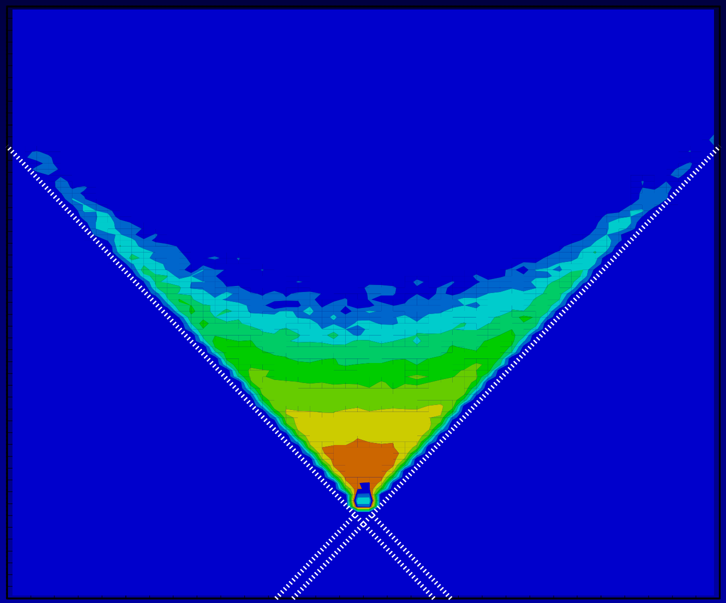
In-Medium modifications of resonances at RHIC

Christian Fuchs

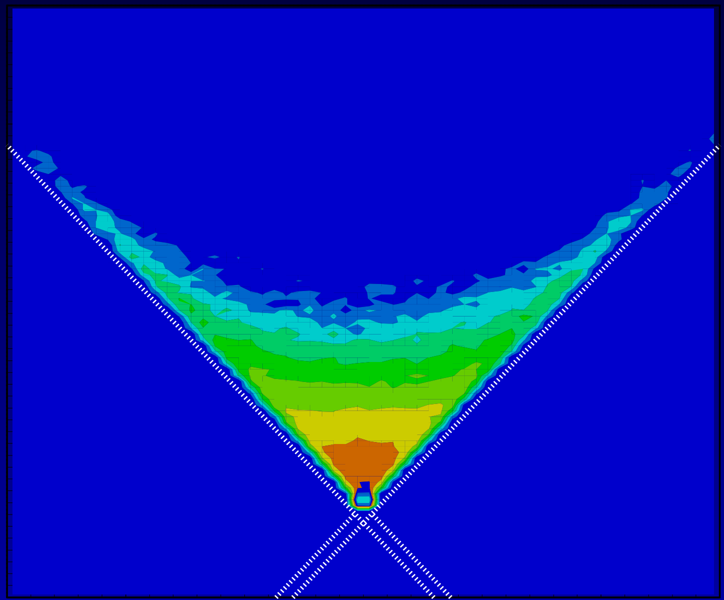
Institut für Theoretische Physik

Eberhard Karls Universität Tübingen

Content

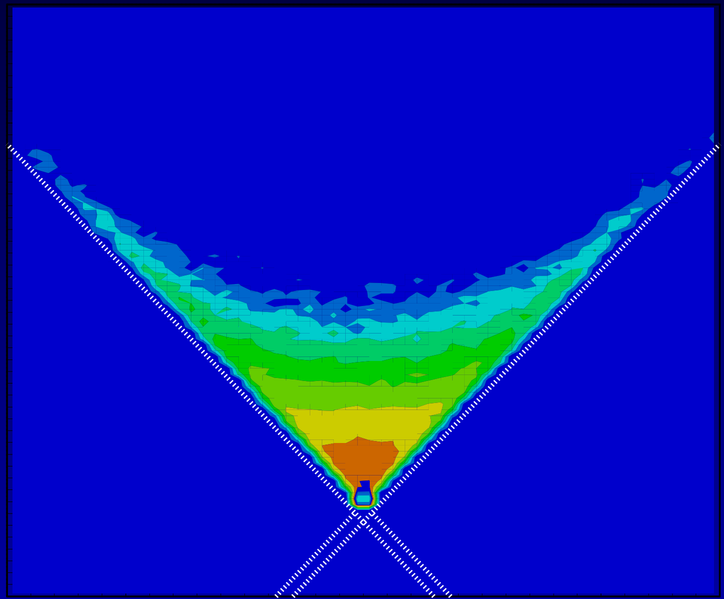


Content



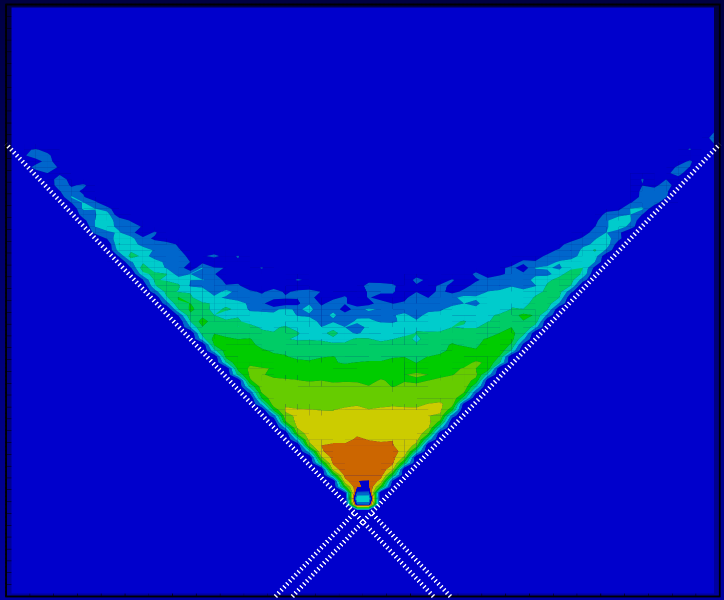
- Motivation: ϕ puzzle

Content



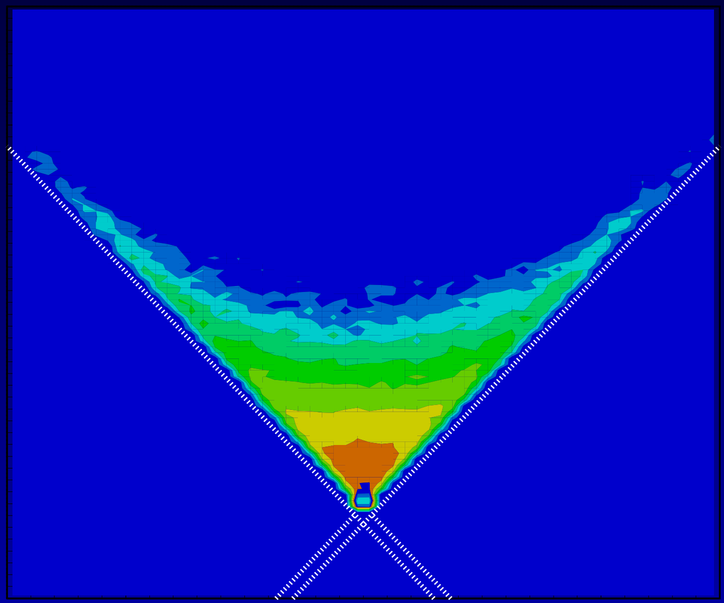
- Motivation: ϕ puzzle
- Current algebra $T << M_\pi$

Content



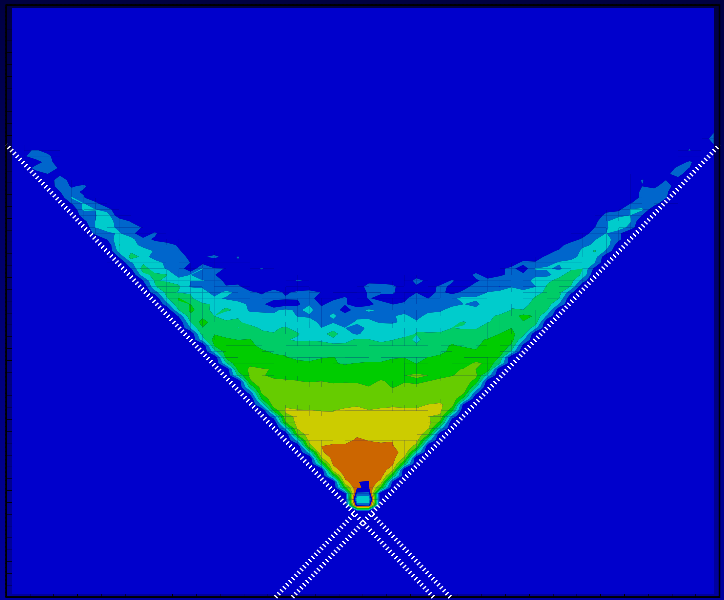
- Motivation: ϕ puzzle
- Current algebra $T << M_\pi$
- One loop ChPT $T << M_\pi$

Content



- Motivation: ϕ puzzle
- Current algebra $T << M_\pi$
- One loop ChPT $T << M_\pi$
- Beyond one loop $T \sim M_\pi$

Content



- Motivation: ϕ puzzle
- Current algebra $T << M_\pi$
- One loop ChPT $T << M_\pi$
- Beyond one loop $T \sim M_\pi$
- Implication for ϕ @ RHIC

The ϕ puzzle

channel	dN_ϕ/dy	stat. error	sys. error
$\phi \mapsto K^+K^-$	2.01	± 0.22	+1.01/-0.52
$\phi \mapsto e^+e^-$	5.4	± 2.5	+3.4/-2.8

Au+Au @ 200 AGeV
PHENIX: Nagle et al., nucl-ex/0209015
similar observation by NA49/NA50

$\Longrightarrow$ in-medium ϕ width ?
Lissauer & Shuryak '91 $\uparrow$
Blaizot & Galain '91 $\downarrow$

Kaons in nuclear matter

HIC's in the SIS/GSI regime: finite density, low temperature

Effective chiral Lagrangian (Kaplan & Nelson 86)

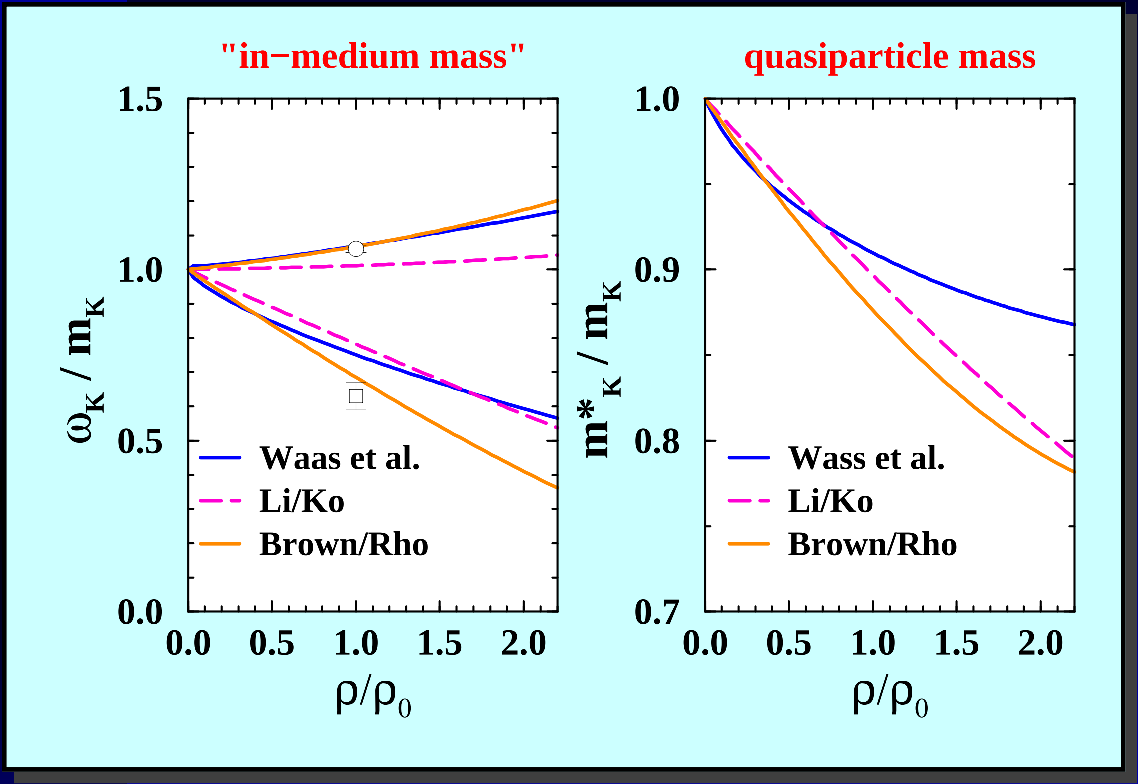
$$\begin{aligned}\mathcal{L}_K &= \partial^\mu \overline{\Phi}_{\mathrm{K}} \partial_\mu \Phi_{\mathrm{K}} - \left(m_{\mathrm{K}}^2 - \frac{\Sigma_{\mathrm{KN}}}{f_\pi^2} \overline{\Psi}\Psi \right) \overline{\Phi}_{\mathrm{K}} \Phi_{\mathrm{K}} \\ &- \frac{3}{8 f_\pi^2} i \overline{\Psi} \gamma_\mu \Psi \overline{\Phi}_{\mathrm{K}} \overset{\leftrightarrow}{\partial^\mu} \Phi_{\mathrm{K}} + \mathcal{O}((1/f_\pi^2)^2)\end{aligned}$$

Klein-Gordon equation:

$$\left[\partial_\mu \partial^\mu \pm \frac{3i}{4 f_\pi^2} j_\mu \partial^\mu + \left(m_{\mathrm{K}}^2 - \frac{\Sigma_{\mathrm{KN}}}{f_\pi^2} \rho_{\mathrm{s}} \right) \right] \Phi_{\mathrm{K}^\pm} = 0$$

$$\text{Vector field}: \; V_\mu = \frac{3}{8 f_\pi^2} j_\mu$$

Quasi-particle picture



$$\left[(\partial_\mu \pm iV_\mu)^2 + m_{\rm K}^{*2}\right]\phi_{\rm K\pm} = 0$$

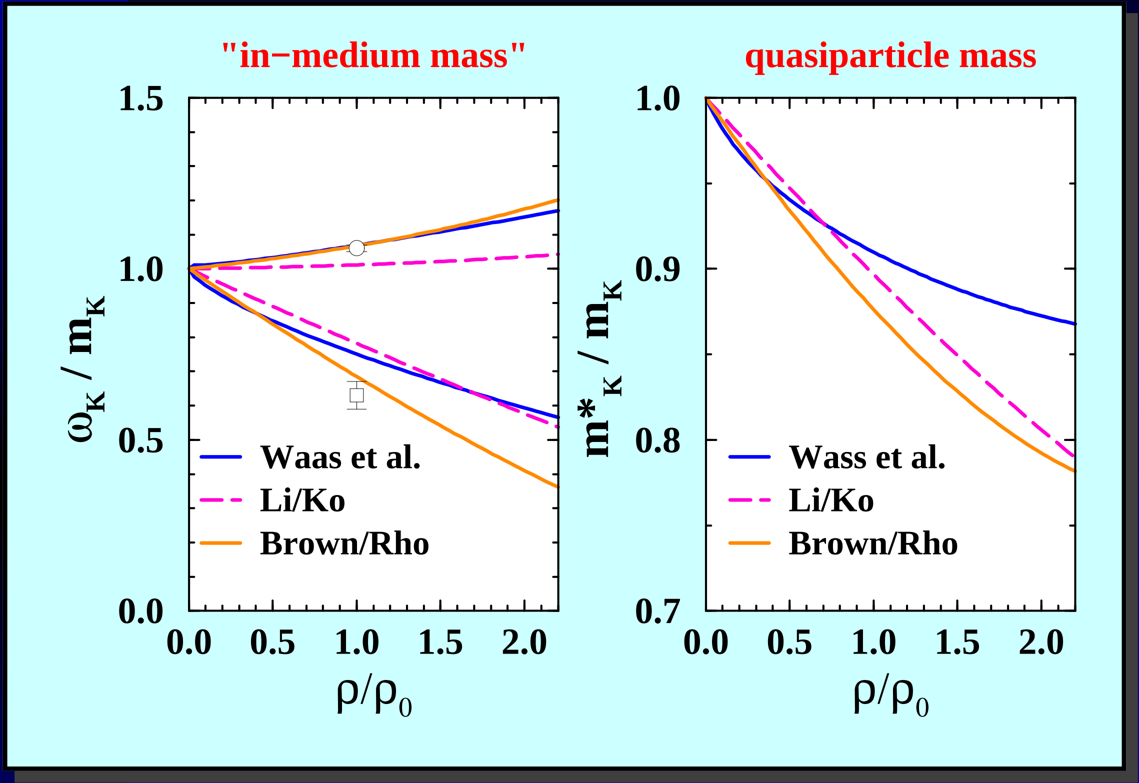
$$m_{\rm K}^* = \sqrt{m_{\rm K}^2 - \frac{\Sigma_{\rm KN}}{f_\pi^2}\rho_{\rm s} + V_\mu V^\mu}$$

$$\left[k^{*2} - m_{\rm K}^{*2}\right]\phi_{\rm K\pm} = 0$$

dispersion relation :

$$\omega = \sqrt{\mathbf{k}^{*2} + m_{\rm K}^{*2}} \pm V_0$$

Quasi-particle picture



$$\left[(\partial_\mu \pm iV_\mu)^2 + m_{\mathrm{K}}^{*2}\right] \phi_{\mathrm{K}^\pm} = 0$$

$$m_{\mathrm{K}}^* = \sqrt{m_{\mathrm{K}}^2 - \frac{\Sigma_{\mathrm{KN}}}{f_\pi^2}\rho_{\mathrm{s}} + V_\mu V^\mu}$$

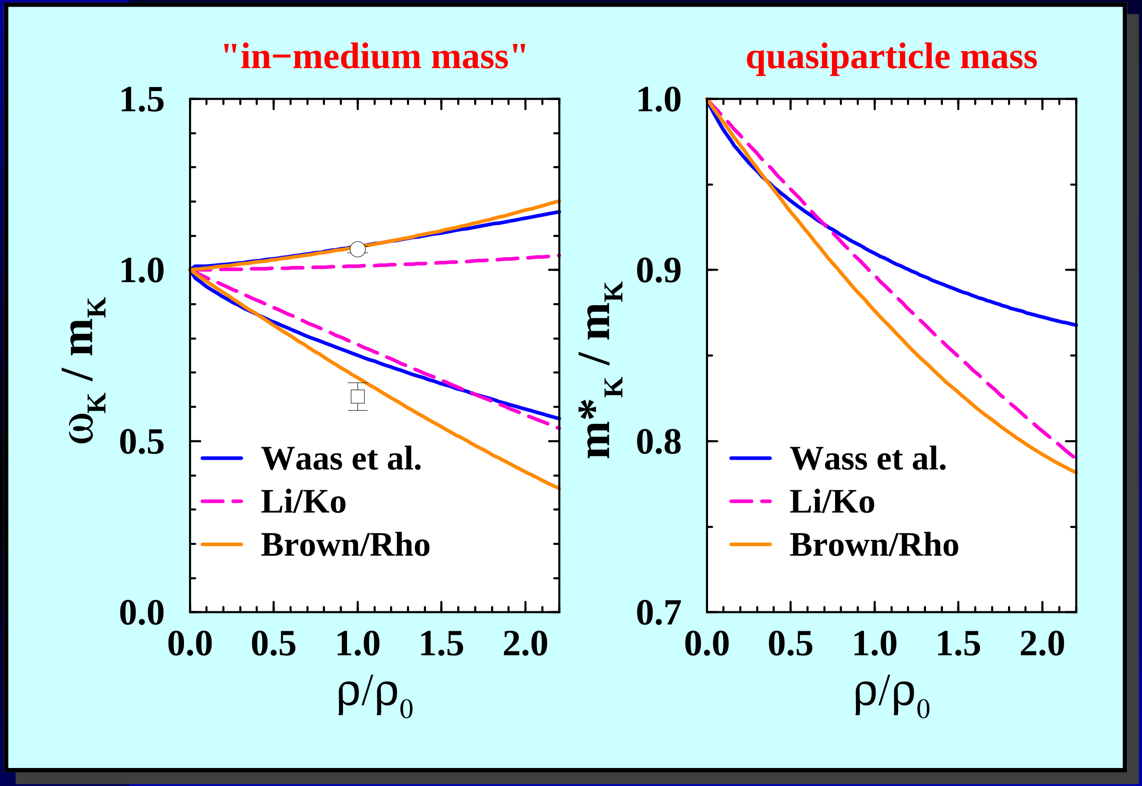
$$\left[k^{*2} - m_{\mathrm{K}}^{*2}\right] \phi_{\mathrm{K}^\pm} = 0$$

dispersion relation :

$$\omega = \sqrt{\mathbf{k}^{*2} + m_{\mathrm{K}}^{*2}} \pm V_0$$

How good is mean field?

Quasi-particle picture



$$\left[(\partial_\mu \pm iV_\mu)^2 + m_{\mathrm{K}}^{*2}\right]\phi_{\mathrm{K}\pm} = 0$$

$$m_{\mathrm{K}}^{*} = \sqrt{m_{\mathrm{K}}^{2} - \frac{\Sigma_{\mathrm{KN}}}{f_\pi^2}\rho_{\mathrm{s}} + V_\mu V^\mu}$$

$$\left[k^{*2} - m_{\mathrm{K}}^{*2}\right]\phi_{\mathrm{K}\pm} = 0$$

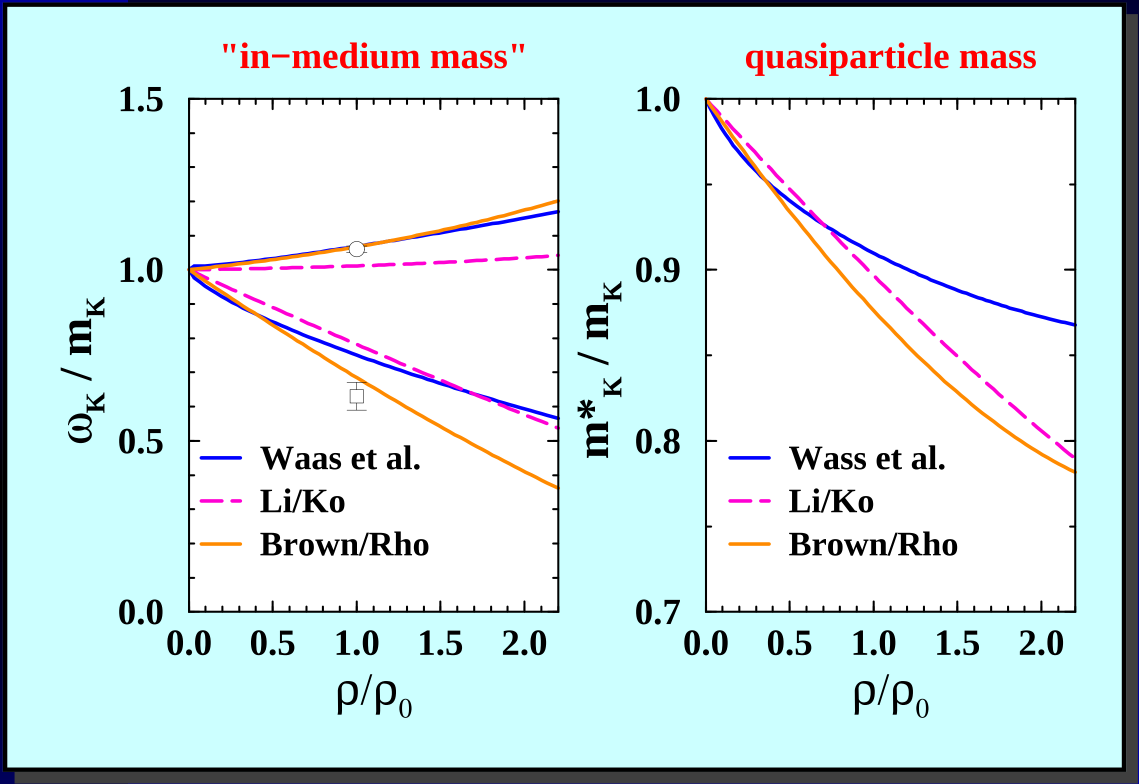
dispersion relation :

$$\omega = \sqrt{\mathbf{k}^{*2} + m_{\mathrm{K}}^{*2}} \pm V_0$$

How good is mean field?

- $\uparrow$ for K^+

Quasi-particle picture



$$\left[(\partial_\mu \pm iV_\mu)^2 + m_{\rm K}^{*2}\right]\phi_{{\rm K}\pm} = 0$$

$$m_{\rm K}^* = \sqrt{m_{\rm K}^2 - \frac{\Sigma_{\rm KN}}{f_\pi^2}\rho_{\rm s} + V_\mu V^\mu}$$

$$\left[k^{*2} - m_{\rm K}^{*2}\right]\phi_{{\rm K}\pm} = 0$$

dispersion relation :

$$\omega = \sqrt{\mathbf{k}^{*2} + m_{\rm K}^{*2}} \pm V_0$$

How good is mean field?

- $\uparrow$ for K^+
- $\downarrow$ for K^- $\Longrightarrow$ Λ_{1405} resonance $\Longrightarrow$ coupled channels

Kaons in pion matter

Interaction of pseudo-scalar mesons @ low energies

$\Longrightarrow$ ChPT

$\Longrightarrow$ Pion self-energy $\Sigma(p^2, E)$ from πK forward scattering amplitudes (on-shell pions ($p^2 = M_\pi^2$) and off-shell kaons ($p^2 \neq M_K^2$))

$$\boxed{\begin{aligned} A^{\pm}(s,t,p^2) &= 8\pi\sqrt{s}\left(a_0^{\pm} + p^{*2}(b_0^{\pm} + 3a_1^{\pm}) + \frac{3}{2}ta_1^{\pm}\right) \\ &+ c^{\pm}(p^2 - M_K^2) \end{aligned}}$$

$a_\ell^{\pm}$: scattering length

$b_\ell^{\pm}$: effective range

p^* : πK c.m. momentum

Pion self-energy

Bose distributions:

$$dn_\pi = \frac{d^3p_\pi}{(2\pi)^3}\left(\exp(\frac{E_\pi - \mu_\pi}{T}) - 1\right)^{-1}$$

chemical potentials: $\mu_{\pi^+} = -\mu_{\pi^-}\ , \quad \mu_{\pi^0} = 0$

Near threshold: $\Longrightarrow$ expand $A^\pm(s,t,p^2)$

Self-energy:

$$\boxed{\begin{aligned} -\Sigma(p^2,E) &= \int A^+(s,0,p^2)(dn_{s\pi^+} + dn_{s\pi^0} + dn_{s\pi^-}) \\ &+ \int A^-(s,0,p^2)(-dn_{s\pi^+} + dn_{s\pi^-}) \end{aligned}}$$

Current algebra

In-medium dispersion law:

$$E_K^{(\pm)}(\mathbf{p}) = \pm\sqrt{\mathbf{p}^2 + M_K^2 + \delta M_K^2} + V_K$$

mass shift: δM_K, vector potential: V_K
nuclear matter: $\delta M_K < 0, \quad V_{K^+} = -V_{K^-} > 0$
current algebra prediction for a, b (Weinberg, Cronin):

$$\delta M_{K^\pm} = 0 \ , \ V_{K^\pm} = \pm\frac{n_{\pi^+} - n_{\pi^-}}{4F^2}$$

RHIC: $n_{\pi^+} \simeq n_{\pi^-}$

$$\boxed{\delta M_K = 0 \ \& \ V_K \simeq 0}$$

One loop ChPT

Current algebra: $a_0^+ = b_0^+ + 3a_1^+ = 0$

One loop ChPT: corr. $\mathcal{O}(p^4)$ Bernard, Kaiser, Meissner ('91)

$$a_0^+ = \frac{0.023 \pm 0.012}{M_\pi} \;,\; b_0^+ + 3a_1^+ = \frac{0.054 \pm 0.008}{M_\pi^3}$$

s and p-waves contribute $\Longrightarrow$ momentum dependence
Extraction of δM_K and V_K more dfifficult!

$$\delta M_K + V_K = \frac{\Sigma}{2M_K} \;,\; V_K = \frac{1}{2}\frac{\partial \Sigma}{\partial E}\bigg|_{E=M_K}$$

$$\boxed{V_K = -\frac{2\pi n_\pi}{M_\pi + M_K}\left(a_0^+ + 2M_\pi M_K(b_0^+ + 3a_1^+)\right)}$$

Beyond one loop

Up to now exact, But $T << M_\pi$

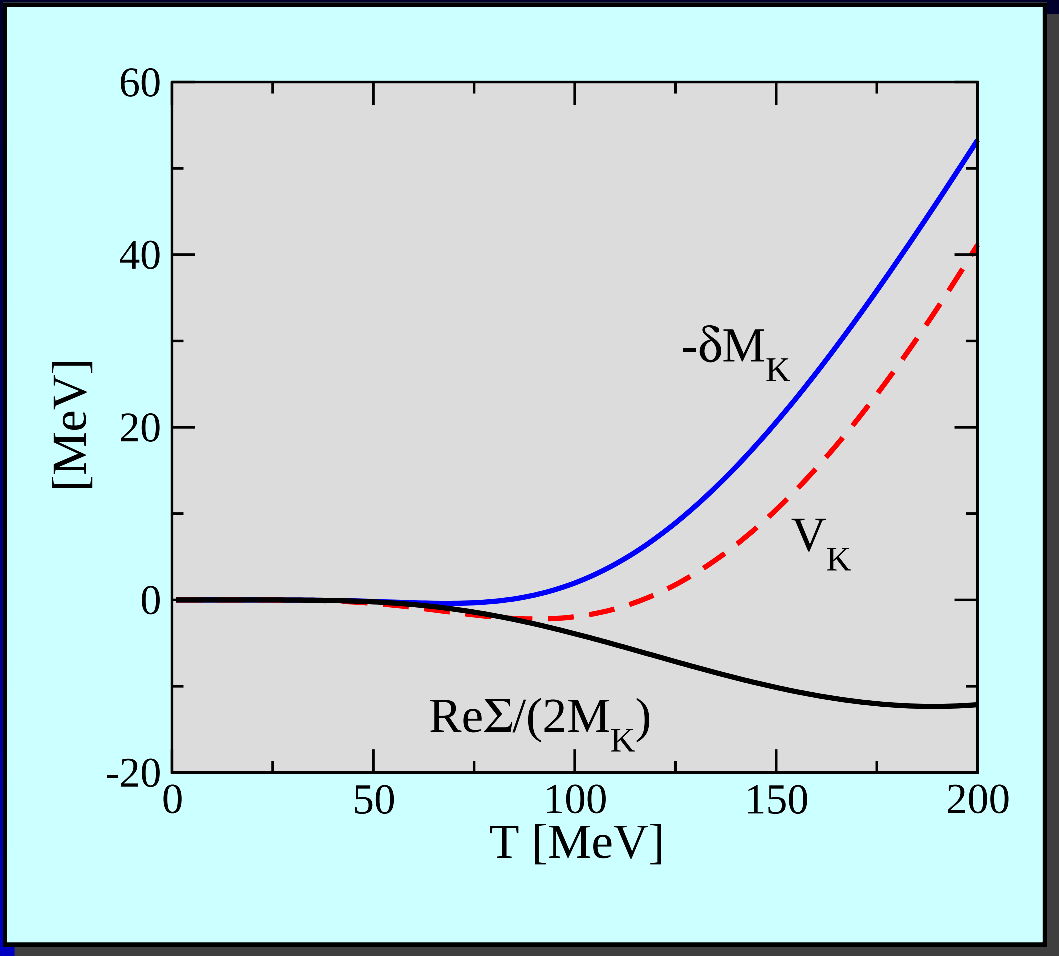
Larger $T \Longrightarrow$ phenomenology !
inculde K^* exchange in p wave (see e.g. Lissauer & Shuryak '91)

Phase shifts:

$$\delta_0^I \approx (a_0^I p^* + (b_0^I + \frac{2}{3} a_0^{I_3}) p^{*3})$$

$$a_1^{1/2} \to a_1^{1/2} \frac{|(M_\pi + M_K)^2 - M_{K^*}^2 + i M_{K^*} \Gamma_{K^*}|}{s - M_{K^*}^2 + i M_{K^*} \Gamma_{K^*}}$$

Kaon self energy



like in nuclear matter: $\delta M_K < 0, \quad V_K > 0$
But now: $V_{K^+} = V_{K^-}$

Consquences for $\phi \to K\bar{K}$

Phase space argument: (Blaizot & Galain 91)

$\delta M_K < 0 \Longrightarrow \phi \to K\bar{K}$ enhanced

$\delta M_K > 0 \Longrightarrow \phi \to K\bar{K}$ reduced

Consquences for $\phi \to K\bar{K}$

Phase space argument: (Blaizot & Galain 91)

$\delta M_K < 0 \Longrightarrow \phi \to K\bar{K}$ enhanced

$\delta M_K > 0 \Longrightarrow \phi \to K\bar{K}$ reduced

But collisional broadening $\Longrightarrow$ finite Γ_K

$$\Gamma^*_K = v n_\pi \sigma^{\text{tot}}_{\pi K}$$

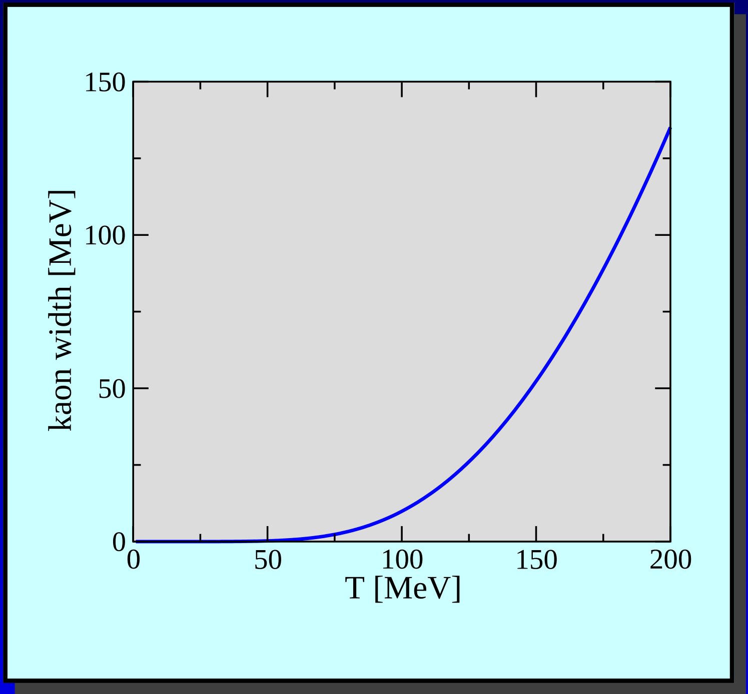
Consquences for $\phi \to K\bar{K}$

Phase space argument: (Blaizot & Galain 91)

$\delta M_K < 0 \Longrightarrow \phi \to K\bar{K}$ enhanced

$\delta M_K > 0 \Longrightarrow \phi \to K\bar{K}$ reduced

But collisional broadening $\Longrightarrow$ finite Γ_K

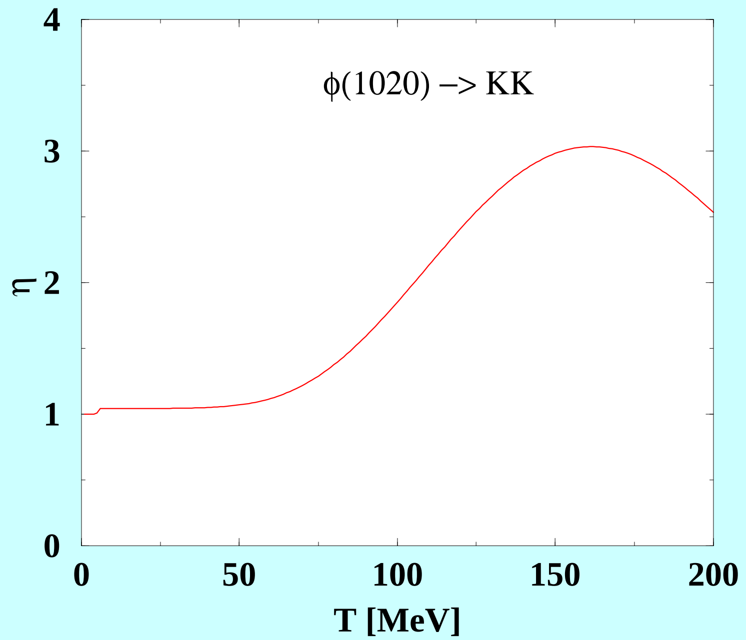


$$\Gamma_K^* = v n_\pi \sigma_{\pi K}^{\rm tot}$$

Final result

$\Sigma < 0 :\Longrightarrow$ enhanced $\phi \to K\bar{K}$ decay

$@\, T = 170$ MeV : $\Gamma_\phi^{\mathrm{med}} \sim 3\Gamma_\phi^{\mathrm{vac}} = 12$ MeV



Towards the ϕ puzzle

No of particles from ϕ decay:
τ = average time to travel through fireball

$$P_{outside} + P_{inside} \cdot P_{survival}$$

$$\boxed{\begin{aligned} N_{K\bar{K}} &\sim e^{-\Gamma^*_\phi \tau} + \frac{\Gamma_\phi}{2\Gamma^*_K - \Gamma^*_\phi}(e^{-\Gamma^*_\phi \tau} - e^{-2\Gamma^*_K \tau}) \\ N_{e^+e^-} &\sim e^{-\Gamma^*_\phi \tau} B + (1 - e^{-\Gamma^*_\phi \tau}) B^* \end{aligned}}$$

RHIC conditions: $T = 120 \div 170$ MeV

effective e^+e^- enhancement of $2 \div 3$

Summary

- Resonances in a pion gas: ϕ
- match low and high T regime
- $\Longrightarrow$ mass modification of kaons
- $\Longrightarrow$ faster $\phi \to K^+K^-$ decay inside fireball
- $\Longrightarrow$ enhanced apparent $\phi \to e^+e^-$ branching

Martemyanov, Faessler, C.F. Krivoruchenko

PRL in press