Electromagnetic probes as messengers of Quark-Gluon Plasma

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ULAM NAWA

Workshop on recent developments from QCD to Nuclear matter
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Institute of Physics, Academia Sinica

Outline

1. How light (dileptons, photons) escapes to tell the story?
2. What have we learned and what remains mysterious?

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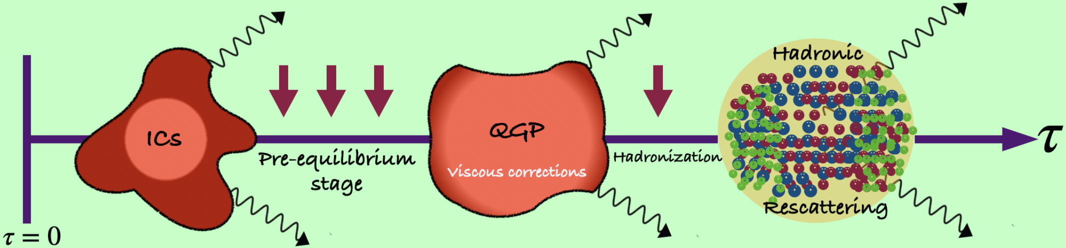
Electromagnetic Probes

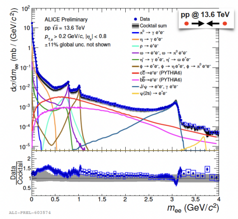


Electromagnetic probes, i.e. Dileptons, Photons are uniquely built

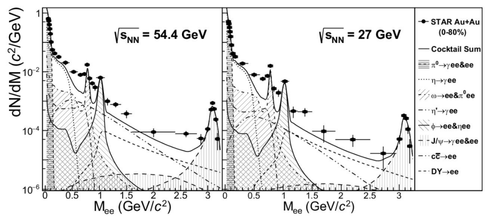
- Carries information from all the important stages of Heavy-Ion-Collisions.
- No strong interaction.
- Mean free path in medium > medium size.
- Escape the medium virtually unscathed.

Experimental measurements of Dilepton Spectra

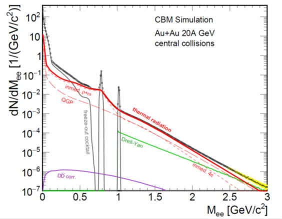
Alice



STAR



CBM



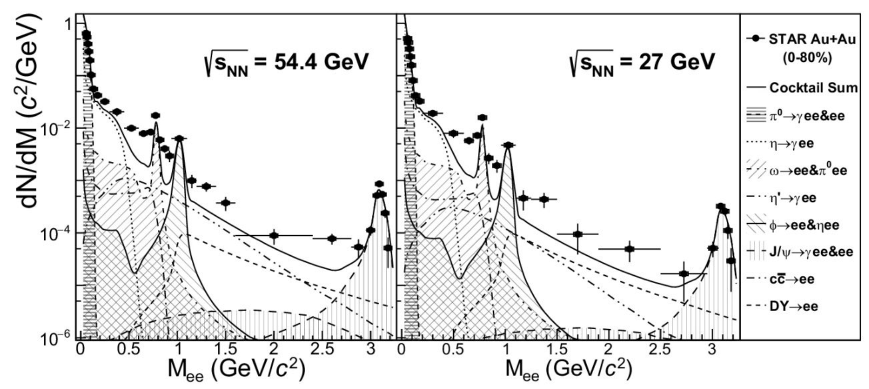
Differentiating between prompt and non-prompt sources

Probing the dense sector of the QCD Phase diagram

Focussing on different aspects of dilepton spectra!

Experimental measurements of Dilepton Spectra

✍[STAR, Nat. Commun. 16, 9098 (2025)]



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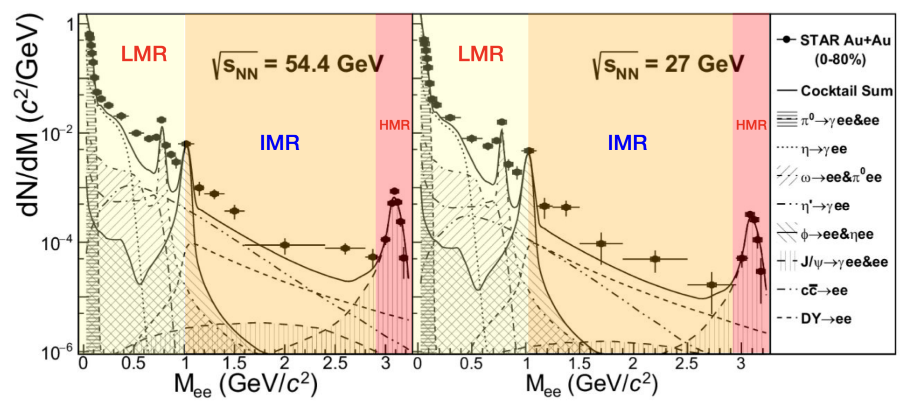


Low Mass Region (LMR)

- Th. emission from hadrons
- Hadronic decays $(\rho/\omega/\phi)$

Intermediate Mass Region (IMR)

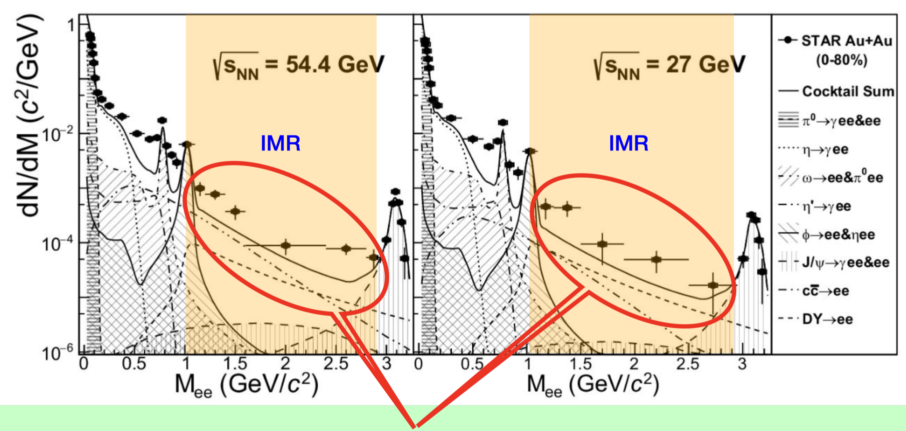
- Thermal emission from QGP
- Miscellaneous contributions

High Mass Region (HMR)

- Drell-Yan processes
- Decays of J/ψ

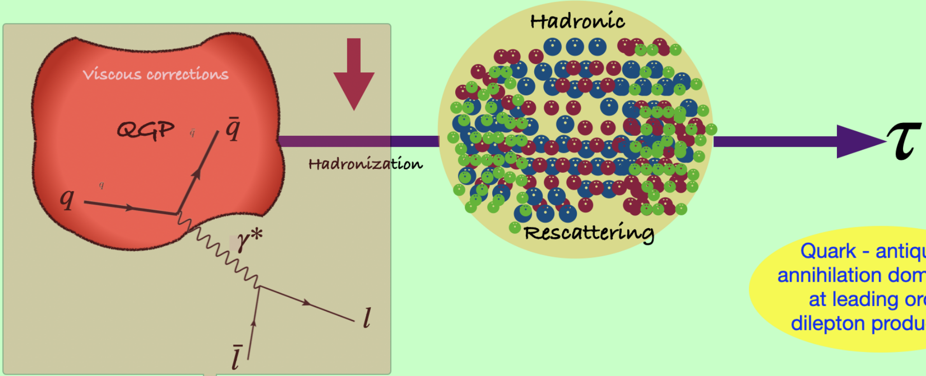
Experimental measurements of Dilepton Spectra

✍[STAR, Nat. Commun. 16, 9098 (2025)]



Clear excesses of experimental data
observed for Intermediate Mass Dileptons

Thermal emission of dileptons from QGP

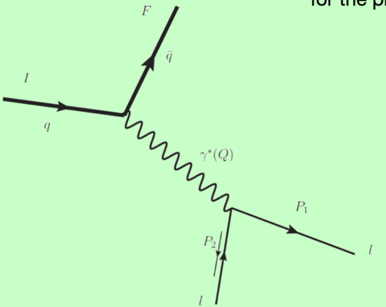


Quark - antiquark annihilation dominates at leading order dilepton production

$$\frac{dN}{d^4Q d^4X} \equiv$$ Dilepton Rate (Static/snapshot property) $\xrightarrow{\text{Spacetime evolution}}$ Dilepton Spectra (Dynamic property) $$\equiv \frac{dN}{d^4Q}$$

Evaluation of Dilepton Rate - Formal approach

✍ McLerran and Toimela, PRD 31 (1985) ; Weldon, PRD 42 (1990)



The thermally averaged dilepton multiplicity in the local rest frame of the plasma for the process $I \to l(P_2)\bar{l}(P_1) + F$

Emission amplitude — Thermal weight — Phase space

$$N = \sum_I \sum_F \left| \langle F, l(P_1), \bar{l}(P_2) \,|\, S \,|\, I \rangle \right|^2 \frac{e^{-\beta E_I}}{Z} \frac{V d^3p_1}{(2\pi)^3} \frac{V d^3p_2}{(2\pi)^3},$$

$$\langle F, l(P_1), \bar{l}(P_2) \,|\, S \,|\, I \rangle = \frac{e_0 \, \bar{u}(P_2)\gamma_\mu v(P_1)}{V\sqrt{4E_1E_2}} \int d^4x \, e^{iq\cdot x} \langle F \,|\, A^\mu(x) \,|\, I \rangle,$$

$$N = e_0^2 \; L_{\mu\nu} \; \mathscr{M}^{\mu\nu} \; \frac{d^3p_1}{E_1(2\pi)^3} \frac{d^3p_2}{E_2(2\pi)^3}$$

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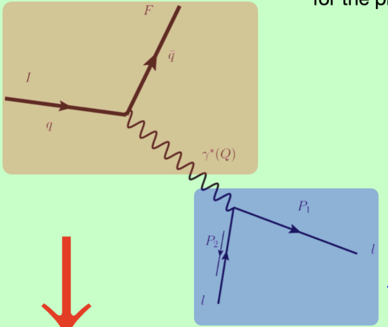

The thermally averaged dilepton multiplicity in the local rest frame of the plasma for the process $I \to l(P_2)\bar{l}(P_1) + F$

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$$\langle F, l(P_1), \bar{l}(P_2)\,|\,S\,|\,I\rangle = \frac{e_0\ \bar{u}(P_2)\gamma_\mu v(P_1)}{V\sqrt{4E_1E_2}} \int d^4x\ e^{iq\cdot x}\ \langle F\,|\,A^\mu(x)\,|\,I\rangle,$$

$$N = e_0^2\ L_{\mu\nu}\ \mathcal{M}^{\mu\nu}\ \frac{d^3p_1}{E_1(2\pi)^3}\frac{d^3p_2}{E_2(2\pi)^3}$$

$$L_{\mu\nu} = \frac{1}{4}\mathrm{Tr}\left[\bar{u}(P_2)\gamma_\mu v(P_1)\bar{v}(P_1)\gamma_\nu u(P_2)\right] = P_{1\mu}P_{2\nu} + P_{1\nu}P_{2\mu} - (P_1\cdot P_2 + m_l^2)g_{\mu\nu}$$

$$\mathcal{M}^{\mu\nu} = \sum_F \sum_I \int d^4x d^4y\ e^{iq\cdot(x-y)}\langle F\,|\,A^\mu(x)\,|\,I\rangle \times \frac{1}{Z}\langle I\,|\,\hat{\rho}\ A^\nu(y)\,|\,F\rangle$$

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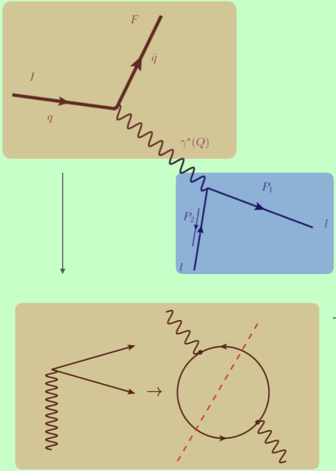

$$\mathcal{M}^{\mu\nu} = \sum_F \sum_I \int d^4x\, d^4y\, e^{iq\cdot(x-y)} \langle F|A^\mu(x)|I\rangle \times \frac{1}{Z}\langle I|\hat{\rho}\, A^\nu(y)\, \hat{\rho}^{-1}\hat{\rho}|F\rangle$$

$$= \int d^4x\, d^4y\, e^{iq\cdot(x-y)} \sum_F \langle F|A^\mu(x)\, A^\nu(y_0 + i\beta, \mathbf{y})\, \hat{\rho}|F\rangle \frac{1}{Z}$$

$$= e^{-\beta q_0} \int d^4x\, d^4y\, e^{iq\cdot(x-y)} \sum_F \langle F|A^\mu(x) A^\nu(y)|F\rangle \frac{e^{-\beta E_F}}{Z}$$

$$= 2\pi\, e^{-\beta q_0}\, \Omega \boxed{\int \frac{d^4x}{2\pi}\, e^{iq\cdot x} \sum_F \langle F|A^\mu(x) A^\nu(0)|F\rangle \frac{e^{-\beta E_F}}{Z}}$$

$$\rho^{\mu\nu}(q) = -\frac{1}{\pi}\, \frac{e^{\beta q_0}}{e^{\beta q_0} - 1}\, \frac{e_f^2}{q^4}\, \mathrm{Im}\left[C^{\mu\nu}(q)\right]$$

$$\frac{dN}{d^4x d^4q} = \frac{\alpha_{em}}{12\pi^3} \frac{e_f^2}{q^2} \frac{1}{e^{\beta q_0} - 1} \sum_{f=u,d} \frac{1}{\pi} \mathrm{Im}\, C^\mu_{\mu,f}(q)$$

$$C^\mu_\mu(q) = \int d^4x\, e^{iq\cdot x}\, \mathrm{Tr}_{Dfc}\left[\gamma^\mu\, S(x,0)\, \gamma_\mu\, S(0,x)\right]$$

Evaluation of Dilepton Rate - Formal approach

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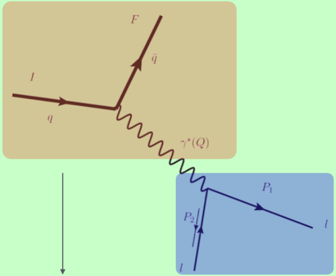

$$\mathcal{M}^{\mu\nu} = \sum_F \sum_I \int d^4x\, d^4y\, e^{iq\cdot(x-y)} \langle F|A^\mu(x)|I\rangle \times \frac{1}{Z} \langle I|\hat{\rho}\, A^\nu(y)\, \hat{\rho}^{-1}\hat{\rho}|F\rangle$$

$$= \int d^4x\, d^4y\, e^{iq\cdot(x-y)} \sum_F \langle F|A^\mu(x)\, A^\nu(y_0 + i\beta, \mathbf{y})\, \hat{\rho}|F\rangle \frac{1}{Z}$$

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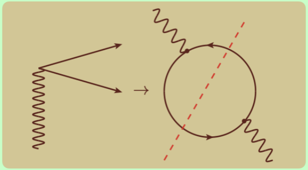
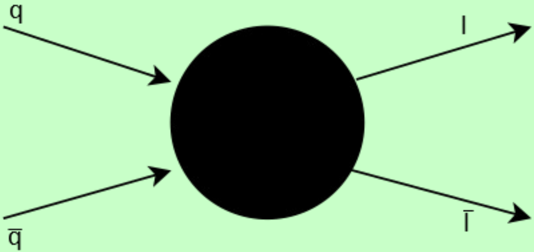


$$\frac{dN}{d^4x d^4q} = \frac{\alpha_{em}}{12\pi^3} \frac{e_f^2}{q^2} \frac{1}{e^{\beta q_0} - 1} \sum_{f=u,d} \frac{1}{\pi}\, \mathrm{Im}\, C^\mu_{\mu,f}(q)$$

$$\left[C^\mu_\mu\right]^*(q) = \int d^4x\, e^{iq\cdot x}\, \mathrm{Tr}_{Dfc}\left[\gamma^\mu\, S^*(x,0)\, \gamma_\mu\, S^*(0,x)\right]$$

Evaluation of Dilepton Rate - Kinetic Theory approach

✍ Kajantie, Kapusta, McLerran, and Mekjian, PRD 34 (1986).



$$\frac{dN}{d^4x d^4q} = \int \frac{d^3\mathbf{p_1}}{(2\pi)^3} f_q(\mathbf{p_1}) \int \frac{d^3\mathbf{p_2}}{(2\pi)^3} f_{\bar{q}}(\mathbf{p_2})\ \sigma_{q\bar{q}\to l\bar{l}}\ v_{q\bar{q}}\ \delta^4(p_1 + p_2 - q)$$

Evaluation of Dilepton Rate - Kinetic Theory approach

$$\frac{dN}{d^4x d^4q} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3} f_q(\mathbf{p}_1) \int \frac{d^3\mathbf{p}_2}{(2\pi)^3} f_{\bar{q}}(\mathbf{p}_2)\, \sigma_{q\bar{q}\to l\bar{l}}\, v_{q\bar{q}}\, \delta^4(p_1 + p_2 - q)$$

Phase space: $\int \frac{d^3\mathbf{p}_1}{(2\pi)^3}$, $\int \frac{d^3\mathbf{p}_2}{(2\pi)^3}$; Distribution function: $f_q(\mathbf{p}_1)$, $f_{\bar{q}}(\mathbf{p}_2)$; Cross section: $\sigma_{q\bar{q}\to l\bar{l}}$; Relative velocity: $v_{q\bar{q}}$; Energy-momentum conservation: $\delta^4(p_1 + p_2 - q)$

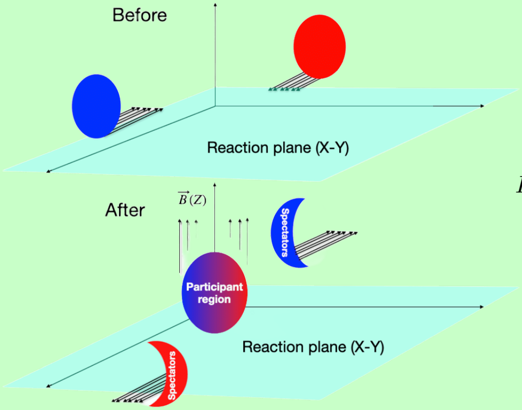
Born Rate : Formal Approach $\equiv$ Kinetic Theory Approach

Born Rate ++ : Formal Approach (Exact) $\neq$ Kinetic Theory Approach (Ansatz-based)

Outline

1. How light (dileptons, photons) escapes to tell the story?
2. What have we learned and what remains mysterious?

Adding the effect of external background magnetic field



Non-central Heavy-Ion Collisions

$$\mathcal{L} = \bar{\psi}\left[i\gamma^{\mu}(\partial_{\mu} + ieA_{\mu}) - m\right]\psi$$

$$S_m(K) = e^{-\frac{k_{\perp}^2}{|q_f B|}} \sum_{l=0}^{\infty} \frac{(-1)^l D_l(q_f B, K)}{K_{\shortparallel}^2 - M^2 - 2lq_f B}$$

$$D_l(q_f B, K) = (\gamma_\mu K_{\shortparallel}^{\mu} + M)\left((1 - i\gamma^1\gamma^2)L_l\left(\frac{2k_{\perp}^2}{q_f B}\right) - (1 + i\gamma^1\gamma^2)L_{l-1}\left(\frac{2k_{\perp}^2}{q_f B}\right)\right) - 4(\gamma\cdot k)_{\perp} L_{l-1}^1\left(\frac{2k_{\perp}^2}{q_f B}\right)$$

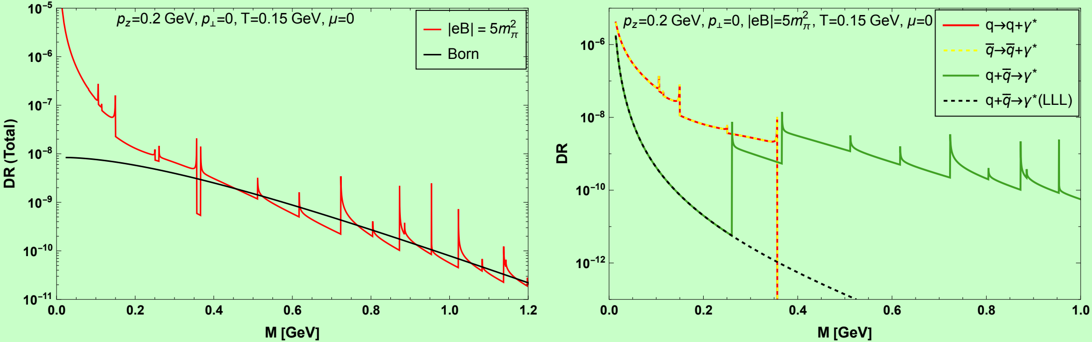
$$S_m^{LLL}(K) = e^{-\frac{k_{\perp}^2}{|q_f B|}} \frac{(\gamma_\mu K_{\shortparallel}^{\mu} + M)}{K_{\shortparallel}^2 - M^2}(1 - i\gamma^1\gamma^2)$$

$K^{\mu} \equiv (K_{\shortparallel}^{\mu}, k_{\perp}^{\mu})$ with $K_{\shortparallel}^{\mu} = (k^0, 0, 0, k^z)$ and $k_{\perp}^{\mu} = (0, k^x, k^y, 0)$
$K^2 = K_{\shortparallel}^2 - k_{\perp}^2$, i.e. $K_{\shortparallel}^2 = k_0^2 - k_z^2$ and $k_{\perp}^2 = k_x^2 + k_y^2$

✍ Schwinger, Phys. Rev. 82 (1951)

Result: Enhancement !

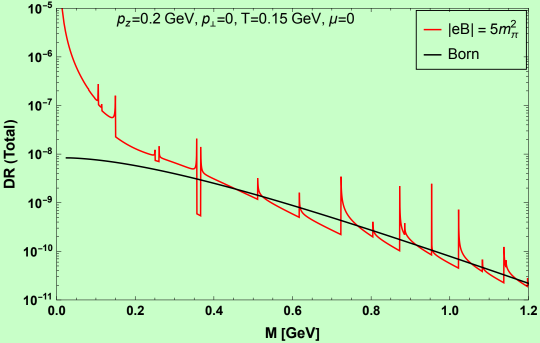
✍ Bandyopadhyay et. al., PRD 94 (2016), PRD 106 (2022)

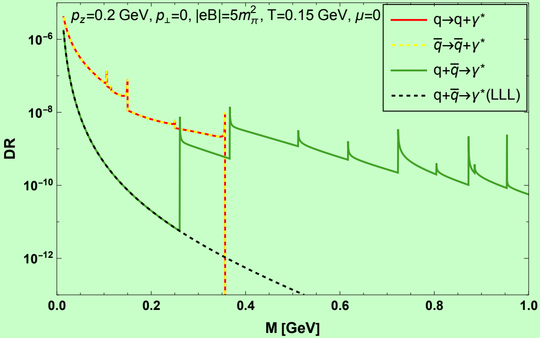


Dilepton Rate as a function of invariant mass M for an arbitrary external magnetic field (left panel). Separate contributions coming from different processes along with the LLL approximated rate in the black dashed line (right panel).

Result: Enhancement !

✍ Bandyopadhyay et. al., PRD 94 (2016), PRD 106 (2022)





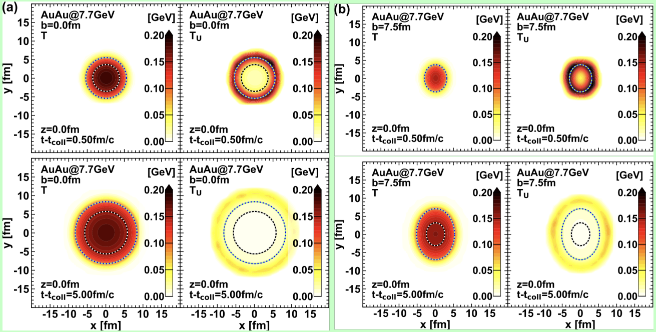
1. Significant enhancement in the lower invariant mass regime due to contributions from the decay processes.
2. Lowest Landau Level approximated result exactly matches with the general result.

Adding the effect of local acceleration

Unruh effect : an observer detects an apparent thermal radiation in an uniformly accelerated frame - $T_U = \frac{a}{2\pi}$.

Ultra-relativistic heavy Ion collisions $\rightarrow$ Large acceleration immediately after the collisions $\rightarrow$ Perfect place to test the effect due to acceleration

✍ Castorina, Kharzeev and Satz, EPJC 52 (2007).



✍ Prokhorov et. al., 2502.10146

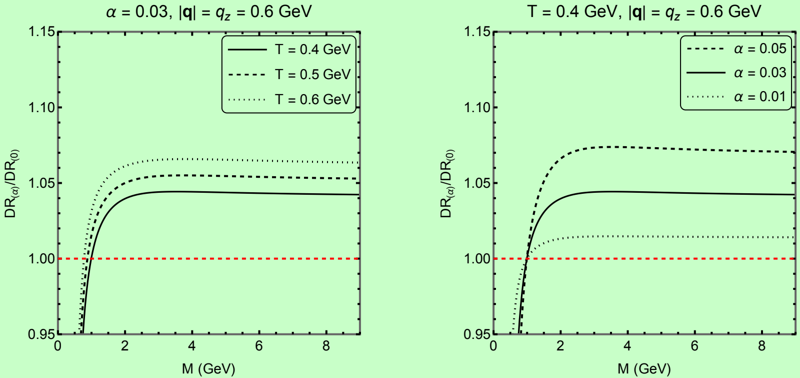
Perturbatively expanded fermion propagator in the limit of weak acceleration $a = \alpha T$:

$$S_E^{(\alpha)}(X, \Delta x) = S_E^0(\Delta x) + \alpha\, S_E^1(X, \Delta x) + \mathcal{O}[\alpha^2] \qquad X = \frac{x + x'}{2},\ \Delta x = x - x'$$

✍ Ambruș and Chernodub, PLB 855 (2024)

Result : Enhancement!

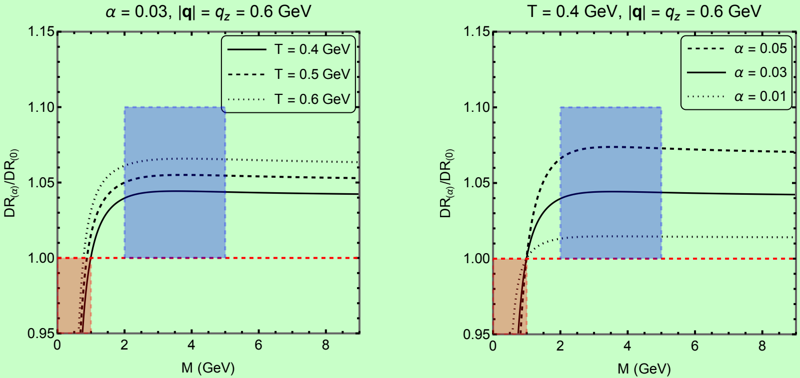
✍ Bandyopadhyay, Kundu, Ambruș and Chernodub - JSPC 5 (2026)



DR as a function of invariant mass for a weakly accelerating medium ($\text{DR}_{(\alpha)}$) is shown in comparison with the Born dilepton rate ($\text{DR}_{(0)}$). With varying T (left panel) and varying α (right panel).

Result : Enhancement!

✍ Bandyopadhyay, Kundu, Ambruș and Chernodub - JSPC 5 (2026)



1. Significant enhancement in the intermediate invariant mass regime.
2. Very low invariant mass → Weak acceleration expansion is not reliable.

What have we learned?

- Electromagnetic probes such as dileptons and photons provide untainted insights into the different phases of a heavy-ion collision.
- An excess of dileptons observed experimentally in the intermediate invariant mass region points to the need for improved theoretical modelling of thermal dilepton production from the QGP phase, incorporating effects such as magnetic fields, and acceleration.
- For both magnetised and accelerating medium, we found encouraging enhancements in the static thermal dilepton production rate, prompting further explorations in these directions.

What remains mysterious?

Dilepton Rate : Extension to arbitrary values of acceleration,
Incorporation of other effects such as isospin asymmetry, rotation, electric fields etc.

Dilepton spectra : Spacetime evolution of the dilepton production rate.

$$\frac{dN}{dM} = \int d^4x \frac{d^3q\ M}{q_0} \left(\frac{dN}{d^4x\ d^4q} \right)$$

with the natural framework of relativistic hydrodynamics.

For magnetised medium : Progress has been made,
✍**[Panda, Das, Dash, Bandyopadhyay, Islam. 2508.15035]**

Collaborators

Magnetic ones

Prof. Munshi G Mustafa

Chowdhury Aminul Islam

Aritra Das

Accelerating ones

Prof. Maxim N Chernodub

Prof. Victor E Ambruș

Moulindu Kundu

Thanksgiving

Thank you for your kind attention