Probing Magnetic Fields During the Pre-Equilibrium Dynamics of Heavy-Ion Collisions

ANA MIZHER*

* Universidade de São Paulo, Brazil

In collaboration with Alejandro Ayala and Javier Rendon

II Latin American Workshop on Electromagnetics Effects in QCD - Nov 2025

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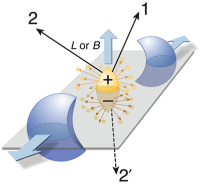
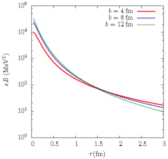
Magnetic fields in heavy-ion collisions

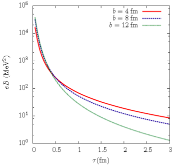
Non-central collisions: the strongest magnetic fields estimated in the laboratory (4 order higher than the strongest magnetic field observed in nature - magnetars).



$eB \approx 10^{19} G$



Au-Au 62GeV



Au-Au 200 GeV

[Kharzeev, McLerran and Warringa, NPA 803, 227 (2008).]

$$eB_s \approx Z\alpha_{EM} exp(-2Y_0)\frac{4b}{\tau^3}$$

$$eB_p \approx cZ_{EM} exp(-Y_0/2)\frac{1}{R^{1/2}\tau^{3/2}} f(b/R)$$

Other estimates

- *Time and space dependence of the electromagnetic field in relativistic heavy-ion collisions*, K. Tuchin, Phys.Rev.C 88 (2013) 2, 024911;
- *Initial value problem for magnetic field in heavy ion collisions, K. Tuchin, Phys.Rev.C 93 (2016) 1, 014905;*
- *Magnetic field in expanding quark-gluon plasma, K. Tuchin and E. Stewart, Phys.Rev.C 97 (2018) 4, 044906*
- *Estimate of the magnetic field strength in heavy-ion collisions, V. Skokov, A. Illarionov, V. Toneev, Int.J.Mod.Phys.A 24 (2009) 5925-5932;*
- *Centrality dependence of photon yield and elliptic flow from gluon fusion and splitting induced by magnetic fields in relativistic heavy-ion collisions, A. Ayala, J. D. Castaño-Yepes,1, I. Dominguez, J. Salinas and M. E. Tejeda-Yeomans, Eur.Phys.J.A 56 (2020) 2, 53.*
- *Incomplete electromagnetic response of hot QCD matter, Z.Wang, J.Zhao , C.Greiner, Z.Xu, and P.Zhuang1, Phys. Rev. C 105, L041901 (2022).*

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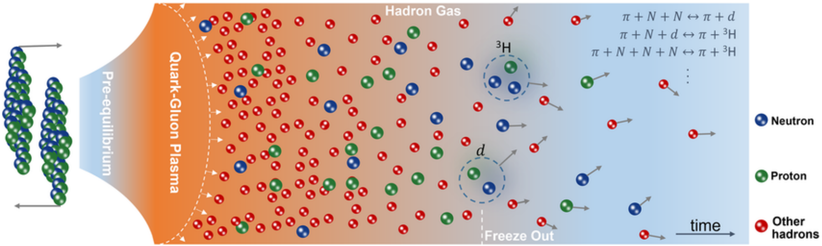
Magnetic field relevant during the first instants after the collision

QGP evolution

Evolution of the system formed after a heavy-ion collision



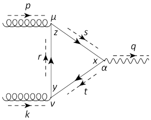
Pre-equilibrium must be affected by the magnetic field

Influence of magnetic fields during pre-equilibrium

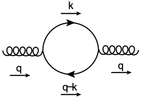
We detected three processes that may be significantly affected by the magnetic field during pre-equilibrium.

- Photon production by gluon fusion (photon puzzle)
  Talk by Santiago Bernal

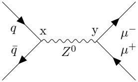
  [Phys.Rev.C 106 (2022) 6, 064905, Phys.Rev.D 110 (2024) 7, 076021]



- Anisotropy of the pressure of gluons



- Decay of the Z^0 boson into dileptons



Anisotropy of the pressure in pre-equilibrium

Calculating the pressure: effective kinetic theory

An appropriate set of Boltzmann equations which will, on sufficiently long time and distance scales, correctly describe the dynamics of typical ultrarelativistic excitations,

$$(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}}) f = -C[f]$$

where $f(\mathbf{x}, \mathbf{p}, t)$ is the phase space density of (quasi-)particles and $C[f]$ is a spatially-local collision term that represents the rate at which particles get scattered out of the momentum state p minus the rate at which they get scattered into this state. To leading order

$$-\frac{df_{\mathbf{p}}}{d\tau} = \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}_{exp}[f_{\mathbf{p}}]$$

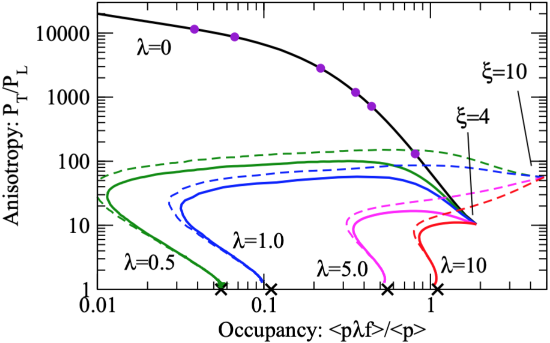
Initial conditions,

$$f(p_z, p_t) = \frac{2}{\lambda} A f_0(p_z \xi / \langle p_T \rangle\rangle, p_\perp / \langle p_T \rangle)$$

$$f_0(\hat{p}_z, \hat{p}_\perp) = \frac{1}{\sqrt{\hat{p}_\perp^2 + \hat{p}_z^2}} e^{-2(\hat{p}_\perp^2 + \hat{p}_z^2)/3}$$

Isotropization in EKT

Ratio of the transverse and parallel pressure from EKT



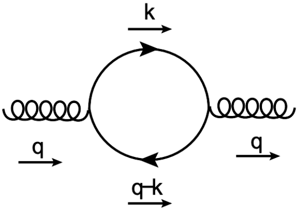
A. Kurkela and Y. Zhu, Phys. Rev. Lett. 115, 182301 (2015)

The gluon polarization tensor

Influence of a magnetic background in pre-equilibrium

[**A.M.** and A. Ayala Phys.Rev.D 110 (2024) 11, L111501]

The medium in pre-equilibrium is saturated by gluons $\rightarrow$ indirect effect of the magnetic field



$$i\Pi^{\mu\nu}_{ab} = -\frac{1}{2}\int \frac{d^4k}{(2\pi)^4} Tr\{igt_b\gamma^\nu iS^{(n)}(k) igt_a\gamma^\mu iS^{(m)}(q)\} + C.C.$$

Schwinger proper time method

The scalar propagator can be written as

$$D = \int_0^\infty \frac{ds}{\cosh(qBs)} e^{-s\left[(\omega_n - i\mu)^2 + p_z^2 + m^2 + p_\perp^2 \frac{\tanh(qBs)}{qBs}\right]}$$

and the fermionic propagator

$$S_B = \int \frac{ds}{cosh(qBs)} e^{s\left(k^2 - k_\perp^2 \frac{tanh(qBs)}{qBs} - m^2\right)} \left[(m_f + \not{k}) e^{iqBs\sigma_3} - \frac{\not{k}_\perp}{cosh(qBs)}\right]$$

The dispersion relations are:

$$E_s = \sqrt{k^2 + m^2 + (2l+1)eB}; \qquad E_f = \sqrt{k^2 + m^2 + (2l+1+s)eB}$$

Landau levels: energy quantization in the direction perpendicular to the field.

The gluon polarization tensor

The Schwinger propagator

$$iS(p) = ie^{-p_\perp^2/|q_f B|} \sum_{n=0}^{+\infty} (-1)^n \frac{D_n(q_f B, p)}{p_\parallel^2 - m_f^2 - 2n|q_f B|},$$

where D_n is a function of Laguerre polynomials.

For the strong field limit the lowest Landau level dominates,

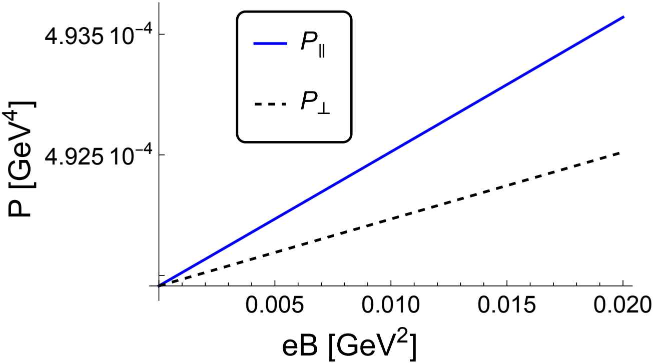
[K. Fukushima, Phys. Rev. D 83, 111501 (2011)]

$$\Pi^{\mu\nu} = g^2 \left(g_\parallel^{\mu\nu} - \frac{q_\parallel^\mu q_\parallel^\nu}{q_\parallel^2} \right) \sum_f \frac{|q_f B|}{8\pi^2} e^{-q_\perp^2/(2|q_f B|)}.$$

- The pressure is given by $P = -V$;
- We regularize separately the integral in $q_\parallel$ and $q_\perp$;
- The perpendicular pressure is given by $P_\perp = P_\parallel + M x_i \partial |eB| \partial x_i$ and $M = -\frac{\partial V}{\partial eB}$.

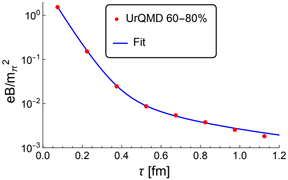
Parallel and transverse pressure

Parallel and transverse pressure as a function of eB.

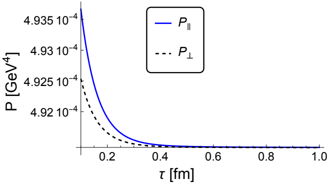


Magnetic field profile

We adopt the magnetic field profile calculated using UrQMD, including participants and spectators in Au+Au semi-central collisions, 60-80% centrality, at $\sqrt{s_{NN}} = 200$ GeV .



Eur.Phys.J.A 56 (2020) 2, 53

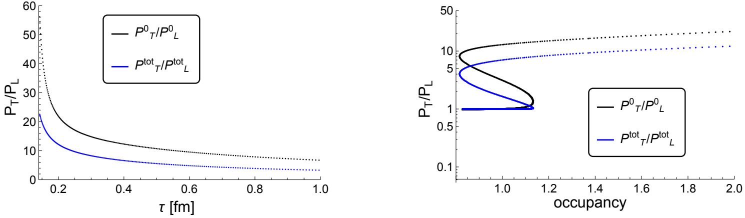


Phys.Rev.D 110 (2024) 11, L111501

Magnetic field as a catalyst of isotropy

[A.Ayala and **A.M.**Phys.Rev.D 110 (2024) 11, L111501]

The magnetic field fastens the isotropization of the medium. This is essential for a hydrodynamical approach.



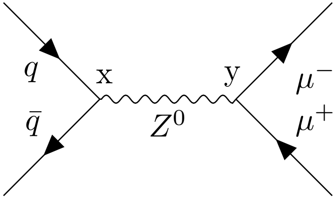
The ratio of P_T/P_L is also lower for all the values of occupancy along the evolution of the system and it reaches 1 for a value slightly higher than in the case of pure EKT. The results for EKT were taken considering $\varepsilon = 10$ and the coupling $\lambda = 10$.

Our calculation is independent from EKT approach. Work in progress: magnetic effects in the Boltzman equation with G.Denicol and K.Kushwah.

Decay of the Z^0 boson in dileptons

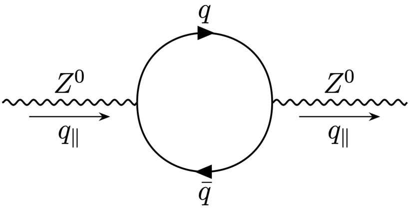
$q - \bar{q}$ annihilation in a strong magnetic background

arXiv:2506.11370



- Decay of the Z^0 in dileptons: weak force has a preferred chirality.
- Correlation between spin and momentum.
- Dileptons are considered hard probes: they do not interact with the medium.

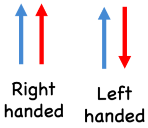
Hadron tensor



- To compute the hadron tensor, we can resort to the optical theorem, which amounts to computing the **imaginary part** of the magnetic field modified Z^0 propagator, which in turn can be obtained from the Z^0 polarization tensor in the presence of the magnetic field, $\Pi^{\mu\nu}$.
- We work at one-loop order and **in the lowest Landau-level (LLL) approximation for the quark propagators in the presence of a constant magnetic field** pointing along the $\hat{z}$-direction, **relevant scenario in the case the magnetic field is much larger than the quark mass squared**.

The electroweak interaction

Chirality and helicity (for small mass particles)



Weak interaction couples to left handed

$$\mathcal{L}_{\text{Fermi}} = -\frac{G_F}{\sqrt{2}} \left(\bar{\psi}\gamma^\mu(1-\gamma^5)\psi\right)\left(\bar{\psi}\gamma_\mu(1-\gamma^5)\psi\right)$$

Electroweak couples differently to right and left

$$\mathcal{L}_Z = \frac{g}{\cos\theta_W}\,\bar{\psi}\gamma^\mu\left(c_V - c_A\gamma^5\right)\psi\, Z_\mu$$

$$\begin{aligned} c_L &= c_V^f - c_A = T_3^f - Q_f \sin^2\theta_W \\ c_R &= c_V^f + c_A = -Q_f \sin^2\theta_W \end{aligned}$$

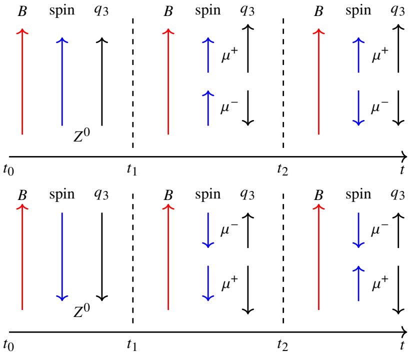
Lepton tensor

- In a magnetic field, charged fermions are not described by plane waves but instead by **Ritus functions.**
- Anticipating the **dominance of the axial coupling of the Z^0 to leptons, $\tilde{C}_A$,** the Lepton tensor can be expressed as

$$
\begin{aligned}
L_{\mu\nu} \quad &\sim \quad \tilde{C}_A^2 \left[p^-_{\parallel\mu} p^+_{\parallel\nu} + p^-_{\parallel\nu} p^+_{\parallel\mu} - g_{\parallel\mu\nu} [(p^- \cdot p^+)_\parallel - m^2] \right] \\
&\times \quad (2\pi)^2 \delta(q_0 - E^- - E^+) \delta(q_3 - p_3^- - p_3^+)
\end{aligned}
$$

- where $p^\pm_{\parallel\mu}$ and $E^\pm$ are the parallel components of the muon $(-)$ and antimuon $(+)$ four-momenta and their corresponding energies, respectively, and m is the muon mass.

Physical interpretation



- Z^0 is preferably polarized along its direction of motion.
- $\mu^{\pm}$ are produced by the electroweak interaction. Given the large mass difference between M_Z and m, $\mu^{\pm}$ behave as if they were massless.
- μ^- are preferably left-handed whereas μ^+ are preferably right-handed.
- **Together, this means that μ^+ are emitted with a larger p_T than μ^-.**

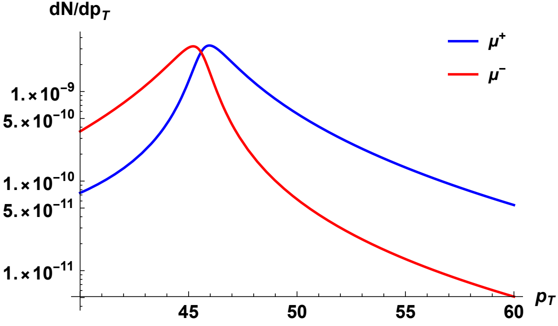
$\mu^{\pm}$ distributions

- To illustrate the expected individual $\mu^{\pm}$ distributions, we parametrize the p_T distribution of produced Z^0 in $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb collisions as

$$\frac{dN}{d^2 p_T dy} \propto 10^{-c p_T^n} e^{-\frac{y^2}{2\Delta^2}}, \quad c = 0.6896, \quad n = 0.4283, \quad \Delta = 3.3034$$

Y. Sun, V. Greco, and X.-N. Wang, Phys. Lett. B 827, 136962 (2022)

$\mu^{\pm}$ distributions



- The μ^+ peak is displaced towards larger values of p_T compared to the μ^- peak.
- The separation between the two peaks is determined by the inverse of the parameter c, which is related to the width of the Z^0 p_T-distribution and is of the order of 2 GeV.
- The ratio of the μ^+ to the μ^- distribution is greater than 1 for p_T larger than the position of the μ^+ peak.

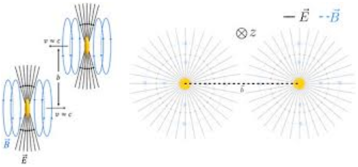
Summarizing

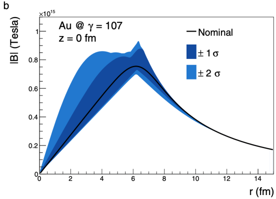
- Evidence that an uterly itense magetic field is generated in non-central heavy-ion collisions.
- Effects of the field must be more intense in pre-equilibrium.
- We propoose three different processes that may capture the presence of the field.
- The magnetic field acts as a catalist for isotropy.
- Z^0 decay in dileptons constitutes a promissing magnetometer, exploring the preferred coupling with left handed particles in the electroweak interaction: correlation between specie and dynamics.

Gracias!

Backup slides

The Breit-Wheeler process in ultraperipheral relativistic heavy-ion collisions





D. Brandenburg et al, Eur. Phys. J. A, 57, 299 (2021).

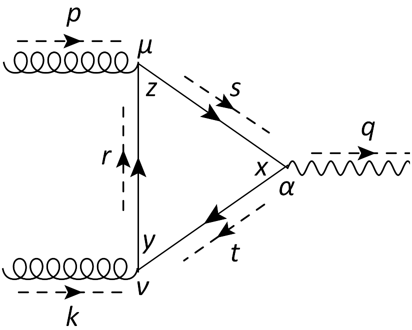
An ultraperipheral heavy-ion collision: The electromagnetic fields are highly Lorentz-contracted with a radial electric component and a circular magnetic component. Because both are perpendicular to each other and to the direction of motion, the resulting photons are linearly polarized.

New channels for photon production at pre-equilibrium

Two-gluon one-photon on shell vertex

[A.Ayala, J.Castaño-Yepes, L.A. Hernández, **A.M.**, M.E. Tejeda-Yeomans Phys.Rev.C 106 (2022) 6, 064905

A.Ayala, S.Bernal-Langarica, J.Jaber-Urquiza, J. J. Medina-Serna, Phys.Rev.D 110 (2024) 7, 076021]



Furry's theorem: if a Feynman diagram consists of a closed loop of fermion lines with an odd number of vertices, its contribution to the amplitude vanishes.

Two-gluon one-photon vertex: General structure

- From gauge invariance, the vertex must be transverse when contracted with the gluons and photons momenta
- The vertex must be symmetric under gluon exchange
- The vertex is invariant under CP
- The basis will be expressed as a set of polarization vectors and the photon's momentum

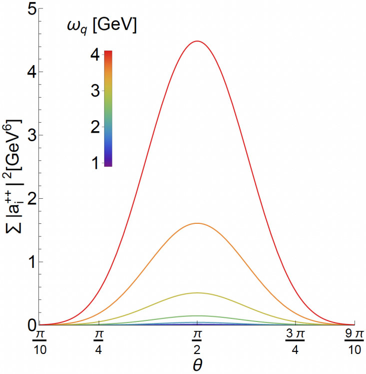
In the end of the day, the task is to calculate three coefficients. But...

$$T^{\mu\nu\alpha}_{\mathcal{A}1} + T^{\mu\nu\alpha}_{\mathcal{B}1} = \mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \not{A}_b \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \not{B}_b \gamma^\alpha \not{B}_a],$$
$$T^{\mu\nu\alpha}_{\mathcal{A}2} + T^{\mu\nu\alpha}_{\mathcal{B}2} = m_f^2\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha e_2 \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu e_2 \gamma^\alpha e_1]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}3} + T^{\mu\nu\alpha}_{\mathcal{B}3} = m_f^2\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha \not{A}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu \not{B}_b \gamma^\alpha e_1]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}4} + T^{\mu\nu\alpha}_{\mathcal{B}4} = m_f^2\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha e_2 \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu e_2 \gamma^\alpha \not{B}_a]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}5} + T^{\mu\nu\alpha}_{\mathcal{B}5} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha e_2 \gamma^\nu_\parallel e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu_\parallel e_2 \gamma^\alpha \not{B}_a]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}6} + T^{\mu\nu\alpha}_{\mathcal{B}6} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu_\parallel e_1 \gamma^\alpha \not{A}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu_\parallel e_3 \gamma^\nu \not{B}_b \gamma^\alpha e_1]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}7} + T^{\mu\nu\alpha}_{\mathcal{B}7} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha_\parallel e_2 \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu e_2 \gamma^\alpha_\parallel e_1]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}8} + T^{\mu\nu\alpha}_{\mathcal{B}8} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha e_2 \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu e_2 \gamma^\alpha \not{B}_a]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}9} + T^{\mu\nu\alpha}_{\mathcal{B}9} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha \not{A}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu \not{B}_b \gamma^\alpha e_1]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}10} + T^{\mu\nu\alpha}_{\mathcal{B}10} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha e_2 \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu e_2 \gamma^\alpha e_1]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}11} + T^{\mu\nu\alpha}_{\mathcal{B}11} = \frac{iq_f B}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \gamma^\nu] + \mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^\alpha \not{B}_a]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}12} + T^{\mu\nu\alpha}_{\mathcal{B}12} = \frac{iq_f B}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha \not{A}_b \gamma^\nu] + \mathrm{Tr}[\gamma^\mu \gamma^\nu \not{B}_b \gamma^\alpha]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}13} + T^{\mu\nu\alpha}_{\mathcal{B}13} = \frac{iq_f B}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \gamma^\alpha]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}14} + T^{\mu\nu\alpha}_{\mathcal{B}14} = -\frac{iq_f B}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \gamma^\nu_\perp] + \mathrm{Tr}[\gamma^\mu \gamma^\nu_\perp \gamma^\alpha \not{B}_a]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}15} + T^{\mu\nu\alpha}_{\mathcal{B}15} = -\frac{iq_f B}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu_\perp \gamma^\alpha \not{A}_b \gamma^\nu] + \mathrm{Tr}[\gamma^\mu_\perp \gamma^\nu \not{B}_b \gamma^\alpha]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}16} + T^{\mu\nu\alpha}_{\mathcal{B}16} = -\frac{iq_f B}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha_\perp \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \gamma^\alpha_\perp]\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}17} + T^{\mu\nu\alpha}_{\mathcal{B}17} = \frac{iq_f B t_1}{2(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \gamma^\beta_\perp \gamma^\nu \gamma^\sigma_\perp]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \gamma^\sigma_\perp \gamma^\nu \gamma^\beta_\perp \gamma^\alpha \not{B}_a]\hat{F}_{\sigma\beta}\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}18} + T^{\mu\nu\alpha}_{\mathcal{B}18} = -\frac{iq_f B t_2}{2(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\beta_\perp \gamma^\alpha \not{A}_b \gamma^\nu \gamma^\sigma_\perp]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \gamma^\sigma_\perp \gamma^\nu \not{B}_b \gamma^\alpha \gamma^\beta_\perp]\hat{F}_{\sigma\beta}\},$$
$$T^{\mu\nu\alpha}_{\mathcal{A}19} + T^{\mu\nu\alpha}_{\mathcal{B}19} = \frac{iq_f B t_3}{2(t_1 t_2 t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\beta_\perp \gamma^\alpha \gamma^\sigma_\perp \gamma^\nu \not{A}_c]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \gamma^\sigma_\perp \gamma^\alpha \gamma^\beta_\perp]\hat{F}_{\sigma\beta}\},$$

$$\not{A}_a = -\left(\frac{s_3\omega_{p_1} + s_2\omega_q}{s\omega_q}\right)\not{q}_\parallel e_1 + \frac{(t_3\omega_{p_1} + t_2\omega_q)\not{q}_\perp - t_2 t_3 \omega_{p_2}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)\omega_q}$$
$$\not{A}_b = \left(\frac{s_1\omega_q + s_3\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_2 - \frac{(t_3\omega_{p_2} + t_1\omega_q)\not{q}_\perp + t_1 t_3 \omega_{p_1}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)\omega_q}$$
$$\not{A}_c = \left(\frac{s_1\omega_{p_1} - s_2\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_3 + \frac{(-t_1\omega_{p_1} + t_2\omega_{p_2})\not{q}_\perp + t_1 t_3 \omega_q\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1 t_2 t_3 - t_1 - t_2 - t_3)\omega_q}$$
$$\not{B} = \left(\frac{s_3\omega_{p_1} + s_2\omega_q}{\ldots}\right) \ldots - \frac{(t_3\omega_{p_1} + t_2\omega_q)\not{q}_\perp + t_2 t_3 \omega_{p_2}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{\ldots}$$

Intermediate field regime

The square of the amplitude peaks at $\pi/2$. This means that besides incrementing the photon production it favors the v_2 of the photons (photon puzzle).



These are real photons that reach the detector. Is it possible to disentangle them from regular direct photons?

Lepton tensor

- Recall that in a magnetic field, charged fermions are not described by plane waves but instead by **Ritus functions.**
- The amplitude for dimuon emission is obtained by integration at the lepton vertex in the space-time point y and amounts to computing the overlap integral of the muon-antimuon pair wave functions which in turn **produces energy-momentum conservation factors except in the direction of the confining oscillation around the magnetic field lines.**
- This oscillation can be described using different gauge choices for the vector potential associated to the magnetic field. We work in the **Landau gauge 2.** The result is, of course, gauge-choice invariant.