Twisting the Quark-Gluon Plasma: Insights into Electromagnetic Emission from a Rotating Medium

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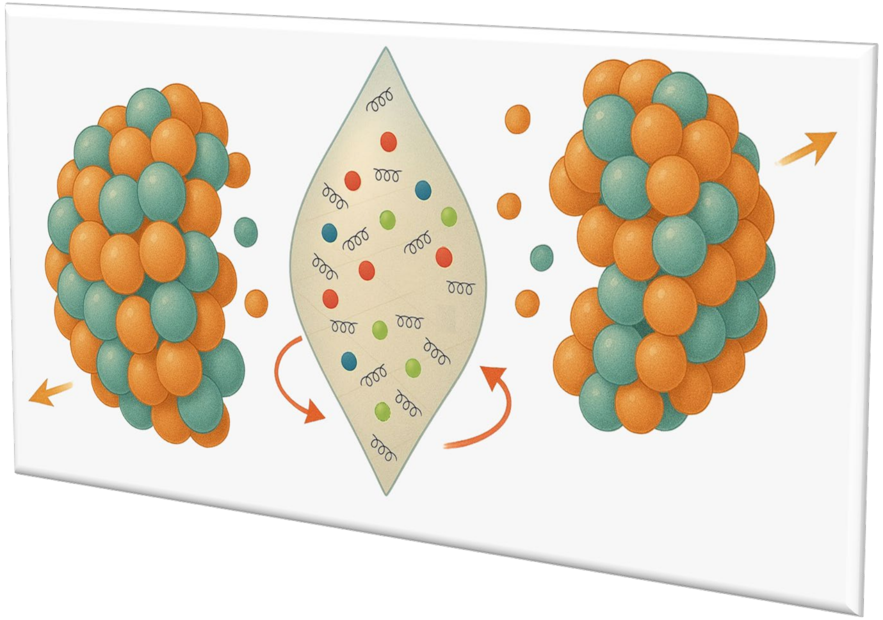
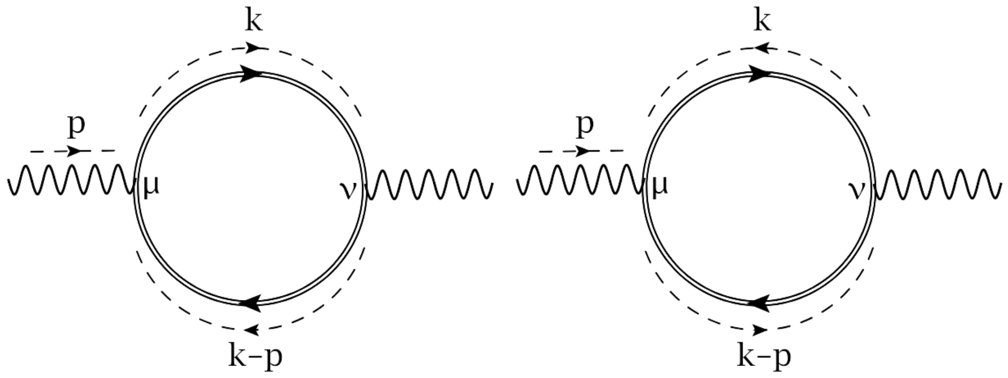


The one-loop photon (like) polarization tensor

Ayala, Villavicencio, and Muñoz discussed this Feynman diagram in their talks.



From a theoretical perspective, the exploration of new effects involves changes in the boson-fermion couplings and the fermion propagator.

$$\mathrm{i}\Pi^{\mu\nu} = -\frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}\Big\{\mathrm{i}q_f\gamma^{\nu}\mathrm{i}S\,(k)\,\mathrm{i}q_f\gamma^{\mu}\mathrm{i}S(k-p)\Big\} + \mathrm{C.C.}.$$

Fermion Propagator in a Vortical Background

This propagator was originally derived by Ayala et al., and subsequently revised by Ayala and J.J. Medina, for a rigid cylindrical rotation

PHYSICAL REVIEW D **103**, 076021 (2021)

Fermion propagator in a rotating environment

Alejandro Ayala,[1,2] L. A. Hernández,[2,3,4] K. Raya,[1,5] and R. Zamora[6,7]

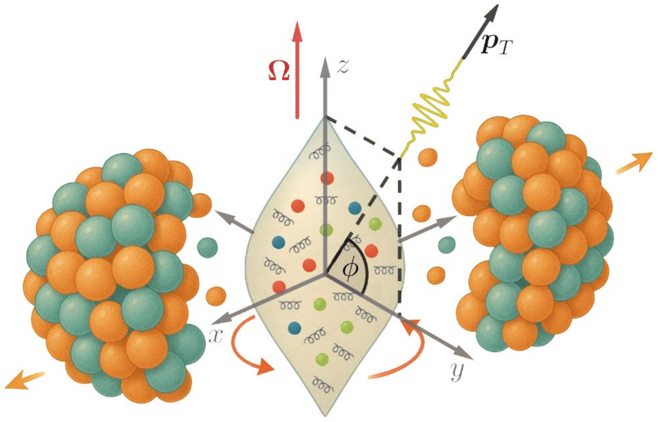
$$S(p) = \frac{\not{p}_+ + m_f}{p_+^2 - m_f^2 + \mathrm{i}\epsilon}\mathcal{O}^{(+)} + \frac{\not{p}_- + m_f}{p_-^2 - m_f^2 + \mathrm{i}\epsilon}\mathcal{O}^{(-)}$$

$$\mathcal{O}^{(\pm)} = \frac{1}{2}\left(\mathbb{1} \pm \frac{\boldsymbol{\Omega}}{\Omega}\cdot\boldsymbol{\Sigma}\right) = \frac{1}{2}\left(\mathbb{1} \pm \mathrm{i}\gamma^1\gamma^2\right)$$

$$p_\pm^\mu \equiv \left(p^0 \pm \frac{\Omega}{2}, p^1, p^2, p^3\right)$$

The photon production rate

This holds at all orders in perturbation theory



$$\mathcal{R}_\gamma \equiv \frac{d^3R}{p_T dp_T d\phi dy} = -\frac{n_{\rm B}(\omega_{\rm ph})}{(2\pi)^3}\,{\rm Im}\left\{g_{\mu\nu}\,\Pi^{\mu\nu}_{\rm R}(p)\right\}$$

$$g_{\mu\nu}\Pi^{\mu\nu} \;=\; -4q_f^2\mathcal{I} + q_f^2\sum_{\sigma=\pm1}\left[12\mathcal{J}_\sigma - 4\mathcal{K}_\sigma\right]$$

$$\mathcal{I} \equiv \int\frac{d^4k}{(2\pi)^4}\left[\frac{\epsilon_{ab}(k-p)^a k^b}{(k_+^2-m^2)((k-p)_-^2-m^2)} + \frac{\epsilon_{ab}k^a(k-p)^b}{(k_-^2-m^2)((k-p)_+^2-m^2)}\right]$$

$$\mathcal{J}_\sigma \equiv {\rm i}\int\frac{d^4k}{(2\pi)^4}\,\frac{5[k_\sigma\cdot(k-p)_\sigma]-2m^2}{(k_\sigma^2-m^2)((k-p)_\sigma^2-m^2)} \qquad \mathcal{K}_\sigma \equiv {\rm i}\int\frac{d^4k}{(2\pi)^4}\,\frac{17[k_\sigma\cdot(k-p)_{-\sigma}]-10m^2}{(k_\sigma^2-m^2)((k-p)_{-\sigma}^2-m^2)}$$

The photon production rate

$$g_{\mu\nu}\Pi^{\mu\nu} = -4q_f^2\mathcal{I} + q_f^2 \sum_{\sigma=\pm 1} \left[12\mathcal{J}_\sigma - 4\mathcal{K}_\sigma\right]$$

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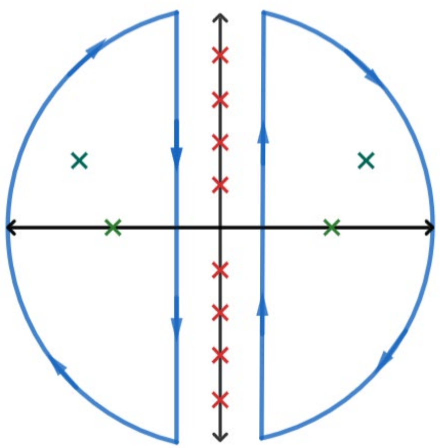

$$\mathcal{J}_\sigma = \mathrm{i}\int \frac{d^3k}{(2\pi)^3}\mathrm{i}\oint_C \frac{dz}{2\pi\mathrm{i}}\frac{1}{e^{\beta z}+1}\frac{5\left(z+\sigma\Omega/2\right)\left(z-\mathrm{i}\nu_l+\sigma\Omega/2\right)-5\mathbf{k}\cdot(\mathbf{k}-\mathbf{p})-2m^2}{\left[\left(z+\sigma\Omega/2\right)^2-E_k^2\right]\left[\left(z-\mathrm{i}\nu_l+\sigma\Omega/2\right)^2-E_{kp}^2\right]}$$

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Although the angular velocity defines a preferred direction in space, it does not break Lorentz symmetry in the sense of separating spatial momenta, as happens in the case of a magnetic field.

This is because the fermion propagator only experiences a shift in energy.

$$S(p) = \frac{\not{p}_+ + m_f}{p_+^2-m_f^2+\mathrm{i}\epsilon}\mathcal{O}^{(+)}+\frac{\not{p}_- + m_f}{p_-^2-m_f^2+\mathrm{i}\epsilon}\mathcal{O}^{(-)}$$

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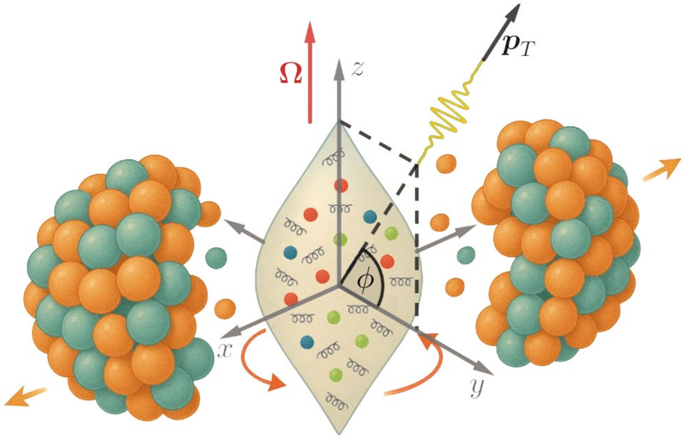


As a result, the yield remains angle-independent, and the flow coefficients are unaffected by this mechanism.

$$v_n = \frac{1}{\mathcal{R}_0}\int_0^{2\pi} d\phi\cos(n\phi)\frac{d^3R}{p_T dp_T d\phi dy}$$

The photon production rate

$$\lim_{\epsilon\to 0}\frac{1}{(A+\mathrm{i}\epsilon)(B+\mathrm{i}\epsilon)}=\mathrm{P.V.}\left(\frac{1}{AB}\right)-\mathrm{i}\pi\frac{\delta(A)}{B-A}+\mathrm{i}\pi\frac{\delta(B)}{B-A}$$

The photon production rate

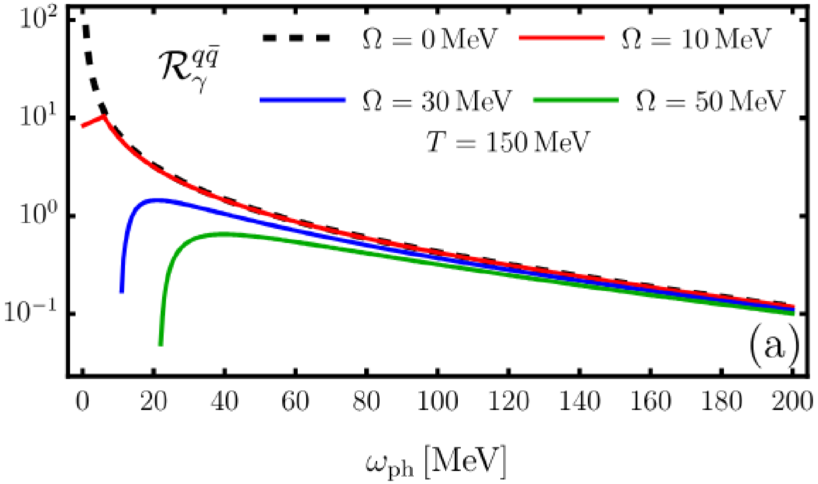
$$\lim_{\epsilon\to 0}\frac{1}{(A+\mathrm{i}\epsilon)(B+\mathrm{i}\epsilon)} = \mathrm{P.V.}\cancel{\left(\frac{1}{AB}\right)} - \mathrm{i}\pi\frac{\delta(A)}{B-A} + \mathrm{i}\pi\frac{\delta(B)}{B-A}$$

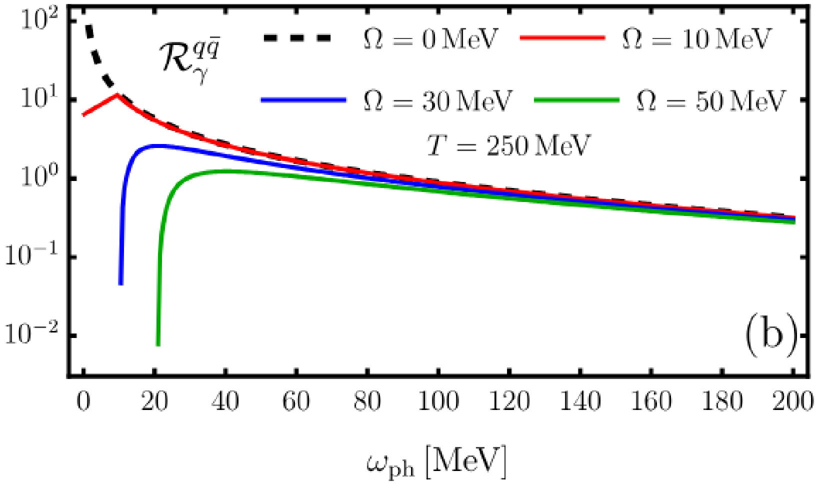
$$\begin{aligned}
\mathrm{Im}\left[\mathcal{J}_\sigma\right] &= -\frac{3m^2\pi}{4\omega_{\mathrm{ph}}(2\pi)^2}\sum_{s=\pm1}\int_m^\infty dE\Bigg\{\left(n_{\mathrm{F}}\left[\beta\left(sE-\frac{\sigma\Omega}{2}\right)\right]-n_{\mathrm{F}}\left[\beta\left(sE-\omega_{\mathrm{ph}}-\frac{\sigma\Omega}{2}\right)\right]\right)\Theta\left[E-s\omega_{\mathrm{ph}}-m\right] \\
&\quad -\left(n_{\mathrm{F}}\left[\beta\left(sE-\frac{\sigma\Omega}{2}\right)\right]-n_{\mathrm{F}}\left[\beta\left(-sE+\omega_{\mathrm{ph}}-\frac{\sigma\Omega}{2}\right)\right]\right)\Theta\left[-E+s\omega_{\mathrm{ph}}-m\right]\Bigg\}
\end{aligned}$$

$$\begin{aligned}
\mathrm{Im}\left[\mathcal{K}_\sigma\right] &= \frac{\pi}{4\omega_{\mathrm{ph}}(2\pi)^2}\left(\omega_{\mathrm{ph}}^2-(\omega_{\mathrm{ph}}+\sigma\Omega)^2+7m^2\right) \\
&\quad\times\sum_{s=\pm1}\int_m^\infty dE\Bigg\{\left(n_{\mathrm{F}}\left[\beta\left(sE-\sigma\frac{\Omega}{2}\right)\right]+n_{\mathrm{F}}\left[\beta(sE-\omega_{\mathrm{ph}}-\sigma\frac{\Omega}{2})\right]\right)\Theta\left[E-s\left(\omega_{\mathrm{ph}}+\sigma\Omega\right)-m\right] \\
&\quad -\left(n_{\mathrm{F}}\left[\beta\left(-sE-\sigma\frac{\Omega}{2}\right)\right]+n_{\mathrm{F}}\left[\beta\left(-sE-\omega_{\mathrm{ph}}-\sigma\frac{\Omega}{2}\right)\right]\right)\Theta\left[-E-s\left(\omega_{\mathrm{ph}}+\sigma\Omega\right)-m\right]\Bigg\}
\end{aligned}$$

The photon production rate

$$\Pi_R^{\mu\nu}(p^0 = \omega_{\rm ph}, \mathbf{p}) = \Pi^{\mu\nu}(\mathrm{i}\nu_n \to \omega_{\rm ph} + \mathrm{i}\epsilon, \mathbf{p})$$





$\Omega > 50$ MeV:
Violates causality

$30 < \Omega < 50$ MeV:
Just for comparison
(but allowed for
some previous
works)

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Vorticity and hydrodynamic helicity in heavy-ion collisions in the hadron-string dynamics model

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(Received 28 January 2015; revised manuscript received 23 April 2015; published 13 July 2015)

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Vorticity in heavy-ion collisions at the JINR Nuclotron-based Ion Collider fAcility

Yu. B. Ivanov[1,2,*] and A. A. Soldatov[2,†]
[1]*National Research Centre "Kurchatov Institute", Moscow 123182, Russia*
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(Received 10 January 2017; published 31 May 2017)

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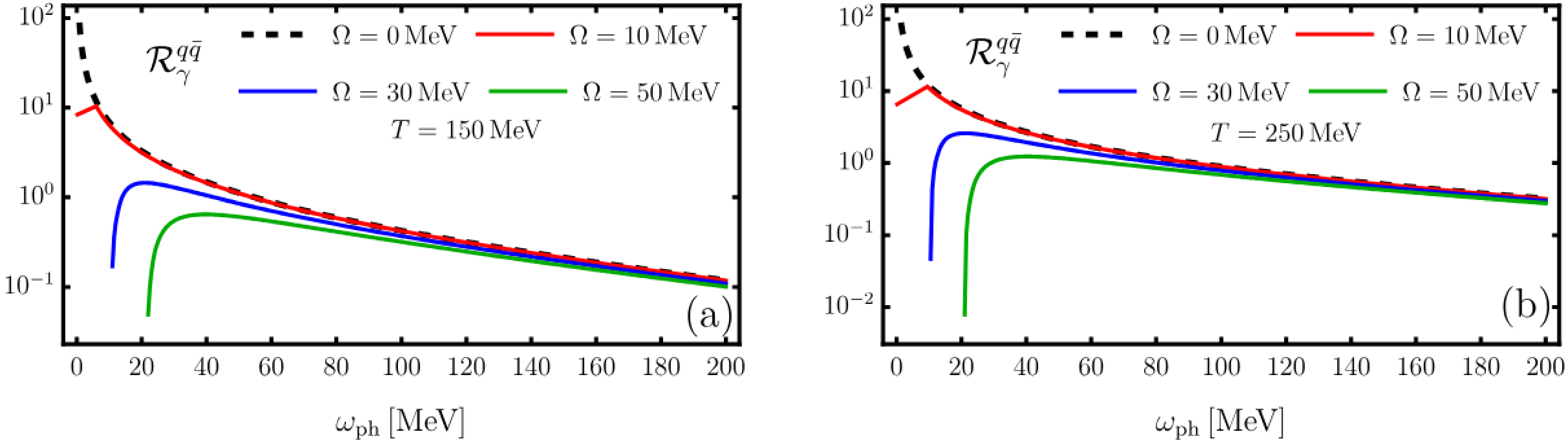

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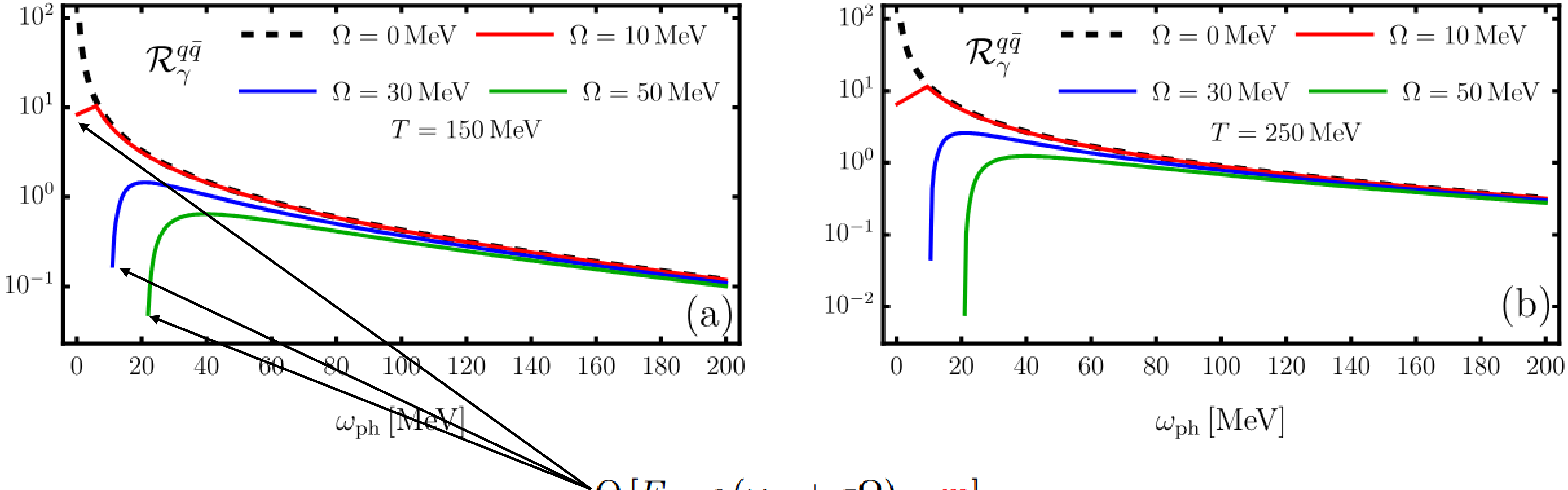
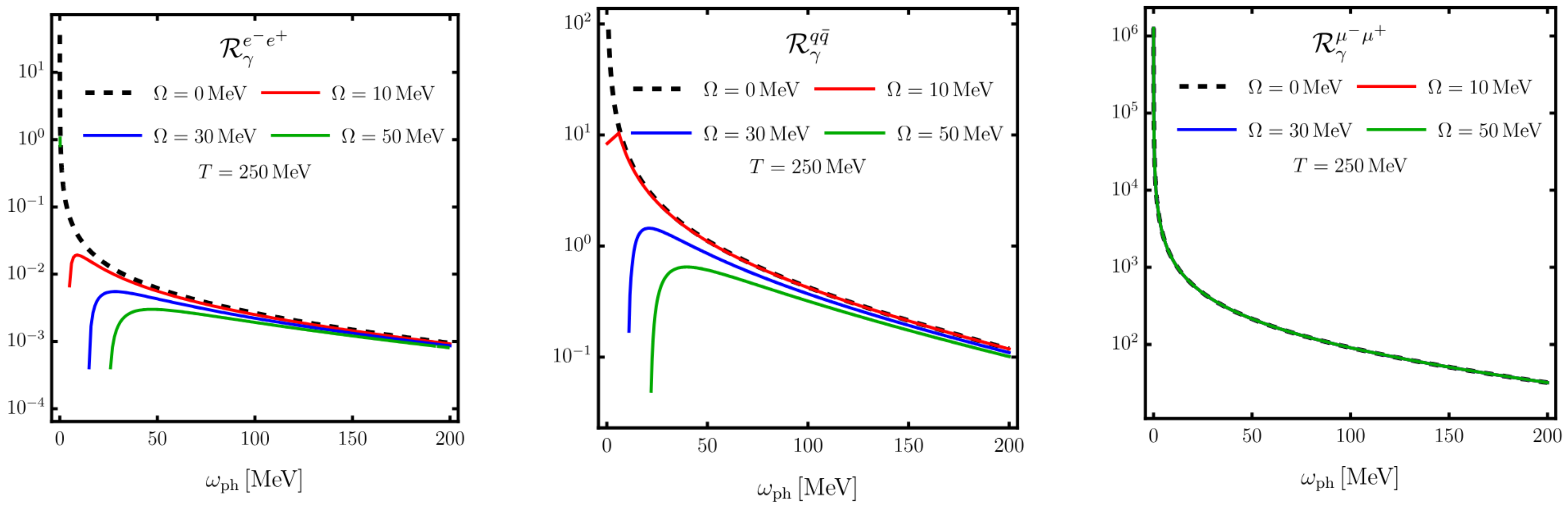


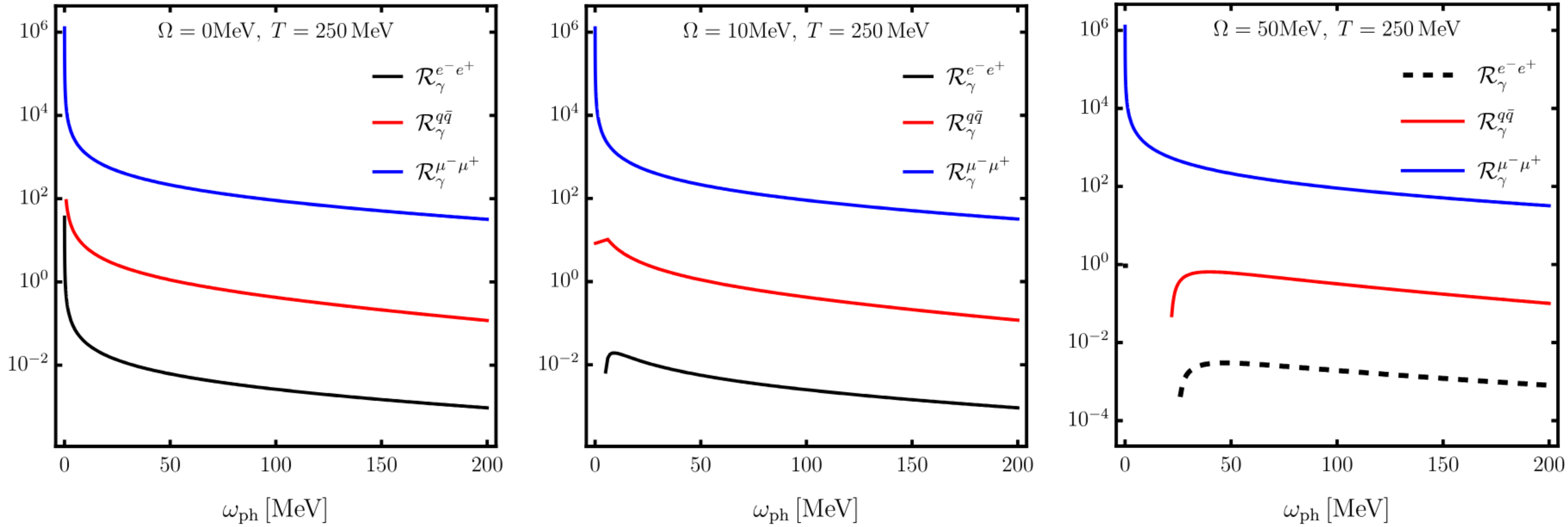
$$\Theta\left[E - s\left(\omega_{\rm ph} + \sigma\Omega\right) - m\right]$$

The photon production rate



The yield is affected by the parent particle’s mass, and the threshold shifts accordingly

The photon production rate



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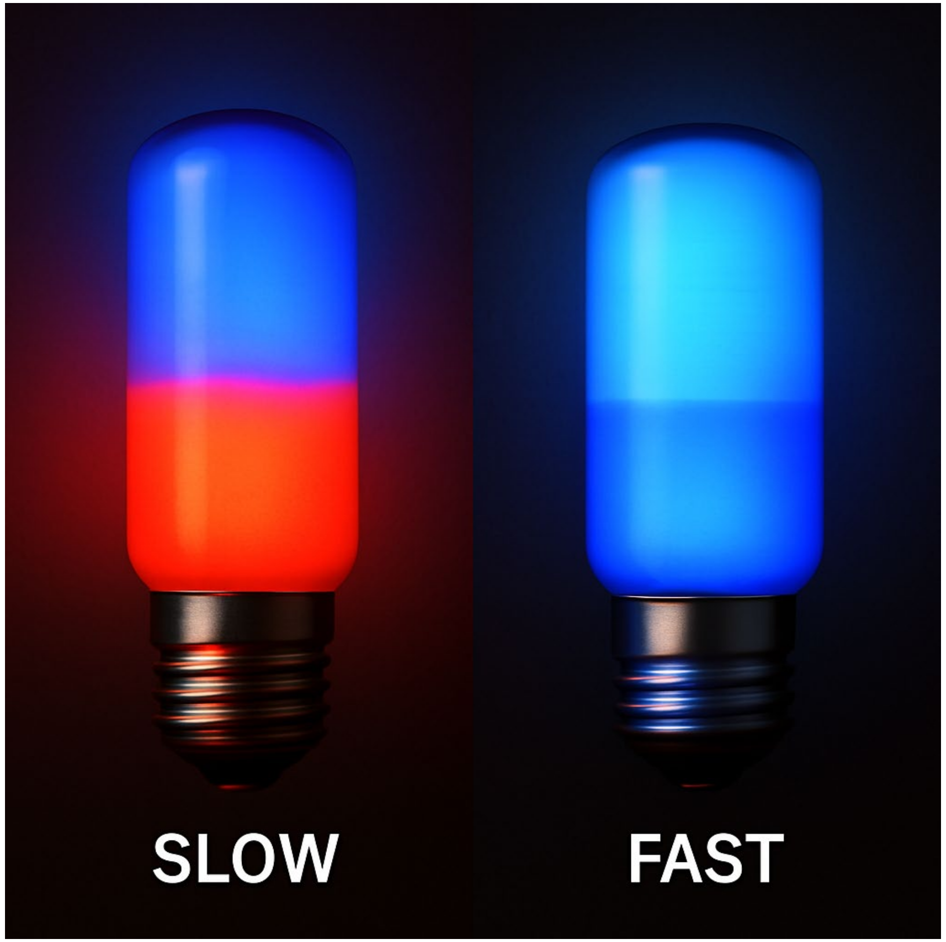

Conclusions and future work

- Under the rigid rotation approximation, vorticity enters as an effective chemical potential.
- Within the same approximation, rapid rotation can suppress low-energy photon production.
- For phenomenological values of angular vorticity, the deviations from the non-rotating case are almost negligible.
- The rigid rotation approximation should be relaxed to capture more realistic dynamics.
- The system's geometry should be generalized beyond the cylindrical configuration.