Signatures of the 1st order phase transition in heavy-ion collisions at FAIR energies

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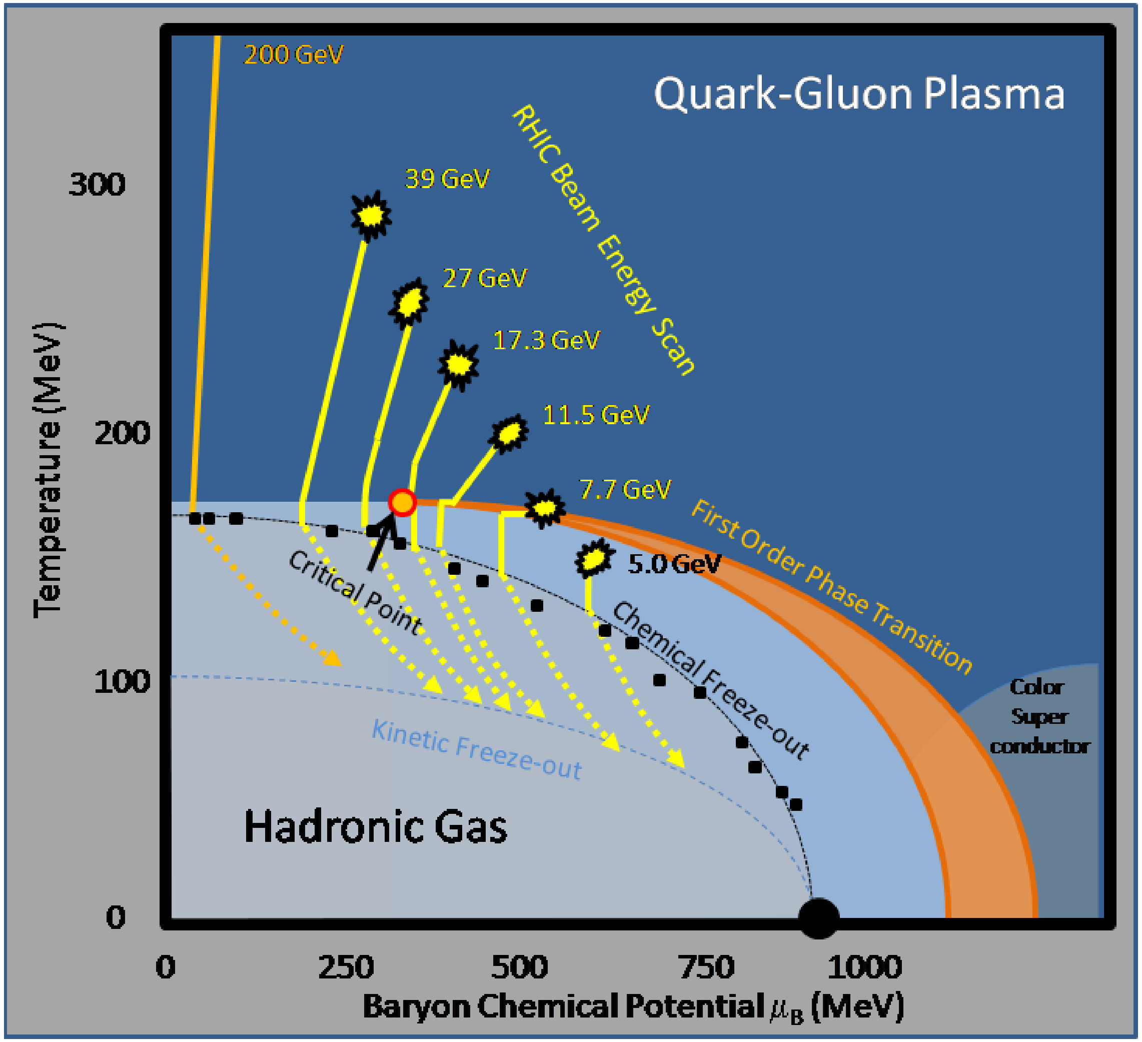
(Akita International University)

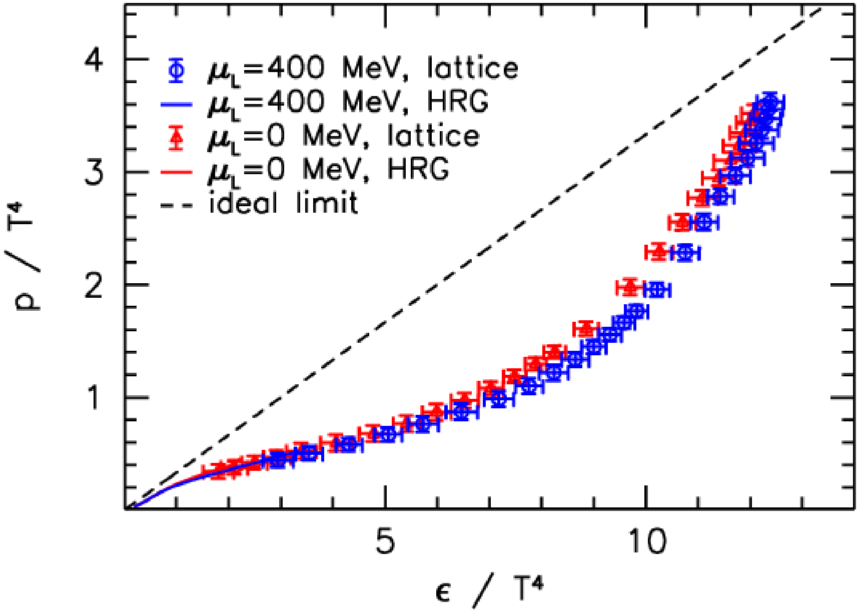
- Introduction
- V1, v2, v4 from JAM Equation of state controlled collision term
- JAM+hydro: A new dynamically integrated transport model

Physics Symposium at 32nd CBM collaboration meeting at GSI Oct. 3, 2018

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



Sz.Borsanyi, et.al JHEP 1208(2013)053

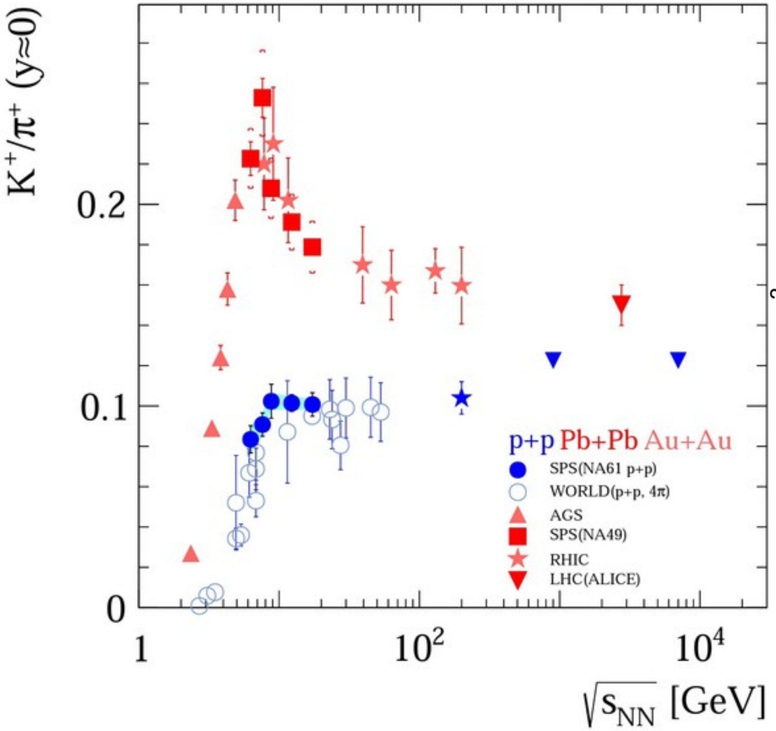


Lattice QCD has not covered the FAIR energy regions.

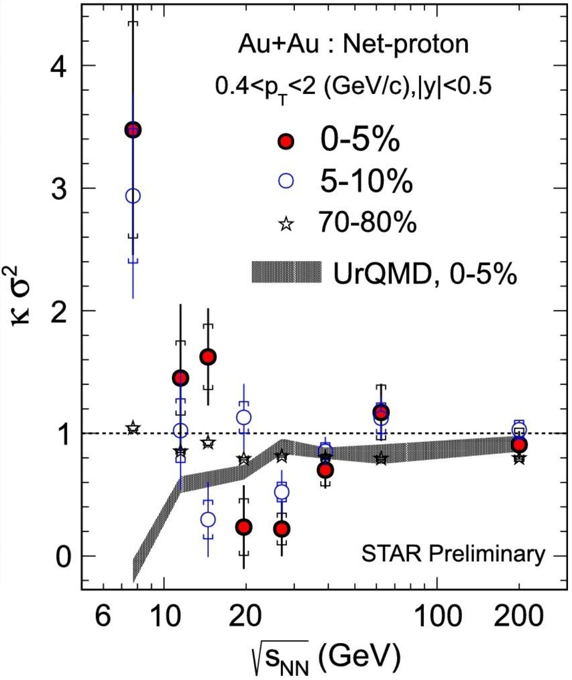
We need effective models:
Such as
NJL, PNJL, PQM,
Quasi-particle model………..

Location of the critical point?

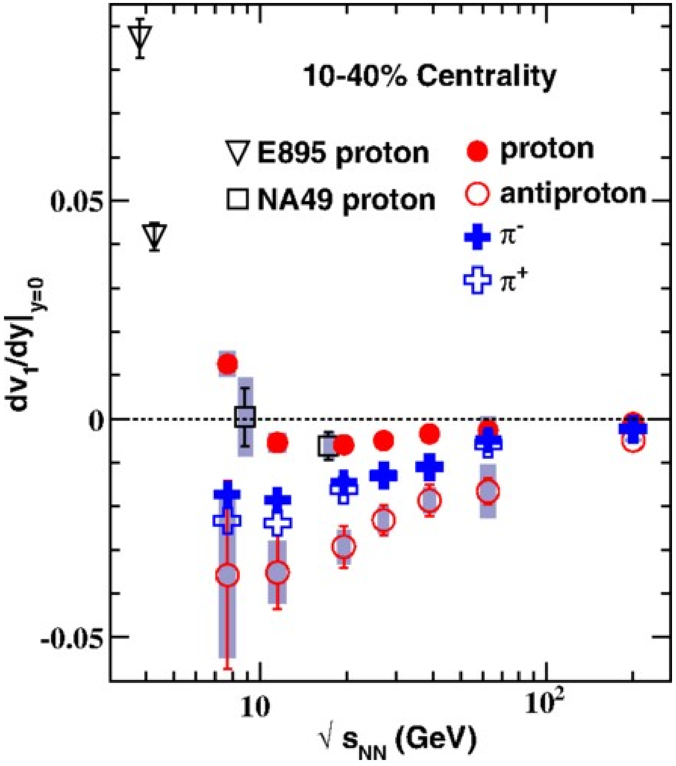
Non-monotonic structures in beam energy dependence



NA49



X. Luo QM15



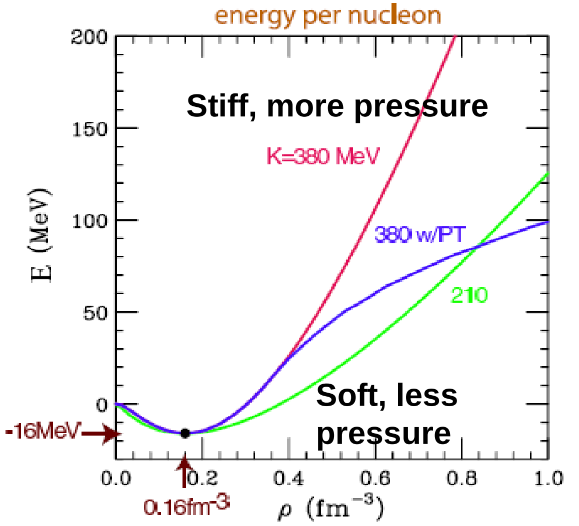
Onset of de-confinement?

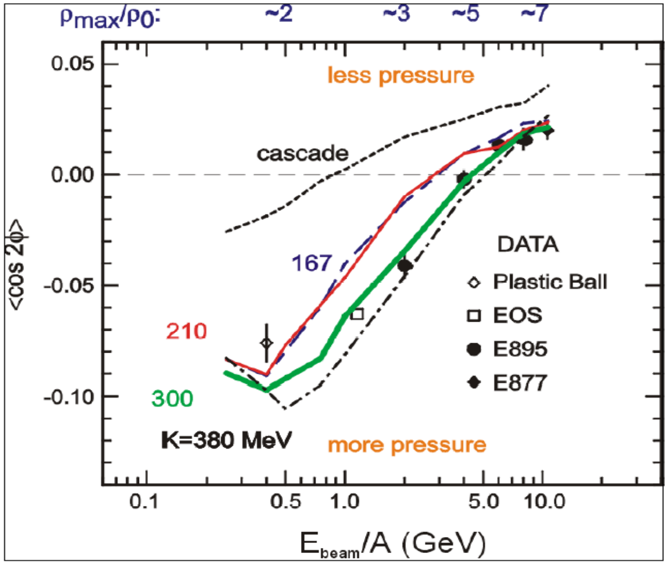
First-order phase transition? End point?

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

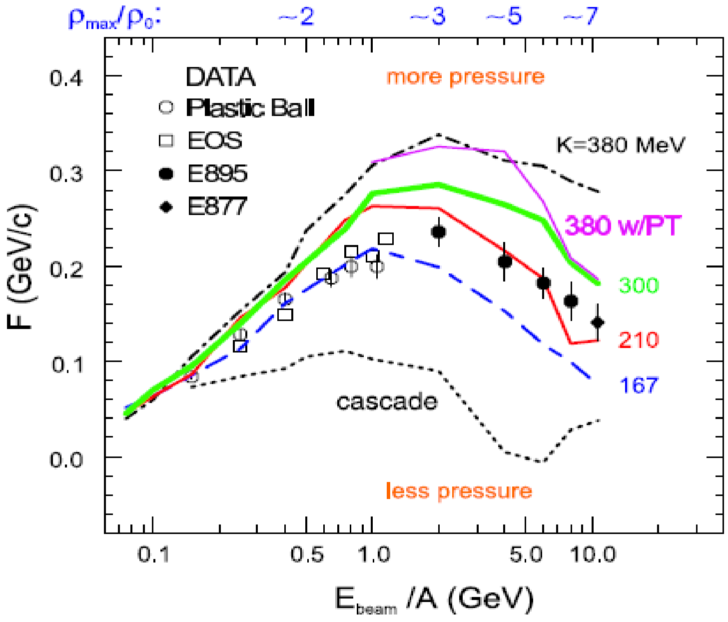
Determination of EOS at high density from an anisotropic flow in heavy ion collisions

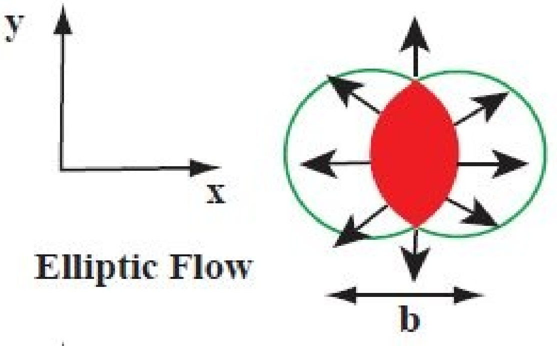
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

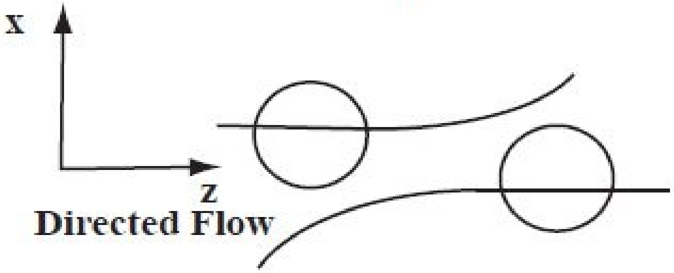




In-plane flow, v1







$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \qquad F = \left. \frac{d\langle p_x/A\rangle}{d(y/y_{cm})} \right|_{y/y_{cm}=1}$$

BUU Transport model predicts strong sensitivities of EOS on the directed and elliptic flows.

See recent work on v3:P.Hillmann, J.Phys.G45(2018)085101

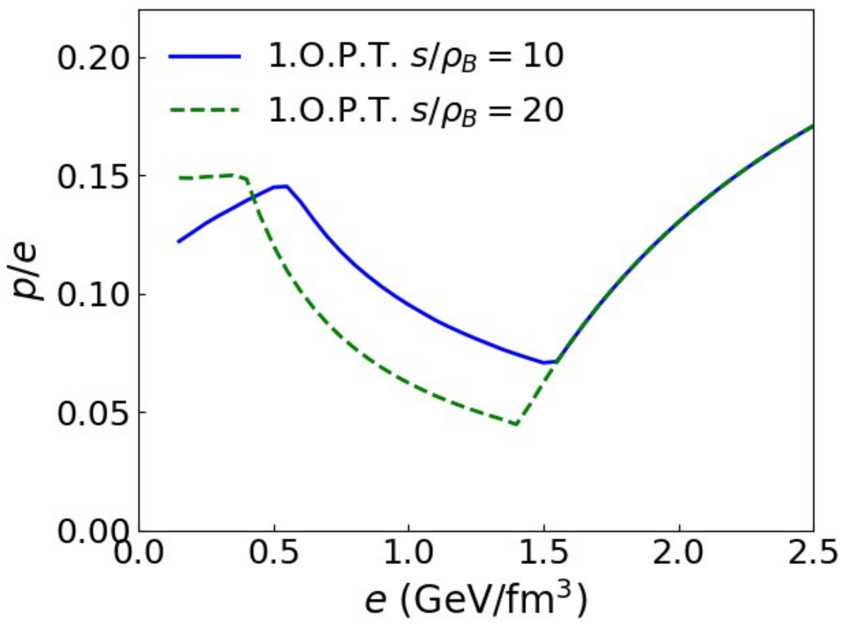
The softest point in the EoS

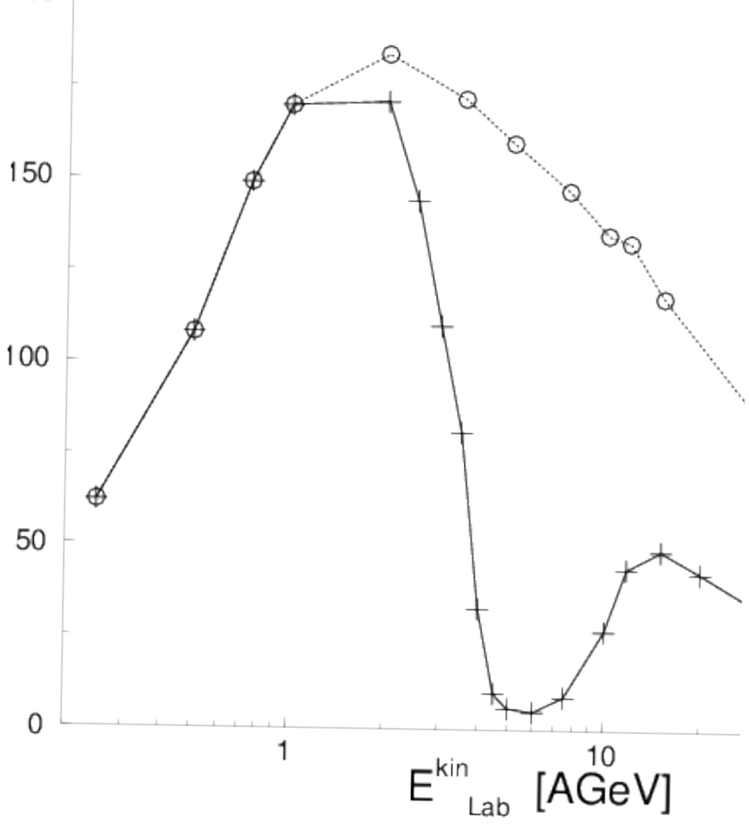
C.M.Hung, E.Shuryak, Phys.Lett.75 (1995), Phys.Rev.C57 (1998)

A minimum in the excitation function of the directed flow.

$$\langle p_x/N\rangle^{dir} = \frac{1}{N}\int_{-y_{CM}}^{y_{CM}} \mathrm{d}y\ \langle p_x/N\rangle(y)\ \frac{\mathrm{d}N}{\mathrm{d}y}\ \mathrm{sgn}(y)$$

EOS-Q: Massless quark-gluon plasma
+ hadron resonance gas



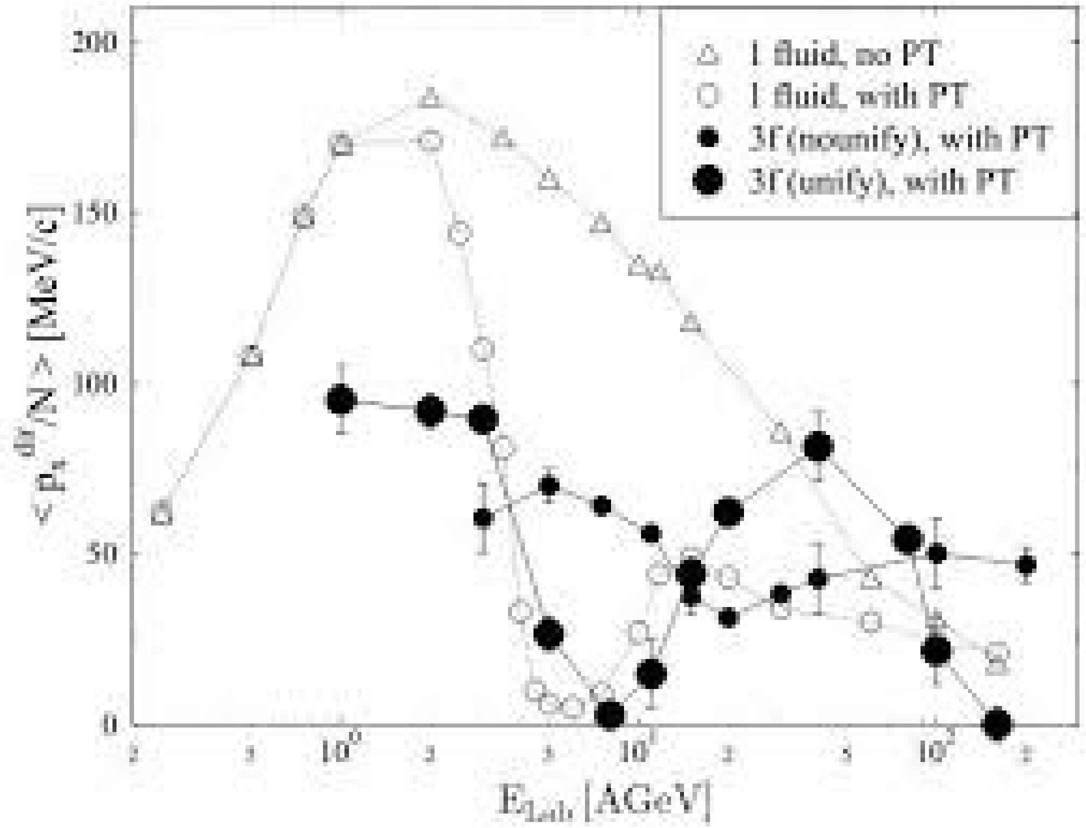


Longer lifetime of a expanding matter.

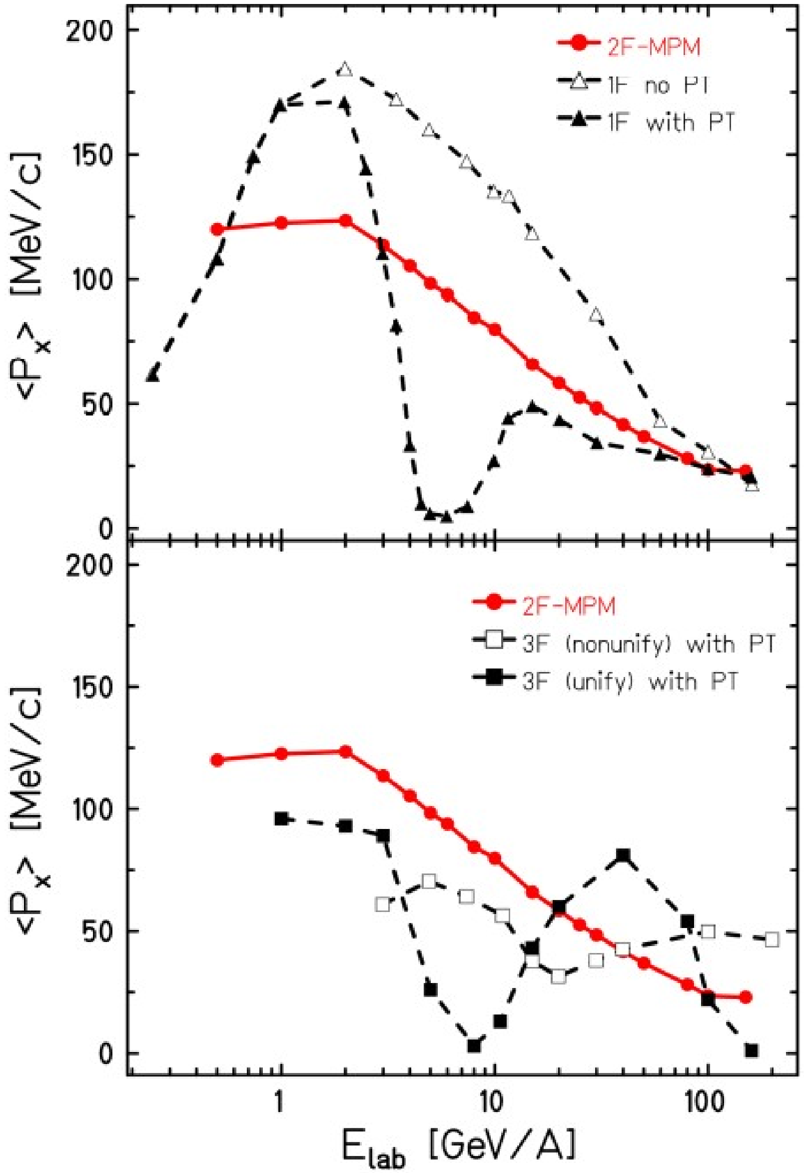
D.H.Rischke, et.al Heavy Ion Phys.1, 309 (1995)

A minimum in the excitation function of the directed flow in 3FD with a first-order PT

J.Brachmann,et.al. Phys.Rev.C61 (2000)



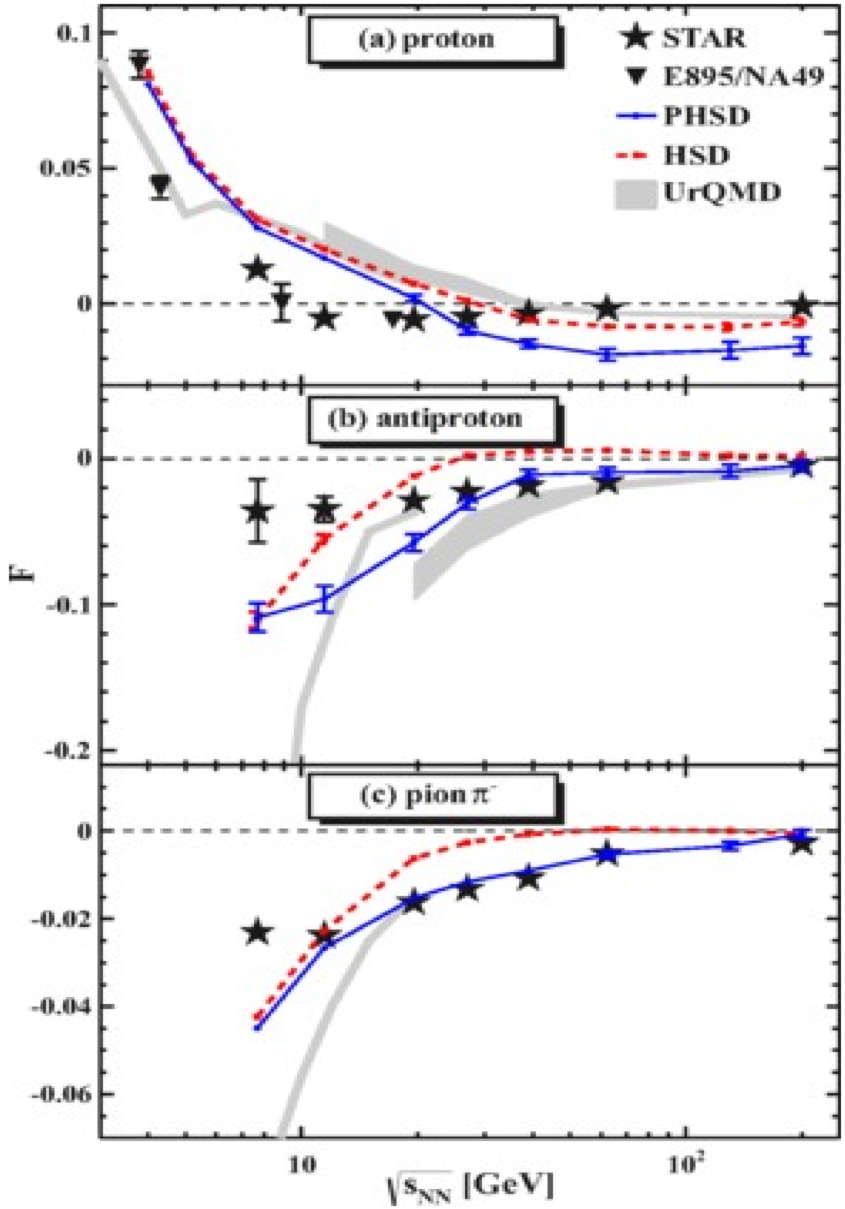
$$\langle p_x/N\rangle^{dir} = \frac{1}{N}\int_{-y_{CM}}^{y_{CM}} \mathrm{d}y\ \langle p_x/N\rangle(y)\ \frac{\mathrm{d}N}{\mathrm{d}y}\ \mathrm{sgn}(y)$$

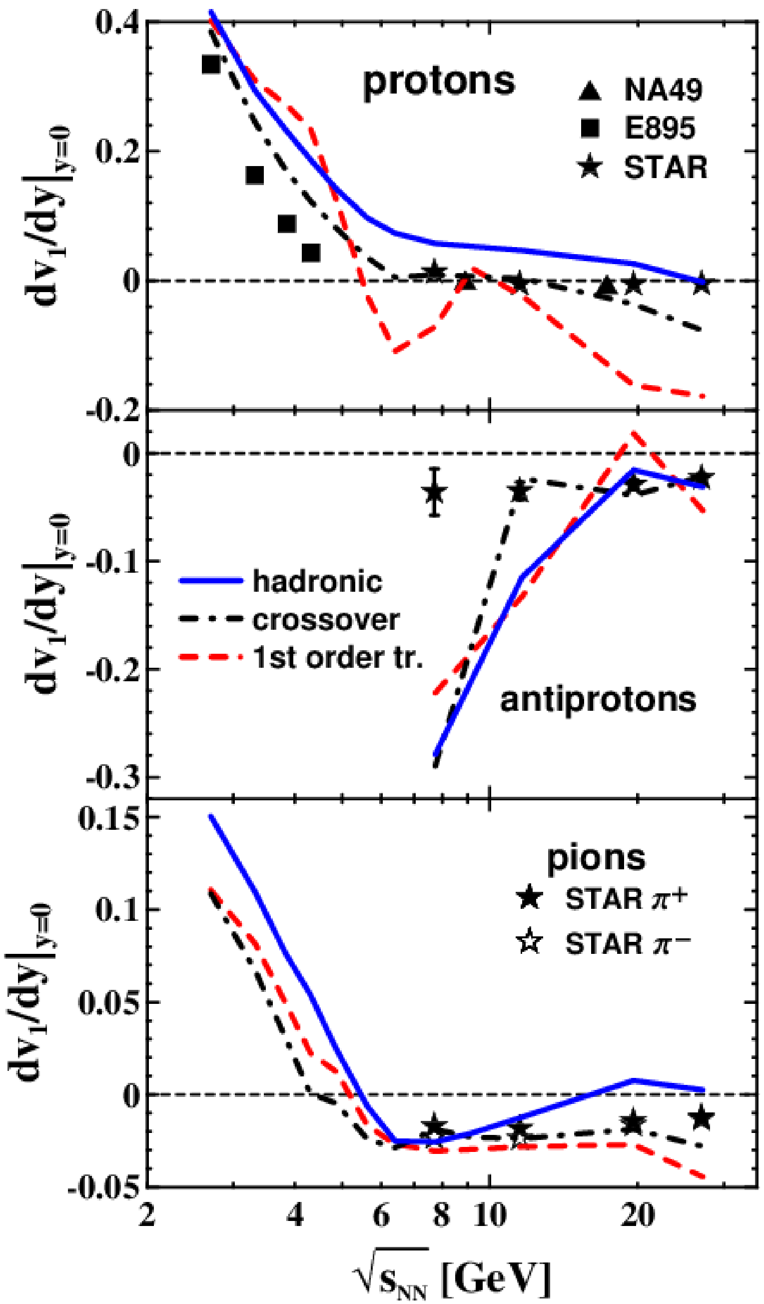


Yu.B.Ivanov, et.al.Heavy IonPhyscs 15 (2012)

PHSD and 3FD predictions

Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C91, 024915 (2015)

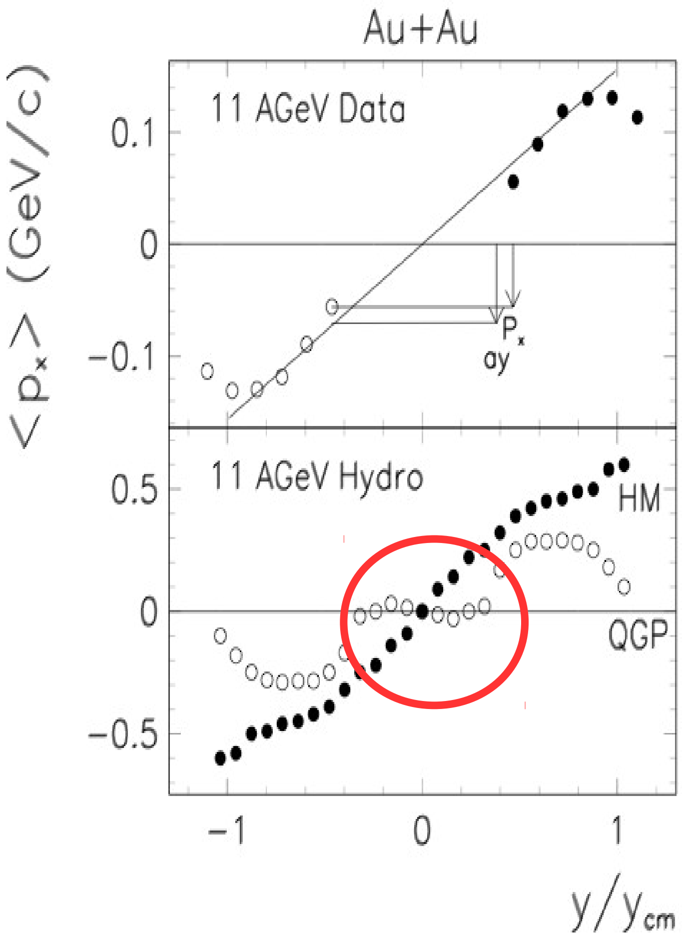




V. P. Konchakovski, W. Cassing, Y. B. Ivanov and V. D. Toneev,
Phys. Rev. C90, no. 1, 014903 (2014)

Negative slope: 1^{st} order phase transiton signal?

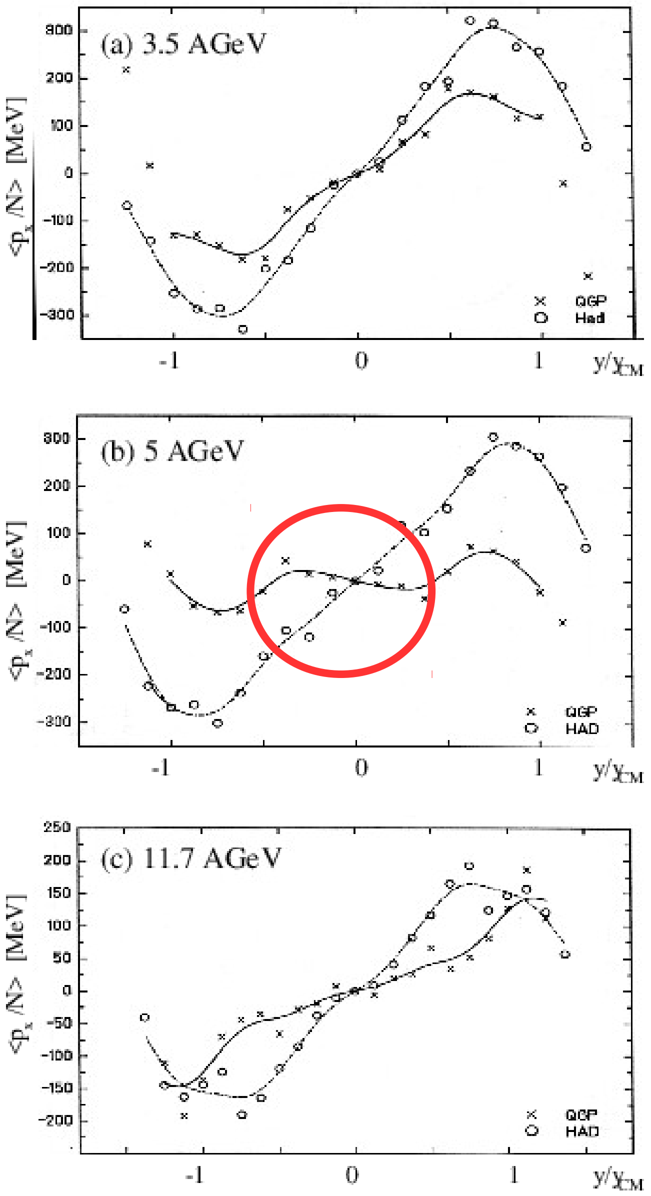
D.H.Rischke, et.al Heavy Ion Phys.1, 309(1995)



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

Fig. 6

Au+Au b=3 fm



1^{st} P.T. EoS predicts wiggle in hydro

QGP signal: formation of tilted ellipsoid

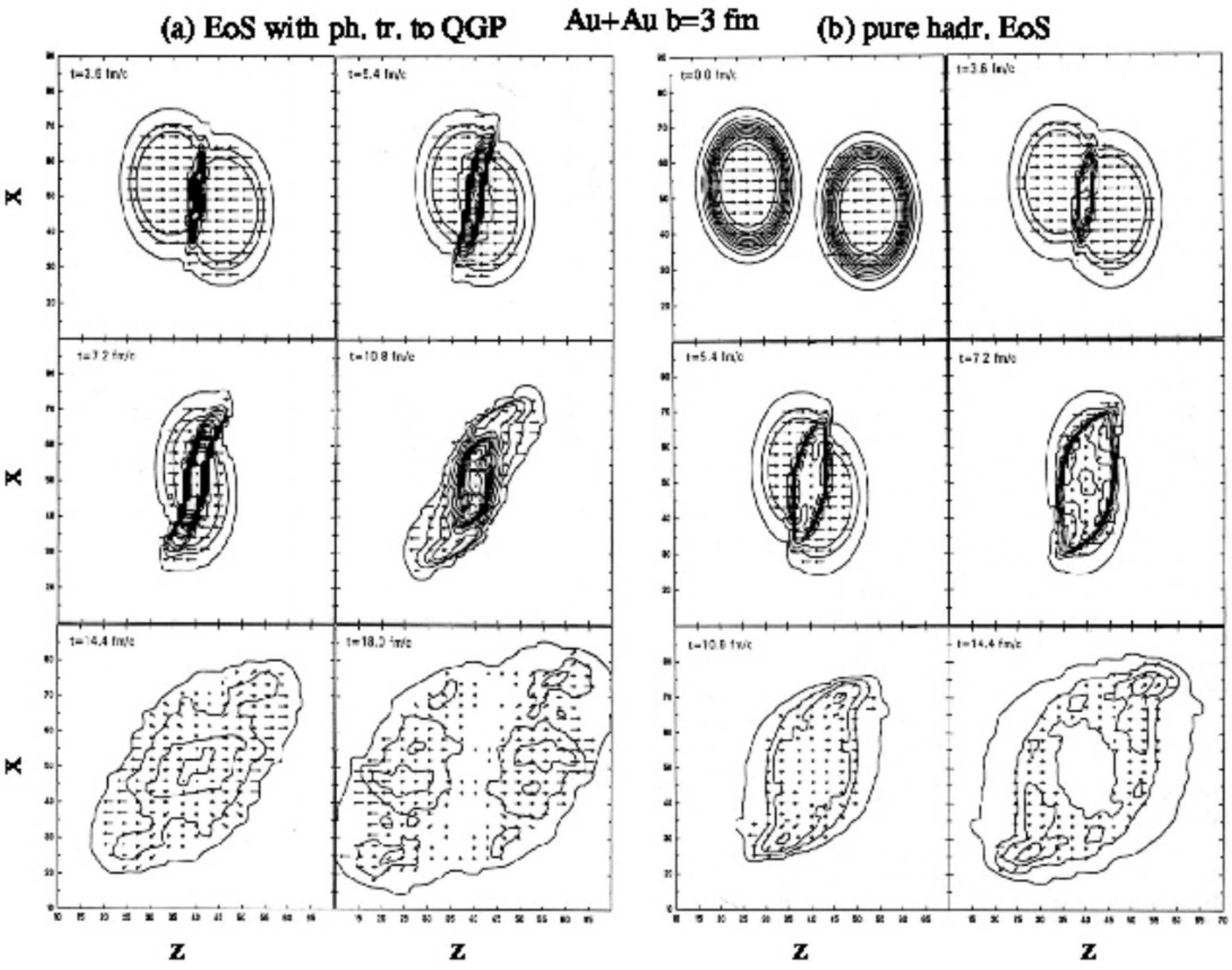
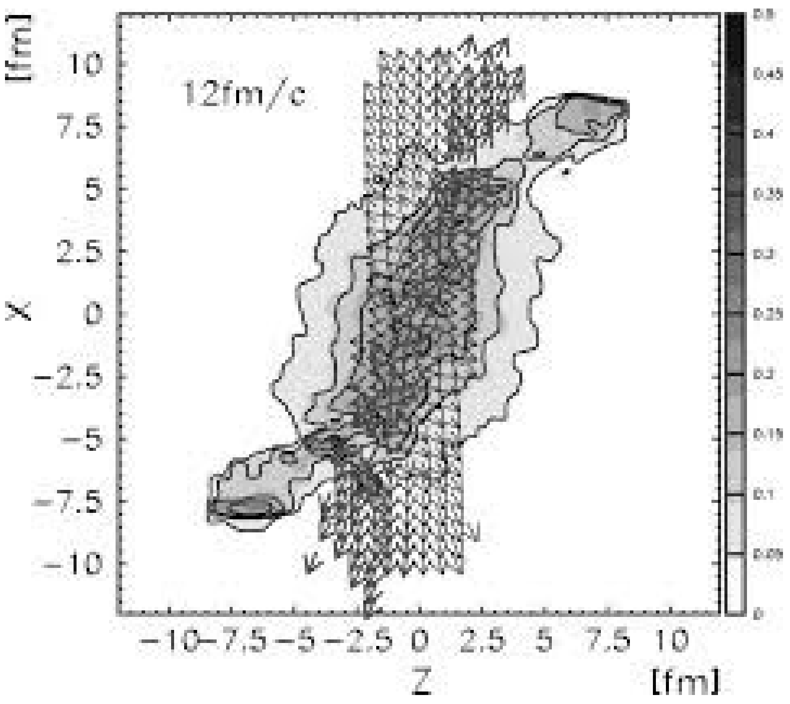


Fig. 5

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

J.Brachmann,et.al. Phys.Rev.C61 (2000)



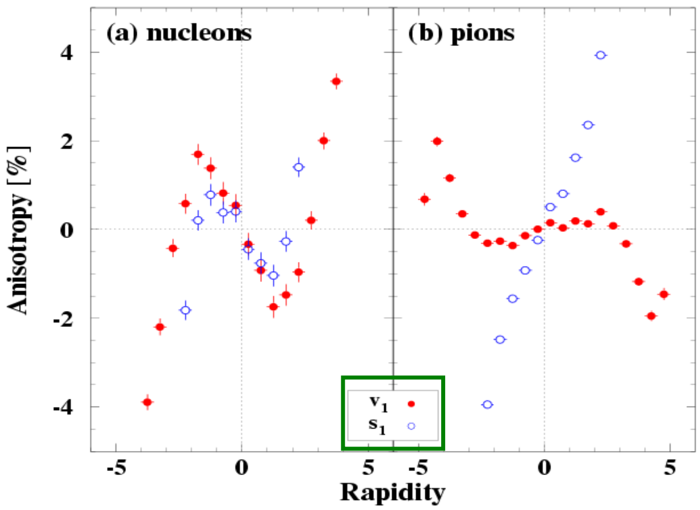
Net baryon density in Au+Au
at Elab=8GeV b=3

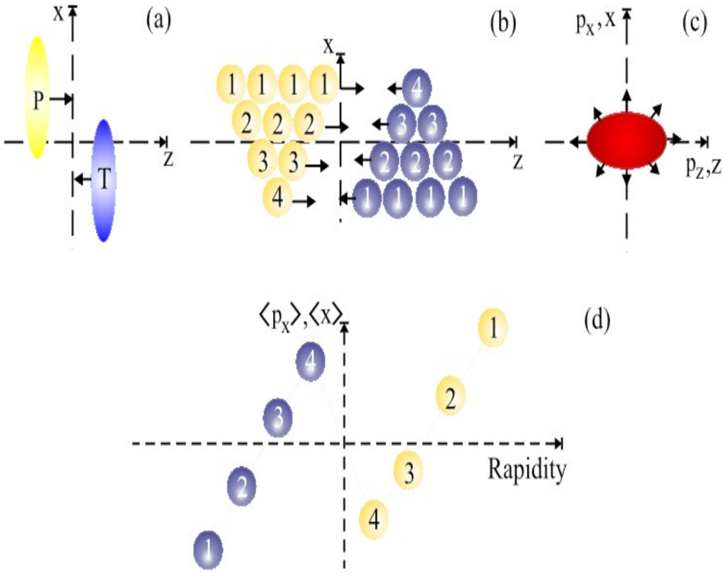
EoS with a a first-order phase transition yields tilted ellipsoid in hydro

Wiggle: QGP signal in the directed flow?

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

RQMD v2.4



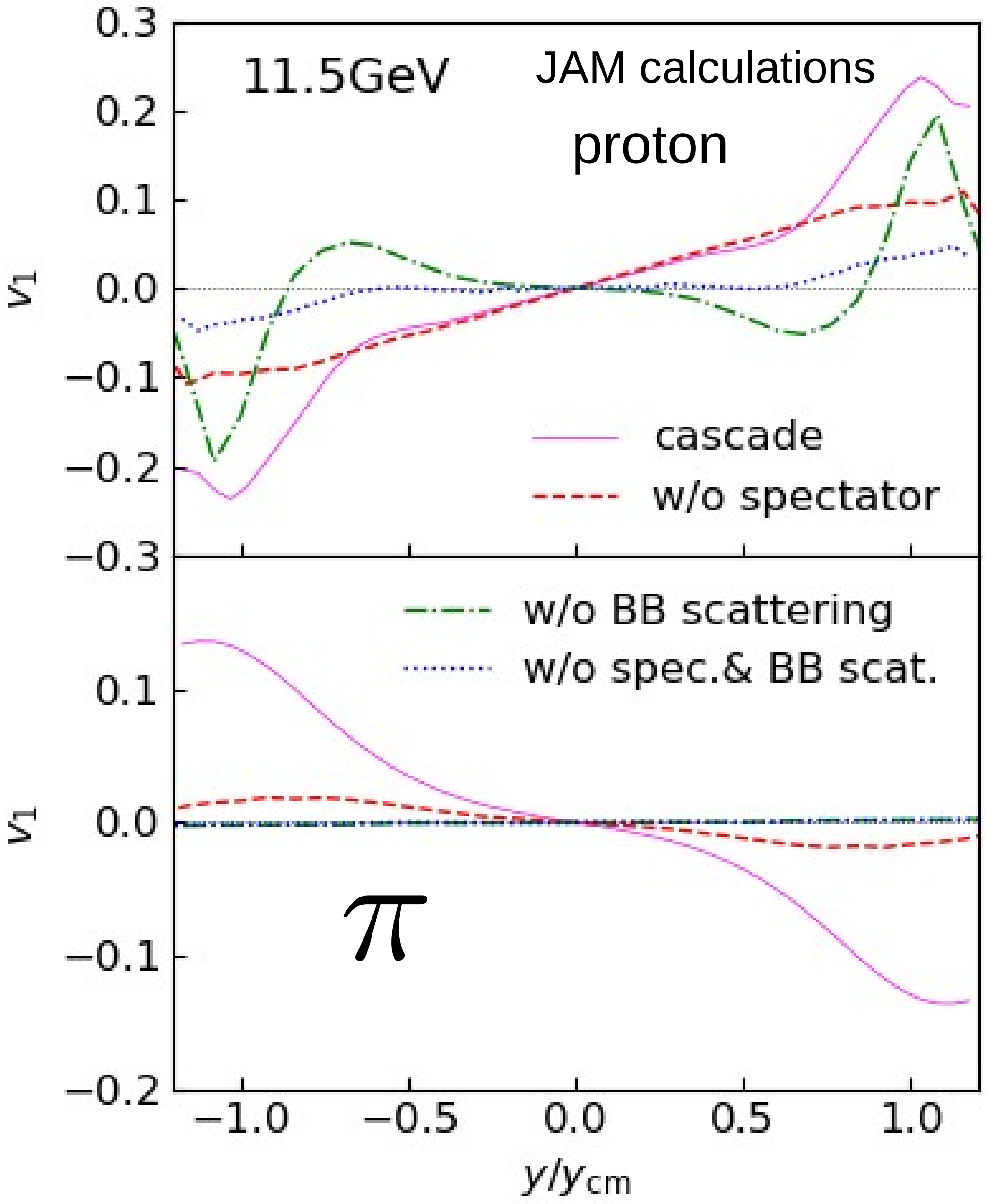


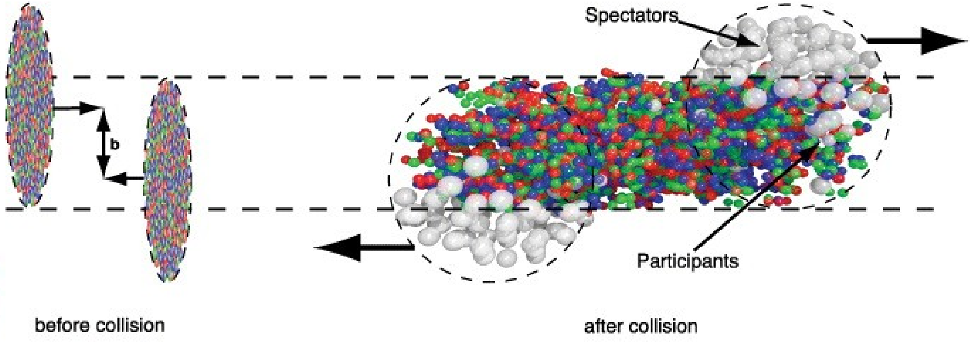
R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

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

This picture is only applicable at Ecm > 30 GeV

v1 : effects of spectator and MB interactions





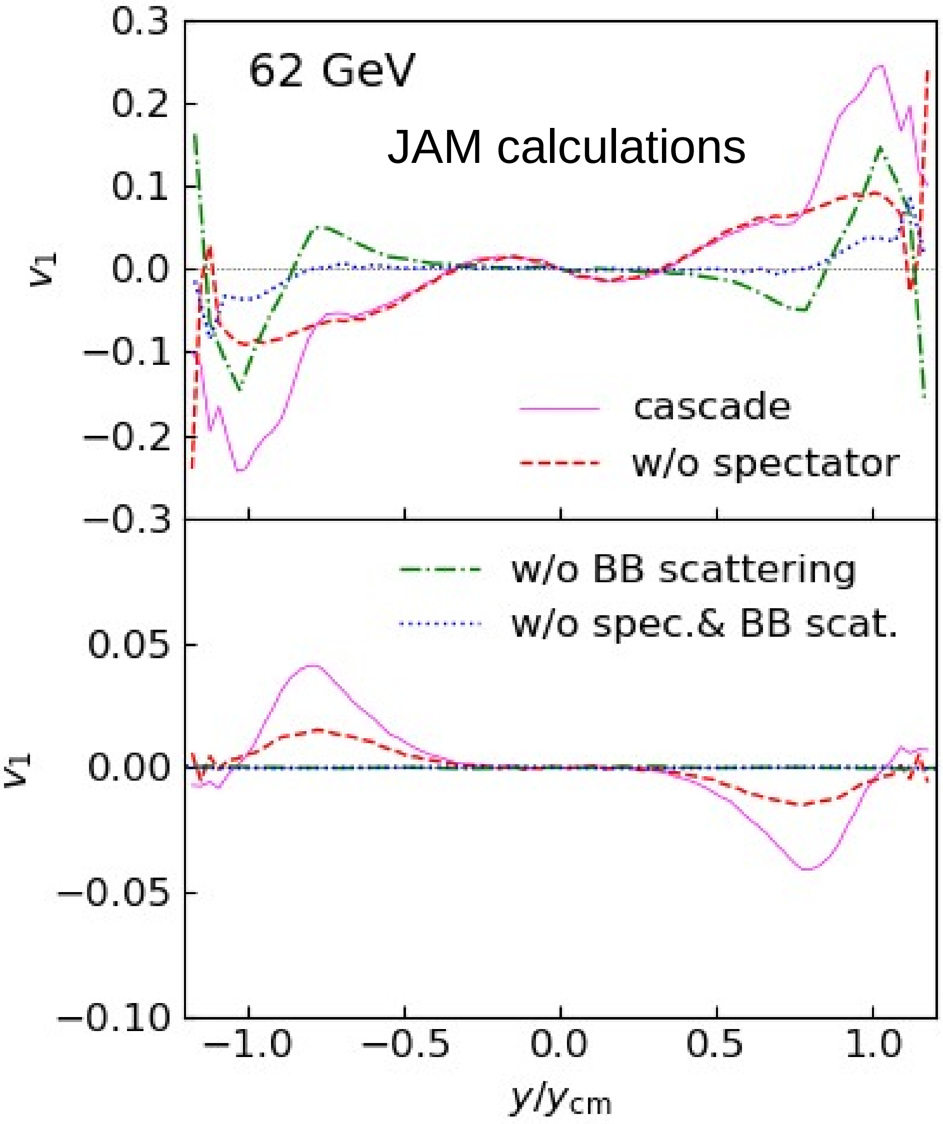
Baryon-Baryon collisions with spectator matter create negative proton v1.

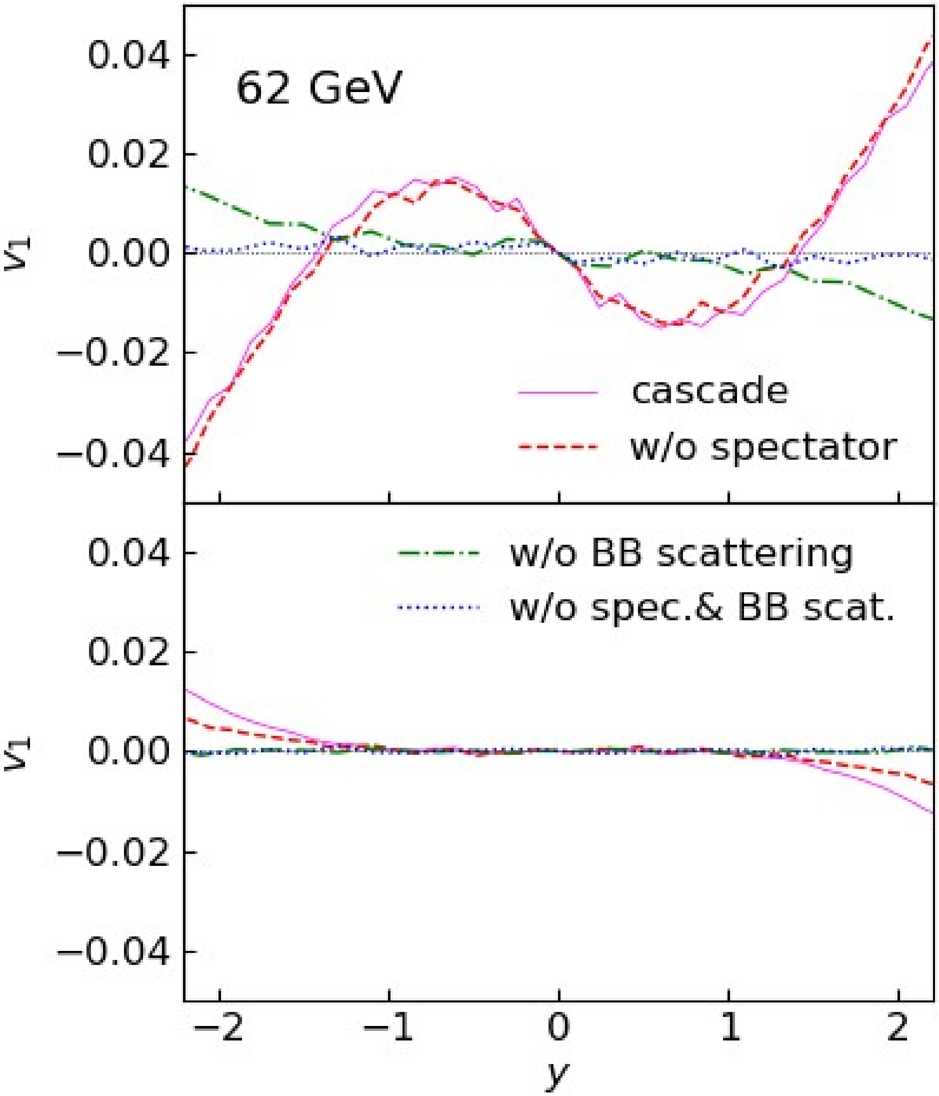
BB collisions without spectator show Zero v1!

Meson-Baryon collisions make proton v1 slope positive.

Pion-spectator nucleon interactions are the source of negative pion v1

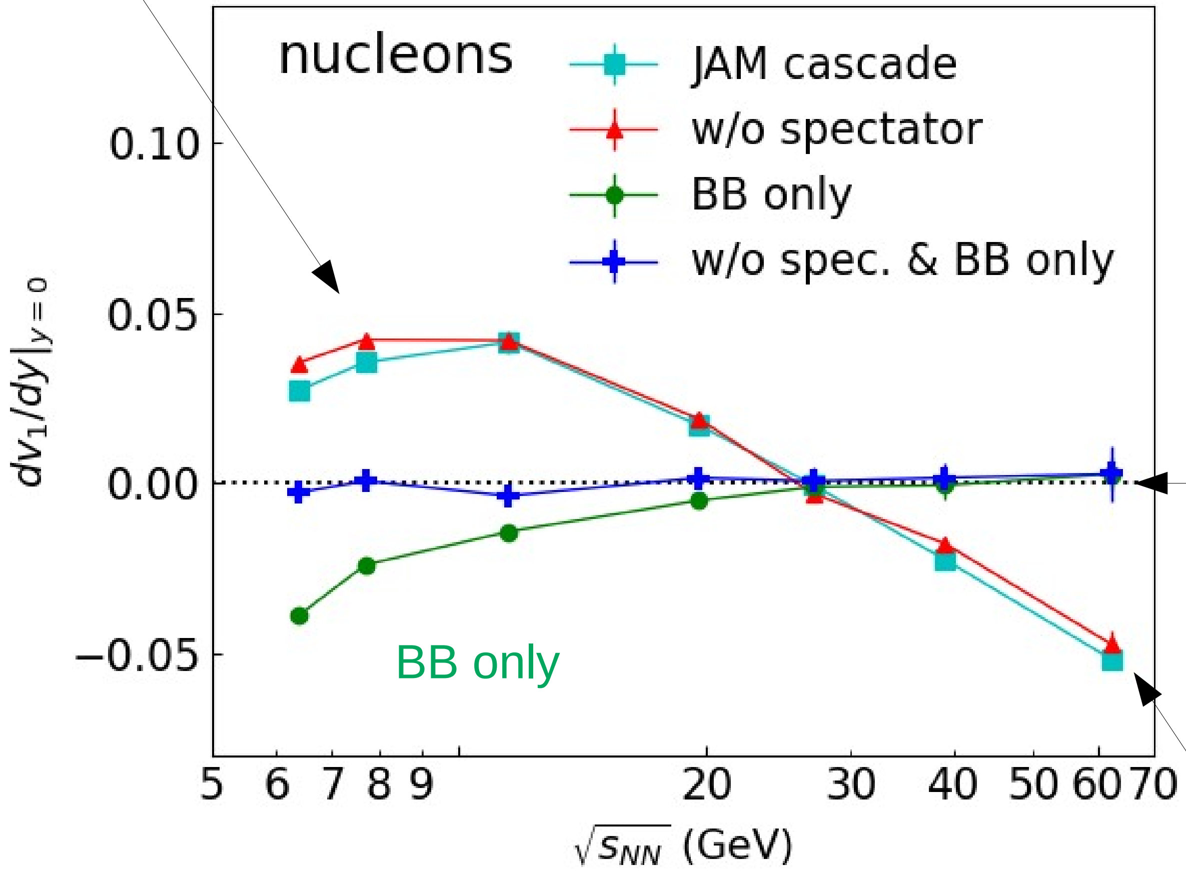
Proton v1 is negative with meson-baryon interactions in transport model at high energies

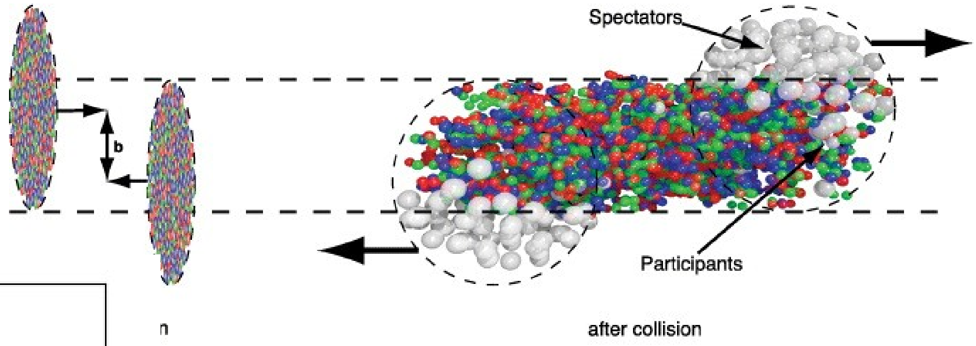

JAM calculations



v1 : effects of spectator and MB interactions

Meson-Baryon collisions make proton v1 slope positive.





BB collisions without spectator show zero v1!

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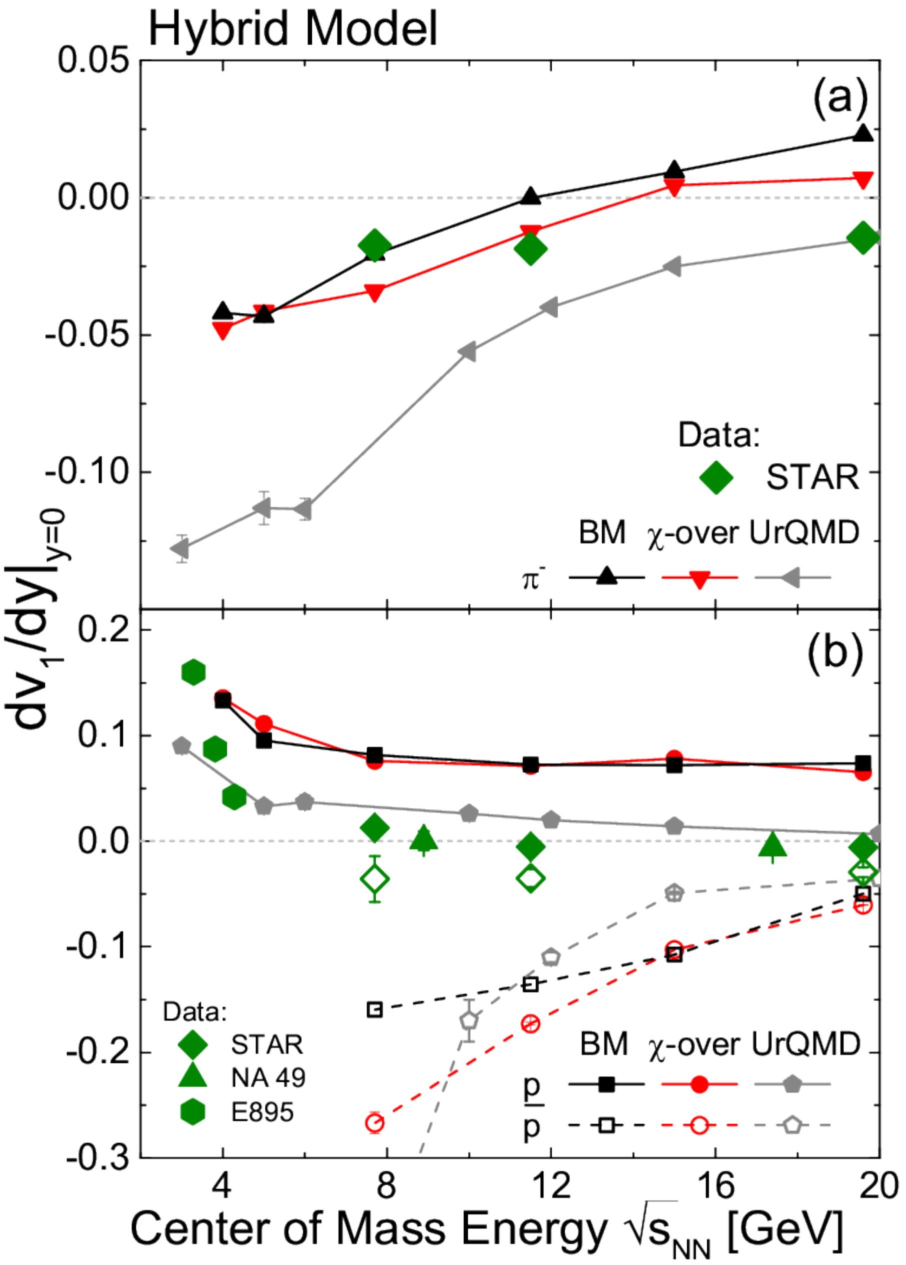
UrQMD + hydro predictions



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

Hydro evolution starts after two nuclei pass through each other in the UrQMD + hydro model

No minimum! No EoS dependence.
Switching time too late?

Correct description of the Initial non-equilibrium stages of the collisions may be important .

Theoretical Predictions of Proton v1

- One-fluid and three-fluid models: negative v1 slope at 3-10 GeV for a first-order phase transition!

  → treatment of initial stages of the collision questionable

- Microscopic transport models: negative v1 above 30 GeV due to geometrical effects

  → Cascade type models only simulate hadron gas EoS
  How to incorporate potentials with softening effects

- UrQMD + hydro model: no sensitivities of EOS on v1 suggests the importance of EoS effects in the initial non-equilibrium stages

  → new hybrid model with dynamical initialization

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
- Nuclear cluster formation and its statistical decay
- EoS controlled collision term
- Dynamical coupling of Fluid dynamics through source terms

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

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.

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

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

EOS modified collision term

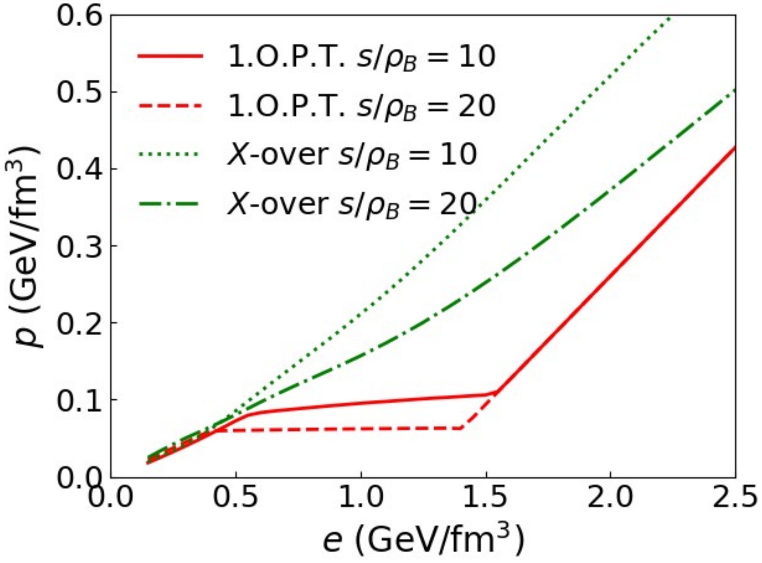
H. Sorge, Phys. Rev. Lett. 82,2048 (1999)   Virial Theorem for two body collisions

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

The momentum change is constrained by

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

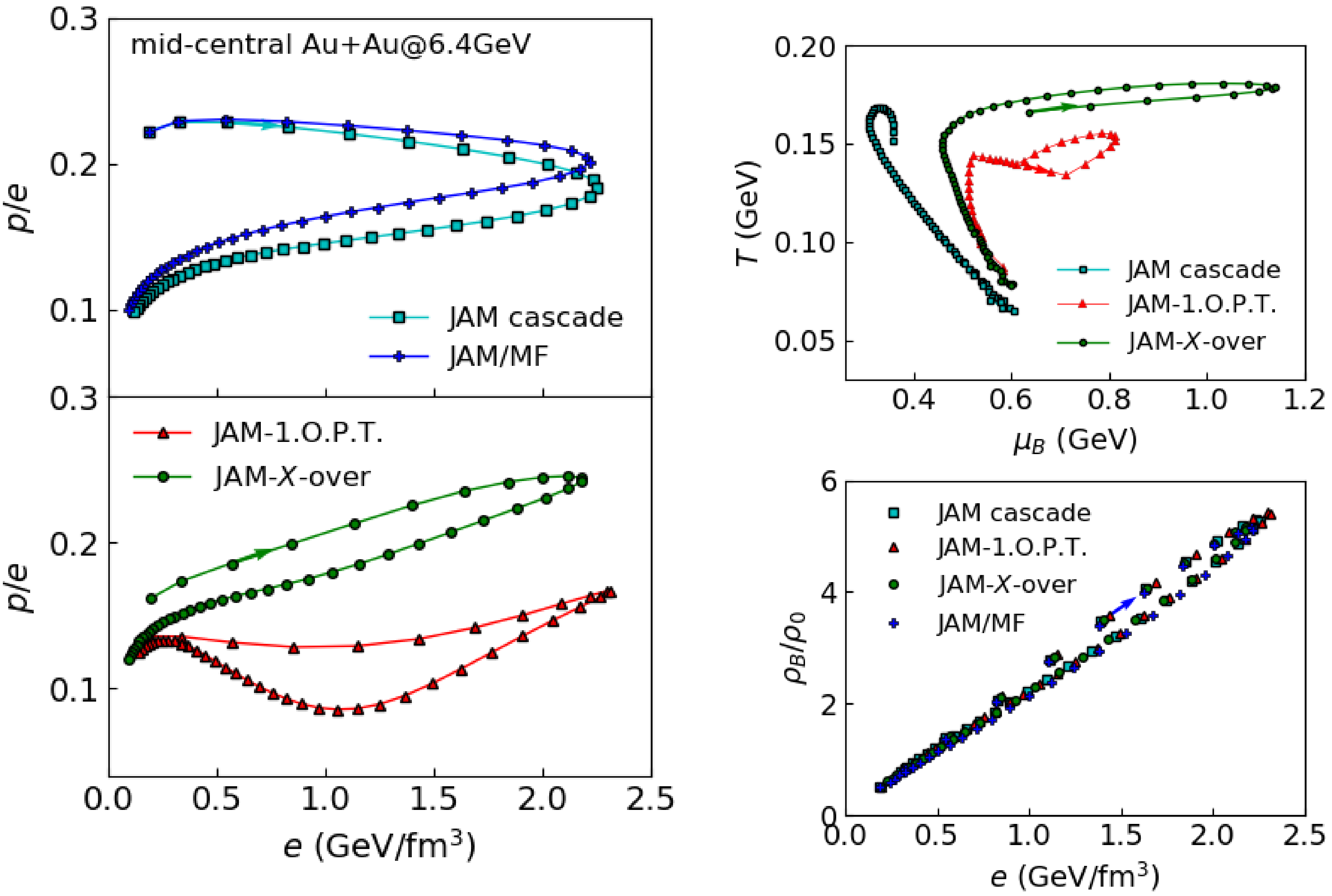
When P < Pfree: attractive orbit in the collision.



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

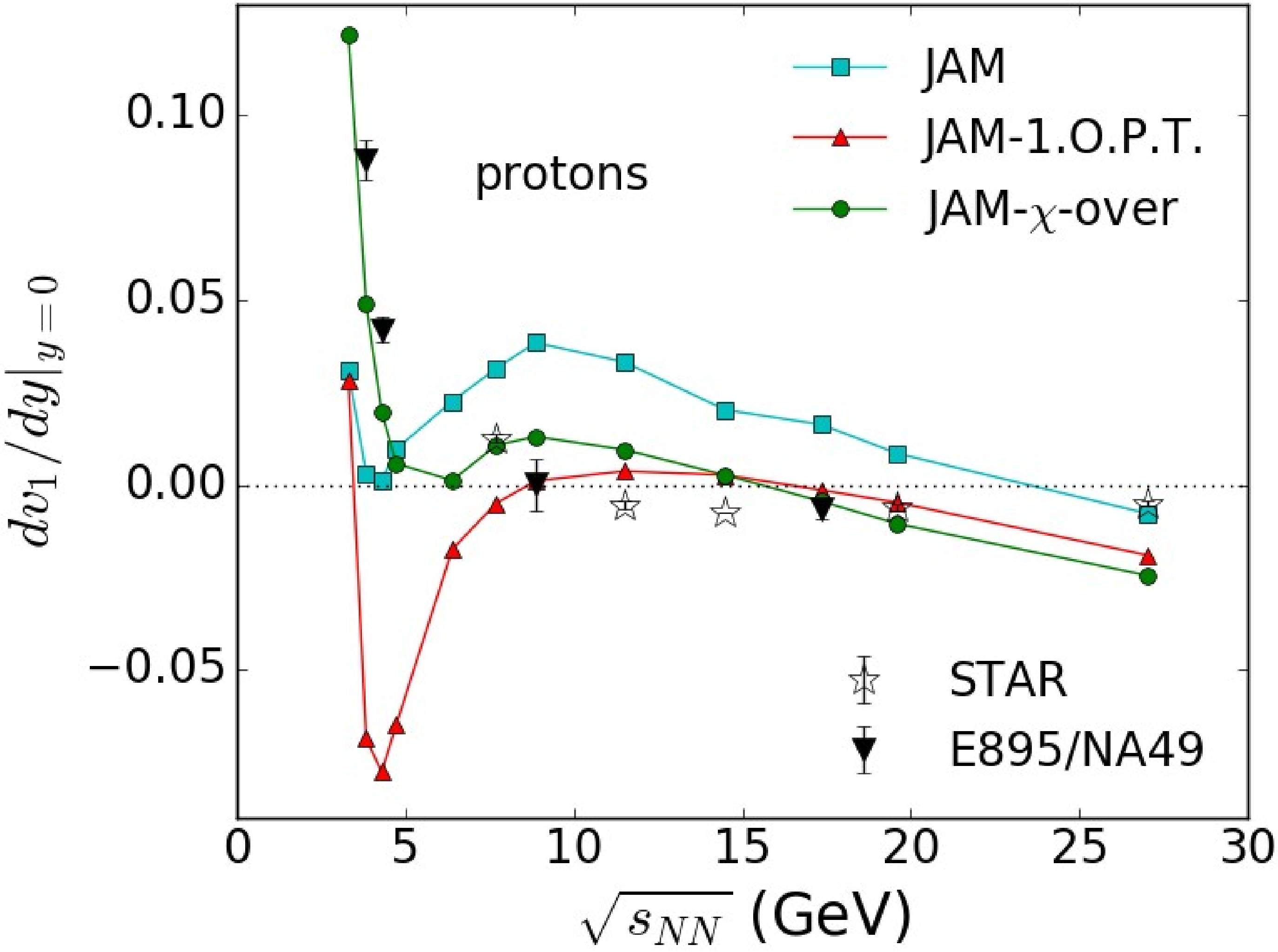
EoS dependence at 6.4 GeV



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

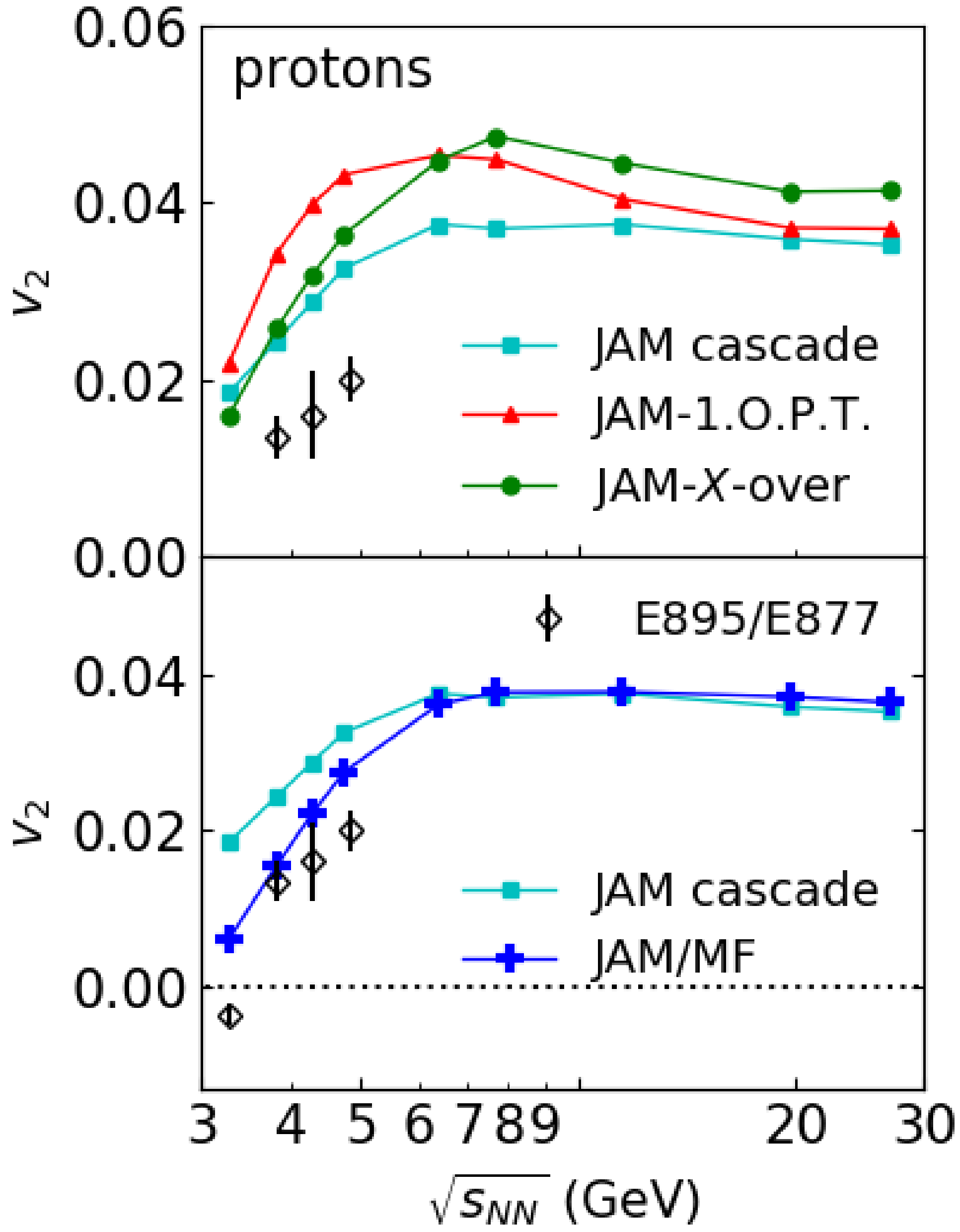
Y. N., H. Niemi, J. Steinheimer, H. Stoecker, PLB769 (2017)

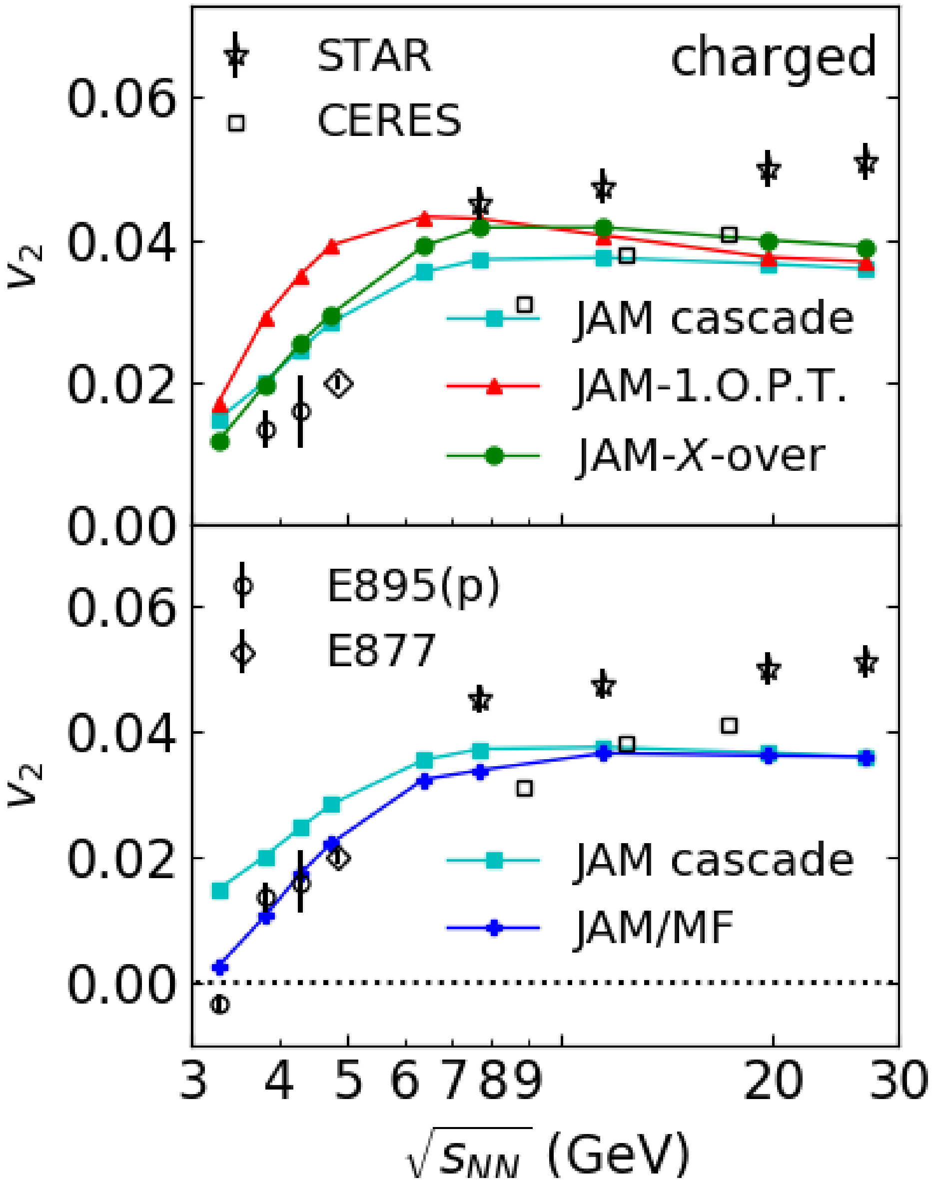
V1 excitation functions



JAM/EOS non-equilibrium transport model predictions show very similar EoS dependence on the v1 as 3-fluid calculations.

Enhancement of V2 for 1st Order P.T.

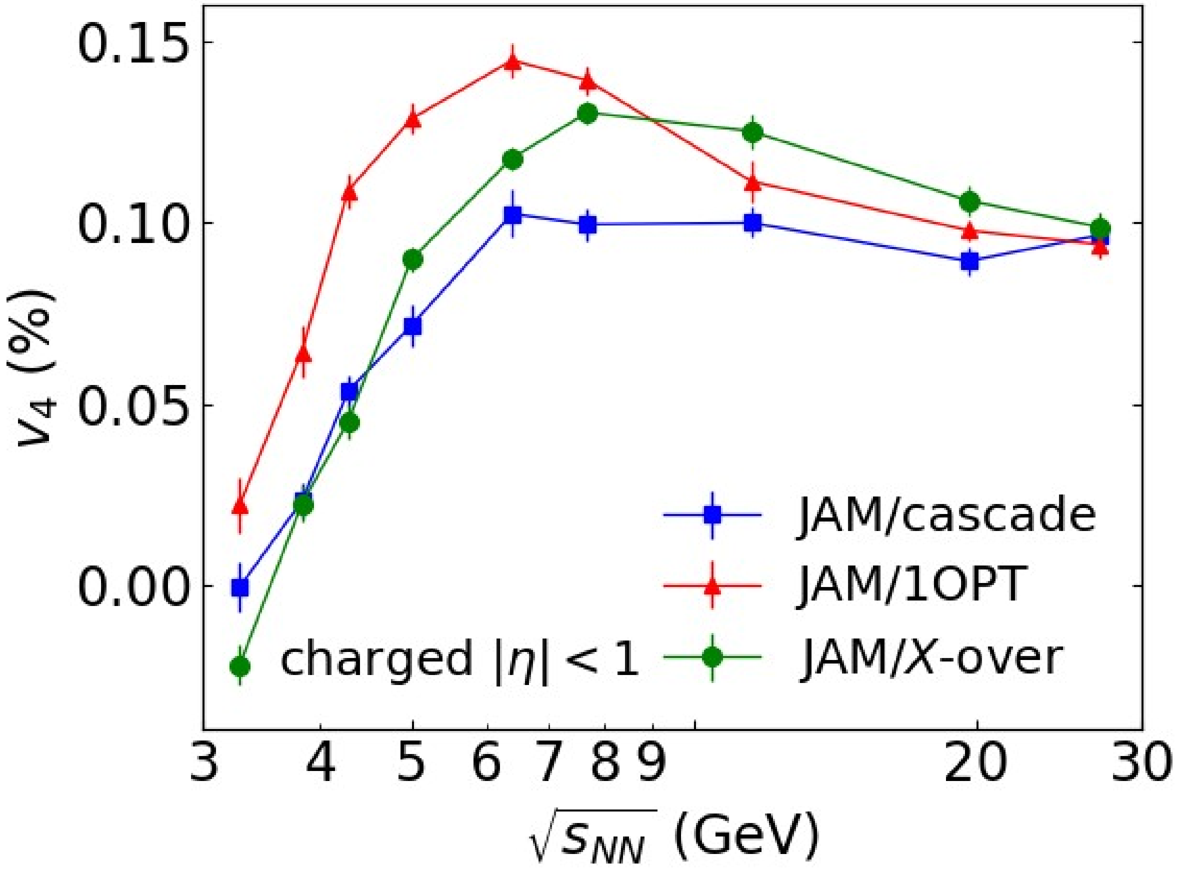




Y. Nara., H. Niemi, A. Ohnishi, J. Steinheimer, X. Luo, H. Stocker, Eur. Phys. J. A54 (2018)

V4 excitation functions

Y. N., J. Steinheimer, H. Stoecker, nucl-th-1809.04237

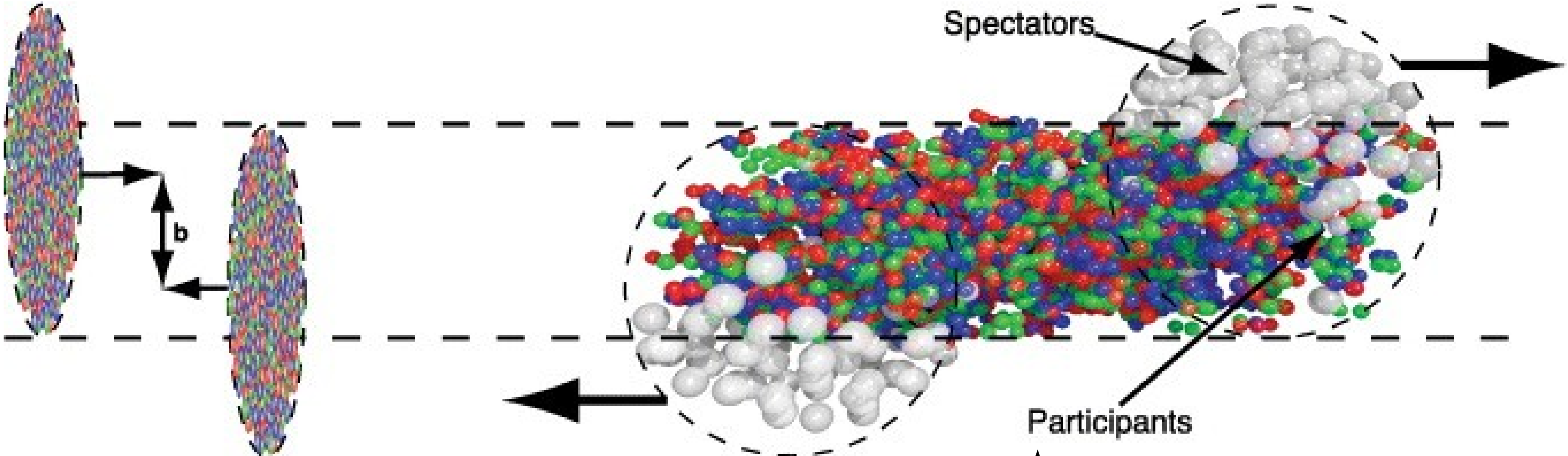


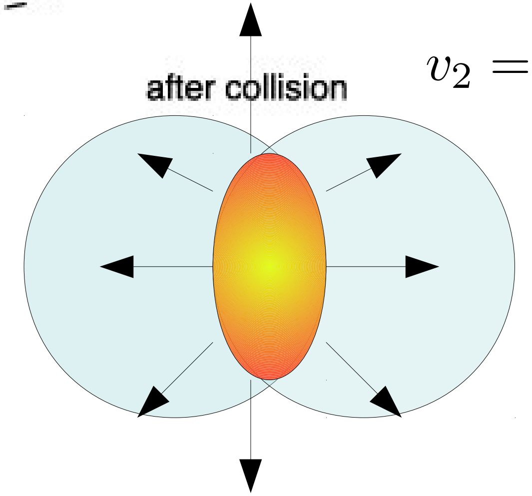
Enhancement of v4 for a 1sr-oder phase transition

V4 can be also positive for the out-of-plane emission (squeeze-out)

Phys.Rev. C97 (2018) no.6, 064913

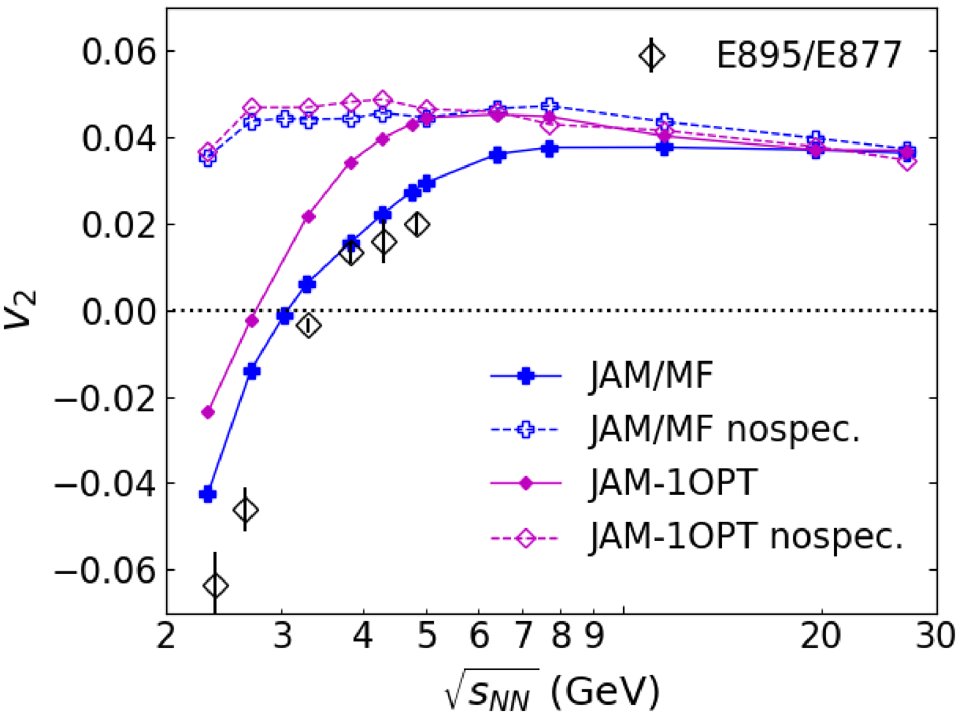
Effects of interaction with spectator





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

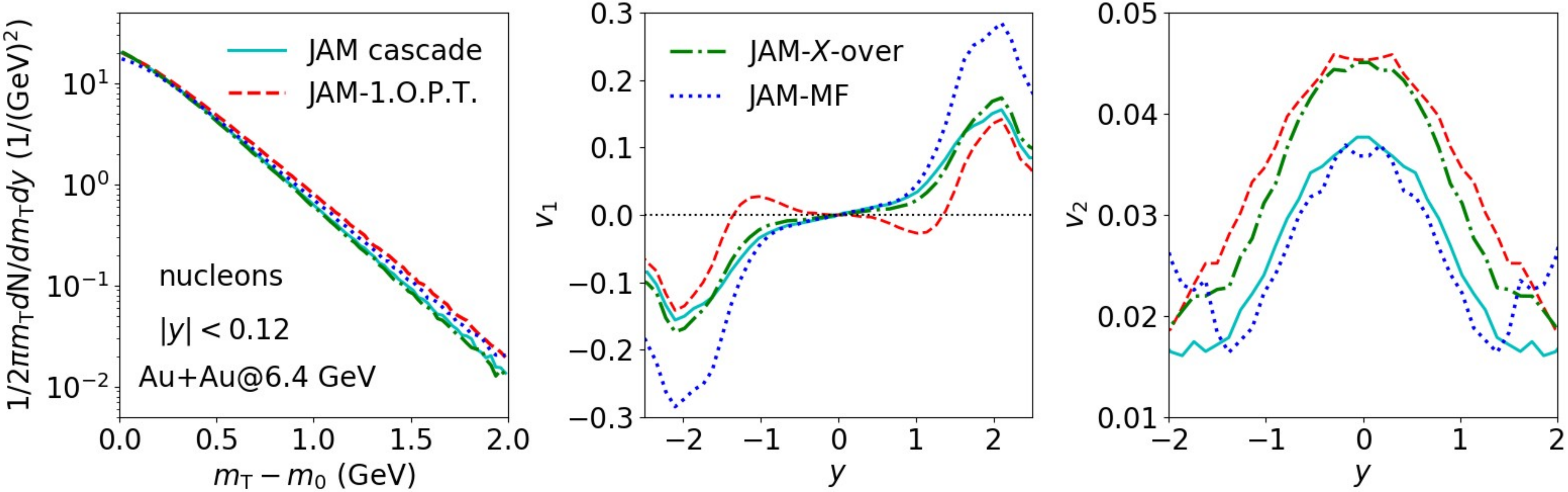
$v_2 = \langle \cos(2\phi) \rangle > 0$



Comparison of the results without spectator interactions

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

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

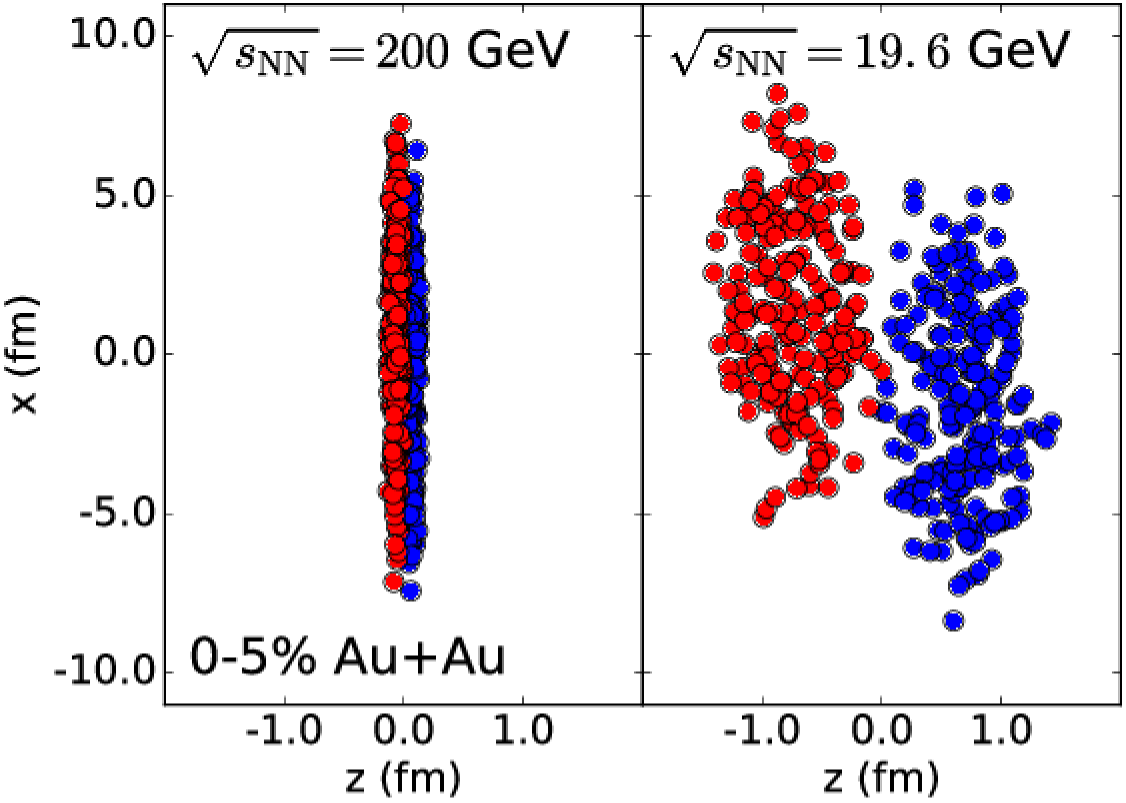
Combined analysis of v0, v1, and v2 should be very useful.

JAM + Hydro for FAIR, NICA, J-PARC

Y. Akamatsu, M. Asakawa, T. Hirano, M. Kitazawa,K. Morita, K. Murase,
Y. Nara, C. Nonaka, A. Ohnishi, Phys.Rev. C98 (2018) no.2, 024909

Initial nucleon positions

Chun Shen and Bjorn Schenke Phys.Rev. C97 (2018) no.2, 024907



Assumption of single thermalization time breaks down at low beam energies, since secondary interactions start before two nuclei pass through each other.

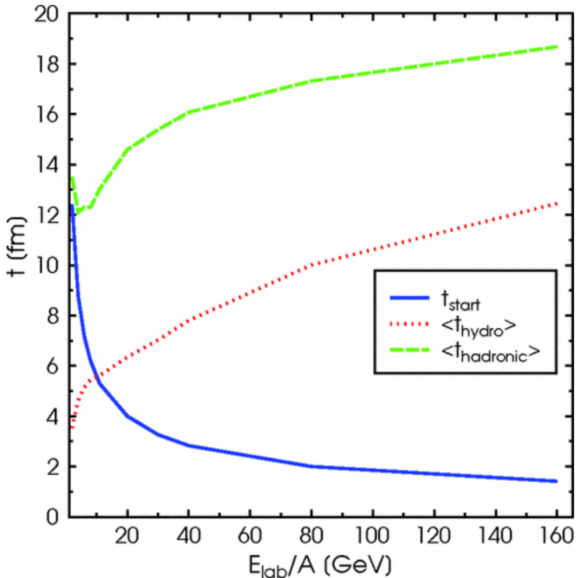
Progresses in hybrid dynamical models at high baryon density region

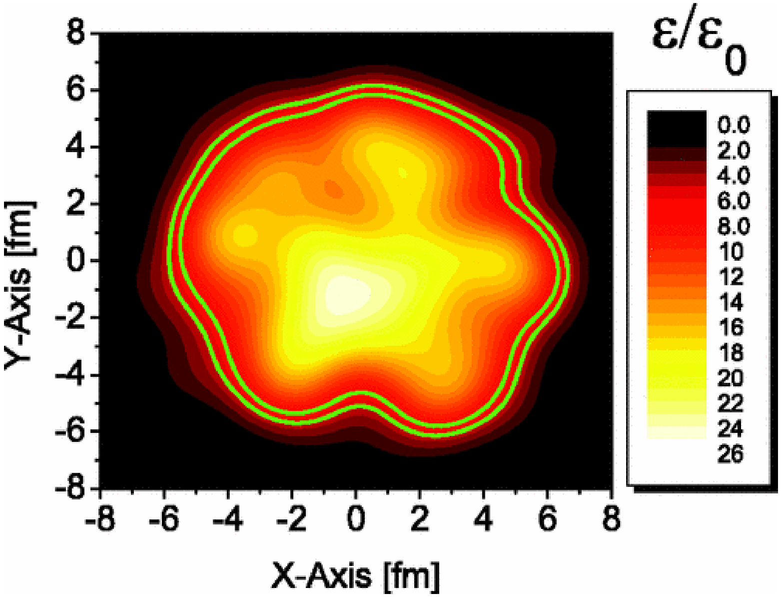
- UrQMD+hydro (2008) Petersen et.al.

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.





Phys.Rev. C98 (2018) no.2, 024909

A new approach: JAM+hydro model

Dynamical coupling of fluids through source terms

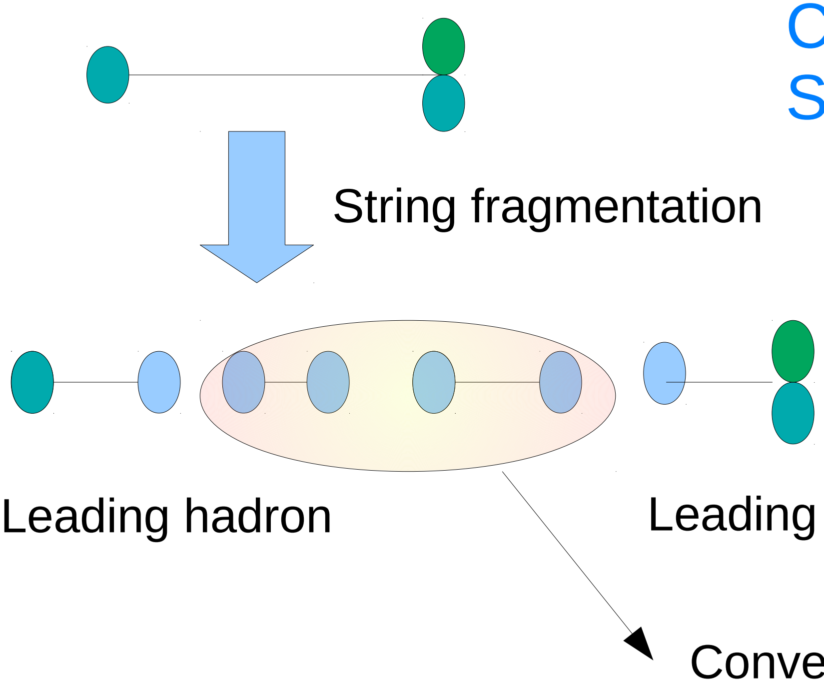
$$\partial_\mu T_f^{\mu\nu} = J^\nu, \quad \partial_\mu N_B^\mu = \rho_B$$

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

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)

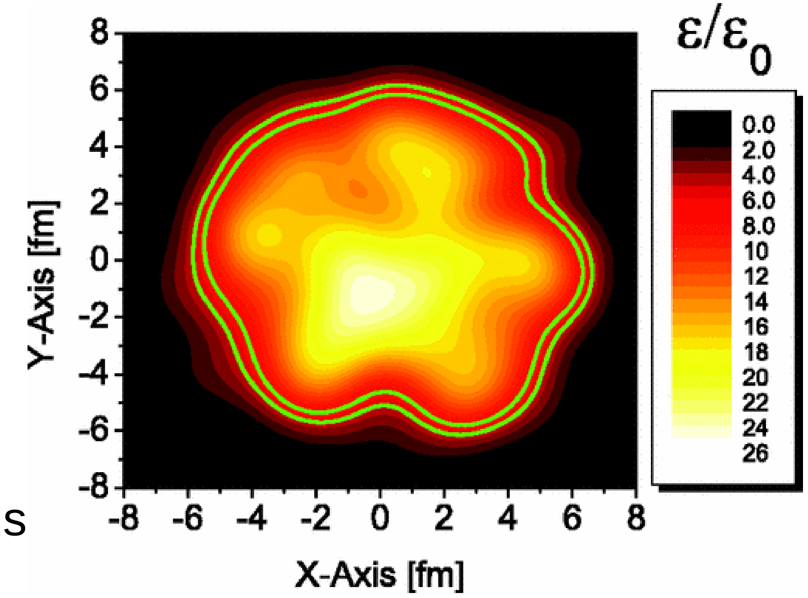


String fragmentation

Leading hadron

Leading hadron

Converted into fluids



Model parameters

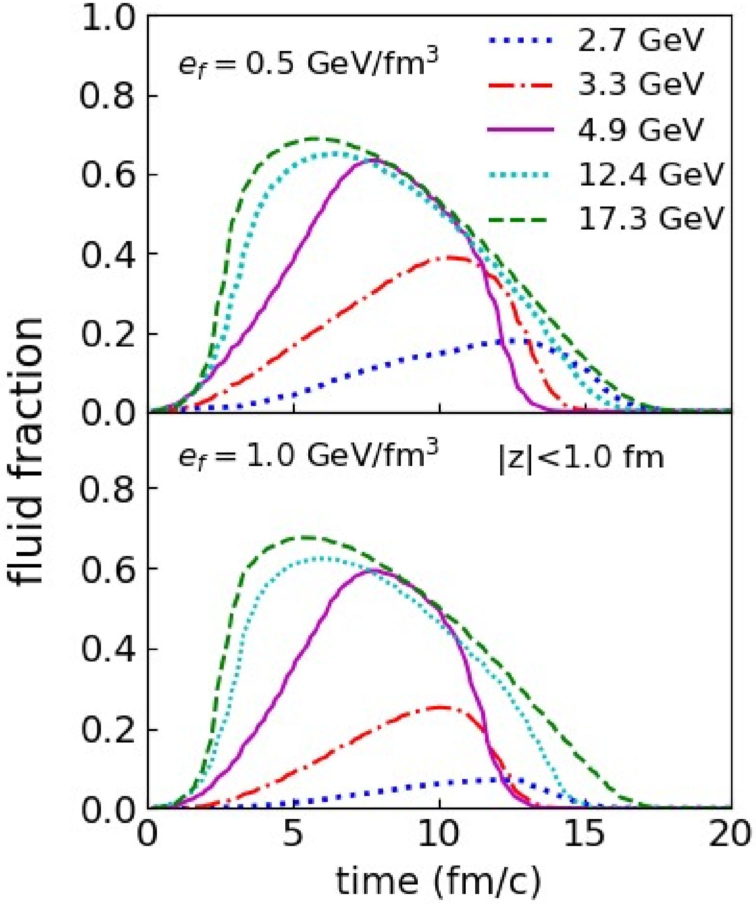
1) fluidization energy density

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

2) particlization energy density

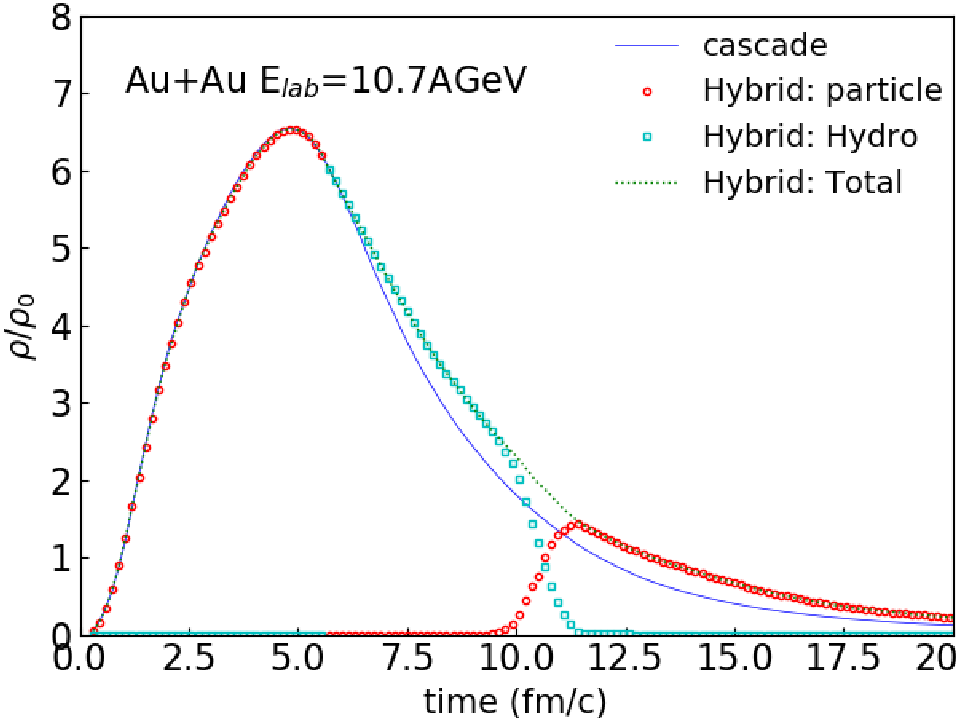
$$e_p = 0.5 \ \mathrm{GeV/fm}^3$$

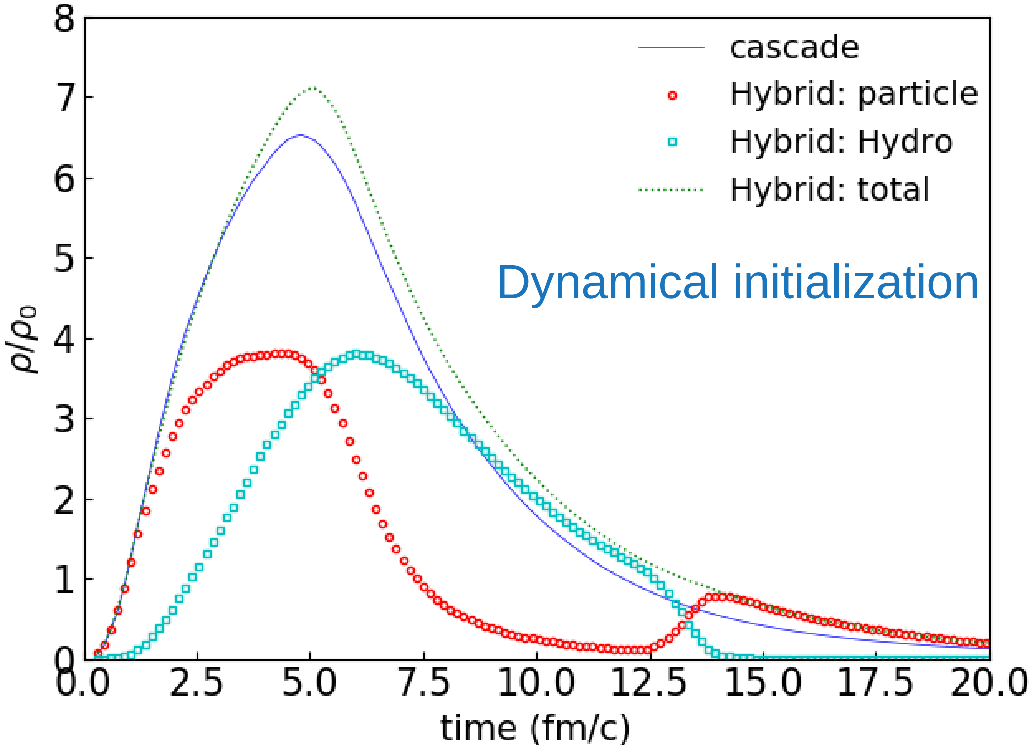
3) equation of state: EOS-Q
 first-order phase transition
 Bag model B=235MeV^4
 hadronic resonances up to 2GeV
 baryon density dependent
 repulsive potential for baryons



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

Hybrid model for AGS and SPS energies





Dynamical initialization

Switch to hydro evolution
after two nuclei pass each other.

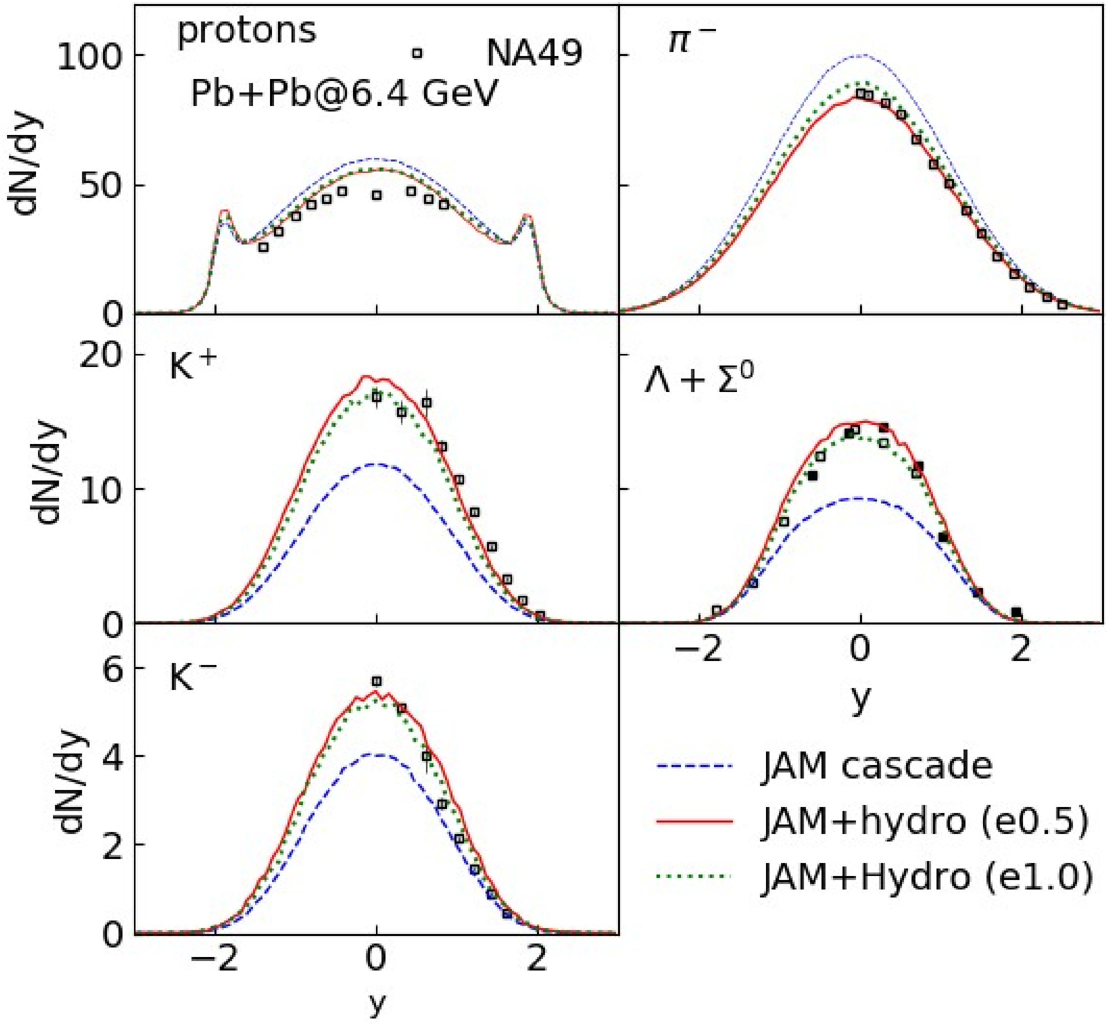
Switch to hadron transport
below a critical energy density.

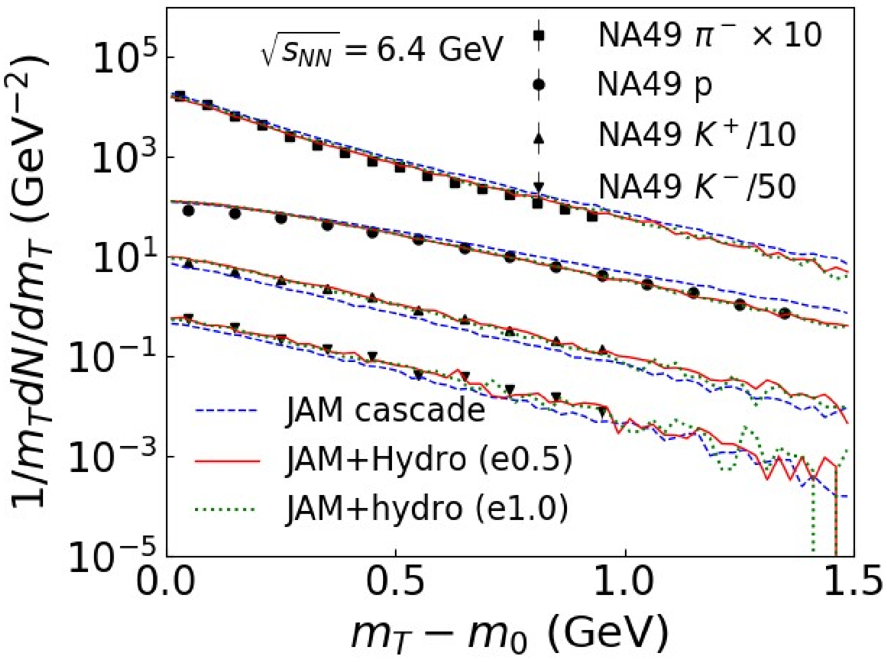
Hadronic EoS is used

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

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

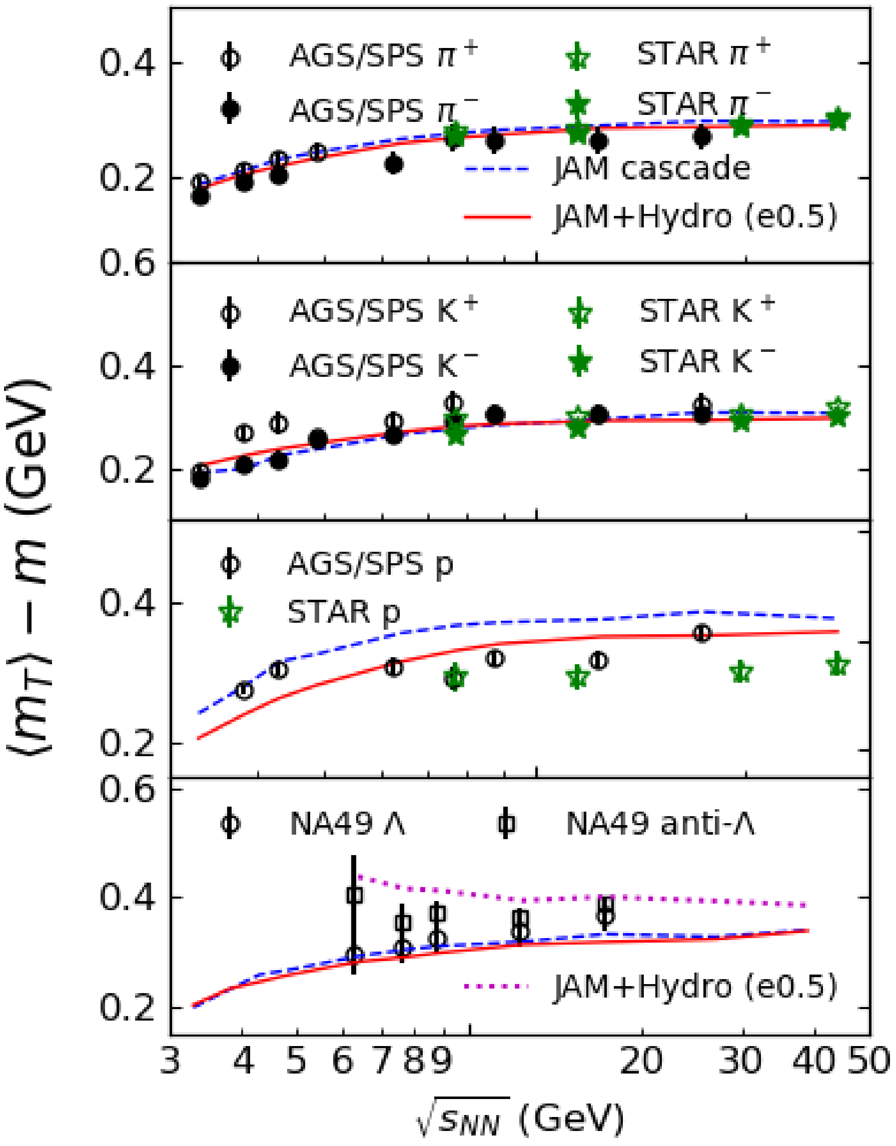
Particle spectra from a new hybrid model in Pb+Pb at Elab=20AGeV

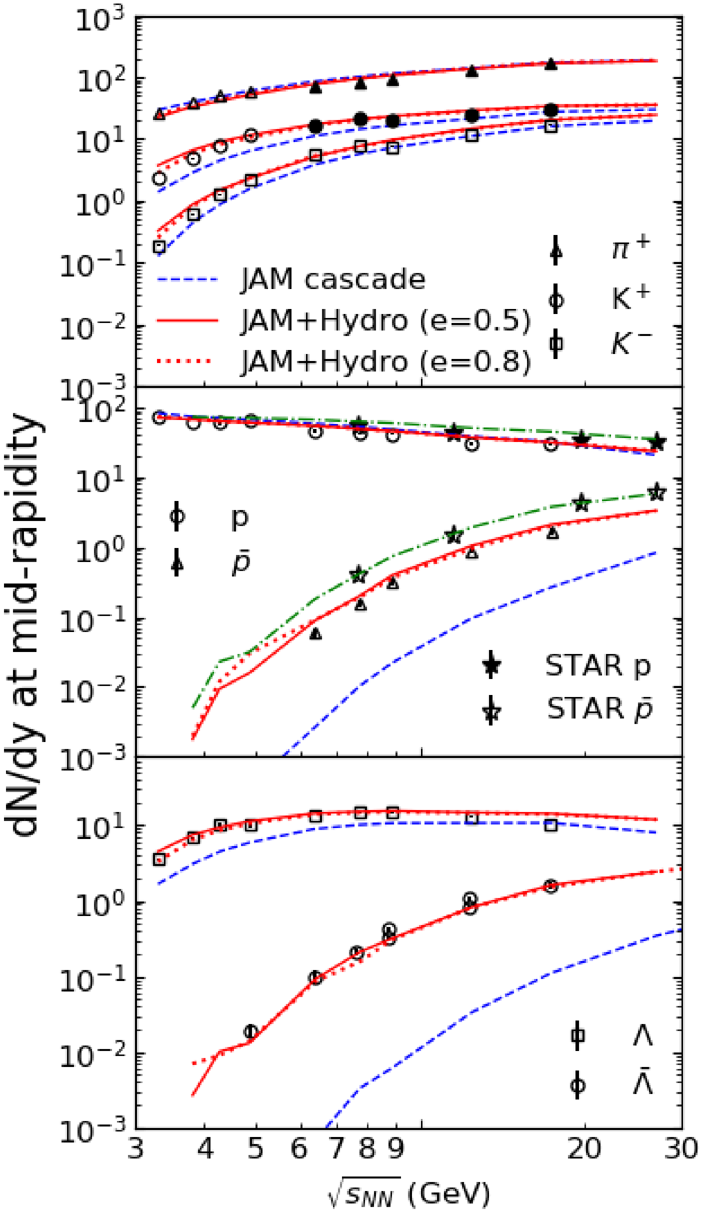




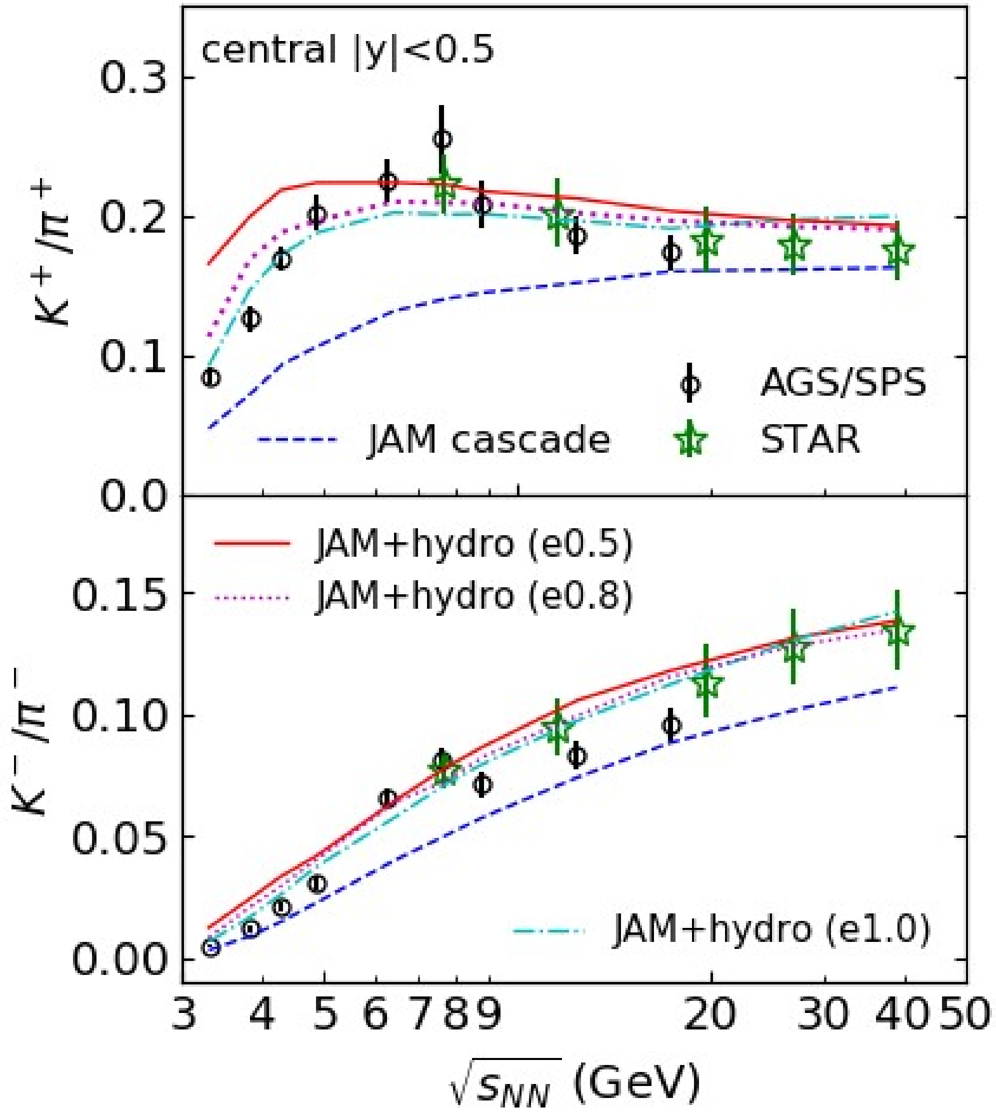
Fluidization energy density 0.5 or 1.0

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



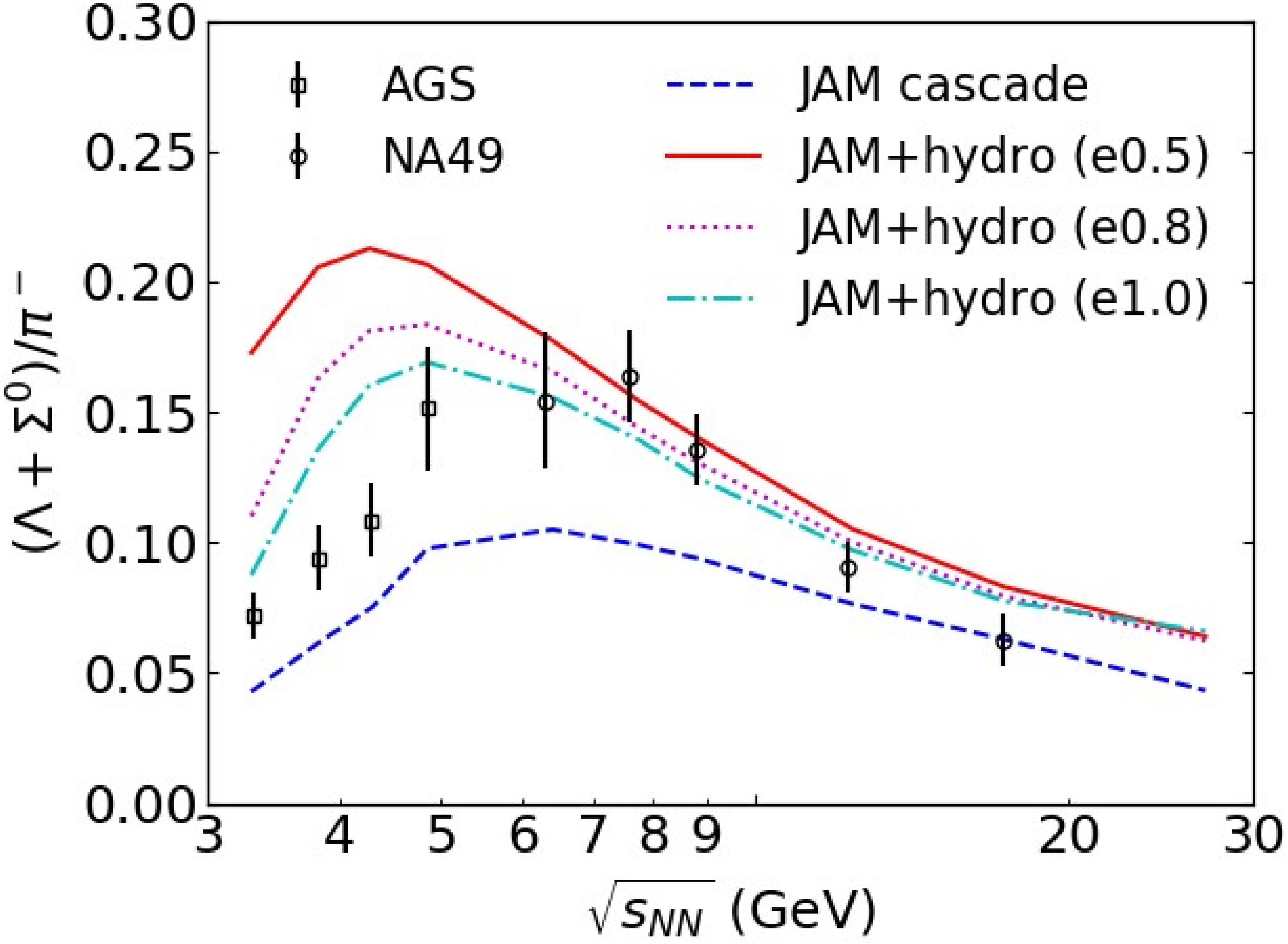


Beam energy dependence of K/pi ratios from hybrid model.



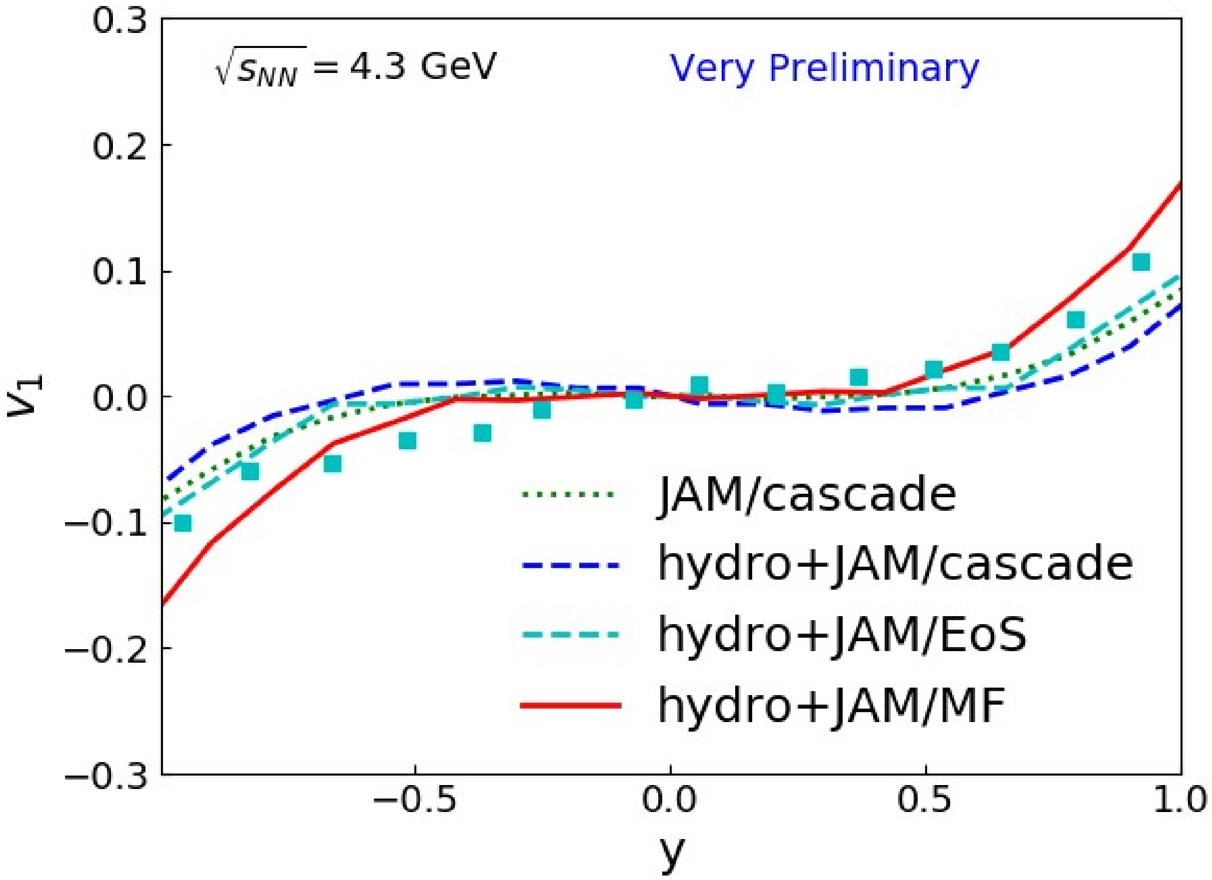
Incomplete thermalization of the sytem
is important for the description of K/pi ratio.

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



Hydro + QMD (JAM/MF) result

Hydro + cascade approach does not reproduce v1 slope at low energies.



Mean-field is very important in the particle phase.

Summary

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

- JAM with the EoS modified scattering style JAM/EoS predicts the same EoS dependence as 1-fluid and 3-fluid model. JAM/EoS model also predicts enhancement of v2 and v4 at FAIR energy.

- 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.