# Properties of neutral pions in a hot and magnetized quark matter

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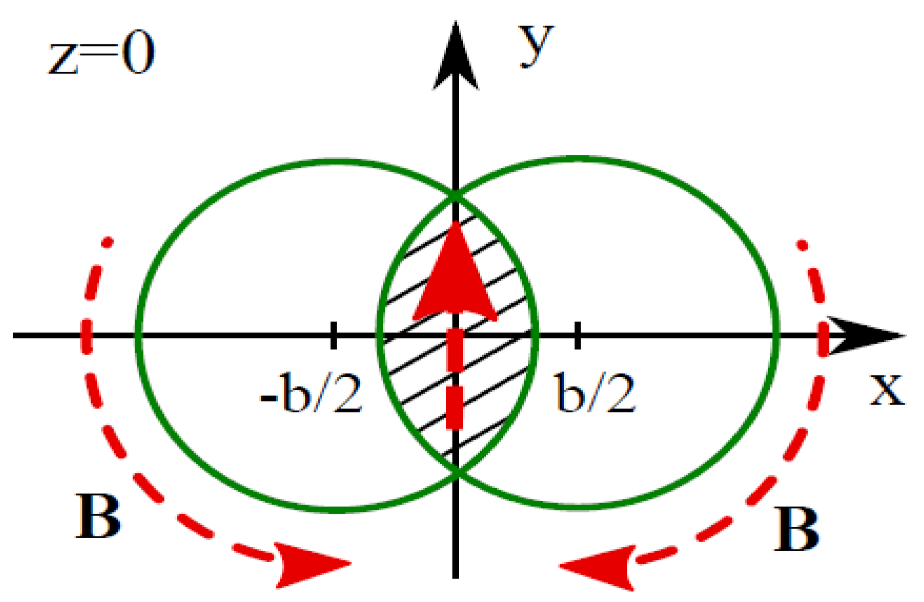
## Creation of strong magnetic fields in HIC

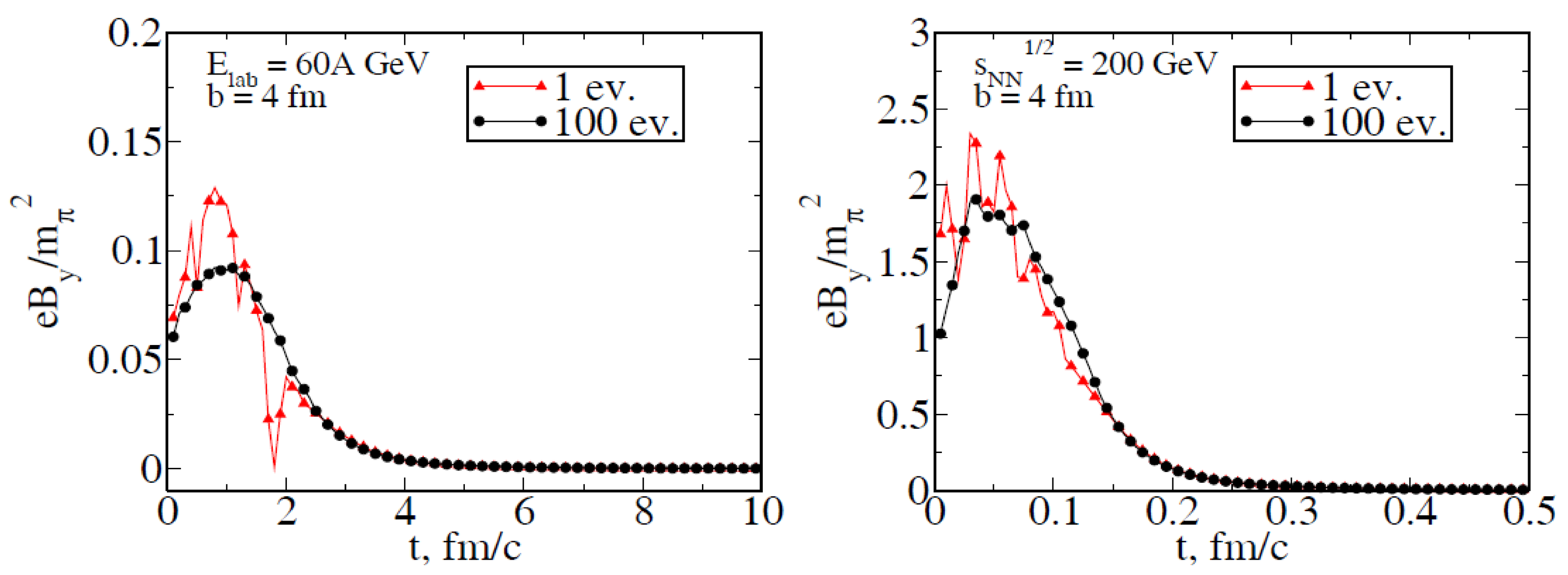
**Collisions between heavy nuclei produce some of the strongest magnetic fields that can be generated under laboratory conditions**

V. Voronyuk et al. Phys. Rev. **C83** (2011) 054911




The transverse plane of a non-central heavy-ion collision (HIC). The impact parameter of the collision is denoted by *b*. A magnetic field is created in the direction perpendicular to the reaction plane (dashed lines)

V. Skokov et al. Int. J. Mod. Phys. **A24** (2009) 5925




The time evolution of the magnetic field strength at the central point in *Au-Au* collisions with impact parameter *b*= 4fm, in one event and averaged over 100 events

**It is shown that the magnetic field emerging in HIC has the magnitude of the order of $eB\sim 0.1 m_\pi^2$ for the SPS energy range and $eB\sim m_\pi^2$ for the RHIC energies. The estimated value of the magnetic field strength for the LHC energy amounts to $eB\sim 15 m_\pi^2$**

[V. Skokov et al. Int. J. Mod. Phys. **A24** (2009) 5925] [Note: $m_\pi\sim 140$ MeV, $eB=1\text{GeV}^2$ equiv. with $B\sim 10^{20}$ G]

## Questions and expectations

**Although the created magnetic field is extremely short living, it may affect the properties of hadrons made of magnetized quarks**

**In particular, we are interested in**

- *T* dependence of neutral pion mass
- *T* dependence of neutral pion's refraction indices

in the presence of **constant magnetic field** at finite *T*

**Effective action of a two-flavor NJL model in a second order derivative expansion**

**Modified energy dispersion relation for $\pi^0$ including directional refraction indices**

[Sh. Fayazbakhsh, S. Sadeghian and N.S. PRD **86** (2012) 085042]

**Modified Gell-Mann-Oakes-Renner (GOR) relation**

**Directional weak decay constants for $\pi^0$**

[Sh. Fayazbakhsh and N.S. PRD **88** (2013) 065030]

## Modified low energy QCD theorems

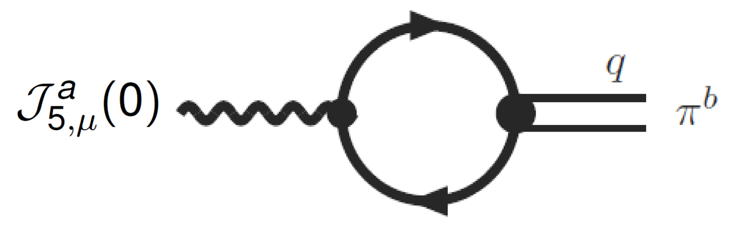
### Modified energy dispersion relation of $\pi^0$

$$\omega^2 = u_1^2 p_1^2 + u_2^2 p_2^2 + u_3^2 p_3^2 + m_\pi^2$$

**$u_i$, i=1,2,3 are $\pi^0$ directional refraction indices and $m_\pi$ is the $\pi^0$ mass**

### Modified PCAC relation

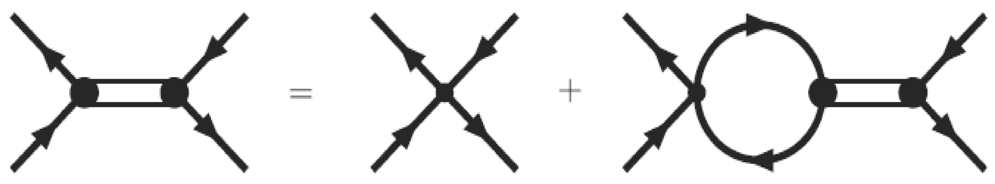
$$\langle 0|\mathcal{J}^a_{5,\mu}(0)|\pi^b(q)\rangle = f_b u_\pi^{(\mu)2} q_\mu \delta^{ab}$$




**$\mathcal{J}^a_{5,\mu}(0)$ is the axial vector current, $f_b$ is a constant**

**One pion-to-vacuum matrix element**

### Modified Gell-Mann-Oakes-Renner (GOR) relation




**The Bethe-Salpeter equation for quark-antiquark scattering in random phase approximation. It leads to the modified GOR relation**

$$m_\pi^2 f_\pi^{(\mu)2} = u_\pi^{(\mu)2}\frac{m_0\sigma_0}{2G} + \mathcal{O}(m_0^2)$$

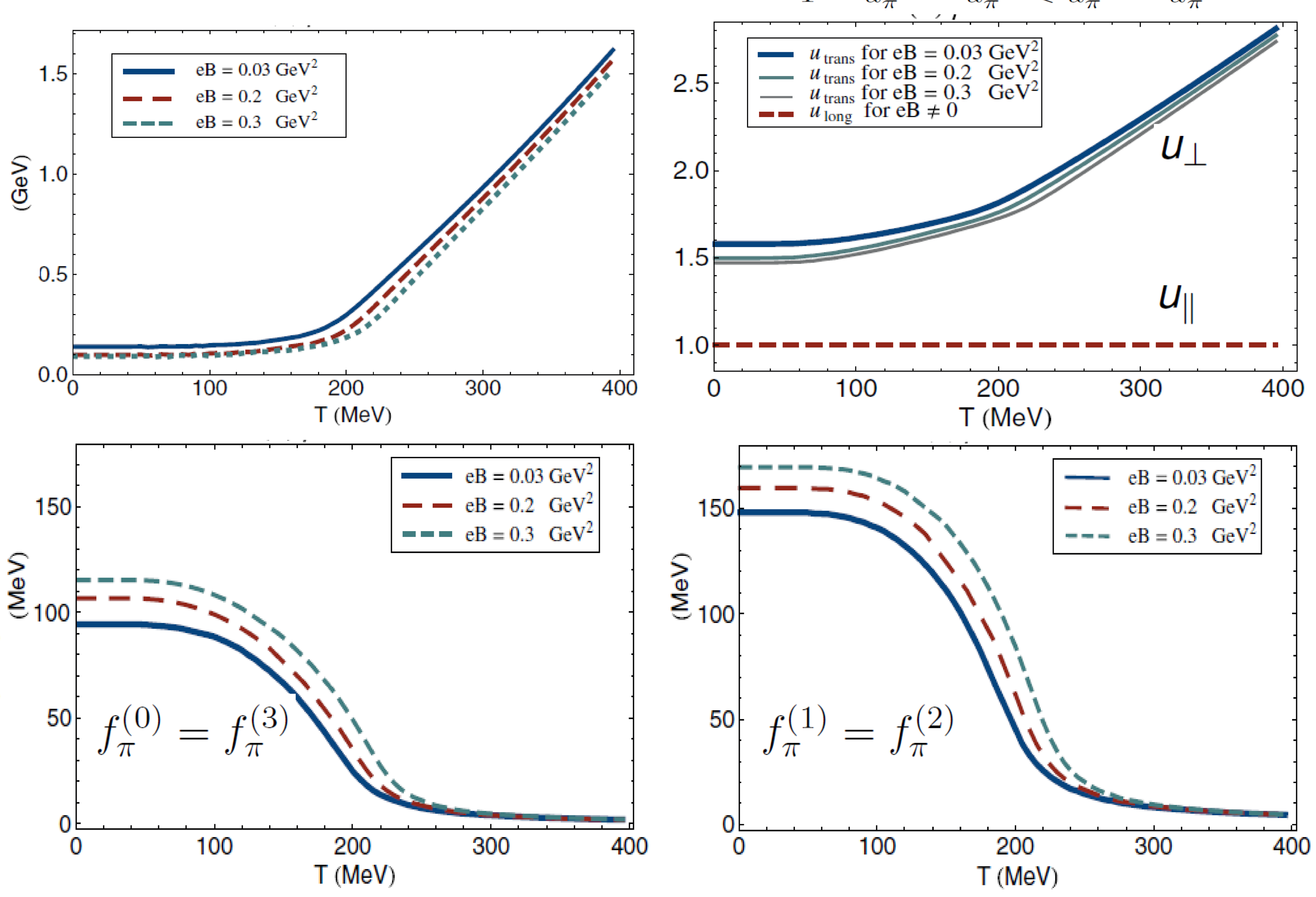
$f_\pi^{(\mu)}$ *μ=0,1,2,3* are **directional weak decay constants** of $\pi^0$
$u_\pi^{(\mu)}$ *μ=0,1,2,3* are **directional refraction indices** of $\pi^0$
$m_0$ is the bare mass of quarks
*G* is the Nambu-Jona-Lasinio (NJL) effective coupling constant
$\sigma_0$ is the chiral condensate of the NJL model $\qquad \sigma_0 = -2G\langle\bar\psi\psi\rangle$

## Results: Sh. Fayazbakhsh and N.S. PRD 88 (2013) 065030

***T* dependence of $m_\pi$ for various magnetic field strengths *eB*: Below the crossover temperature, pions are Goldstone bosons and therefore (approximately) massless**

***T* dependence of directional refraction indices $u_\pi^{(\mu)}$ for various magnetic field strengths eB: In general we have**

$$1 = u_\pi^{(0)} = u_\pi^{(3)} < u_\pi^{(1)} = u_\pi^{(2)}$$




***T* dependence of directional weak decay constant of $\pi^0$ for various magnetic field strengths *eB***

## Summary

**Uniform magnetic field breaks the Lorentz invariance and induces certain anisotropy in the refraction indices and weak decay constants of neutral pions. They are related through modified low energy theorems of QCD.**

**Based on:**
[1] Sh. Fayazbakhsh, S. Sadeghian and **N. Sadooghi**, Phys. Rev. **D86** (2012) 085042
[2] Sh. Fayazbakhsh and **N. Sadooghi**, Phys. Rev. **D88** (2013) 065030

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