# **Cooper-Frye sampling** with short-range repulsion

### Volodymyr Vovchenko (University of Houston)

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Reference: VV, Phys. Rev. C 106, 0640906 (2022)

# **QCD** phase structure and heavy-ion collisions







- Scanning the QCD phase diagram with heavy-ion collisions at different energies
- Event-by-event fluctuations probe the QCD phase structure, in particular the critical point
- Effects like baryon conservation are essential and make even non-critical baseline non-trivial

### Heavy-ion collisions and particlization





MADAI Collaboration

Anchishkin, VV, Csernai, PRC '13

**Particlization:** Mapping the expanding hydrodynamic fluid into hadron resonance gas on a Cooper-Frye hypersurface (typically constant energy density surface)

$$\omega_p \frac{dN_j}{d^3 p} = \int_{\Sigma(x)} d\Sigma_\mu(x) \, p^\mu \, f_j[u^\mu(x)p_\mu; T(x), \mu_j(x)],$$

What is the fate of event-by-event fluctuations?

### **Existing particlization techniques**



- Standard Cooper-Frye (grand-canonical) particlization
  - Examples: iSS, frzout, BEST sampler, ... [C. Shen et al.; J. Bernhard; S. Pratt,...]
  - Conservation laws are enforced on average + viscous corrections
    - Ok for spectra and flow
  - Each hydrodynamic cell is sampled independently
    - Hadron number fluctuations follow Poisson statistics
    - Not very suitable for event-by-event fluctuations
- (Micro)canonical particlization [Oliinychenko, Koch, PRL 123, 182302 (2019); Schwartz et al., JPG 45, 015001 (2018)]
  - Exact conservation of conserved charges, energy and momentum
  - No hadronic interactions
- **FIST** sampler VV, Phys. Rev. C 106, 064906 (2022) <u>https://github.com/vlvovch/fist-sampler</u>
  - Exact conservation of baryon number, electric charge, and strangeness
  - Hard-core repulsion

As well as analytical approaches to critical [Pradeep, Stephanov, PRL '23] and non-critical [VV, V. Koch, C. Shen, PRC '22] fluctuations 4

### **Hard-core repulsion**





• Box setup reproduces the fluctuations in **excluded volume model**  $(V \rightarrow V - bN$  with  $b = \frac{16\pi r_c^3}{3}$ )

\*For Cooper-Frye hypersurface,  $|\mathbf{r_i} - \mathbf{r_i}|$  is calculated as the equal-time distance in the center-of-mass frame



#### Full algorithm

- 1. Sample the total number of each hadron species from Poisson distribution based on Cooper-Frye integral
- 2. Optionally enforce canonical treatment of global conservation laws via rejection sampling
- 3. Sample coordinates and momenta of hadrons one-by-one
  - Choose hydro cell from multinomial distribution
  - Momentum from thermal distribution + Lorenz boost
- 4. Reject the configuration if any two hadrons with hard-core repulsion overlap

#### Inputs

- List of hadrons and hard-core radii  $\sigma_{ij}$  for each pair of hadron species
  - $b \sim 1 \text{ fm}^3$  in baryon-baryon interaction is motivated by lattice QCD [Karthein, Koch, Ratti, VV, PRD 104, 094009 (2021)]
- Cooper-Frye hypersurface: numerical from hydro (e.g. MUSIC) or parameterized blast-wave

### **FIST** sampler: Implementation



#### Implementation: available in Thermal-FIST out-of-the box since version 1.4 open source: https://github.com/vlvovch/Thermal-FIST

| rticle list file: /Users/Vvovch/Code/Thermal-FIST-Extended/Thermal-FIST/Input/list/PDG2020/list-withnuclei.dat + decays.dat |      |             |        |          |                |                |                                 |               |                   |              | Load particle list Load de  | acays |
|---|------|-------------|--------|----------|----------------|----------------|---------------------------------|---------------|-------------------|--------------|---|-------|
|   |      |             |        |          |                |                |                                 |               |                   |              |   |       |
|   |      |             |        |          |                |                | Thermal model                   | Thermal fits  | Equation of state | Event genera | tor Particle list editor  |       |
|   |      |             |        |          |                |                |                                 |               |                   |              | HRG model configuration:  |       |
| Pa  | rtic | le list:    |        |          |                |                | Edit particle list for analysis |               |                   |              |   |       |
|   |      | Name        | PDG ID | m [GeV]  | Multiplicity   | Variance       | Scaled variance                 | Skewness      | Kurtosis          | <pt> [G</pt> | Model: Excluded volume (X-terms) 😋 Ensemble: Canonical                              |       |
| 1   |      | pi0         | 111    | 0.134977 | 11.231 ± 0.028 | 11.295 ± 0.140 | 1.006 ± 0.012                   | 1.198 ± 0.122 | 2.196 ± 1.208     | 0.581 ± 0    | Statistics: Boltzmann Quantum for All particles 🚱 🛛 Use quadratures                 |       |
| -   |      | pi+         | 211    | 0.13957  | 10.960 ± 0.024 | 8.110 ± 0.096  | 0.740 ± 0.009                   | 0.554 ± 0.093 | -0.048 ± 0.698    | 0.584 ± 0    |   |       |
| 3   |      | pi-         | -211   | 0.13957  | 10.963 ± 0.024 | 8.170 ± 0.096  | 0.745 ± 0.009                   | 0.483 ± 0.092 | -0.170 ± 0.672    | 0.585 ± 0    | Resonance widths: Zero-width  |       |
| 4   |      | K+          | 321    | 0.493677 | 3.154 ± 0.014  | 2.679 ± 0.032  | 0.849 ± 0.010                   | 0.679 ± 0.061 | 0.174 ± 0.360     | 0.771 ± 0    |   |       |
| 6   |      | к-          | -321   | 0.493677 | 3.137 ± 0.014  | 2.667 ± 0.033  | 0.850 ± 0.011                   | 0.739 ± 0.063 | 0.641 ± 0.327     | 0.780 ± C    | Conservation laws EV/vdW interactions PCE/Saha/Other                                |       |
| e   |      | anti-K0     | -311   | 0.497611 | 3.109 ± 0.014  | 2.758 ± 0.035  | 0.887 ± 0.011                   | 0.844 ± 0.068 | 0.872 ± 0.408     | 0.783 ± 0    |   |       |
| 7   |      | к0          | 311    | 0.497611 | 3.106 ± 0.014  | 2.651 ± 0.032  | 0.854 ± 0.010                   | 0.669 ± 0.056 | 0.135 ± 0.260     | 0.779 ± 0    | Chemical freeze-out parameters:   |       |
| ε   |      | anti-p      | -2212  | 0.938272 | 0.686 ± 0.007  | 0.641 ± 0.010  | 0.935 ± 0.014                   | 0.889 ± 0.048 | 0.772 ± 0.183     | 1.056 ± 0    | T <sub>ch</sub> (MeV): 155.00 🗘 y <sub>4</sub> : 1.0000 🗘 y <sub>5</sub> : 1.0000 🗘 |       |
| g   |      | p           | 2212   | 0.938272 | 0.688 ± 0.007  | 0.654 ± 0.010  | 0.951 ± 0.015                   | 0.925 ± 0.049 | 0.880 ± 0.186     | 1.051 ± 0    | μ <sub>8</sub> (MeV): 0.00  |       |
| 1   | 0    | n           | 2112   | 0.939565 | 0.674 ± 0.007  | 0.635 ± 0.010  | 0.943 ± 0.014                   | 0.909 ± 0.045 | 0.790 ± 0.149     | 1.055 ± 0    | R (fm): 40000 🗘 R <sub>SC</sub> (fm): 4.0000 🗘 V (fm³): 268.083                     |       |
| 1   | 1    | anti-n      | -2112  | 0.939565 | 0.696 ± 0.007  | 0.633 ± 0.009  | 0.909 ± 0.013                   | 0.832 ± 0.042 | 0.590 ± 0.136     | 1.067 ± 0    | B: 0 🗘 Q: 0 🗘 S: 0 🗘  |       |
| 1   | 2    | Lambda      | 3122   | 1.11568  | 0.269 ± 0.004  | 0.263 ± 0.005  | 0.976 ± 0.019                   | 0.960 ± 0.045 | 0.902 ± 0.119     | 1.175 ± 0    | Blast-wave momentum spectrum:   |       |
| 1   | 3    | anti-Lambda | -3122  | 1.11568  | 0.279 ± 0.004  | 0.270 ± 0.005  | 0.970 ± 0.018                   | 0.943 ± 0.044 | 0.848 ± 0.121     | 1.171 ± 0    | Spherically symmetric O Cylindrically symmetric Cracow model                        |       |
|   |      | Classe -    | 2000   | 1 40007  | 0.470 - 0.004  |                | 0.000 - 0.000                   | 0.001 - 0.045 | 0.040 - 0.407     | 4 000 - 0    | Two (MeV): 155.00 C Rr(fm): 9.000 C (8) -: 0.500 C n: 1.000 C n=                    | ^     |
|   |      |             |        |          |                |                |                                 |               |                   |              |   |       |
| Distribution: dN/dy 🧿 Binning Perform decays  |      |             |        |          |                |                |                                 |               |                   |              |   |       |
|   |      |             |        |          |                |                |                                 |               |                   |              | Events: 100000  |       |
|   |      | 3           |        |          |                |                |                                 |               |                   |              |   |       |
|   | e :  | 2.5         |        |          | 1              |                |                                 |               |                   |              | Stop  |       |
| 1   | ND ' | 1.5         |        | Ĵ        | <i>i</i>       |                | 1                               |               |                   |              |   |       |
|   | (    | 0.5         |        |          |                |                |                                 |               |                   |              | Effective event number = 13765<br>CE acceptance rate: 1                             |       |
|   |      | -4          |        | -2       |                | 0<br>y         | 2                               |               | 4                 |              | Per event = 0.729096 ms   |       |
|   |      |             |        |          |                |                |                                 |               |                   |              |   |       |

• Examples for use at LHC and RHIC: <u>https://github.com/vlvovch/fist-sampler</u>



Using the blast-wave model hypersurface (~20 million events)

Proton cumulants



Effects of hadronic afterburner UrQMD (mainly baryon annihilation) investigated in

[Savchuk et al., PLB 827, 136983 (2023)]

Proton-deuteron correlations

# **FIST** sampler at **RHIC-BES**



Using the single-shot hydro hypersurfaces from MUSIC (sample several million events per energy)



- Validating earlier analytic calculations [VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)] within Monte Carlo event generator
- Baryon conservation + excluded volume describe the data above 20 GeV
- New element: Simultaneous effects of baryon, charge, strangeness, and excluded volume
  - Electric charge conservation becomes essential below 7.7 GeV

# **FIST** sampler at **HADES**



Using Siemens-Rasmussen-Hubble fireball parameterization



VV, Phys. Rev. C 106, 064906 (2022)

- Strong effect of simultaneous baryon and electric charge conservation
- No description of HADES data

# Summary and outlook



- FIST sampler is a fast Monte Carlo routine for Cooper-Frye particlization
  - Canonical treatment of conservation laws
  - Short-range hard-core repulsion among hadrons
  - Included in Thermal-FIST since v1.4 and available publicly
- Provides an **event generator** giving non-critical baseline for event-by-event fluctuations observables
- Outlook:
  - Effects of hadronic afterburner
  - Observables other than proton number cumulants
  - Viscous corrections

# Thanks for your attention!