.8$ fm/c ($t_f = \gamma\tau_f$ in calculational frame) is not reached. For example in BB initial hard collisions, the leading quarks and diquarks from the string are still prehadrons. When $t > t_f$ the pre-hadrons become hadrons and can collide and interact again. We also consider as pre-hadrons the hadrons which are in the high density phase where the energy density ε is greater than the critical energy density $\varepsilon_c = 0.5$ GeV/fm^3. In the plasma phase, the hadrons can only decay.

Baryon properties:

- `ID(I,1)` = type (+1000 if pre-hadron), anti-baryons get a negative sign,
- `ID(I,2)` = charge,
- `ID(I,3)` = last colliding partner,
- `ID(I,4)` = for resonances: how many times the meson was created,
- `ID(I,5)` = type of process from which the particle comes,
- `ID(I,6)` = abs: number of baryon collision; sign: target or projectile,
- `ID(I,7)` = strangeness content,
- `ID(I,8)` = 3 formed hadron; = 2 pre-hadron/leading baryon (have a formation time τ_f). Leading baryons are still allowed to interact with reduced cross sections:
  - $\sigma(q - B) = 1/3\ \sigma(BB) \approx 10$ mb,
  - $\sigma(qq - B) = 2/3\ \sigma(BB) \approx 20$ mb,
  - $\sigma(q - qq) = 2/9\ \sigma(BB) \approx 7$ mb.
- `R(1-3,I)` = coordinates x, y, z in fm,
- `E(I)` = mass (on/off-shell) in GeV,
- `P(1-3,I)` = momentum p_x, p_y, p_z in GeV,
- `P(4,I)` = production (creation) time,

- `P(5,I)` = individual formation time τ_f.

Description of `ID(I,5)` for baryons, which gives the reaction where the baryon was created:

- = 200: string or non-string baryon formation from qqq,
- = 201: meson formation from qqq-string,
- = 220: hadronization from recombinaison (in `RECOM`).

Mesons properties:

- `IPI(I,1)` = type (+1000 if pre-hadron),
- `IPI(I,2)` = charge,
- `IPI(I,3)` = ID of the parent resonance of meson I
- `IPI(I,4)` = how many time the meson was created (+ for π, − for η),
- `IPI(I,5)` = type of the parent resonance (`ID(IPI(I,3)),1)`) or reaction (see list below),
- `IPI(I,6)` = recording of kaons channel,
- `IPI(I,7)` = strangeness content,
- `IPI(I,8)` = 3 final meson; else quark or antiquark; = 1: leading mesons (`IPI(I,1)` ¡ 1000),
- `RPI(1-3,I)` = coordinates x, y, z in fm,
- `PPI(1-3,i)` = momentum p_x, p_y, p_z in GeV,
- `PPI(4,i)` = energy (on/off-shell) in GeV,
- `PPI(5,i)` = production (creation) time,
- `PPI(6,i)` = `PPI(8,i)` = baryon density at creation time,
- `PPI(7,i)` = individual formation time τ_f.

Description of `IPI(I,5)` for mesons, , which gives the reaction where the meson was created:

- = 4: from η'-decay,
- = 5: from ϕ-decay,
- = 6: from ω-decay,
- = 7: from $K^\star$-decay,
- = 8: π from ρ-decay,
- = 9: ρ from $\pi + \pi \to \rho$ or ϕ from $K + \tilde{K} \to \phi$,
- = 10: K from $\pi + \pi \to K + \tilde{K}$,
- = 11: K from $N + N \to N + N + K + \tilde{K}$,
- = 12: $\tilde{K}$ from $\pi + N \to N + K + \tilde{K}$,
- = 13: K from $N + N \to N + Y + K$ or $\pi + N \to N + K + \tilde{K}$,
- = 14: a_1 from $\pi + \rho \to a_1$,
- = 15: ϕ from $\pi + \rho \to \phi$,
- = 16: π from $N + N \to N + N + \pi$ $(s - state)$,
- = 17: String from BB-interactions,
- = 18: annihilation,
- = 19: String from mB-interactions,
- = 20: from $K + N \to \pi + Y$,
- = 21: from $\pi + Y \to K + N$,
- = 22: from $\pi + N \to K + Y$,

- = 25: from $K + Y \to \pi + N$,
- = 26: from $K + \bar{K} \to pi + pi$,
- = 27: from $K + \pi \to K^{\star}$,
- = 28: from $a_1 \to \pi + \rho$,
- = 34: from $\pi + K^* \to K(1400)$,
- = 37: from $K^*(1440)$ decay,
- = 39: from $\pi + \eta \to a_0$,
- = 47: from a_0 decay,
- = 77: from κ decay,

kaons from NN collisions:

- = 1: from $N + N \to N + \Lambda + K$,
- = 2: from $N + N \to N + \Sigma + K$,
- = 3: from $N + \Delta \to N + \Lambda + K$,
- = 4: from $N + \Delta \to N + \Sigma + K$,
- = 5: from $\Delta + \Delta \to N + \Lambda + K$,
- = 6: from $\Delta + \Delta \to N + \Sigma + K$,

with photons:

- = 40: $m + m \to m + m + \gamma$,
- = 50: $\pi + \pi \to \rho + \gamma$,
- = 51: $\omega \to \pi_0 + \gamma$,
- = 60: $\pi + \rho \to \pi + \gamma$,
- = 70: $\omega \to \pi^0 + \gamma$,
- = 80: η from ϕ-decay : $\phi \to \eta + \gamma$,
- = 90: $a_1 \to \pi + \gamma$,
- = 100: vector meson production by low energy BB collisions ($BB \to V + BB$),
- = 101: vector meson production by low energy mB collisions ($mB \to V + B$),
- = 102: rho meson production by low energy BB collisions ($NN \to N(1520) + N \to \rho + NN$),
- = 103: rho meson production by low energy mB collisions ($pi + N \to N(1520) \to \rho + N$),
- = 103: $\eta + m \to \phi + \pi$,
- = 104: $\phi + \pi \to \eta + m$,
- = 105: elastic collisions $V + N \to V + N$,
- = 30: η from $NN \to \eta + NN$ (Lund),
- = 31: ϕ from $NN \to \phi + NN$ (Lund),
- = 88: η from $\pi n \to \eta + \Delta$,
- = 89: η from $\pi n \to \eta + n$,
- = 36: $K + Y \leftrightarrow \pi + \Xi$ and $K + \Xi \leftrightarrow \pi + \Omega$,
- = ICHAN (in NEWCHAN, by default = 0): $Y + Y \leftrightarrow \Xi + N$,

with Charm:

- = 160: Charm from hard BB collisions,

- $= 161$: $DB \to \Lambda_c \pi$,
- $= 165$: D^* decay ($\to D + \pi$ or γ),

from parton phase:

- $= 200$: non-string meson formation from qq,
- $= 201$: meson formation from qq-string,
- $= 220$: hadronization from recombinaison (in `RECOM`),
- $= 99$: 'quasiparticle' ρ-meson from $\pi + \pi$ annihilation.

with $K = (K^+, K^0, K^{+\star}, K^{0\star})$ and $\tilde{K} = (K^-, \bar{K}^0, K^{-\star}, \bar{K}^{0\star})$.
Output of kaon statistics from field `kprod`, for production:

- `kprod(1,-1)=` K from BB-string,
- `kprod(1,1)=` $\tilde{K}$ from BB-string,
- `kprod(2,-1)=` K from mB-string,
- `kprod(2,1)=` $\tilde{K}$ from mB-string,
- `kprod(3,-1)=` should be 0,
- `kprod(3,1)=` $\tilde{K}$ from $\Upsilon + \pi \to K + N$,
- `kprod(4,-1)=` K from $N + \pi \to \Upsilon + K$,
- `kprod(4,1)=` should be 0,
- `kprod(5,-1)=` K from $m + m \to K + \tilde{K}$,
- `kprod(5,1)=` $\tilde{K}$ from $m + m \to K + \tilde{K}$,
- `kprod(6,-1)=` K from $B\bar{B}$ annihilation,
- `kprod(6,1)=` $\tilde{K}$ from $B\bar{B}$ annihilation,
- `kprod(7,-1)=` K from ϕ-decay,
- `kprod(7,1)=` $\tilde{K}$ from ϕ-decay,

and for absorption:

- `kprod(-2,-1)=` K absorption from mB-string,
- `kprod(-2,1)=` $\tilde{K}$ absorption from mB-string,
- `kprod(-3,-1)=` K absorption from $K + N \to \Upsilon + \pi$,
- `kprod(-3,1)=` $\tilde{K}$ absorption from $\tilde{K} + \Upsilon \to N + \pi$.

Possible state of the parameter `gpa`:

- `gpa(1)` : rescattering on/off,
- `gpa(2)` : time step size: $= 1$ fixed time step resc(1); $= 2$ dynamical time step size, parameters `resc(2)`, `resc(3)`,
- `gpa(3)` : calculation and output of density on/off,
- `gpa(4)` : `RELCOL` on/off,
- `gpa(5)` : Fermi motion in/out,
- `gpa(7)` : J/Ψ production on/off,
- `gpa(8)` : string fragmentation on or off (0 or 1),
- `gpa(9)` : meson scattering on or off (1 or 0)(default=1),
- `gpa(10)`: meson-meson scattering on or off (1 or 0)(default=1),
- `gpa(11)`: annihilation on/off (default=1),
- `gpa(12)`: momentum output of p, π, K at the end [0/1] ?,

- gpa(13): $\rho + \pi \to a_1/\phi$ included/excluded [1/0],
- gpa(14): production or $B\bar{B}$-pairs from mm-collisions on/off [1/0],
- gpa(15): elastic $\pi\pi$ scattering,
- gpa(16): grid size in z-direction: $1 \to dz = 1$; $2 \to dz = 1/\gamma_{cm}$,
- gpa(22): number of different string radii in 0.1 fm steps starting from resc(22),
- gpa(40): $3D$-plot output for Mathematica, only if NUM=1.

Possible state of the parameter resc:

- resc(1) : time step size for gpa(2)=1 (default 0.2),
- resc(2) : time step size for gpa(2)=2 during high density phase: dt = resc(2)$/\gamma_{cm}$ (default 0.5),
- resc(3) : time step size for gpa(2)=2 during formation phase: dt = resc(2)$/\gamma_{cm}$ (default 2.0),
- resc(4) : max. impact parameter for $\pi + N$ in fm (default 4.0),
- resc(5) : max. impact parameter for $m + m$ in fm (default 2.0),
- resc(6) : low energy ϕ absorption cross-section (5.0 mb),
- resc(7) : low energy ρ absorption cross-section (10.0 mb),
- resc(8) : low energy η' absorption cross-section (10.0 mb),
- resc(9) : low energy ω absorption cross-section (10.0 mb),
- resc(10): fraction of $\tilde{K}N \to \Lambda$ of the total $\tilde{K}$ absorption cross-section. (default value: 0.2),
- resc(11): fraction of $\tilde{K}N \to \Sigma$ of the total $\tilde{K}$ absorption cross-section. (default value: 0.15),
- resc(12): $c\bar{c}N$ absorption cross-section in mb (default 6.0 mb),
- resc(13): $J/\Psi N$ absorption cross-section in mb (default 3.0 mb),
- resc(14): formation time $c\bar{c} \to J/\Psi$ in fm (default 0.3 fm),
- resc(15): b_{max} for $nn \to J/\Psi$ in fm (default=1.0),
- resc(17): impact parameter for $mm \to B\bar{B}$ in fm, (gpa(14)=1),
- resc(18): cross-section for $mm \to K\tilde{K}$ in mb (for each isospin-chanal),
- resc(19): string threshold BB in GeV,
- resc(20): string threshold mB in GeV,
- resc(21): 'formation time' for J/Ψ in fm (default -1.5),
- resc(22): minimal string-radius for J/Ψ absorption,
- resc(23): elastic cross section for baryon meson,
- resc(40): time step size of output for Schertler movie.

Internal parameter in RELCOL and PIONAB:

- IBLOCK = 0, nothing has happened,
- IBLOCK = 1, elastic nn collision,
- IBLOCK = 2, $n + n \to n + \Delta$,
- IBLOCK = 3, $n + \Delta \to n + n$,
- IBLOCK = 4, $n + n \to n + N^\star$,
- IBLOCK = 5, $n + N^\star \to n + n$,
- IBLOCK = 6, $n + n \to n + N^{\star 2}$,

- IBLOCK = 7, $n + N^{\star 2} \to n + n$,
- IBLOCK = 8, $n + \Delta \to n + N^{\star 1}$,
- IBLOCK = 9, $n + N^{\star 1} \to n + D$,
- IBLOCK =10, $n + \Delta \to n + N^{\star 2}$,
- IBLOCK =11, $n + N^{\star 2} \to n + D$,
- IBLOCK =12, $n + N^{\star 1} \to n + N^{\star 2}$,
- IBLOCK =13, $n + N^{\star 2} \to n + N^{\star 1}$,
- IBLOCK =14, $\Delta + \Delta \to n + N^{\star 1}$,
- IBLOCK =15, $\Delta + \Delta \to n + N^{\star 2}$,
- IBLOCK =16, $n + n \to n + n + \pi$ s-state,
- IBLOCK =17, string fragmentation.

Identification of hadrons in (P)HSD, see the routines in *fritzi.f*:

- TRANSPOSECODE() to convert from (P)HSD to LUND using KFHSD(ID1,ID2)= number in LUND (e.g. KFHSD(1,1)= 2212 is the proton),
- HSDID() to convert from LUND to (P)HSD using the number from LUND to ID1+1000.

2.5 Heavy flavors

2.5.1 Charm quark dynamics

2.5.2 Open/hidden heavy flavors

Modifications are done in:

- **main.f** – follow flag IHARD,
- **charm.f**, **charm1.f**, **charm_in.f** – new subroutines,
- **fritzi.f** – in subroutine FRITZI, FRITZIPI, STRINGSNEW,
- **pribig.f** – in subroutine STATTIMEOUT,
- **COMMON**.

Production of $c\bar{c}$ pairs in primary hard collisions

[1] Initial flag for hard collision
- IHARD = 1 read in **main.f** from *input* and stored in COMMON,
- IHARD $\neq$ 1 compute hard collisions.

[2] Call SUBROUTINE HARDCOLL(...) from **main.f**
Pre-calculation of the primary hard collisions using the Glauber model and "free trajectories" (in file **charm.f**).

Code charm.f

```
SUBROUTINE HARDCOLL(TIME,IAVOID)
! calculates all possible hard primary NN collision
    in each
! event IRUN and store hard collision partners,
    time and
! position in BINCOLL(...)

JNC=INCOUNT(IRUN)
BINCOLL(IRUN,JNC,1)=FLOAT(I1) ! Collision partner
    I1
BINCOLL(IRUN,JNC,2)=FLOAT(I2) ! Collision partner
    I2
BINCOLL(IRUN,JNC,3)=TIME-TSHIFT1 ! Actual collision
    time
BINCOLL(IRUN,JNC,4)=(X1+X2)/2. ! Actual x-posit. of
    vertex
BINCOLL(IRUN,JNC,5)=(Y1+Y2)/2. ! Actual y-posit. of
    vertex
BINCOLL(IRUN,JNC,6)=(Z1+Z2)/2. ! Actual z-posit. of
    vertex
```

[3] Call `SUBROUTINE COLLPART(SRT)` from **main.f**
Select from `BINCOLL` (all pre-calculated hard events) hard primary collision events where charm will be produced by Monte-Carlo with respect to the probability $P = \sigma_{c\bar{c}}/\sigma_{NN\text{inel}}$. Here binomial distribution is used! All done is `SUBROUTINE COLLPART(SRT)` called from **main.f**. The selected NN collisions, which will produce charm pair, are stored in the vectors:

Code charm.f

```
CHARMSTORE(IRUN,MEVE,1)= PROPER(I1,ITRY,1) ! time
    for the ccbar production
! Precalculated position in (x,y,z) for the charm
    pair production:
CHARMSTORE(IRUN,MEVE,2)= PROPER(I1,ITRY,2) ! x
CHARMSTORE(IRUN,MEVE,3)= PROPER(I1,ITRY,3) ! y
CHARMSTORE(IRUN,MEVE,4)= PROPER(I1,ITRY,4) ! z
! Store successful collision partners for event
    MEVE in ICHARMSTORE(..)
ICHARMSTORE(IRUN,MEVE,1)= I1+INB          ! partner 1
ICHARMSTORE(IRUN,MEVE,2)= HARD(I1,ITRY) ! partner 2
```

[4] Call `SUBROUTINE CC4PHSDConversion` from **main.f**
subroutine to simulate $D\bar{D}$ (or $c\bar{c}$) pairs and store them in the general PHSD meson vectors (`IPI(JK)` and `PPI(K,J)`, `RPI(K,J)`) using the precalculated hard vertexes from subroutine `COLLPART(SRT)` stored in `ICHARMSTORE(IRUN,K,1)` and `CHARMSTORE(IRUN,K,L)`, `L=1-4` – (precalculated time and position for the charm production) using `MEVE=CHARMS`

(IRUN) – the total number of successful charm production "events" (i.e. hard NN collisions) for each IRUN.
For the production of $D\bar{D}$ (or $c\bar{c}$) the event generator from Taesoo Song is used which is base on the PYTHIA events keeping the angular correlations between $D\bar{D}$. The produced D-mesons get id's ID_Dmeson + 1000, i.e. stored as prehadrons.
Important: the produced $D\bar{D}$ got the formation time at the local frame TFORMA= 0.3 fm/c, the formation time in the calculational frame t_F =TFORMA$\cdot\gamma$. The D-meson can become a "real" or "formed' (with ID < 1000)only after passing the total formation time, i.e. if $t_F = 0.3$ fm $+t_{\rm creation}$ (stored in PPI(7,J)) and being in a cell with energy density $\varepsilon < \varepsilon_c = 0.5$ GeV/fm^3.

Energy lost of colliding nucleons is accounted. The "chemistry" (or type) of produced $D\bar{D}$ pairs is defined as ratio of the partial cross section to the total cross section:

- STOT is $D\bar{D}$ (or $c\bar{c}$) pair cross section at energy SRT in mb,
- SDMES(12) is the partial charm production cross sections for $D/\bar{D}$-mesons of type i=1,12.

[5] The produced $D\bar{D}$ mesons appear as a prehadrons and can become hadrons only after passing "formation time" which is in reality the shifted production time ($+0.3\gamma-$ real formation time) due to the precalculation technic.
They can be dissolve if the production time PPI(4,J) is above the actual time and they still have ID>1000 (i.e under formation time = 0.3γ and in a hot cell) The dissolution is realized in SUBROUTINE DISSOLVE(TIME,IV) (stored in **parton.f**) look for meson loop.

[6] Interaction in QGP described via parton+parton elastic and inelastic scattering $q/\bar{q}$,g with SUBROUTINE GLUESCAT(DTO,TIME,IFUSE). Presently done with respect to the "standard" DPQM cross sections which are temperature dependent (cf. Vitalii PhD Thesis and Fig. 2 in Ref. [24]).

[7] Hadronization from **main.f**

- SUBROUTINE HADRONIZATION(DTO,TIMEO,IV): formed mesons from $q+\bar{q}$ (color neutral) and baryons from $q+q+q$ using mixed ensemble method in **main.f**: use IBSKIP=1 to skip baryon formation,
- SUBROUTINE STR_Hadronize(...): quark-quark(-quark) interaction with further hadronization by LUND string fragmentation model. Produced hadrons are stored, initial string is "killed".

Table 2.1: ID's in the production subroutine `DmesonCR(...)`.

IDin	type	mass [GeV]
1	D^0	1.864
2	$\bar{D}^0$	1.864
3	D^+	1.869
4	D^-	1.869
5	D^{0*}	2.007
6	$\bar{D}^{0*}$	2.007
7	D^{+*}	2.010
8	D^{-*}	2.010
9	D_s^+	1.969
10	D_s^-	1.969
11	D_s^{+*}	2.110
12	D_s^{-*}	2.110

Table 2.2: The **open charm mesons** identification code and content.

IPI(j,1)	type	IDin	content
15	$D^\pm$	3/4	$c\bar{d}/\bar{c}d$
16	D^0	1	$c\bar{u}$
17	$\bar{D}^0$	2	$\bar{c}u$
18	$D^{\star\pm}$	7/8	$c\bar{d}/\bar{c}d$
19	$D^{\star 0}$	5	$c\bar{u}$
20	$\bar{D}^{\star 0}$	6	$\bar{c}u$
23	D_s^+	9	$c\bar{s}$
24	D_s^-	10	$\bar{c}s$
25	$D_s^{\star +}$	11	$c\bar{s}$
26	$D_s^{\star -}$	12	$\bar{c}s$

Table 2.3: The **perturbative charm meson** identification codes.

IPPI(j,1)	type	mass [GeV]
1	D^0	1.864
2	$\bar{D}^0$	1.864
3	D^+	1.869
4	D^-	1.869
5	D^{0*}	2.007
6	$\bar{D}^{0*}$	2.007
7	D^{+*}	2.010
8	D^{-*}	2.010
9	D_s^+	1.969
10	D_s^-	1.969
11	D_s^{+*}	2.110
12	D_s^{-*}	2.110
13	χ_c	3.510
14	J/Ψ	3.097
15	Ψ'	3.686

2.5.3 Perturbative charm

Input file

Input file (*input*) for Au+Au @ 200 GeV - min bias

```
197,      MASSTA:   target mass
79,       MSTAPR:   protons in target
197,      MASSPR:   projectile mass
79,       MSPRPR:   protons in projectile
21300.,   ELAB:     lab energy per nucleon
0.5,      BMIN:     minimal impact parameter [fm]
6.0,      BMAX:     maximal impact parameter [fm]
0.5,      DBIMP:    impact parameter step [fm]
10,       NUM:      number of parallel events
1,        ISUBS:    number of subsequent runs
4567,     ISEED:    initial random seed [integer]
1,        ICHARM:   perturbative charm degrees of freedom =0 no, =1 yes
0,        IDILEPT:  =0 no dileptons, =1 electron pair, =2 muon pair
0,        ICQ:      =0 free, =1 drop. mass, =2 broad., =3 drop.+broad.
1,        IGLUE:    =1 with partons, =0 w/o partons
40.,      FINALT:   final time of calculation [fm/c]
0,        IHARD:    =1 hard collisions + direct charm/beauty, =0 no
10,       ILOW:     output level
```

Output files

Besides the standard output files – *fort.300* and *fort.301* - PHSD provides the output *fort.570* for perturbative charm (if the ICHARM option is set to 1).

Output file *fort.570* - final charm mesons

IPI(j,1)	IPI(j,2)	ISUB	IRUN	P_X	P_Y	P_Z	P_0	weight(j)	b
...	...	...	...	...	...	...	...	...	...

- IPPI(j,1) is the type of charm meson j (cf. Tables 3)
- IPPI(j,2) is the electric charge
- ISUB is the number of subsequent run, changes from 1 to ISUBS (maximum, defined in *input* file)
- IRUN is the number of current event, changes from 1 to NUM (maximum, defined in *input* file)
- P_X, P_Y, P_Z, P_0 are the 3-momentum and energy of particle j in the nucleon center-of-mass frame
- $weight(j)$ is the weight of perturbative charm meson j
- b is the current impact parameter in fm; it changes from b_{min} to b_{max} (defined in *input* file).

fort.570 is written after the electromagnetic decay of $\chi_c \to \gamma + J/\Psi$. The decay fraction is taken as in Ref. [25]).

Note: The multiplicity of perturbative particles of type i (for given impact parameter b) is defined as the sum of all particles (type i) with the weight divided by the factor (NUM·ISUBS):

$$A_i^{\text{pert}}(b) = \sum_{j=1}^{N_i} \frac{\text{weight}(j)}{\text{NUM} \cdot \text{ISUBS}}. \tag{2.5.1}$$

Chapter 3

Electromagnetic probes

3.1 Dileptons

The dilepton routines are included in PHSD v2.3. This version has been extended also for simulations of elementary pp and pd reactions as well as for low energy nucleus-nucleus collisions.

This version of PHSD can be used also for π^-p and π^-A reactions. It includes also **in-medium effects for vector mesons**, i.e. the dropping mass scenario and collisional broadening. The vector mesons are produced and propagated with their in-medium spectral functions using off-shell dynamics (see Refs. [26, 27, 28, 29]).

The dilepton ($l^+l^- = e^+e^-$ or $\mu^+\mu^-$) spectra are calculated perturbatively with the time integration method. For the details of the dilepton implementation see our review [13] and also Refs. [30, 29, 22, 31, 32, 33, 34, 35]. The time integration is perfomed over the actual dilepton emission rate during the full reaction time (contrary to the 'spontaneous decay' assumption which counts the dilepton radiation only at freeze-out). All branching ratios, electromagnetic partial and total decay widths are taken from the PDG [36].

The pn and $\pi^\pm N$ bremstrahlungs are calculated in the soft-photon approximation (SPA). Only elastic pn and $\pi^\pm N$ collisions are accounted in the bremsstrahlung (i.e. $pn \to pne^+e^-$, $\pi^\pm N \to \pi N e^+e^-$). We stress that the SPA approximation might be considered as an upper limit for the bremsstrahlung contribution (especially for πN !). The bremsstrahlung channels are switched off for $E_{\rm lab} \geq 6$ GeV since it is very questionable to use the SPA at high energies.

The channel $\rho \to e^+e^-$ includes the dilepton radiation by all rho mesons produced in baryon-baryon, meson-baryon or meson-meson (e.g. $\pi^+\pi^-$ annihilation) collisions. The same holds for the other mesons – $\rho, \eta, \omega, \phi, J/\Psi, \Psi'$.

3.1.1 Dalitz decays $A \to B\ l^+l^-$

Here l^+l^- are electron e^+e^- or muon $\mu^+\mu^-$ pairs, i.e. $m_l = m_e = 0.511 \cdot 10^{-3}$ GeV or $m_l = m_\mu = 0.105658389$ GeV. For convenience, one can define the quantity:

$$A = \left(1 - 4\frac{m_l^2}{M^2}\right)^{1/2} \left(1 + 2\frac{m_l^2}{M^2}\right) \tag{3.1.1}$$

where M if the mass of the decaying particle.

Table 3.1: Dilepton channels

i	Dilepton channels	
1	Dalitz decay of π^0:	$\pi^0 \to \gamma e^+ e^-$
2	Dalitz decay of η:	$\eta \to \gamma l^+ l^-$
3	Dalitz decay of ω:	$\omega \to \pi^0 l^+ l^-$
4	Dalitz decay of Δ:	$\Delta \to N l^+ l^-$
5	Direct decay of ω:	$\omega \to l^+ l^-$
6	Direct decay of ρ:	$\rho \to l^+ l^-$
7	Direct decay of ϕ:	$\phi \to l^+ l^-$
8	Direct decay of J/Ψ:	$J/\Psi \to l^+ l^-$
9	Direct decay of Ψ':	$\Psi' \to l^+ l^-$
10	Dalitz decay of η':	$\eta' \to \gamma l^+ l^-$
11	pn bremsstrahlung:	$pn \to pn l^+ l^-$
12	$\pi^\pm N$ bremsstrahlung:	$\pi^\pm N \to \pi N l^+ l^-$

Dalitz decay $\pi^0 \to \gamma\ l^+ l^-$

$$\frac{d\Gamma^{\pi^0 \to \gamma\ l+l-}}{dM} = \frac{4\alpha}{3\pi}\frac{\Gamma^{\pi^0\to\gamma\gamma}}{M}|F^{\pi^0\to\gamma\gamma}(M)|^2 A \left(1 - \frac{M^2}{m_\pi^2}\right)^3, \tag{3.1.2}$$

where

$$\begin{cases} F^{\pi^0\to\gamma\gamma}(M) = 1 + B_{\pi^0} M^2, \\ \qquad \text{with } B_{\pi^0} = 5.5 \text{ GeV}^{-2}, \\ \Gamma^{\pi^0\to\gamma\gamma} = 7.8 \cdot 10^{-9} \text{ GeV}, \\ \Gamma^{\pi^0}_{\text{tot}} \simeq \Gamma^{\pi^0\to\gamma\gamma}, \\ Br^{\pi^0\to\gamma\gamma} = 0.988. \end{cases} \tag{3.1.3}$$

Dalitz decay $\eta \to \gamma\ l^+ l^-$

$$\frac{d\Gamma^{\eta\to\gamma\ l+l-}}{dM} = \frac{4\alpha}{3\pi}\frac{\Gamma^{\eta\to\gamma\gamma}}{M}|F^{\eta\to\gamma\gamma}(M)|^2 A \left(1 - \frac{M^2}{m_\eta^2}\right)^3, \tag{3.1.4}$$

where

$$\begin{cases} F^{\eta\to\gamma\gamma}(M) = \left(1 - \frac{M^2}{\Lambda_\eta^2}\right)^{-1}, \\ \qquad \text{with } \Lambda_\eta = 0.72 \text{ GeV}, \\ \Gamma^{\eta\to\gamma\gamma} = 4.6 \cdot 10^{-7} \text{ GeV}, \\ \Gamma^{\eta}_{\text{tot}} = 1.18 \cdot 10^{-6} \text{ GeV}, \\ Br^{\eta\to\gamma\gamma} = 0.3933. \end{cases} \tag{3.1.5}$$

Dalitz decay $\omega \to \gamma\ l^+l^-$

$$\begin{aligned}\frac{d\Gamma^{\omega\to\pi^0\ l+l-}}{dM} =& \frac{2\alpha}{3\pi}\frac{\Gamma^{\omega\to\pi^0\gamma}}{M}|F^{\omega\to\pi^0\gamma}(M)|^2 A \\ & \left[\left(1+\frac{M^2}{(m_\omega^2-m_\pi^2)}\right)^2-\frac{4m_\omega^2M^2}{(m_\omega^2-m_\pi^2)^2}\right]^{3/2},\end{aligned} \tag{3.1.6}$$

where

$$\begin{cases}|F^{\omega\to\pi^0\gamma}(M)|^2=\frac{\Lambda_\omega^4}{(\Lambda_\omega^2-M^2)^2+\Lambda_\omega^2\Gamma_\omega^2}, \\ \quad \text{with } \Lambda_\omega=0.65 \text{ GeV}, \\ \quad \text{and } \Gamma_\omega=0.075 \text{ GeV}, \\ \Gamma^{\omega\to\pi^0\gamma}=7.17\cdot10^{-4} \text{ GeV}, \\ \Gamma^{\omega}_{\text{tot}}=8.44\cdot10^{-3} \text{ GeV}, \\ Br^{\omega\to\pi^0\gamma}=0.085\end{cases} \tag{3.1.7}$$

Dalitz decay $\eta' \to \gamma\ l^+l^-$

$$\frac{d\Gamma^{\eta'\to\gamma\ l+l-}}{dM}=\frac{4\alpha}{3\pi}\frac{\Gamma^{\eta'\to\gamma\gamma}}{M}|F^{\eta'\to\gamma\gamma}(M)|^2 A\left(1-\frac{M^2}{m_{\eta'}^2}\right)^3, \tag{3.1.8}$$

where

$$\begin{cases}|F^{\eta'\to\gamma\gamma}(M)|^2=\frac{\Lambda_{\eta'}^4}{(\Lambda_{\eta'}^2-M^2)^2+\Lambda_{\eta'}^2\Gamma_{\eta'}^2}, \\ \quad \text{with } \Lambda_{\eta'}=0.75 \text{ GeV}, \\ \quad \text{and } \Gamma_{\eta'}=0.14 \text{ GeV}, \\ \Gamma^{\eta'\to\gamma\gamma}=4.28\cdot10^{-6} \text{ GeV}, \\ \Gamma^{\eta'}_{tot}=0.202\cdot10^{-3} \text{ GeV}, \\ Br^{\eta'\to\gamma\gamma}=0.0212 \\ m_{\eta'}=0.95778 \text{ GeV}.\end{cases} \tag{3.1.9}$$

Dalitz decay $\Delta \to N\ l^+l^-$

$$\frac{d\Gamma^{\Delta\to N\ l+l-}}{dM}=\frac{2\alpha}{3\pi}\frac{\Gamma_0(M,M_\Delta)}{M}, \tag{3.1.10}$$

with

$$\Gamma_0(M,M_\Delta)=\frac{\lambda^{1/2}(M^2,m_N^2,M_\Delta^2)}{16\pi M_\Delta^2}\cdot m_N\cdot[2m_T(M,M_\Delta)+m_L(M,M_\Delta)], \tag{3.1.11}$$

and

$$\begin{aligned}m_L(M,M_\Delta)=&(efg)^2\frac{M_\Delta^2}{9m_N}M^2\cdot4(M_\Delta-m_N-q_0), \\ m_T(M,M_\Delta)=&(efg)^2\frac{M_\Delta^2}{9m_N}\left[q_0^2(5M_\Delta-3(q_0+m_N))-M^2(M_\Delta+m_N+q_0)\right]\end{aligned} \tag{3.1.12}$$

where

$$\begin{cases} \lambda(M^2, m_N^2, M_\Delta^2) = M^4 + m_N^4 + M_\Delta^4 \\ \qquad\qquad -2(M^2 m_N^2 + M^2 M_\Delta^2 + m_N^2 M_\Delta^2), \\ e^2 = 4\pi\alpha, \\ f = -1.5 \frac{M_\Delta + m_N}{m_N((m_N+M_\Delta)^2 - M^2)}, \\ g = 5.44, \\ q_0 = \sqrt{M^2 + p_f^2}, \\ p_f^2 = (M_\Delta^2 - (m_N + M)^2)(M_\Delta^2 - (m_N - M)^2)/4M_\Delta^2. \end{cases} \tag{3.1.13}$$

Here M_Δ is the current mass of the Δ-resonance, calculated according to the spectral function with the total width from Ref. [37] (cf. also Ref. [38]):

$$\Gamma_{tot}^{\Delta}(M_\Delta) = \Gamma_R \frac{M_{\Delta 0}}{M_\Delta} \cdot \left(\frac{q}{q_r}\right)^3 \cdot F^2(q), \tag{3.1.14}$$

where

$$\begin{cases} F(q) = \frac{\beta_r^2 + q_r^2}{\beta^2 + q^2}, \\ q^2 = (M_\Delta^2 - (m_N + m_\pi)^2)(M_\Delta^2 - (m_N - m_\pi)^2)/4M_\Delta^2, \\ q_r^2 = 0.051936, \\ \beta_r^2 = 0.09, \\ \Gamma_R = 0.11 \text{ GeV}, \\ M_{\Delta 0} = 1.232 \text{ GeV}. \end{cases} \tag{3.1.15}$$

3.1.2 Direct decay of vector mesons $V \to l^+l^-$

The dilepton decay width of vector meson V with the mass M (calculated in HSD according to the spectral function) is

$$\Gamma^{V\to l^+l^-}(M) = C\frac{m_V^4}{M^3}, \tag{3.1.16}$$

where $C = \frac{\Gamma^{V\to l^+l^-}(m_V)}{m_V}$, m_V is the pole mass of the vector meson V.

For broad resonances such as ρ meson, the branching ratio to dileptons depends on the mass M:

$$Br^{V\to l^+l^-}(M) = \frac{\Gamma^{V\to l^+l^-}(M)}{\Gamma_{\text{tot}}^V(M)}. \tag{3.1.17}$$

Here the total width of the ρ meson is

$$\Gamma_{\text{tot}}^{\rho}(M) \simeq \Gamma_{\rho\to\pi\pi} = \Gamma_0 \left(\frac{m_V}{M}\right)^2 \left(\frac{q}{q_V}\right)^3, \tag{3.1.18}$$

with

$$\begin{cases} q = (M^2 - 4m_\pi^2)^{1/2}/2, \\ q_V = (m_V^2 - 4m_\pi^2)^{1/2}/2. \end{cases} \tag{3.1.19}$$

For narrow resonances such as $\omega, \phi, J/\Psi, \Psi'$ a constant total width and branching ratio are used: $\Gamma_{\text{tot}}^V \equiv \Gamma_{\text{tot}}(m_V)$, $Br_0^{V\to l^+l^-} \equiv Br^{V\to l^+l^-}(m_V)$.

Table 3.2: The parameters for dilepton decay of vector mesons.

mesons	$\rightarrow e^+e^-$	$\rightarrow \mu^+\mu^-$
ρ	$Br = 4.49 \cdot 10^{-5}$ $\Gamma = 6.77 \cdot 10^{-6}$ GeV $C = 8.814 \cdot 10^{-6}$	$Br = 4.6 \cdot 10^{-5}$ $\Gamma = 6.9 \cdot 10^{-6}$ GeV $C = 8.96 \cdot 10^{-6}$
ω	$Br = 7.07 \cdot 10^{-5}$ $\Gamma = 0.6 \cdot 10^{-6}$ GeV $C = 0.767 \cdot 10^{-6}$	$Br = 8.06 \cdot 10^{-5}$ $\Gamma = 0.68 \cdot 10^{-6}$ GeV $C = 0.863 \cdot 10^{-6}$
ϕ	$Br = 2.91 \cdot 10^{-4}$ $\Gamma = 1.297 \cdot 10^{-6}$ GeV $C = 1.27 \cdot 10^{-6}$	$Br = 3.7 \cdot 10^{-4}$ $\Gamma = 1.649 \cdot 10^{-6}$ GeV $C = 1.618 \cdot 10^{-6}$
J/Ψ	$Br = 5.93 \cdot 10^{-2}$ $\Gamma = 5.26 \cdot 10^{-6}$ GeV $C = 1.698 \cdot 10^{-6}$	$Br = 5.88 \cdot 10^{-2}$ $\Gamma = 5.12 \cdot 10^{-6}$ GeV $C = 1.652 \cdot 10^{-6}$
Ψ'	$Br = 8.8 \cdot 10^{-3}$ $\Gamma = 2.12 \cdot 10^{-6}$ GeV $C = 0.575 \cdot 10^{-6}$	$Br = 1.03 \cdot 10^{-2}$ $\Gamma = 2.853 \cdot 10^{-6}$ GeV $C = 0.774 \cdot 10^{-6}$

3.1.3 Input file

Input file (*input*) for Ca+Ca @ 2 AGeV - min bias

```
40,     MASSTA:   target mass
20,     MSTAPR:   protons in target
40,     MASSPR:   projectile mass
20,     MSPRPR:   protons in projectile
2.0,    ELAB:     lab energy per nucleon
0.5,    BMIN:     minimal impact parameter [fm]
10.,    BMAX:     maximal impact parameter [fm]
0.5,    DBIMP:    impact parameter step [fm]
200,    NUM:      number of parallel events
10,     ISUBS:    number of subsequent runs
4567,   ISEED:    initial random seed [integer]
0,      ICHARM:   charm degrees of freedom =0 no, =1 yes
1,      IDILEPT:  =0 no dileptons, =1 electron pair, =2 muon pair
0,      ICQ:      =0 free, =1 drop. mass, =2 broad., =3 drop.+broad.
0,      IGLUE:    =1 with partons, =0 w/o partons
40.,    FINALT:   final time of calculation [fm/c]
0,      IHARD:    =1 compute hard collisions, =0 no
10,     ILOW:     output level
```

3.1.4 Output files

Besides the standard output files – *fort.300* and *fort.301* - PHSD 2.3 provides the output *fort.925* for **dileptons** (if the IDILEPT option is set to 1).

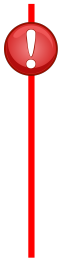
The output file *fort.925* contains the the differential dilepton yield (multiplicity) $\frac{dN_i}{dMdp_Tdy}$ calculated dynamically in PHSD using the time integration method for each impact parameter b for all dilepton channels i (cf. Table 4).

Output file *fort.925* - final dileptons

b [fm]

M [GeV]	y	p_T [GeV]	$\frac{dN_i(b)}{dMdp_Tdy}$ [GeV^{-2}]
...	...	...	...

- b is the impact parameter in fm
- M is the invariant mass of dileptons in GeV.
  The grid is defined in the dilepton routine *diltimeint* in *dilepton.f* as: $M_J = \Delta_M \cdot j,\ j = 1, ..., N_M,\ \Delta_M = 0.01$ is the step in invariant mass in GeV; the number of steps $N_M = 400$ for CBM and $N_M = 200$ for HADES.
- y is the dilepton rapidity in the calculational frame (e.g. in the center-of-mass system for $A + A$).
  The grid in y: $-\Delta_y \cdot N_y \leq y \leq \Delta_y \cdot N_y$, $\Delta_y = 0.2$ is the step in y, $N_y = 25$.
- p_T is the dilepton transverse momentum in GeV/c.
  The grid in p_T: $p_{T\,j} = \Delta_{p_T} \cdot k,\ k = 1, ..., N_{p_T},\ \Delta_{p_T} = 0.1$ is the step in p_T, $N_{p_T} = 50$.
- $dN_i(b)/dMdp_Tdy$ is the differential dilepton multiplicity for individual channels $i = 1, 2, ..., N, N + 1$ from Table 4. Presently there are 12 channels ($N = 12$), the last column corresponds to the sum over all channels ($N + 1 = 13$).
  Here $dN_i(b)/dMdp_Tdy$ is avaraged over the number of subsequent runs (ISUBS) and parallel events (NUM) for each impact parameter b (cf. Eq. (2)).
  New: $\pi^{\pm}N$ bremsstrahlung (N=12) is excluded from the sum over all channels (N=13) in updated HSD 2.5, however, it is still written out in file *fort.925*.



We DO NOT recommend to reconstruct the dilepton yield per each INDIVIDUAL event (e.g. each $A + A$ collision) since the statistical fluctuations in the dilepton spectra per event are large. In our opinion it is more reasonable to consider that in each physical event (for given b) the dilepton production is the same, so the final yield for one event corresponds to the "average" over manyevents (ISUBS and NUM).

Using the differential dilepton yield $dN_i(b)/dMdp_Tdy$ one can calculate the differential

dilepton cross section by integration over the impact parameter, i.e.

$$\frac{d\sigma_i}{dMdp_Tdy}\left[\frac{\text{mb}}{\text{GeV}^2}\right] = 10\int_{b_{min}}^{b_{max}} db\ 2\pi\ b\ \frac{dN_i(b)}{dMdp_Tdy}$$
$$\Rightarrow 10\sum_{b_{min}}^{b_{max}} \Delta b\ 2\pi\ b\ \frac{dN_i(b)}{dMdp_Tdy}. \tag{3.1.20}$$

Also by integrating over M, y or p_T one can obtain the dilepton mass spectra (cross section or multiplicity) dN/dp_T, rapidity distribution dN/dy or p_T distribution dN/dp_T.

3.1.5 Analysis

dil-925b.f

In order to demonstrate how to use the output *fort.925* and to calculate the dilepton spectra (integrated over the impact parameter) we provide the analysis program *dil-925b.f*. The program has an internal description and many comments.

dil-sim.f

This program has been written for CBM and HADES experiments. The program allows to simulate e^+e^- or $\mu^+\mu^-$ pairs for given impact parameter b using the calculated differential dilepton spectra $dN_i(b)/dMdp_Tdy$ from *fort.925*.

The idea is to simulate dilepton pairs – as many as one needs, i.e. N_{ee} for each bin in the grid (M, y, p_T) and for each dilepton channel $i = 1, .., N$ – in order to propagate it later on through the detector system (or employ the experimental filter). The 'weight' for each dilepton pair (and single e^+ or e^-) which passed the acceptance is $dN_i(b)/dMdp_Tdy \cdot 1/N_{ee}$.

smear925.f

That is an example program to smear the mass spectra with the experimental mass resolution in Gaussian form. As an example there are two options: smearing with BEVALAC mass resolution and with 10 MeV mass resolution.

The analysis programs are stored in the HSD subdirectory *analysis*. There is also an example program **analyse.f** to calculate the general observables using *fort.300* and *fort.301* for each A+A event individually and for an average over all events.

3.2 Photons

Chapter 4

List of output files

- `unit=15` : general output,
- `unit=80` : control file,
- `unit=888` : parameter settings,
- `unit=3` : neutral transverse energy for NA50,
- `unit=7` : error file,
- `unit=9` : meson-meson statistics,
- `unit=10` : report of baryon-antibaryon annihilation,
- `unit=11` : statistics of low energy meson-baryon reactions,
- `unit=167` : absorption of mesons with `FRITIOF`,
- `unit=12` : statistics of baryons,
- `unit=13` : statistics of antibaryons,
- `unit=14` : $z, V0(z), Vs(z), \rho(z), j_0(z)$ for different time (*densout.f*),
- `unit=16` : baryon density from *pribig.f* $\rho(x, 0, z, t)$ (`MATRI2`),
- `unit=17` : baryon density $\rho(0, 0, z, t)$ for `SPLOT` (densout.f) last column is pion-density,
- `unit=18` : count pions,
- `unit=19` : baryon momentum distribution from *pribig.f* (`MATRI2`),
- `unit=22` : baryon phase-space distribution from *pribig.f* (`MATRI2`),
- `unit=20` : `APART(IRUN,B)`,
- `unit=30` : picture of baryon density distribution $\rho(x, 0, z, t)$,
- `unit=23` : integer plot of energy density (only mesons) for $y = 0$, pseudoparticles in string included,
- `unit=24` : time, volume of energy density above n GeV/fm^3, pseudoparticles in string included (only mesons),
- `unit=25` : integer plot of energy density (baryons + mesons) for $y = 0$, pseudoparticles in string included,
- `unit=26` : time, volume of energy density above n GeV/fm^3, pseudoparticles in string included,
- `unit=123` : as `unit=23` but pseudoparticles in string NOT included (only mesons),
- `unit=124` : as `unit=24` but pseudoparticles in string NOT included (only mesons),
- `unit=125` : as `unit=31` but pseudoparticles in string NOT included,
- `unit=126` : as `unit=32` but pseudoparticles in string NOT included,
- `unit=127` : integer plot of string energy density,

- `unit=128` : averaged energy-density of field energy in different central cylinders,
- `unit=234` : strangeness and charge conservation as a function of time,
- `unit=434` : perturbative strangeness conservation as a function of time,
- `unit=235` : baryon number conservation as a function of time,
- `unit=236` : total energy as a function of time,
- `unit=237` : baryon species as a function of time,
- `unit=337` : antibaryon species as a function of time,
- `unit=437` : perturbative strangeness evolution as a function of time,
- `unit=620` : BB collision rate as a function of time,
- `unit=521` : mB collision rate as a function of time,
- `unit=33` : rapidity spectrum of protons,
- `unit=133` : rapidity spectrum of hyperons,
- `unit=34` : $1/m_T dN/dm_T$ transverse energy spectrum of baryons,
- `unit=35` : rapidity spectrum of negative mesons π^-, K^-, without hyperons,
- `unit=36` : rapidity spectrum of neutral mesons $\pi^0, \bar{K}^0, K^0$, without hyperons,
- `unit=37` : rapidity spectrum of positive mesons π^+, K^+, without hyperons
- `unit=135` : transverse energy spectrum of negative mesons: π^-, K^-,
- `unit=136` : transverse energy spectrum of neutral mesons: $\pi^0, \bar{K}^0, K^0$,
- `unit=137` : transverse energy spectrum of positive mesons: π^+, K^+,
- `unit=39` : rapidity spectrum of neutrons (1:3 symmetrized), without hyperons,
- `unit=40` : transverse energy spectrum of neutrons, without hyperons,
- `unit=142` : time dependent rapidity distribution of protons $(1:2)$ and pions $(1:3)$,
- `unit=115` : mesons (in string) as a function of time,
- `unit=239` : formed mesons as a function of time,
- `unit=240` : total baryon and meson momentum as a function of time,
- `unit=444` : time, timestep, boundary for control of grid,
- `unit=470` : $B\bar{B}$ annihilation events,
- `unit=471` : $B\bar{B}$ creation events by 3 mesons,
- `unit=472` : baryons/antibaryons from `FRITIOF` as a function of time,
- `unit=539` : open charm mesons as a function of time,
- `unit=565` : $D\bar{D} \to J/\Psi + m$,
- `unit=566` : $c\bar{c}$ absorption by mesons,
- `unit=567` : $c\bar{c}$ absorption by baryons,
- `unit=568` : D-meson absorption by baryons,
- `unit=570` : final charmed mesons,
- `unit=1600` : $J/\Psi + m$ absorption in time,
- `unit=1601` : $D\bar{D} \to J/\Psi + X$ in time,
- `unit=636` : hyperons as a function of time (compare with 637),
- `unit=637` : perturbative hyperons as a function of time,
- `unit=638` : mesons as a function of time (compare with 639),
- `unit=639` : perturbative mesons as a function of time,
- `unit=41` : rapidity spectrum (symmetrized) of protons,

- unit=141 : rapidity spectrum (symmetrized) of hyperons,
- unit=42 : $1/m_T dN/dm_T$ transverse energy spectrum of baryons,
- unit=43 : rapidity spectrum of neutrons ($1:3$ sym.),
- unit=44 : transverse energy spectrum of n,
- unit=45 : rapidity spectrum of negative mesons ($1:2$-9),
- unit=46 : rapidity spectrum of neutral mesons ($1:2$-9),
- unit=47 : rapidity spectrum of positive mesons ($1:2$-9),
- unit=145 : transverse energy spectrum of positive mesons: π^+, K^+,
- unit=146 : transverse energy spectrum of neutral mesons: $\pi^0, K^0, \bar{K}^0$,
- unit=147 : transverse energy spectrum of negative mesons: π^-, K^-,
- unit=74 : density of ρ in time, (x,z)-plot,
- unit=75 : π^0-density in time,
- unit=76 : total π density in time,
- unit=77 : total π rapidity y versus z distribution in time,
- unit=78 : average pions: $t:z:dN/dz:dN/dz*sign(rapidity)$ (from *phdpi.f*),
- unit=79 : average pions: $t:y:dN/dy:dN/dy*sign(z)$ (from *phdpi.f*),
- unit=89 : pseudo-rapidity η of charged particles; ($1:3$ sym); ($1:4$ rapidity), ($1:5$ sym),
- unit=90 : central baryon density (formed) for different rapidity cuts $1:2(y<0.7)$, $1:3(y<1.0)$, $1:4(y<1.5)$, $1:5(y<2.0)$, $1:6$(all y) in cylinder ($4\times4\times4/\gamma_{cm}$ fm^3) as a function of time,
- unit=91 : central baryon density for different rapidity cuts $1:2(y<0.7)$, $1:3(y<1.0)$, $1:4(y<1.5)$, $1:5(y<2.0)$, $1:6$(all y) in cylinder ($4\times4\times4/\gamma_{cm}$ fm^3) as a function of time,
- unit=92 : central meson-density in central cylinder ($4\times4\times4/\gamma_{cm}$ fm^3) as a function of time,
- unit=95 : $Y, Px(y)/A$ proton flow,
- unit=96 : ρ-mass distribution ($1:2$), ρ creation versus density ($3:4$),
- unit=100 : interacting baryon species in central cylinder,
- unit=101 : baryons in central volume (total-interacting),
- unit=104 : length-distribution of the strings,
- unit=105 : number of strings; t :all: in the middle 1 fm,
- unit=106 : averaged string length,
- unit=107 : time evolution of the ratio $\langle\bar{s}\rangle/(\langle\bar{u}\rangle+\langle\bar{d}\rangle)$,
- unit=108 : flavor statistics,
- unit=150 : Statistics of $\tilde{K}$ as a function of time,
- unit=151 : Statistics of K as a function of time,
- unit=167 : absorption of mesons in PIONAB by strings,
- unit=171 : charge control file,
- unit=175 : strangeness control file for strings,
- unit=190 : baryon density for $DY=1,1.5,\ldots$ (Formed baryons),
- unit=191 : baryon density for $DY=1,1.5,\ldots$ (all baryons),

- `unit=192` : time,$\langle p_z\rangle$, $\langle p_T\rangle$ of pions; $\rho_B, \langle B\rangle, \langle\bar{B}\rangle, \langle\pi\rangle$ for (T,μ) analysis,
- `unit=198` : time dependent proton rapidity distribution in central cylinder ($4\times4\times4/\gamma_{cm}$ fm^3) as a function of time,
- `unit=199` : time dependent pion rapidity distribution in central cylinder ($4\times4\times4/\gamma_{cm}$ fm^3) as a function of time,
- `unit=200` : density of Ω, Ξ, Υ, N with time in central volume,
- `unit=201` : $dN/d\sqrt{s}$ from K^*+m^* and m^*+m^* ($b_{rel}<1$ fm) (important for $B\bar{B}$ production in mm collisions),
- `unit=202` : m_T-scaling of $\pi, \eta, K^+, K^-, \rho, \omega$,
- `unit=203` : srt-distribution of all possible geom. BB, mB and mm collisions,
- `unit=250` : output of kaons,
- `unit=650` : output of perturbative kaons,
- `unit=251` : output of pions,
- `unit=252` : output of nucleons,
- `unit=253` : output of hyperons,
- `unit=254` : output of perturbative hyperons,
- `unit=300` : y-target,y-projectile,num,
- `unit=320` : final J/Ψ: typ,run,p_x, p_y, p_z,e,cr-time,weight,
- `unit=310` : absorbed J/Ψ: abtyp=1 or 2 for absorption on baryon or string : abtyp,typ,run,abs-time,p_x, p_y, p_z,e,cr-time,weight,
- `unit=322` : spectral functions of baryons,
- `unit=323` : spectral functions of mesons,
- `unit=393` : p_x for baryons from collisions as a function of time,
- `unit=394` : mean-field p_x for baryons as a function of time,
- `unit=395` : mean-field p_x for kaons as a function of time,
- `unit=695` : mean-field p_x for perturbative kaons as a function of time,
- `unit=925` : output for dileptons,
- `unit=999` : strangeness counter,
- `unit=310` : statistics of baryons in time,
- `unit=311` : statistics of mesons in time,
- `unit=621` : output from `PIONAB`,
- `unit=858` : hadrons deleted in `DISSOLVE`,
- `unit=830` : partons from `DISSOLVE`,
- `unit=831` : partons from `DISSOLVE`,
- `unit=836` : Baryons dissolved,
- `unit=849` : Baryons in `DISSOLVE` when ended (TIME,NFAIL,NSUC),
- `unit=858` : mesons deleted in `DISSOLVE`,
- `unit=834` : mesons dissolved,
- `unit=819` : hadrons destroyed,
- `unit=849` : mesons in `DISSOLVE` when ended (TIME,NFAIL,NSUC),
- `unit=951` : now the $\rho/K^\star$-meson is stored (from `PIPIRHO`),
- `unit=820` : $\pi\pi\to\rho$ or $K^\star$,

- unit=832 : partons from GLUEDECAY,
- unit=823 : gluon decay rate (compare with 822),
- unit=485 : fraction of energy from all species (baryons, mesons, strings, ...),
- unit=833 : gluon formation in GLUESCAT,
- unit=826 : interaction rates in GLUESCAT,
- unit=822 : gluon formation rate in GLUESCAT,
- unit=220 : momentum changes of partons due to scattering in GLUESCAT,
- unit=841 : v_2 of partons, mesons, baryons versus p_T,
- unit=842 : rapidity distribution of formed mesons from different origin,
- unit=840 : v_2 as function of time,
- unit=837 : partons from DQDECAY,
- unit=829 : decay rate in DQDECAY,
- unit=977 : hadrons from string,
- unit=877 : hadrons from low energy fusion,
- unit=876 : information about fusing partons from RECOM or HADRONS,
- unit=816 : mesons and baryons formation rate from RECOM,
- unit=442 : baryons formation in HADRONS,
- unit=827 : hadrons formation rates,
- unit=936 : invariant mass distribution of partons in time,
- unit=621 : number of strings in time,
- unit=623 : string decay rate in STRINGDEC,
- unit=695 : leading-leading scattering from BARS,
- unit=722 : rate of leading-leading scattering from BARS,
- unit=832 : gluons also from PIPIGLUE,
- unit=828 : gluon formation rate from PIPIGLUE,
- unit=320 : momentum increment of quarks and antiquarks as well as v_2 (PROPGLUE),
- unit=821 : fermion and gluon number as a function of time,
- unit=939 : rapidity distribution of quarks, antiquarks, gluons as a function of time,
- unit=825 : spectral functions of partons as a function of time,
- unit=824 : formation rate for $gg \to g$,
- unit=818 : diquark formation rate,
- unit=940 : longitudinal and transverse mass spectra of partons in time,
- unit=848 : average parton number and fluctuations over the ensemble,
- unit=436 : differential plot of mass distribution of partons in time,
- unit=431 : differential plot of mass distribution of partons in time,
- unit=234 : difference between strange and antistrange quarks,
- unit=959 : rapidity distribution of remaining quark and formed hadrons (FINALPART),
- unit=595 : momentum increment in PROPGLUEV,
- unit=446 : dynamical grid in time,
- unit=437 : energy distribution,
- unit=432 : local gamma factors,
- unit=435 : parton density,

- `unit=438` : interaction energy density,
- `unit=439` : hadron density,
- `unit=433` : total energy density,
- `unit=490` : energy conservation in different steps,
- `unit=499` : particle number conservation in different steps,
- `unit=333` : output of kaon mean fields,
- `unit=899` : output of internal parameters,
- `unit=629` : statistics about pre-baryon collisions,
- `unit=937` : statistics about hadron srt-distributions,
- `unit=203` : collisional srt distribution for BB, mB and mm,
- `unit=809` : collisional srt distribution of partons,
- `unit=250` : kaons before hyperons decay,
- `unit=251` : pions before hyperons decay,
- `unit=252` : protons before hyperons decay,
- `unit=598` : precoll-distribution.

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