NuclearScience
Computing CenteratCCNU

Hot and Magnetized QCD Matter: Recent Lattice Results

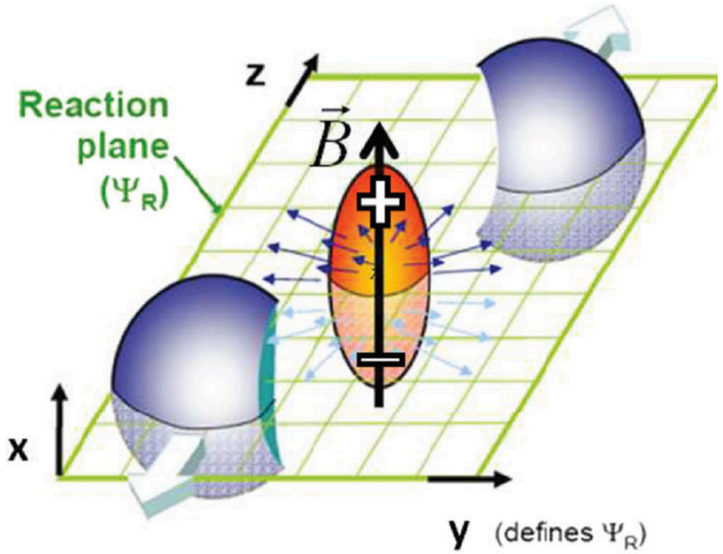
Heng-Tong Ding (丁亨通)
Central China Normal University (华中师大)

Chirality 2026

Nov.15-21, 2026@zhuhai

Hot and Magnetized QCD Matter

Heavy-Ion collisions



$10^{17\text{-}18}$ Gauss

- How does QCD topology response to the quark mass ?
- How do magnetic fields modify chiral observables and meson properties ?
- How do magnetic fields affect fluctuations of conserved charges and how can we connect them to EXP ?

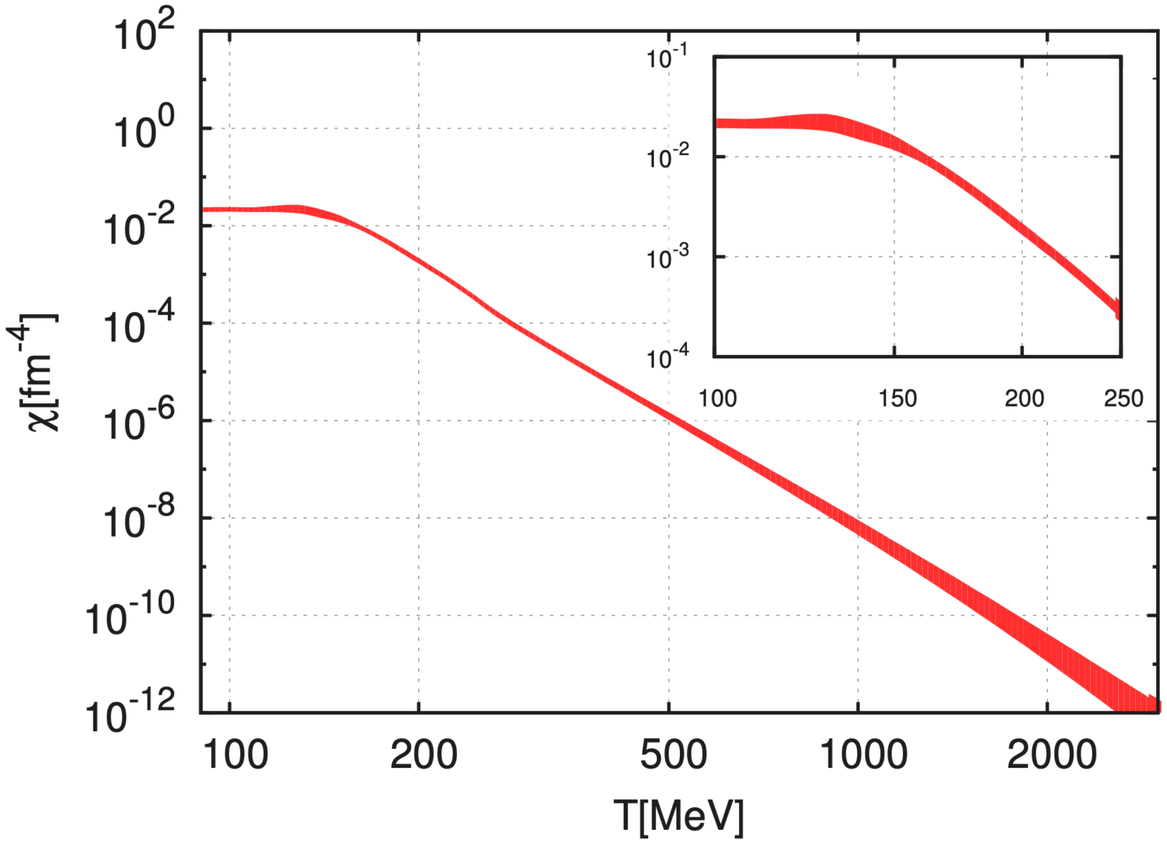
$$\Lambda_{QCD}^2 \sim 10^4 \text{ MeV}^2 \sim 10^{17} \text{ Gauss}$$

$$1 \text{ Gauss} = 1.95 \times 10^{-14} \text{ MeV}^2$$

Near-equilibrium:
see next talk by Eduardo

How does the topology feel about the QCD transition

topological susceptibility



[Wuppertal-Budapest], arXiv:1606.07494, Nature 2016

Topological charge:

$$Q[U] = \int d^4x\, q(x), \qquad q(x) \propto F^a_{\mu\nu}\, \widetilde{F}^a_{\mu\nu}\,.$$

Topological susceptibility:

$$\chi_{\text{top}}(T) = \left.\frac{\partial^2 f}{\partial\theta^2}\right|_{\theta=0} = \frac{\langle Q^2\rangle}{V_4}$$

Topological fluctuations and quark masses

- Index theorem: $Q[U] = \text{index}(\mathscr{D})$

- Q is gluonic, but the fermion determinant controls its equilibrium weight

$$\chi_{top} \propto < Q^2 > = \int DU\ P[U]\ Q^2, \qquad P[U] \propto e^{-S_g[U]} \det(\mathscr{D} + m_\ell)^2 \det(\mathscr{D} + m_s)\,.$$

However, thermal suppression of χ_{top} does not determine its mass dependence

$$q_u \mapsto e^{i\alpha\gamma_5} q_u, \qquad \theta \mapsto \theta - 2\alpha$$

In the chiral limit: $\quad m_u = 0: \quad f(T,\theta) = f(T,0), \qquad \chi_{\text{top}} = \dfrac{\partial^2 f}{\partial \theta^2} = 0$

The chiral response measures a local mass slope



Chiral response of QCD topology

$$C_{\text{top}}(T) = \left.\frac{\partial \ln \chi_{\text{top}}}{\partial \ln m_\ell}\right|_{T,V_4,m_s} \qquad \chi_{\text{top}} \propto m_\ell^p \quad \Longrightarrow \quad C_{\text{top}} = p$$

- Low temperature: chiral perturbation theory

$$\chi_{\text{top}}^{\text{LO}} = \frac{\Sigma}{2/m_\ell + 1/m_s}, \qquad C_{\text{top}}^{\text{LO}} = \frac{2m_s}{2m_s + m_\ell}$$

Grilli di Cortona et al., JHEP 01(2016) 034 ,Leutwyler & Smilga, PRD46 (1992) 5607.

- High temperature: leading quadratic dependence

$$\chi_{\text{top}}(T) \propto m_\ell^2 \quad (m_s \text{ fixed}), \qquad C_{\text{top}} \simeq 2$$

Gross, Pisarski & Yaffe 1981, Schafer & Shuryak 1998, Kanazawa & Yamamoto 2015



Mass derivative of O: $\dfrac{\partial O}{\partial x} = \lim_{\epsilon \to 0} \dfrac{O(x+\epsilon) - O(x)}{\epsilon}$

HTD, J.-B. Gu, J. Hernández Hernández, S.-T. Li & J. Ni, arXiv:2611.09150

A single-ensemble estimator for the mass derivative

- QCD partition function: $Z = \int \mathcal{D}U\, e^{-S_g} \det(D + m_\ell)^2 \det(D + m_s)$

- Quark mass derivative of χ_{top} wo additional simulations at shifted quark masses

$$\frac{\partial \chi_{\rm top}}{\partial m_\ell} = \frac{\langle Q^2 X_1 \rangle - \langle Q^2 \rangle \langle X_1 \rangle}{V_4} \qquad X_1 \equiv \partial_{m_\ell} \ln \det(D + m_\ell)^2 = 2\,\mathrm{Tr}(D + m_\ell)^{-1}$$

- The covariance supplies the response directly $\qquad C_{\rm top} = m_\ell \dfrac{\langle Q^2 X_1 \rangle_c}{\langle Q^2 \rangle}$

- The same method gives higher order derivatives

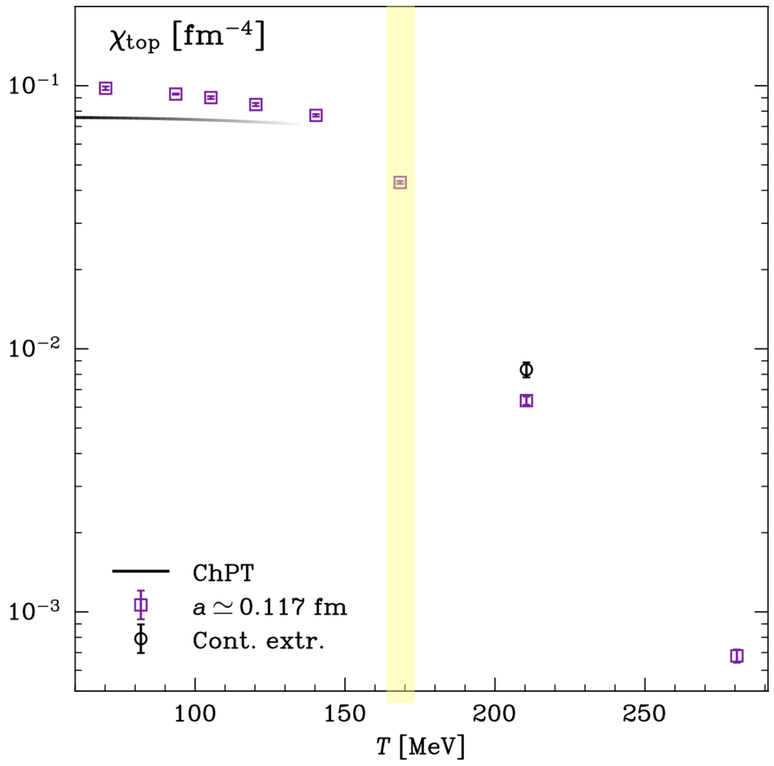
HTD, J.-B. Gu, J. Hernández Hernández, S.-T. Li & J. Ni, arXiv:2611.09150

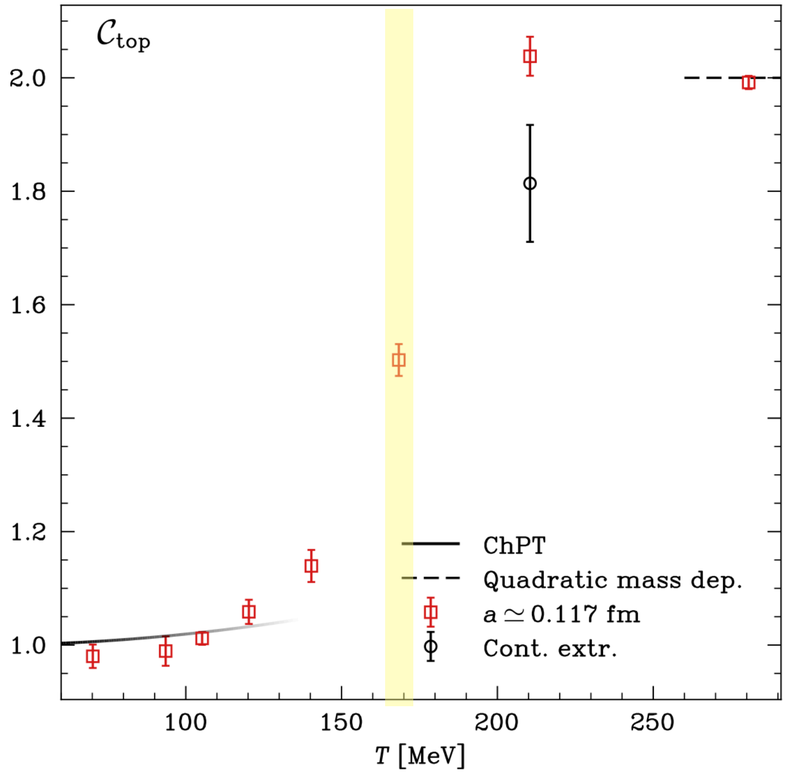
Chiral response of QCD topology across the thermal crossover

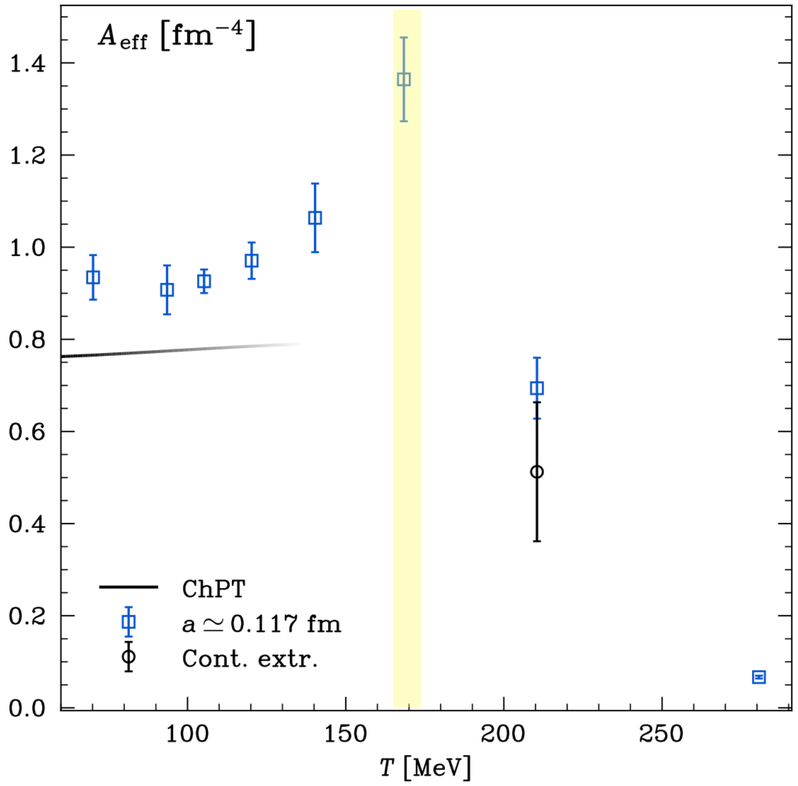
Topological susceptibility $\chi_{\rm top}$: suppression

$C_{top} = \partial \ln \chi_{top} / \partial \ln m_l$: increasing response

$A_{eff} = \chi_{top} H^{-C_{top}}$: a crossover peak





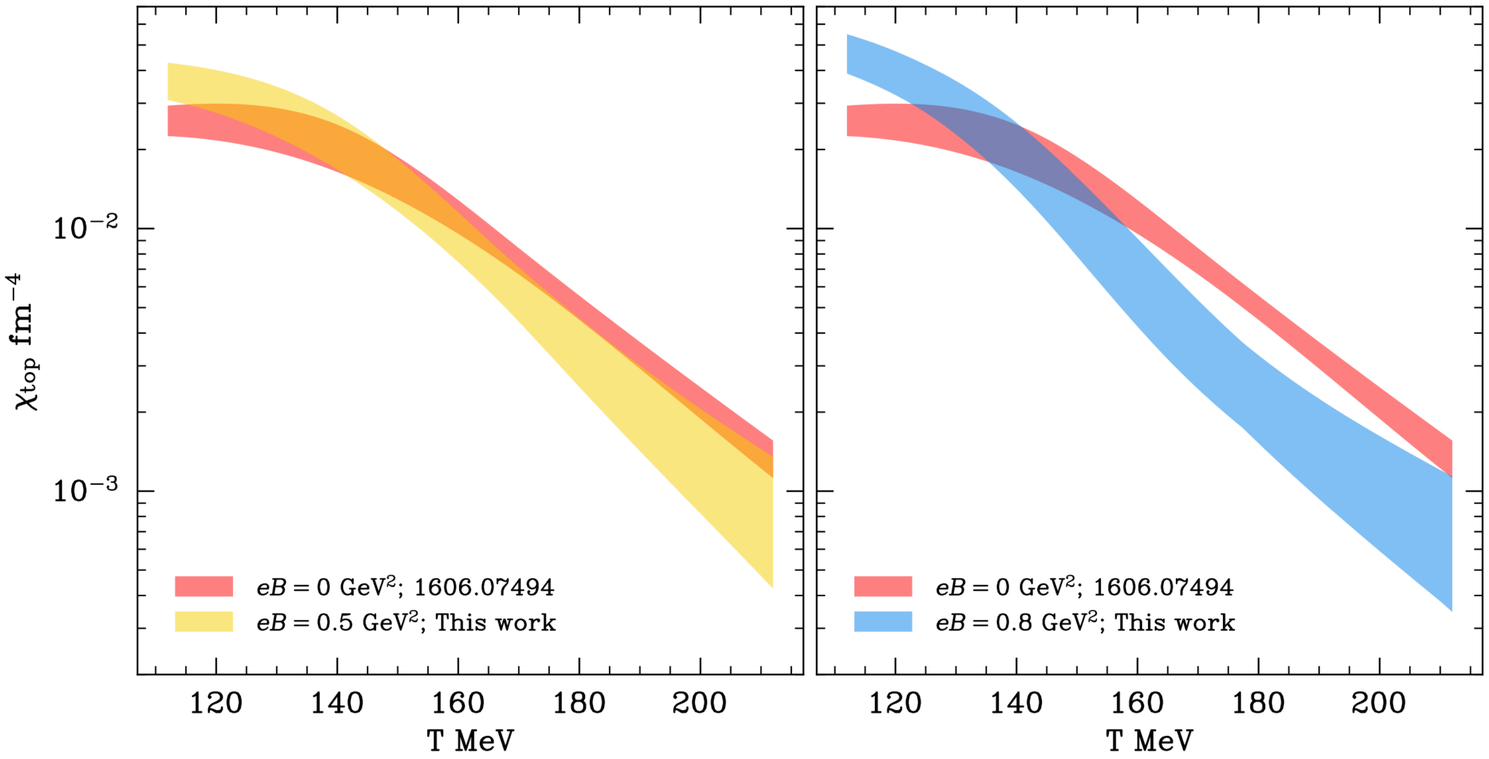


$T_{pc} \approx 170$ MeV for this lattice setup ($m_\pi = 220$ MeV, $\mathrm{H} \equiv \mathrm{m_l/m_s} = 1/10$)

HTD, J.-B. Gu, J. Hernández Hernández, S.-T. Li & J. Ni, arXiv:2611.09150

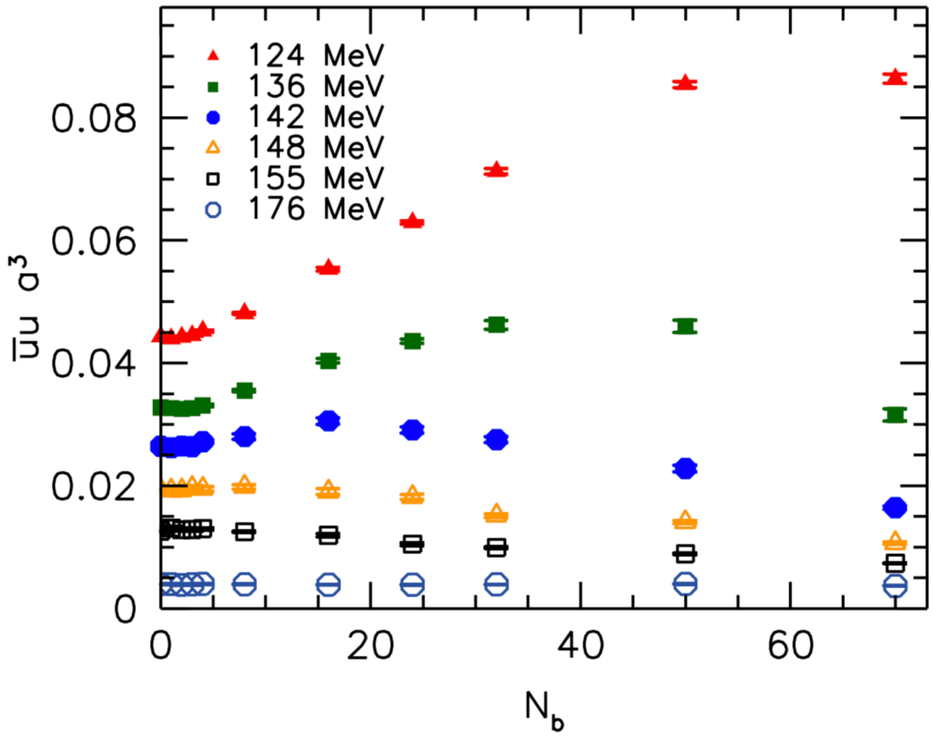
Topological susceptibility at nonzero magnetic fields

Enhanced χ_{top} at $T \lesssim 130$ MeV but suppressed at higher T



B.B. Brandt , G. Endrődi , J.J. Hernández Hernández and G. Markó, JHEP 12(2024)228

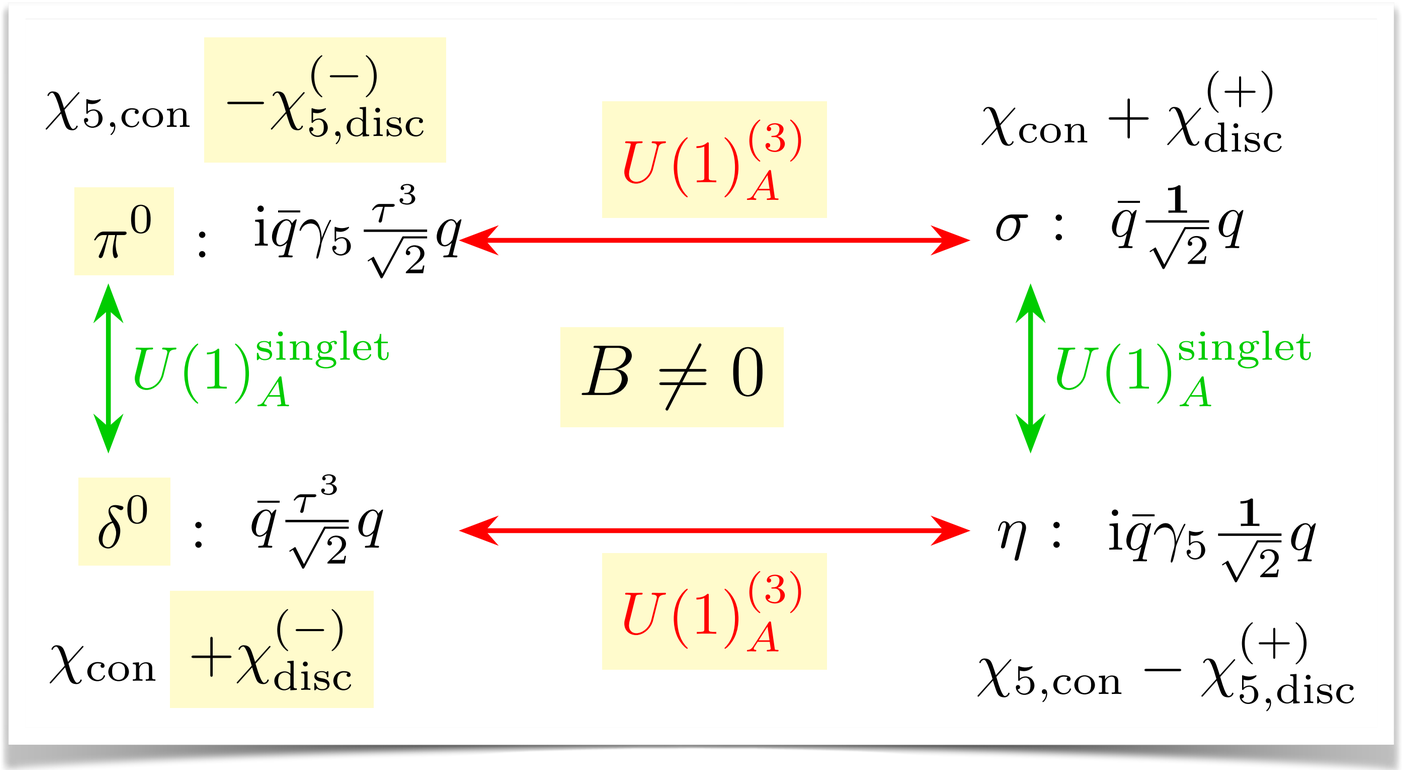
Inverse Magnetic Catalysis (IMC)



Bali et al., JHEP02(2012)044

Signatures of symmetry restoration at $eB \neq 0$

Chiral symmetry: $SU(2)_V \to U(1)_A^{(3)}$; Axial $U(1)$ symmetry: $U(1)_A \to U(1)_A^{\text{singlet}}$



- $U(1)_A^{(3)}$: $\pi^0 \leftrightarrow \sigma$, $\delta^0 \leftrightarrow \eta$

  Probe: $O_\chi \propto \chi_{\pi^0} - \chi_\sigma$

- $U(1)_A^{\text{singlet}}$: $\pi^0 \leftrightarrow \delta^0$, $\sigma \leftrightarrow \eta$

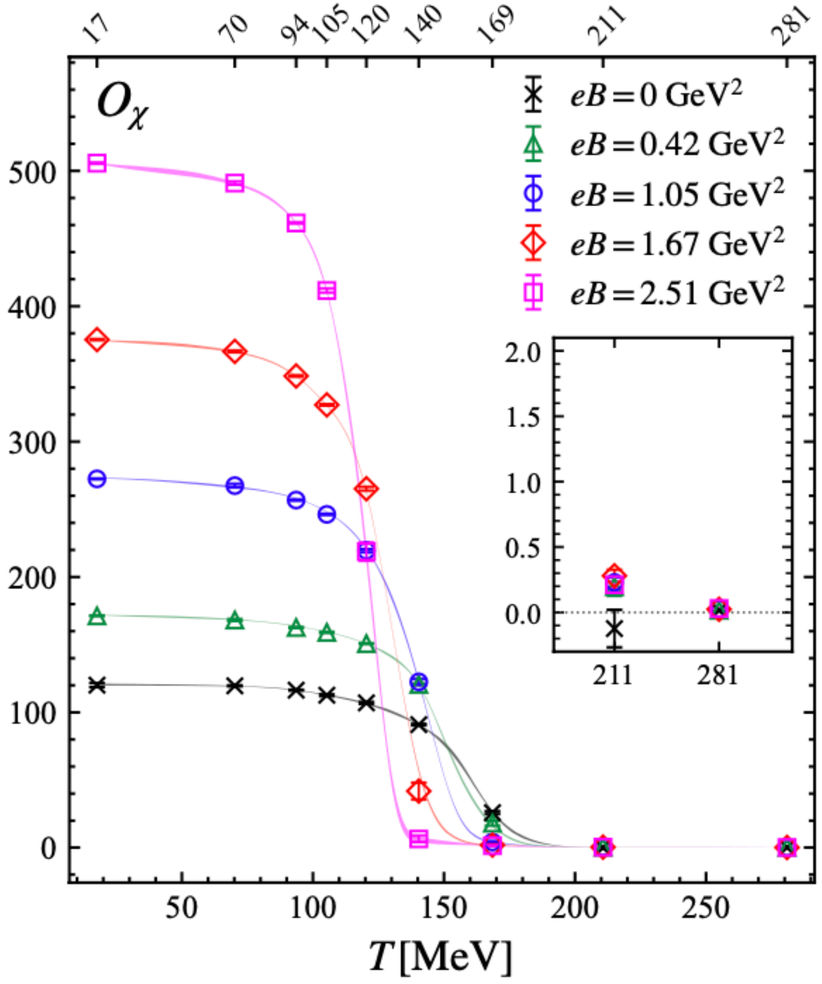
  Probe: $O_A \propto \chi_{\pi^0} - \chi_{\delta^0}$

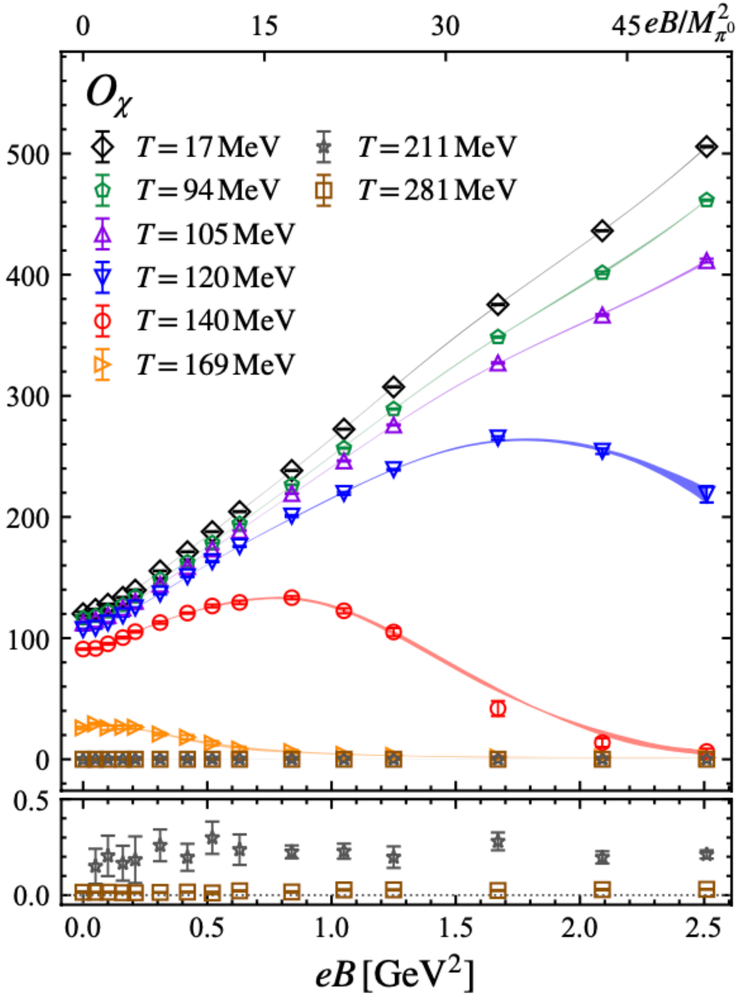
HTD, José Javier Hernández Hernández & Dan Zhang, arXiv:2607.11625

Measure of chiral symmetry breaking

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

Javi Hernandez Hernandez
Wed 3:05 PM





$$O_\chi(B,T) \equiv \frac{m_s^2}{f_K^4}\left[\chi_{\pi^0}(B,T) - \chi_\sigma(B,T)\right]$$

At low T: $O_\chi \uparrow$

- $eB \uparrow$:

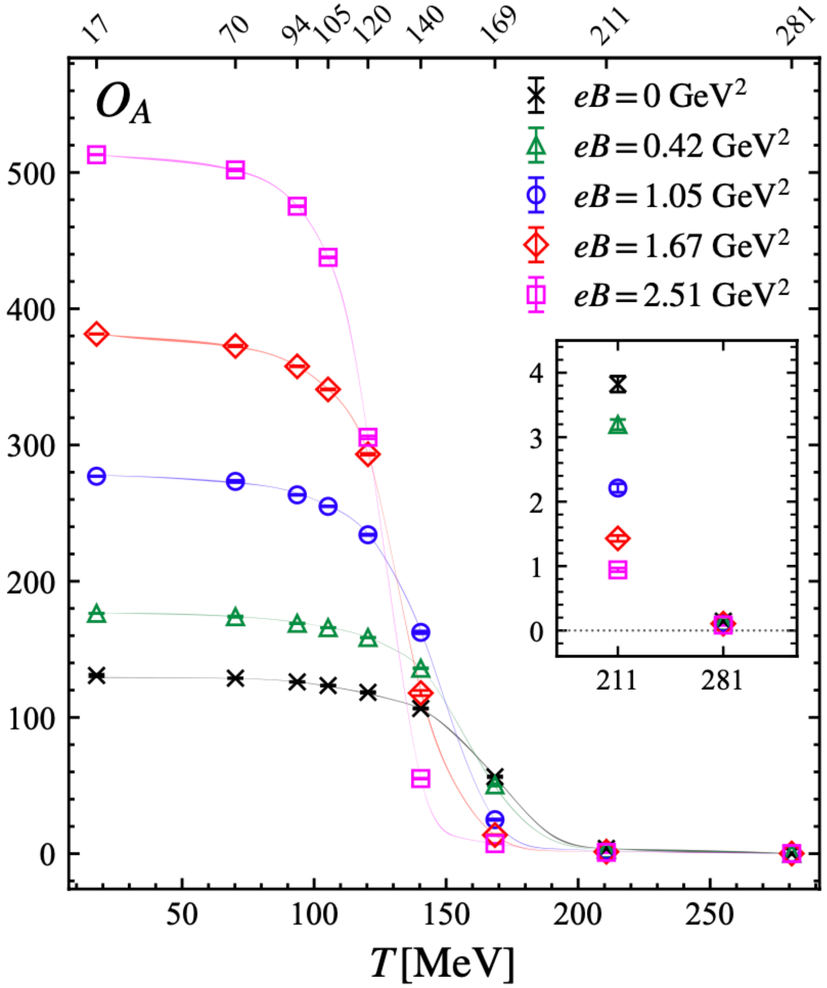
At high T: $O_\chi \downarrow$

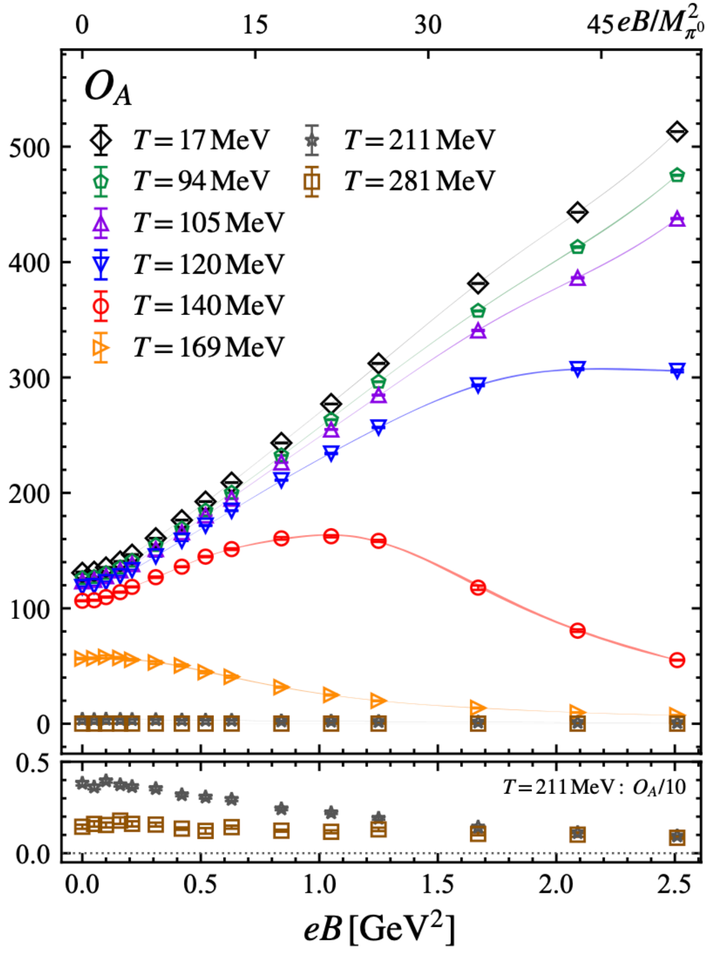
- counterparts of IMC & MC

HTD, José Javier Hernández Hernández & Dan Zhang, arXiv:2607.11625

Measure of singlet $U(1)_A$ breaking

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





HTD, José Javier Hernández Hernández & Dan Zhang, arXiv:2607.11625

Javi Hernandez Hernandez
Wed 3:05 PM

$$O_A(B,T) \equiv \frac{m_s^2}{f_K^4}\left[\chi_{\pi^0}(B,T) - \chi_\delta(B,T)\right]$$

At low T: $O_A \uparrow$

- $eB \uparrow$:

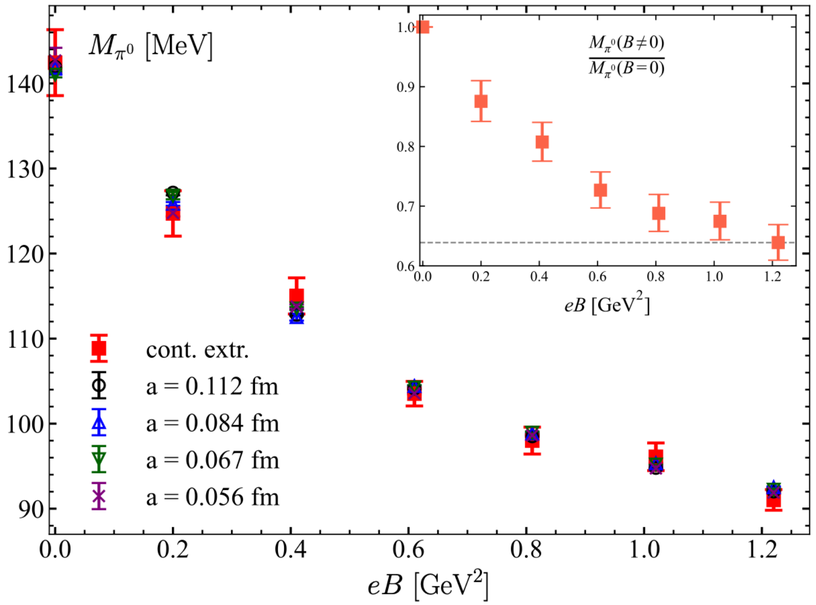
At high T: $O_A \downarrow$

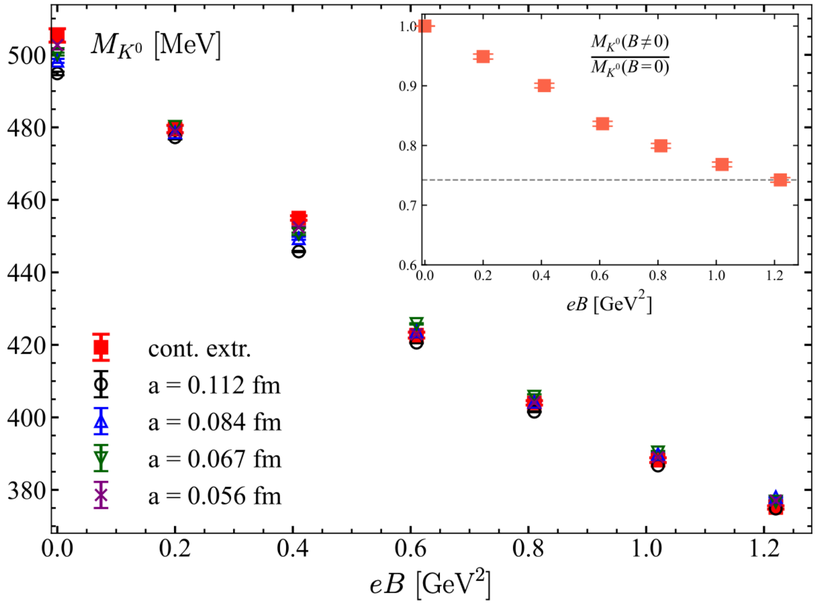
- Similar to O_χ

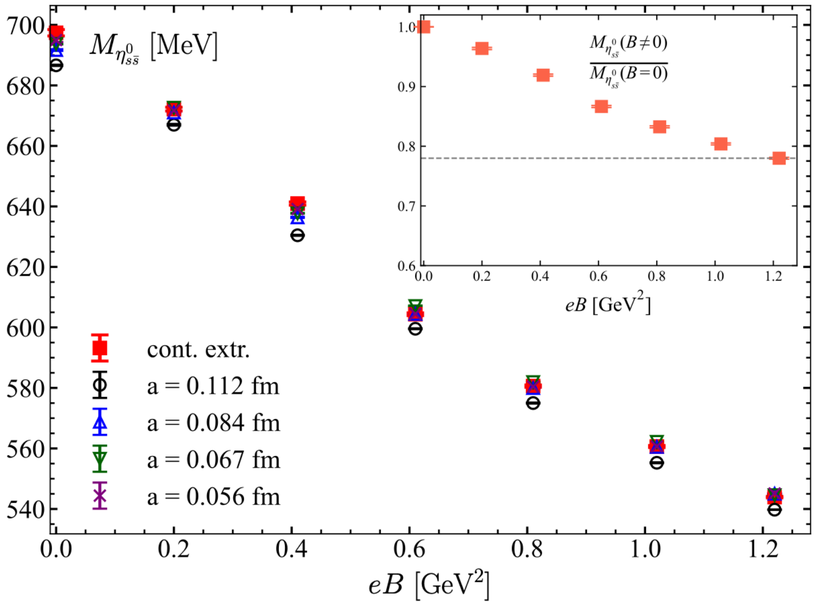
See NJL model studies
Xin-Nan Zhu
Thur 11:30 AM

Masses of neutral pseudoscalar (PS) mesons in the vacuum with physical pion mass

N_f=2+1 QCD with $M_\pi(eB=0) \approx 140$ MeV



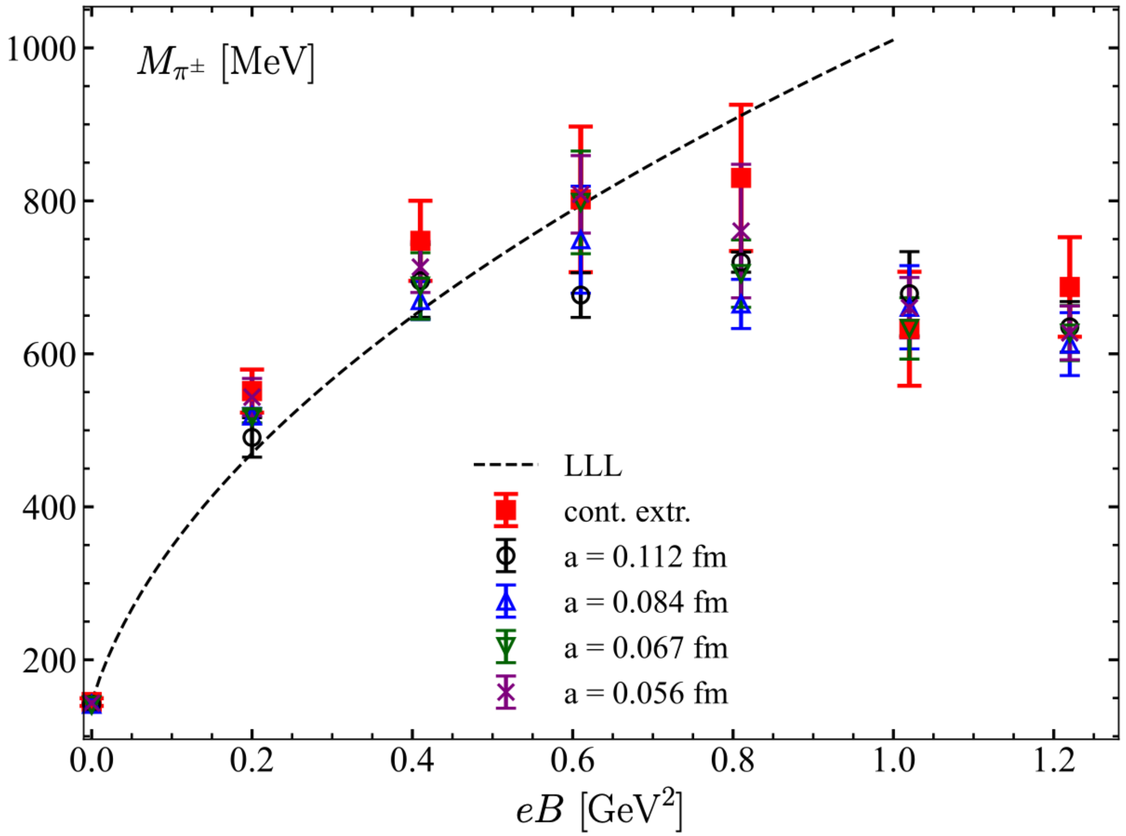


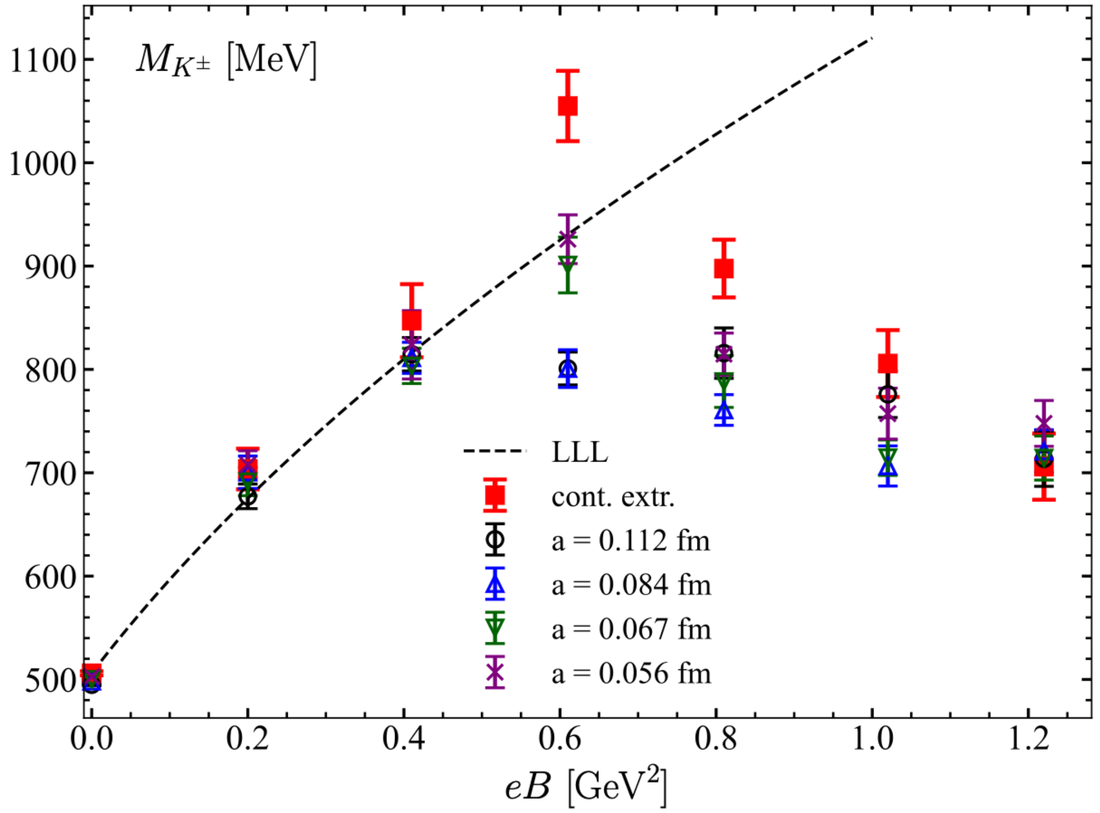


HTD, Dan Zhang, Phys.Rev.D 113 (2026) 9, 094503

See similar results with larger than physical pion mass at one single lattice cutoff:
HTD, S.-T. Li, A. Tomiya, X.-D. Wang and Y. Zhang, PRD 104(2021) 014505

Masses of charged PS mesons in the vacuum



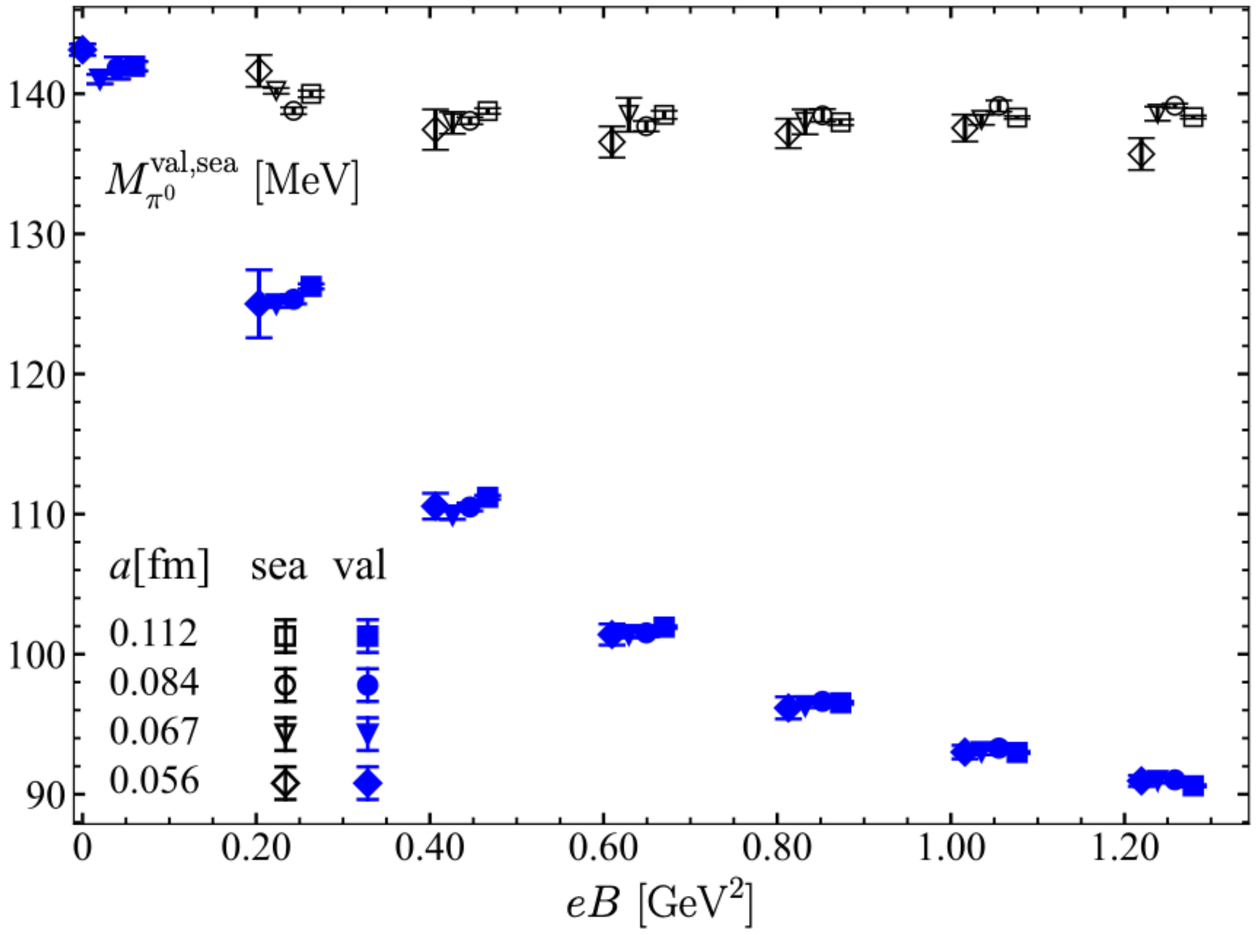


Non-monotonic behavior in eB, not observed in quenched QCD

HTD, Dan Zhang, Phys.Rev.D 113 (2026) 9, 094503

See similar results with larger than physical pion mass at one single lattice cutoff:
HTD, S.-T. Li, A. Tomiya, X.-D. Wang and Y. Zhang, PRD 104(2021) 014505

Masses From Sea and Valence Quark Contributions



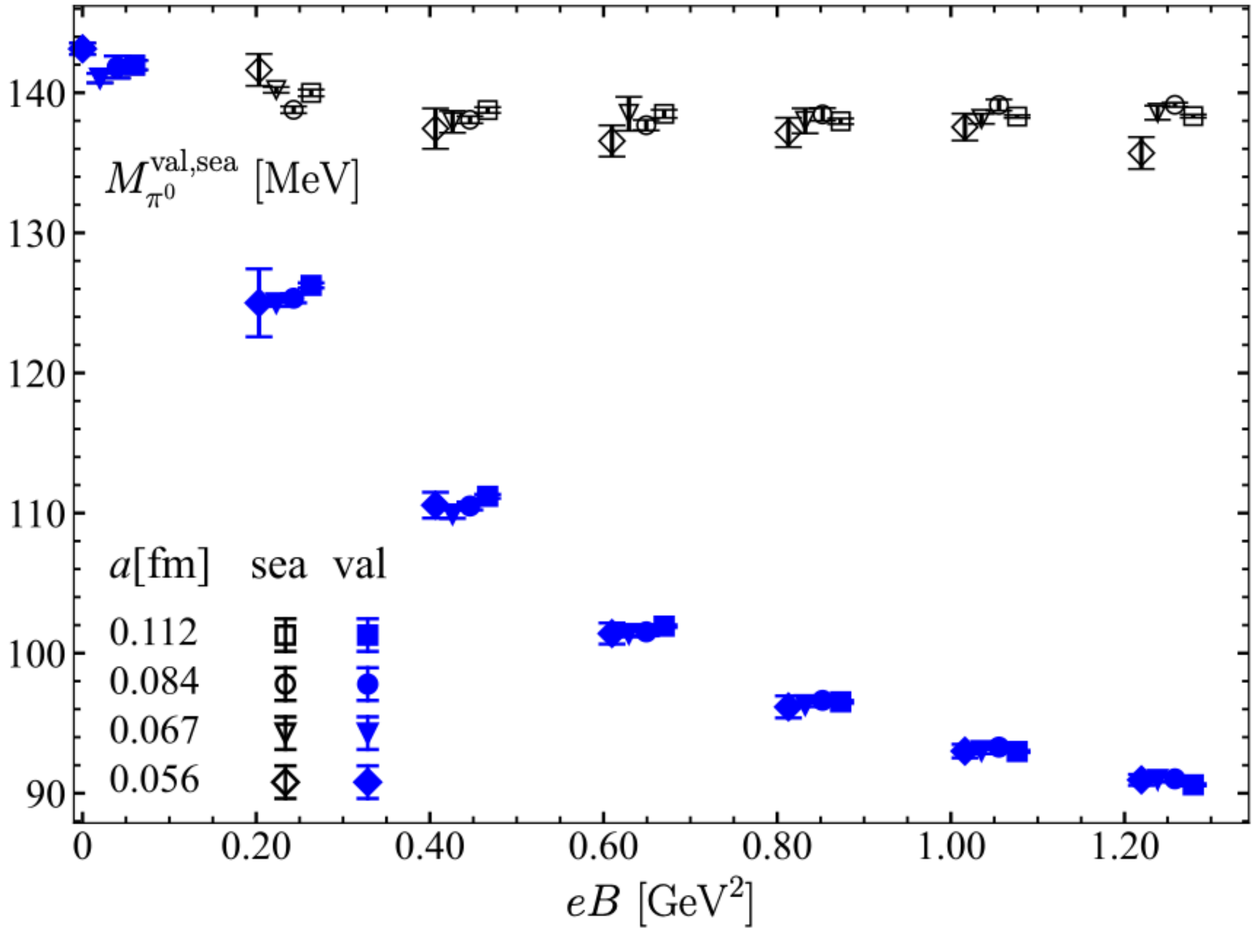
$$\langle O\rangle_{sea}(eB) = \frac{\int DUe^{-S_G}\mathrm{det}M(eB)\ O(eB=0)}{Z(eB)}$$

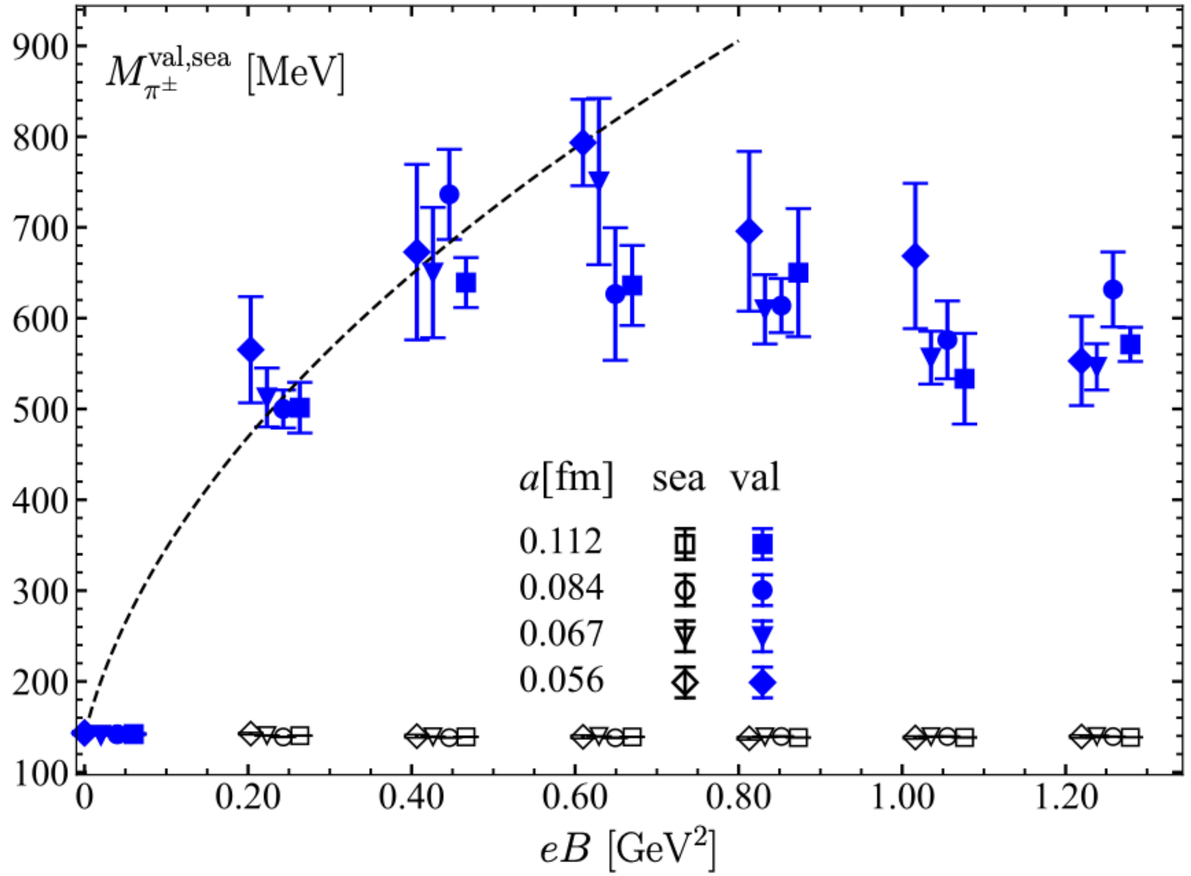
$$Z(eB) = \int DUe^{-S_G}\ \mathrm{det}M(eB)$$

$$\langle O\rangle_{valence}(eB) = \frac{\int DUe^{-S_G}\ \mathrm{det}M(eB=0)\ O(eB)}{Z(eB=0)}$$

HTD, Dan Zhang, Phys.Rev.D 113 (2026) 9, 094503

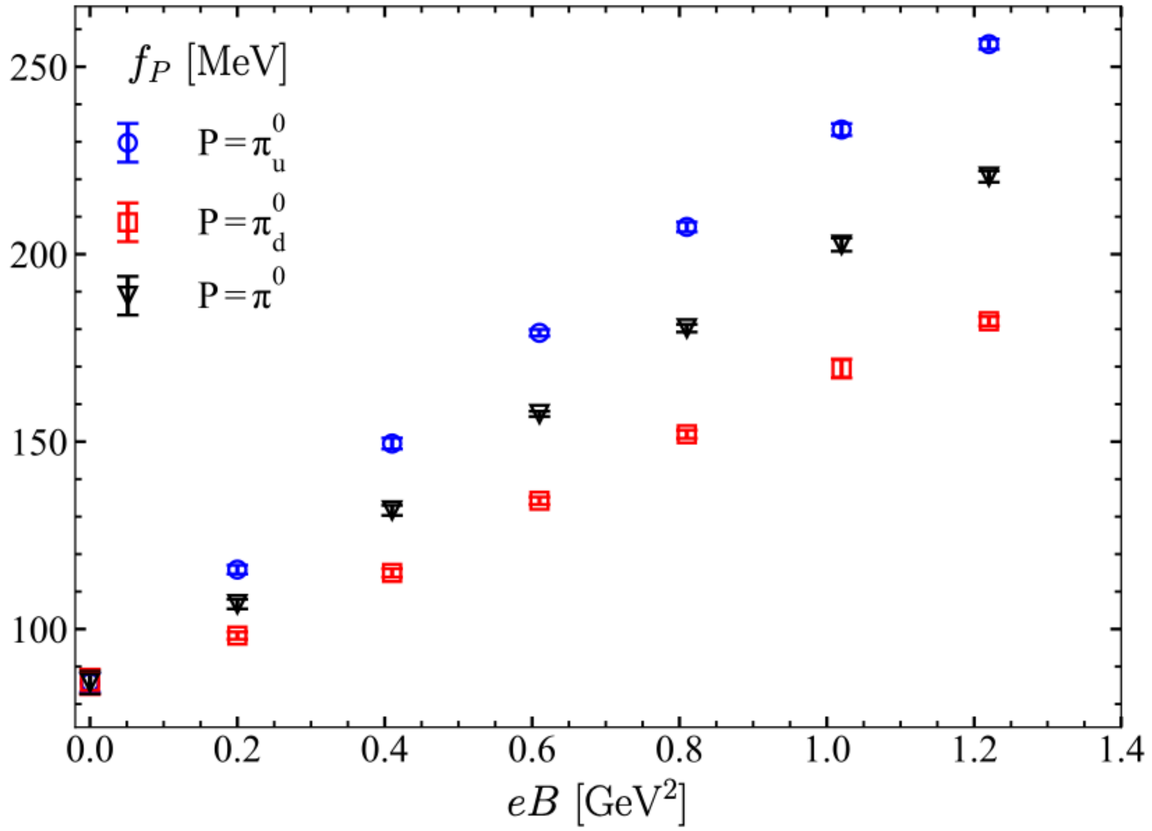
Masses From Sea and Valence Quark Contributions

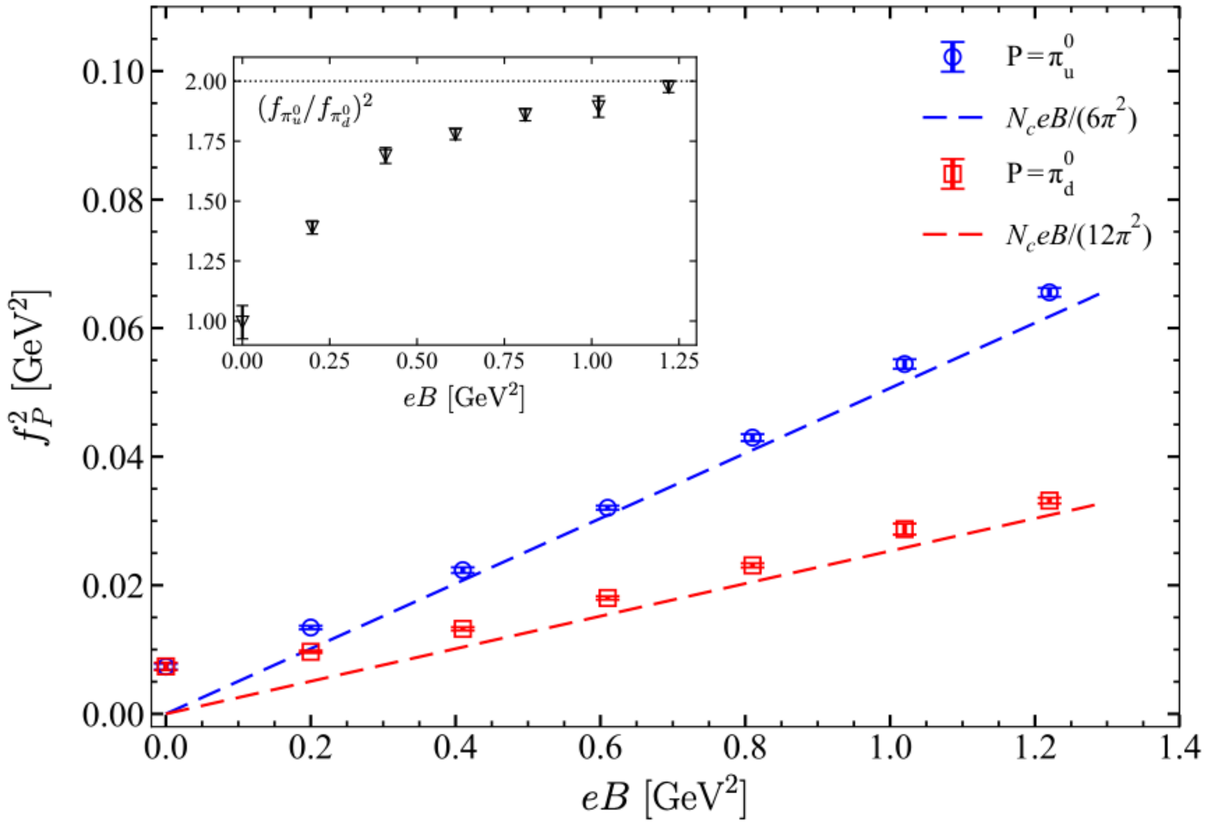




HTD, Dan Zhang, Phys.Rev.D 113 (2026) 9, 094503

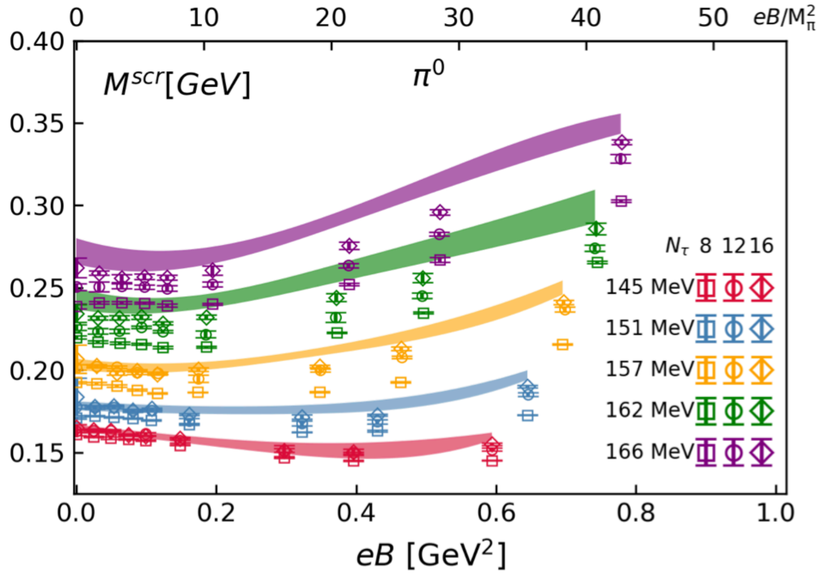
Pion decay constants in nonzero magnetic fields

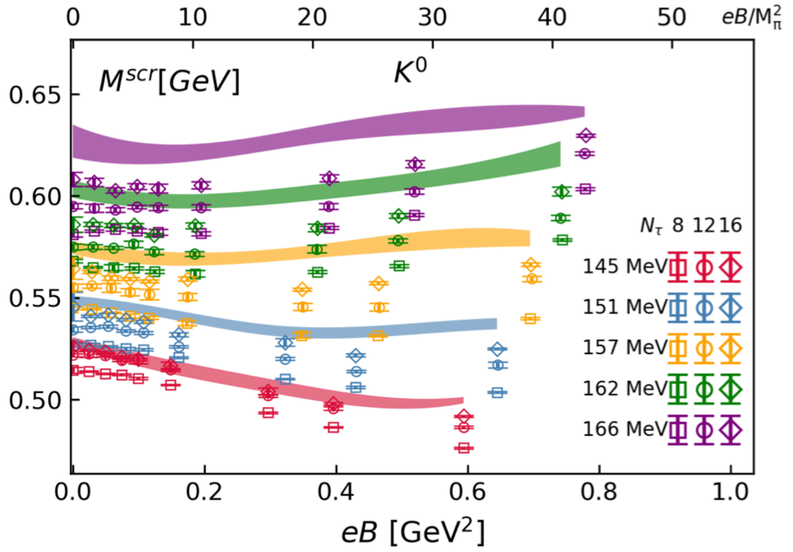


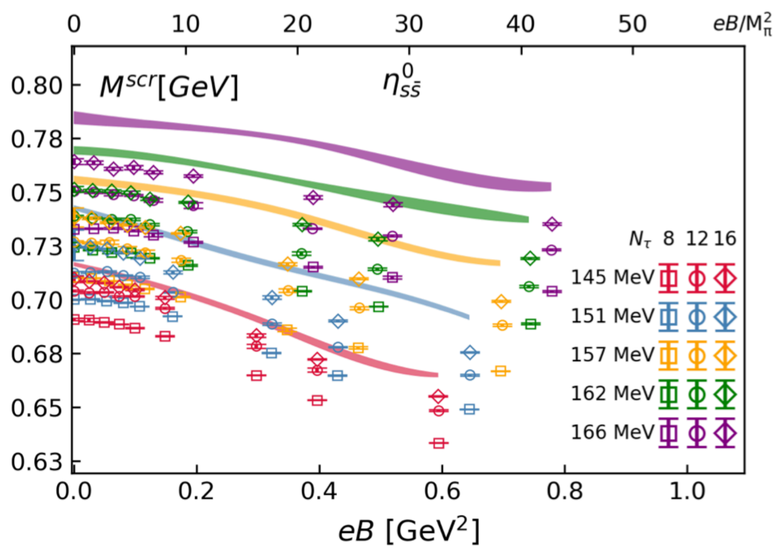


HTD, Dan Zhang, Phys.Rev.D 113 (2026) 9, 094503

Screening mass of Pseudo-scalar mesons at the physical point





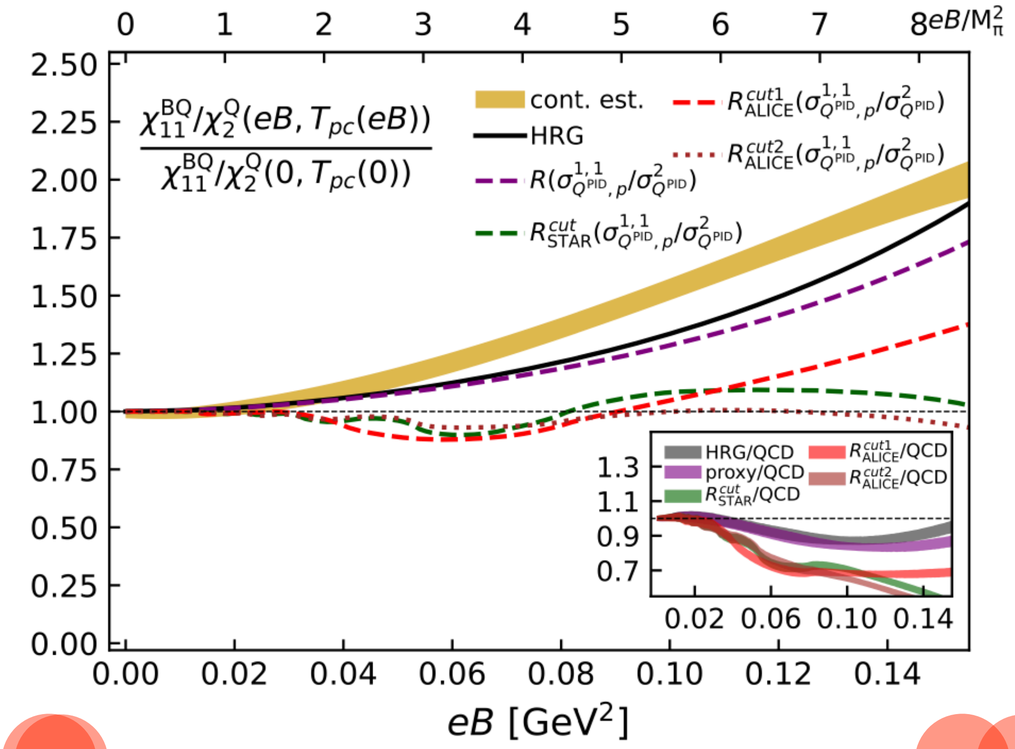


HTD, J.-B. Gu, S.-T. Li, R. Thakkar, Phys.Rev.D 111 (2025) 7, 074513

See similar results with large-than-physical pion mass: HTD, S.-T. Li, J.-H. Liu & X.-D. Wang, Phys.Rev.D 105 (2022) 3, 034514

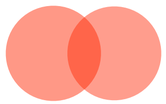
QCD Magnetometer: Lattice v.s. EXP

Baryon-electric charge correlation over electric charge fluctuations

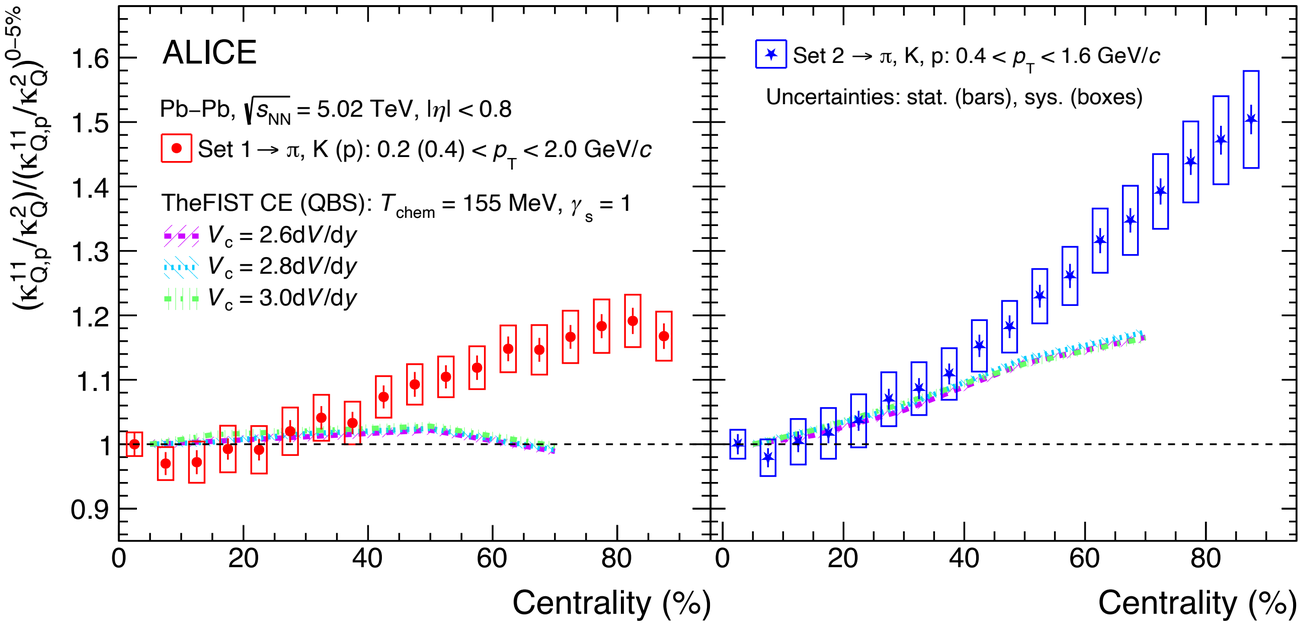




Central collision



Peripheral collision

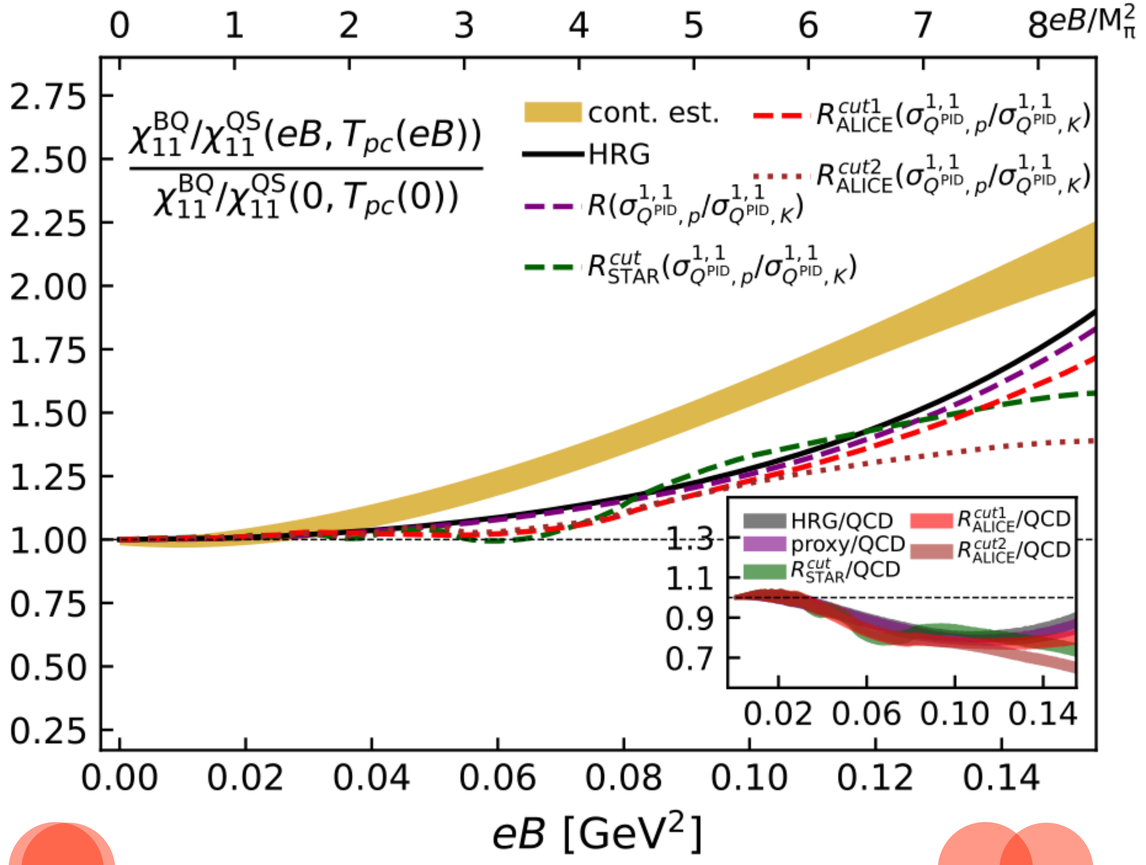


ALICE Collaboration, *JHEP* 08 (2025) 210

HTD, Jin-Biao Gu, Arpith Kumar, Sheng-Tai Li,
Phys.Rev.D 111 (2025) 11, 114522
Phys.Rev.Lett. 132 (2024) 20, 201903

A similar trend appears in the ALICE data

A better probe: double ratio of $\chi_{11}^{\mathrm{BQ}}/\chi_{11}^{QS}$



Central collision

Peripheral collision

~ 2.2 Lattice QCD

~ 1.6 – 1.75 Proxies

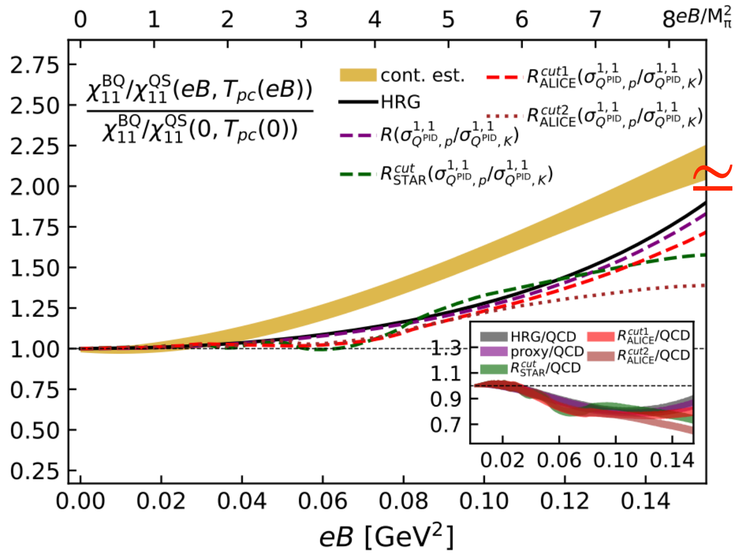
~ 75 – 84 % Proxies/LQCD

$R(\chi_{11}^{\mathrm{BQ}}/\chi_{11}^{\mathrm{QS}})$

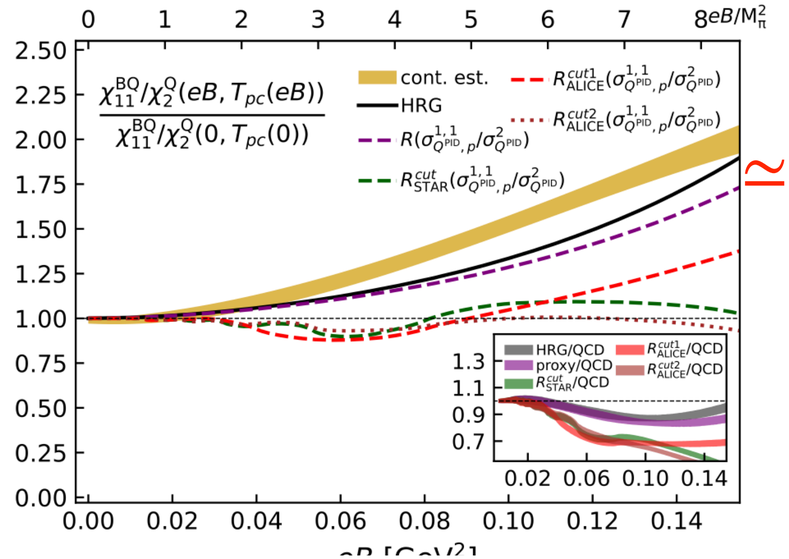
A more sensitive probe for both ALICE & STAR!

HTD, J.-B. Gu, A. Kumar, S.-T. Li, arXiv:2503.18467

Ordering in magnetic responses of 2nd order conserved charge susceptibilities



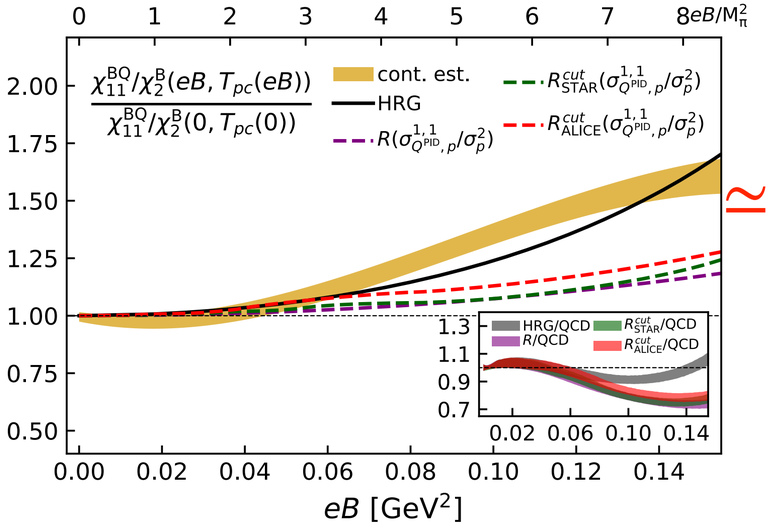
$\simeq 2.2$



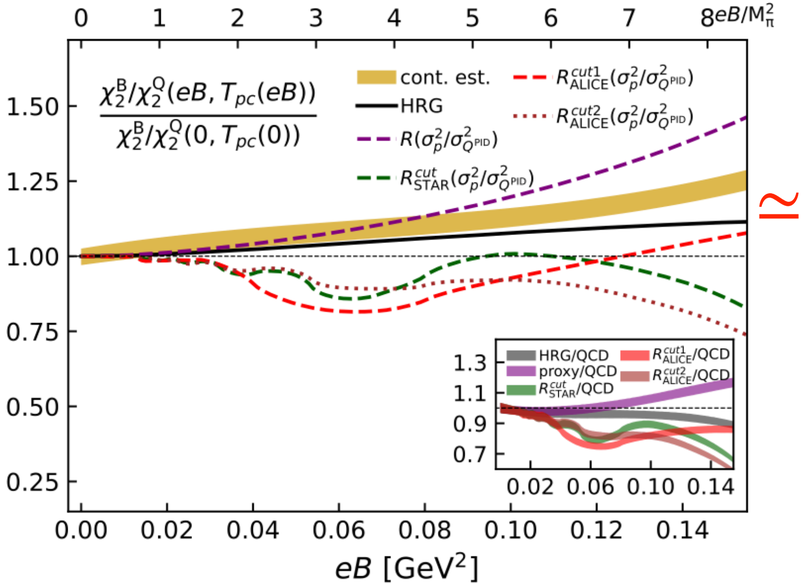
$\simeq 2$

- Ordering from LQCD

$$R\left[\frac{\chi_{11}^{BQ}}{\chi_{11}^{QS}}\right] > R\left[\frac{\chi_{11}^{BQ}}{\chi_{2}^{Q}}\right] > R\left[\frac{\chi_{11}^{BQ}}{\chi_{2}^{B}}\right] > R\left[\frac{\chi_{2}^{B}}{\chi_{2}^{Q}}\right]$$



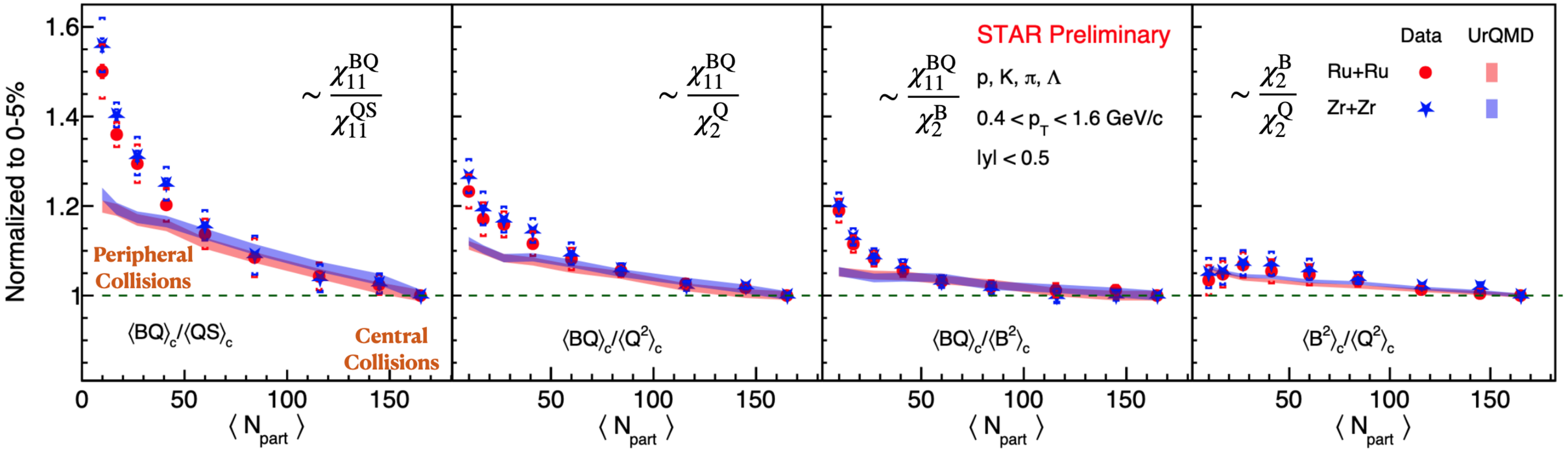
$\simeq 1.6$



$\simeq 1.2$

Ordering in magnetic responses of 2nd order conserved charge susceptibilities

LQCD predicts: $\frac{\chi_{11}^{BQ}}{\chi_{11}^{QS}} > \frac{\chi_{11}^{BQ}}{\chi_{2}^{Q}} > \frac{\chi_{11}^{BQ}}{\chi_{2}^{B}} > \frac{\chi_{2}^{B}}{\chi_{2}^{Q}}$



Presented by Changfeng Li(STAR) @SQM 2026

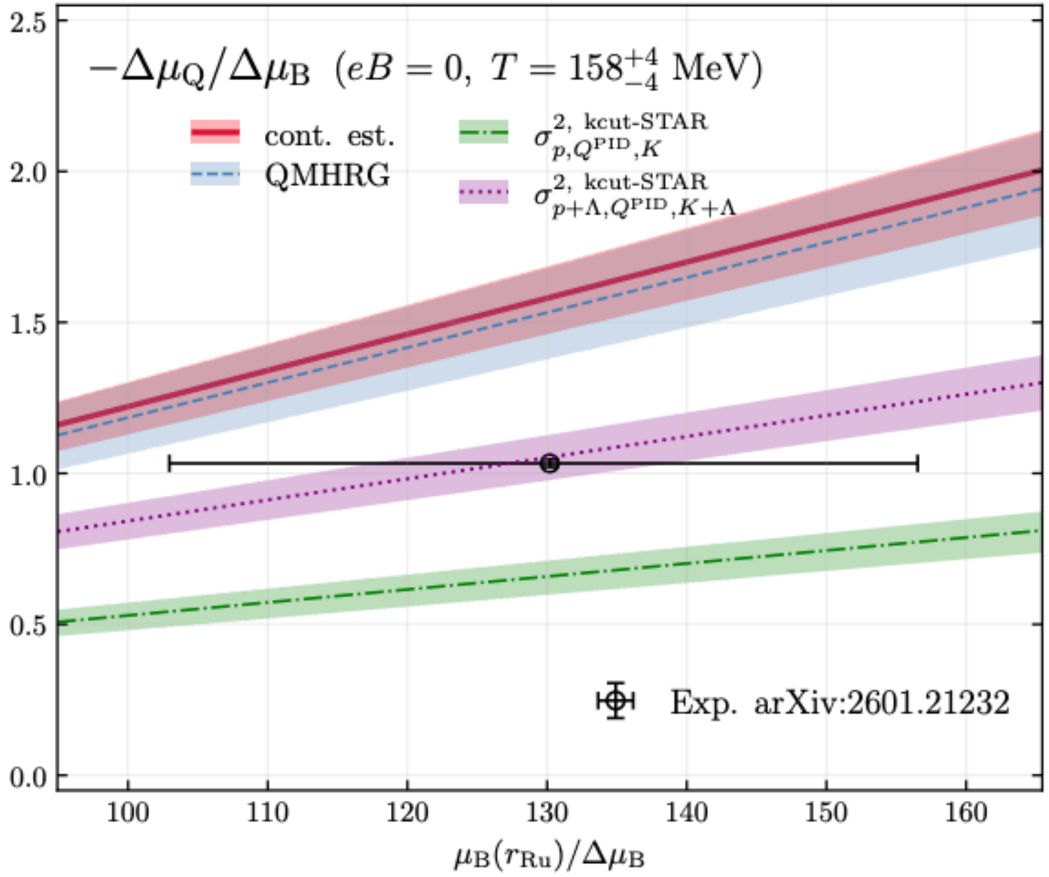
STAR observes a similar ordering in the centrality dependence

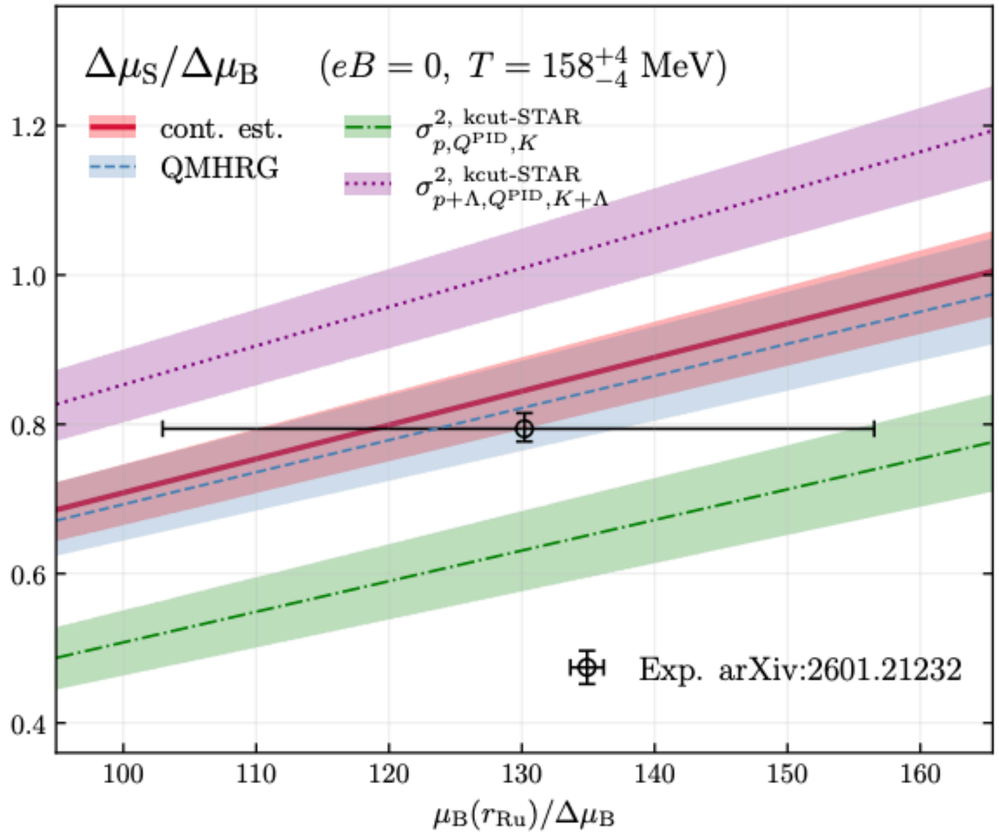
Chemical-potential differences: Lattice v.s. EXP

Jia Ni
Thur 2:40 PM

$$\frac{\Delta\mu_{\rm Q}}{\Delta\mu_{\rm B}} \equiv q_1(r_{\rm Zr}) + \Big[q_1(r_{\rm Zr}) - q_1(r_{\rm Ru})\Big]\frac{\mu_{\rm B}(r_{\rm Ru})}{\Delta\mu_{\rm B}}$$

$$\frac{\Delta\mu_{\rm S}}{\Delta\mu_{\rm B}} \equiv s_1(r_{\rm Zr}) + \Big[s_1(r_{\rm Zr}) - s_1(r_{\rm Ru})\Big]\frac{\mu_{\rm B}(r_{\rm Ru})}{\Delta\mu_{\rm B}}$$

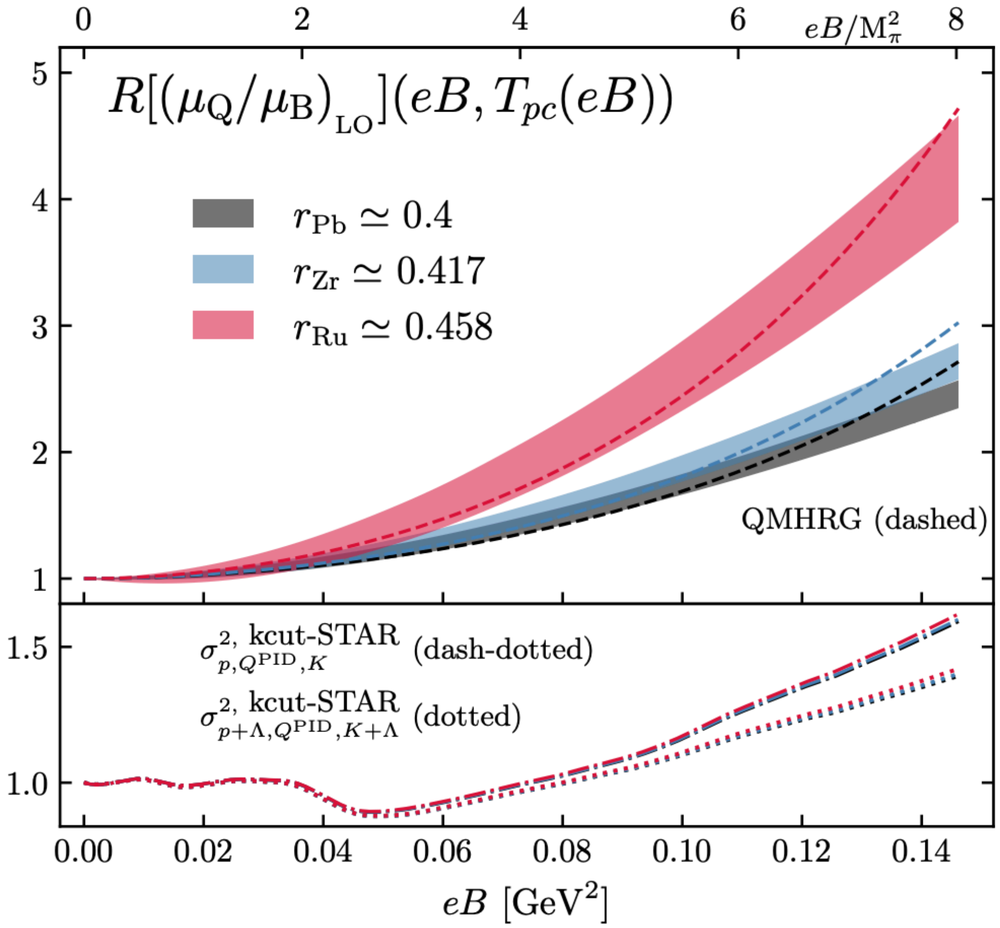


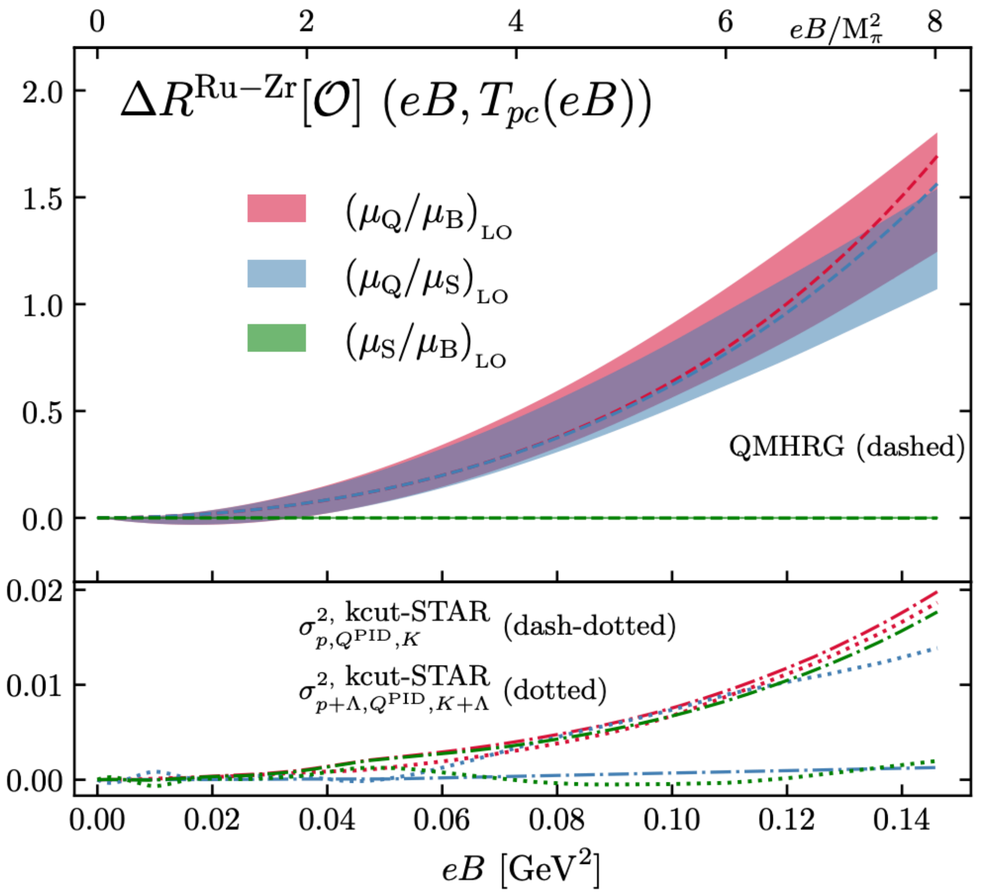


HTD, Jin-Biao Gu, Arpith Kumar, Jia Ni, arXiv: 2606.30164

Magnetic responses of chemical-potential ratios

Jia Ni
Thur 2:40 PM





HTD, Jin-Biao Gu, Arpith Kumar, Jia Ni, arXiv: 2606.30164

Summary

- **Chiral response of QCD topology:** Across the crossover, the local mass exponent rises from ≈1 toward 2. The effective amplitude peaks near the crossover.
- **Chiral and axial U(1) symmetry breaking:** Magnetic fields enhance both neutral-partner splittings at low T. Strong fields suppress these splittings near the crossover.
- **Vacuum mesons:** Neutral PS meson masses fall. Charged PS meson masses are nonmonotonic. Valence quark effects dominate the observed mass trends.
- **QCD magnetometers:** Conserved-charge ratios and isobar chemical potentials provide complementary probes. ALICE/STAR trends motivate further quantitative tests.

Backup

QCD symmetries at nonzero magnetic fields

- Magnetic field couples through electric charge $\mathcal{Q} = \begin{pmatrix} 2/3 & 0 \\ 0 & -1/3 \end{pmatrix} = \frac{1}{6}\mathbf{1} + \frac{1}{2}\tau^3,$
  - $[\tau^3, \mathcal{Q}] = 0$: neutral direction survives
  - $[\tau^{1,2}, \mathcal{Q}] \neq 0$: charged directions are explicitly broken by B

Symmetry condition: $[T, \mathcal{Q}] = 0$

- Chiral symmetry: $SU(2)_L \times SU(2)_R$:

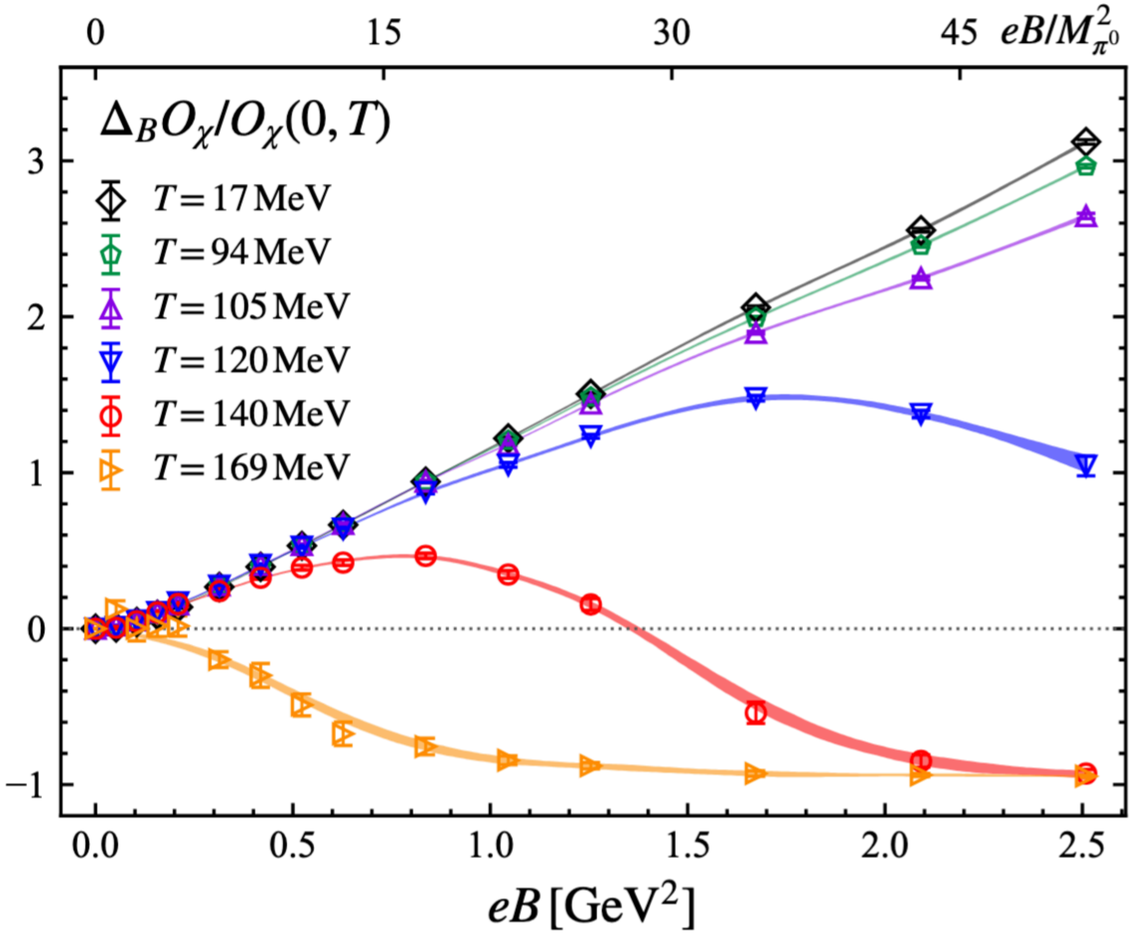
  Isospin symmetry: $SU(2)_V \longrightarrow U(1)_V^{(3)},$

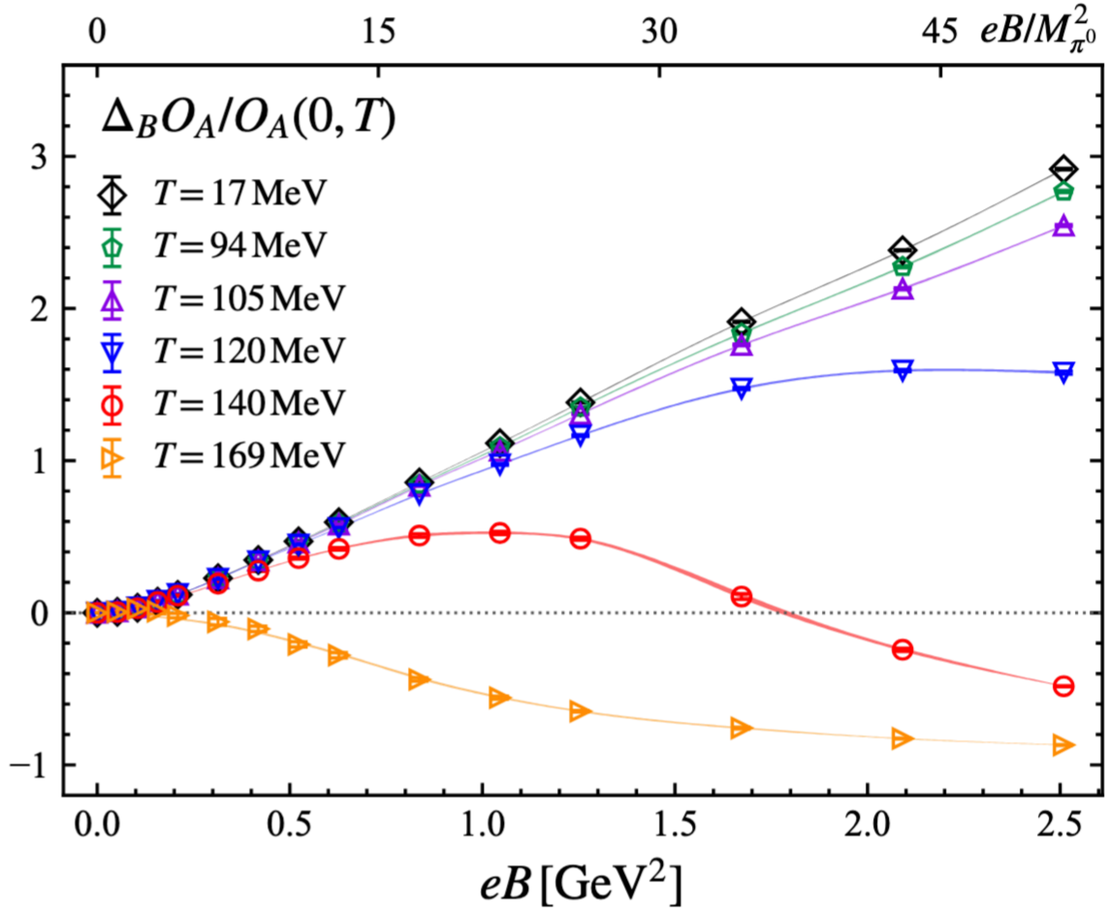
  Remaining chiral symmetry: $SU(2)_A \longrightarrow U(1)_A^{(3)}$

- Divergence of axial current: $\partial_\mu J^\mu_{5,T} = i\bar{\psi}\{M_q, T\}\gamma_5\psi + 2\,\mathrm{tr}_f(T)\,q(x) + \frac{e^2}{8\pi^2} N_c \mathrm{tr}_f(TQ^2) F^{\mathrm{em}}_{\mu\nu} \widetilde{F}^{\mathrm{em}\,\mu\nu}$

  In pure magnetic fields $F^{\mathrm{em}}_{\mu\nu} \widetilde{F}^{\mathrm{em}\,\mu\nu} \propto \mathbf{E} \cdot \mathbf{B} = 0$

Fate of axial U1 and chiral symmetries in Hot and Magnetized QCD





Flow time dependence and time history of Q

