The Hadron-String-Dynamics transport approach

HSD user guide

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The code is available from:
http://www.th.physik.uni-frankfurt.de/~brat/hsd.html

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1 Introduction

The **Hadron-String Dynamics** (HSD) transport approach is a covariant microscopic transport model developed to simulate

- relativistic heavy-ion collisons
- proton-nucleus reactions
- pion-nucleus reactions

in the energy range from SIS to RHIC.

The HSD transport approach provides the numerical testparticle solution of a coupled set of relativistic transport equations for particles with in-medium selfenergies (optionally). It is based on quark, diquark, string and hadronic degrees of freedom. High energy inelastic hadron-hadron collisions in HSD are described by the FRITIOF 7.02 string model (including PYTHIA and JETSET) [1] whereas low energy hadron-hadron collisions are modeled based on experimental cross sections. The transport approach is matched to reproduce the nucleon-nucleon, meson-nucleon and meson-meson cross section data in a wide kinematic range. HSD takes into account the formation and multiple rescattering of leading pre-hadrons and hadrons.

The major aim of HSD is - within a single transport model - to gain an understanding about the nuclear dynamics, the creation of dense and hot hadronic matter and the modification of hadron properties in a medium.

General references to the HSD model:

- W. Ehehalt and W. Cassing,
  'Relativistic transport approach for nucleus-nucleus collisions from SIS to SPS',
  Nucl. Phys. **A 602** (1996) 449 [hep-ph/9507274]
- J. Geiss, W. Cassing and C. Greiner,
  'Strangeness production in the HSD transport approach from SIS to SPS energies',
  Nucl. Phys. **A 644** (1998) 107 [nucl-th/9805012]
- W. Cassing and E.L. Bratkovskaya,
  'Hadronic and electromagnetic probes of hot and dense nuclear matter',
  Phys. Reports **308** (1999) 65.

2 Copyright

The HSD source and documentation are provided freely for the purpose of checking and reproducing published results of the authors.

The Open Standard Codes and Routines (OSCAR-Group) has established - for good reasons - guidelines for reproducibility, usage and quality control of stimulation codes for pA and AA collisions.

HSD is a complex model. In order to ensure that it is used correctly that all results are reproducible and that the proper credits are given we ask for your agreement to the following copyright and safeguard mechanisms in the OSCAR spirit.

The HSD collaboration favors cooperation and joint projects with outside researchers. We encourage experimental collaborations to compare their results to HSD. We support you and/or cooperate on any sensible project related to HSD.

If you are interested in a project, **please contact us**.

Projects without the participation of the HSD-Collaboration are accepted, if the project is not a current thesis topic of any HSD-Collaboration member.

We expect that the code authors are informed about any changes and modifications made to the code. Any changes to the official version must be documented.

The code or any fragments of it shall **not** be given away to third parties. Similarly, events generated with HSD shall not be given to third parties without consent of the code authors.

3 Important notes about HSD version 2.0 (presently open release)

Presently we open for the general public the 'standard' version of the full HSD model. This HSD 2.0 version is suited to investigate the general nuclear dynamics (as well as pA and πA collisions) from low AGS (3 A·GeV) up to RHIC ($\sqrt{s} = 200$ GeV) energies (cf. [2, 3, 4]).

HSD 2.0 is a **cascade** version of the full HSD code, i.e. all routines for propagation in nuclear potentials are **not** included. Thus, this version is **not** applicable for SIS and low AGS energies where the potential effects are important. Also one has to be cautious to use the code for an investigation of collective effects (as flow) at low AGS energies.

HSD 2.0 **does not include** the following routines from the full HSD (to use these routines one needs some general experience in transport theory or/and an extended guide):

- perturbative strangeness dynamics at SIS energies [5, 6, 7]
- off-shell dynamics with dynamical spectral functions of nucleons and strange particles (important at SIS energies) [8, 9, 10, 11]
- dynamics for multi-strange particles (with $|S| \geq 2$)
- perturbative open and hidden charm dynamics [12, 13] (HSD 2.4 – cf. Section 8)
- dilepton and real photon emissions (e.g. [14, 15]) (HSD 2.5 – cf. Section 9)
- perturbative high p_T dynamics at SPS and RHIC [16]
- multi-meson fusion reactions (important for anti-baryon physics!) [17]

However, all these routines are **available** for **common projects** with the authors! Please, contact us if you are interested in the latest HSD developments!

References

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'Final state interactions in the (nuclear) FRITIOF string interaction scenario,
Z. Phys. **C 57** (1993) 485.

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'Hadronic observables at relativistic energies: Anything strange with strangeness ?',
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4 Particle identification codes used in HSD

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. [1, 2, 3]). The argument here is that the resonance structure (above the Δ-peak) is not seen experimentally even in photoabsorption on light nuclei [4].

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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

Note: **all perturbative particles** (e.g. strange, open and hidden charm particles, dileptons) are stored in *special* vectors and **NOT included** in HSD 2.0 ! Also the full dynamics for the baryon with ID$\geq$ 8 and the mesons with IPI$\geq$ 15 is not included here (cf. Section 3).

Table 1: The **baryon** identification codes used in HSD.

ID(j,1)	type	mass[1] [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	Σ^*	1.385
8	Ξ	1.315
9	Ξ^*	1.530
10	Ω^-	1.672
11	Λ_c	2.285
12	Σ_c	2.455
13	Ξ_c	2.467
...		

[1] For broad resonances the mass is indicated by the pole of the spectral function.

Table 2: **The meson identification codes used in HSD.**

ID(j,1)	type	mass[1] [GeV]
1	π	0.138
2	η	0.549
3	K^+, K^-	0.494
4	K^{*+}, K^{*-}	0.892
5	ρ	0.775
6	ω	0.783
7	ϕ	1.020
8	η'	0.958
9	a_1	1.260
10	empty	-
11	K^0	0.498
12	$\bar{K}^0$	0.498
13	K^{0*}	1.430
14	$\bar{K}^{0*}$	1.430
15-...	D-mesons	

5 Compiling and running the program

To compile HSD one needs a FORTRAN-90 compiler (under UNIX, LINUX or Windows platforms). Compilation is initiated by the *make* [1] command at the command-prompt in the HSD subdirectory. After successful compilation the executable (binary) file has the name *hsd.exe*.

<u>Note:</u> **Random number generator**.

The internal FORTRAN random number generator RAN(ISEED) (where ISEED is any integer number) is used in the HSD code. However, the internal random number generator can be replaced by another routine which specifies a random number in the interval [0,1]. For example, one can use RAN(ISEED) from 'Numerical recipes in Fortran' by William H. Press et al. - cf. file *gnrandom.f*. For that one has to include *gnrandom.f* in the *makefile*.

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[1] *makefile* - which initiates the compilation is just a list of the necessary fortran files

6 HSD input description

In order to run HSD one has to specify the **initial parameters** in the input file - *input*.

Input file (*input*) for A+A; example 1

197,	MASSTA: target mass
79,	MSTAPR: protons in target
197,	MASSPR: projectile mass
79,	MSPRPR: protons in projectile
21300.,	ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.5,	BMIN: minimal impact parameter in fm
6.0,	BMAX: maximal impact parameter in fm
0.5,	DBIMP: impact parameter step in fm
10,	NUM: number of parallel events (use at least 10)
1,	ISUBS: number of subsequent runs
139,	ISEED: for initialization of random number generator (ANY INTEGER number)

Input file (*input*) for p+A; example 2

197,	MASSTA: target mass
1,	MSTAPR: protons in target
1,	MASSPR: projectile mass
1,	MSPRPR: protons in projectile
21300.,	ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.0,	BMIN: minimal impact parameter in fm (**NOT USED for p+A**)
0.0,	BMAX: maximal impact parameter in fm (**NOT USED for p+A**)
0.0,	DBIMP: impact parameter step in fm (**NOT USED for p+A**)
100	NUM: number of parallel events (use at least 10)
50,	ISUBS: number of subsequent runs
675,	ISEED: for initialization of random number generator (ANY INTEGER number)

Description of the initial parameters in file *input*:

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 energy per nucleon in A·GeV in laboratory frame

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

$$\sigma_\pi = 10 \int_{b_{min}}^{b_{max}} db\ 2\ \pi\ b\ A_\pi(b) \Rightarrow 10 \sum_{b=b_{min}}^{b_{max}} \Delta b\ 2\ \pi\ b\ A_\pi(b). \tag{1}$$

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):

$$A_i(b) = \sum_{j=1}^{N_i} \frac{1}{\mathrm{NUM} \cdot \mathrm{ISUBS}}\ . \tag{2}$$

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.).

Note: 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): NUM=50-100 for Pb+Pb at AGS or SPS and NUM=10-20 at RHIC.

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

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.

Note: final propagation time t_{max}

The HSD code is running with a dynamical time step (not a constant!) 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 ($\sqrt{s}$):

$$t_{max} = 35 + \frac{170}{\sqrt{s}\ [\mathrm{GeV}]} [\mathrm{fm/c}] \tag{3}$$

Eq. (3) 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*. Please, contact us for further explanations (or increase NTMAX in *main.f*) !

7 Output

- 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).

Used output format: FORMAT(1X,4I6,8E16.8).

! 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.

8 HSD 2.4 - version with perturbative charm

In this version the charmonium and open charm routines are added. The HSD version 2.4 is **available** from authors for **common projects** or simulations for experiments!
Note, that the charm degrees of freedom are treated perturbatively (cf. [12, 13]).

Table 3: The **perturbative charm meson** identification codes used in HSD 2.4.

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

Input file (*input*) for A+A; example

197,	MASSTA: target mass
79,	MSTAPR: protons in target
197,	MASSPR: projectile mass
79,	MSPRPR: protons in projectile
21300.,	ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.5,	BMIN: minimal impact parameter in fm
6.0,	BMAX: maximal impact parameter in fm
0.5,	DBIMP: impact parameter step in fm
10,	NUM: number of parallel events (use at least 10)
1,	ISUBS: number of subsequent runs
139,	ISEED: for initialization of random number generator (ANY INTEGER number)
1,	**ICHARM:** charm degrees of freedom: 0=no; 1=yes

- **ICHARM** - flag to activate perturbative charm:
  ICHARM=0 - without charm degrees of freedom,
  ICHARM=1 - with charm degrees of freedom

Output file *fort.570* - final charm mesons (D-mesons and $J/\Psi, \Psi'$)

IPPI(j,1)	IPPI(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 $\chi_c \rightarrow \gamma + J/\Psi$. The decay fraction is taken as in Ref. [13]).

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):

$$A_i^{pert}(b) = \sum_{j=1}^{N_i} \frac{weight(j)}{\mathrm{NUM} \cdot \mathrm{ISUBS}} \ . \tag{4}$$

9 HSD 2.5 (updated) - version with perturbative charm and dileptons

Additionally to version 2.4 (cf. Section 8) dilepton routines are added in version 2.5. This version has been **extended** also for simulations of elementary pp **and** pd **reactions** as well as for **low energy** nucleus-nucleus collisions.

NEW: The updated HSD 2.5 version can be used also for $\pi^- p$ **and** $\pi^- A$ **reactions**. It includes also **in-medium effects for vector mesons**, i.e. the dropping mass scenario and collisional broadening. In the updated HSD 2.5 version the vector mesons are produced and propagated with their in-medium spectral functions using off-shell dynamics (see Refs. [8,9,10] from Sec. 3 and [3]).

The HSD version 2.5 is **available** from the authors for simulations for dilepton experiments (e.g. CBM and HADES) or **common projects** with the authors!
The dilepton (e^+e^- or $\mu^+\mu^-$) spectra are calculated perturbatively using the time integration method. For details of the dilepton implementation see our review [1] and also Refs. [2, 3, 4, 5, 6, 7, 8, 9]. The time integration is perfomed over the actual dilepton emission rate during the full reaction time (contrary to the 'spontaneous decay' assumption).

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9.1 Dilepton channels

Table 4: **Dilepton channels in HSD 2.5**

i	Dilepton channel	
1	Dalitz decay of π^0:	$\pi^0 \to \gamma e^+e^-$
2	Dalitz decay of η:	$\eta \to \gamma e^+e^-$ (or $\mu^+\mu^-$, also for channels below)
3	Dalitz decay of ω:	$\omega \to \pi^0 e^+e^-$
4	Dalitz decay of Δ:	$\Delta \to N e^+e^-$
5	direct decay of ω:	$\omega \to e^+e^-$
6	direct decay of ρ:	$\rho \to e^+e^-$
7	direct decay of ϕ:	$\phi \to e^+e^-$
8	direct decay of J/Ψ:	$J/\Psi \to e^+e^-$
9	direct decay of Ψ':	$\Psi' \to e^+e^-$
10	Dalitz decay of η':	$\eta' \to \gamma e^+e^-$
11	pn bremsstrahlung:	$pn \to pne^+e^-$
12	$\pi^\pm N$ bremsstrahlung:	$\pi^\pm N \to \pi N e^+e^-$, where $N = p$ or n

All branching ratios, electromagnetic partial and total decay widths are taken from the PDG [10]. For more detailed explanations about the implementation of individual dilepton channels please contact the authors.

Note:

1. 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 $E_{lab} \geq 6$ GeV since it is very questionable to use the SPA at high energies.

2. 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 – $\rho, \eta, \omega, \phi, J/\Psi, \Psi'$.

9.2 Input file for HSD 2.5 – *input*

There are a couple of examples for an 'input' file in the HSD directory. Here we show how to initilize the code for low energy A+A, p+p and p+d collisions as well as for $\pi^- A$ and $\pi^- p$ reactions (**new !**).

Input file for A+A; example: Ca+Ca at 2 A·GeV

40,	MASSTA: target mass
20,	MSTAPR: protons in target
40,	MASSPR: projectile mass
20,	MSPRPR: protons in projectile
2.0,	ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.5,	BMIN: minimal impact parameter in fm
10.,	BMAX: maximal impact parameter in fm
0.5,	DBIMP: impact parameter step in fm
200,	NUM: number of parallel events (use at least 10)
10,	ISUBS: number of subsequent runs
139,	ISEED: for initialization of random number generator (ANY INTEGER number)
0,	ICHARM: charm degrees of freedom: 0=no; 1=yes
1,	**IDILEPT:** =0 no dileptons; =1 electron pairs; =2 muon pairs
0,	**ICQ:** =0 free, =1 dropping mass, =2 coll. broadening, =3 drop. mass + coll. broad.

- **IDILEPT** - flag to activate perturbative dileptons:
  IDILEPT=0 - without dileptons,
  IDILEPT=1 or 2 - with dileptons: 1= electron pairs (e^+e^-), 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) for vector mesons,
  with in-medium effects:
  ICQ=1 - dropping mass scenario,
  ICQ=2 - collisional broadening,
  ICQ=3 - dropping mass + collisional broadening

Input file for p+p; example: p+p at 1.5 GeV

1,	MASSTA: target mass
1,	MSTAPR: protons in target
1,	MASSPR: projectile mass
1,	MSPRPR: protons in projectile
1.5,	ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.0,	BMIN: minimal impact parameter in fm
0.0,	BMAX: maximal impact parameter in fm
1.0,	DBIMP: impact parameter step in fm
1000,	NUM: number of parallel events (use at least 10)
100,	ISUBS: number of subsequent runs
139,	ISEED: for initialization of random number generator (ANY INTEGER number)
0,	ICHARM: charm degrees of freedom: 0=no; 1=yes
1,	IDILEPT: =0 no dileptons; =1 electron pairs; =2 muon pairs
0,	ICQ: =0 free, =1 dropping mass, =2 coll. broadening, =3 drop. mass + coll. broad.

Input file for p+d; example: p+p at 4.0 GeV

2,	MASSTA: target mass
1,	MSTAPR: protons in target
1,	MASSPR: projectile mass
1,	MSPRPR: protons in projectile
4.0,	ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.0,	BMIN: minimal impact parameter in fm
0.0,	BMAX: maximal impact parameter in fm
1.0,	DBIMP: impact parameter step in fm
1000,	NUM: number of parallel events (use at least 10)
100,	ISUBS: number of subsequent runs
139,	ISEED: for initialization of random number generator (ANY INTEGER number)
0,	ICHARM: charm degrees of freedom: 0=no; 1=yes
1,	IDILEPT: =0 no dileptons; =1 electron pairs; =2 muon pairs
0,	ICQ: =0 free, =1 dropping mass, =2 coll. broadening, =3 drop. mass + coll. broad.

Note: Please, even for p+p or p+d set DBIMP=1 (or some NONzero 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 ahigh momentum tail – for the details see Ref. [4].

Input file for $\pi^- A$; example: $\pi^- Pb$ at 1.3 GeV

```
208,  MASSTA: target mass
82,   MSTAPR: protons in target
0,    MASSPR: projectile mass
0,    MSPRPR: protons in projectile
1.3,  ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.0,  BMIN: minimal impact parameter in fm
0.0,  BMAX: maximal impact parameter in fm
1.0,  DBIMP: impact parameter step in fm
100,  NUM: number of parallel events (use at least 10)
100,  ISUBS: number of subsequent runs
139,  ISEED: for initialization of random number generator (ANY INTEGER number)
0,    ICHARM: charm degrees of freedom: 0=no; 1=yes
1,    IDILEPT: =0 no dileptons; =1 electron pairs; =2 muon pairs
1,    ICQ: =0 free, =1 dropping mass, =2 coll. broadening, =3 drop. mass + coll. broad.
```

Input file for $\pi^- p$; example: $\pi^- p$ at 1.3 GeV

```
1,     MASSTA: target mass
1,     MSTAPR: protons in target
0,     MASSPR: projectile mass
0,     MSPRPR: protons in projectile
1.3,   ELAB: bombarding energy per nucleon in A GeV (LAB-FRAME)
0.0,   BMIN: minimal impact parameter in fm
0.0,   BMAX: maximal impact parameter in fm
1.0,   DBIMP: impact parameter step in fm
1000,  NUM: number of parallel events (use at least 10)
100,   ISUBS: number of subsequent runs
139,   ISEED: for initialization of random number generator (ANY INTEGER number)
0,     ICHARM: charm degrees of freedom: 0=no; 1=yes
1,     IDILEPT: =0 no dileptons; =1 electron pairs; =2 muon pairs
0,     ICQ: =0 free, =1 dropping mass, =2 coll. broadening, =3 drop. mass + coll. broad.
```

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).

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.

9.3 Output files for HSD 2.5

Besides the standard output files – *fort.300* and *fort.301* - HSD 2.5 provides the output *fort.570* for perturbative charm (if the ICHARM option is set to 1 – cf. Section 8) and also 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 HSD using the time integration method for each impact parameter b for all dilepton channels i (cf. Table 4).

Output file ***fort.925***

b [fm]			
M [GeV]	y	p_T [GeV/c]	$\frac{dN_i}{dMdp_Tdy}(b)\ \left[\frac{1}{\mathrm{GeV}^2}\right],\quad i = 1, 2, ..., N, N+1$
M_1	y_1	p_{T1}	...
M_1	y_1	p_{T2}	...
...	...	...	...
M_1	y_1	$p_{T N_{p_T}}$	...
M_1	y_2	p_{T1}	...
M_1	y_2	p_{T2}	...
...	...	...	...
M_1	y_2	$p_{T N_{p_T}}$	...
...	...	...	...
M_1	y_{N_y}	p_{T1}	...
M_1	y_{N_y}	p_{T2}	...
...	...		
M_1	y_{N_y}	$p_{T N_{p_T}}$	...
...	...	...	...
...	...	...	...
M_{N_M}	y_{N_y}	p_{T1}	...
M_{N_M}	y_{N_y}	p_{T2}	...
...	...	...	...
M_{N_M}	y_{N_y}	$p_{T N_{p_T}}$	...

- 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: $p_{Tj} = \Delta_{p_T} \cdot k,\ k = 1, ..., N_{p_T},\ \Delta_{p_T} = 0.1$ is the step in p_T, $N_{p_T} = 50$.

- $\dfrac{dN_i}{dMdp_Tdy}(b)$ 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 $\dfrac{dN_i}{dMdp_Tdy}(b)$ 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* !

Note (for the experimental simulation groups): 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 many events (ISUBS and NUM).

Using the differential dilepton yield $\dfrac{dN_i}{dMdp_Tdy}(b)$ one can calculate the differential dilepton cross section by integration over the impact parameter – cf. Eq. (1), i.e.

$$\frac{d\sigma_i}{dMdp_Tdy}\left[\frac{mb}{\mathrm{GeV}^2}\right] = 10 \int_{b_{min}}^{b_{max}} db\ 2\ \pi\ b \frac{dN_i}{dMdp_Tdy}(b)$$
$$\Rightarrow 10 \sum_{b=b_{min}}^{b_{max}} \Delta b\ 2\ \pi\ b\ \frac{dN_i}{dMdp_Tdy}(b). \tag{5}$$

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.

9.4 Analysis programs for HSD 2.5

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 $\frac{dN_i}{dMdp_Tdy}(b)$ 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 $\frac{dN_i}{dMdp_Tdy}(b) \cdot \frac{1}{N_{ee}}$.

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.

Please see the comments inside the programs!

The analysis programs are stored in thr HSD subdirectory 'analprog'
There is also an example program **analyse.f** (suited for HSD 2.0 - 2.5) to calculate the general observables using *fort.300* and *fort.301* for each A+A event individually and for an average over all events (cf. Section 7).