Dynamics of the η' meson at finite temperature

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Outline

Symmetries of QCD

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \bar{q}[iD_\mu \gamma^\mu - \mathcal{M}]q$$

- gluon field-strength tensor $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f_{abc} A^b_\mu A^c_\nu$
- covariant derivative $D_\mu = \partial_\mu - igA^a_\mu \lambda_a/2$
- six dimensional column vector $q_{i,A}$ where $i = 1, .., 6$ and $A = 1, 2, 3$
- quark mass matrix $\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s, m_c, m_b, m_t)$

In the approximation $m_u = m_d = m_s = 0$, the QCD Lagrangian gains the chiral symmetry:

$$U(3)_R \times U(3)_L \simeq SU(3)_V \times SU(3)_A \times U(1)_V \times U(1)_A$$

SSB and anomalous symmetry

The ground state is only symmetric w.r.t. $SU(3)_V \times U(1)_V$

- $U(1)_V$: baryon number conservation
- $SU(3)_V$: flavor multiplets

The spontaneous breaking of the $SU(3)_A$ symmetry gives rise to 8 Goldstone bosons:

$$3\pi_s, 4K_s, \eta$$

- $U(1)_A$ is anomalous *i.e.* is not symmetry of quantized theory

The Noether current corresponding to the $U(1)_A$ symmetry $J_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$ is not conserved:

$$\partial_\mu J_5^\mu = \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

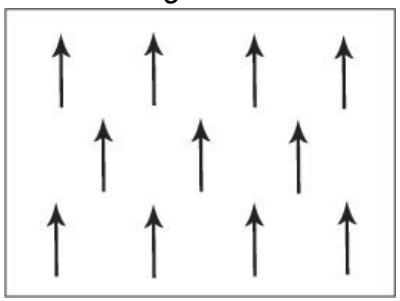
where $\tilde{F}^{\mu\nu}_a = \frac{1}{2}\epsilon^{\mu\nu\lambda\rho}F_{a\lambda\rho}$ is the dual field-strength tensor.

If there was no anomaly, the $U(1)_A$ symmetry would also be spontaneously broken and the η' would be the 9th Goldstone boson

Phase transition → Change in symmetry

An example: the spin model of a ferromagnet

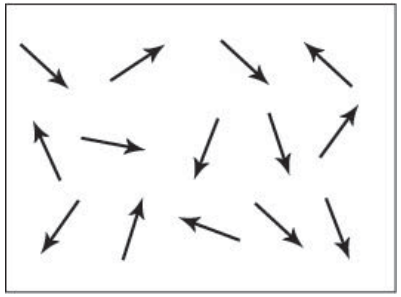
$T < T_c$



$\langle M \rangle \neq 0$

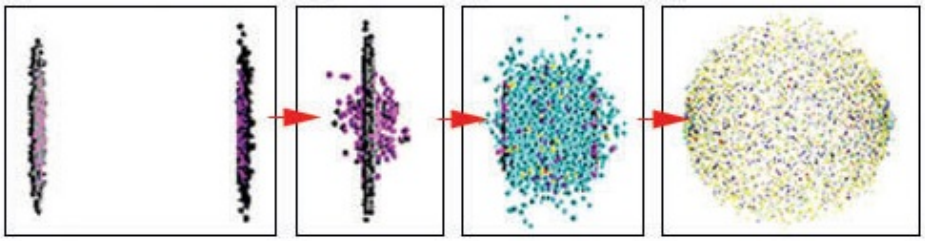
$\longrightarrow$

$T > T_c$



$\langle M \rangle = 0$

In heavy-ion collisions → new state of matter: Quark-Gluon Plasma



- production of *fireballs* ($\tau_{fb} \approx 10 - 20$ fm/c)
- deconfinement transition around $T_c \approx 170$ MeV

Chiral symmetry restoration

Lattice QCD studies indicate that at $T \approx 170$ MeV the order parameter $\langle q\bar{q} \rangle \to 0$

- the chiral symmetry should be restored
- chiral multiplets (L,R) should replace flavor multiplets

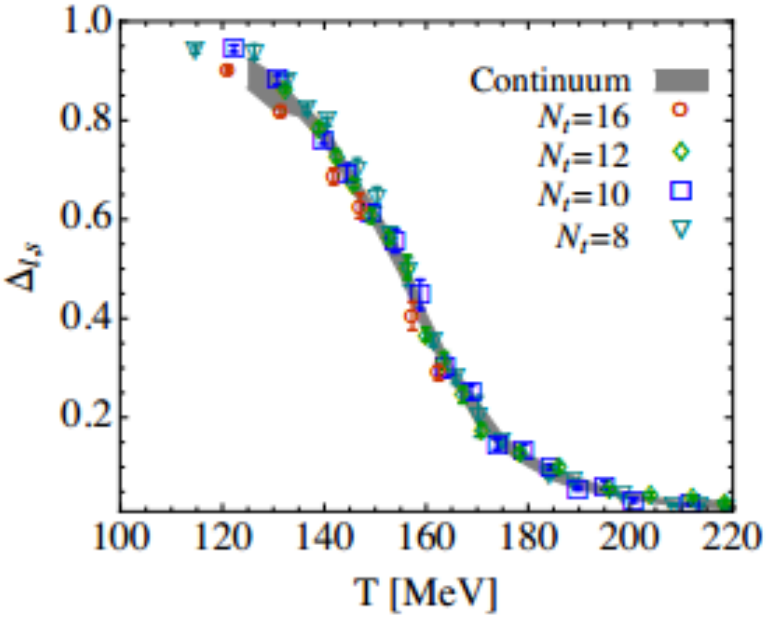


figure from Borsanyi et al., Nucl.Phys.A904-905:270c (2013)

What about the $U(1)_A$ anomaly?
$\to$ deduce information from the behaviour of the η'

$\eta' \longleftrightarrow U(1)_A$

Determine temperature dependence of

- mass of η':

  a light η' might imply effective restoration of $U(1)_A$

- mixing of η' and η

  (Tytgat et al.)

- decay constant of η'

- lifetime of η'

Low-temperature calculations$\rightarrow$ thermal medium$\approx$ gas of pions

-Does η' survive in the medium?
-Can we see the effect of the medium on the η'?

$\rightarrow$ Compare: in-medium lifetime of the η' with lifetime of a *fireball* ($\tau_{\eta'}^{vac} \approx 600\ \tau_{fb}$)

Width increase in a thermal medium

The width Γ of a particle with finite lifetime can be derived from its self-energy:

$$m\Gamma = -\mathrm{Im}\,\Pi(m^2)$$

We want to calculate the in-medium width of the η'

- Every medium particle has thermal energy according to the Bose-Einstein distribution $n_B(E_p) = \frac{1}{e^{E_p/T}-1}$

The collisional broadening is the main contribution to the in-medium width addition:

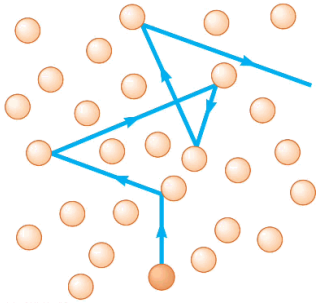
$$\Gamma_{coll} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_B(E_p) \frac{|\bar{p}|}{E_p} \sum_i \sigma_i(E_p)$$

where we need to sum over all the inelastic cross sections involving an η' and any type of pion in the initial state.

Collisional broadening

From classical kinetic theory:

-particle in a medium = probe that travels with velocity v
-mean free path λ
-cross section σ for the probe to interact with a medium particle
-medium made of bosonic gas



$\rightarrow$ density of the medium particles $n = \int \frac{d^3p}{(2\pi)^3} n_B(E_p)$

We have:

lifetime of the probe $\tau_p = \frac{\lambda}{v} = \frac{1}{n\sigma v} \longrightarrow$ in-medium width $\Gamma = n\langle\sigma v\rangle$

Average for some observable $\mathcal{O}$:

$$\langle\mathcal{O}\rangle = \frac{\int \frac{d^3p}{(2\pi)^3} \mathcal{O} n_B(E_p)}{\int \frac{d^3p}{(2\pi)^3} n_B(E_p)} = \frac{1}{n}\int \frac{d^3p}{(2\pi)^3} \mathcal{O} n_B(E_p)$$

$\rightarrow$ Average of the probe's in-medium width:

$$\Gamma_{coll} = \int \frac{d^3p}{(2\pi)^3} v\sigma(E_p) n_B(E_p)$$

Note: the same result can be obtained using field theory

Relevant processes

We consider two types of interactions that contribute to collisional broadening:

$$\eta'\pi \to \eta\pi$$

$$\eta'\pi \to \bar{K}K$$

where

$$\pi = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix} \quad K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \quad \bar{K} = \begin{pmatrix} \bar{K}^0 \\ K^- \end{pmatrix}$$

Large-N_c limit

In the large-N_c limit, the divergence of the axial current vanishes:

$$\partial_\mu J_5^\mu = \frac{1}{N_c}\frac{N_f\lambda}{16\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

since $\lambda = N_c g^2 = const$ for $N_c \to \infty$.

$\to$ The η' formally becomes the 9th Goldstone boson

In the combined chiral and large-N_c limit there are 9 light pseudoscalars

Why Resonance Chiral Theory?

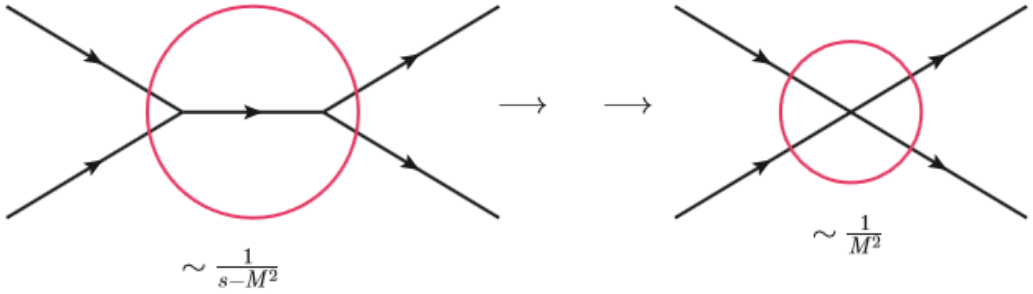
When the energy of the process is of the order of the resonance mass...

- resonance effects must be taken into account

$\rightarrow$ Resonance Chiral Theory (*RChT*)

(Ecker/Gasser/Pich/de Rafael, Nucl.Phys. B321, 311 (1989))

- no systematic effective field theory
- correct low-energy, large-N_c limit
- better high energy behaviour



$$RChT \xrightarrow{low-energy\ lim} ChPT$$

How to include resonances

Ingredients:

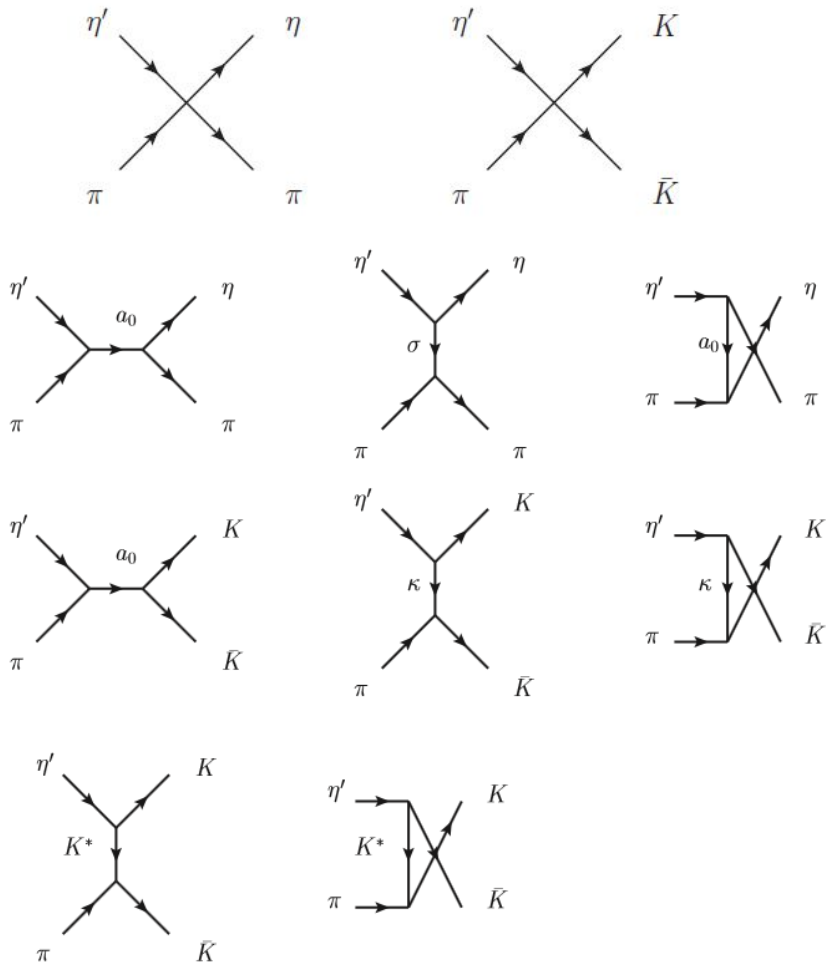
- nonet field S which contains the lowest-lying scalar resonances ($J^{PC} = 0^{++}$)

$$S = \begin{pmatrix} \frac{a_0^0}{\sqrt{2}} + \frac{\sigma}{\sqrt{2}} & a_0^+ & \kappa^+ \\ a_0^- & -\frac{a_0^0}{\sqrt{2}} + \frac{\sigma}{\sqrt{2}} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & f_{0s} \end{pmatrix}$$

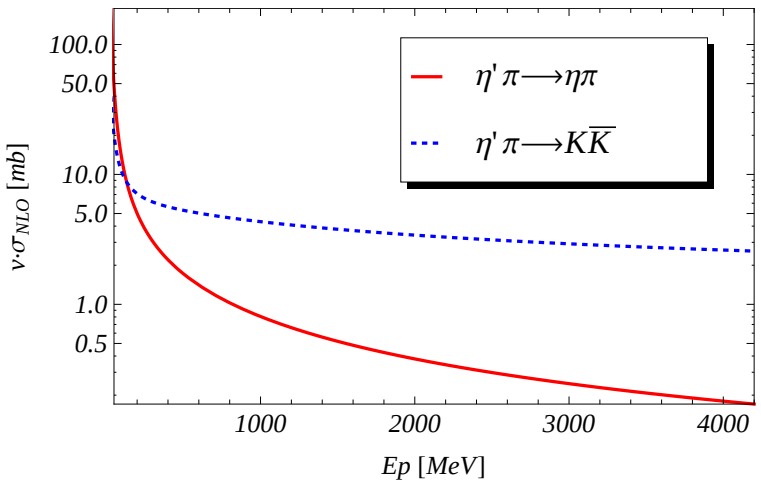
- nonet field V which contains the lowest-lying vector resonances ($J^{PC} = 1^{--}$)

$$V_{\mu\nu} = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_{\mu\nu}$$

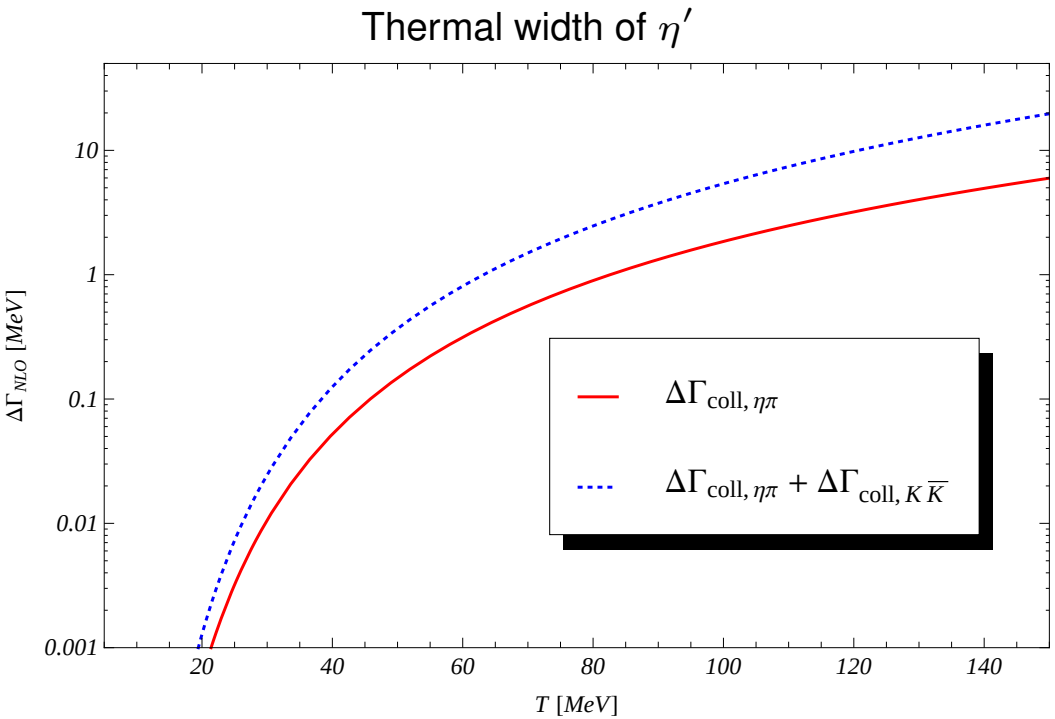
RChT diagrams



$\rightarrow$ small cross section for large E_p



RChT results

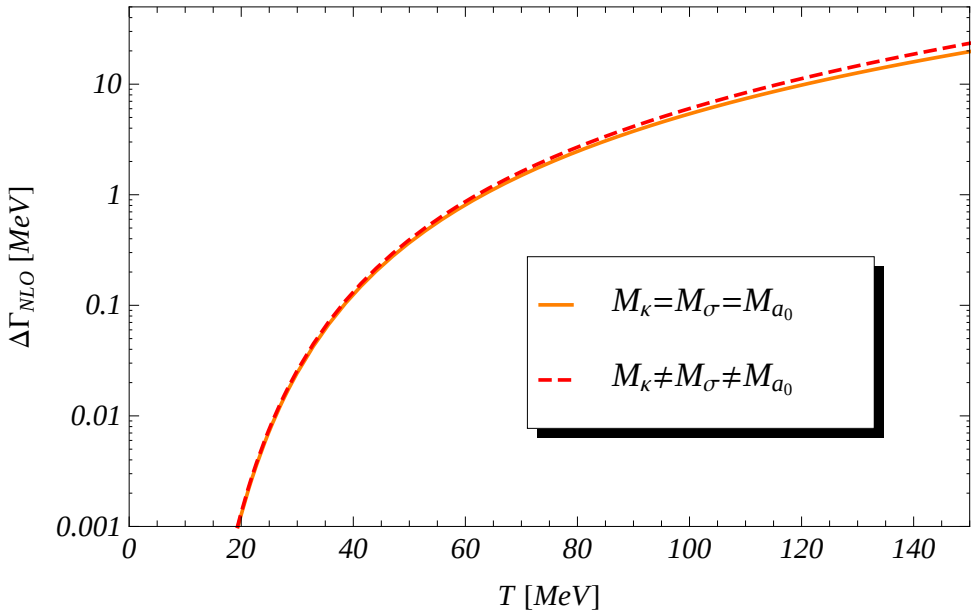


sizeable width increase,
$\approx$ 10 MeV at $T \approx$ 120 MeV

(vacuum width $\approx$ 200 keV)

-importance of $K\bar{K}$ final state

Mass modification



- modify propagators

for each resonance use the correspondent mass

$$\frac{1}{t, u - M_{a_0}^2} \rightarrow \frac{M_{\kappa,\sigma}^2}{M_{a_0}^2 (t, u - M_{\kappa,\sigma}^2)}$$

Good agreement between the width increase obtained using:

- one single mass for all scalar resonances (M_{a_0})
- three different masses for κ, σ, a_0 resonances

Conclusion

Even if approximating the medium by a pion gas does not work close to T_c

- for $T < T_c$ we can trust our results $\rightarrow$ look for the onset of changes at low T

Around $T \approx 120$ MeV we have $\Delta\Gamma \approx 10$ MeV
$\rightarrow$ comparable with $1/\tau_{fb}$

$\rightarrow$ Future studies on the η' can be performed in the framework of heavy-ion collisions

Thank you!