

# Mean-field effects on elliptic flow

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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 and their effects on elliptic flow

Based on work with Jun Xu [PRC 85, 041901(R) (2012)] and preliminary results from Taesoo Song, Greco & Plumari

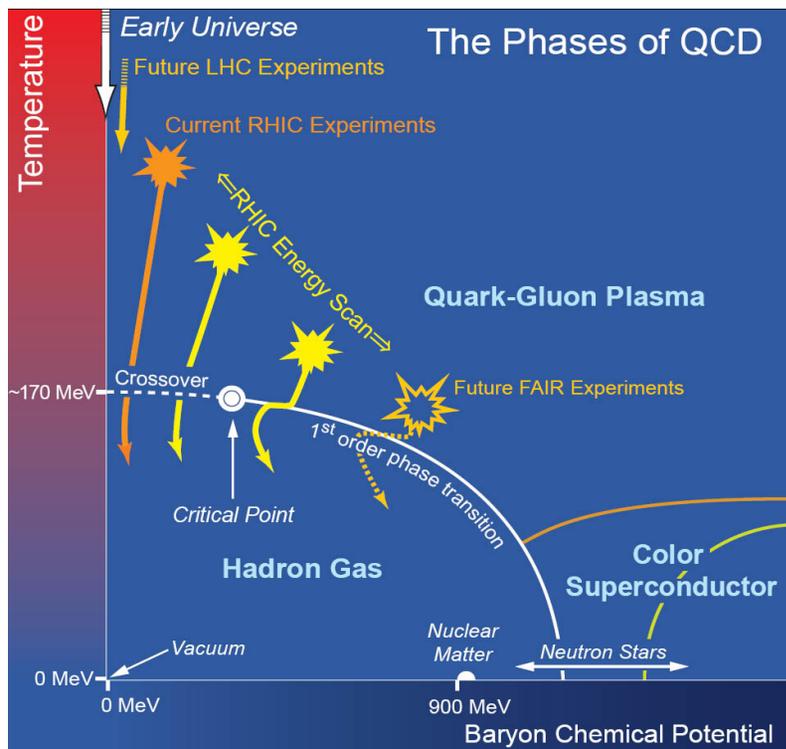
Supported by National Science Foundation and the Welch Foundation

# Beam energy scan at RHIC

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

## Motivations:

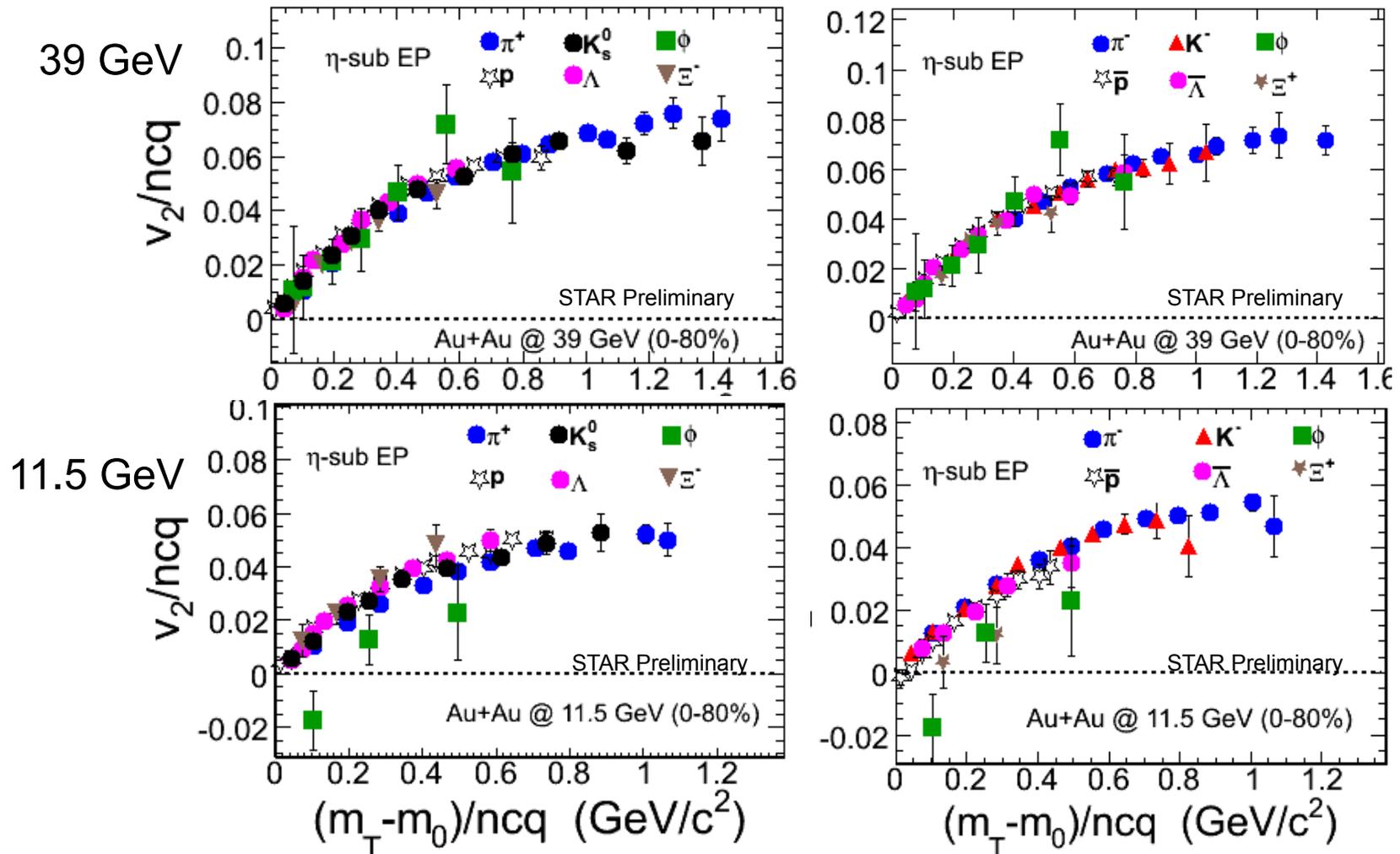
Study QCD phase diagram at finite baryon chemical potential: critical point (CP), onset of de-confinement



## Experimental observations:

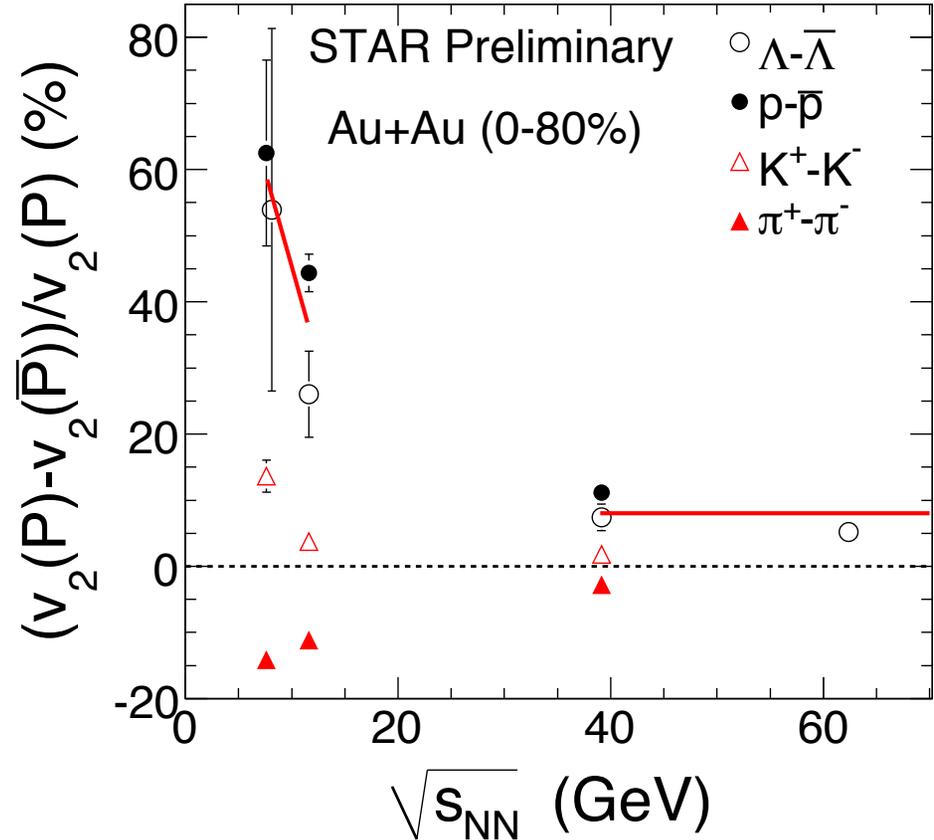
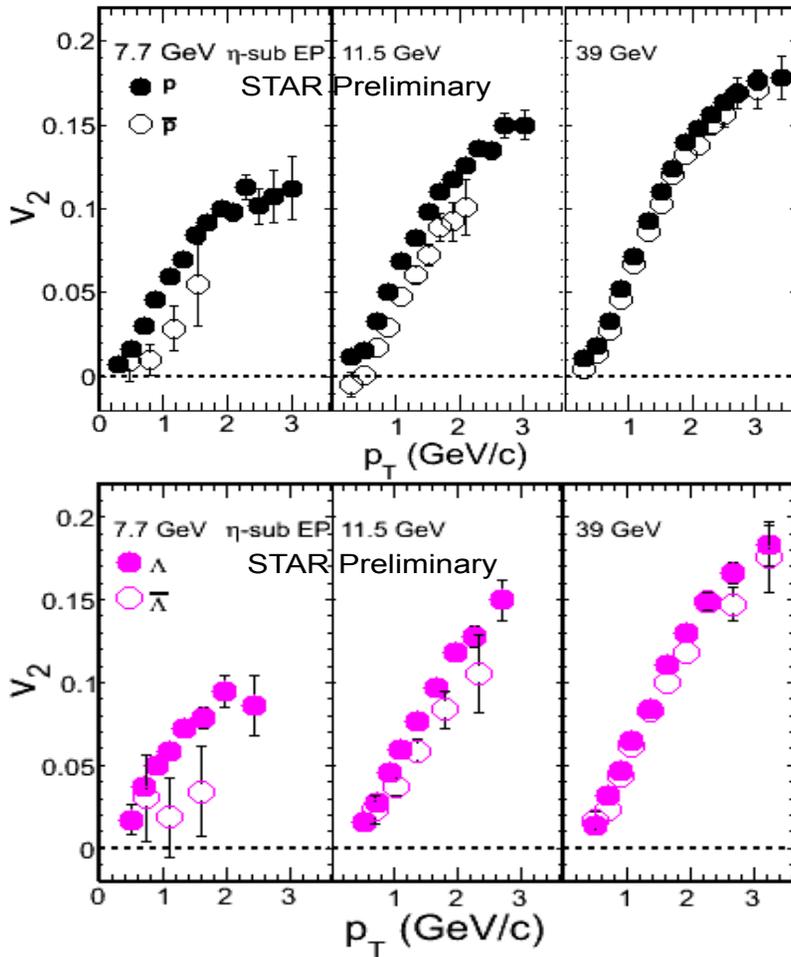
- **Particle ratios:** increasing baryon chemical potential with decreasing beam energy (DBE), reaching  $\sim 400$  MeV at  $s^{1/2}_{NN} = 7.7$  GeV
- **Dynamic charge correlations:** decreasing difference in same and opposite charges correlations with DBE (hadronic dominance?)
- **Freeze-out eccentricity:** 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  $v_{dyn}(K/\pi)$  (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



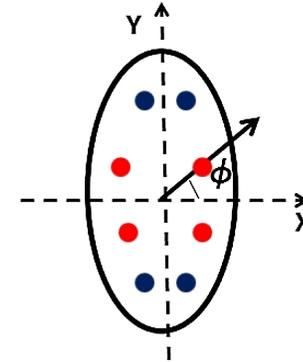
- Particle and antiparticle elliptic flows become significantly different below  $s_{NN}^{1/2} < 11.5$  GeV:  $v_2(\text{baryon}) > v_2(\text{anti-baryon})$ ,  $v_2(K^+) > v_2(K^-)$ , and  $v_2(\pi^+) < v_2(\pi^-)$
- $P_T$ -integrated relative  $v_2$  difference between particles and antiparticles: 63%,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

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



- Electric quadrupole moment in QGP
- radial flow leads to decreasing positive hadron and increasing negative hadron elliptic flows
- $v_2(\pi^+) < v_2(\pi^-)$

- Effects on p and  $\bar{p}$  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

## ▪ **Baryon charge, strangeness and isospin conservations** [Steubheimer, Koch & Bleicher, arXiv:1207.2791 [nucl-th]]: Decreasing pbar/p ratio with radial distance

## ▪ **Different particle and antiparticle potentials** [Xu & Ko, PRC 85, 041901(R) (2012)]:

Potentials are repulsive for particles and attractive for antiparticles

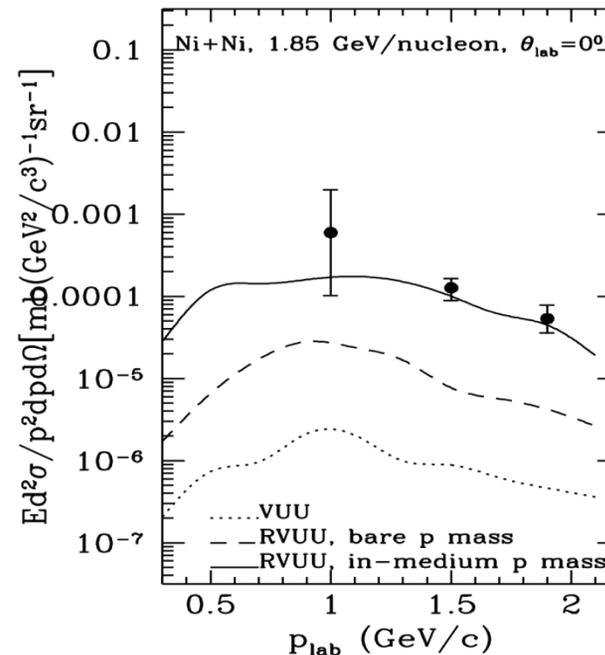
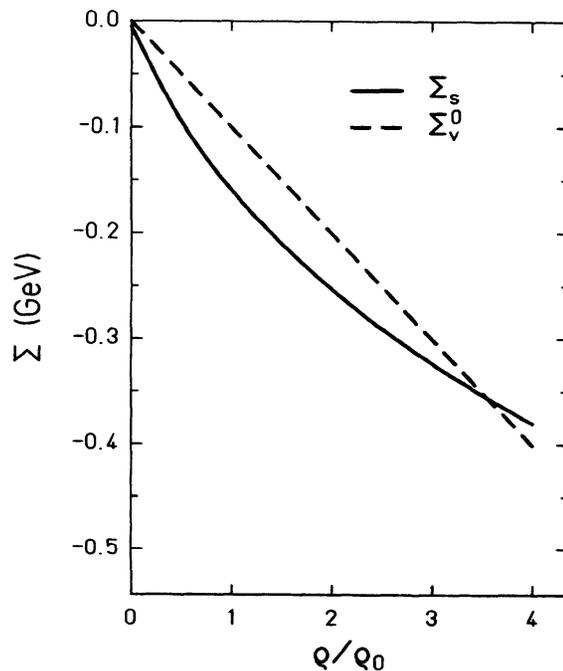
# Hadron potentials in nuclear medium (I)

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

- **Nucleons and antinucleons:** Relativistic mean-field model → attractive scalar potential  $\Sigma_s$  and repulsive vector potential  $\Sigma_v$  (“+” for nucleons and “-” for antinucleons due to G-parity)

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

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



- 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  $\rightarrow$  repulsive potential for kaons and attractive potential for antikaons

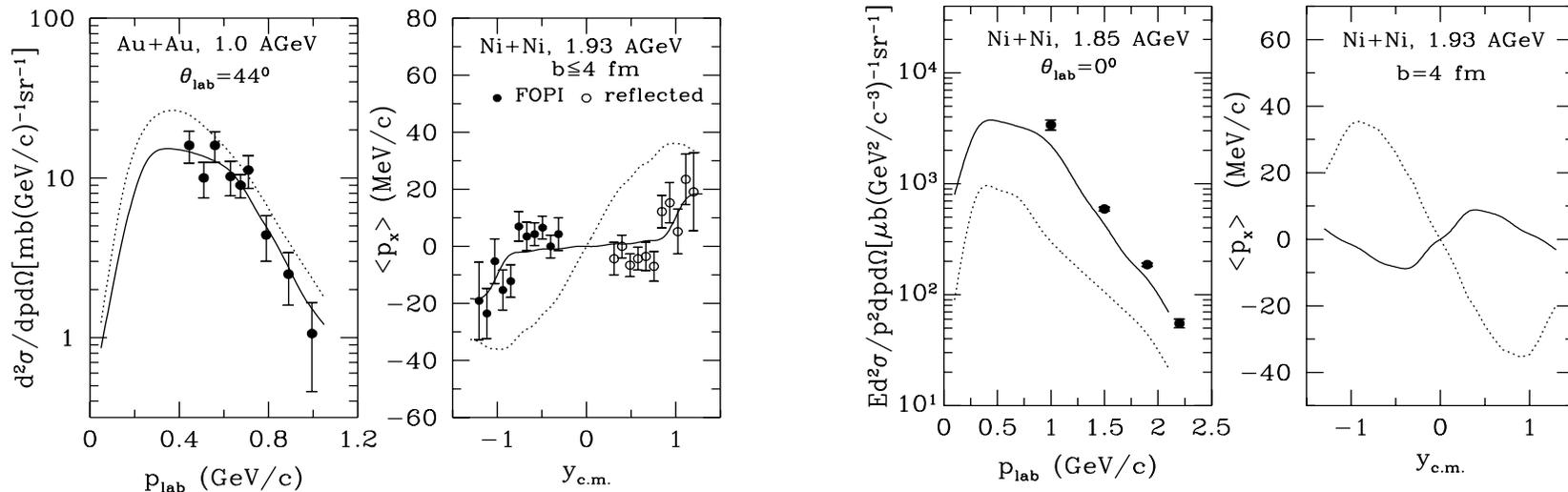
$$U_{K,\bar{K}} = \omega_{K,\bar{K}} - \omega_0, \quad \omega_0 = \sqrt{m_K^2 + p^2}$$

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

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

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

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

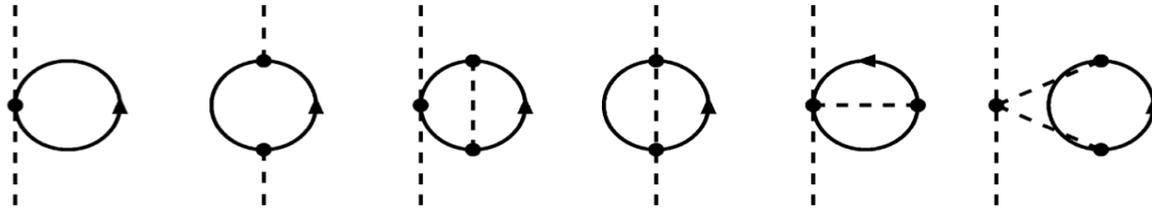


- Experimental data on spectrum and directed flow are consistent with repulsive kaon and attractive antikaon potentials

## Hadron potentials in nuclear medium (III)

Kaiser & Weise,  
PLB 512, 283 (2001)

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



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

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

$$\Pi^0(\rho_n, \rho_p) = -(\rho_p + \rho_n)T_{\pi N}^+ + \Pi_{\text{cor}}^0(\rho_n, \rho_p)$$

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

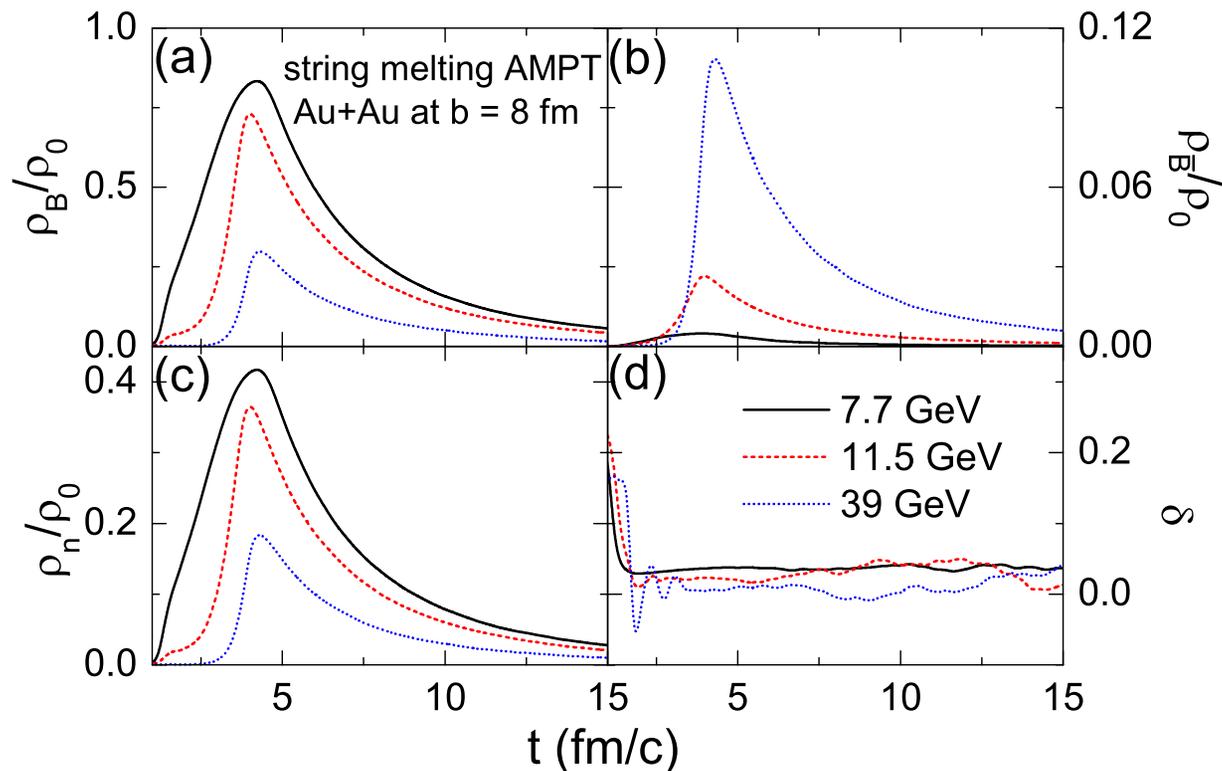
$$T_{\pi N}^+ \approx 1.847 \text{ fm} \quad \text{and} \quad T_{\pi N}^- \approx -0.045 \text{ fm}$$

At normal nuclear density  $\rho=0.165 \text{ fm}^{-3}$  and isospin asymmetry  $\delta=0.2$  such as in Pb,

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

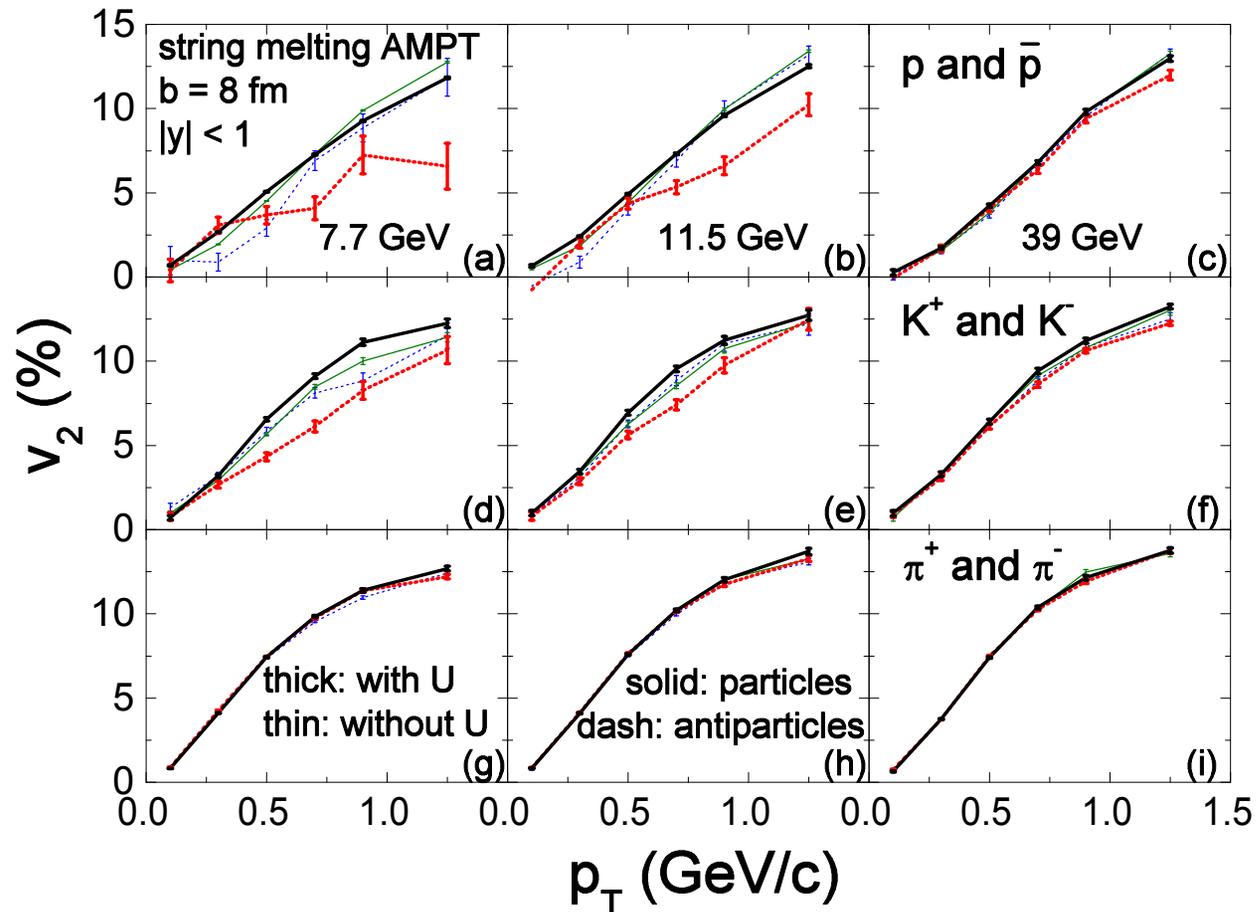
## Hadron density evolutions in AMPT

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



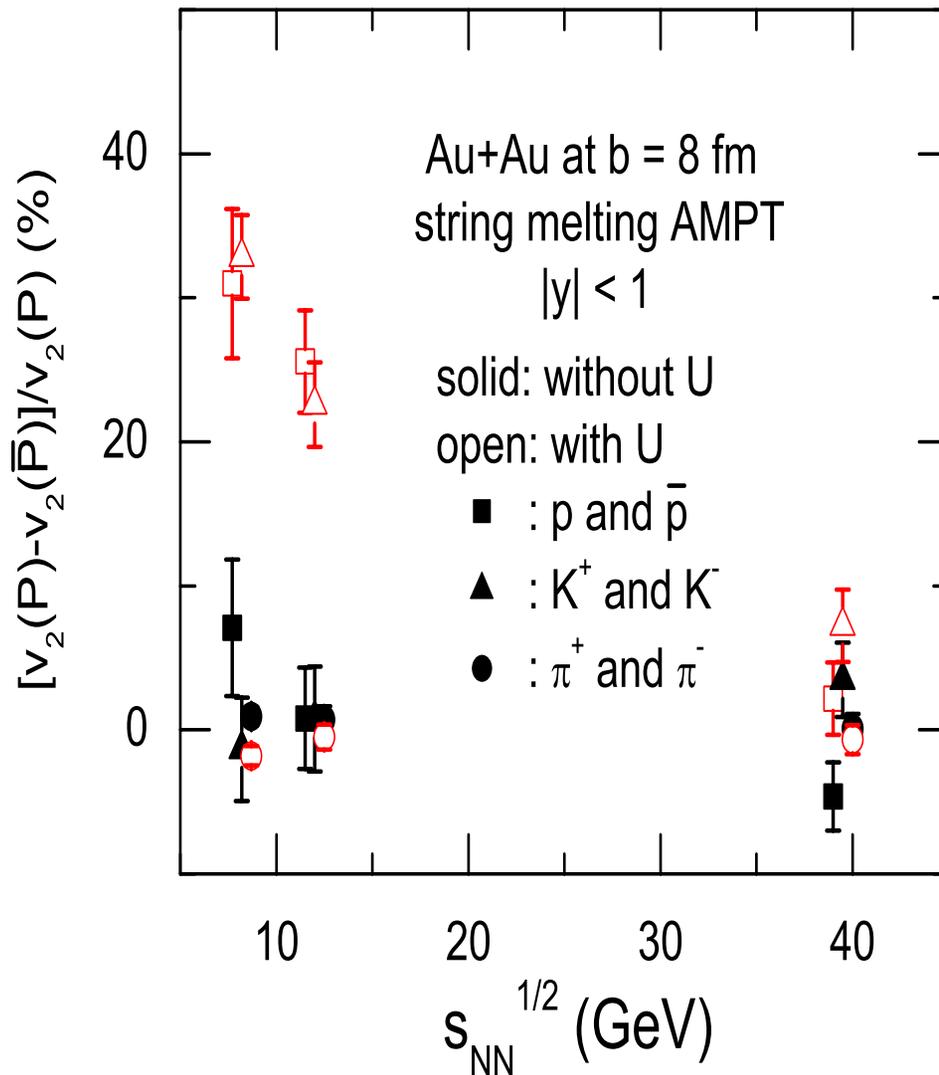
- Increasing baryon and decreasing antibaryon densities with decreasing energy
- Increasing neutron density with decreasing energy, but isospin asymmetry  $\delta=0.02$  is small due to production of  $\Lambda$  hyperon and pions

## 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  $\pi^+$  and  $\pi^-$   $v_2$  are small

## $P_T$ -integrated particle and antiparticle elliptic flow difference



- Difference very small without hadronic potentials  $\rightarrow$  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  $\pi^+$  and  $\pi^-$
- Compared to experimental values of 63%, 44%, and 12% for (p,pbar), 13%, 3%, and 1% for ( $K^+,K^-$ ), -5%, -10%, and -13% for ( $\pi^+,\pi^-$ ) at 7.7, 11.5, and 39 GeV, ours are smaller for (p,pbar) and ( $\pi^+,\pi^-$ ) 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  $G = \frac{4N_c + 1}{4N_c} g$

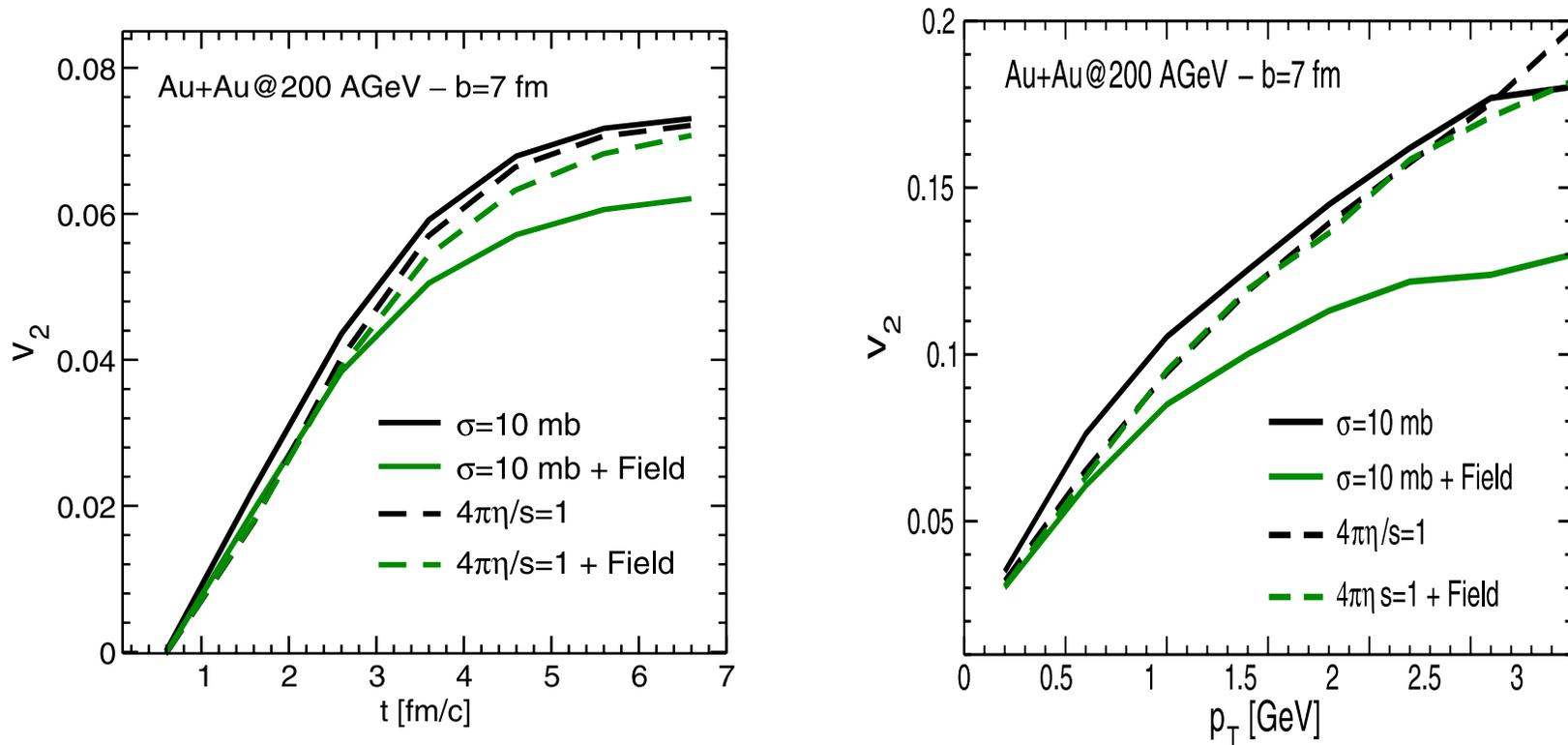
$$H_{MF} = -i\bar{q}\gamma\cdot\nabla q + (m - 2G\langle\bar{q}q\rangle)\bar{q}q + \frac{g}{N_c}\langle\bar{q}\gamma_0 q\rangle\bar{q}\gamma_0 q + G\langle\bar{q}q\rangle^2 - \frac{g}{2N_c}\langle\bar{q}\gamma_0 q\rangle^2$$

- 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 antiquarks
  - 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

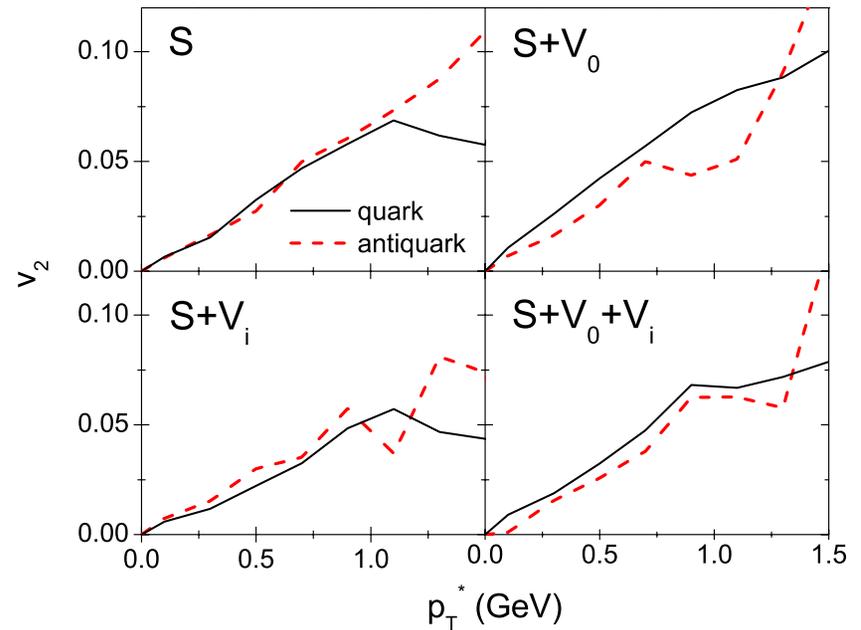
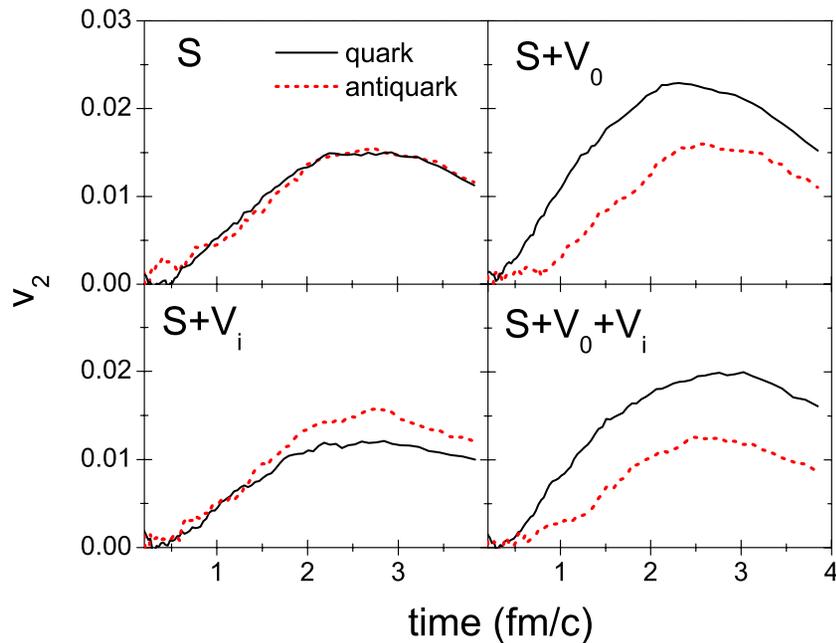
# Effects of attractive scalar potential in quark matter

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



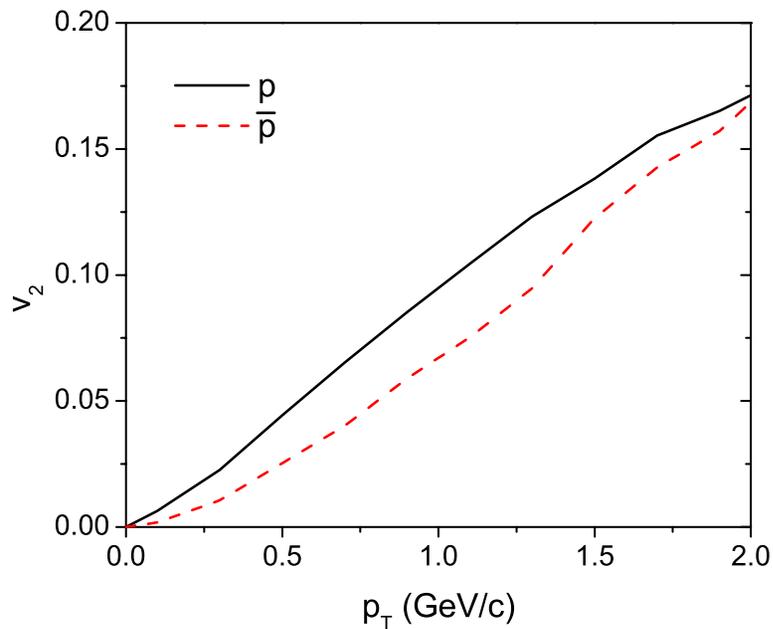
- Attractive scalar potential reduces  $v_2$  of both quark and antiquark
- Effects are reduced when parton scattering cross section is large

## Effects of Vector potential in quark matter

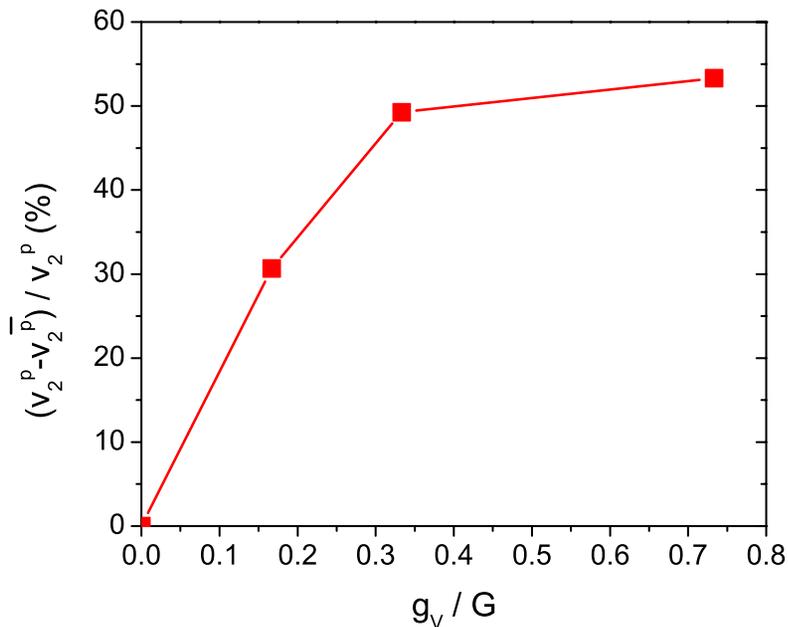


- Time (electric) component of vector potential increases quark but decreases antiquark elliptic flows
- Space (magnetic) component of vector potential has a similar effect at low  $p_T$  but an opposite effect at high  $p_T$
- Net effect of vector potential: larger quark than antiquark elliptic flows

## Partonic mean-field effects on proton and antiproton $v_2$



- Using recombination or coalescence model to produce protons and antiprotons from quarks and antiquarks at hadronization
- Smaller quark than antiquark  $v_2$  leads to smaller proton than antiproton  $v_2$



- Relative  $v_2$  difference between protons and antiprotons increases with the strength of quark vector interactions ( $g_v$ ); linearly for small  $g_v$  then leveling off for large  $g_v$

## 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 antiquarks
  - larger quark than antiquark  $v_2$  in baryon-rich QGP
  - larger proton than antiproton  $v_2$  after hadronization
- Information on quark and antiquark potentials at finite baryon chemical potential is useful for understanding the EOS of QGP