Fluctuations of conserved charges in strong magnetic fields in (2+1)-flavor QCD

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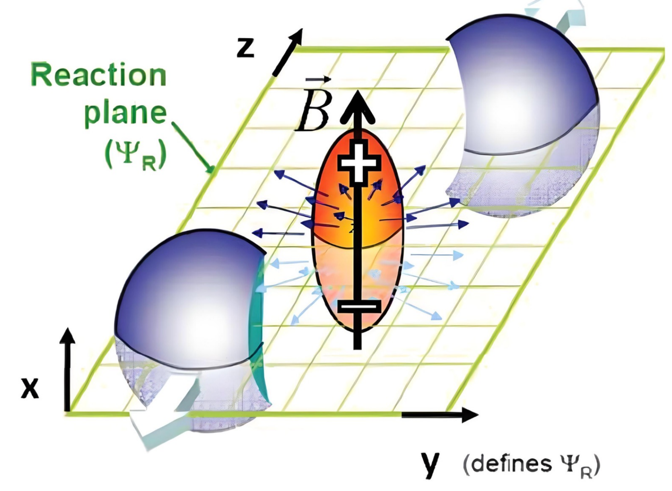
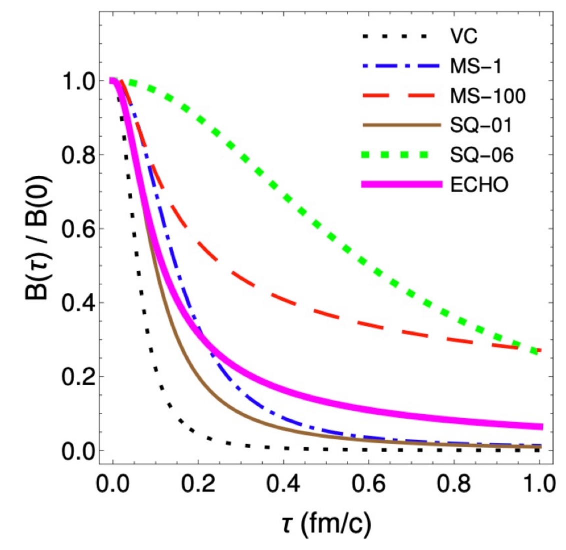
Introduction





- A strong magnetic field can be generated in off-central heavy-ion collisions (HIC), and it may have a considerable impact on QCD interactions[1]
- This strong magnetic field, produced in the early stage, is expected to decay rapidly[2]
- The magnetic field is the key ingredient for the chiral magnetic effect

How to probe magnetic fields in HIC?

Fluctuations of conserved charges have been used for a long time to explore QCD phase structure, they are defined as[3]

$$\hat{\chi}_{ijk}^{\mathrm{BQS}} = \left. \frac{\partial^{i+j+k} p/T^4}{\partial\left(\mu_{\mathrm{B}}/T\right)^i \partial\left(\mu_{\mathrm{Q}}/T\right)^j \partial\left(\mu_{\mathrm{S}}/T\right)^k} \right|_{\mu_{\mathrm{B,Q,S}}=0}$$

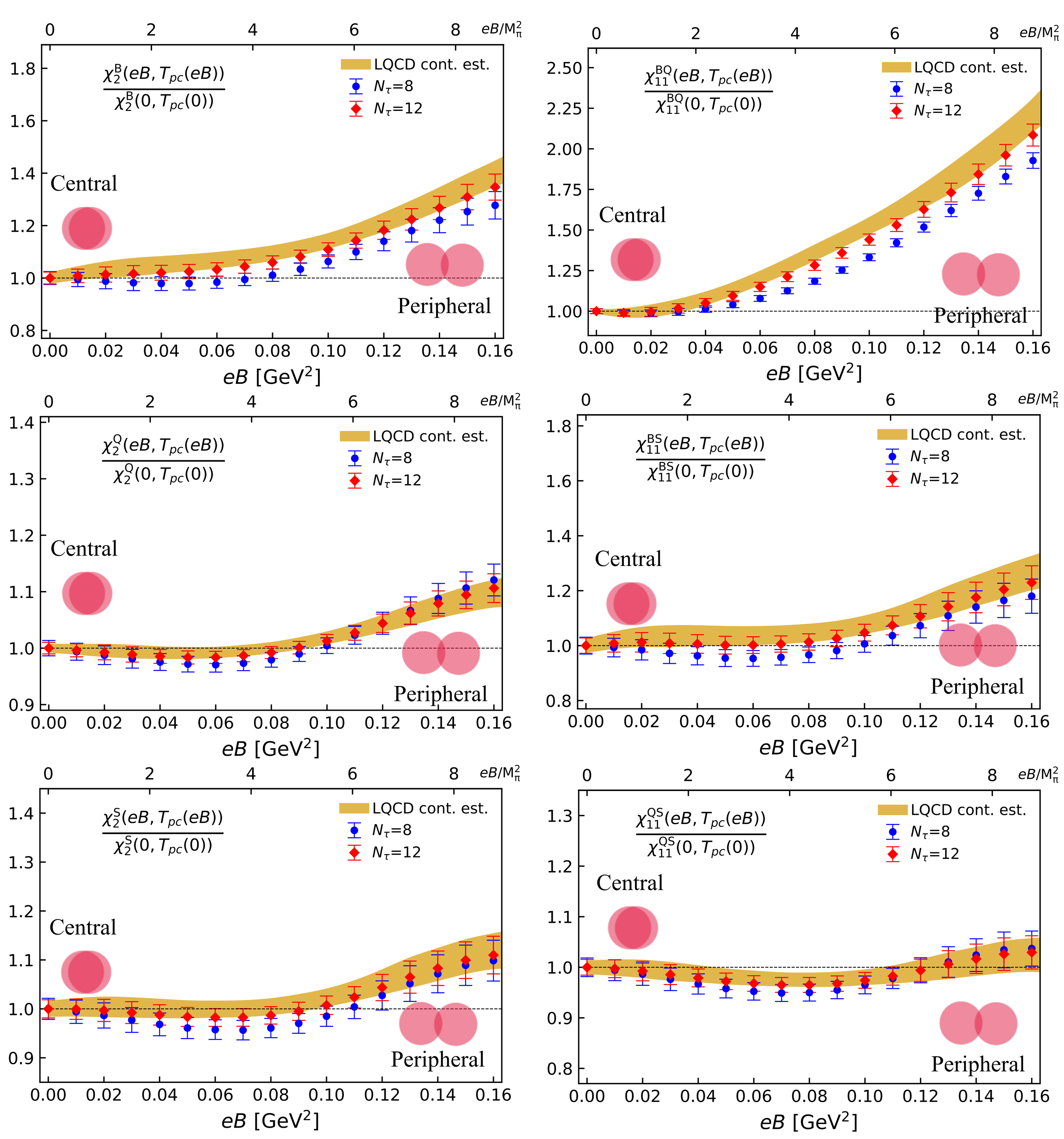
However, at non-zero *eB*, studies on it are limited. The impact of magnetic fields on the fluctuations of conserved charges requires further research.

Lattice QCD calculations

Lattice setup

In this study, (2+1) flavor lattice QCD calculations are based on

- **Action**: Highly improved staggered fermions and a tree-level improved Symanzik gauge action
- **Lattice sizes**: $32^3\times 8$, $48^3\times 12$
- **Quark mass**: $m_s^{phy}/m_l = 27$, $m_\pi \approx 135$ MeV
- ***T* window**: (144 MeV, 165 MeV), i.e. (0.9 T_{pc}, 1.1 T_{pc})
- ***eB* window**: $0 \leq eB \lesssim 9m_\pi^2$



- ✓ Weak (strong) magnetic fields correspond to central (peripheral) collisions
- ✓ The ratio of fluctuations in a strong magnetic field to those in a zero magnetic field is a R_{cp}-like quantity
- ✓ Each 2nd-order cumulant shows different dependencies on the magnetic field
- ✓ χ_{11}^{BQ} is **most affected** by the magnetic field and can perhaps be used as a magnetometer

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Hadron resonance gas model

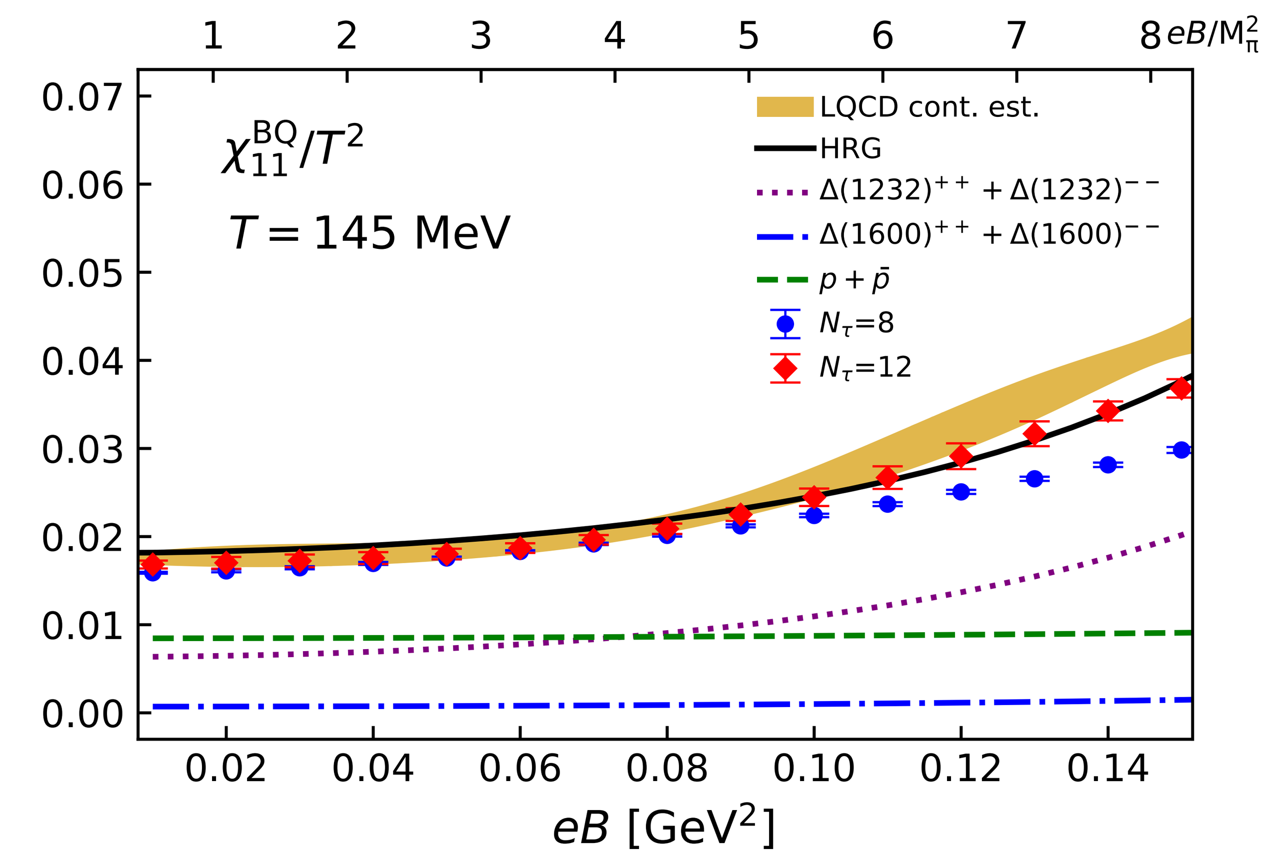
Pressure arising from charged hadrons[4]:

$$\frac{p_c^{M/B}}{T^4} = \frac{|q_i| B}{2\pi^2 T^3} \sum_{s_z=-s_i}^{s_i} \sum_{l=0}^{\infty} \varepsilon_0 \sum_{k=1}^{\infty} (\pm 1)^{k+1} \frac{e^{k\mu_i/T}}{k} \mathrm{K}_1\left(\frac{k\varepsilon_0}{T}\right)$$

where the energy of charged particles in a magnetic field is

$$\varepsilon_0 = \sqrt{m_i^2 + 2|q_i| B\left(l + 1/2 - s_z\right)}$$

and K_1 is the first-order modified Bessel function.



- The results of HRG model are **consistent** with LQCD up to $\boldsymbol{eB\sim 6m_\pi^2}$
- Contributions from proton(p) are **almost independent** on *eB*
- $\Delta^{++}(1232)$ and $\Delta^{--}(1232)$ give **most of the contributions** to the magnetic field dependence of χ_{11}^{BQ}
- However, $\Delta^{++}(1232)$ and $\Delta^{--}(1232)$ are not measurable in HIC experiments

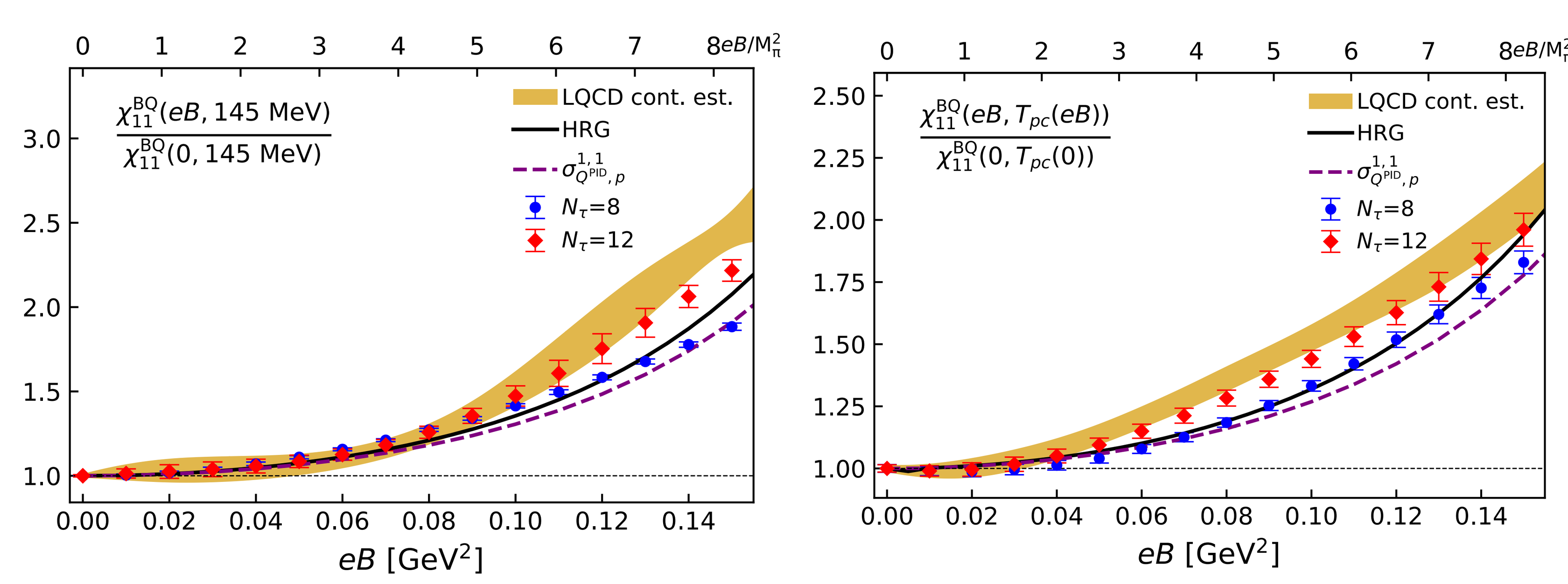
Proxy

Fluctuations expressed in terms of stable hadronic states[5]:

$$\chi_{ijk}^{\mathrm{BQS}}\left(T, \hat{\mu}_{\mathrm{B}}, \hat{\mu}_{\mathrm{Q}}, \hat{\mu}_{\mathrm{S}}\right) = \sum_R \mathrm{B}_R^i \mathrm{Q}_R^j \mathrm{S}_R^k \frac{\partial^l p_R/T^4}{\partial \hat{\mu}_R^l}$$

In experiment, fluctuations are related to the variance or covariance of the net particle numbers identified as π, K and p[6].

For instance, the proxy for χ_{11}^{BQ} is $\sigma_{\mathrm{Q}^{PID},p}^{1,1} = \sigma_p^2 + \sigma_{p,\pi}^{1,1} + \sigma_{p,K}^{1,1}$



- At low temperature, the results of HRG model and proxy are **consistent** with LQCD up to $eB\sim\mathbf{0.08\ GeV^2}$, at $eB > 0.08$ GeV^2, the difference between the proxy and lattice ~ **20%**
- At T_{pc}, the proxy $\sigma_{\mathrm{Q}^{PID},p}^{1,1}$ can represent approximately **85%** of the LQCD results

Summary

- QCD benchmarks are provided for the 2nd order fluctuations of conserved charges based on LQCD computation on N_τ = 8 and 12 lattices
- χ_{11}^{BQ} is significantly influenced by the magnetic field
- R_{cp}-like quantity could be useful to detect the existence of the magnetic field in HIC
- A reasonable proxy is provided for measurements in HIC

[1] *V. Skokov et al. Int. J. Mod. Phys. A 24 (2009) 5925*
[2] *Anping Huang et al. Phys.Lett.B 777 (2018) 177-183*
[3] *Allton et al., Phys.Rev. D66 (2002) 074507*
[4] *H.-T.Ding et al., Eur. Phys. J. A 57 (2021) 6, 202*
[5] *R. Bellwied et al. ,Phys. Rev. D 101, 034506 (2020)*
[6] *STAR, Phys.Rev.C 105(2019) 2, 029901*

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