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Finite Temperature Effects on Particle Decays

20TH MCNET MEETING 2020: STUDENT TALK BY TORBJÖRN LUNDBERG

SUPERVISED BY ROMAN PASECHNIK



Who am I and what will I present?

Outline

Motivation

TFT

Thermal decays

Some results

Outlook

Me

- Torbjörn Lundberg, PhD student, Lund.
 - Leif Lönnblad, Angantyr and heavy ions.
-
- Why *thermal* quantum field theory (TFT)?
 - How to incorporate temperature?
-
- What have I done?
 - Where are we going?



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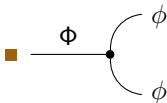
Some results

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Me

- Torbjörn Lundberg, PhD student, Lund.
- Leif Lönnblad, Angantyr and heavy ions.

- Why *thermal* quantum field theory (TFT)?
- How to incorporate temperature?



Power law increase in rate!

- What have I done?
- Where are we going?



Why TFT?

Outline

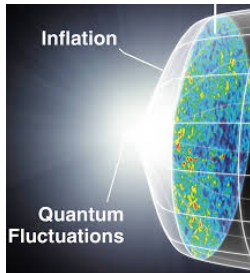
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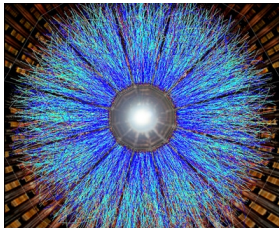
Outlook



<https://lecospa.ntu.edu.tw>



<https://en.wikipedia.org/wiki/Supernova>



<http://news.mit.edu/2010/exp-quark-gluon-0609>



Defining thermal observables

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- Marry statistical mechanics with QFT!

Thermal observable

$$\langle \hat{\mathcal{O}} \rangle = \text{Tr } \hat{\rho} \hat{\mathcal{O}}, \quad \hat{\rho}_{T=0} = \mathbb{1}.$$

- Expressions of interest are Green's functions

$$G_C(x_1, x_2, \dots, x_n) = \langle T_C \hat{\phi}(x_1) \hat{\phi}(x_2) \cdots \hat{\phi}(x_n) \rangle$$

with

$$\hat{\phi}(x) = e^{it\hat{H}} \hat{\phi}(0, \mathbf{x}) e^{-it\hat{H}}.$$

- The density operator often comes as $\hat{\rho} \propto e^{b\hat{\mathcal{B}}}$.
- Note the formal equivalence between $\hat{\rho}$ and the time-evolution operator if $\hat{\mathcal{B}}$ contains \hat{H} . (Bloch, 1932)



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The contour propagator

Outline

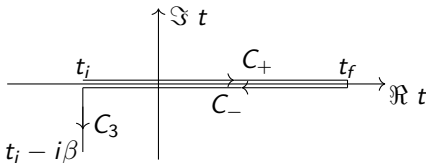
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- Due to the doubling of the d.o.f. on the Keldysh contour, the propagator acquires a matrix structure. (Keldysh, 1964)

Matrix propagator

$$\tilde{D}(k) = \begin{pmatrix} \tilde{D}^{++}(k) & \tilde{D}^{+-}(k) \\ \tilde{D}^{-+}(k) & \tilde{D}^{--}(k) \end{pmatrix}.$$

- Example of propagator component:

$$i\tilde{D}^{++}(k) = \frac{i}{k^2 - m^2 + i\epsilon} + \eta 2\pi n(|k_0|) \delta(k^2 - m^2).$$



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Thermal decay rates

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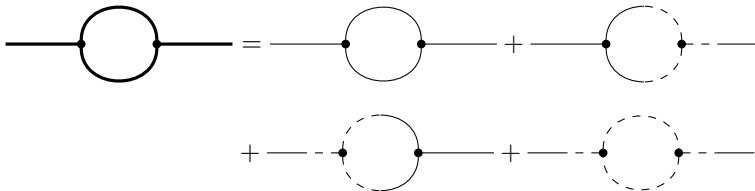
- At $T = 0$, the decay rate given by the optical theorem reads

$$\gamma_D = -\frac{\text{Im } \Pi_{T=0}(E_0)}{E_0}.$$

- In the thermal bath, this must be modified to $\Gamma = -\frac{\text{Im } \Pi(E)}{E}$.

Distribution approach rate

$$\Gamma = -\frac{\text{Im } \Pi(E)}{E}. \quad (\text{Weldon, 1983})$$



What is Γ ?

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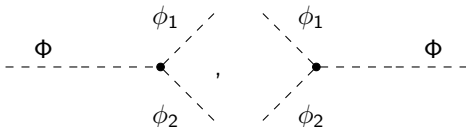
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- $\Gamma = \Gamma_D - \eta \Gamma_I.$

Thermal decay rate

$$\Gamma_D = \frac{1}{1 - \eta e^{-\beta E}} \left(-\frac{\text{Im } \Pi(E)}{E} \right) \quad (\text{Weldon, 1983})$$



- $R = \Gamma_D / \gamma_D$ characterises the missing factor between zero-temperature and $T \neq 0$ -theory. (Ho&Scherrer, 2015)



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Comparison to $T = 0$: scalars

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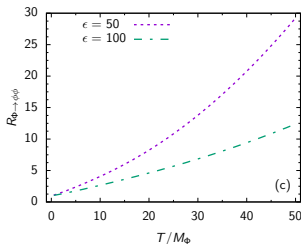
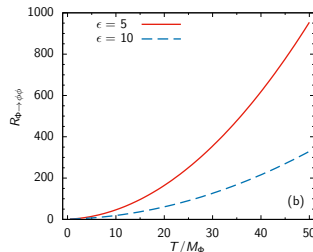
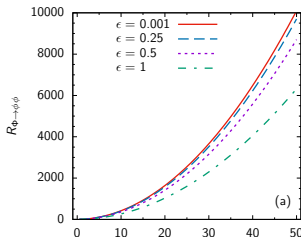
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(Agrees with results of Ho&Scherrer, 2015)

- $R_{\Phi \rightarrow \phi\phi} = \Gamma_D / \gamma_D$, $\epsilon = |\mathbf{p}| / M_\Phi$.
- Results plotted for $m_\phi \approx 0$.
- Temperature effects kick in \sim a few-10 MeV. (Zheng et al. 2014)



Comparison to $T = 0$: fermions

Outline

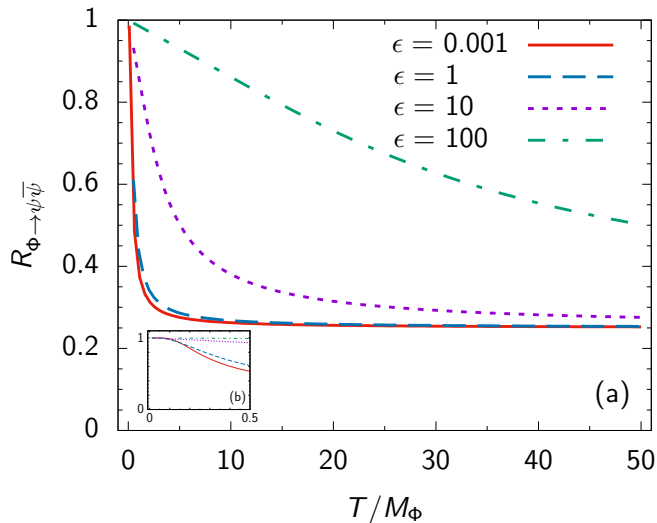
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(Agrees with results of Ho&Scherrer, 2015)



Comparison to $T = 0$: scalar emission

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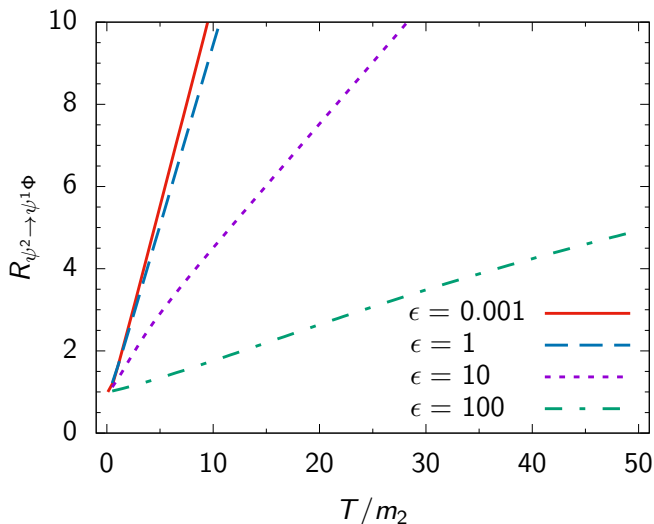
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What is to be done?

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- Thermal decays involving gauge particles.
- Study thermal effects on cosmological models.
- Work towards non-equilibrium.



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What is to be done?

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- Thermal decays involving gauge particles.
- Study thermal effects on cosmological models.
- Work towards non-equilibrium.
- Excess radiation from QCD matter (HADES collab., Oct. 2019)

Thank you for listening!



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Bonus frames!

Lorentz covariance

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- Feynman rules break Lorentz invariance.
- Consider a local observer $U^\mu(x)$, $U^2 = 1$.
- Define Hamiltonian and charges as

$$\begin{aligned}\hat{H} &= U_\mu \hat{P}^\mu, & \text{and} & & \beta_\mu &= \beta U_\mu. \\ \hat{Q}_a &= U_\mu \hat{J}_a^\mu,\end{aligned}$$

- A *covariant* formulation of the Gibbs ensemble is feasible.

$$n_\eta^\pm = \frac{1}{\exp\{\beta(|P \cdot U| \pm \mu)\} - \eta}. \quad (\text{Niemi\&Semenoff, 1984}).$$



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Path-integral formulation

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Matrix element in trace:

$$\langle \varphi(\mathbf{x}); t_i | e^{-\beta \hat{H}} \hat{O} | \varphi(\mathbf{x}); t_i \rangle = \langle \varphi(\mathbf{x}); t_i - i\beta | \hat{O} | \varphi(\mathbf{x}); t_i \rangle.$$

- The FSM-formula allows this matrix element to be written as a path-integral over the action. (Matthews&Salam, 1955 and Feynman&Hibbs, 1965)

- The path integral must now be evaluated along C , a contour from t_i to $t_i - i\beta$.

$$\Rightarrow G_{0,C}(x_1, x_2, \dots, x_n) = \frac{1}{Z_0[0]} \frac{\delta^n Z_0[j]}{i\delta j_+(x_1) \cdots i\delta j_+(x_n)} \Big|_{j=0}$$

$$\text{with } Z_0[j] = Z_0[0] \exp \left\{ -\frac{i}{2} \int_C dx \int_C dx' j(x) D_C(x - x') j(x') \right\}.$$

- Note: the propagator explicitly depends on the contour C !



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Multi-component multi-spin fields

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Very generally it has been shown (Takahashi, 1969) that for a field carrying both a Lorentz- and an internal spin-structure $\phi_{\alpha\beta}^{ij}$ the propagator of the free field is

Free field propagator

$$D_{\alpha\beta,C}^{ij}(x-x') = d_{\alpha\beta}^{ij}(i\partial) D_C(x-x').$$

The *Klein-Gordon divisor* is constructed so that

$$d_{\alpha\beta}^{ij}(i\partial) \Lambda_{\beta\gamma}^{jk}(i\partial) = \delta_{\alpha\gamma} \prod_l (-\partial^2 - m_l^2).$$

The periodicity condition of the trace imposes

$$D_{\alpha\beta,C}^{ij}(t_i - i\beta - t') = \eta e^{-\beta\mu} D_{\alpha\beta,C}^{ij}(t_i - t').$$



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Interpretation of Γ

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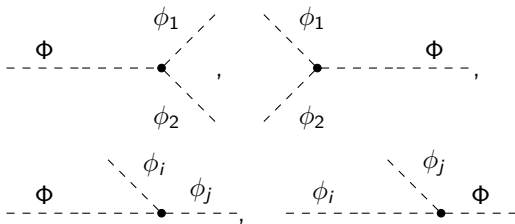
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- $\Gamma = \Gamma_D - \eta\Gamma_I$.
- If $s \geq (m_1 + m_2)^2$
 - Φ will decay to ϕ_1 and ϕ_2 contributing to Γ_D .
 - Also, real ϕ_1 and ϕ_2 in the medium will produce Φ thereby contributing to Γ_I .
- If $-|m_1^2 - m_2^2| < s < (m_1 - m_2)^2$
 - Φ will decay through absorption of ϕ_1 or ϕ_2 from the medium. This contributes to Γ_D .
 - A real ϕ_1 or ϕ_2 in the medium will produce Φ thereby contributing to Γ_I .



Interesting properties of the decay

Outline

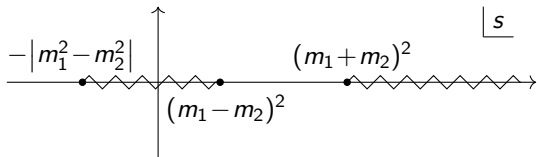
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- The non-thermal part of $\text{Im } \Pi^{++}(p; m_1, m_2)$ vanishes below threshold $s = (m_1 + m_2)^2$.
- The thermal part of $\text{Im } \Pi^{++}(p; m_1, m_2) \neq 0$ in interesting regions.
 - $s \geq (m_2 + m_1)^2$
 - $(m_2 - m_1)^2 \leq s < (m_2 + m_1)^2$
 - $0 \leq s < (m_2 - m_1)^2$
 - $(s < 0)$



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