流体からハドロンへ

奈良 寧 (国際教養大学)

JAM2: 量子分子流体力学(Quantum molecular fluid dynamics,QMFD)

RQMD modeによるdirected flowの入射エネルギー依存性について発表する。

Y.N. and A.Ohnishi nucl-th2109.07594

QCD相転移やQGP生成のモデル化による重イオン衝突の時空発展の理解に向けた理論・実験共同研究会」
協賛：Heavy Ion Cafe, Heavy Ion Pub , 2021年9月24日

相対論的重イオン衝突

高エネルギー原子核衝突実験は、現在同時に2GeVから5TeVまで行われている!

SIS
Ecm = 2.3 GeV

AGS,STAR-FXT
Ecm = 5 GeV

SPS, BES
Ecm = 17.3 GeV

RHIC
Ecm = 200GeV

LHC
Ecm = 5.02 TeV

高バリオン密度物質の生成
中性子星内部

高温低バリオン密度QGP
宇宙初期の状態

FAIR, NICA, J-PARC-HI
最高バリオン密度物質

ハドロンカスケード模型
ブラソフ･ボルツマン方程式
量子分子動力学(QMD)
流体模型(3FD)

両方のアプローチ
の intersection

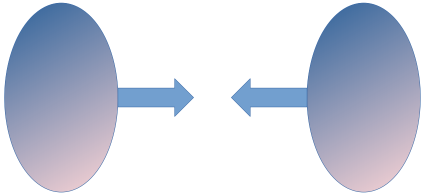
カラーグラス凝縮(CGC)
古典ヤングミルズ
パートンカスケード模型
粘性流体模型+ハドロン輸送模型

相対論的重イオン衝突

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

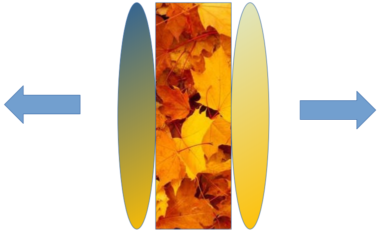
Collision dynamics changes around this beam energy.

30GeV以下:
衝突しながら(圧縮されながら)
2次相互作用が起こりQGPが
生成されるかもしれない。



衝突前からのシミュレーションが必要
UrQMD, GiBUU,PHSD,SMASH,JAM, 3FD

30Gev以上:
原子核がすり抜けた後に2次相互作用が起こり
QGPが生成されると考えられている。

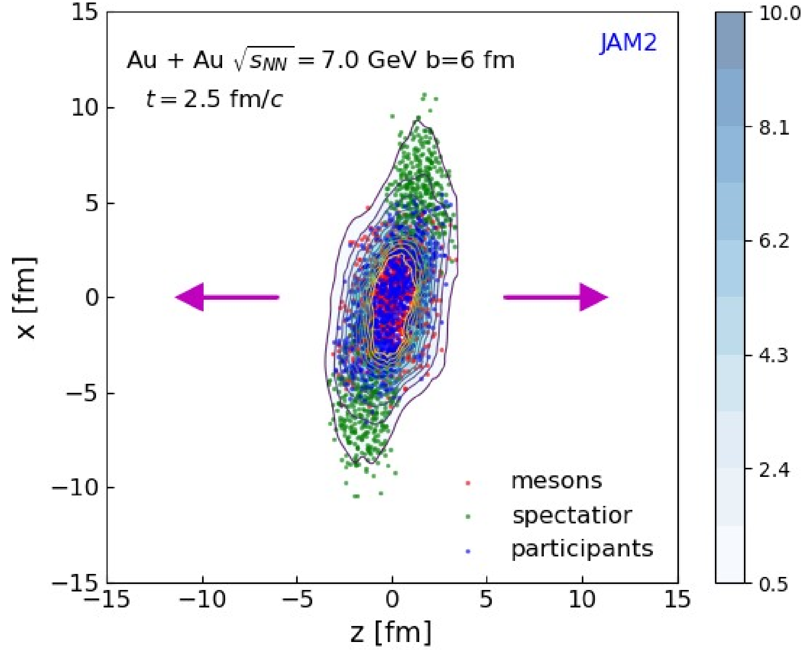


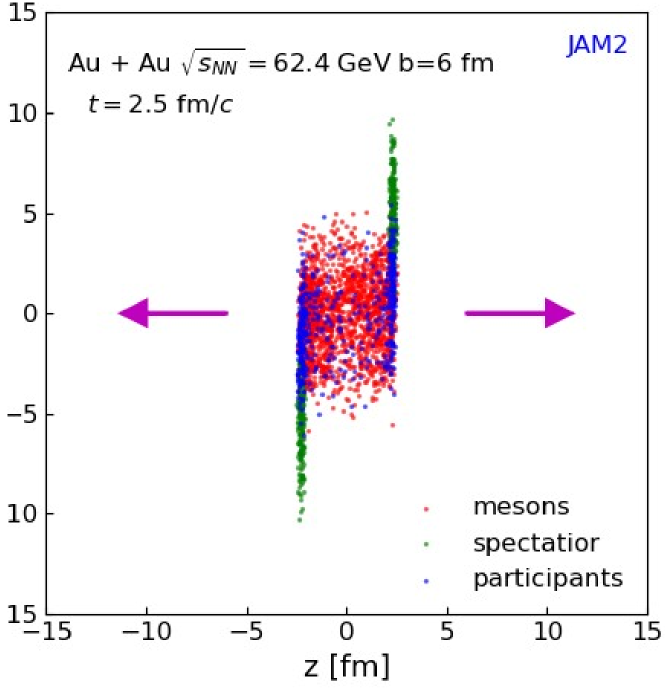
衝突直後だけ:
HIJING, Pythia8/Angantyr

衝突直後からのシミュレーション:
Hydro models at RHIC/LHC, Epos,AMPT,DCCI

相対論的重イオン衝突

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





mid-rapidity付近に興味がある場合は、spectator nucleonやparticipant baryonは無視してよい。

RHIC/LHCでも前方に興味がある場合は、超高密度バリオンの物理ができる。tau=0.6fm/c
20倍 at RHIC(y=2.5)
100倍 at LHC (y=4)

Ming Li and J. I. Kapusta
Phys. Rev. C 99,(2019)

30GeV以下の重イオン衝突ではspectator-participant interactionを考慮する必要がある。
(例えば、低エネルギーでの負のパイオンv1や負の陽子v2)

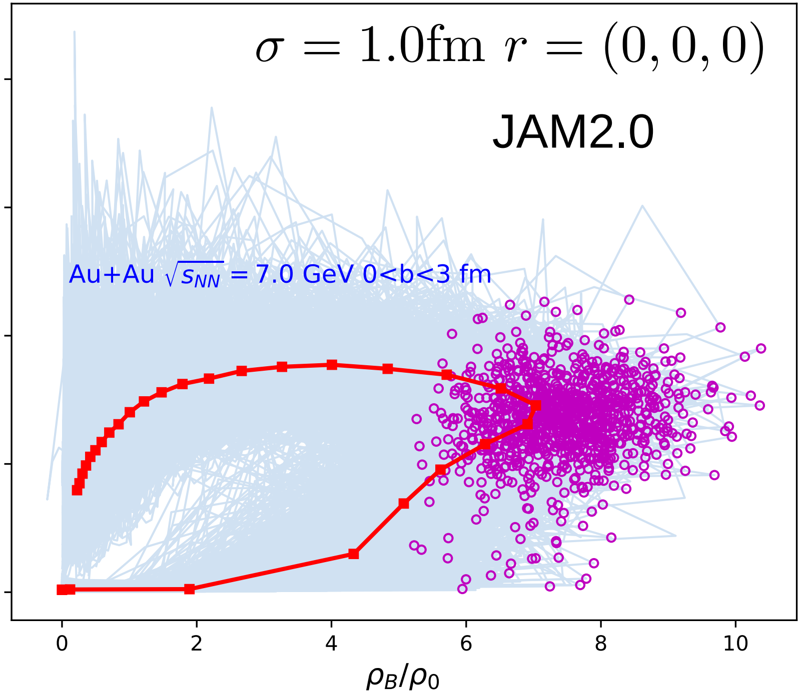
Ohnishi plot for the time evolution of rho-T in Au+Au at 7.0 GeV

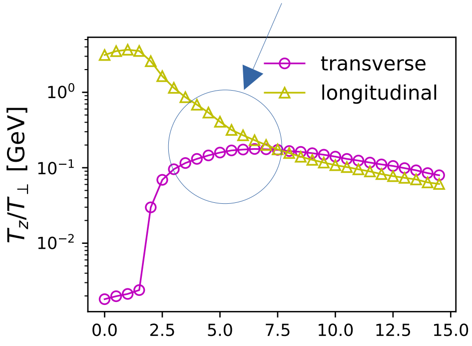
$$T^{\mu\nu}(\boldsymbol{r}) = \sum_i \frac{p_i^\mu p_i^\nu}{p_i^0} G(\boldsymbol{r} - \boldsymbol{r}_i)$$

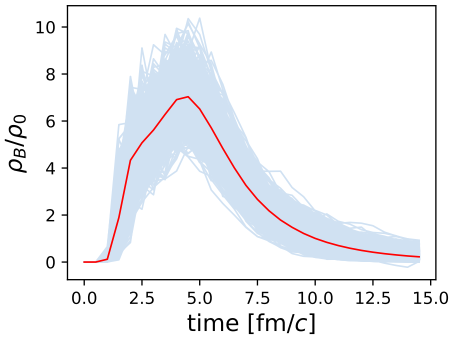
$$G(\boldsymbol{r}) = \frac{\gamma}{(2\pi\sigma^2)^{3/2}} \exp\left(-\frac{\boldsymbol{r}^2 + (\boldsymbol{r}\cdot\boldsymbol{u})^2}{2\sigma^2}\right), \; u = (\gamma, \boldsymbol{p}/m)$$

$$J^\mu(\boldsymbol{r}) = \sum_i \frac{p_i^\mu}{p_i^0} G(\boldsymbol{r} - \boldsymbol{r}_i)$$

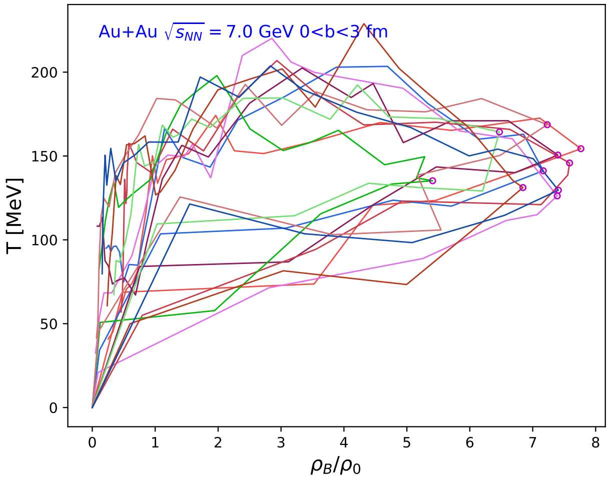
What is happening in reality?





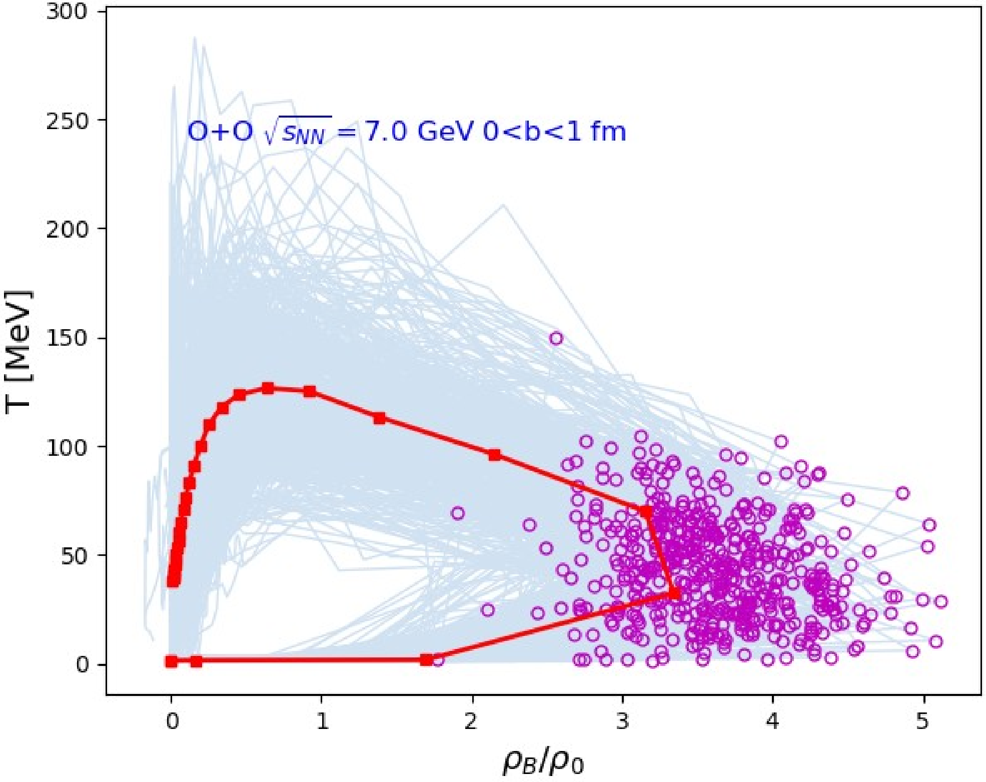


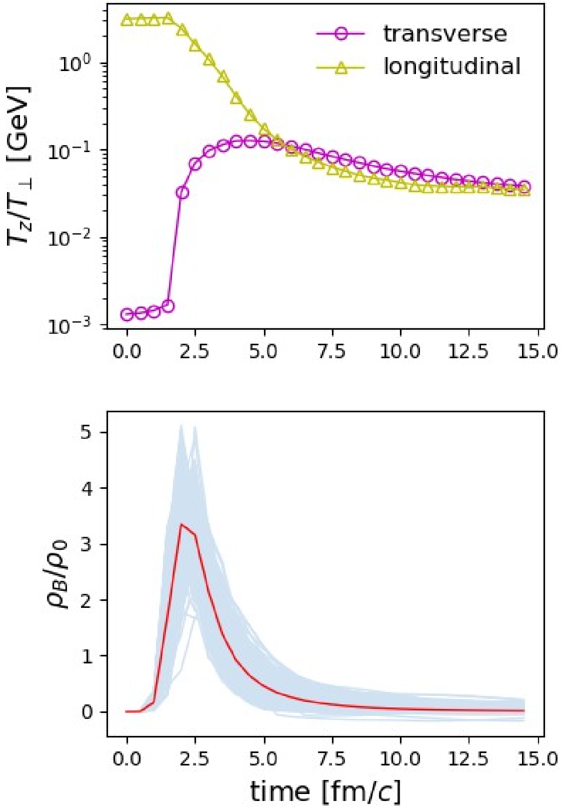
Hadronic transport model predicts thermalizaton at very late times.



Small system: O+O at 7.0 GeV

$\sigma = 1.0\mathrm{fm}\ V = 1^3/\gamma$



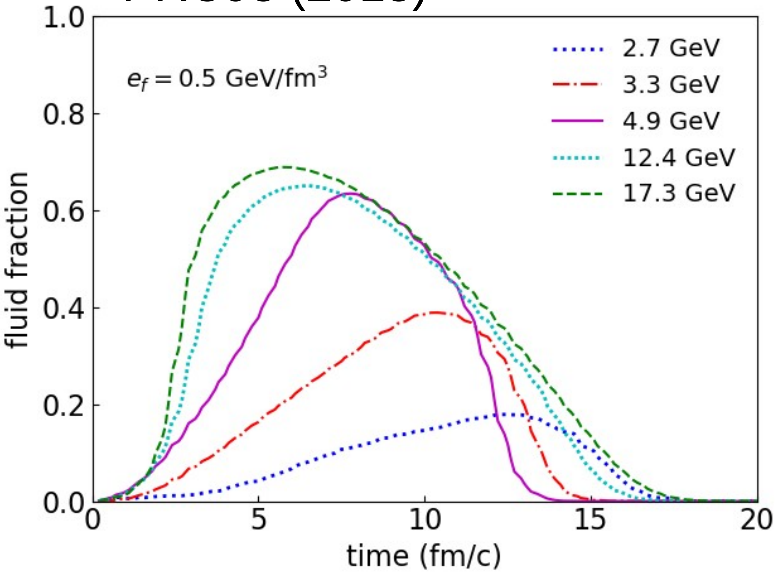


高バリオン密度領域における流体模型

- 時空依存の流体化を導入する。
- Dynamical initial condition 上智グループ M. Okai, et.al PRC95,054914(2017)

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

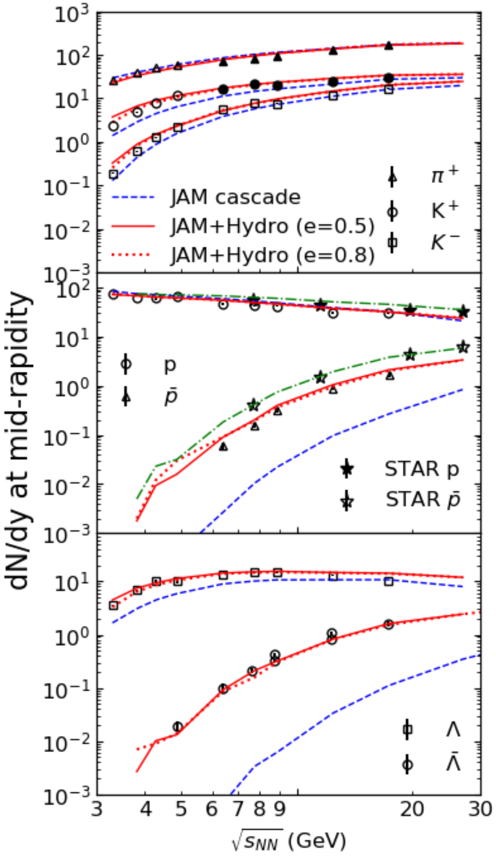
PRC98 (2018)

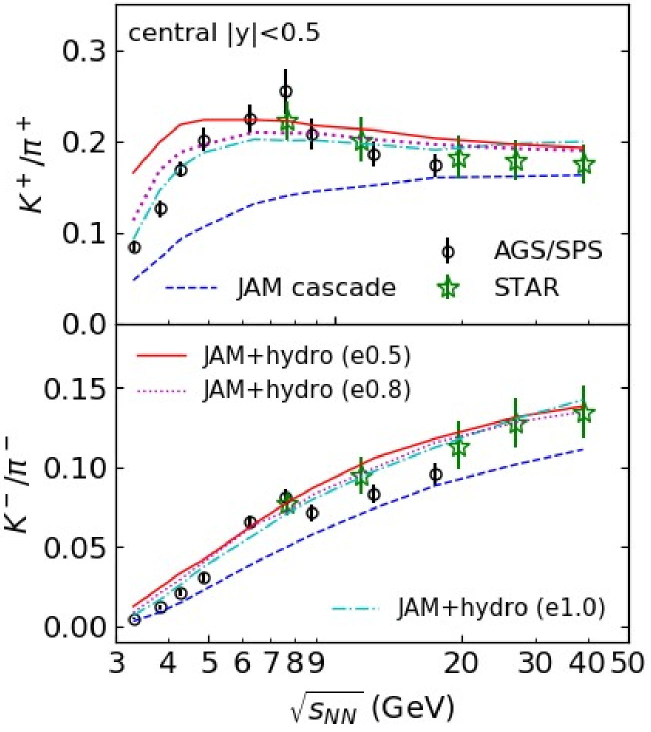


粒子と流体の時間発展を同時に解く。
JAM Dynamical integration of Hydrodynamics and cascade mode

20% of fluid is predicted at 2.7 GeV

Beam energy dependence of fluid fraction, 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.

このアプローチでフローは説明できない。

量子分子流体力学
(Quantum molecular fluid dynamics)

QMFD = Boltzmann type collision term (cascade model)

+ fluid dynamics

+ relativistic quantum molecular dynamics (RQMD)

粒子と流体の時間発展を粒子と流体素片を変換させながら同時に解くアプローチ。

量子分子流体力学

We consider the system of fluid $f_f(x,p)$ and particles $f_p(x,p)$:

$$\{(\partial^p_\mu V(x,p))\partial^\mu_x - (\partial^x_\mu V(x,p))\partial^\mu_p\} f_f(x,p) = C_{fp}$$

$$\{(\partial^p_\mu V(x,p))\partial^\mu_x - (\partial^x_\mu V(x,p))\partial^\mu_p\} f_p(x,p) = C_{pp} + C_{pf}$$

$$V(x,p) = \frac{1}{2}(p^{*\mu} p^*_\mu - m^{*2}) \qquad m^* = m - S(x,p), \quad p^*_\mu = p_\mu - U_\mu(x,p)$$

Particles: RQMD equations of motion:

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

量子分子流体力学(cont.)

Taking the moments of the transport equation, we obtain

$$\partial^x_\nu T^{\mu\nu}_f = I^\nu_{fp}\,,$$

$$\partial^x_\mu J^\mu_f = \int d^4p\, C_{fp} \qquad T^{\mu\nu}_f = T^{\mu\nu}_{f0} + J^\mu_f U^\nu - g^{\mu\nu}\left(\int J_{f\nu} dU^\nu - \int \rho_{fs} dS\right)$$

For the momentum-independent potential,

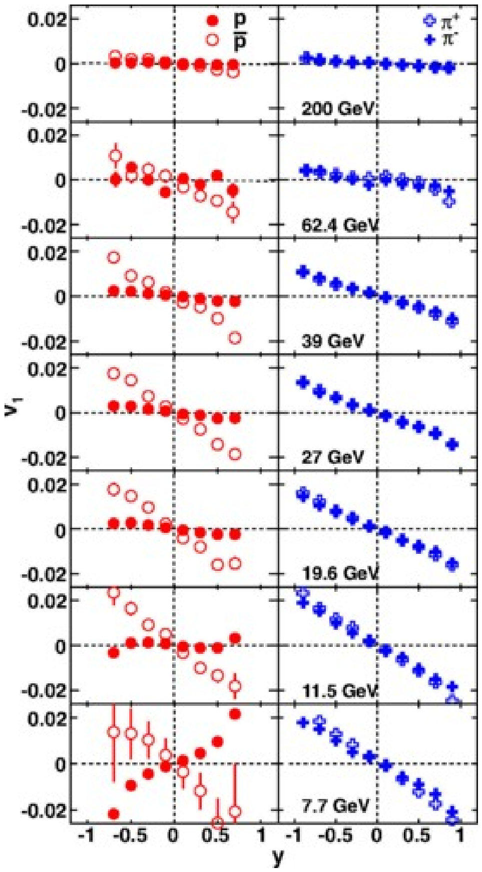
$$T^{\mu\nu}_{f0} = \int d^4p\, p^{*\mu} p^{*\nu} f_f(x,p) \quad J^\mu_f = \int d^4p\, p^{*\mu} f_f(x,p), \quad \rho_{f_s} = \int d^4p\, m^*\, f_f(x,p)$$

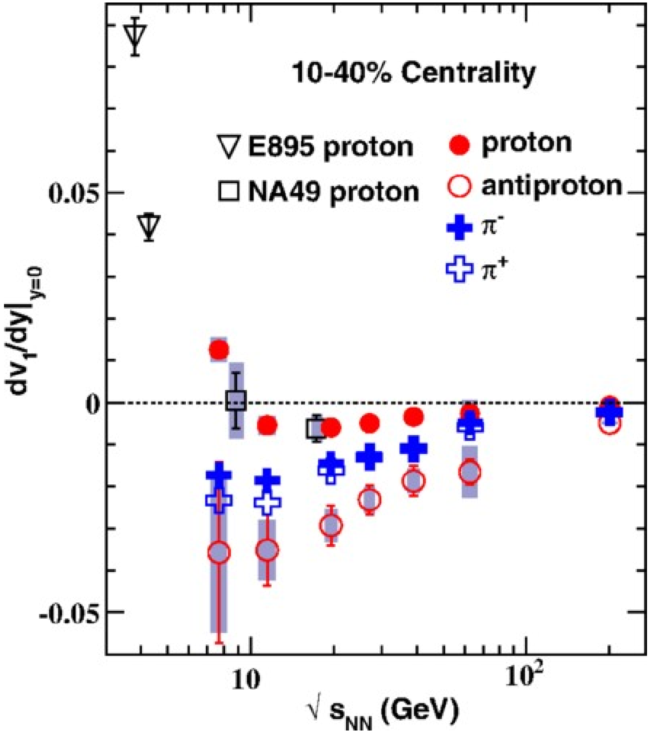
$$I^\mu_{fp} = \int d^4p\, p^\mu C_{fp} = n_f n_p \left\langle v_{rel} \int d\sigma (p' - p)^\mu \right\rangle$$

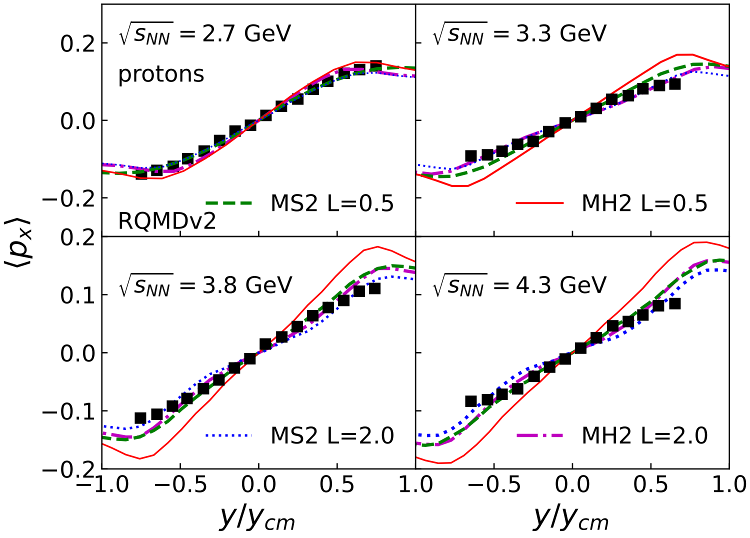
The collision rate times the average 4-momtnum loss $(p' - p)^\mu$

Beam energy dependence of v1

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







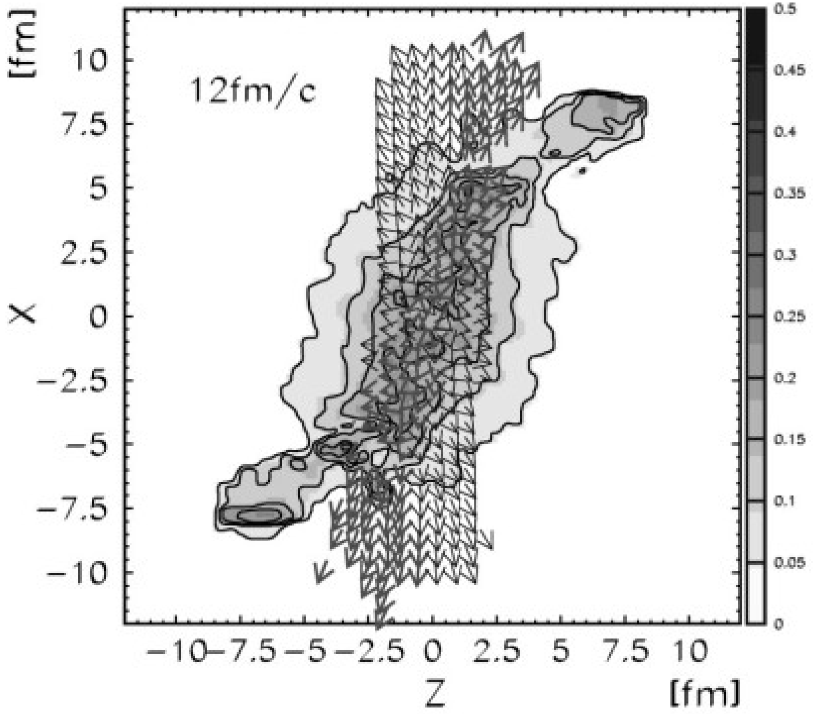
Hadronic transport model can explain v1 below AGS energies.

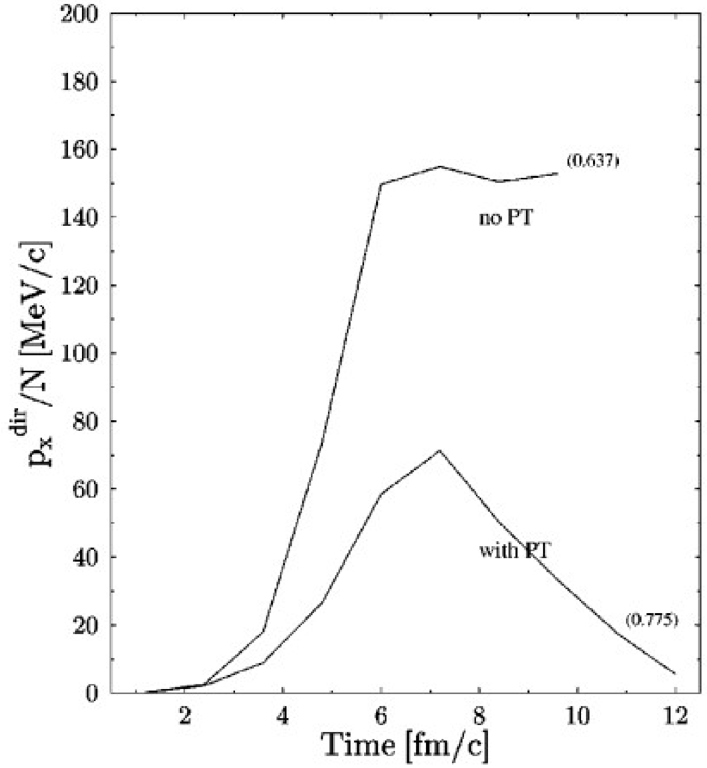
Signal of the 1st-order phase transition?

Tilted baryon density in 3FD

J.Brachmann,et.al. PRC61(2000)   1FD prediction: D.H.Rischke, et.al Acta.Phsy.Hung (1995)

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

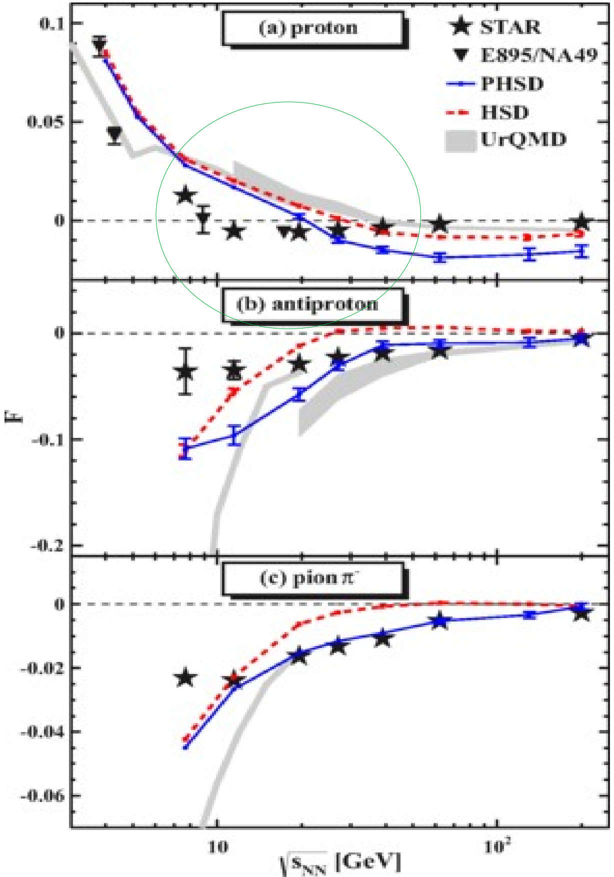




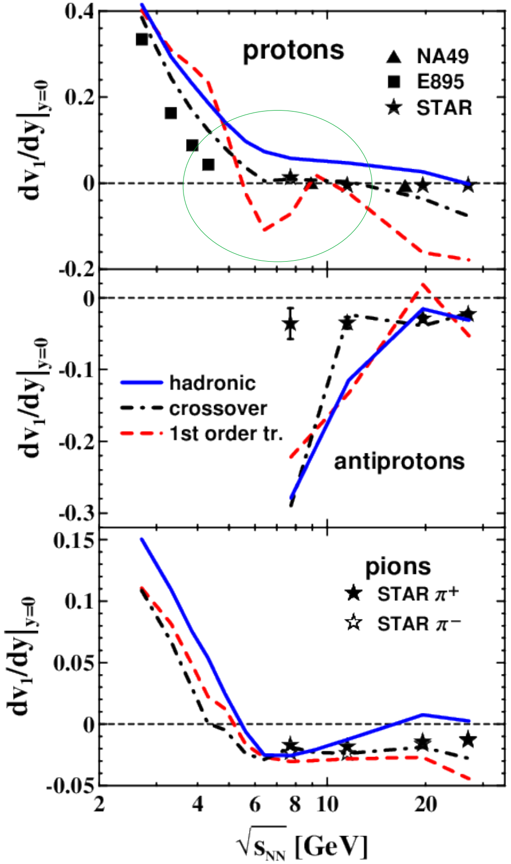
PHSD/HSD and 3FD predictions

V. P. Konchakovski,et.al,
Phys. Rev. C90, no. 1, 014903 (2014)

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



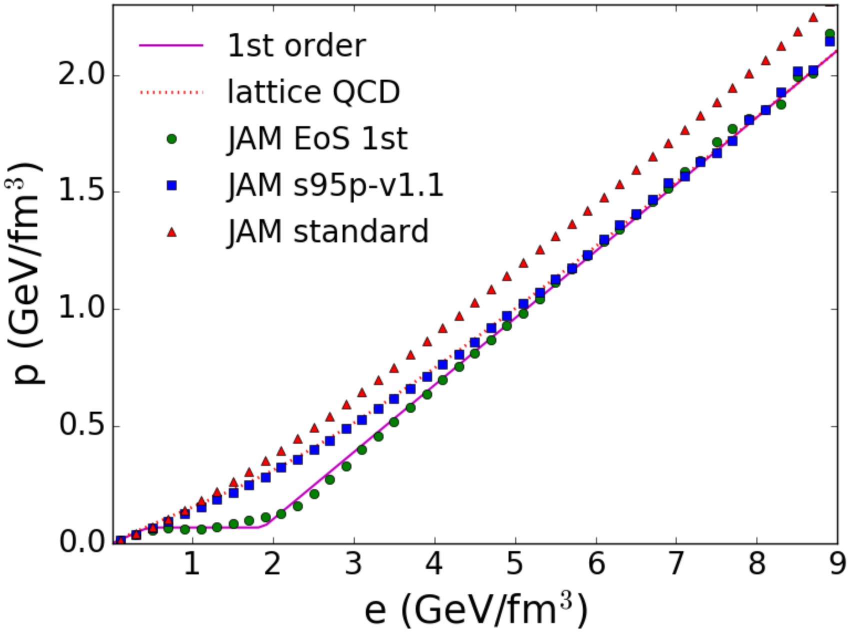
PHSD: negative above 27 GeV



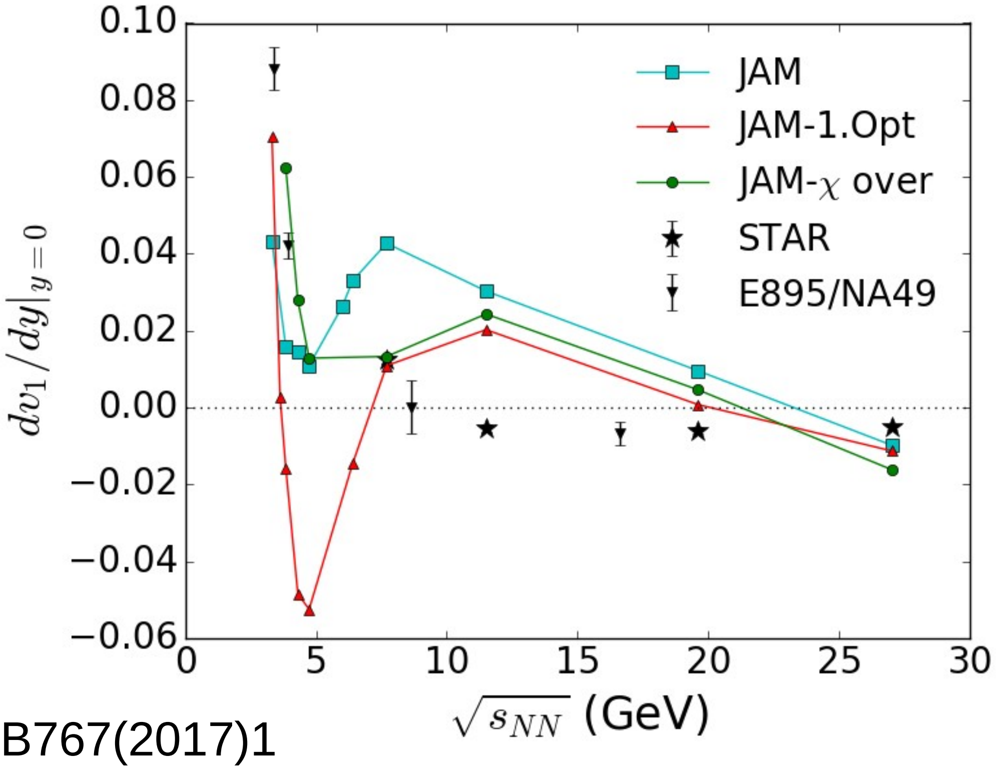
3FD:minium at 6GeV

v1 from EoS modified collision term

EoS modified collision term
provides efficient method
to control EoS in a
microscopic transport model.



JAM with fully baryon density dependent EoS meets hydro

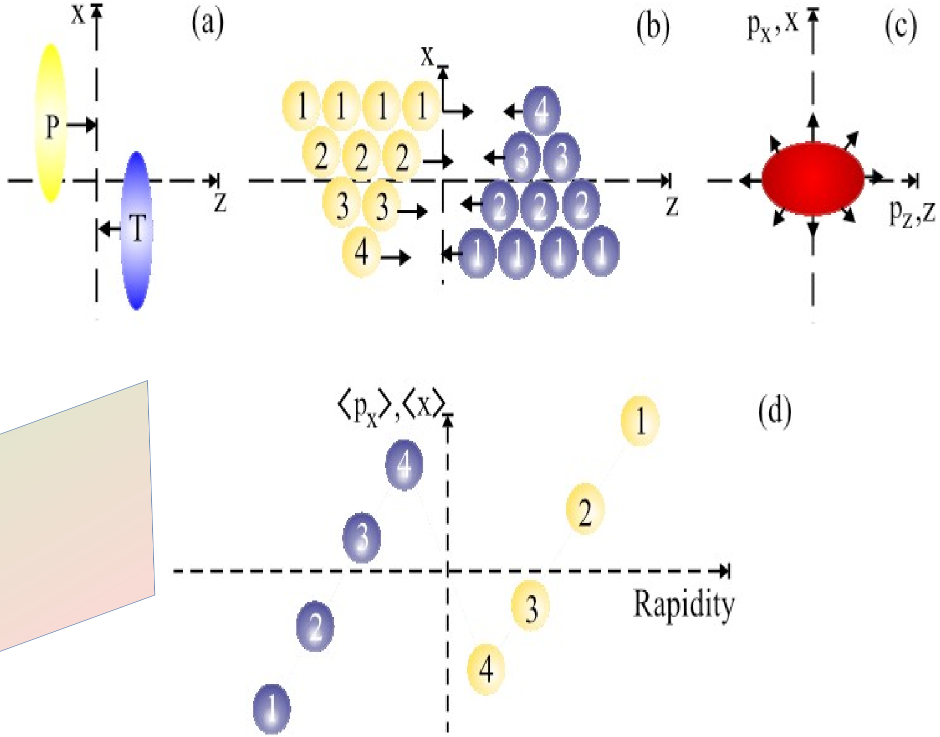


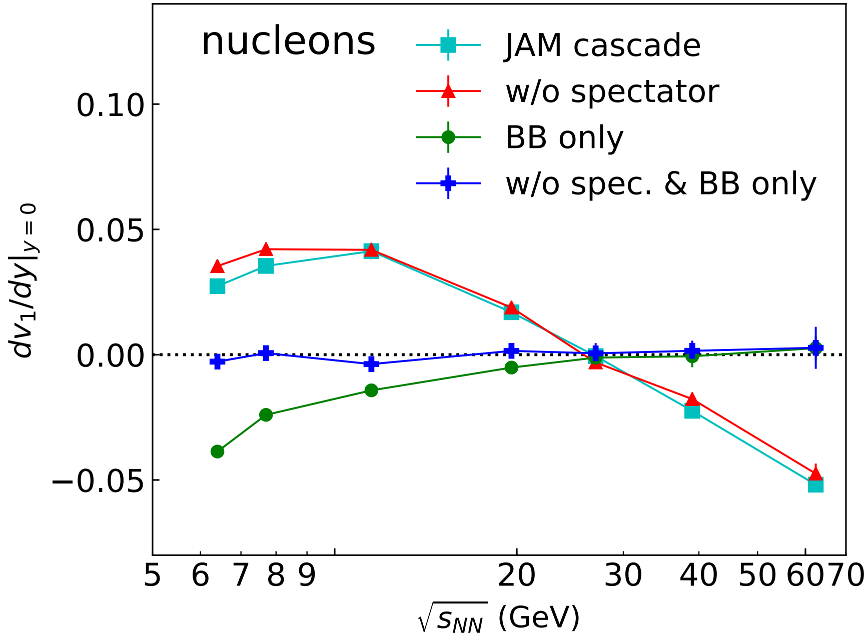
Y.Nara, PLB767(2017)1

Wiggle in the directed flow

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

Baryon stopping + Positive space-momentum correlation leads to negative v1 at mid-rapidity(wiggle)

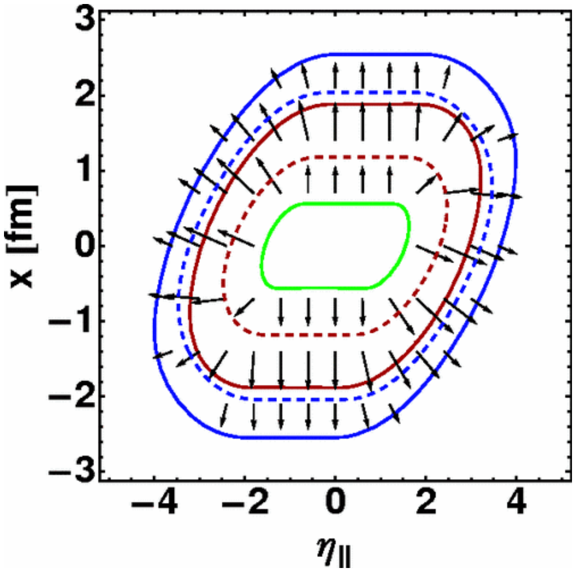




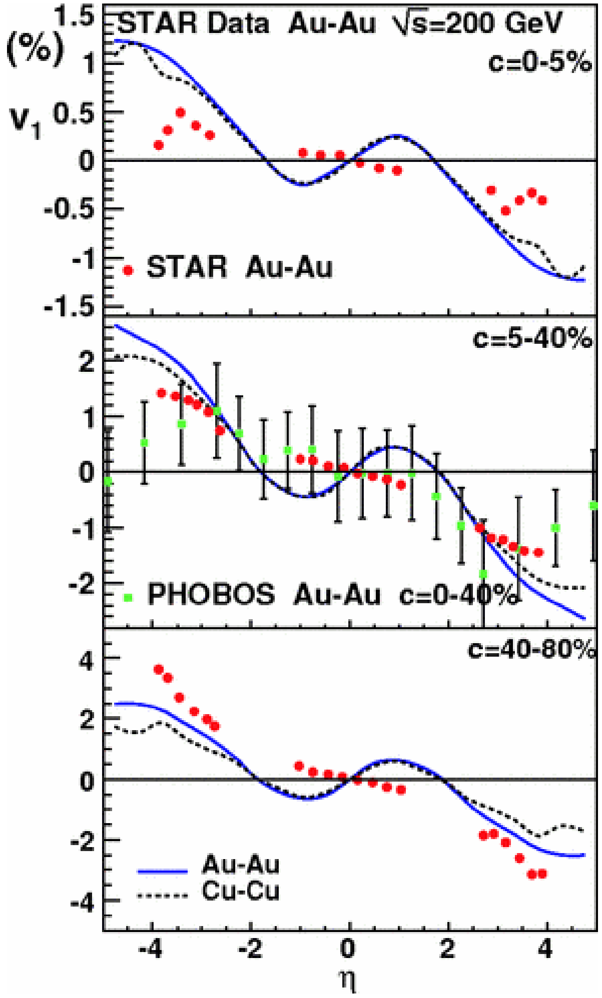
C.Zhang, et.al. PRC 97, 064913 (2018)

shifted initial condition for hydro

Hirano and Tsuda,PRC66(2002)
Hirano,Morita,Muroya,Nonaka,PRC65(2002)



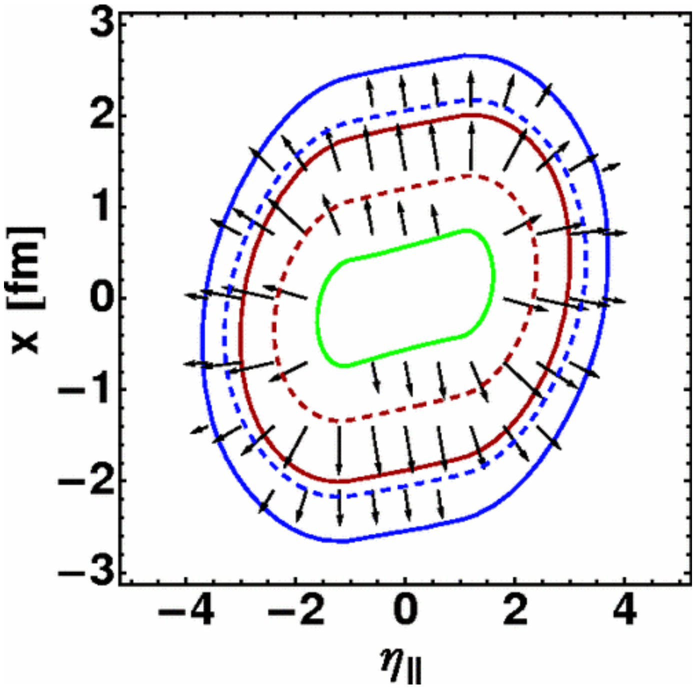
P.Bozek and I. Wyskiel,
PRC 81, 054902 (2010)

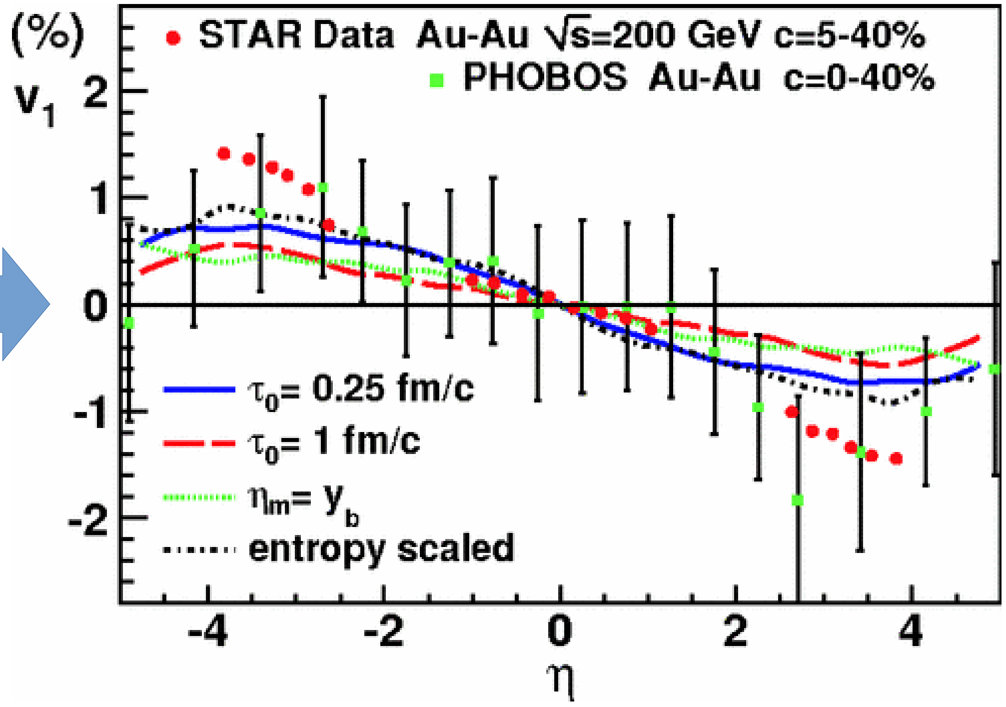


Shifted initial condition generates normal flow at mid-rapidity

Tilted initial condition for hydro

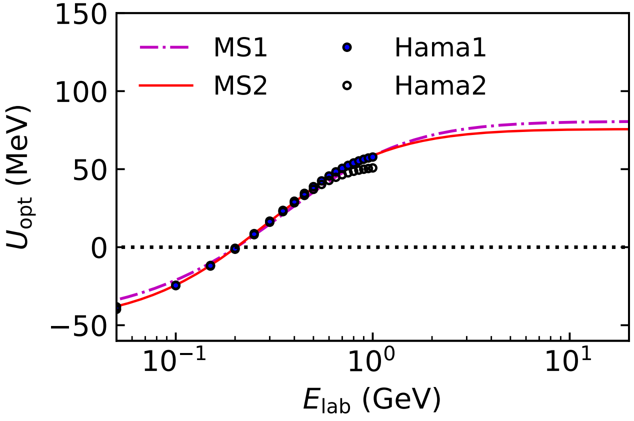
P.Bozek and I. Wyskiel, PRC 81, 054902 (2010)

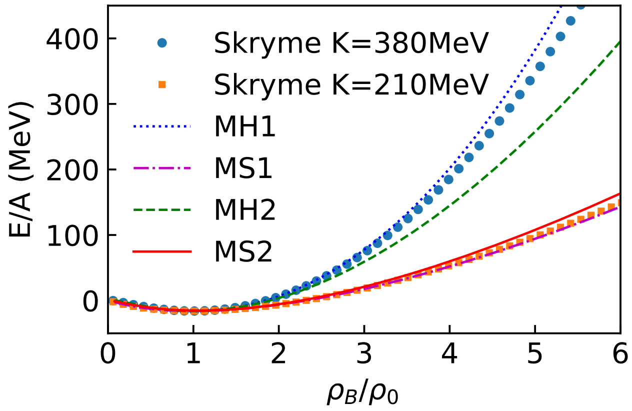




c.f. Adil,Gyulassy,Hirano, PRD73(2006) Twisted CGC predicts negative v1.

JAM2/RQMDv modeで用いられる状態方程式





スキルムベクターポテンシャル

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

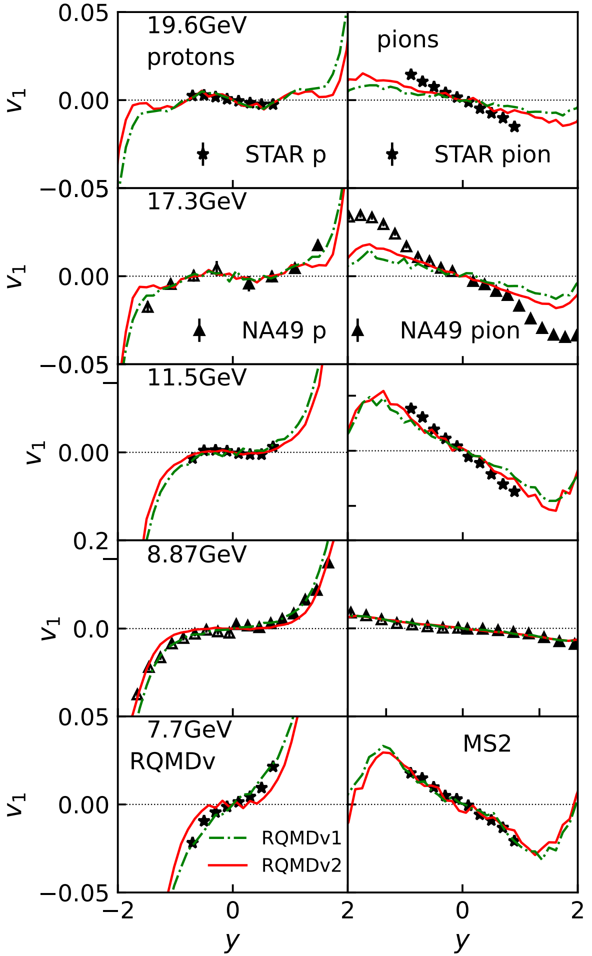
$$U_{\mathrm{sk}}(\rho) = \alpha\left(\frac{\rho}{\rho_0}\right) + \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma},$$

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

エネルギー密度:

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

A new result from RQMDv

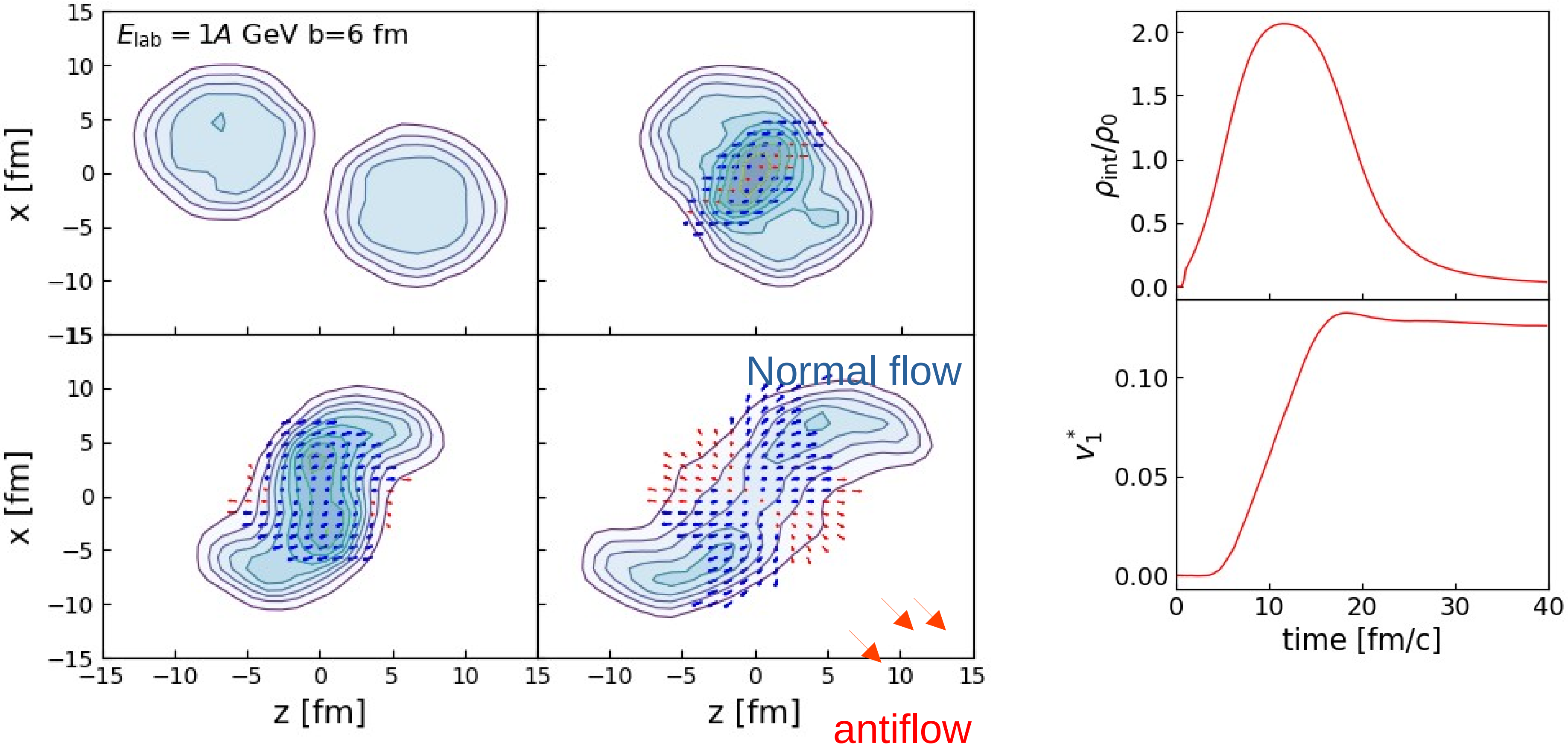


Beam energy dependence of v1 is explained by a new mean-field mode in JAM2.

原子核がすり抜けたあとの相互作用の強さ(圧力)でv1の符号が決定される。

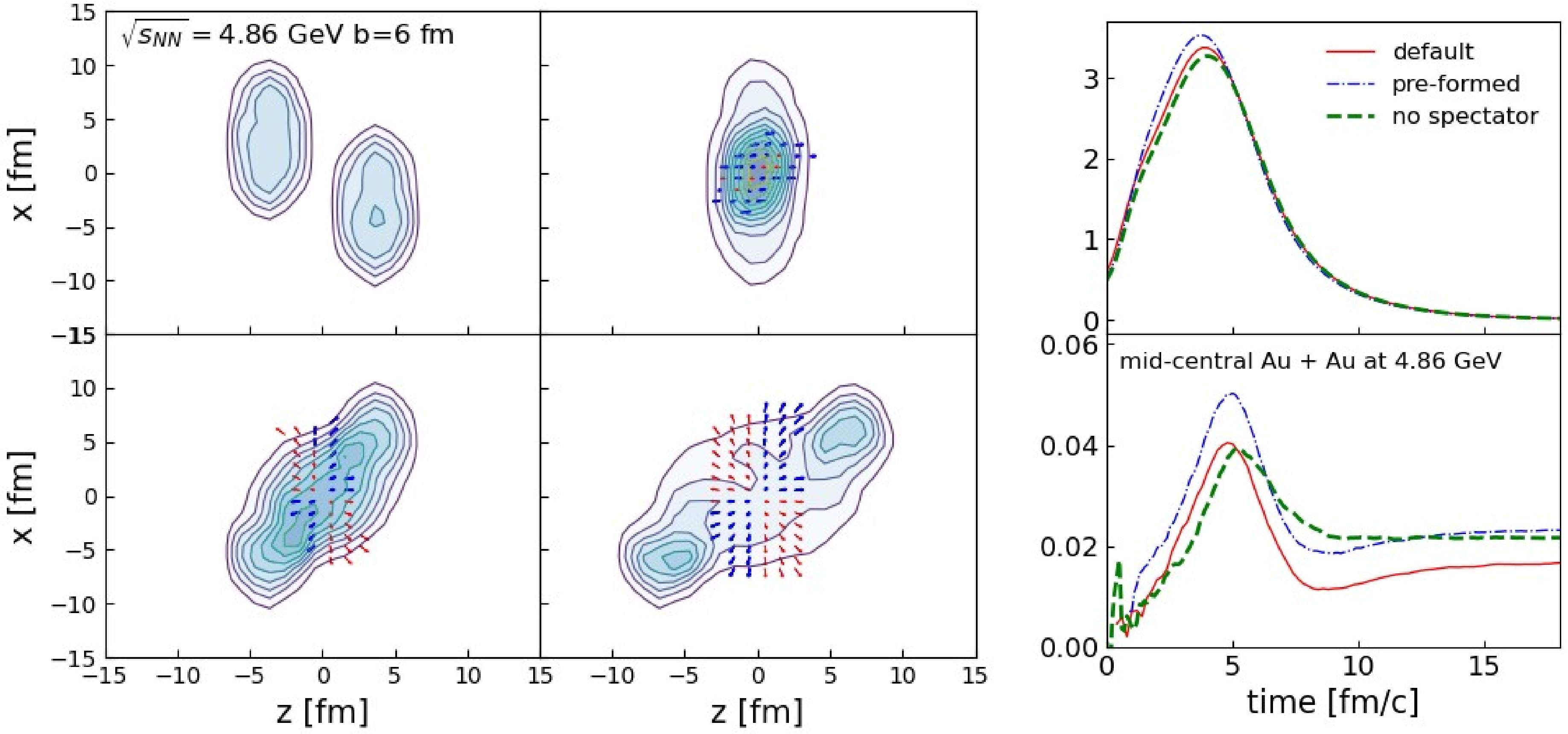
重イオン衝突における反応機構

Au+Au Elab=1AGeV, mid-central collision (b=6fm)のバリオン密度の時間発展



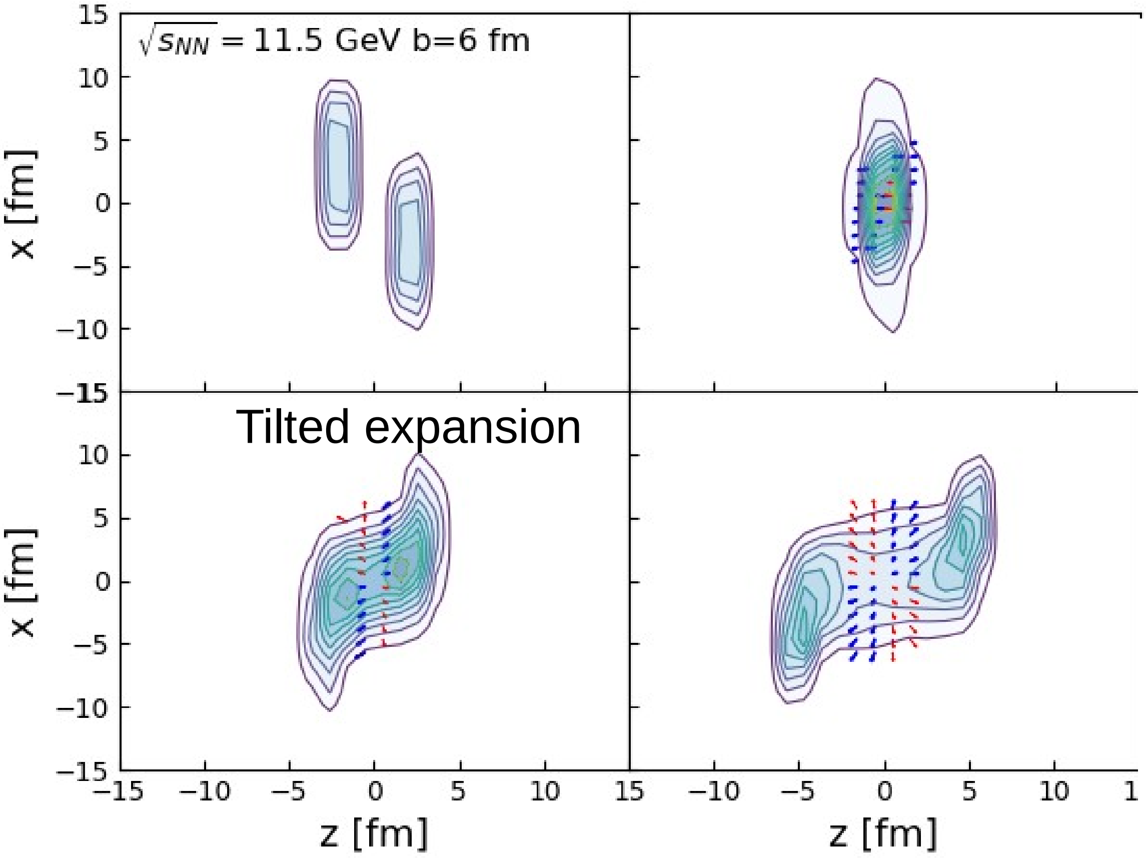
重イオン衝突における反応機構

Au+Au mid-central collision (b=6fm)のバリオン密度の時間発展

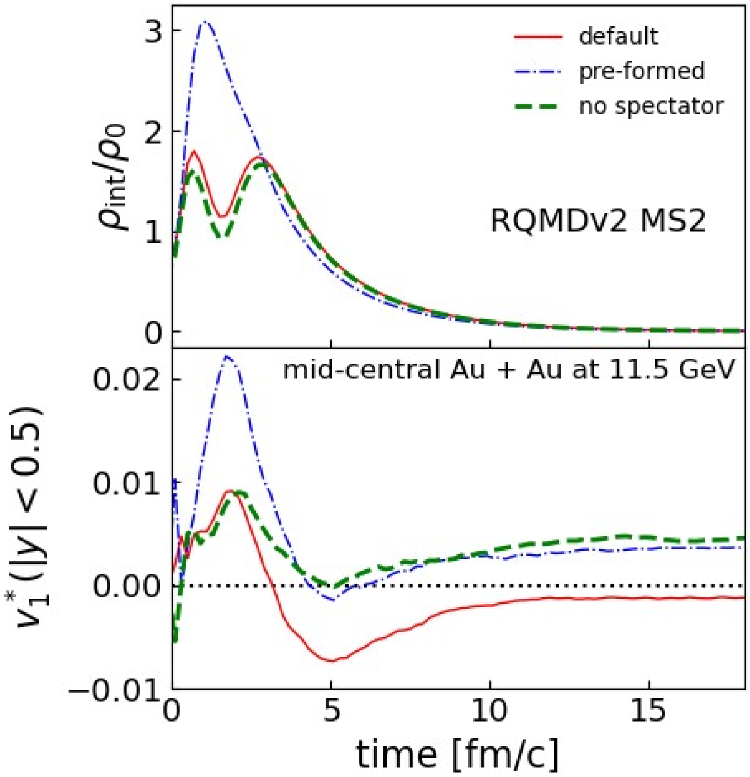


重イオン衝突における反応機構の変化

Au+Au mid-central collision (b=6fm)のバリオン密度の時間発展



Tilted expansion

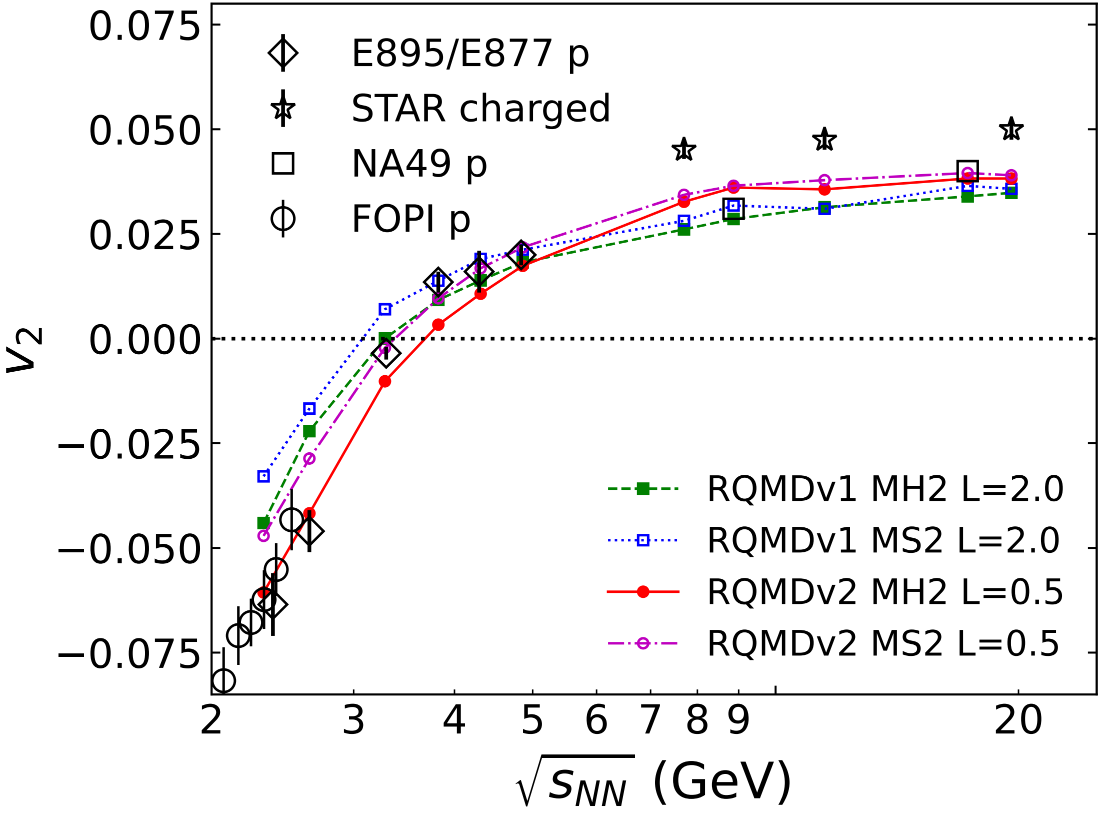


まとめ

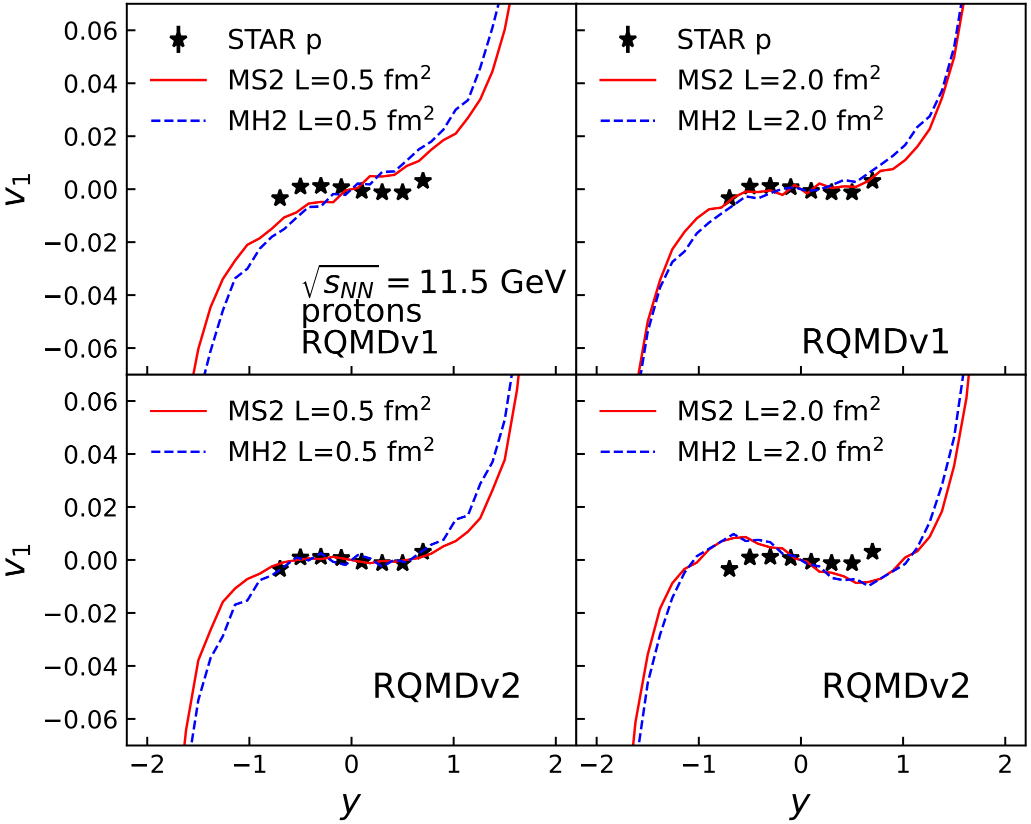
- 量子分子流体力学 (Quantum Molecular Fluid Dynamics)によるシミュレーションを行うために、C++で新しく開発したJAM2へ移行した。
- QMFD = Boltzmann type collision term + Fluid + RQMD
- 新開発したJAM2/RQMDv modeを用いて、directed flowの入射エネルギー依存性を説明することに成功した。
- N体非平衡微視的輸送モデルであるRQMDを用いてバリオン数高次揺らぎの計算を今後行いたい。

バックアップ

V2 from JAM2/RQMDv



Interaction dependence



原子核がすり抜けたあとの相互作用の強さ(圧力)でv1の符号が決定される。

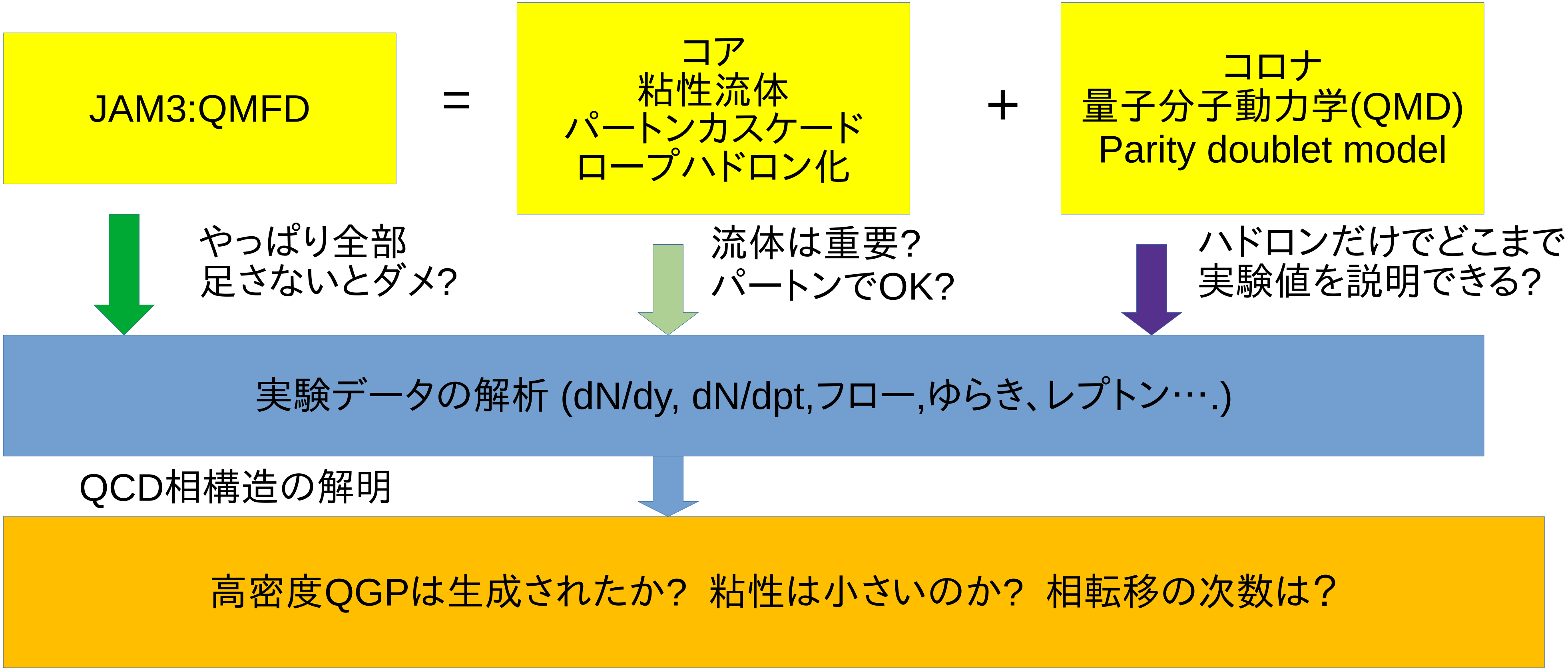
JAM2:micro-macro transport model
Quantum Molecular Fluid Dynamics (QMFD)

- 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

RHIC/LHCでの流体+ハドロンカスケードモデルは、AA collisionのdN/dy,dN/dmtはインプットであるが、このイベントジェネレーターではAAのインプットはない。

JAM3:量子分子流体力学
(Quantum Molecular Fluid Dynammics)



JAM3:QMFD

=

コア
粘性流体
パートンカスケード
ロープハドロン化

+

コロナ
量子分子動力学(QMD)
Parity doublet model

やっぱり全部
足さないとダメ?

流体は重要?
パートンでOK?

ハドロンだけでどこまで
実験値を説明できる?

実験データの解析 (dN/dy, dN/dpt,フロー,ゆらき、レプトン….)

QCD相構造の解明

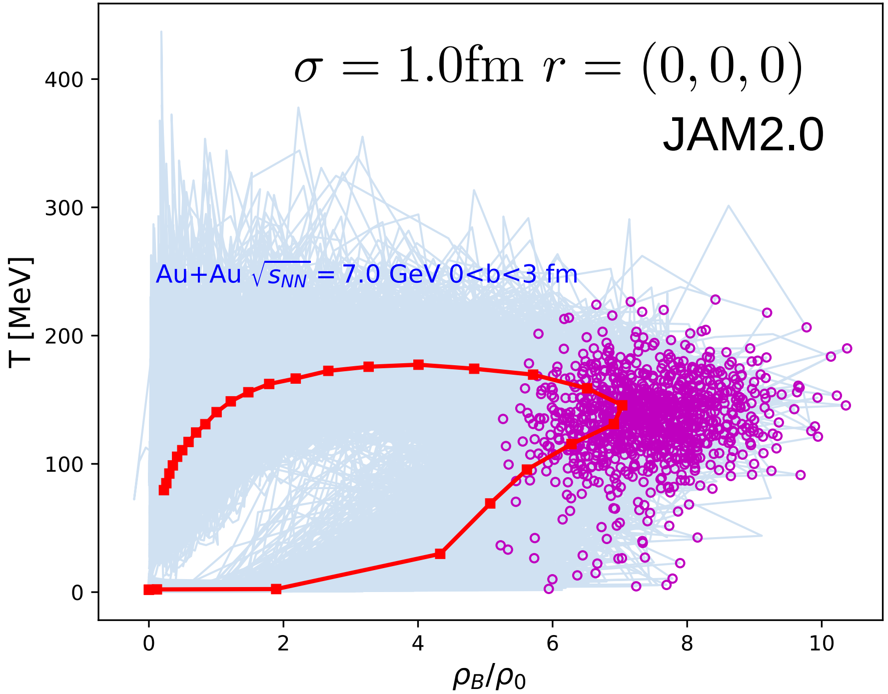
高密度QGPは生成されたか？ 粘性は小さいのか？ 相転移の次数は？

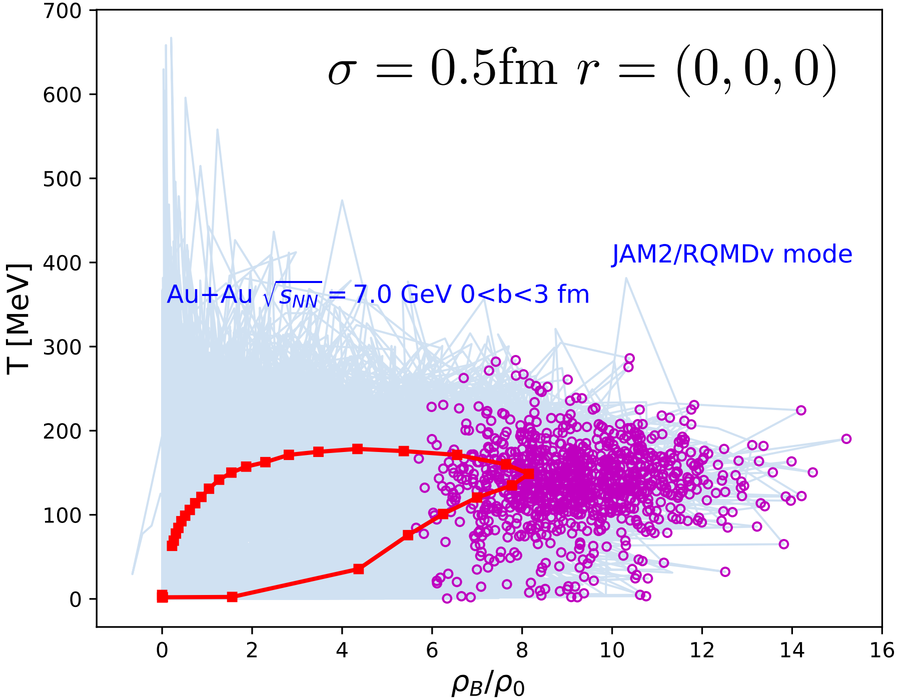
Time evolution of rho-T in Au+Au at 7.0 GeV

$$T^{\nu}(\boldsymbol{r}) = \sum_i \frac{p^{\mu}p^{\nu}}{p^0} G(\boldsymbol{r} - \boldsymbol{r}_i)$$

$$J^{\mu}(\boldsymbol{r}) = \sum_i \frac{p^{\mu}}{p^0} G(\boldsymbol{r} - \boldsymbol{r}_i)$$

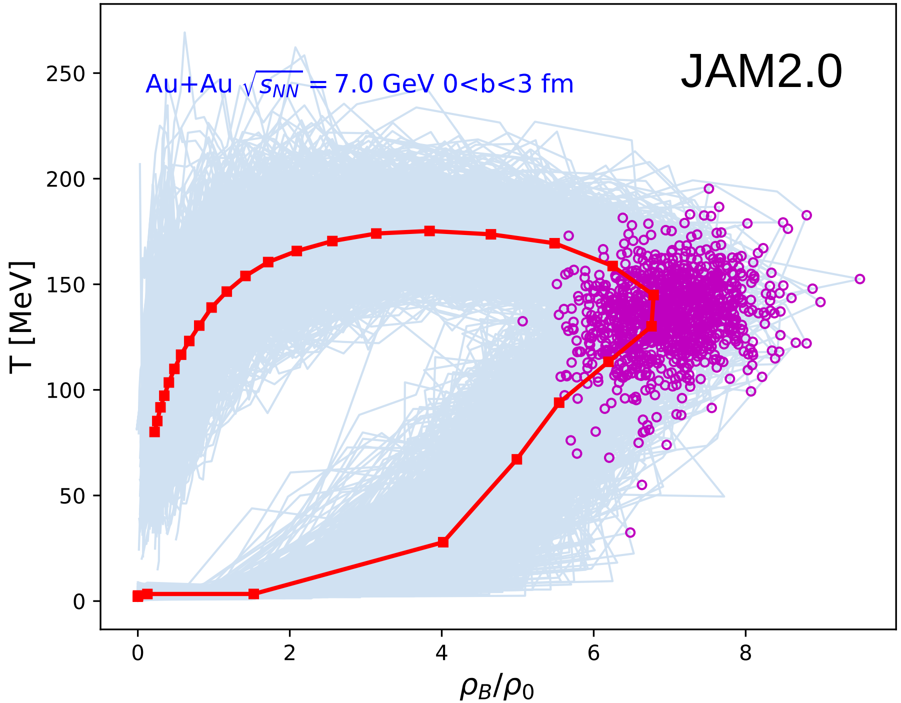
$$G(\boldsymbol{r}) = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left(-\frac{\boldsymbol{r}^2 + (\boldsymbol{r}\cdot\boldsymbol{u})^2}{2\sigma^2}\right)$$



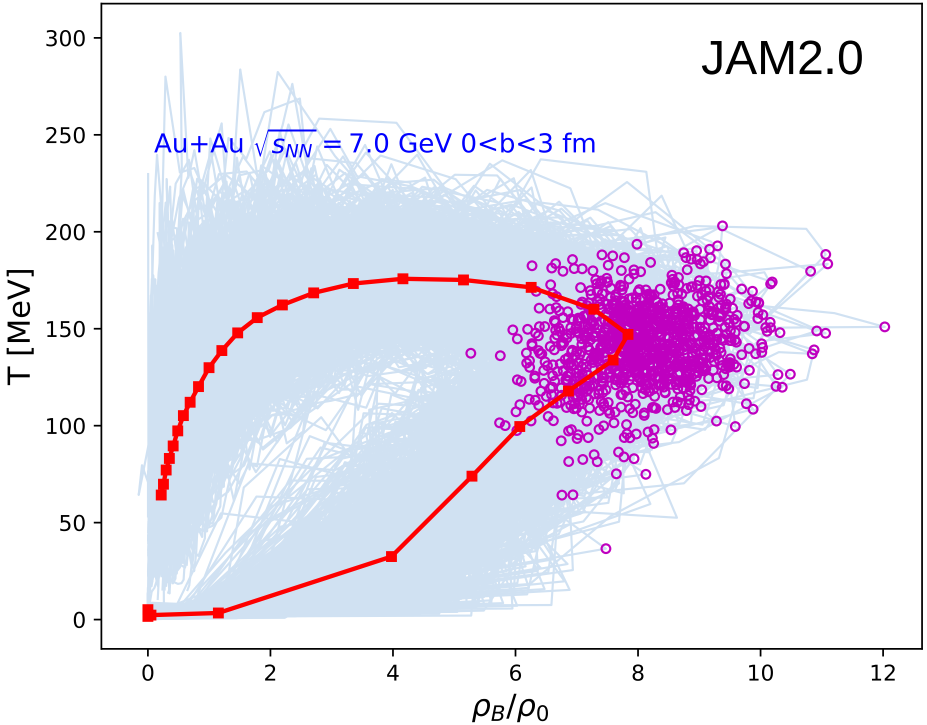


Time evolution of rho-T in Au+Au at 7.0 GeV

$\sigma = 1.0\text{fm}\ V = 1^3/\gamma$

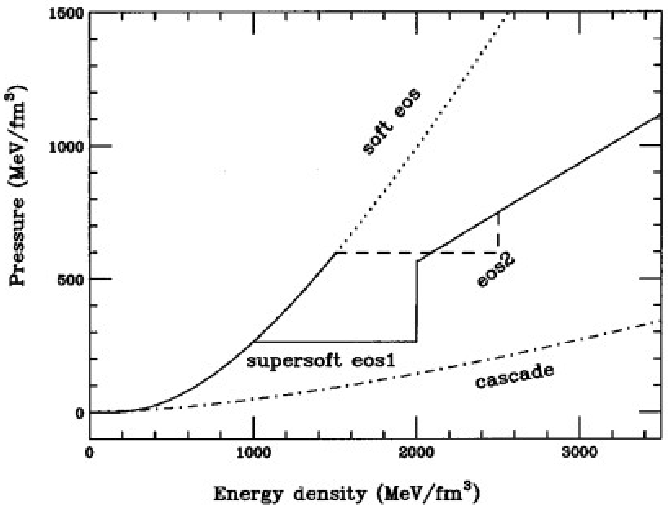


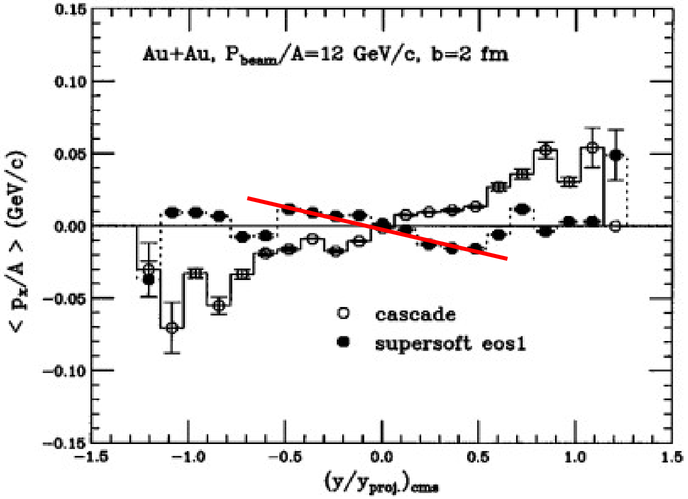
$\sigma = 0.5\text{fm}\ V = 1^3/\gamma$

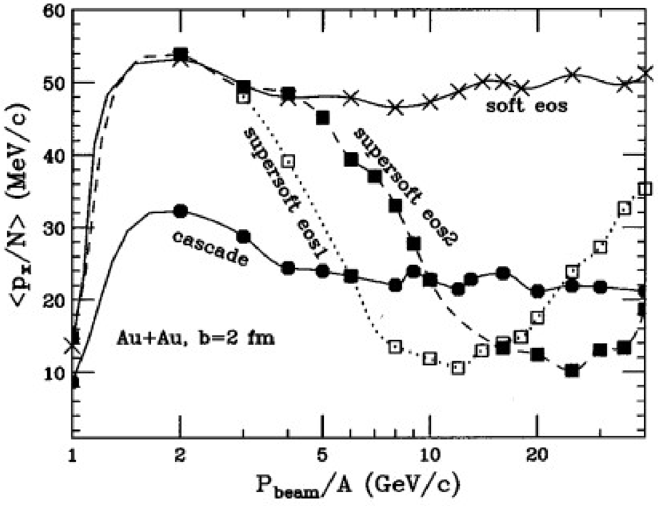


ART transport model with phase transition

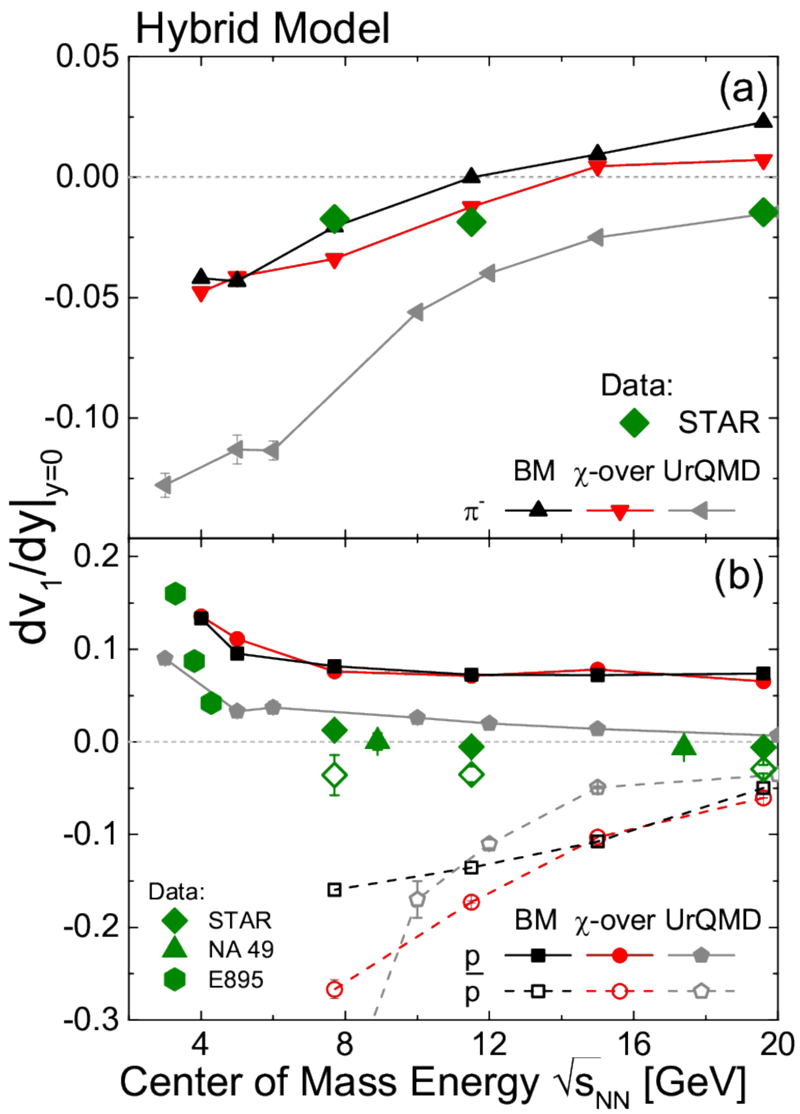
B-A. Li and C.M. Ko, PRC58(1998)R1382







$$\langle P_x/N\rangle = \frac{1}{N}\int \langle P_x/N\rangle(y)\,\frac{dN}{dy}\,\mathrm{sgn}(y)\,dy$$



Hybrid transport + hydro results

J. Steinheimer et al. PRC89, 054913(2014)

Hybrid modelの低エネルギーへの適用の例

流体は原子核が通り抜けた後からはじまると仮定

7.7 GeV → 3.2 fm/c
19.6 GeV → 1.22 fm/c

BM: Bag-model 1st-order EoS
X-over: Crossover from chiral model