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Fluctuations of conserved charges in strong magnetic fields

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H.-T. Ding, S.-T. Li, Q. Shi, X.-D. Wang, Eur.Phys.J.A 57 (2021) 6, 202

and work in progress

Strangeness in Quark Matter
2022.06.13

Fluctuations of B, Q and S in external magnetic fields

Taylor expansion of the QCD pressure:

Allton et al., Phys.Rev. D66 (2002) 074507
Gavai & Gupta et al., Phys.Rev. D68 (2003) 034506

$$\frac{p}{T^4} = \frac{1}{VT^3}\ln \mathcal{Z}\left(T, V, \hat{\mu}_u, \hat{\mu}_d, \hat{\mu}_s\right) = \sum_{i,j,k=0}^{\infty} \frac{\chi_{ijk}^{BQS}}{i!j!k!}\left(\frac{\mu_B}{T}\right)^i\left(\frac{\mu_Q}{T}\right)^j\left(\frac{\mu_S}{T}\right)^k$$

B : baryon number

Q : electric charge

S : strangeness

Fluctuations of B, Q and S are computable in LQCD

$$\hat{\chi}_{ijk}^{uds} = \frac{\partial^{i+j+k} p/T^4}{\partial\left(\mu_u/T\right)^i \partial\left(\mu_d/T\right)^j \partial\left(\mu_s/T\right)^k}\Bigg|_{\mu_{u,d,s}=0}$$

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

$$\mu_u = \frac{1}{3}\mu_\mathrm{B} + \frac{2}{3}\mu_\mathrm{Q}$$

$$\mu_d = \frac{1}{3}\mu_\mathrm{B} - \frac{1}{3}\mu_\mathrm{Q}$$

$$\mu_s = \frac{1}{3}\mu_\mathrm{B} - \frac{1}{3}\mu_\mathrm{Q} - \mu_\mathrm{S}\,.$$

See recent reviews:
LQCD: H.-T.Ding, F. Karsch, S.Mukherjee, Int. J. Mod. Phys. E 24 (2015) no.10, 1530007
Exp.: X.-F. Luo & N. Xu, Nucl. Sci. Tech. 28 (2017) 112

Huge magnetic fields can be produced at the initial time of heavy-ion collisions. The strength of the magnetic fields could reach $3\ m_\pi^2$ in RHIC and to $40\ m_\pi^2$ in LHC. However, the prediction of the life time of magnetic fields varies from different models.

At $eB = 0$: Fluctuations of B,Q and S have been extensively employed to study the changes in the degree of freedom in the system as well as QCD phase structure

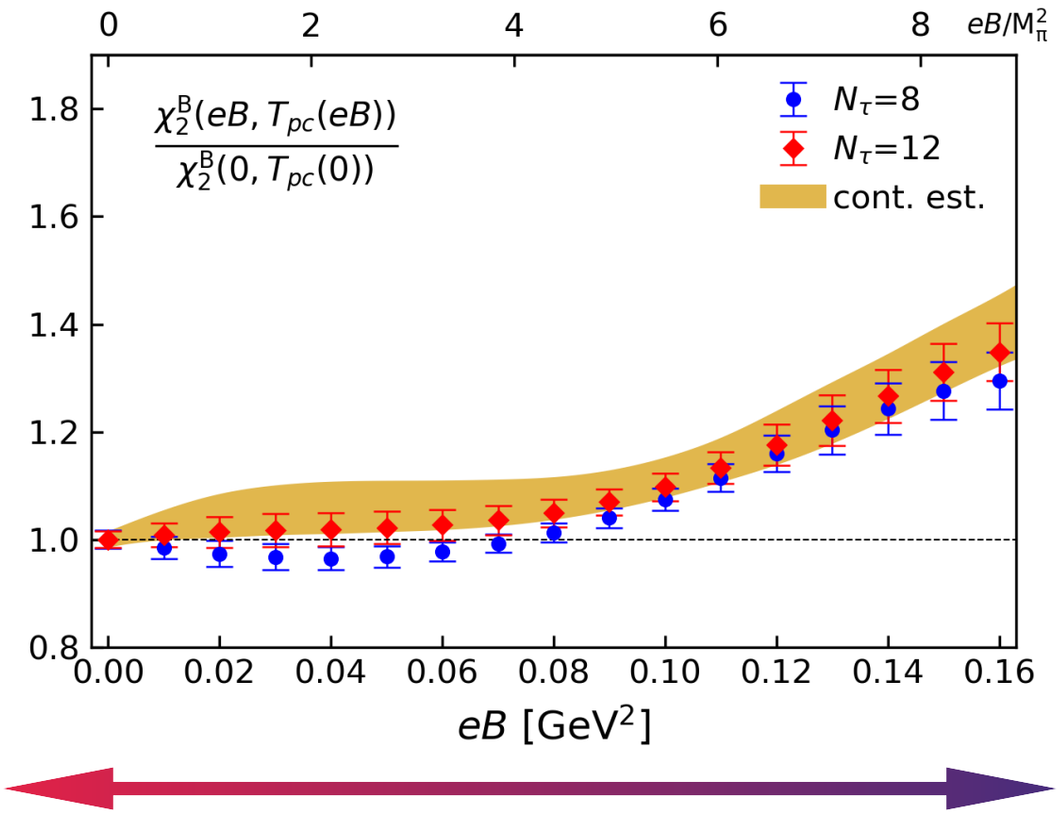
At $eB \neq 0$: we propose that fluctuations of B,Q and S can be used as a probe for magnetic fields as they are both theoretically computable and experimentally measurable. *See H.-T.Ding et al. , Eur.Phys.J.A 57 (2021) 6, 202*

Fluctuations along the transition line($T_{pc}(eB)$)

Initial magnetic fields are strongly related to the collision's impact parameter. I.e. peripheral collisions with large *eB* while central collisions with small *eB*.

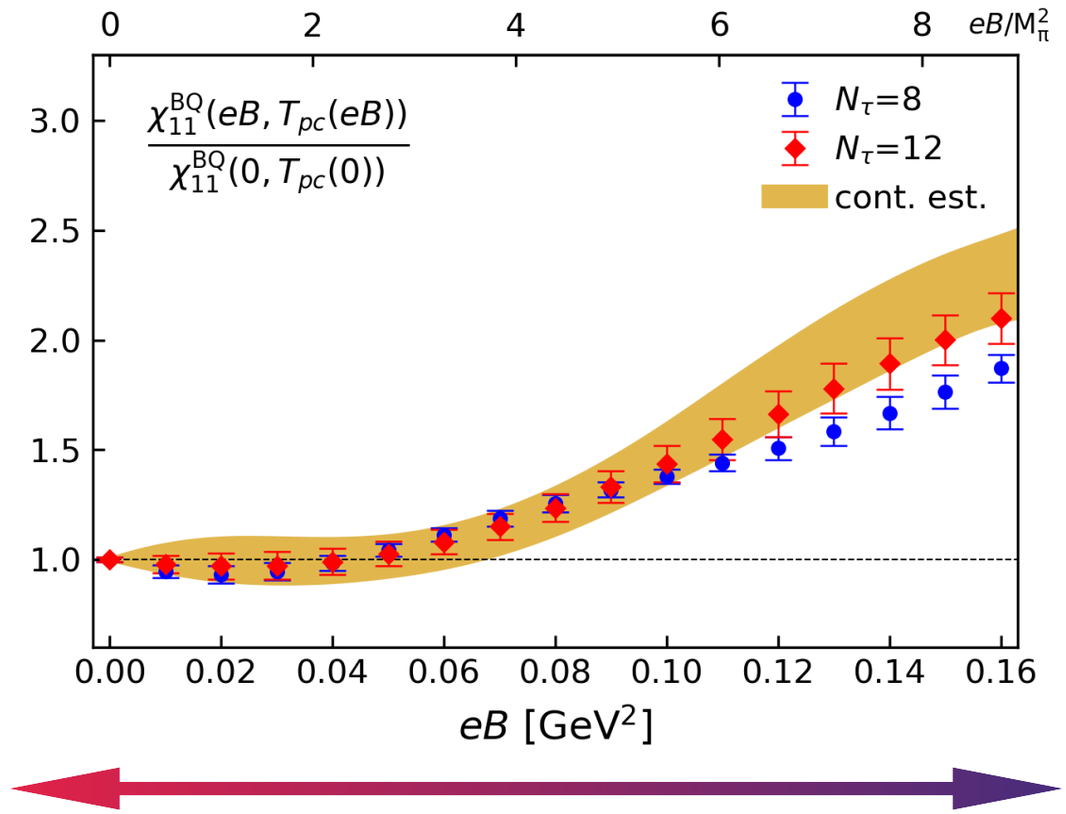
We propose an Rcp-like (ratio between central collisions and peripheral collisions) quantity to detect the existence of magnetic in HIC: $X\left(\mathrm{eB}, T_{pc}(\mathrm{eB})\right)/X\left(0, T_{pc}(0)\right)$. The X is the fluctuation of conserved charges along the transition line

Lattice setup:
N_f=2+1 QCD,
$M_\pi(eB=0) \approx 135$ MeV,
$T_{pc}(eB=0) \approx 157$ MeV,
with HISQ action



Central Collisions — Peripheral Collisions

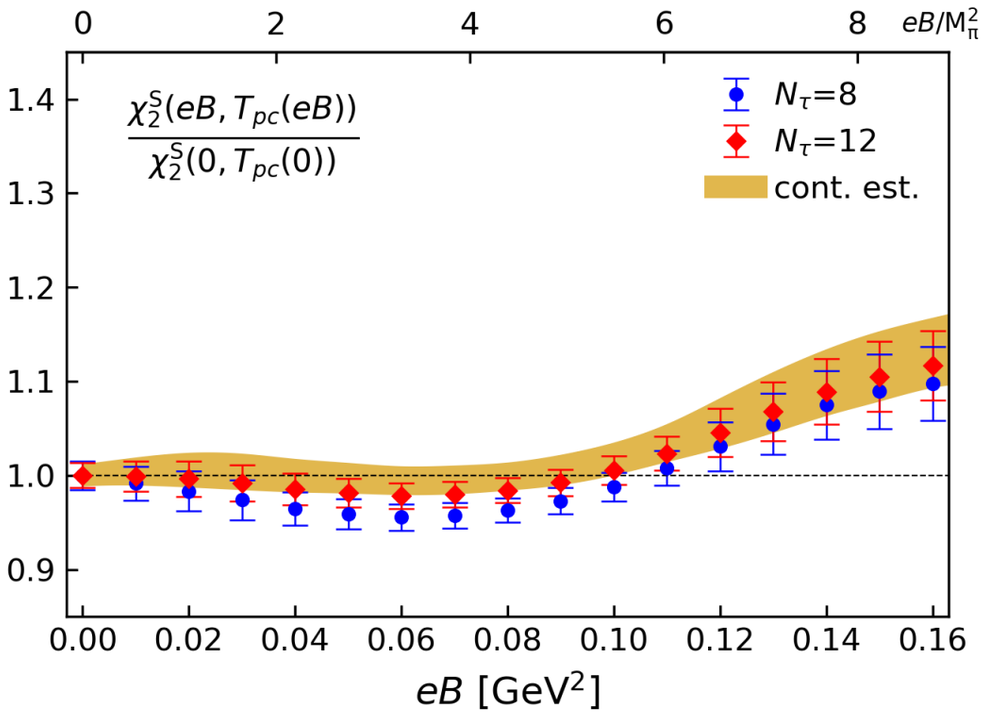
Small *eB* — **Large *eB***

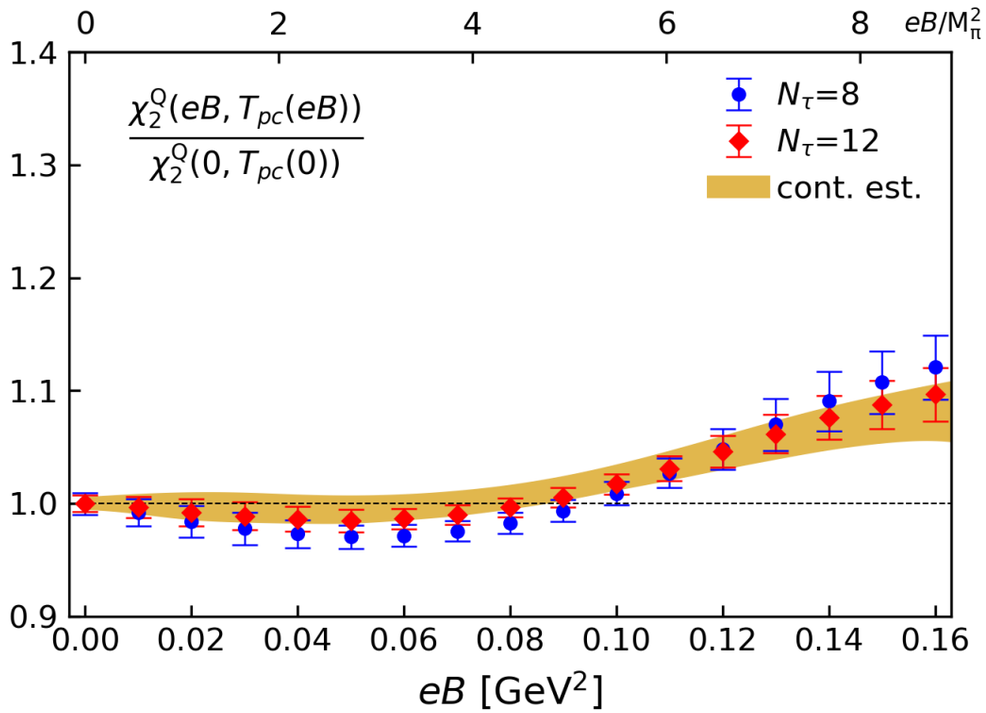


Central Collisions — Peripheral Collisions

Small *eB* — **Large *eB***

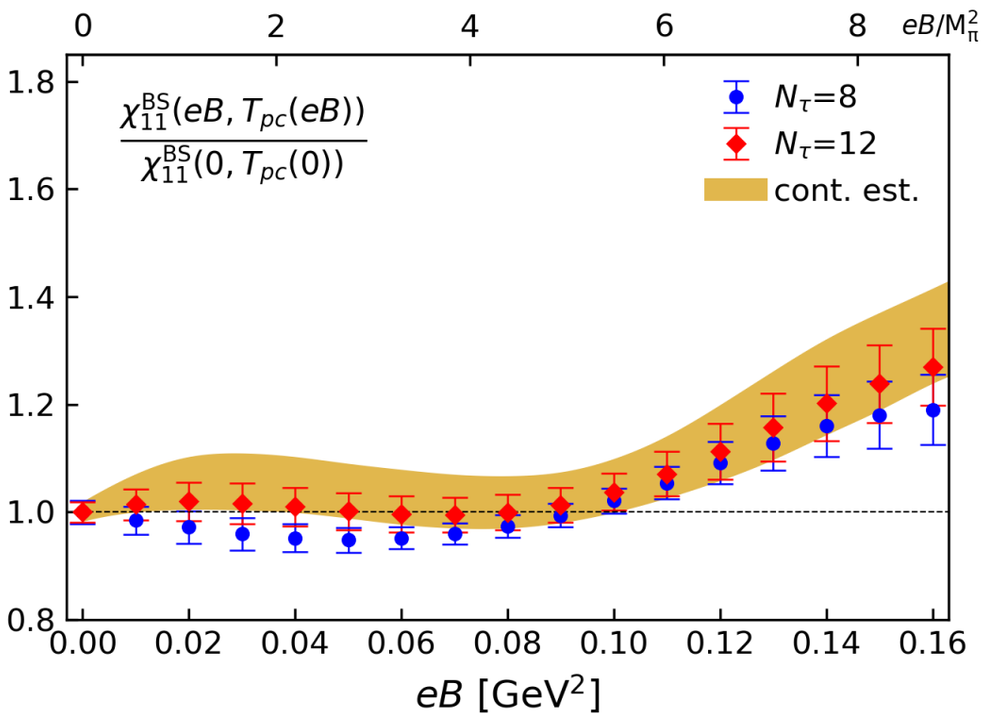
Other 2nd order fluctuations and correlations

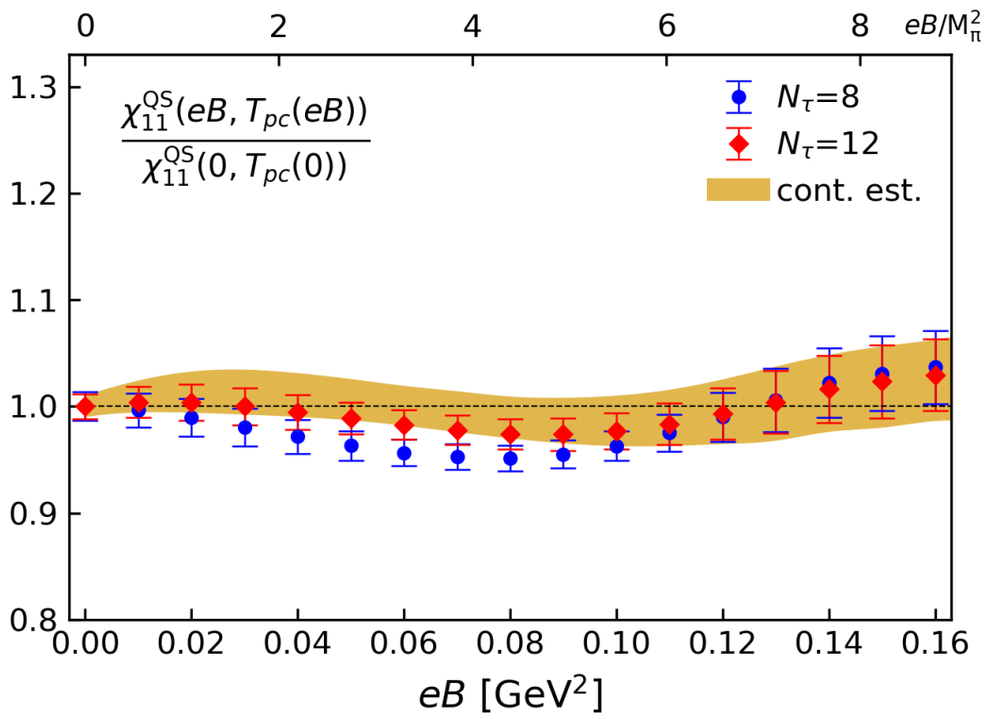




At $eB \simeq 9M_\pi^2$:

Ratio of χ_2^S ~ 1.1
Ratio of χ_2^Q ~ 1.07

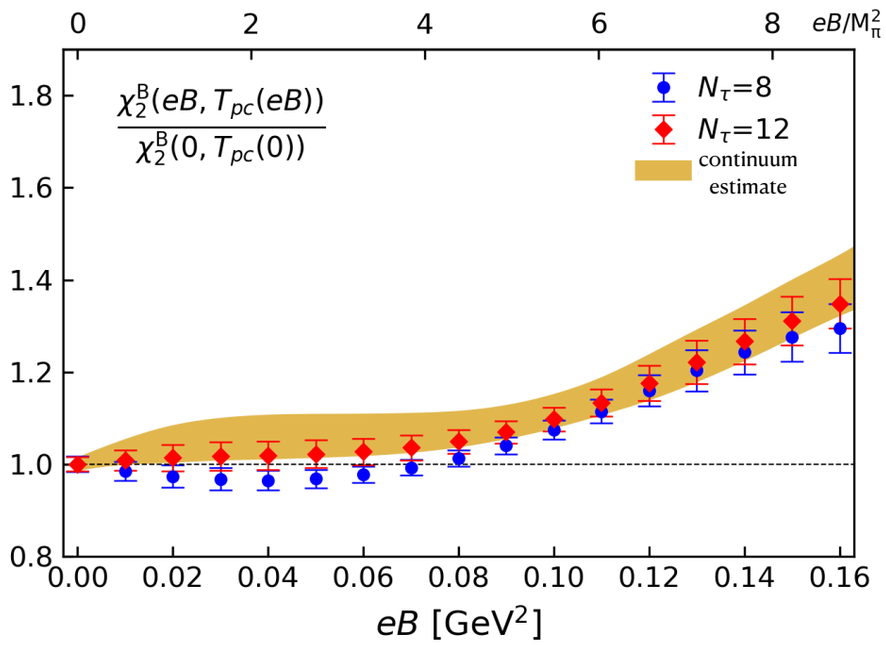


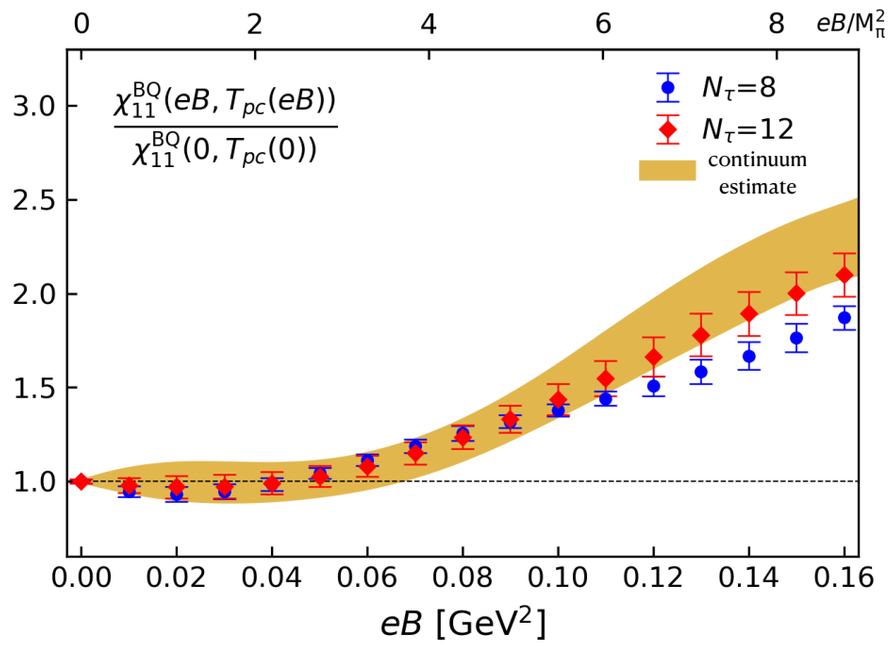


Ratio of χ_{11}^{BS} ~ 1.25
Ratio of χ_{11}^{QS} ~ 1.03

Summary

- The 2nd order fluctuations and correlations of B,Q & S are strongly affected by eB
- R_{cp} like quantity could be useful to detect the existence of the magnetic field in HIC





- LQCD provides a benchmark for the fluctuations of conserved charges at thermal equilibrium. For a realistic comparison with heavy-ion collisions experimental data, additional effective models are required.