Effects of Dissipative Baryon Current in Heavy-Ion Collisions at RHIC-BES Energies

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Outline

Introduction

Model Setup

- (3+1)-dimensional CLVisc hydrodynamics model with dissipative baryon current

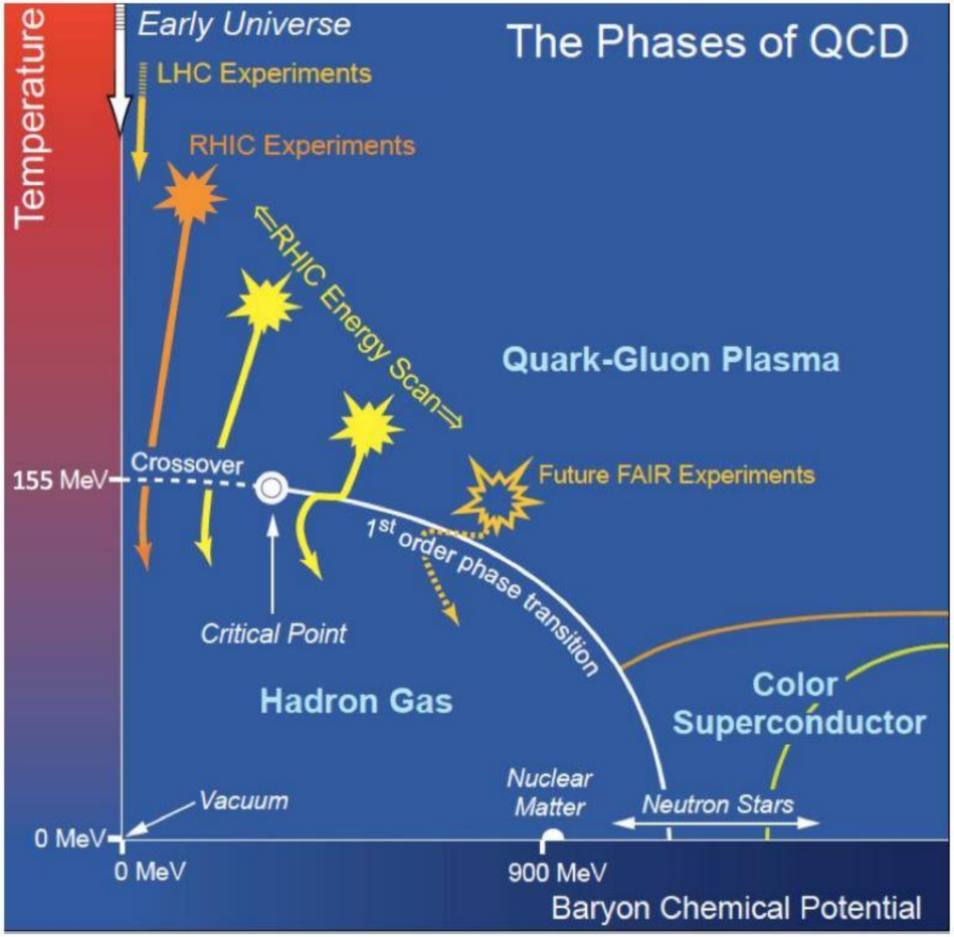
Numerical Results

Effects of dissipative baryon current on

- particle yield
- transverse momentum spectra of π, K, net-proton
- elliptic flow of π, net-proton

Conclusion

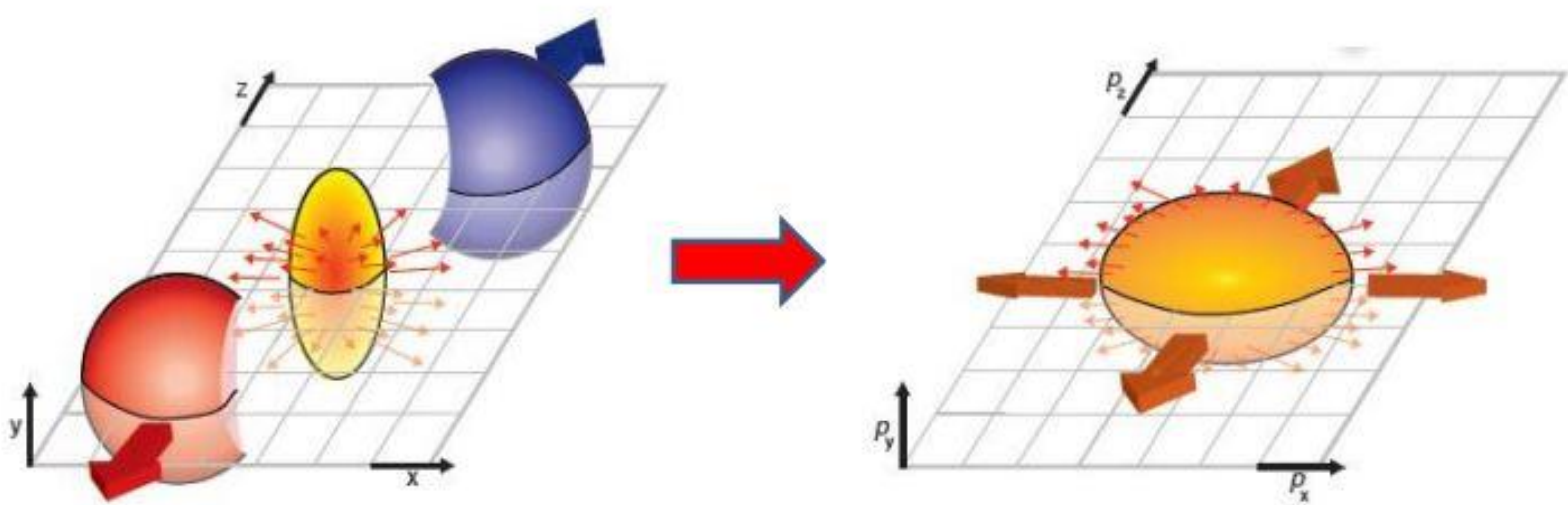
QCD phase diagram



At LHC & top RHIC collision energy,
QGP -> Hadron Gas:
Crossover

At Beam energy scan region,
QGP -> Hadron Gas:
1^{st} order phase transition or
Critical Point

Collective flow

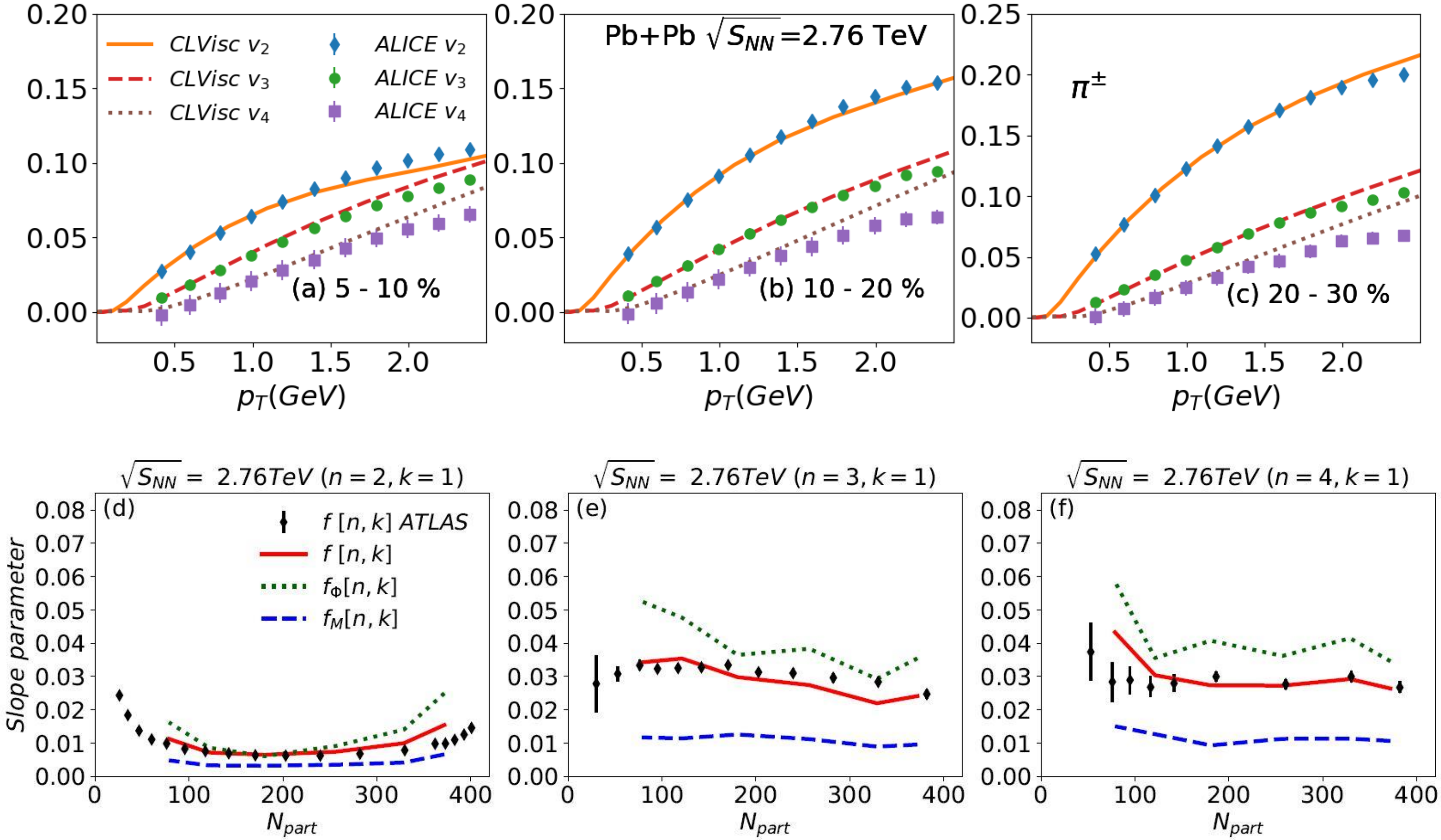


$$\frac{dN}{p_T\,dp_T\,dy\,d\phi} = \frac{dN}{2\pi p_T\,dp_T\,dy}\left[1 + 2\sum_n v_n(p_T, y)\cos\left(n\left(\phi - \Psi_n(p_T, y)\right)\right)\right]$$

The collective flow of the QGP fireball converts initial state geometric anisotropy to final state momentum anisotropy.

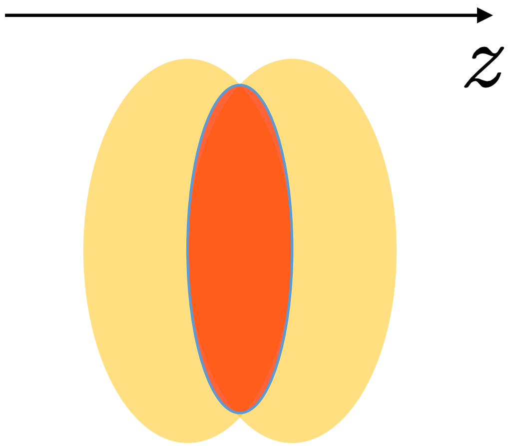
Hydrodynamics at high collision energy

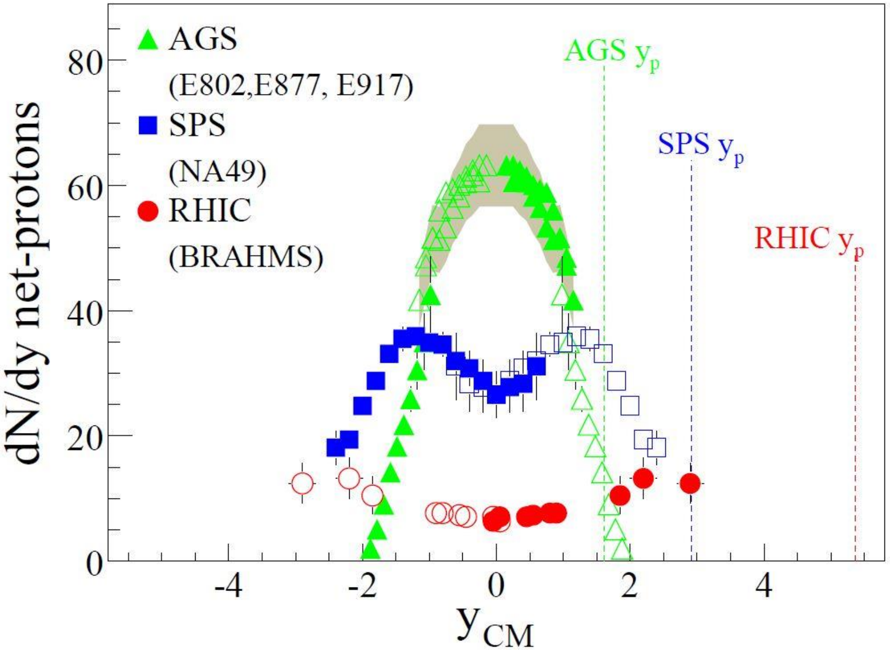
Hydrodynamic simulation is successful in describing the collective behavior of QGP fireball at zero chemical potential both in transverse plane and longitudinal direction .



[Wu, Xiang-Yu *et al.* Phys.Rev. C98 (2018) no.2, 024913 arXiv:1805.03762 [nucl-th]]

Hydrodynamics at low collision energy





BRAHMS Collaboration (Bearden, I.G. *et al.*) Phys.Rev.Lett. 93 (2004) 102301 nucl-ex/0312023

More net-baryons are observed at central rapidity region due to stronger baryon stopping at lower collision energy.

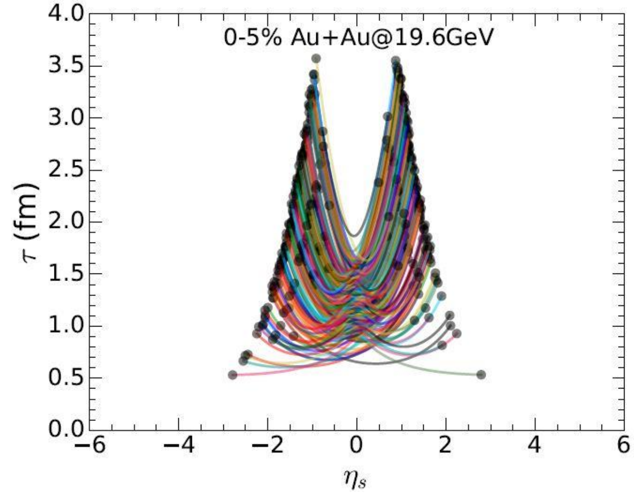
The dissipation of net-baryon current plays an important role at BES energies.

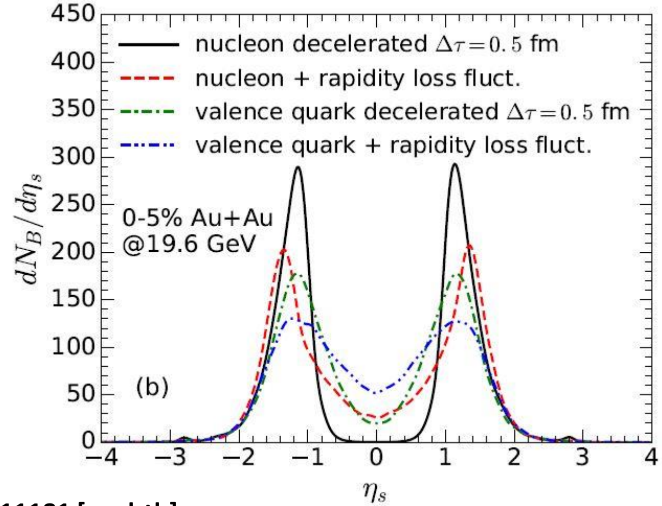
Theoretical progress

3D Monte-Carlo Glauber model + MUSIC

Denicol, Gabriel S. *et al.* Phys.Rev. C98 (2018) no.3, 034916 arXiv:1804.10557 [nucl-th]

Shen, Chun *et al.* Phys.Rev. C97 (2018) no.2, 024907 arXiv:1710.00881 [nucl-th]

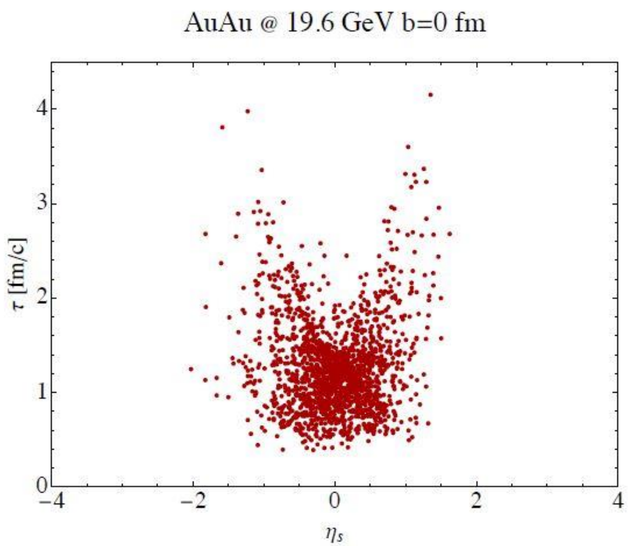


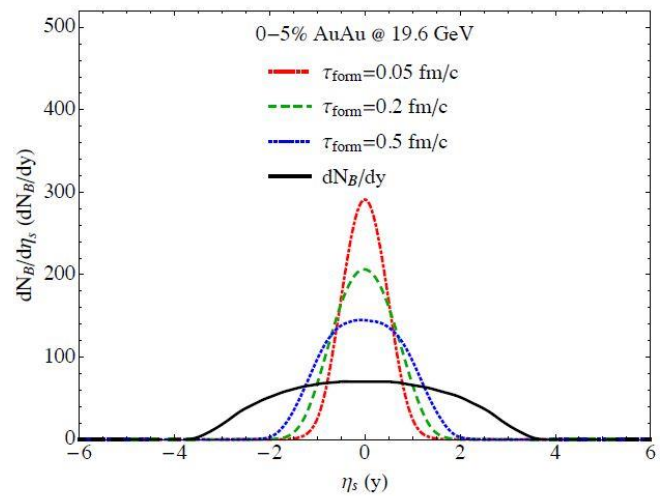


URQMD+BESHYDRO

Du, Lipei *et al.* arXiv:1906.11181 [nucl-th]

Du, Lipei *et al.* Nucl.Phys. A982 (2019) 407-410 arXiv:1807.04721 [nucl-th]





CLVisc at non-zero μ_B

We extend the CLVisc hydrodynamic model to a non-zero baryon environment.

Energy – momentum conservation and net baryon current conservation:

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = eU^\mu U^\nu - (P + \Pi) + \pi^{\mu\nu}$$

$$\partial_\mu J^\mu = 0 \qquad J^\mu = nU^\mu + V^\mu$$

Equation of motion of dissipative current:

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - \eta\sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha\langle}\,\sigma^{\mu\nu\rangle}_{\alpha} + \frac{9}{70}\frac{4}{e+P}\pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}$$

$$\Delta^{\mu\nu} DV_\mu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}$$

The shear viscosity η

$$\frac{\eta T}{e+P} = C_\eta$$

The baryon diffusion coefficient κ_B (Boltzmann equation by relaxation time approximation)

$$\kappa_B = \frac{C_B}{T} n\left(\frac{1}{3}\cot\left(\frac{\mu_B}{T}\right) - \frac{nT}{e+P}\right)$$

Denicol, Gabriel S. *et al.* Phys.Rev. C98 (2018) no.3, 034916 arXiv:1804.10557 [nucl-th]

CLVisc at non-zero μ_B

Equation of state P(e, n): NEOSB (Based on Taylor expansion, LQCD+hadron gas, crossover)

Monnai, Akihiko *et al.* Phys.Rev. C100 (2019) no.2, 024907 arXiv:1902.05095 [nucl-th]

Akihiko Monnai's talk@6 Nov, 16:20

Initial condition: MC Glauber model

Local entropy density
$$s(x,y,\eta)|_{\tau_0} = \frac{K}{\tau_0}\left(H_P^s(\eta)s_p(x,y) + H_T^s s_T(x,y)\right)$$

Local baryon density
$$n(x,y,\eta)|_{\tau_0} = \frac{1}{\tau_0}\left(H_P^n(\eta)s_p(x,y) + H_T^n s_T(x,y)\right)$$

where
$$s_{P/T}(x,y) = \sum_{i=1}^{N_{\rm part}^{P/T}} \frac{1}{2\pi\sigma_r{}^2}\exp\left(-\frac{(x-x_i)^2+(y-y_i)^2}{2\pi\sigma_r^2}\right),\ \tau_0 = \tau_{\rm overlap} = \frac{2R}{\sqrt{\gamma^2-1}}$$

Longitudinal profile

$$H^s_{P/T} = \theta(\eta_{\rm max}-|\eta|)\left(1\pm\frac{\eta}{y_{\rm beam}}\right)\left[\theta(|\eta|-\eta_0^s)\exp\left(-\frac{(|\eta|-\eta_0^s)^2}{2\sigma_s{}^2}\right)+\theta(\eta_0^s-|\eta|)\right]$$

$$H^n_{P/T} = \frac{1}{N}\left[\theta(\eta-\eta_0^{n,P/T})\exp\left(-\frac{(\eta-\eta_0^{n,P/T})^2}{2\sigma_{P/T}^2}\right)+\theta(\eta_0^{n,P/T}-\eta)\exp\left(-\frac{(\eta-\eta_0^{n,P/T})^2}{2\sigma_{T/P}^2}\right)\right]$$

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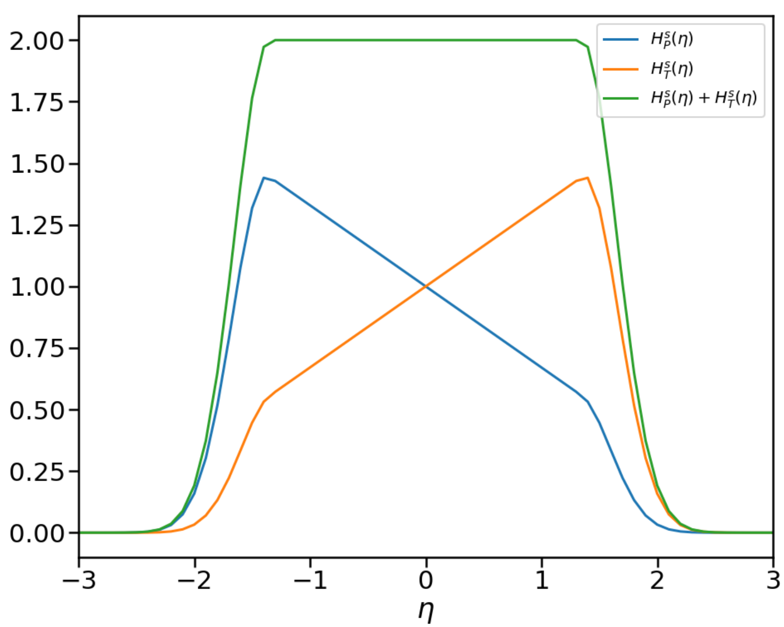
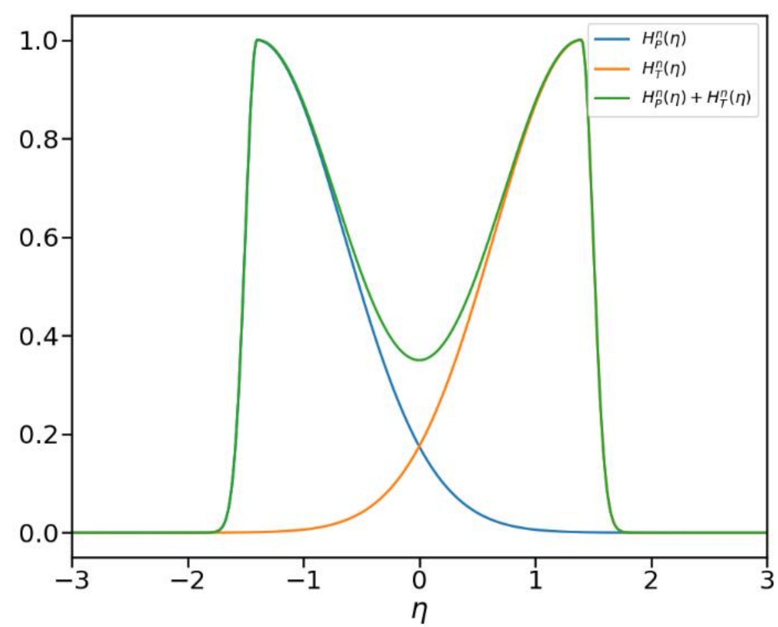
Longitudinal profile





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Cooper-Frye Formula

$$E\frac{dN_h}{d^3p} = \frac{g_h}{(2\pi)^3}\int_\Sigma p^\mu d^3\sigma^\mu f(x,p)$$

where the phase-space distribution $f(x,p) = f^{eq}(x,p) + \delta f^\pi(x,p) + \delta f^n(x,p)$

In relaxation time approximation, the baryon diffusion correction

$$\delta f^n(x,p) = f^{eq}(1 \pm f^{eq}(x,p))\left(\frac{n}{e+P} - \frac{b}{u^\mu p_\mu}\right)\frac{p^\mu V_\mu}{\overline{\kappa}_B}$$

Denicol, Gabriel S. *et al.* Phys.Rev. C98 (2018) no.3, 034916 arXiv:1804.10557 [nucl-th]

Transverse: Gubser flow

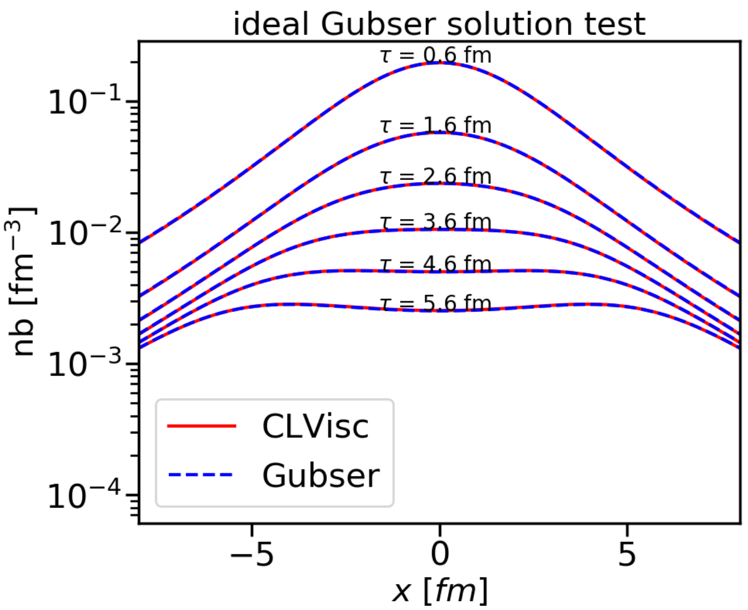
To test the numerical accuracy of new CLVisc code, we compare our numerical results with both analytical solutions of the hydrodynamic equations and other independent codes.

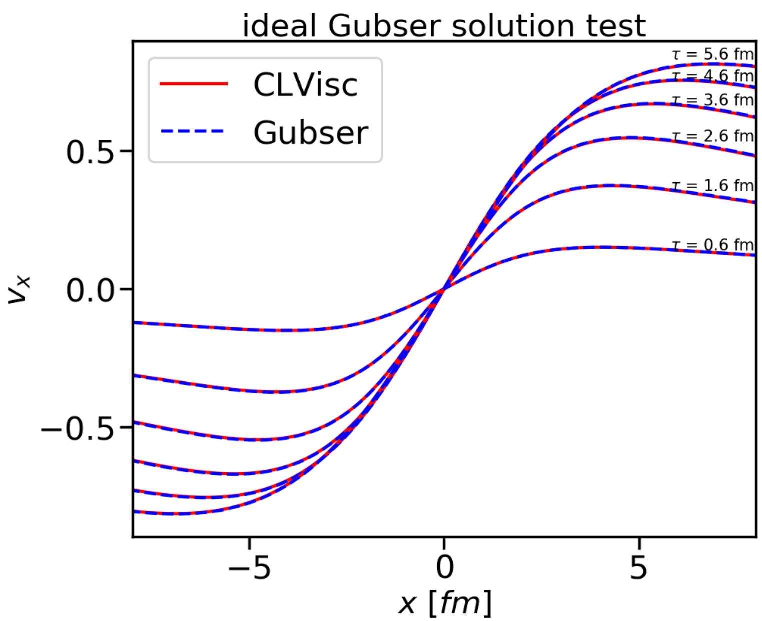
Gubser flow: strong radial flow, longitudinal invariance in conformal system.

$$\varepsilon(\tau,r)=\frac{\varepsilon}{\tau^4}\frac{(2q\tau)^{\frac{8}{3}}}{[1+2q^2(\tau^2+r^2)+q^4(\tau^2-r^2)^2]^{\frac{4}{3}}}$$

$$n(\tau,r)=\frac{n_0}{\tau^4}\frac{(2q\tau)^2}{[1+2q^2(\tau^2+r^2)+q^4(\tau^2-r^2)^2]}$$

with $v_\perp(\tau,r)=\dfrac{2q^2\tau r}{1+(q\tau)^2+(qr)^2}$





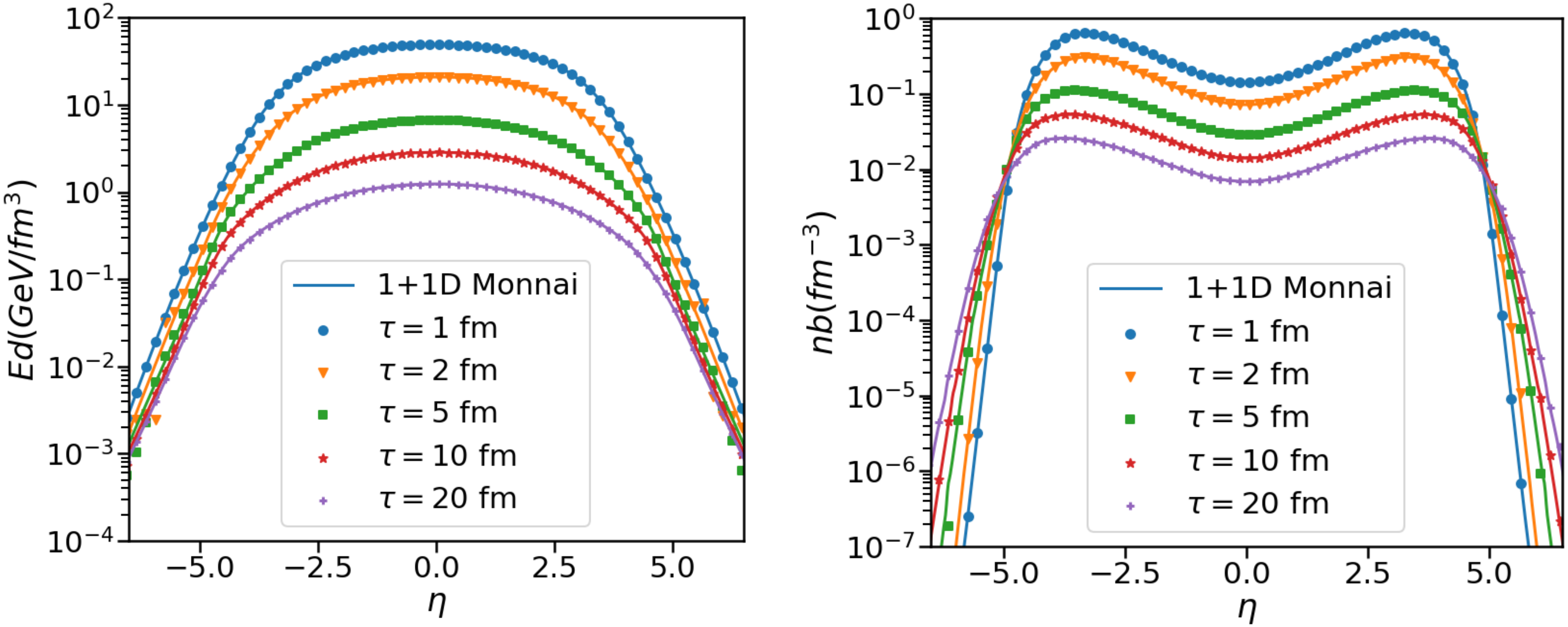
Longitudinal: (1+1)D Monnai's code

In longitudinal direction, we compare between the CLVisc's numerical results and (1+1) D hydrodynamic code by Monnai.

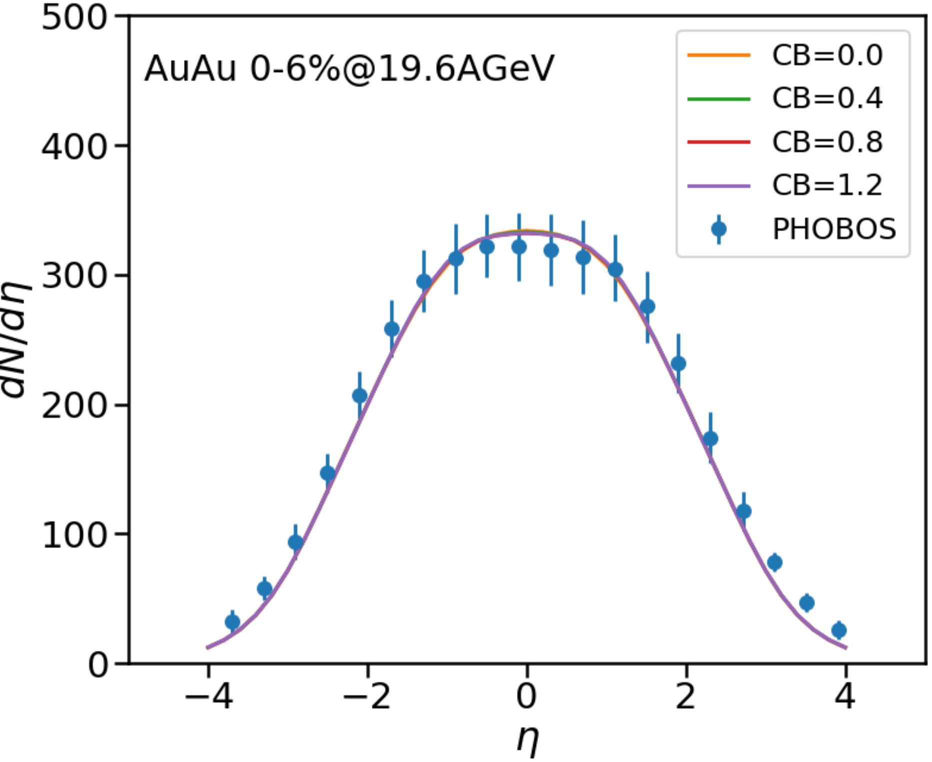
$$\Delta^{\mu\nu} DV_{\mu} = -\frac{1}{\tau_{V}}\left(V^{\mu} - \kappa_B \nabla^{\mu}\frac{\mu}{T}\right)$$

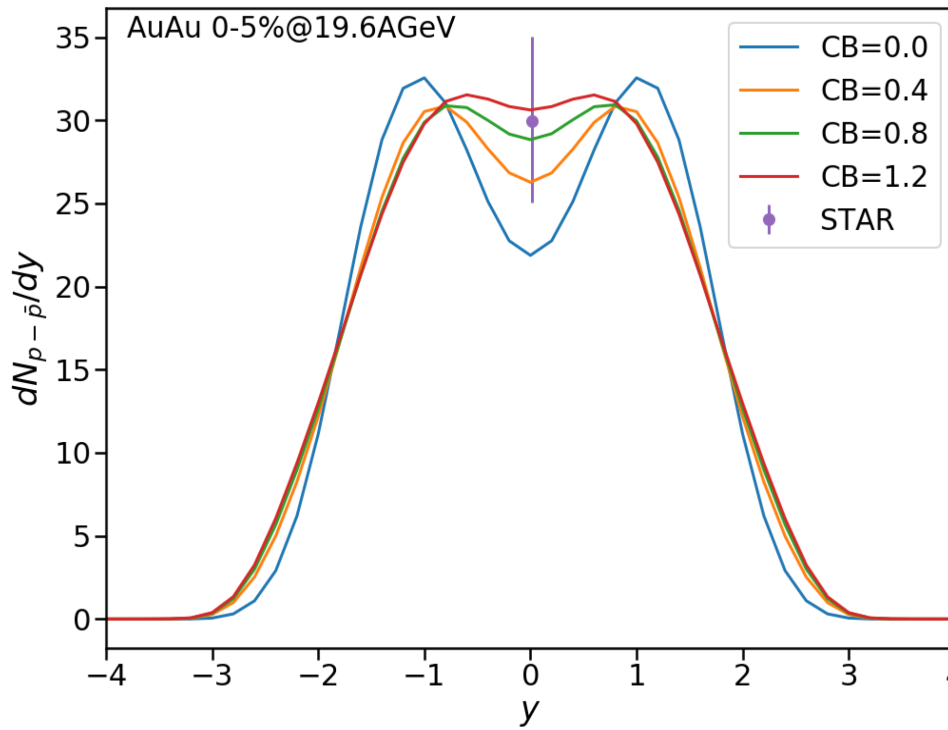
where $\kappa_B = \dfrac{0.2n}{\mu_B}$ $\quad \tau_V = \dfrac{0.2}{T}$

Denicol, Gabriel S. *et al.* Phys.Rev. C98 (2018) no.3, 034916 arXiv:1804.10557 [nucl-th]
Monnai, Akihiko Phys.Rev. C86 (2012) 014908 arXiv:1204.4713 [nucl-th]



Particle yield

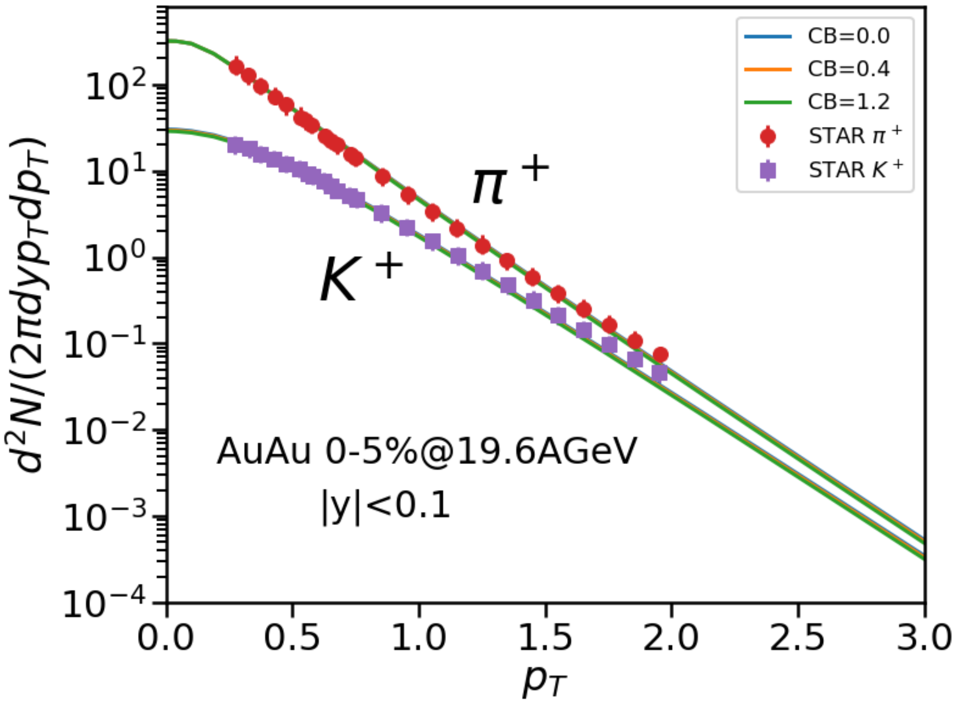


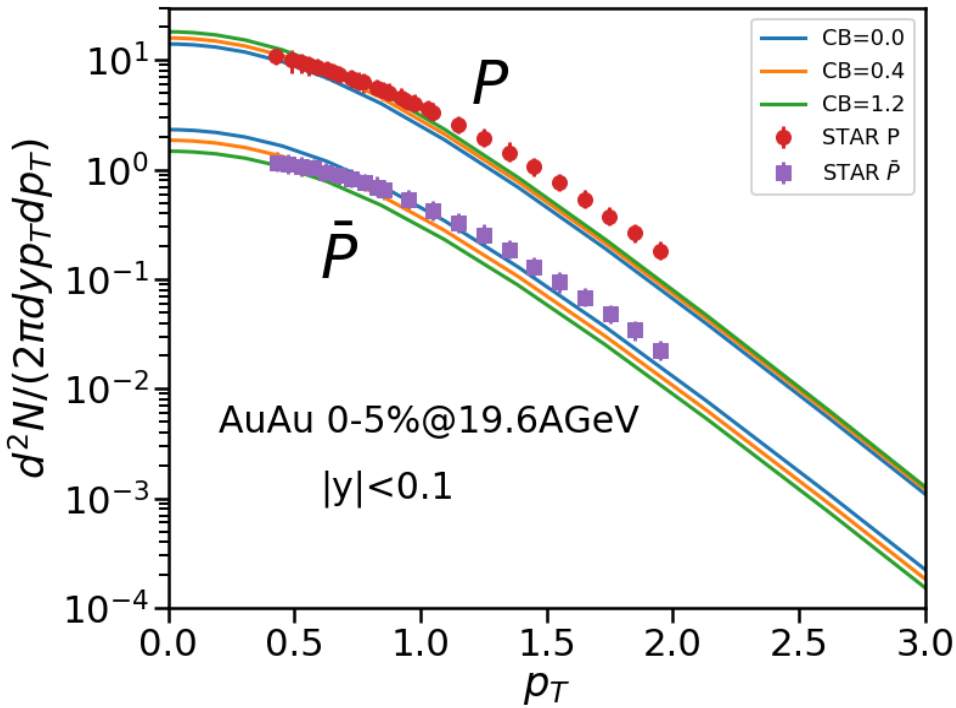


The effects of baryon current diffusion on pseudo-rapidity distribution of charged hadrons is negligible.

Larger baryon current diffusion will transport more net baryons to mid-rapidity.

p_T spectra



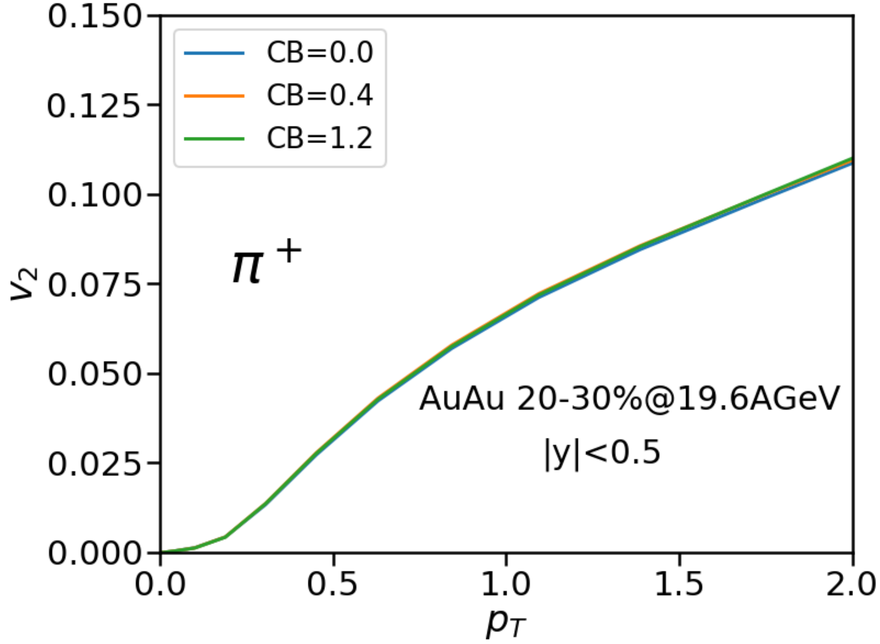


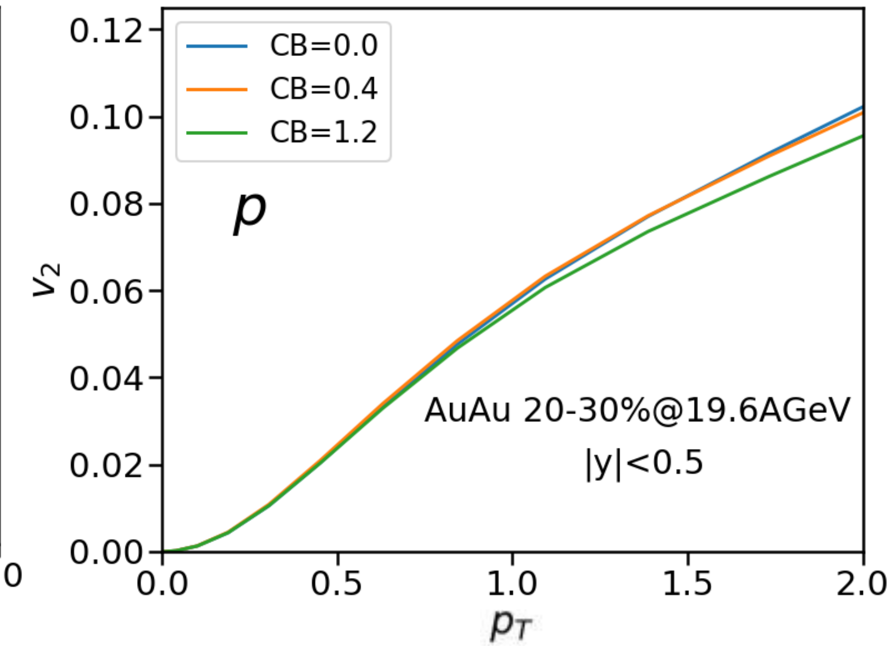
The meson spectra are insensitive to different baryon dissipative coefficient C_B.

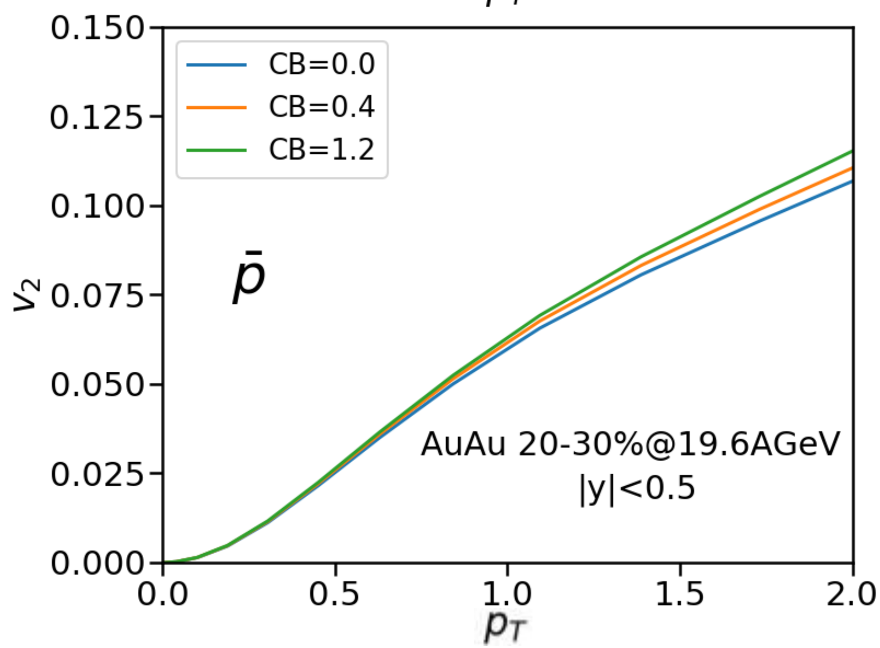
The small & opposite effects are observed for proton and anti-proton spectra.

Steeper spectra for p and flatter spectra for anti-p when the C_B is larger.

Elliptical flow







Mesons: little effect on elliptical flow.

Protons: (1) small & opposite effects for protons and anti-protons; (2) suppress v_2 for protons & enhance v_2 for anti-protons with increasing C_B.

Conclusion

Extend the CLVisc hydrodynamic model to include net baryon charge conservation and dissipative baryon current using the equation of state from NEOSB.

The effects of baryon current diffusion:

The pseudo-rapidity distribution of charged hadrons and the p_T spectra & elliptical flows of mesons are insensitive to C_B .

The rapidity distribution of net-protons has strong dependence on C_B .

The baryon current diffusion provides small & opposite contributions to the p_T spectra and elliptical flows of protons and anti-protons.

Outlook:

Code-checking by comparing with MUSIC and BESHYDRO.

Apply CLVisc to different BES energies for searching the critical point.

Add hadron afterburner.