Extreme magnetic fields during pre-equilibrium in heavy-ion collisions

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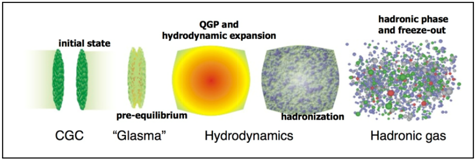
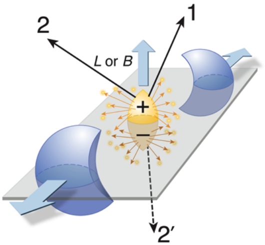
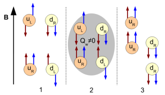
Magnetic fields in HIC



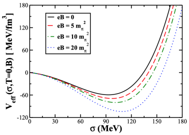
Non-central collisions: the strongest magnetic fields observed in the laboratory (4 orders higher than the strongest magnetic field observed in nature - magnetars).



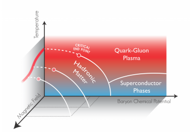
Effects of magnetic fields in QCD matter



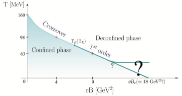
Chiral Magnetic Effect



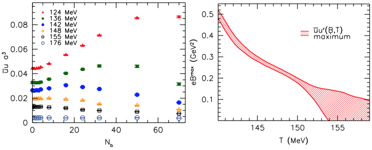
Magnetic catalysis



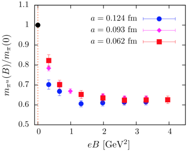
QCD phase diagram



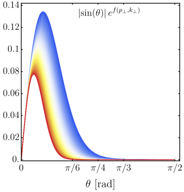
Critical end-point



Inverse magnetic catalysis



Pion mass



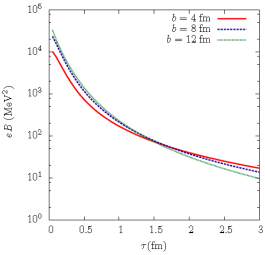
Particle production and distribution

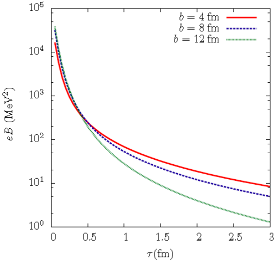
https://www.ictp-saifr.org/laqcd/

https://www.youtube.com/@LatinAmericanEM-QCD-og7gf

Estimating the strength of magnetic field

First estimate of the strength of magnetic fields





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

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

Nucl.Phys.A 803 (2008) 227-253

Other estimates

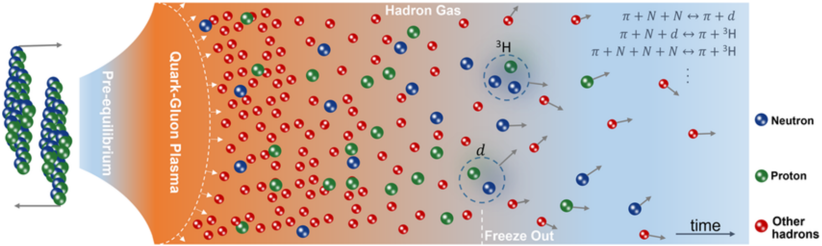
- *Time and space dependence of the electromagnetic field in relativistic heavy-ion collisions*, K. Tuchin, Phys.Rev.C 88 (2013) 2, 024911;
- *Initial value problem for magnetic field in heavy ion collisions, K. Tuchin, Phys.Rev.C 93 (2016) 1, 014905;*
- *Magnetic field in expanding quark-gluon plasma, 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.*

⋮

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

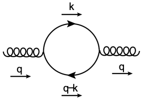
Pre-equilibrium

- During pre-equilibrium the energy is deposited in strong color fields that dominate from $\tau \sim 1/Q_s$.
- Once the system has reached a local thermal equilibrium, or at least approximately isotropized, the matter is described by relativistic fluid dynamics.
- Classical Yang-Mills theory does not isotropize when the system is subject to a rapid longitudinal expansion.
- The gap between YM and hydrodynamic evolution has been bridged by effective kinetic theory (EKT).

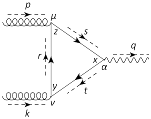
Influence of magnetic fields during pre-equilibrium

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

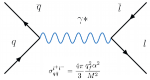
- Anisotropy of the pressure of gluons



- Photon production by gluon fusion



- Decay of virtual photons into dileptons



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

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

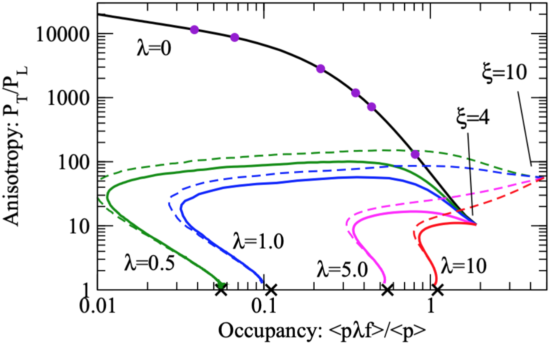
Initial conditions,

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

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

Isotropization in EKT

Ratio of the transverse and parallel pressure from EKT



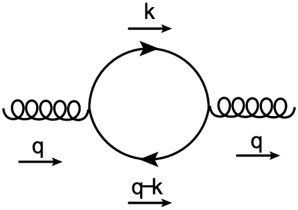
A. Kurkela and Y. Zhu, Phys. Rev. Lett. 115, 182301 (2015)

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 → indirect effect of the magnetic field



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

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.

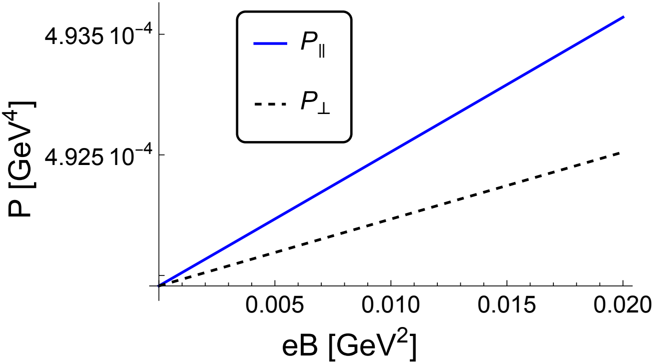
For the strong field limit the lowest Landau level dominates,
[K. Fukushima, Phys. Rev. D 83, 111501 (2011)]

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

- 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 $M = -\frac{\partial V}{\partial eB}$.

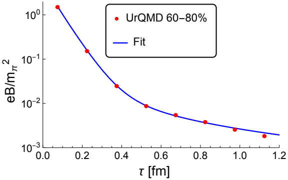
Parallel and transverse pressure

Parallel and transverse pressure as a function of eB.

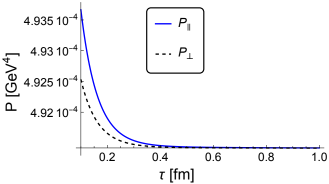


Magnetic field profile

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 .



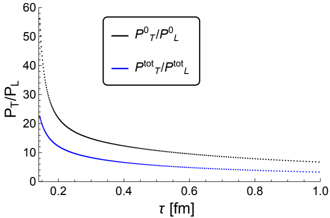
Eur.Phys.J.A 56 (2020) 2, 53

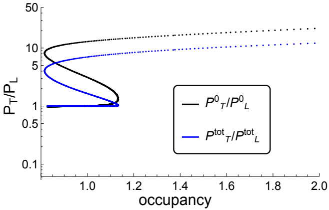


Phys.Rev.D 110 (2024) 11, L111501

Magnetic field as a catalyst of isotropy

Comparing the results from pure EKT (PRL 115, 182301 (2015)) and our results summed up to EKT, we see that when the magnetic field is taken into account the isotropization is reached faster.



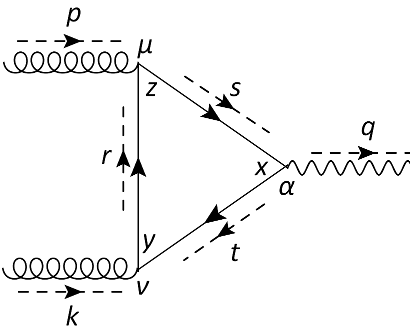


The ratio of P_T/P_L is also lower for all the values of occupancy along the evolution of the system and it reaches 1 for a value slightly higher than in the case of pure EKT. The results for EKT were taken considering $\varepsilon = 10$ and the coupling $\lambda = 10$.

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...

$$T^{\mu\nu\alpha}_{\mathcal{A}1} + T^{\mu\nu\alpha}_{\mathcal{B}1} = \mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \not{A}_b \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \not{B}_b \gamma^\alpha \not{B}_a],$$

$$T^{\mu\nu\alpha}_{\mathcal{A}2} + T^{\mu\nu\alpha}_{\mathcal{B}2} = m_f^2\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha e_2 \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu e_2 \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}3} + T^{\mu\nu\alpha}_{\mathcal{B}3} = m_f^2\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha \not{A}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu \not{B}_b \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}4} + T^{\mu\nu\alpha}_{\mathcal{B}4} = m_f^2\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha e_2 \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu e_2 \gamma^\alpha \not{B}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}5} + T^{\mu\nu\alpha}_{\mathcal{B}5} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha e_2 \gamma^\nu_\parallel e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu_\parallel e_2 \gamma^\alpha \not{B}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}6} + T^{\mu\nu\alpha}_{\mathcal{B}6} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu_\parallel e_1 \gamma^\alpha \not{A}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu_\parallel e_3 \gamma^\nu \not{B}_b \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}7} + T^{\mu\nu\alpha}_{\mathcal{B}7} = \frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha_\parallel e_2 \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu e_2 \gamma^\alpha_\parallel e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}8} + T^{\mu\nu\alpha}_{\mathcal{B}8} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha e_2 \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu e_2 \gamma^\alpha \not{B}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}9} + T^{\mu\nu\alpha}_{\mathcal{B}9} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha \not{A}_b \gamma^\nu e_3] + \mathrm{Tr}[\gamma^\mu e_3 \gamma^\nu \not{B}_b \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}10} + T^{\mu\nu\alpha}_{\mathcal{B}10} = -\frac{i}{s}\{\mathrm{Tr}[\gamma^\mu e_1 \gamma^\alpha e_2 \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu e_2 \gamma^\alpha e_1]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}11} + T^{\mu\nu\alpha}_{\mathcal{B}11} = \frac{iq_f B}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \gamma^\nu] + \mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^\alpha \not{B}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}12} + T^{\mu\nu\alpha}_{\mathcal{B}12} = \frac{iq_f B}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha \not{A}_b \gamma^\nu] + \mathrm{Tr}[\gamma^\mu \gamma^\nu \not{B}_b \gamma^\alpha]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}13} + T^{\mu\nu\alpha}_{\mathcal{B}13} = \frac{iq_f B}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \gamma^\alpha]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}14} + T^{\mu\nu\alpha}_{\mathcal{B}14} = -\frac{iq_f B}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \gamma^\nu_\perp] + \mathrm{Tr}[\gamma^\mu \gamma^\nu_\perp \gamma^\alpha \not{B}_a]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}15} + T^{\mu\nu\alpha}_{\mathcal{B}15} = -\frac{iq_f B}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu_\perp \gamma^\alpha \not{A}_b \gamma^\nu] + \mathrm{Tr}[\gamma^\mu_\perp \gamma^\nu \not{B}_b \gamma^\alpha]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}16} + T^{\mu\nu\alpha}_{\mathcal{B}16} = -\frac{iq_f B}{(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\alpha_\perp \gamma^\nu \not{A}_c] + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \gamma^\alpha_\perp]\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}17} + T^{\mu\nu\alpha}_{\mathcal{B}17} = \frac{iq_f B t_1}{2(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \not{A}_a \gamma^\alpha \gamma^\beta_\perp \gamma^\nu \gamma^\sigma_\perp]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \gamma^\sigma_\perp \gamma^\nu \gamma^\beta_\perp \gamma^\alpha \not{B}_a]\hat{F}_{\sigma\beta}\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}18} + T^{\mu\nu\alpha}_{\mathcal{B}18} = -\frac{iq_f B t_2}{2(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\beta_\perp \gamma^\alpha \not{A}_b \gamma^\nu \gamma^\sigma_\perp]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \gamma^\sigma_\perp \gamma^\nu \not{B}_b \gamma^\alpha \gamma^\beta_\perp]\hat{F}_{\sigma\beta}\},$$

$$T^{\mu\nu\alpha}_{\mathcal{A}19} + T^{\mu\nu\alpha}_{\mathcal{B}19} = \frac{iq_f B t_3}{2(t_1t_2t_3 - t_1 - t_2 - t_3)}\{\mathrm{Tr}[\gamma^\mu \gamma^\beta_\perp \gamma^\alpha \gamma^\sigma_\perp \gamma^\nu \not{A}_c]\hat{F}_{\beta\sigma} + \mathrm{Tr}[\gamma^\mu \not{B}_c \gamma^\nu \gamma^\sigma_\perp \gamma^\alpha \gamma^\beta_\perp]\hat{F}_{\sigma\beta}\},$$

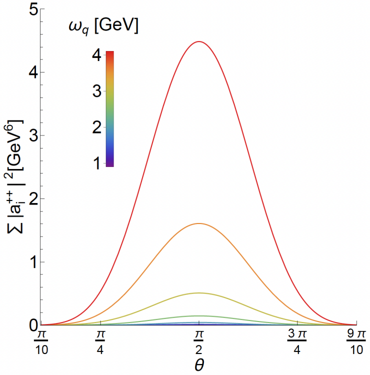
$$\not{A}_a = -\left(\frac{s_3\omega_{p_1} + s_2\omega_q}{s\omega_q}\right)\not{q}_\parallel e_1 + \frac{(t_3\omega_{p_1} + t_2\omega_q)\not{q}_\perp - t_2t_3\omega_{p_2}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

$$\not{A}_b = \left(\frac{s_1\omega_q + s_3\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_2 - \frac{(t_3\omega_{p_2} + t_1\omega_q)\not{q}_\perp + t_1t_3\omega_{p_1}\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

$$\not{A}_c = \left(\frac{s_1\omega_{p_1} - s_2\omega_{p_2}}{s\omega_q}\right)\not{q}_\parallel e_3 + \frac{(-t_1\omega_{p_1} + t_2\omega_{p_2})\not{q}_\perp + t_1t_3\omega_q\gamma^\sigma \hat{F}_{\sigma\beta} q^\beta_\perp}{(t_1t_2t_3 - t_1 - t_2 - t_3)\omega_q}$$

Intermediate field regime

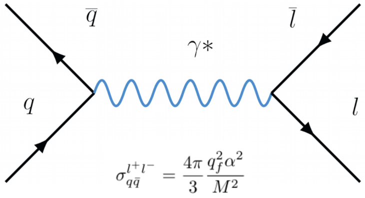
The square of the amplitude peaks at $\pi/2$. This means that besides incrementing the photon production it favors the v_2 of the photons (photon puzzle).



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

Dilepton production

TO DO: Dileptons may be produced from virtual photons generated by quark-antiquark annihilation. Scarse at pre-equilibrium but still existent.



$$\frac{dN^{l^+l^-}}{d^4x d^4K} = \int \frac{d^3p_1}{(2\pi)^3 2p_1}\frac{d^3p_2}{(2\pi)^3 2p_2} f_q(x,\mathbf{p}_1) f_{\bar{q}}(x,\mathbf{p}_2)|\mathcal{A}|^2(2\pi)^4\delta^{(4)}(P_1+P_2-K),$$

[M. Coquet, X. Du, J.Y. Ollitrault, S. Schlichting, M. Winn, Phys.Let.B, 821, 136626]

- A magnetic background will affect the coupling and the distribution;
- Gluon fusion may generate off-mass shell photons.

Summarizing

- We detected three ways a magnetic background can affect the system produced in heavy-ion collisions during pre-equilibrium.
- Magnetic fields may indirectly affect gluon fields via quantum fluctuations involving quarks.
- We calculated the parallel and perpendicular pressure in a regime saturated of gluon fields in the presence of a magnetic field and showed that comparing to calculations that use EKT, the effect of the magnetic field is to accelerate the isotropization.
- A magnetic background can open a new channel of photon production via gluon fusion. The calculation can be generalized to describe off-shell photons.
- The effects of an intense magnetic field probably can be observed in dileptons. Very involving calculation...

Thank you!