NuclearScience
Computing CenteratCCNU

Baryon electric charge correlation as a magnetometer of QCD

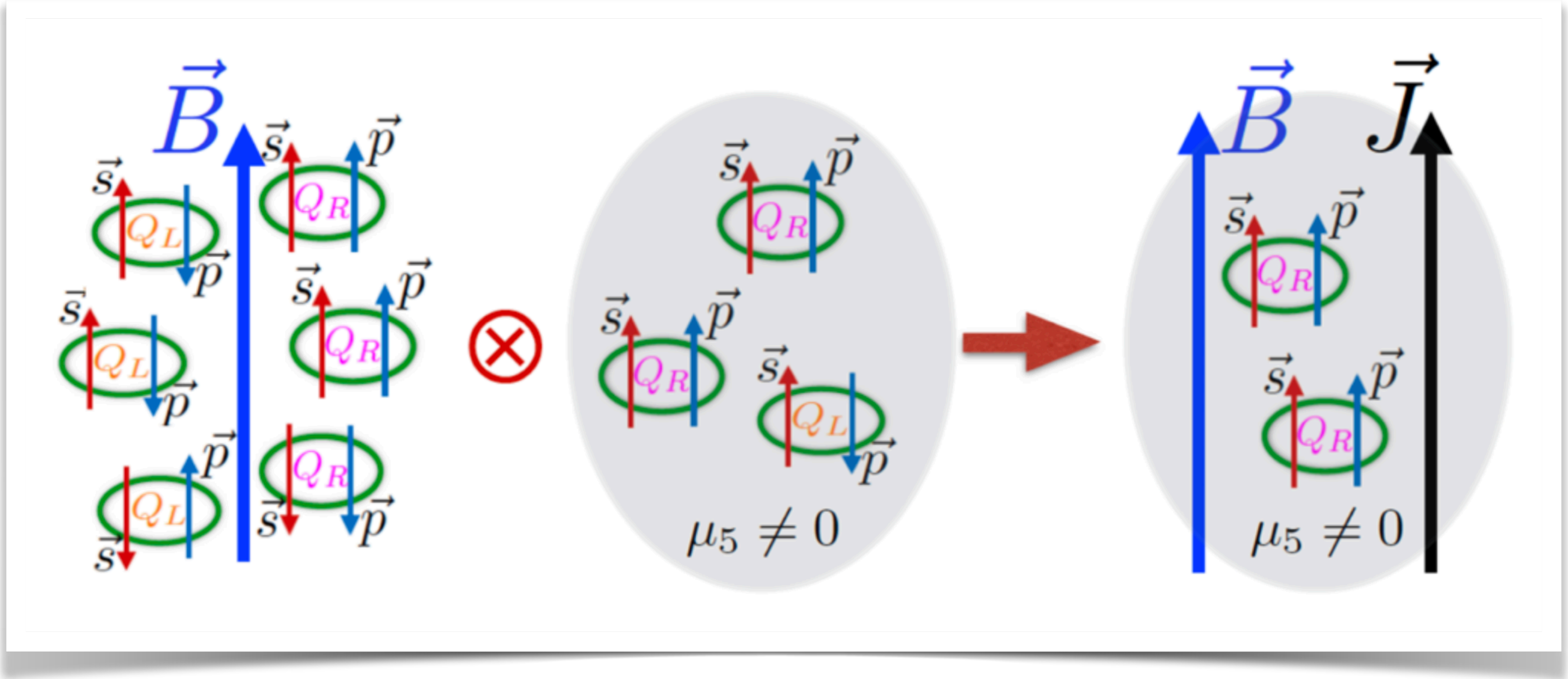
Heng-Tong Ding (丁亨通)
Central China Normal University (华中师范大学)

HTD, J.-B. Gu, A. Kumar, S.-T. Li, J.-H. Liu, arXiv:2312.08860

The 2nd Workshop on Ultra-Peripheral Collision Physics: Strong Electromagnetic fields, UPC and EIC/EicC

April 13-15, 2024 @USTC

Chiral magnetic effect

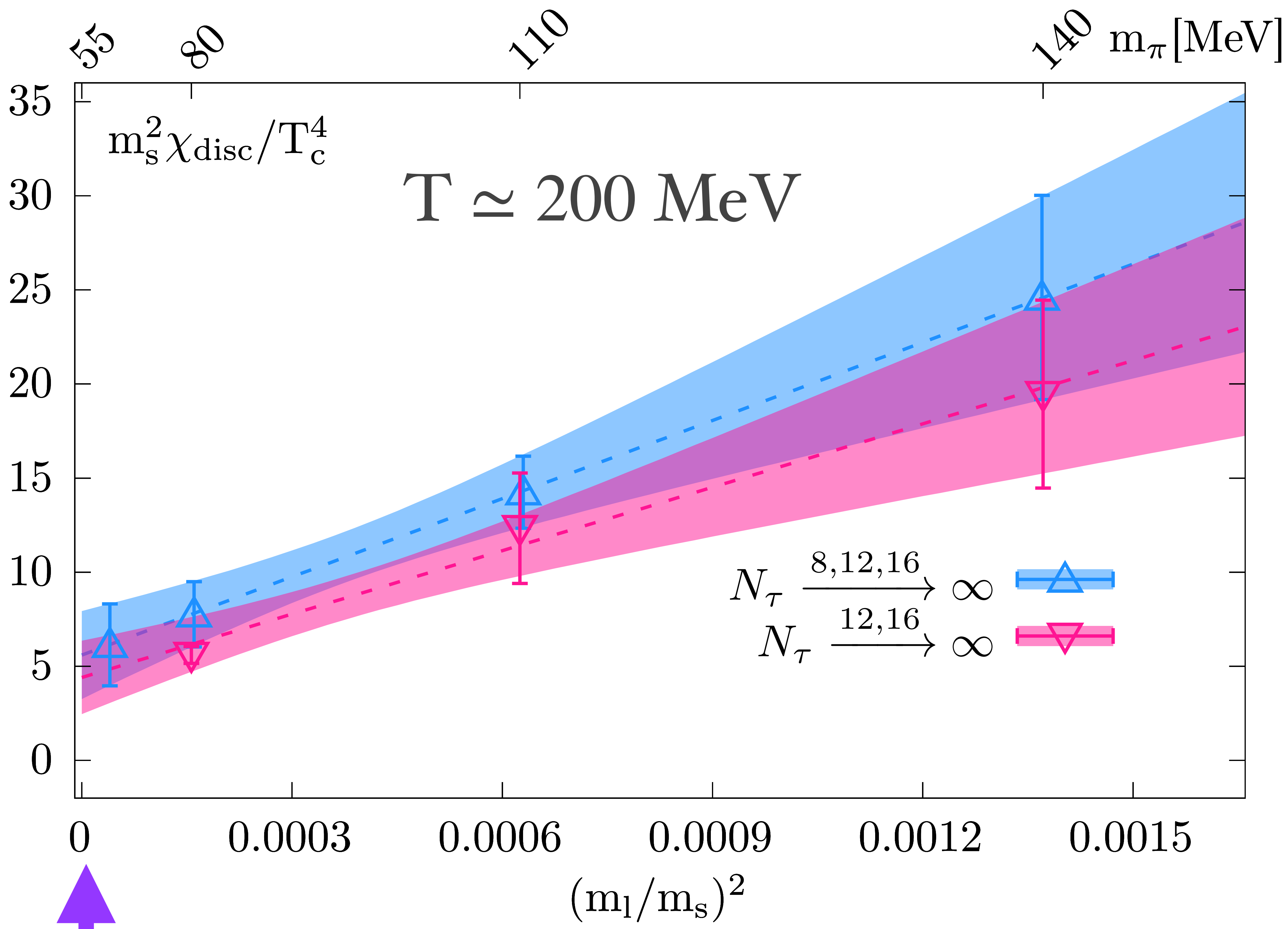


See recent reviews e.g.
D.E. Kharzeev and J. Liao, Nature Rev. Phys. 3(2021)55

- Axial U(1) anomaly
- Strong magnetic field

Axial U1 anomaly at zero magnetic fields

LQCD results for Nf=2+1 QCD with HISQ fermions



chiral limit

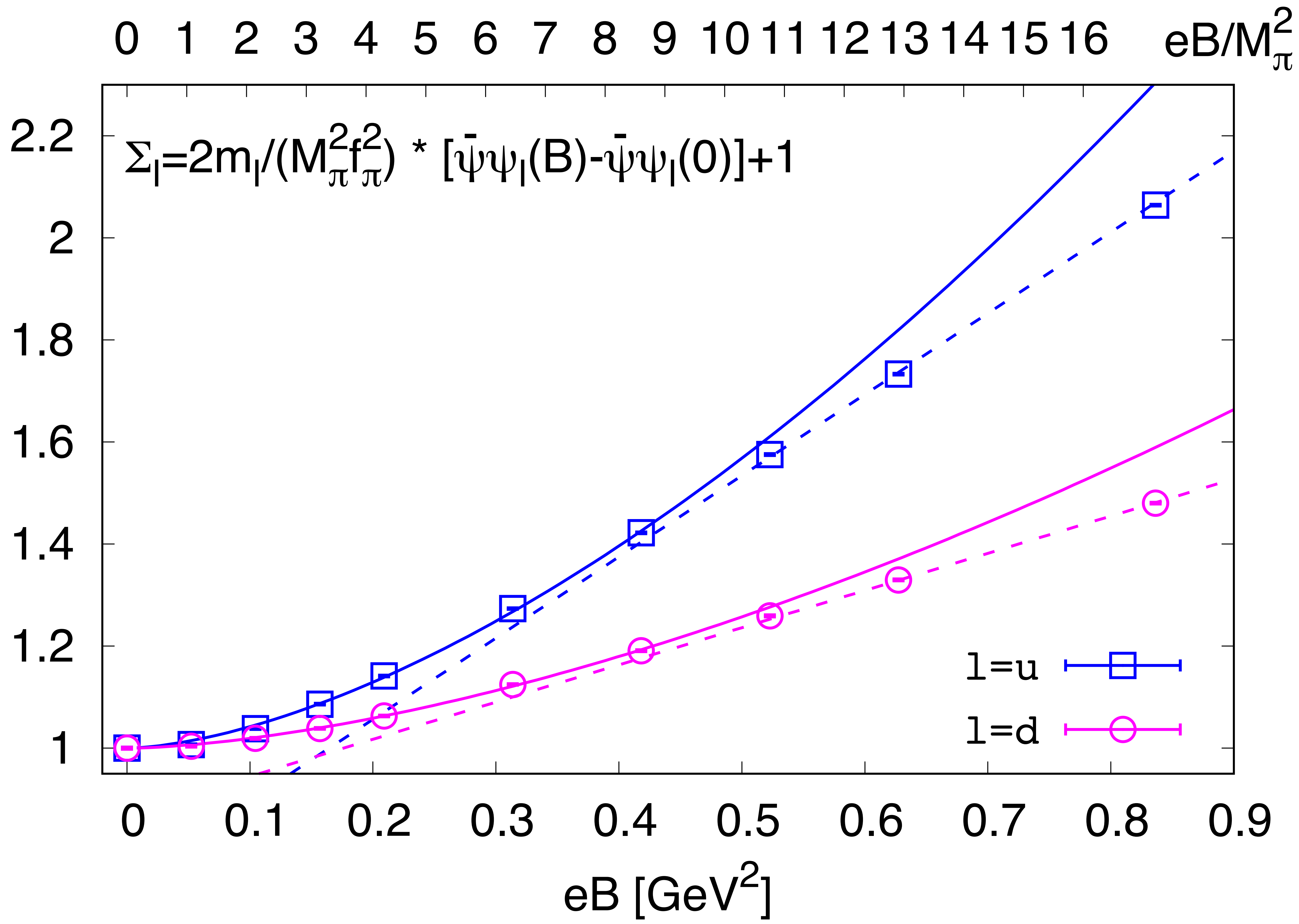
eB=0 & T ≃ 200 MeV

Axial anomaly remains manifested in the two U(1)$_A$ measures at a 2-3 sigma level

HTD, S.-T. Li, A. Tomiya, S. Mukherjee, X.-D. Wang, Y. Zhang, PRL 126 (2021) 082001

Whether imprints of a strong magnetic field exist in the final stage of heavy-ion collisions?

Isospin symmetry breaking at $eB \neq 0$ manifested in chiral condensates



Not accessible in HIC experiments

HTD, S.-T. Li, A. Tomiya, X.-D. Wang and Y. Zhang, PRD 126 (2021) 082001

See also in e.g. Bali et al., Phys.Rev.D86(2012)071502

Fluctuations of net baryon number(B), electric charge (Q) and strangeness (S)

- Taylor expansion of the QCD pressure:

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

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

- Taylor expansion coefficients at μ=0 are computable in LQCD

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

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

$$\mu_u = \frac{1}{3}\mu_{\mathrm{B}} + \frac{2}{3}\mu_{\mathrm{Q}}\,, \quad \mu_d = \frac{1}{3}\mu_{\mathrm{B}} - \frac{1}{3}\mu_{\mathrm{Q}}\,, \quad \mu_s = \frac{1}{3}\mu_{\mathrm{B}} - \frac{1}{3}\mu_{\mathrm{Q}} - \mu_{\mathrm{S}}\,.$$

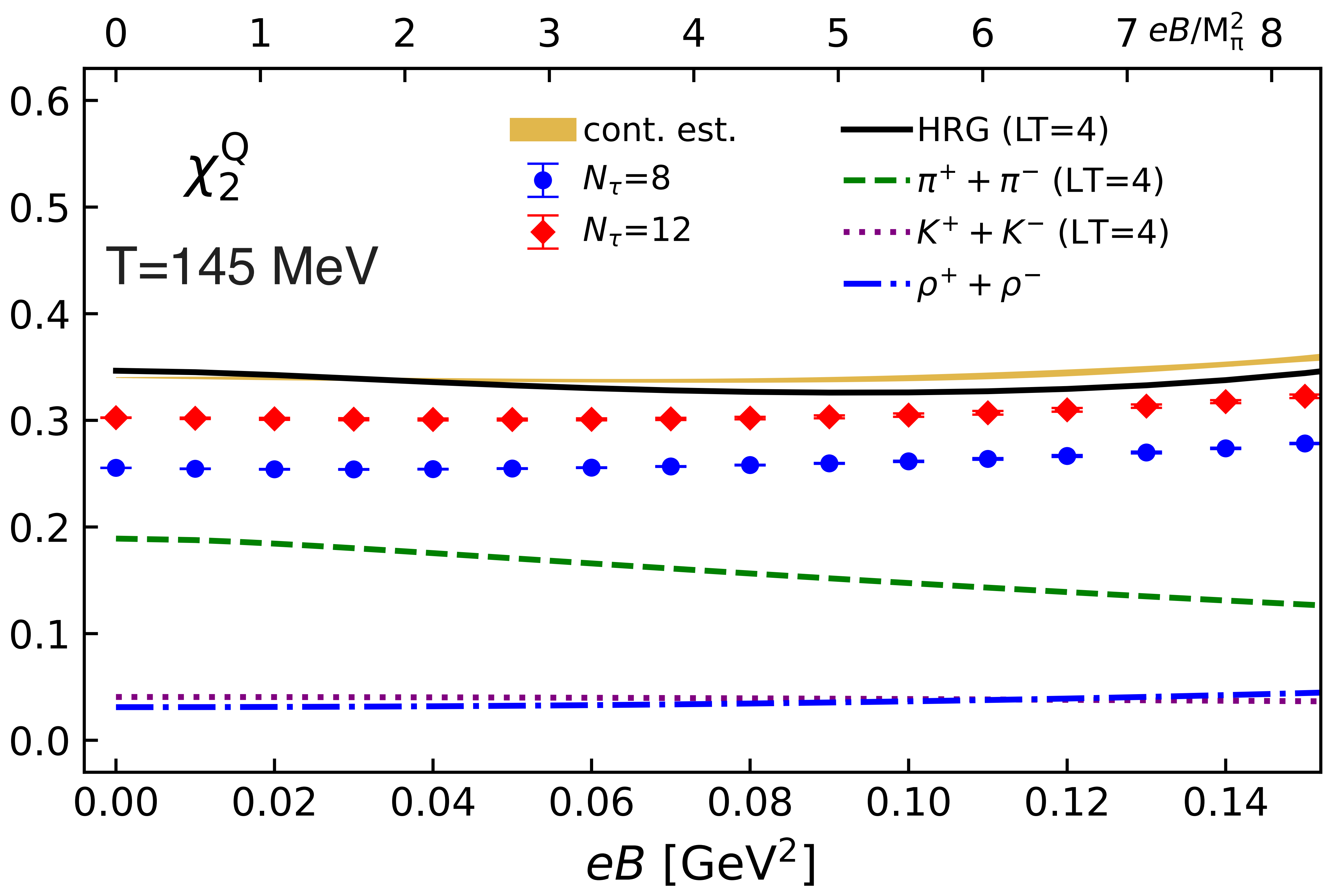
- At eB=/=0 a lot more need to be explored

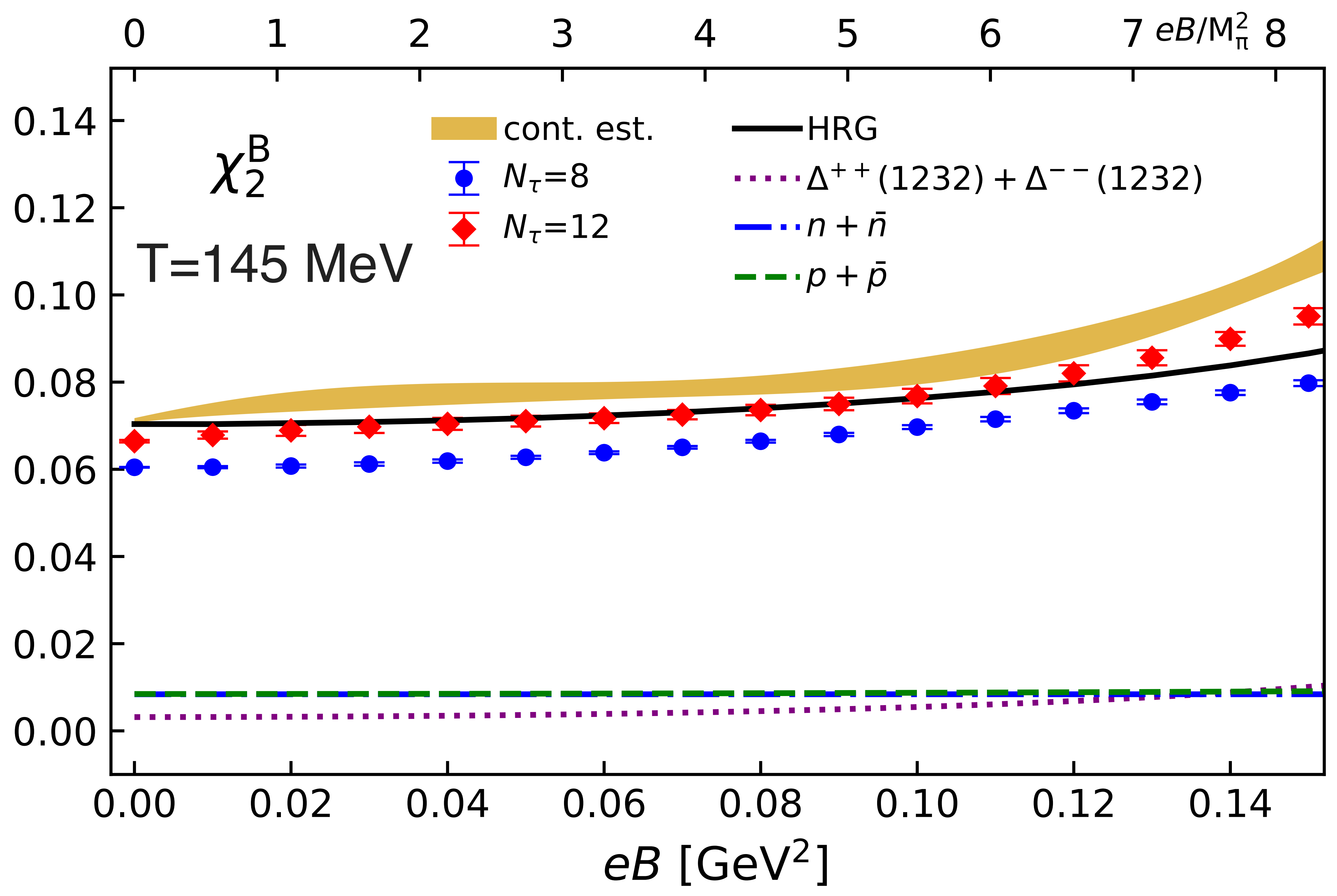
HRG: G. Kadam et al., JPG 47 (2020) 125106, Ferreira et al., PRD 98(2018)034003, Fukushima and Hidaka, PRL117 (2016)102301 Bhattacharyya et al., EPL115(2016)62003

PNJL: W.-J. Fu, Phys. Rev. D 88 (2013) 014009

Net baryon number and electric charge fluctuations at T=145 MeV at the physical point

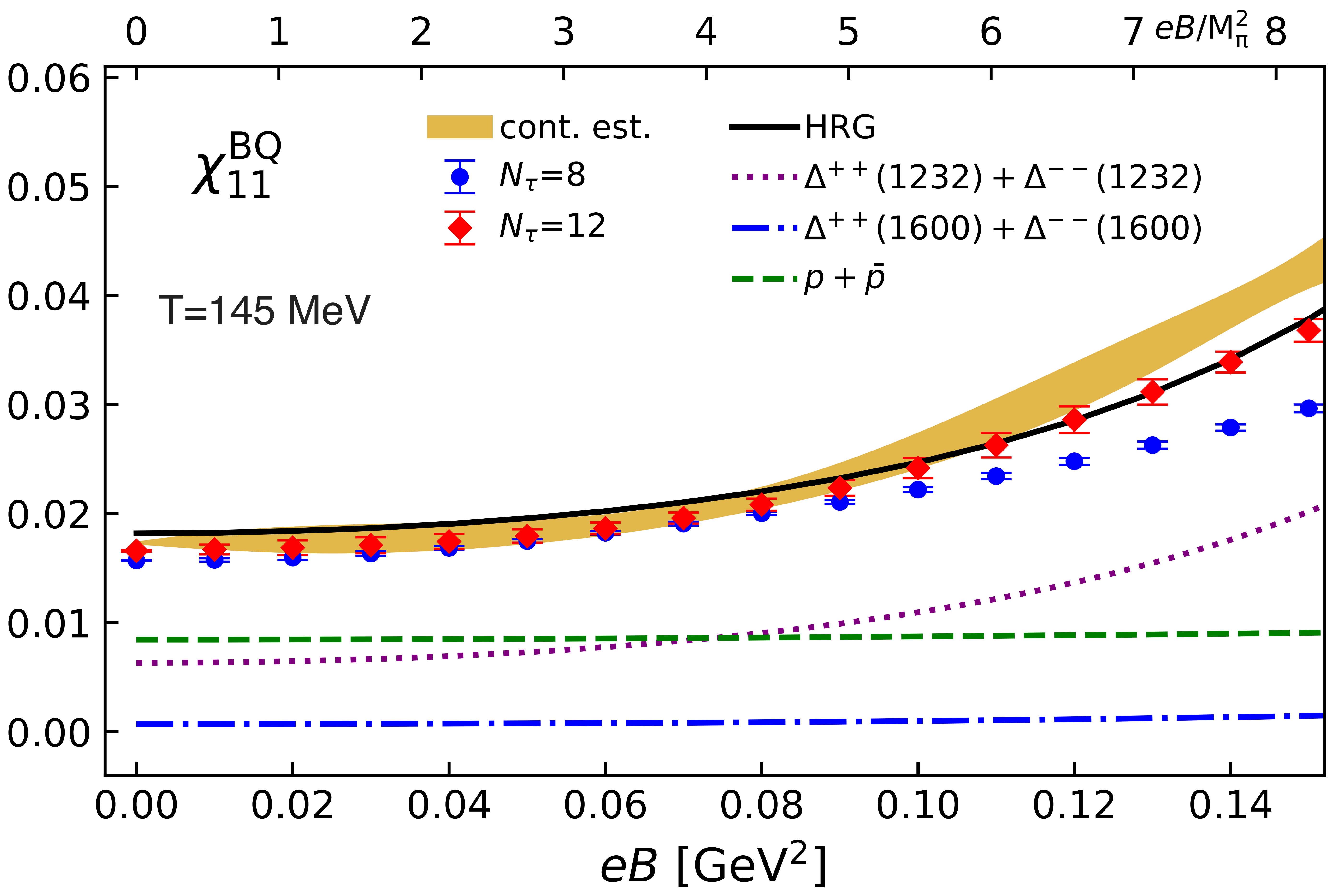
N_{f}=2+1 Lattice QCD, $M_\pi(eB=0) = 135$ MeV





HTD, J.-B. Gu, A. Kumar, S.-T. Li, J.-H. Liu, arXiv:2312.08860

Baryon electric charge correlation at T=145 MeV at the physical point



χ_{11}^{BQ}: Magnetometer of QCD

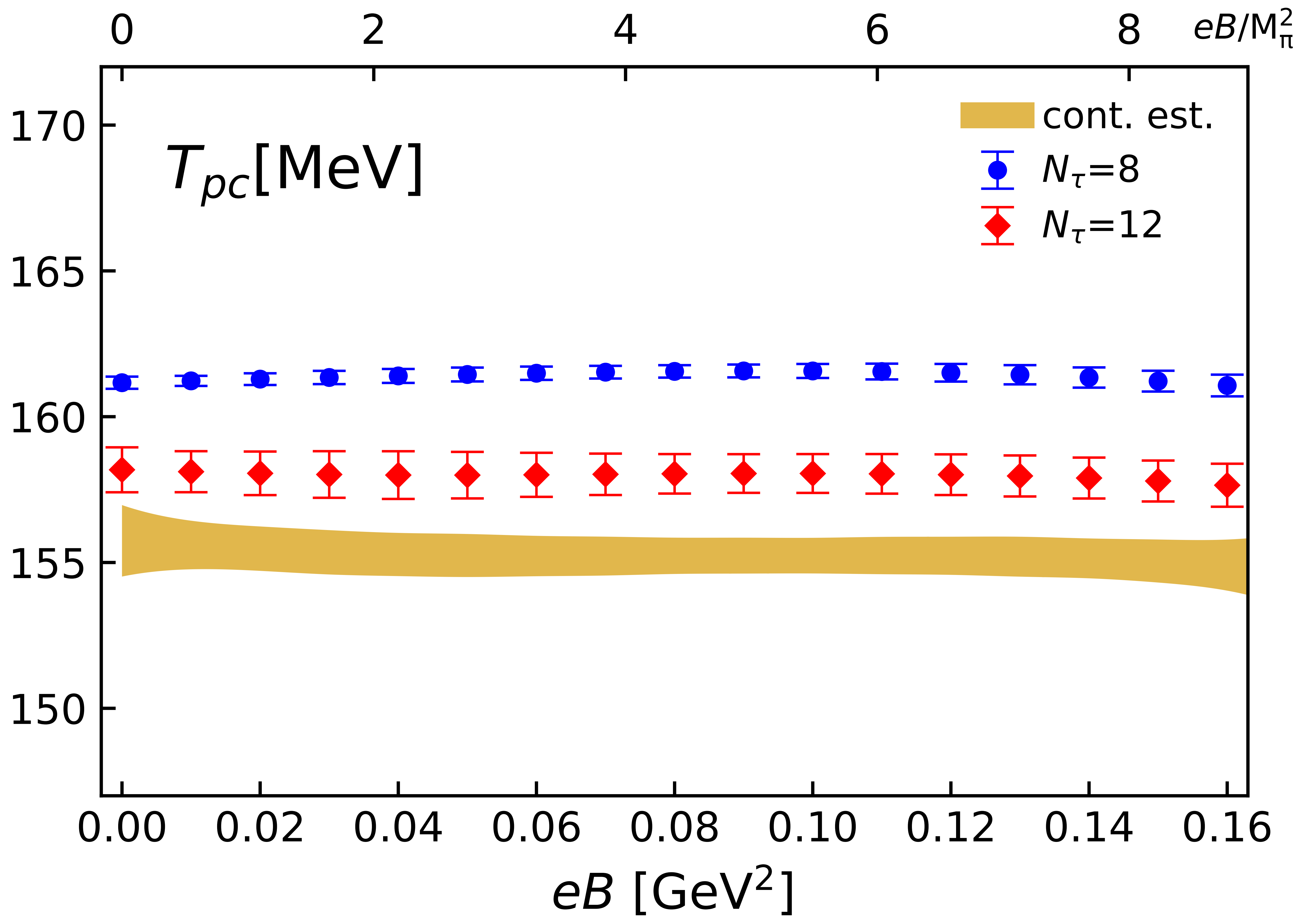
Most of the eB-dependences comes from doubly charged Delta baryons

Delta baryons: not-measurable in HIC experiments

$\Delta^{++} \rightarrow p + \pi^{+}$

HTD, J.-B. Gu, A. Kumar, S.-T. Li, J.-H. Liu, arXiv:2312.08860

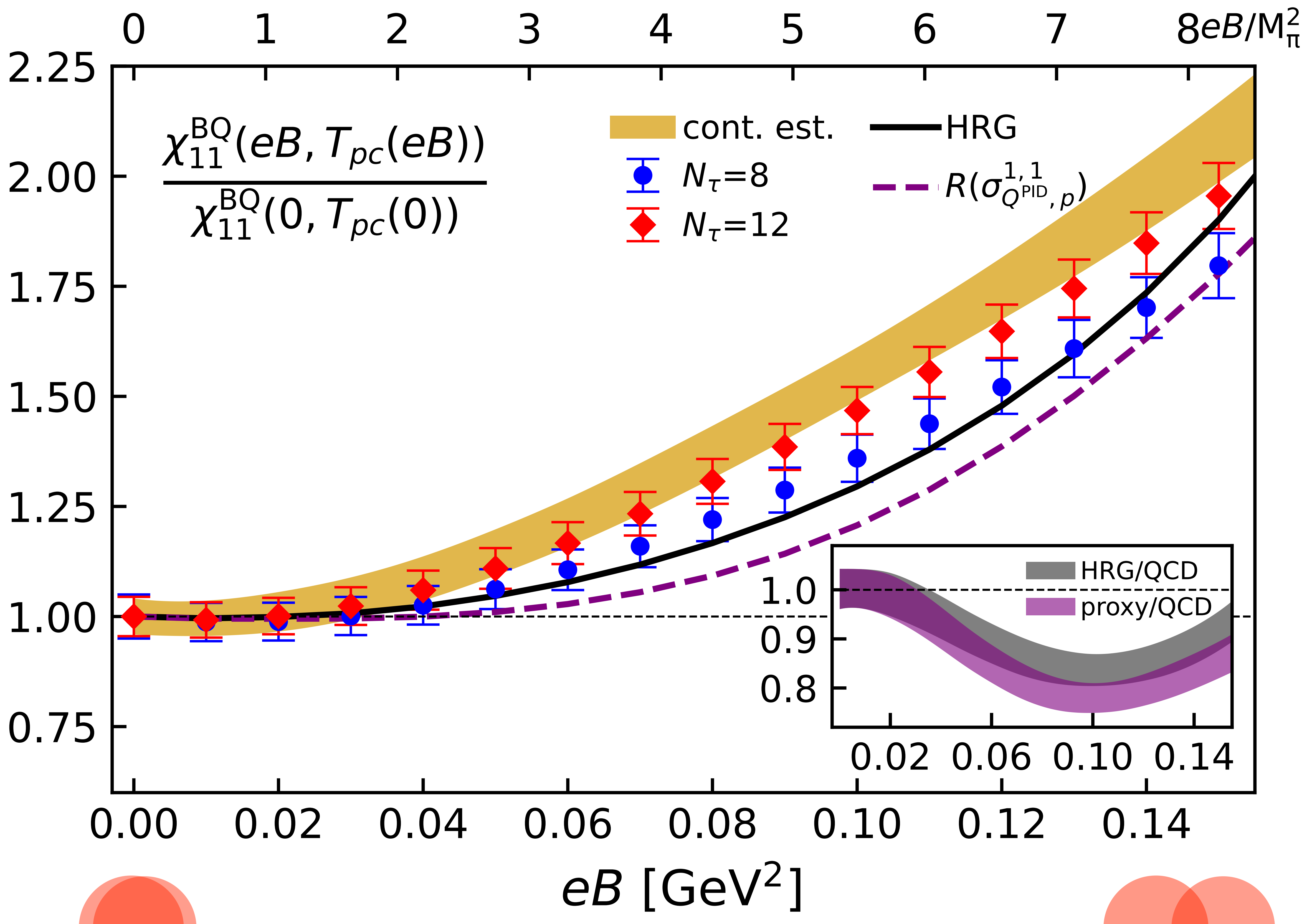
QCD transition temperature in nonzero magnetic fields



Determined as the peak location of chiral susceptibility

Negligible *eB*-independence at eB<0.16 GeV^2

Ratio X(eB)/X(eB=0) for 2nd order diagonal fluctuations along the transition line

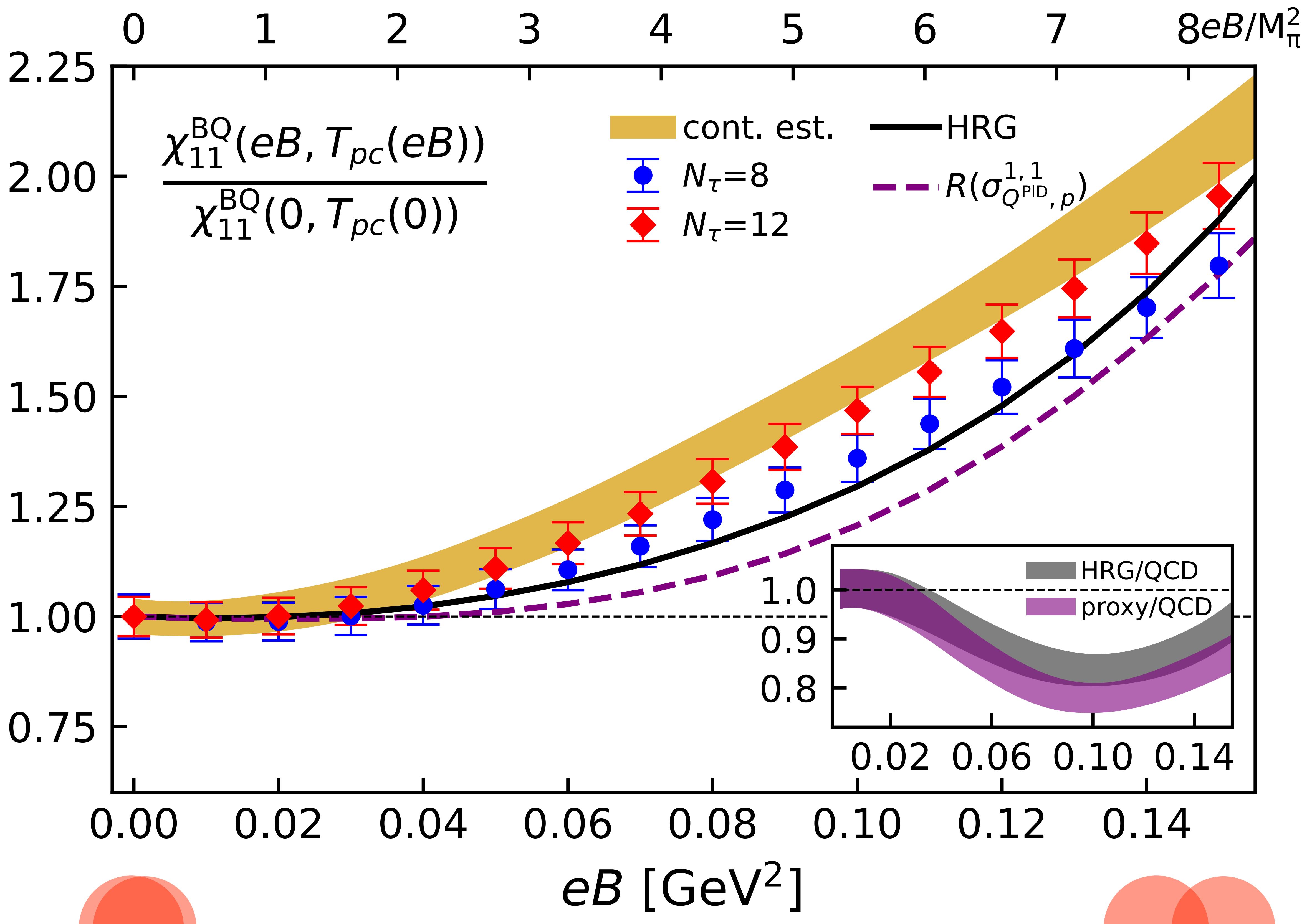


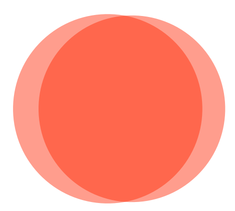
X(eB)/X(eB=0) : Rcp like observable

At $eB \lesssim M_\pi^2$: consistent with unity

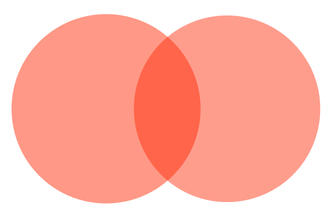
At $eB \simeq 8M_\pi^2$: ~2 !

Ratio X(eB)/X(eB=0) for 2nd order diagonal fluctuations along the transition line





Central collision



Peripheral collision

Memory carried by the decays of Δ^{++}:

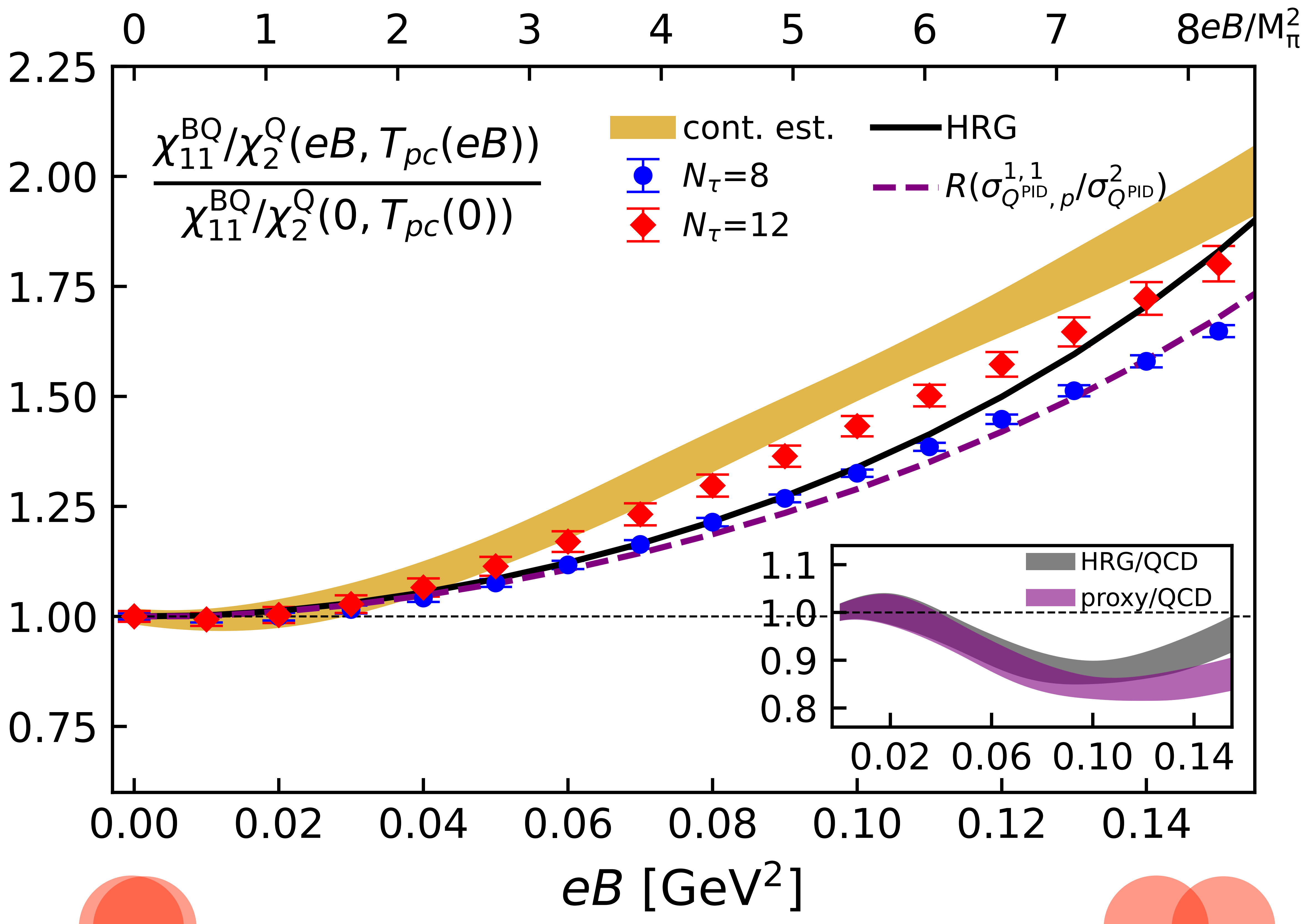
$$\Delta^{++} \to p + \pi^+$$

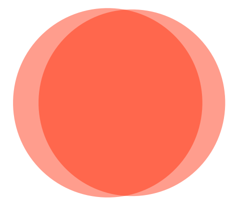
$$\sum_R B_R^l Q_R^m S_R^n I_p^R \to \sum_{i \in \text{stable}} \sum_R (P_{R\to i})^p B_i^l Q_i^m S_i^n I_p^R,$$

net-B approximated by Q^{PID}: $\tilde{p}$

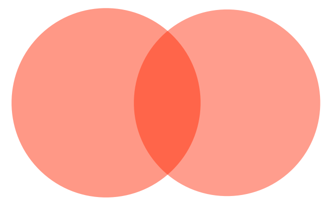
net-Q approximated by Q^{PID}: $\tilde{\pi}^+, \tilde{K}^+, \tilde{p}$

Ratio $X(eB)/X(eB=0)$ for 2nd order diagonal fluctuations along the transition line





Central collision



Peripheral collision

Memory carried by the decays of Δ^{++}:

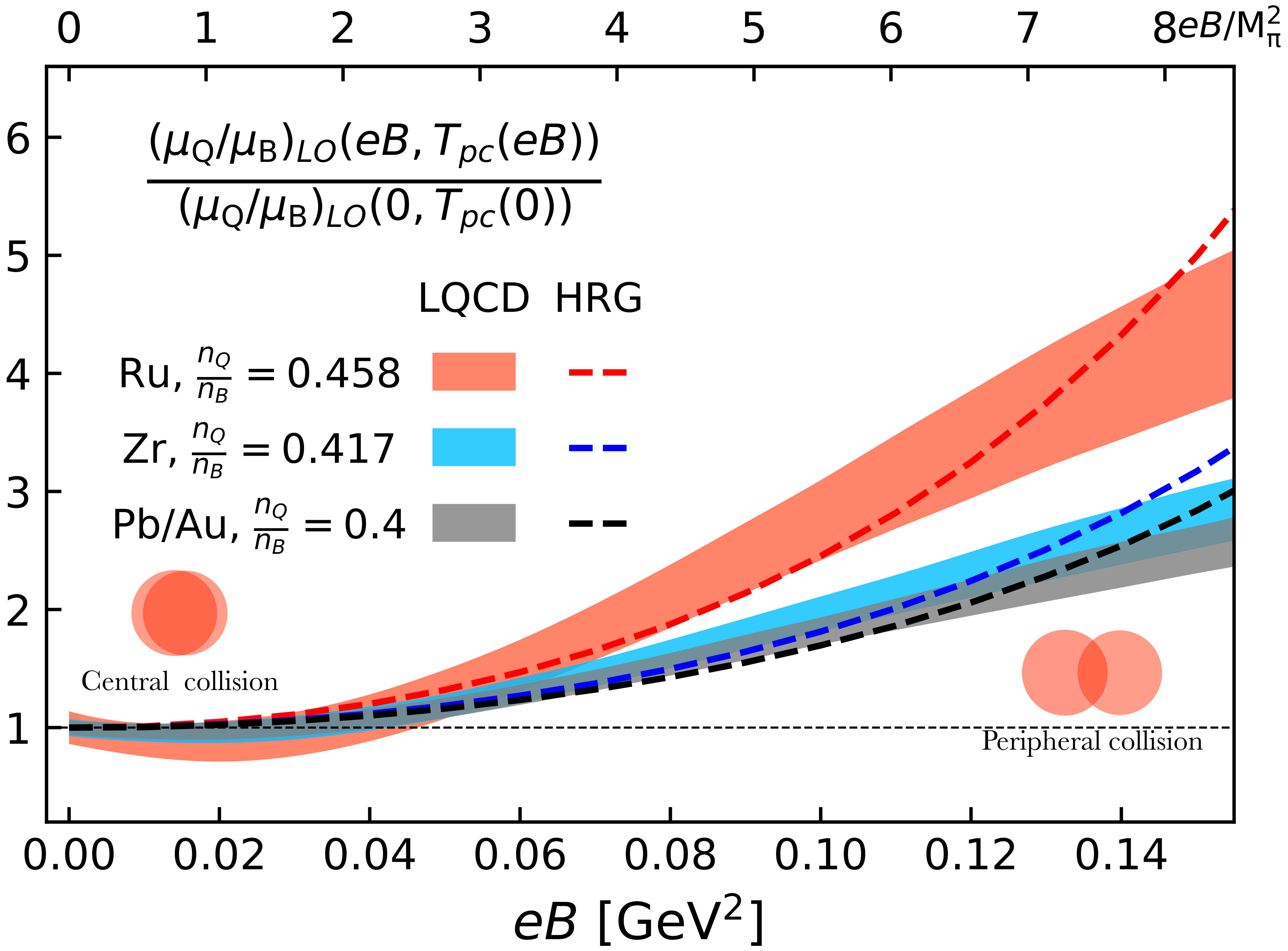
$$\Delta^{++} \to p + \pi^+$$

$$\sum_R B_R^l Q_R^m S_R^n I_p^R \to \sum_{i \in \text{stable}} \sum_R (P_{R\to i})^p B_i^l Q_i^m S_i^n I_p^R,$$

net-B approximated by Q^{PID}: $\tilde{p}$

net-Q approximated by Q^{PID}: $\tilde{\pi}^+, \tilde{K}^+, \tilde{p}$

μ_Q/μ_B in different collision systems



$$\mu_Q/\mu_B = q_1 + q_3\mu_B^2 + \mathcal{O}(\mu_B^4)$$

$$q_1 = \frac{r(\chi_2^B\chi_2^S - \chi_{11}^{BS}\chi_{11}^{BS}) - (\chi_{11}^{BQ}\chi_2^S - \chi_{11}^{BS}\chi_{11}^{QS})}{(\chi_2^Q\chi_2^S - \chi_{11}^{QS}\chi_{11}^{QS}) - r(\chi_{11}^{BQ}\chi_2^S - \chi_{11}^{BS}\chi_{11}^{QS})}$$

$$r = n_Q/n_B$$

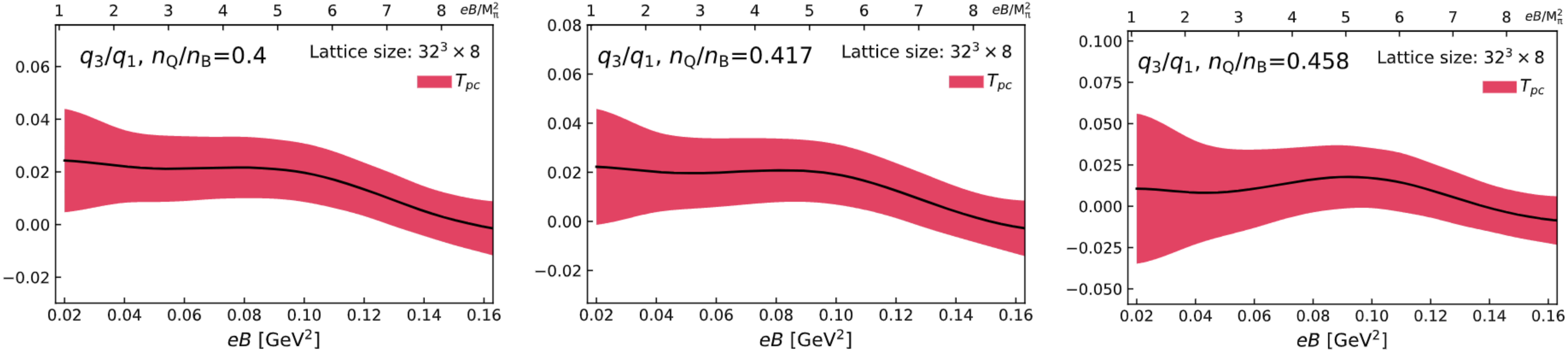
${}^{96}_{44}\text{Ru} + {}^{96}_{44}\text{Ru}$: r=0.458

${}^{96}_{40}\text{Zr} + {}^{96}_{40}\text{Zr}$: r=0.417

${}^{208}_{82}\text{Pb} + {}^{208}_{82}\text{Pb}$: r=0.4

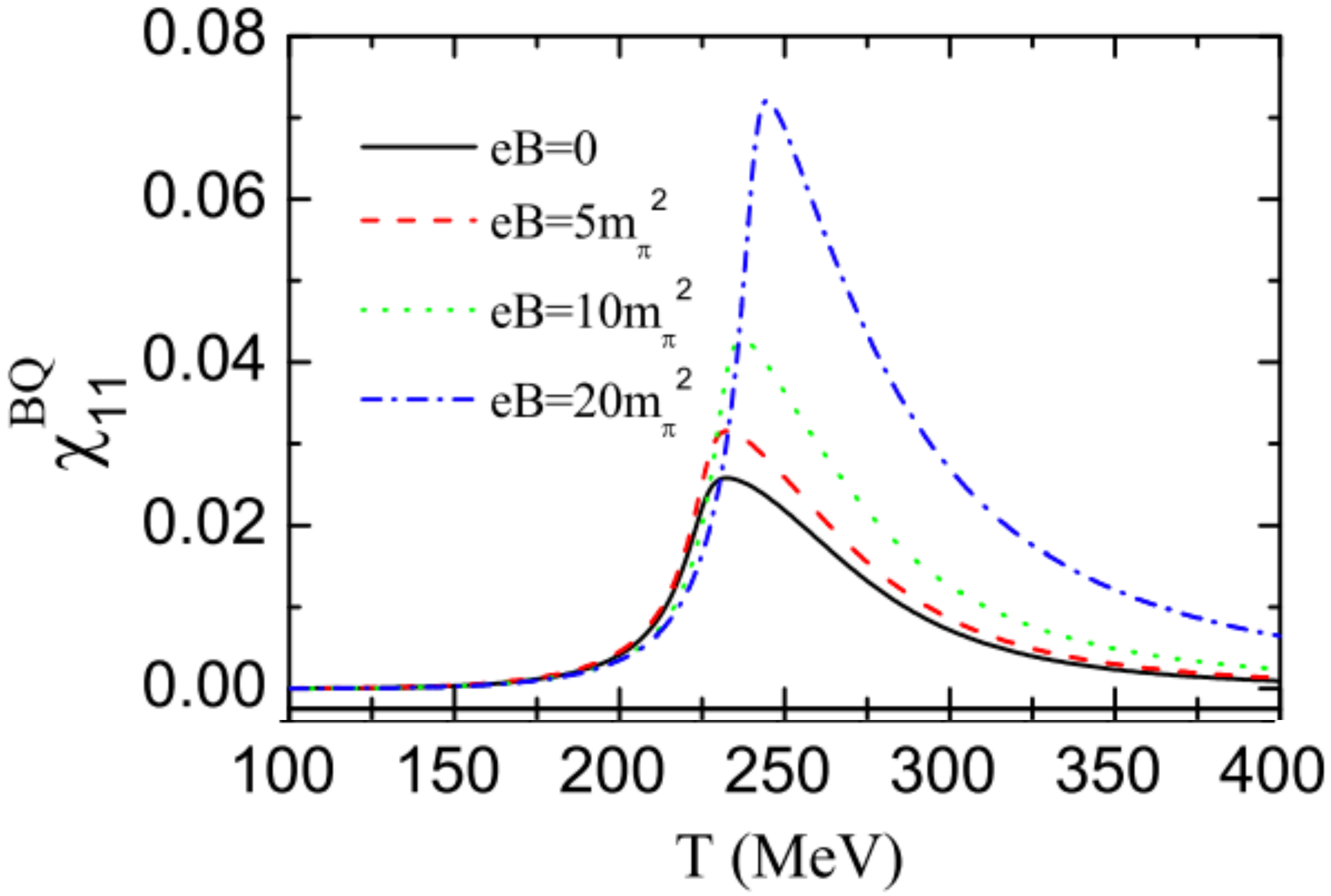
μ_Q/μ_B in different collision systems

$$\mu_Q/\mu_B = q_1 + q_3\mu_B^2 + \mathcal{O}(\mu_B^4)$$

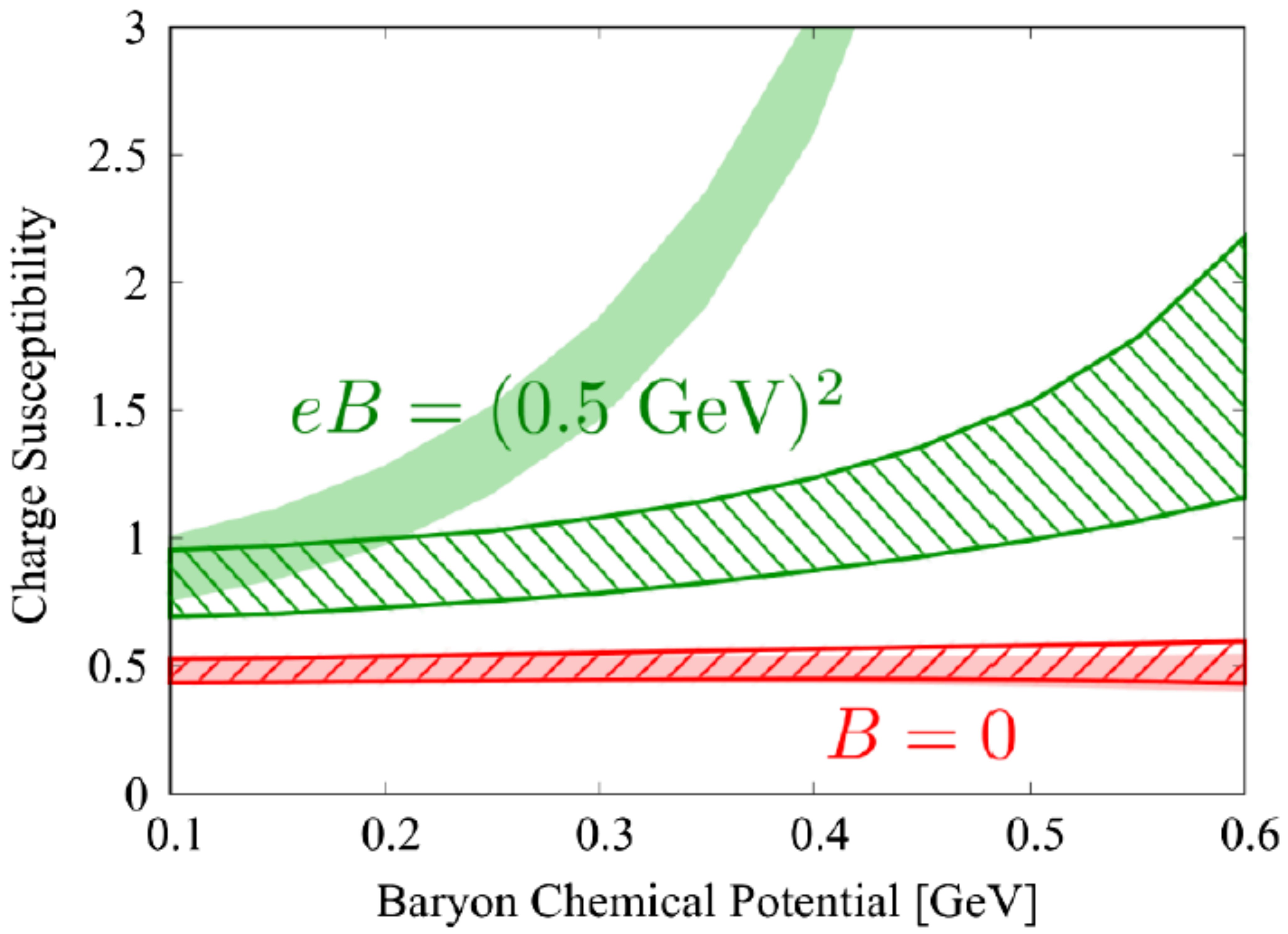


Negligible next-to-leading order correction

Lattice QCD v.s. effective theory & model studies



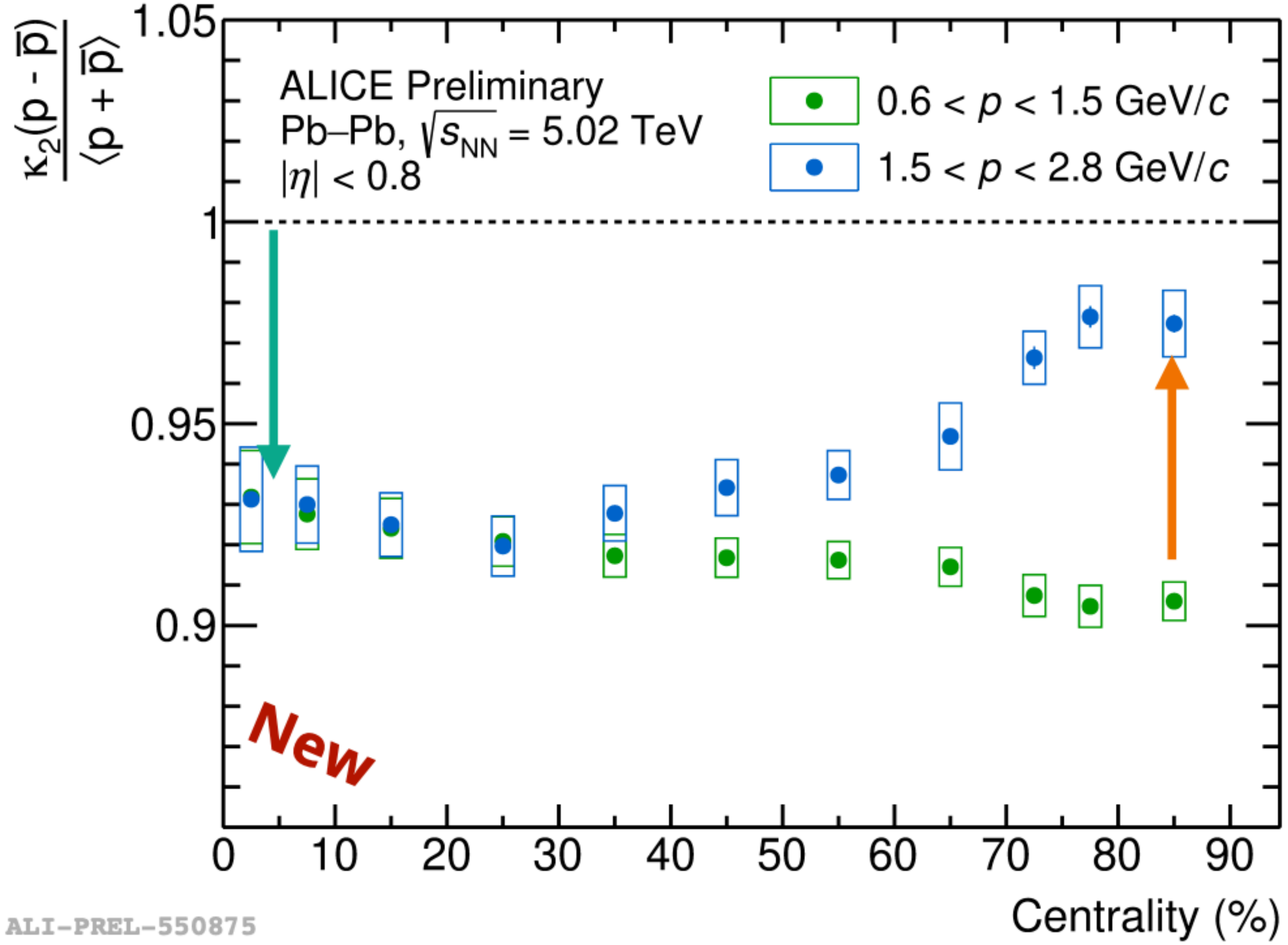
Results obtained from PNJL from
W.-J. Fu, Phys. Rev. D 88 (2013) 014009

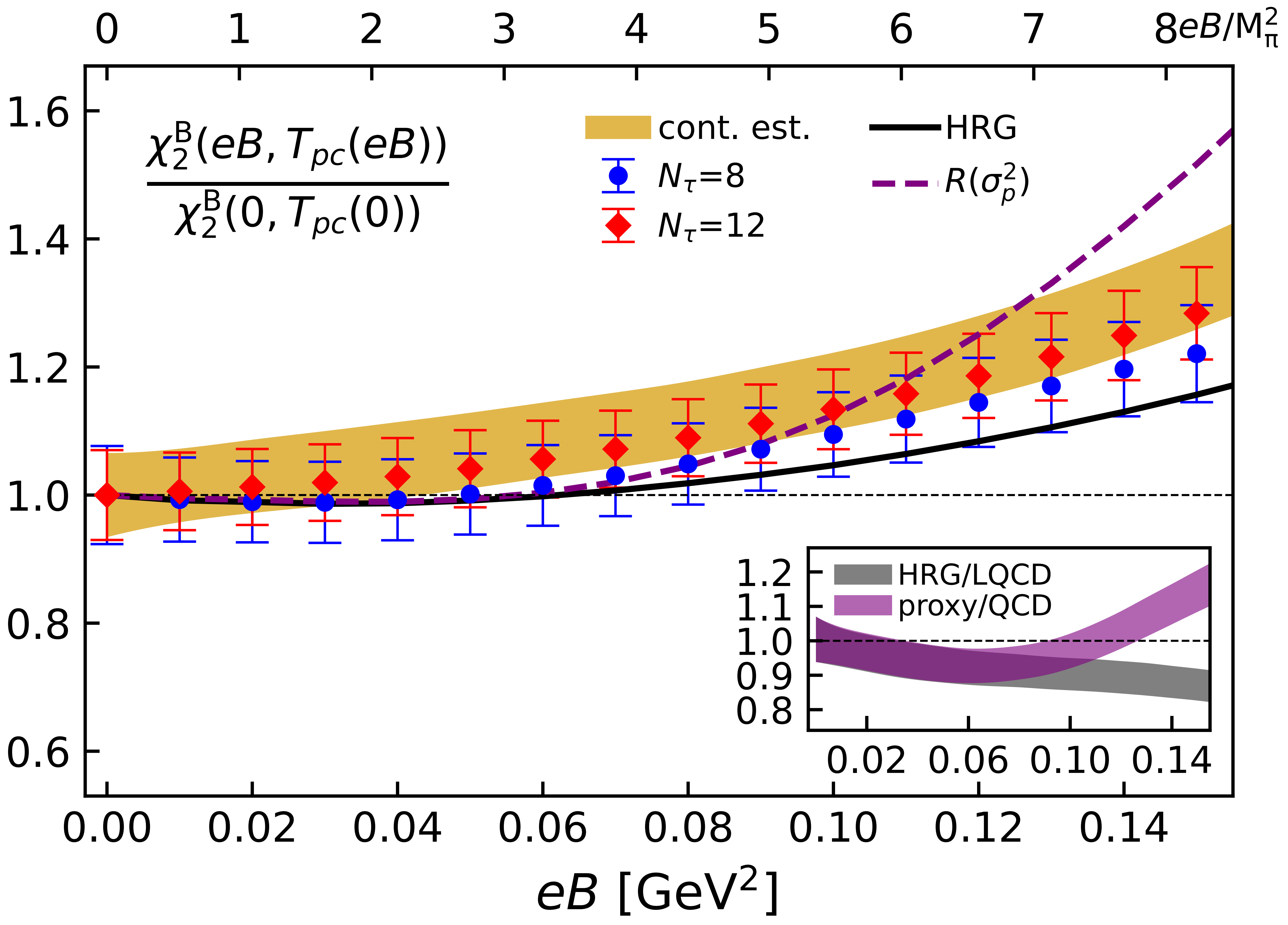


Results obtained from HRG model
K. Fukushima and Y. Hidaka , Phys. Rev. Lett. 117 (2016) 102301

Both above two results are inconsistent with LQCD results!

Lattice QCD v.s. experiments

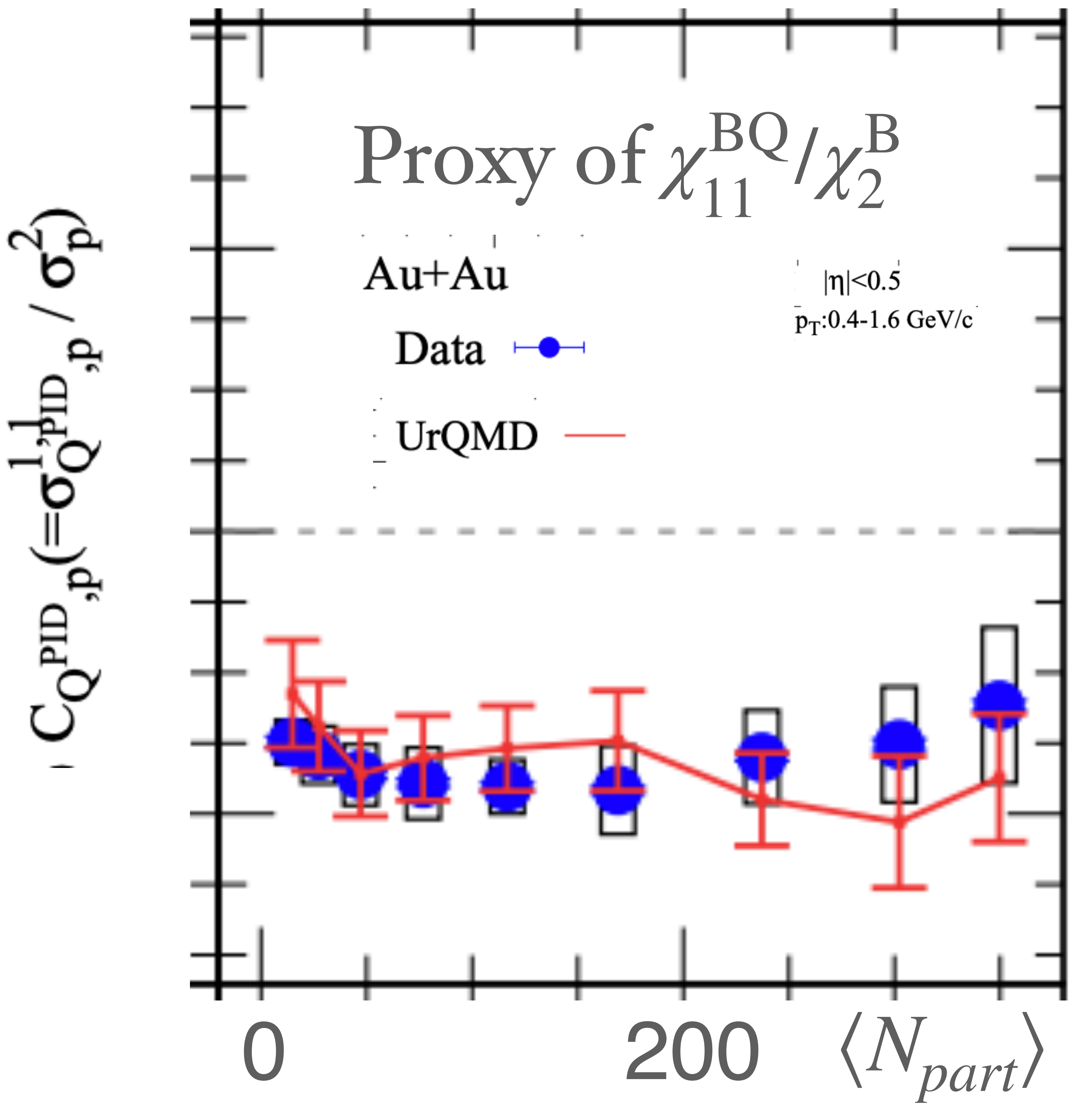




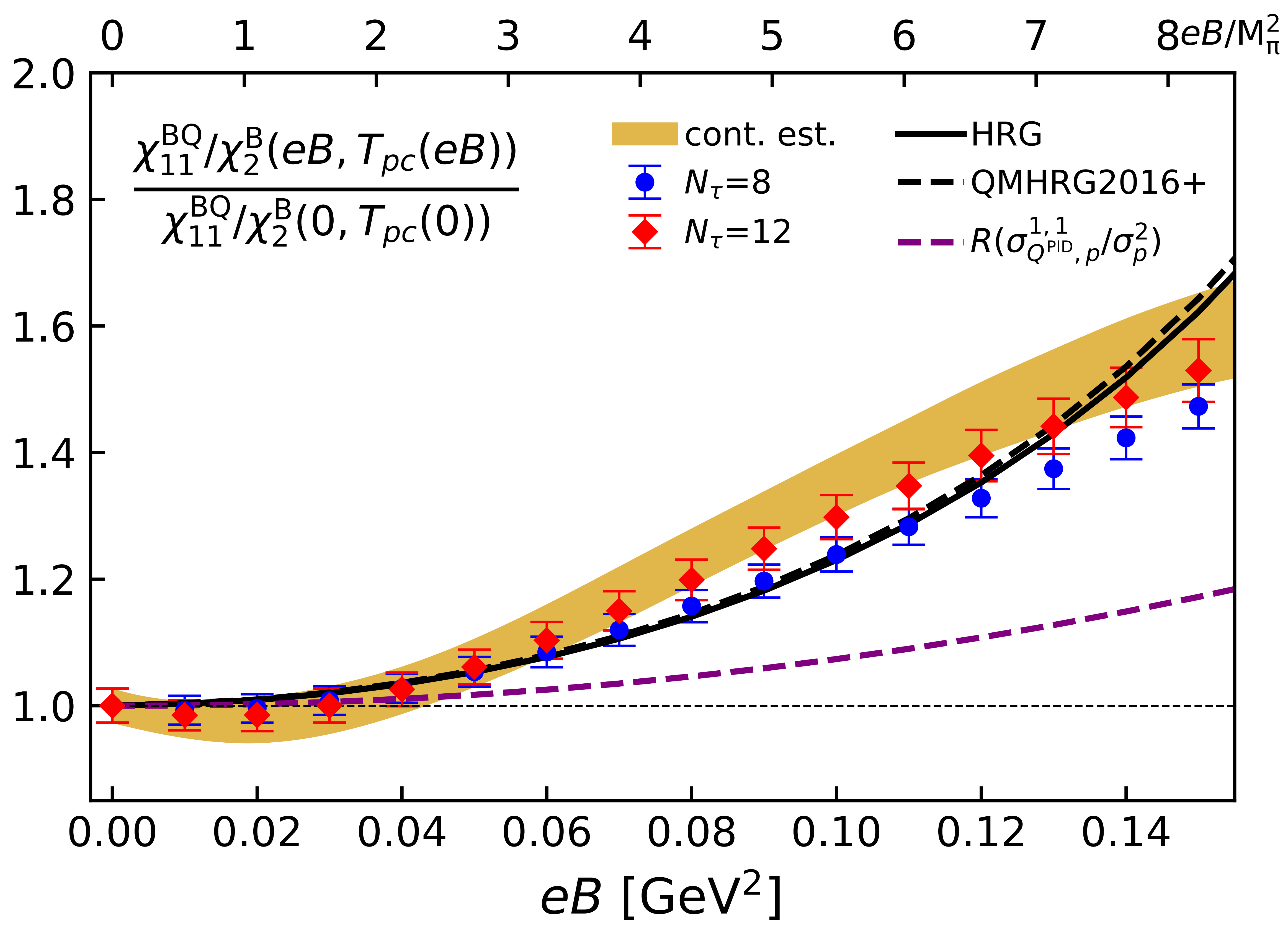
Ilya Fokin, ALICE, Quark Matter 2023

HTD, J.-B. Gu, A. Kumar, S.-T. Li, J.-H. Liu, arXiv:2312.08860

Lattice QCD v.s. experiments



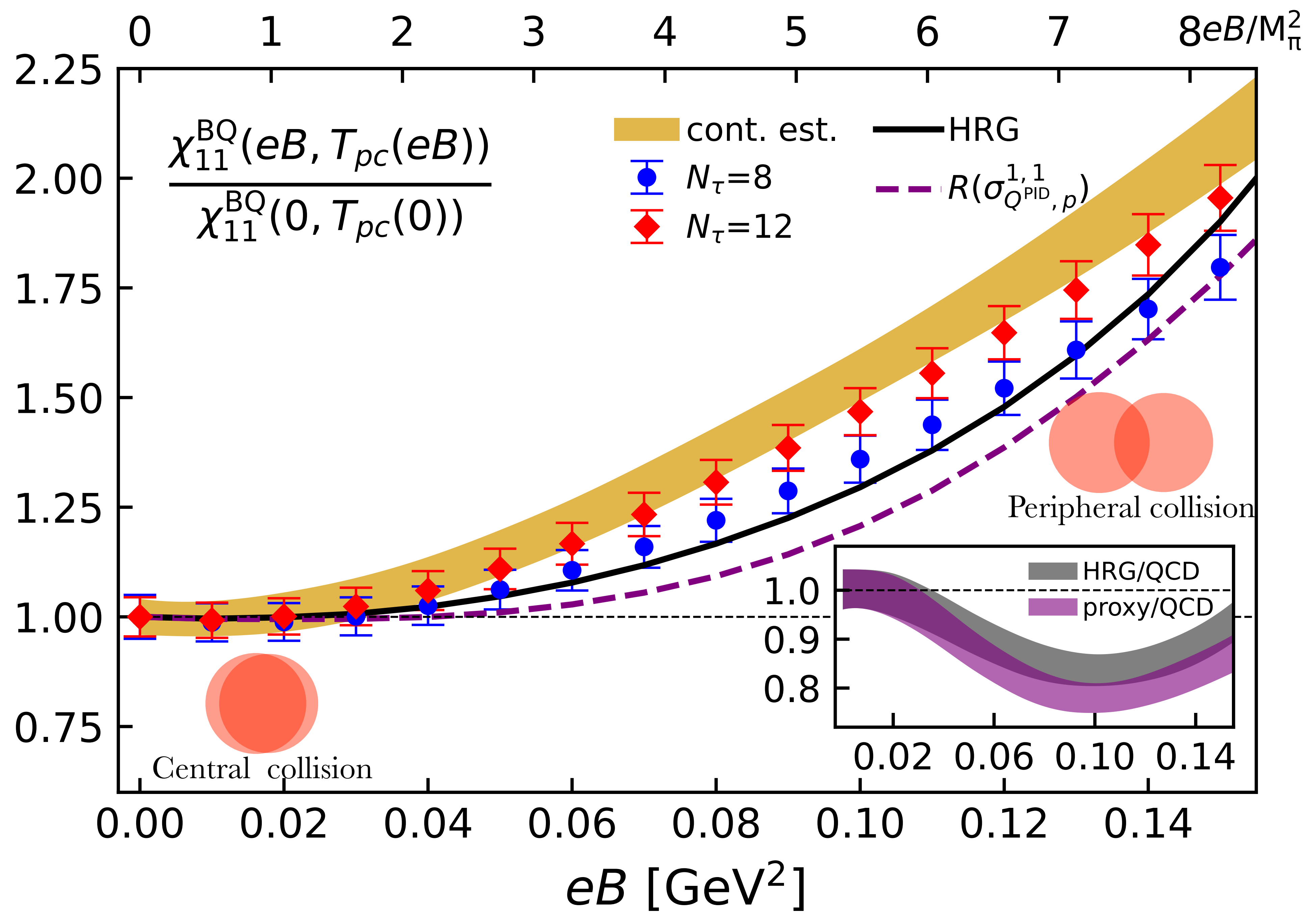
STAR: Phys.Rev. C 105, 029901(E) (2022)

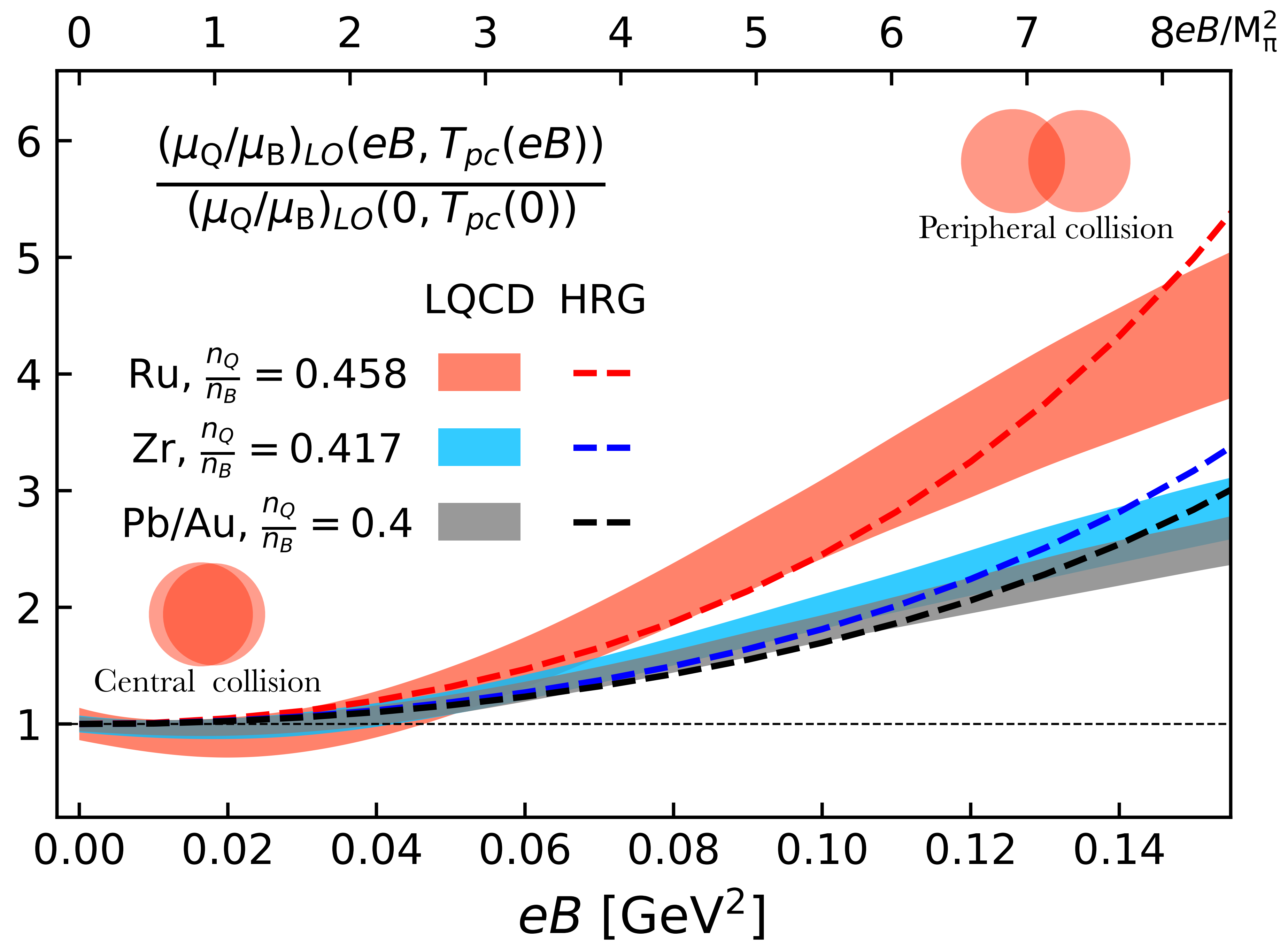


HTD, J.-B. Gu, A. Kumar, S.-T. Li, J.-H. Liu, arXiv:2312.08860

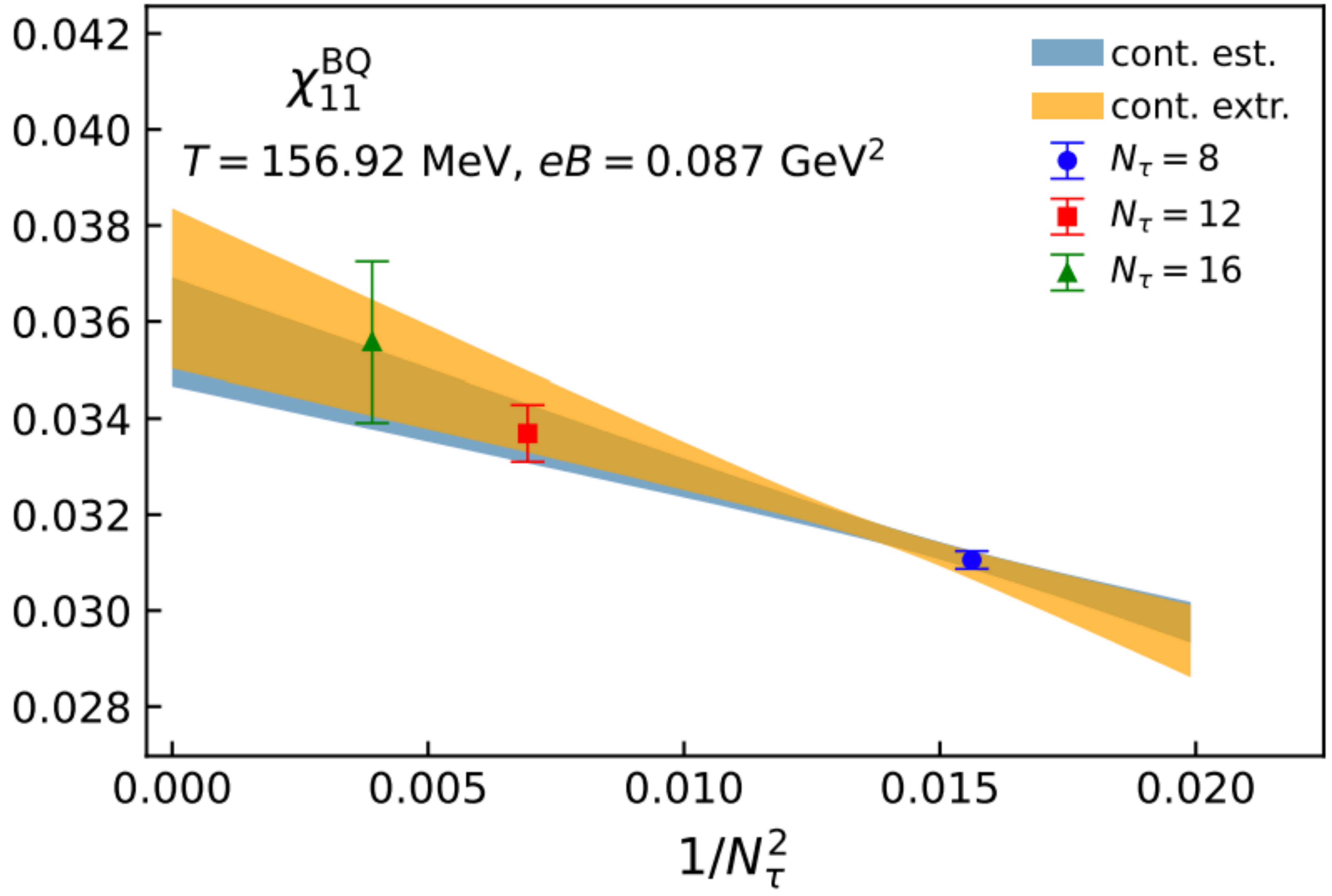
Summary

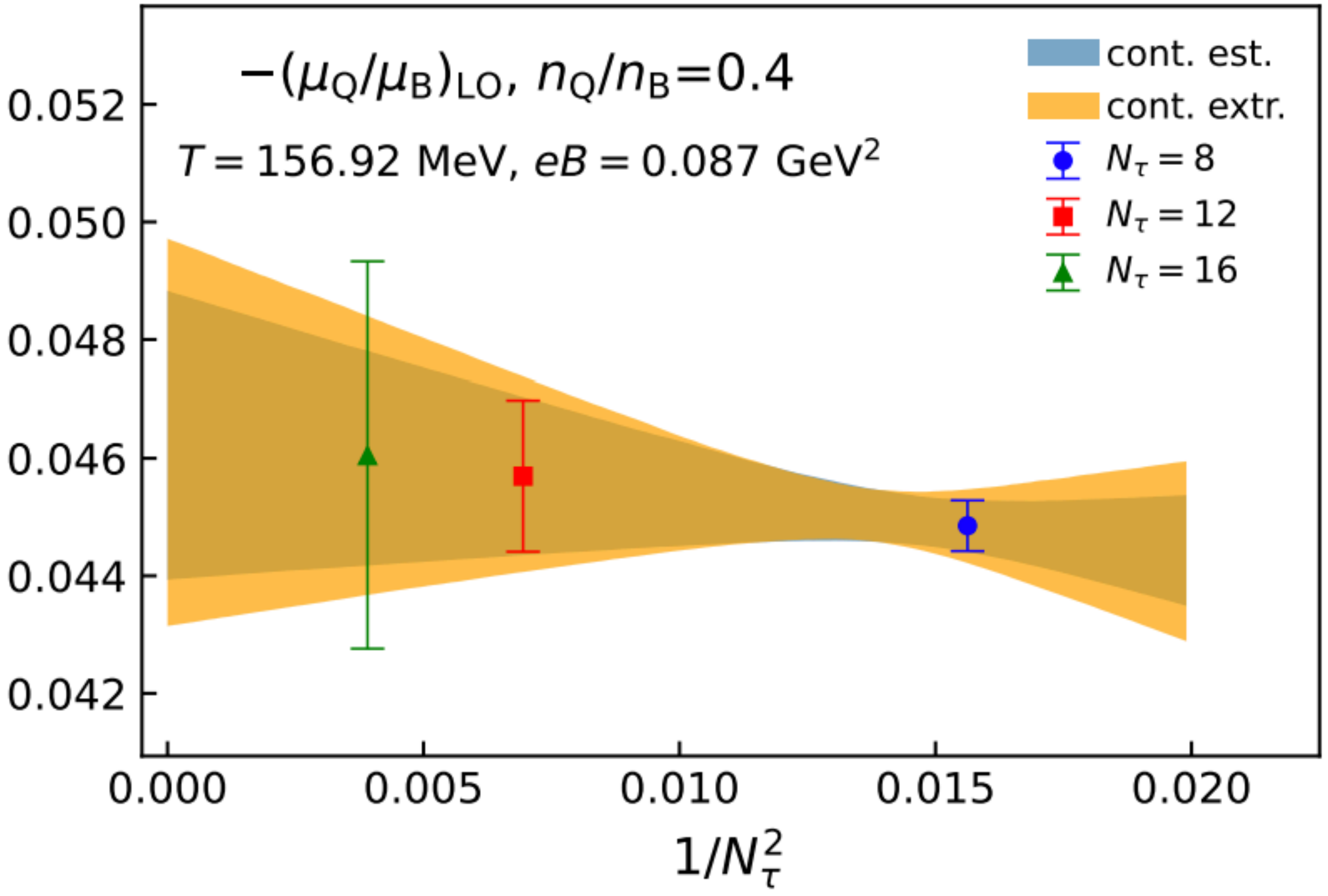
- A first lattice QCD computation of fluctuations of B, Q at the physical point in nonzero magnetic fields
- QCD baselines for effective theories and model studies
- Probes to detect imprints of magnetic fields in HIC: χ_{11}^{BQ} measured from proxy and μ_Q/μ_B obtained from thermal fits to particle yields in HIC



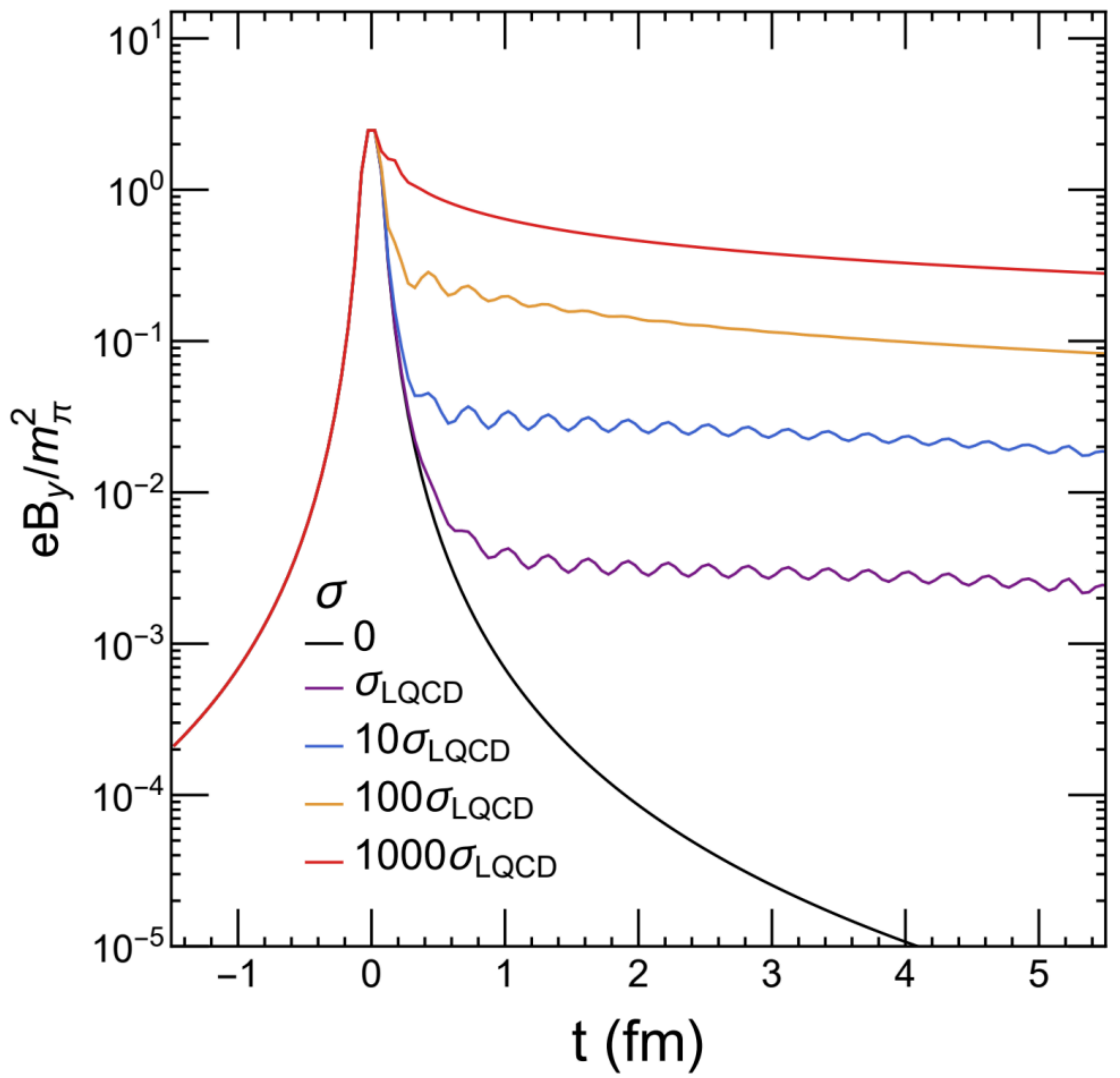


Continuum extrapolation v.s. continuum estimate

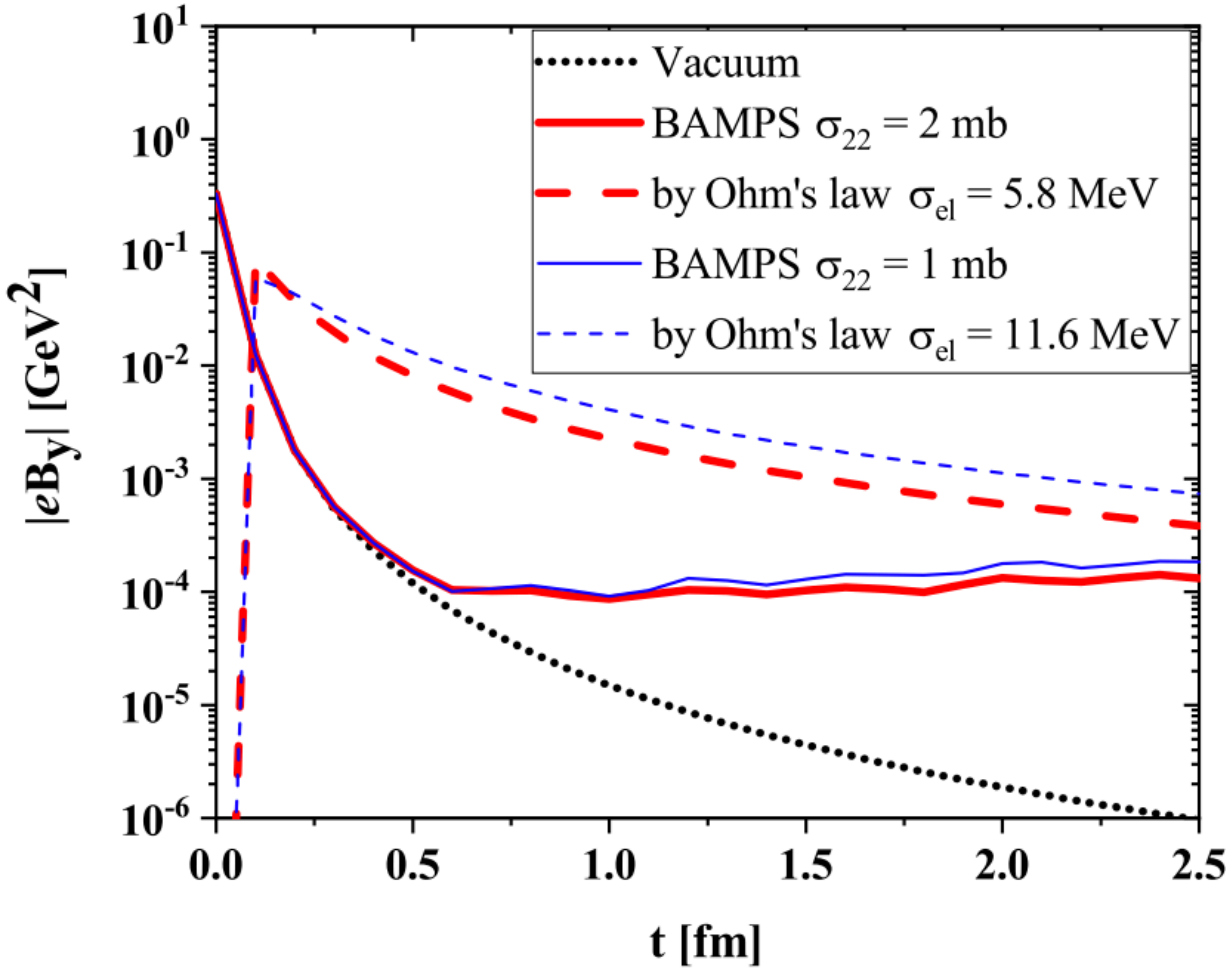




Magnetic field created in the early stage of HIC



Anping Huang et al., Phys. Rev. C 107 (2023) 034901



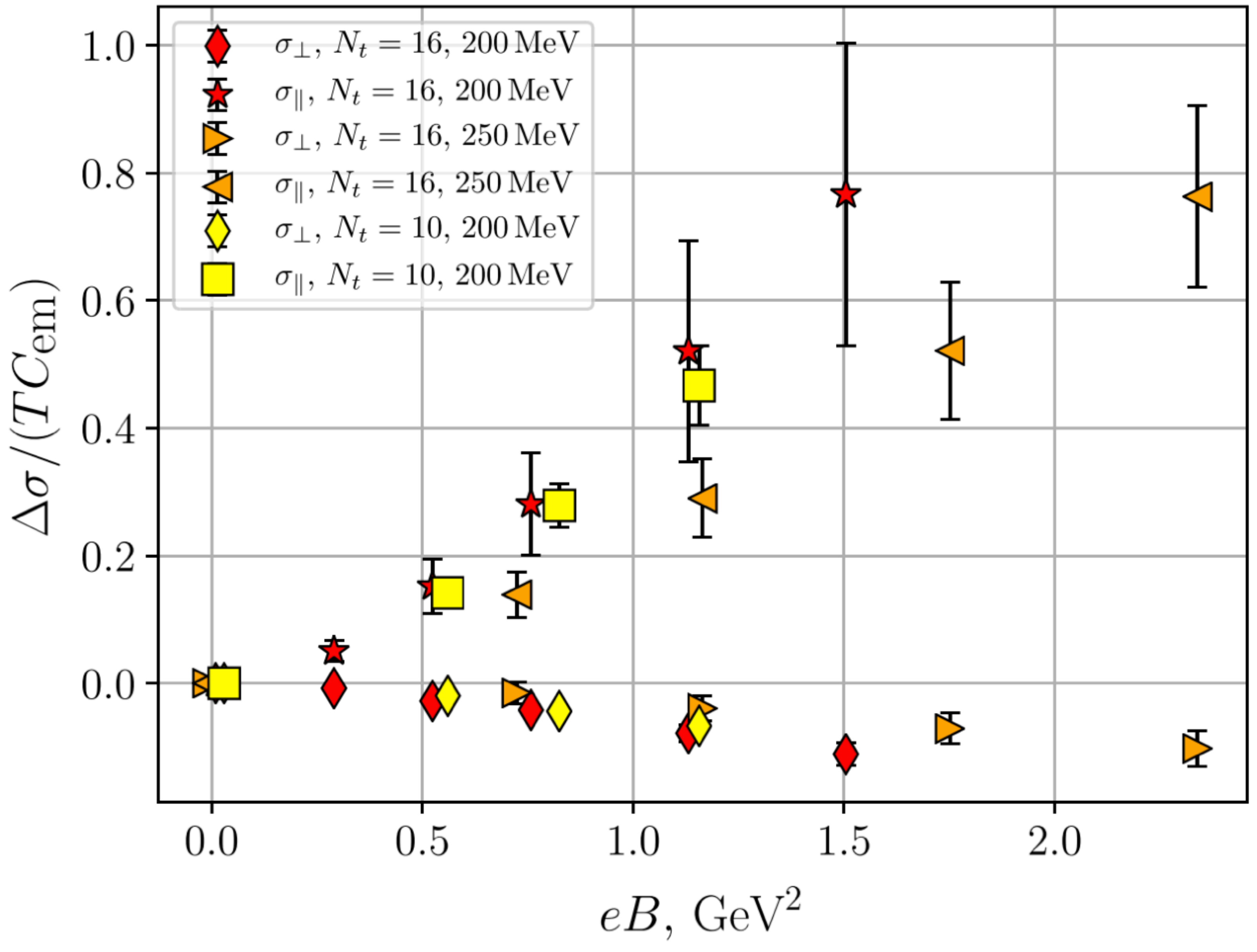
Zeyan Wang et al., Phys. Rev. C 105 (2022) L041901

t=0: RHIC: $eB \sim 5M_\pi^2$; LHC:$eB \sim 70M_\pi^2$

Skokov, Illarionov and V.Toneev, IJMPA 24 (2009) 5925

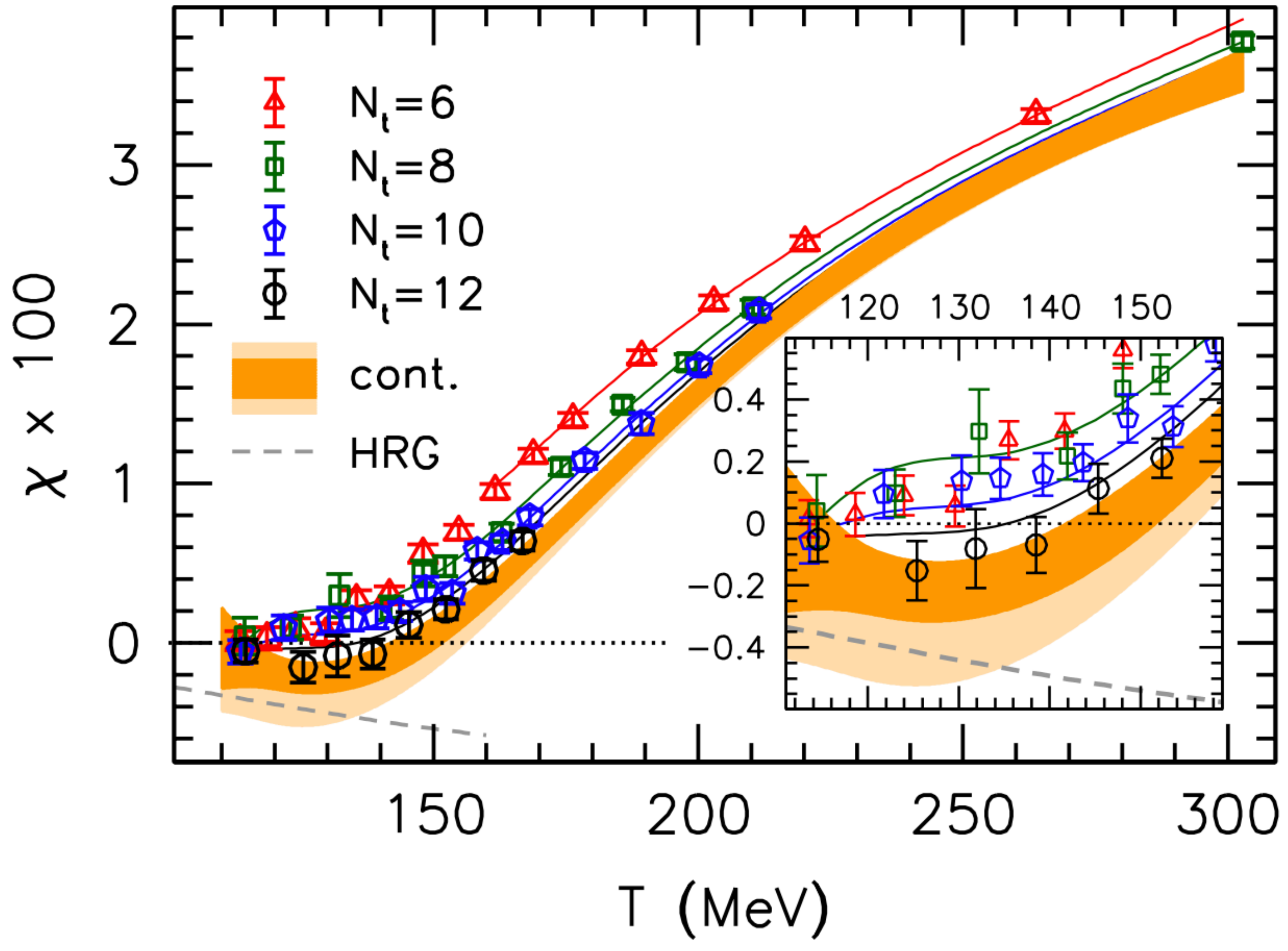
Electric conductivity in nonzero magnetic fields and type of magnetism of QGP

Difference to electromagnetic conductivity at eB=0



Astrakhantsev et al., PRD 102 (2020) 054516

Magnetic susceptibility



Bali, Endrodi, Piemonte, JHEP 07 (2020) 183

Parallel: ↑

Transverse: ↓

T> 155 MeV: Paramagnetic

T<155 MeV: Diamagnetic