Transport Theoretical approach for heavy-ion collisions at high baryon densities

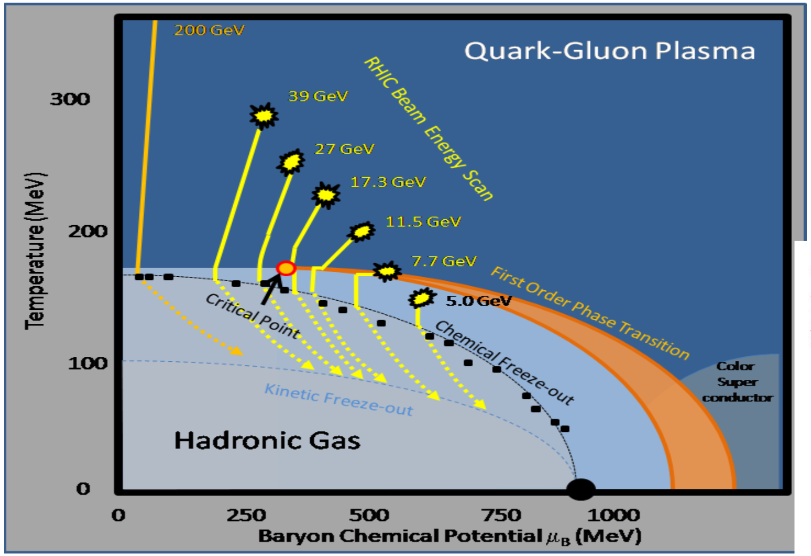
Yasushi Nara (Akita International University)

- Dynamics of the heavy-ion collision at high baryon density region
- Transport approach: Quantum molecular fluid dynamics (QMFD)
- Beam energy dependence of the directed flow from the RQMD model.
- Summary

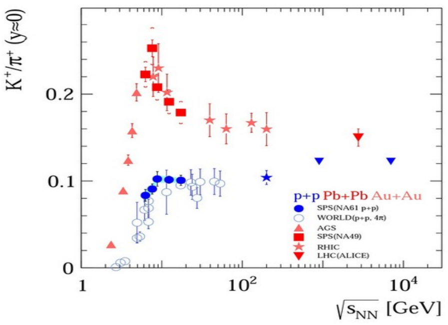
Akamatsu, et.al PC98,024909 (2018)
Y.N, T. Maruyama, and H. Stoecker, PRC102,024913(2020)
Y.N. and A.Ohnishi nucl-th2109.07594

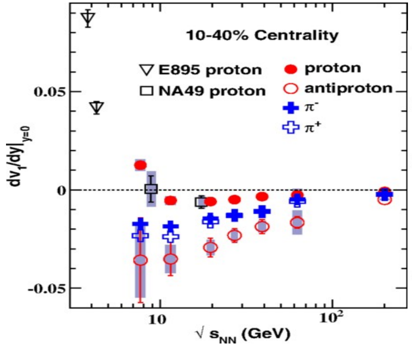
RBRC seminar Oct.21 2021

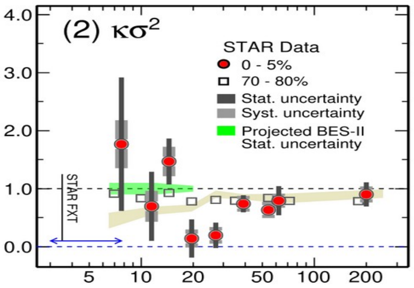
Beam scan to study phase structure of QCD matter



On going RHIC BES II, FXT and NA61/SHINE explore the phase structure of QCD matter.
New experiments FAIR, NICA, J-PARC-HI,HIAF are planned.







Lattice QCD has not covered the FAIR, NICA J-PARC energy regions.

Discovery of non-monotonic behavior of beam energy dependence in K+/pi+,v1,kurtosis,$N_t N_p/N_d^2$.

Are they signals of a phase transition?

To extract the information about EoS, dynamical model is needed.

High energy heavy-ion collisions

Experiments from 2GeV to 5TeV are being performed now.

SIS	AGS,STAR-FXT	SPS, BES	RHIC	LHC
Ecm = 2.3 GeV	Ecm = 5 GeV	Ecm = 17.3 GeV	Ecm = 200GeV	Ecm = 5.02 TeV

High baryon density
Inside neutron stars

Very low baryon density QGP
Creating early universe

FAIR, NICA, J-PARC-HI
Highest baryon density

Hadronic cascade model
Vlasov- Boltzmann
Quantum Molecular Dynamics
Three fluid dynamics

→ The intersection of both approaches ←

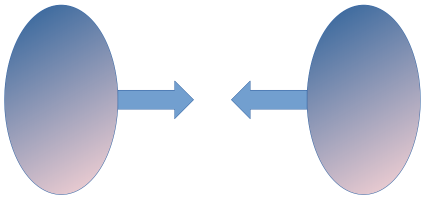
Color glass condensate(CGC)
Classical YM
Parton cascade model
Viscous hydro +hadron transport

Collision dynamics changes at 30GeV

$$t_{\text{pass}} = 2R/\gamma \approx 1\ \text{fm/c at}\ \sqrt{s_{NN}} = 30\ \text{GeV}$$

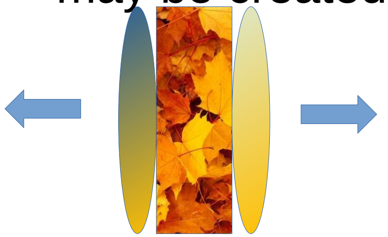
Collision dynamics changes around this beam energy.

Below 30GeV:
Secondary interactions can occur during the compression stages of the collisions.



Need to simulate compression stages:
UrQMD, GiBUU,PHSD,SMASH,JAM, 3FD

Above 30GeV:
After two nuclei pass through each other, Secondary interactions occur, and QGP may be created.

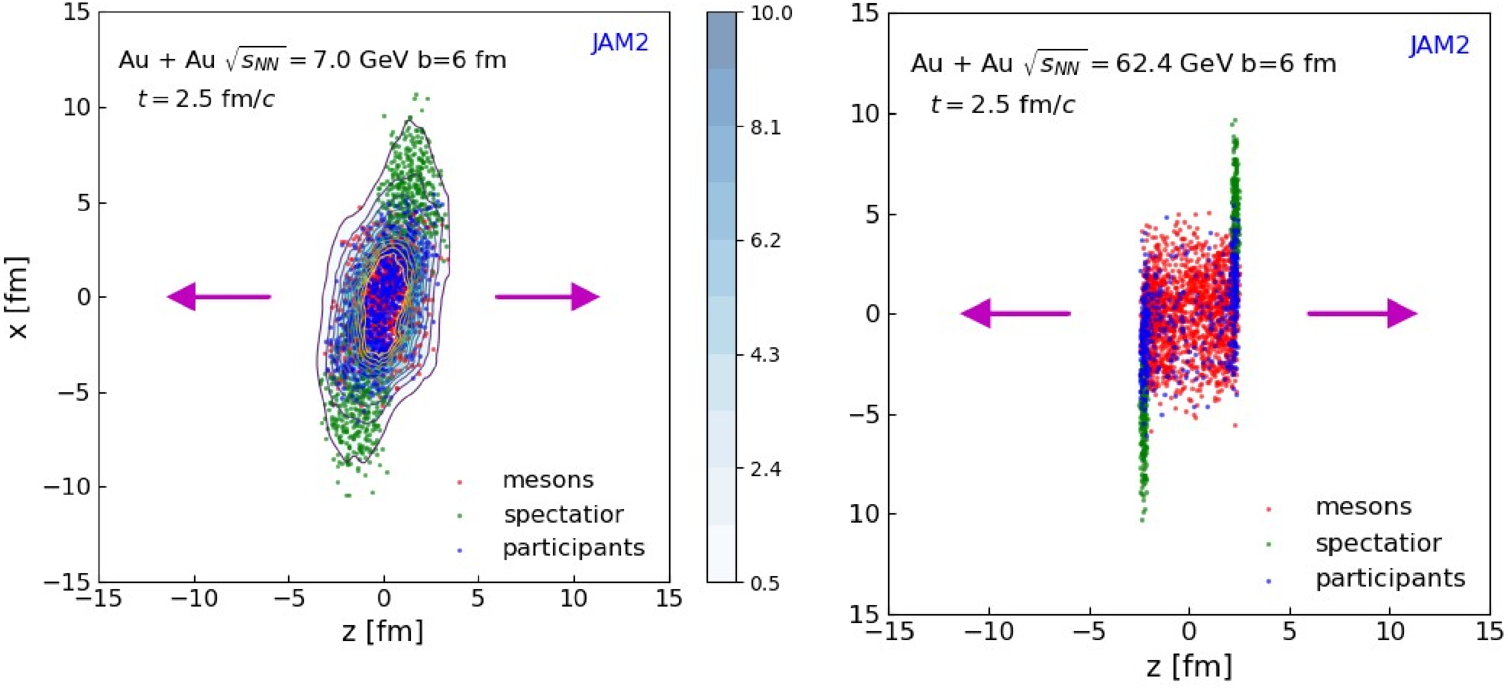


Particle production:
HIJING, Pythia8/Angantyr

Dynamical simulation after the collision:
Hydro models at RHIC/LHC, Epos,AMPT,DCCI

Importance of spectator matter

$$t_{\text{pass}} = 2R/\gamma \approx 1 \text{ fm/c at } \sqrt{s_{NN}} = 30 \text{ GeV}$$



Spectator matter can be neglected when we are interested in mid-rapidity above 30 GeV.

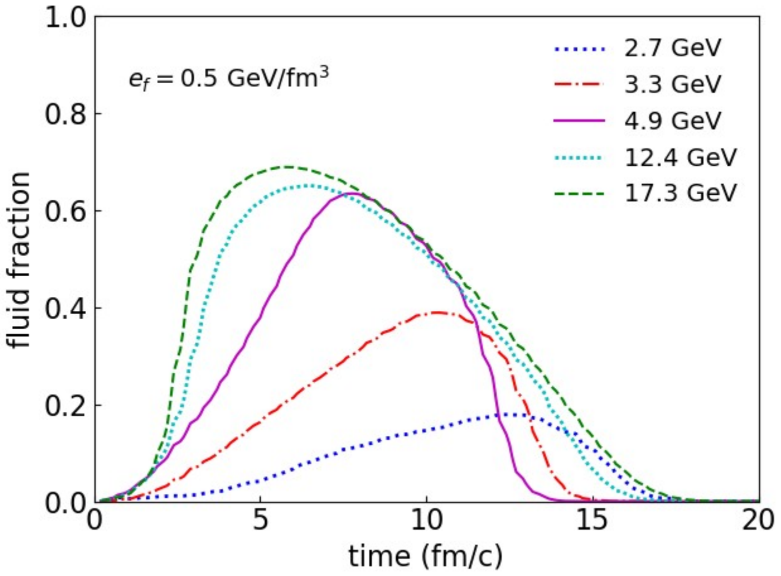
Spectator-participant interaction is important below 30 GeV.

(for example, negative elliptic flow below 3GeV and negative pion directed flow)

Initial conditions for fluid dynamics below 30 GeV

Dynamical initial condition: spacetime dependent fluidzation
M. Okai, et.al PRC95,054914 (2017), Y.Kanakubo,PRC101,024912(2020)
Chun Shen and Bjorn Schenke PRC97,024907 (2018),
Akamatsu, et.al PC98,024909 (2018).

PRC98 (2018)

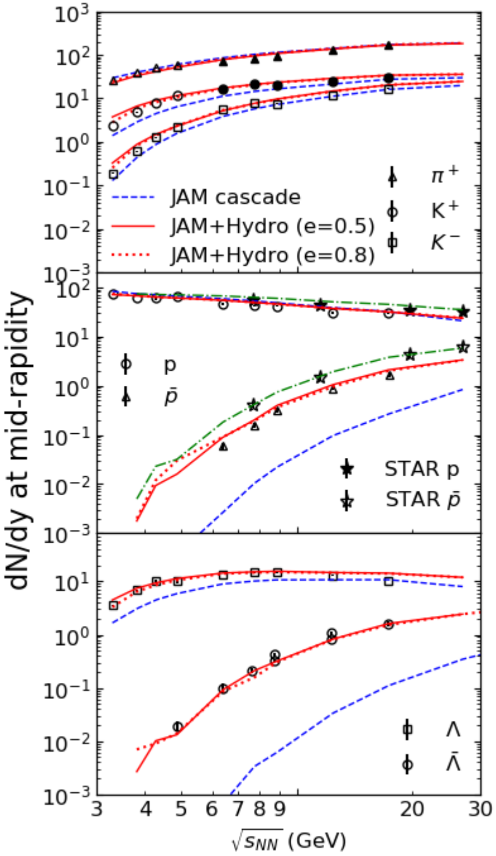


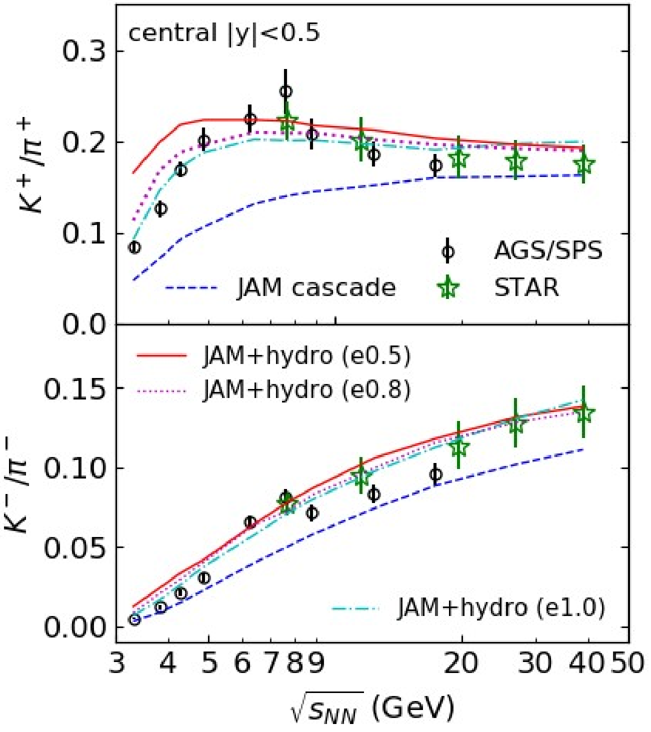
$$\partial_\mu T^{\mu\nu} = J^\mu$$

Solving the time evolution of particles and fluid.
JAM Dynamical integration of
Hydrodynamics and cascade mode

20% of fluid is predicted at 2.7 GeV

Beam energy dependence of multiplicities from hydro+JAM cascade integrated model





Hydro suppresses pion yields.

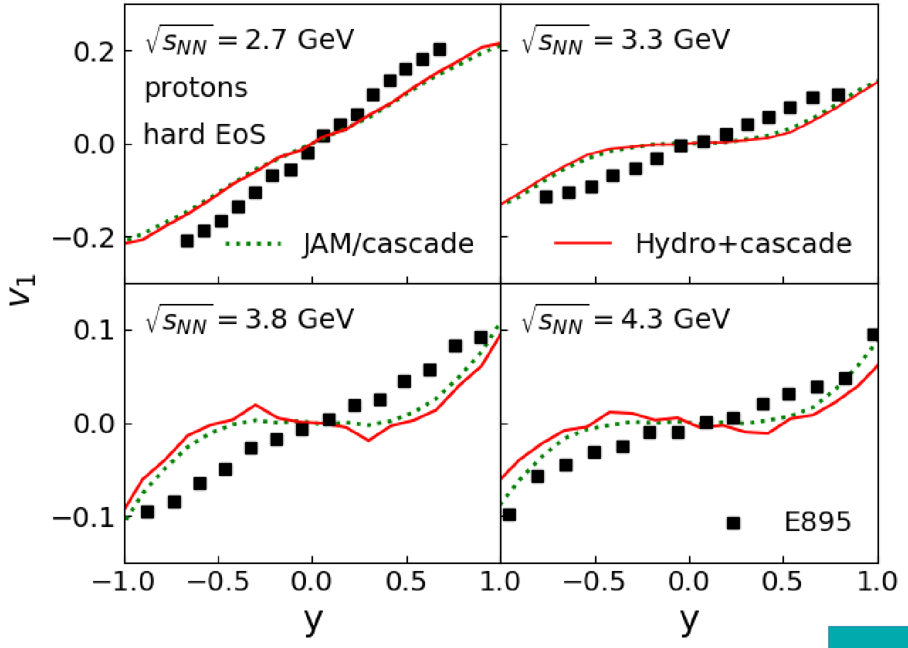
Y. Akamatsu, M. Asakawa, T. Hirano, M. Kitazawa,K. Morita, K. Murase,Y. Nara, C. Nonaka, A. Ohnishi, Phys.Rev. C98 (2018) no.2, 024909

Significant improvements of strangeness and anti-baryon productions.

How about collective flow?

V1 from Hydro + JAM/cascade model

Hydro+cascade yields the same v1 as the cascade model.



Hydrodynamics + Cascade model

EOS: Hadron Gas

Problem:
EoS in the cascade is inconsistent with the EoS in the hydrodymamics.

Solution:

Hydrodynamics + quantum molecular dynamics

Quantum molecular fluid dynamics

We solve the time evolution of particle and fluid at the same time.

QMFD = Boltzmann type collision term (cascade model)

+ fluid dynamics $\partial^x_\nu T^{\mu\nu}_f = I^\nu_{fp}\,,\quad \partial^x_\mu J^\mu_f = \int d^4p\, C_{fp}$

+ potential interaction by using

the relativistic quantum molecular dynamics (RQMD)

$$\dot{x}_i = \frac{p^*_i}{p^{*0}_i} + \sum_j \left(\frac{m^*_j}{p^{*0}_j} \frac{\partial m^*_j}{\partial p_i} + v^{*\mu}_j \frac{\partial V_{j\mu}}{\partial p_i} \right), \quad \dot{p}_i = -\sum_j \left(\frac{m^*_j}{p^{*0}_j} \frac{\partial m^*_j}{\partial r_i} + v^{*\mu}_j \frac{\partial V_{j\mu}}{\partial r_i} \right)$$

$$m^* = m - S(x,p), \quad p^*_\mu = p_\mu - U_\mu(x,p)$$

EoS in the RQMD.RMF model

PRC102(2020)

Scalar and vector potential in the relativistic mean field theory:

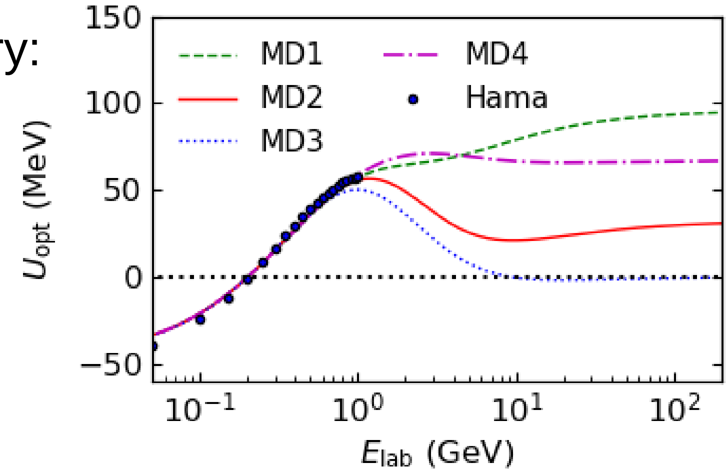
$$m^* = m - g_\sigma \sigma - S_m(p),$$
$$p^{*\mu} = p^\mu - g_\omega \omega^\mu(\rho) - V_m^\mu(p).$$

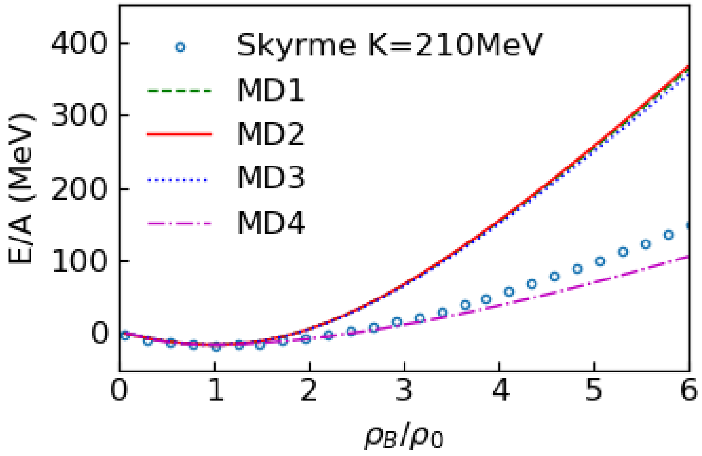
Momentum-dependent potential:

$$V_s^{\mathrm{MD}} = \frac{\bar{g}_s^2}{m_s^2} \int d^3p \frac{m^*}{p_0^*} \frac{f(x,p)}{1 + (\boldsymbol{p} - \boldsymbol{p}')^2/\Lambda_s^2},$$
$$V_\mu^{\mathrm{MD}} = \frac{\bar{g}_v^2}{m_v^2} \int d^3p \frac{p_\mu^*}{p_0^*} \frac{f(x,p)}{1 + (\boldsymbol{p} - \boldsymbol{p}')^2/\Lambda_v^2},$$

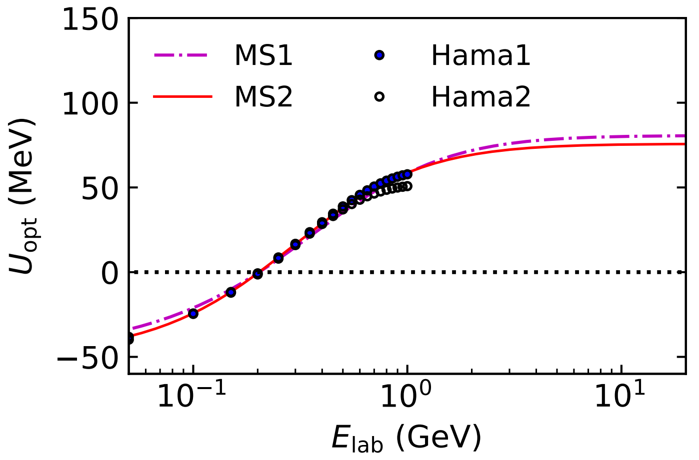
Energy density:

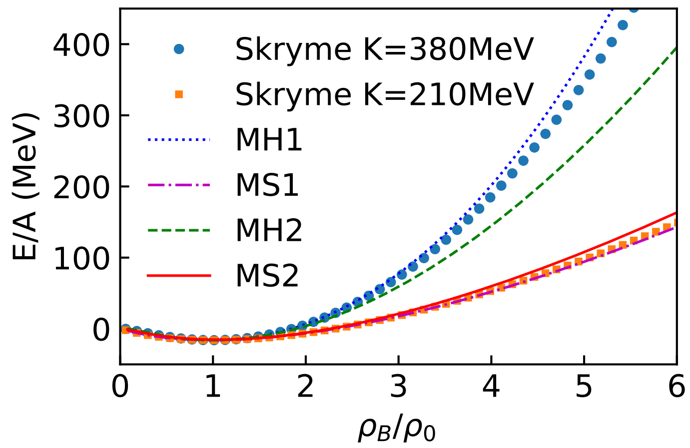
$$e = \int d^3p\, p_0 f(p) + U(\sigma)$$
$$+ \frac{1}{2} \int \frac{d^3p}{p_0^*} \left(m^* V_s^{\mathrm{MD}} - p^{*\mu} V_\mu \right) f(p).$$





EoS in the RQMDv mode





Skyrme type vector potential

$$\mathrm{p}^{*\mu} = p^\mu - U^\mu(\rho) - U^\mu_m(p).$$

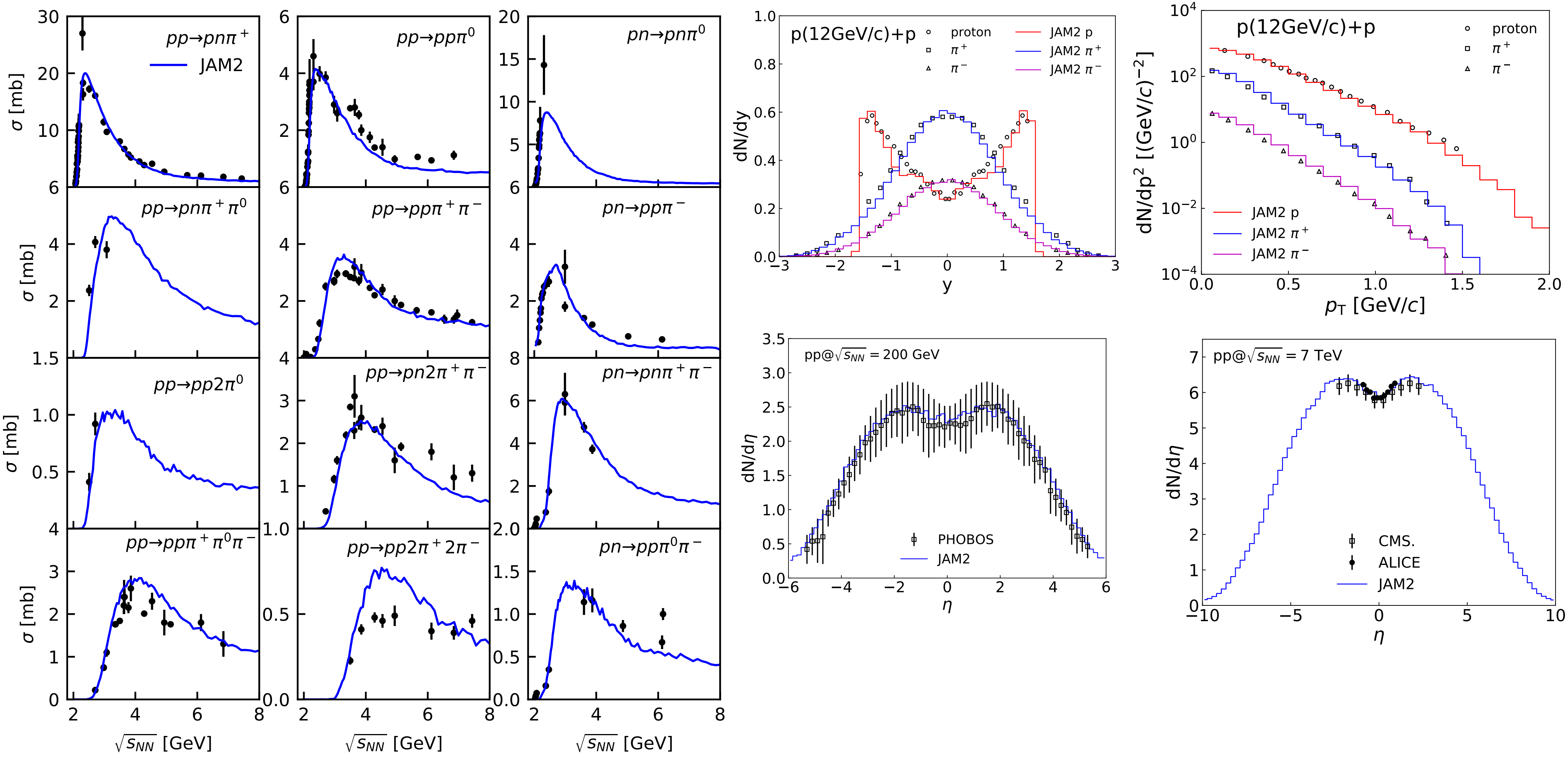
$$U_{\rm sk}(\rho) = \alpha\left(\frac{\rho}{\rho_0}\right) + \beta\left(\frac{\rho}{\rho_0}\right)^\gamma,$$

$$U^\mu_m(p) = \frac{C}{\rho_0}\int d^3p' \frac{p^{*\prime\mu}}{e^*}\frac{f(x,p')}{1+[(\boldsymbol{p}-\boldsymbol{p}')/\mu_k]^2},$$

Energy density is given by

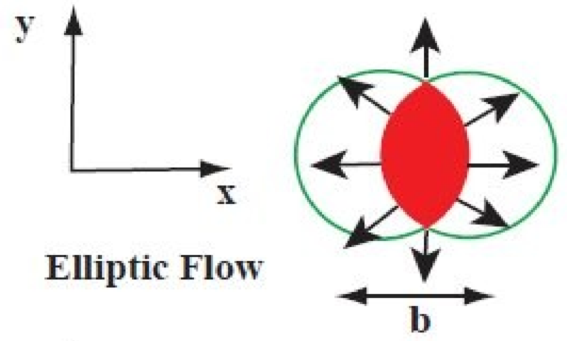
$$e = \int d^3p\left(e^* + U^0_m - \frac{1}{2}\frac{p^*_\mu}{e^*}U^\mu_m(p)\right)f(p) + \int_0^\rho U^0_{\rm sk}(\rho')d\rho'$$

Multi pion production cross sections in JAM2 for proton-proton collisions

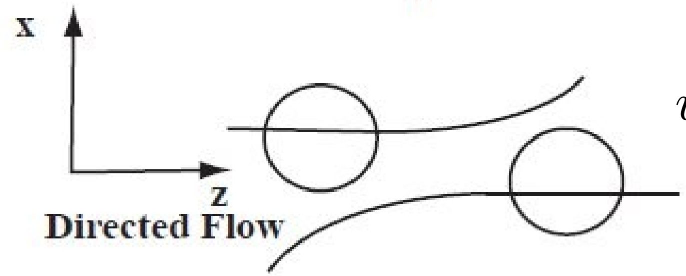


Anisotropic collective flows

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



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



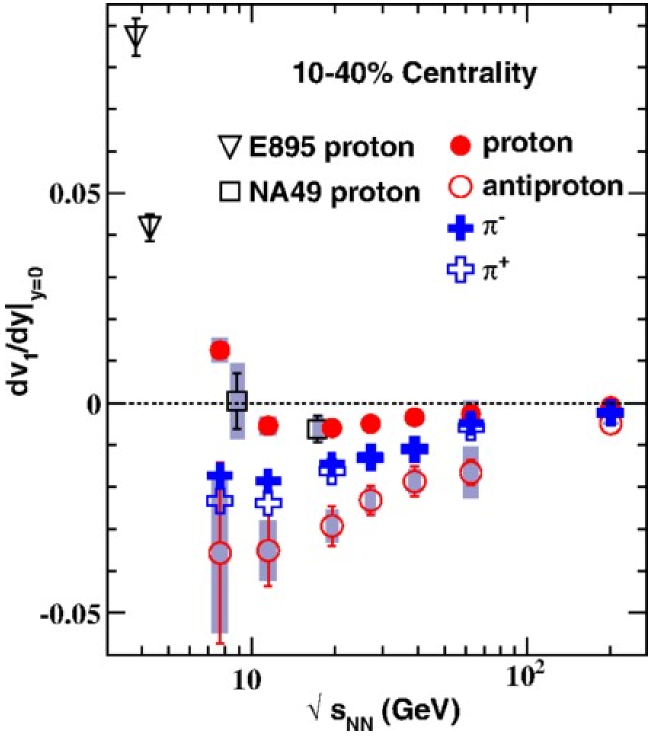
$$v_1 = \langle \cos \phi \rangle = \left\langle \frac{p_x}{p_T} \right\rangle$$

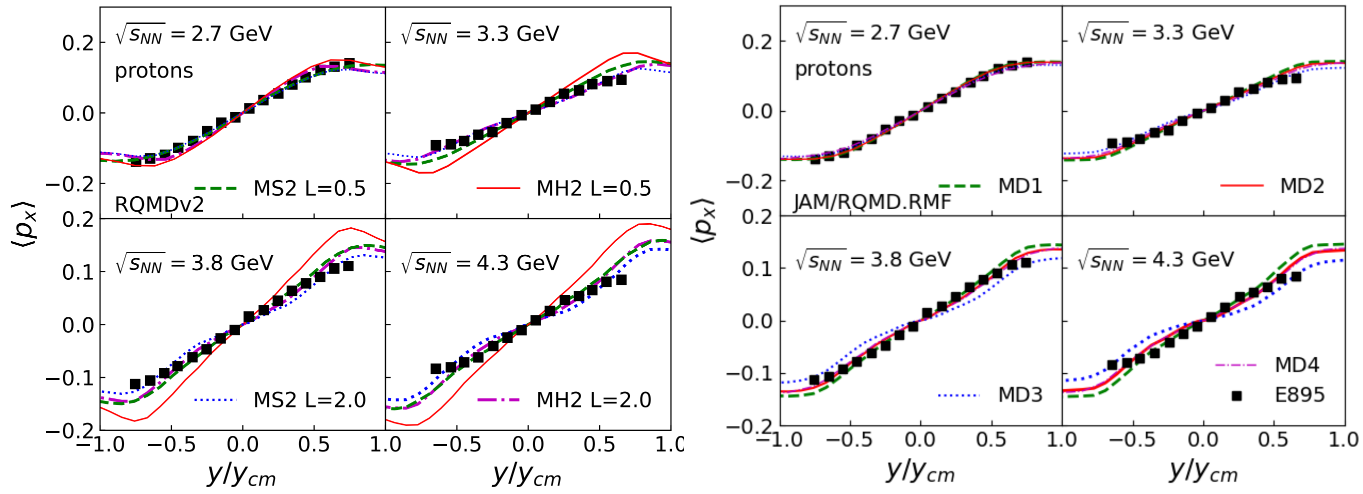
BUU Transport model predicts strong sensitivities of EOS on the directed and elliptic flows.

Beam energy dependence of v1

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

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





Hadronic transport model with mean-field can explain v1 below AGS energies < 5GeV.

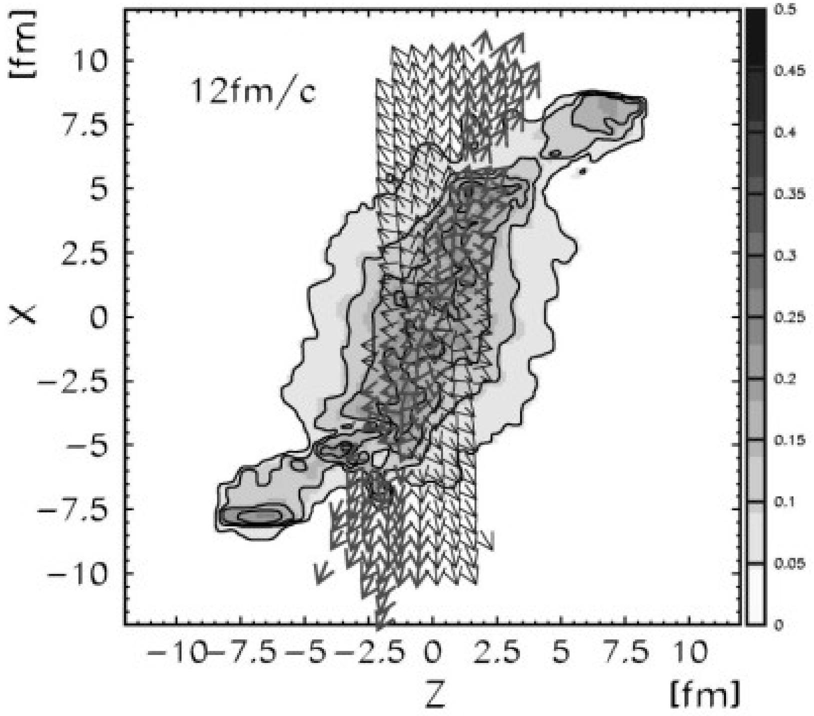
Signal of the 1st-order phase transition?

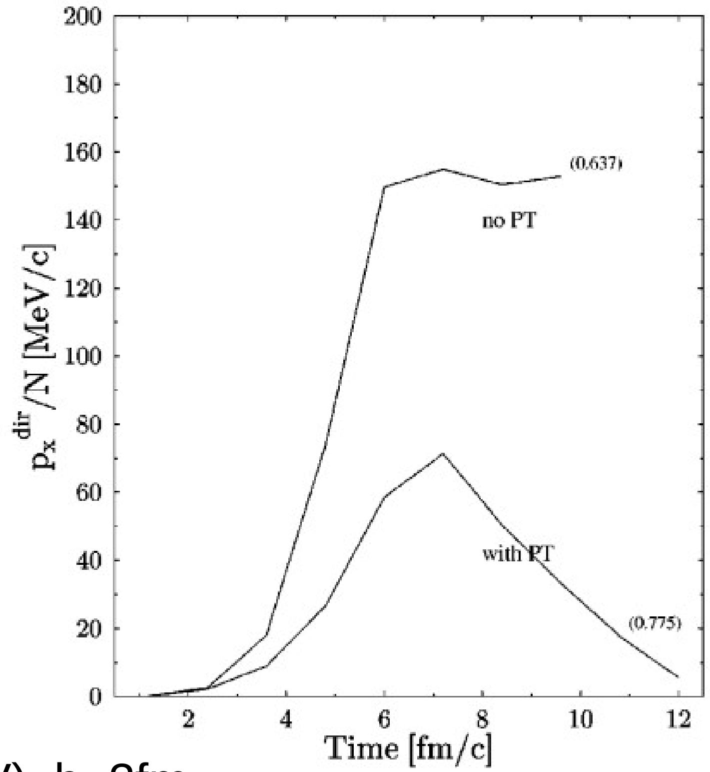
Tilted baryon density in 3FD

1FD prediction: D.H.Rischke, et.al Acta.Phsy.Hung (1995)

3FD prediction: J.Brachmann,et.al. PRC61(2000)

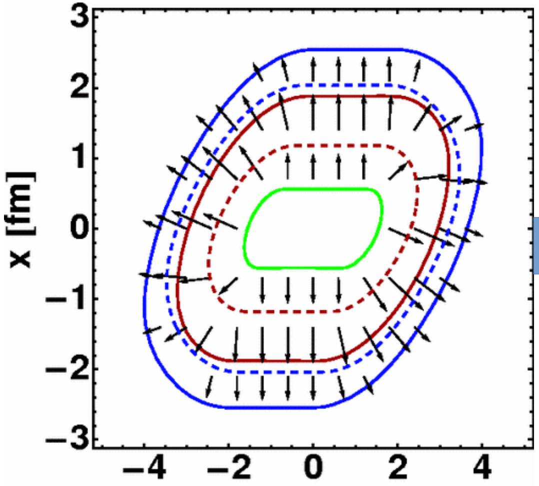
Fluid dynamics predicts the collapse of v1 for 1st order phase transition.



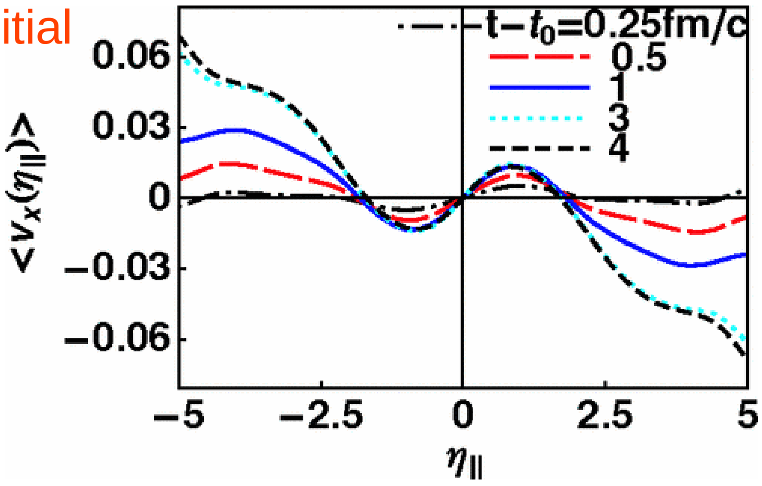


Au+Au at Elab=8AGeV (Ecm=4.3GeV), b=3fm

Tilted initial condition for hydro at 200 GeV

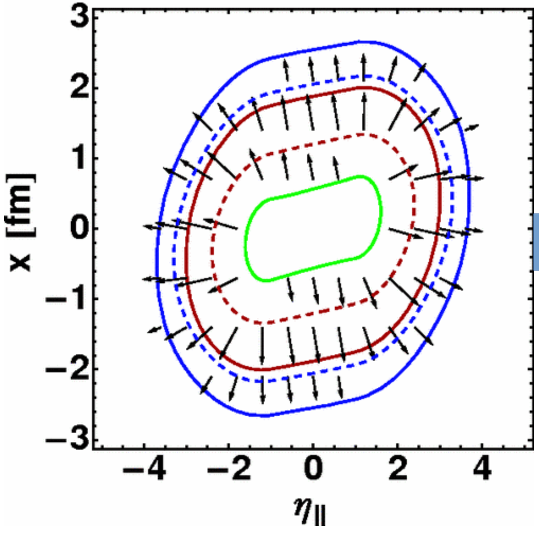


shifted initial condition

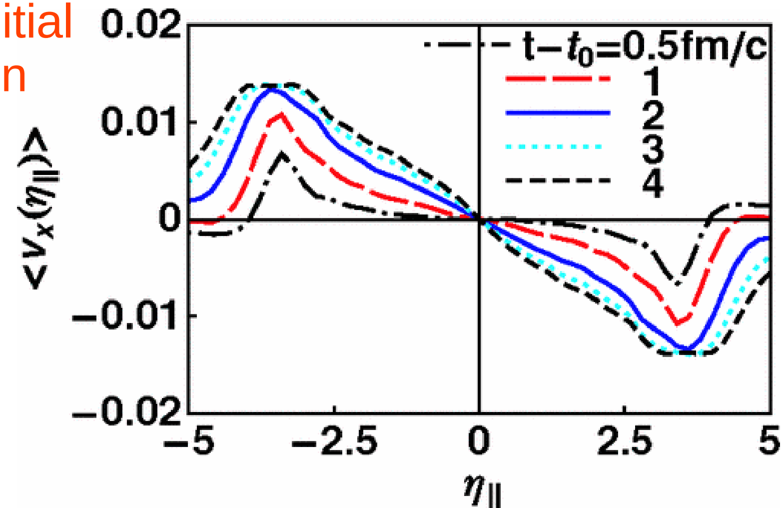


Positive v1 (normal flow)

P.Bozek and I. Wyskiel, PRC 81, 054902 (2010)



Tilted initial condition



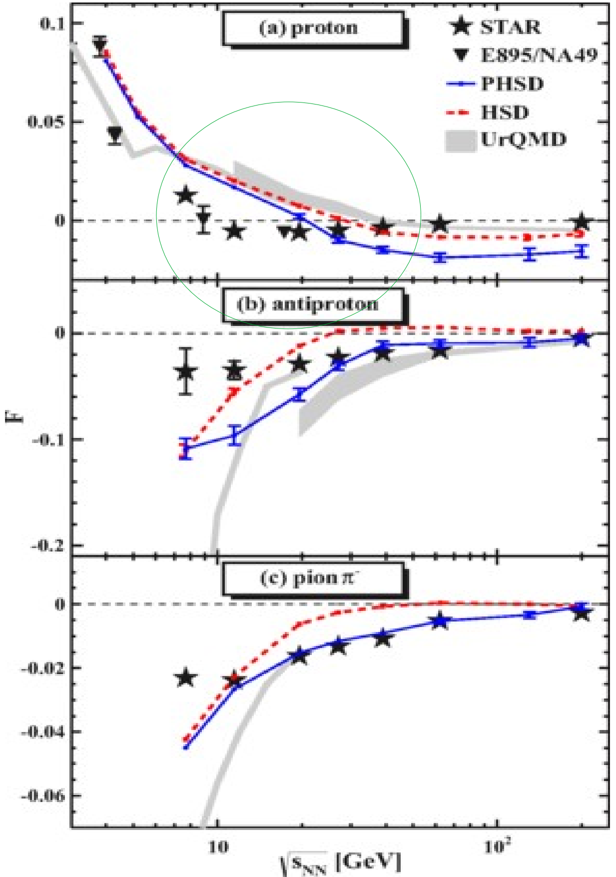
negative v1 (anti-flow)

Adil,Gyulassy,Hirano, PRD73(2006) twisted CGC predicts negative v1.

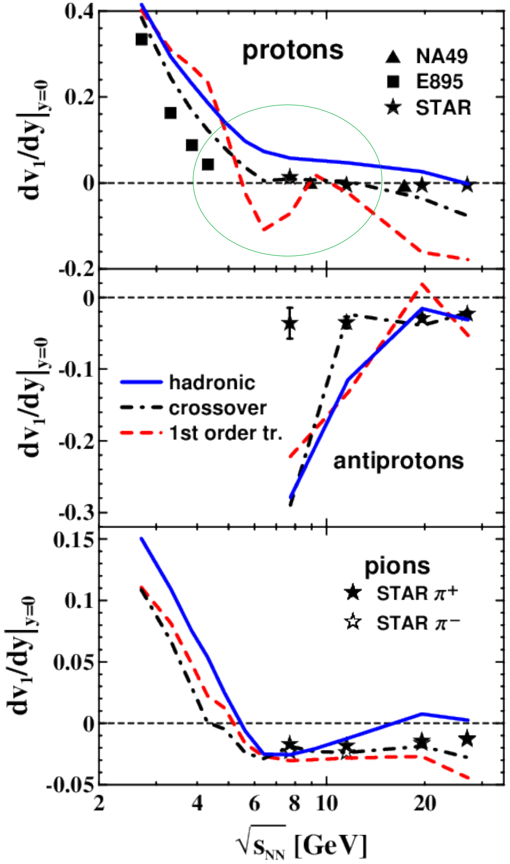
PHSD: negative
above 27 GeV

Transport model predictions

V. P. Konchakovski,et.al,
Phys. Rev. C90,014903 (2014)



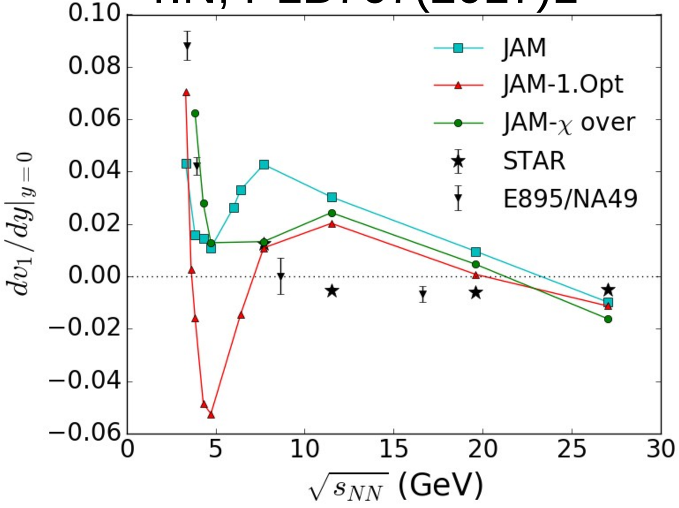
Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C91, 024915 (2015)



1st order PT:minium at 5-6GeV

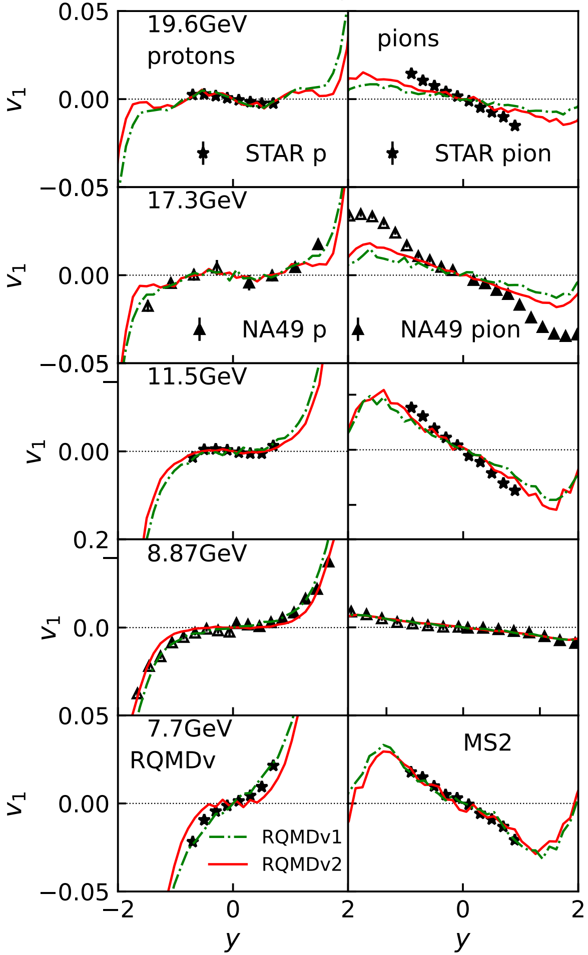
Both crossover and 1PT do not explain the beam energy dependence of the directed flow v1.

Y.N, PLB767(2017)1

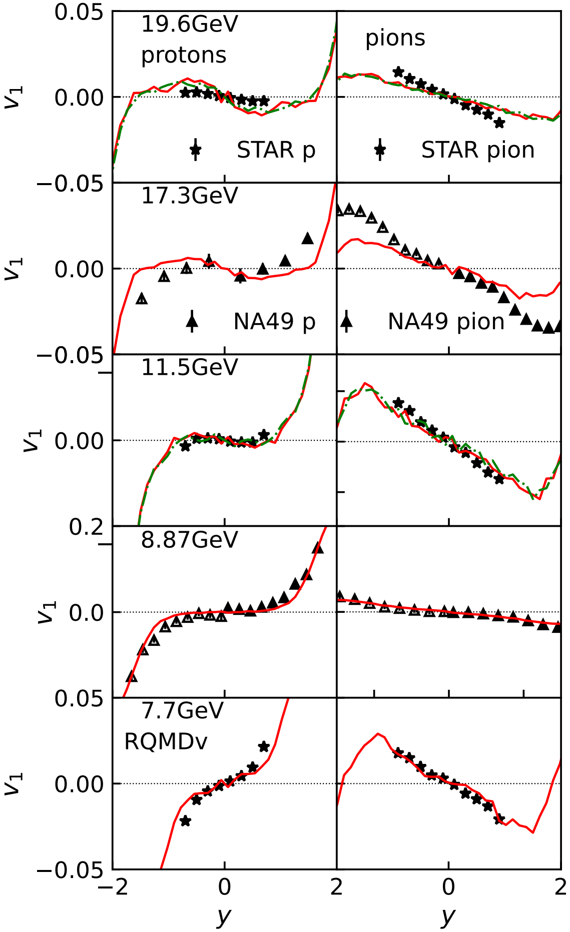


Beam energy dependence of v1 from RQMD

RQMDv



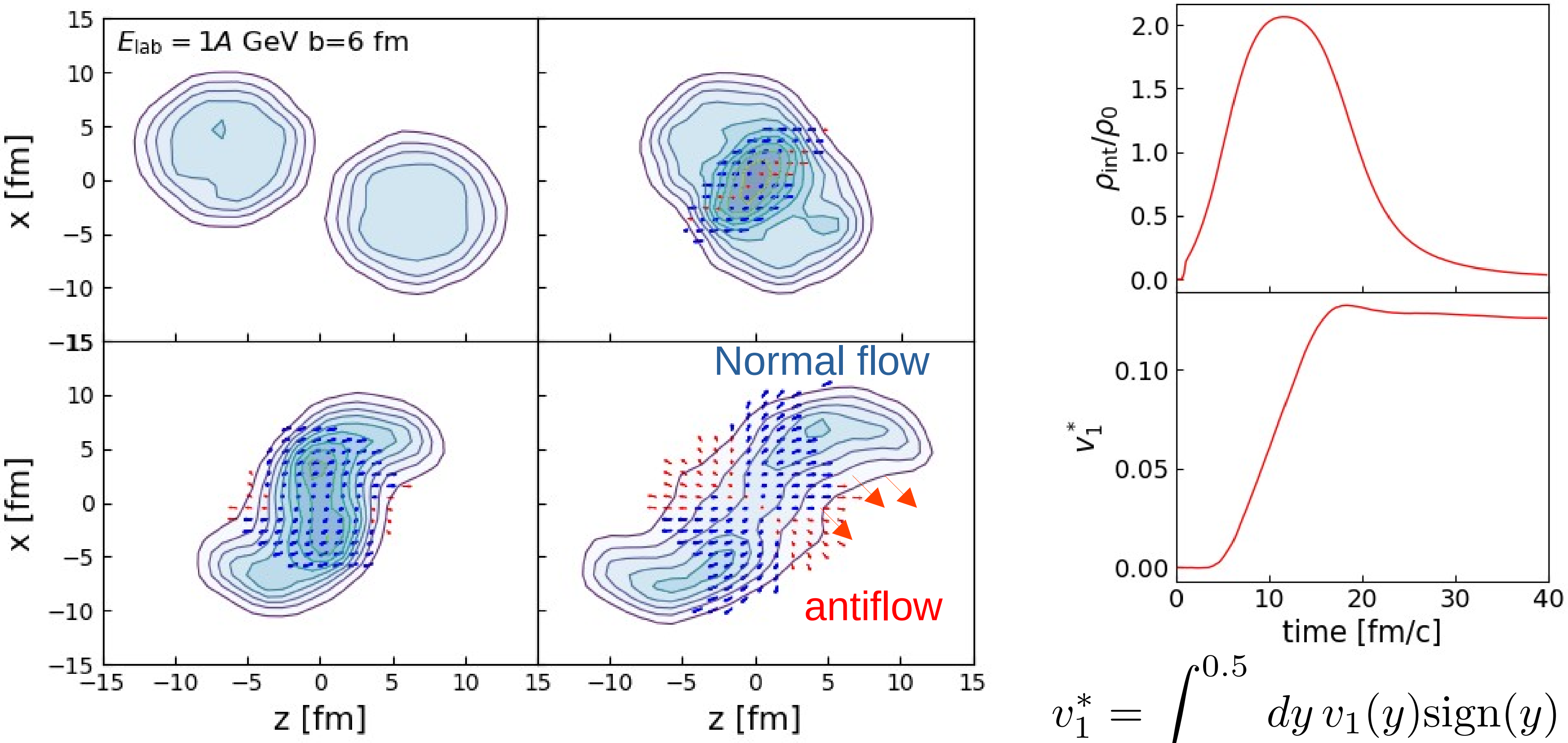
RQMD.RMF



Beam energy dependence of v1 is explained by a mean-field both Skyrme type and sigama-omega.

Development of v1 at Elab=1AGeV

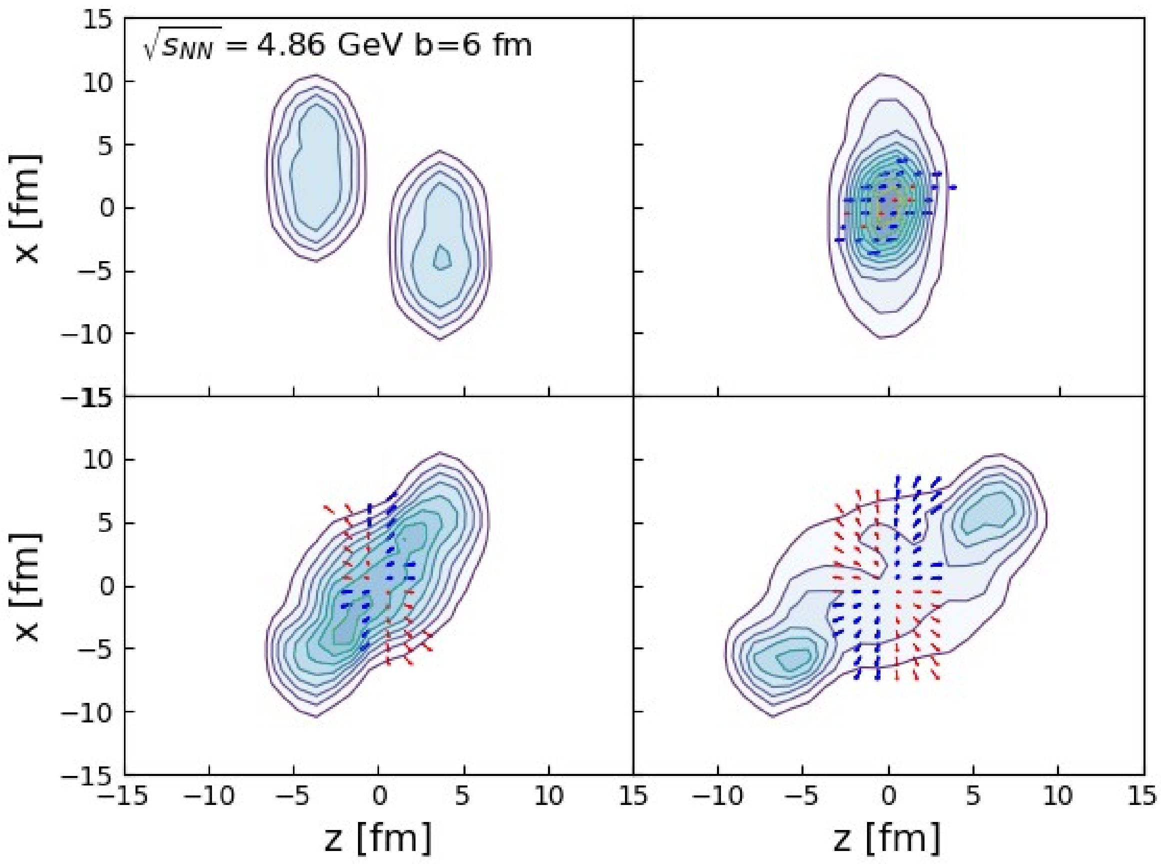
Time evolution of the baryon density in Au+Au Elab=1AGeV, mid-central collision (b=6fm)

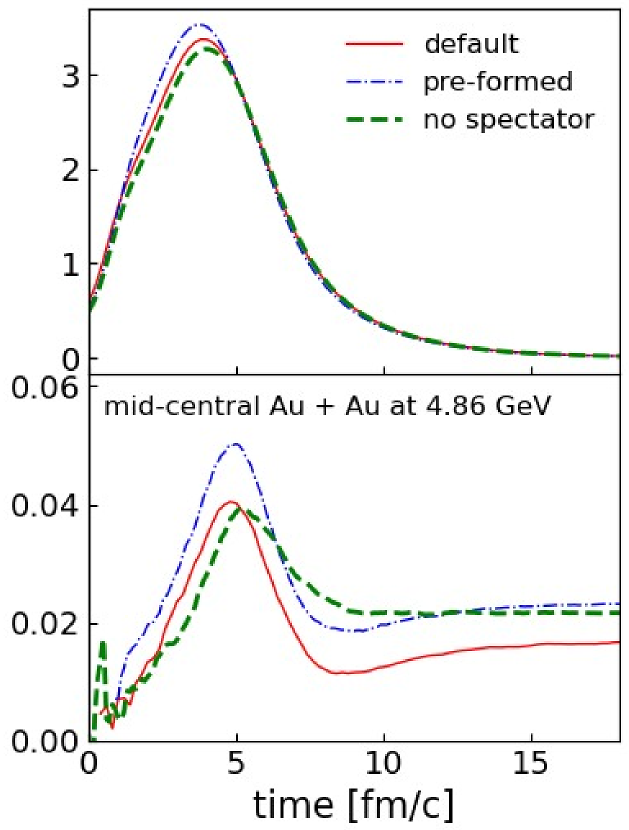


$$v_1^* = \int_{-0.5}^{0.5} dy\, v_1(y)\mathrm{sign}(y)$$

Development of v1 at 4.86 GeV

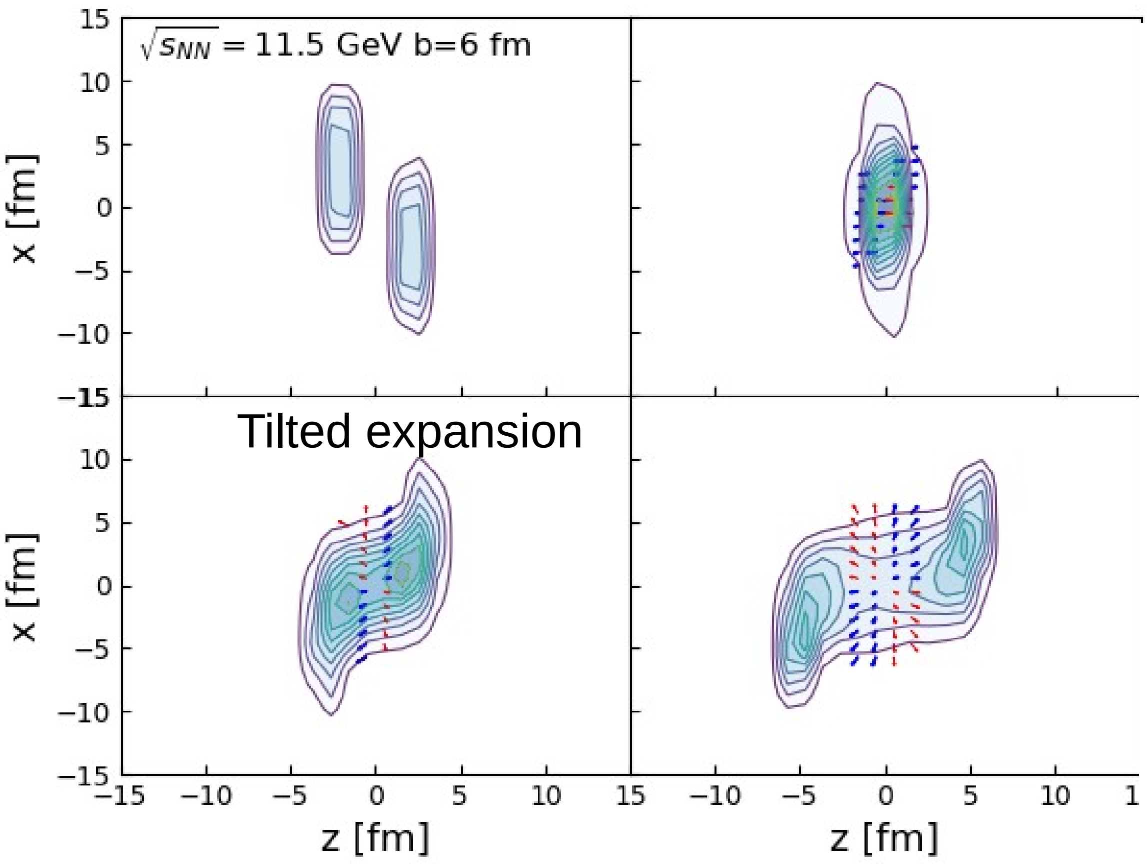
Time evolution of the baryon density in Au+Au mid-central collision (b=6fm)

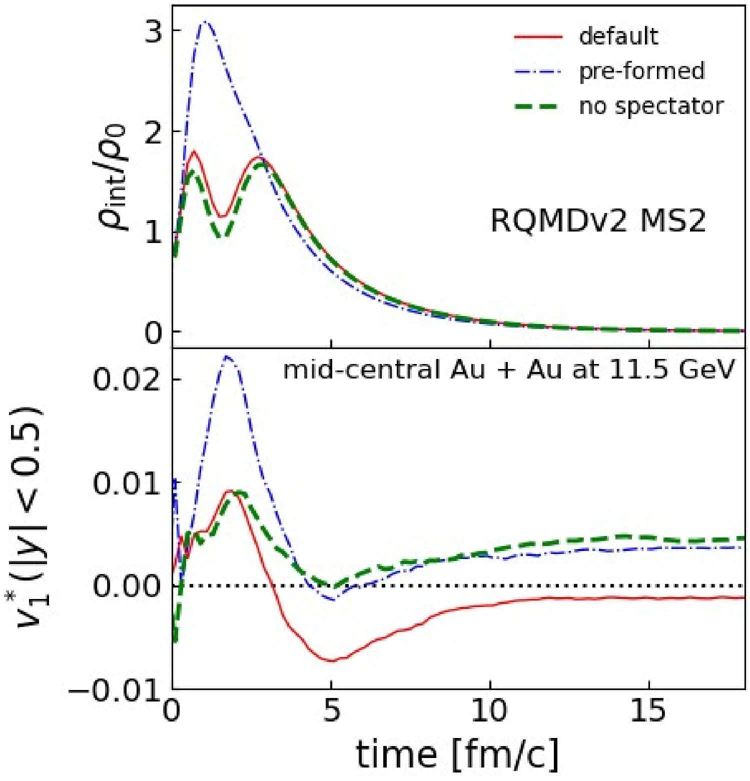




Development of v1 at 11.5GeV

Time evolution of the baryon density in Au+Au mid-central collision (b=6fm)





Summary

- Quantum Molecular Fluid Dynamics (QMFD) may be a promising approach to understand the spacetime evolution of heavy-ion collisions at high baryon density region.
- The beam energy dependence of the directed flow is explained by the conventional hadronic mean-field. We need systematic study.
- Final v1 is determined by the interplay between positive v1 generated in the compression stages and the negative v1 generated during the expansion stage.
- RQMD simulation by the potential with phase transition: A. Sorense and V. Koch, PRC104 (2021) 3, 034904.
- Baryon number fluctuations by using N-body transport model RQMD.

backup

JAM2:micro-macro transport model
Quantum Molecular Fluid Dynamics (QMFD)

- Fortran77 → C++
- Pythia6 → Pythia8
- Update of collision term: include new data for pp
  - ✓ New total hadronic cross section at high energies (PDG2016)
  - ✓ New resonance cross section (Ecm< 4GeV)
  - ✓ New string excitation low (4 < Ecm < 20 GeV)
  - ✓ New multiple-parton scattering (Pythia8) (Ecm > 20GeV)

- Quantum Molecular Fluid Dynamics (QMFD): 3D perfect hydro + RQMD model
- RQMD with Skyrme force (Lorentz scalar and vector)
- RQMD.RMF with momentum-dependent potential
- Speeding up computational time by introducing expanding box for both collision term and potential evaluation

V2 from JAM2/RQMDv