Mesons in Magnetic Fields

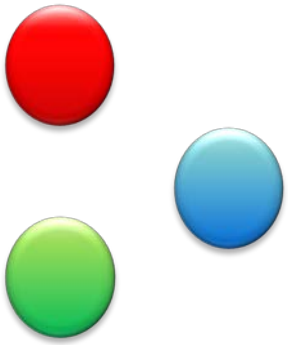
Arata Yamamoto (U. Tokyo)

Koichi Hattori, AY, PTEP 2019, in press (2019)

Introduction

gluons

quarks



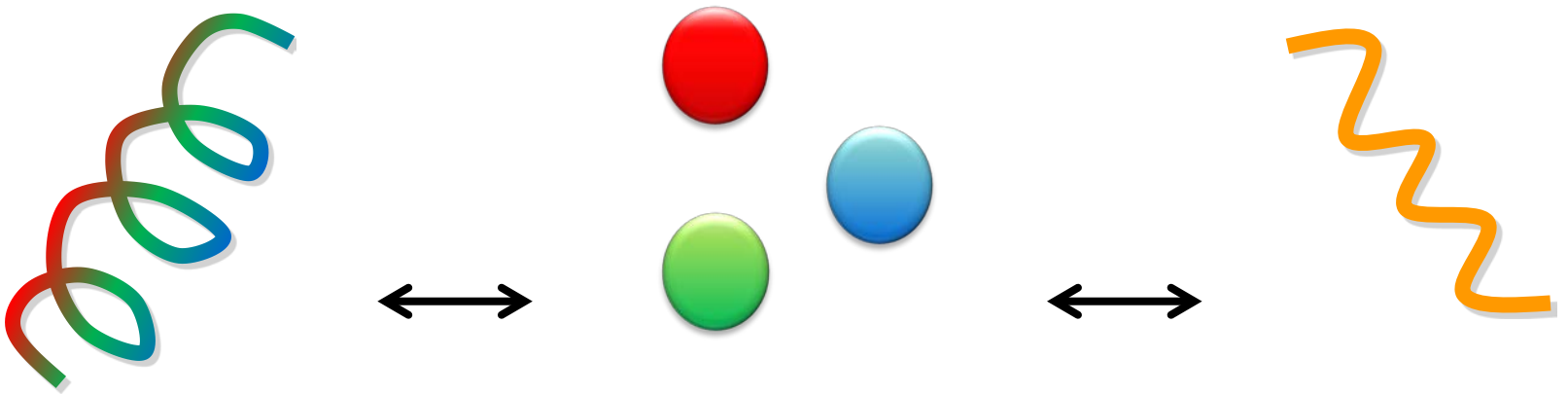
photons

$g \gg e$

small effect…

Introduction

gluons quarks photons

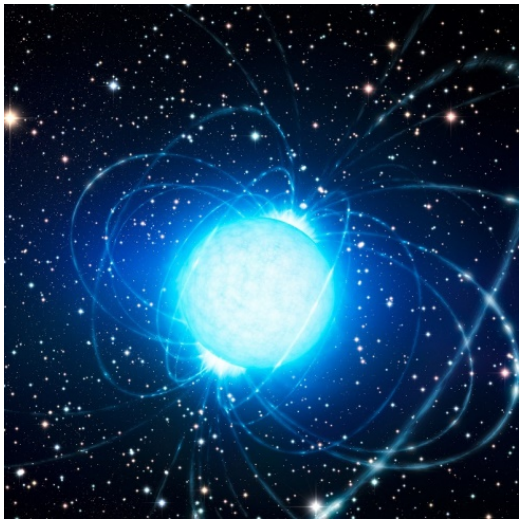


$\Lambda_{\mathrm{QCD}} < \sqrt{eB}$

large effect !

Introduction

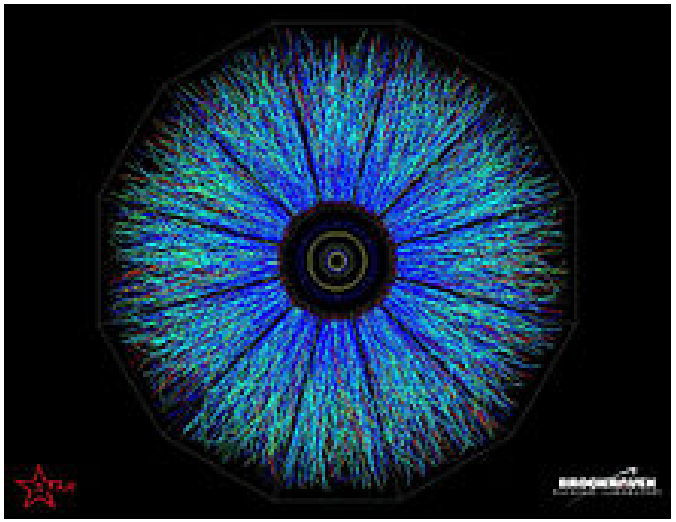
magneter



https://en.wikipedia.org/wiki/Magnetar

$eB \sim 10\ MeV^2$

heavy-ion collision



https://en.wikipedia.org/wiki/Relativistic_Heavy_Ion_Collider

$eB \sim 10^4\ MeV^2$

Introduction

lattice QCD + external U(1) link variables

$$S = S_{\rm YM}[U] + S_{\rm quark}[\bar{\psi}, \psi, U, u] + \cancel{S_{\rm EM}[u]}$$

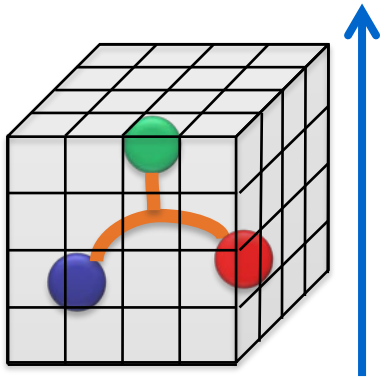
$$U_\mu(x) \longrightarrow U_\mu(x) \times u_\mu(x)$$

SU(3) → SU(3) × U(1)

Introduction

lattice QCD + external U(1) link variables

$$S = S_{\mathrm{YM}}[U] + S_{\mathrm{quark}}[\bar{\psi}, \psi, U, u] + \cancel{S_{\mathrm{EM}}[u]}$$



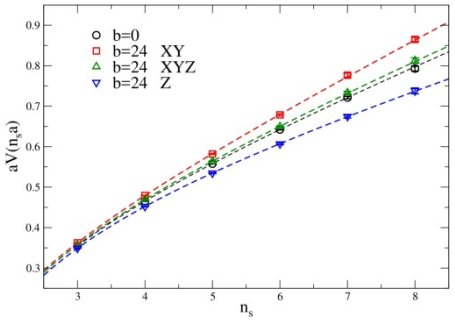
homogeneous magnetic field

B

Introduction

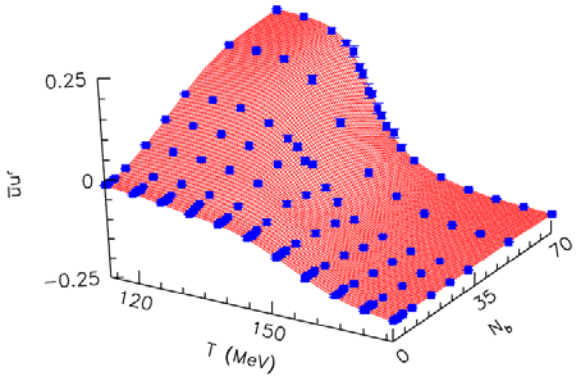
quark-antiquark potential

Bonati, D'Elia, Mariti, Mesiti, Negro (2014)



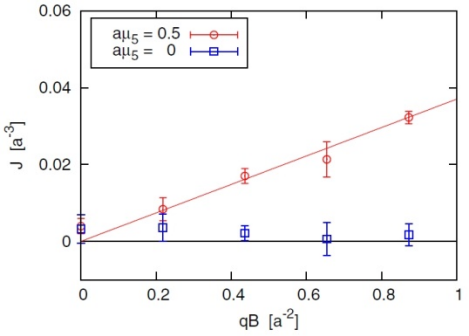
magnetic catalysis

Bali, Bruckmann, Endrődi, Fodor, Katz, Krieg, Schäfer, Szabó (2012)



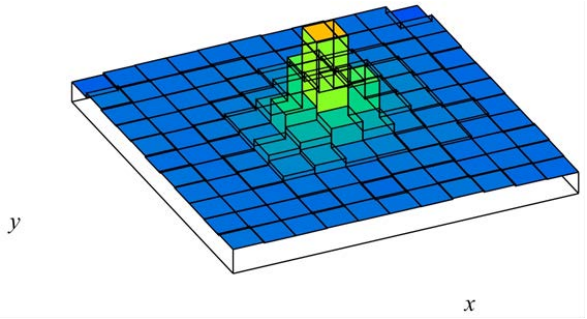
chiral magnetic effect

Yamamoto (2011)



topological vortex

Yamamoto (2018)



Mesons in Magnetic Fields

positively charged pion

$$\pi \equiv \bar{d}\gamma_5 u$$

positively charged and polarized ρ meson

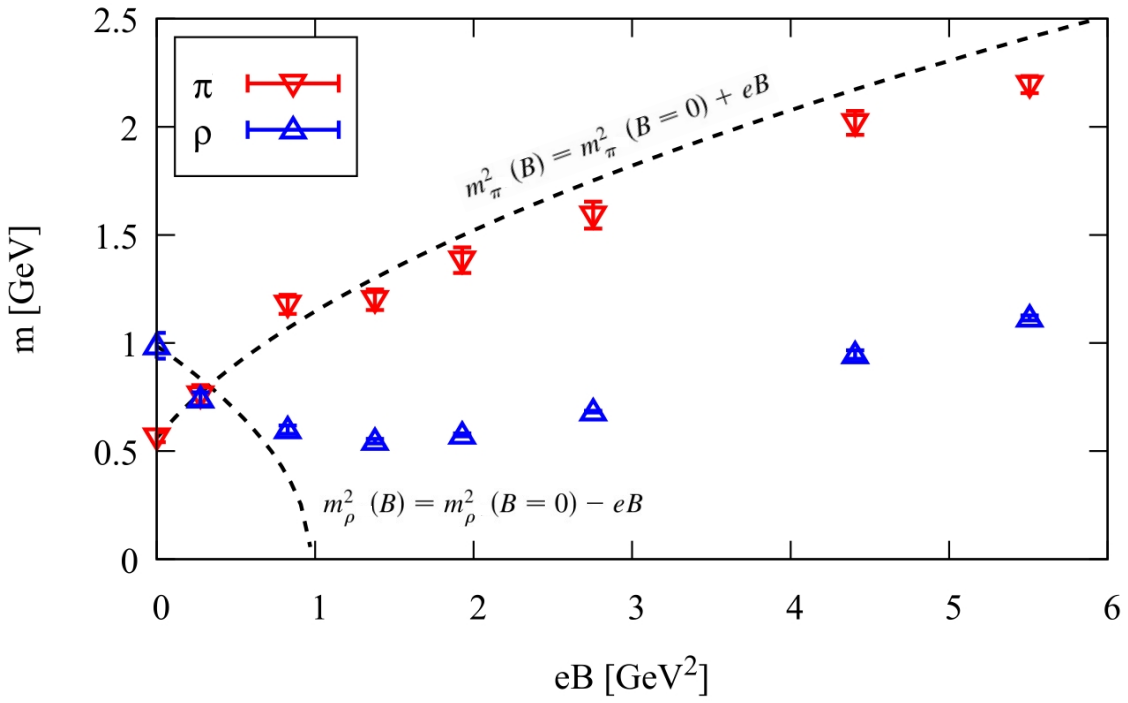
$$\rho \equiv \bar{d}\left(\frac{\gamma_1 - i\gamma_2}{\sqrt{2}}\right) u$$

These mesons are the ground states even at $B \neq 0$.

Mesons in Magnetic Fields

mass shift

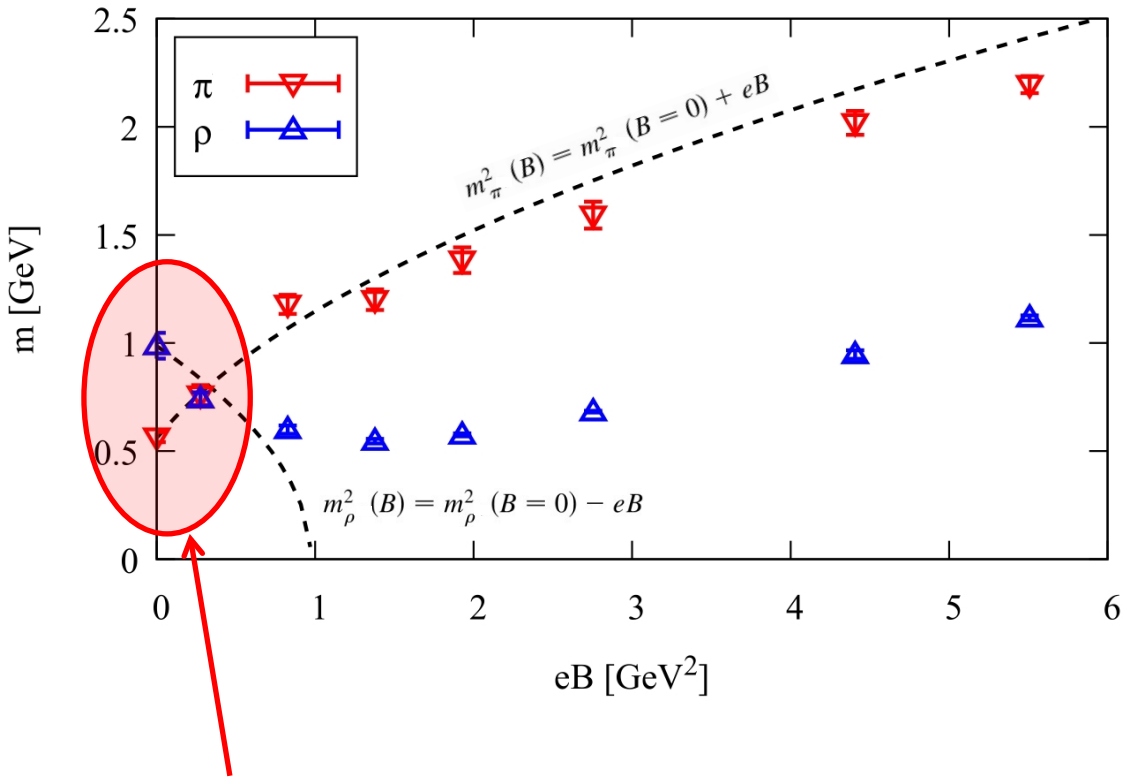
Hidaka, Yamamoto (2013)



Mesons in Magnetic Fields

mass shift

Hidaka, Yamamoto (2013)

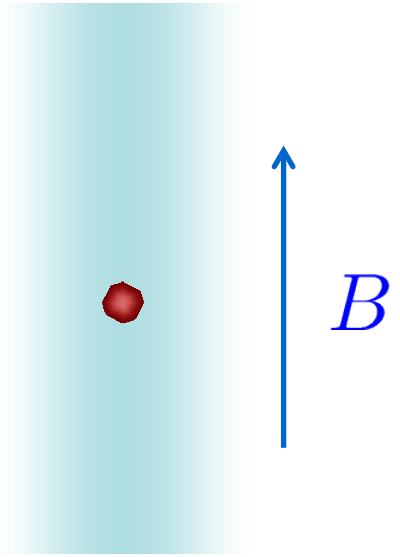


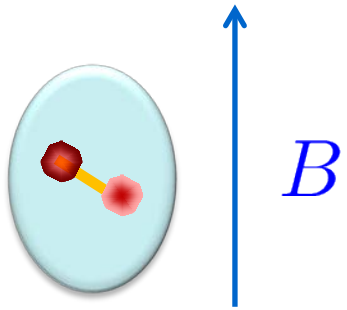
point-particle approximation? internal structure?

Mesons in Magnetic Fields

point particle

composite particle





"Landau quantization"

Mesons deform?

Mesons in Magnetic Fields

form factor?

$$\langle \pi(p_f) | J_\mu | \pi(p_i) \rangle$$

	pion form factor	nucleon form factor
$B = 0$	connected diagram	connected diagram disconnected diagram

Mesons in Magnetic Fields

form factor?

$$\langle \pi(p_f) | J_\mu | \pi(p_i) \rangle$$

	pion form factor	nucleon form factor
$B = 0$	connected diagram	connected diagram disconnected diagram
$B \neq 0$	connected diagram disconnected diagram	connected diagram disconnected diagram

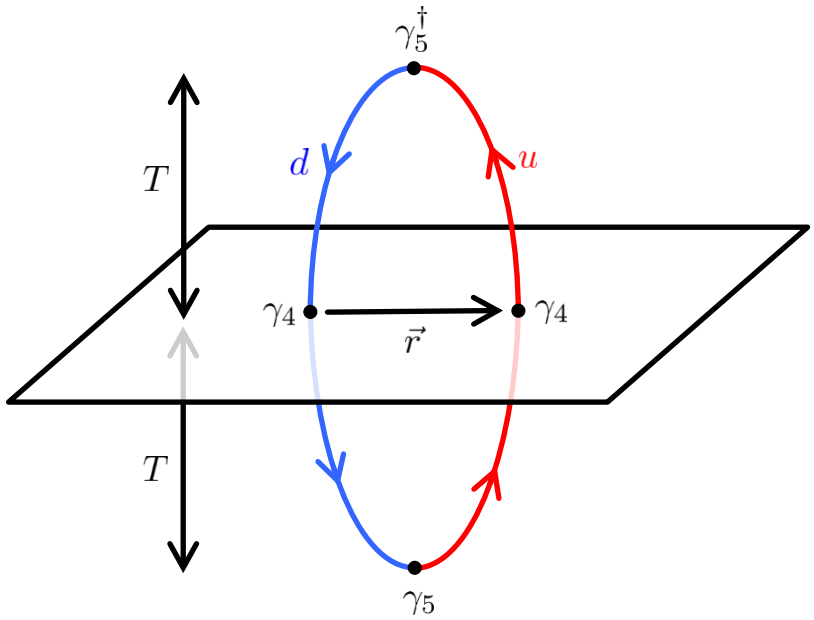
Simulation

density-density correlation in coordinate space

Burkardt, Grandy, Negele (1995) Alexandrou, de Forcrand, Tsapalis (2002)

$$C_\pi(\vec{r}) \propto \sum_{\vec{R}} \langle \pi | n_u(\vec{R}+\vec{r}) n_d(\vec{R}) | \pi \rangle$$

$$\begin{aligned} n_u &= :\bar{u}\gamma_4 u: &&= \bar{u}\gamma_4 u - \langle 0|\bar{u}\gamma_4 u|0\rangle \\ n_d &= :\bar{d}\gamma_4 d: &&= \bar{d}\gamma_4 d - \langle 0|\bar{d}\gamma_4 d|0\rangle \end{aligned}$$



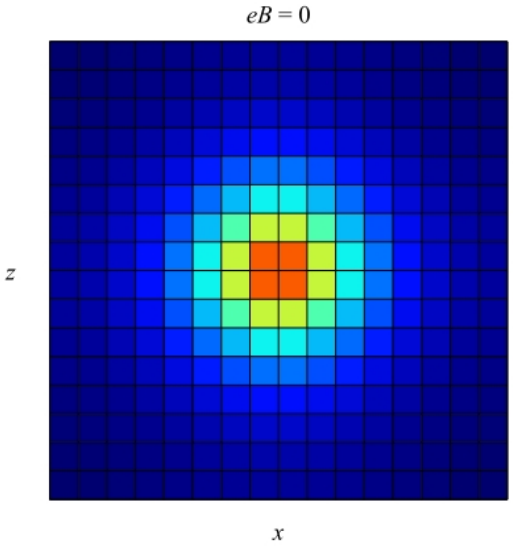
Simulation

- ✓ quenched Wilson fermion
- ✓ lattice spacing ~ 0.10 fm
- ✓ spatial volume ~ $(1.6\ \mathrm{fm})^3$
- ✓ pion mass ~ 0.49 GeV
- ✓ same quark mass, but different electric charge

$$m_u = m_d \qquad \frac{2}{3}e \neq -\frac{1}{3}e$$

Results

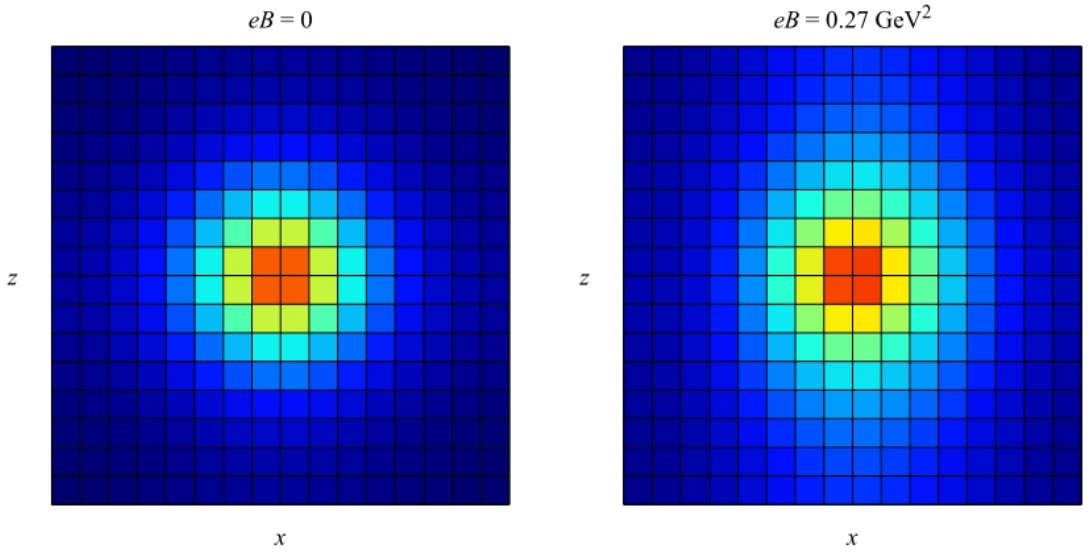
$$\pi \equiv \bar{d}\gamma_5 u$$



spherical

Results

$$\pi \equiv \bar{d}\gamma_5 u$$



spherical

Results

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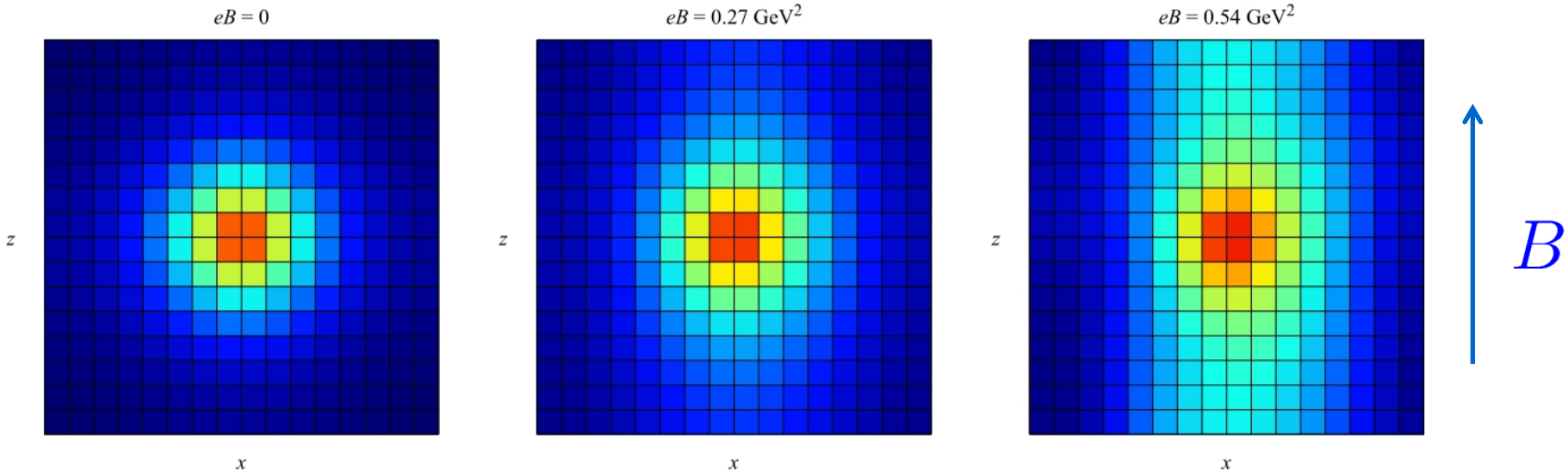
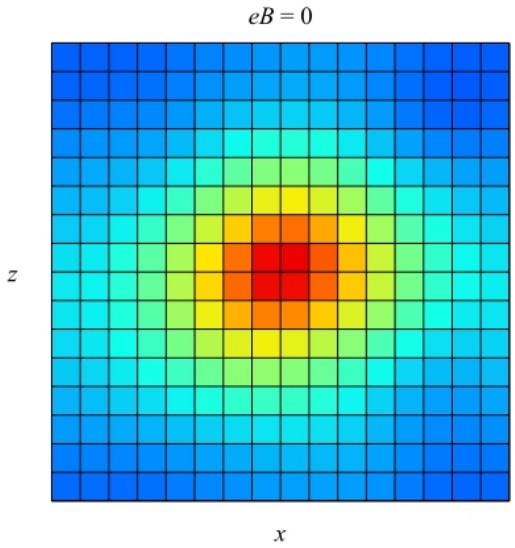


spherical

"prolate" (cigar-like)

Results

$$\rho \equiv \bar{d}\left(\frac{\gamma_1 - i\gamma_2}{\sqrt{2}}\right) u$$

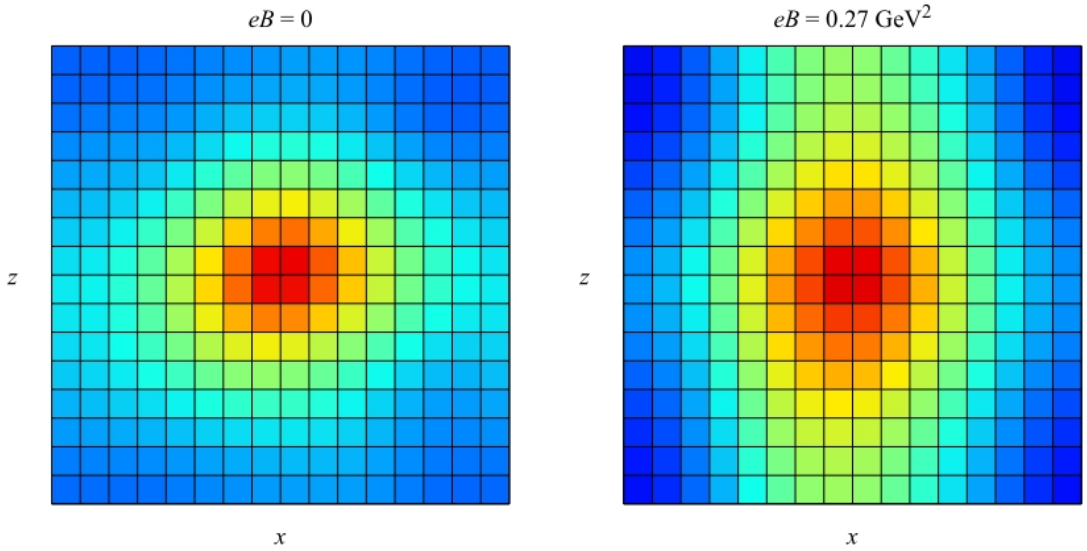


polarization

"oblate" (disk-like)

Results

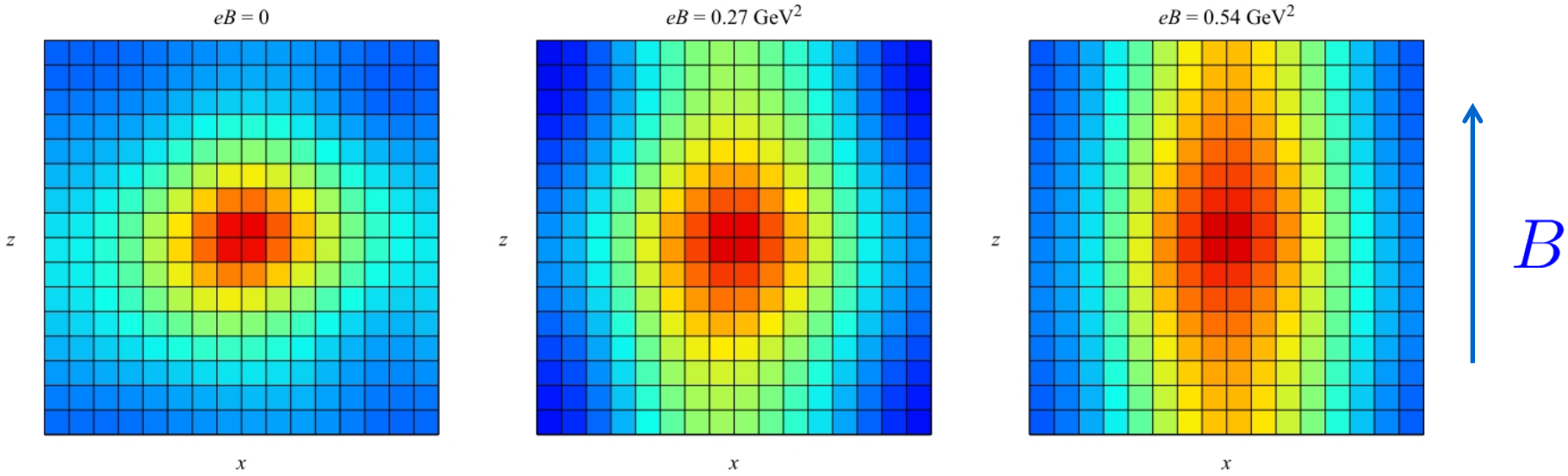
$$\rho \equiv \bar{d}\left(\frac{\gamma_1 - i\gamma_2}{\sqrt{2}}\right) u$$



"oblate" (disk-like)

Results

$$\rho \equiv \bar{d}\left(\frac{\gamma_1 - i\gamma_2}{\sqrt{2}}\right) u$$



"oblate" (disk-like)

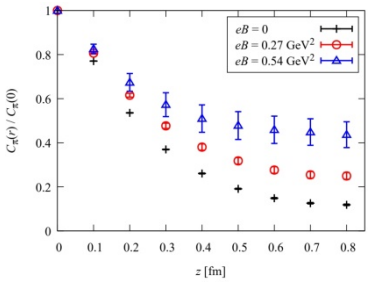
"prolate" (cigar-like)

Results

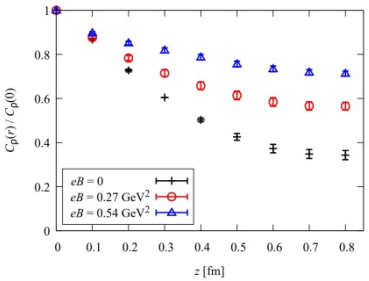
"Why does the mesons deform?"

Results

longitudinal deformation



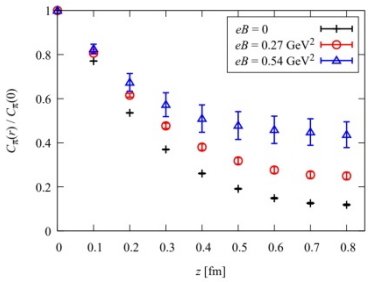
$\Longrightarrow$ pion size ↗



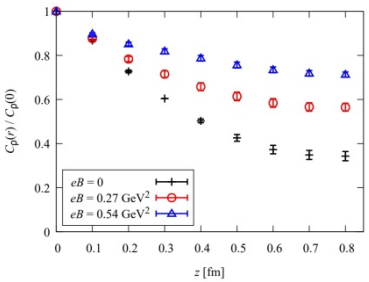
$\Longrightarrow$ ρ meson size ↗

Results

longitudinal deformation



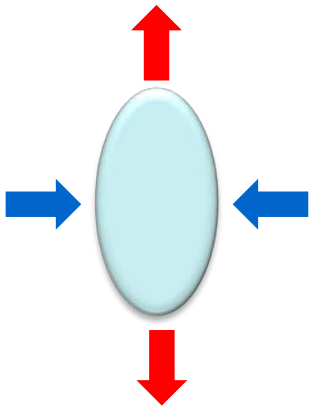
$\Longrightarrow$ pion size ↗



$\Longrightarrow$ ρ meson size ↗

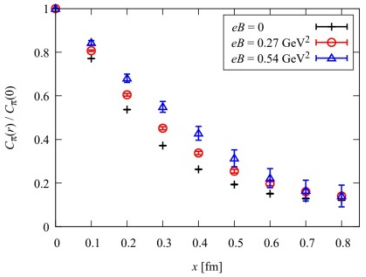
$\Longleftrightarrow$

cyclotron motion
(Landau quantization)

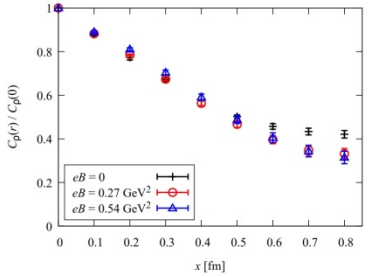


Results

transverse deformation



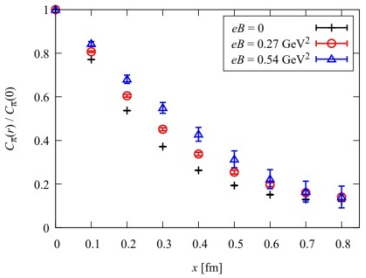
$\Longrightarrow$ pion size ↗



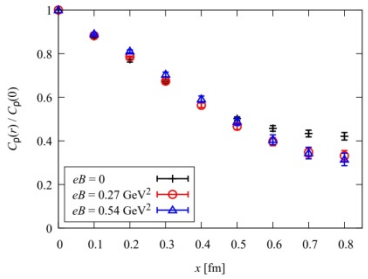
$\Longrightarrow$ ρ meson size ↘

Results

transverse deformation



$\Longrightarrow$ pion size ↗ $\Longleftrightarrow$ pion mass ↗, binding energy ↘

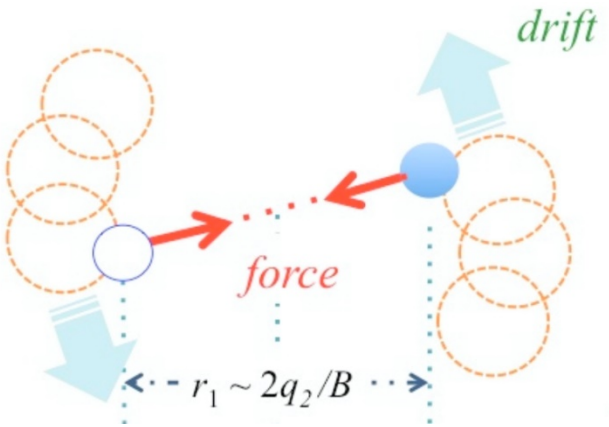


$\Longrightarrow$ ρ meson size ↘ $\Longleftrightarrow$ ρ meson mass ↘, binding energy ↗

Results

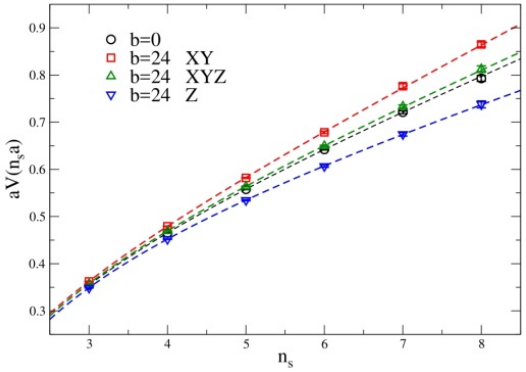
other possibilities

rotational modes of quarks



Hattori, Kojo, Su (2016)

anisotropic string tension
(only in full QCD)



Bonati, D'Elia, Mariti, Mesiti, Negro (2014)

Results

$$\frac{\bar{z}^2}{\bar{x}^2} = \frac{\sum_{\vec{r}} z^2 C(\vec{r})}{\sum_{\vec{r}} x^2 C(\vec{r})}$$

Results

$$\frac{\bar{z}^2}{\bar{x}^2} = \frac{\sum_{\vec{r}} z^2 C(\vec{r})}{\sum_{\vec{r}} x^2 C(\vec{r})}$$

$$\left(\frac{\bar{z}}{\bar{x}}\right)_\pi = 1.09 \pm 0.02 \quad \left(\frac{\bar{z}}{\bar{x}}\right)_\rho = 1.10 \pm 0.03 \quad \text{at} \quad eB \simeq 0.27 \text{ GeV}^2 \sim m_\pi^2$$

$$\left(\frac{\bar{z}}{\bar{x}}\right)_\pi = 1.25 \pm 0.11 \quad \left(\frac{\bar{z}}{\bar{x}}\right)_\rho = 1.14 \pm 0.02 \quad \text{at} \quad eB \simeq 0.54 \text{ GeV}^2 \sim 2m_\pi^2$$

The deformation is 10-20 %.

Summary

We studied meson deformation in strong magnetic fields.

- ✓ 10-20% deformation
- ✓ physical point?

$m_\pi \searrow \Longrightarrow$ deformation $\nearrow$

$eB \searrow \Longrightarrow$ deformation $\searrow$

- ✓ relevant for phenomenology or experiments?