Mean-field effects on particle and antiparticle elliptic flows in the beam-energy scan program at RHIC

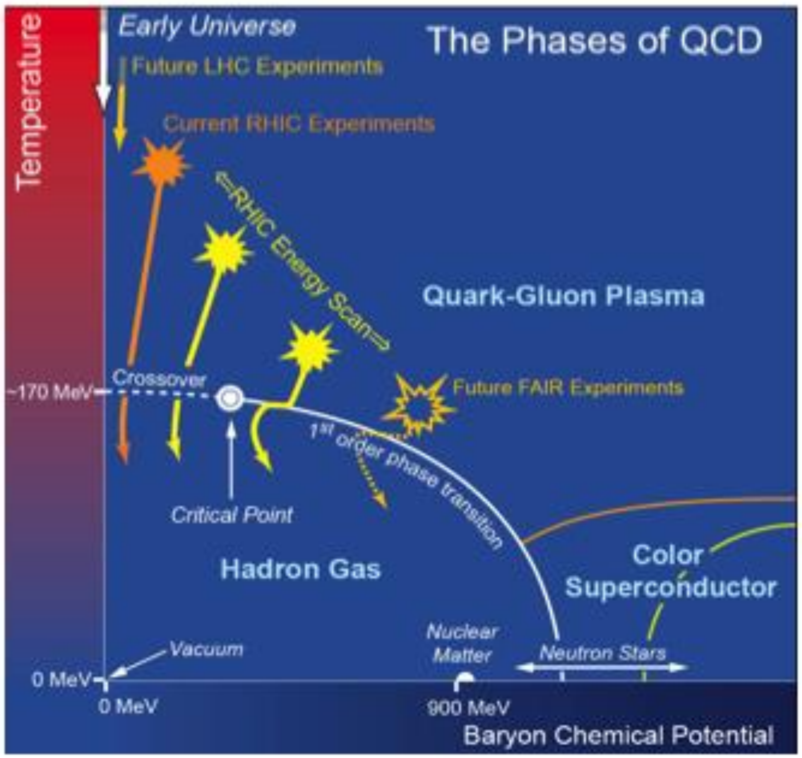
Taesoo Song

in collaboration with

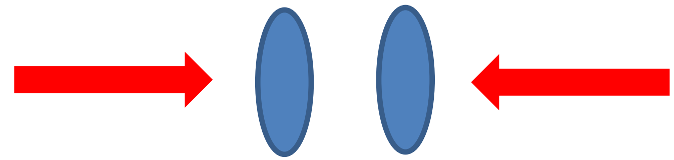
Jun Xu, Che Ming Ko, Feng Li,

Salvatore Plumari, Vincenzo Greco

Relativistic heavy-ion collisions

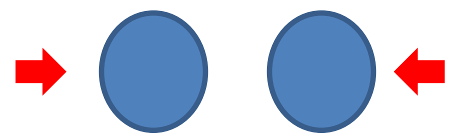


- in very high energy collisions



- Two nuclei pass through each other.
- Large, but almost same numbers of particles and antiparticles are produced. (high temperature, low net baryon density)

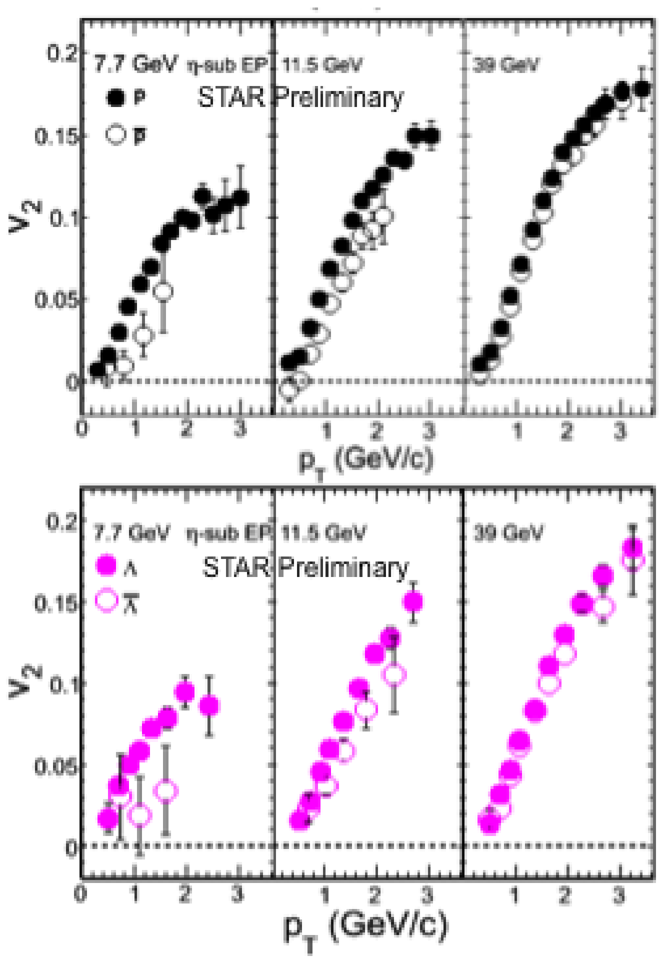
- in low energy collisions



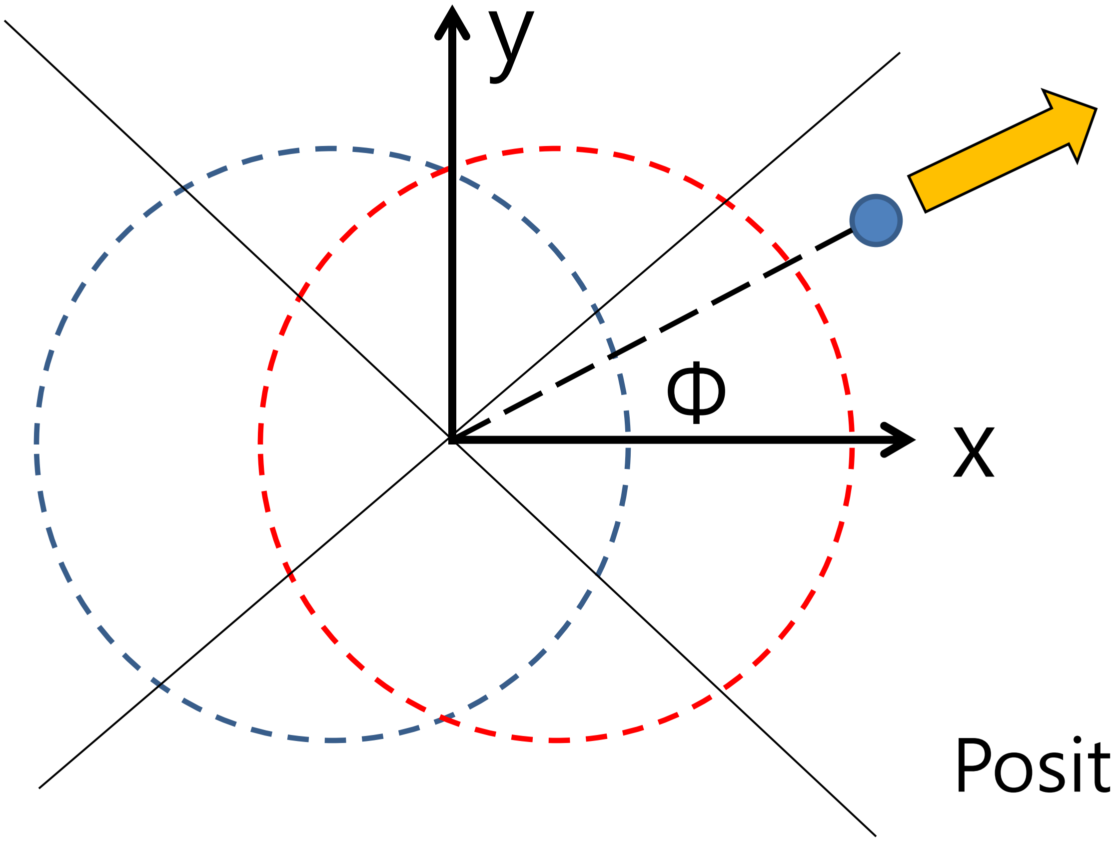
- Two nuclei stop and are compressed.
- Small numbers of particles and antiparticles are produced and many particles from colliding nuclei remain in the middle. (low temperature, high net baryon density)

Beam energy scan at RHIC

- To find the QCD phase diagram, the Beam Energy Scan (BES) program has been recently carried out at several low collision energies by the STAR Collaboration
- One of most interesting results is different elliptic flows of particles and antiparticles.
- As collision energy lowers, the difference between particle elliptic flow and that of antiparticles becomes large.



$V_2 = \langle \cos 2\Phi \rangle$



Positive v2

Partonic mean-fields

- QCD Phase boundary is highly nonperturbative region
$\rightarrow$ pQCD is not available
- Lattice QCD is available in small baryon chemical potential region ($\mu/T \ll 1$)
- So we use Nambu-Jona-Lasinio (NJL) model as effective Lagrangian for strong interaction

Nambu-Jona-Lasinio (NJL) model

- $L = \bar{\psi}(i\partial\!\!\!/ - M)\psi$

$$+\frac{G}{2}\sum_a[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2]$$

$U(N_f)_R \times U(N_f)_L$
symmetric interaction

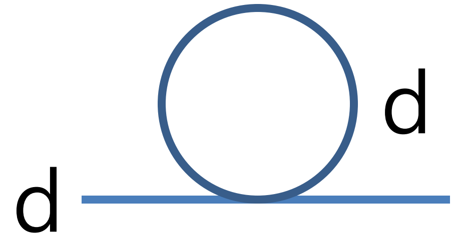
$$+K[det_f\{\bar{\psi}(1+\gamma_5)\psi\} + det_f\{\bar{\psi}(1-\gamma_5)\psi\}]$$

't Hooft interaction
breaking $U_A(1)$ symmetry

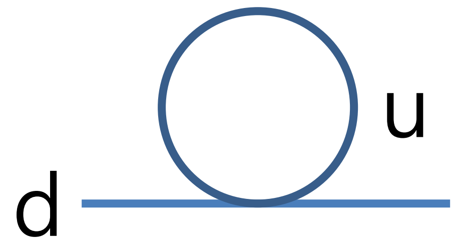
't Hooft interaction
for SU(2) $\sum_{i,j}\varepsilon_{ij}\,(\bar{u}\Gamma\psi_i)(\bar{d}\Gamma\psi_j)$
for SU(3) $\sum_{i,j,k}\varepsilon_{ijk}\,(\bar{u}\Gamma\psi_i)(\bar{d}\Gamma\psi_j)(\bar{s}\Gamma\psi_k)$

Mean-field interactions

- Symmetric interaction
  $(\bar{\psi}\Gamma\psi)^2 \to \langle\bar{\psi}\Gamma\psi\rangle\,\bar{\psi}\Gamma\psi$



- 't Hooft interaction

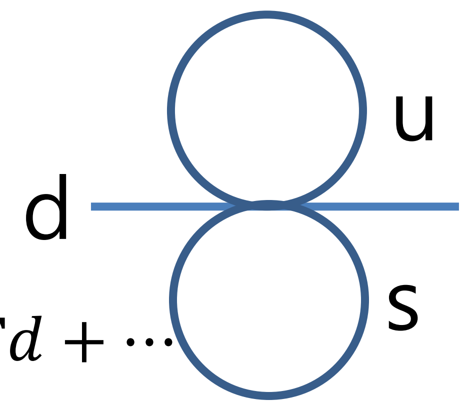


for SU(2)

$$\sum_{i,j}\varepsilon_{ij}\,(\bar{u}\Gamma\psi_i)\big(\bar{d}\Gamma\psi_j\big) \to \langle\bar{u}\Gamma u\rangle\bar{d}\Gamma d + \cdots$$

for SU(3)

$$\sum_{i,j,k}\varepsilon_{ijk}\,(\bar{u}\Gamma\psi_i)\big(\bar{d}\Gamma\psi_j\big)(\bar{s}\Gamma\psi_k) \to \langle\bar{u}\Gamma u\rangle\langle\bar{s}\Gamma s\rangle d\Gamma d + \cdots$$

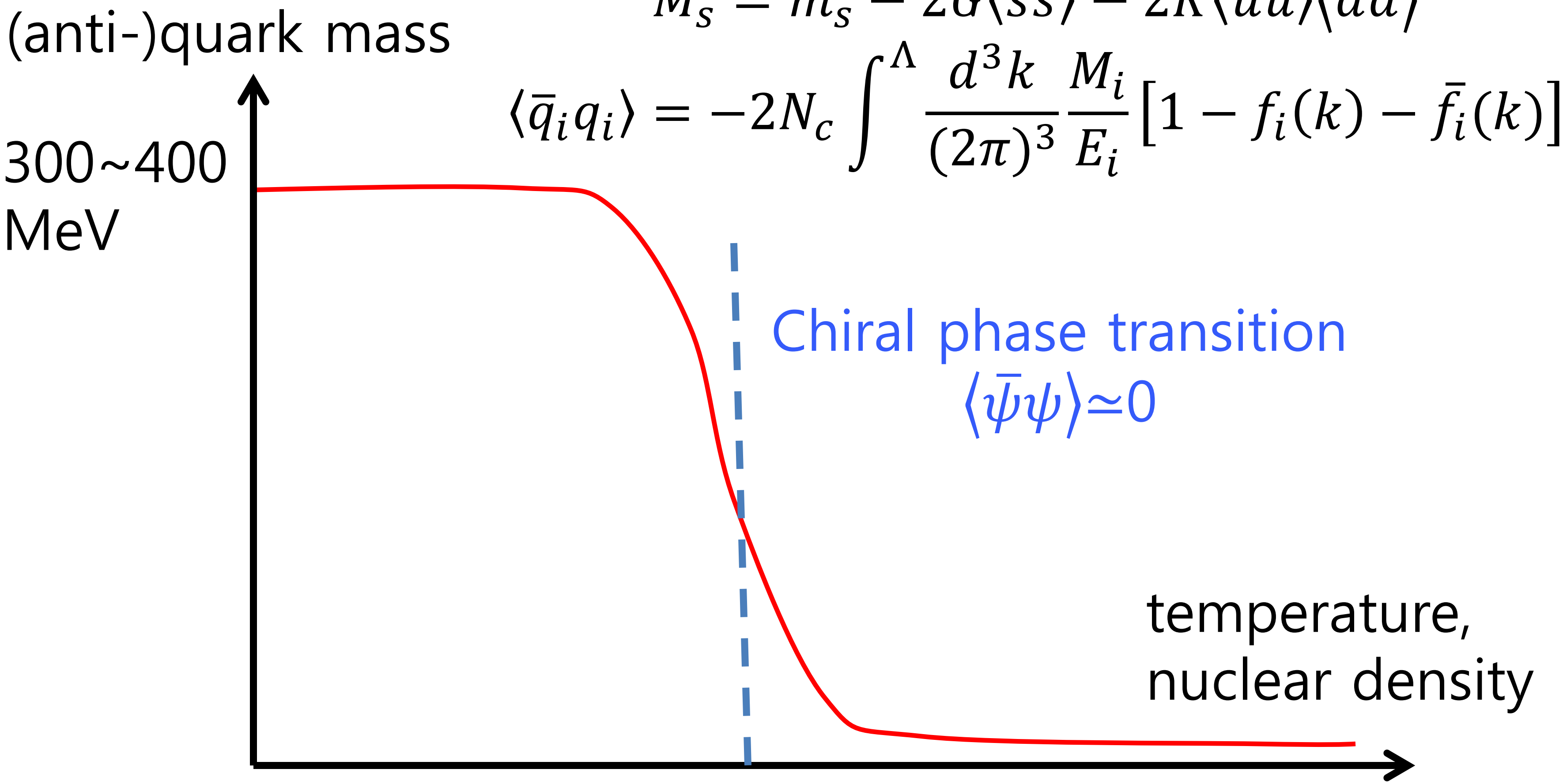


"Scalar mean field" generates quark mass

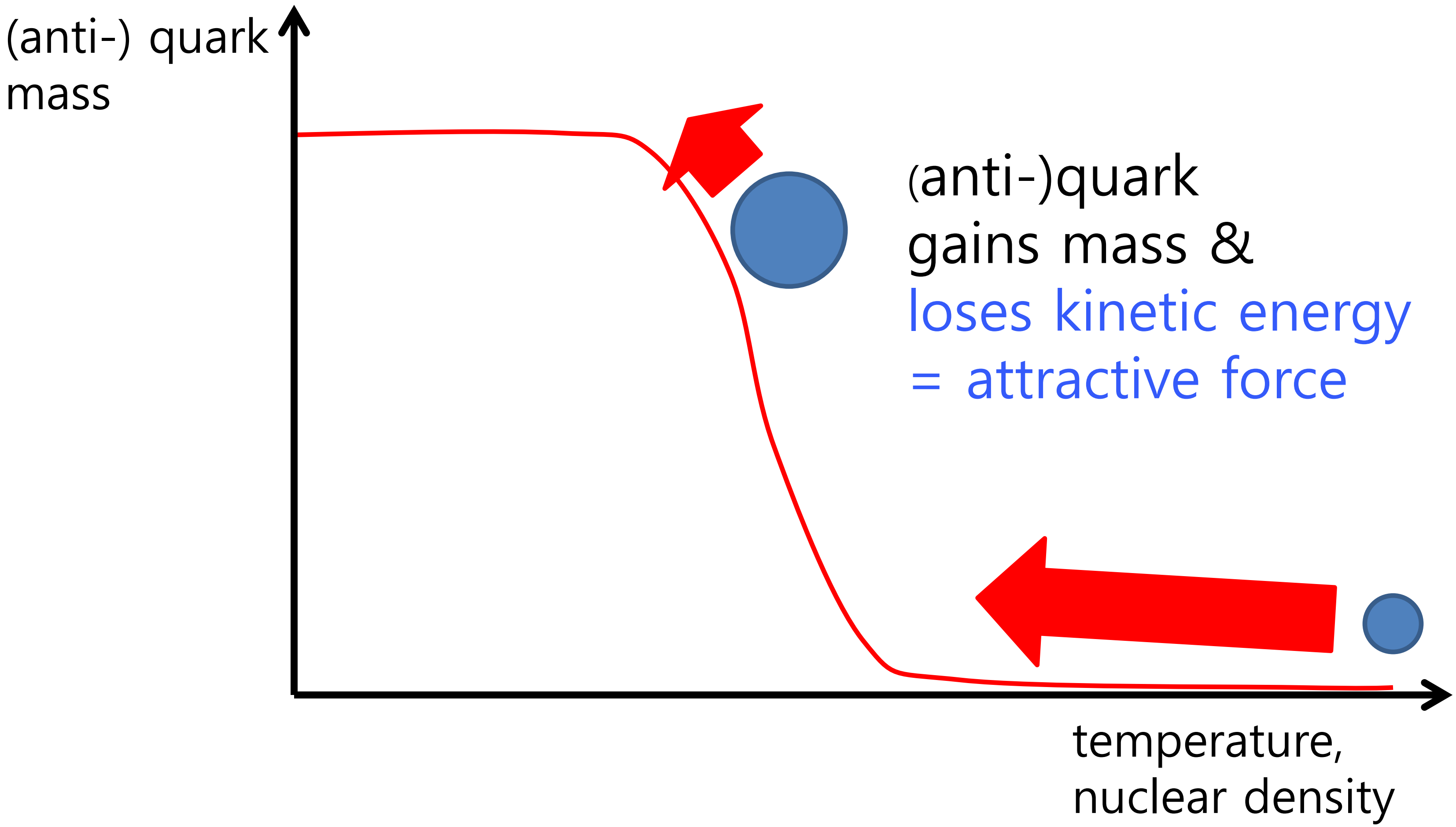
$$M_d = m_d - 2G\langle \bar{d}d \rangle - 2K\langle \bar{u}u \rangle \langle \bar{s}s \rangle$$

$$M_s = m_s - 2G\langle \bar{s}s \rangle - 2K\langle \bar{u}u \rangle \langle \bar{d}d \rangle$$

$$\langle \bar{q}_i q_i \rangle = -2N_c \int^{\Lambda} \frac{d^3k}{(2\pi)^3} \frac{M_i}{E_i} \left[1 - f_i(k) - \bar{f}_i(k)\right]$$



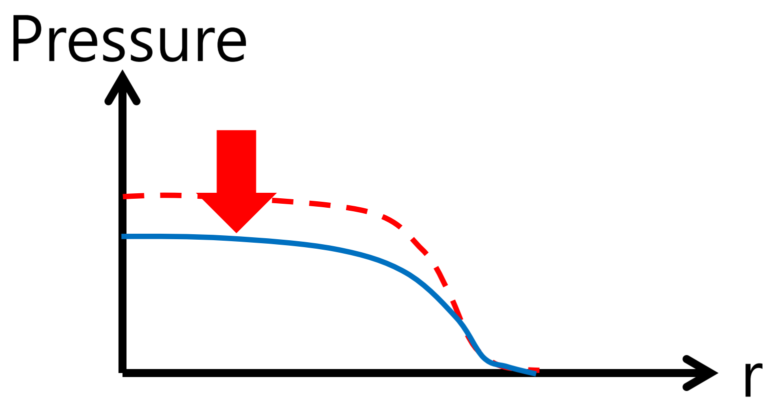
"Scalar mean field" acts attractive force both to quarks and to antiquarks in heavy-ion collisions



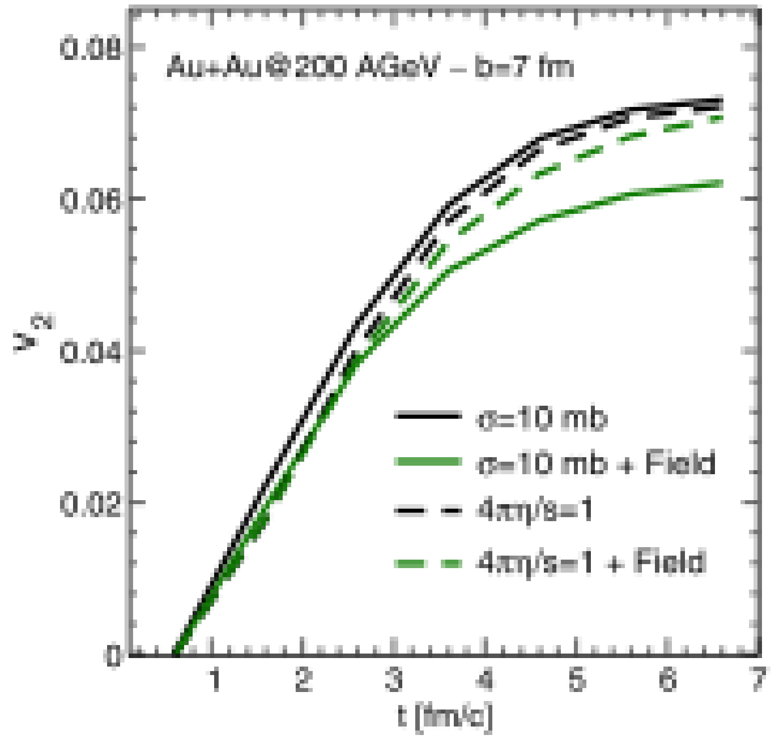
Scalar mean-field reduces elliptic flow (v2)

- The attractive force from the scalar mean field decreases pressure gradient for both quarks and antiquarks.

  (→ v2 decreases)



- Plumari, Baran, Di Tori, Ferini, and Greco, PLB 689, 18 (2010)



(axial-) vector interactions

- Fierz transformations

$\bar{\psi}\Gamma\psi\bar{\psi}\Gamma\psi$ (Hartree type) + $\bar{\psi}\Gamma\psi\bar{\psi}\Gamma\psi$ (Fock type)

- Put by hand considering symmetries

$$L_V = -\sum_a \left[\frac{G_V}{2}(\bar{\psi}\gamma_\mu\lambda^a\psi)^2 + \frac{G_A}{2}(\bar{\psi}\gamma_5\gamma_\mu\lambda^a\psi)^2\right]$$

$$\rightarrow -\frac{g_V}{2}(\bar{\psi}\gamma_\mu\psi)^2 \rightarrow -g_V\langle\bar{\psi}\gamma_\mu\psi\rangle\bar{\psi}\gamma^\mu\psi$$

Isoscalar vector Int. Mean-field Approx.

Canonical momentum $p_\mu = p_\mu^* \pm g_V\rho_\mu$

Mechanical momentum

Time-evolution of partonic matter (relativistic Vlasov equation)

$$\frac{\partial}{\partial t}f + v \cdot \nabla_x f - \nabla_x H \cdot \nabla_p f = C$$

C : collision term ($\sigma_{qq} = 2$ mb)

H : Hamiltonian of a (anti)quark in mean-fields

$$H = \sqrt{M^{*2} + p^{*2}} \pm g_V \rho^0$$

$$\frac{dx_i}{dt} = \frac{\partial H}{\partial p_i} = \frac{p_i^*}{E^*} = v_i$$

$$\frac{dp_i}{dt} = -\frac{\partial H}{\partial x_i} = -\frac{M^*}{E^*}\frac{\partial M^*}{\partial x_i}$$

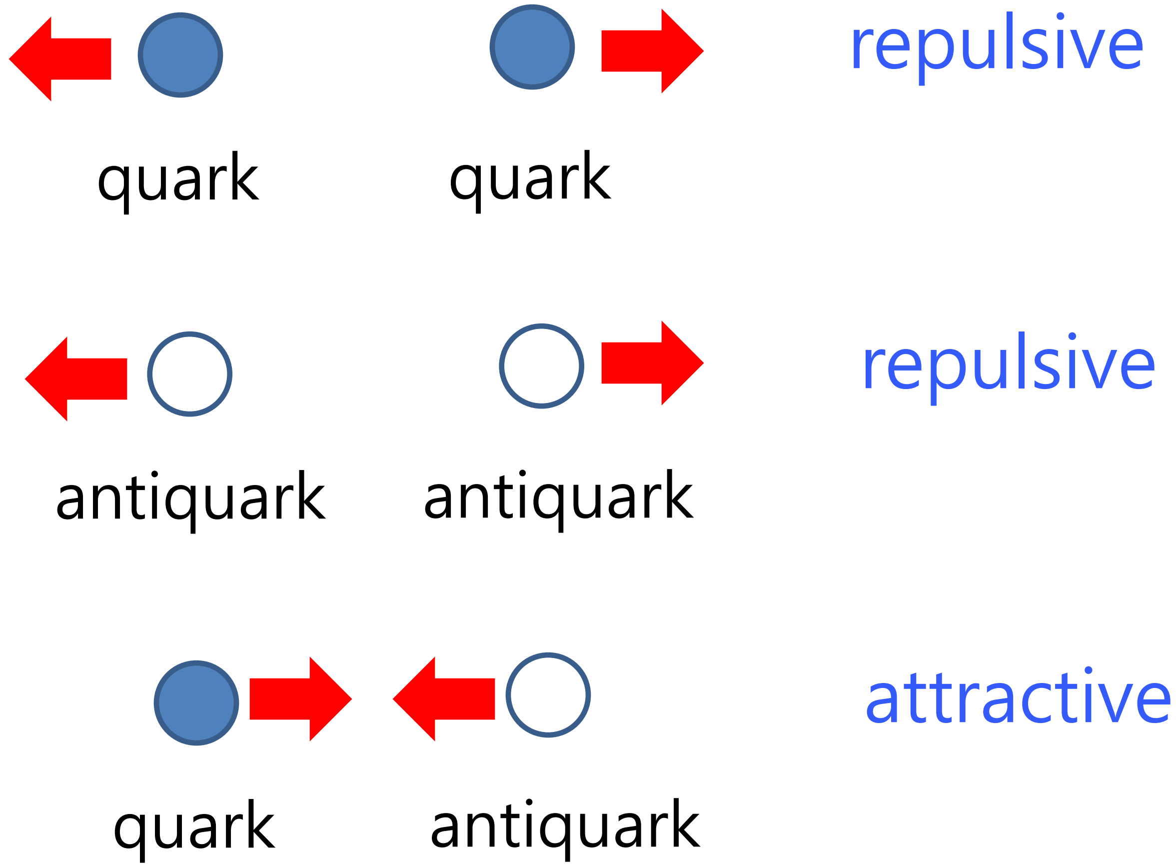
$$\pm g_V \left(v_j \frac{\partial \rho_j}{\partial x_i} - \frac{\partial \rho_0}{\partial x_i} \right)$$

contributes to Lorentz force

$$\begin{aligned} F_i &= \frac{dp_i^*}{dt} = \frac{dp_i}{dt} - g_V \frac{d\rho_i}{dt} \\ &= g_V \left(v_j \frac{\partial \rho_j}{\partial x_i} - \frac{\partial \rho_0}{\partial x_i} - \frac{\partial \rho_i}{\partial t} - v_j \frac{\partial \rho_i}{\partial x_j} \right) \\ &= g_V (\mathbf{v} \times \mathbf{B} + \mathbf{E})_i, \end{aligned}$$

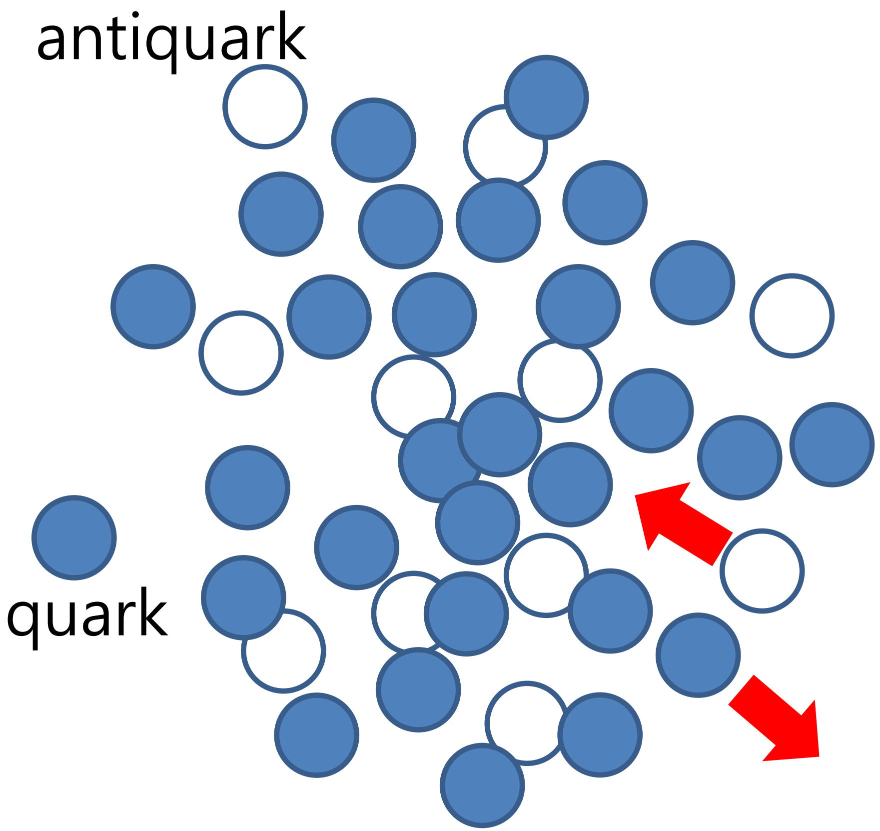
with $\mathbf{B} = \nabla \times \rho$ and $\mathbf{E} = -\nabla \rho^0 - \partial \rho / \partial t$.

(time-component) vector interactions



in baryon-rich nuclear matter

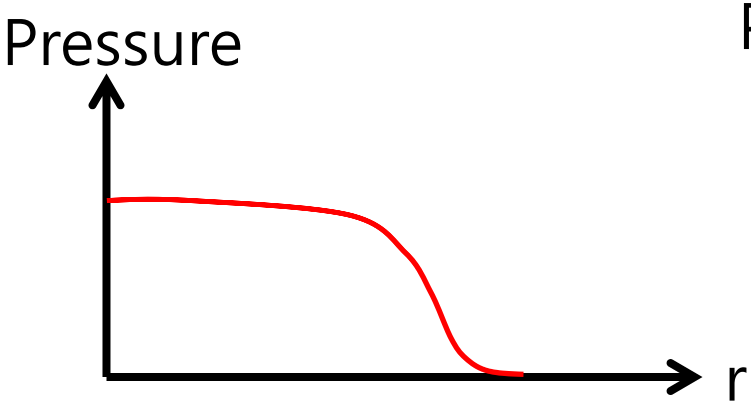
- More quarks than antiquarks
- Quarks feel repulsive force but antiquarks attractive force.



Pressure distributions change

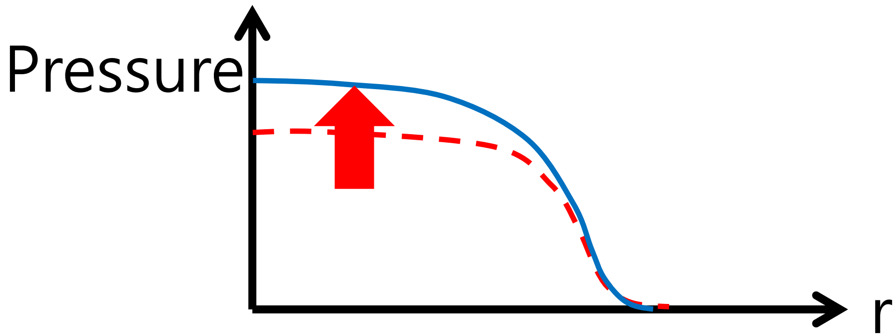
without vector interactions

- For (anti-)quark

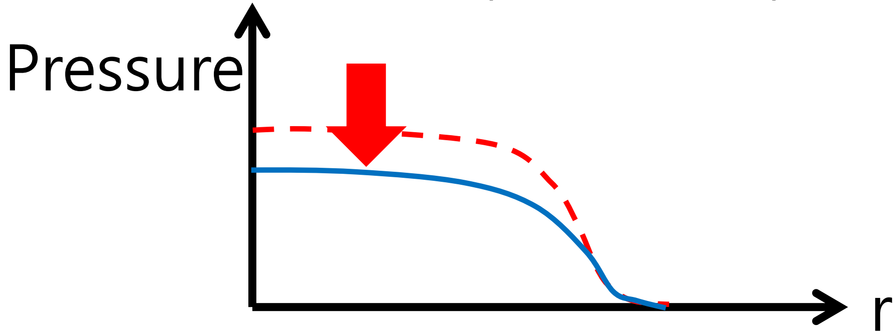


with vector interactions

- For quark, pressure gradient increases (v2 increases)

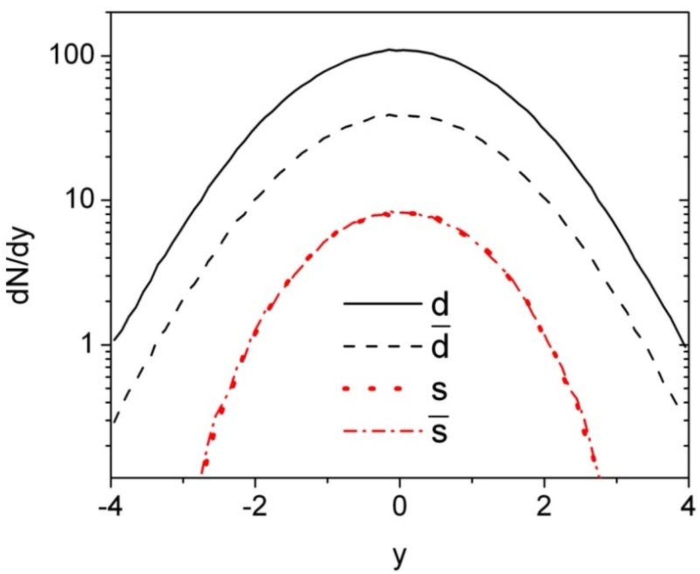


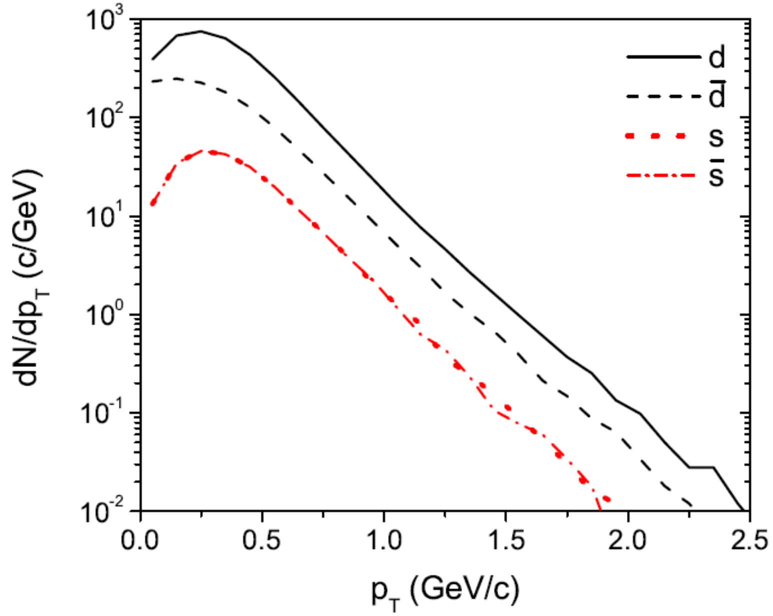
- For antiquark, pressure gradient decreases (v2 decreases)



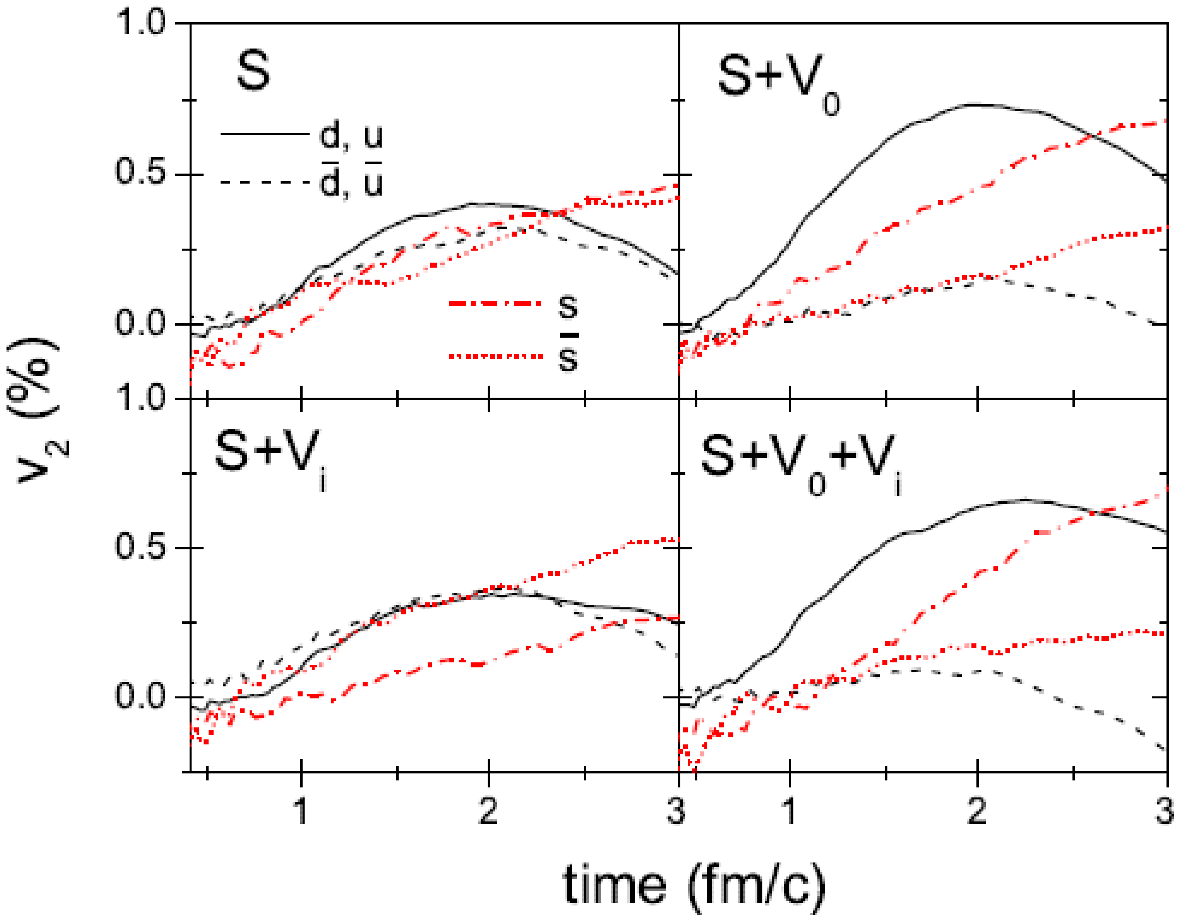
baryon-rich initial conditions

for Au+Au collisions @ 7.7 GeV, b=8 fm
from AMPT (a multiphase transport model)

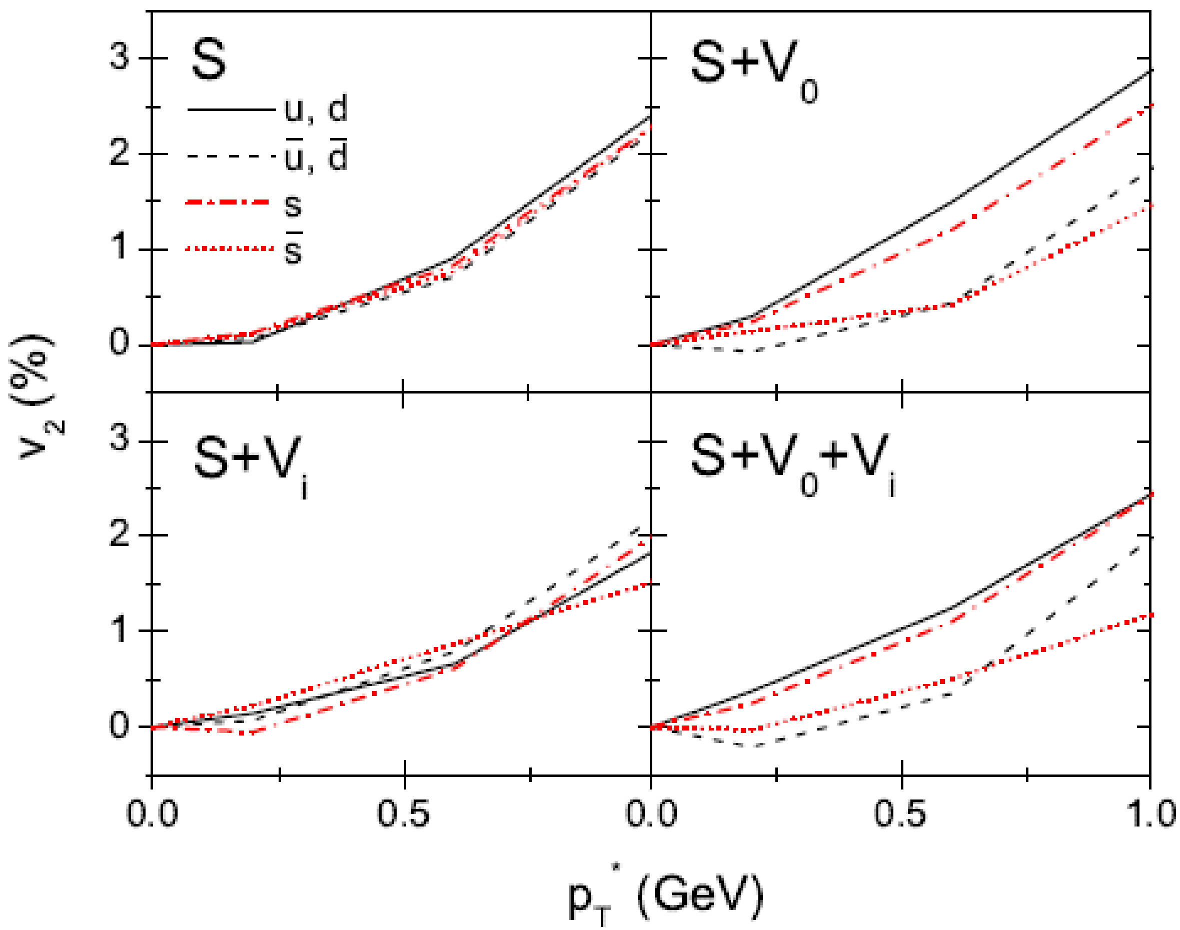




Integrated v_2 of quarks and antiquarks as functions of time



V_2 of quarks and antiquarks as functions of p_T when energy density of central cells equals 0.8 GeV/fm^3



AMPT hadronization

- Spatial coalescence.
- Quark and antiquark are converted into hadron whose invariant mass is closest to that of quark and antiquark.
- Same for (anti)baryon.

Hadronic mean-fields

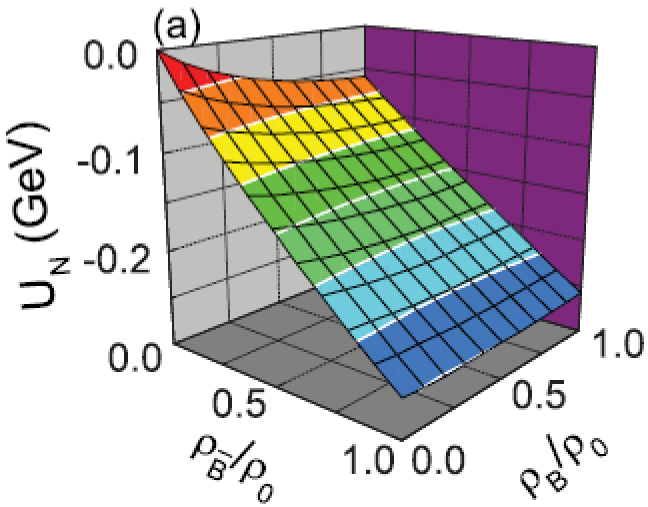
Nucleon & antinucleon potentials

- From relativistic mean-field model,

$$U_{N,\bar{N}}(\rho_B, \rho_{\bar{B}}) = \Sigma_s(\rho_B, \rho_{\bar{B}}) \pm \Sigma_v^0(\rho_B, \rho_{\bar{B}}),$$

- $\Sigma_s = \int \frac{d^3p}{(2\pi)^3} \frac{m}{E} (\rho_B + \rho_{\bar{B}})$
- $\Sigma_v^0 = \int \frac{d^3p}{(2\pi)^3} \frac{p^0}{E} (\rho_B - \rho_{\bar{B}})$

+(-) for nucleon(antinucleon)



Kaon & antikaon potentials

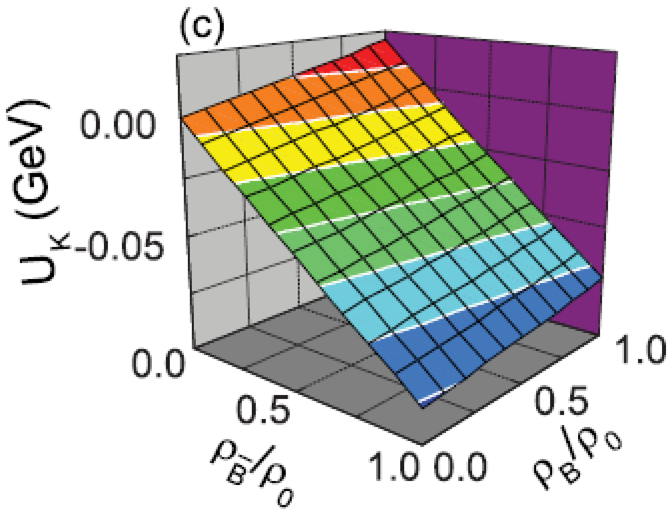
- From the chiral effective Lagrangian,

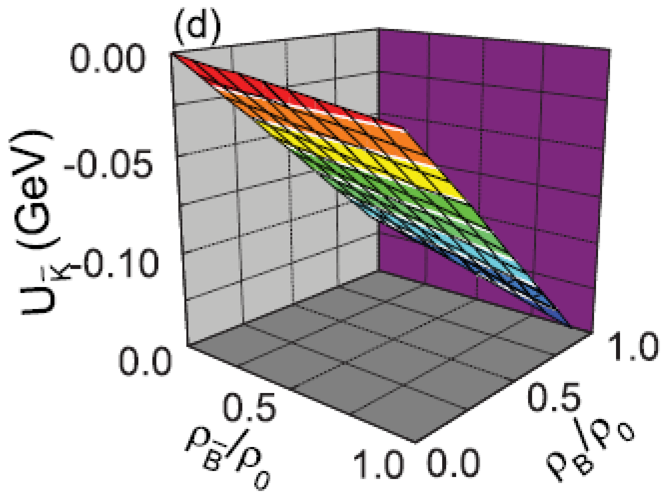
(PRL79,5214, NPA625,372)

$$U_{K,\bar{K}} = \omega_{K,\bar{K}} - \omega_0,$$

$$\omega_{K,\bar{K}} = \sqrt{m_K^2 + p^2 - a_{K,\bar{K}}\rho_s + \left(b_K\rho_B^{\rm net}\right)^2} \pm b_K\rho_B^{\rm net}$$

$$\omega_0 = \sqrt{m_K^2 + p^2},$$

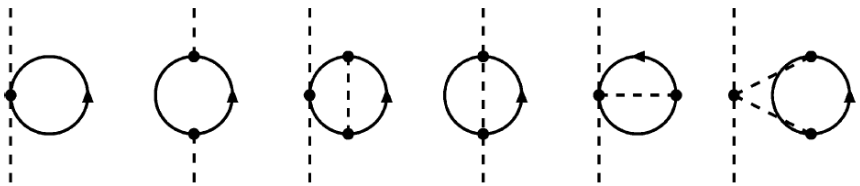




Pion potentials

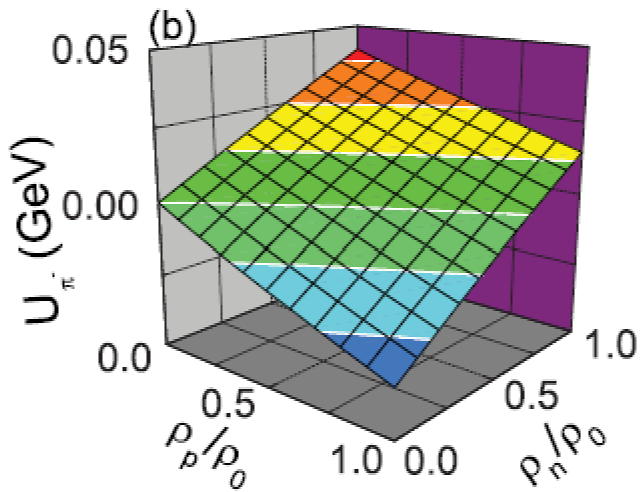
- From pion self-energy with pion-nucleon *s*-wave interaction,

  (PLB512,283)



$$\Pi_s^-(\rho_p,\rho_n) = \rho_n[T_{\pi N}^- - T_{\pi N}^+] - \rho_p[T_{\pi N}^- + T_{\pi N}^+] + \Pi_{\rm rel}^-(\rho_p,\rho_n) + \Pi_{\rm cor}^-(\rho_p,\rho_n),$$

$$\Pi_s^+(\rho_p,\rho_n) = \Pi_s^-(\rho_n,\rho_p).$$



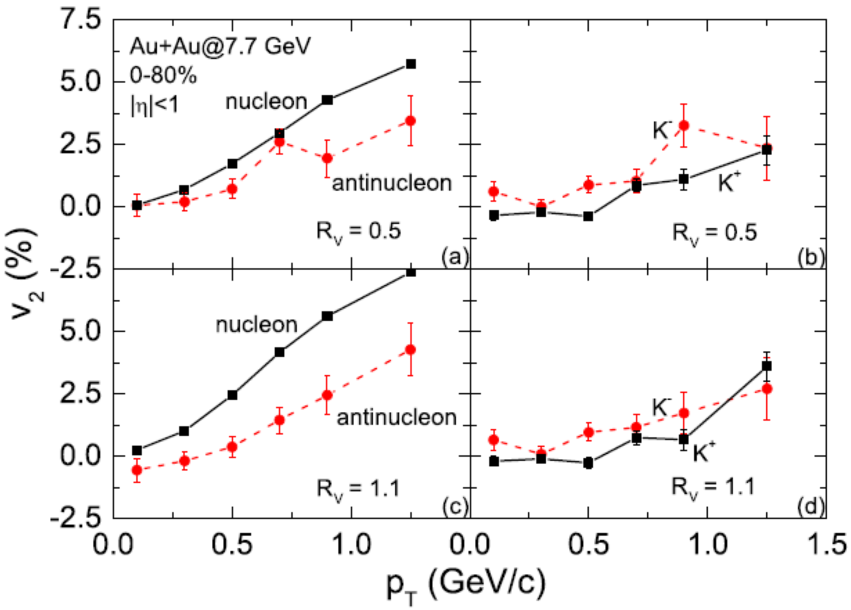
$T_{\pi N}^{\pm}$: isospin even(odd) πN s wave scattering T matrix

$\Pi_{rel}^- = \Pi_{rel}^+$: relativistic correction

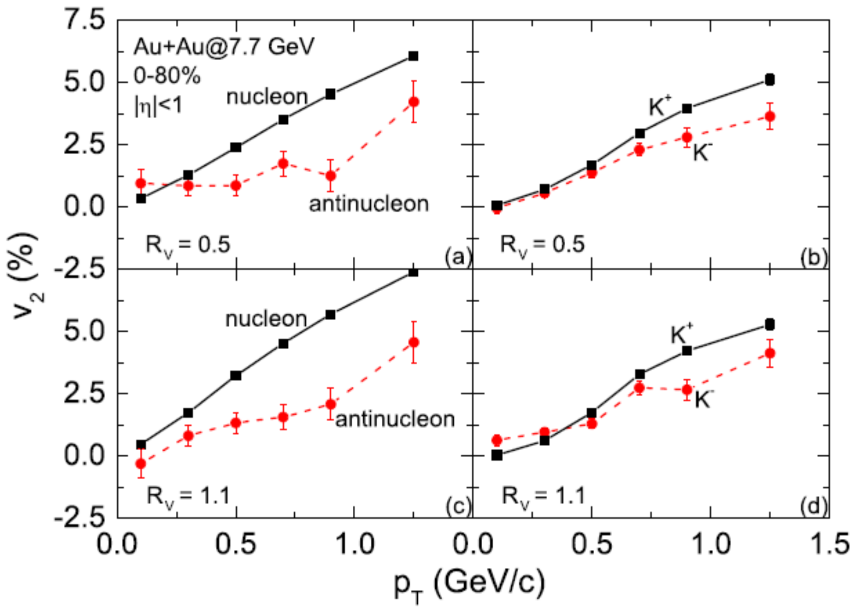
$\Pi_{cor}^- = -\Pi_{cor}^+$: two-loop correction

Elliptic flows of $p/\bar{p}$ and K^+/K^-

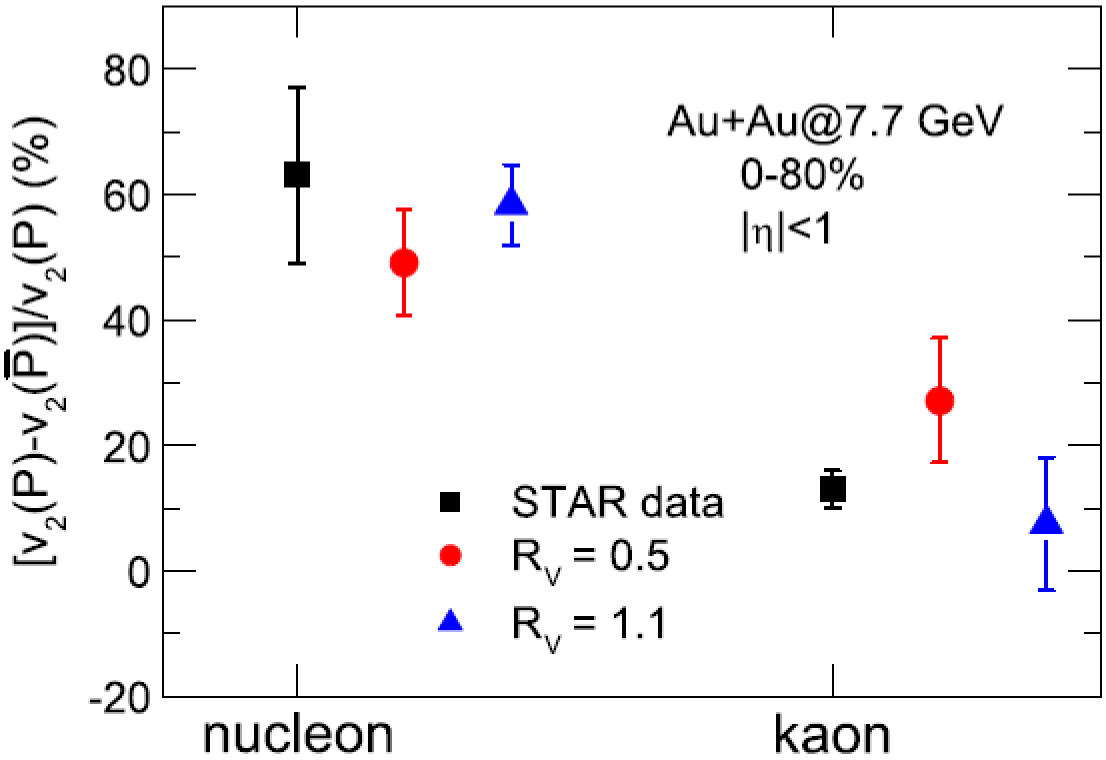
At hadronization



At freeze-out



The differences of integrated v_2 between $p/\bar{p}$ and K^+/K^-



Vector interaction & QCD phase diagram

Vector coupling strength and chiral phase diagram

Phys. Lett. B719 (2013) 131-135, N. M. Bratovic, T. Hatsuda, W. Weise

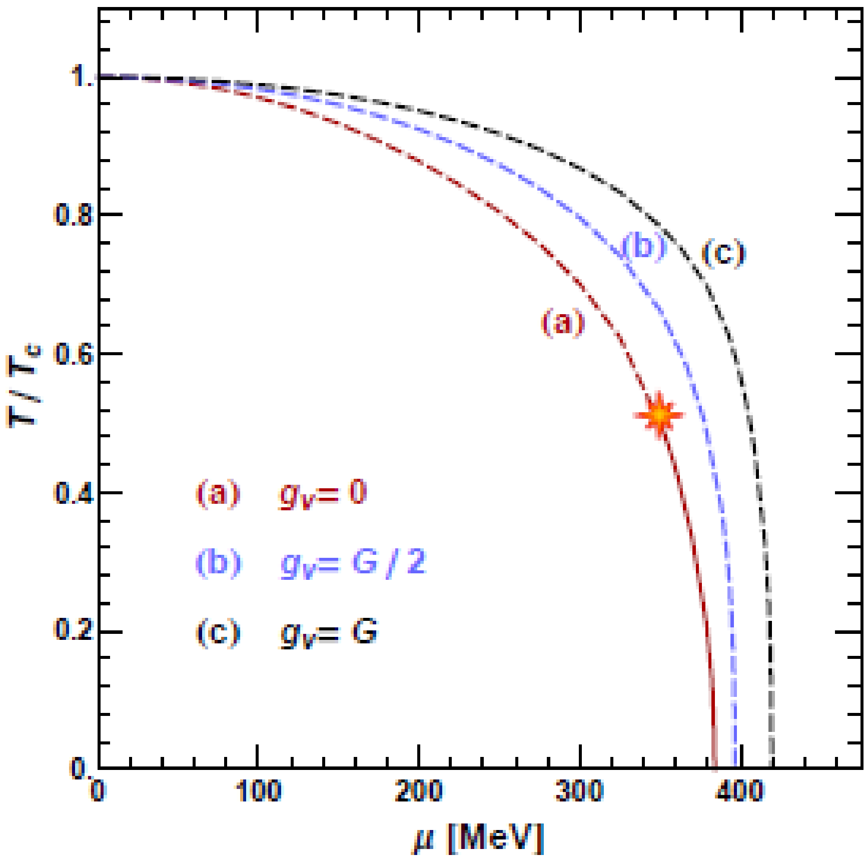
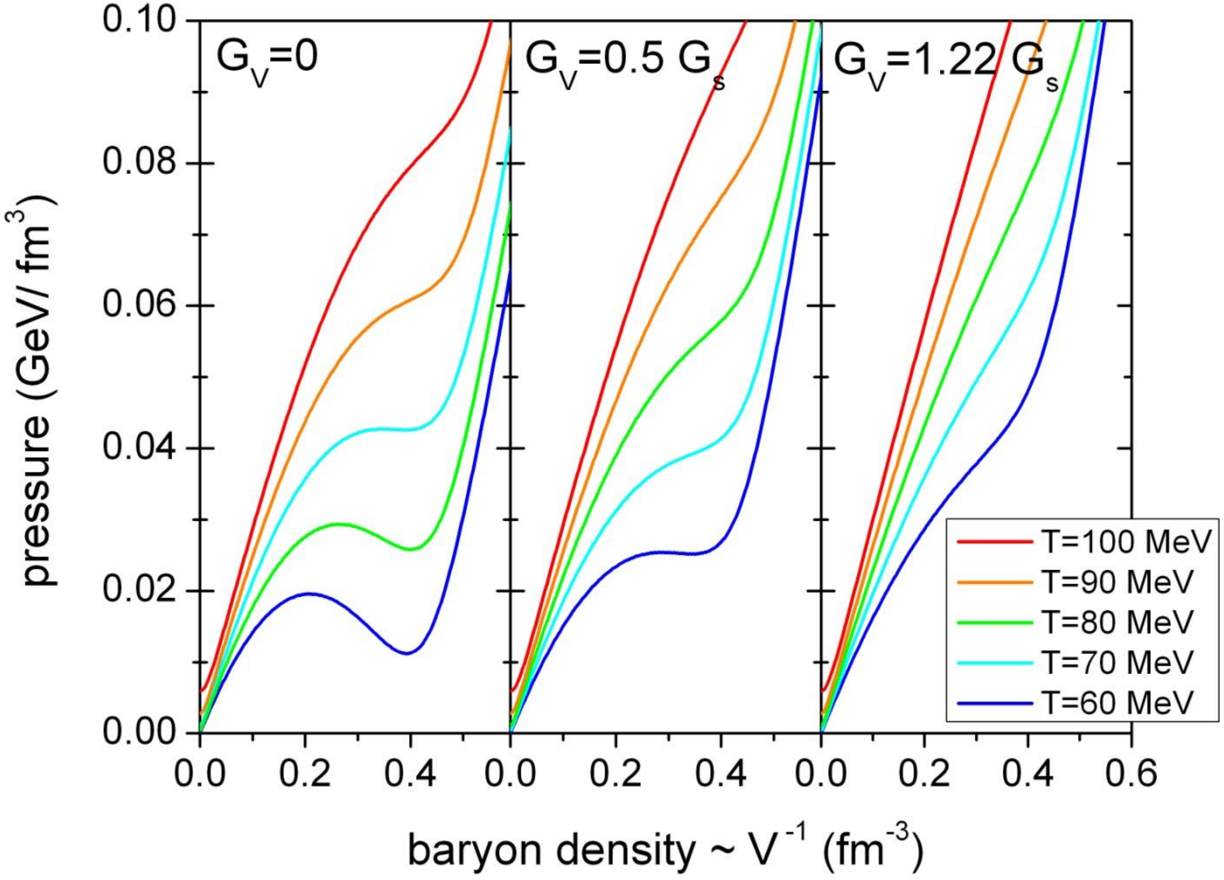


Figure 1: PNJL phase diagrams for three different vector coupling strengths: (a) $g_V = 0$, (b) $g_V = G/2$ and (c) $g_V = G$. Dashed lines denote $\sigma_u(T,\mu)/\sigma_u(T=0,\mu=0) = 0.5$ at crossover transitions. The solid line is the first order transition ending in the critical point.

Isothermal lines in the NJL model



summary

- We studied the effect of partonic and hadronic mean-fields on the elliptic flows of particles and antiparticles which were recently measured by STAR Collaboration.
- We found that not small vector interaction in partonic phase is required to explain large difference between particle and antiparticle elliptic flows from the Beam Energy Scan program.
- It implies that QCD phase transition is crossover even at large baryon chemical potential.