Recent development and future perspectives in dynamical simulation of heavy ion collisions at the highest baryon density region

Yasushi Nara (Akita International University)

- Development of Transport and hybrid approach

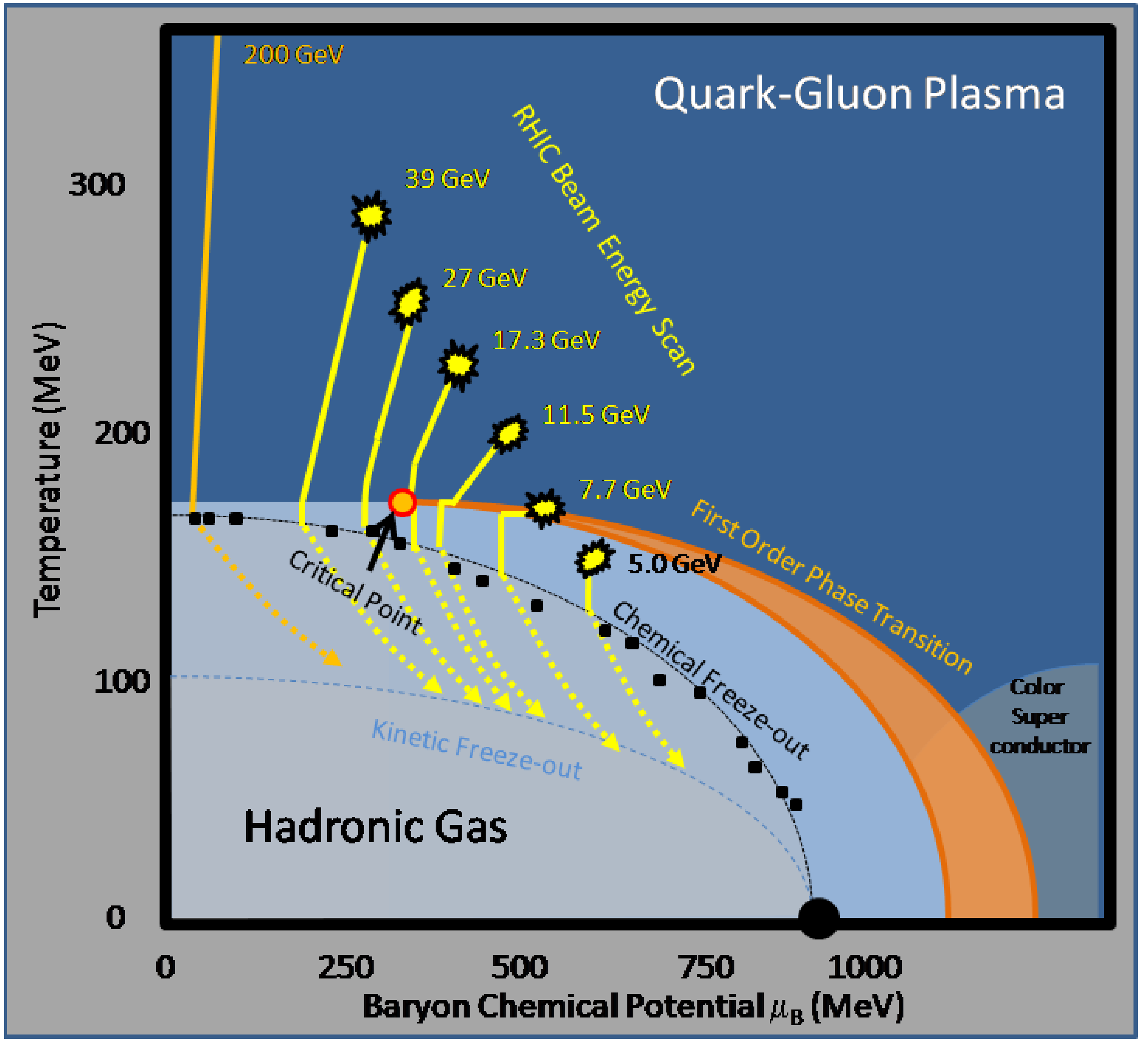
  EoS and directed and elliptic flow

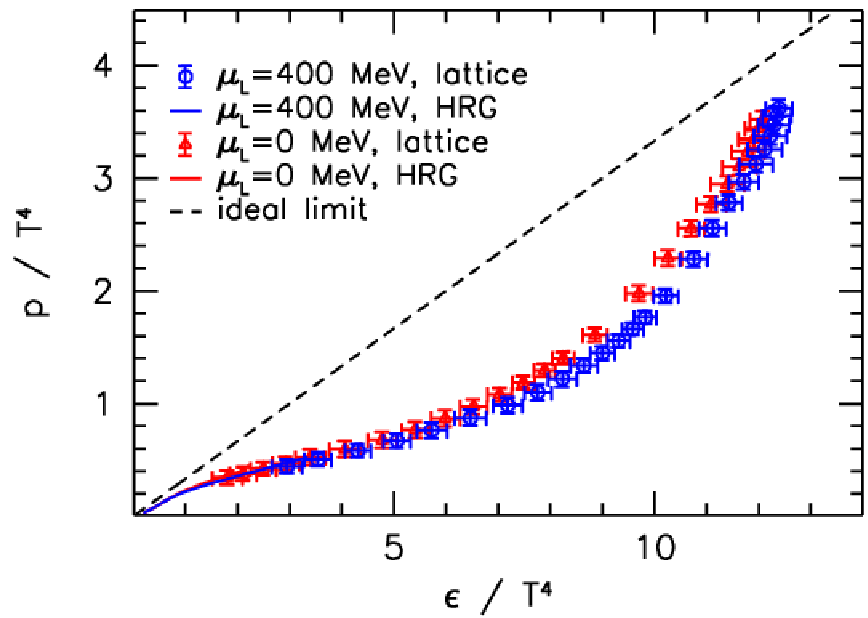
- Next generation dynamical model at J-PARC

  dynamical integration of micro and macro approaches

2017年度 KEK理論センターJ-PARC分室活動 総括研究会 Feb. 1-2 2018

Search for the QCD EoS by the beam energy scan





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

Location of the critical point?

Effective models:

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

Progresses in dynamical models

- Inclusion of partonic phase:

  explicit propagation of quarks and gluon
  AMPT: mean-field for both quakrs and hadrons
  PHSD: effects of chiral symmetry breaking

- EoS- controlled collision term in JAM

  can simulate any EoS such as crossover, 1st order

- Three-Fluid model (Ivanov et.al)

- Hybrid model (UrQMD + Hydrodynamics)

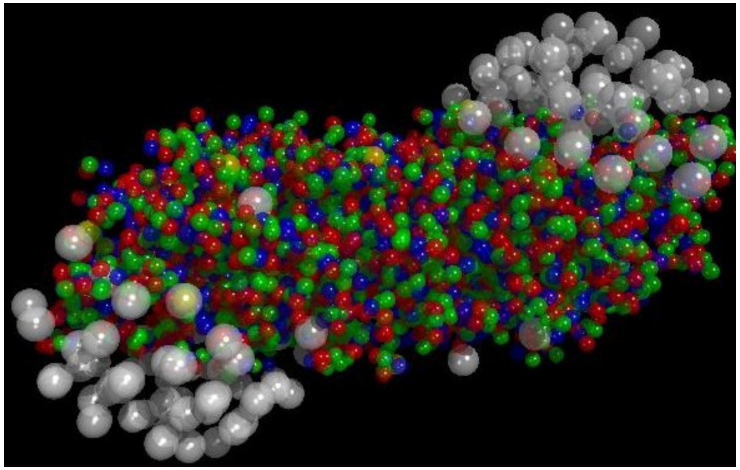
Non-equilibrium Transport approach

We need to follow the space-time evolution of all particles.

1) Relativistic Boltzmann equation (BUU)

Time evolution of one-particle distribution function

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{p}}{E} \cdot \nabla f + \boldsymbol{F} \cdot \frac{\partial f}{\partial \boldsymbol{p}} = \left(\frac{\partial f}{\partial t} \right)_{\mathrm{coll}}$$

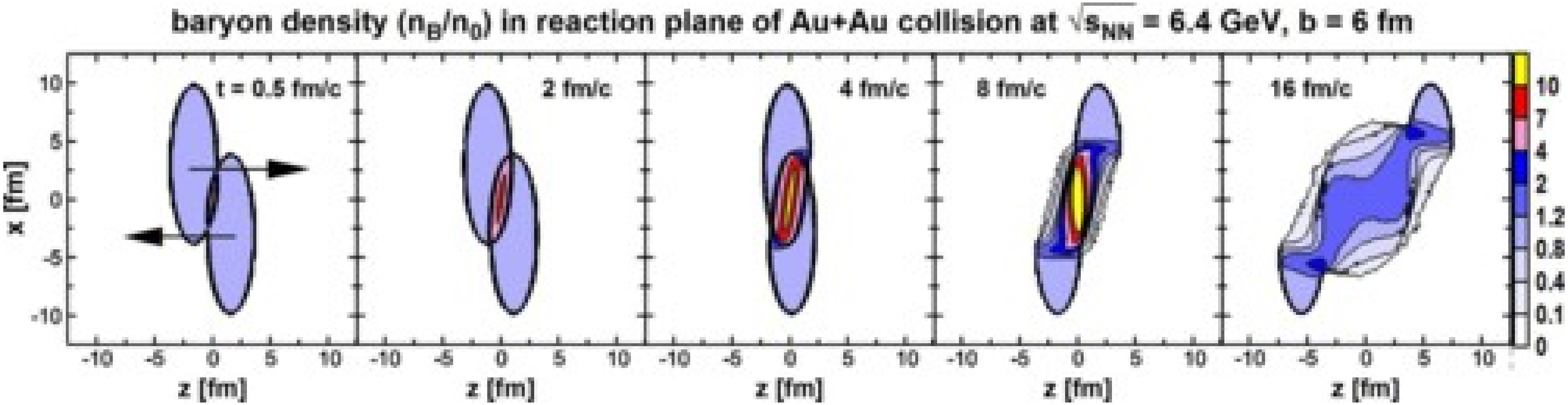


2) Quantum Molecular dynamics (N-body simulation)

$$\frac{d\boldsymbol{r}_i}{dt} = \frac{\partial H}{\partial \boldsymbol{p}_i}, \qquad \frac{d\boldsymbol{p}_i}{dt} = -\frac{\partial H}{\partial \boldsymbol{r}_i}$$

3fluid simulation

P. Batyuk et.al. PRC94(2016)044817



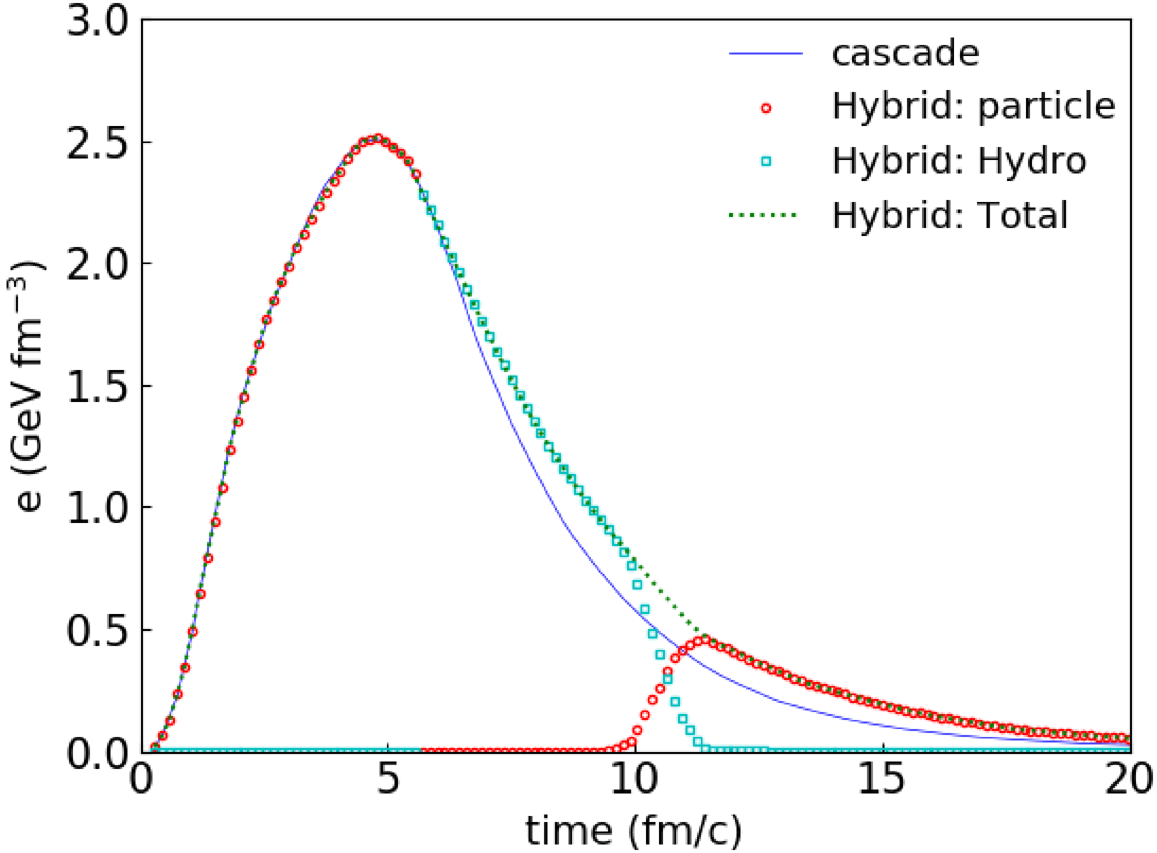
J. Brachmann, A. Dumitru, J. A. Maruhn, H. Stoecker, W. Greiner, D.H. Rischke , NPA619 (1997) 391

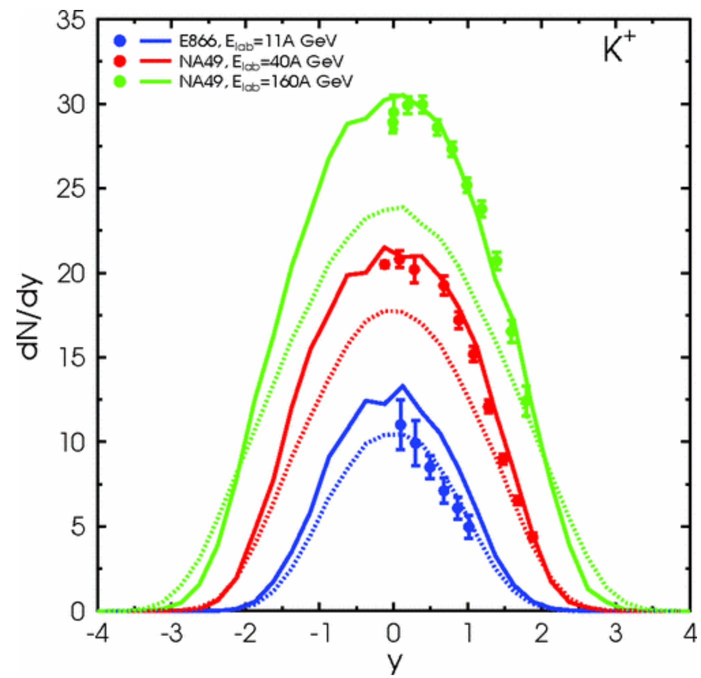
$$\partial T_1^{\mu\nu} = f_{exch}^{\nu} - f_{loss}^{\nu},$$
$$\partial T_2^{\mu\nu} = -f_{exch}^{\nu} - f_{loss}^{\nu},$$
$$\partial T_3^{\mu\nu} = 2f_{loss}^{\nu}$$

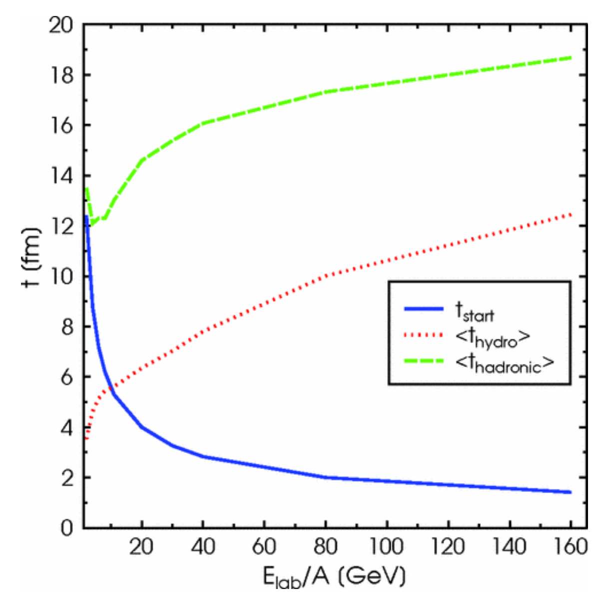
Third fluid is baryon free.

Hybrid model for AGS and SPS energies

H. Petersen ,et.al. Phys.Rev.C78 044901 (2008)







Switch to hydro evolution after two nuclei pass each other.

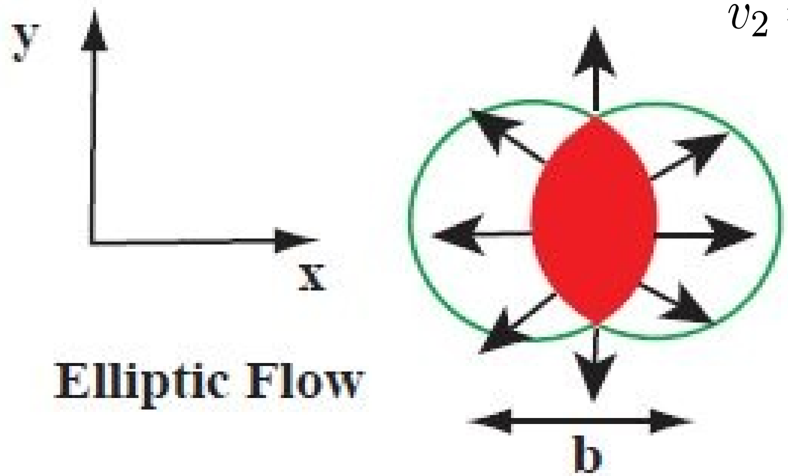
Switch to hadron transport below a critical energy density.

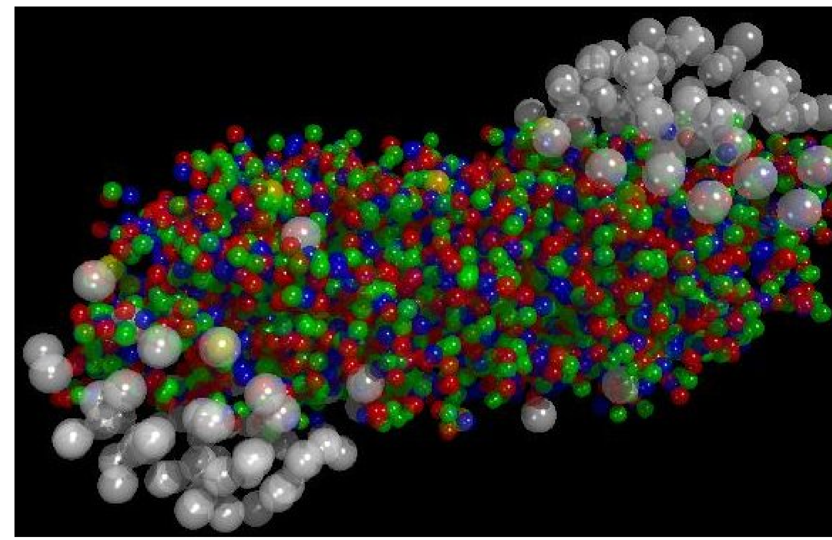
Determination of EOS at high density from an anisotropic flow in heavy ion collisions

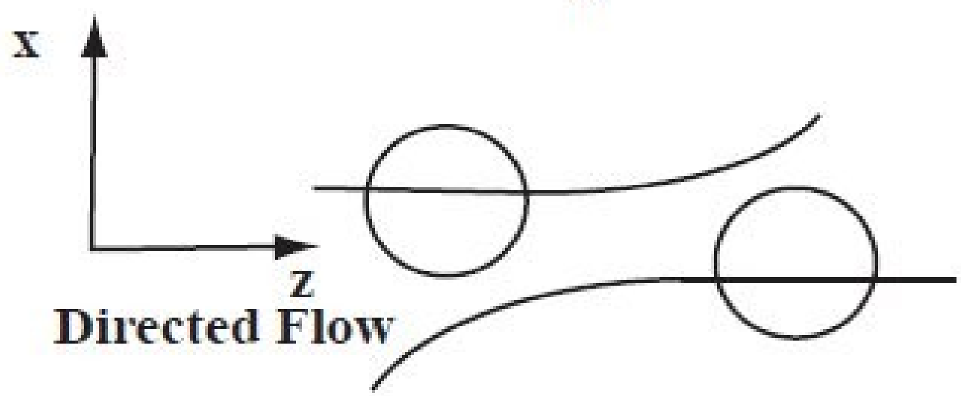
Fourier decomposition of single particle inclusive spectra:

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

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$





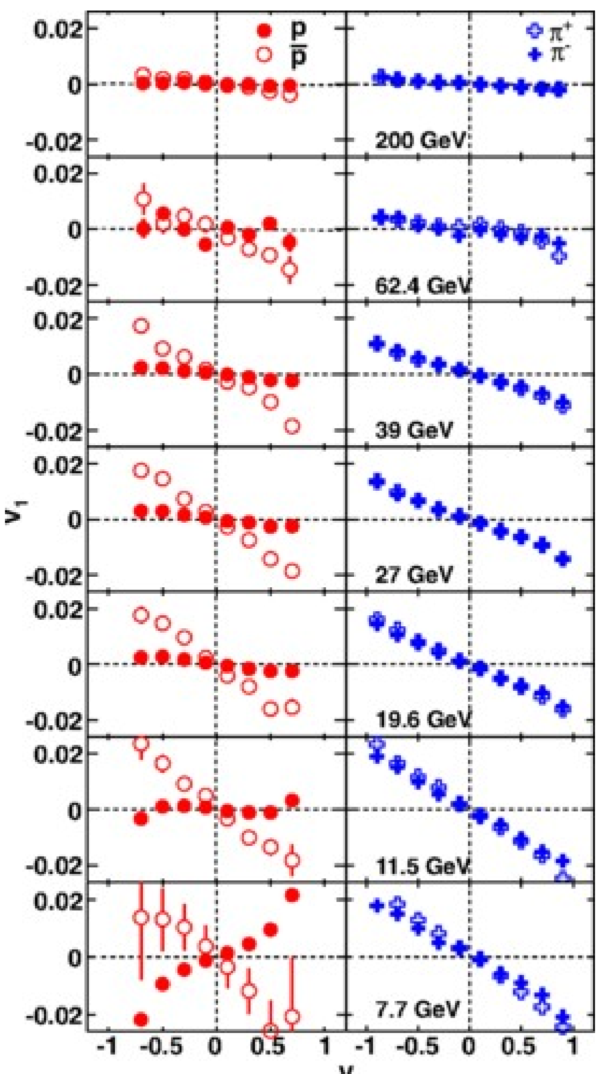


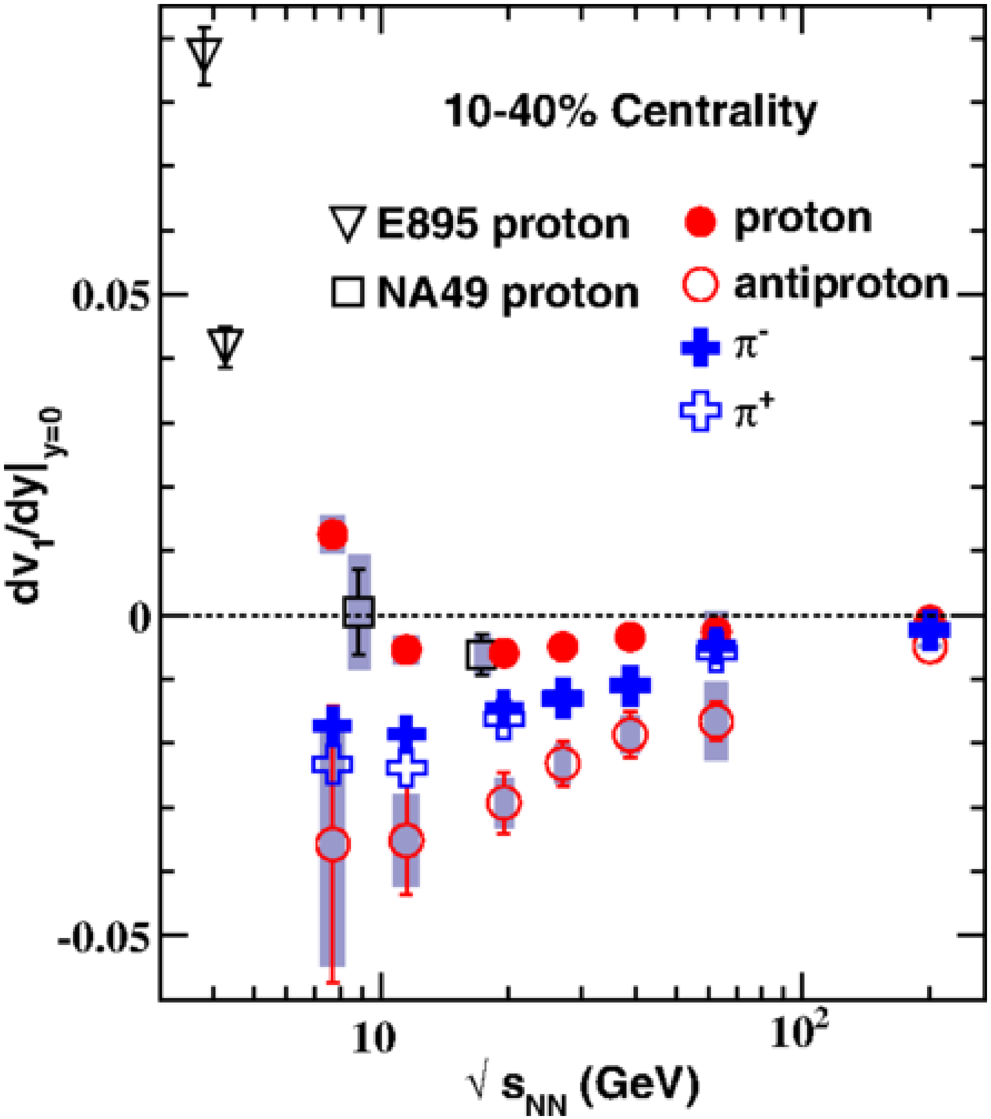
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \qquad F = \left.\frac{dv_1}{dy}\right|_{y=0}$$

P. Danielewicz, R. Lacey, W.G. Lynch,
Science 298 (2002) 1592

Beam energy dependence of v1 from STAR BES

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



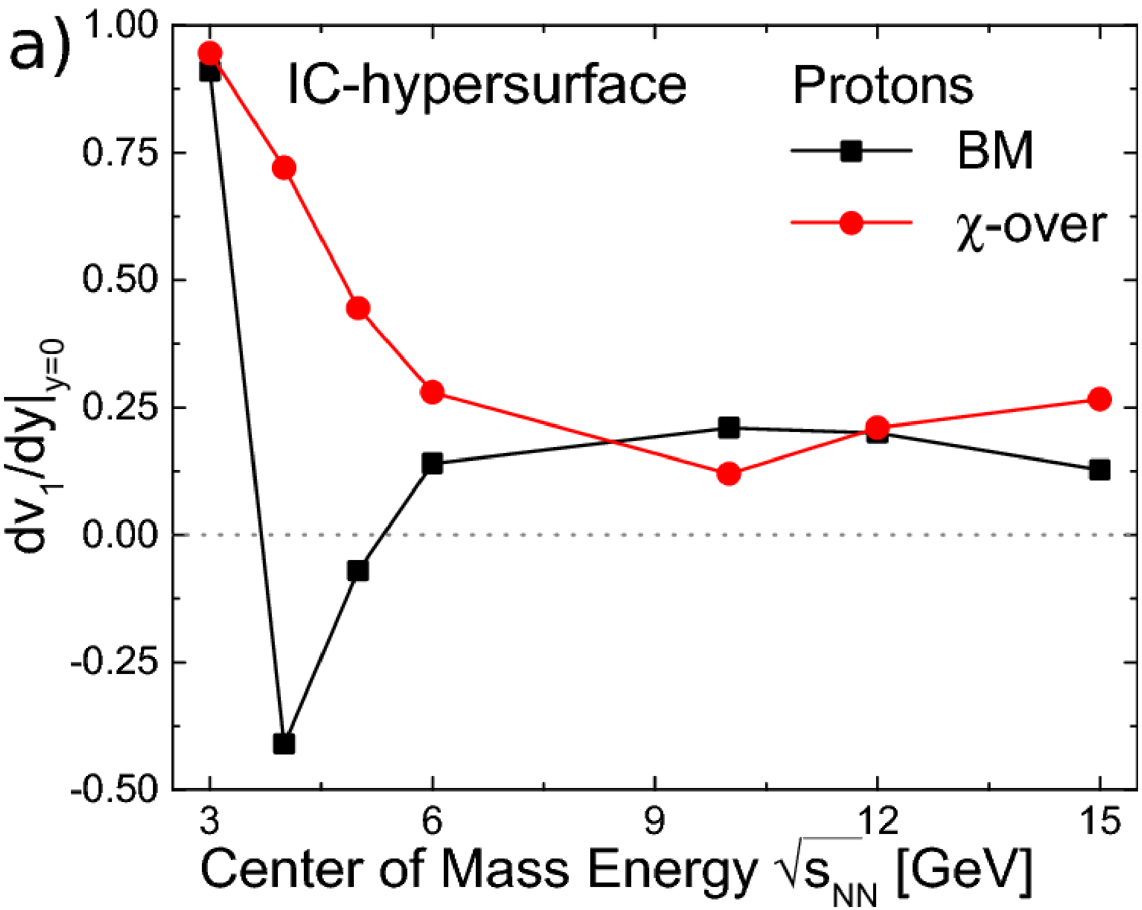


A minimum in the excitation function of the directed flow

D.H.Rischke, et.al Heavy Ion Phys.1, 309(1995)

The effect of the softening of the EoS

J.Steinheimer,et.al.Phys.Rev.C89(2014)



$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Minimum in the excitation function of v1 is seen only in first-order phase transition in one fluid simulation.

QGP signal: formation of tilted ellipsoid

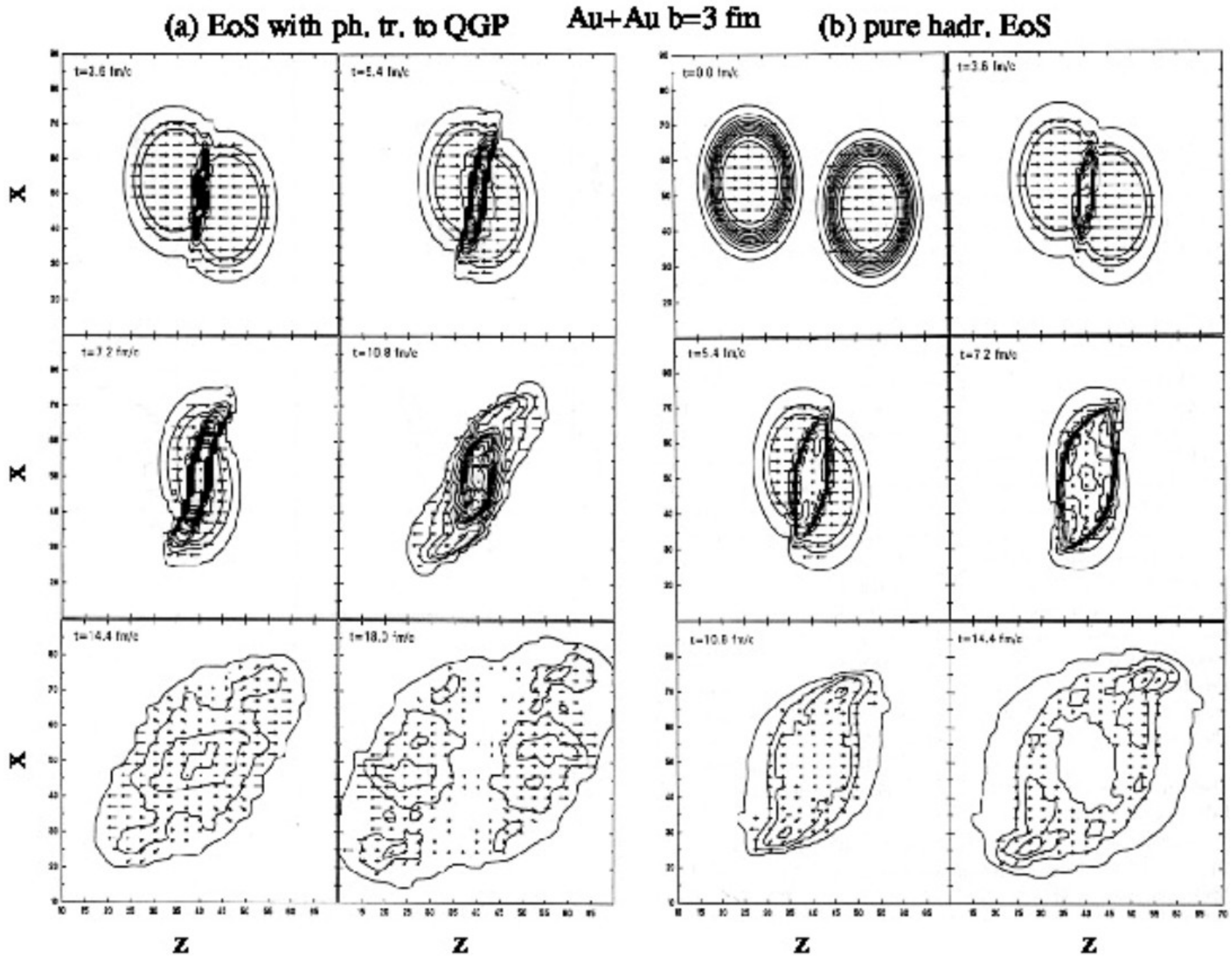


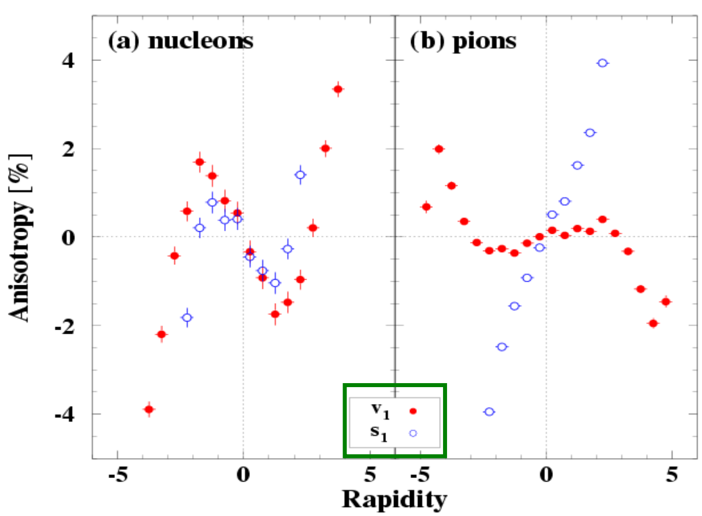
Fig. 5

D.H.Rischke, Y.Pursun,J.A.Maruhn,H.Stoeckeer,W.Greiner, Heavy Ion Phys. 1, 309 (1995)

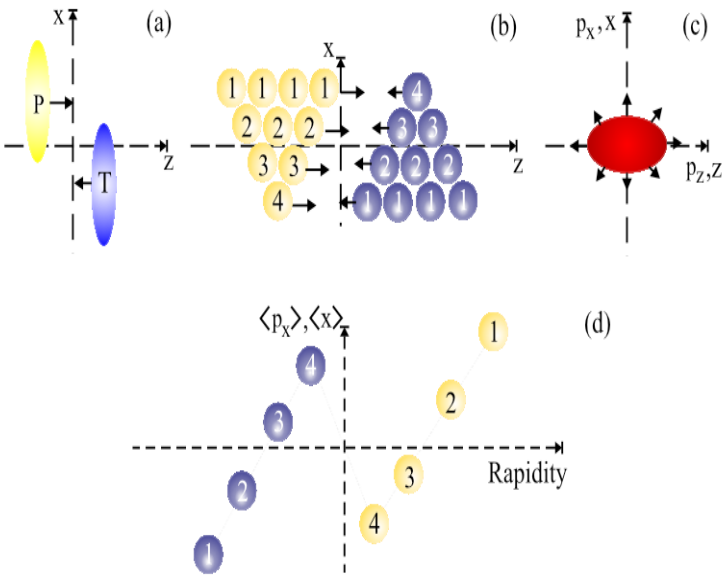
QGP EoS predicts wiggle in hydro

Wiggle: QGP signal in the directed flow?

RQMD v2.4



Baryon stopping + Positive space-momentum correlation leads wiggle (no QGP)

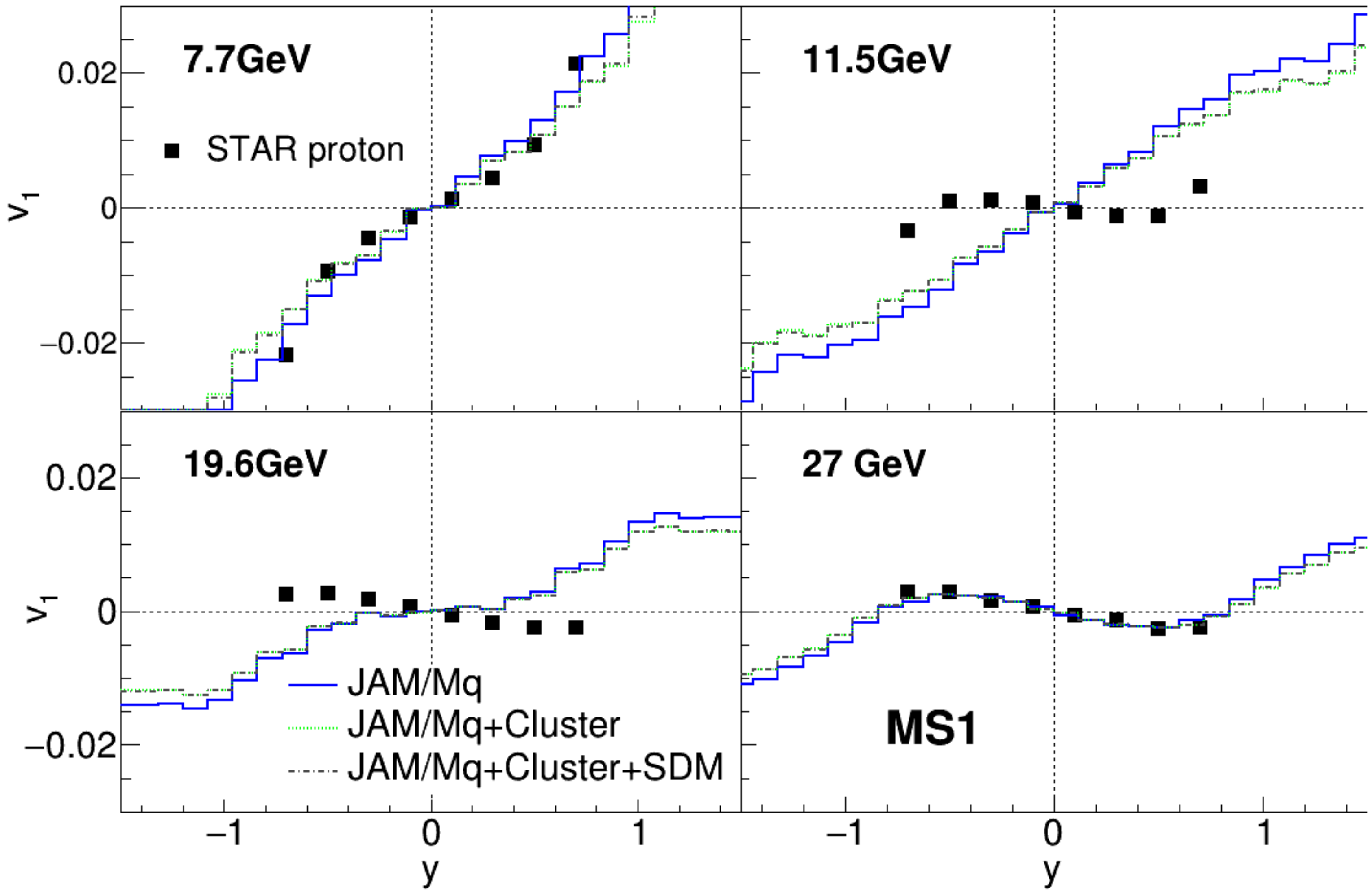


R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

L. P. Csernai, D. Röhrich, PLB 45 (1999), 454.

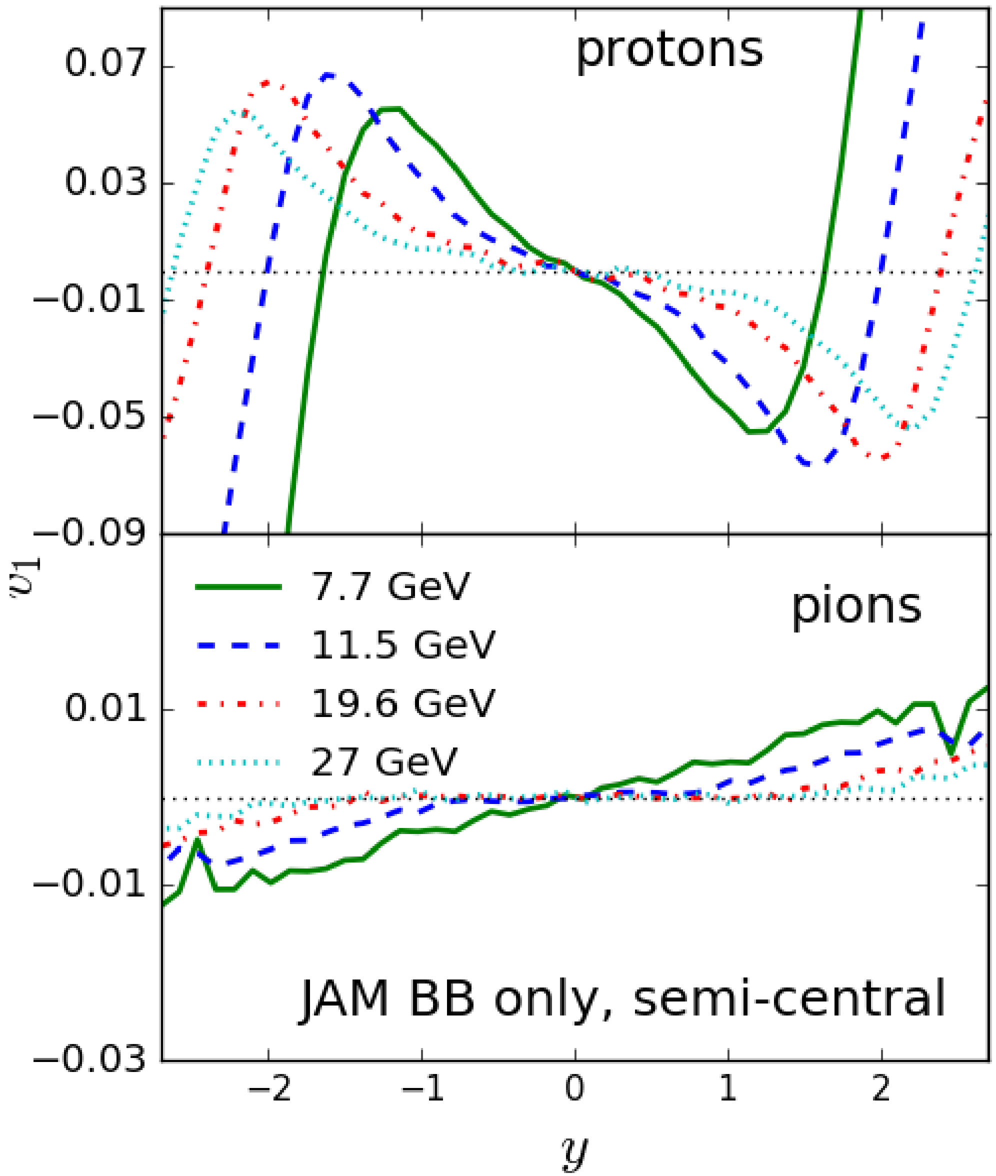
This picture is only applicable at Ecm > 30 GeV

JAM-MF at STAR energies



Effect of the nuclear cluster formation is about 15%.
No effect of statistical decay of nuclear fragment on v1

Proton v1 is negative without meson-baryon interactions in transport model



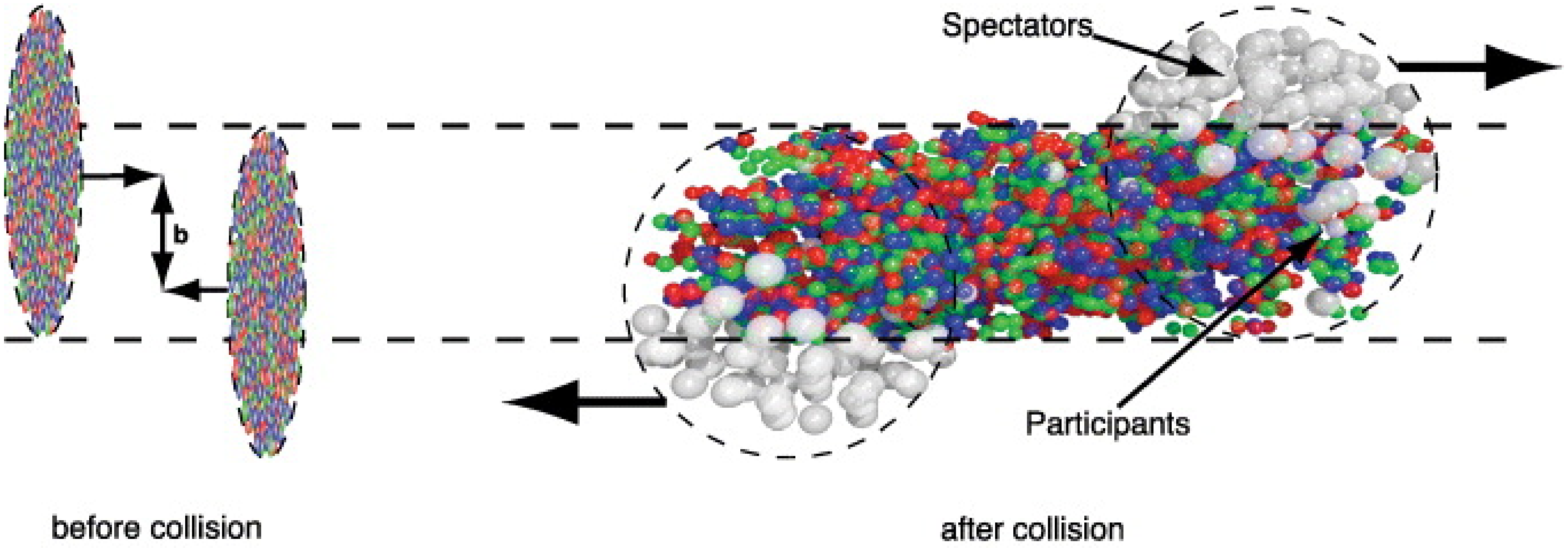
Note that initial Galuber collision only cannot reproduce space-momentum correlation.

Meson-baryon scattering →

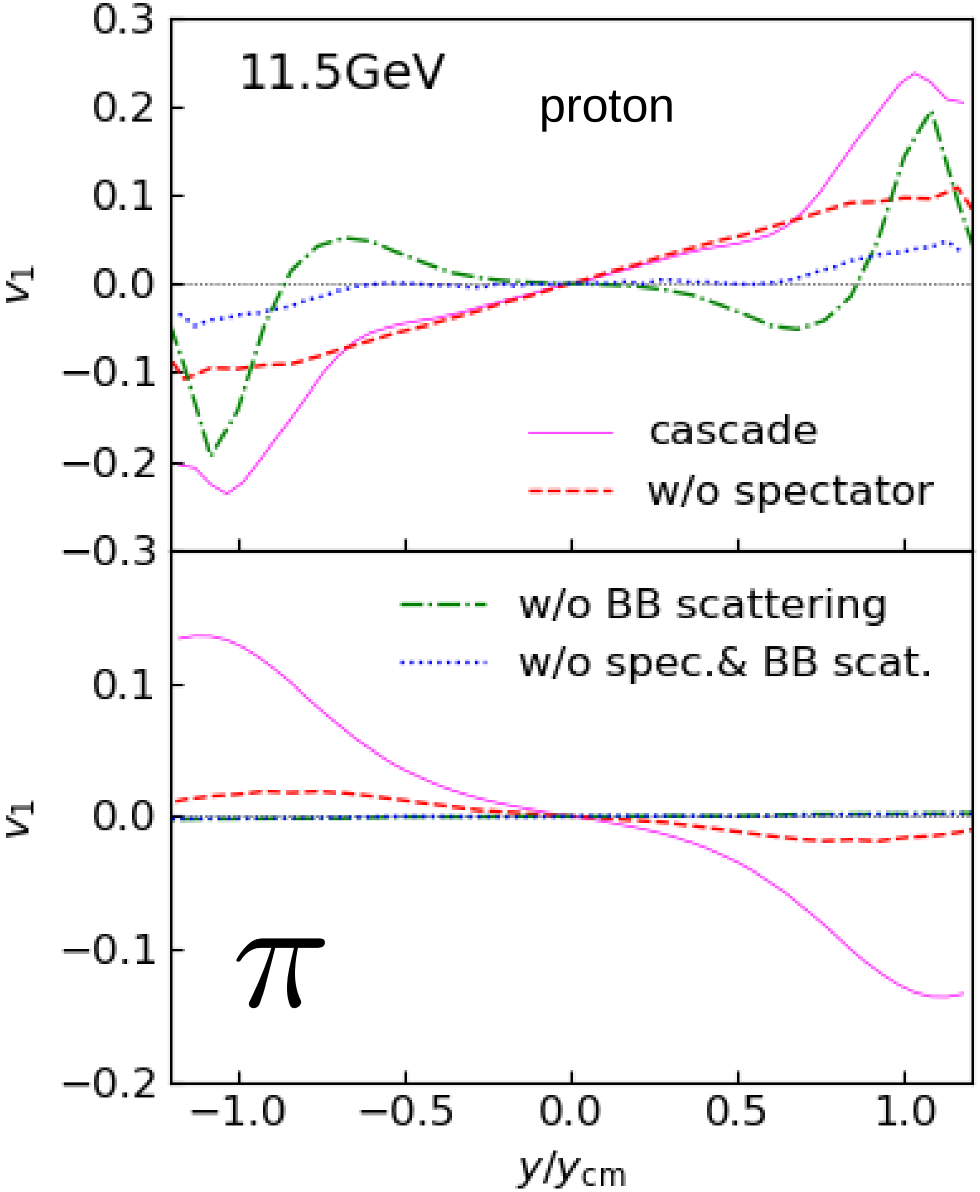
Proton v1 becomes positive,
pion v1 becomes negative.

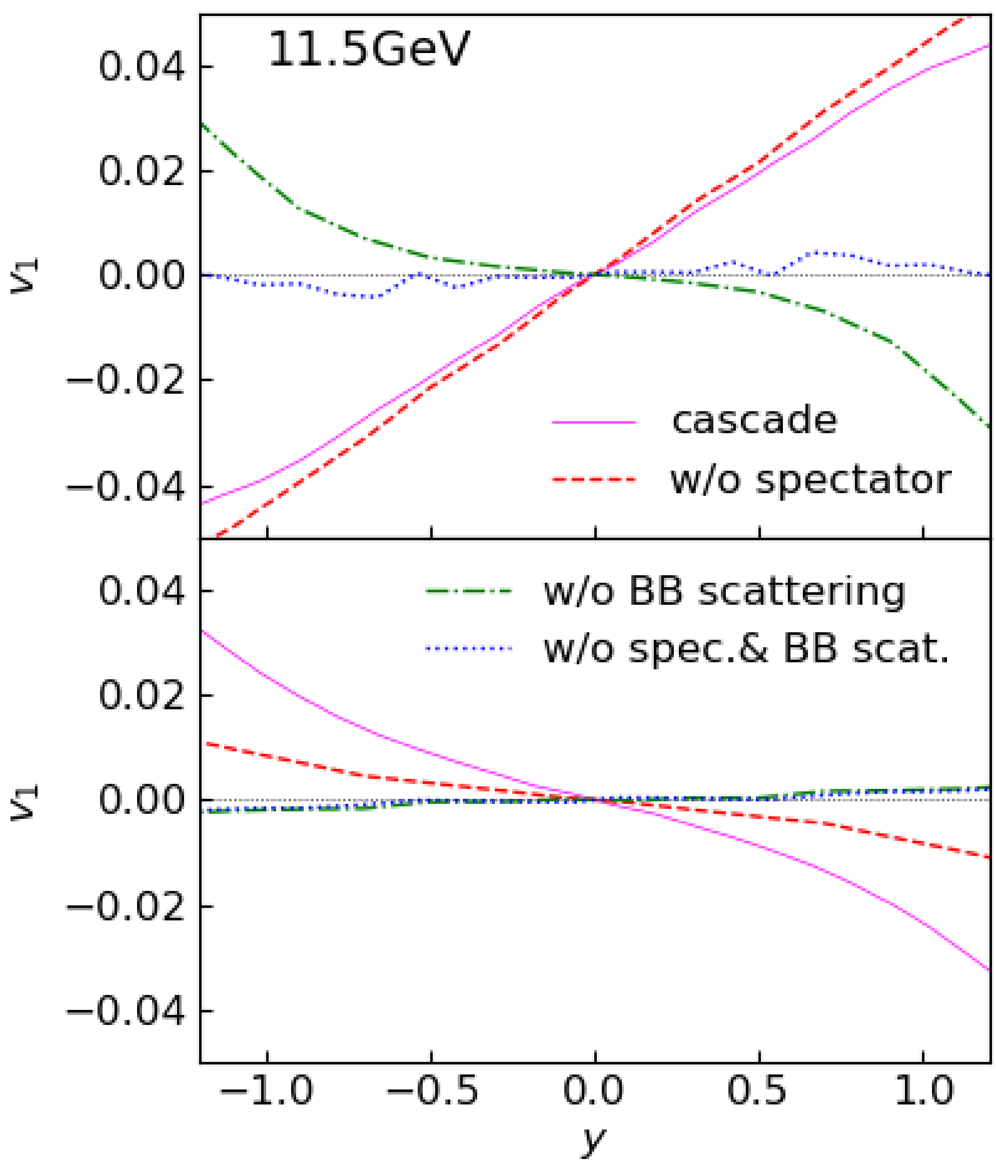
Y. N., H. Niemi, A. Ohnishi, H. Stoecker, PRC94, (2016)

Effects of interaction with participants

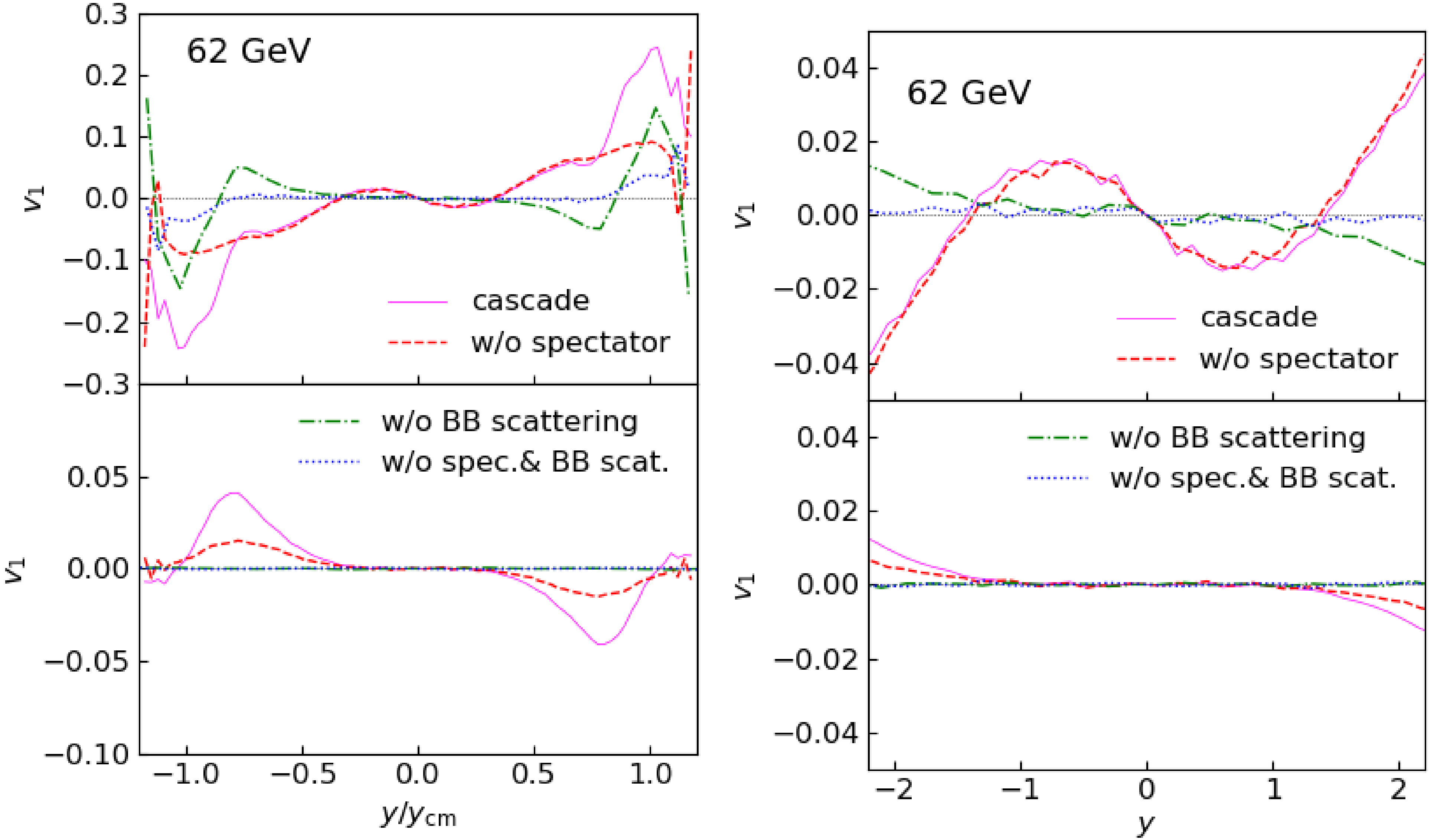


v1 : effects of spectator and MB interactions





Proton v1 is negative with meson-baryon interactions in transport model at high energies



Pressure in the collision term

Virial Theorem

$$P = P_{free} + \underbrace{\frac{1}{3TV}\sum_{(i,j)}\left[(\boldsymbol{p}_i' - \boldsymbol{p}_i)\cdot\boldsymbol{r}_i + (\boldsymbol{p}_j' - \boldsymbol{p}_j)\cdot\boldsymbol{r}_j\right]}_{\text{Contribution from two-body scattering}}$$

$$P_{free} = \frac{1}{3TV}\int dt \sum_i \boldsymbol{p}_i \cdot \boldsymbol{v}_i$$

Momentum conservation $\boldsymbol{p}_i' + \boldsymbol{p}_j' = \boldsymbol{p}_i + \boldsymbol{p}_j$

Repulsive orbit $(\boldsymbol{p}_i' - \boldsymbol{p}_i)\cdot(\boldsymbol{r}_i - \boldsymbol{r}_j) > 0$ enhances the pressure

Attractive orbit $(\boldsymbol{p}_i' - \boldsymbol{p}_i)\cdot(\boldsymbol{r}_i - \boldsymbol{r}_j) < 0$ reduces the pressure

Impose attractive orbit in the collision → softening of EoS

EOS modified collision term

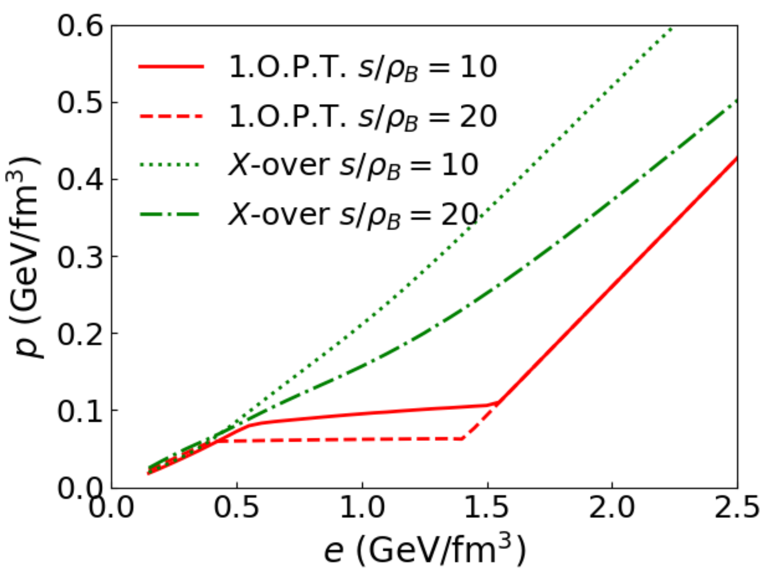
H. Sorge, Phys. Rev.Lett. 82,2048 (1999)

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

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.



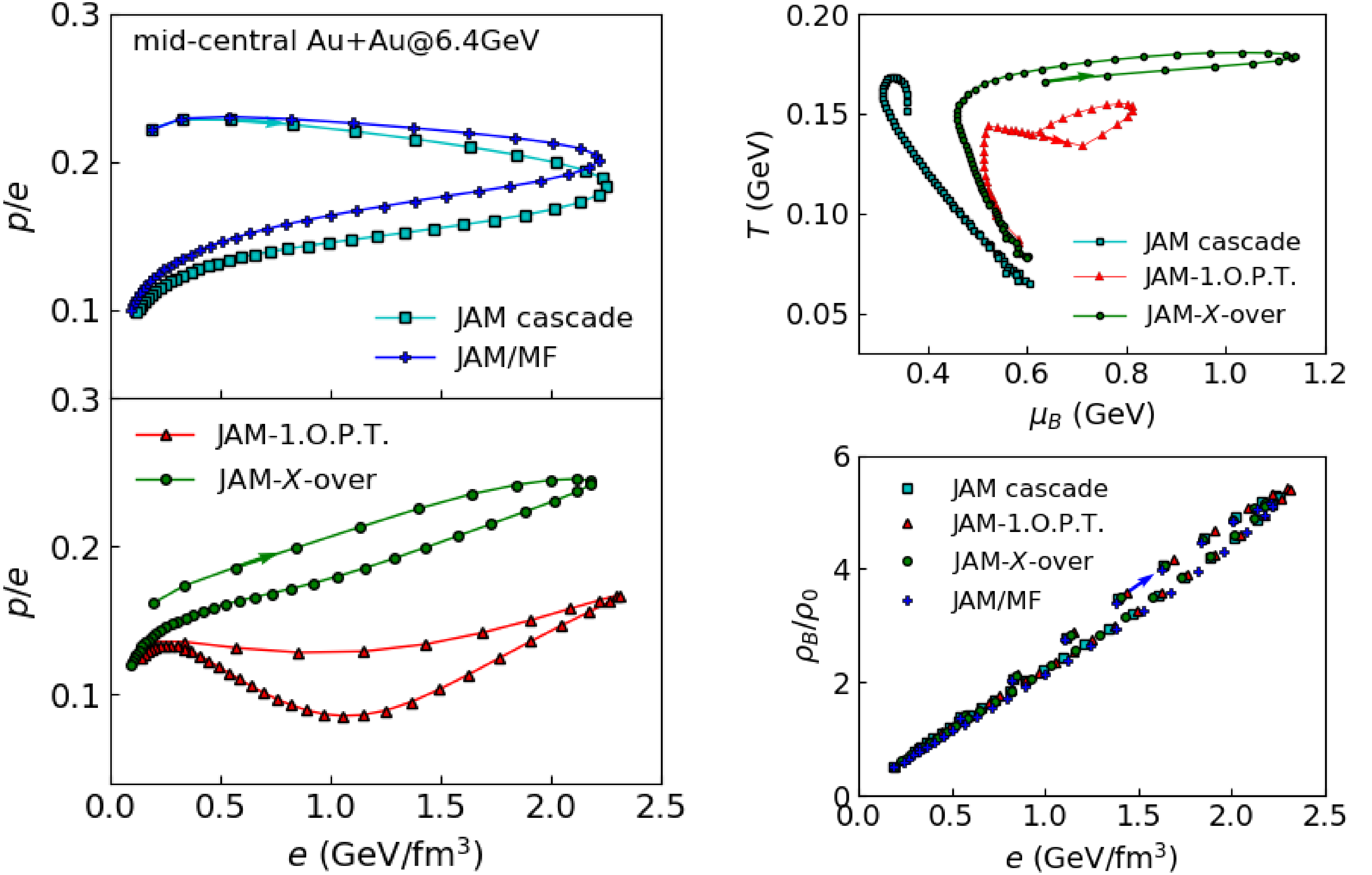
Fully baryon density dependent EoSs are implemented.

Cross-over EOS: J. Steinheimer

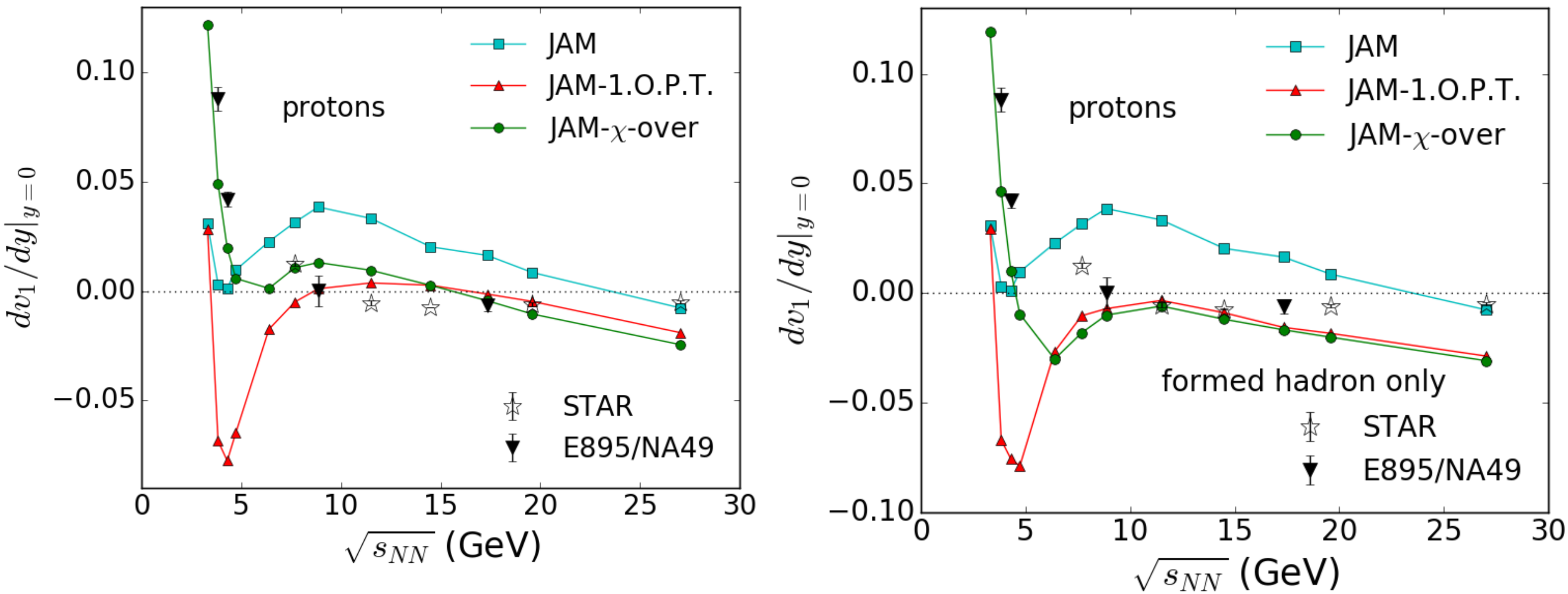
EOS-Q: Kolb, Sollfrank, Heinz

- Any EoS can be incorporated
- CPU time is as fast as standard cascade simulation

EoS dependence at 6.4 GeV

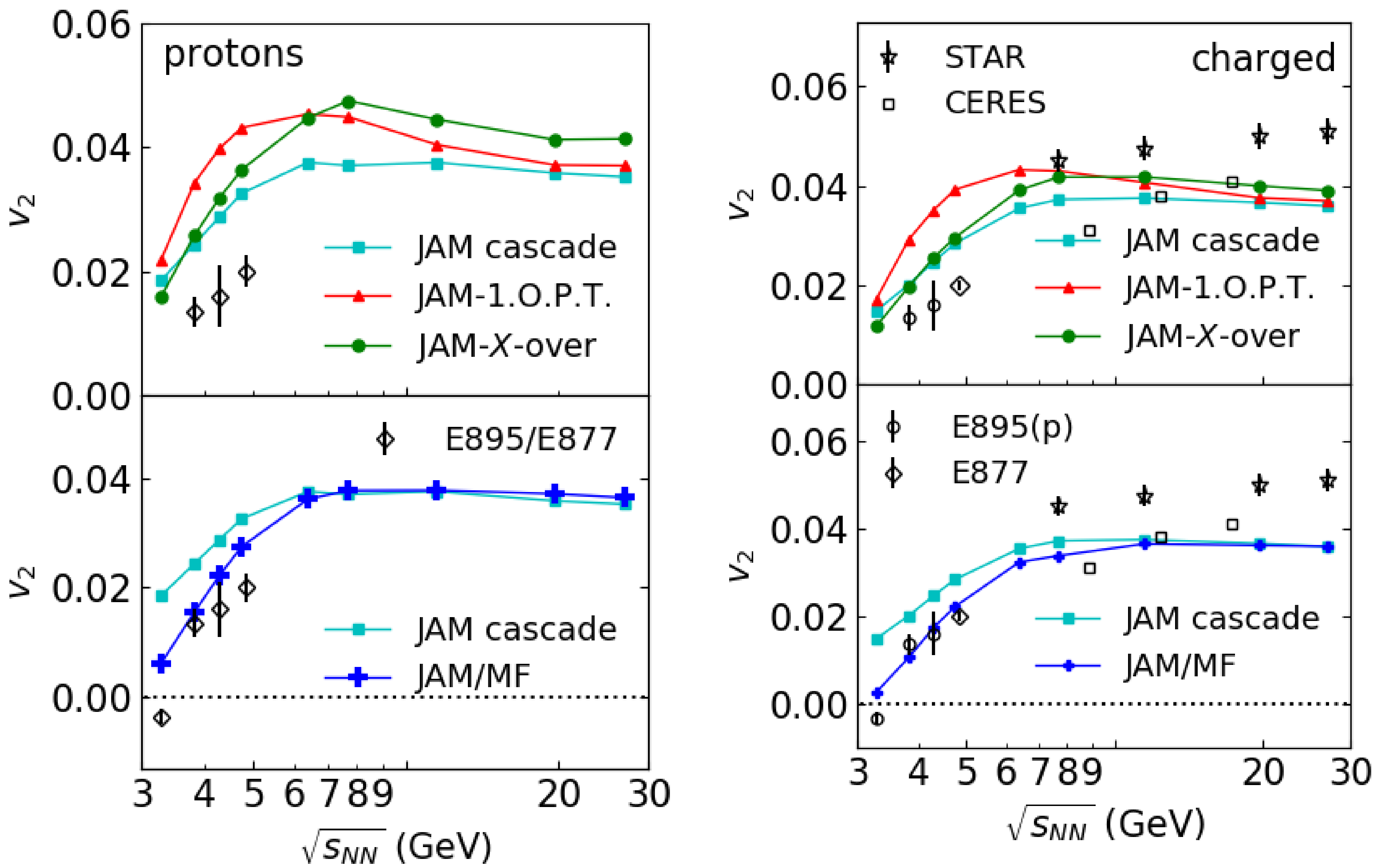


V1 excitation functions



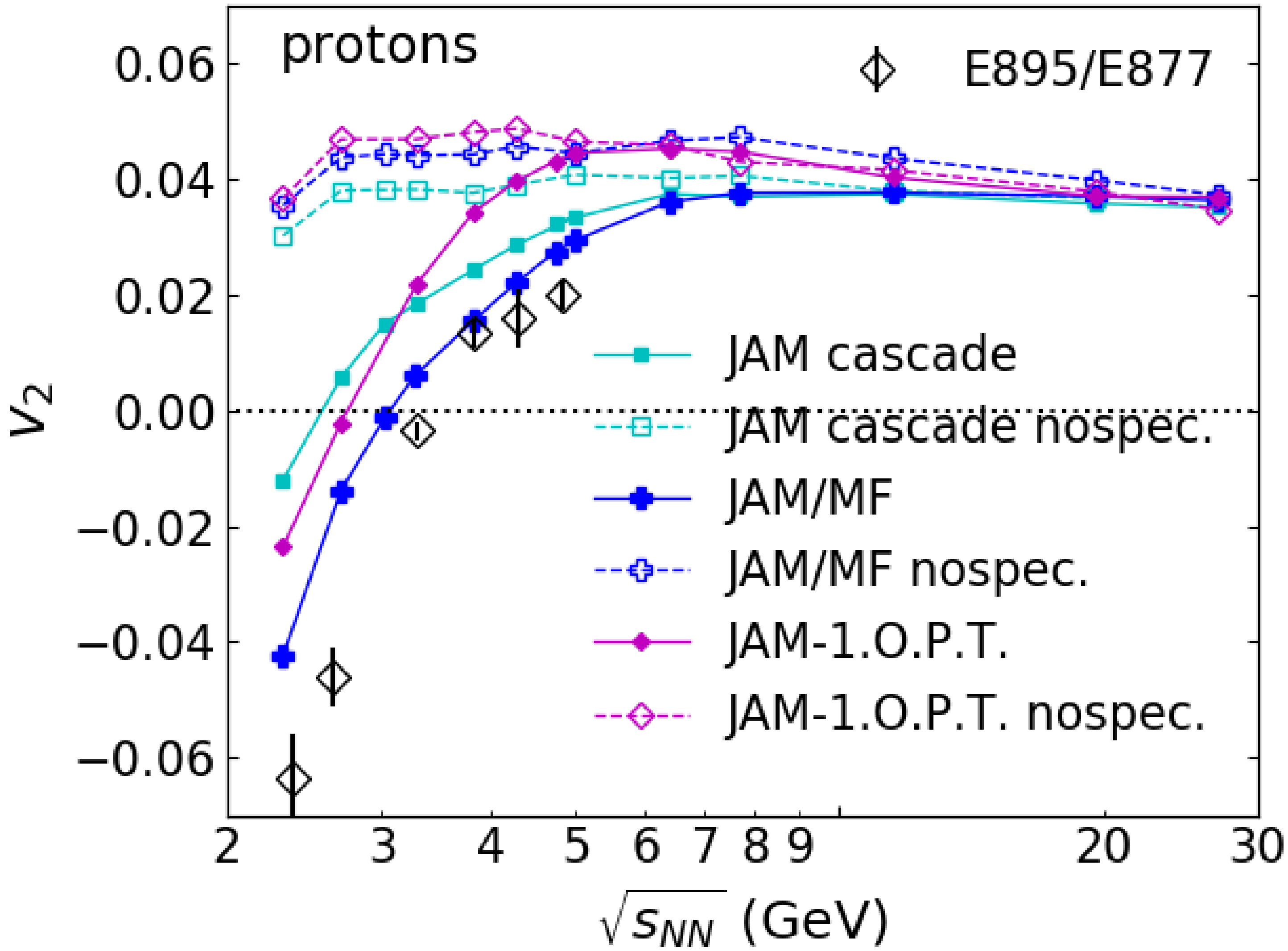
Y. N., H. Niemi, J. Steinheimer, H. Stoecker, PLB769 (2017)

V2 excitation functions



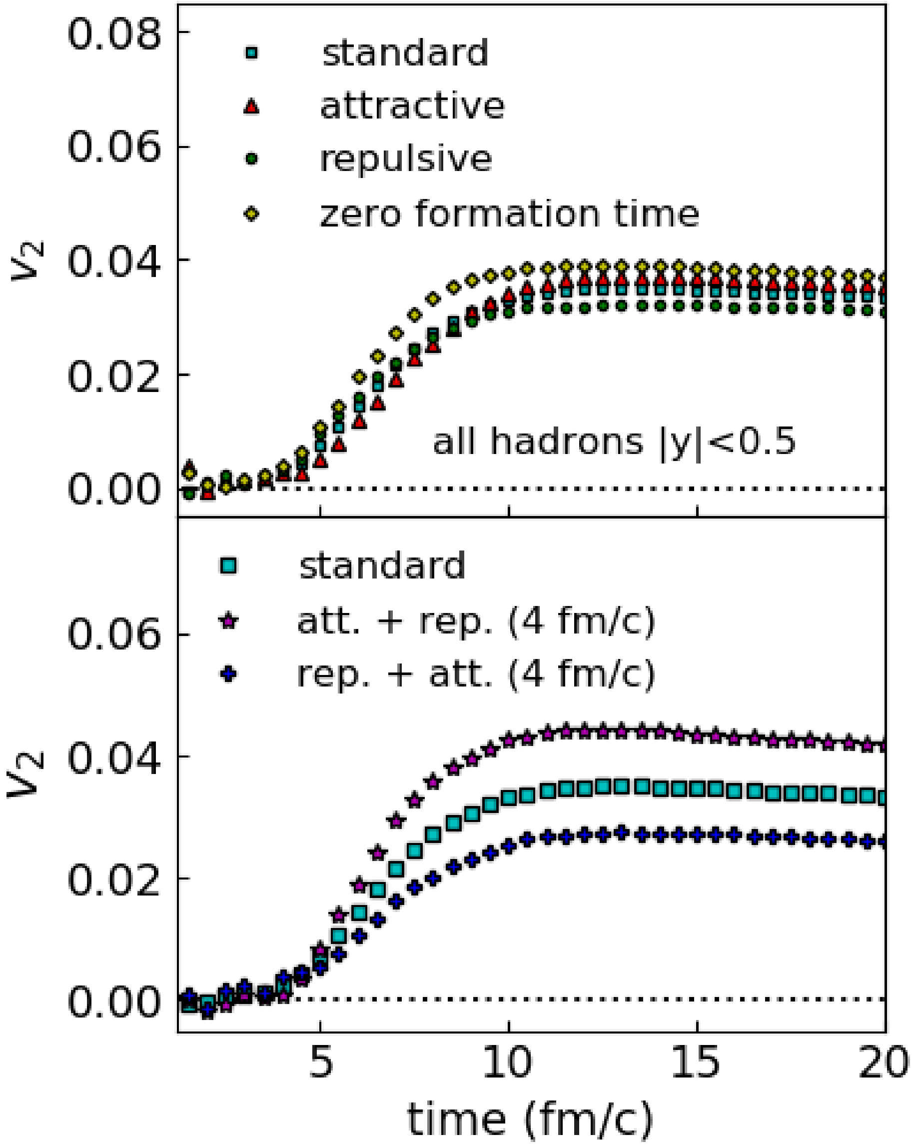
Y. N., H. Niemi, A. Ohnishi, J. Steinheimer, X. Luo, H. Stocker, nucl-th-1708.05617

Effects of Spectator on the V2 excitation functions



Spectator effect is not seen in the first-order phase transition above 5GeV!

Time evolution of v2



Squeeze-out

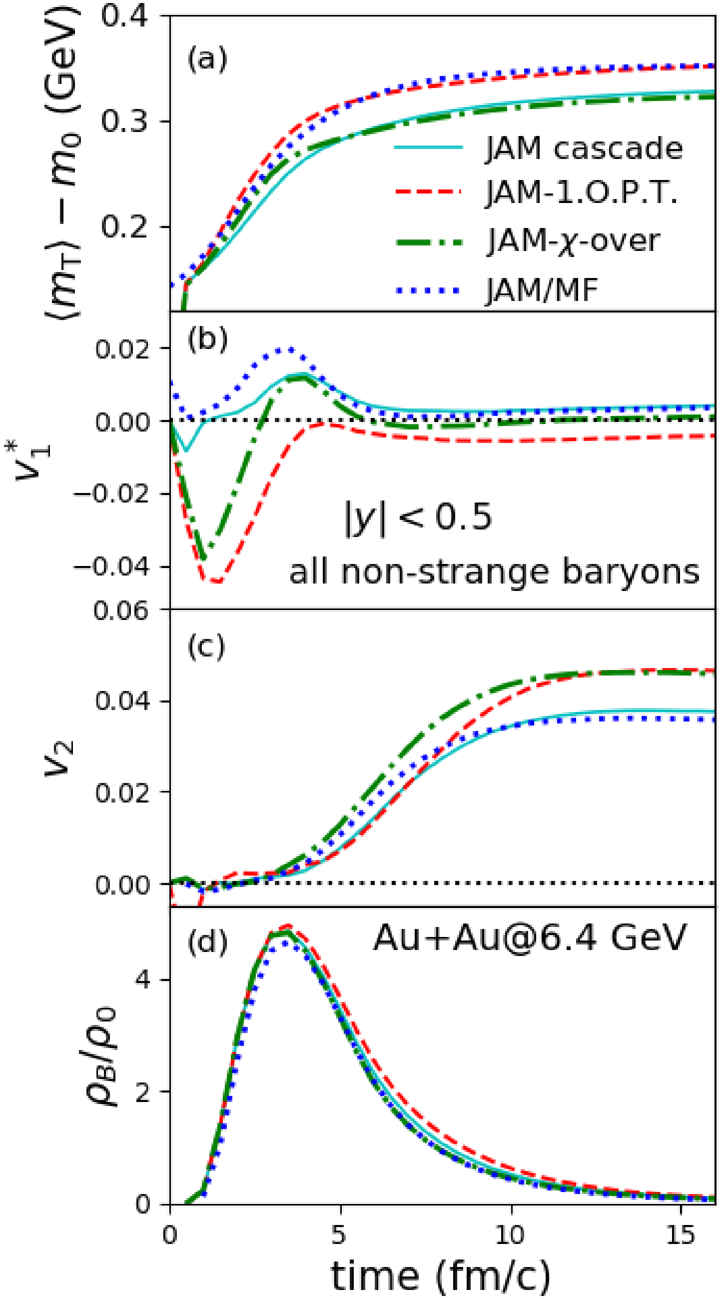
$t < t_{\mathrm{pass}}$: v$_2$ is small for hard EoS

$t > t_{\mathrm{pass}}$: v$_2$ is large for hard EoS

Att. + rep. (4fm/c) → attractive orbit before 4fm/c
repulsive orbit after 4fm/c
→ strong enhancement of v2

Rep. + att. (4fm/c) → repulsive orbit before 4fm/c
attractive orbit after 4fm/c
→ strong reduction of v2

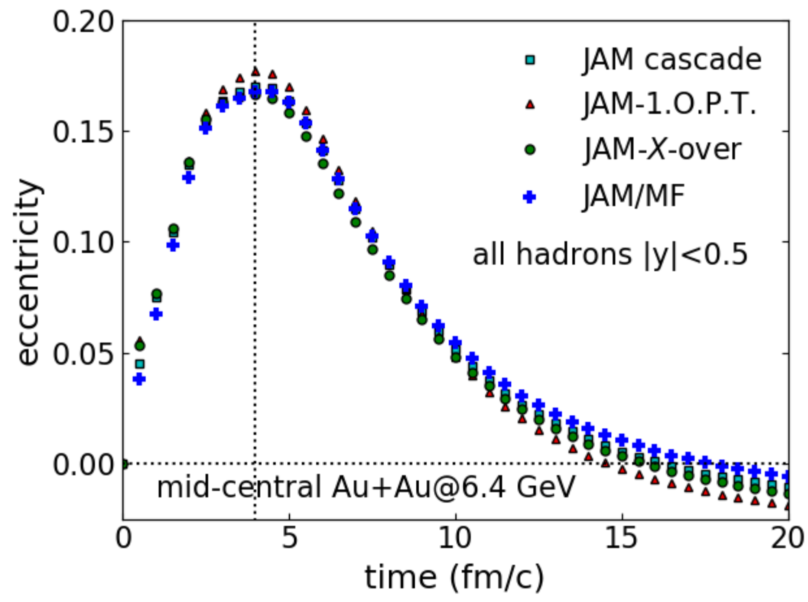
Time evolution of v0, v1, v2



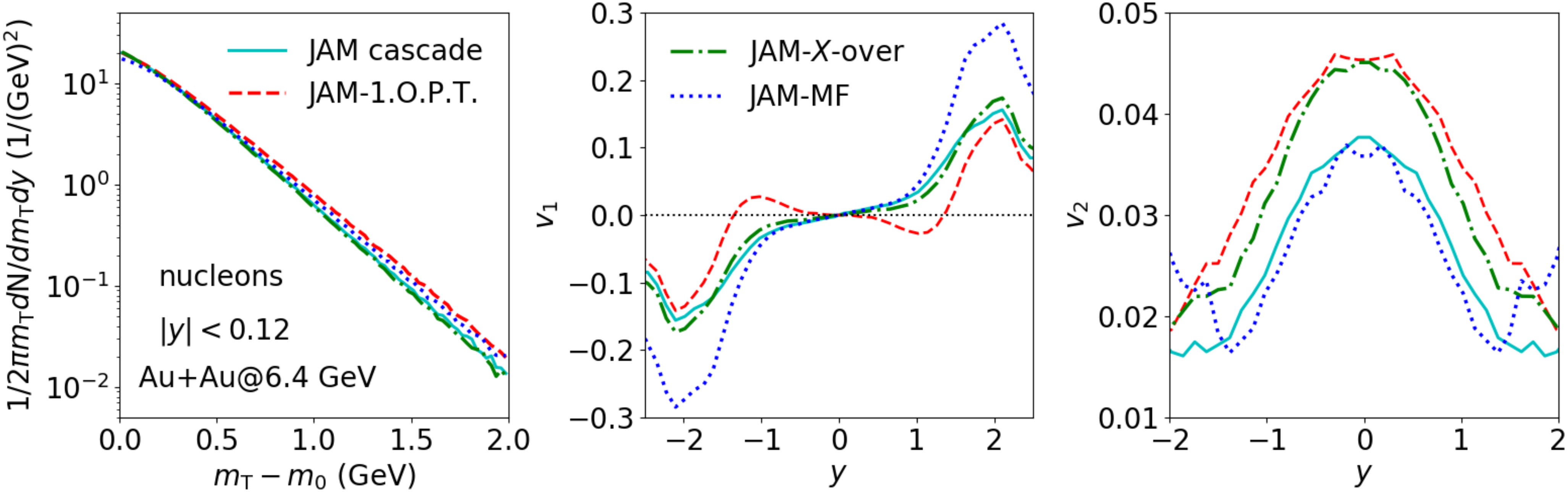
V0 is enhanced by both 1.O.P.T and mean-field

V1 is negative for 1.O.P.T.

V2 is enhanced by 1.O.P.T and crossover



v0,v1, v2 at 6.4 GeV

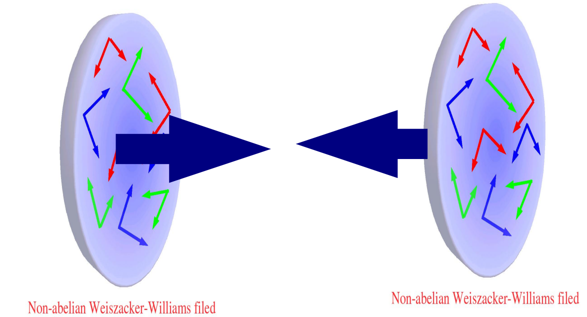


	Mt	v1	v2
Cascade			
Hadronic mean-field	enhanced	positive	reduced
First-order P.T.	enhanced	negative	enhanced
Crossover	same	positive	enhanced

Combined analysis of v0, v1, and v2 should be very useful.

Next generation dynamical model

Modeling at RHIC/LHC
Factorization in time works



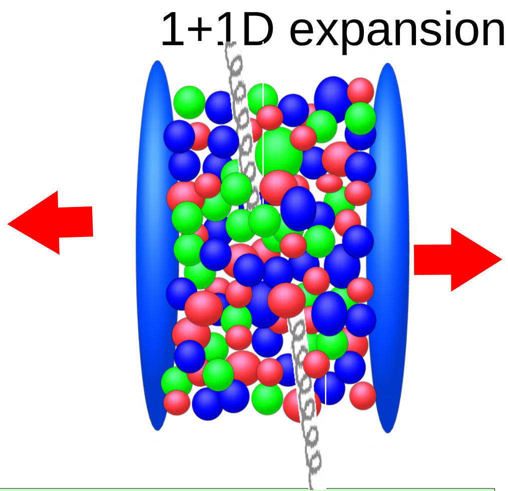
Initial conditions: Glauber, CGC, event generators

Hydrodynamics: viscous-hydro, anisotropic hydro

Hadron gas: hadron transport models

EoS: crossover from lattice QCD

Jet production and its Energy loss: pQCD

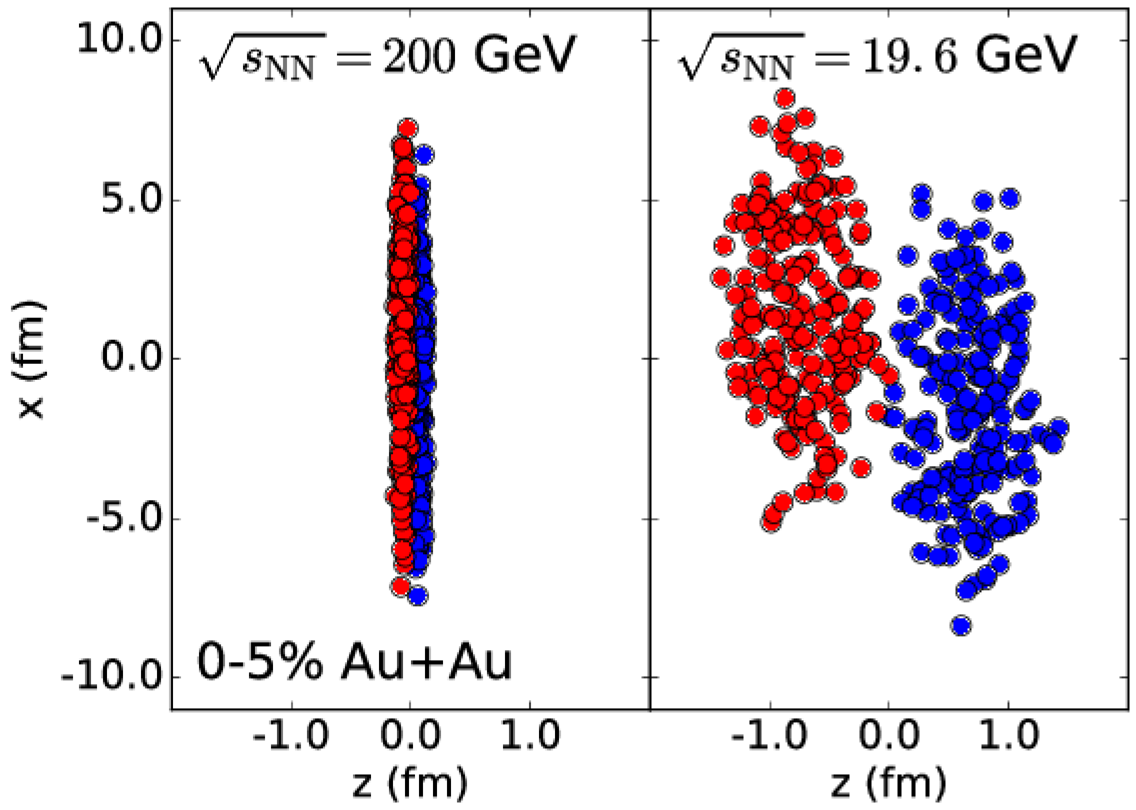


At high energies, factorization in time and energy works:

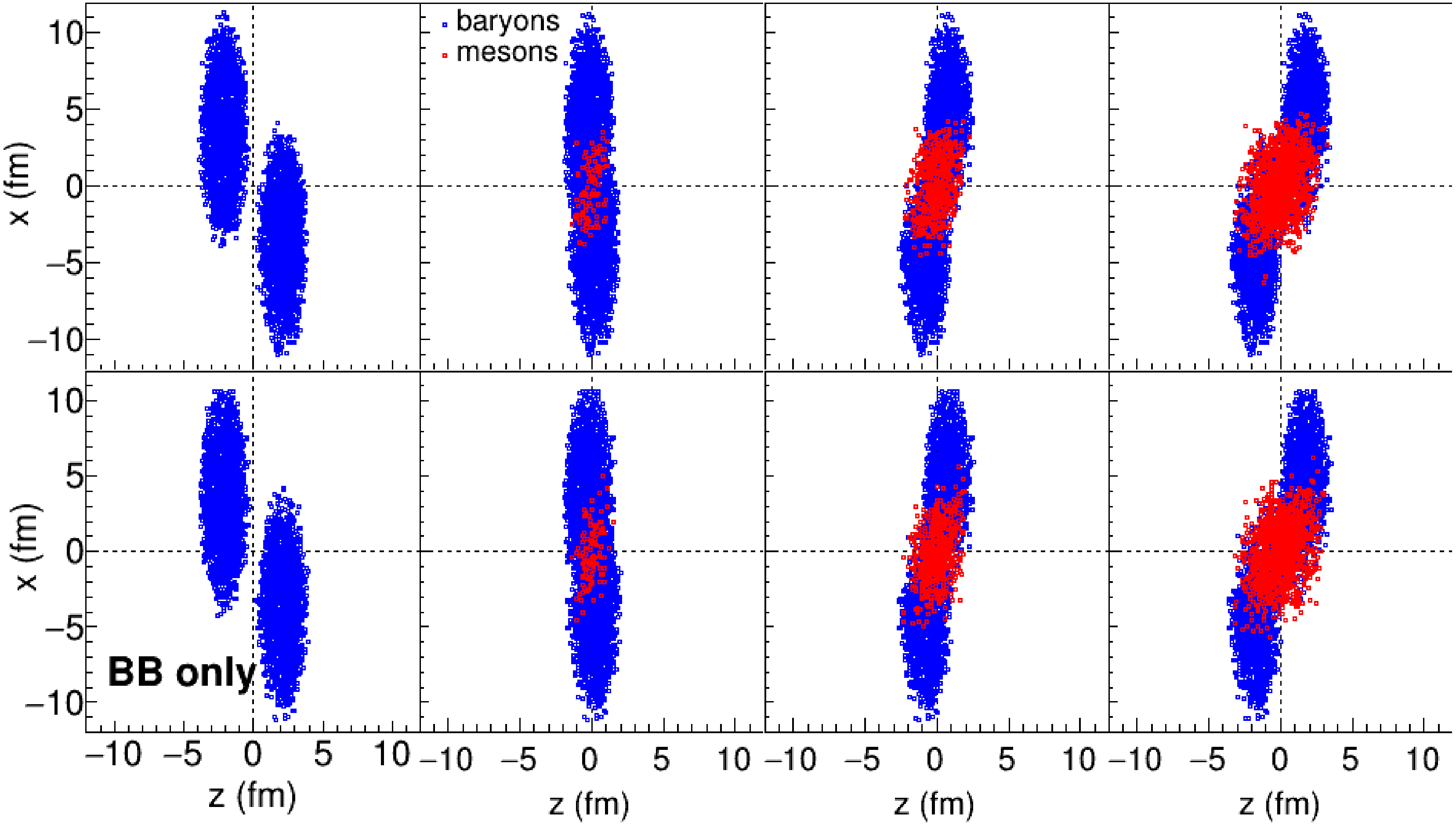
e.g. CGC + hydrodynamics + energy loss of jets + hadron transport model

Initial nucleon positions

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



Time evolution



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

What is needed for J-PARC

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

1) Hybrid $\rightarrow$ integrated approach

dynamical coupling of Hydro + Boltzmann

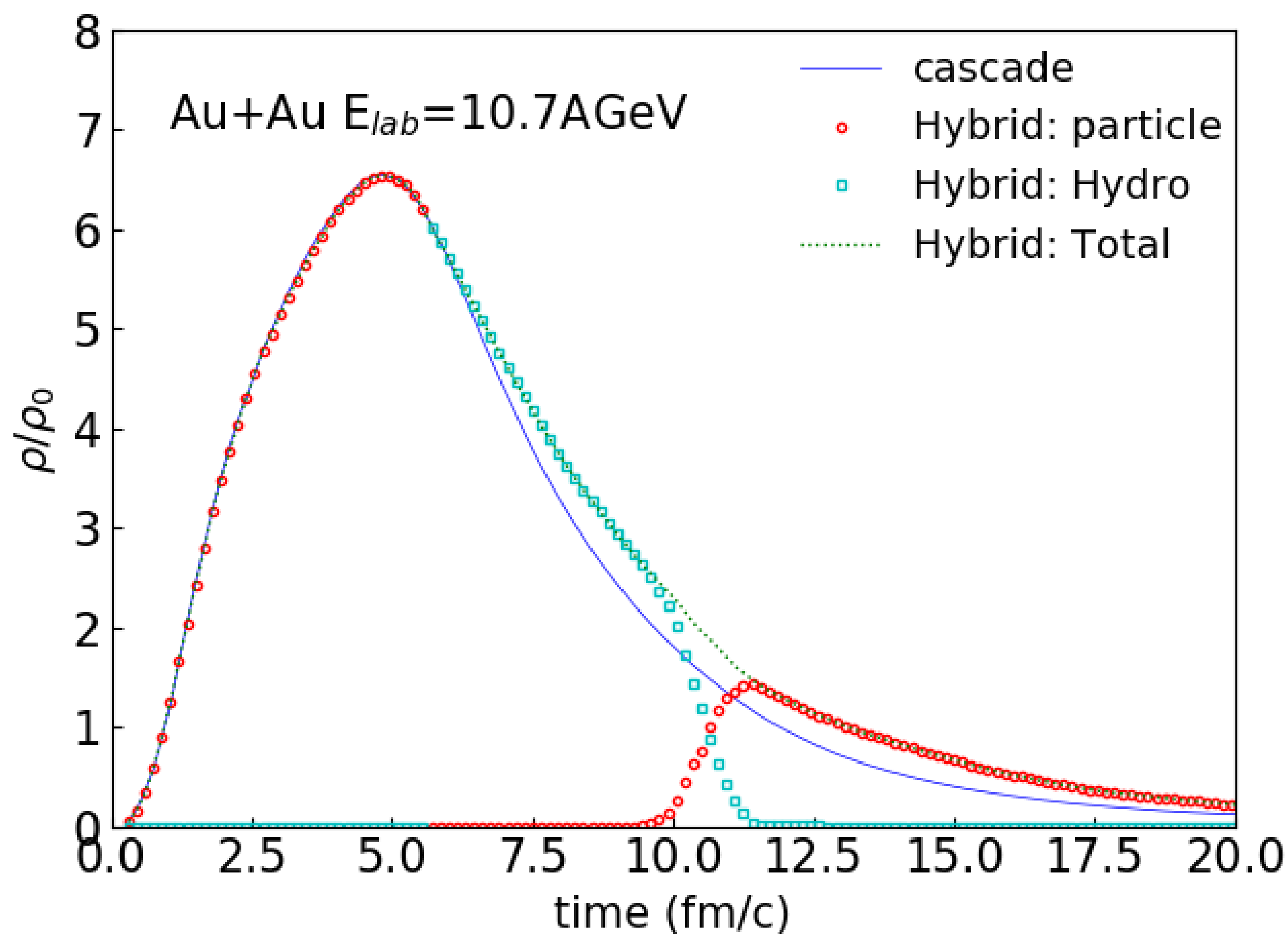
Hydrodynamics with source term $\partial_\mu T_f^{\mu\nu} = J^\nu$

hydro+jet by Y.Tachibana and T.Hirano

hydrokinetic model by Iu. A. Karpenko

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

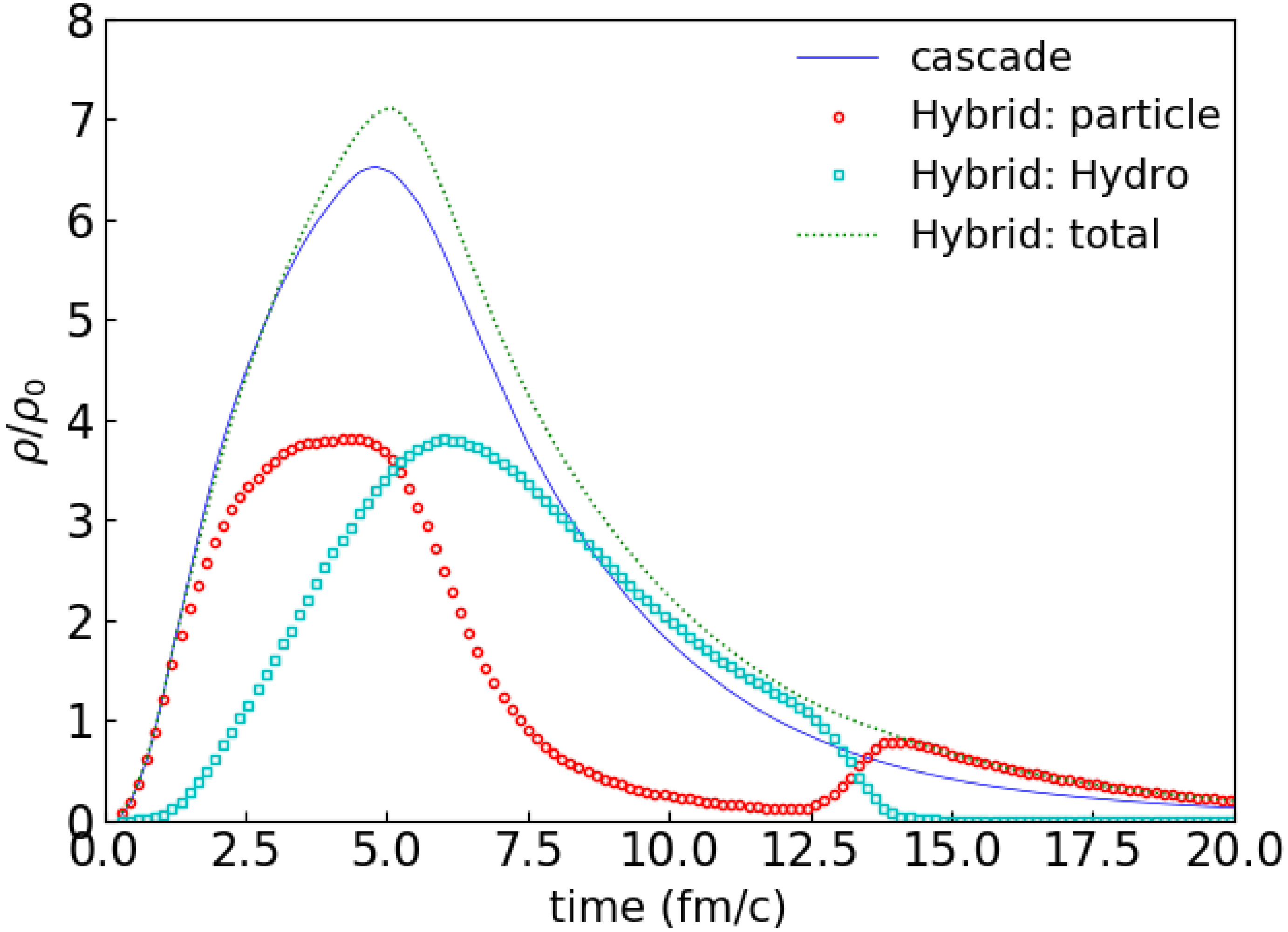
Hybrid model for AGS and SPS energies



Switch to hydro evolution after two nuclei pass each other.

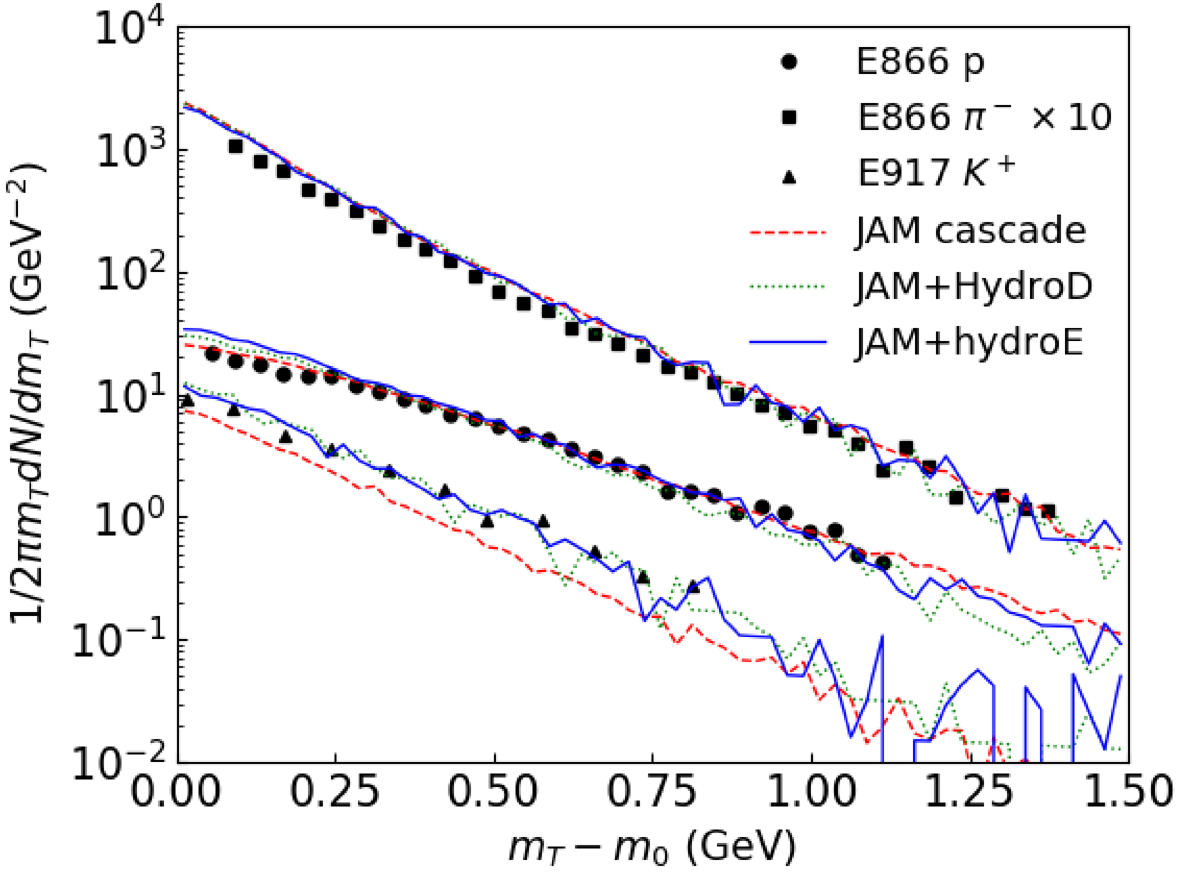
Switch to hadron transport below a critical energy densiy.

A new hybrid model for J-PARC energies



Dynamical transition to hydro evolution.
Switch to hadron transport below a critical energy densiy.

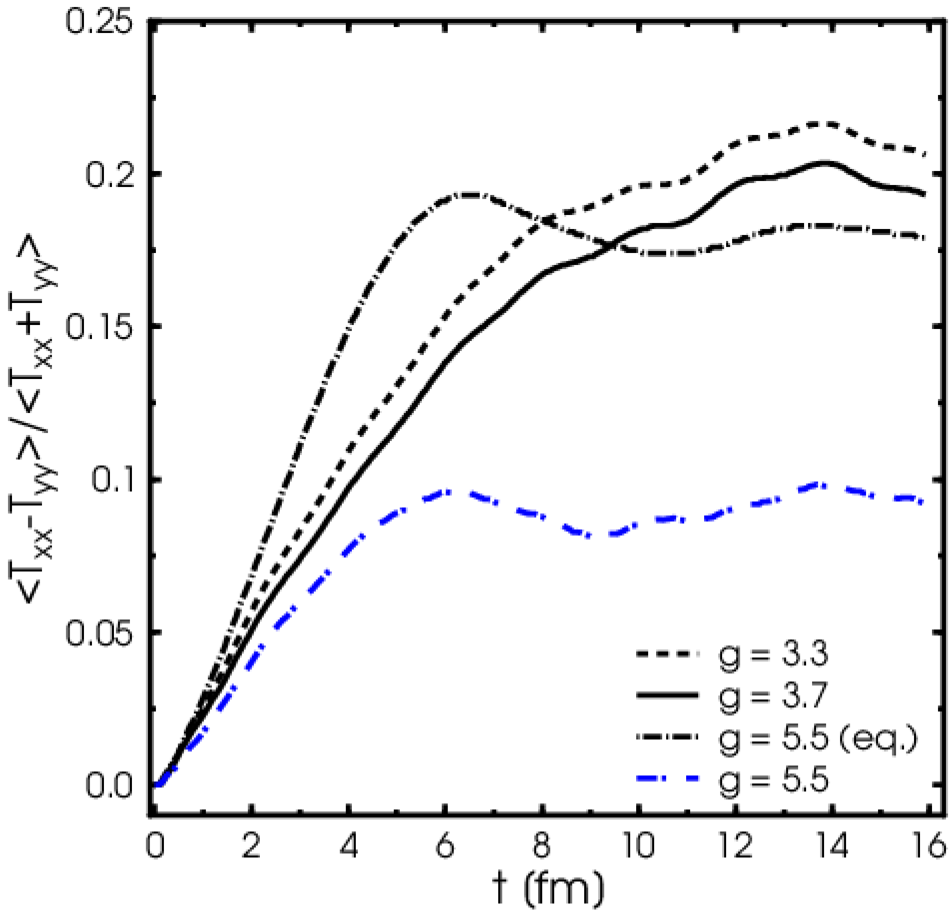
Preliminary reslult from a new hybrid model for J-PARC energies



V2 is reduced by non.eq-1.O.P.T

K. Paech, H. Stoecker, A. Dumitru, PRC68 (2003)

Hydro + linear sigma field simulation predicts the reduction of v2 by the non-quilibrium chiral dynamics

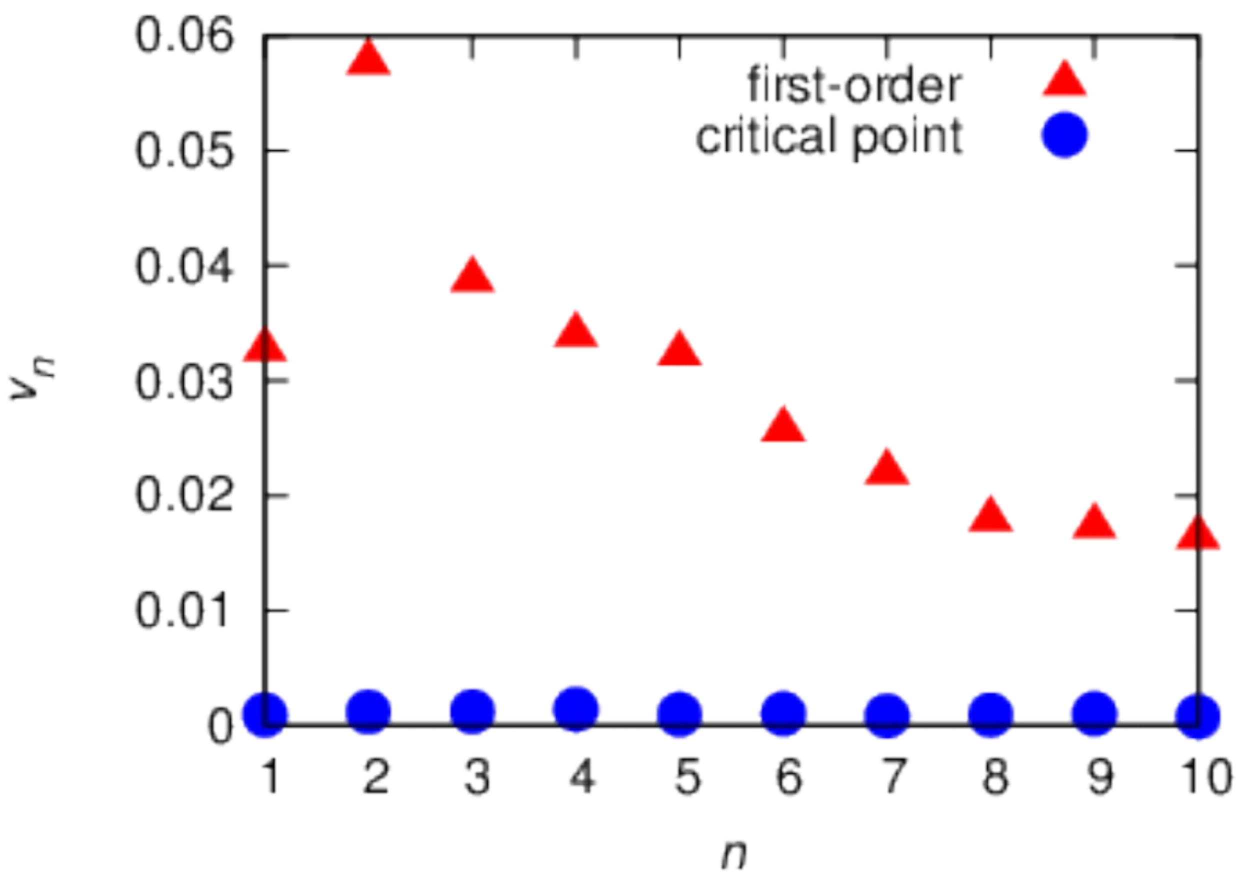


G=3.3 cross over
G=3.7 2nd P.T.
G=5.5 1st P.T.

V2 is enhanced by non.eq-1.O.P.T

C. Herold, M. Nahrgang, I. Mishustin, M. Bleicher, NPA925 (2014)

Hydro + linear sigma field simulation predicts the enhancement of vn by the non-quilibrium chiral dynamics



summary

- We proposed a efficient method to incorporate the effect of EoS into the microscopic hadronic transport model JAM, and find a strong EoS dependence of collective flows.

- This non-equilibrium approach predicts the similar beam energy dependence of directed flow as hydrodynamics.
  e.g. Negative slope of proton.

- This model predicts an enhancement of elliptic flow at high baryon density region (AGS-SPS region) due to softening of EoS.

- Combined analysis of collective flows v0,v1, v2 at high baryon region e.g. at 5 GeV < Ecm < 7.7 GeV will provide important information on the EoS.

Summary

- We need to develop a new dynamical approach by dyanmical integration of microscopic transport approach and hydrodynammics in order to simulate heavy ion collision at j-PARC energy region.

- It is also important to improve hadronic transport models:

  Effect of N-body collision
  Inclusion of EoS by vector and scalar potentials.
  Chial Symmetry restoration
  dynamical treatment of phase transition

- Study of non-equilibrium chiral dynamics