Inverse magnetic catalysis: Marcelo's quest for the strong and the extreme

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Conference on non-perturbative aspects of QFT and Loewe's Fest

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Overview

Talents: accomplished lecturer

Talents: gifted musician

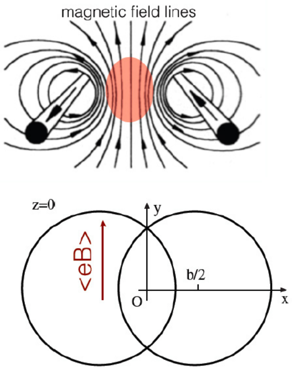
The strong

The strong and the extreme

A joint adventure

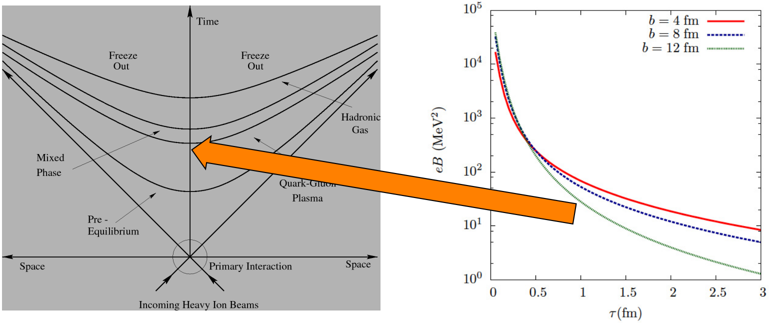
Magnetic fields in peripheral HICs

1. Generated in the middle of the interaction region by currents produced by the (charged) colliding nuclei.



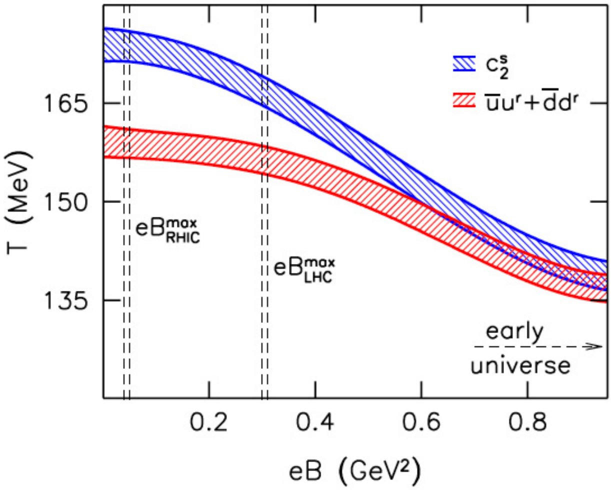
Time evolution of magnetic fields in HICs

The field intensity is a rapidly decreasing function of time



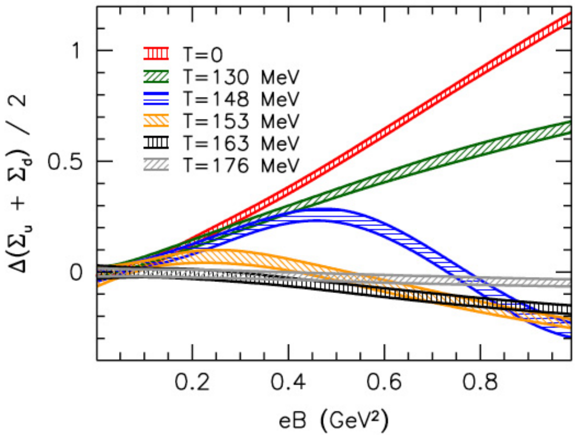
D. E. Kharzeev, L. D. McLerran, H. J. Warringa, Nucl. Phys. **A** 803, 227-253 (2008)

Inverse magnetic catalysis



G. S. Bali *et al.*, JHEP **02** (2012) 044

Inverse magnetic catalysis

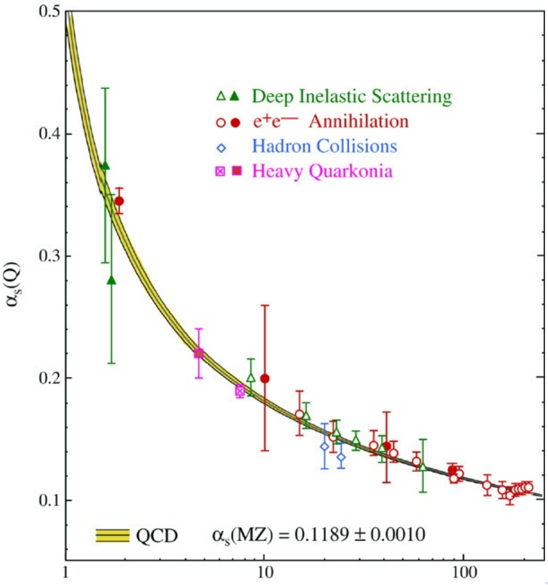


G. S. Bali *et al.*, Phys. Rev. D **86**, 071502 (2012)

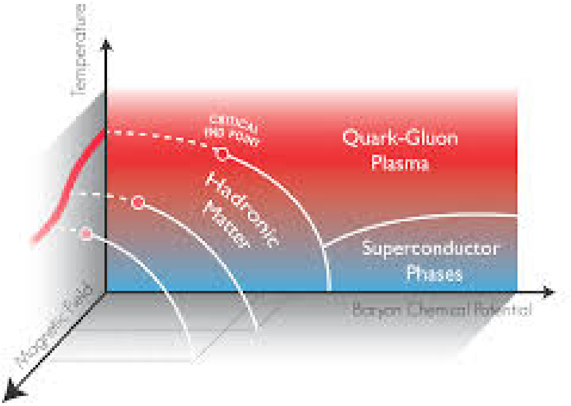
Inverse magnetic catalysis

1. Competition between **valence** and **sea** quarks:
   G. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S. Katz, *et. al*, J. High Energy. Phys. 1202, 044 (2012)
2. Efective models **coupling constant decrement** with B:
   R. L. S. Farias, K. P. Gomes, G. Krein and M. B. Pinto, Phys. Rev. C **90**, 025203 (2014); M. Ferreira, P. Costa, O. Lourenço, T. Frederico, C. Providência, Phys. Rev. D **89**, 116011 (2014); A. A., M. Loewe, A. Mizher, R. Zamora, Phys. Rev. D **90**, 036001 (2014); A. A., M. Loewe, R. Zamora, Phys. Rev. D **91**, 016002
3. Non-local chiral quark models
   V.P. Pagura, D. Gomez Dumm, S. Noguera, N.N. Scoccola, Phys. Rev. D **95**, 034013 (2017).

Running coupling constant

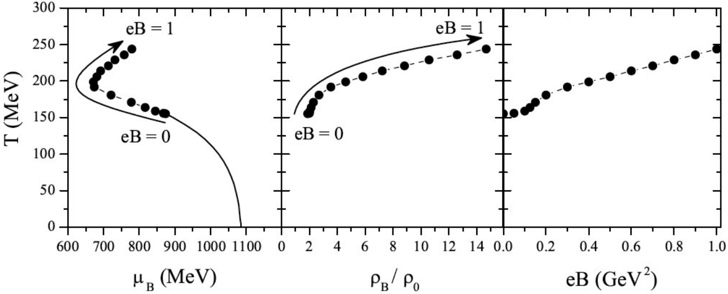


Magnetized phase diagram



Chemical freeze-out curve closer to transition curve

P. Costa, M. Ferreira, D. P. Menezes, J. Moreira, C. Providência, Phys. Rev. D **92**, 036012 (2015)

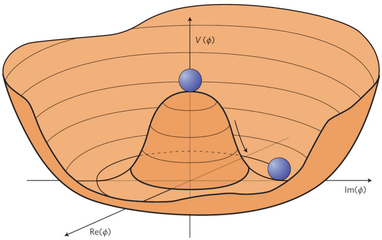


1. If the pseudo critical line for $B \neq 0$ **happens for higher temperatures and lower densities,** this can be closer to the chemical freeze-out curve.
2. Distance between CEP and freeze-out curve decreases.
3. **Signals of criticality can be revealed.**

Effective QCD model: Linear sigma model with quarks

- Effective QCD models (linear sigma model with quarks)

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + \frac{a^2}{2}(\sigma^2+\vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2+\vec{\pi}^2)^2 \\ &+ i\bar{\psi}\gamma^\mu\partial_\mu\psi - g\bar{\psi}(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\psi,\end{aligned}$$



$$\begin{aligned}\sigma &\to \sigma + v, \\ m_\sigma^2 &= \frac{3}{4}\lambda v^2 - a^2, \\ m_\pi^2 &= \frac{1}{4}\lambda v^2 - a^2 \\ m_f &= gv \\ v_0 &= \sqrt{\frac{a^2}{\lambda}}\end{aligned}$$

Schwinger proper-time effective potential

$$
\begin{aligned}
V_b^{(1)} &= \frac{T}{2}\sum_n \int dm_b^2 \int \frac{d^3k}{(2\pi)^3}\int_0^\infty \frac{ds}{\cosh(q_bBs)} \\
&\times \quad e^{-s(\omega_n^2+k_3^2+k_\perp^2\frac{\tanh(q_bBs)}{q_bBs}+m_b^2)},
\end{aligned}
$$

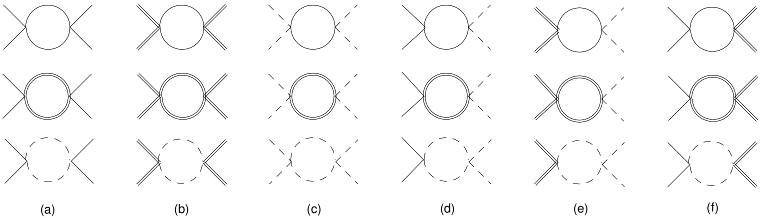
$$
\begin{aligned}
V_f^{(1)} &= -\sum_{r=\pm 1} T\sum_n \int dm_f^2 \int \frac{d^3k}{(2\pi)^3}\int_0^\infty \frac{ds}{\cosh(q_fBs)} \\
&\times \quad e^{-s(\tilde{\omega}_n^2+k_3^2+k_\perp^2\frac{\tanh(q_fBs)}{q_fBs}+m_f^2+rq_fB)},
\end{aligned}
$$

Schwinger proper-time propagators: weak field limit

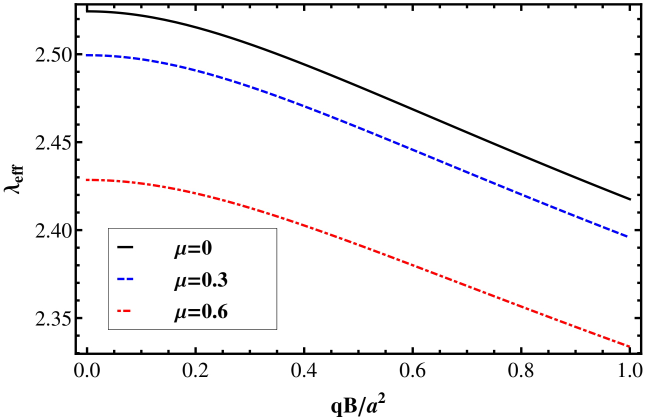
$$D_B(\omega_{n\neq 0},\mathbf{k}) = \frac{1}{\omega_n^2+\mathbf{k}^2+m_i^2}\left[1-\frac{(qB)^2}{(\omega_n^2+\mathbf{k}^2+m_i^2)^2}+\frac{2(qB)^2\ k_\perp^2}{(\omega_n^2+\mathbf{k}^2+m_i^2)^3}\right]$$

$$S_B(K,m_f) = \frac{(m_f-\not{K})}{K^2+m_f^2} - i\frac{\gamma_1\gamma_2(qB)(m_f-\not{K}_\parallel)}{(K^2+m_f^2)^2}$$
$$+ \frac{2(qB)^2K_\perp^2}{(K^2+m_f^2)^4}\left[(m_f-\not{K}_\parallel)+\frac{\not{K}_\perp(m_f^2+K_\parallel^2)}{K_\perp^2}\right].$$

Effective scalar coupling λ as a function of B

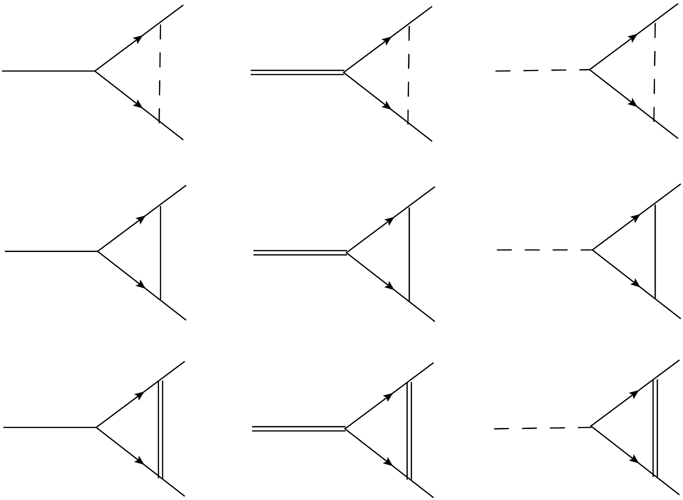


Effective scalar coupling λ as a function of B



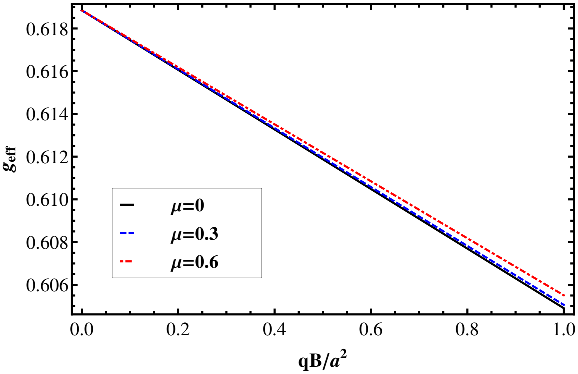
A. A., M. Loewe, R. Zamora, Phys. Rev. D **91**, 016002 (2015)

Effective fermion-scalar coupling g as a function of B



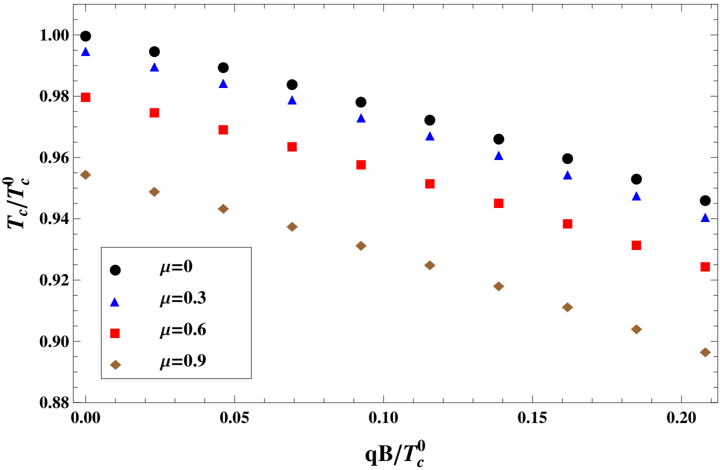
(a) (b) (c)

Effective fermion-scalar coupling g as a function of B

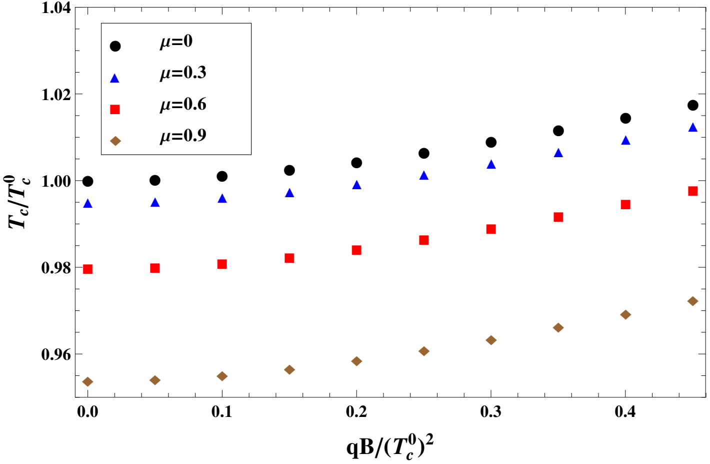


A. A., M. Loewe, R. Zamora, Phys. Rev. D **91**, 016002 (2015)

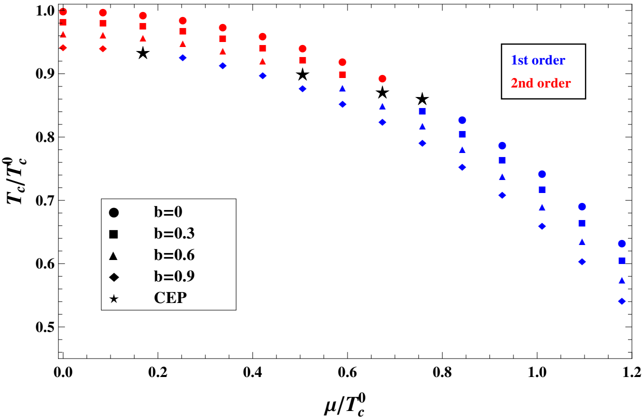
With couplings B-dependence, T_c decreases



Without couplings B-dependence, T_c increases

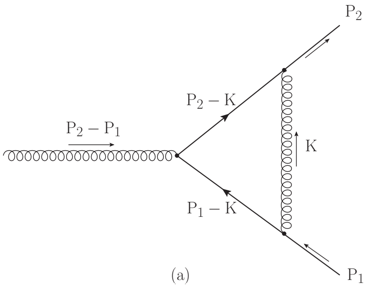


Magnetized phase diagram



A. A., C. Dominguez, L. A. Hernández, M. Loewe, R. Zamora, Phys. Rev. D **92**, 096011 (2015)

QCD case: Quark-gluon vertex with a magnetic field



$$S(K) = \frac{m - \not{K}}{K^2 + m^2} - i\gamma_1\gamma_2 \frac{m - \not{K}_\parallel}{(K^2 + m^2)^2}(qB)$$

A. A., M. Loewe, J. Cobos-Martínez, M. E. Tejeda-Yeomans, R. Zamora, Phys. Rev. D **91**, 016007 (2015)

QCD case: **high temperature**

$$\begin{aligned}\delta\Gamma_\mu^{(a)} &= -ig^2(C_F - C_A/2)(qB)T\sum_n\int\frac{d^3k}{(2\pi)^3}\\ &\times \gamma_\nu\left[\gamma_1\gamma_2\not{K}_\parallel\gamma_\mu\not{K}\widetilde{\Delta}(P_2-K)\right.\\ &+ \left.\not{K}\gamma_\mu\gamma_1\gamma_2\not{K}_\parallel\widetilde{\Delta}(P_1-K)\right]\gamma_\nu\\ &\times \Delta(K)\widetilde{\Delta}(P_2-K)\widetilde{\Delta}(P_1-K)\end{aligned}$$

$$\begin{aligned}\delta\Gamma_\mu^{(b)} &= -2ig^2\frac{C_A}{2}(qB)T\sum_n\int\frac{d^3k}{(2\pi)^3}\\ &\times \left[-\not{K}\gamma_1\gamma_2\not{K}_\parallel\gamma_\mu + 2\gamma_\nu\gamma_1\gamma_2\not{K}_\parallel\gamma_\nu K_\mu\right.\\ &- \left.\gamma_\mu\gamma_1\gamma_2\not{K}_\parallel\not{K}\right]\\ &\times \widetilde{\Delta}(K)^2\Delta(P_1-K)\Delta(P_2-K).\end{aligned}$$

QCD coupling as a function of B **high temperature**

$$\delta\vec{\Gamma}_{\parallel}(p_0) = \left(\frac{2}{3p_0^2}\right) 4g^2 C_F M^2(T, m, qB)\vec{\gamma}_{\parallel}\Sigma_3$$

$$M^2(T, m, qB) = \frac{qB}{16\pi^2}\left[\ln(2) - \frac{\pi}{2}\frac{T}{m}\right].$$

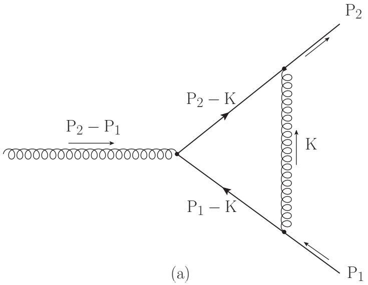
$$g_{\text{eff}}^{\text{therm}} = g\left[1 - \frac{m_f^2}{T^2} + \left(\frac{8}{3T^2}\right) g^2 C_F M^2(T, m_f, qB)\right],$$

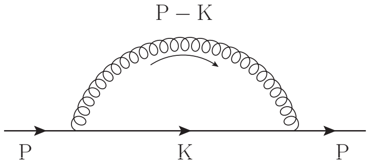
QCD coupling as a function of B **zero temperature**

$$
\begin{aligned}
\delta\Gamma^{\mu}_{(a)} &= ig^3(qB)\left(C_F - \frac{C_A}{2}\right)\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \\
&\times \left\{\gamma^{\nu}\frac{(\not{p}_2-\not{k})}{(p_2-k)^2}\gamma^{\mu}\frac{\gamma_1\gamma_2\left[\gamma\cdot(p_1-k)\right]_{\parallel}}{(p_1-k)^4}\gamma_{\nu}\right. \\
&+ \left.\gamma^{\nu}\frac{\gamma_1\gamma_2\left[\gamma\cdot(p_2-k)\right]_{\parallel}}{(p_2-k)^4}\gamma^{\mu}\frac{(\not{p}_1-\not{k})}{(p_1-k)^2}\gamma_{\nu}\right\},
\end{aligned}
$$

$$
\begin{aligned}
\delta\Gamma^{\mu}_{(b)} &= -2ig^3(qB)\frac{C_A}{2}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^4}\left[g^{\mu\nu}(2p_2-p_1-k)^{\rho}\right. \\
&+ \left. g^{\nu\rho}(2k-p_2-p_1)^{\mu} + g^{\rho\mu}(2p_1-k-p_2)^{\nu}\right] \\
&\times \gamma_{\rho}\frac{\gamma_1\gamma_2(\gamma\cdot k)_{\parallel}}{(p_2-k)^2(p_1-k)^2}\gamma_{\nu},
\end{aligned}
$$

Quark-gluon vertex satisfies Ward-Takahashi identity with quark self-energy in the presence of weak B-fields





QCD coupling grows (decreases) at zero (high) T as a function of B

$$
\begin{aligned}
g_{\text{eff}}^{\text{vac}} &= g - \left[g^2 \frac{1}{3\pi^2} \frac{q\vec{\Sigma} \cdot \vec{B}}{Q^2} \right] \\
&\times \left\{ \left(C_F - \frac{C_A}{2} \right) [1 + \ln(4)] + \frac{C_A}{5} [-1 + \ln(4)] \right\} \\
&= g - \left[g^2 \frac{1}{3\pi^2} \frac{q\vec{\Sigma} \cdot \vec{B}}{Q^2} \right] \\
&\times \left\{ [1 + \ln(4)]\, C_F - \frac{[7 + 3\ln(4)]}{10} C_A \right\}. \\
C_F &= \frac{N^2 - 1}{2N} \qquad C_A = N
\end{aligned}
$$

For $N = 3$, $g_{\text{eff}}^{\text{vac}}$ **grows** whereas $g_{\text{eff}}^{\text{therm}}$ **decreases** with B.

Conclusions

1. Magnetic fields provide extra handle to probe QCD properties under extreme conditions.
2. Effective model calculations show that magnetic field-induced changes in couplings describe **inverse magnetic catalysis.**
3. QCD quark-gluon vertex-B field dependent: Coupling decreases at high T and increases at zero T.
4. Effect due to subtle competition between the charges associated to quarks and gluons.
5. Vertex satisfies WT identity with quark self-energy.
6. Study turn-over case where B and T have similar strength. Stay tuned.

Happy Birthday Marcelo! Congratulations for the many years of successes! May it be many more!