K/pi ratios from a dynamically integrated transport approach

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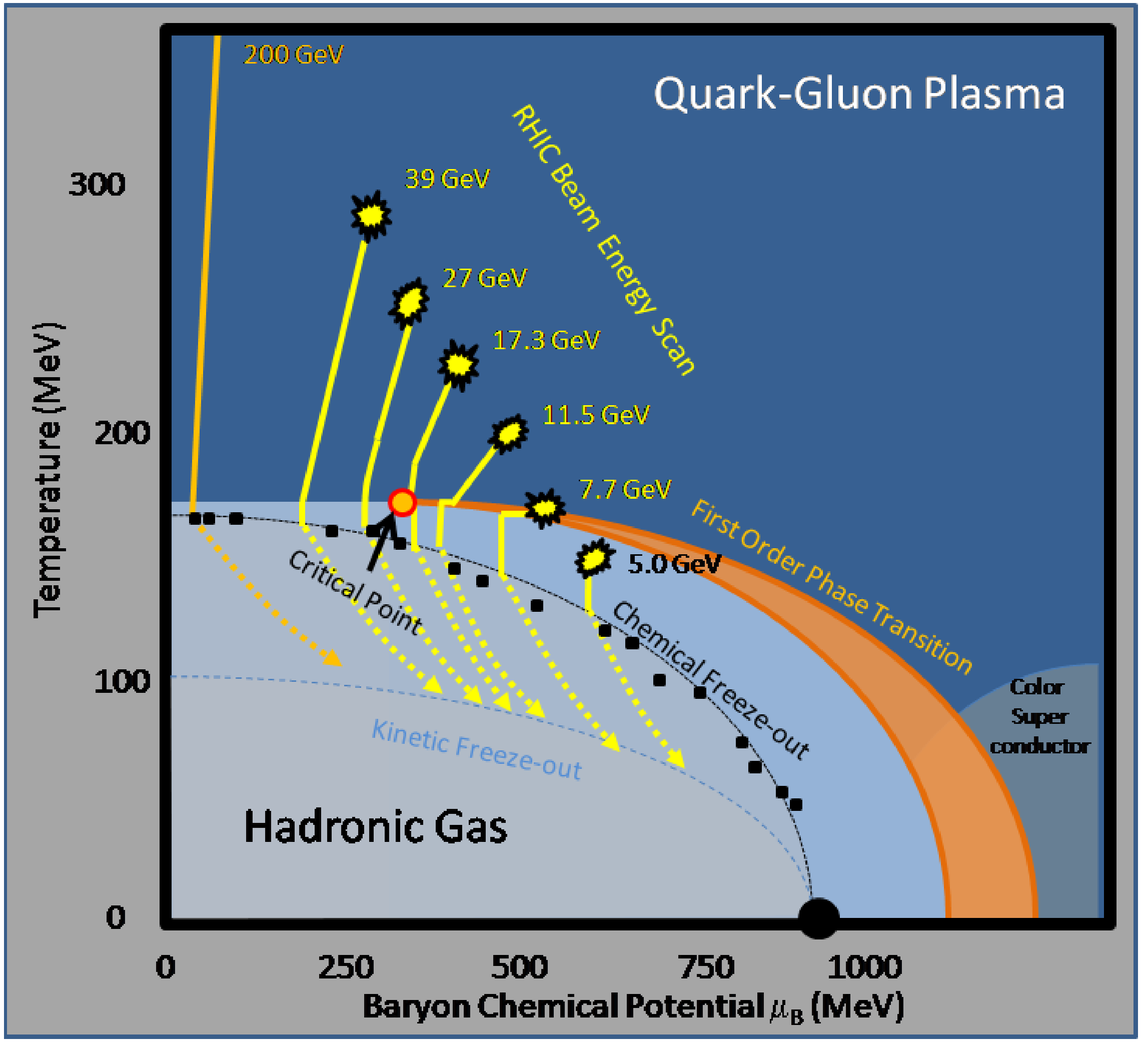
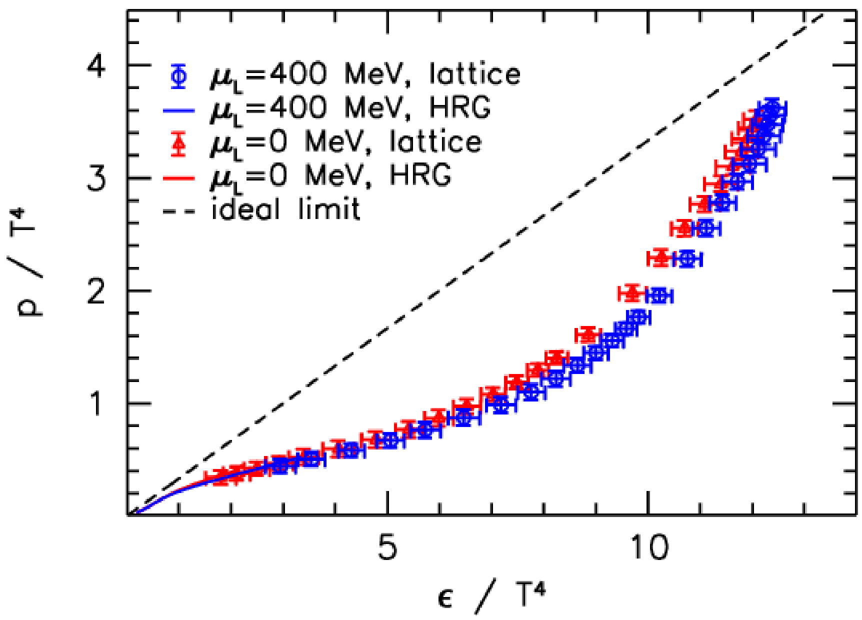
- Introduction
- JAM+hydro: A new dynamically integrated transport model
- Equation of state (EoS) controlled collision term

This talk is baed on arXiv:1805.09024

NFQCD2018 at Kyoto June. 4, 2018

Search for the QCD equation of state (EoS) by the beam energy scan





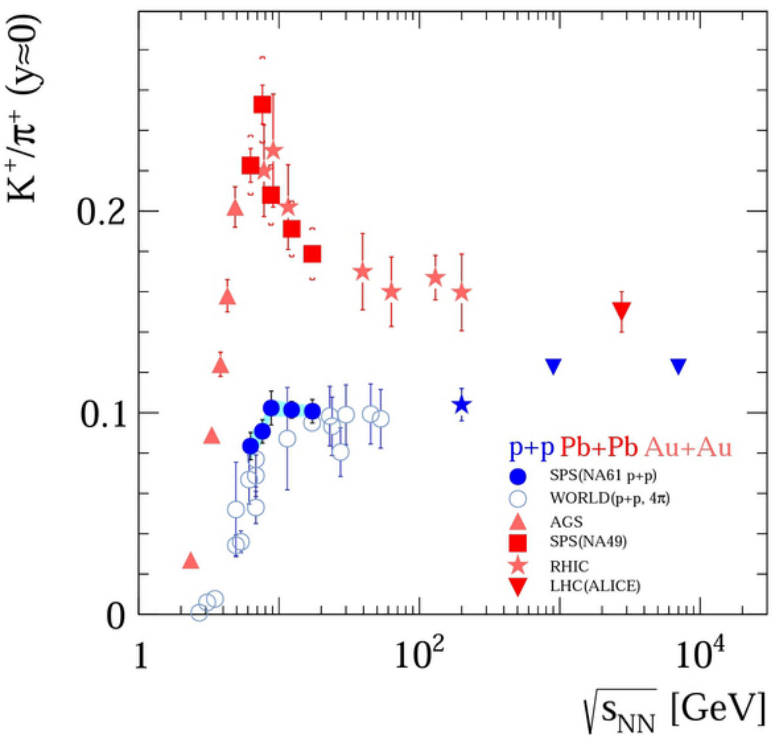
EoS from lattice QCD
Sz.Borsanyi, et.al JHEP 1208(2013)053

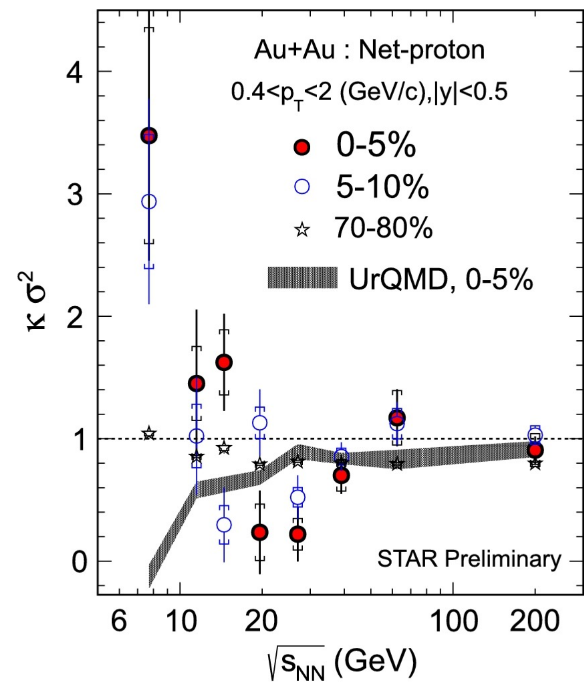
Effective models:

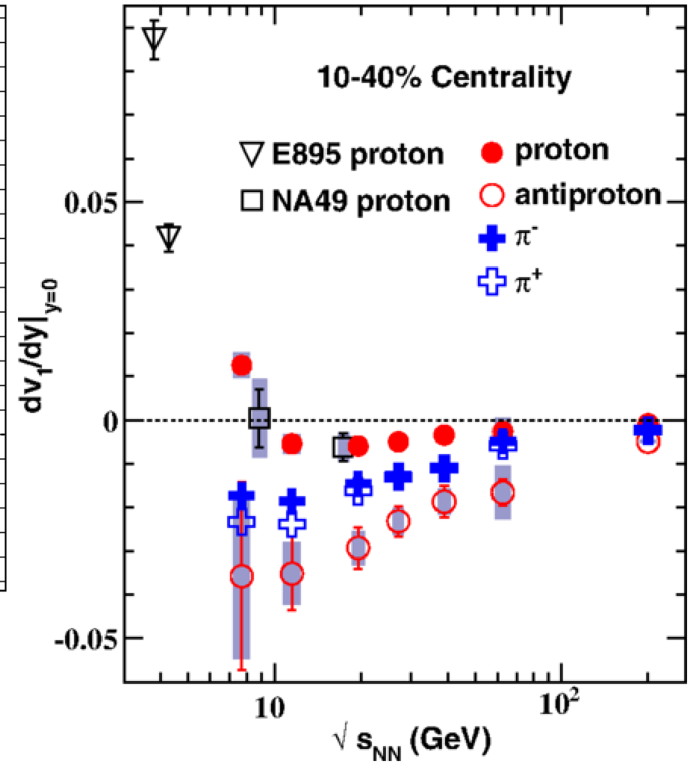
NJL, PNJL, PQM,
Quasi-particle model……….

Location of the critical point?

Non-monotonic structures in beam energy dependence







NA49

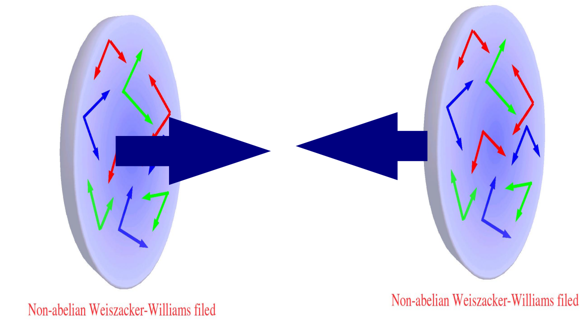
X. Luo QM15

Onset of de-confinement?

First-order phase transition? End point?

L. Adamczyk et al. (STAR Collaboration)
Phys. Rev. Lett. 112, 162301 – Published 23 April 2014

Modeling at RHIC/LHC
hybrid approach works



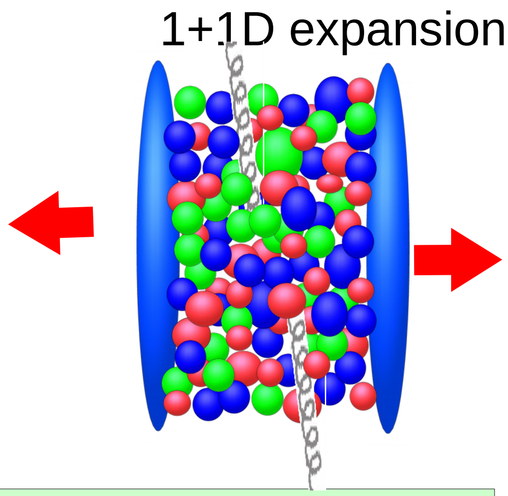
Initial conditions: Glauber, CGC, event generators

Hydrodynamics: viscous-hydro, anisotropic hydro

Hadron gas: hadron transport models

EoS: crossover from lattice QCD

Jet production and its Energy loss: pQCD



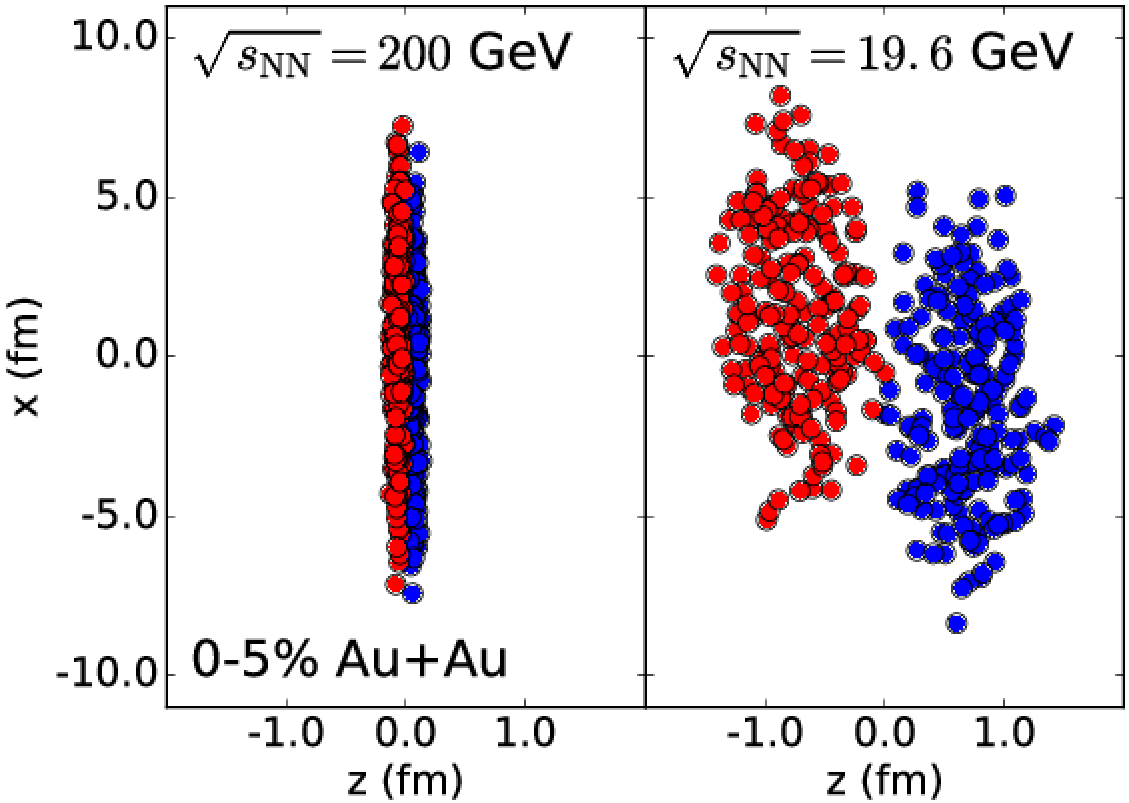
Single thermalization time at tau = 0.6 fm/c

At high energies, factorization in time and energy works:

e.g. CGC + hydrodynamics + energy loss of jets + hadron transport model

Initial nucleon positions

Chun Shen, Bjorn Schenke arXiv:1710.00881 [nucl-th]

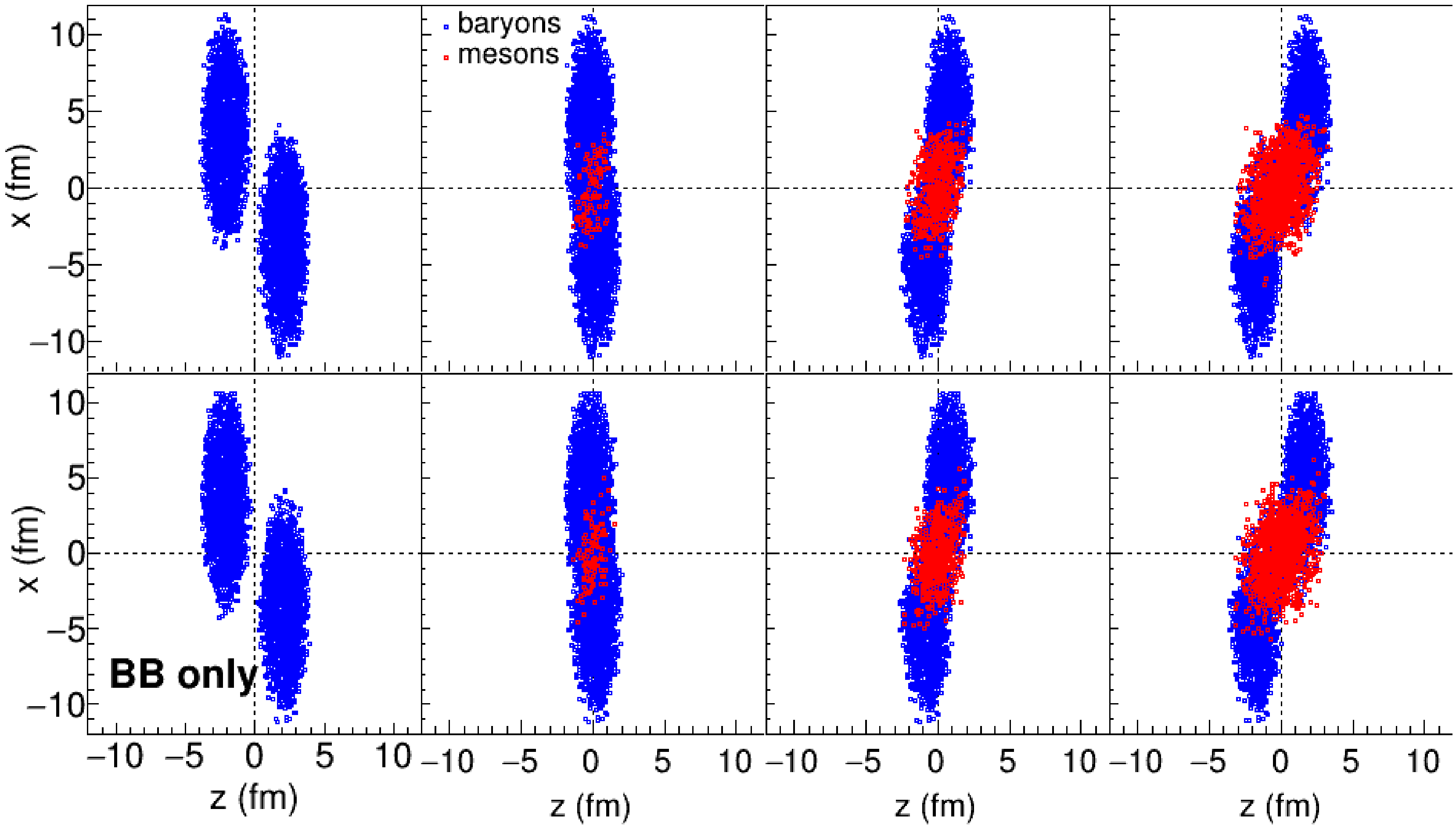


Assumption of single thermalization time breaks down at low beam energies

Time evolution

Red:mesons. Meson-baryon interactions are important before two Nuclei pass each other.

$$\sqrt{s_{NN}} = 7.7\,\mathrm{GeV}$$



What is needed for HI at high baryon density

Cannot apply factorization in time;
models at RHIC/LHC does not work

1) Hybrid approach:

coupling of Hydro + Boltzmann

2) Initial stages of collisions have to be described by the non-equilibrium transport models

3) How to model EoS with non-vanishing chemical potentials?

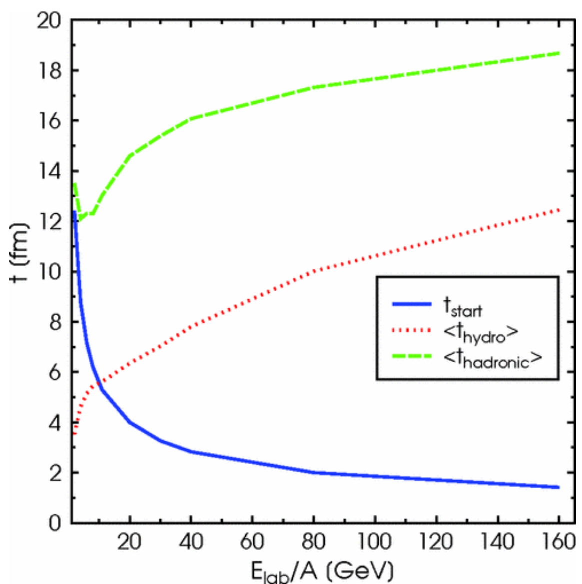
Progresses in hybrid dynamical models at high baryon density region

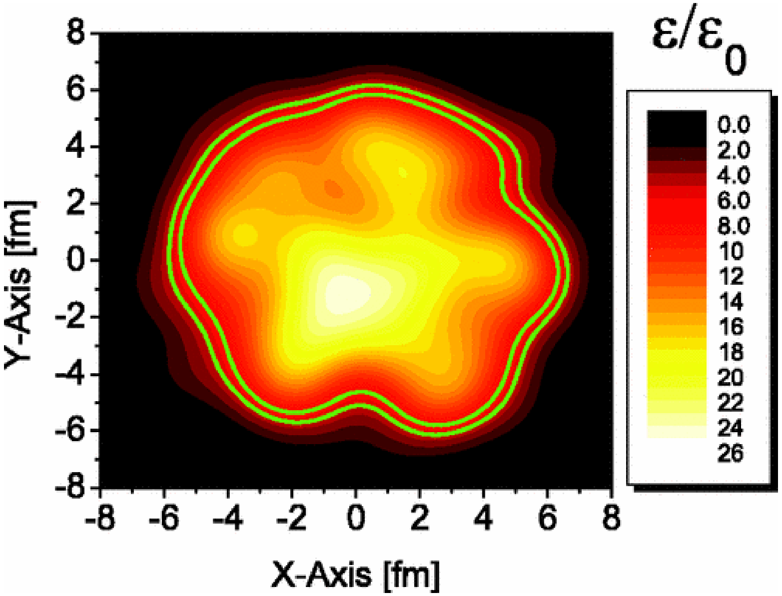
- UrQMD+hydro (2008) Petersen et.al.

initial condition from UrQMD → hydrodynamics → UrQMD

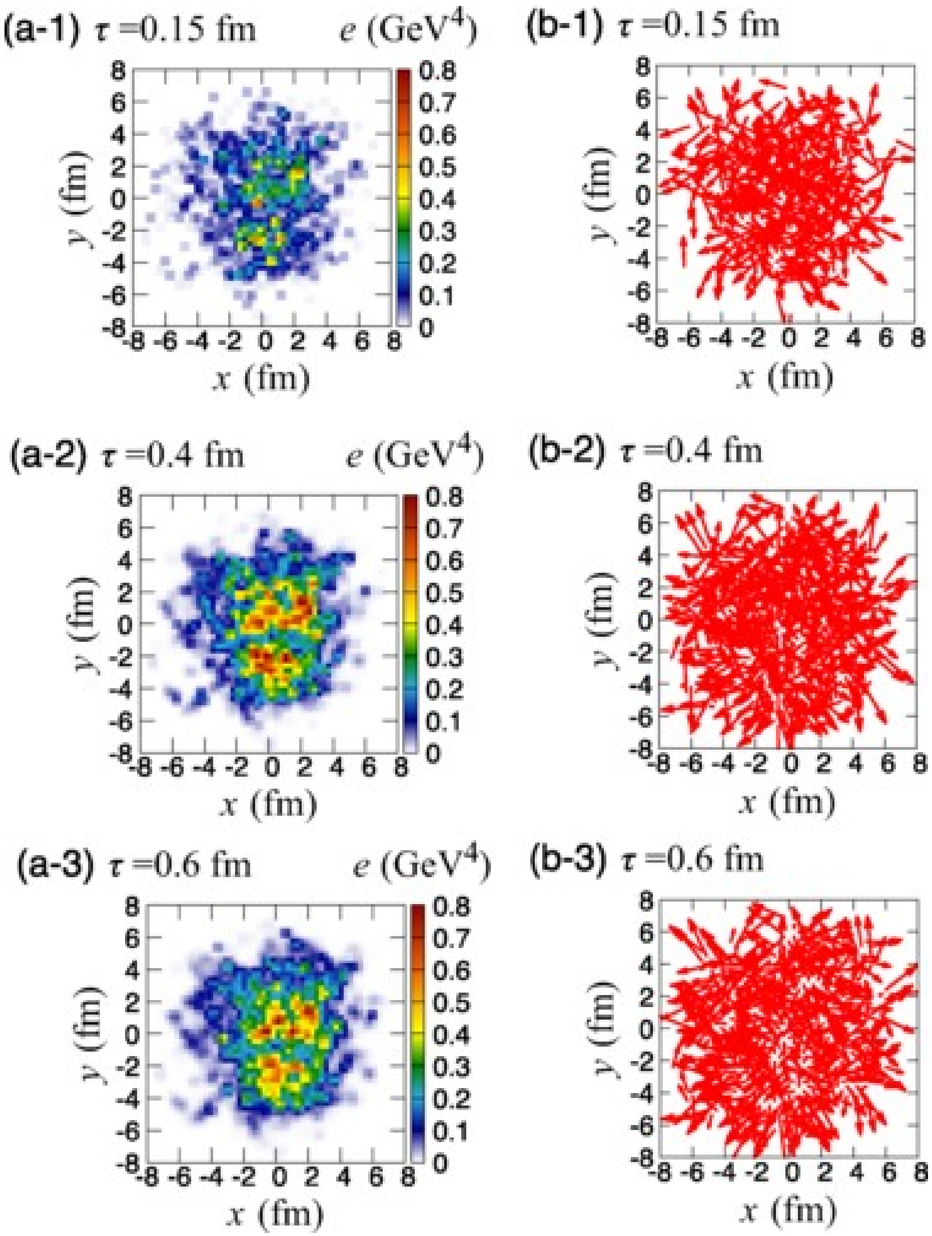
- Core-corona separation (K, Werner, 2007) in space configurations Steinheimer and Bleicher (2011)

- Dynamical initialization (2018) Shen and Schenke core-corona separation in time direction.





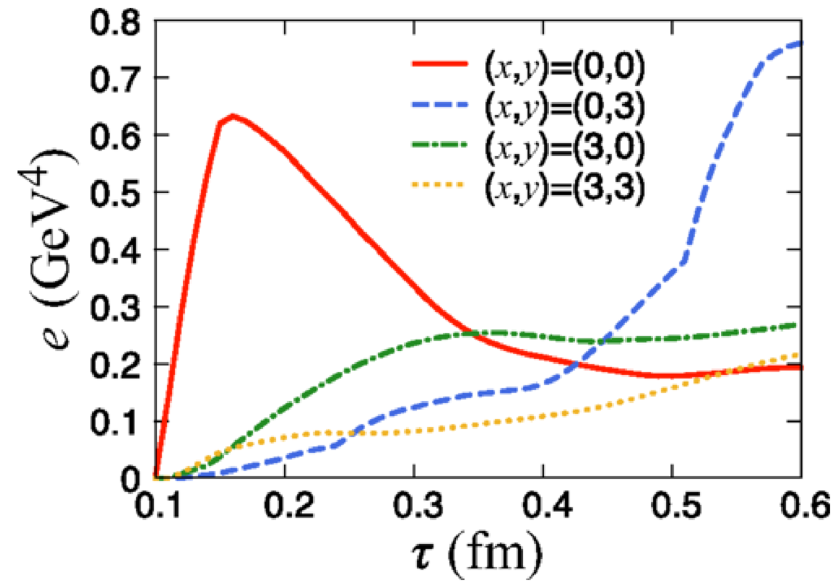
Dynamical Initialization of fluid at LHC



Dynamical initial condition for hydrodynamics as introduced by
M. Okai, et. al Phys. Rev C 95, 054914 (2017)

$$\partial_\mu T_f^{\mu\nu} = J^\nu$$

$$J^\mu = -\sum_i \frac{dp^\mu}{dt} \delta(\boldsymbol{r} - \boldsymbol{r}_i)$$



Motivations

Dynamically integrated transport model:
microscopic transport model + hydrodynamics

Dynamical initial condition for hydrodynamics through source terms

$$\partial_\mu T_f^{\mu\nu} = J^\nu, \quad \partial_\mu N_f^\mu = n_B$$

Some particles are converted into fluid elements with Gaussian profile.

$$J^\mu = \sum_i \frac{p_i^\mu(t)}{\Delta t} G(\boldsymbol{r} - \boldsymbol{r}_i(t)), \quad n_B = \sum_i \frac{B_i}{\Delta t} G(\boldsymbol{r} - \boldsymbol{r}_i(t))$$

JAM microscopic transport model

- spece-time propagation of particles based on cascade method
- Resonance (up to 2GeV) and string excitation and decays
- Re-scattering among all hadrons
- DPM type string excitation law as in HIJING.
- Use Pythia6 for string fragmentation
- Propagation by the hadronic mean-fields within RQMD/S formulation
- EoS controlled collision term

$$\dot{\boldsymbol{r}}_i = \frac{\boldsymbol{p}_i}{p_i^0} + \sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \boldsymbol{p}_i} \qquad \dot{\boldsymbol{p}}_i = -\sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \boldsymbol{r}_i} \qquad p_i^0 = \sqrt{\boldsymbol{p}_i^2 + m_i^2 + 2m_i V_i}$$

Arguments of potential $\boldsymbol{r}_i - \boldsymbol{r}_j$ and $\boldsymbol{p}_i - \boldsymbol{p}_j$ are replaced by the distances in the two-body c.m.

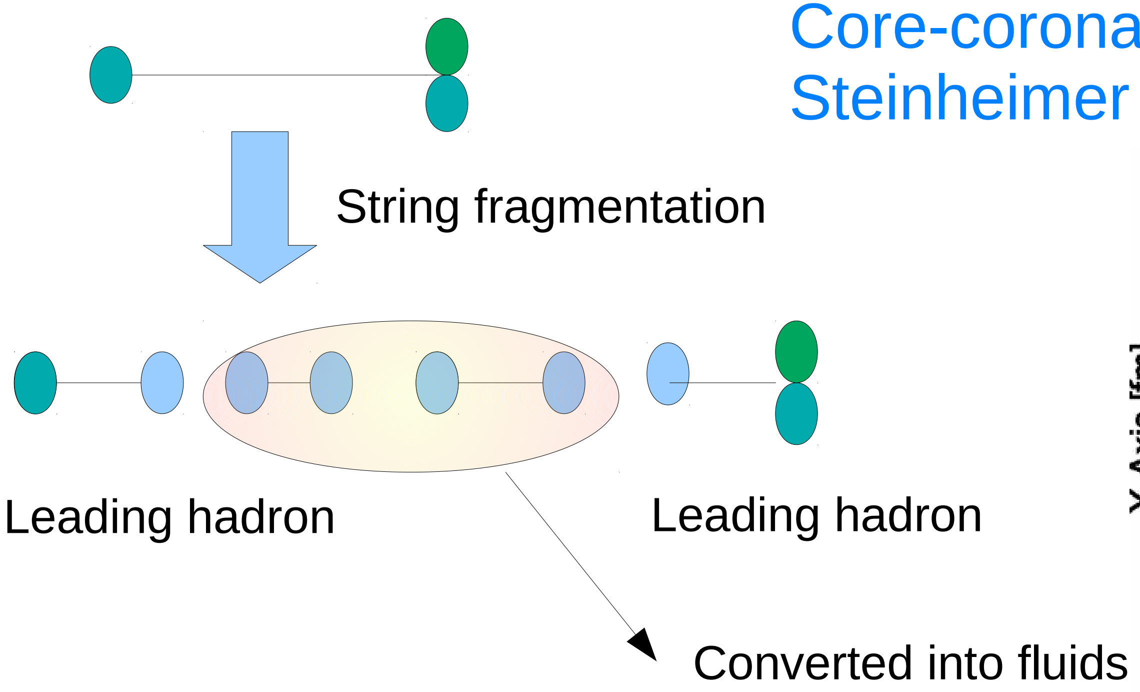
A new approach: JAM+hydro model

Dynamical coupling of fluids through source terms

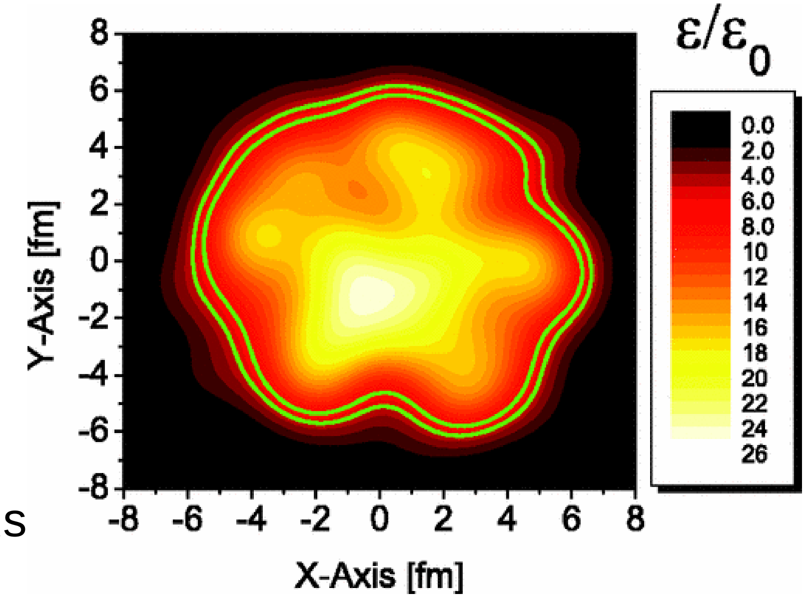
$$\partial_\mu T_f^{\mu\nu} = J^\nu, \quad \partial_\mu N_B^\mu = \rho_B$$

Time dependent Core-corona separation

Put Hadrons from string or resonance decay into fluids after their formation time
except leading hadrons when local energy density exceeds a hydronization energy density



Core-corona separation (K. Werner, 2007)
Steinheimer and Bleicher (2011)



Model parameters

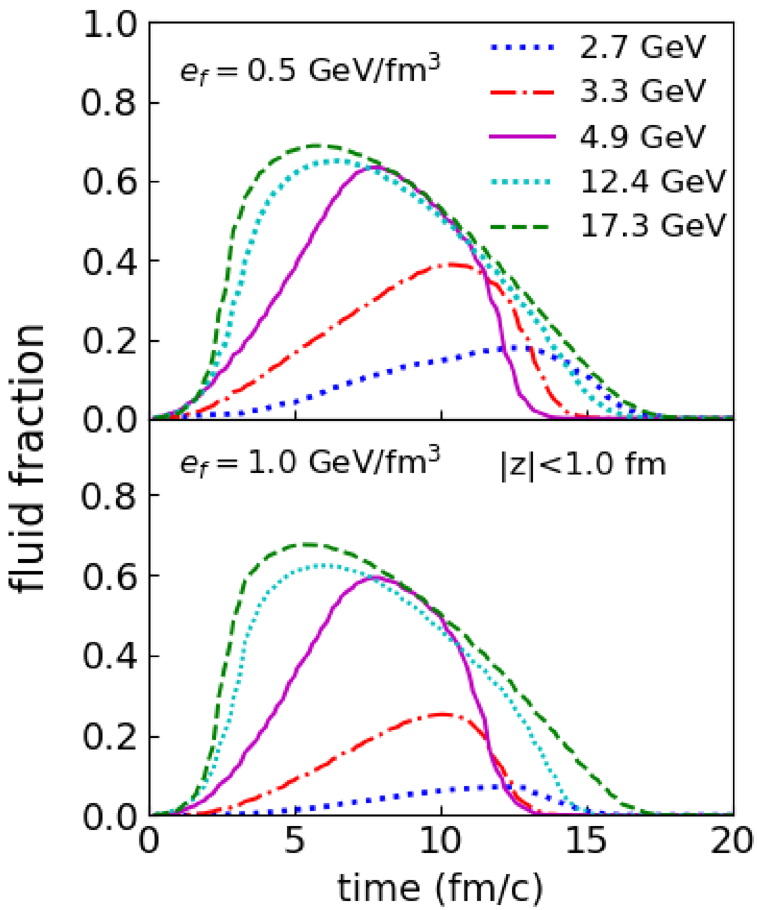
1) fluidization energy density

$$e_f = 0.5 - 1.0 \ \mathrm{GeV/fm}^3$$

2) particlization energy density

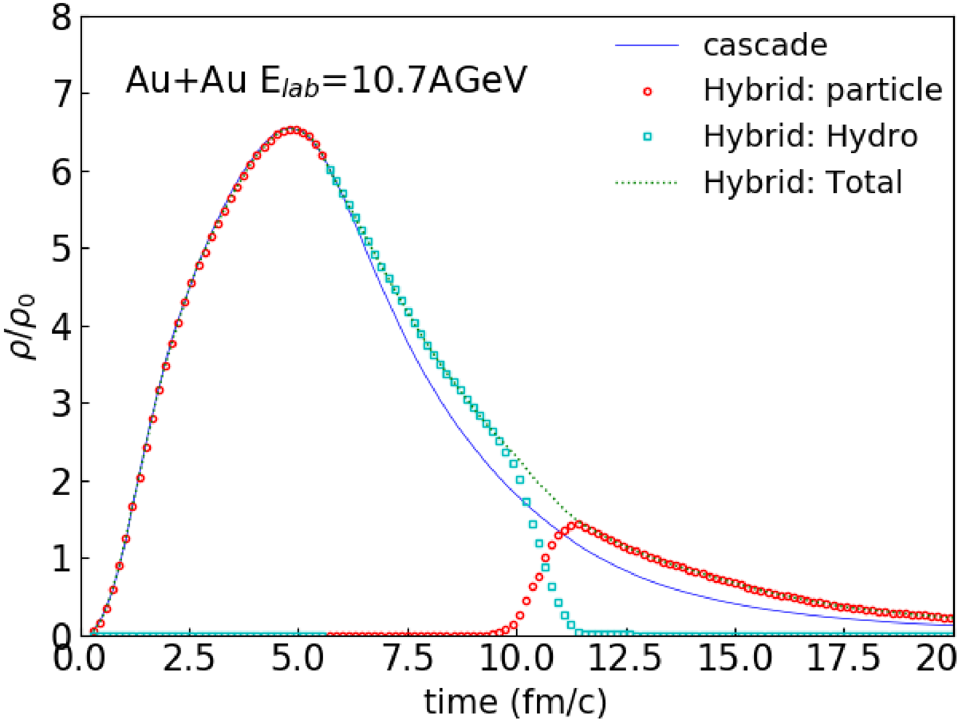
$$e_p = 0.5 \ \mathrm{GeV/fm}^3$$

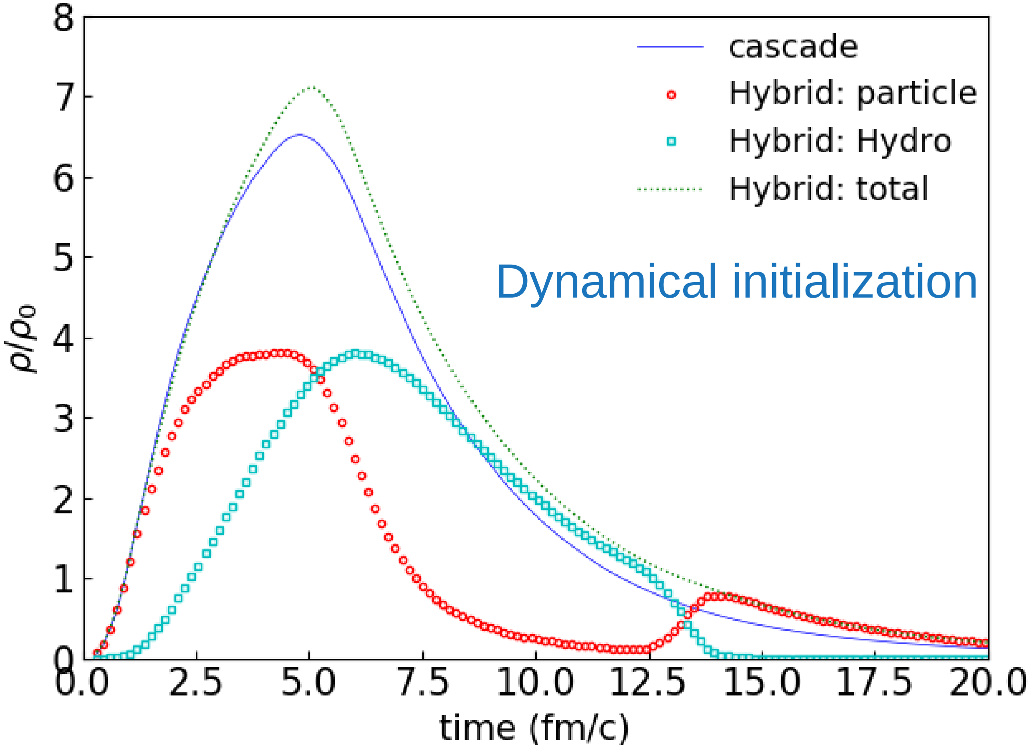
3) equation of state: EOS-Q
- first-order phase transition
- Bag model B=235MeV^4
- hadronic resonances up to 2GeV
- baryon density dependent
- repulsive potential for baryons



Fraction of fluid energy at central region is about 70% at top SPS energy.

Hybrid model for AGS and SPS energies





Switch to hydro evolution
after two nuclei pass each other.

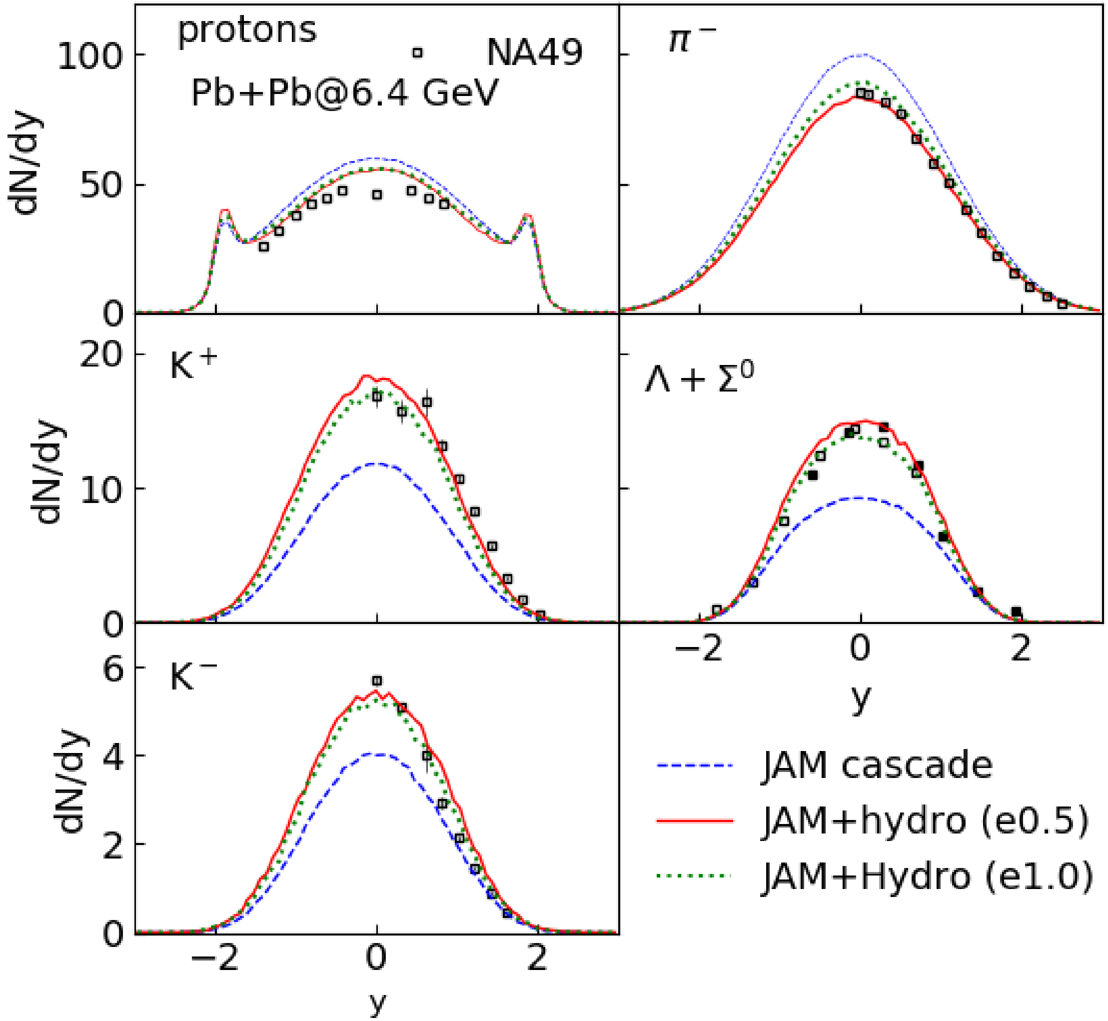
Hadronic EoS is used

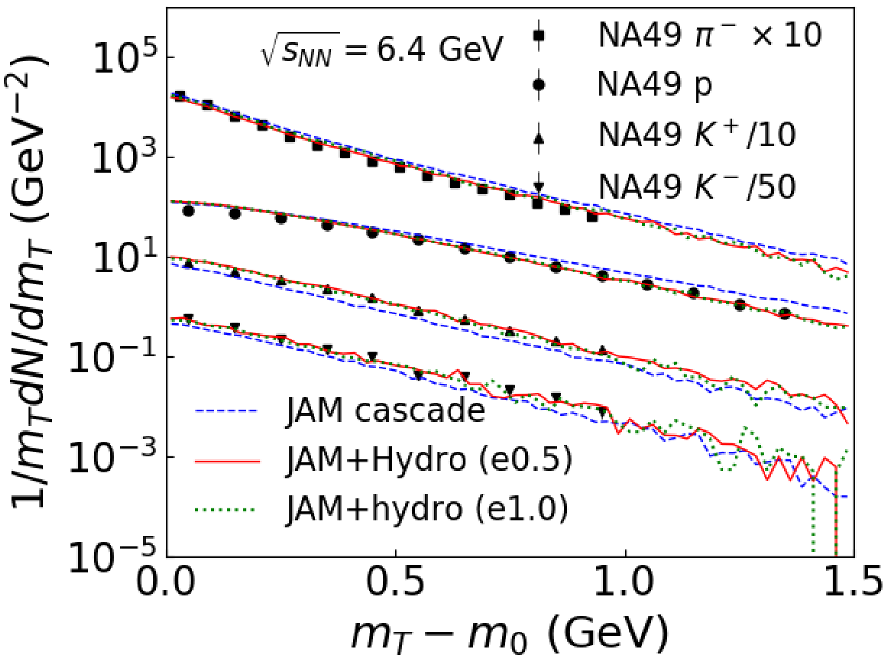
Switch to hadron transport
below a critical energy density.

It is important to take into account potential effect in the Cooper-Fry formula
to ensure smooth transition from fluid to particles.

$$\mu = B\mu_B + S\mu_S \to B(\mu_B - V(\rho_B)) + S\mu_S$$

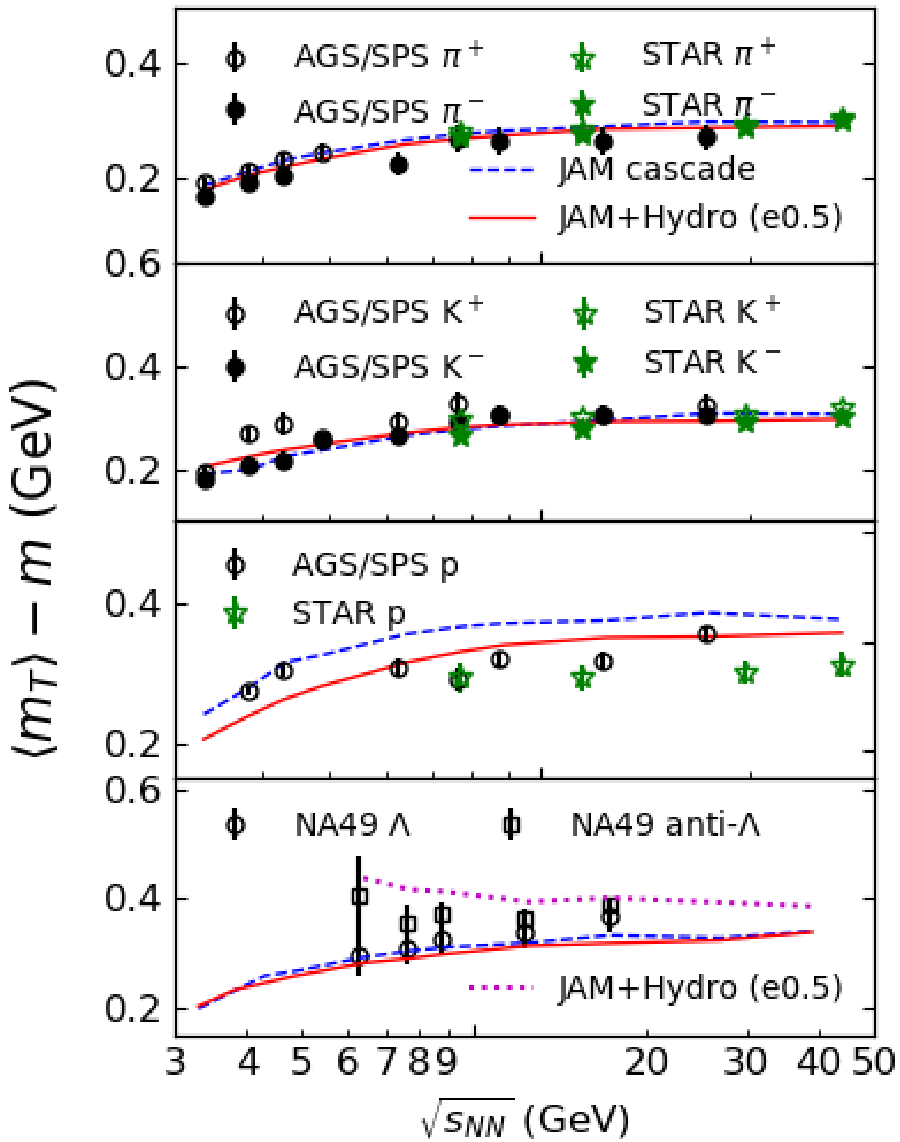
Particle spectra from a new hybrid model in Pb+Pb at Elab=20AGeV

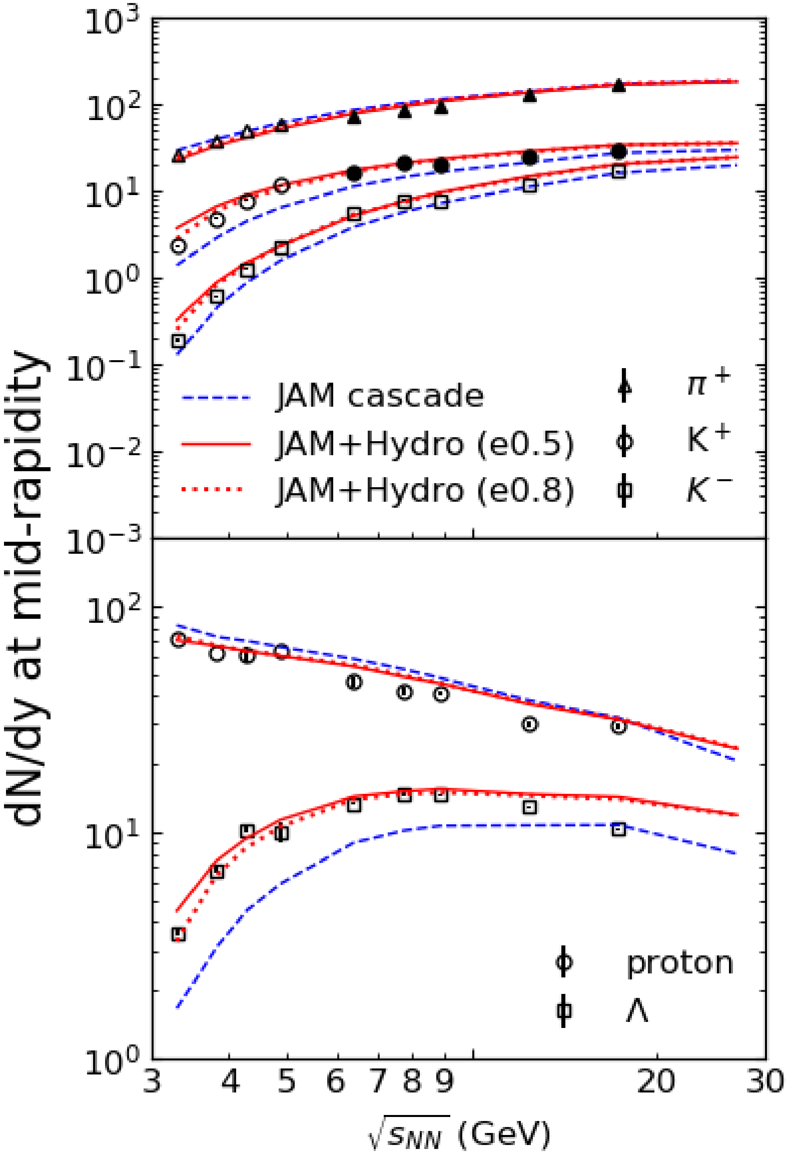




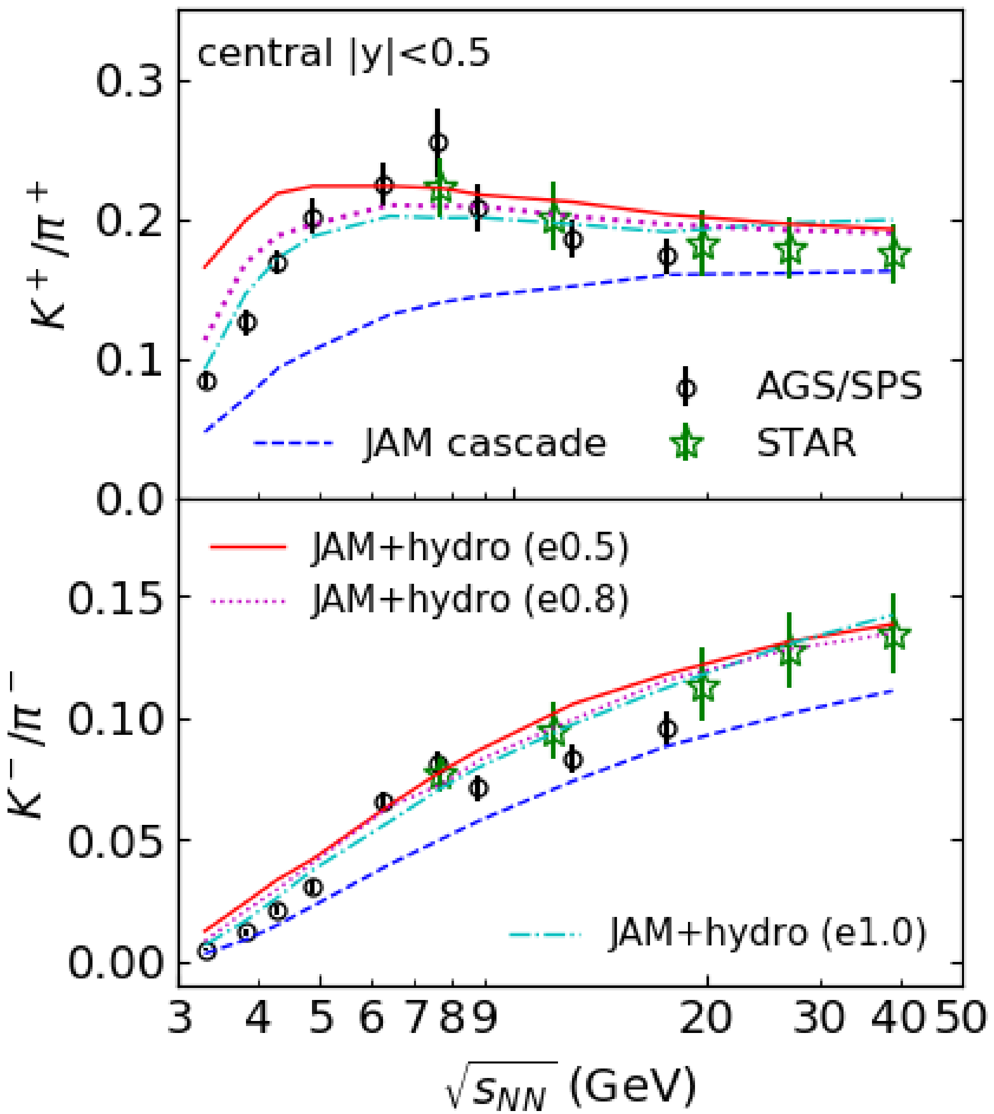
Fluidization energy density 0.5 or 1.0

Beam energy dependence of transverse mass and multiplicities from a new hybrid model.



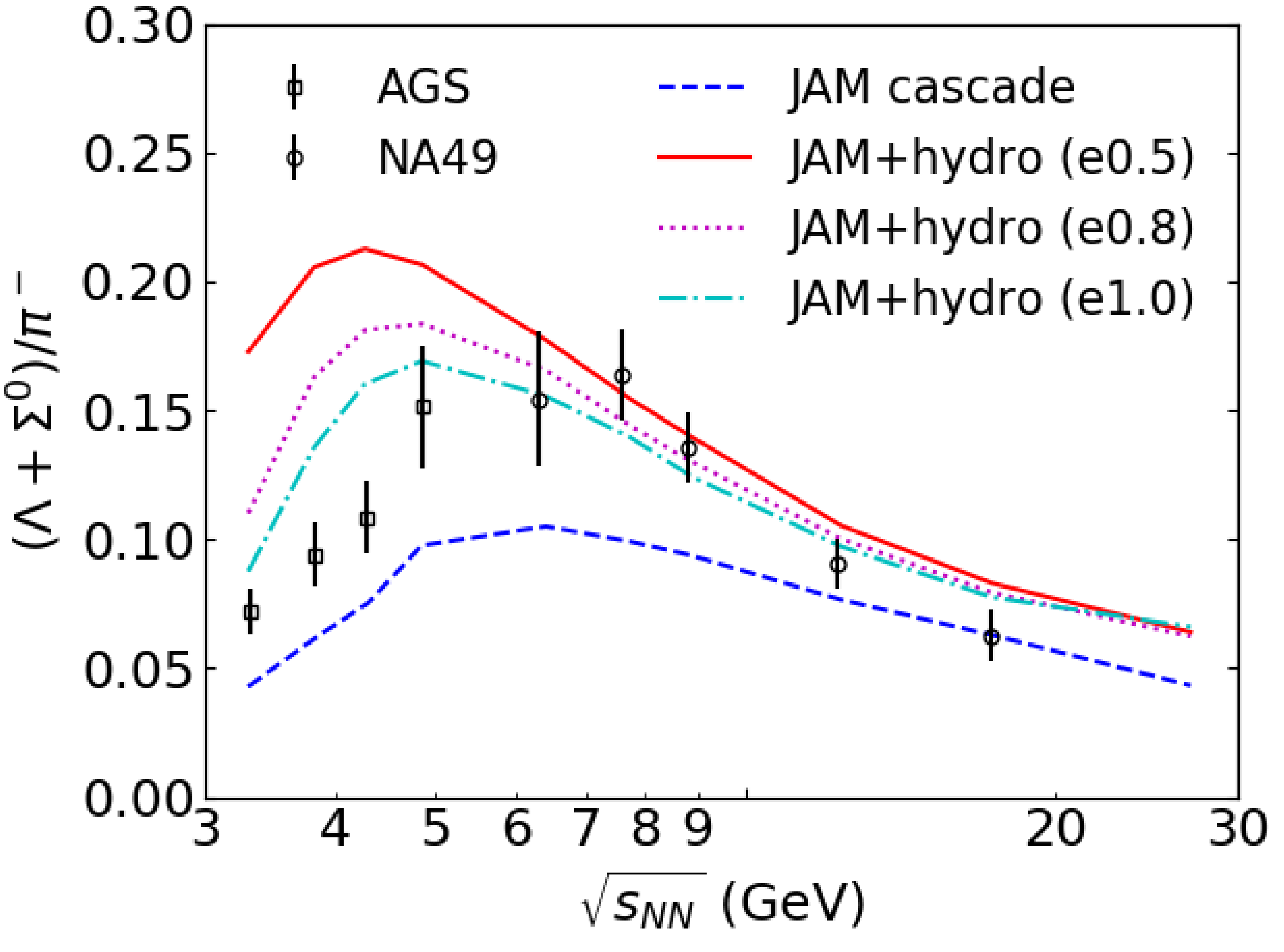


Beam energy dependence of K/pi ratios from hybrid model.



Incomplete thermalization of the sytem
is important for the description of K/pi ratio.

Beam energy dependence of Lambfa/pi ratios from a new hybrid model.



Y. N., H. Niemi, J. Steinheimer, H. Stoecker, PLB769 (2017)

EOS modified collision term

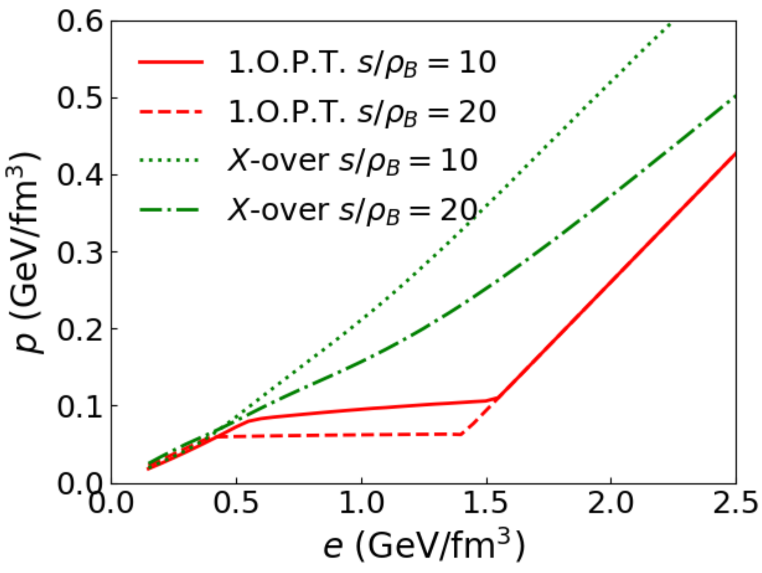
H. Sorge, Phys. Rev. Lett. 82,2048 (1999)   Virial Theorem for two body collisions

$$P = P_{free} + \frac{1}{3TV}\sum_{(i,j)}[(\boldsymbol{p}_i' - \boldsymbol{p}_i)\cdot\boldsymbol{r}_i + (\boldsymbol{p}_j' - \boldsymbol{p}_j)\cdot\boldsymbol{r}_j]$$

The momentum change is constrained by

$$(\boldsymbol{p}_i' - \boldsymbol{p}_i)\cdot(\boldsymbol{r}_i - \boldsymbol{r}_j) = 3\frac{(P - P_{free})}{\rho}(\Delta t_i + \Delta t_j)$$

When P < Pfree: attractive orbit in the collision.



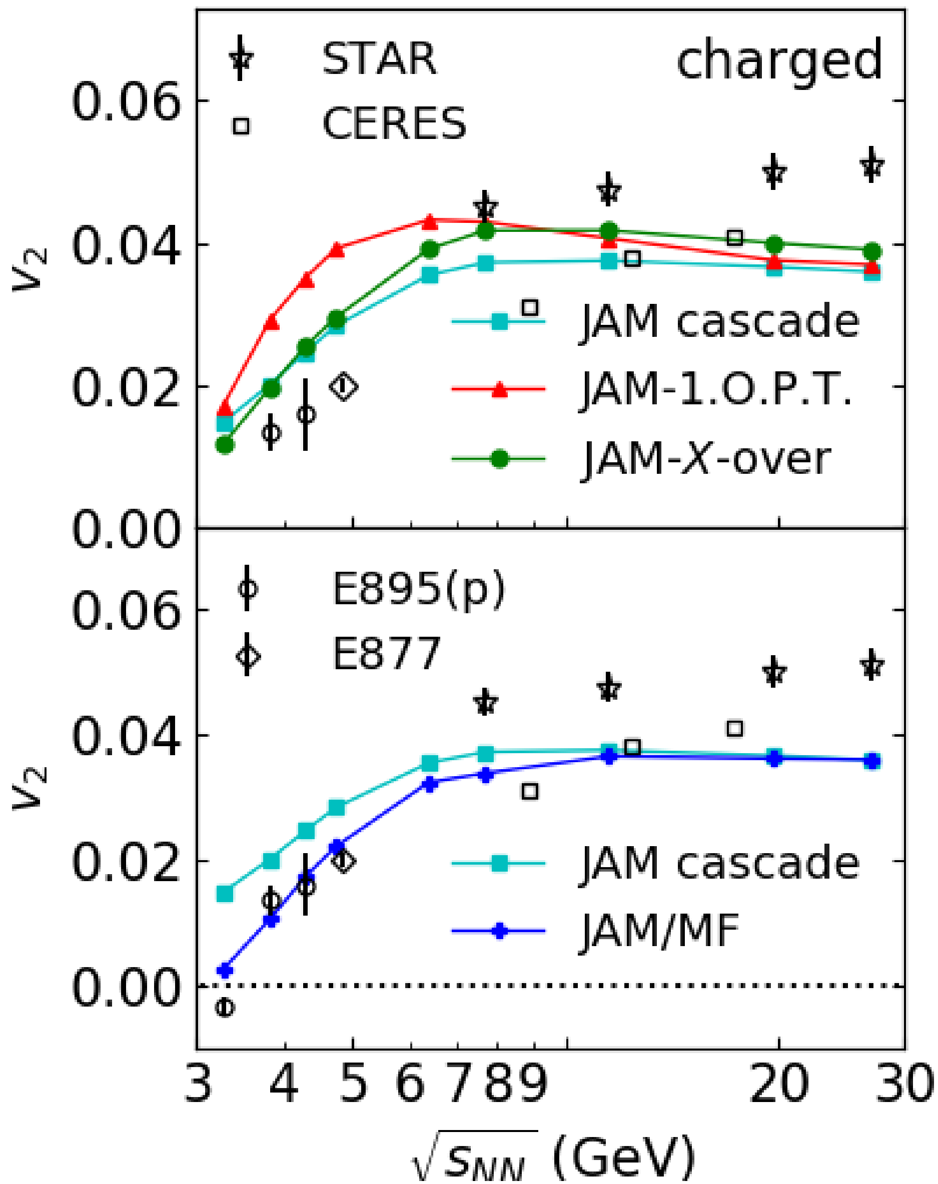
Fully baryon density dependent EoSs are implemented.
Cross-over EOS: J. Steinheimer
EOS-Q: Kolb, Sollfrank, Heinz

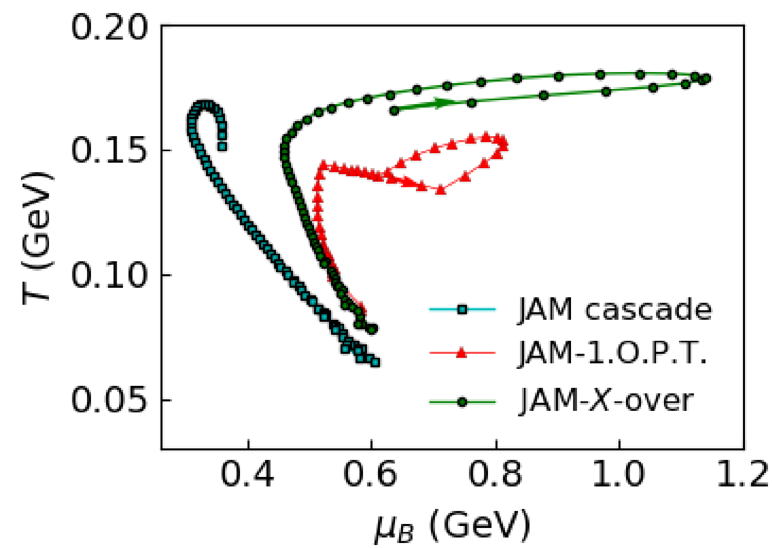
- Any EoS can be incorporated
- CPU time is as fast as standard cascade simulation
- Fully non-equilibrium transport approach

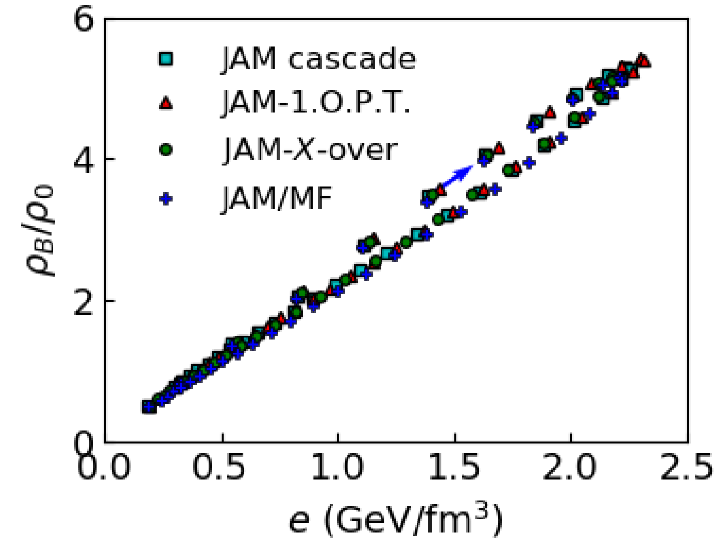
$$\frac{dN}{dyd^2p_T} = \frac{d^2N}{2\pi dp_T dy}(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots)$$

V2 excitation functions

$$v_n = \langle\cos(n\phi)\rangle$$

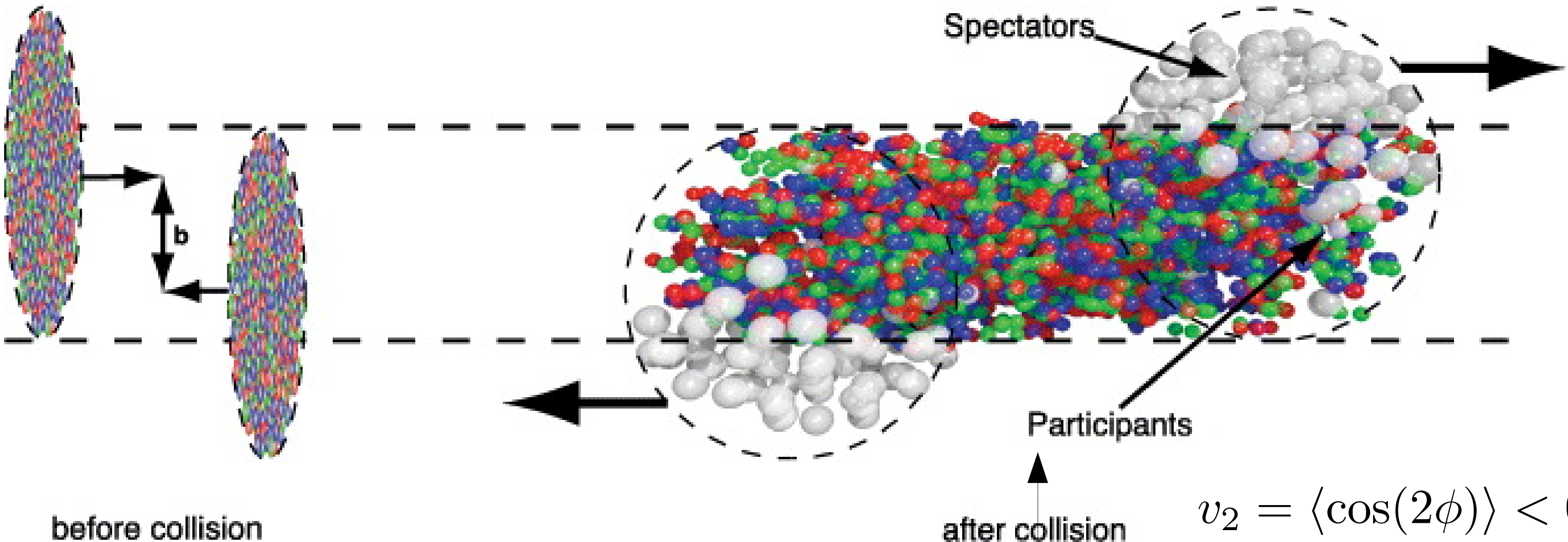


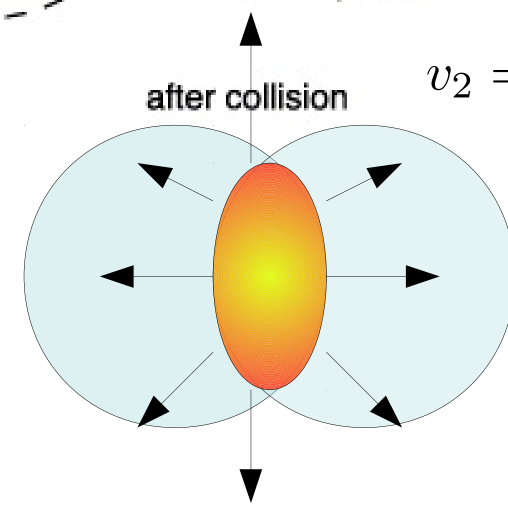




Y. N., H. Niemi, A. Ohnishi, J. Steinheimer, X. Luo, H. Stocker, Eur. Phys. A54 (2018) 18

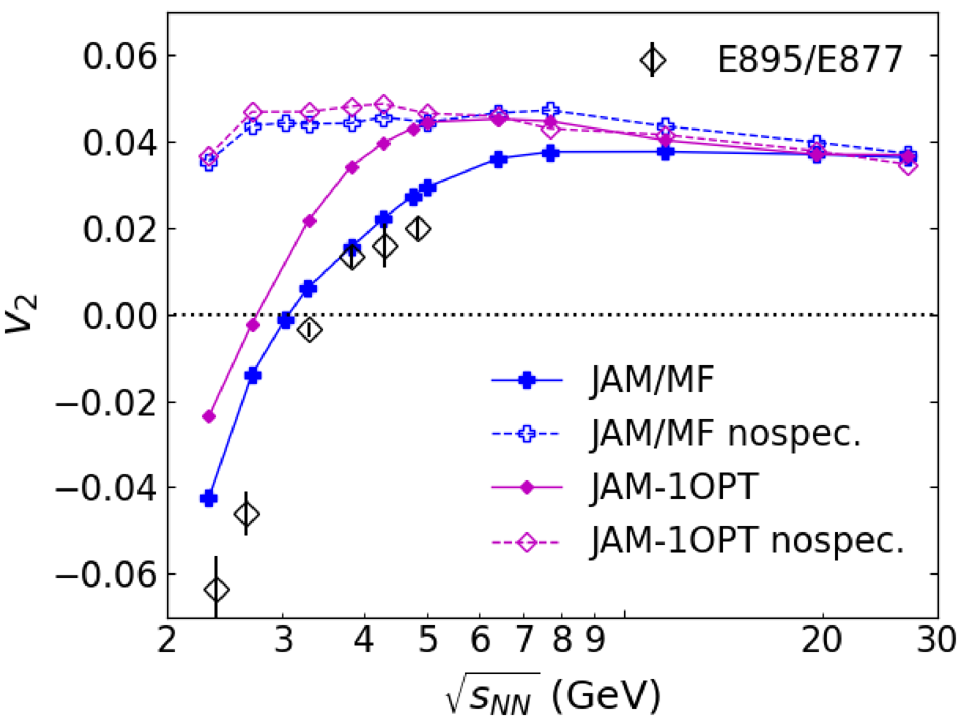
Effects of interaction with spectator





$$v_2 = \langle \cos(2\phi) \rangle < 0$$

$$v_2 = \langle \cos(2\phi) \rangle > 0$$



Comparison of the results without spectator interactions

In the case of first-order phase transition shadowing effects are weak.

Summary

- JAM is a microscopic transport model for high energy nuclear collisions based on strings and hadronic resonances

- We have developed a new hybrid approach by dynamical initialization of hydrodynamics which takes into account time dependent core-corona picture in order to simulate heavy ion collision at high baryon energy region.

- K/pi ratios from JAM+hydro approach is in good agreement with the data, which is explained by the incomplete thermailzation of the system.