Asymmetric muon-antimuon emission from Z^0 decays: a clear magnetometer in relativistic heavy-ion collisions

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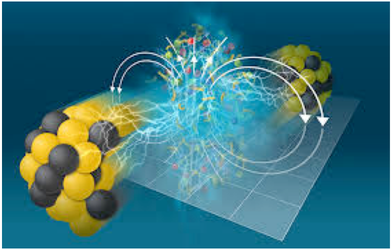
Magnetic fields in heavy-ion collisions

- Heavy-ion collisions are an excellent tool for exploring the properties of hadron matter subject to extreme conditions.

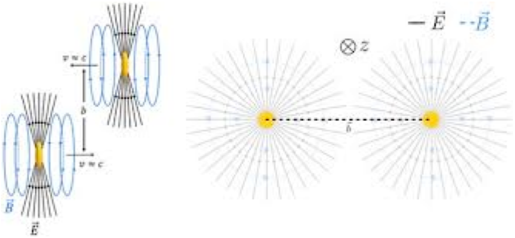
- In recent times, it has been recognized that such conditions include not only large temperatures and densities but also the possible presence of strong electromagnetic fields.



Not very many direct experimental measurements of the field intensity

- However, in spite of the many efforts aimed at identifying clear probes directly linked to the presence of such fields, up to now the clearest signal comes from the detection of the linear Breit-Wheeler process in ultraperipheral collisions.

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

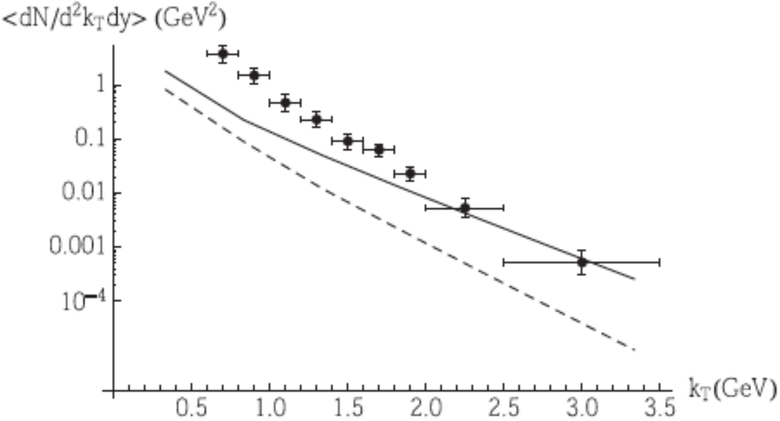


W. Zha, J. D. Brandenburg and Z. Xu, Nucl. Phys. News, 33:3, 27-31

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.

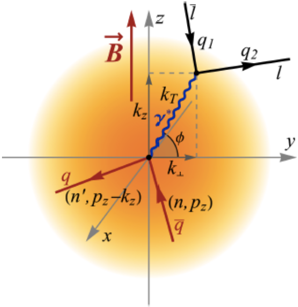
Synchrotron radiation in the QGP

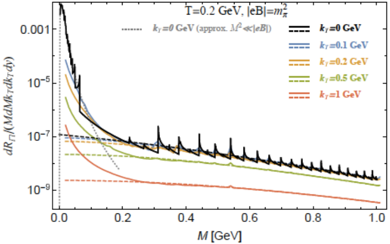
- Although synchrotron photons alone cannot account neither for the total photon spectrum, nor for its azimuthal asymmetry, they nevertheless give an important contribution to both.



K. Tuchin, Phys. Rev. C 91 014902, (2015).

- In a magnetized quark-gluon plasma, a magnetic field enhances the dilepton rate and ellipticity at small values of the invariant mass $M < \sqrt{eB}$.

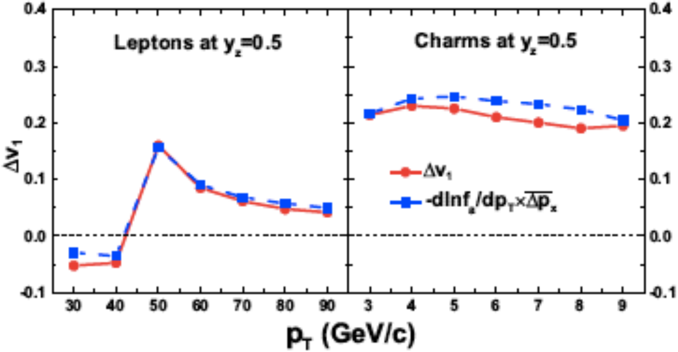




X. Wang, I.A. Shovkovy, Phys. Rev. D 106 , 036014 (2022).

Z^0 and charm in the QGP

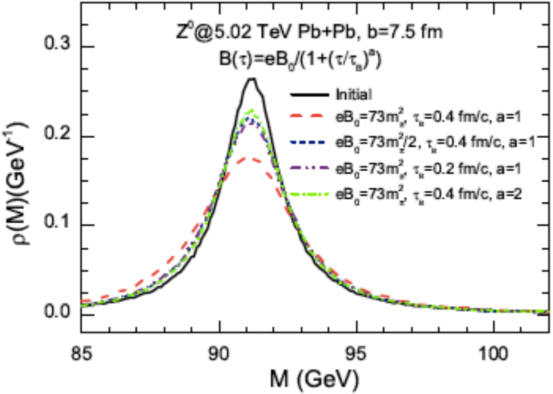
- Good penetrating probes during the QGP are dilepton pairs that originate from the decay of Z^0 bosons.
- v_1 splitting of leptons from Z^0 decay and also of charm quarks



Y. Sun, S. Plumari, V. Greco, Phys. Lett. B 816, 136271 (2021)

Z^0 width in the QGP

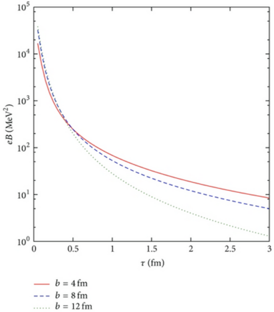
- The Z^0 width may experience a small but perhaps detectable modification



Y. Sun, S. Plumari, V. Greco, Phys. Lett. B 827, 136962 (2022)

Time evolution of the magnetic field after a heavy-ion collision

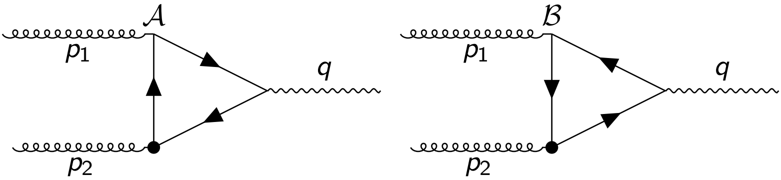
- The fast decrease of the field strength with time makes it more difficult to identify its imprints with probes produced during the QGP or hadronic stage.



K. Tuchin: Physics of Quark Gluon Plasma: An update and status Report

Look at electromagnetic signals from pre-equilibrium

- A better chance to identify the presence of such fields can be provided by penetrating probes produced during the earliest stages, where the field is close to its peak intensity.
- Direct photons–when produced during pre-equilibrium when gluons are abundant– from magnetic-field-induced gluon fusion and splitting also serve as good penetrating probes carrying out the information of the magnetic field strength.

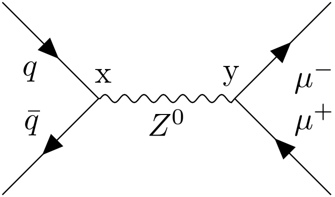


A.A., S. Bernal-Langarica, J. Jaber-Urquiza, J.J. Medina-Serna, Phys. Rev. D 110, 076021 (2024)

Dimuons from Z^0 decays during pre-equilibrium

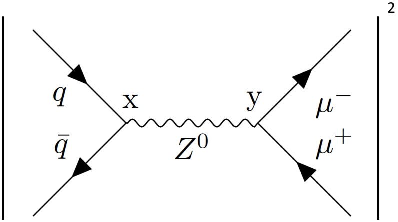
- During pre-equilibrium, the putative magnetic field must be at its highest strength.
- Hard probes are also produced at the very early stages of the collision.
- Penetrating probes such as dileptons, produced from the decay of heavy particles such as Z^0 potentially provide a clear signal of the presence of magnetic fields in semi-central heavy-ion collisions during pre-equilibrium.

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



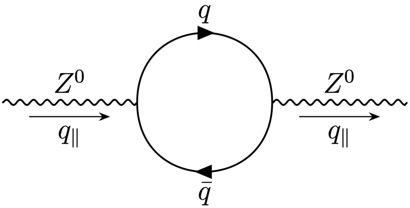
- Look at the current-current correlator describing the production of a Z^0 from quark-antiquark annihilation in a nucleus-nucleus collision at a given space-time point x followed by its subsequent decay into a dimuon pair in the final state at another space-time point y, in the presence of a strong magnetic field.
- Integration over the space-time points x and y at the production and decay vertices provides the amplitude of the process.

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



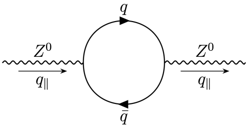
- The probability of dimuon production, per unit volume and time, is obtained by squaring this amplitude and dividing it by the space-time volume where the reaction is active.
- The calculation can be written in terms of the product of a tensor describing the process on the hadron side, $H^{\mu\nu}$ and a tensor describing the process on the lepton side, $L_{\mu\nu}$.

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**.

Hadron tensor

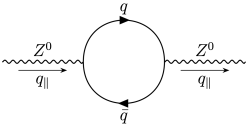


- In this approximation, the polarization tensor can be expressed as

$$\boxed{\begin{aligned}
&\Pi^{\mu\nu}(q_\parallel^2, q_\perp^2) = \Pi_\parallel(q_\parallel^2, q_\perp^2)P_\parallel^{\mu\nu} + \Pi_L(q_\parallel^2, q_\perp^2)P_L^{\mu\nu};\\
&P_\parallel^{\mu\nu} \equiv g_\parallel^{\mu\nu} - q_\parallel^\mu q_\parallel^\nu / q_\parallel^2, \quad P_L \equiv q_\parallel^\mu q_\parallel^\nu / q_\parallel^2\\
&g_\parallel^{\mu\nu} = \mathrm{Diag}(1, 0, 0, -1),\\
&q_\parallel^\mu = (q_0, 0, 0, q_3), \quad q_\perp^\mu = (0, q_1, q_2, 0)
\end{aligned}}$$

- The tensor structures represent the possible Z^0 polarization states.

Hadron tensor

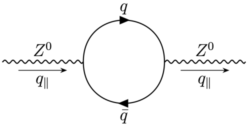


$$\boxed{\mathrm{Im}\left\{\Pi_\parallel,\Pi_L\right\}=g_Z^2\frac{|e_qB|}{4\pi}e^{-\frac{q_\perp^2}{2|e_qB|}}\left\{-C_V^2,C_A^2\right\}\left(\frac{m_q^2}{q_\parallel^2}\right)\sqrt{\frac{q_\parallel^2}{q_\parallel^2-4m_q^2}}\,\theta(q_\parallel^2-4m_q^2)}$$

Im $\Pi^{\mu\nu}$ features:

- Written in terms transverse and longitudinal polarization tensors with respect to $q_\parallel^\mu$.
- $C_A^2 \gg C_V^2$: **the longitudinal polarization dominates.**

Hadron tensor



$$\text{Re }\Pi_\parallel = g_Z^2 \frac{|e_q B|}{8\pi^2} e^{-\frac{q_\perp^2}{2|e_q B|}} \left\{ C_V^2 \left[\left(\frac{m_q^2}{q_\parallel^2} \right) \sqrt{\frac{q_\parallel^2}{q_\parallel^2 - 4m_q^2}} G(q_\parallel^2) - 1 \right] - C_A^2 \right\}$$

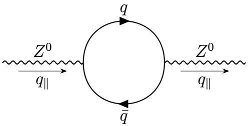
$$\text{Re }\Pi_L = -g_Z^2 \frac{|e_q B|}{8\pi^2} e^{-\frac{q_\perp^2}{2|e_q B|}} C_A^2 \left(\frac{m_q^2}{q_\parallel^2} \right) \sqrt{\frac{q_\parallel^2}{q_\parallel^2 - 4m_q^2}} G(q_\parallel^2);$$

$$G(q_\parallel^2) \equiv \ln \left(\left[\sqrt{q_\parallel^2 - 4m_q^2} - \sqrt{q_\parallel^2} \right] / \left[\sqrt{q_\parallel^2 - 4m_q^2} + \sqrt{q_\parallel^2} \right] \right)^2; \; q_\parallel^2 > 4m_q^2$$

Re $\Pi^{\mu\nu}$ features:

- **Dominant mode suppressed by m_q^2/m_Z^2 at the Z^0-peak.**

Hadron tensor



Given that the Z^0 is a finite width resonance described in vacuum by a relativistic Breit-Wigner function, the contribution from the hadron side to the dimuon production rate in a constant magnetic field can be written, in terms of the above functions, as

$$H^{\mu\nu} = \sum_{i=\parallel,L} \frac{2\ \mathrm{Im}\ \Pi_i\ P_i^{\mu\nu}}{(q^2 - M_Z^2 - \mathrm{Re}\ \Pi_i)^2 + (M_Z\Gamma_Z + \mathrm{Im}\ \Pi_i)^2}$$

where Γ_Z is the Z^0 total decay width.

- Since Re $\Pi_{\parallel,L}$ are small compared to M_Z^2 or $M_Z\Gamma_Z$, **we expect a small change of the Z^0 width.**

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.

Lepton tensor

- Anticipating the **dominance of the axial coupling of the Z^0 to leptons,** $\tilde{C}_A$, the Lepton tensor can be expressed as

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

- 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.

Dimuon emission rate

- Contracting the hadron and lepton tensors and in terms of the pair invariant mass $M = \sqrt{q_0^2 - q_3^3}$ we obtain the expression for the invariant mass distribution of the magnetic field-induced number of dimuons emitted per unit time and volume, $(dN/dVdt)$, as

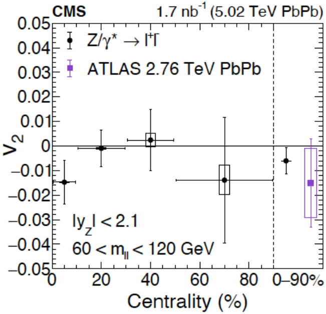
$$\boxed{\begin{aligned}\frac{dN/dVdt}{dM^2 d\phi} = & \tilde{C}_A^2 \left(\frac{|eB|^2}{\pi}\right)\left(\frac{m^2}{M^2}\right)\frac{e^{-a\frac{q_\perp^2}{|eB|}}}{\sqrt{1-4m^2/M^2}} \\ & \times \sum_{i=\parallel,L} \frac{|\mathrm{Im}\ \Pi_i|}{(M^2 - q_\perp^2 - M_Z^2 - \mathrm{Re}\ \Pi_i)^2 + (M_Z\Gamma_Z + \mathrm{Im}\ \Pi_i)^2}\end{aligned}}$$

- where $a = (1 + 2|e_q/e|)$.

v_2 from the azimuthal angle dilepton distribution

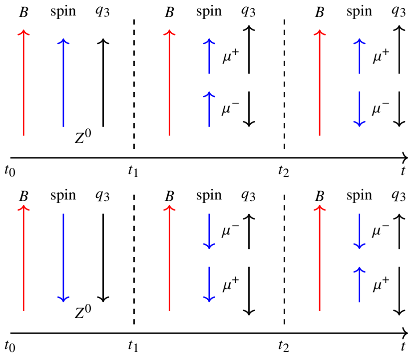
$$dN/d\phi \sim e^{-a\cos^2\phi}$$

$$v_2 \sim \int_0^{2\pi} e^{-a\cos^2\phi}\cos 2\phi d\phi = -2\pi e^{-a/2} I_1(a) < 0$$



A. M. Sirunyan *et al.* (CMS), Phys. Rev. Lett. 127, 102002 (2021)

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^-.**

Physical interpretation

- To reconcile this picture with the requirement that in the LLL the spin for negative charge particles is opposite to the field direction, recall that, **whereas the electroweak dimuon production can be considered as instantaneous, a short but finite time is required before the spins of the muons and antimuons are influenced by the presence of the magnetic field.**
- This relaxation time is of the order of the inverse of the Larmor frequency $\tau \sim m/|eB|$, showing that the smaller the mass of the produced particle and/or the larger the field strength, τ is shorter.

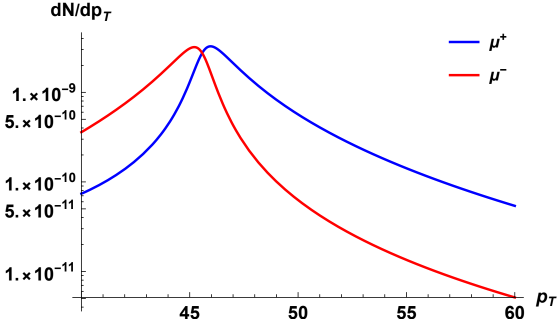
$\mu^{\pm}$ distributions

- 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.

Conclusions

- The search for signatures of the presence of magnetic fields in semi-central heavy-ion collisions represents a challenge because of the many sources of background, particularly if looked for with probes with imprints in the QGP part of the evolution.
- More promising probes are those produced during the early stages of the collision (pre-equilibrium), where the field is at its highest intensity.
- Electromagnetic probes, being penetrating, are more likely to carry the imprints of the putative magnetic field.

Conclusions

- We have studied the production of dimuon pairs from $q\bar{q}$ annihilation around the Z^0 peak, in the strong field approximation.
- **The main feature of the process is that μ^+ are produced in average with larger momentum than μ^- due to the correlation between the Z^0 polarization and direction of motion and the large mass difference between Z^0 and $\mu^\pm$ which makes the latter to be produced almost with definite chirality states.**
- More refined studies are needed to include the relaxation of the strong field limit. This venue is currently being pursued.

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