Why Do Particles and Antiparticles Flow differently?

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- Beam energy scan at RHIC
- Particle and antiparticle elliptic flows
- Hadronic potentials in nuclear medium
- Effects of hadronic potentials on elliptic flow
- Partonic potentials in QGP

Based on work with Jun Xu [PRC 85, 041901(R) (2012)]

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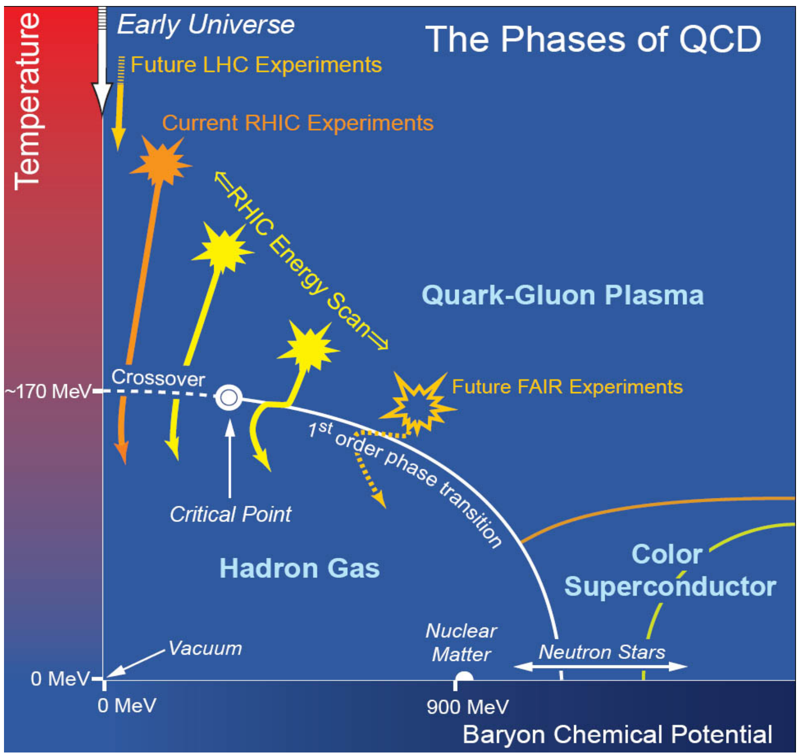
Beam energy scan at RHIC

STAR Collaboration, arXiv: 1007.2613; 1106.5902 [nucl-ex]

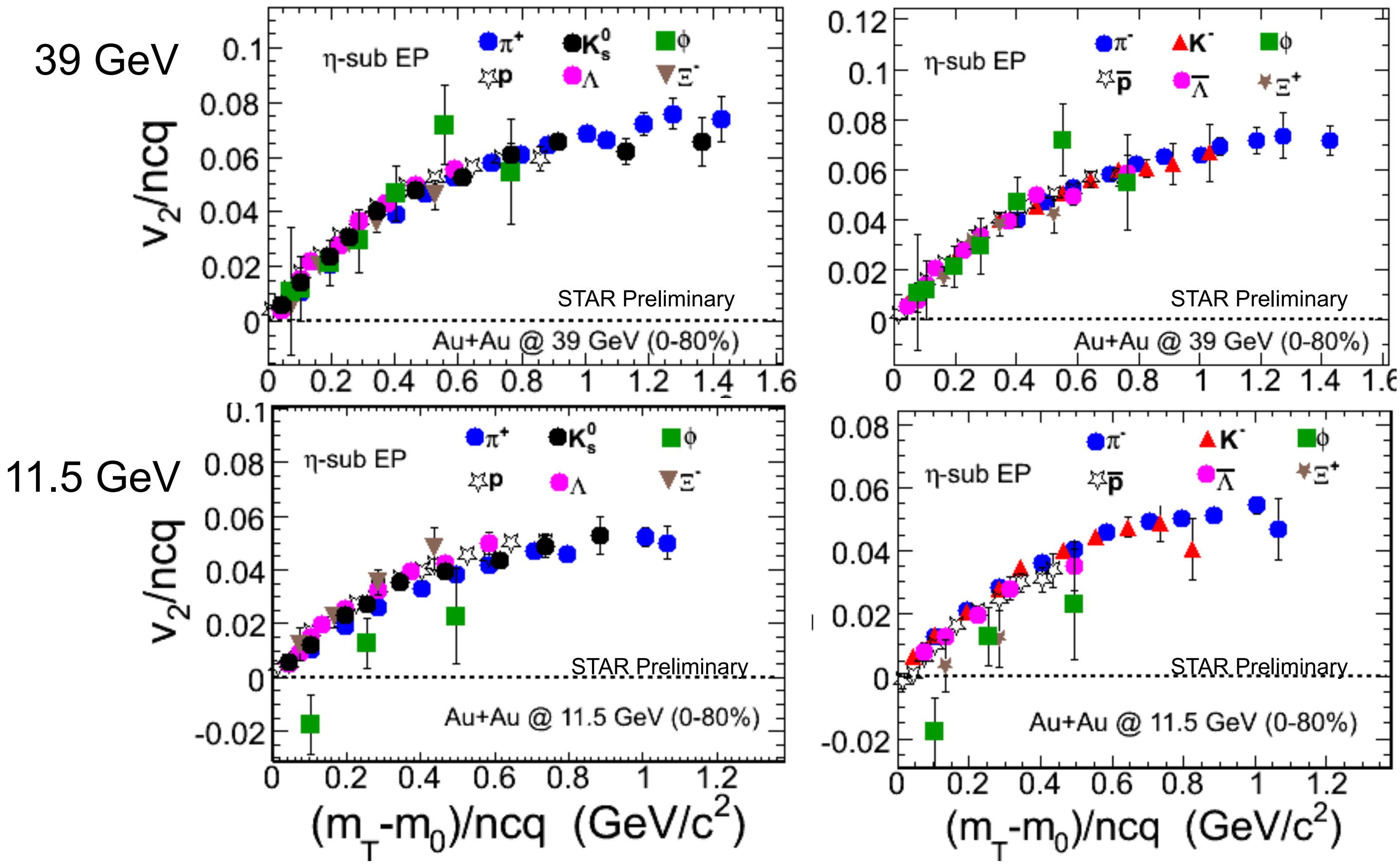
- Motivations:

  Study QCD phase diagram at finite baryon chemical potential: critical poin (CP), onset of de-confinement



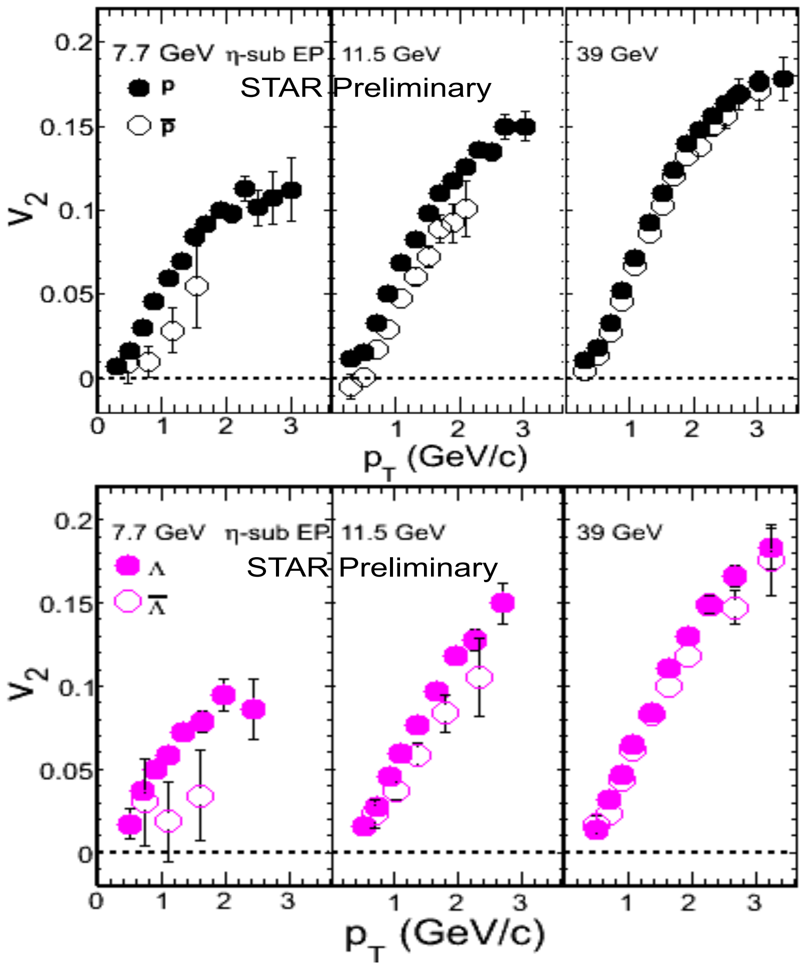
- Experimental observations:
  - **Particle ratios**: increasing baryon chemical potential with decreasing beam energy (DBE), reaching ~ 400 MeV at $s^{1/2}_{NN}$ = 7.7 GeV
  - **Dynamic charge correlations:** decreasing difference in same and opposite charges correlations with DBE (hadronic dominance?)
  - **Freeze-out eccentricity:** increasing with DBE (softening of EOS?)
  - **Directed flow:** dv_1/dy changes sign (softening of EOS?) and increasing difference in proton and antiproton dv_1/dy with DBE (hadronic dominance?)
  - **Moments of net-proton distributions:** both skewness and kurtosis deviate from HRG for $s^{1/2}_{NN}$ < 39 GeV (presence of CP?)
  - **Particle ratio fluctuations:** nonzero $\nu_{dyn}(K/\pi)$ (correlated emission or presence of CP?)
  - **Elliptic flow:** breakdown of NCQ scaling and increasing difference between particles and anti-particles with DBE (hadronic dominance? chiral magnetic effect?)

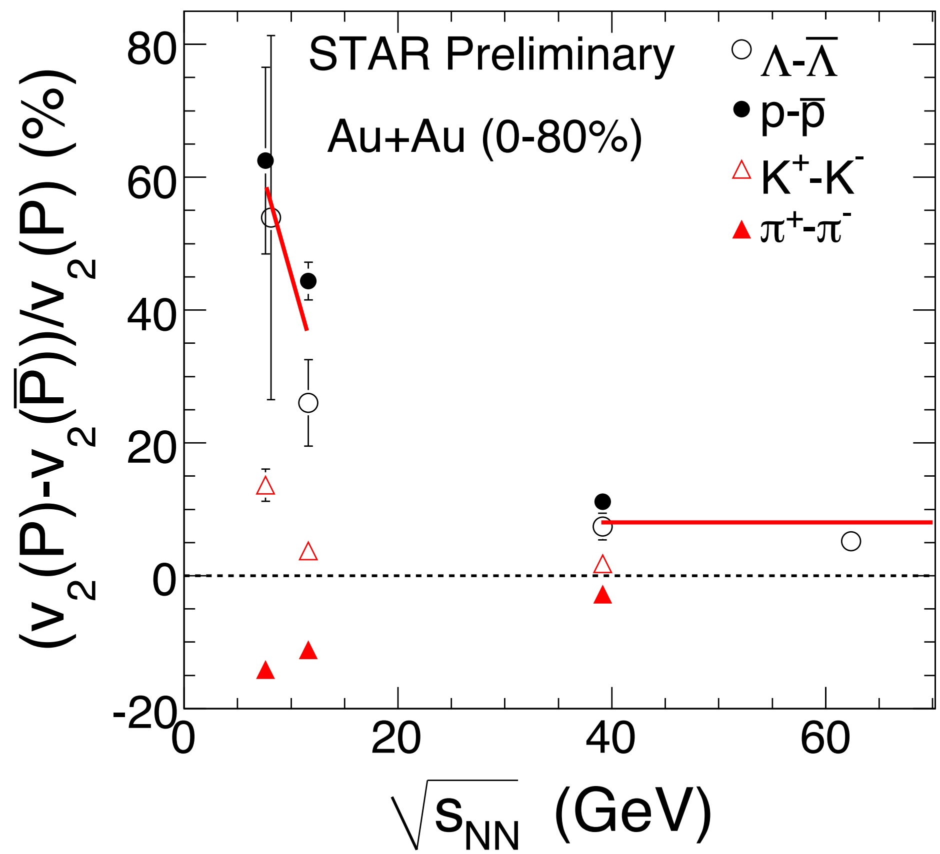
Beam energy dependence of CQN scaled elliptic flow



- Phi meson falls off trend at $s^{1/2}_{NN}$ = 11.5 GeV (hadronic dominance?)

Particle and antiparticle elliptic flows





- Particle and antiparticle elliptic flows become significantly different below $s^{1/2}_{NN}$ < 11.5 GeV: v_2(baryon) > v_2(anti-baryon), $v_2(K^+) > v_2(K^-)$, and $v_2(\pi^+) < v_2(\pi^-)$
- P_T-integrated relative v_2 difference between particles and antiparticles: 63%, 44%, and 12% for (p, pbar), 53%, 25%, and 7% for (Λ, Λbar), 13%, 3%, and 1% for (K^+,K^-), -15%, -10%, and -3% for (π^+,π^-) at 7.7, 11.5, and 39 GeV

Possible explanations for different particle and antiparticle elliptic flows

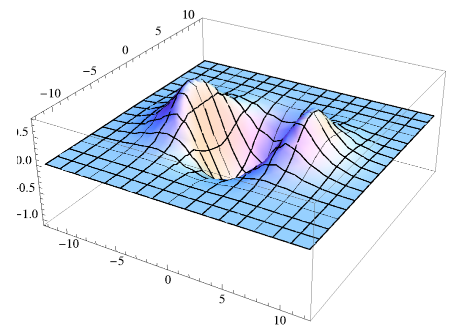
- **Chiral magnetic wave** [Bumier, Kharzeev, Liao & Yee, PRL 107, 052303 (2011)]
  - Stemming from the coupling of the density waves of electric and chiral charge induced by the axial anomaly in the presence of an external magnetic field

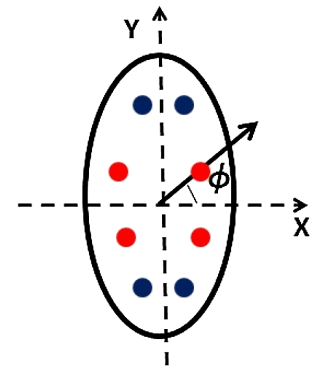
    → Electric quadrupole momentum in QGP

    → decreasing positive hadron and increasing negative hadron elliptic flows

    → $v_2(\pi^+) < v_2(\pi^-)$

$$j_V = \frac{N_c e}{2\pi^2}\mu_A B, \quad j_A = \frac{N_c e}{2\pi^2}\mu_V B$$





  - Effects on p and $\overline{\mathrm{p}}$ as well as K^+ and K^- are masked by different absorption cross sections

- **Transport versus produced particles** [Dunlop, Lisa & Sorensen, PRC 84, 044914 (2011)]: Elliptic flow is larger for transport than for produced (anti) particles

- **Different particle and antiparticle transport coefficients** [Greco, Mitrovski, & Torrieri, arXiv:1201.4800v2 [nucl-th]] : antiparticles have larger absorption cross sections

- **Different particle and antiparticle potentials** [Xu & Ko, PRC 85, 041901(R) (2012)]: Potentials are repulsive for particles and attractive for antiparticles

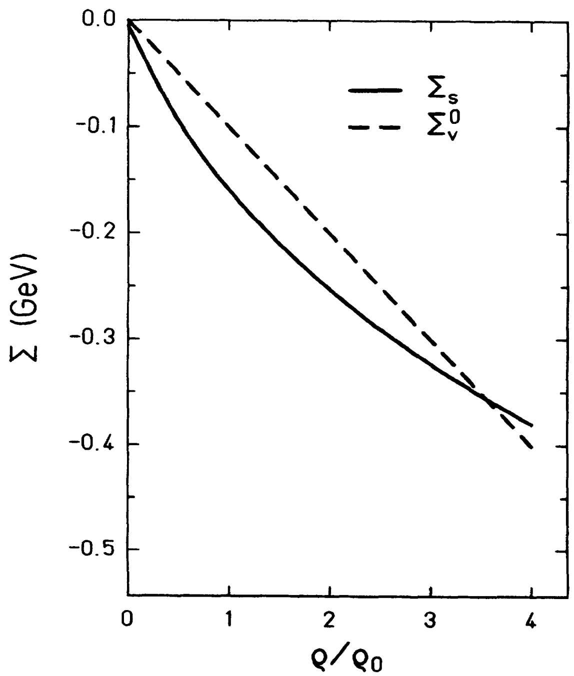
Hadron potentials in nuclear medium (I)

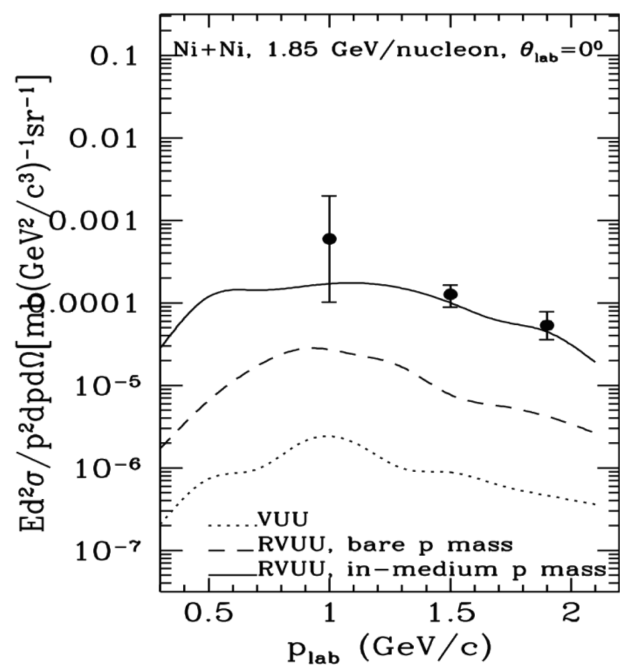
Ko & Li, JPG 22, 1673 (1996); Ko, Koch & Li, ARNPS 47, 505 (1997)

- **Nucleons and antinucleons:** Relativistic mean-field model → attractive scalar potential Σ_s and repulsive vector potential Σ_v ("+" for nucleons and "-" for antinucleons due to G-parity)

$$U_{N,\bar{N}}(\rho_s,\rho_B) = \Sigma_s(\rho_s,\rho_B) \pm \Sigma_v^0(\rho_s,\rho_B) = \frac{g_\sigma^2}{m_\sigma^2}\rho_s \pm \frac{g_\omega^2}{m_\omega^2}\rho_B$$

$$U_N = -60\ \mathrm{MeV}, U_{\bar{N}} = -260\ \mathrm{MeV\ at}\ \rho_0 = 0.16\ \mathrm{fm}^{-3}$$





- Deep antiproton attractive potential reduces its production threshold and thus enhances its yield in subthreshold heavy ion collisions

Hadron potentials in nuclear medium (II)

Ko & Li, JPG 22, 1673 (1996); Ko, Koch & Li, ARNPS 47, 505 (1997)

- **Kaons and antikaons:** Chiral effective Lagrangian → repulsive potential for kaons and attractive potential for antikaons

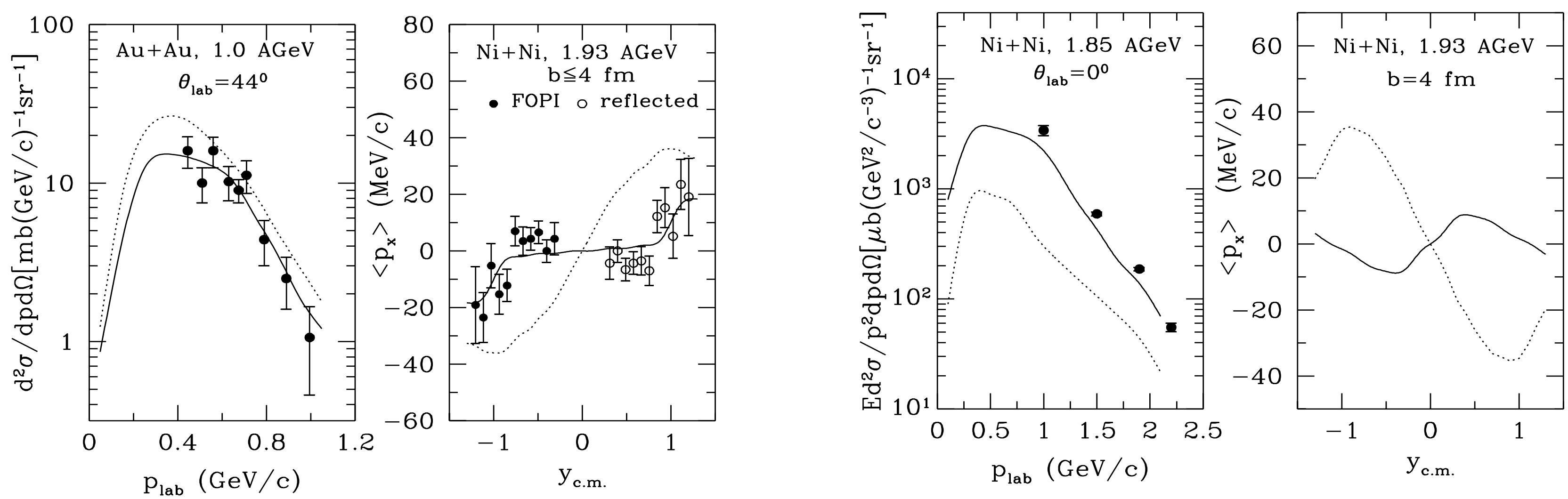
$$U_{K,\bar{K}} = \omega_{K,\bar{K}} - \omega_0, \quad \omega_0 = \sqrt{m_K^2 + p^2}$$

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

$$a_K = 0.22\ \mathrm{GeV}^2\mathrm{fm}^3, \quad a_{\bar{K}} = 0.45\ \mathrm{GeV}^2\mathrm{fm}^3$$

$$b_K = 0.33\ \mathrm{GeV}^2\mathrm{fm}^3$$

$$\Rightarrow \quad U_K = 20\ \mathrm{MeV}, U_{\bar{K}} = -120\ \mathrm{MeV}\ \mathrm{at}\ \rho_0 = 0.16\ \mathrm{fm}^{-3}$$

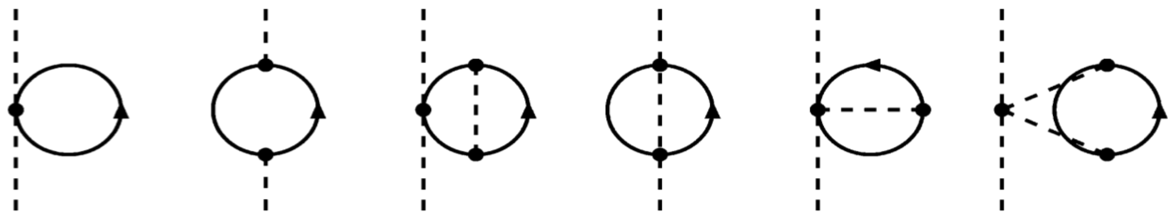


- Experimental data on spectrum and directed flow are consistent with repulsive kaon and attractive antikaon potentials

Hadron potentials in nuclear medium (III)

Kaiser & Weise, PLB 512, 283 (2001)

- **Pions**: $U_\pi = \Pi/(2m_\pi)$ in terms of pion selfenergies



$$\Pi^-(\rho_n,\rho_p) = \rho_n[T^-_{\pi N} - T^+_{\pi N}] - \rho_p[T^-_{\pi N} + T^+_{\pi N}] + \Pi^-_{\rm rel}(\rho_n,\rho_p) + \Pi^-_{\rm cor}(\rho_n,\rho_p)$$

$$\Pi^+(\rho_p,\rho_n) = \Pi^-(\rho_n,\rho_p)$$

$$\Pi^0(\rho_n,\rho_p) = -(\rho_p + \rho_n)T^+_{\pi N} + \Pi^0_{\rm cor}(\rho_n,\rho_p)$$

Isospin even and odd πN-scattering matrices extracted from energy shift and width of 1s level in pionic hydrogen atom

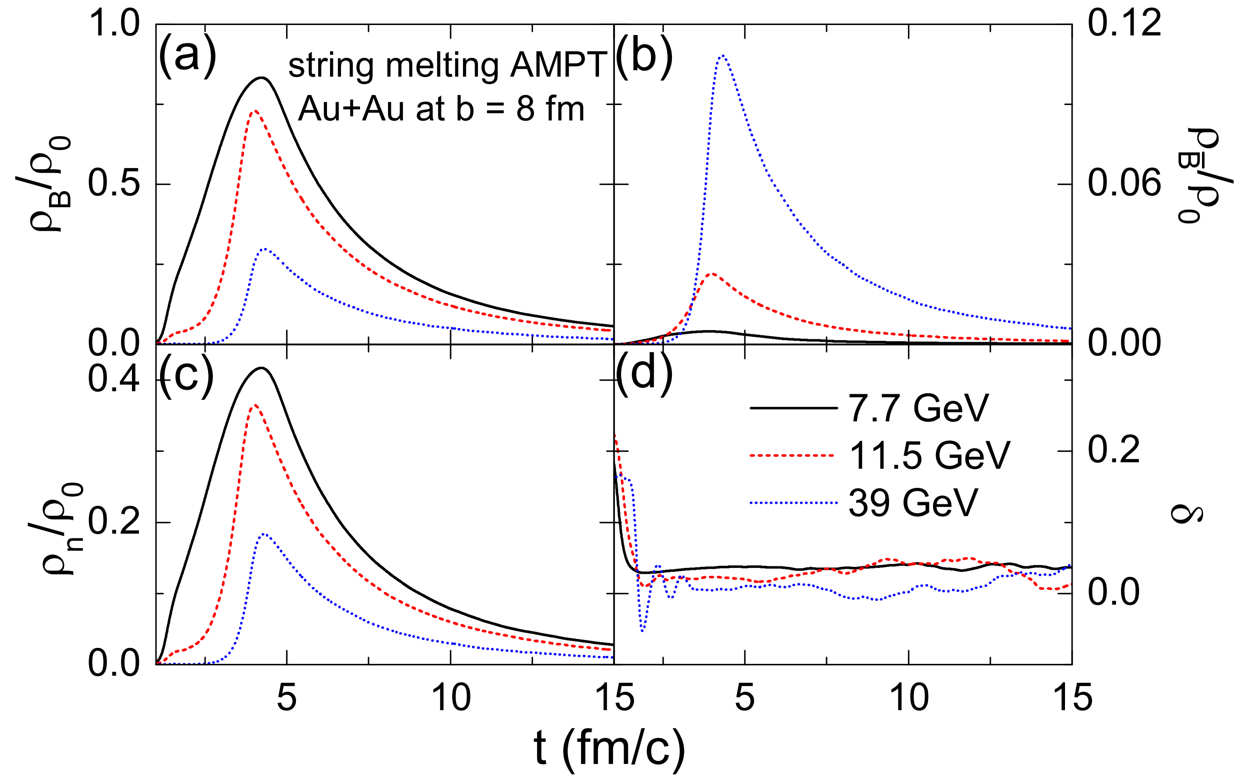
$$T^+_{\pi N} \approx 1.847\,\text{fm} \quad \text{and} \quad T^-_{\pi N} \approx -0.045\,\text{fm}$$

At normal nuclear density ρ=0.165 fm^{-3} and isospin asymmetry δ=0.2 such as in Pb,

$$U_{\pi^-} = 14\ \text{MeV},\ U_{\pi^+} = -1\ \text{MeV},\ U_{\pi^0} = 6\ \text{MeV}$$

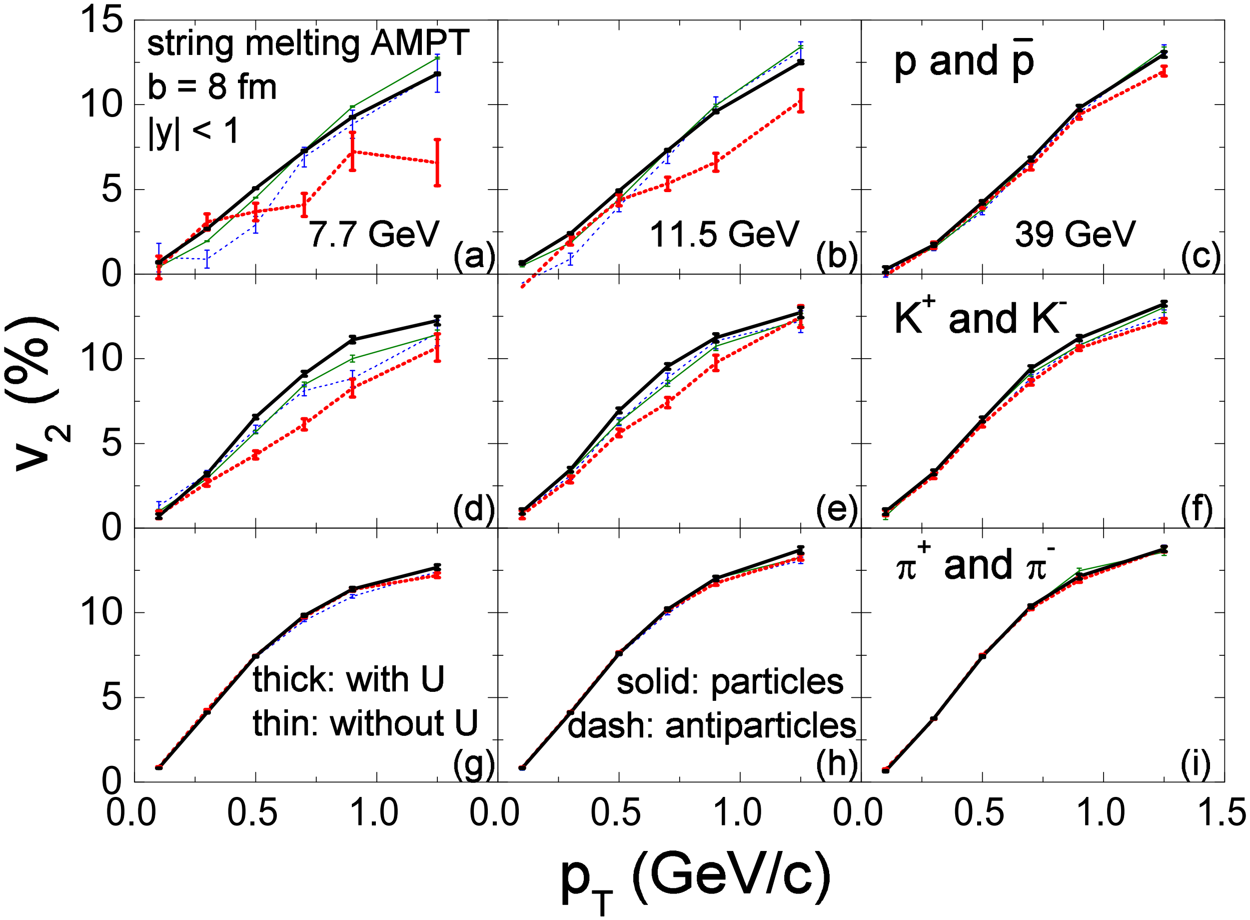
Hadron density evolutions in AMPT

Adjust parton scattering cross section and ending time of partonic stage to approximately reproduce measured elliptic flows and extracted hadronic energy density (~ 0.35 GeV/fm^3): isotropic cross sections of 3, 6 and 10 mb, and parton ending time of 3.5, 2.6, 2.9 fm/c for $s^{1/2}_{NN}$= 7.7, 11.5, and 39 GeV, respectively



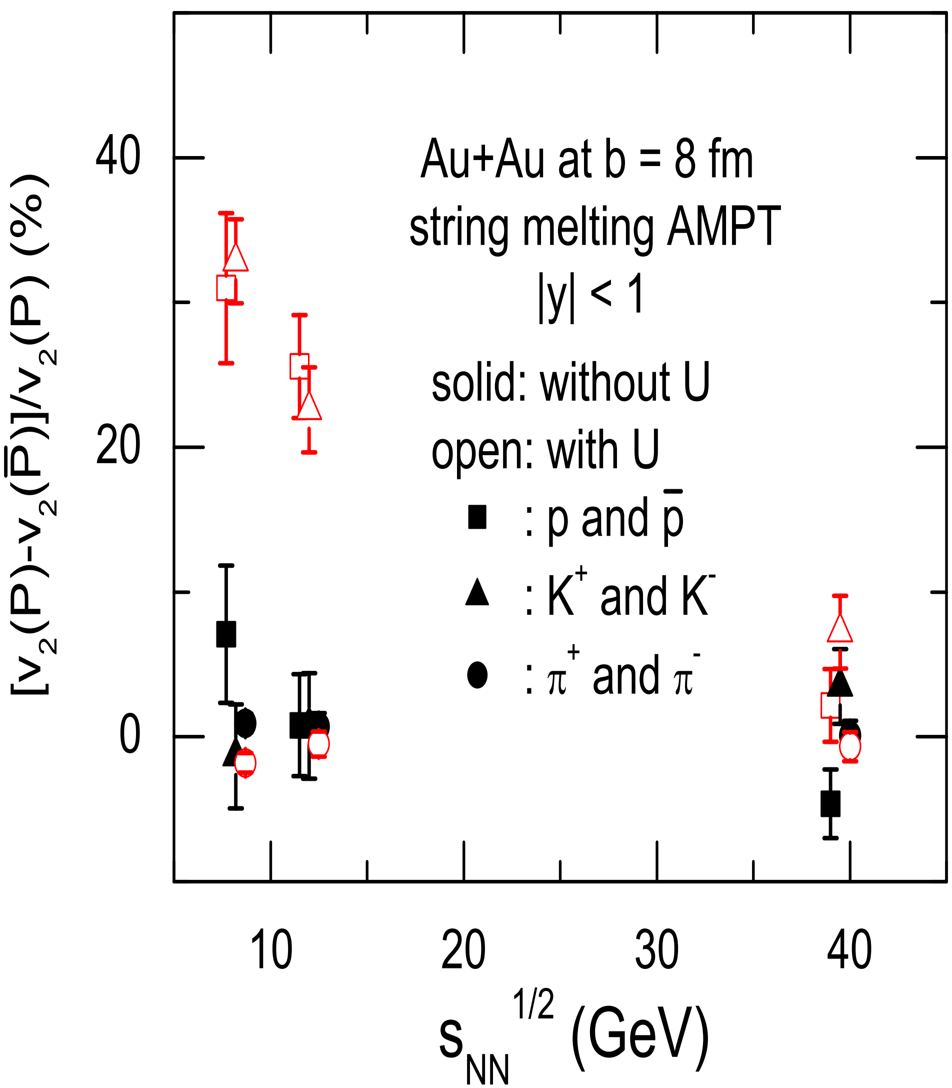
- Increasing baryon and decreasing antibaryon densities with decreasing energy
- Increasing neutron density with decreasing energy, but isospin asymmetry δ=0.02 is small due to production of Λ hyperon and pions

Particle and antiparticle differential elliptic flows



- Similar particle and antiparticle elliptic flows without hadronic potentials
- Hadronic potentials increase slightly p and pbar v_2 at p_T<0.5 GeV but reduce slightly (strongly) p (pbar) v_2 at high p_T
- Hadronic potentials increase slightly v_2 of K^+ and reduce v_2 of K^-
- Effects of hadronic potentials on π^+ and π^- v_2 are small

P_T-integrated particle and antiparticle elliptic flow difference



- Difference very small without hadronic potentials → different particle and antiparticle scattering and absorption cross sections have small effects
- Hadronic potentials lead to relative v_2 difference between p and pbar and between K^+ and K^- of 30% at 7.7 GeV, 20% at 11.5 GeV, and negligibly small value at 39 GeV, only very small negative value between π^+ and π^-
- Compared to experimental values of 63%, 44%, and 12% for (p,pbar), 13%, 3%, and 1% for (K^+,K^-), -5%, -10%, and -13% for (π^+,π^-) at 7.7, 11.5, and 39 GeV, ours are smaller for (p,pbar) and (π^+,π^-) and larger for (K^+,K^-)

Quark and antiquark potentials in QGP

- NJL model [Asakawa & Yazaki, NPA 504, 668 (1989)]

$$H = -i\bar{q}\gamma\cdot\nabla q + m\bar{q}q - g\left[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2\right]$$

- Fierz transformation of last term and mean-field approximation $G = \frac{4N_c+1}{4N_c}g$

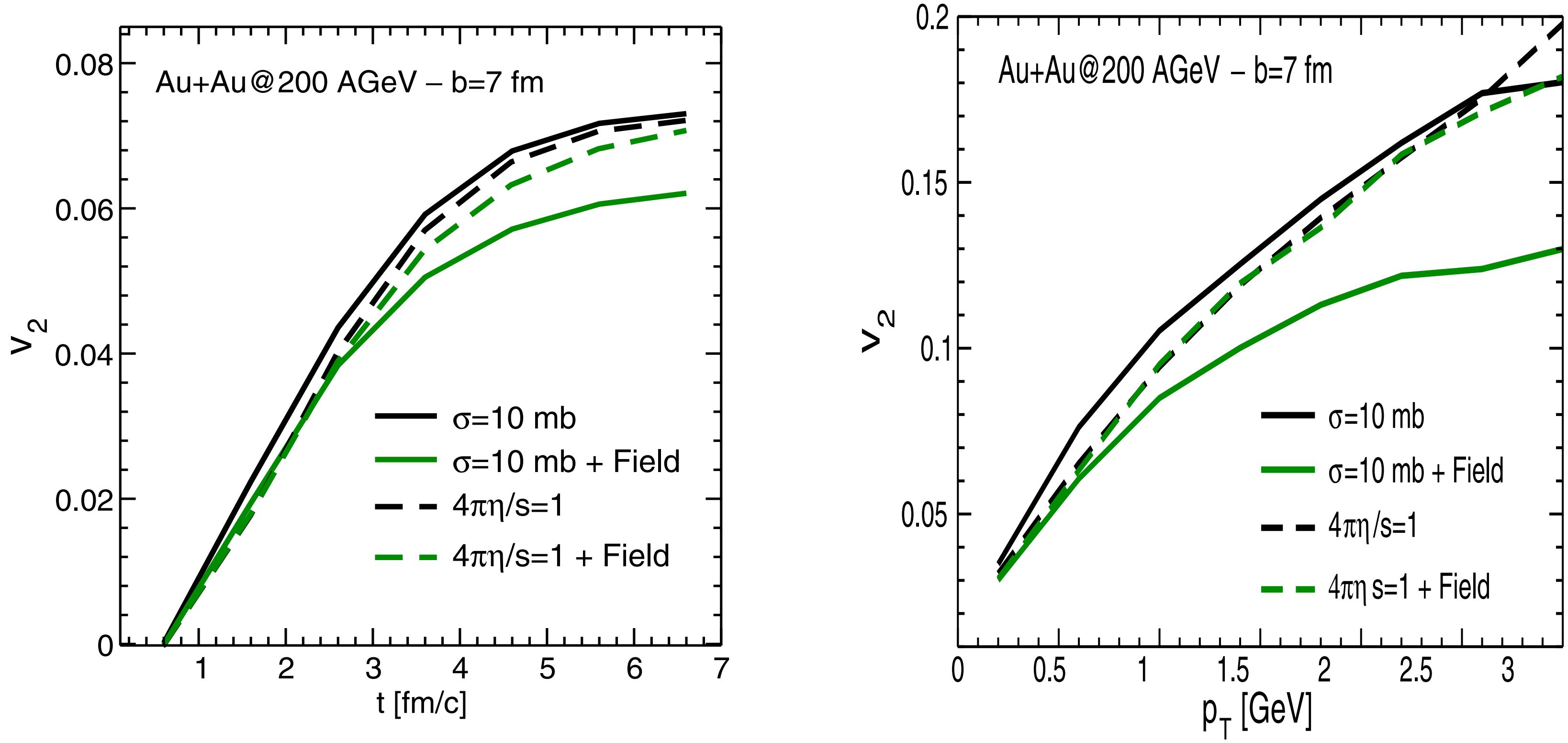
$$H_{MF} = -i\bar{q}\gamma\cdot\nabla q + \left(m - 2G\langle\bar{q}q\rangle\right)\bar{q}q + \frac{g}{N_c}\langle\bar{q}\gamma_0 q\rangle\bar{q}\gamma_0 q + G\langle\bar{q}q\rangle^2 - \frac{g}{2N_c}\langle\bar{q}\gamma_0 q\rangle^2$$

- Quark mass is modified by the quark condensate
  - Attractive scalar potential on both quark and antiquark
- Vector potential is repulsive for quark and attractive for antiquark: enhances relative v_2 difference between quarks and antiquarsk
  - Enhances relative v_2 difference between p and pbar
  - Reduces relative v_2 difference between K^+ and K^-

→ Would bring results with only hadronic potentials closer to experimental data

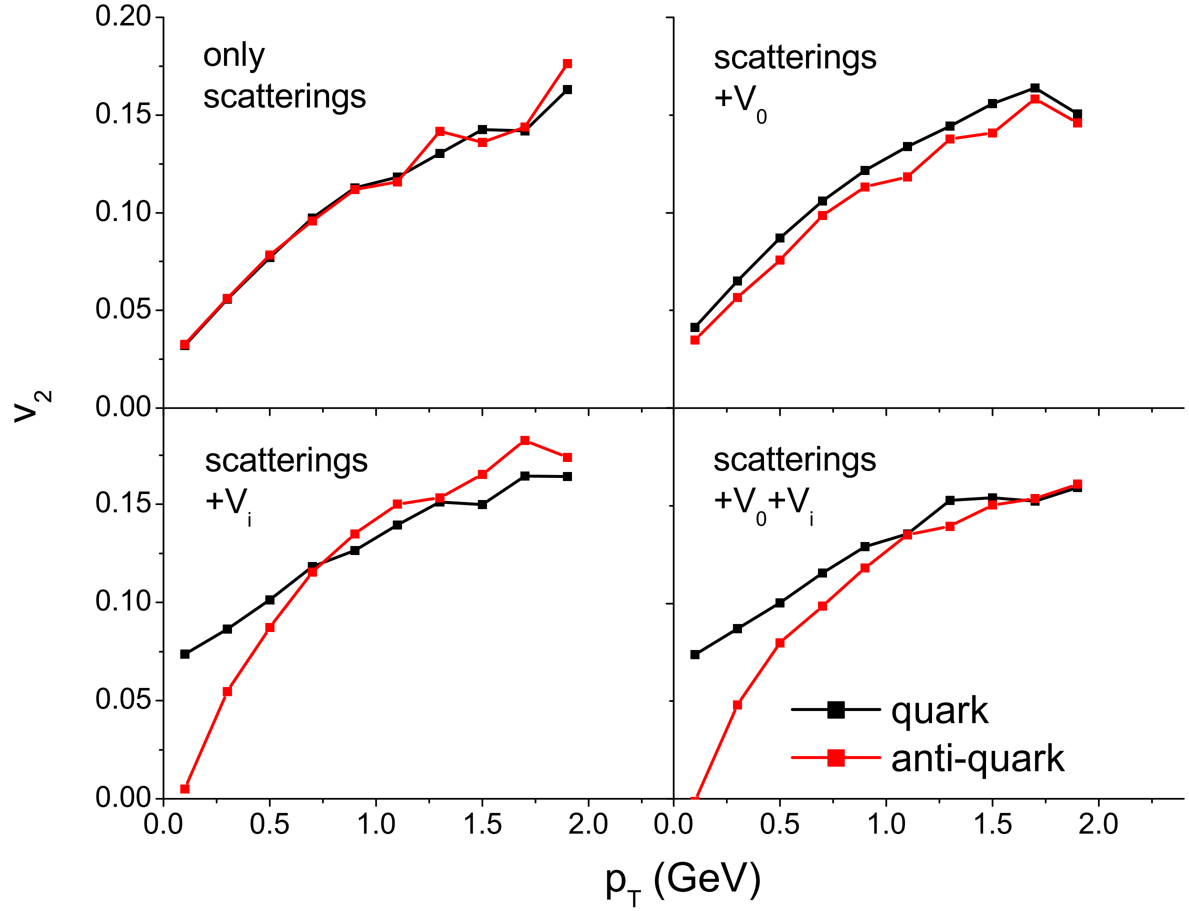
Effects of attractive scalar potential in quark matter

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



- Attractive scalar potential reduces v_2 of both quark and antiquark
- Effects are reduced when parton scattering cross section is large

Effects of Vector potential in quark matter



Preliminary results from Taesoo Song

- Time (electric) component of vector potential increases quark but decreases antiquark elliptic flows
- Space (magnetic) component of vector potential has a similar effect at low p_T but an opposite effect at high p_T
- Net effect of vector potential: larger quark than antiquark elliptic flows

Summary

- Different particle and antiparticle v_2 is observed in BES at RHIC where produced matter has a large finite baryon chemical potential
- Taking into account different potentials for hadrons and antihadrons can partially account for the experimental observation
- Quarks and antiquarks are expected to be affected by scalar and vector potentials in QGP
  - reduced v_2 due to attractive scalar potential
  - vector potential becomes nonzero at finite baryon chemical potential; repulsive for quarks and attractive for anitquarks
- Information on quark and antiquark potentials at finite baryon chemical potential is useful for understanding the EOS of QGP