Effects of phase transition on Collective flows from microscopic transport model

Yasushi Nara (Akita International University)

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

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

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

EMMI workshop at CCNU, Wuhan Oct. 10-14 2017

Outline

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

- Introduction: beam energy dependence of v1 and v2
- Non-equilibrium transport model JAM with EoS effect
- Results on v0, v1 and v2 at high baryon density region

  first-order phase transition:
  v0: harder, v1: negative v2: larger

- Summary

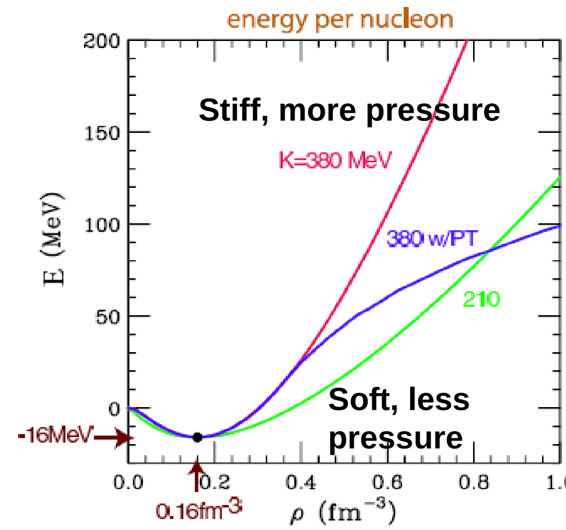
Determination of EOS at high density from an anisotropic flow in heavy ion collisions

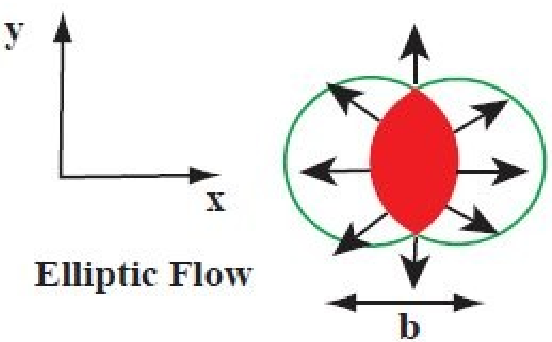
Fourier decomposition of single particle inclusive spectra:

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

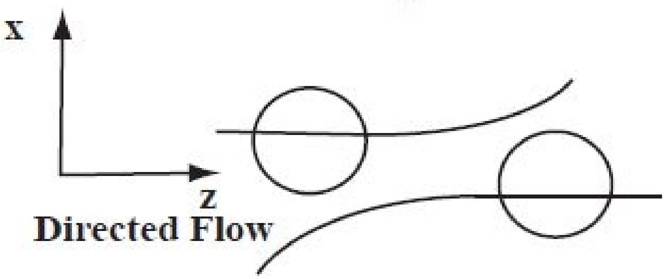
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \quad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

$$F = \left.\frac{dv_1}{dy}\right|_{y=0}$$



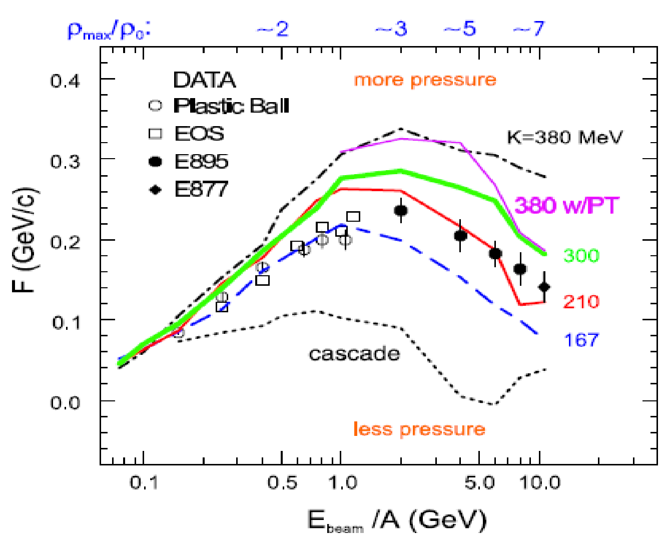


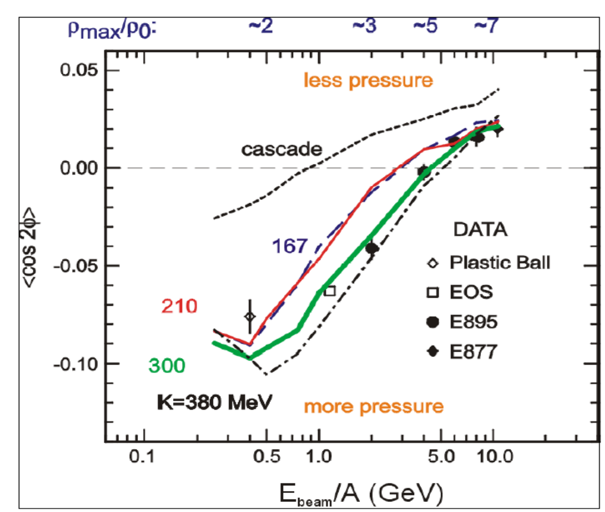
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



$$F = \left.\frac{\langle p_x/A\rangle}{d(y/y_{cm})}\right|_{y/y_{cm}=1}$$

In-plane flow, v1





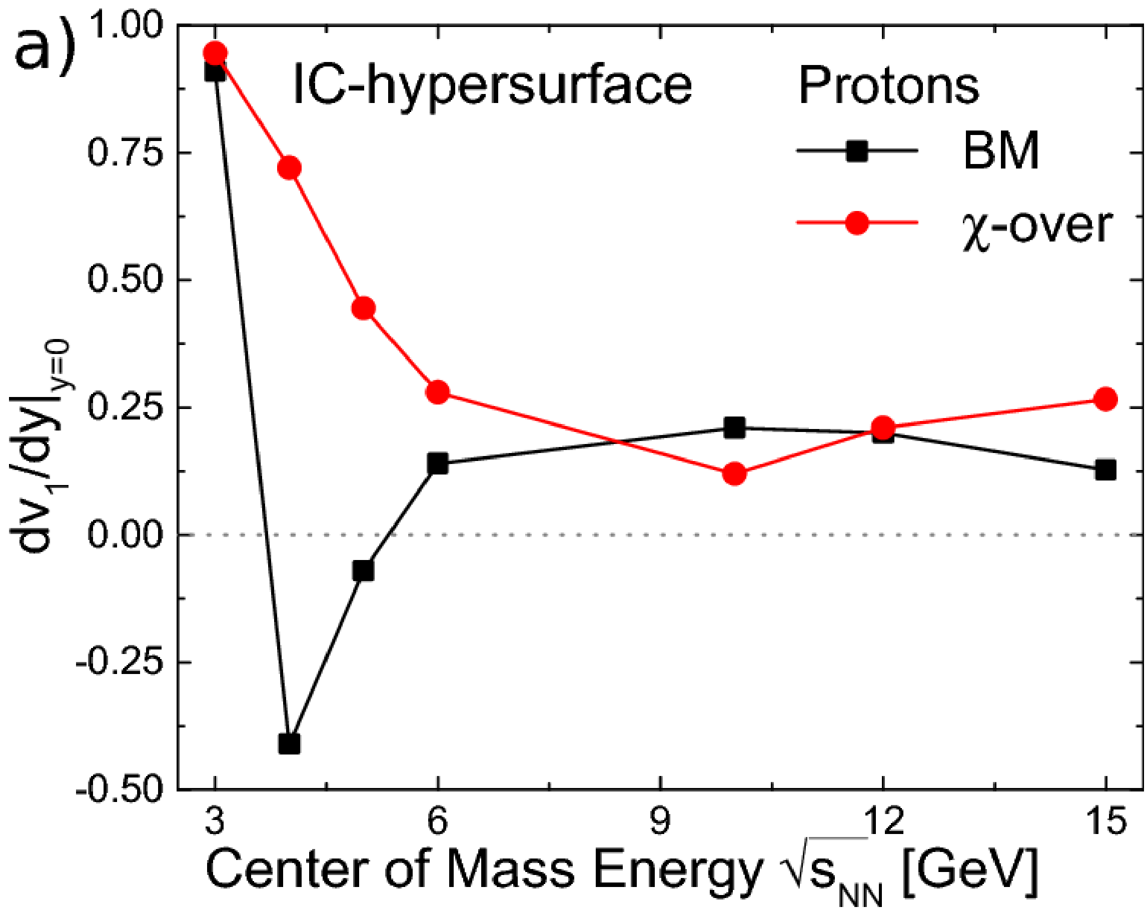
A minimum in the excitation function of the directed flow

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

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

The effect of the softening of the EoS

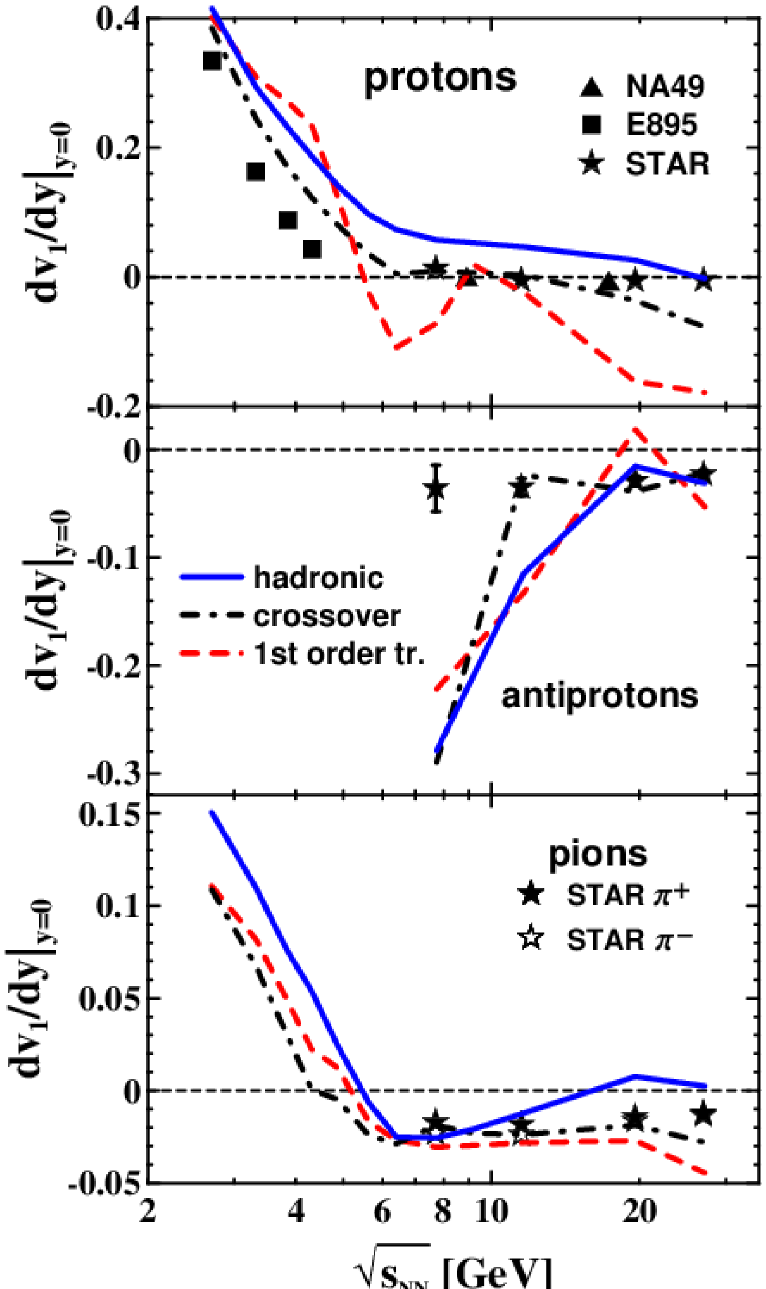
J.Steinheimer,et.al.Phys.Rev.C89(2014)



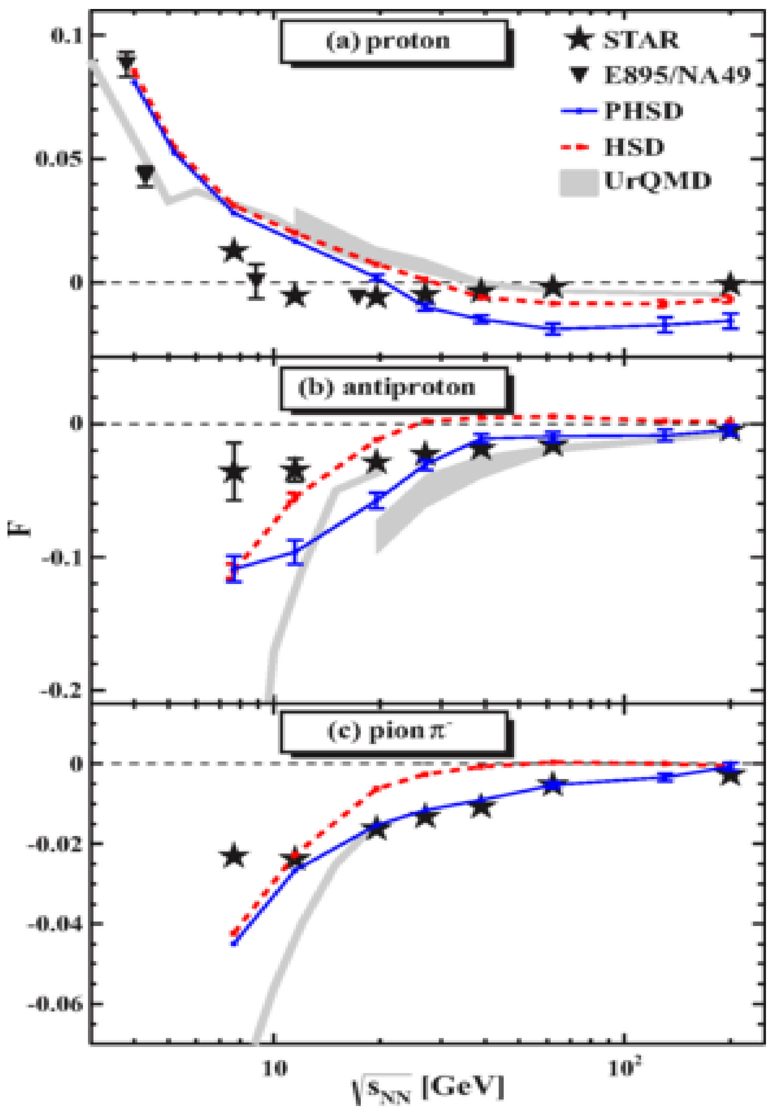
Minimum in the excitation function of v1 is seen only in first-order phase transition in one fluid simulation.

V1 from hydrodynamics and PHSD

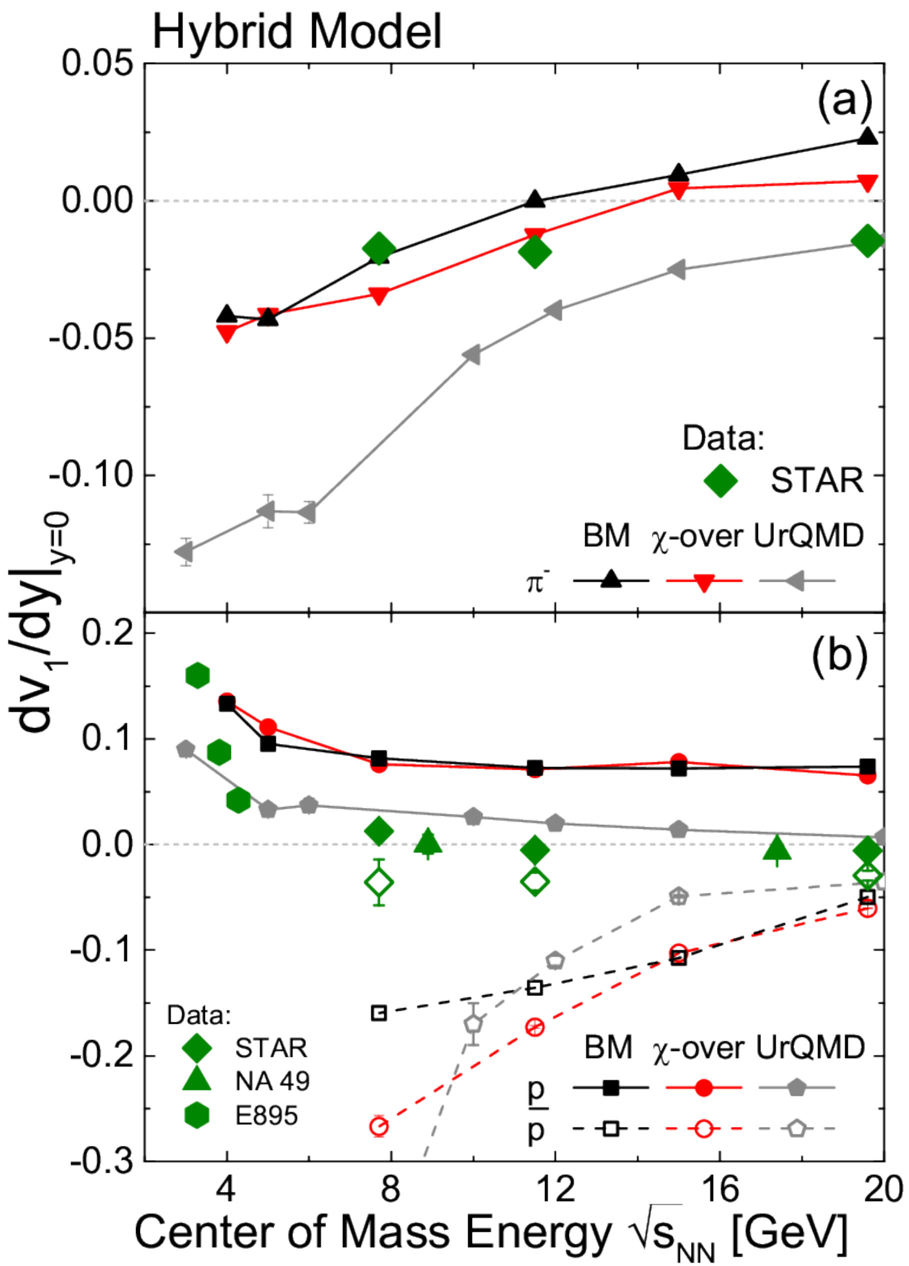
Y. B. Ivanov, A.A.Soldatov,
Phys. Rev. C91, no. 2, 024915 (2015)



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



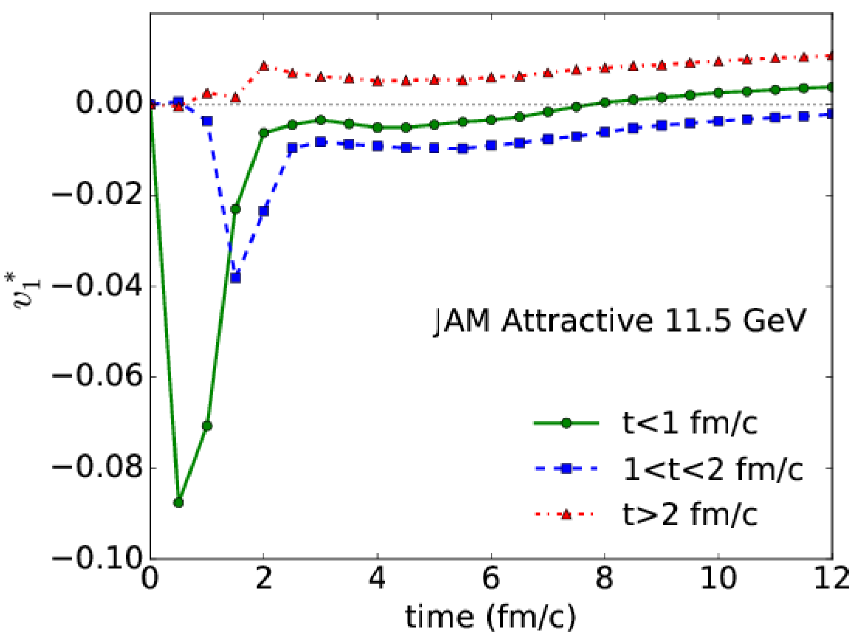
UrQMD + hydro predictions



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

No minimum! Switching time too late?

JAM+soft EoS supports this conjecture.



QGP signal: formation of tilted ellipsoid

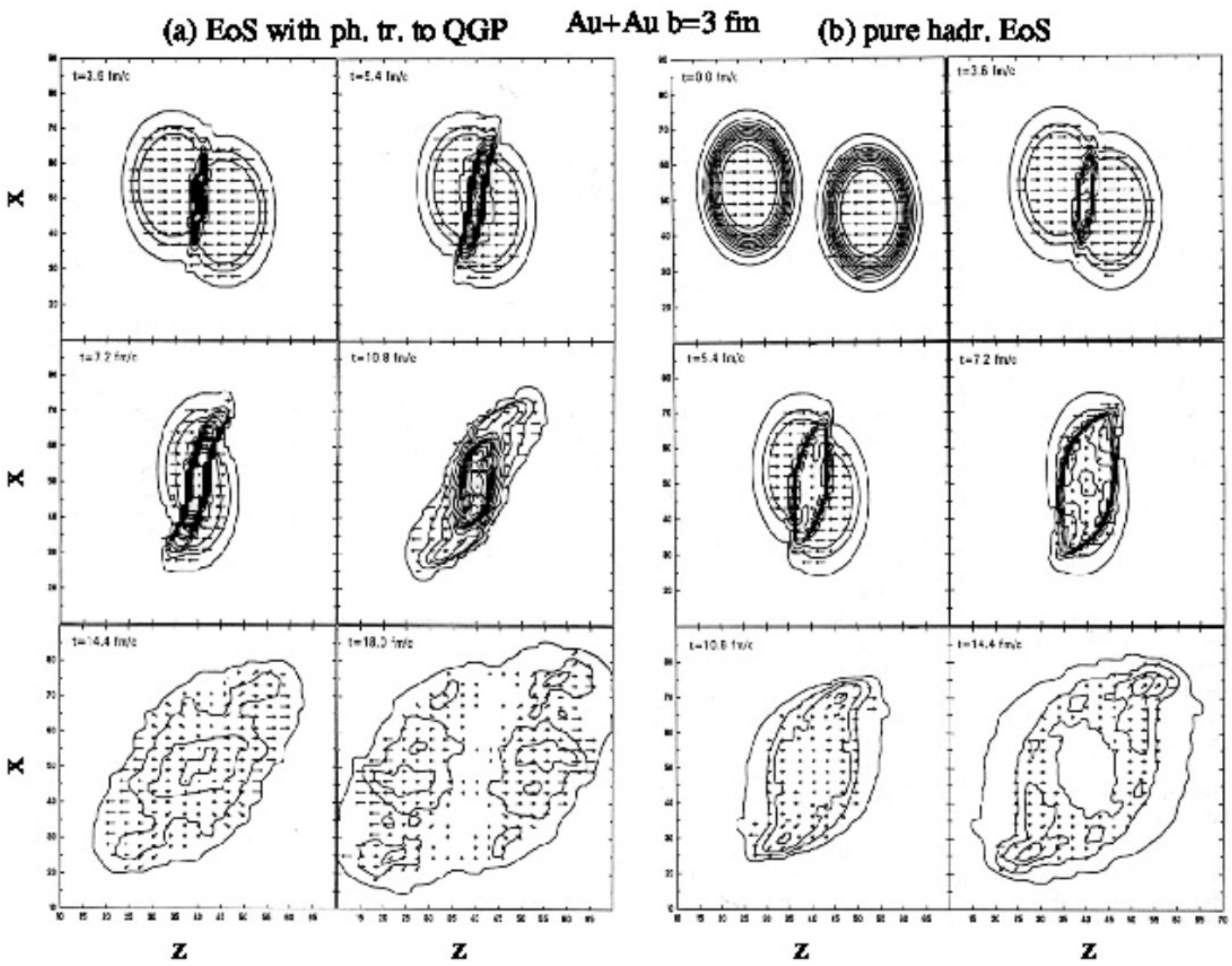
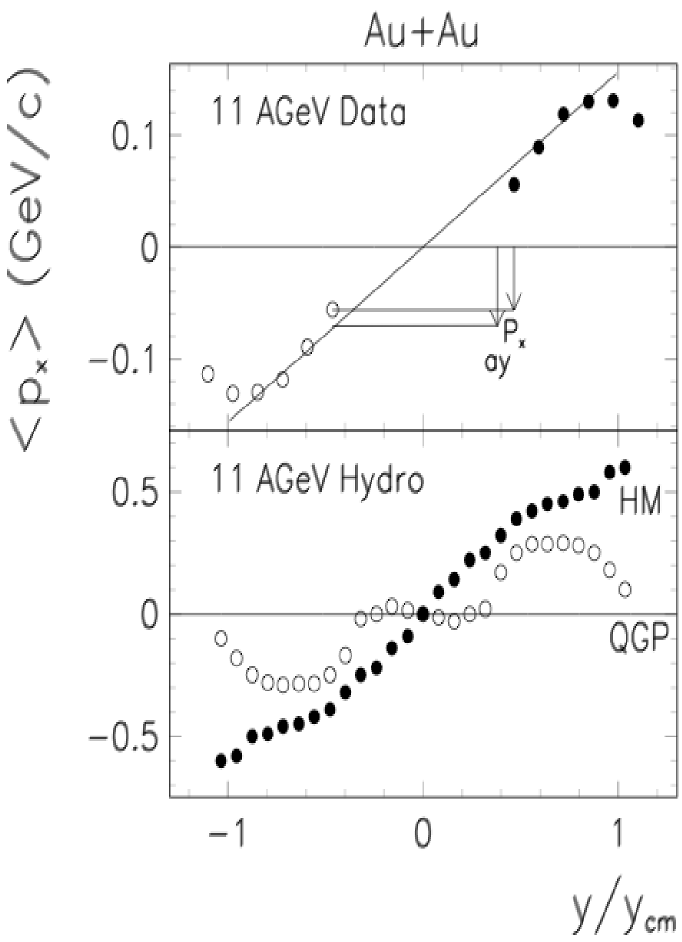


Fig. 5

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

QGP EoS predicts wiggle in hydro

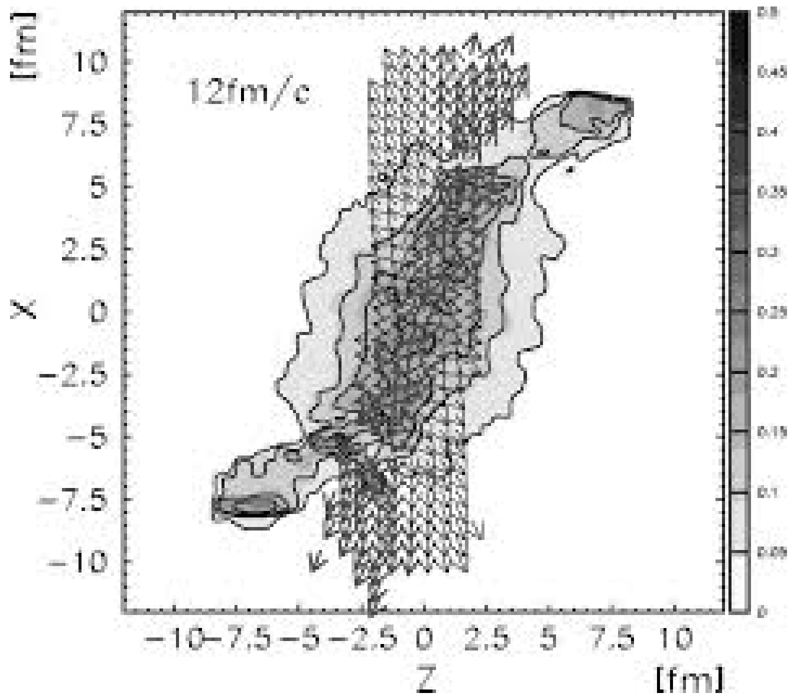
Wiggle: QGP signal in the directed flow?



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

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

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



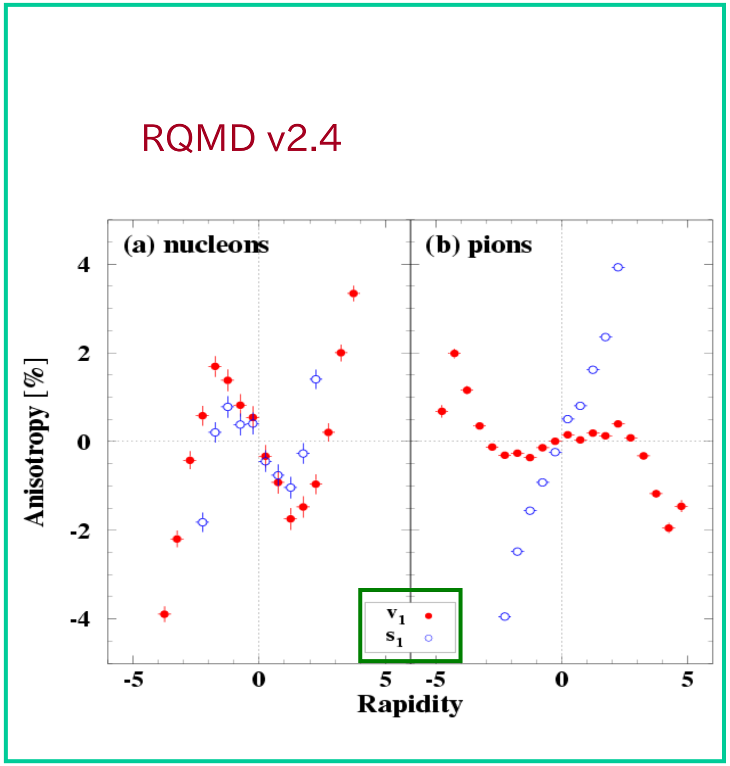
$$p_x \sim \int pA_\perp dt$$

QGP EoS predicts wiggle in hydro

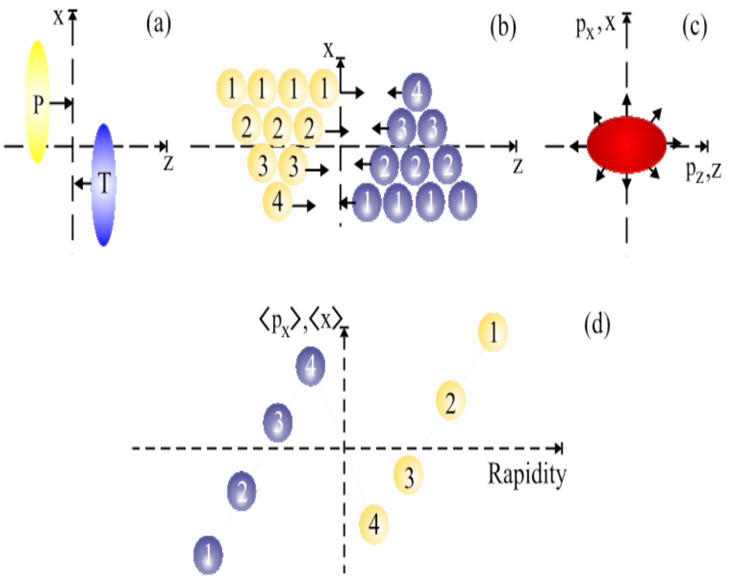
Baryon stopping + Positive space-momentum correlation leads wiggle (no QGP)

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

Wiggle: QGP signal in the directed flow?



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

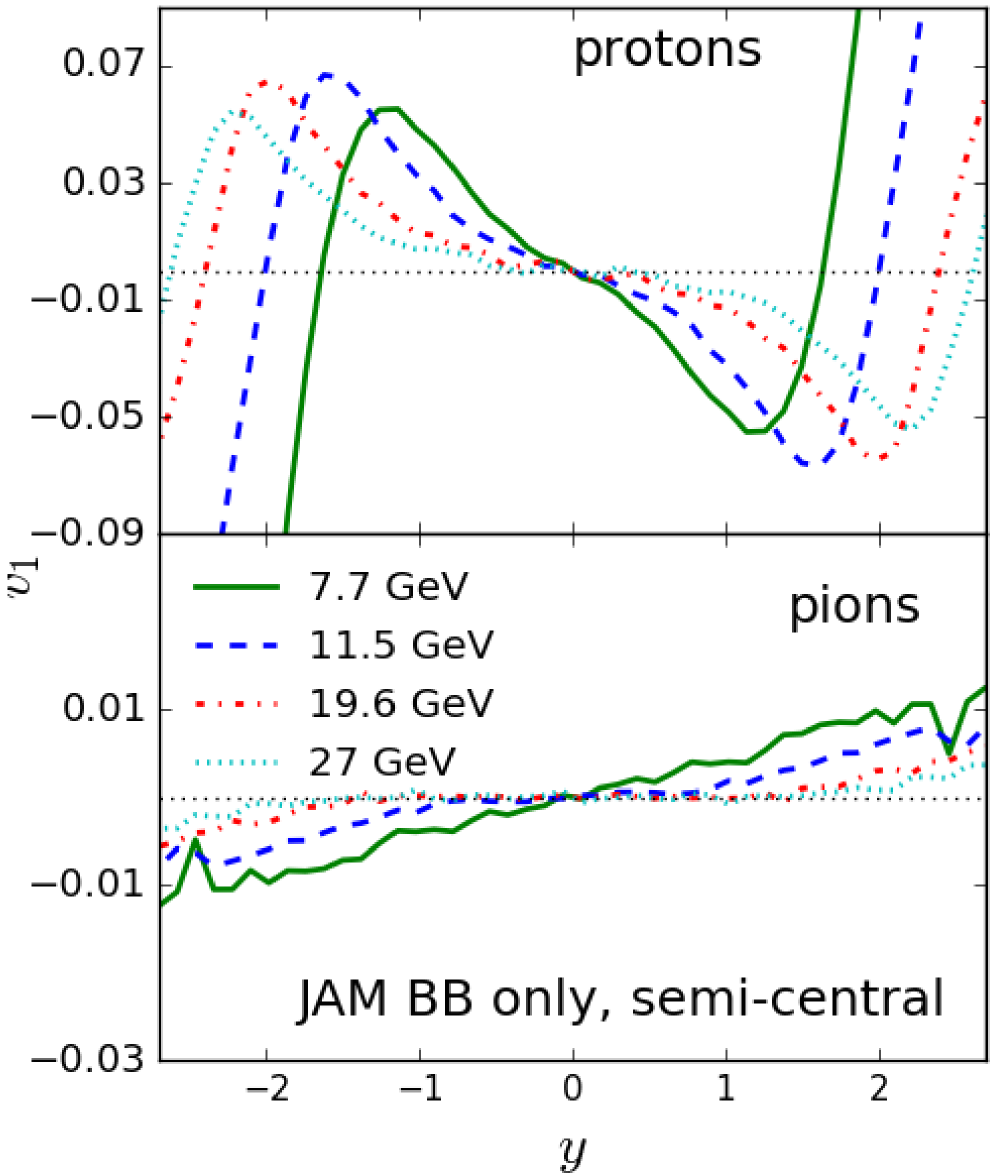


R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

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

This picture is only applicable at Ecm > 30 GeV

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



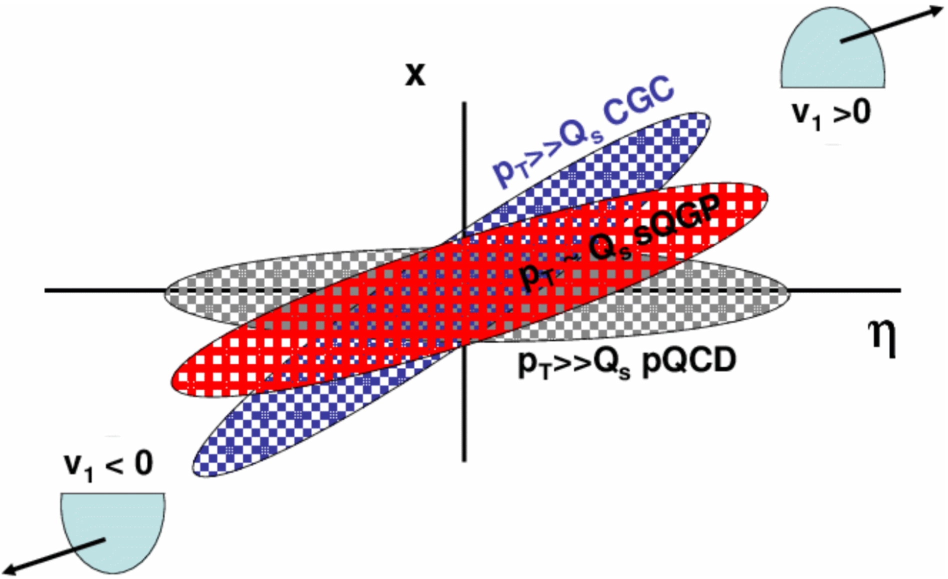
Note that initial Galuber collision only cannot reproduce space-momentum correlation.

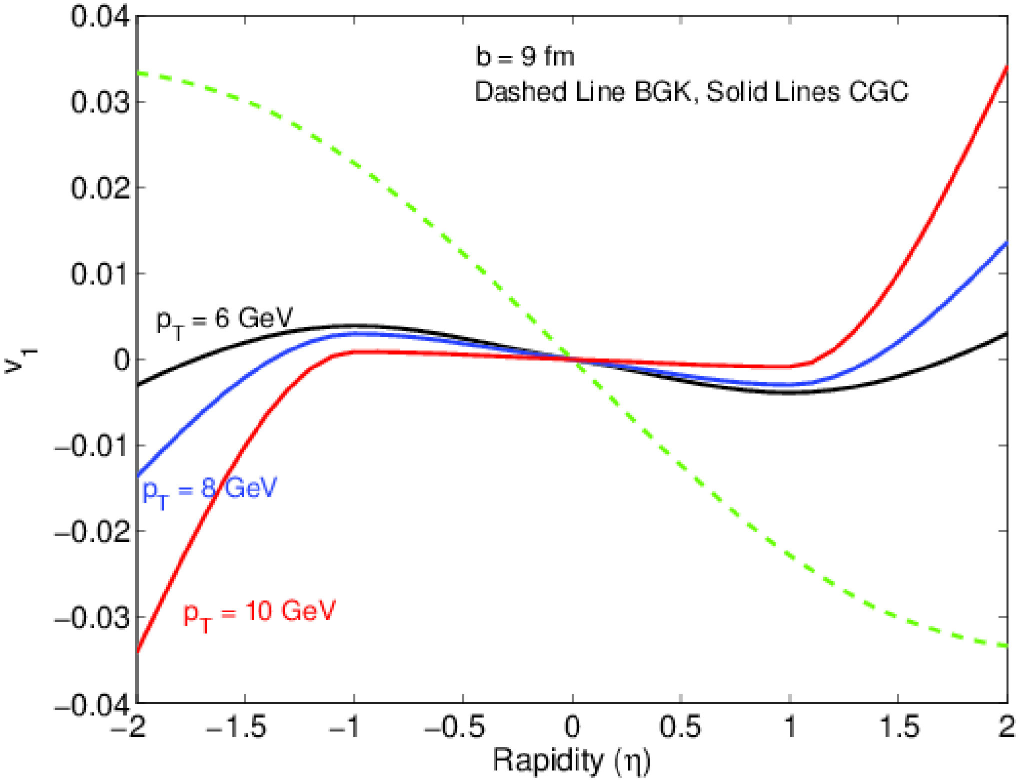
Meson-baryon scattering →

Proton v1 becomes positive,
pion v1 becomes negative.

Twisted initial condition from CGC

A. Adil, M. Gyulassy, T.Hirano, Phys. Rev. D73, 054902(2006)





JAM microscopic transport model

- Follow spece-time propagation of particles based on cascade method
- Resonance and string excitation and decays
- Rescattering among all hadrons

RQMD based on Constraint Hamiltonian Dynamcis

Sorge, Stoecker, Greiner, Ann. Phys. 192 (1989), 266.

RQMD/S: Tomoyuki Maruyama, et al. Prog. Theor. Phys. 96(1996),263.

Single particle energy:

$$p_i^0 = \sqrt{\boldsymbol{p}_i^2 + m_i^2 + 2m_i V_i}$$

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

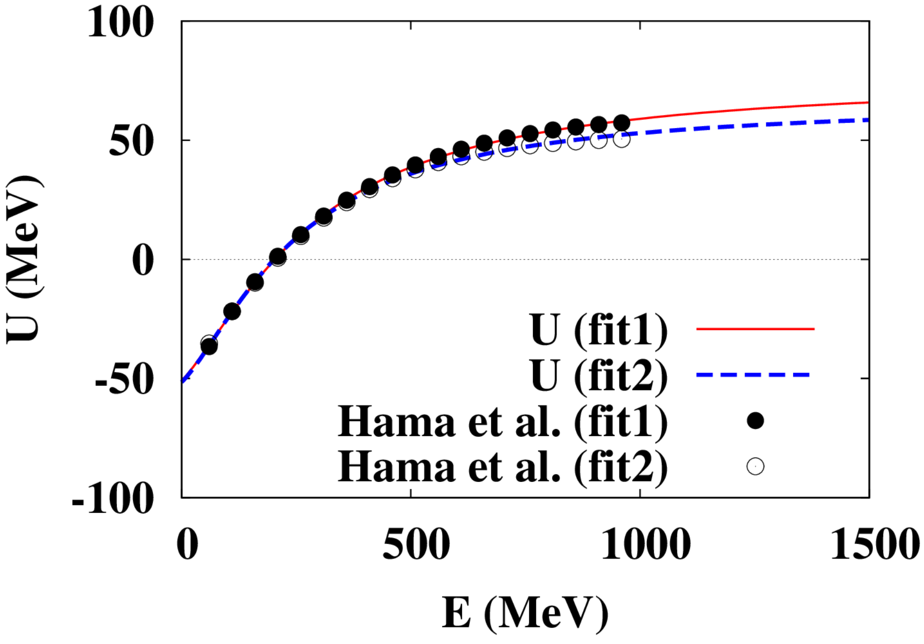
Arguments of potential $\boldsymbol{r}_i - \boldsymbol{r}_j$ and $\boldsymbol{p}_i - \boldsymbol{p}_j$ are replaced by the distances in the two-body c.m.

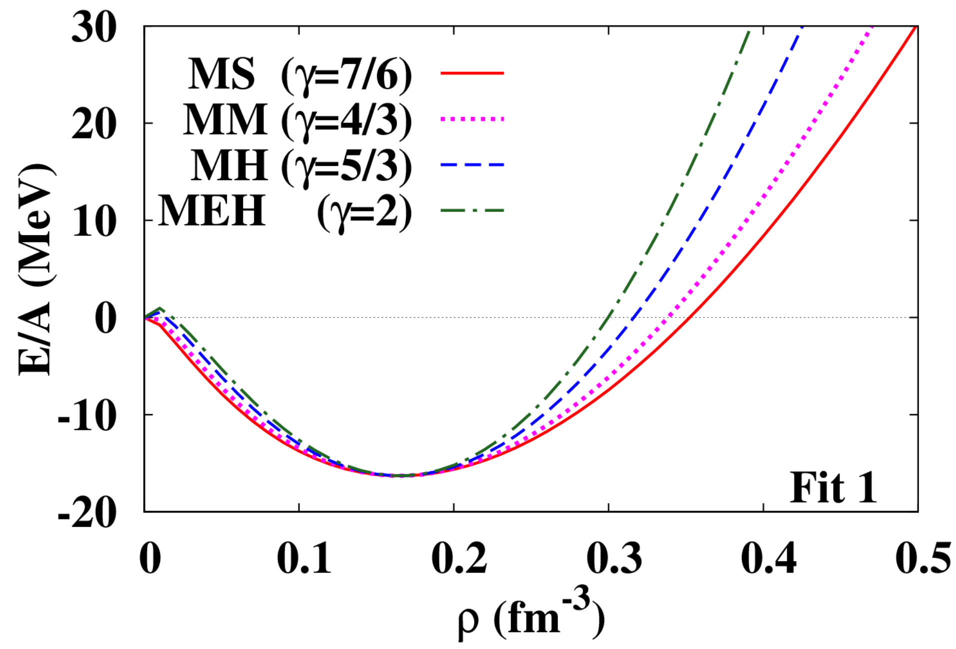
Mean field potential

Skyrme type density dependent + Lorentzian momentum dependent potential

$$V = \sum_i V_i = \int d^3r \left[\frac{\alpha}{2} \left(\frac{\rho}{\rho_0} \right)^2 + \frac{\beta}{\gamma+1} \left(\frac{\rho}{\rho_0} \right)^{\gamma+1} \right] + \sum_k \int d^3\boldsymbol{r} d^3\boldsymbol{p} d^3\boldsymbol{p}' \frac{C_{ex}^{(k)}}{2\rho_0} \frac{f(\boldsymbol{r},\boldsymbol{p}) f(\boldsymbol{r},\boldsymbol{p}')}{1 + (\boldsymbol{p}-\boldsymbol{p}')^2/\mu_k^2}$$

Type	α (MeV)	β (MeV)	γ	$C_{\rm ex}^{(1)}$ (MeV)	$C_{\rm ex}^{(2)}$ (MeV)	μ_1 ($\rm fm^{-1}$)	μ_2 ($\rm fm^{-1}$)	K (MeV)
MH1	-12.25	87.40	5/3	-383.14	337.41	2.02	1.0	371.92
MS1	-208.89	284.04	7/6	-383.14	337.41	2.02	1.0	272.6





Pressure in the collision term

Virial Theorem

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

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

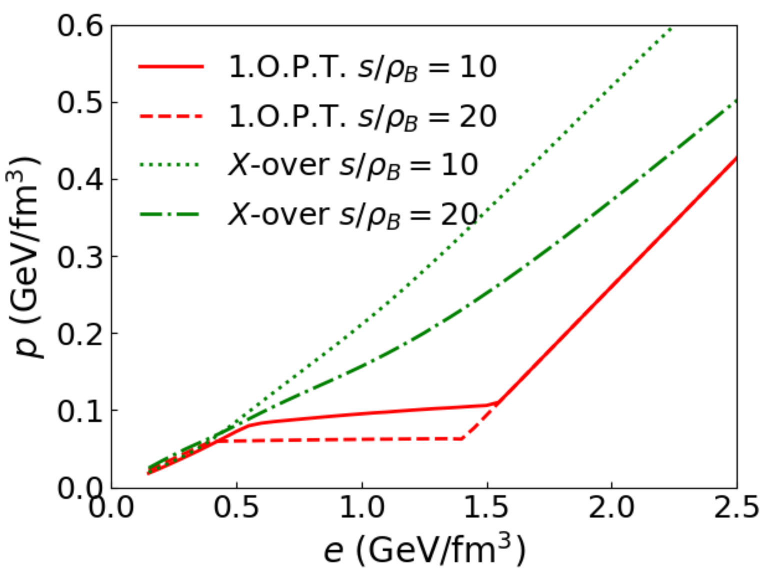
H. Sorge, Phys. Rev.Lett. 82,2048 (1999)

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

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.



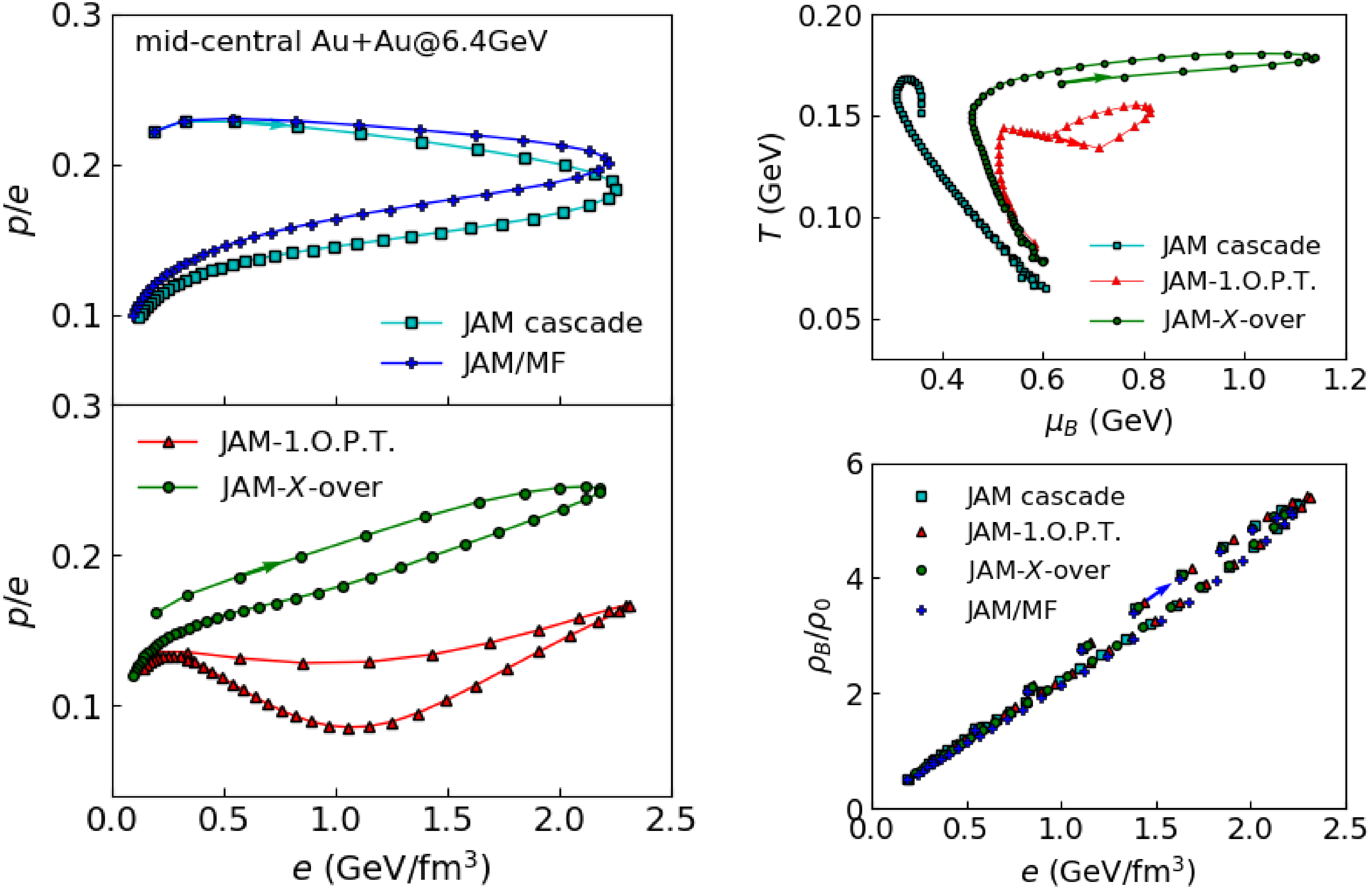
Fully baryon density dependent EoSs are implemented.

Cross-over EOS: J. Steinheimer

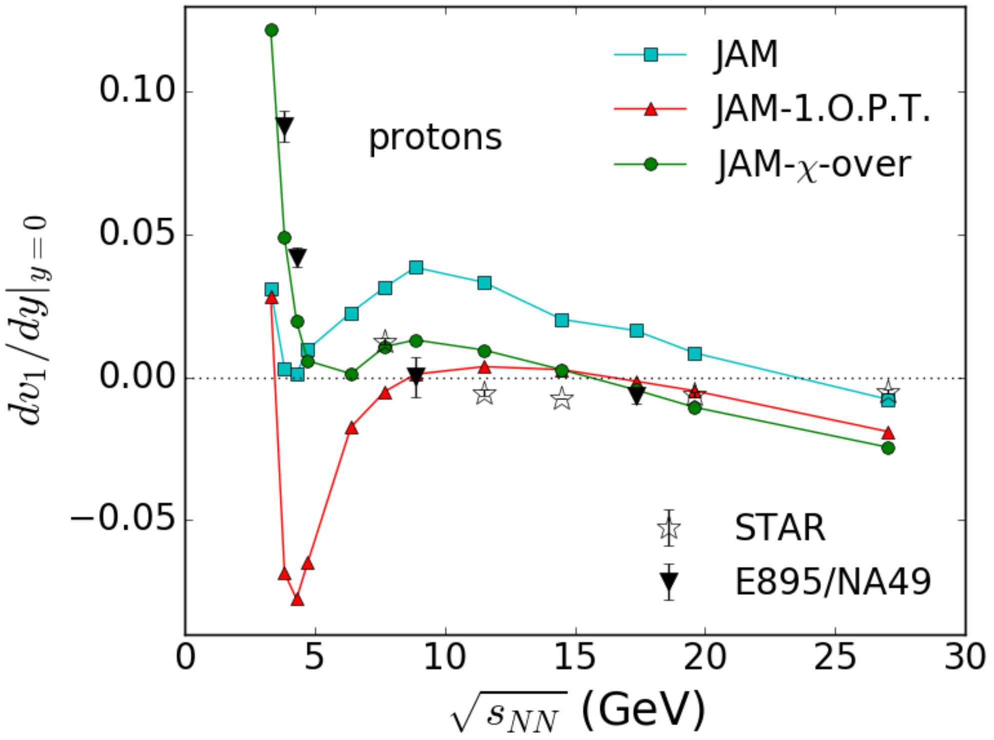
EOS-Q: Kolb, Sollfrank, Heinz

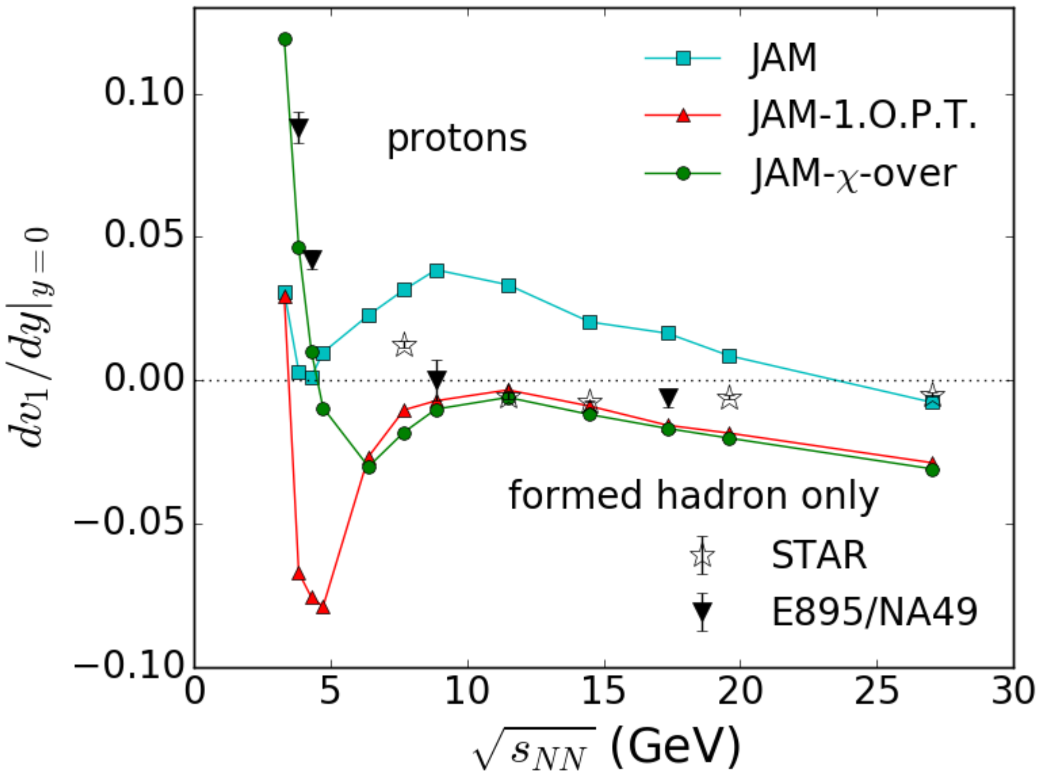
- Any EoS can be incorporated
- CPU time is as fast as standard cascade simulation

EoS dependence at 6.4 GeV

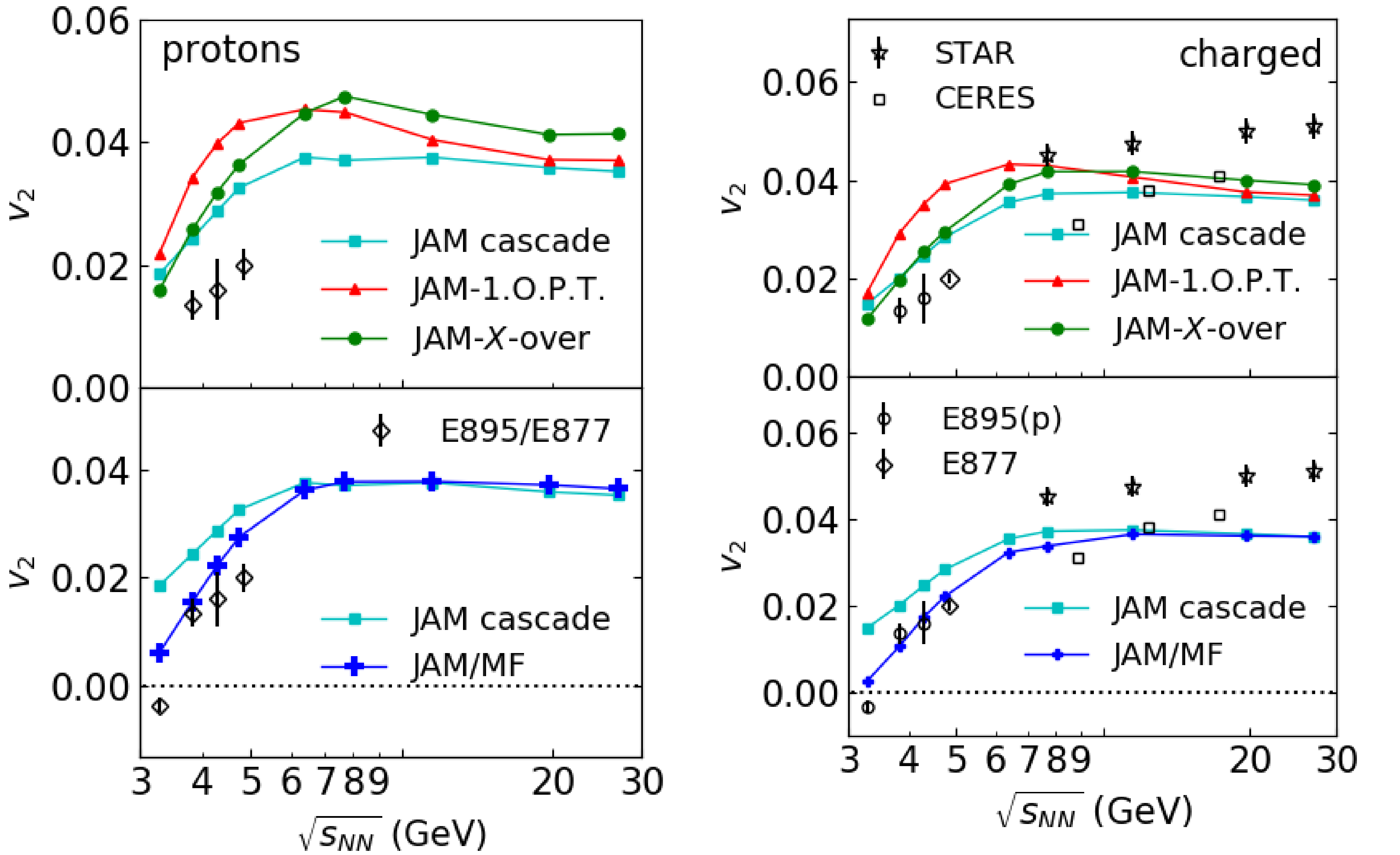


V1 excitation functions

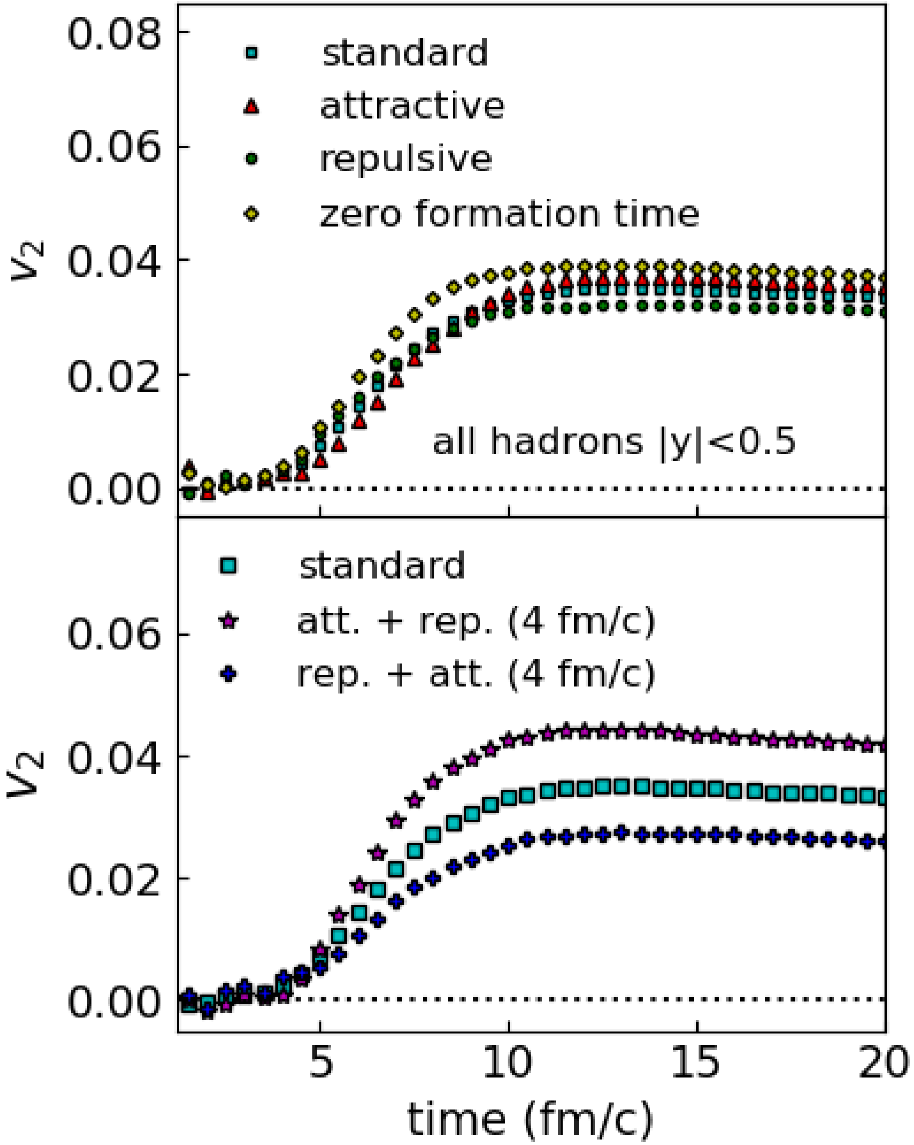




V2 excitation functions



Time evolution of v2



Squeeze-out

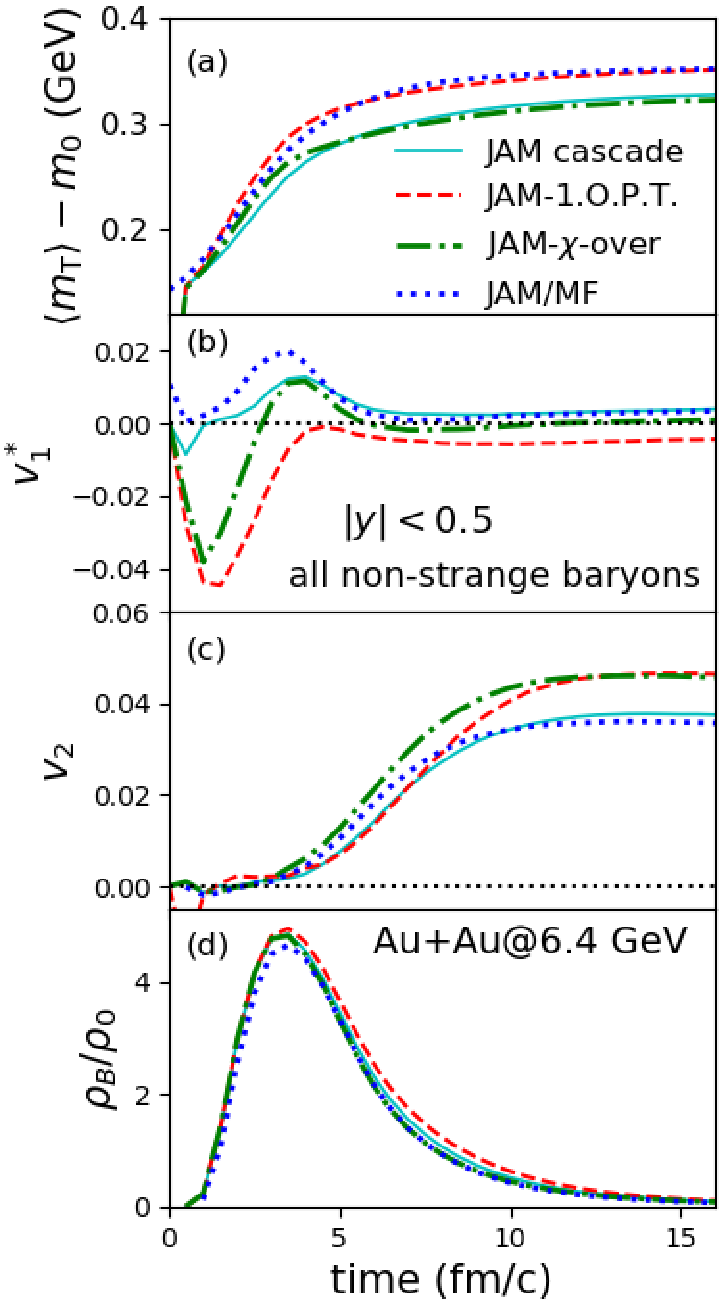
$t < t_{\mathrm{pass}}$: v_2 is small for hard EoS

$t > t_{\mathrm{pass}}$: 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

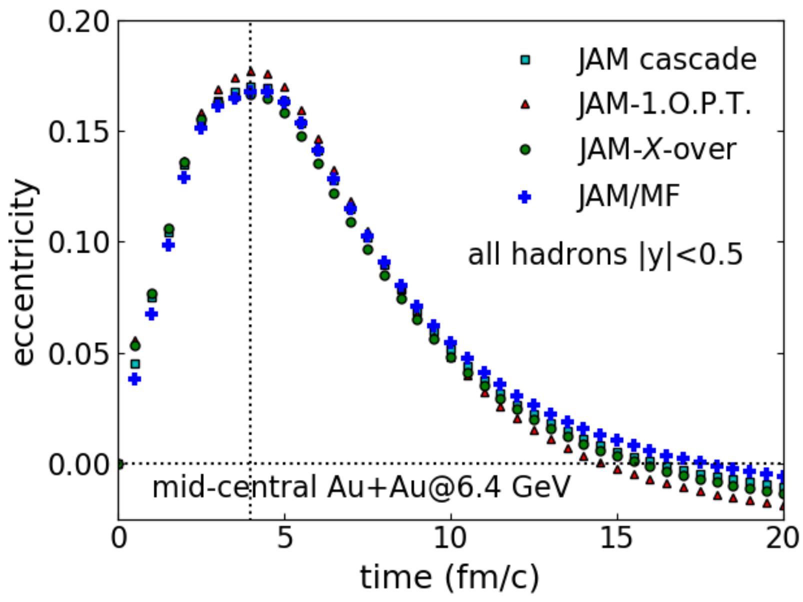
Time evolution of v0, v1, v2



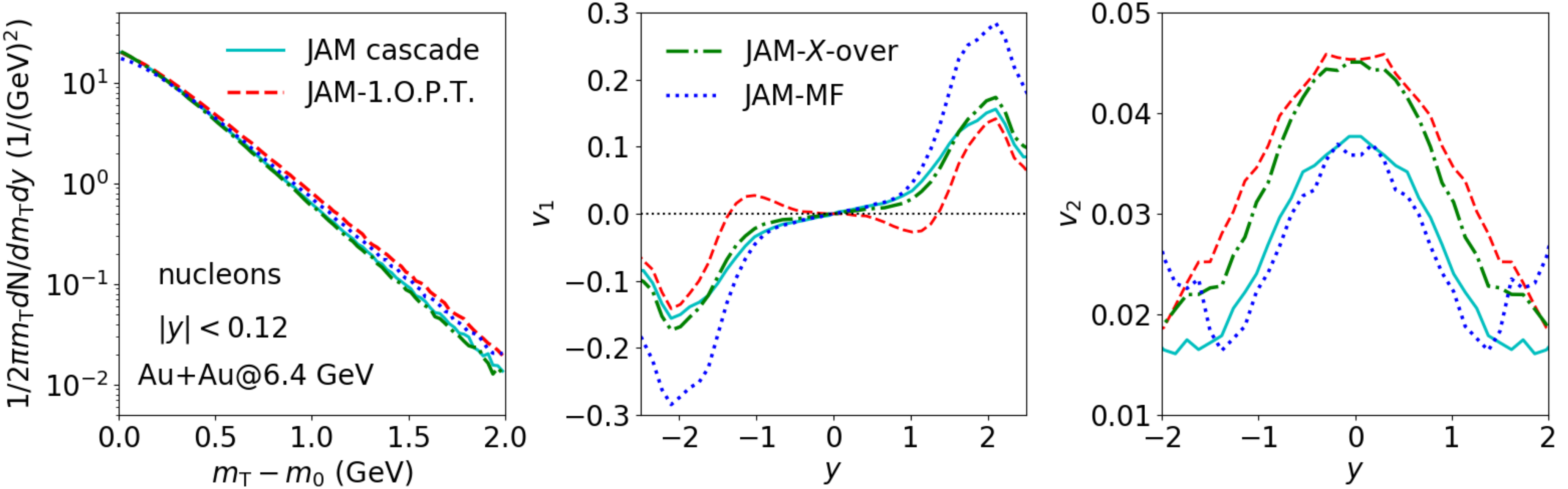
V0 is enhanced by both 1.O.P.T and mean-field

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



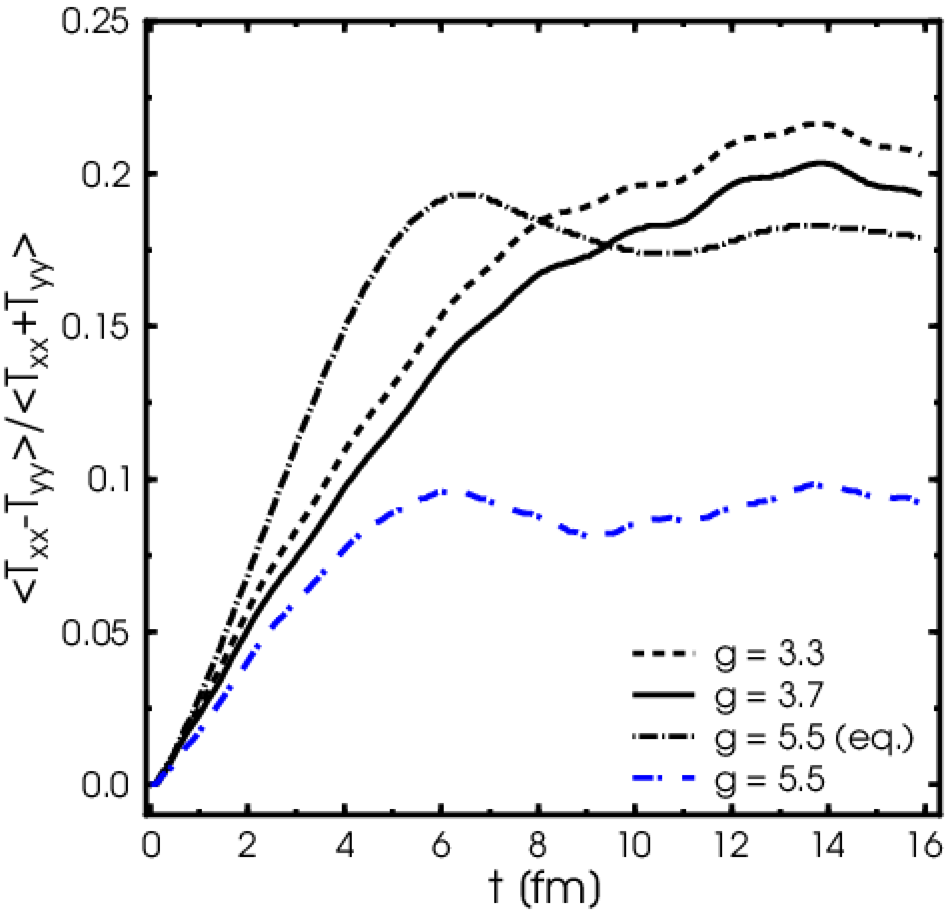
	Mt	v1	v2
Cascade			
Hadronic mean-field	enhanced	positive	reduced
First-order P.T.	enhanced	negative	enhanced
Crossover	same	positive	enhanced

analysis should be very useful.

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

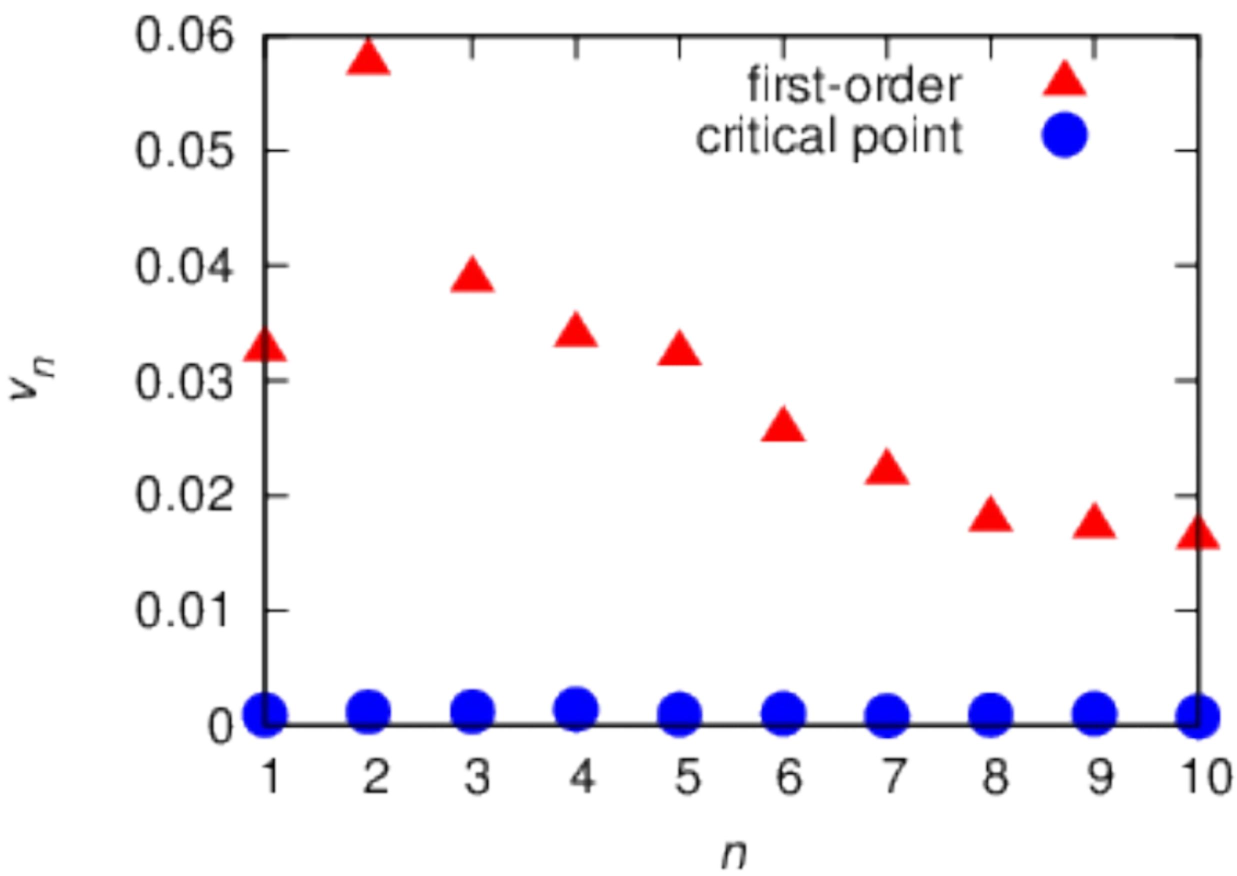


G=3.3 cross over
G=3.7 2nd P.T.
G=5.5 1st P.T.

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.

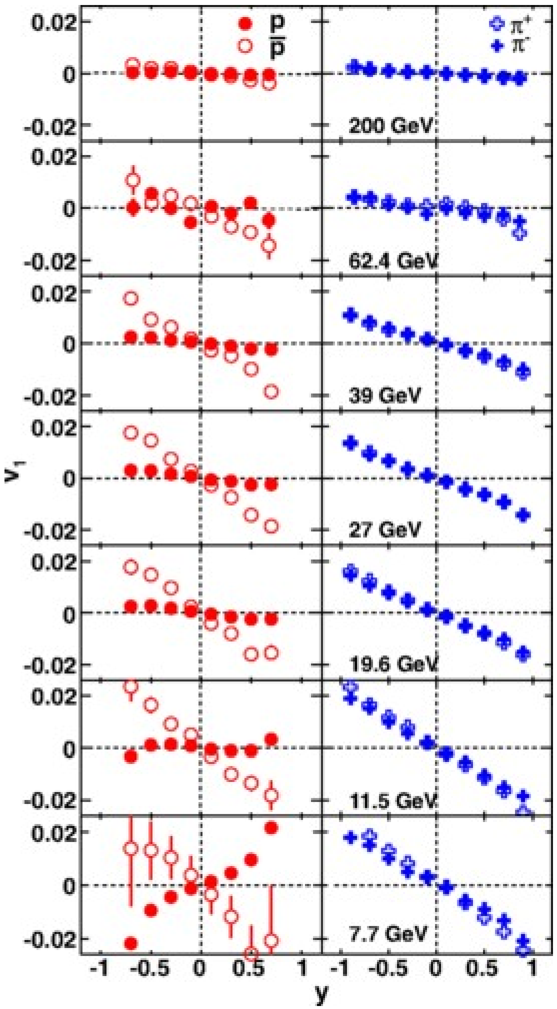
- This model predicts an enhancement of elliptic flow at high baryon density region (AGS-SPS region) due to softening of EoS.

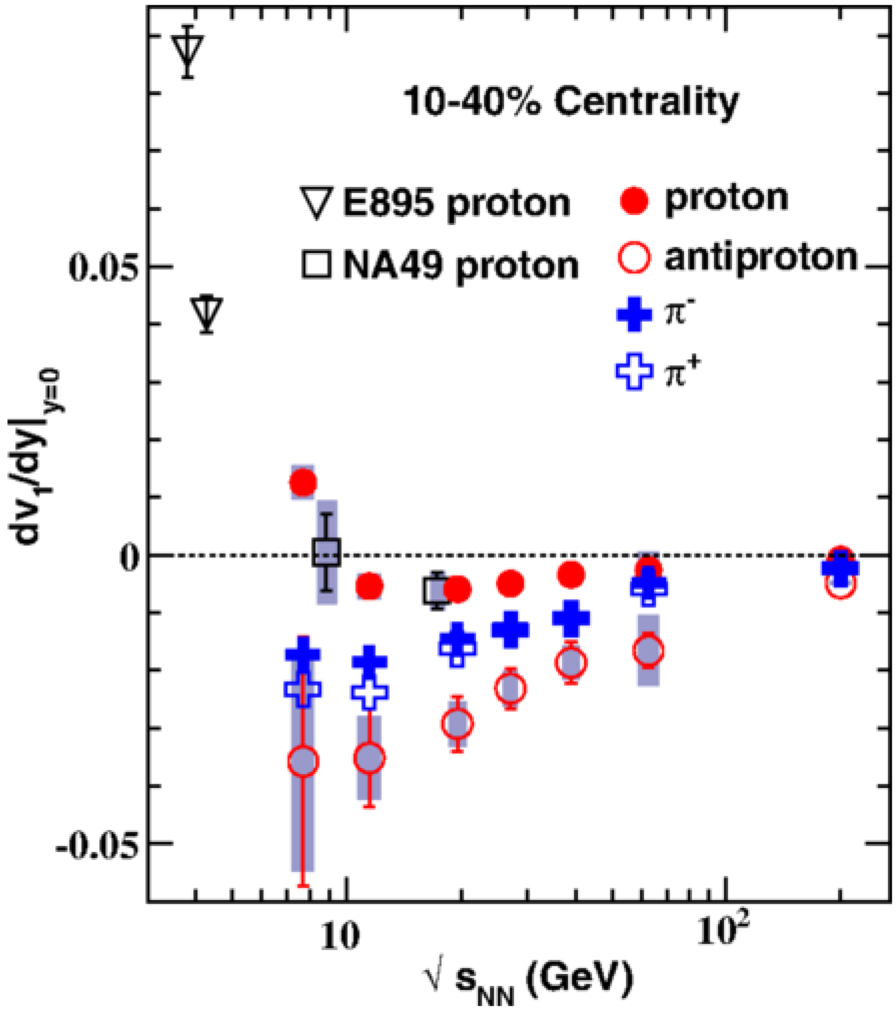
- Combined analysis of collective flows v0,v1, v2 at high baryon region
  e.g. at 5 GeV < Ecm < 7.7 GeV will provide important inoformation on the EoS.

★ Study of non-equilibrium chiral dynamics

Beam energy dependence of v1

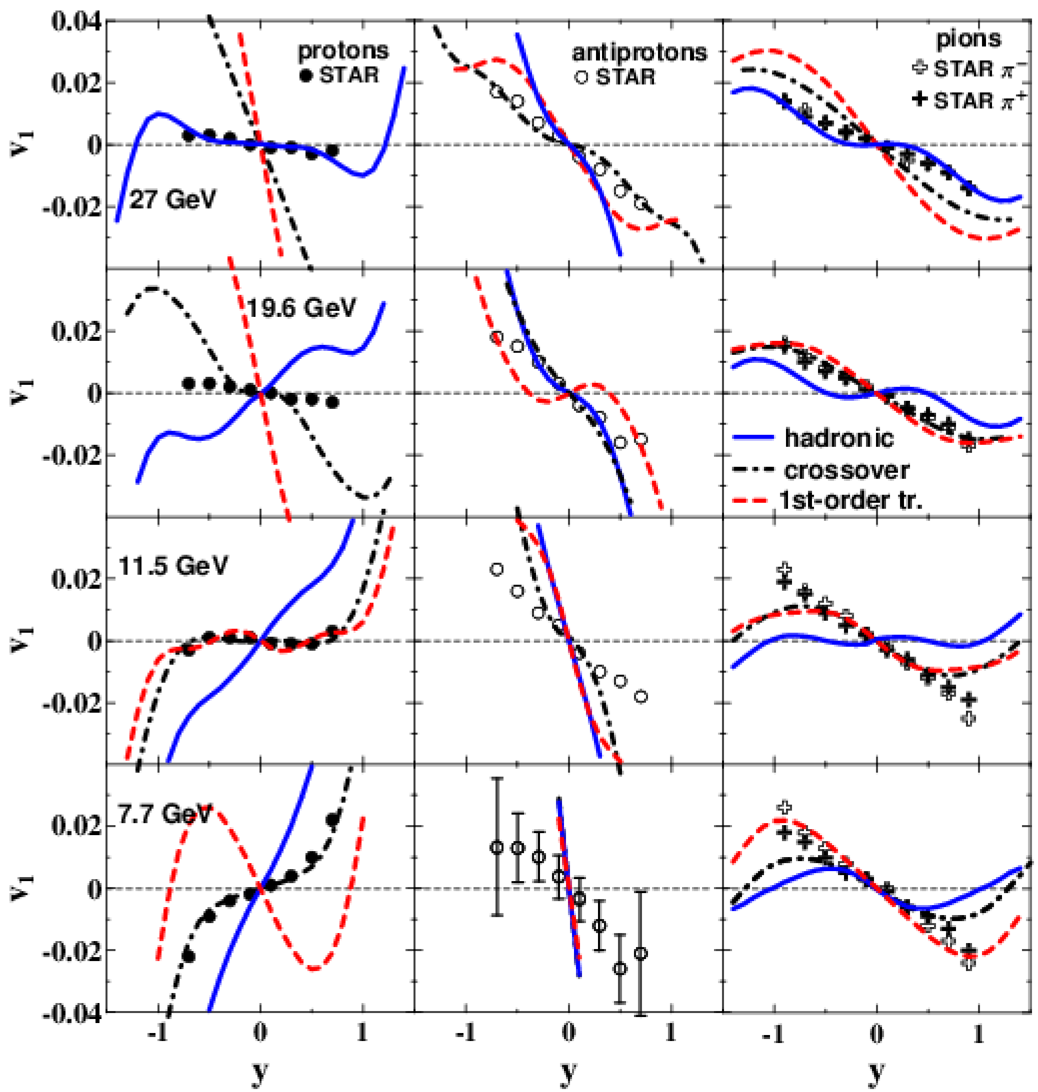
L. Adamczyk et al. (STAR Collaboration)
Phys. Rev. Lett. 112, 162301 – Published 23 April 2014





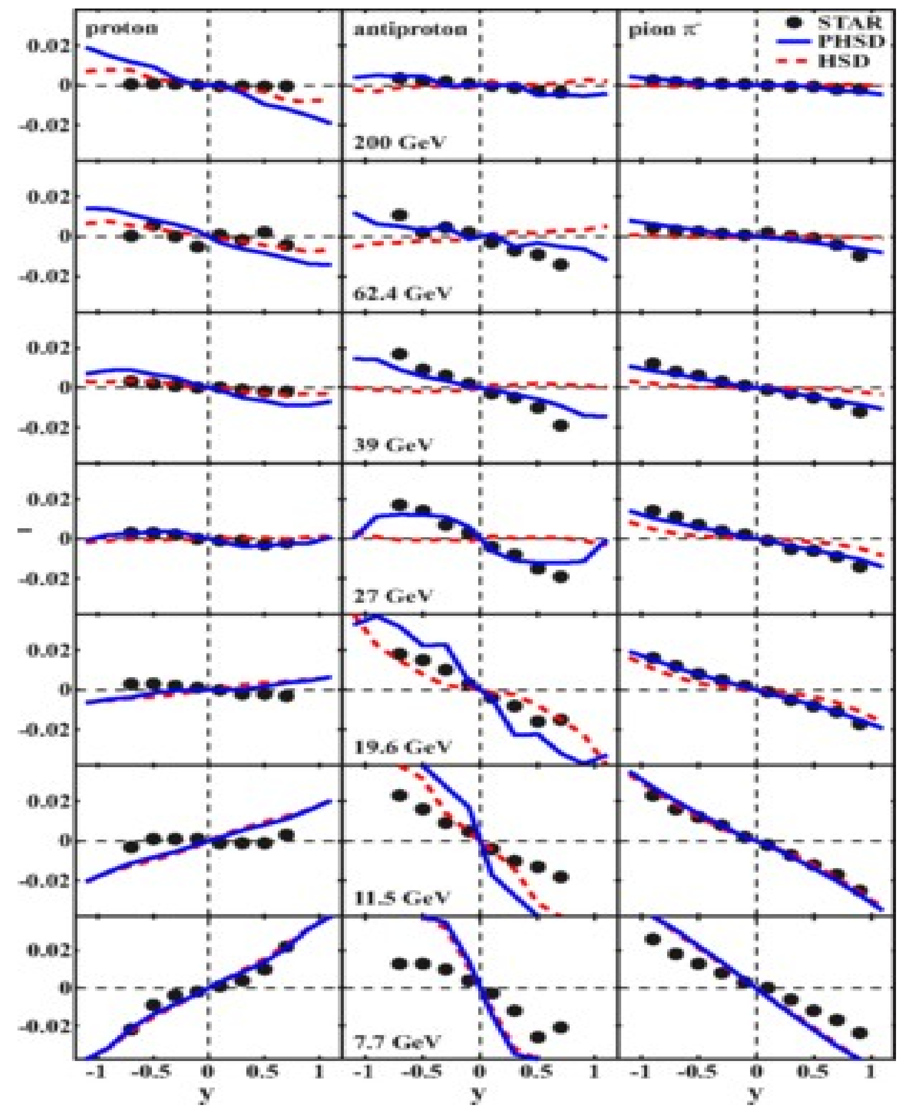
V1 from hydrodynamics

Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C91, no. 2, 024915 (2015)



PHSD/HSD predictions

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



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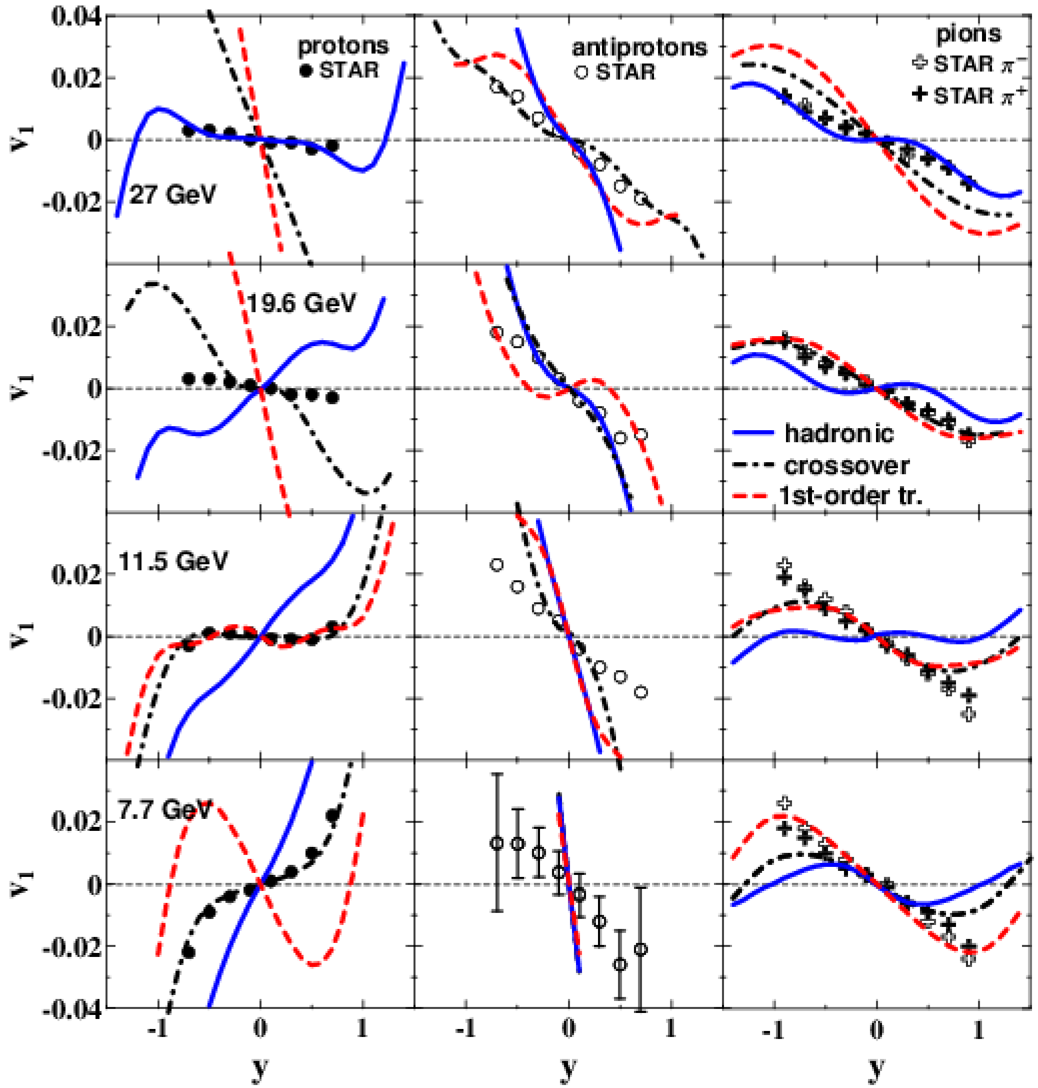
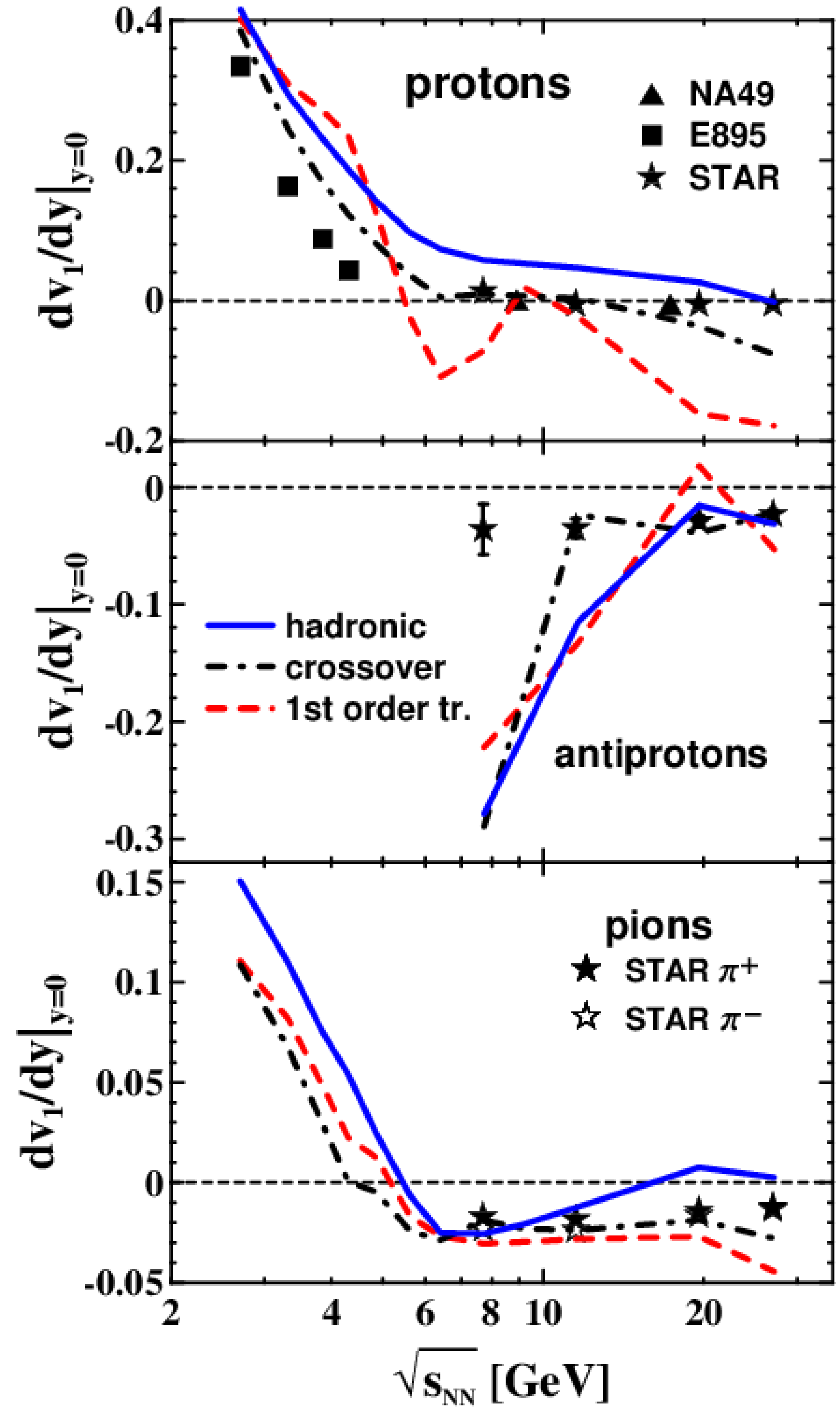
Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C91, no. 2, 024915 (2015)





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