The Photon/Gluon Polarization Tensor in a Fluctuating Magnetic Field Background

Jorge David Castaño Yepes

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In collaboration with:

Enrique Muñoz and Marcelo Loewe

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PRELIMINARY

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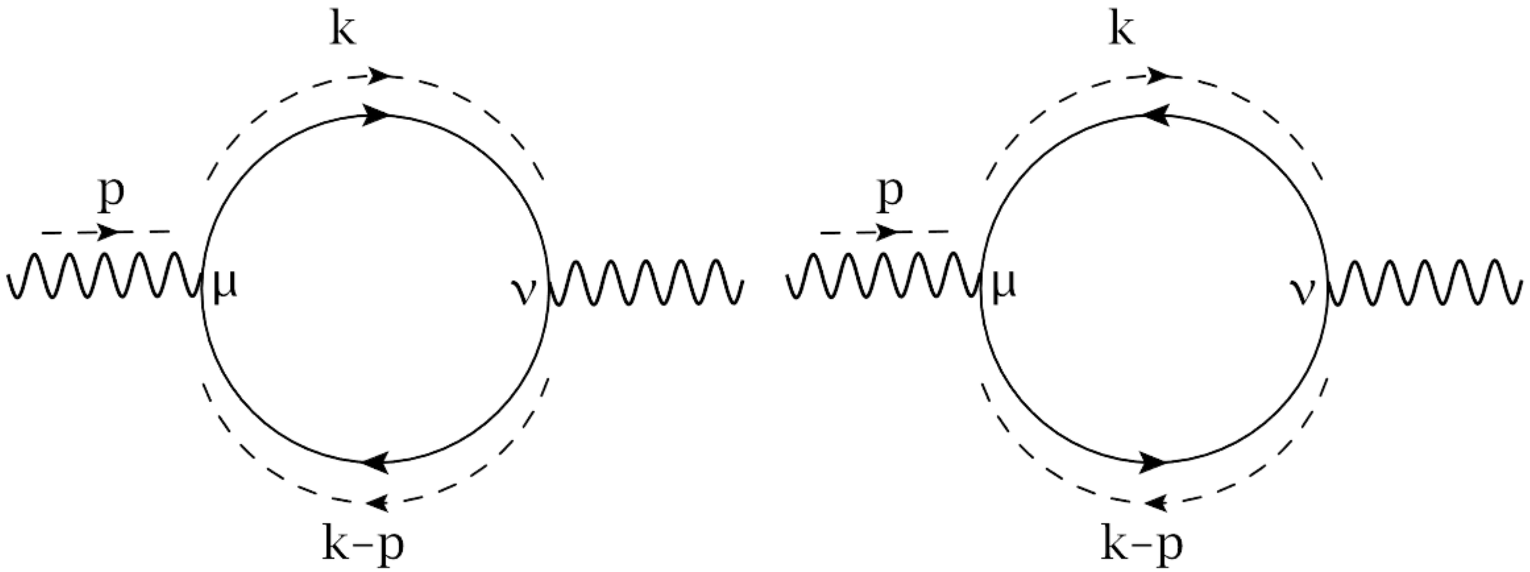
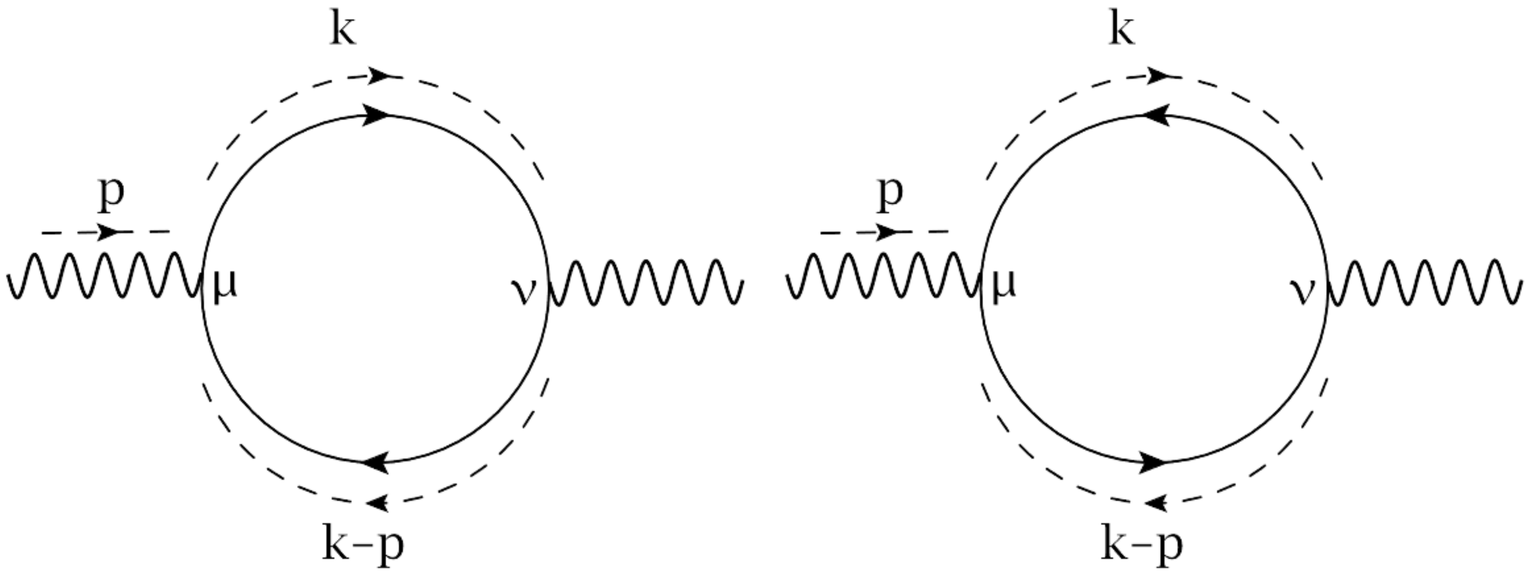
Outline

- Why this?
- The Replica formalism (again)
- The Photon/Gluon Polarization Tensor in a Fluctuating Magnetic Field Background
- Conclusions

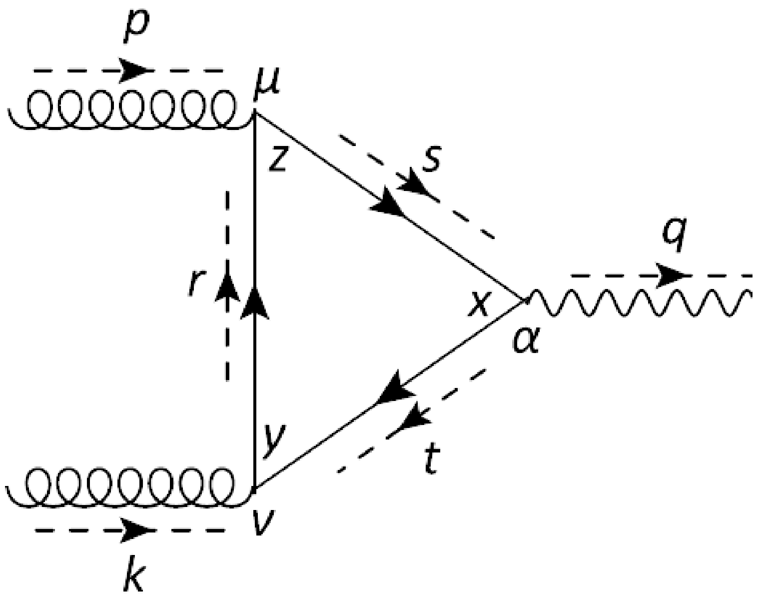
Why this?

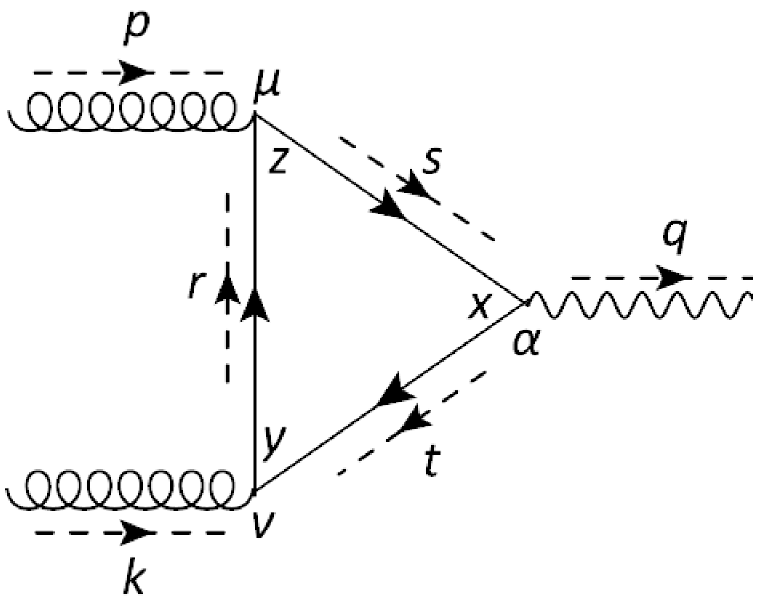


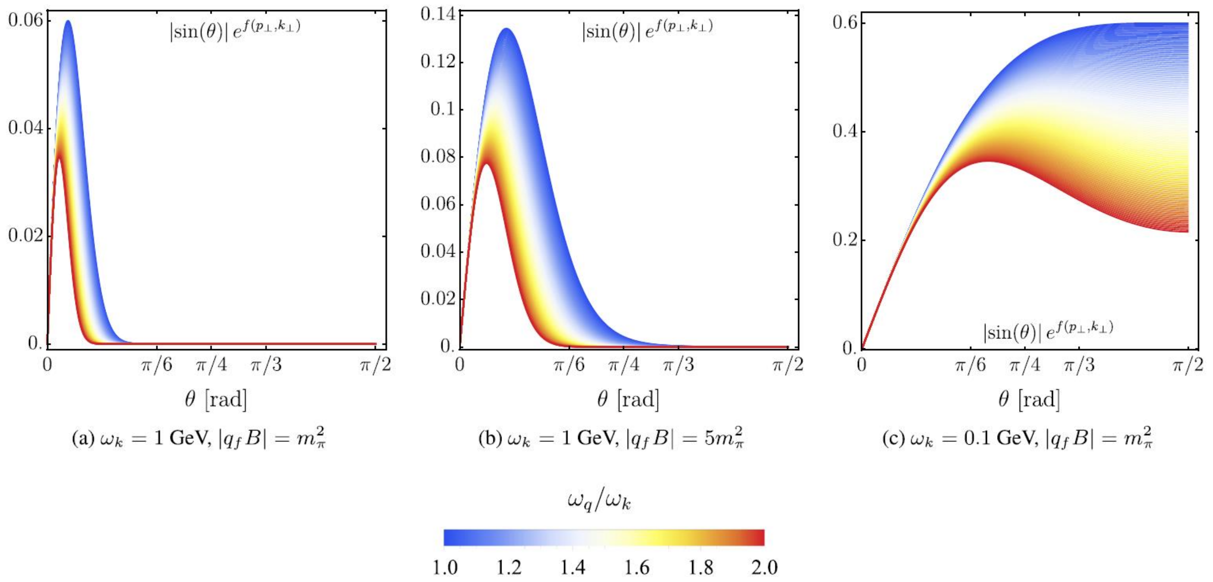
Why this?



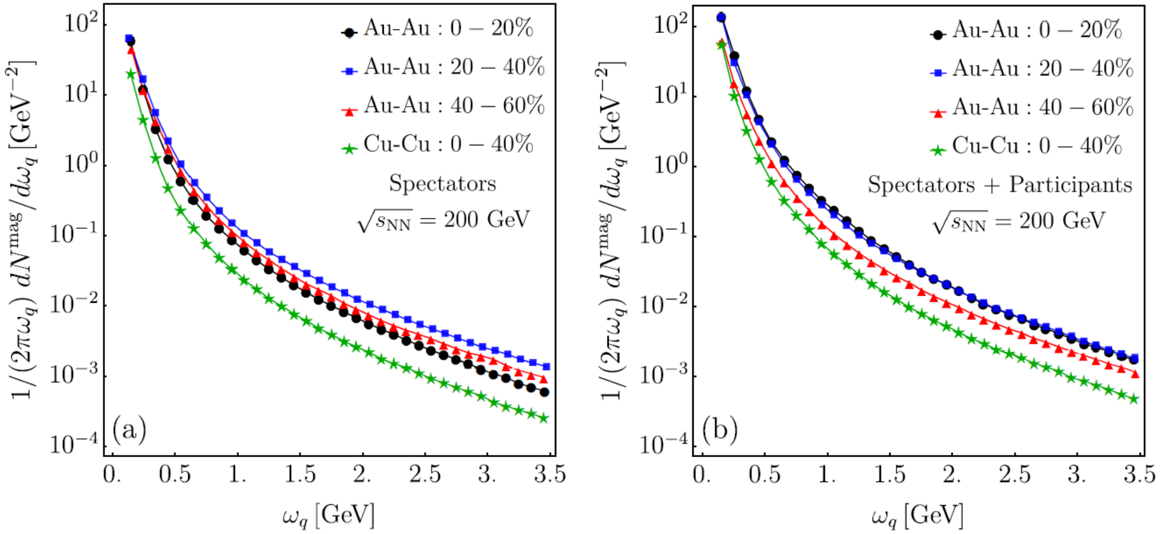
Because this

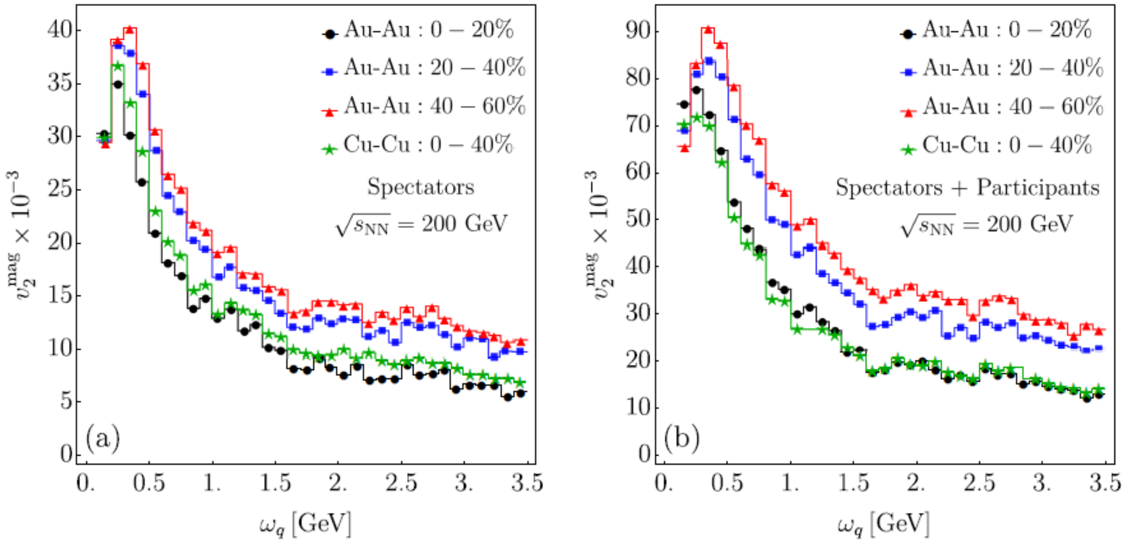




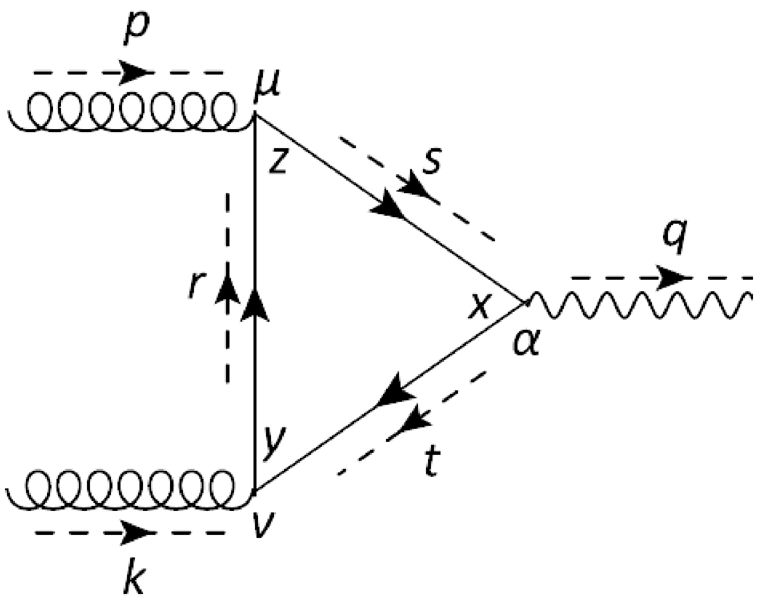


(a) $\omega_k = 1$ GeV, $|q_f B| = m_\pi^2$ (b) $\omega_k = 1$ GeV, $|q_f B| = 5m_\pi^2$ (c) $\omega_k = 0.1$ GeV, $|q_f B| = m_\pi^2$





$$p^\mu = \left(\frac{\omega_p}{\omega_q}\right) q^\mu, \quad k^\mu = \left(\frac{\omega_k}{\omega_q}\right) q^\mu, \quad \rightarrow \sigma_{gg} \propto \frac{1}{\mathbf{p}_1 - \mathbf{p}_2}$$

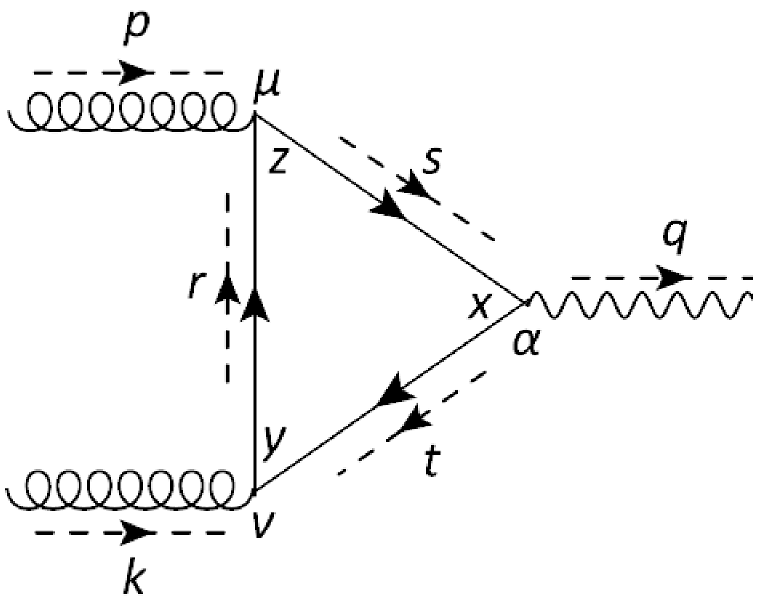


$$k^\mu = \left(\frac{\omega_k}{\omega_q}\right) q^\mu,$$

$$p^\mu = \left(\frac{\omega_p}{\omega_q}\right) q^\mu,$$

Can photons/gluons develop a magnetic mass?

$$\text{angle}(p^\mu, k^\mu) \neq 0$$



$$k^{\mu} = \left(\frac{\omega_k}{\omega_q}\right) q^{\mu},$$

$$p^{\mu} = \left(\frac{\omega_p}{\omega_q}\right) q^{\mu},$$

Can photons/gluons develop a magnetic mass?

$$\text{angle}(p^{\mu}, k^{\mu}) \neq 0$$

Effects of Intense Magnetic Fields, High Temperature and Density on QCD-Related Phenomena

Jorge David Castaño-Yepes

The effects of high-temperature, dense systems, and strong magnetic fields on Quantum Chromodynamics related phenomena are studied in different perspectives: in the high-temperature and densities, the QCD-phase diagram from the Linear Sigma Model point of view is computed. In particular, the CEP location and transition lines for chiral restoration were found. In the intense magnetic fields and high-gluon density, the gluon fusion and gluon splitting channels are proposed as new photon production sources to better explain the experimental data in the so-called "photon puzzle". Finally, the thermal and magnetic screening properties for gluons encoded into the polarization tensor were addressed in terms of the Debye mass.

Comments: Ph.D. Thesis. 183 pages. Tittle and some typos corrected
Subjects: **High Energy Physics - Phenomenology (hep-ph)**
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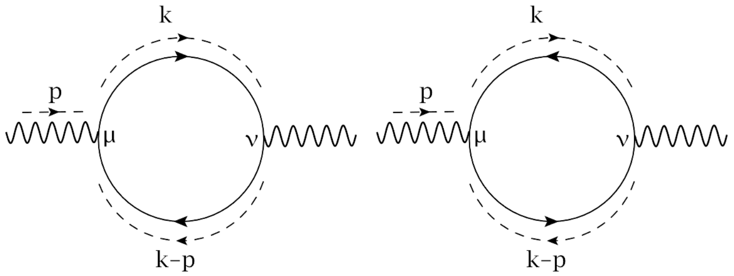
(or arXiv:2103.12898v2 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2103.12898



In a presence of B

- It played a central role in our research
- We didn't find such a mass
- Are there other mechanism to generate it?

PHYSICAL REVIEW D **101**, 036016 (2020)

Gluon polarization tensor in a magnetized medium: Analytic approach starting from the sum over Landau levels

Alejandro Ayala,[1,2] Jorge David Castaño-Yepes,[1,*] M. Loewe,[3,2,4] and Enrique Muñoz[3,5]

Eur. Phys. J. A (2021) 57:140
https://doi.org/10.1140/epja/s10050-021-00429-4
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Regular Article - Theoretical Physics

Gluon polarization tensor and dispersion relation in a weakly magnetized medium

Alejandro Ayala[1,2], Jorge David Castaño-Yepes[1], L. A. Hernández[1,2,3,4,a], Jordi Salinas San Martín[1], R. Zamora[5,6]

Revista Mexicana de Física **66** (4) 446–461 JULY-AUGUST 2020

Thermal corrections to the gluon magnetic Debye mass

Alejandro Ayala[a,b], Jorge David Castaño-Yepes[a], C. A. Dominguez[b], S. Hernández-Ortiz[a], L. A. Hernández[a,b], M. Loewe[b,c,d], D. Manreza Paret[e] and R. Zamora[f,g]

PHYSICAL REVIEW D **107**, 096014 (2023)

The Replica formalism

QED fermions in a noisy magnetic field background

Jorge David Castaño-Yepes,[1,*] Marcelo Loewe,[1,2,3,4,†] Enrique Muñoz,[1,5,‡] Juan Cristóbal Rojas,[6,§] and Renato Zamora[7,8,∥]

$$A^{\mu}(x) \to A^{\mu}(x) + A^{\mu}_{\mathrm{BG}}(x) + \delta A^{\mu}_{\mathrm{BG}}(\mathbf{x}).$$

$$\overline{\ln Z[A]} = \lim_{n\to 0} \frac{\overline{Z^n[A]} - 1}{n}.$$

$$\langle \delta A^{j}_{\mathrm{BG}}(\mathbf{x}) \delta A^{k}_{\mathrm{BG}}(\mathbf{x}') \rangle = \Delta_B \delta_{j,k} \delta^3(\mathbf{x} - \mathbf{x}'),$$
$$\langle \delta A^{\mu}_{\mathrm{BG}}(\mathbf{x}) \rangle = 0.$$

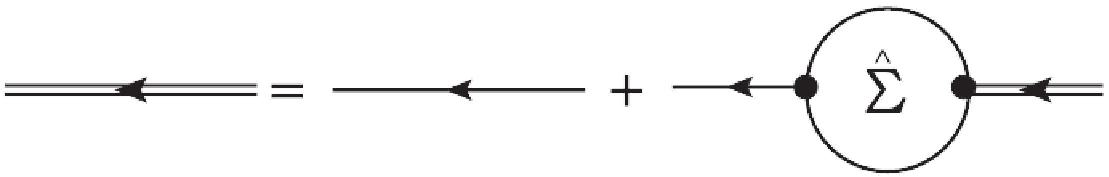
$$\bar{S}[\bar{\psi}^a, \psi^a; A] = \int d^4x \left(\sum_a \bar{\psi}^a (i\partial\!\!\!/ - e A\!\!\!/_{\mathrm{BG}} - e A\!\!\!/ - m)\psi^a - \frac{1}{4} F_{\mu\nu}F^{\mu\nu} \right)$$
$$+ i \frac{e^2 \Delta_B}{2} \int d^4x \int d^4y \sum_{a,b} \sum_{j=1}^{3} \bar{\psi}^a(x)\gamma^j \psi^a(x) \bar{\psi}^b(y) \gamma_j \psi^b(y) \delta^3(\mathbf{x} - \mathbf{y}).$$

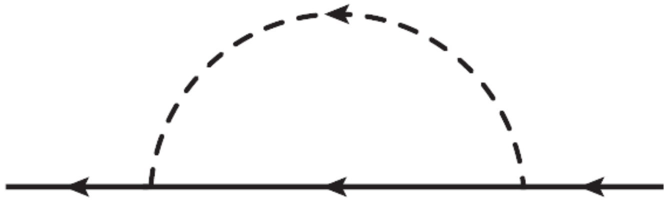
The Replica formalism

PHYSICAL REVIEW D **107,** 096014 (2023)

QED fermions in a noisy magnetic field background

Jorge David Castaño-Yepes,[1,*] Marcelo Loewe,[1,2,3,4,†] Enrique Muñoz,[1,5,‡] Juan Cristóbal Rojas,[6,§] and Renato Zamora[7,8,∥]





SELF-ENERGY AT ORDER Δ

$$iS_{\Delta}^{(\pm)}(p) = C(p)\left(m + \gamma_0 p^0 + \frac{\gamma_3 p^3}{z(p)}\right)\mathcal{P}^{(\pm)}(p)$$

$$C(p) = i\frac{z(p)\, e^{-\mathbf{p}_\perp^2/|qB|}}{p_\parallel^2 - z^2(p)m^2},$$

$$z(p) = 1 + \frac{3}{4}\frac{\Delta|qB|e^{-\mathbf{p}_\perp^2/|qB|}}{\pi\sqrt{p_0^2 - m^2}}$$

$$z_3(p) = \frac{1}{z(p)}\left(1 + \frac{\Delta|qB|e^{-\mathbf{p}_\perp^2/|qB|}}{4\pi\sqrt{p_0^2 - m^2}}\right)$$

$$\mathcal{P}^{(\pm)}(p) = \left[1 + \mathrm{sign}(|qB|)iz_3(p)\gamma^1\gamma^2\right]$$

The Replica formalism

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QED fermions in a noisy magnetic field background

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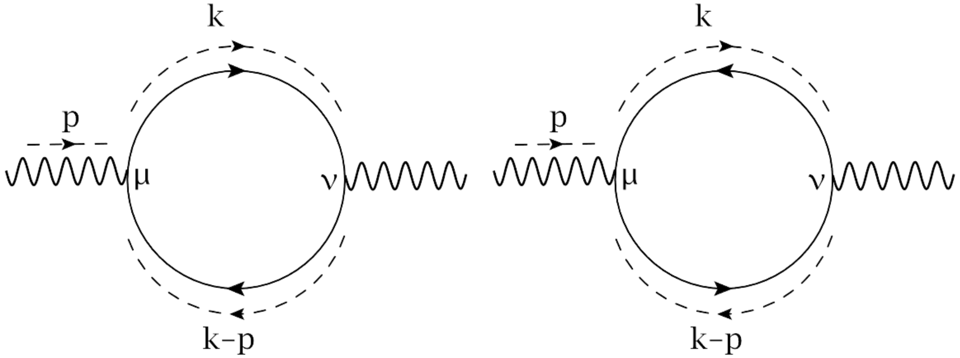
PROPAGATOR AT ORDER Δ

$$
\begin{aligned}
\mathrm{i}S_{\Delta}^{(\pm)}(p) &= \mathrm{i}S_0^{(\pm)}(p) \mp \mathrm{i}\Delta\left(\frac{|qB|}{2\pi}\right)\frac{e^{-2\mathbf{p}_\perp^2/|qB|}}{(p_\parallel^2-m^2)\sqrt{p_0^2-m^2}}(\not{p}_\parallel+m)\mathrm{i}\gamma^1\gamma^2 - \mathrm{i}\Delta\left(\frac{3|qB|}{2\pi}\right)\frac{e^{-2\mathbf{p}_\perp^2/|qB|}}{(p_\parallel^2-m^2)\sqrt{p_0^2-m^2}}p_3\gamma^3\mathcal{O}^{(\pm)} \\
&+ \mathrm{i}\Delta\left(\frac{3|qB|}{2\pi}\right)\frac{(p_\parallel^2+m^2)e^{-2\mathbf{p}_\perp^2/|qB|}}{(p_\parallel^2-m^2)^2\sqrt{p_0^2-m^2}}(\not{p}_\parallel+m)\mathcal{O}^{(\pm)} + \mathrm{O}(\Delta^2)
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{i}S_0^{(\pm)}(p) &= 2\mathrm{i}\frac{e^{-\mathbf{p}_\perp^2/|qB|}}{p_\parallel^2-m^2}(\not{p}_\parallel+m)\mathcal{O}^{(\pm)} \\
\mathcal{O}^{(\pm)} &= \frac{1}{2}\left(1\pm\mathrm{i}\gamma^1\gamma^2\right).
\end{aligned}
$$

The Photon/Gluon Polarization Tensor in a Fluctuating Magnetic Field Background



$$
\begin{aligned}
\mathrm{i}\Pi^{\mu\nu}_{\Delta} &= -\frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}\Big\{\mathrm{i}q\gamma^{\nu}\mathrm{i}S^{(-)}_{\Delta}(k)\,\mathrm{i}q\gamma^{\mu}\mathrm{i}S^{(-)}_{\Delta}(k-p)\Big\} \\
&- \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}\Big\{\mathrm{i}q\gamma^{\nu}\mathrm{i}S^{(+)}_{\Delta}(-k+p)\mathrm{i}q\gamma^{\mu}\mathrm{i}S^{(+)}_{\Delta}(-k)\Big\}
\end{aligned}
$$

$$
\mathrm{i}S^{(\pm)}_{\Delta}(p) = \mathrm{i}S^{(\pm)}_{0}(p) + \mathrm{i}\Delta\left(\frac{|qB|}{2\pi}\right)\Big[\Sigma_1(p)(\not{p}_{\parallel}+m)\mathcal{O}^{(\pm)} - \Sigma_2(p)\gamma^3\mathcal{O}^{(\pm)} \pm \Sigma_3(p)\mathrm{i}\gamma^1(\not{p}_{\parallel}+m)\gamma^2\Big] + \mathrm{O}(\Delta^2)
$$

$$
\mathrm{i}\Pi^{\mu\nu}_{\Delta} = \mathrm{i}\Pi^{\mu\nu}_{0} + \mathrm{i}\frac{q^2|qB|\Delta}{4\pi}\sum_{i=1}^{12}\int \frac{d^4k}{(2\pi)^4}t^{\mu\nu}_{i}(k)
$$

The Photon/Gluon Polarization Tensor in a Fluctuating Magnetic Field Background

$$\mathrm{i}\Pi^{\mu\nu}_{\Delta} = \mathrm{i}\Pi^{\mu\nu}_{0} + \mathrm{i}\frac{q^2|qB|\Delta}{4\pi}\sum_{i=1}^{12}\int\frac{d^4k}{(2\pi)^4}t_i^{\mu\nu}(k)$$

$$t_1^{\mu\nu} = \Sigma_1(k-p)\mathrm{Tr}\left\{\gamma^\nu \mathrm{i}S_0^{(-)}(k)\gamma^\mu(\not{k}_\parallel - \not{p}_\parallel + m)\mathcal{O}^{(-)}\right\},$$

$$t_2^{\mu\nu} = -\Sigma_2(k-p)\mathrm{Tr}\left\{\gamma^\nu \mathrm{i}S_0^{(-)}(k)\gamma^\mu\gamma^3\mathcal{O}^{(-)}\right\},$$

$$t_3^{\mu\nu} = -\mathrm{i}\Sigma_3(k-p)\mathrm{Tr}\left\{\gamma^\nu \mathrm{i}S_0^{(-)}(k)\gamma^\mu(\not{k}_\parallel - \not{p}_\parallel + m)\gamma^1\gamma^2\right\},$$

$$t_4^{\mu\nu} = \Sigma_1(k)\mathrm{Tr}\left\{\gamma^\nu(\not{k}_\parallel + m)\mathcal{O}^{(-)}\gamma^\mu \mathrm{i}S_0^{(-)}(k-p)\right\},$$

$$t_5^{\mu\nu} = -\Sigma_2(k)\mathrm{Tr}\left\{\gamma^\nu\gamma^3\mathcal{O}^{(-)}\gamma^\mu \mathrm{i}S_0^{(-)}(k-p)\right\},$$

$$t_6^{\mu\nu} = -\mathrm{i}\Sigma_3(k)\mathrm{Tr}\left\{\gamma^\nu(\not{k}_\parallel + m)\gamma^1\gamma^2\gamma^\mu \mathrm{i}S_0^{(-)}(k-p)\right\},$$

$$t_7^{\mu\nu} = \Sigma_1(-k)\mathrm{Tr}\left\{\gamma^\nu \mathrm{i}S_0^{(+)}(-k+p)\gamma^\mu(-\not{k} + m)\mathcal{O}^{(+)}\right\},$$

$$t_8^{\mu\nu} = -\Sigma_2(-k)\mathrm{Tr}\left\{\gamma^\nu \mathrm{i}S_0^{(+)}(-k+p)\gamma^\mu\gamma^3\mathcal{O}^{(+)}\right\},$$

$$t_9^{\mu\nu} = \mathrm{i}\Sigma_3(-k)\mathrm{Tr}\left\{\gamma^\nu \mathrm{i}S_0^{(+)}(-k+p)\gamma^\mu(-\not{k}_\parallel + m)\gamma^1\gamma^2\right\},$$

$$t_{10}^{\mu\nu} = \Sigma_1(-k+p)\mathrm{Tr}\left\{\gamma^\nu(-\not{k}_\parallel + \not{p}_\parallel + m)\mathcal{O}^{(+)}\gamma^\mu \mathrm{i}S_0^{(+)}(-k)\right\},$$

$$t_{11}^{\mu\nu} = -\Sigma_2(-k+p)\mathrm{Tr}\left\{\gamma^\nu\gamma^3\mathcal{O}^{(+)}\gamma^\mu \mathrm{i}S_0^{(+)}(-k)\right\},$$

$$t_{12}^{\mu\nu} = \mathrm{i}\Sigma_3(-k+p)\mathrm{Tr}\left\{\gamma^\nu\gamma^1\gamma^2\gamma^\mu(-\not{k}_\parallel + \not{p}_\parallel + m)\mathrm{i}S_0^{(+)}(-k)\right\}.$$

The Photon/Gluon Polarization Tensor in a Fluctuating Magnetic Field Background

After some “trazology”

$$T_1^{\mu\nu} = \left(\mathcal{I}_1^{(+)} + \mathcal{I}_1^{(-)}\right) P_\parallel^{\mu\nu} + \left(\mathcal{J}_1^{(+)} + \mathcal{J}_1^{(-)}\right) g_\parallel^{\mu\nu} + \left(\mathcal{K}_1^{(+)} + \mathcal{K}_1^{(-)}\right) \frac{p_\parallel^\mu p_\parallel^\nu}{m^2}$$

$$P_\parallel = g_\parallel^{\mu\nu} - \frac{p_\parallel^\mu p_\parallel^\nu}{p_\parallel^2}$$

$$T_2^{\mu\nu} = \left(\mathcal{I}_2^{(+)} + \mathcal{I}_2^{(-)}\right) \left(g_\parallel^{\mu\nu} + 2\delta_3^\mu \delta_3^\nu\right) + \left(\mathcal{J}_2^{(+)} + \mathcal{J}_2^{(-)}\right) \left(g_\parallel^{\mu\nu} - \frac{p_\parallel^\mu \delta_3^\nu + p_\parallel^\nu \delta_3^\mu}{p_3}\right)$$

$$T_3^{\mu\nu} = \left(\mathcal{I}_3^{(+)} + \mathcal{I}_3^{(-)}\right) \left(P_\parallel^{\mu\nu} - g_\perp^{\mu\nu}\right) + \left(\mathcal{J}_3^{(+)} + \mathcal{J}_3^{(-)}\right) \left(g_\parallel^{\mu\nu} - g_\perp^{\mu\nu}\right) + \left(\mathcal{K}_3^{(+)} + \mathcal{K}_3^{(-)}\right) \frac{p_\parallel^\mu p_\parallel^\nu}{m^2}$$

The Photon/Gluon Polarization Tensor in a Fluctuating Magnetic Field Background

After some “trazology”

$$\mathcal{I}_1^{(\pm)} \equiv -\frac{8i\pi|qB|}{(2\pi)^4}\exp\left(-\frac{2\mathbf{p}_\perp^2}{3|qB|}\right)\omega^2\sin^2\theta\int_0^\infty\frac{\lambda^2 d\lambda}{(1+\lambda)^5}\int\frac{d^2\ell_E}{(2\pi)^2}\frac{\left(\ell\pm\frac{\lambda}{1+\lambda}p\right)_E^2-m^2}{\sqrt{\left(\ell_4\mp\frac{i\lambda}{1+\lambda}\omega\right)^2+m^2}\left[\ell_E^2+\frac{\lambda}{(1+\lambda)^2}\omega^2\sin^2\theta+m^2\right]^3}$$

$$\mathcal{J}_1^{(\pm)} \equiv \frac{8i\pi|qB|m^2}{(2\pi)^4}\exp\left(-\frac{2\mathbf{p}_\perp^2}{3|qB|}\right)\int_0^\infty\frac{\lambda d\lambda}{(1+\lambda)^3}\int\frac{d^2\ell_E}{(2\pi)^2}\frac{\left(\ell\pm\frac{\lambda}{1+\lambda}p\right)_E^2-m^2}{\sqrt{\left(\ell_4\mp\frac{i\lambda}{1+\lambda}\omega\right)^2+m^2}\left[\ell_E^2+\frac{\lambda}{(1+\lambda)^2}\omega^2\sin^2\theta+m^2\right]^3}$$

$$\mathcal{K}_1^{(\pm)} \equiv -\frac{8i\pi|qB|}{(2\pi)^4}\exp\left(-\frac{2\mathbf{p}_\perp^2}{3|qB|}\right)\int_0^\infty\frac{\lambda^2 d\lambda}{(1+\lambda)^5}\int\frac{d^2\ell_E}{(2\pi)^2}\frac{\left(\ell\pm\frac{\lambda}{1+\lambda}p\right)_E^2-m^2}{\sqrt{\left(\ell_4\mp\frac{i\lambda}{1+\lambda}\omega\right)^2+m^2}\left[\ell_E^2+\frac{\lambda}{(1+\lambda)^2}\omega^2\sin^2\theta+m^2\right]^3},$$

The Photon/Gluon Polarization Tensor in a Fluctuating Magnetic Field Background

After some "trazology"

$$T_1^{\mu\nu} = \left(\mathcal{I}_1^{(+)} + \mathcal{I}_1^{(-)}\right) P_\parallel^{\mu\nu} + \left(\mathcal{J}_1^{(+)} + \mathcal{J}_1^{(-)}\right) g_\parallel^{\mu\nu} + \left(\mathcal{K}_1^{(+)} + \mathcal{K}_1^{(-)}\right) \frac{p_\parallel^\mu p_\parallel^\nu}{m^2}$$

$$P_\parallel = g_\parallel^{\mu\nu} - \frac{p_\parallel^\mu p_\parallel^\nu}{p_\parallel^2}$$

$$T_2^{\mu\nu} = \left(\mathcal{I}_2^{(+)} + \mathcal{I}_2^{(-)}\right)\left(g_\parallel^{\mu\nu} + 2\delta_3^\mu \delta_3^\nu\right) + \left(\mathcal{J}_2^{(+)} + \mathcal{J}_2^{(-)}\right)\left(g_\parallel^{\mu\nu} - \frac{p_\parallel^\mu \delta_3^\nu + p_\parallel^\nu \delta_3^\mu}{p_3}\right)$$

$$T_3^{\mu\nu} = \left(\mathcal{I}_3^{(+)} + \mathcal{I}_3^{(-)}\right)\left(P_\parallel^{\mu\nu} - g_\perp^{\mu\nu}\right) + \left(\mathcal{J}_3^{(+)} + \mathcal{J}_3^{(-)}\right)\left(g_\parallel^{\mu\nu} - g_\perp^{\mu\nu}\right) + \left(\mathcal{K}_3^{(+)} + \mathcal{K}_3^{(-)}\right)\frac{p_\parallel^\mu p_\parallel^\nu}{m^2}$$

Consequences:

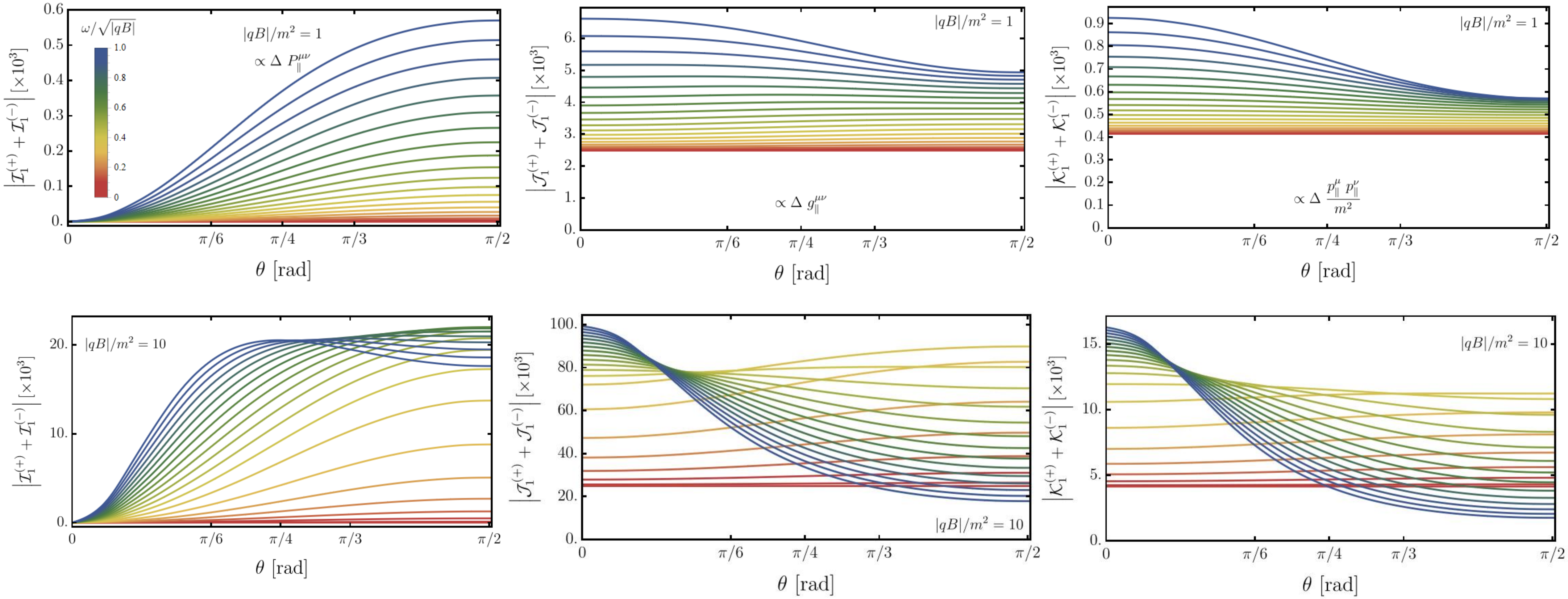
- If the integrals are non-zero, Ward identity is not preserved:

$$\Pi_0^{\mu\nu} \propto g_\parallel^{\mu\nu} - \frac{p_\parallel^\mu p_\parallel^\nu}{p_\parallel^2} \to p_\mu \Pi_0^{\mu\nu} = 0$$

$$i\Pi_\Delta^{\mu\nu} = i\Pi_0^{\mu\nu} + i\frac{q^2|qB|\Delta}{4\pi}\sum_{i=1}^{12}\int \frac{d^4k}{(2\pi)^4} t_i^{\mu\nu}(k)$$

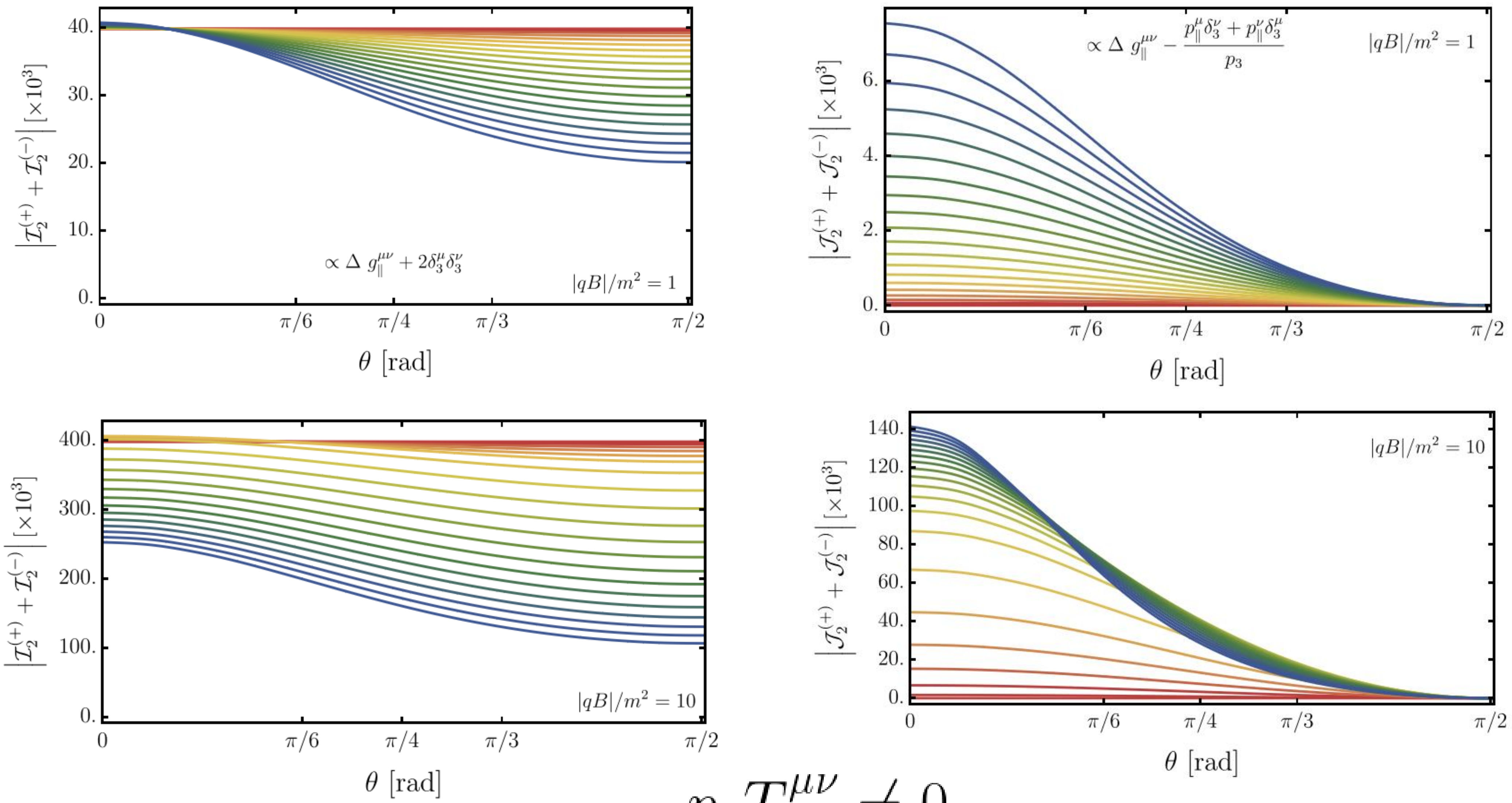
$$p_\mu T_i^{\mu\nu} \neq 0$$

$$T_1^{\mu\nu} = \left(\mathcal{I}_1^{(+)} + \mathcal{I}_1^{(-)}\right) P_\parallel^{\mu\nu} + \left(\mathcal{J}_1^{(+)} + \mathcal{J}_1^{(-)}\right) g_\parallel^{\mu\nu} + \left(\mathcal{K}_1^{(+)} + \mathcal{K}_1^{(-)}\right) \frac{p_\parallel^\mu p_\parallel^\nu}{m^2}$$



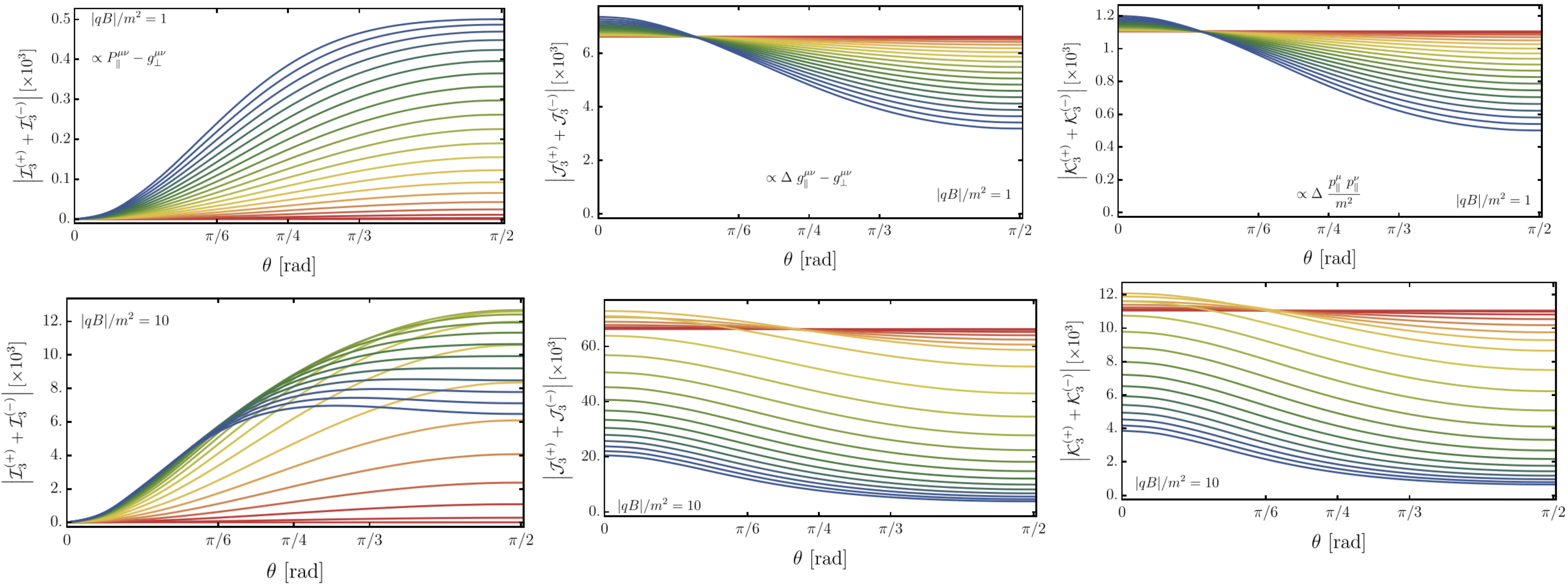
$$p_\mu T_1^{\mu\nu} \neq 0$$

$$T_2^{\mu\nu} = \left(\mathcal{I}_2^{(+)} + \mathcal{I}_2^{(-)}\right)\left(g_\parallel^{\mu\nu} + 2\delta_3^\mu\delta_3^\nu\right) + \left(\mathcal{J}_2^{(+)} + \mathcal{J}_2^{(-)}\right)\left(g_\parallel^{\mu\nu} - \frac{p_\parallel^\mu\delta_3^\nu + p_\parallel^\nu\delta_3^\mu}{p_3}\right)$$



$$p_\mu T_2^{\mu\nu} \neq 0$$

$$T_3^{\mu\nu} = \left(\mathcal{I}_3^{(+)} + \mathcal{I}_3^{(-)}\right)\left(P_\parallel^{\mu\nu} - g_\perp^{\mu\nu}\right) + \left(\mathcal{J}_3^{(+)} + \mathcal{J}_3^{(-)}\right)\left(g_\parallel^{\mu\nu} - g_\perp^{\mu\nu}\right) + \left(\mathcal{K}_3^{(+)} + \mathcal{K}_3^{(-)}\right)\frac{p_\parallel^\mu p_\parallel^\nu}{m^2}$$



$$p_\mu T_3^{\mu\nu} \neq 0$$

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After some “trazology”

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Consequences:

- If the integrals are non-zero, Ward identity is not preserved.
- If Ward identity is not preserved, can a photon acquire an effective mass due to magnetic quenched noise? [work in process].

Conclusions

- We applied the findings of the replica methos to compute the one-loop gluon/photon polarization tensor.

- This leads to a non-transverse structure.

- The latter arises from the breaking of the U(1) symmetry due the effective potential induced by the magnetic noise.

- Conjecture: If the Ward identity is not satisfied, then there may be an effective magnetic-induced mass for photons and gluons.