Departamento de Física
Área de Física Teórica

Casa abierta al tiempo

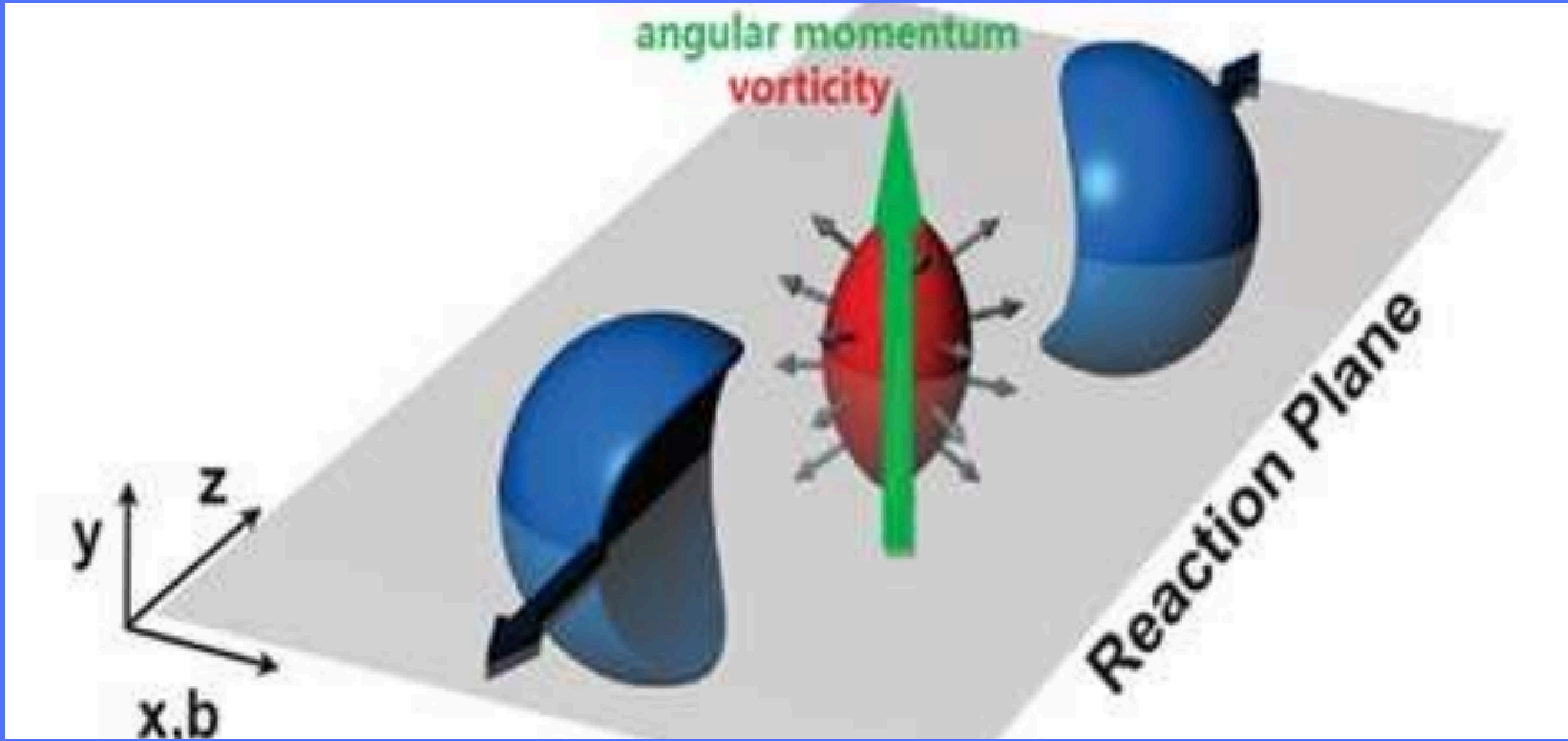
ANOTHER PHASE DIAGRAM FOR THE STRONGLY INTERACTING MATTER

LUIS ALBERTO HERNÁNDEZ ROSAS
UNIVERSIDAD AUTÓNOMA METROPOLITANA

IN COLLABORATION WITH R. ZAMORA

First Latin American Workshop on Electromagnetic Effects in QCD
july 22th, 2024

CONTENT

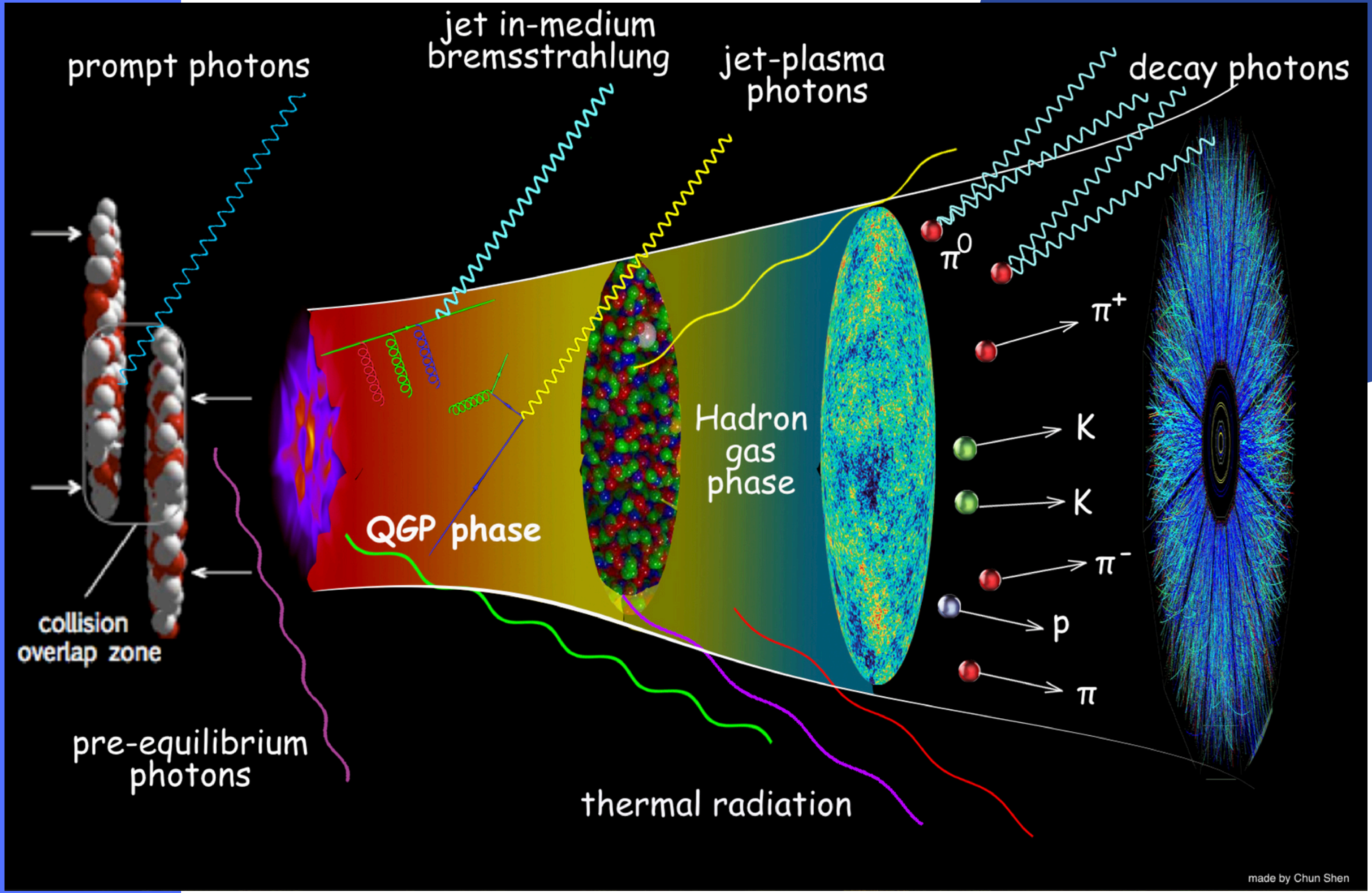


- PHYSICS MOTIVATION

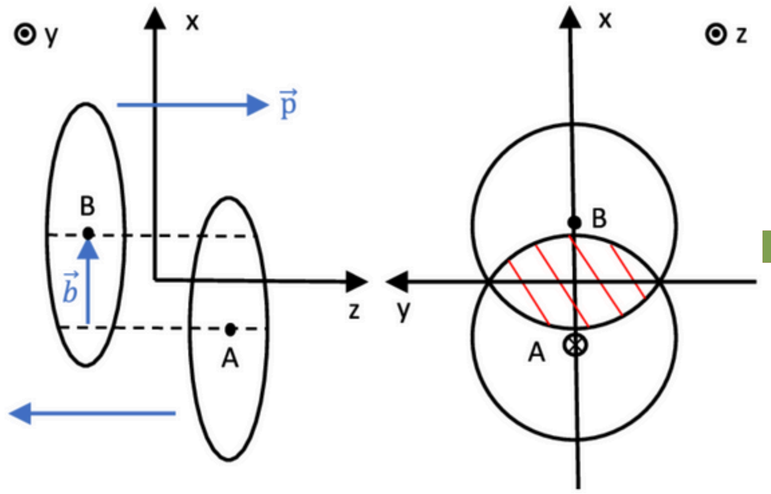
- LSMQ AND THE EFFECTIVE POTENTIAL

- PHASE DIAGRAMA AND FINAL REMARKS

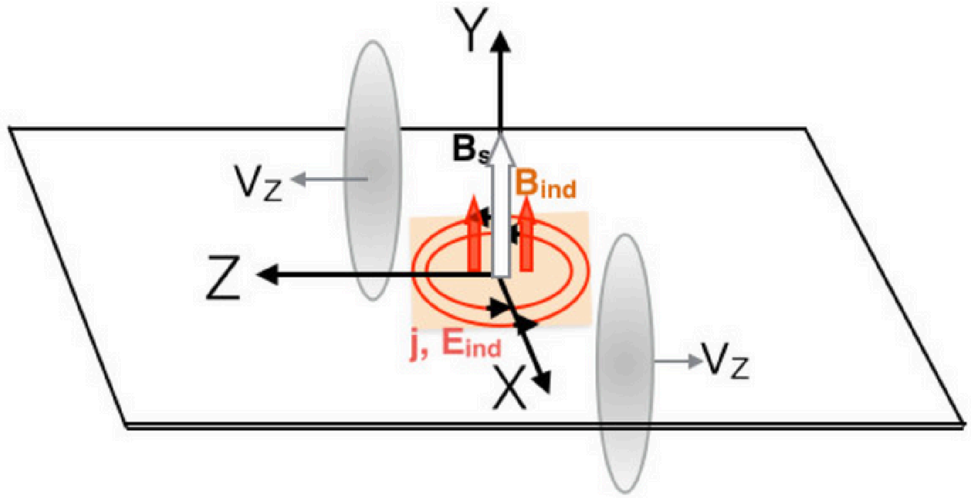
HIC


prompt photons
jet in-medium bremsstrahlung
jet-plasma photons
decay photons
collision overlap zone
QGP phase
Hadron gas phase
π^0
π^+
K
K
π^-
p
π
pre-equilibrium photons
thermal radiation
made by Chun Shen

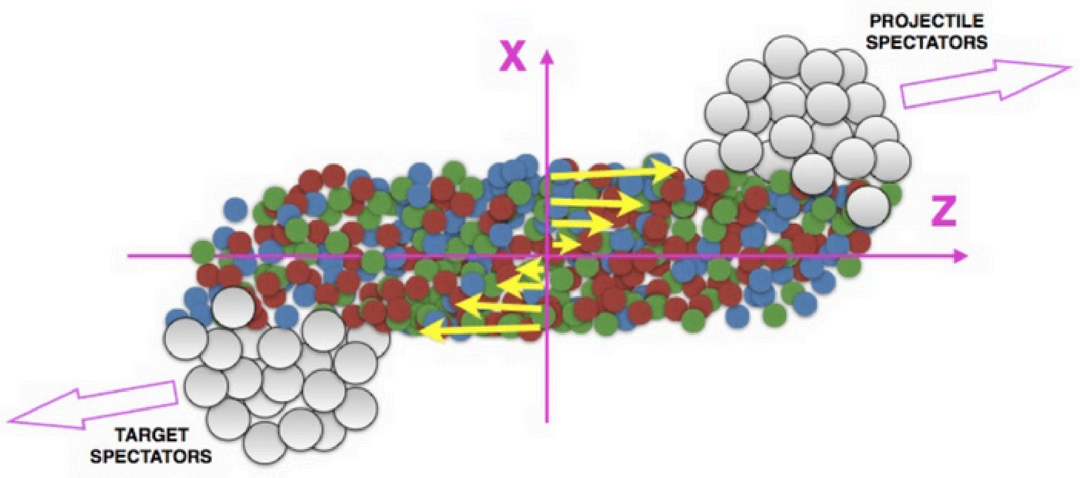
NON CENTRAL COLISION



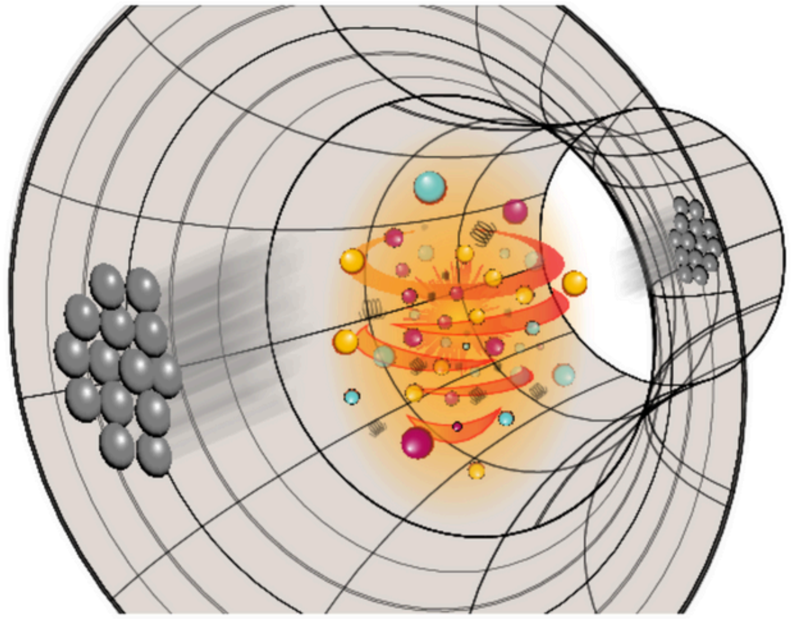
Eur.Phys.J.C 83 (2023) 1, 96



Phys.Rev.C 96 (2017) 5, 054909

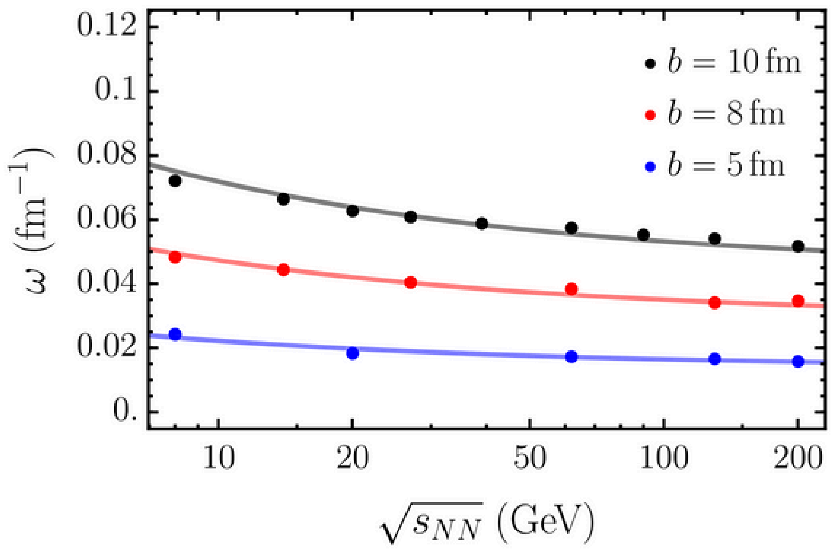


EPJ Web Conf. 171 (2018) 07002

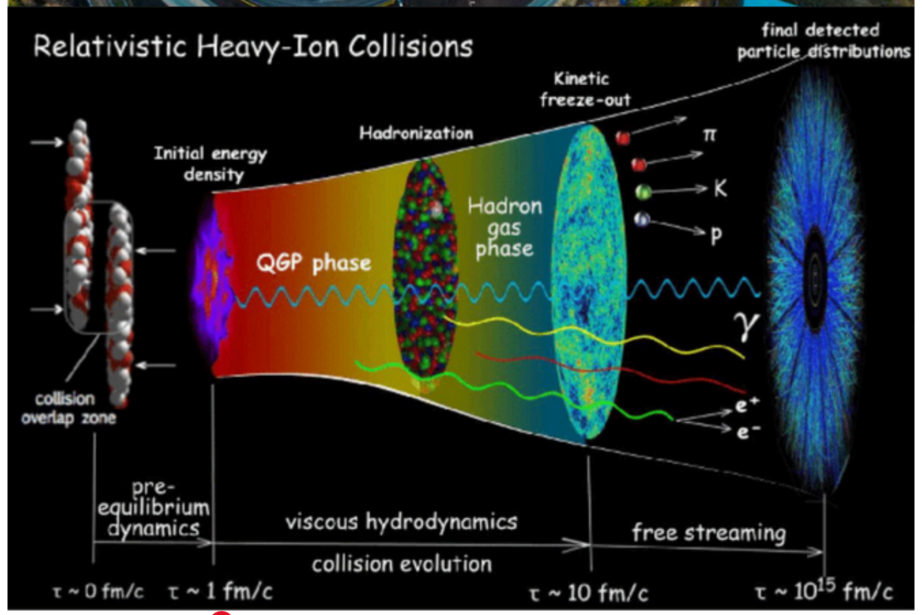


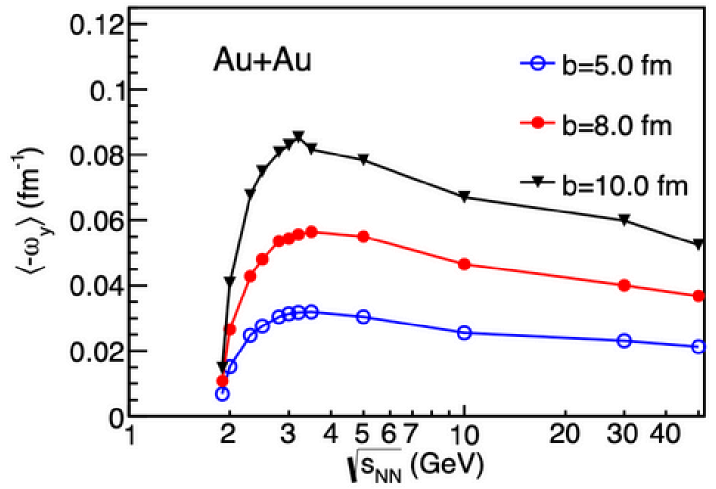
Nucl.Sci.Tech. 34 (2023) 1, 15

ANGULAR VELOCITY

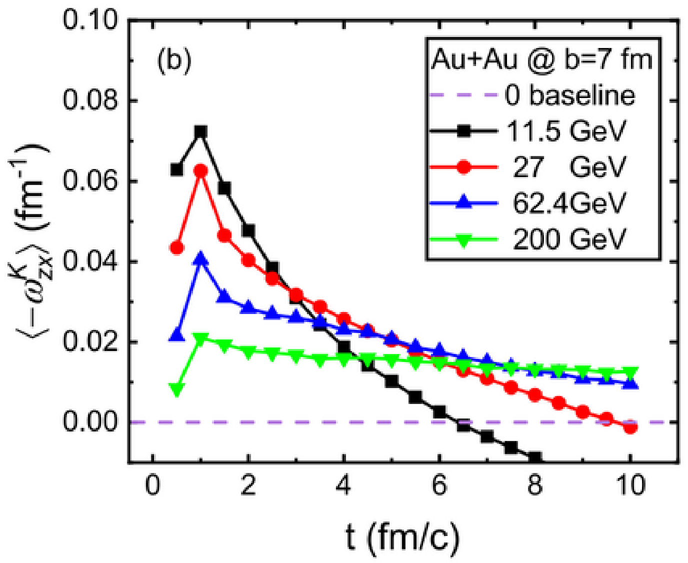


Initial angular velocity ω for Au + Au collisions at impact parameters b= 5, 8, 10 fm as functions of collision energy (UrQMD). Phys. Rev. D **102** (2020), 056019

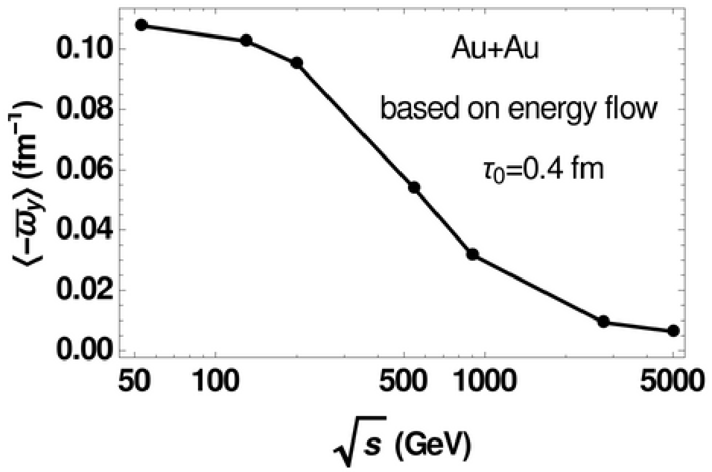




Initial angular velocity at mid rapidity as a function of the collision energy for impact parameters b = 5, 8, and 10 fm (UrQMD). Phys.Rev.C **101** (2020) 6, 064908



Time evolution of angular velocity at b=7 fm and four different energies (PACIAE). Phys.Rev.C **104** (2021) 5, 054903



Angular velocity at fixed τ = 0.4 fm and η = 0 as function of collision energy (HIJING). Phys. Rev. C **93** (2016), 064907

HICs

1 **Phase transition**
Quark-gluon plasma->Chiral symmetry

2 **Non central collisions**
Finite impact parameter b.

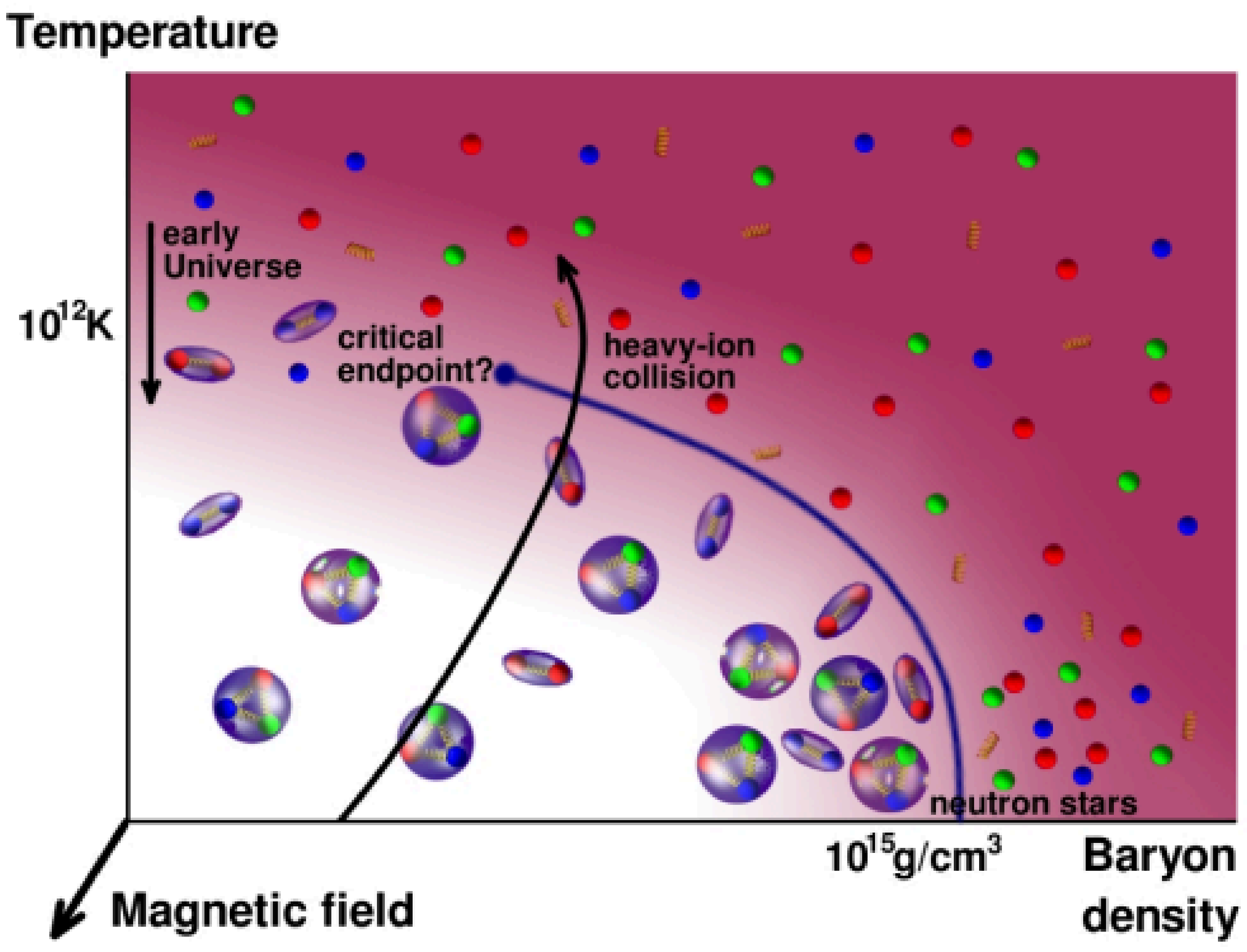
3 **Angular velocity**
Maximum value around 0.1 1/fm aprox. 20 MeV.

4 **Collision energy**
Angular velocity is more important at low collision energies.

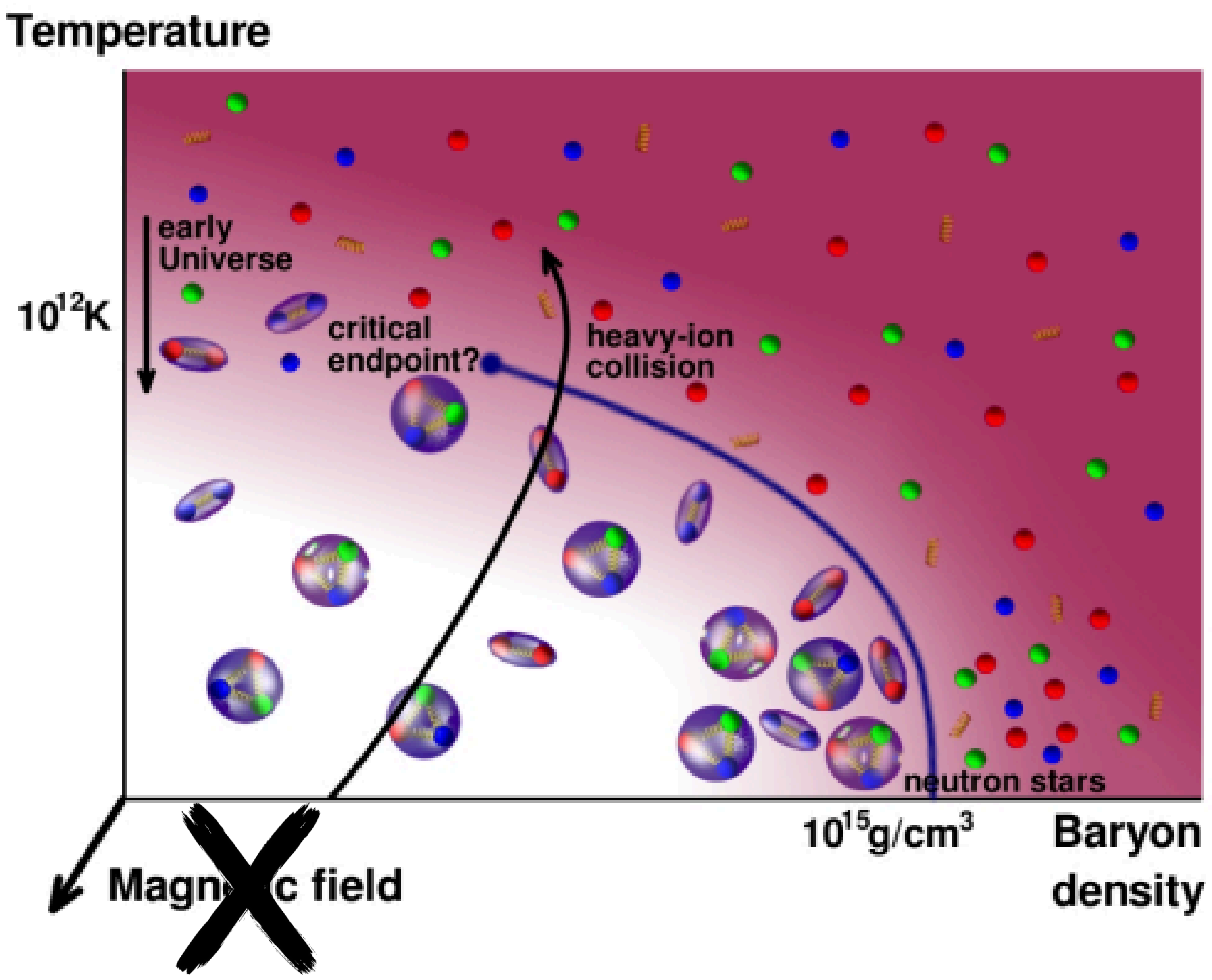
5 **Baryon chemical potential**
Region of maximum baryon density works MPD-NICA.

6 **Effective models**
Low energies of QCD.

QCD phase diagram



J.Phys.Conf.Ser. 503 (2014) 012009



Vorticity

Linear Sigma model coupled to quarks

Effective theory which is usefull to emulate the low energy regime of Quantum Chromodynamics. It exhibits a symmetry spontaneously broken.

$$\mathscr{L} = \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 + \frac{a^2}{2}(\sigma^2 + \vec{\pi}) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 + i\bar{\psi}\gamma^\mu\partial_\mu\psi - ig\bar{\psi}\gamma^5\vec{\tau}.\vec{\pi}\psi - g\bar{\psi}\psi\sigma$$

letting the sigma-field to develop a vacuum expectation value v, we have

$$V^{tree} = -\frac{a^2}{2}v^2 + \frac{\lambda}{4}v^4$$

$$m_\sigma^2 = 3\lambda v^2 - a^2 \quad , \quad m_0^2 = \lambda v^2 - a^2 \quad , \quad m_f = gv$$

Effective potential

We compute the 1-loop corrections of bosons and fermions

$$V_b^1 = -\frac{i}{2}\int \frac{d^4k}{(2\pi)^4}\ln(D_b^{-1}(k)) \ , \ V_f^1 = iN_c \int \frac{d^4k}{(2\pi)^4} Tr[\ln(S_f^{-1}(k))]$$

where the propagators are

$$S(\tilde{\omega}_n, \Omega, \vec{k}) = -\frac{(i\tilde{\omega}_n + \frac{\Omega}{2} - k_z + ik_\perp)(\gamma_0+\gamma_3) + m_f(1+\gamma_5)}{(\tilde{\omega}_n - i\frac{\Omega}{2})^2 + \vec{k}^2 + m_f^2}\mathcal{O}^+ - \frac{(i\tilde{\omega}_n - \frac{\Omega}{2} + k_z - ik_\perp)(\gamma_0-\gamma_3) + m_f(1+\gamma_5)}{(\tilde{\omega}_n + i\frac{\Omega}{2})^2 + \vec{k}^2 + m_f^2}\mathcal{O}^-,$$

- Phys.Rev.D **103** (2021) 7, 076021

$$D(p) = \frac{1}{(p_0+\Omega)^2 - p_\perp^2 - p_z^2 - m^2 + i\epsilon}$$

- Phys.Rev.D **108** (2023) 9, 094020

1-loop boson contribution

Working within the Matsubara formalism

$$V_{\rm b}^{1} = T\sum_{n=-\infty}^{\infty}\int\frac{d^3k}{(2\pi)^3}\ln D(\omega_n,\Omega,\vec{k})^{1/2},$$

We perform the sum over the Matsubara frequencies

$$V_{\rm b}^{1} = \frac{1}{4}\int\frac{d^3k}{(2\pi)^3}\int dm_\phi^2\frac{1}{E}\left[1+\frac{1}{e^{\beta(E-\Omega)}-1}+\frac{1}{e^{\beta(E+\Omega)}-1}\right],$$

$$V_{\rm b,vac}^{1} = \frac{1}{4}\int\frac{d^3k}{(2\pi)^3}\int dm_\phi^2\frac{1}{\sqrt{k^2+m_\phi^2}},$$

$$V_{\rm b,mat}^{1} = \frac{1}{4}\int\frac{d^3k}{(2\pi)^3}\int dm_\phi^2\frac{1}{\sqrt{k^2+m_\phi^2}} \times\left[\frac{1}{e^{\beta(\sqrt{k^2+m_\phi^2}-\Omega)}-1}+\frac{1}{e^{\beta(\sqrt{k^2+m_\phi^2}+\Omega)}-1}\right].$$

1-loop boson contribution

Vacuum term. We use the $\overline{\text{MS}}$ scheme and then we obtain

$$V^1_{\text{b,vac}} = -\frac{m_\phi^4}{64\pi^2}\left[\ln\left(\frac{\mu^2}{m_\phi^2}\right) + \frac{3}{2}\right].$$

Dynamic mass of a boson

$$m_\sigma^2 = 3\lambda v^2 - a^2 \quad , \quad m_0^2 = \lambda v^2 - a^2$$

Matter term. We have

$$V^1_{\text{b,mat}} = \frac{T^4}{2\pi^2}\int_0^\infty x^2 dx\left\{\ln[1 - e^{-\sqrt{x^2+y^2}+zy}] + \ln[1 - e^{-\sqrt{x^2+y^2}-zy}]\right\}.$$

$$V_{\text{b,mat}} = \frac{2T^{n+1}}{(4\pi)^{n/2}\Gamma(n/2)}\int_0^\infty x^{n-1}dx \times\left\{\ln[1 - e^{-\sqrt{x^2+y^2}+zy}] + \ln[1 - e^{-\sqrt{x^2+y^2}-zy}]\right\},$$

J.Math.Phys. 23 (1982) 1852

High T approximation

$$V^1_{\text{b,mat}} = -\frac{\pi^2 T^4}{90} + \frac{T^2}{24}(m_\phi^2 - 2\Omega^2) - \frac{T}{12\pi}(m_\phi^2 - \Omega^2)^{3/2} - \frac{\Omega^2}{48\pi^2}(3m_\phi^2 - \Omega^2) - \frac{m_\phi^4}{64\pi^2}\left[\ln\left(\frac{m_\phi^2}{16\pi^2 T^2}\right) + 2\gamma_E - \frac{3}{2}\right].$$

1-loop fermion contribution

Working within the Matsubara formalism

$$V_{\mathrm{f}}^{1} = -T \sum_{n=-\infty}^{\infty} \int \frac{d^3k}{(2\pi)^3} \mathrm{Tr}\left[\ln S(\tilde{\omega}_n, \mu_q, \Omega, \vec{k})^{-1}\right],$$

$$V_{\mathrm{f}}^{1} = -\frac{T}{2} \sum_{n=-\infty}^{\infty} \int dm_f^2 \int \frac{d^3k}{(2\pi)^3} \Big[\frac{1}{(\omega_n - i\mu_1)^2 + \vec{k}^2 + m_f^2} + \frac{1}{(\omega_n - i\mu_2)^2 + \vec{k}^2 + m_f^2}\Big]$$

$$V_{\mathrm{f,vac}}^{1} = \frac{m_f^4}{16\pi^2}\left[\ln\left[\frac{\mu^2}{m_f^2}\right] + 2\gamma_E + \frac{3}{2}\right]$$

with

$$\mu_1 = \mu_q + \frac{\Omega}{2}, \qquad \mu_2 = \mu_q - \frac{\Omega}{2}$$

$$\begin{aligned} V_{\mathrm{f,mat}}^{1} = {} & \frac{m_f^4}{16\pi^2}\left[\ln\left[\frac{m_f^2}{\pi^2 T^2}\right] + 2\gamma_E - \frac{3}{2}\right] - \frac{7T^4\pi^2}{360} \\ & - \frac{T^2}{24}\left(\left(\mu_q + \frac{\Omega}{2}\right)^2 + \left(\mu_q - \frac{\Omega}{2}\right)^2\right) \\ & + \frac{T^2 m_f^2}{4\pi^2}\Bigg(\mathrm{Li}_2\left(-e^{\frac{\mu+\frac{\Omega}{2}}{T}}\right) + \mathrm{Li}_2\left(-e^{\frac{\mu-\frac{\Omega}{2}}{T}}\right) \\ & + \mathrm{Li}_2\left(-e^{-\frac{\mu+\frac{\Omega}{2}}{T}}\right) + \mathrm{Li}_2\left(-e^{-\frac{\mu-\frac{\Omega}{2}}{T}}\right)\Bigg) \\ & + \frac{\left(\mu + \frac{\Omega}{2}\right)^4 + \left(\mu - \frac{\Omega}{2}\right)^4}{48\pi^2} \end{aligned}$$

Ring diagrams

$$V^{\text{ring}} = \frac{T}{2}\sum_{n=-\infty}^{\infty}\int\frac{d^3k}{(2\pi)^3}\ln\left(1+\Pi D(\omega_n,\Omega,\vec{k})\right),$$

We work with the high T approximation

$$V^{\text{ring}} = \frac{T}{2}\int\frac{d^3k}{(2\pi)^3}\ln\left(1+\Pi D(\omega_n,\Omega,\vec{k})\right)$$

We obtain

$$V^{\text{ring}} = -\frac{T}{12\pi}(m_\phi^2-\Omega^2+\Pi)^{3/2}+\frac{T}{12\pi}(m_\phi^2-\Omega^2)^{3/2}.$$

Effective Potential

$$V^{\text{eff}} = -\frac{a^2}{2}v^2 + \frac{\lambda}{4}v^4 + \sum_{b=\sigma,\vec{\pi}} \Bigg\{ -\frac{m_b^4}{64\pi^2}\left[\ln\left(\frac{\mu^2}{16\pi^2T^2}\right) + 2\gamma_E\right]$$
$$-\frac{\pi^2T^4}{90} + \frac{T^2}{24}\left(m_b^2 - 2\Omega^2\right) - \frac{T\left(\Pi + m_b^2 - \Omega^2\right)^{3/2}}{12\pi}$$
$$-\frac{\Omega^2}{48\pi^2}\left(3m_b^2 - \Omega^2\right)\Bigg\} + N_f N_c \Bigg\{ \frac{m_f^4}{16\pi^2}\left[\ln\left(\frac{\mu^2}{\pi^2T^2}\right) + 2\gamma_E\right]$$
$$-\frac{7T^4\pi^2}{360} - \frac{T^2}{24}\left(\left(\mu_q + \frac{\Omega}{2}\right)^2 + \left(\mu_q - \frac{\Omega}{2}\right)^2\right)$$
$$+\frac{T^2m_f^2}{4\pi^2}\left(\mathrm{Li}_2\left(-e^{\frac{\mu+\frac{\Omega}{2}}{T}}\right) + \mathrm{Li}_2\left(-e^{\frac{\mu-\frac{\Omega}{2}}{T}}\right)\right.$$
$$\left.+\mathrm{Li}_2\left(-e^{-\frac{\mu+\frac{\Omega}{2}}{T}}\right) + \mathrm{Li}_2\left(-e^{-\frac{\mu-\frac{\Omega}{2}}{T}}\right)\right)$$
$$+\frac{\left(\mu + \frac{\Omega}{2}\right)^4 + \left(\mu - \frac{\Omega}{2}\right)^4}{48\pi^2}\Bigg\}$$

where the self-energy is

$$\Pi_\sigma = \frac{\lambda}{4}\left[12I(m_\sigma) + 4I(m_0) + 8I(m_b)\right] + N_f N_c \Pi_f$$

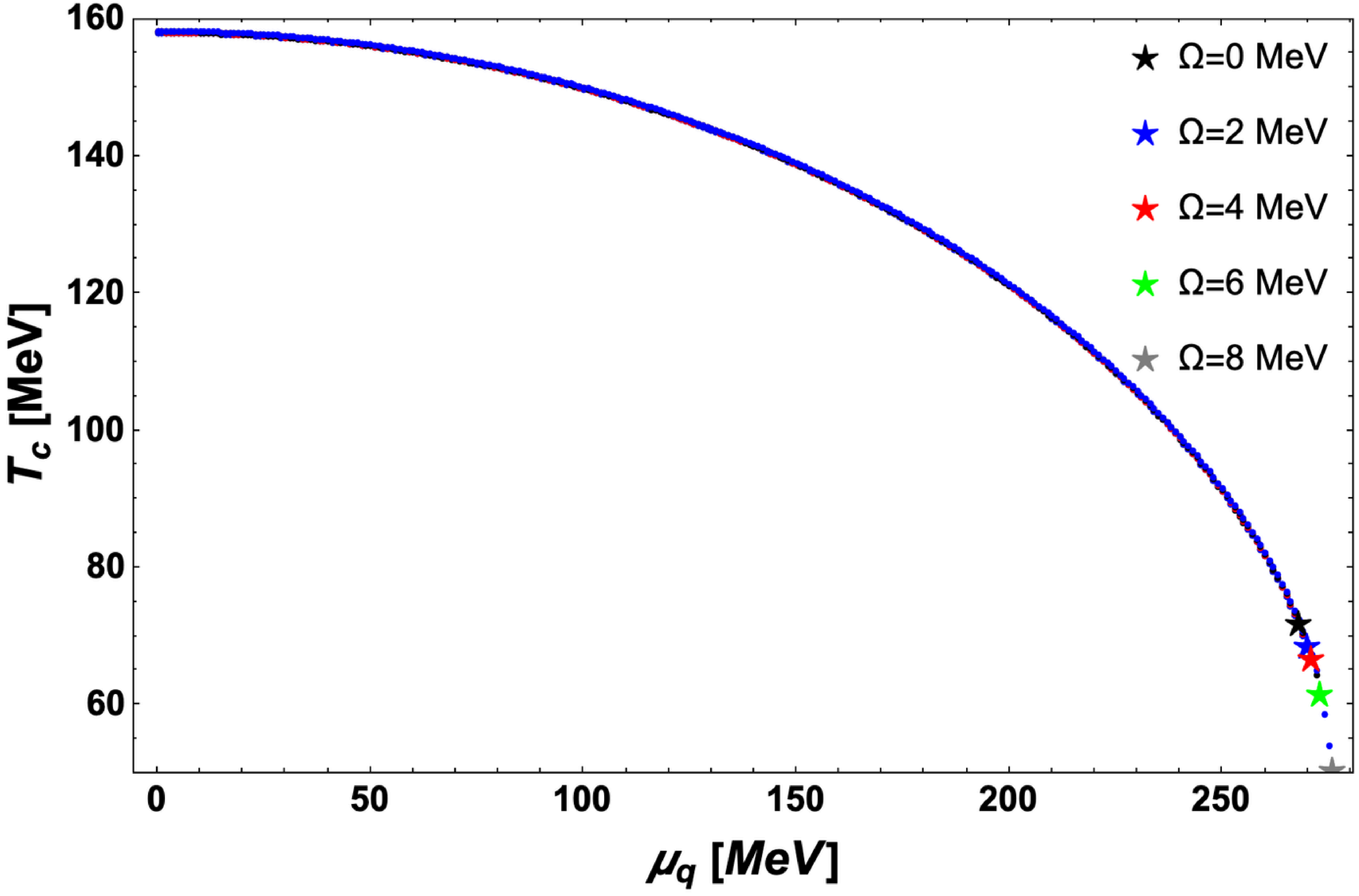
$$\Pi_0 = \frac{\lambda}{4}\left[4I(m_\sigma) + 12I(m_0) + 8I(m_b)\right] + N_f N_c \Pi_f$$

with

$$I(m_b) = 2\frac{dV_b^1}{dm_b^2}$$

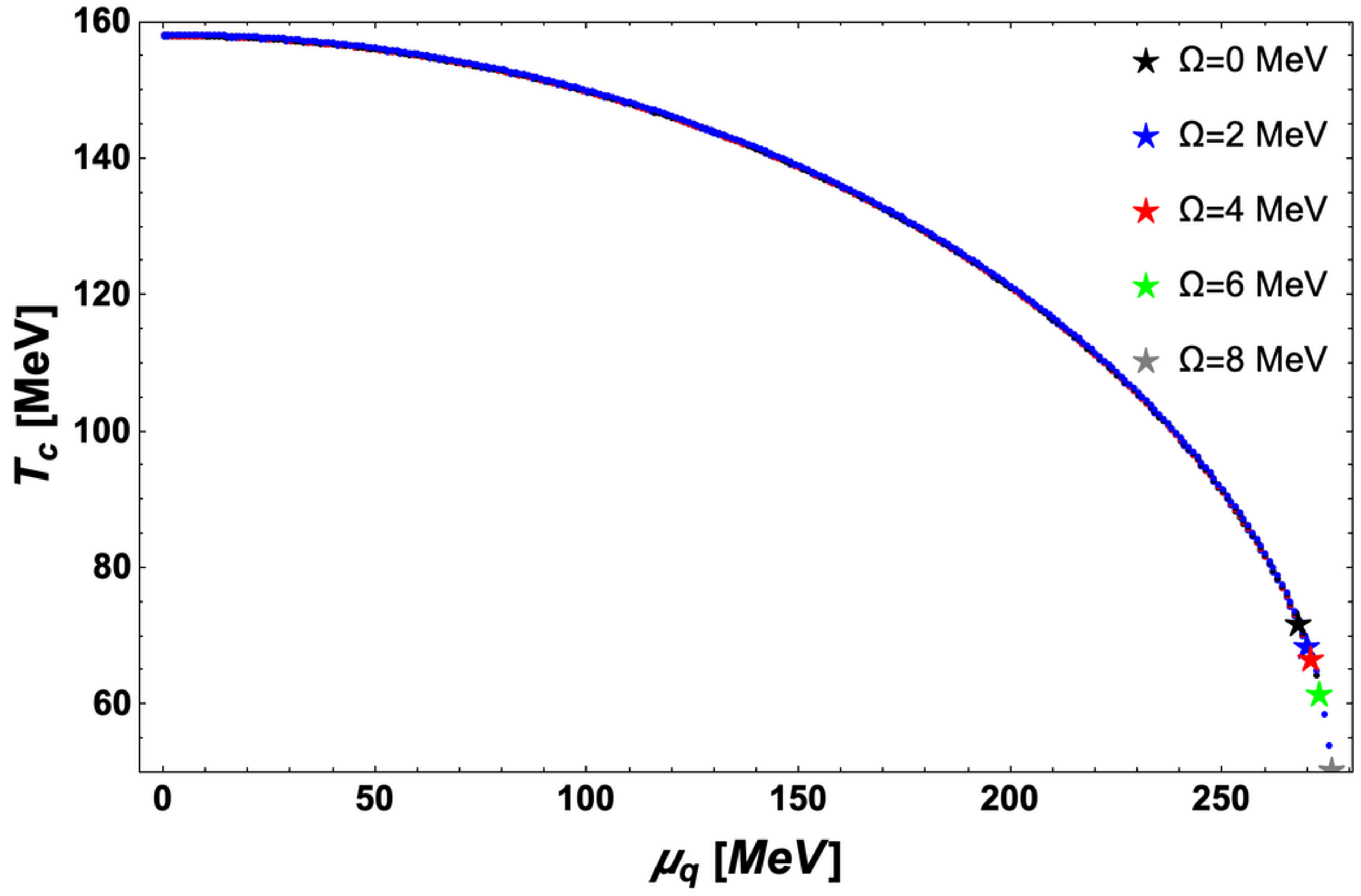
$$\Pi_f = 2g^2\frac{dV_f^1}{dm_f^2}$$

Phase diagram



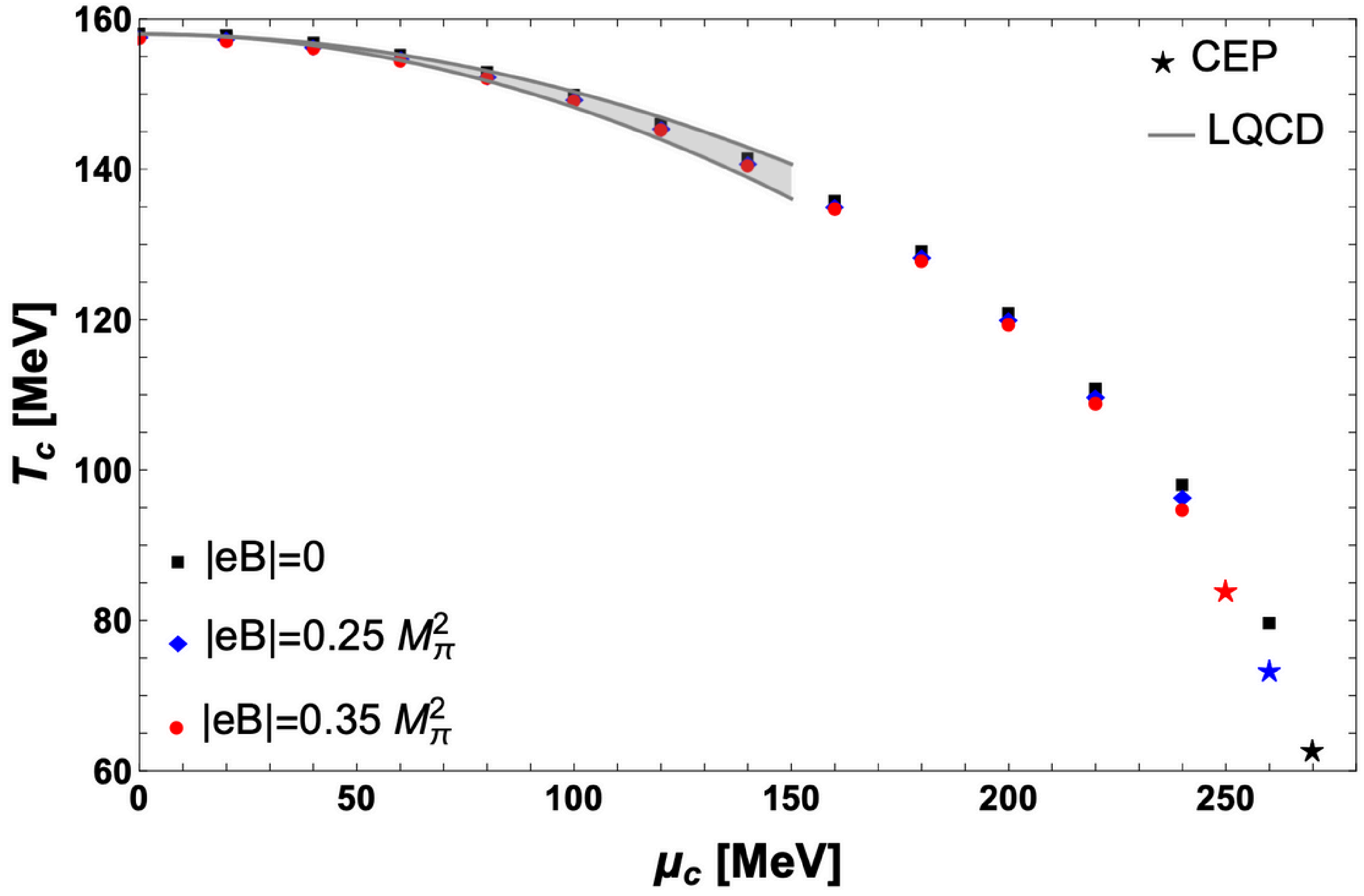
- Tc decreases as angular velocity increases (Inverse Vortical Catalysis).
- The CEP is moving to the right and downwards

Phase diagram



Vorticity

Eur.Phys.J.A 57 (2021) 7, 234



Magnetic field

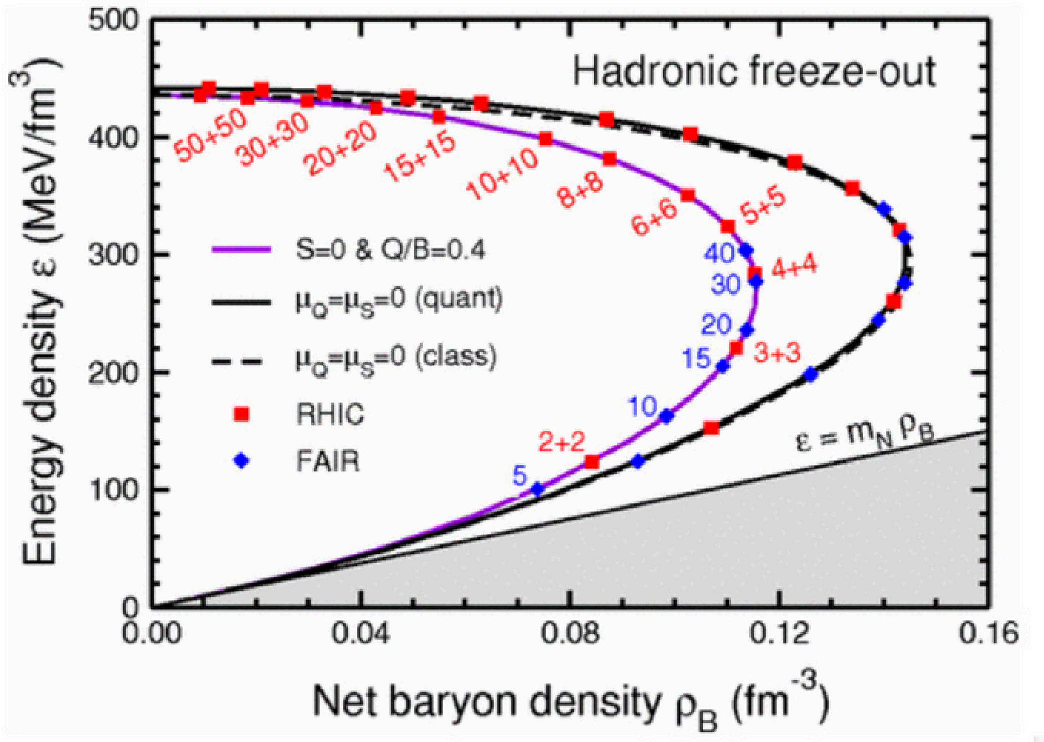
Conclusions and

1. The angular velocity promotes the restoration of chiral symmetry
2. The CEP changes its position as a function of angular velocity
3. Computation of the low T approximation
4. Enough equations to fix the free parameters.
5. Translate the information found to conditions of the collision.

¡Muchas gracias por su atención!

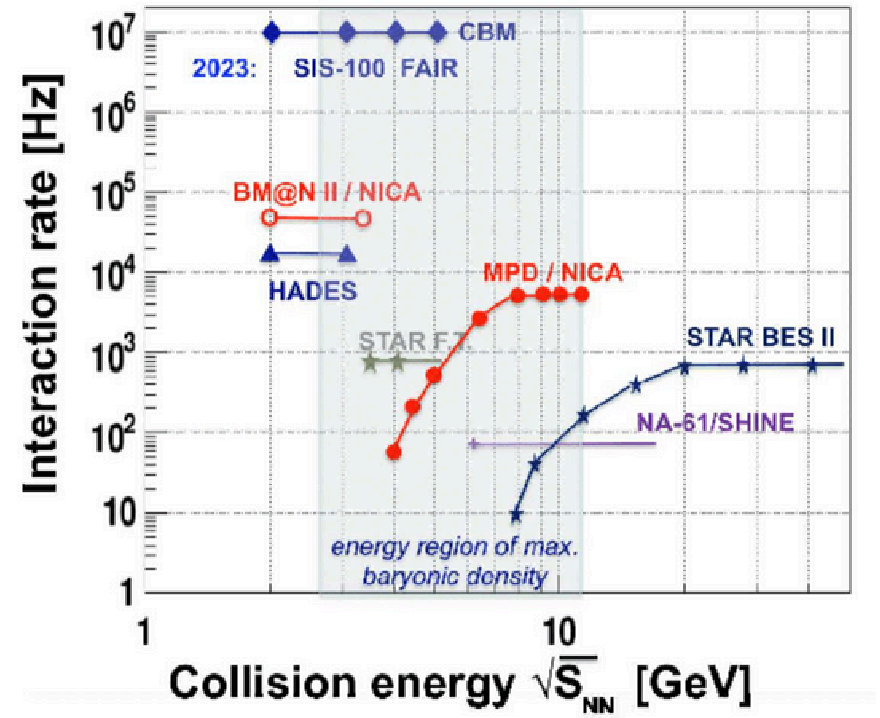
Signals of criticality

Phys.Rev.C 74 (2006) 047901

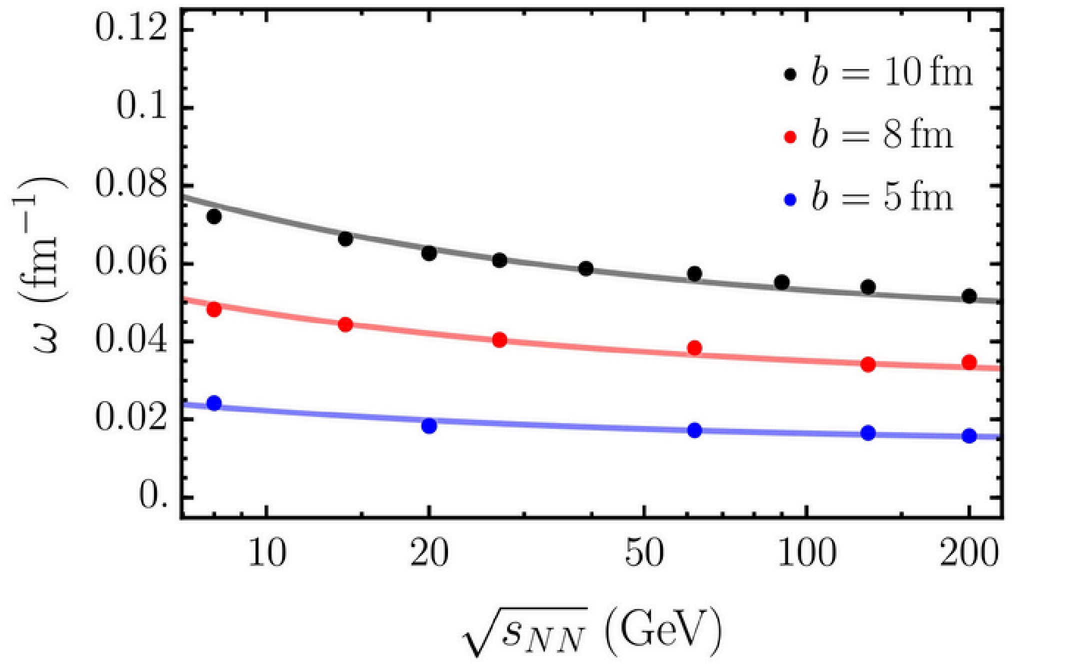


$$\mu_B(\sqrt{s_{NN}}) = \frac{d}{1+e\sqrt{s_{NN}}},$$

PoS ICHEP2018 (2019) 493



Phys. Rev. D 102 (2020), 056019



$$\omega = \frac{\omega_0}{2}\frac{b^2}{V_N}\left[1+2\left(\frac{m_N}{\sqrt{s_{NN}}}\right)^{1/2}\right],$$

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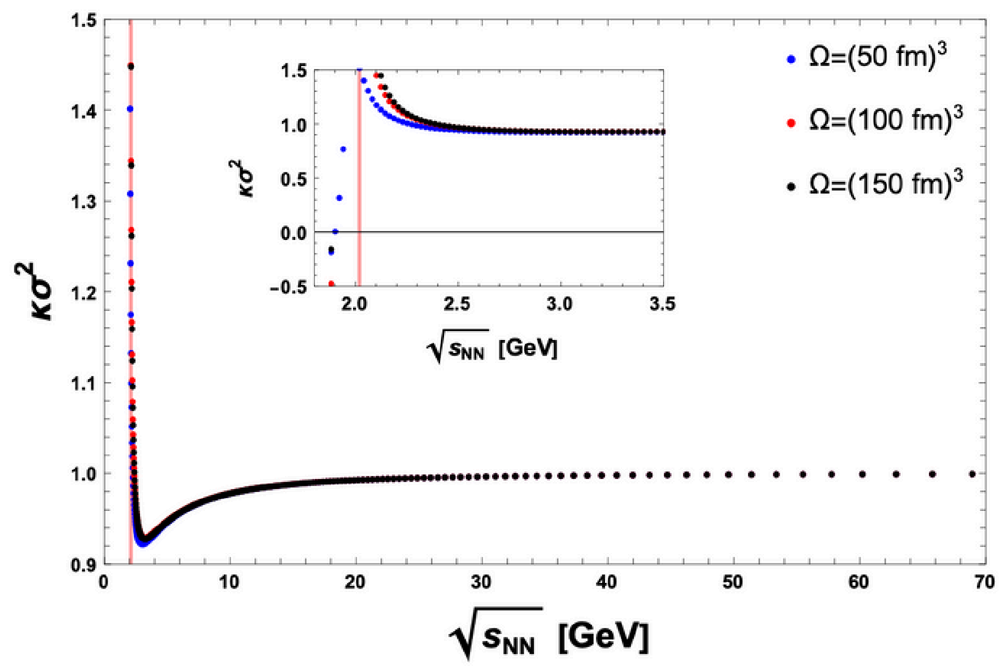
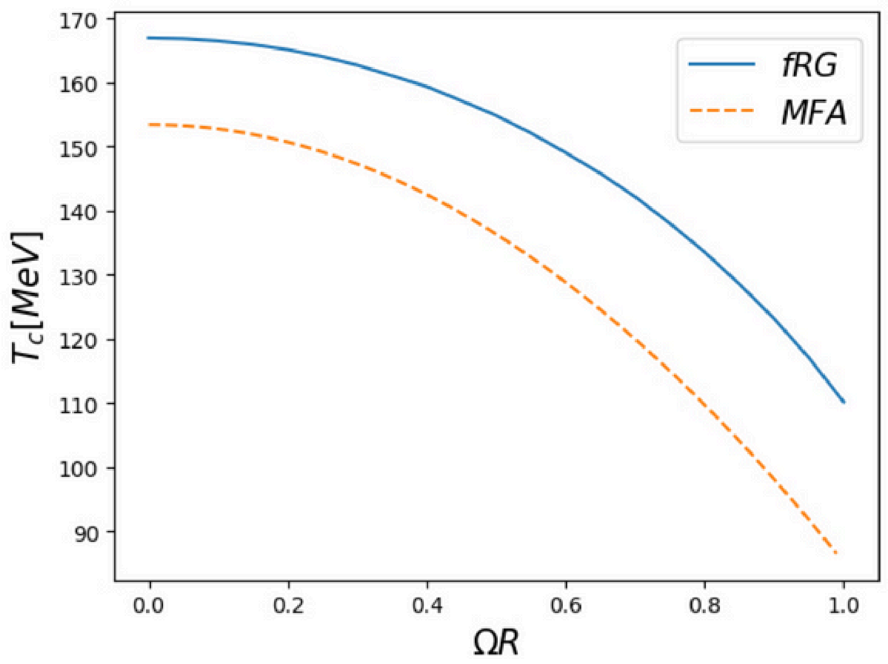
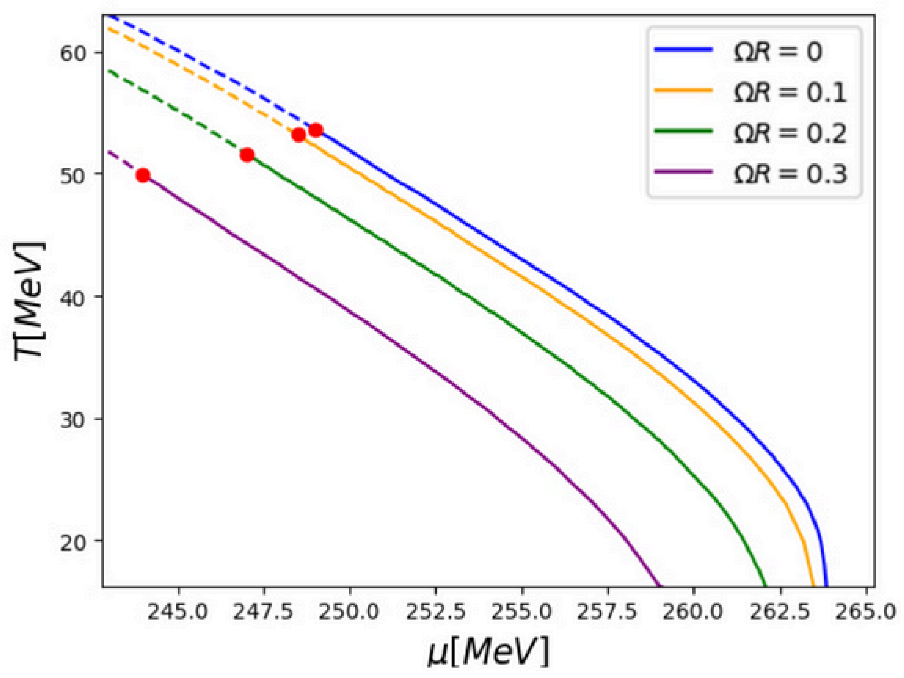
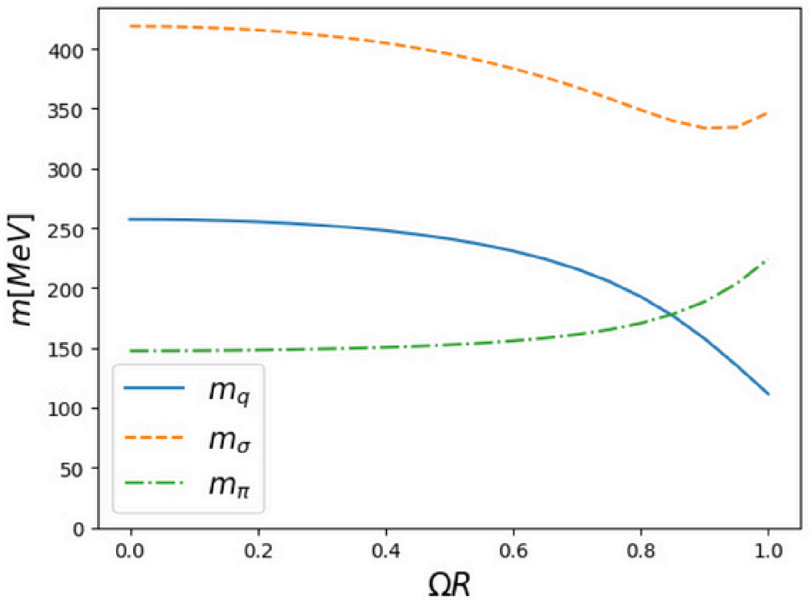


Result in the literature with Quark-Meson model

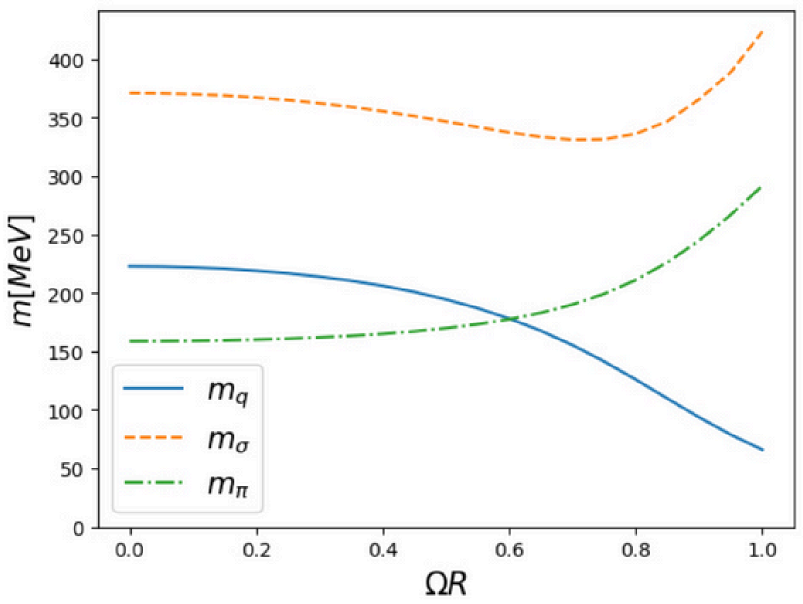


fRG-> functional renormalization group
MFA->mean-field approximation





T=120 MeV



T=140 MeV