Cooper-Frye sampling with short-range repulsion

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

QCD phase structure and heavy-ion collisions

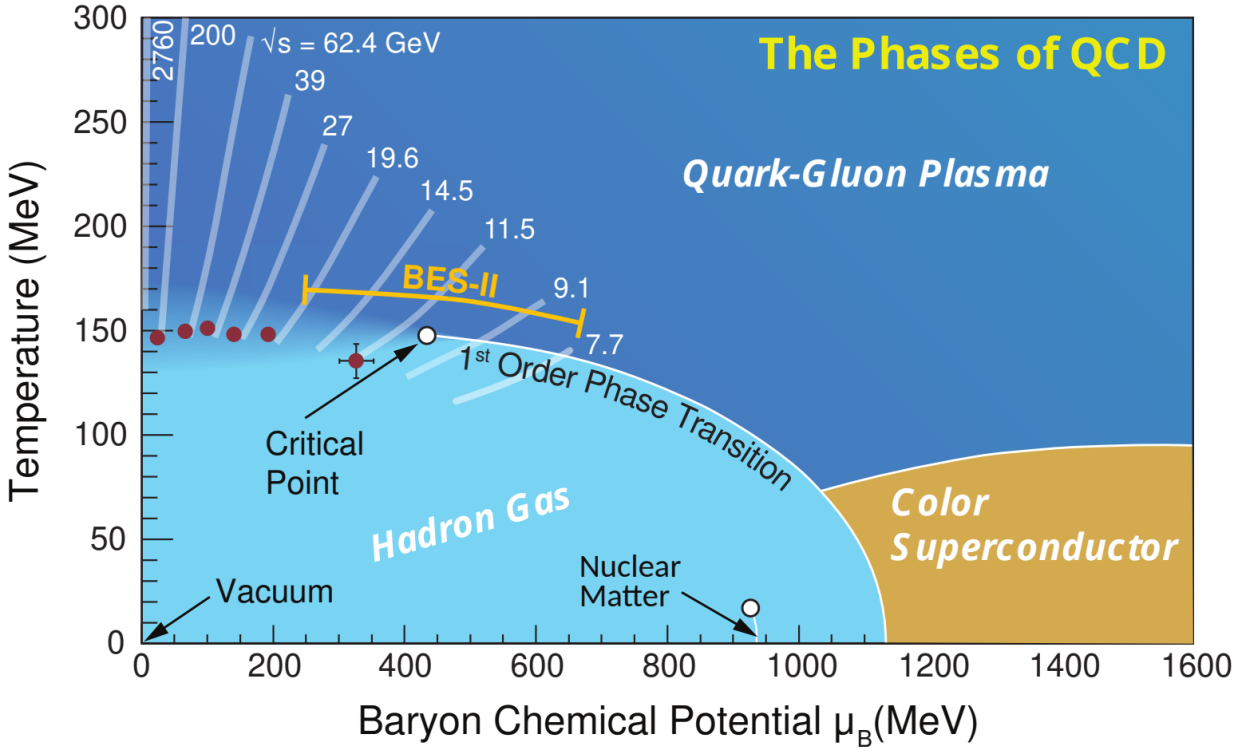
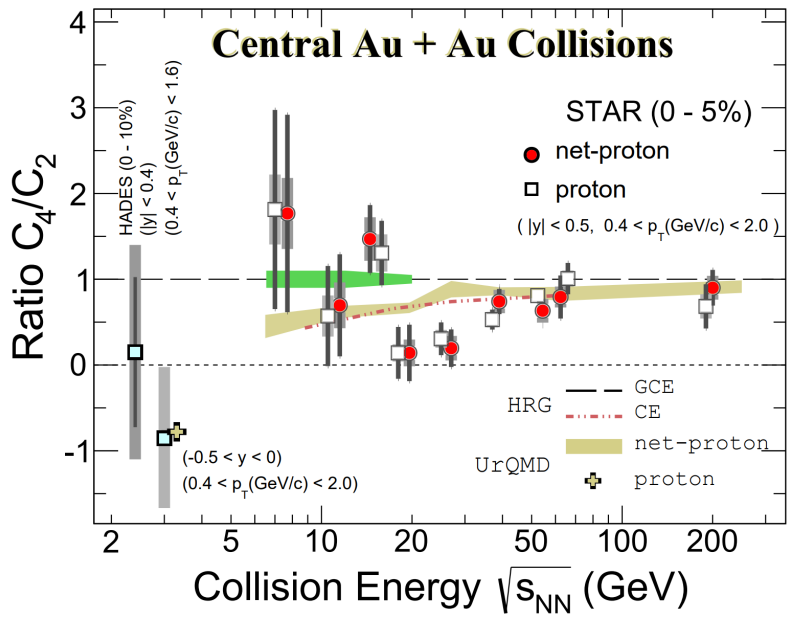


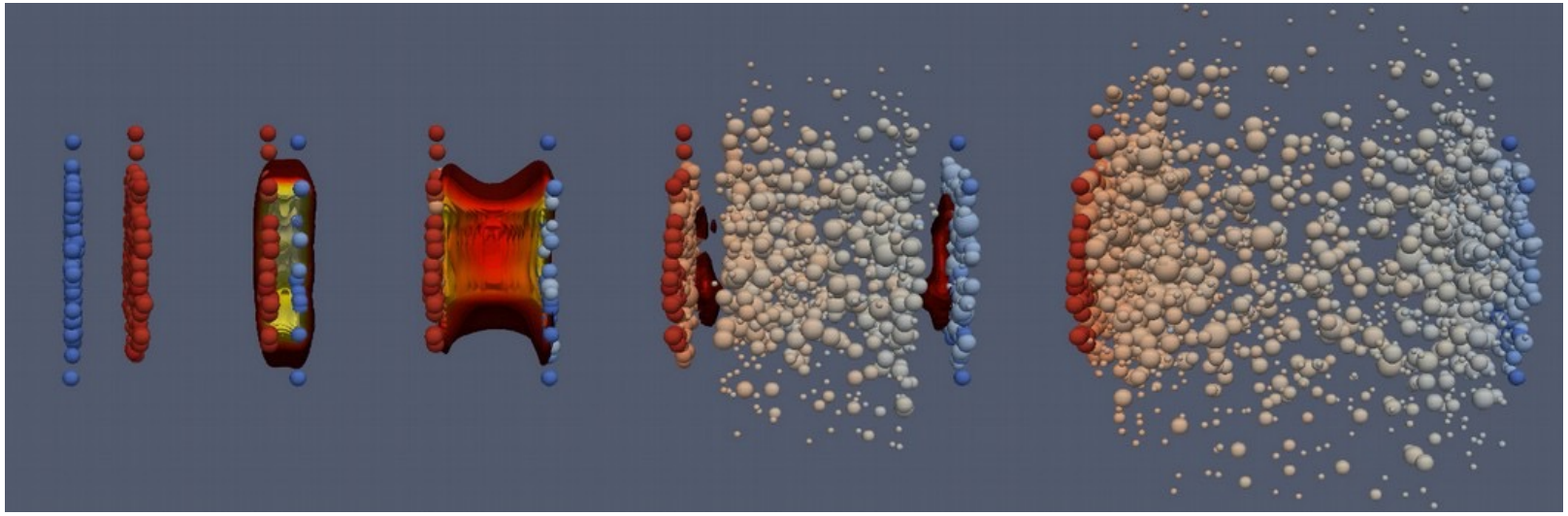
Figure from Bzdak et al., Phys. Rept. '20 & 2015 Long Range Plan



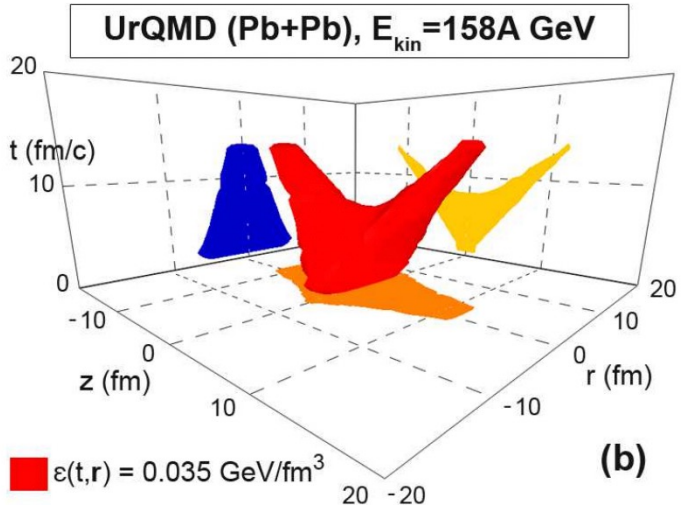
STAR Coll., PRL 126, 092301 (2021), PRL 128, 202303 (2022)

- 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)

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

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

Existing particlization techniques

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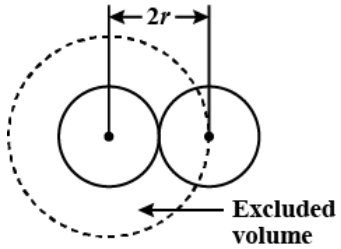
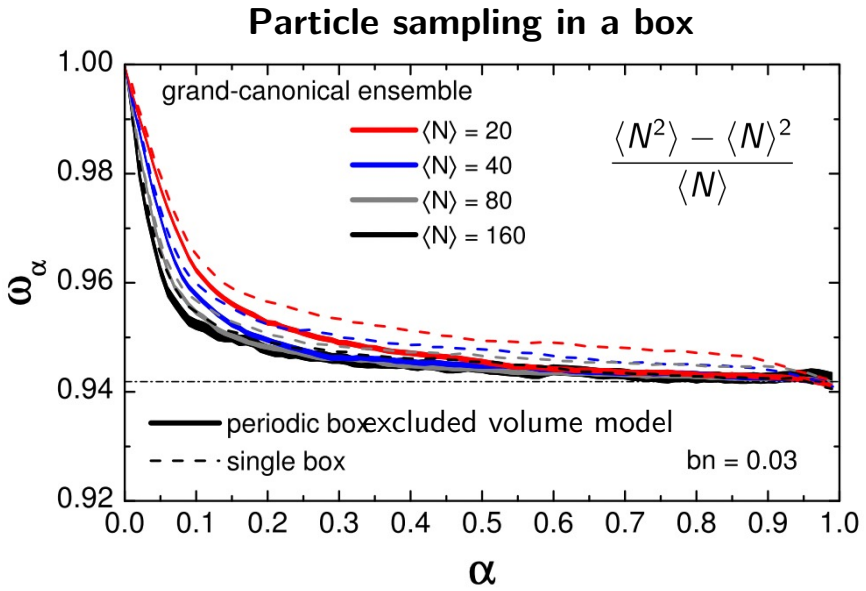
- **Standard Cooper-Frye (grand-canonical) particlization**
  - Examples: iSS, frzout, BEST sampler, ... [C. Shen et al.; J. Bernhard; S. Pratt,...]
  - Conservation laws are enforced on average + viscous corrections
    - Ok for spectra and flow
  - Each hydrodynamic cell is sampled independently
    - 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) https://github.com/vlvovch/fist-sampler
  - 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

Hard-core repulsion

- Two hadrons with hard-core repulsion cannot overlap
  - Reject the configuration if hadrons overlap* $|\mathbf{r}_i-\mathbf{r}_j| < 2r_c$





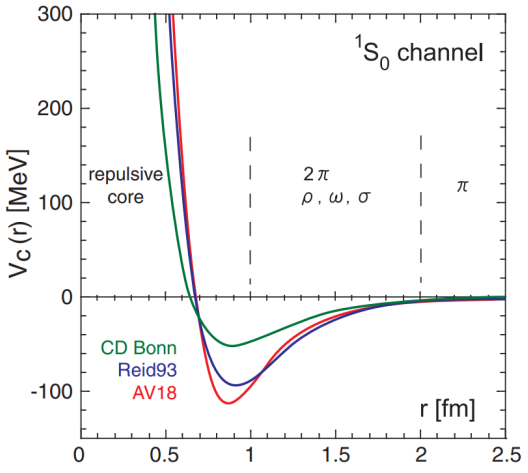
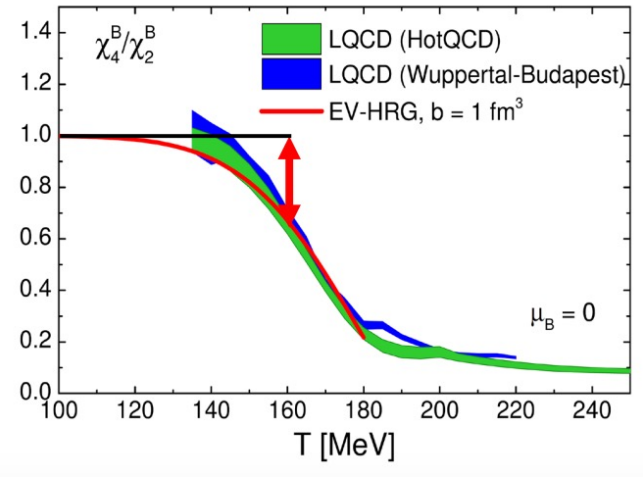


Figure from Ishii et al., PRL '07



VV et al., Phys. Lett. B 755, 71 (2017)

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

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

FIST sampler

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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 σ_{ij} for each pair of hadron species
  - b $\sim$ 1 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

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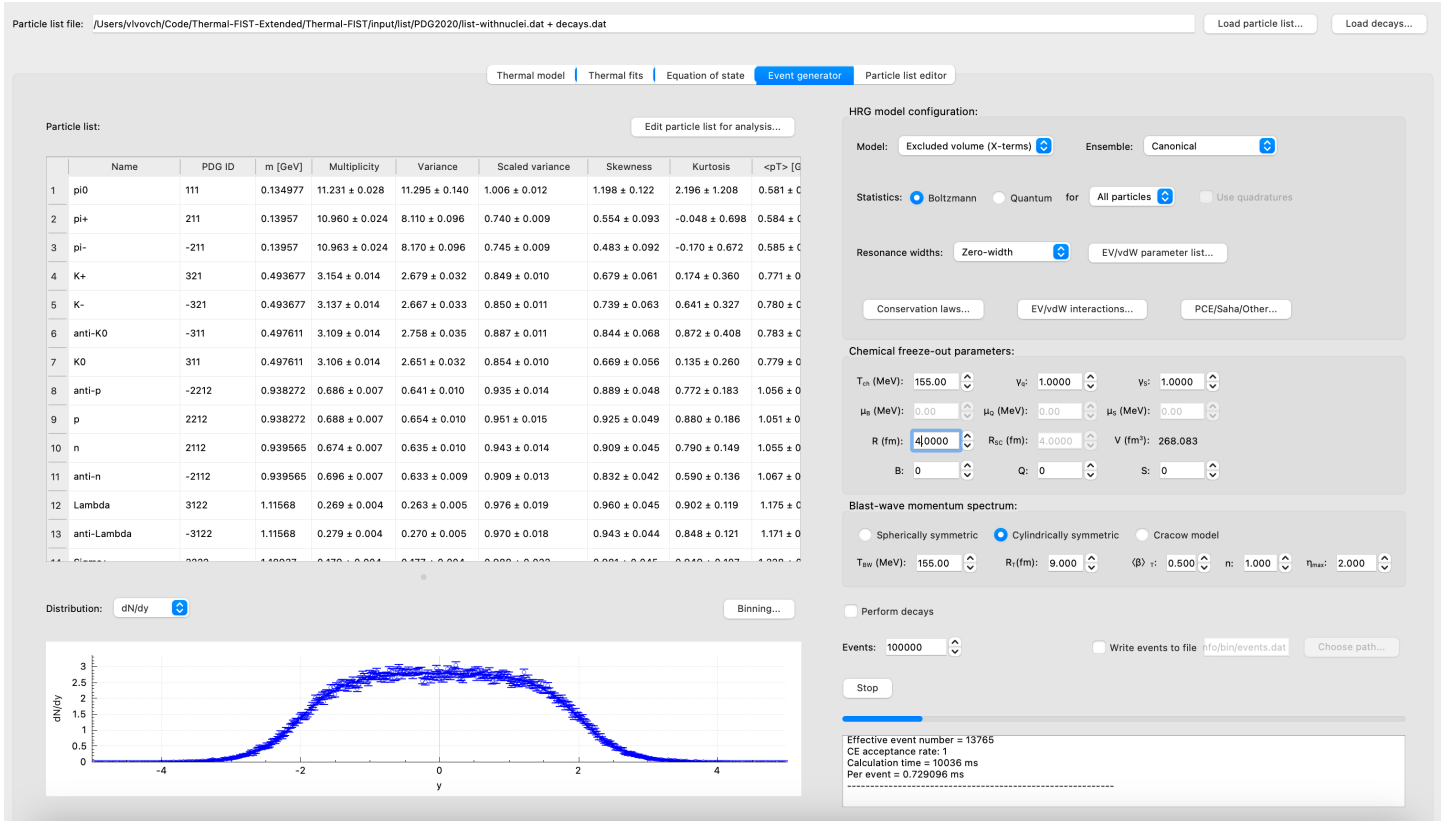
Implementation: available in **Thermal-FIST** out-of-the box since version 1.4

open source: https://github.com/vlvovch/Thermal-FIST



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

FIST sampler at LHC

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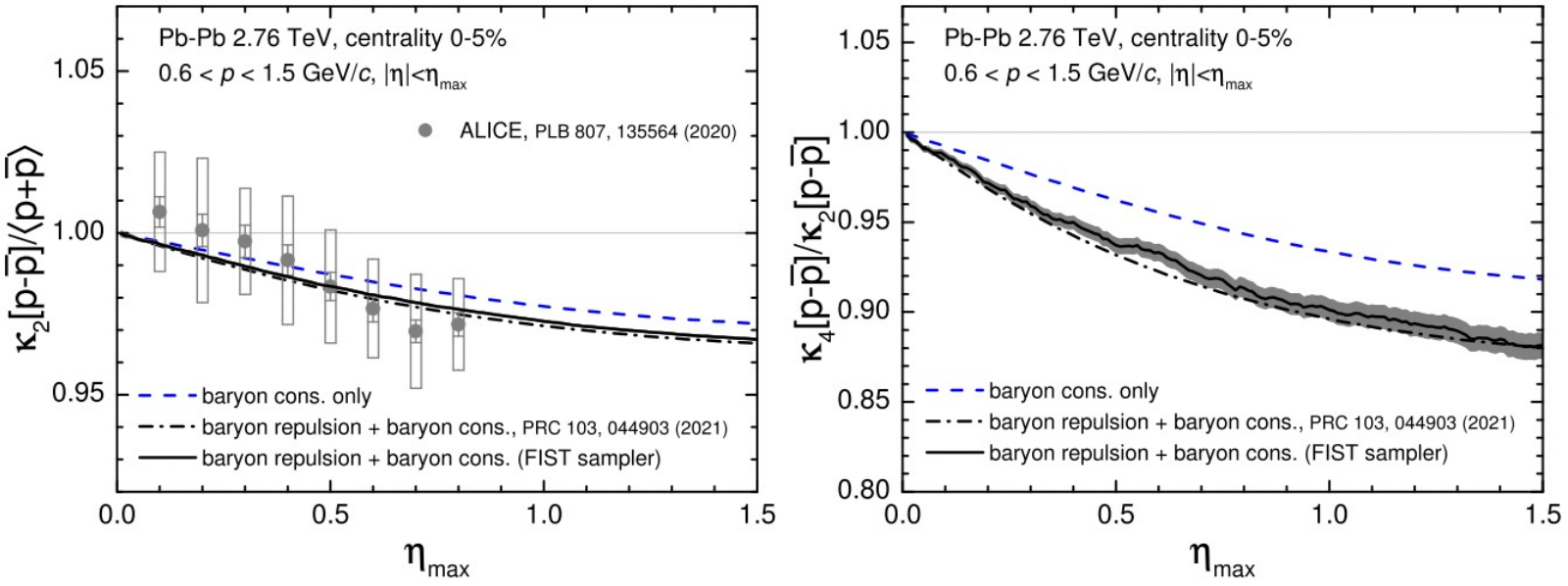
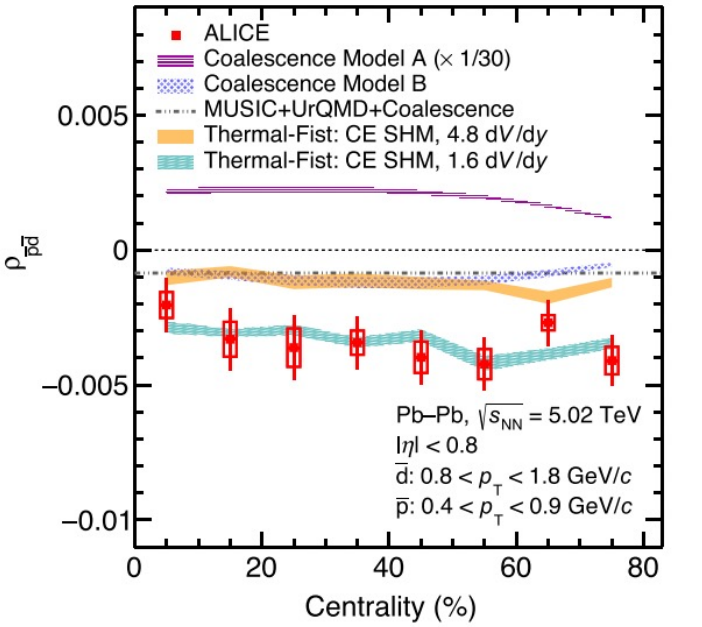
Using the blast-wave model hypersurface (~20 million events)

Proton cumulants



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

Proton-deuteron correlations

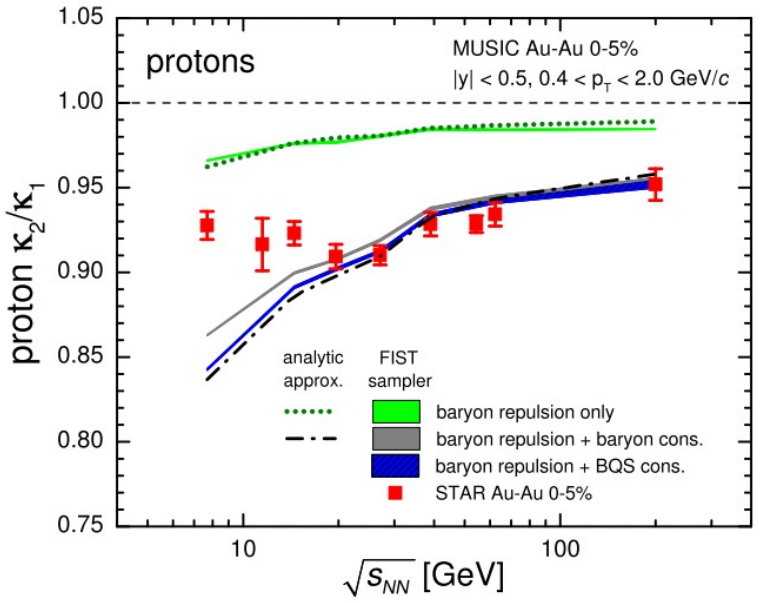


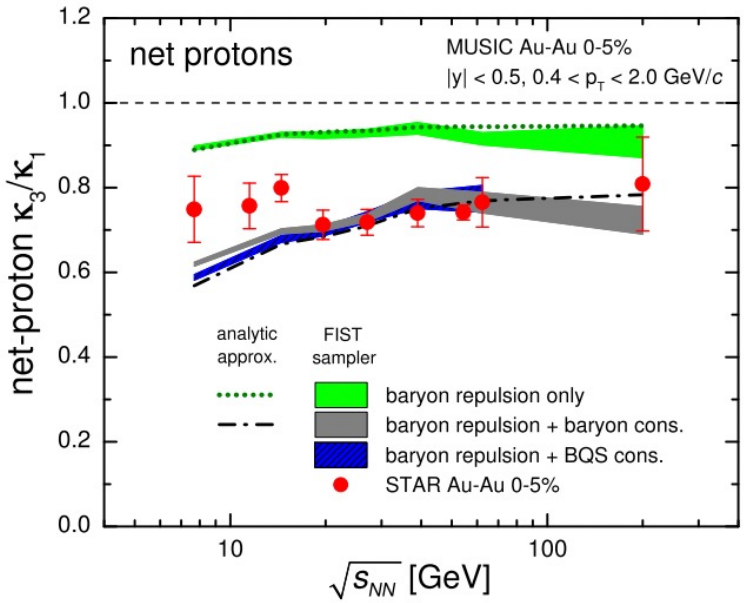
ALICE Coll., PRL 131, 041901 (2023)

Effects of hadronic afterburner UrQMD (mainly baryon annihilation) investigated in [Savchuk et al., PLB 827, 136983 (2023)]

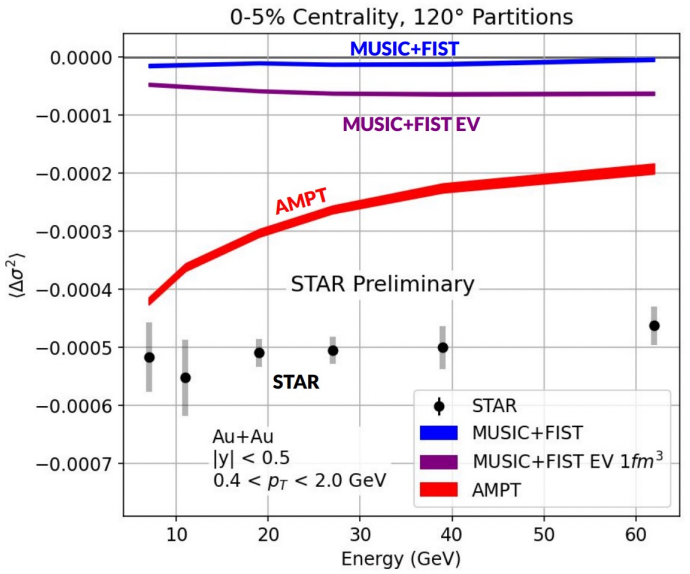
FIST sampler at RHIC-BES

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





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



D. Neff, QM2023

- 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

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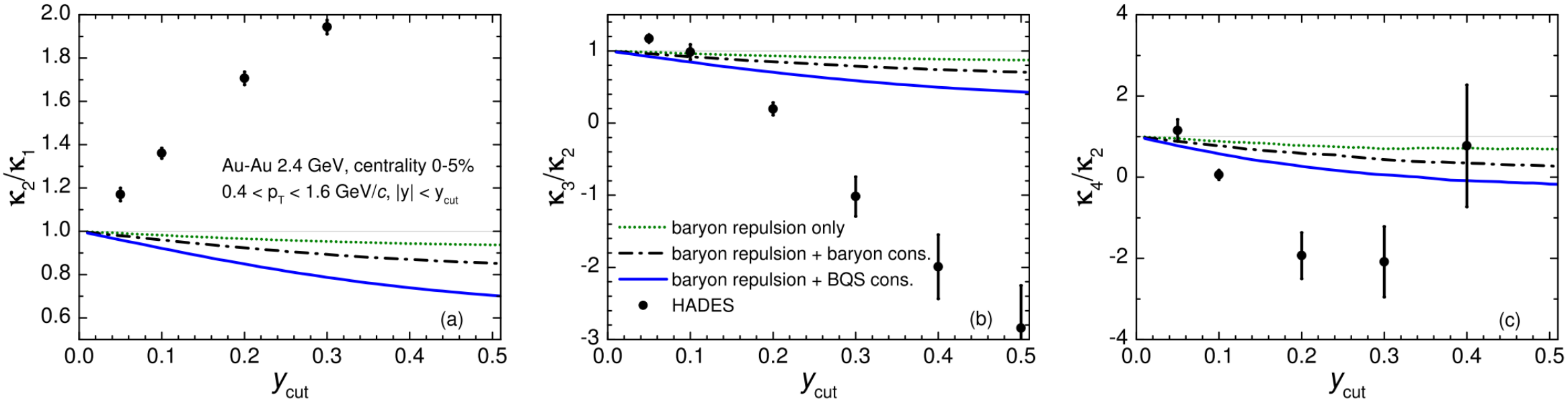
Using Siemens-Rasmussen-Hubble fireball parameterization



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

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

Summary and outlook

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- 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!