Effective models for heavy mesons in a plasma inspired by gauge gravity duality

Light-Cone 2023: Hadrons and Symmetries

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Based on Colaborations with:

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Summary

Important Physical Problem:

- Heavy ion collisions form a quark gluon plasma

- Heavy Mesons (charmonium and bottomonium) provide information about the plasma

One tool to describe this situation:

- Holographic Models inspired in the AdS/CFT correspondence.

auxiliary tool: Configuration Entropy

How can one describe the thermal dissociation of heavy mesons inside a plasma using holography?

In particular: dependence on: Temperature, background magnetic fields, density, and angular momentum

Holography

AdS/CFT correspondence, J. Maldacena, 1997 (simplified version of a particular case)

Exact equivalence between String Theory in a 10-dimensional space and a gauge theory on the 4-dimensional boundary.

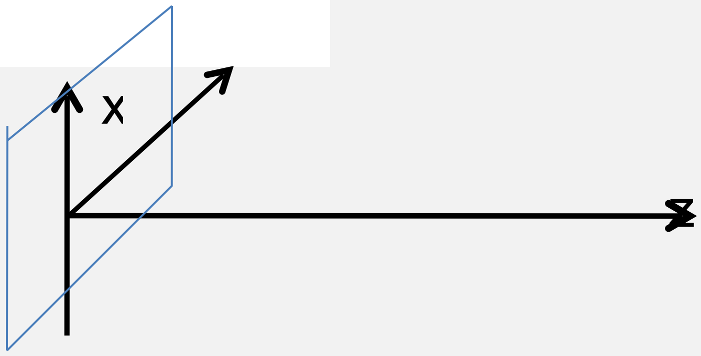
String theory space = $AdS_5 \times S^5$
AdS = anti-de Sitter; S = sphere

Gauge theory: SU(N) with very large N
(supersymmetric and conformal).

Anti-de Sitter space with 5 dimensions:

$$ds^2 = \frac{R^2}{(z)^2}\left(dz^2 + (d\vec{x})^2 - dt^2\right)$$

The 4-dim boundary is at z = 0 →



Holographic mapping: bulk ↔ boundary

Holographic Models: conformal invariance broken by introduction of energy parameters

Example: Hard Wall model:

Polchinski and Strassler (PRL 2002) IR cut in AdS space geometry.

Glueball masses from AdS/CFT N.B. and H. Boschi-Filho, JHEP 2003, EPJC 2004.

Gauge/String duality at finite temperature.

Witten (1998): finite temperature version of AdS/CFT

Black hole in anti-de Sitter space $\Leftrightarrow$ Gauge Theory at finite temperature

The Hawking temperature of the black hole (B.H) is the temperature of the gauge theory.

Gauge/String duality at finite temperature.

Witten (1998): finite temperature version of AdS/CFT

Black hole in anti-de Sitter space ⇔ Gauge Theory at finite temperature

Medium with **finite density:** Charged Black hole

Charge of the B.H. ➔ Density of the medium

Medium with **Magnetic field** (generated by the motion of the charges)

Einstein-Maxwell action + Magnetic field => Metric with eB field

D'Hoker and P.Kraus,JHEP 0910, 088 (2009);1003, 095 (2010)

Plasma with Angular Momentum => Coordinate Transformation representing rotation of the medium

Gauge string duality: vector fields in the dual space work as sources for current correlators. **The model:**

$$I = \int d^4x dz \sqrt{-g}\, e^{-\Phi(z)} \left\{ -\frac{1}{4g_5^2} F_{mn}F^{mn} \right\}$$

$$F_{mn} = \partial_m V_n - \partial_n V_m$$

$$\phi(z) = k^2 z^2 + Mz + \tanh\left(\frac{1}{Mz} - \frac{k}{\sqrt{\Gamma}} \right)$$

$$\text{charmonium}: \quad k_c = 1.2\,\text{GeV}; \;\; \sqrt{\Gamma_c} = 0.55\,\text{GeV}; \;\; M_c = 2.2\,\text{GeV};$$

$$\text{bottomonium}: \quad k_b = 2.45\,\text{GeV}; \;\; \sqrt{\Gamma_b} = 1.55\,\text{GeV}; \;\; M_b = 6.2\,\text{GeV}.$$

3 parameters (“related to”): **quark mass, string tension , large mass scale** associated with the mass change in the non hadronic transition: heavy meson ➔ leptons

Holographic (and experimental) Results for Charmonium		
State	Mass (MeV)	Decay constants (MeV)
$1S$	$2943\ (3096.916 \pm 0.011)$	$399\,(416 \pm 5.3)$
$2S$	$3959\ (3686.109 \pm 0.012)$	$255\,(296.1 \pm 2.5)$
$3S$	$4757\ (4039 \pm 1)$	$198\,(187.1 \pm 7.6)$
$4S$	$5426\ (4421 \pm 4)$	$169\,(160.8 \pm 9.7)$

Holographic (and experimental) Results for Bottomonium		
State	Mass (MeV)	Decay constants (MeV)
$1S$	$6905\ (9460.3 \pm 0.26)$	$719\,(715.0 \pm 2.4)$
$2S$	$8871\,(10023.26 \pm 0.32)$	$521\,(497.4 \pm 2.2)$
$3S$	$10442\ (10355.2 \pm 0.5)$	$427\,(430.1 \pm 1.9)$
$4S$	$11772\,(10579.4 \pm 1.2)$	$375\,(340.7 \pm 9.1)$

Finite temperature and density:

$$ds^2 = \frac{R^2}{z^2}\left(-f(z)dt^2 + \frac{dz^2}{f(z)} + d\vec{x}\cdot d\vec{x}\right)$$

$$f(z) = 1 - \frac{z^4}{z_h^4} - q^2 z_h^2 z^4 + q^2 z^6$$

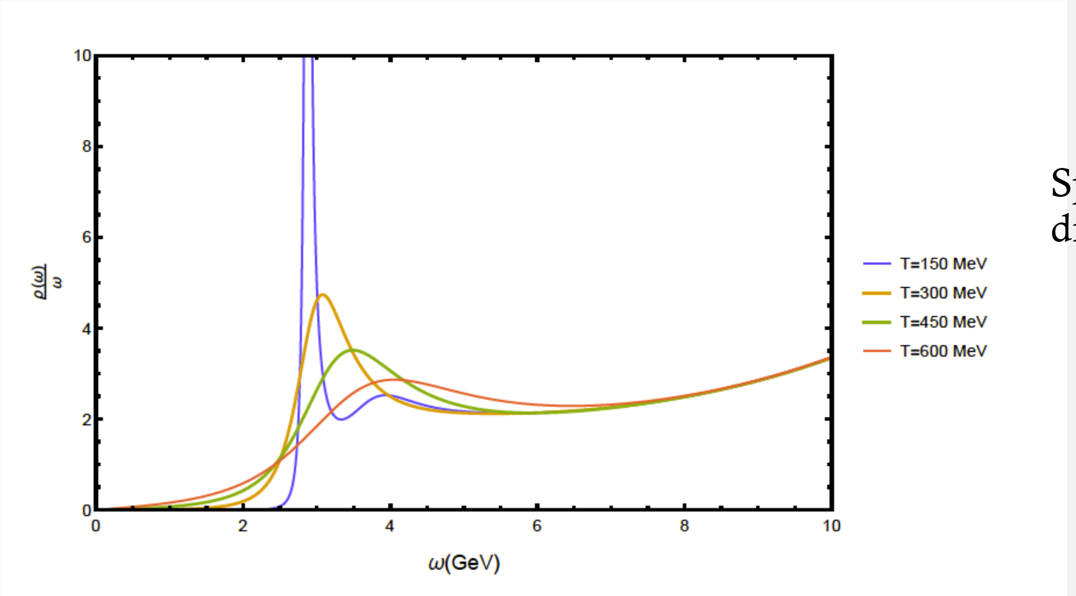
$$T = \frac{|f'(z)|_{(z=z_h)}}{4\pi} = \frac{1}{\pi z_h} - \frac{q^2 z_h^5}{2\pi}$$

Finite temperature and background B field

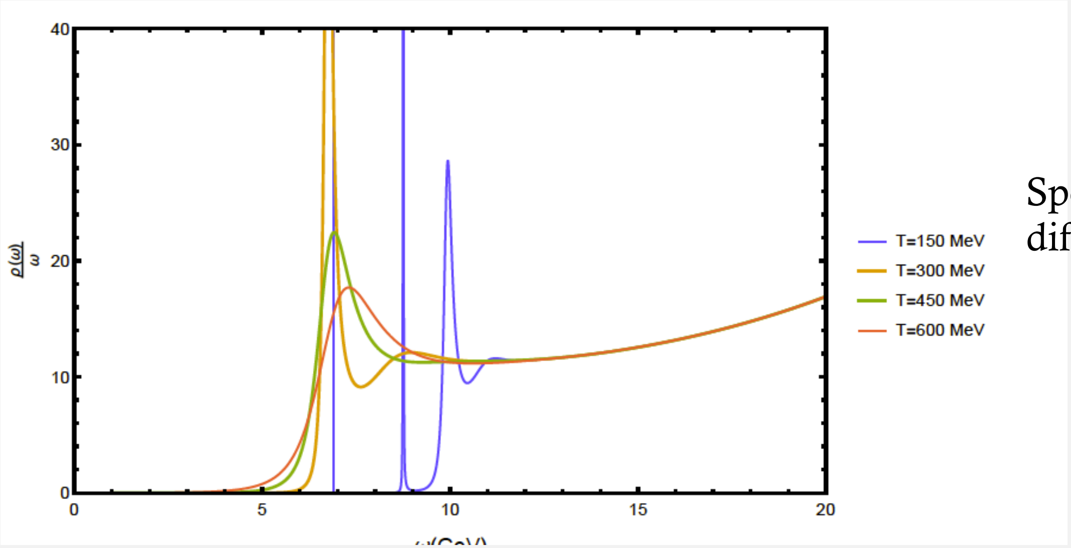
$$ds^2 = \frac{R^2}{z^2}\left(-f(z)dt^2 + \frac{dz^2}{f(z)} + (dx_1^2 + dx_2^2)d(z) + dx_3^2 q(z)\right)$$

$$f(z) = 1 - \frac{z^4}{z_h^4} + \frac{2}{3}\frac{e^2 B^2 z^4}{1.6^2}\ln\left(\frac{z}{z_h}\right)$$

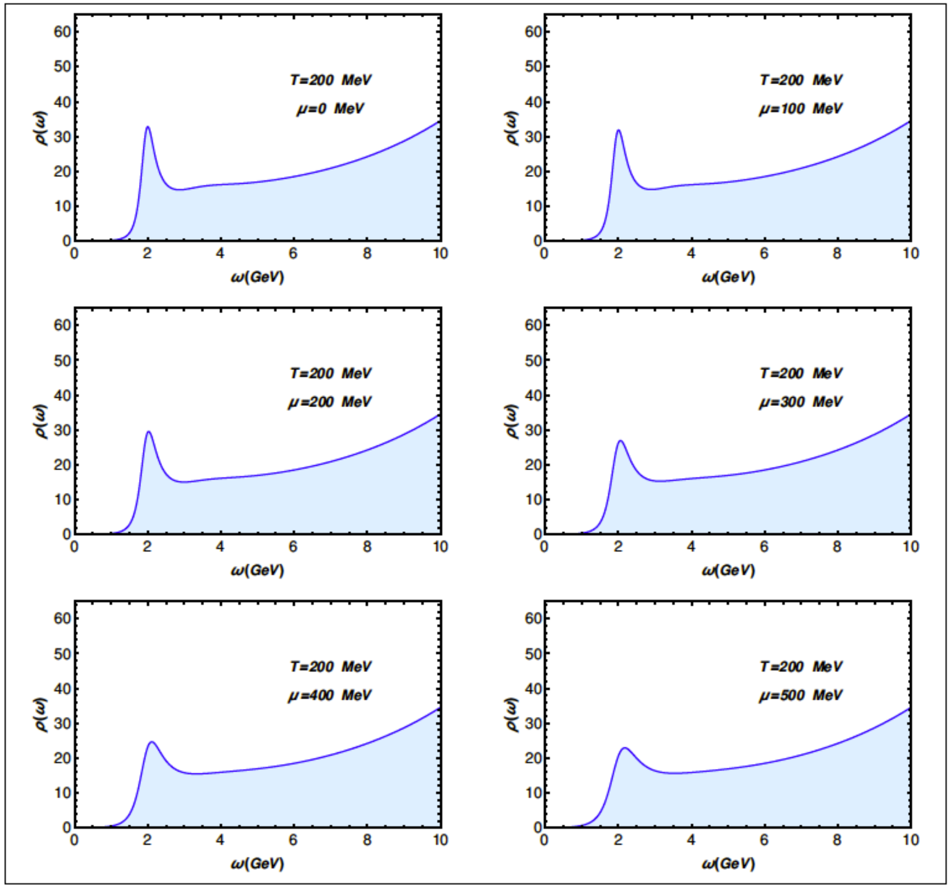
where d(z) , q(z) = functions of T , B.



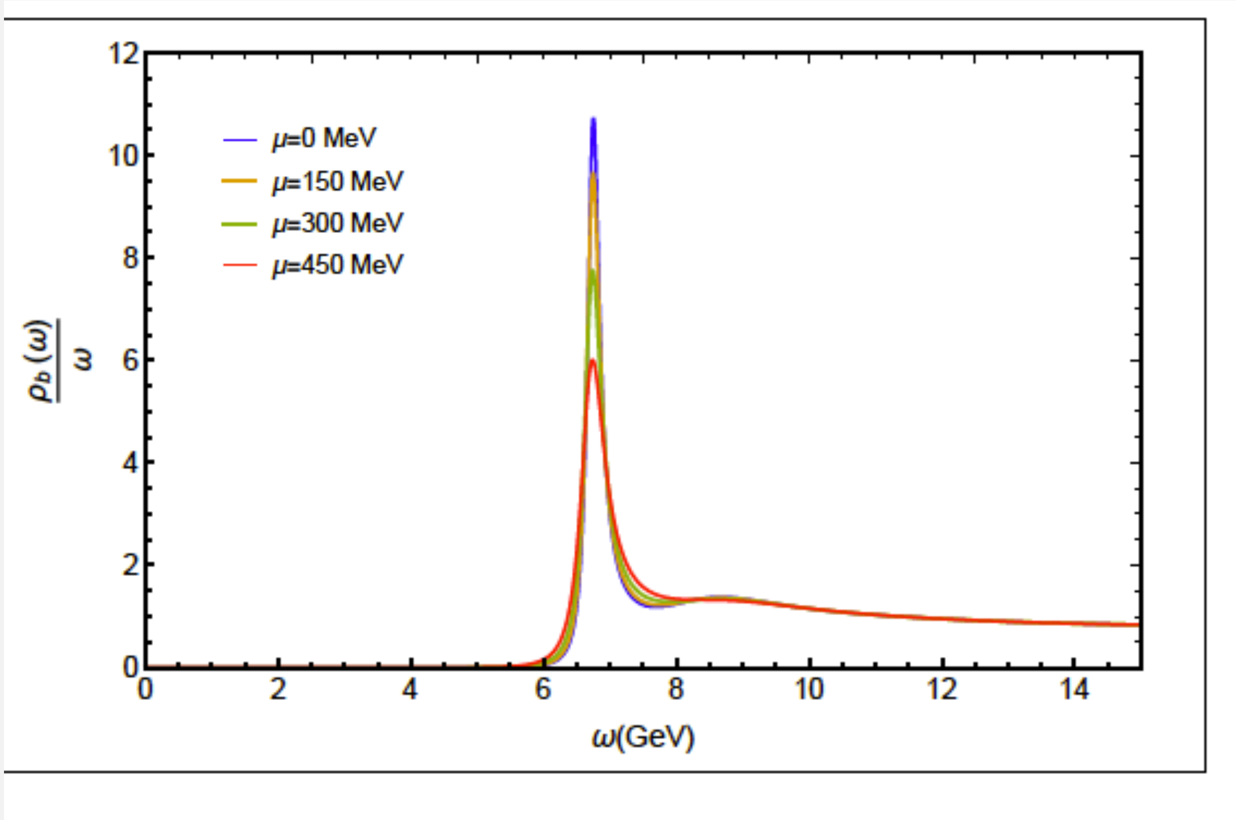
Spectral function for charmonium at different temperatures



Spectral function for bottomonium at different temperatures

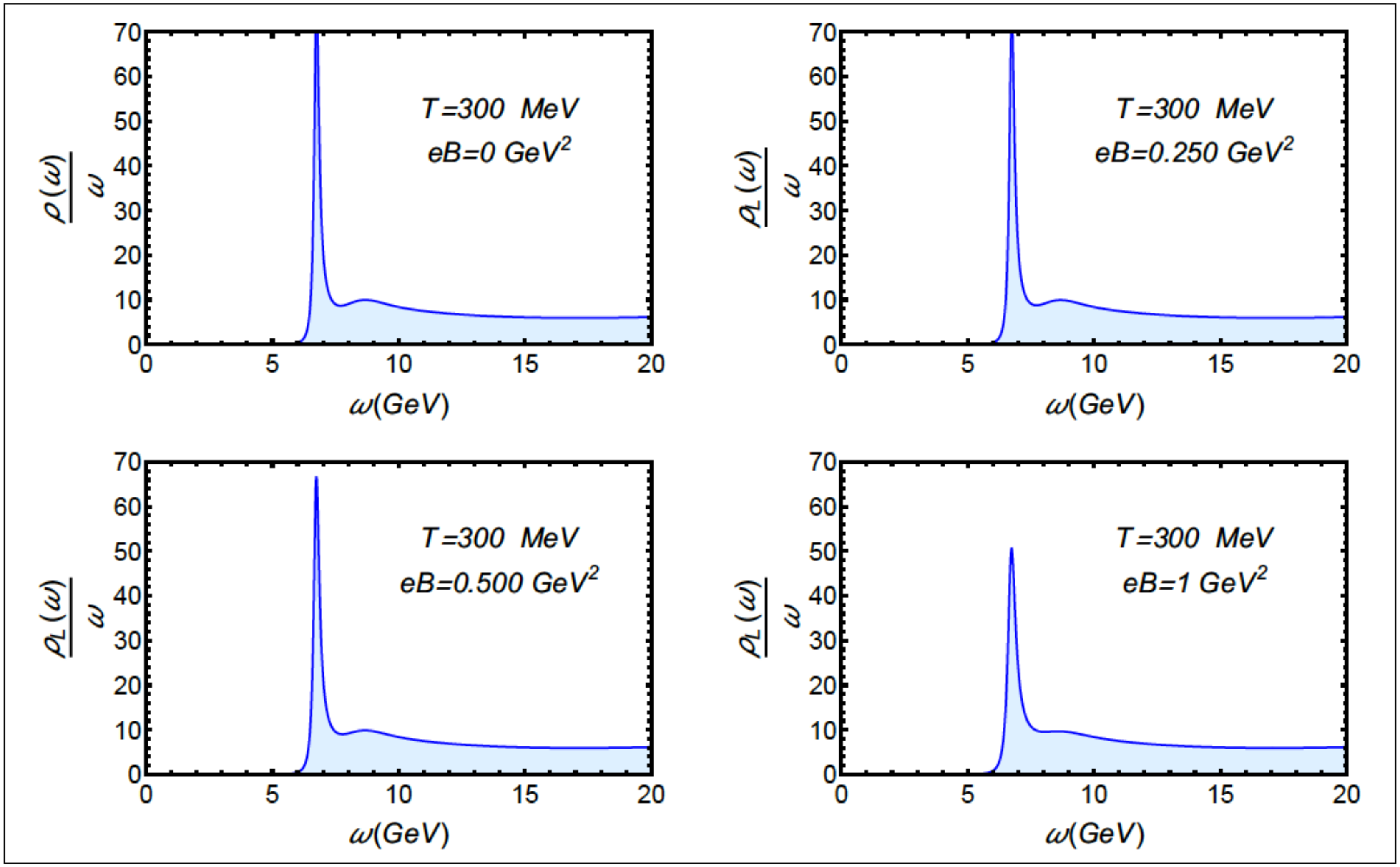


Charmonium spectral function at T = 200 MeV for different values of the quark chemical potential

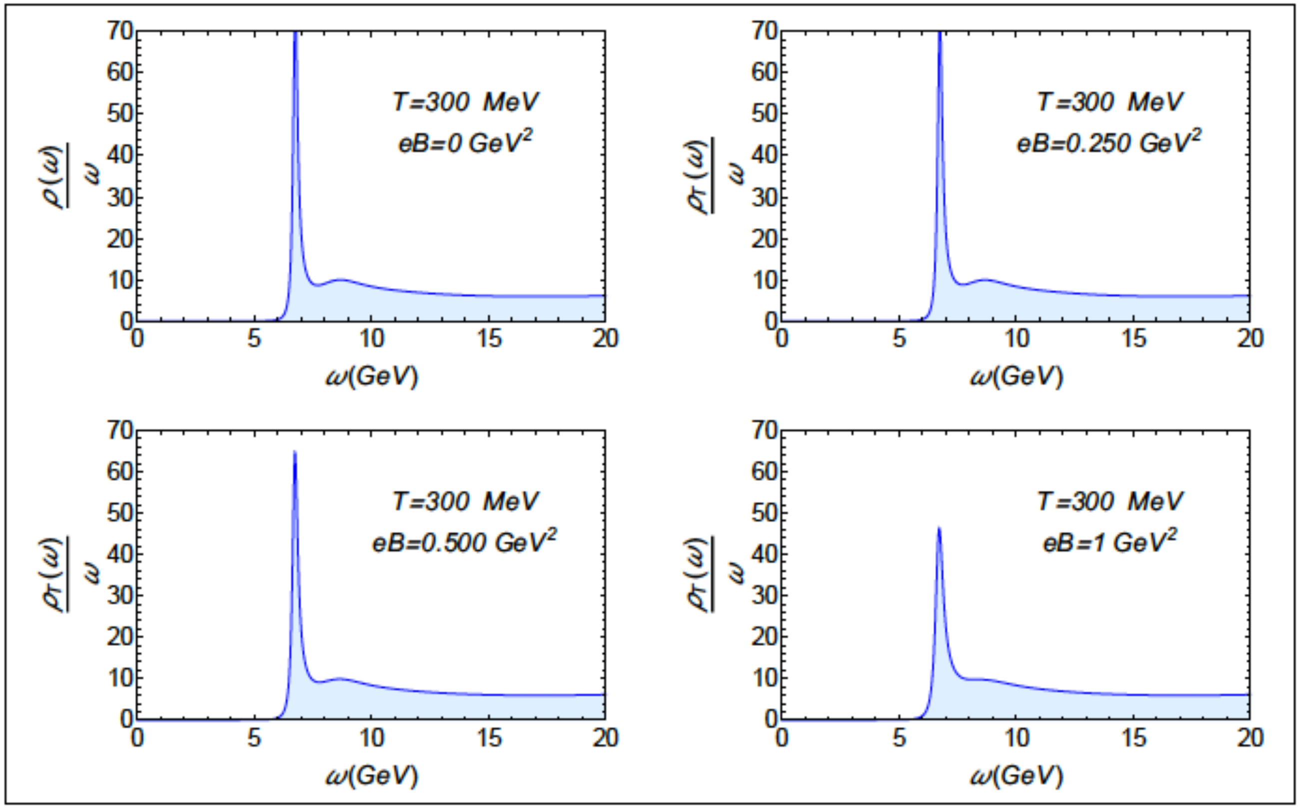


Spectral function for Bottomonium at T= 300 MeV for different values of the quark chemical potential

Effect of magnetic field in Bottomonium. Magnetic field paralell to polarization



Effect of magnetic field in Bottomonium. Magnetic field perpendicular to polarization



Plasma Rotation

First step: Cylindrical Geometry

$$ds^2 = \frac{L^2}{z^2}\left(-dt^2 + l^2 d\phi^2 + \sum_{i=1}^{2} dx_i^2 + dz^2\right)$$

Anti-de Sitter (AdS) with cylindrical boundary

$$ds^2 = \frac{L^2}{z^2}\left(-f(z)dt^2 + l^2 d\phi^2 + \sum_{i=1}^{2} dx_i^2 + \frac{dz^2}{f(z)}\right)$$

AdS Black Hole with cylindrical boundary and horizon

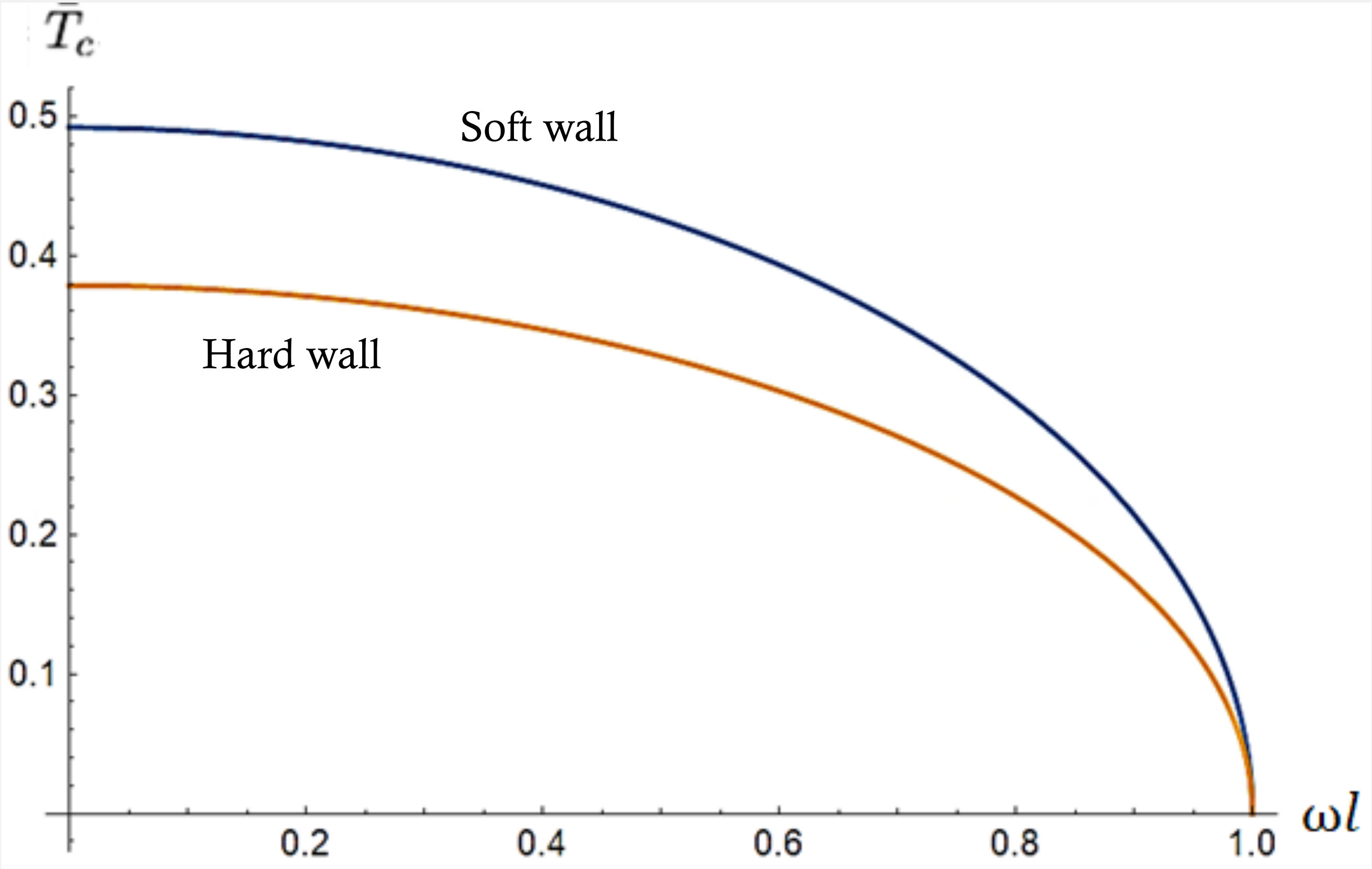
Transformação de coordenadas (=> Rotação):

$$t \rightarrow \frac{1}{\sqrt{1 - l^2\omega^2}} \left(t + l^2\omega\phi\right)$$

$$\phi \rightarrow \frac{1}{\sqrt{1 - l^2\omega^2}} \left(\phi + \omega t\right)$$

The metric changes. The new black hole has angular momentum.

=> the confinement/deconfinement temperature
also changes (Hawking -Page transition)



Critical temperature as a function of rotational speed for **hard wall** e **soft wall models.**

Configuration Entropy (CE) - Gleiser & Stamatopoulos

Inspired in Shannon information entropy

$$S = -\sum_n p_n \ln p_n$$

Momentum space energy density

$$\tilde{\rho}(\vec{k}) = \frac{1}{(2\pi)^{d/2}} \int d^d r \, \rho(\vec{r}) \exp(-i\vec{k}\cdot\vec{r}) \, .$$

Modal fraction:

$$\epsilon(\vec{k}) = \frac{|\rho(\vec{k})|^2}{|\rho_{max}(\vec{k})|^2}$$

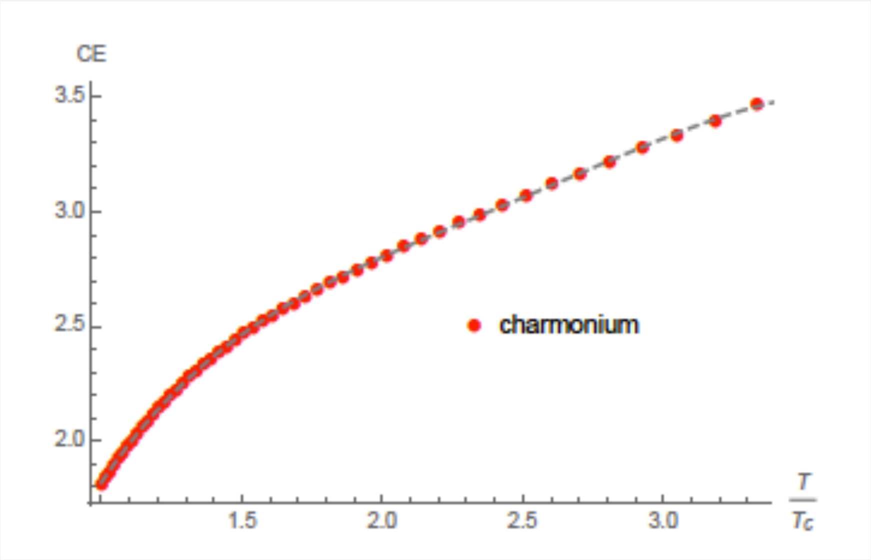
(D)CE:

$$S = -\int d^d k \, \epsilon(\vec{k}) \, \log \epsilon(\vec{k}) \, ,$$

Energy momentum tensor

$$T_{mn}(z) = \frac{2}{\sqrt{-g}}\left[\frac{\partial(\sqrt{-g}\mathcal{L})}{\partial g^{mn}} - \frac{\partial}{\partial x^p}\frac{\partial(\sqrt{-g}\mathcal{L})}{\partial\left(\frac{\partial g^{mn}}{\partial x^p}\right)}\right]$$

$$\rho(z) = T_{00}(z) = \frac{e^{-\phi(z)}}{g_5^2}\left[g_{00}\left(\frac{1}{4}g^{mp}g^{nq}F_{mn}F_{pq}\right) - g^{mn}F_{0n}F_{0m}\right]$$



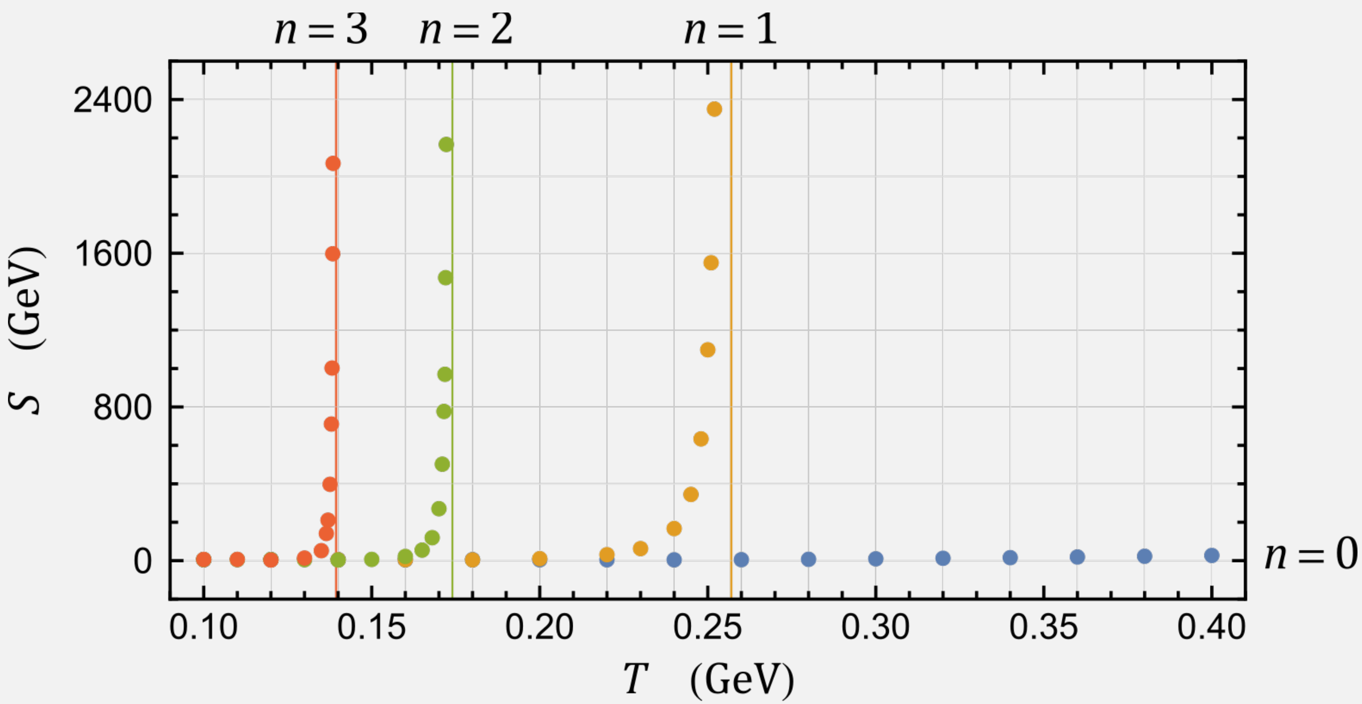
Configuration Entropy for charmonium as a function of the temperature

CE increases as the system becomes more unstable.

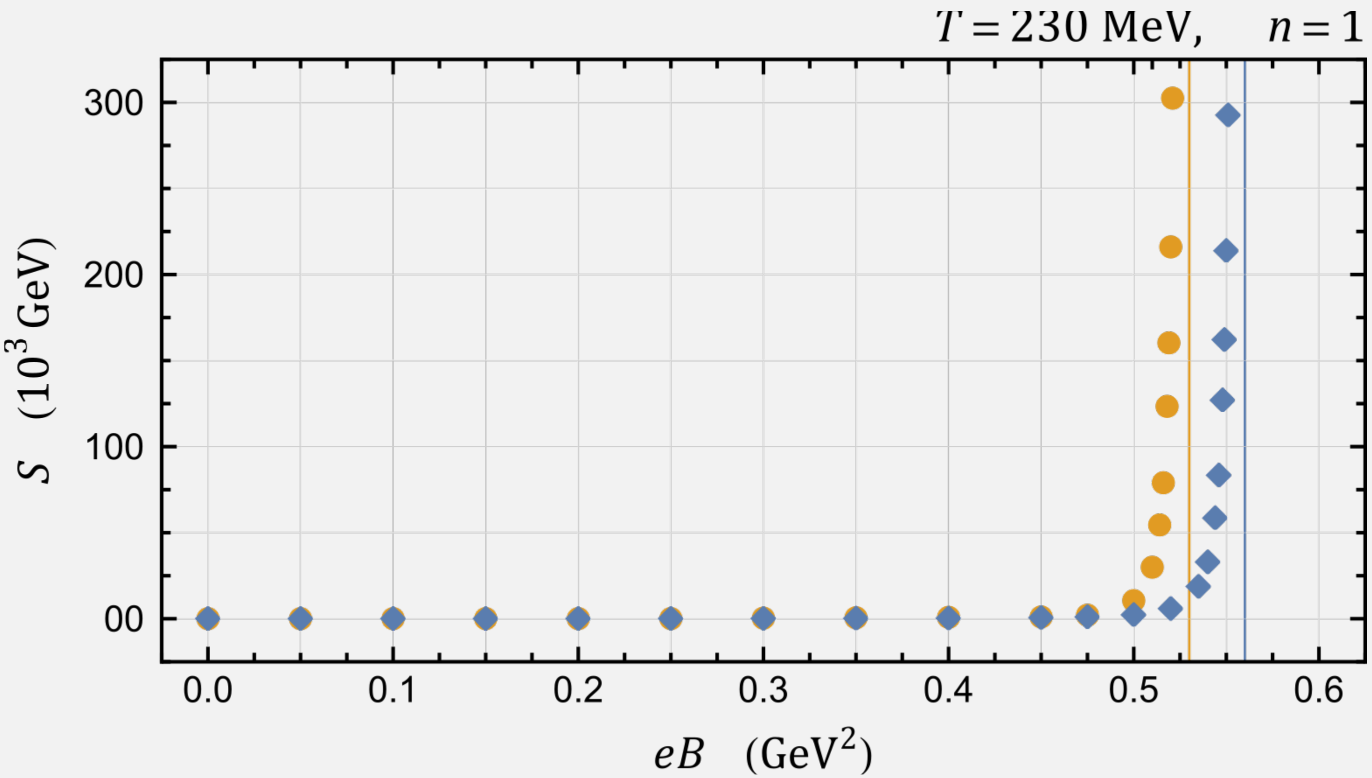
How does the CE tells us about the Complete dissociation of Bottomonium in the thermal medium??

Recent result: **singularity of the CE**

N.B., Y. F. Ferreira and L. F. Ferreira; Phys. Rev. D 105 (2022) 11.

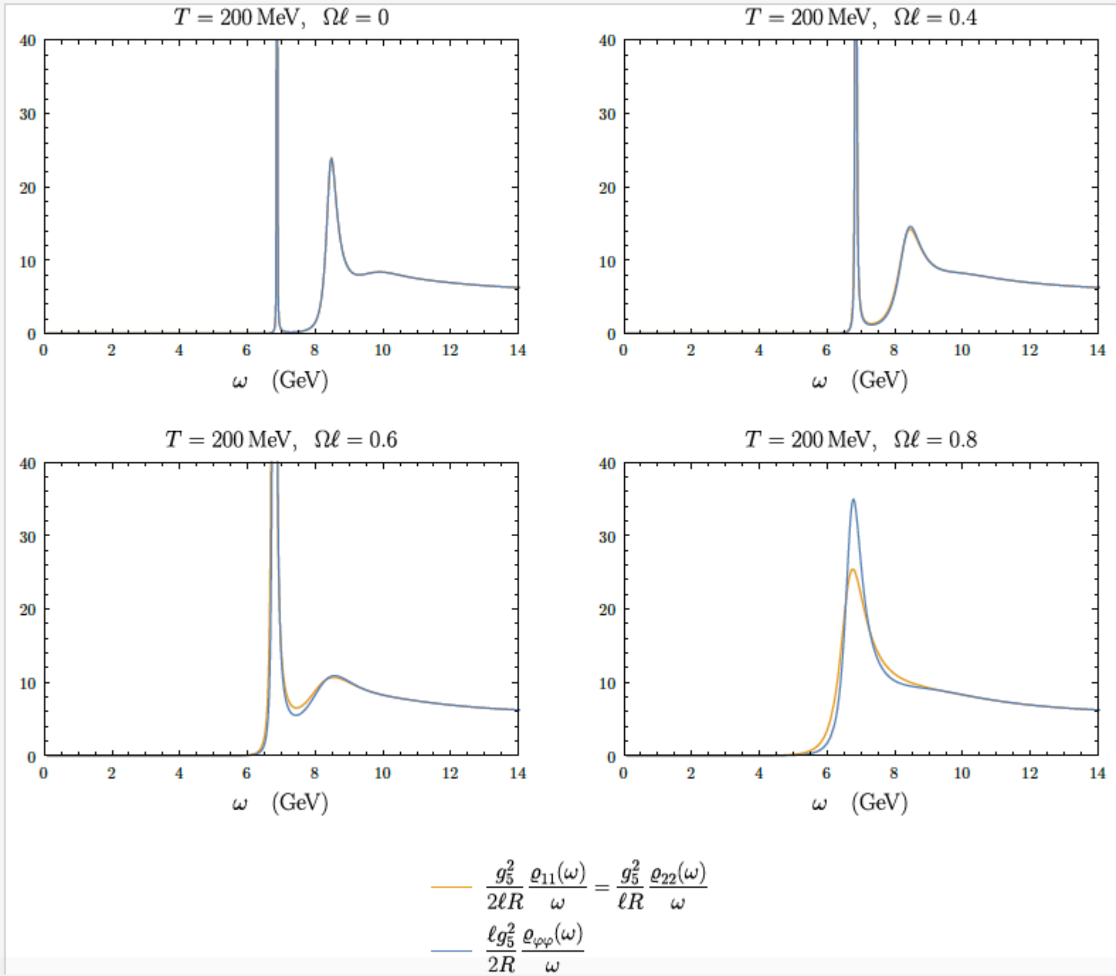


CE for the first 4 (quasi) states of bottomonium as functions of temperature.



CE as function of the magnetic field for the first excited quasi-state of bottomonium.

Effect of rotation in the bottomonium spectrum
(work with Yan Ferreira, to appear in arXiv ~ Tomorrow)



Conclusion

It is possible to describe the dissociation of heavy mesons in a plasma as a function of temperature, density, magnetic fields and **rotation,** using holography

Holographic models also describe the variation of the deconfinement temperature with the rotational speed.

The Configuration entropy measures the stability of a physical system. The higher the CE, the more unstable is the system.

Thank you !!