Documentation for the Garcia-Montero:2023gex package

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I. INTRODUCTION

This is the documentation for the Garcia-Montero:2023gex package. It includes a list of the options which can be included in the input file for the creation of initial conditions. For details of the analytical formulas, and the physical meaning of the parameters, please consult the main reference of this work, ref. [1].

II. INPUT OPTIONS

The Garcia-Montero:2023gex code uses `.yaml` input files. These files have strict spacing rules for the header and subheader options, each subheader needs to be included the corresponding (sub-)header with exactly *four spaces*. So, each subsequent indentation uses an extra indentation of that size.

Two independent headers are to be included in the first part of the input file. These are the level of terminal output (verbosity) and, anticipating the future imporvements, the version of the code (for now only 1.0). These are to be included

- `Version`: Code Version.
- `Logging`: Terminal output header,
  - Followed by the subheader `Verbose`: `False` (no terminal output) or `True` (All terminal output available)

The rest of the main headers are

- `General`: General aspects of the collision.
- `Grid`: Parameters for the spatial grid.
- `Model Parameters`: Parameters of the saturation model.
- `Output`: Output commands.

These headers will be detailed in the next sections.

A. General

The general subheader corresponds to the general information needed for the creation of the initial state of the collision. The subheaders available to the user are the following:

- `SqrtsNN`: Collisional energy of the heavy ion collision per nucleon, $\sqrt{s_{\rm NN}}$, in GeV. Under the energy of the collision, one need to specificy the incoming nuclei, which can be done using the following structure:

```
Nucleus1:
    A:    208
    Z:    82
    mode: 0
Nucleus2:
    A:    208
    Z:    82
    mode: 0
```

where `Z`, `A` correspond to the atomic number and mass number relatively. The keyword `mode` corresponds to

  - Spherical Nuclei (`mode`: 0) Included are ${}^{16}_{8}$O, ${}^{40}_{18}$Ar, ${}^{63}_{29}$Cu, ${}^{129}_{54}$Xe, ${}^{197}_{79}$Au and ${}^{208}_{82}$Pb
  - Deformed Nuclei (`mode`: 1) Included are ${}^{27}_{13}$Al, ${}^{63}_{29}$Cu, ${}^{129}_{54}$Xe, ${}^{197}_{79}$Au and ${}^{238}_{92}$U

  These parameters can be found in file `nuclear_data.h`, and are taken from Ref.[2]. Additionally, configurations for deuteron, ${}^{2}_{1}$H, and ${}^{3}_{2}$He are included in the `nuclear` folder, and can be used in the input file normally by listing A and Z. More can be included by petition.

- `Events`: Number of events to be created.
- `GlauberAcceptance`: Nucleons are sampled from the Woods-Saxon distribution using a rejection sampling (see eq. (17) in the main paper). This flag chooses the geometry of the nucleons for that sampling. The default is `Gaussian`.
- `Model`: Saturation model to include in the computation of the energy and charge deposition.
  - GBW model (`Model`: 0)
  - IP-Sat model (`Model`: 1)
- `Impact`: Impact parameter options. There are two modes: fixed value and sampling.
  - `Value`: Fixed value of the impact parameter, has to be given in units of fm, e.g. `Value: 3.2`.
  - For the range sampling, an example is given below,

```
Impact:
    Range: [0, 20]
    Sampling: Quadratic
```

    The flag `Sampling` stands for the two possibility for sampling of the sampling of the absolute value of the impact parameter, `Quadratic` and `Uniform`. The first stands for the dbdb sampling, while the second stands for simple db sampling.

- `PDFs`: User parameters to use with the LHAPDF library.
  - `PDFSet`: This is the PDF parametrization used in the computation of quark quantities, they need to be previously downloaded using the instructions in the LHAPDF webpage. In the main reference we have mostly used the CT18NNLO PDF set.
  - `ForcePositive`: Enforce positivity on the PDF set (`ForcePositive: 1`). This is particularly important for our purposes as the PDF interpolation gets unstable at low virtuality. These low Q^2 pieces don't contribute to the energy and number density, but can increase the relative error of the integration routines.
- `K-Factor` The free parameter of the Garcia-Montero:2023gex framework. Needs to be fitted (see main paper). For most purposes its inclusion is linear in the gluon observables *except* the multiplicity estimator which is given by a power law of the sum of the energies, $\int \mathrm{d}^2\boldsymbol{x}[\tau K_g \epsilon_g + \epsilon_q]^{2/3}$.

B. Grid

Under the `Grid` header, all parameters defining the spatial output of the initial state must be given. These are the following.

- `NX`: Number of points along the x direction
- `NY`: Number of points along the y direction
- `NETA`: Number of points along the η_s direction.
- `X_RANGE`: Domain of the x dimension, needs to be given as, for example, `[-12,12]`
- `Y_RANGE`: Domain of the y dimension, needs to be given as, for example, `[-12,12]`
- `ETA_RANGE`: Domain of the $x\eta_s$ dimension, needs to be given as, for example, `[-8,8]`
- `BG`: Effective size of the nucleon, as defined from its thickness function, see eq. (9) from the main paper. Given in units of (fm^2).

C. Model Parameters

- GBW model (`Model`: 0): Controls the parameters of the GBW model, see eq. (14) of the main reference, $Q^2(x) = Q_0^2(x/x_0)^\lambda(1-x)$.
  - `Q02`: Saturation scale, given in units of GeV^2
  - `x0`: Fixing value if value of the saturation scale is known from a model at a specific x, say $Q_0^2 = Q^2(x_0)$. This should be normally specified at small x. In the case of the main reference, the saturation scale is known from a fit, so `x0` is set to 1.
  - `lambda`: Power law for the saturation scale.
  - `XCut`: Large-x cutoff for the GBW model. At $x >$XCut the dipole is set to 0. This is included to test the gluon production influence on the observables at large rapidities. Set it to XCut= 1 as a default.
- IP-Sat model (`Model`: 1)
  - `Set`: Chooses the parameter set of the IP-Sat fits from ref. [3]. `Set:1` corresponds to the fits for the charm mass, $m_c = 1.27$, while `Set:2` corresponds to the fits for $m_c = 4$.
  - `XScaling`: Sets the switch to a geometrical scaling behaviour for the IP-Sat dipole for $x >$`XScaling`. We recommend using values between $0.01 - 0.1$, as the data becomes sensitive to numerical resolution above those values, and below, the IP-Sat dynamics is washed out.

D. Output

- `path_to_output`: Path to output folder. Default: `out/`
- `run_name`: Output folder name. Default is set to `Run`i. The code will find the last run (say `Run10`) and set it to the next integer `Run11`.
- `Format`: Output format. Included are three available options:
  - `Charges`: Only the information about charges is included. The output file format reads

$$1.\eta_s \quad 2.x \quad 3.y \quad 4.(\tau\,\epsilon_g)_0 \quad 5.(\tau\,\epsilon_q)_0 \quad 6.(\tau\,n_u)_0 \quad 7.(\tau\,n_d)_0 \quad 8.(\tau\,n_s)_0$$

  - `EMoments`: Includes the moments of the energy distribution. Say we define the moments of this distribution as

$$\begin{aligned} E_{I,i,n} &= \int \mathrm{d}^2\boldsymbol{r}(\tau\epsilon_i)_0\,|\boldsymbol{r}|^n \\ E_{C,i,n} &= \int \mathrm{d}^2\boldsymbol{r}(\tau\epsilon_i)_0\,|\boldsymbol{r}|^n\cos(n\varphi) \\ E_{S,i,n} &= \int \mathrm{d}^2\boldsymbol{r}(\tau\epsilon_i)_0\,|\boldsymbol{r}|^n\sin(n\varphi) \end{aligned} \tag{1}$$

    Additionally the quantity

$$E_{2/3} = \int \mathrm{d}^2\boldsymbol{r}\left[K_g(\tau\epsilon_g)_0 + (\tau\epsilon_q)_0\right]^{2/3} \tag{2}$$

    here $i = g, q$ and $n = 0, 1, 2....$ The default maximum moment is $n = 4$. The format of the file is then given by

$$1.\eta_s \quad 2.E_{2/3} \quad 3.E_{I,g,0} \quad 4.E_{I,q,0} \quad 5.E_{C,g,0} \quad 6.E_{C,q,0} \quad 7.E_{S,g,0} \quad 8.E_{S,q,0} \quad 9.E_{I,g,1} \quad 10.E_{I,q,1} \ \ldots$$

  - `NMoments`: Includes moments of the charges distributions. Now we define the moments of these distributions as

$$\begin{aligned} N_{I,f,n} &= \int \mathrm{d}^2\boldsymbol{r}(\tau n_f)_0\,|\boldsymbol{r}|^n \\ N_{C,f,n} &= \int \mathrm{d}^2\boldsymbol{r}(\tau n_f)_0\,|\boldsymbol{r}|^n\cos(n\varphi) \\ N_{S,f,n} &= \int \mathrm{d}^2\boldsymbol{r}(\tau n_f)_0\,|\boldsymbol{r}|^n\sin(n\varphi) \end{aligned} \tag{3}$$

for each flavour $f = u, d$[1]. The file for each value of f is printed out using the following format

$$1.\eta_s \qquad 2.N_{I,f,0} \qquad 3.N_{C,f,0} \qquad 4.N_{S,f,0} \qquad 5.N_{I,f,1} \qquad 6.N_{C,f,1} \qquad 7.N_{S,f,1} \ \ldots$$

These options have to be included in a list form, e.g. `["EMoments","Charges"]`.

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[1] O. Garcia-Montero, H. Elfner, and S. Schlichting, (2023), arXiv:2308.11713 [hep-ph].
[2] D. d'Enterria and C. Loizides, Ann. Rev. Nucl. Part. Sci. **71**, 315 (2021), arXiv:2011.14909 [hep-ph].
[3] A. H. Rezaeian, M. Siddikov, M. Van de Klundert, and R. Venugopalan, Phys. Rev. D **87**, 034002 (2013), arXiv:1212.2974 [hep-ph].

[1] We have included only light quarks since strangeness density is trivially vanishing in our framework. We are working on the implementation of fluctiations, which will eventually show hotspots on the strangeness density, and therefore moments.