Modeling low energy heavy ion collisions with a dynamically initialized hybrid approach

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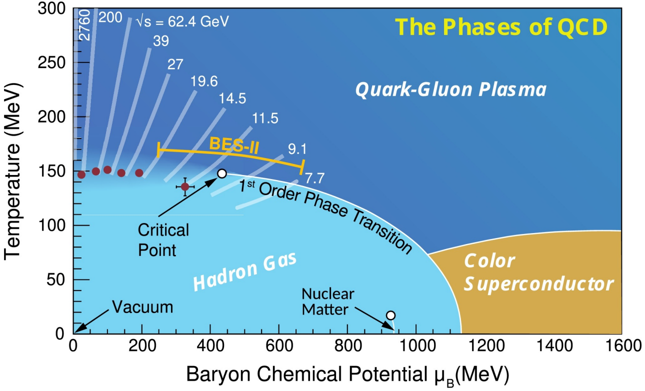
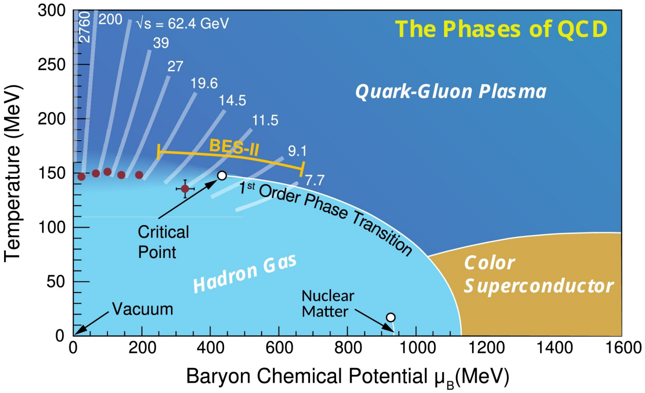
Motivation

QCD Phase diagram



- **High energies:** hydrodynamics-based approaches
- **Low energies:** hadron transport

picture from Xin An et al.: Nucl.Phys.A 1017 (2022) 122343



- **High energies:** hydrodynamics-based approaches
- **Intermediate energies:** a combination of the two $\rightarrow$ hybrid approach
- **Low energies:** hadron transport

picture from Xin An et al.: Nucl.Phys.A 1017 (2022) 122343

SMASH-vHLLE hybrid

Four-step approach

https://github.com/smash-transport/smash-vhlle-hybrid

1. **SMASH** for the initial non-equilibrium phase of the evolution:
   - hadronic transport approach
   - initial conditions extracted at proper time hypersurface – nuclei passing:

$$\tau_0 = (R_P + R_T)\left[\left(\frac{\sqrt{s_{NN}}}{2m_N}\right)^2 - 1\right]^{-1/2} \qquad (1)$$

https://github.com/smash-transport/smash

2. **vHLLE** for hydrodynamics:
   - 3D viscous hydrodynamics code
   - charge conservation: B, Q

https://github.com/yukarpenko/vhlle

3. **hadron sampler** for particlization
4. **SMASH** for afterburner

SMASH-vHLLE hybrid

Four-step approach

https://github.com/smash-transport/smash-vhlle-hybrid

1. **SMASH** for the initial non-equilibrium phase of the evolution:
2. **vHLLE** for hydrodynamics:
3. **hadron sampler** for particlization
   - Cooper-Frye formula with viscous correction
   - SMASH HRG equation of state
4. **SMASH** for afterburner
   - hadronic cascade for final state interactions and resonance decays

- special care: energy and charge conservation at interfaces

A. Schäfer et al.: Eur.Phys.J.A 58 (2022) 11, 230

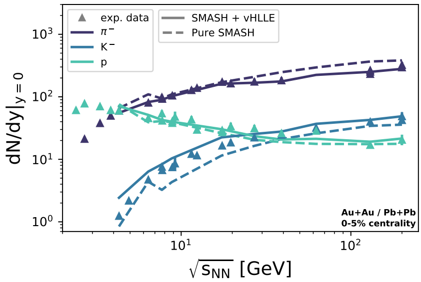
J. Weil et al.: Phys.Rev.C 94 (2016) 5, 054905

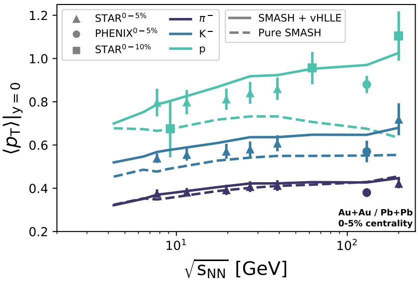
Iu. Karpenko et al.: Comput.Phys.Commun. 185 (2014) 3016

Iu. Karpenko et al.: Phys.Rev.C 91 (2015) 6, 064901

SMASH-vHLLE hybrid

Model results





- the model works for a wide range of energies (namely for RHIC Beam Energy Scan range)
- inclusion of hydrodynamics presents a good improvement when compared to hadron transport alone

Dynamical initialization

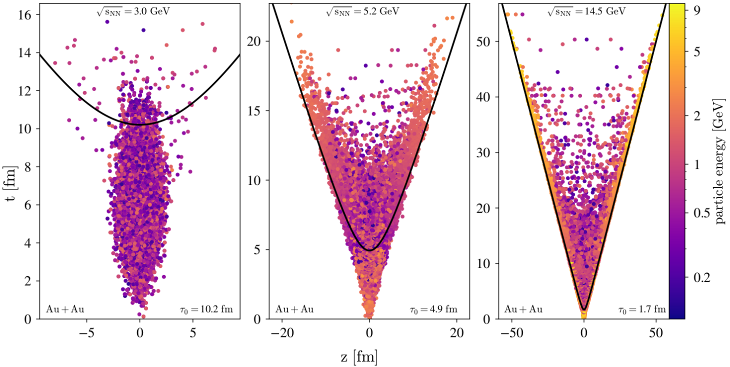
Model description

- for lower energies the geometry of the collision is very different, proper time to initialize hydro as defined is very high
  $\rightarrow$ too late to have meaningful hydro evolution
- we need a different condition for initialization
- there might be **smaller bubbles** of fluid in certain dense enough regions of the interaction volume
- new criterion: check energy density in the hadronic system: if above threshold $\epsilon_{sw} = 0.5\ \mathrm{GeV/fm^3}$ particles fluidize
- hydrodynamics is not initialized as a whole at one time: particles enter into the evolution gradually as energy, momentum and charge sources

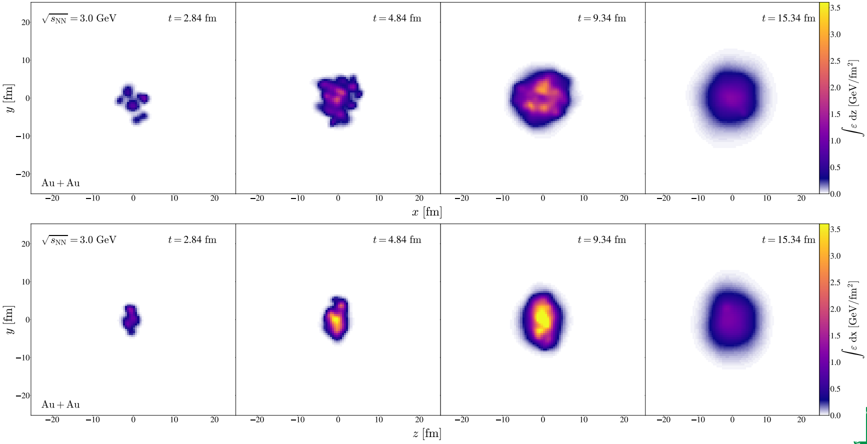
Inspired by Y.Akamatsu et al.:Phys.Rev.C 98 (2018) 2, 024909

Dynamical initialization
Initialization criteria

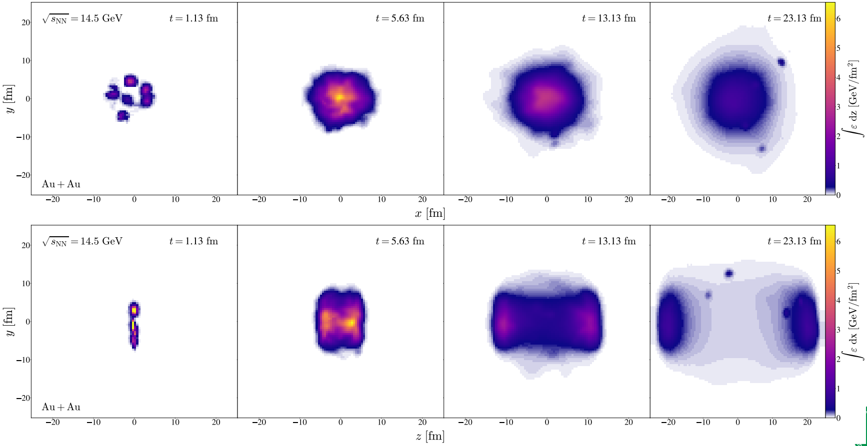
- fluidization based on energy density happens much earlier than nuclei passing time τ_0 for lower energies



AuAu @ 3.0 GeV


$\sqrt{s_{NN}} = 3.0$ GeV
$t = 2.84$ fm
$t = 4.84$ fm
$t = 9.34$ fm
$t = 15.34$ fm
Au + Au
y [fm]
x [fm]
z [fm]
$\int \varepsilon$ dz [GeV/fm^2]
$\int \varepsilon$ dx [GeV/fm^2]

AuAu @ 14.5 GeV

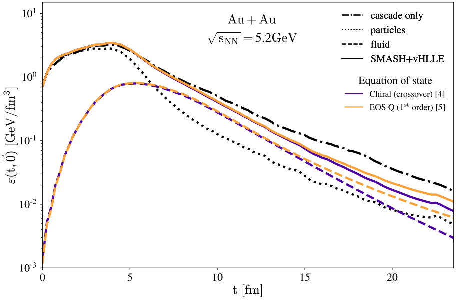


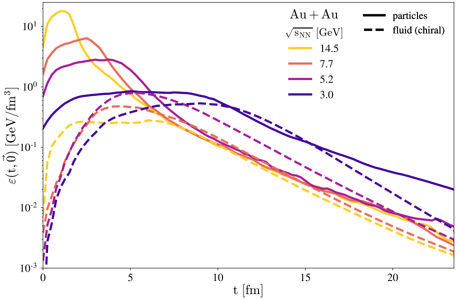
$\sqrt{s_{NN}} = 14.5$ GeV
$t = 1.13$ fm
$t = 5.63$ fm
$t = 13.13$ fm
$t = 23.13$ fm
Au + Au
x [fm]
y [fm]
z [fm]
$\int \varepsilon$ dz [GeV/fm^2]
$\int \varepsilon$ dx [GeV/fm^2]

Dynamical initialization

Energy density evolution

- we compare energy density in the central cell throughout the collisions
- different evolution scenarios/phases and energies





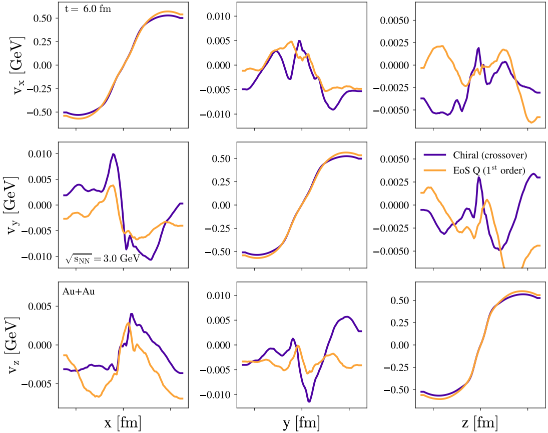
Chiral model EoS: J.Steinheimer et al.: J.Phys.G 38 (2011) 035001

EOS-Q: P.F.Kolb et al.: Phys.Rev.C 62 (2000) 054909

Dynamical initialization

EoS variation

- we can see the difference in x,y components of velocity in z direction
- could we see it in the flow?



Conclusion

- standard hybrid model at intermediate energies: initial phase + hydrodynamics + hadron transport
- lower energies: for a meaningful hydrodynamic phase there cannot be a sharp switching of phases
- dynamical initialization at low energies allows us to have a longer meaningful hydrodynamic phase where we can study the equation of state
- now working on: concurrent running of SMASH and vHLLE, enabling their communication