Nuclear Science Computing Center at CCNU

QCD phase structure in strong magnetic fields

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based on *Phys. Rev. D 104 (2021) 014505 & Eur.Phys.J.A* 57 (2021) 6, 202,
in collaboration with
Heng-Tong Ding, Jun-Hong Liu, Qi Shi, Akio Tomiya, Xiao-Dan Wang, Yu Zhang

Outline

- Motivation and Introduction
- Lattice Setup
- Results
- Summary

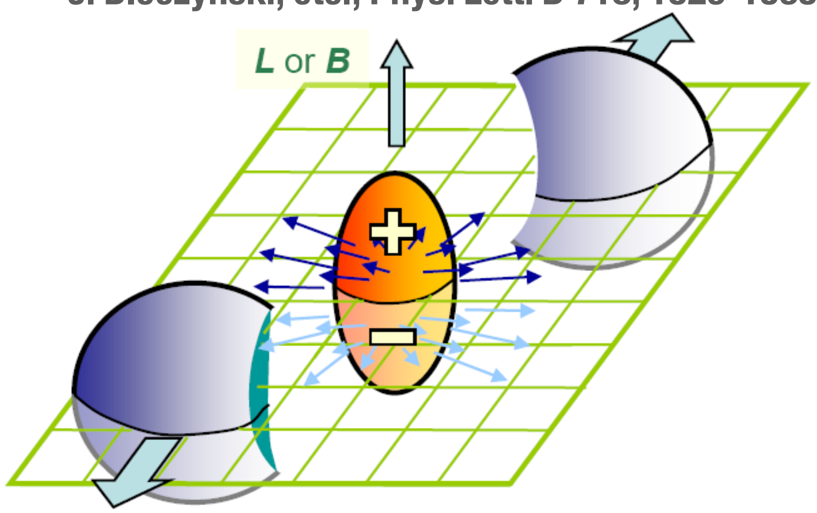
Motivation

Heavy-Ion collisions

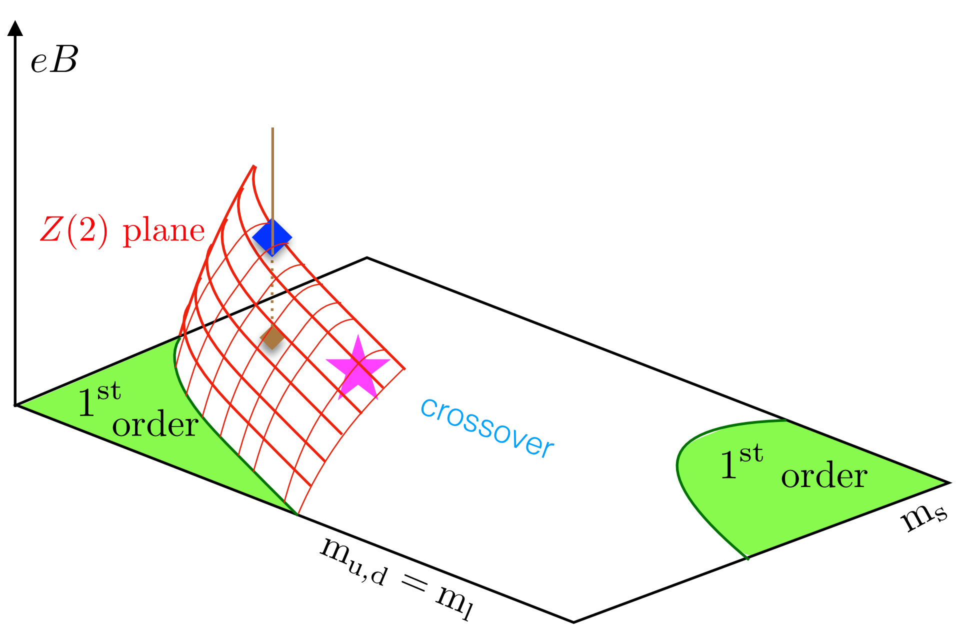
RHIC: $eB \sim O(1)m_\pi^2$

LHC: $eB \sim O(10)m_\pi^2$

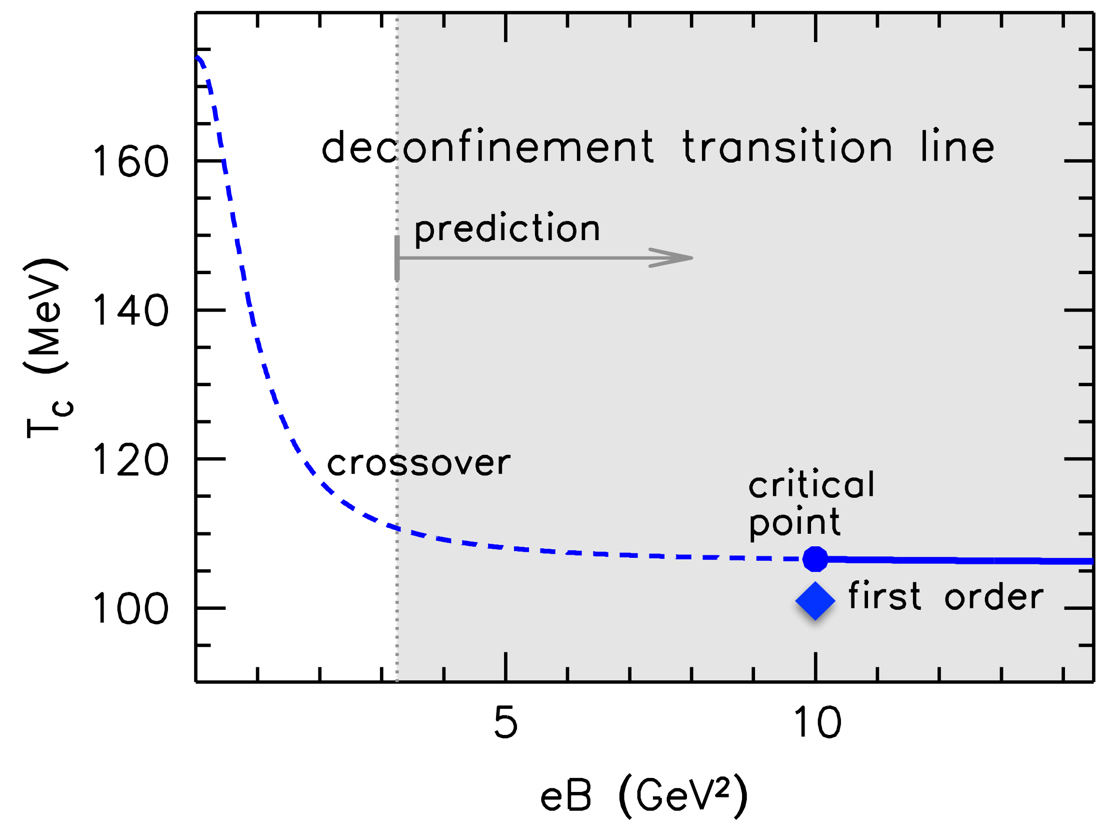
V. Skokov, etc., Int.J.Mod.Phys.A 24 (2009) 5925-5932
A. Bzdak, etc., Phys. Rev. Lett. 110, 192301 (2013).
J. Bloczynski, etc., Phys. Lett. B 718, 1529-1535 (2013).



STAR Collaboration (B.I. Abelev (Illinois U., Chicago) et al.). Phys.Rev. C81 (2010) 054908



T-eB plane

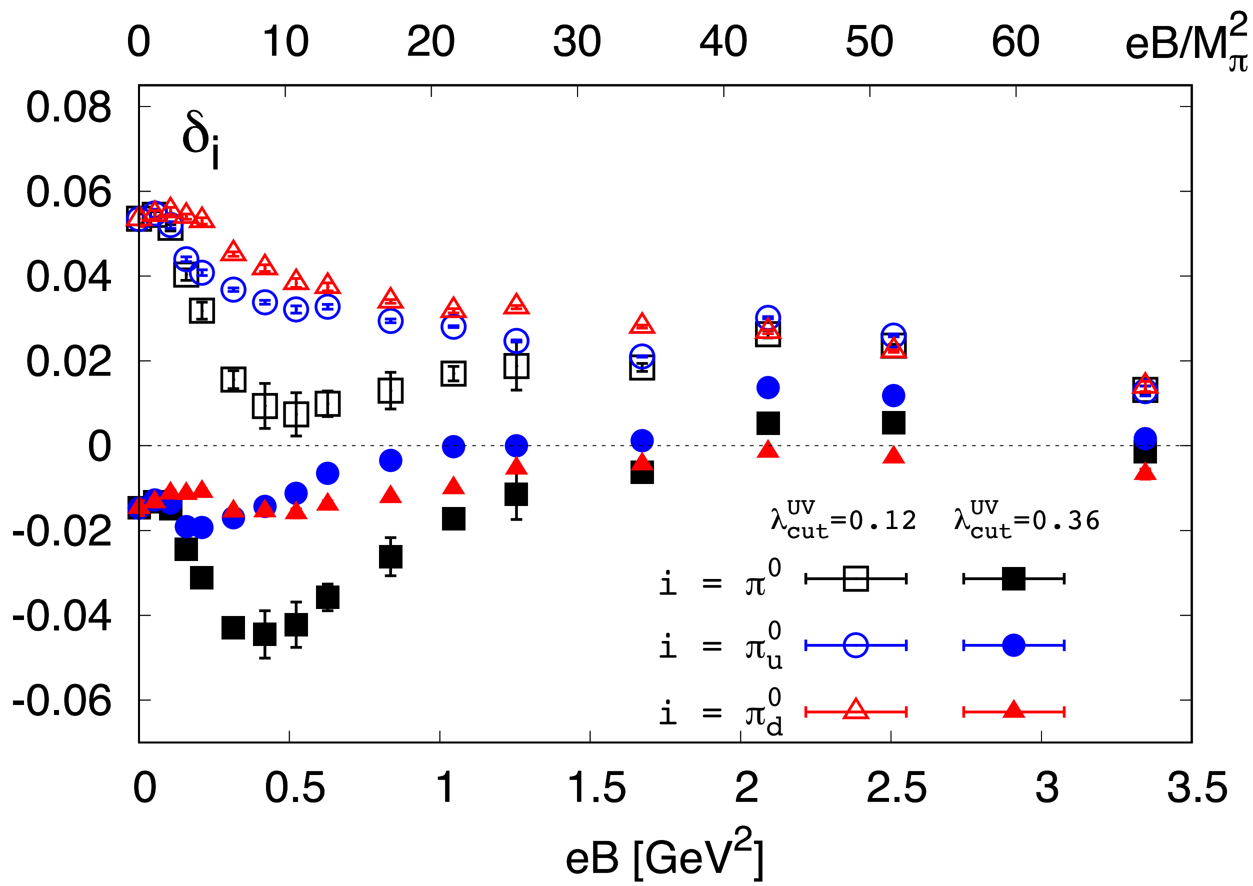


Gergely Endrodi(Regensburg U.) JHEP 07 (2015) 173 arxiv: 1504.08280

- **A possible Z(2) critical end point in T-eB plane ?**
- **How to detect eB in HIC experiments ?**

First LQCD study on GMOR relation at eB≠0 and T=0

N_f=2+1 QCD, $M_\pi(eB=0) \approx 220$ MeV,
$32^3 \times 96$ **lattices with** $a^{-1} \approx 1.7$ GeV **and HISQ action**



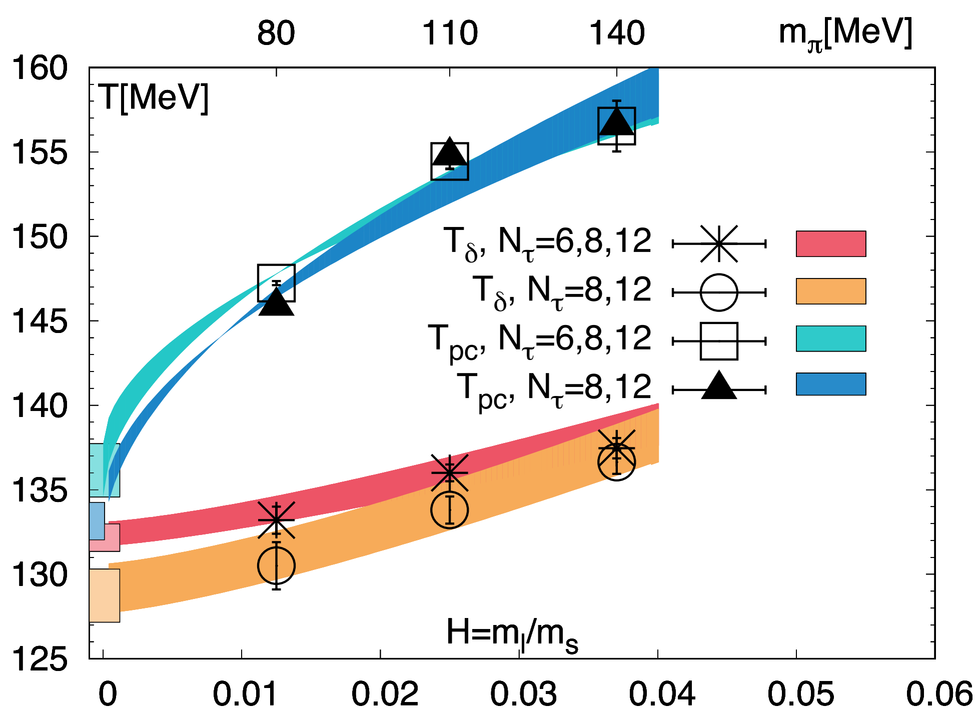
H.T. Ding, STL, A. Tomiya, X.-D. Wang, Y. Zhang, PRD 126 (2021) 082001

- $4m_u \langle\bar\psi\psi\rangle_u = 2f^2_{\pi^0_u} M^2_{\pi^0_u}(1-\delta_{\pi^0_u})$
- $4m_d \langle\bar\psi\psi\rangle_d = 2f^2_{\pi^0_d} M^2_{\pi^0_d}(1-\delta_{\pi^0_d})$
- $(m_u+m_d)\ \left(\langle\bar\psi\psi\rangle_u + \langle\bar\psi\psi\rangle_d\right) = 2\, f^2_{\pi^0}\, M^2_{\pi^0}(1-\delta_{\pi^0})$

Neutral pion remains as a Goldstone boson with eB up to ~3.5 GeV^2

GMOR relation holds in the presence of strong magnetic field

Masses of $\pi^{0,\pm}$ and $K^{0,\pm}$ and pressure



H.-T. Ding, STL, P. Hegde O. Kaczmarek et al.[HotQCD], Phys. Rev. Lett. 123 062002
H.-T. Ding, STL, et al. Nuclear Physics A 1005 (2021):121940

N_f=2+1 QCD, $M_\pi(eB=0) \approx 220$ MeV,
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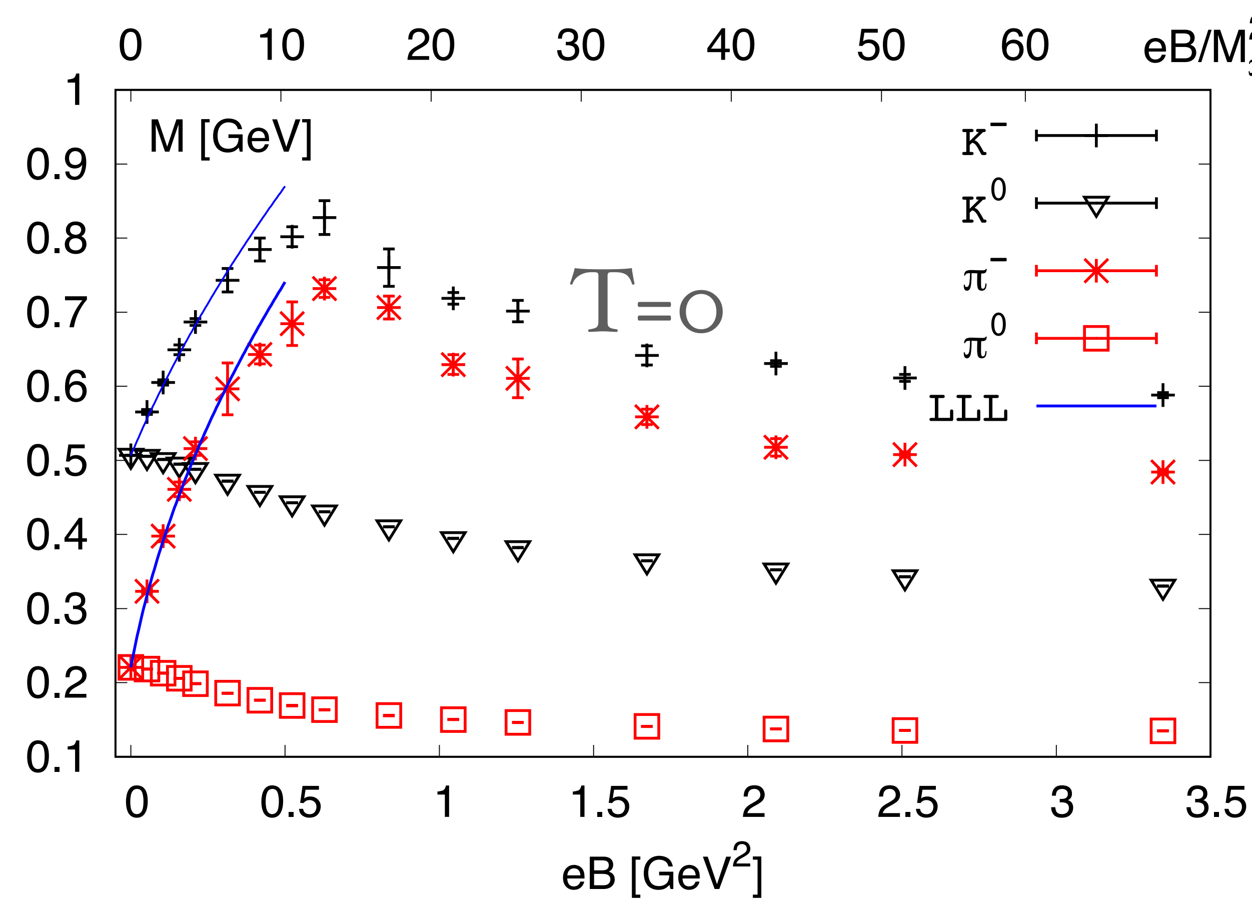

H.-T. Ding, STL, A. Tomiya, X.-D. Wang, Y. Zhang, PRD 126 (2021) 082001

☑ **Pion is the lightest Goldstone boson**

T_{pc} decrease as decrease M_π

See quenched LQCD results in Bali et al., PRD 97 (2018) 034505,
Luschevskaya et al., NPB 898 (2015) 627

Masses of $\pi^{0,\pm}$ and $K^{0,\pm}$ and pressure

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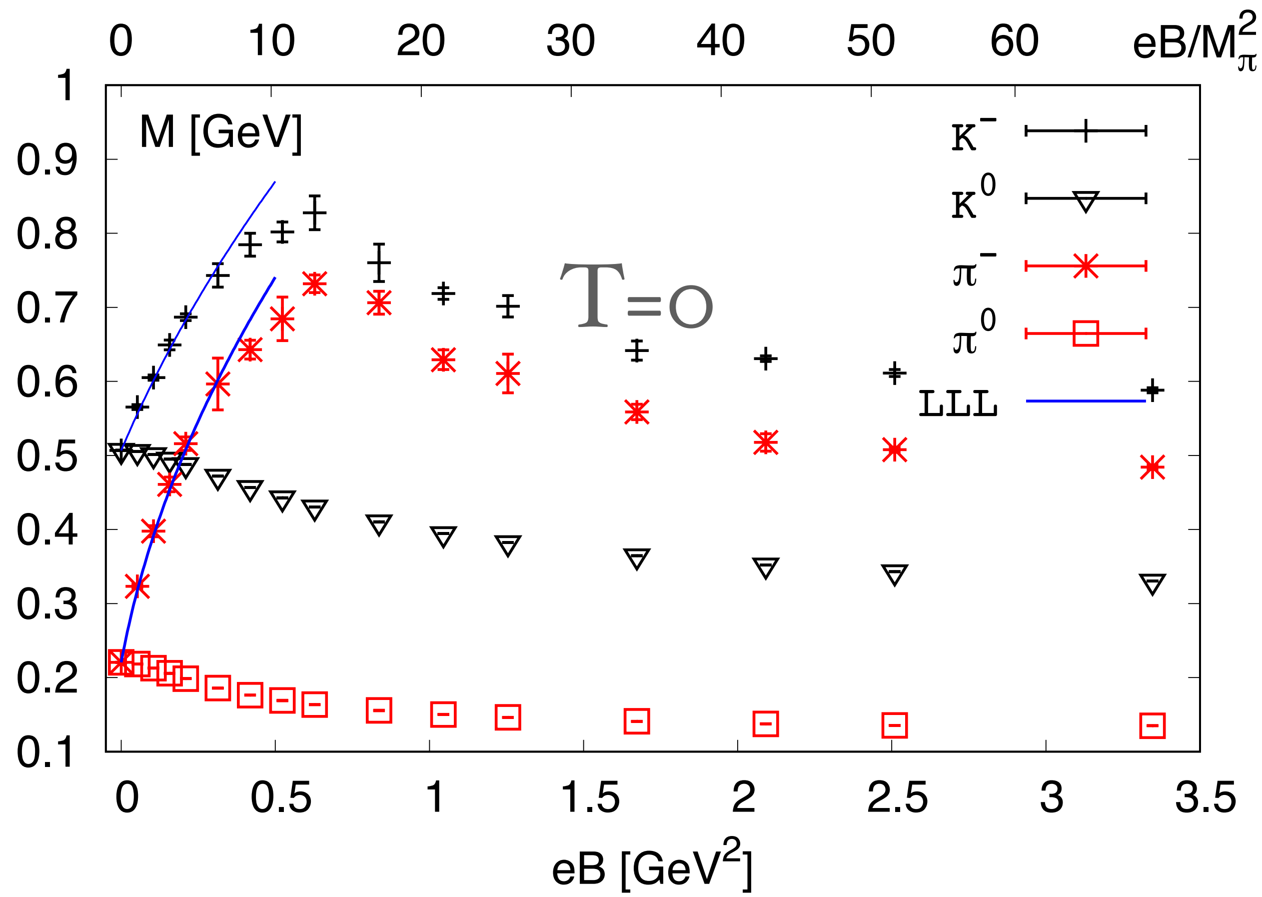
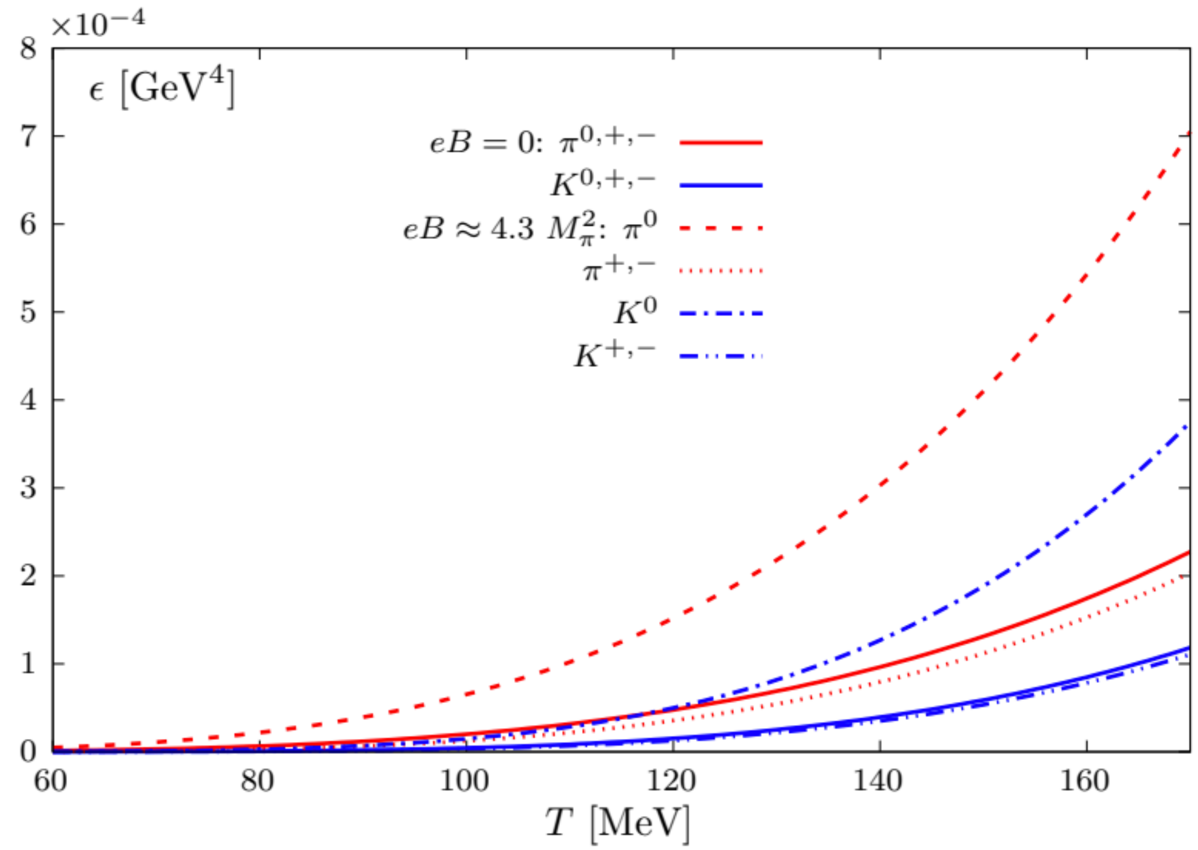


Energy density in Hadron resonance gas model



H.T. Ding, STL, A. Tomiya, X.-D. Wang, Y. Zhang, PRD 126 (2021) 082001

See quenched LQCD results in Bali et al., PRD 97 (2018) 034505, Luschevskaya et al., NPB 898 (2015) 627

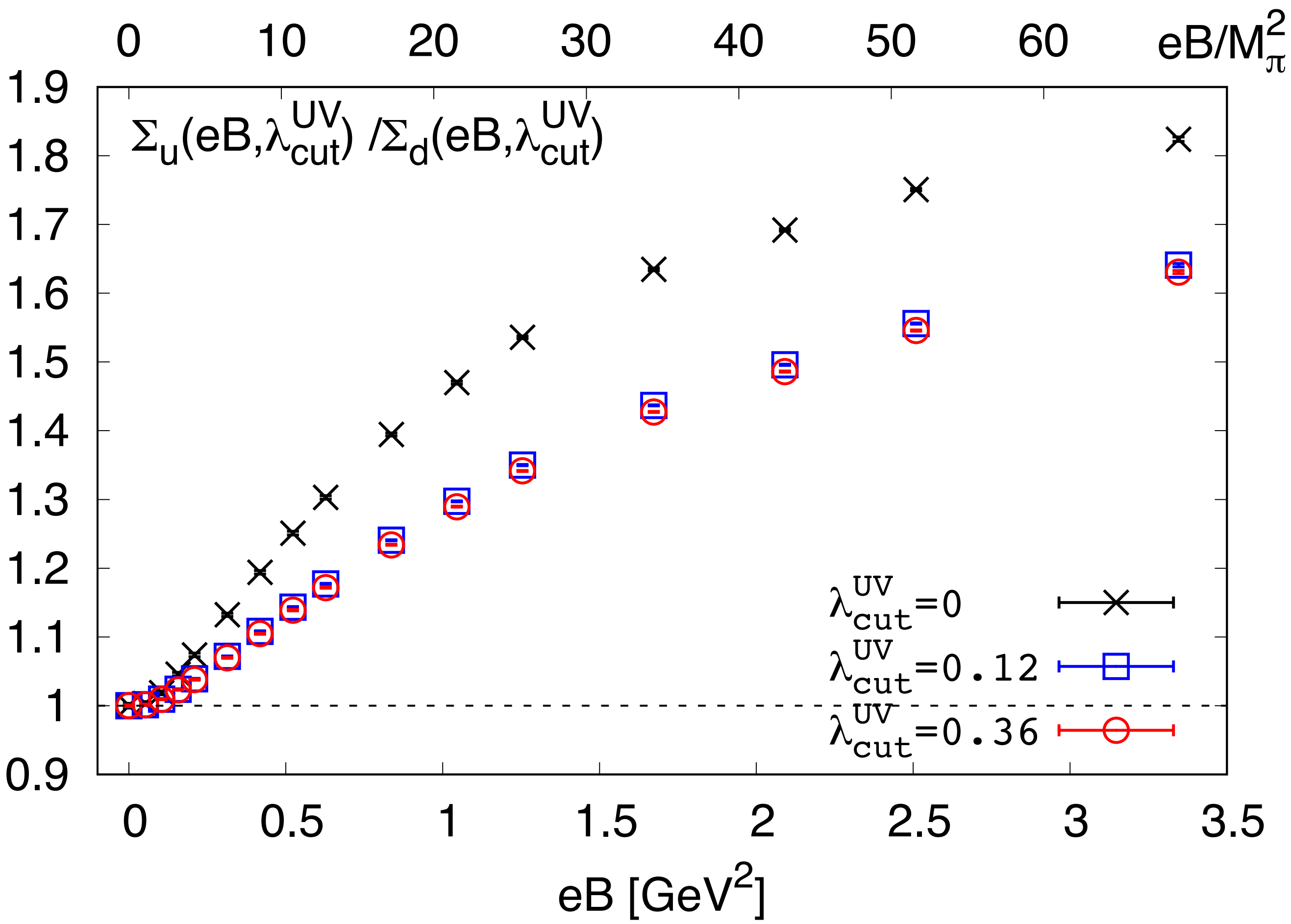
H.T. Ding, STL, Q. Shi, A. Tomiya, X.-D. Wang, Y. Zhang, arXiv: 2011.04870

Chiral Condensates

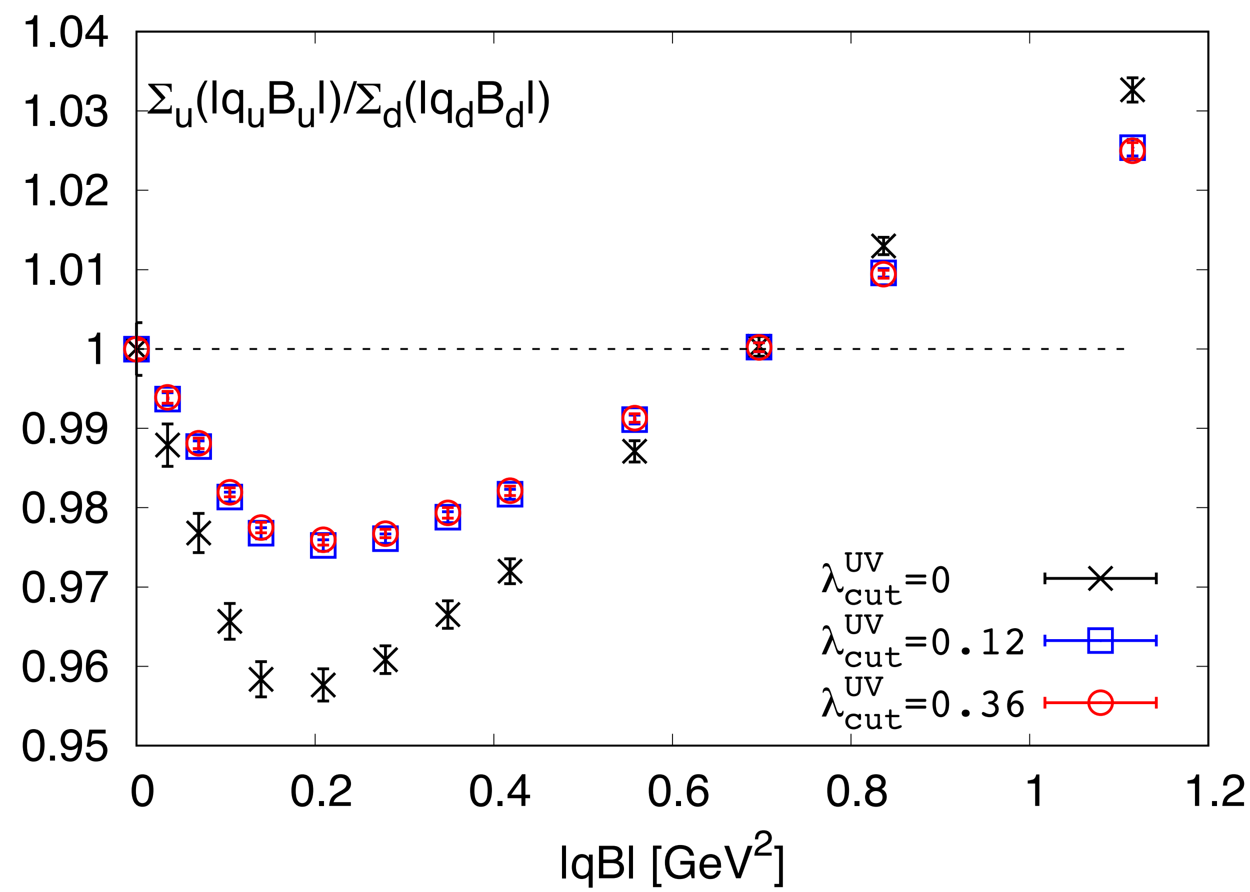
complete Dirac eigenvalue spectrum

H.-T. Ding, S.-T. Li, Swagato Mukherjee, A. Tomiya, X.-D. Wang, and Y. Zhang
Phys. Rev. Lett. 126, 082001(2021)

$$\Sigma_l(B, \lambda_{cut}^{\mathrm{UV}}) = \frac{2m_l}{M_\pi^2 f_\pi^2}\left(\langle\bar{\psi}\psi\rangle_l(B) - \langle\bar{\psi}\psi\rangle_l^{\mathrm{UV}}(B=0,\ \lambda_{cut}^{\mathrm{UV}})\right) + 1$$



$\boxed{|qB| = |q_u B_u| = |q_d B_d|}$

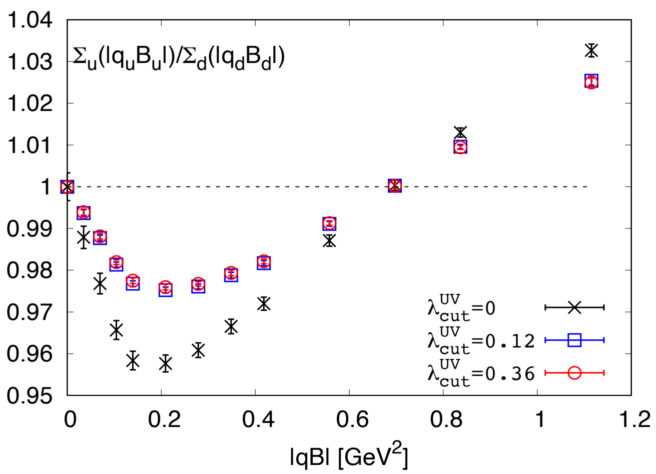


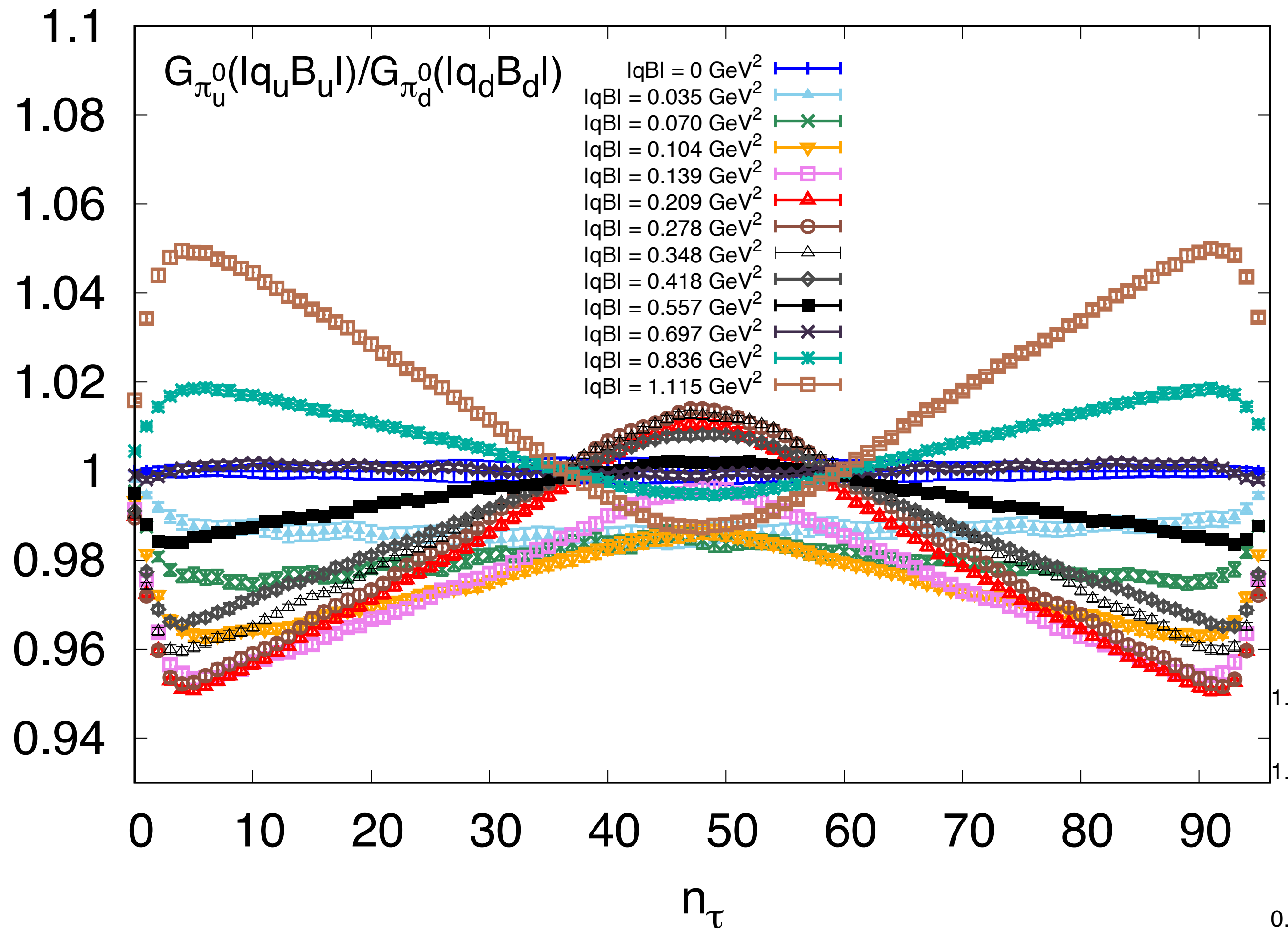
qB scaling:

It is the qB that affects the behavior of quantities

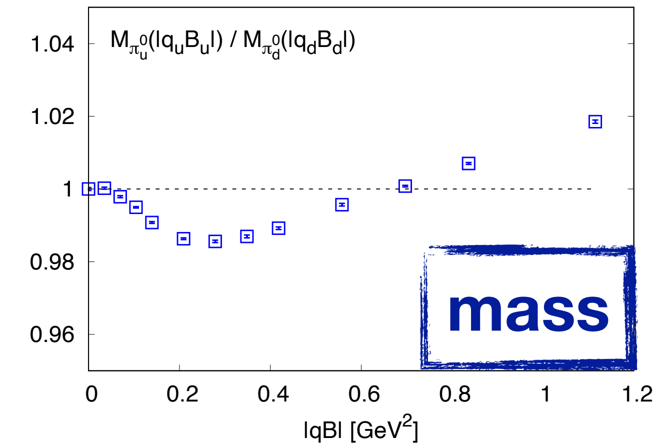
qB scaling

chiral condensate

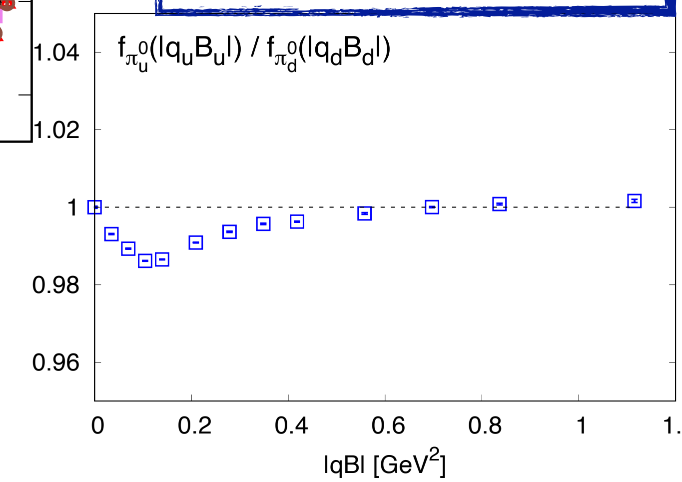




mass

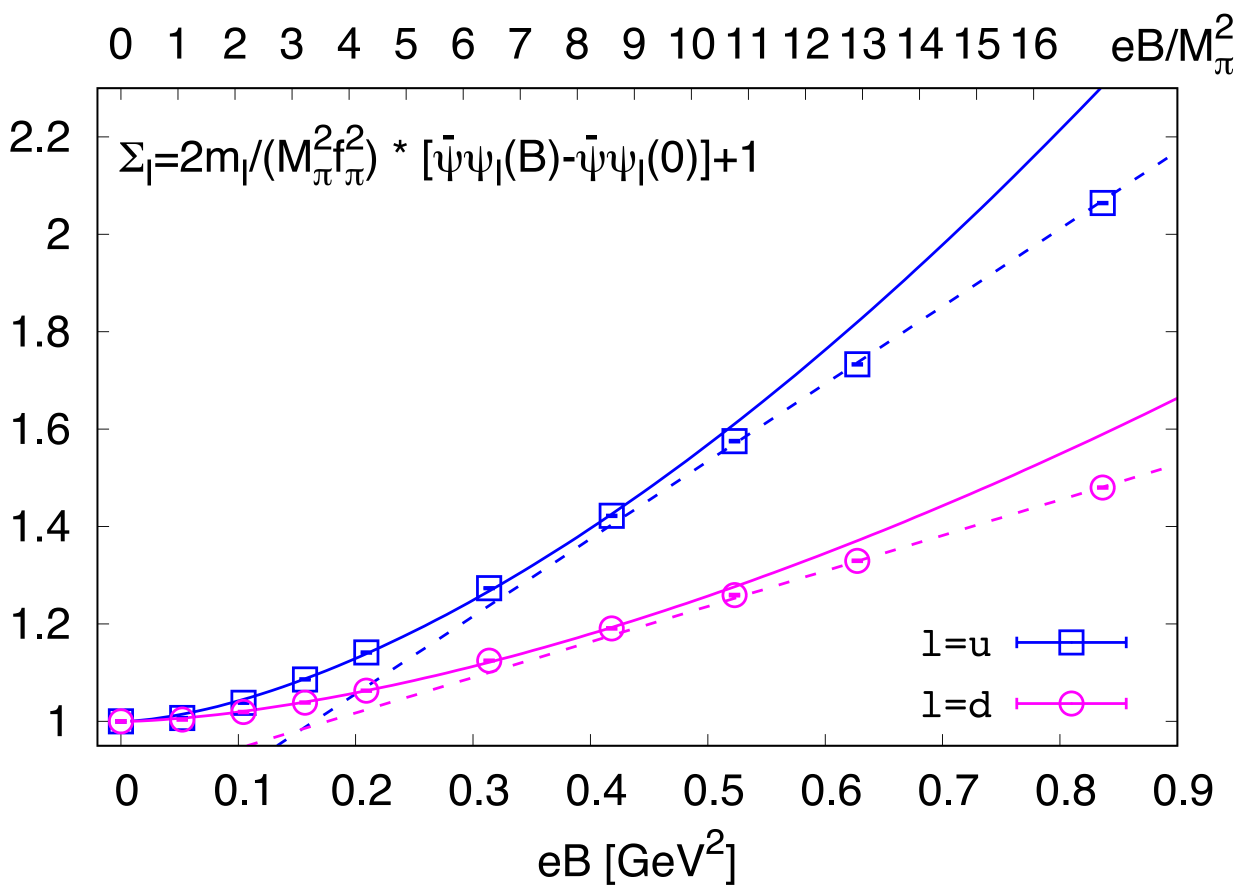


decay constant



☑ **The origin of all is the correlator, $G_{\pi_u^0}(\tau, q_uB_u)/G_{\pi_d^0}(\tau, q_dB_d)$ itself holds for qB scaling.**

Isospin symmetry breaking at eB≠0 manifested in chiral condensates



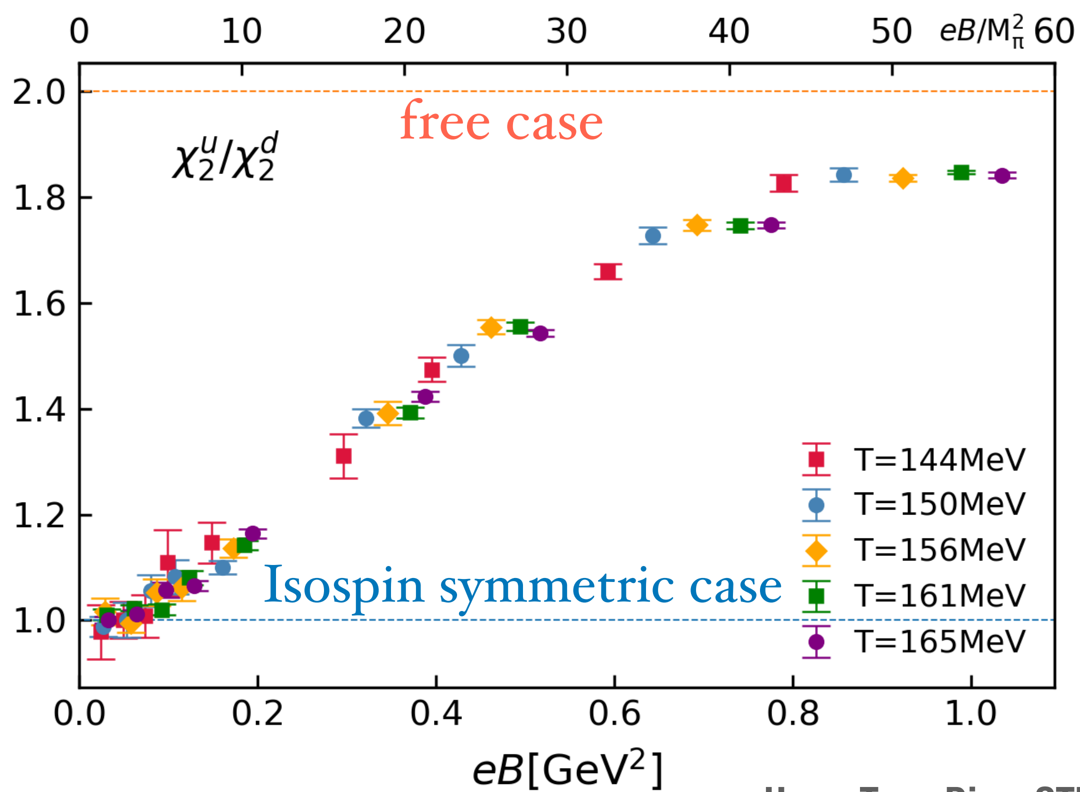
H.-T. Ding, STL, A. Tomiya, X.-D. Wang and Y. Zhang, PRD 126 (2021) 082001

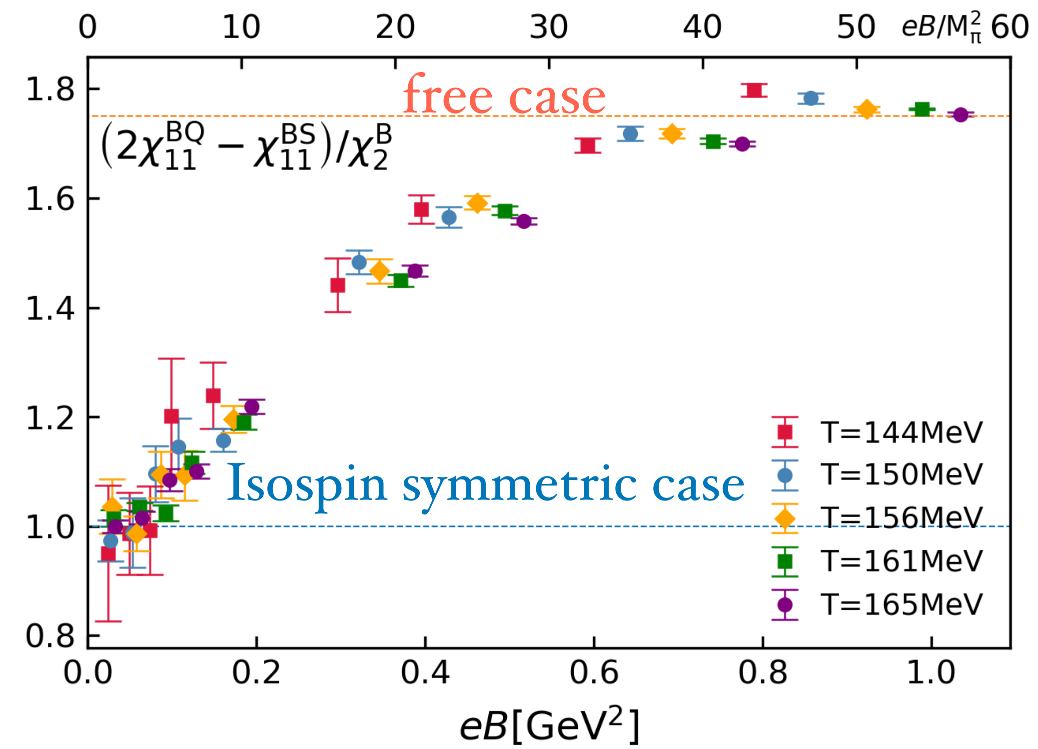
See also in reviews e.g. M. D'Elia, Lect.NotesPhys.871(2013)181

Not accessible in HIC experiments

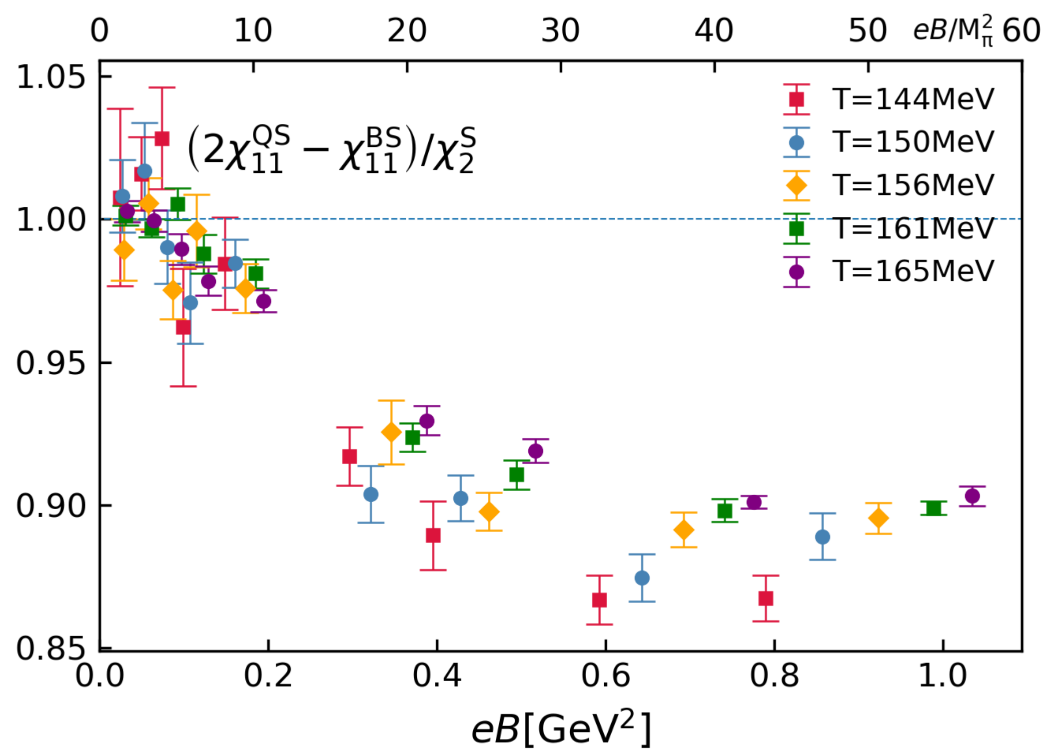
Isospin symmetry breaking at eB≠0 with physical pion mass

N_f=2+1 QCD, $M_\pi(eB=0) \approx 135$ MeV, $T_{pc}(eB=0) \approx 157$ MeV, $32^3 \times 8$ lattices with HISQ action





Heng-Tong Ding, STL, Jun-Hong Liu, Xiao-Dan Wang, work in progress



At eB=0: $\chi_2^u/\chi_2^d = 1,$

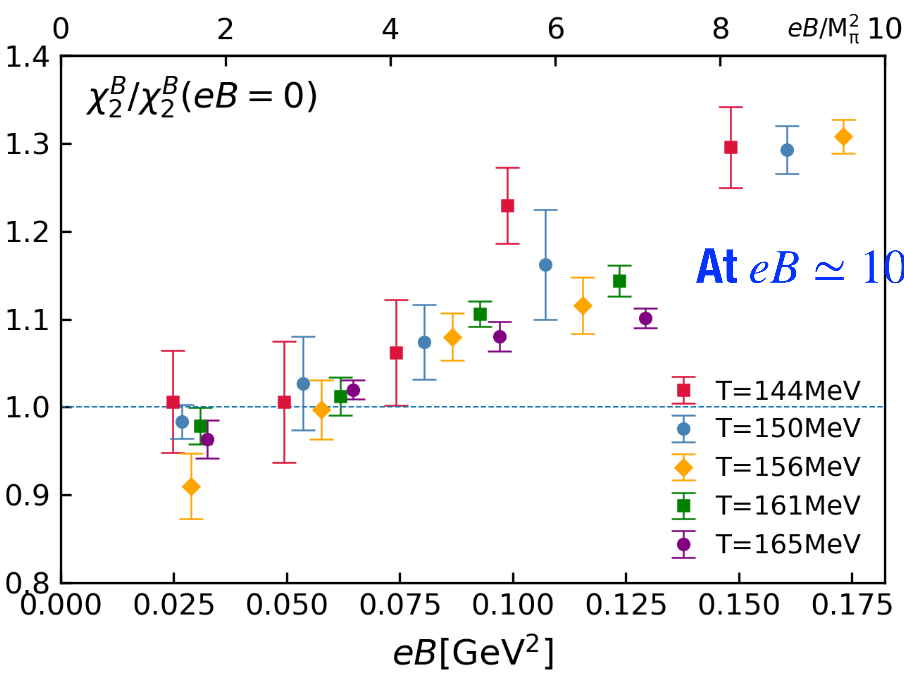
$$2\chi_{11}^{BQ} - \chi_{11}^{BS} = \chi_2^B,$$

$$2\chi_{11}^{QS} - \chi_{11}^{BS} = \chi_2^S$$

Quantities to study isospin symmetry at eB≠0

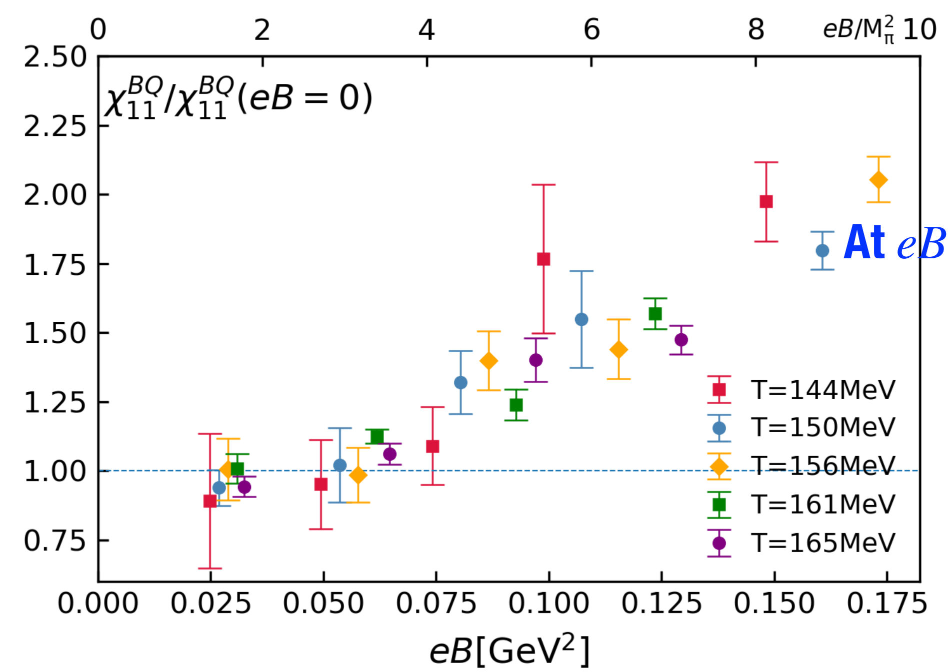
Conversed charge number fluctuation and their correlations at T≠0, eB≠0

$M_\pi(eB=0) \approx 135$ MeV



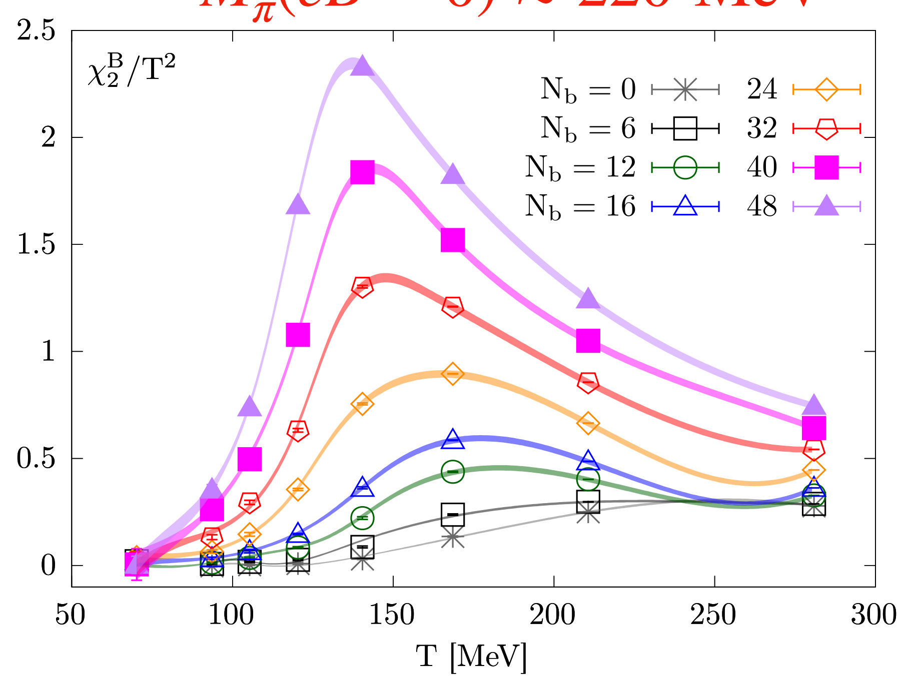
At $eB \simeq 10M_\pi^2$: ~1.3

$M_\pi(eB=0) \approx 135$ MeV



At $eB \simeq 10M_\pi^2$: ~2 !

$M_\pi(eB=0) \approx 220$ MeV

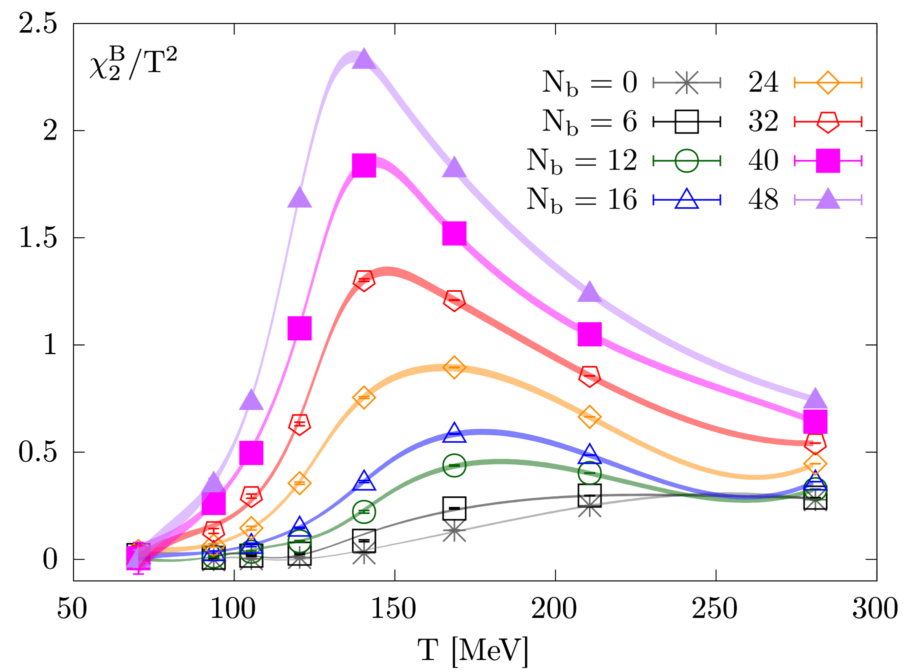


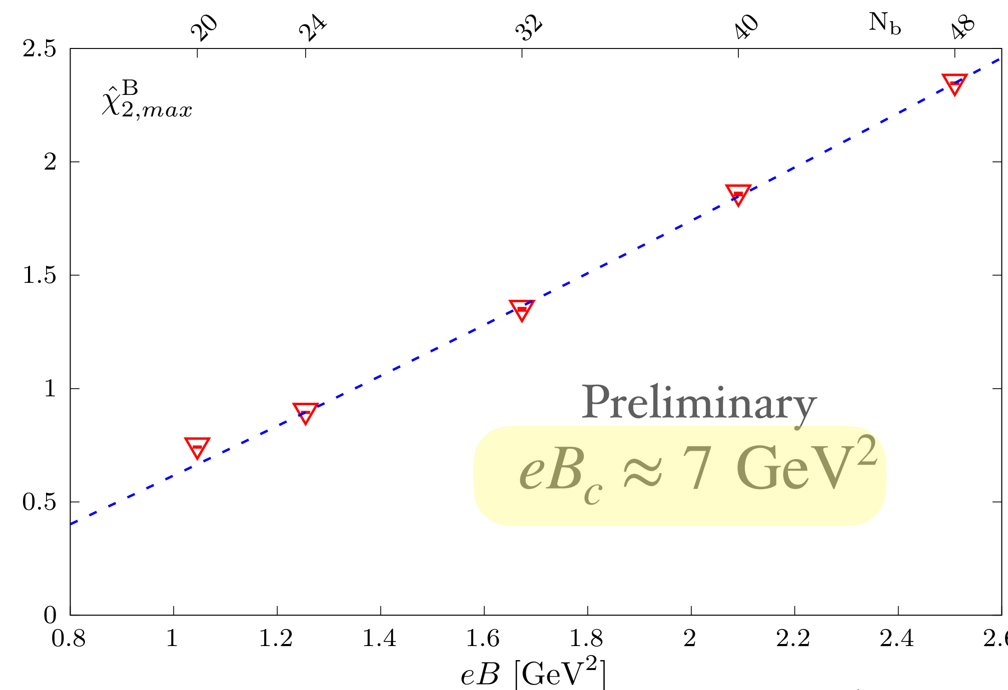
- ☑ The quantities to detect eB in HIC experiments
- ☑ eB↑, T_{pc}↓ , stronger phase transition & closer to Z(2) critical point in T-eB plane

H.T. Ding, STL, X.-D. Wang, Y. Zhang, Qi Shi, Eur.Phys.J.A 57 (2021) 6, 202,

Conversed charge number fluctuation and their correlations at T≠0, eB≠0

N_f=2+1 QCD, $M_\pi(eB=0) \approx 220\ \mathrm{MeV}$**, with** $a^{-1} \approx 1.7\ \mathrm{GeV}$ **and HISQ action, fixed** a **approach (**$T = a^{-1}/N_\tau$**)**





Junhong Liu, work in progress

$$\chi^B_{2,max} = b\,(eB_c - eB)^{(1-\alpha)/\beta\delta} + d$$

At eB=0: $\chi_n^B \propto (-2\kappa_q)^{n/2}\, h^{(2-\alpha-n/2)/\beta\delta} f_f^{(n/2)}(z)$

Friman et al., Eur. Phys. J. C 71(2011)1694

Model	(1-α)/βδ
Z(2)	0.5693
O(4)	0.6643

☆ The possible eB_c is around 7 GeV^2

Summary

- GMOR relations valid with small corrections at zero T
- M_{π^0} decreases with increasing eB at T=0
- The 2nd order fluctuations and correlations of B, Q & S are strongly affected by eB

(1) Could be useful to detect the existence of a magnetic field in HIC

(2) Analogy to study the QCD critical point in the T-μ_B plane

Thank you for your attention!