



Nuclear Science
Computing Center at CCNU



Baryon Electric Charge Correlation as a Magnetometer of QCD

Jin-Biao Gu

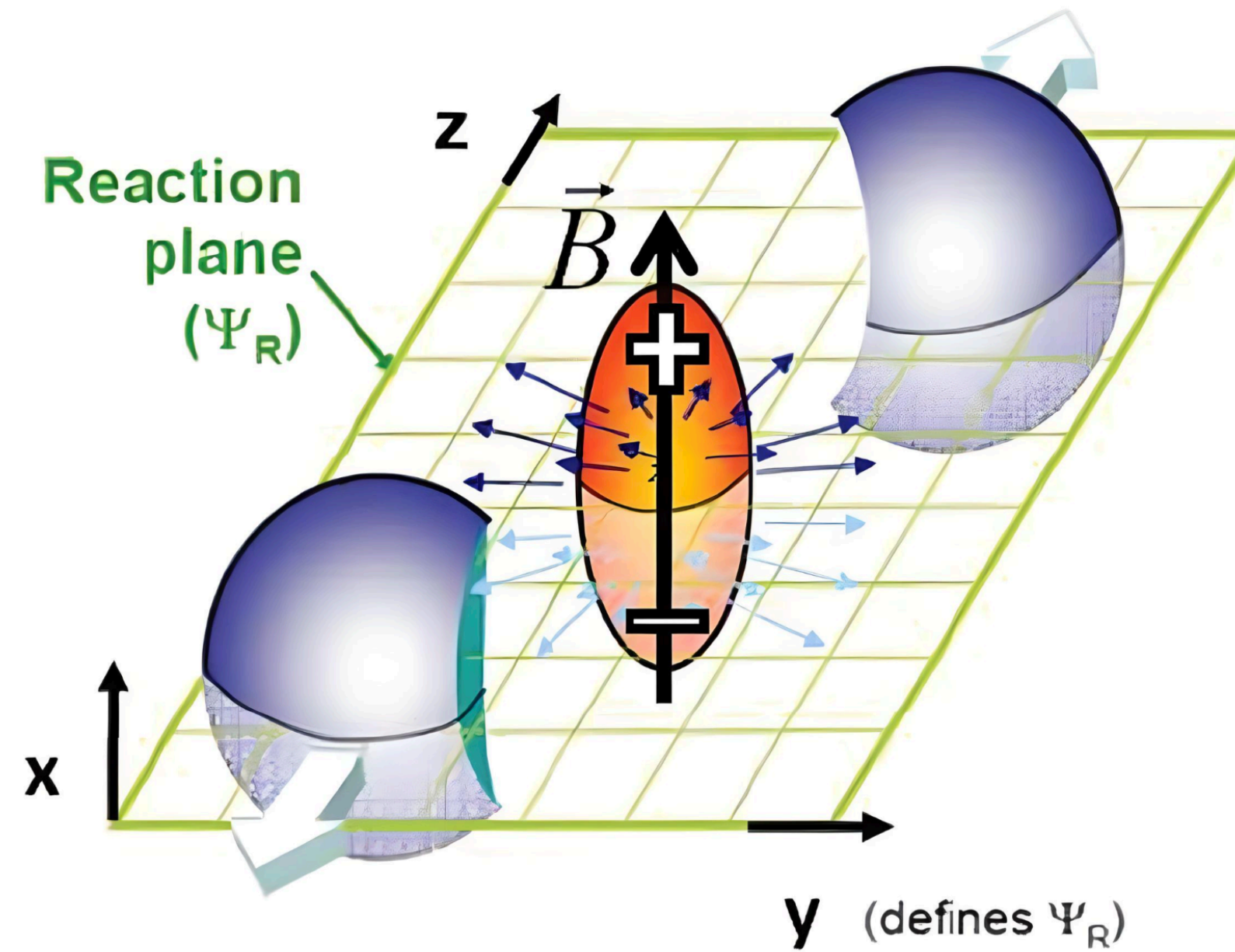
Central China Normal University

Based on *Phys. Rev. Lett.* **132**, 201903 (2024) and *Phys. Rev. D* **111**, 114522 (2025)

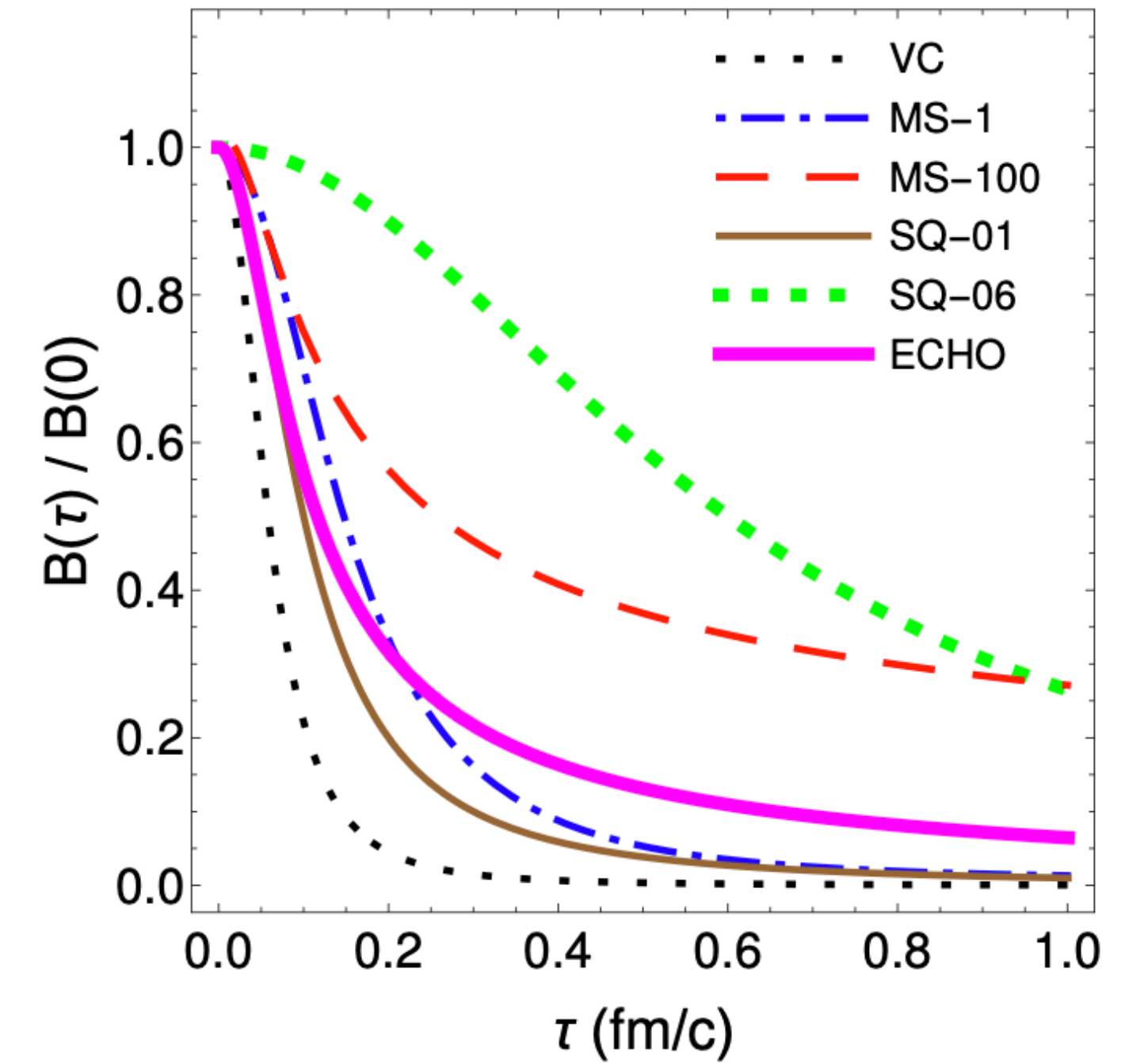
In collaboration with H.-T. Ding, A. Kumar and S.-T. Li

The QCD Phase Diagram: From Theory to Experimental Signatures,
Oct. 8th - 11th, 2025 @ Dalian, Liaoning

Strong magnetic fields in heavy-ion collisions



J. Zhao and F. Wang, Prog.Part.Nucl.Phys. 107 (2019) 200-236



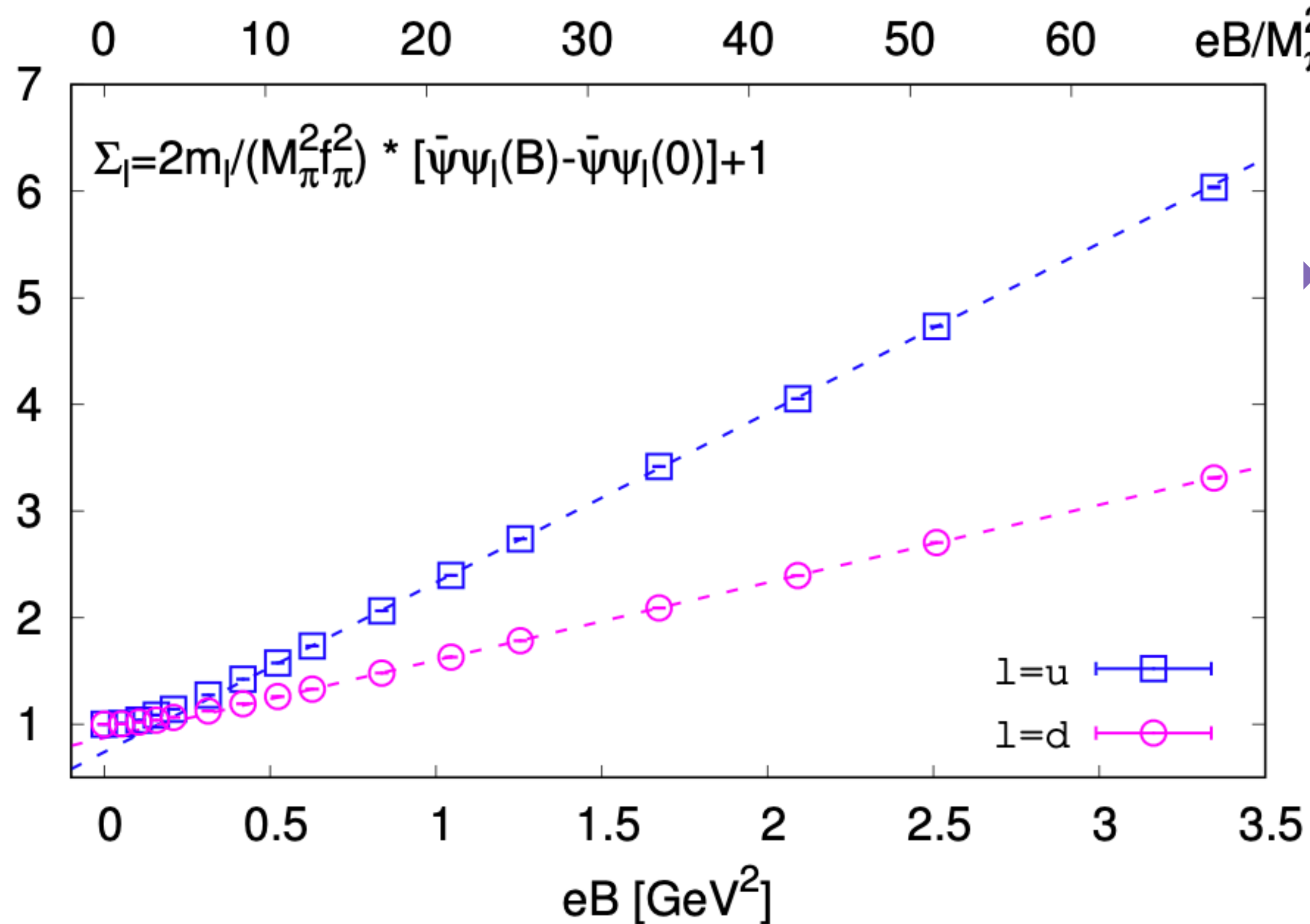
A. Huang et al. Phys.Lett.B 777 (2018) 177-183

$$eB_{\tau=0} \sim 5 M_\pi^2 \text{ in RHIC, } eB_{\tau=0} \sim 70 M_\pi^2 \text{ in LHC}$$

W.-T.Deng, X.-G. Huang, Phys.Rev.C 85, 044907 (2012)

Does this strongly decaying magnetic field manifest itself in the final stage of HIC?

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



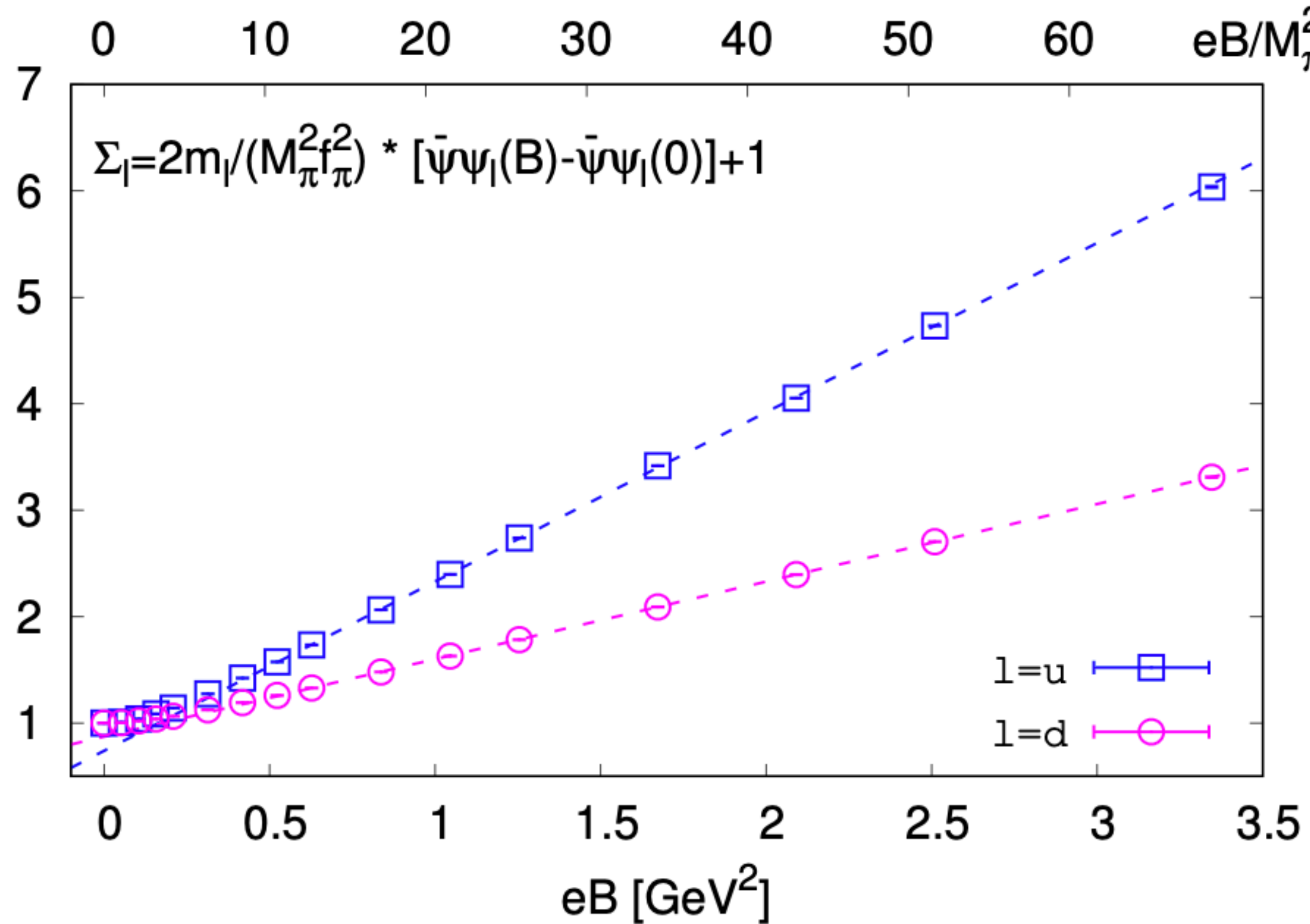
► Sign of isospin symmetry breaking:

Non-degeneracy of u and d condensates at strong magnetic fields

H.-T.Ding, S.-T. Li, A. Tomiya, X.-D. Wang and Y. Zhang, Phys.Rev.D 104, 014505 (2021)

See also in e.g. Bali et al., Phys.Rev.D 86, 071502(2012)

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



A clear effect but Not
accessible in HIC
experiments!

H.-T.Ding, S.-T. Li, A. Tomiya, X.-D. Wang and Y. Zhang, Phys.Rev.D 104, 014505 (2021)

See also in e.g. Bali et al., Phys.Rev.D 86, 071502(2012)

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

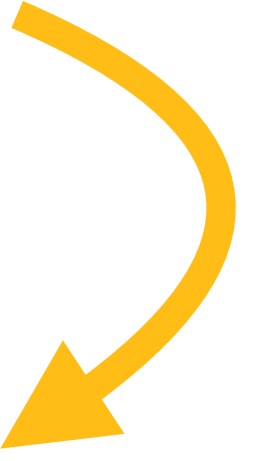
Taylor expansion of the QCD pressure:

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

C. Allton et al., Phys.Rev. D 66, 074507 (2002)

Taylor expansion coefficients at $\mu = 0$ are computable in LQCD

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

$$\chi_{ijk}^{\text{BQS}} = \left. \frac{\partial^{i+j+k} p/T^4}{\partial (\mu_B/T)^i \partial (\mu_Q/T)^j \partial (\mu_S/T)^k} \right|_{\mu_{B,Q,S}=0}$$


$$\begin{aligned} \mu_u &= \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q \\ \mu_d &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q \\ \mu_s &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S \end{aligned}$$

Lattice computable & Experimentally measurable

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

Effective model investigation at $eB \neq 0$

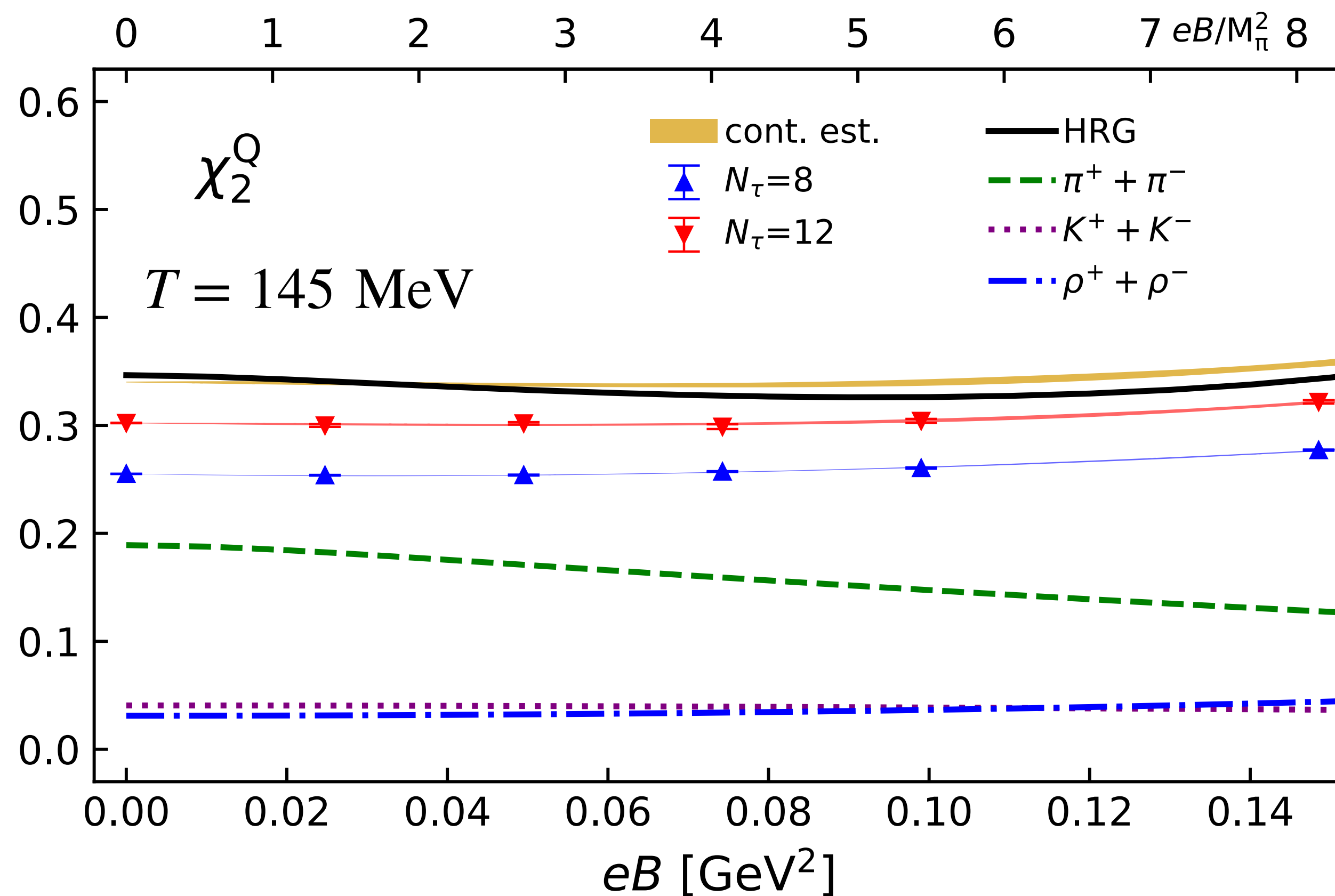
HRG: G. Kadam et al., *JPG* 47, 125106 (2020); M. Ferreira et al., *Phys. Rev. D* 98, 034003 (2018); K. Fukushima and Y. Hidaka, *Phys. Rev. Lett.* 117, 102301 (2016); A. Bhattacharyya et al., *EPL* 115, 62003 (2016); M. Marczenko et al., *Phys.Rev.C* 110, 065203, (2024)

PNJL: W.-J. Fu, *Phys. Rev. D* 88, 014009 (2013); S.-J. Mao, *Chin.Phys.C* 49, 063106, (2025)

- ◆ Highly improved staggered fermions and a tree-level improved Symanzik gauge action
- ◆ $N_f = 2 + 1$
- ◆ Lattice sizes : $32^3 \times 8, 48^3 \times 12; 64^3 \times 16$
- ◆ $m_s^{\text{phy}}/m_l = 27, M_\pi(eB = 0) \approx 135 \text{ MeV}$
- ◆ T window : (144 MeV, 166 MeV), i.e. $(0.9T_{pc}, 1.1T_{pc})$
- ◆ eB window: $eB \lesssim 8M_\pi^2 \sim 0.15 \text{ GeV}^2$

$$eB = \frac{6\pi N_b}{N_x N_y} a^{-2}, \quad N_b = 1, 2, 3, 4, 6$$

Electric charge fluctuations at $T = 145$ MeV



H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, *Phys. Rev. Lett.* 132, 201903 (2024)

❖ χ_2^Q almost independent of eB

❖ Hadron Resonance Gas model (HRG):
Pressure arising from charged hadrons
($eB \neq 0$):

$$\frac{p_i^{M/B}}{T^4} = \frac{|q_i| B}{2\pi^2 T^3} \sum_{s_z = -s_i}^{s_i} \sum_{l=0}^{\infty} \epsilon_0 \sum_{n=1}^{\infty} (\pm 1)^{n+1} \frac{e^{n\mu_i/T}}{n} K_1 \left(\frac{n\epsilon_0}{T} \right)$$

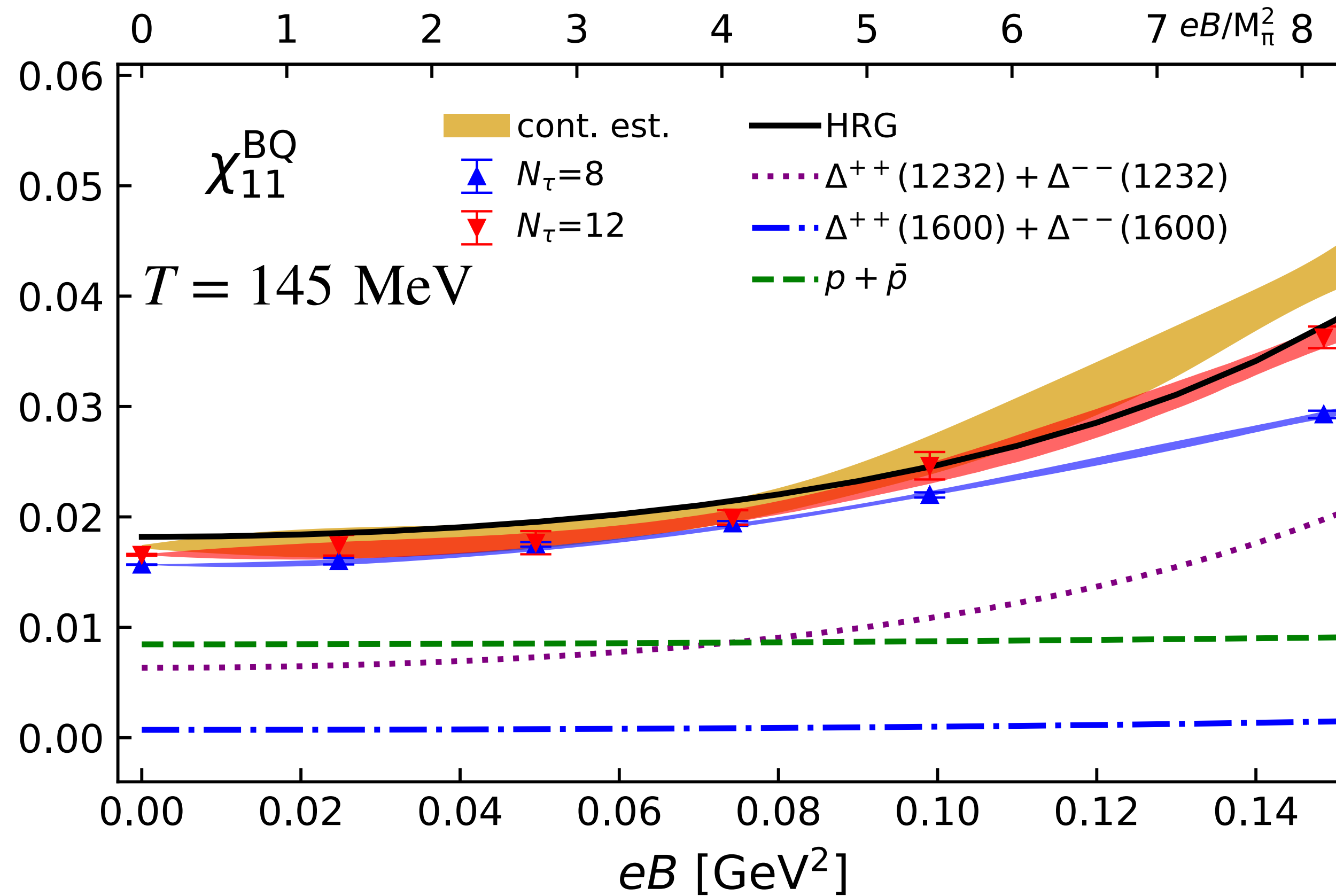
Quantized energy level:

$$\epsilon_0 = \sqrt{m_i^2 + 2 |q_i| B (l + 1/2 - s_z)}$$

$(l + 1/2 - s_z) > 0$: ϵ_0 increases
 $(l + 1/2 - s_z) < 0$: ϵ_0 decreases
 with eB

H.-T. Ding et al., *Eur. Phys. J. A* 57 (2021) 6, 202

Baryon electric charge correlation at $T = 145$ MeV



H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, Phys. Rev. Lett. 132, 201903 (2024)

◆ χ_{11}^{BQ} increases $\sim$ **140%** at $eB \sim 8M_\pi^2$,

Magnetometer of QCD

◆ The results of HRG model are consistent with LQCD up to $eB \sim 5M_\pi^2$

◆ $\Delta^{++}(1232)$ and $\Delta^{--}(1232)$ give **most of the contributions** of magnetic field dependence of χ_{11}^{BQ}

◆ $\Delta^{++}(1232)$ and $\Delta^{--}(1232)$ are **not measurable** in HIC experiments



Proxy construction based on the HRG

$\Delta^{++}(1232) \rightarrow p + \pi^+$: branching ratio almost **100%** !

HRG: Fluctuations expressed in terms of stable hadronic states:

$$\chi_{ijk}^{\text{BQS}} \left(T, \hat{\mu}_B, \hat{\mu}_Q, \hat{\mu}_S \right) = \sum_R B_R^i Q_R^j S_R^k \frac{\partial^l p_R / T^4}{\partial \hat{\mu}_R^l}$$

net- B : $\tilde{p} + \tilde{n} + \tilde{\Lambda} + \tilde{\Sigma}^+ + \tilde{\Sigma}^- + \tilde{\Xi}^0 + \tilde{\Xi}^- + \tilde{\Omega}^-$
 net- Q : $\tilde{\pi}^+ + \tilde{K}^+ + \tilde{p} + \tilde{\Sigma}^+ - \tilde{\Sigma}^- - \tilde{\Xi}^- - \tilde{\Omega}^-$
 net- S : $\tilde{K}^+ + \tilde{K}^0 - \tilde{\Lambda} - \tilde{\Sigma}^+ - \tilde{\Sigma}^- - 2\tilde{\Xi}^0 - 2\tilde{\Xi}^- - 3\tilde{\Omega}^-$

B_R, Q_R, S_R are the baryon number, electric charge and strangeness of the species R

R. Bellwied et al., Phys. Rev. D 101, 034506 (2020)

HIC: fluctuations are related to the variance or covariance of net-multiplicity for identified π, K, p

STAR, Phys.Rev.C 100, 014902 (2019); STAR, Phys.Rev.C 105, 029901 (2019)

$\sigma_{Q^{\text{PID}},p}^{1,1}$ as proxy for χ_{11}^{BQ}

$$\sum_R B_R Q_R \frac{\partial^2 p_R / T^4}{\partial \mu_R^2} \rightarrow \sum_R (\omega_{R \rightarrow \tilde{p}})(\omega_{R \rightarrow \tilde{Q}^{\text{PID}}}) \frac{\partial^2 p_R / T^4}{\partial \mu_R^2}$$

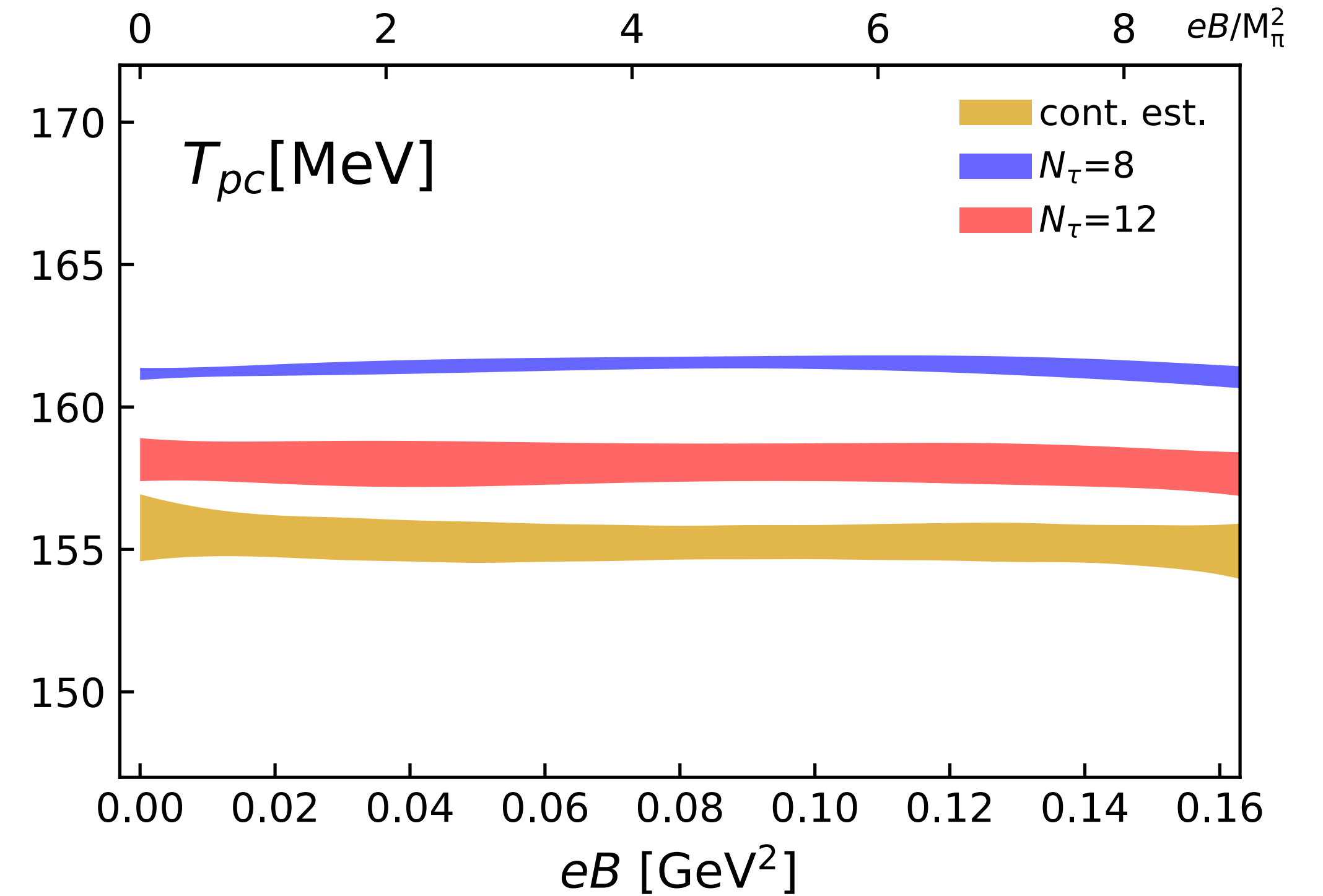
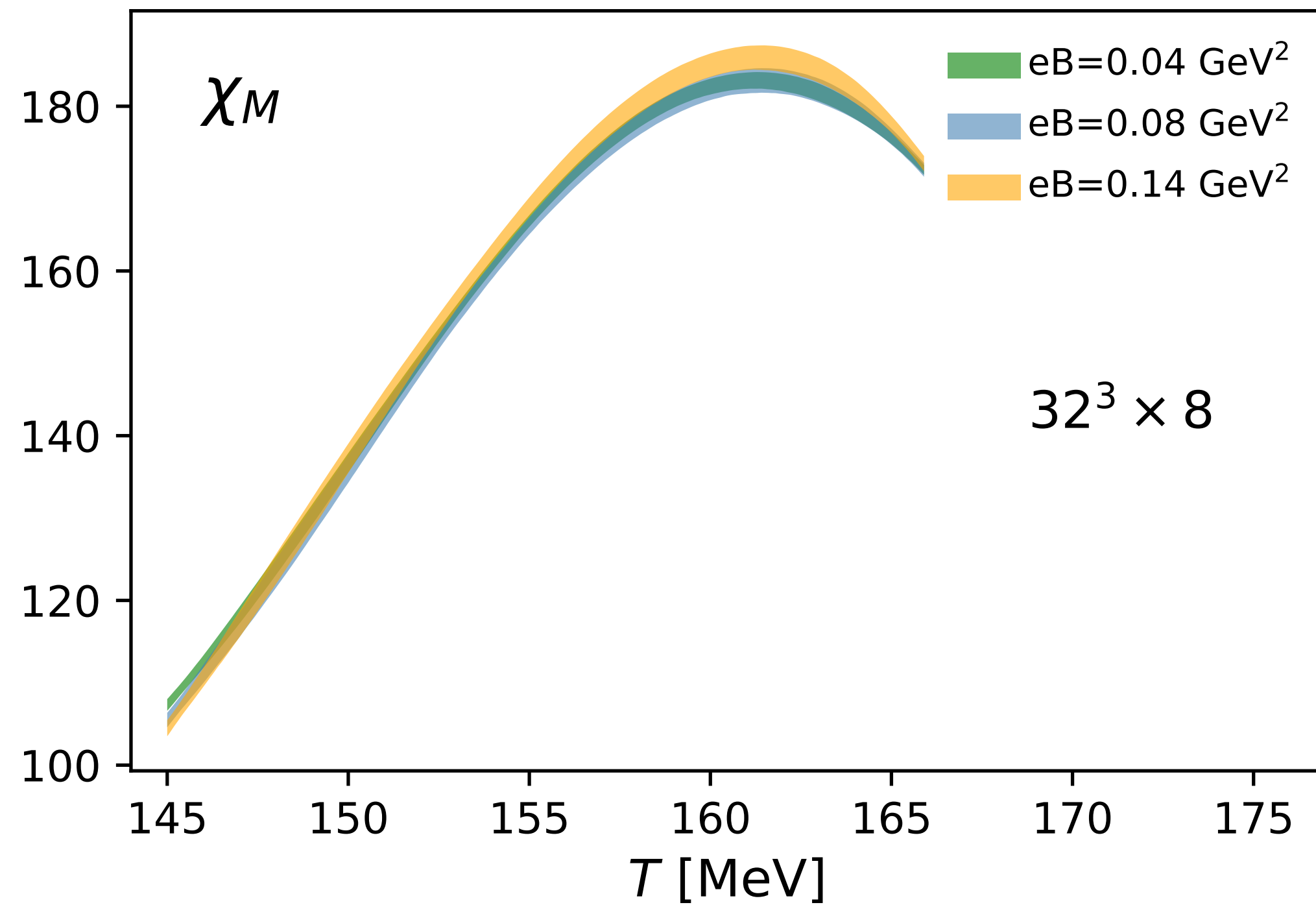
net-B $\rightarrow \tilde{p} : \omega_{R \rightarrow \tilde{p}}$

net-Q $\rightarrow \tilde{Q}^{\text{PID}} : \omega_{R \rightarrow \tilde{\pi}^+} + \omega_{R \rightarrow \tilde{K}^+} + \omega_{R \rightarrow \tilde{p}}$

Where $\omega_{R \rightarrow \tilde{i}}$ represents net number of **stable** particle i produced by particle R after the **entire decay chain**

In proxy, contributions from **all resonance decays** are considered!

QCD transition temperature in nonzero magnetic field

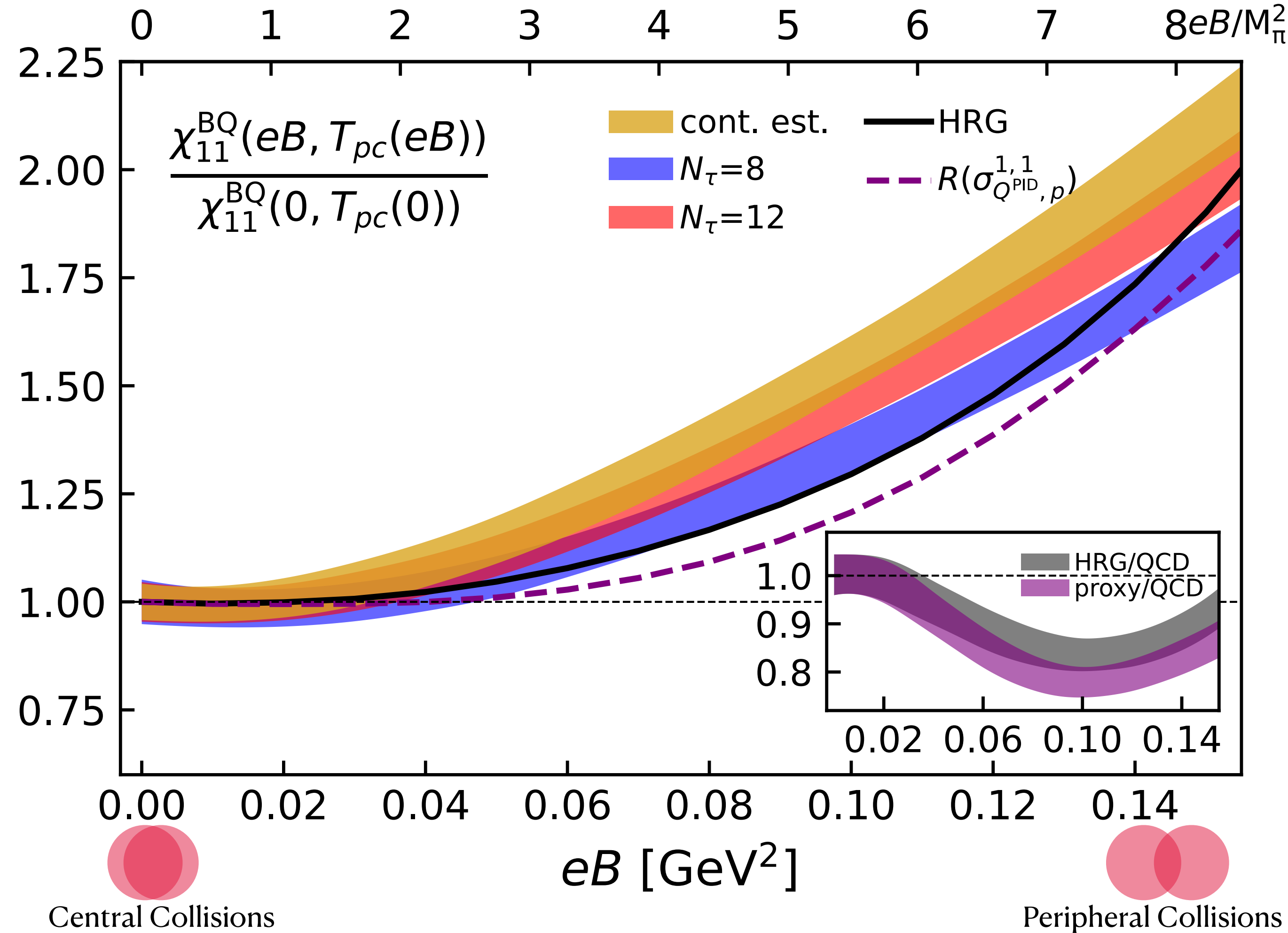


$$\chi_M(eB) = \frac{m_s}{f_K^4} \left[m_s \chi_l(eB) - 2 \langle \bar{\psi} \psi \rangle_s(eB = 0) - 4 m_l \chi_{sl}(eB = 0) \right]$$

$T_{pc}(eB)$ determined as the peak location of chiral susceptibility (χ_M) at each eB value

T_{pc} almost **independent** of eB
at $eB \lesssim 0.16$ GeV²

Proxy for $R(\chi_{11}^{\text{BQ}})$ along the transition line (T_{pc})



H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, Phys. Rev. Lett. 132, 201903 (2024)

◆ R_{cp} –like observables:

$$R(\mathcal{O}) \equiv \frac{\mathcal{O}(eB, T_{pc}(eB))}{\mathcal{O}(eB = 0, T_{pc}(0))}$$

◆ At $eB \simeq 8M_\pi^2$, $R(\chi_{11}^{\text{BQ}}) \sim \mathbf{2.1}$

$$\chi_{11}^{\text{BQ}} \rightarrow \sigma_{Q^{\text{PID}},p}^{1,1}$$

◆ The proxy $R(\sigma_{Q^{\text{PID}},p}^{1,1})$ can represent **80~85%** of the LQCD results

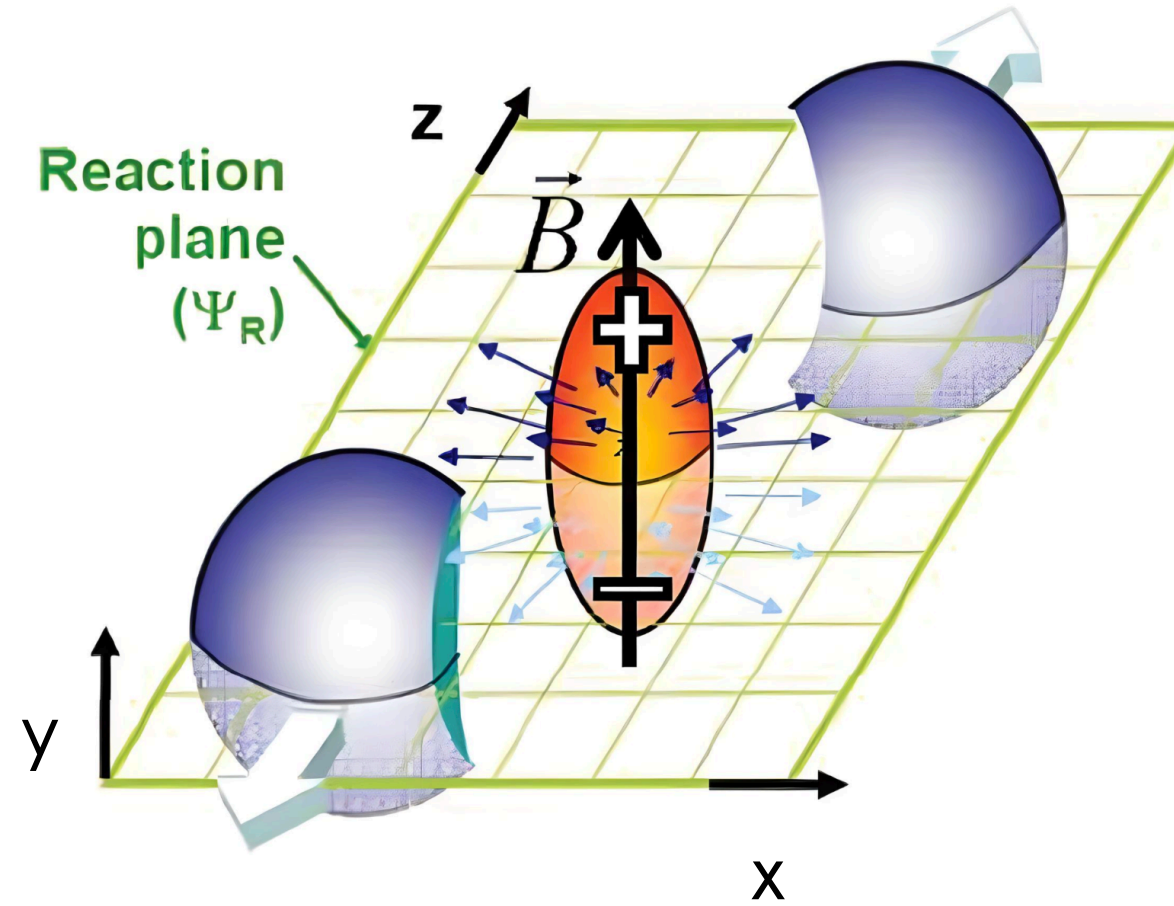
net- B : $\tilde{p}$

net- Q : $\tilde{\pi}^+ + \tilde{K}^+ + \tilde{p}$

Proxy for $R(\chi_{11}^{\text{BQ}})$ with kinematic cuts along the transition line (T_{pc})

- ◆ Proxies with kinematic cuts on p_T and η within HRG framework:

$$\int d^3p \times \Theta(p_{T_{\min}}, p_{T_{\max}}, \eta_{\min}, \eta_{\max})$$

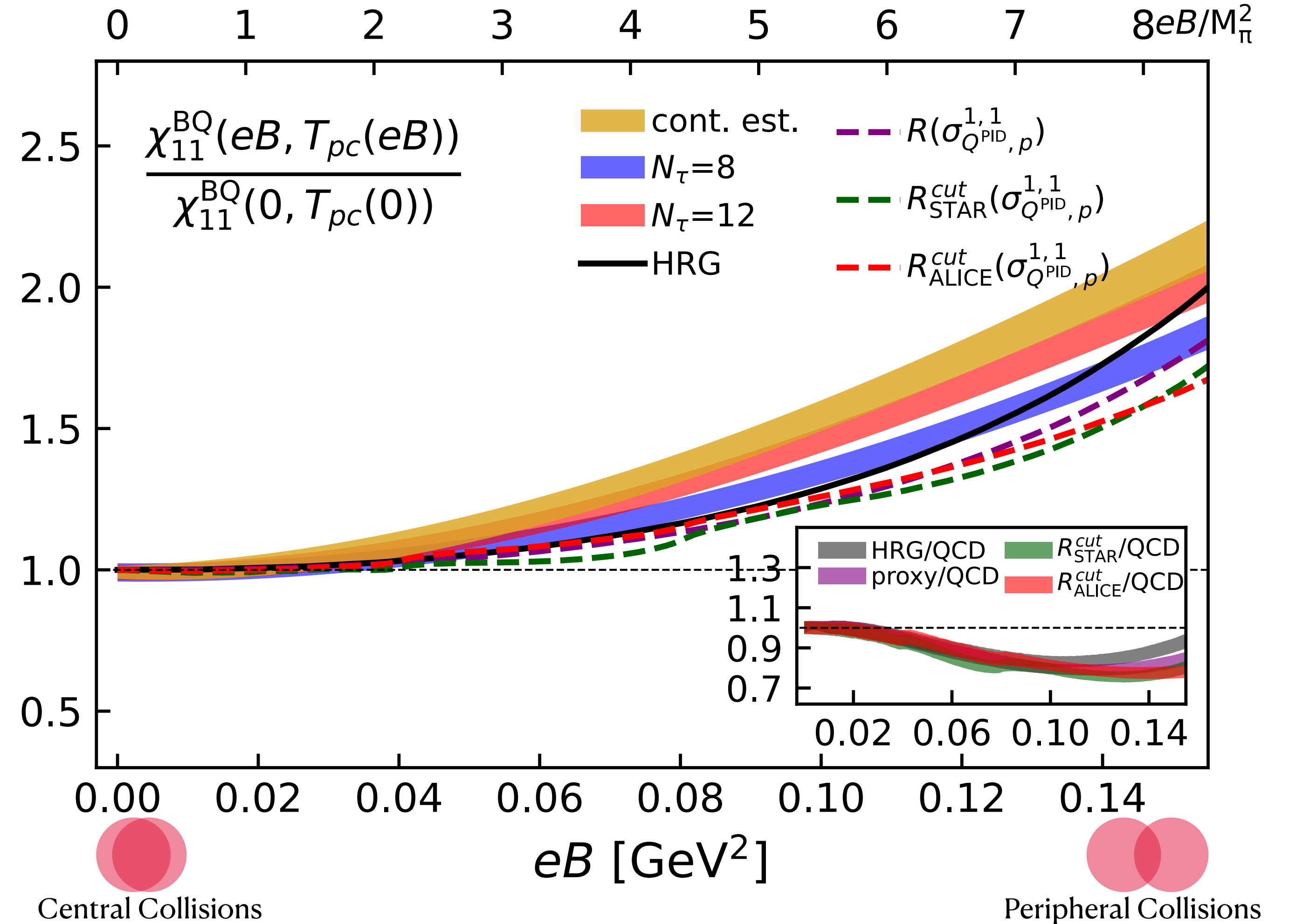


Quantized momentum in reaction plane:

$$p_{xz}(l, s_y) = \sqrt{2|q|B(l + 1/2 + s_y)}$$



$$\eta = \text{arcsinh}(p_{xz} \cos \phi_{xz} / p_T) \quad p_T = \sqrt{(p_{xz} \sin \phi_{xz})^2 + p_y^2}$$



H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, *Phys.Rev.D* 111, 114522 (2025)

Proxy for $R(\chi_{11}^{\text{BQ}})$ with kinematic cuts along the transition line (T_{pc})

◆ Proxies with kinematic cuts on p_T and η within HRG framework:

$$\int d^3p \times \Theta(p_{T_{\min}}, p_{T_{\max}}, \eta_{\min}, \eta_{\max})$$

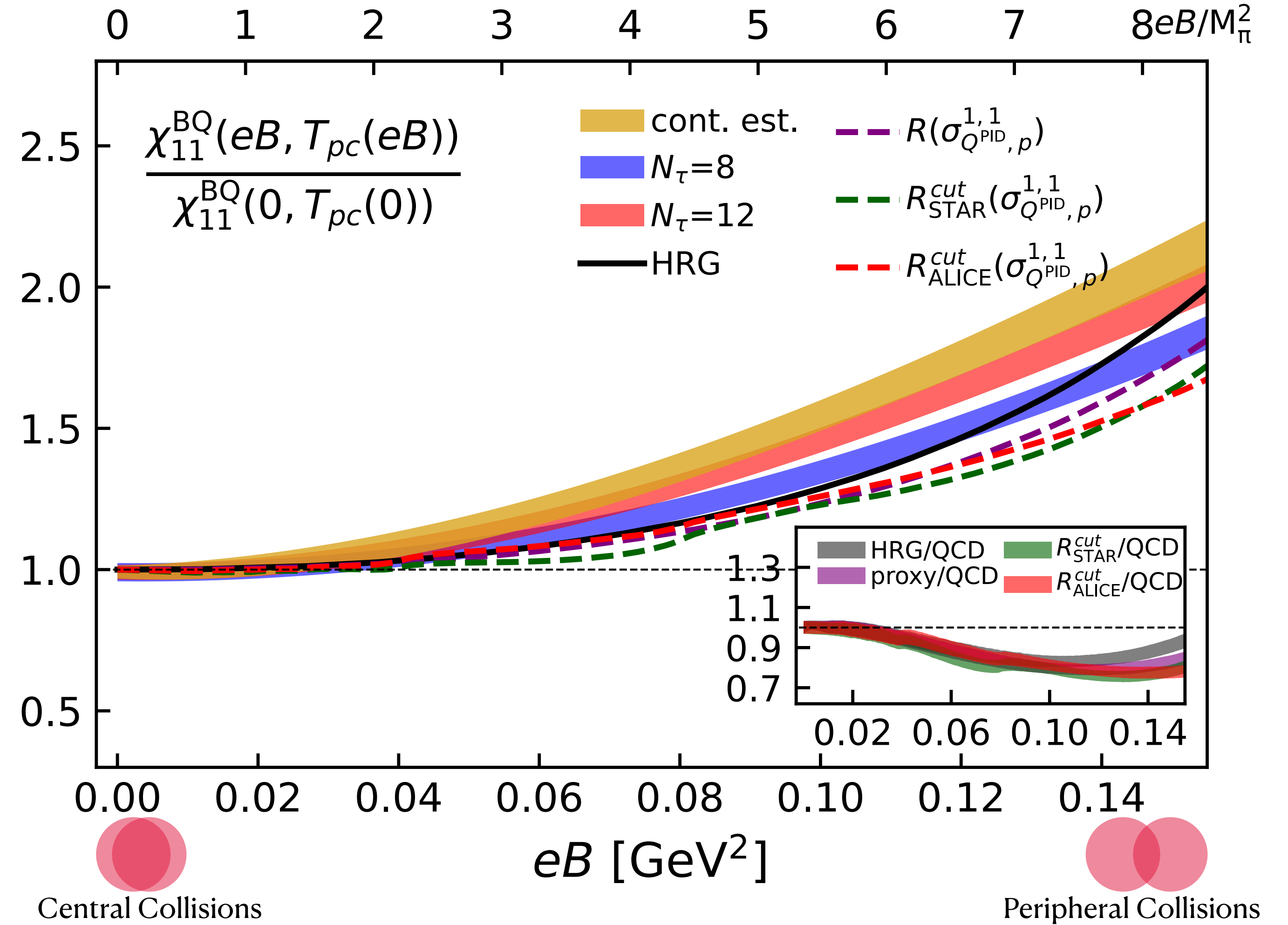
$$R_{\text{STAR}}^{\text{cut}} : |\eta| < 0.5,$$

$$\pi^\pm, K^\pm \text{ and } p(\bar{p}) : 0.4 < p_T < 1.6 \text{ GeV}/c$$

$$R_{\text{ALICE}}^{\text{cut}} : |\eta| < 0.8,$$

$$\pi^\pm \text{ and } K^\pm : 0.2 < p_T < 2 \text{ GeV}/c$$

$$p(\bar{p}) : 0.4 < p_T < 2 \text{ GeV}/c$$

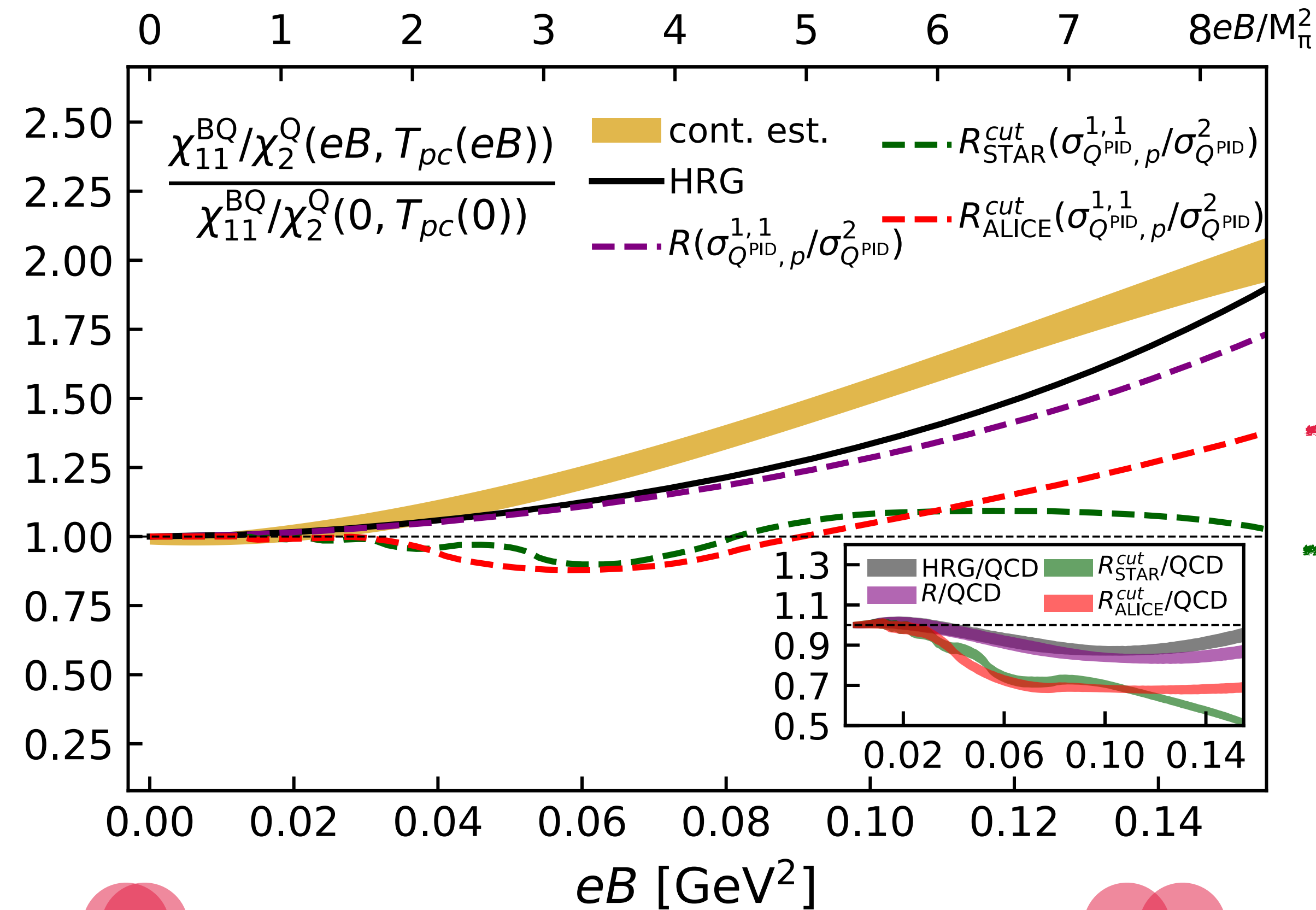


H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, *Phys.Rev.D* 111, 114522 (2025)

STAR collaboration, *Phys.Rev.C* 100 (2019) 1, 014902

ALICE collaboration, *arXiv:2503.18743*

Double ratio $R(\sigma_{Q^{\text{PID}},p}^{1,1}/\sigma_{Q^{\text{PID}}}^2)$ in Lattice QCD



Central Collisions

Peripheral Collisions

H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)

◆ R_{cp} –like observables:

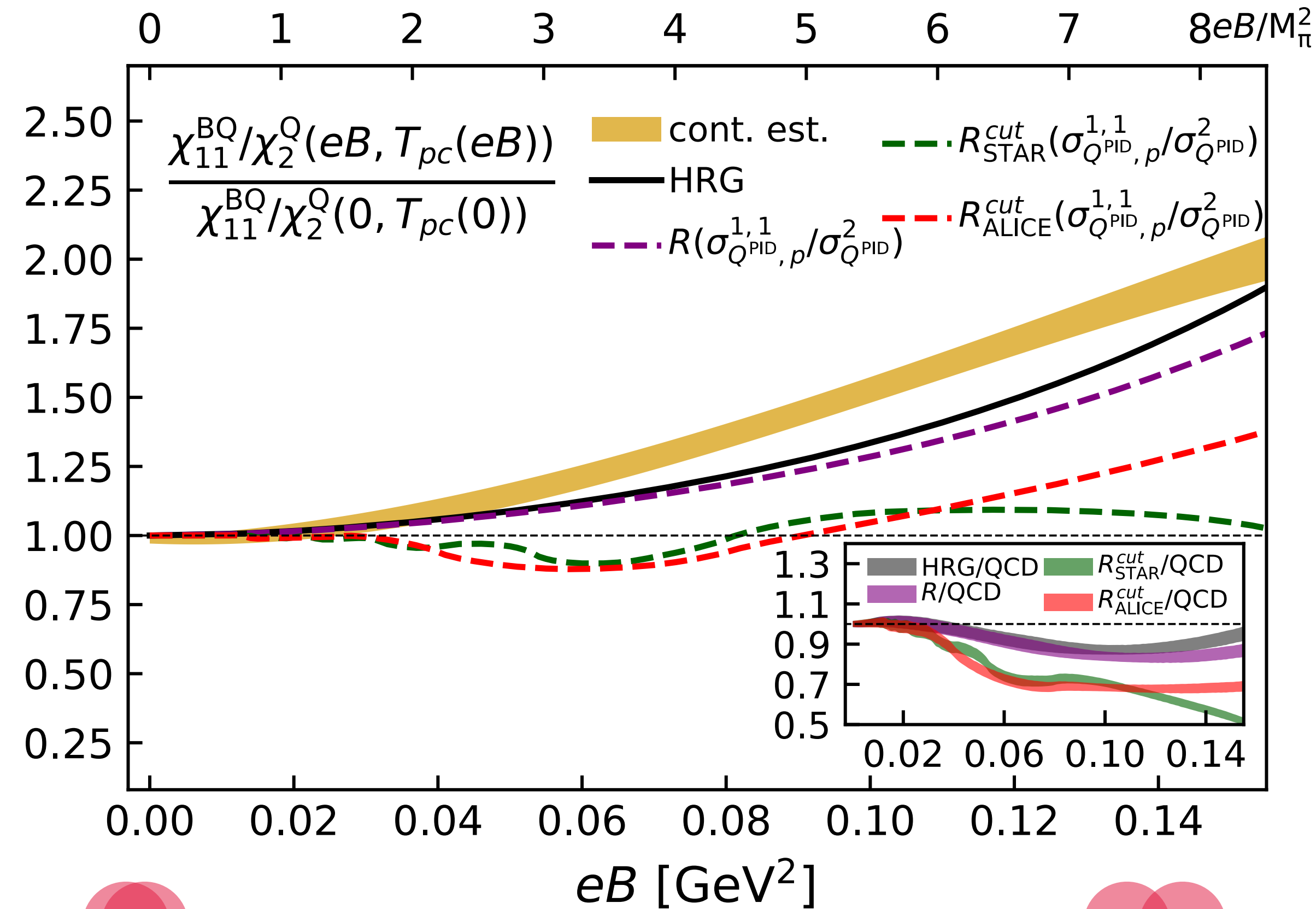
$$R(\mathcal{O}) \equiv \frac{\mathcal{O}(eB, T_{pc}(eB))}{\mathcal{O}(eB = 0, T_{pc}(0))}$$

◆ At $eB \simeq 8M_\pi^2$, $R(\chi_{11}^{\text{BQ}}/\chi_2^{\text{Q}}) \sim 2$

ALICE cut: $\sim 25\%$ enhancement

No clear dependence on eB

Double ratio $R(\sigma_{Q^{PID},p}^{1,1}/\sigma_{Q^{PID}}^2)$ in Lattice QCD and HIC

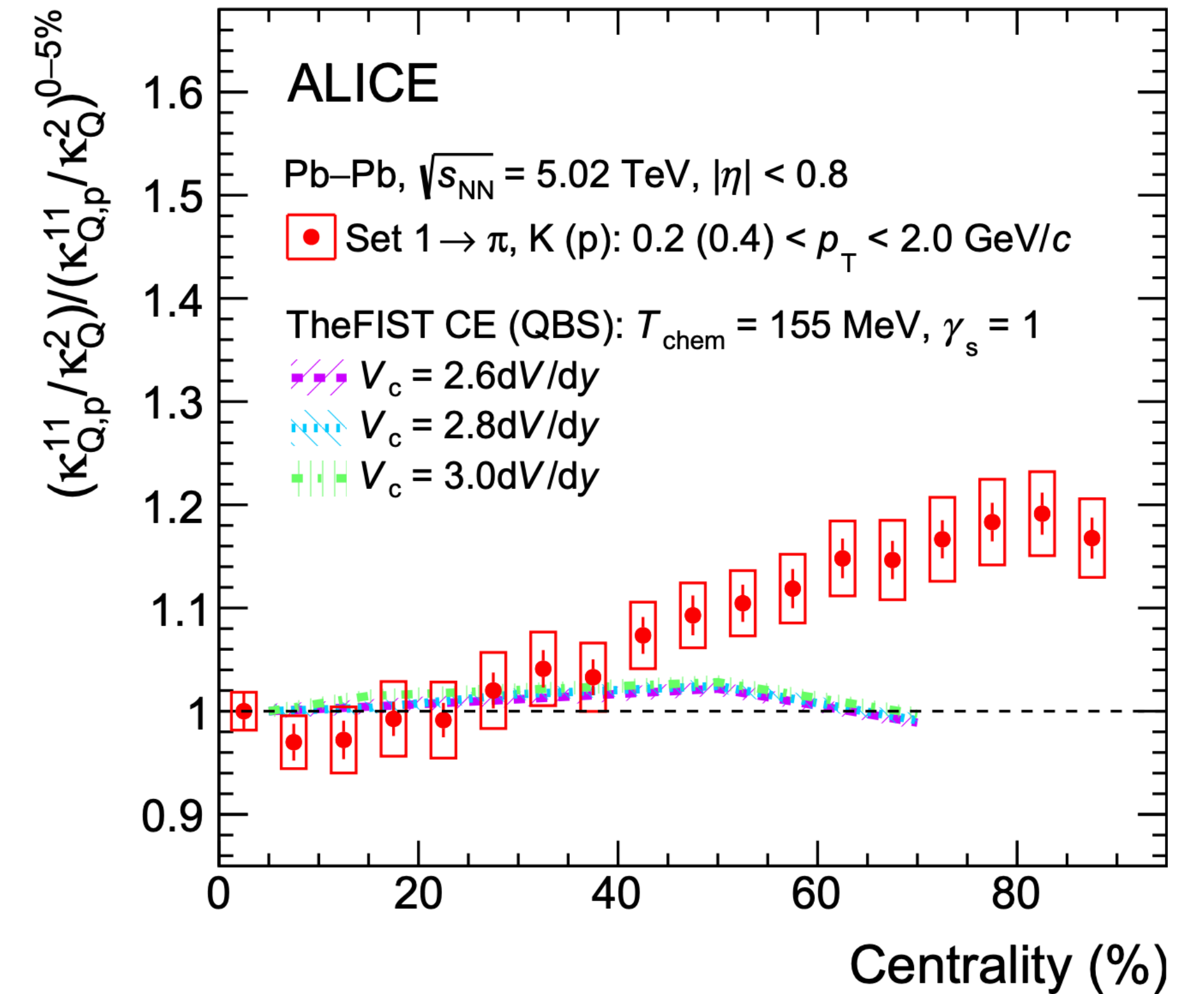


Central Collisions

Peripheral Collisions

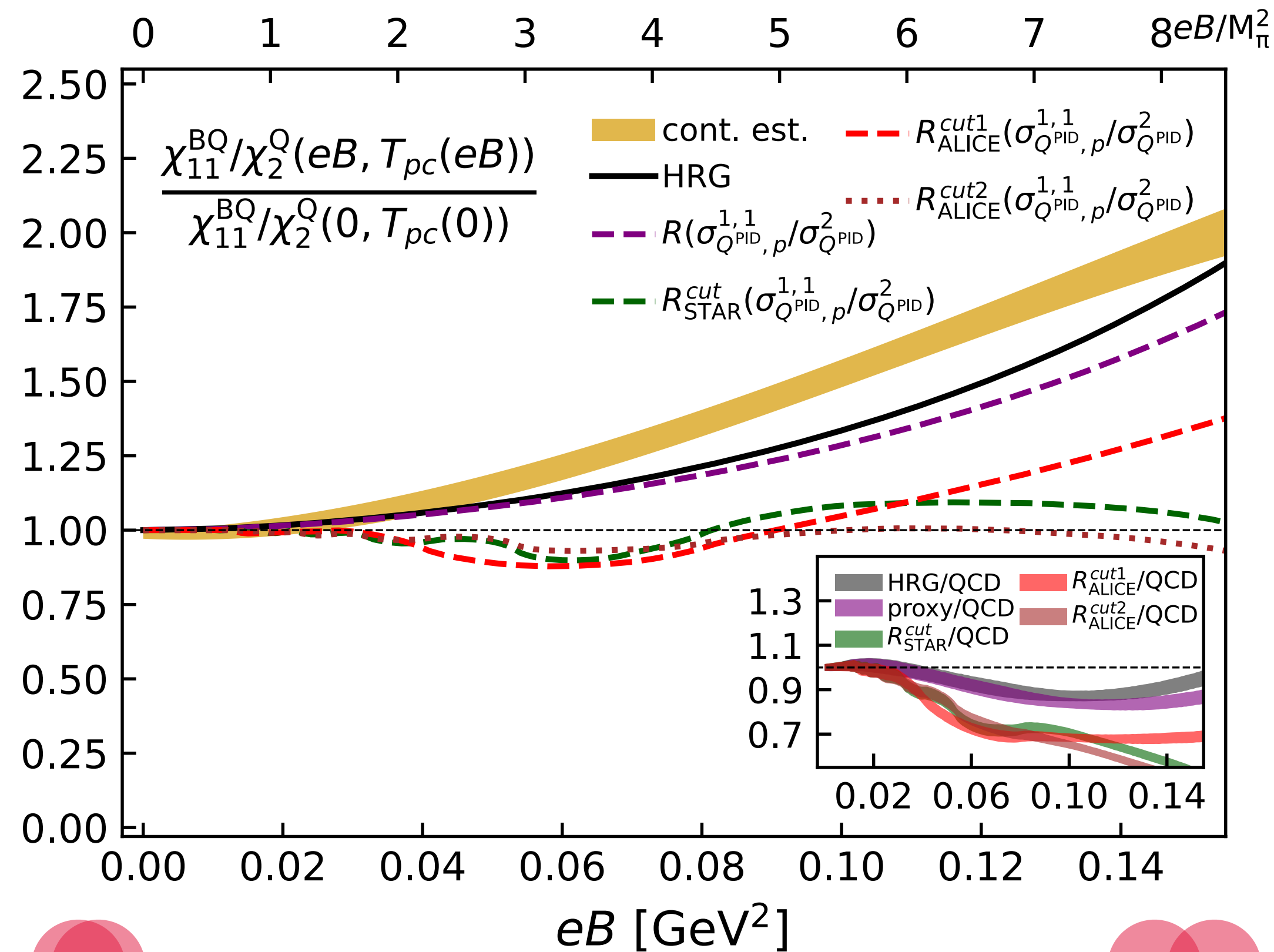
H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)

Proxy for $R(\chi_{11}^{BQ}/\chi_2^Q)$ from ALICE

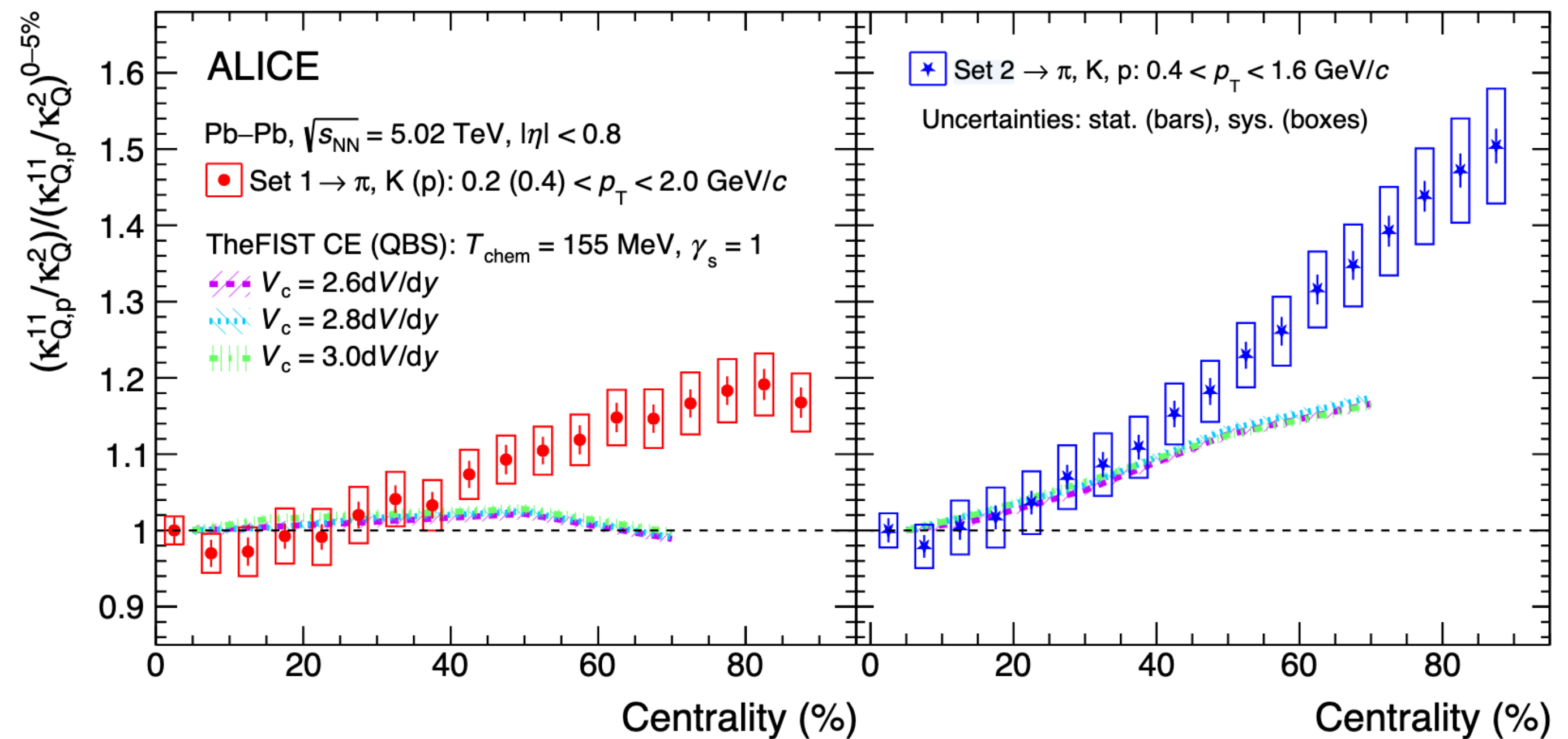


ALICE collaboration, JHEP 08 (2025) 210

Double ratio $R(\sigma_{Q^{PID},p}^{1,1}/\sigma_{Q^{PID}}^2)$ in Lattice QCD and HIC



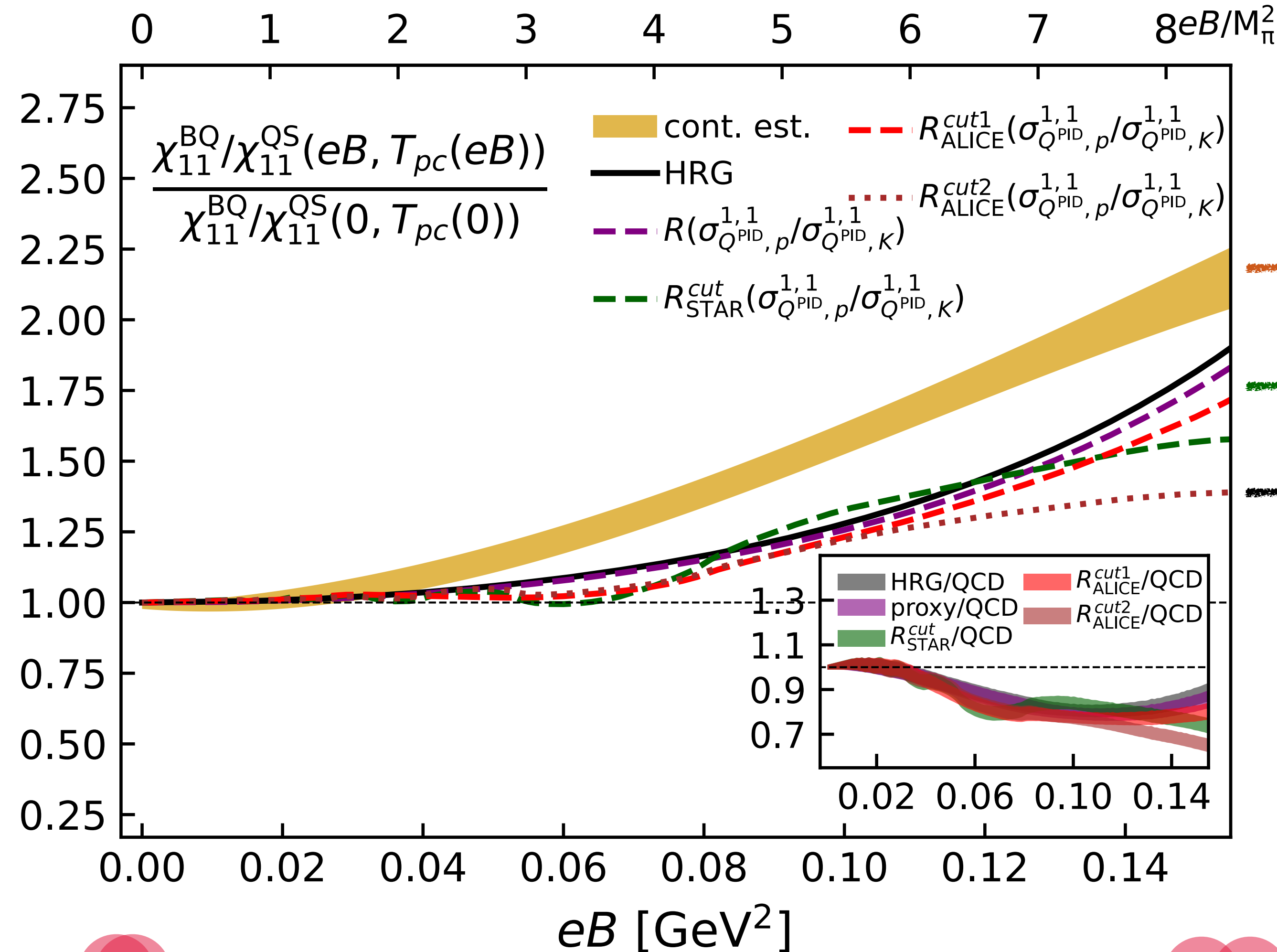
Proxy for $R(\chi_{11}^{BQ}/\chi_2^Q)$ from ALICE



ALICE collaboration, JHEP 08 (2025) 210

H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)

$R(\chi_{11}^{\text{BQ}}/\chi_{11}^{\text{QS}})$ from Lattice QCD and Proxies



$$R(\chi_{11}^{\text{BQ}}/\chi_{11}^{\text{QS}}) = \frac{\chi_{11}^{\text{BQ}}/\chi_{11}^{\text{QS}}(eB, T_{pc}(eB))}{\chi_{11}^{\text{BQ}}/\chi_{11}^{\text{QS}}(eB = 0, T_{pc}(0))}$$

→ ~ 2.1

→ ~ 1.5 – 1.75

→ ~ 1.3

◆ Weaker dependence on the kinematic cuts

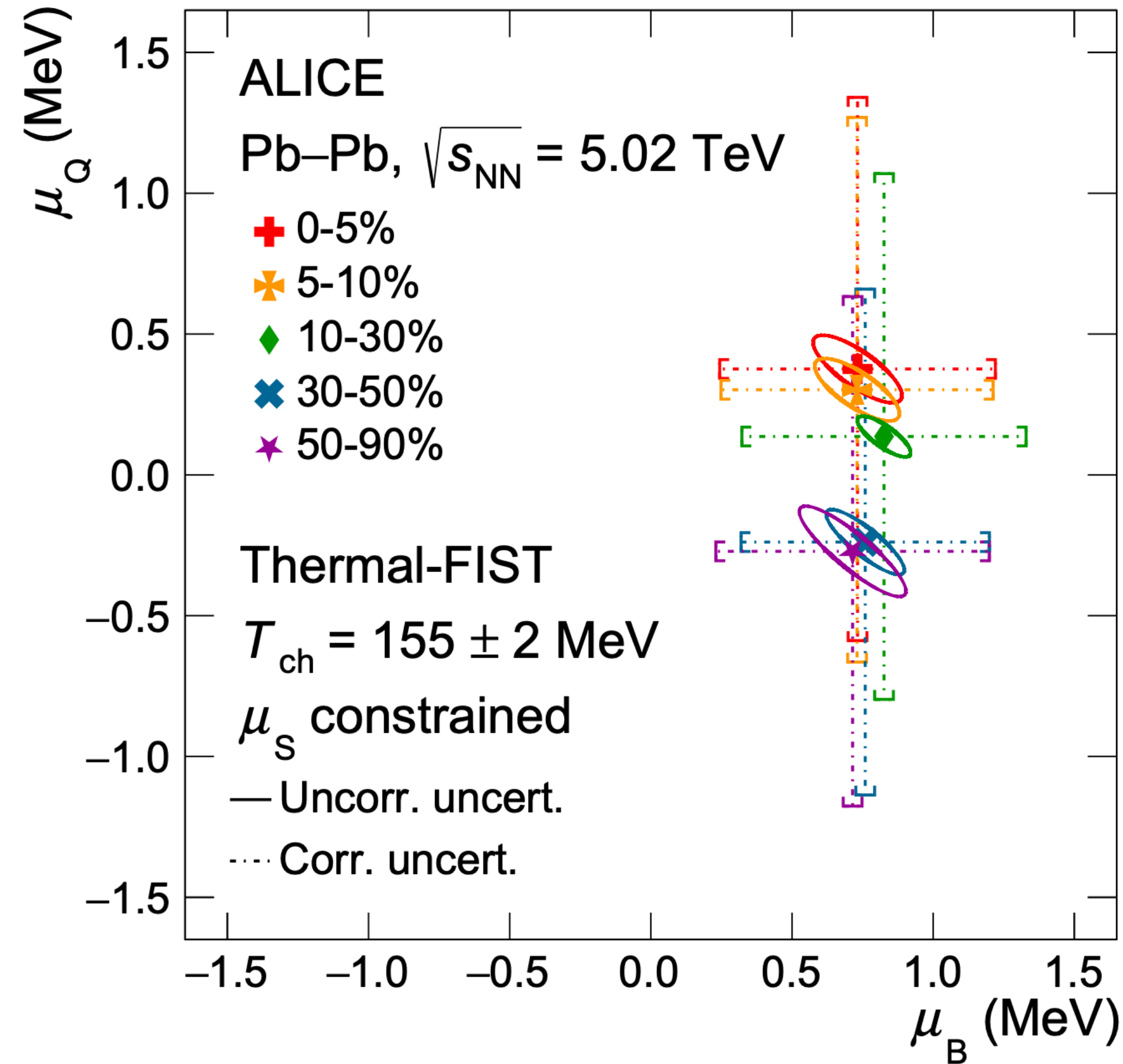
◆ More effective probe!

Central Collisions

Peripheral Collisions

H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)

Electric charged chemical potential over baryon chemical potential



ALICE, *Phys. Rev. Lett.* 133, 092301 (2024)

- μ_Q/μ_B can be obtained from the thermal statistics fits to particle yields
- μ_Q/μ_B also can be obtained from fluctuations of B, Q, S

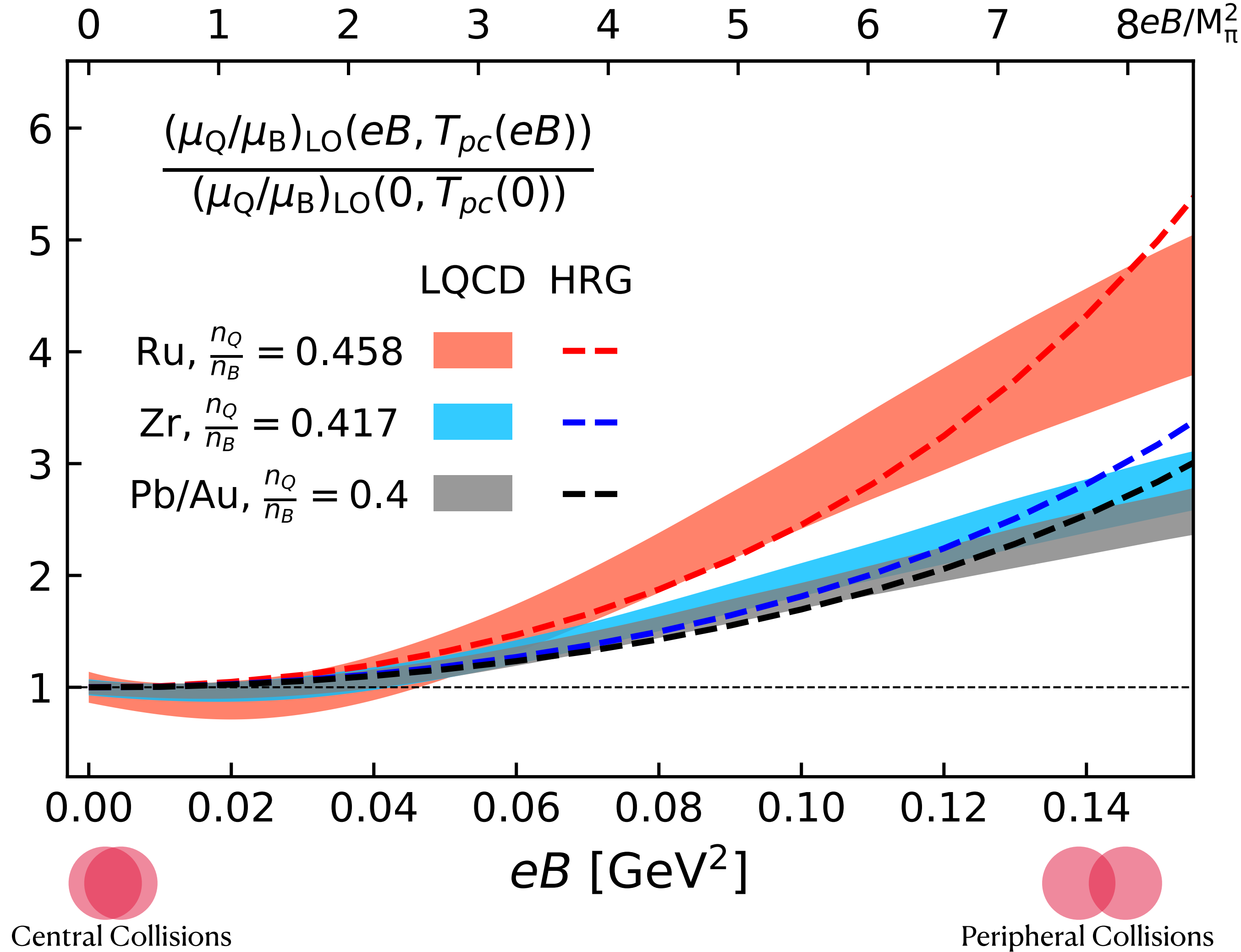
$$\mu_Q/\mu_B = q_1 + q_3 \hat{\mu}_B^2 + \mathcal{O}(\hat{\mu}_B^4)$$

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

with constraints: $r = n_Q/n_B$, $n_S = 0$

HotQCD, *Phys. Rev. Lett.* 109 (2012) 192302

$(\mu_Q/\mu_B)_{\text{LO}}$ in different collision system



H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, Phys. Rev. Lett. 132, 201903 (2024)

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

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

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

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

◆ At $eB \simeq 8M_\pi^2$,

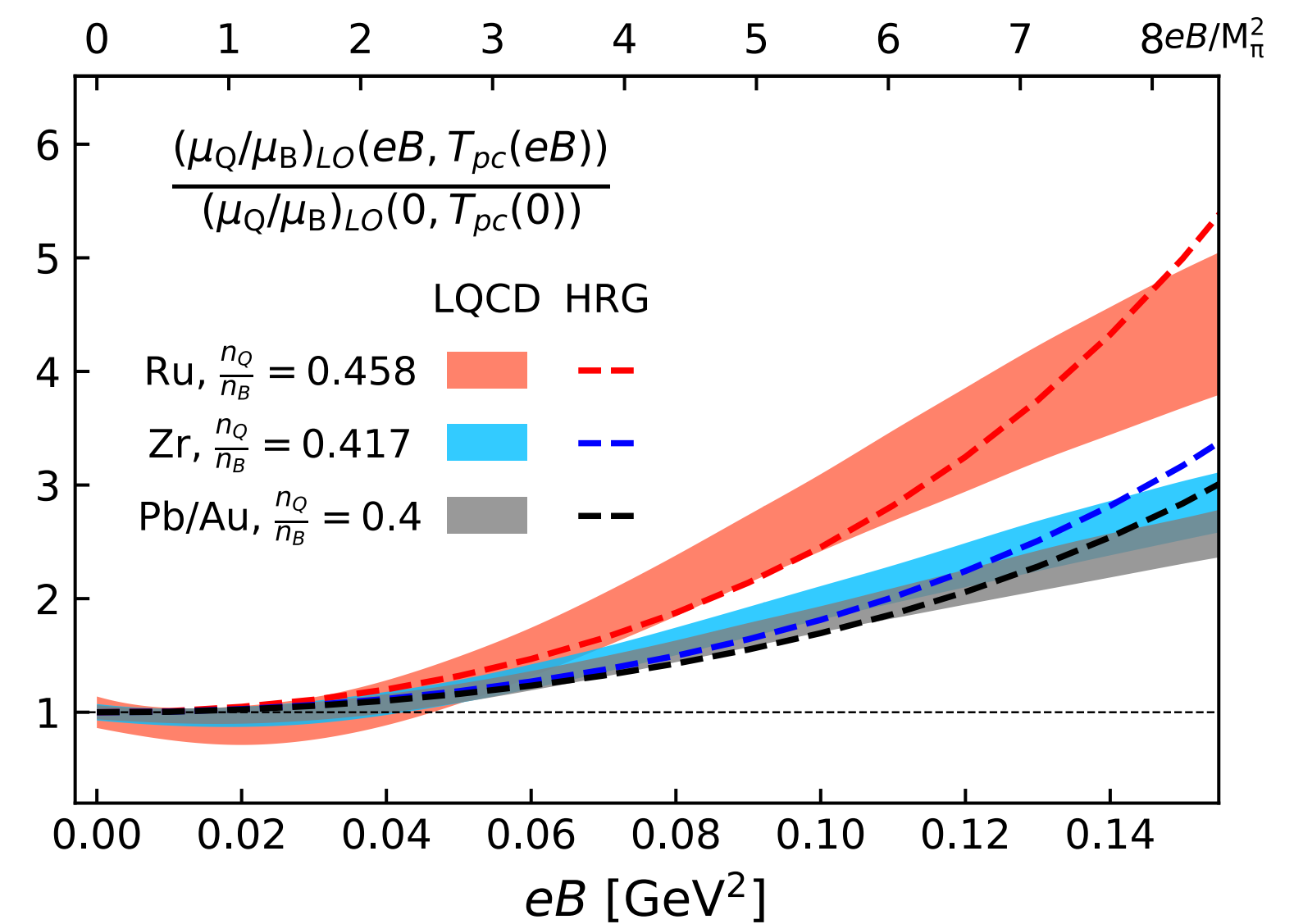
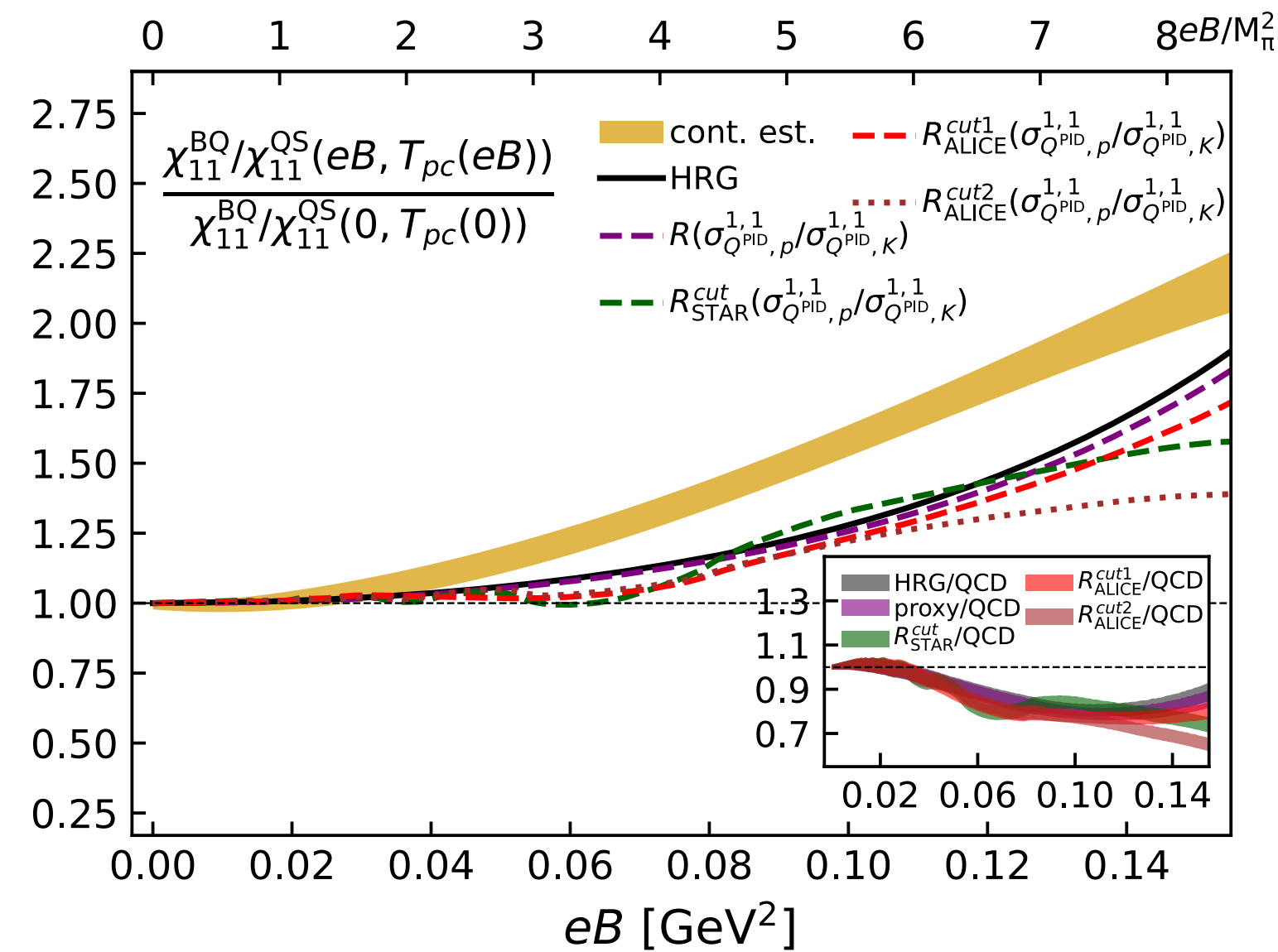
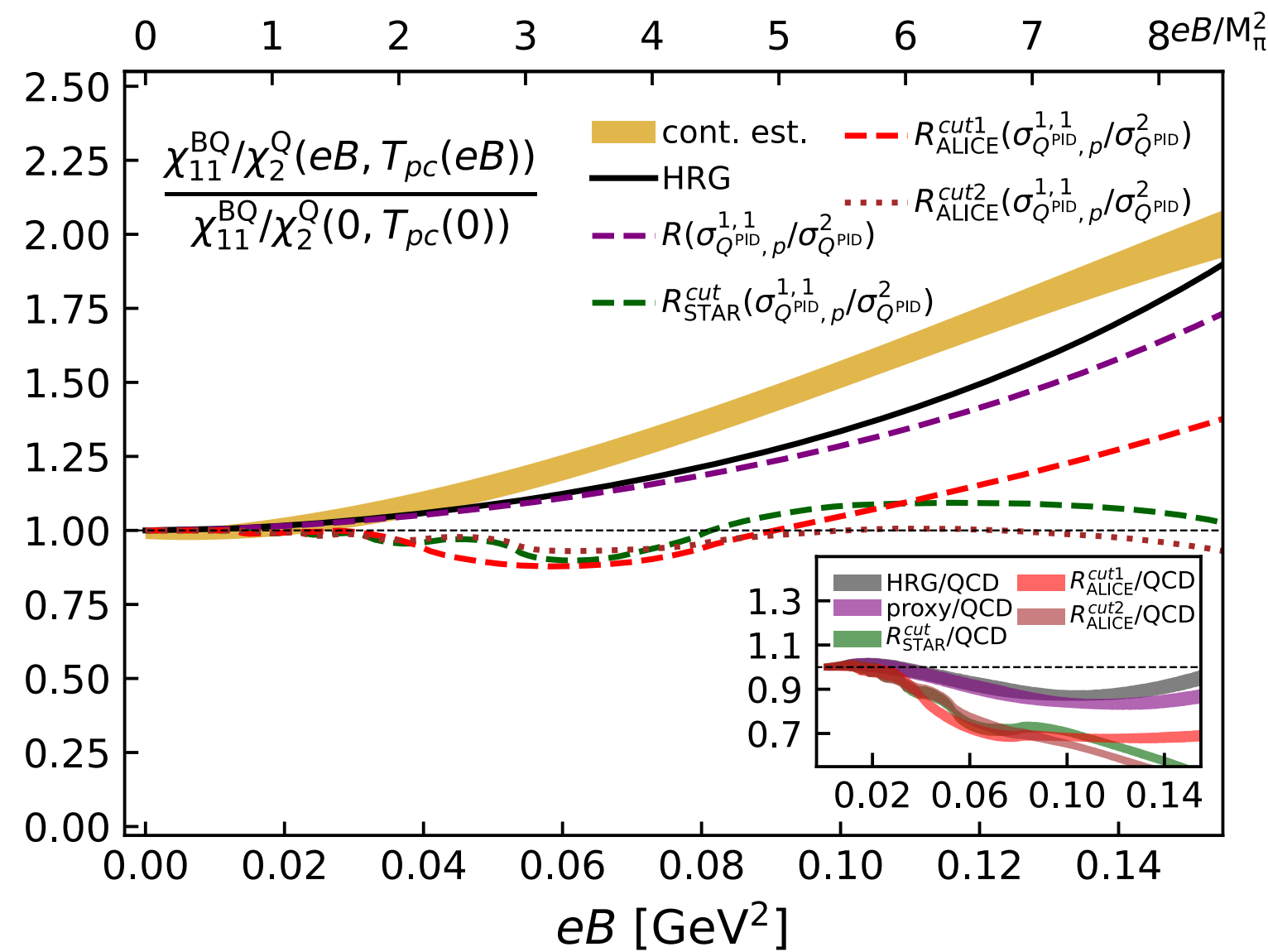
Ratio of $(\mu_Q/\mu_B)_{\text{LO}}$ for Pb, Au, Zr ~ 2.4

Ratio of $(\mu_Q/\mu_B)_{\text{LO}}$ for **Ru** ~ 4

See also Arpith's talk:
Oct. 11, 9:50 AM

Summary

- QCD benchmarks are provided for the 2nd order fluctuations of conserved charges based on LQCD computation on $N_\tau = 8$ and 12 lattices
- χ_{11}^{BQ} is strongly affected by eB , and a reasonable proxy is provided for measurement in HIC
- The μ_Q/μ_B depends significantly on the magnetic field and is sensitive to the initial n_Q/n_B



Thank you!

Backup

B pointing along the z direction

$$u_x(n_x, n_y, n_z, n_\tau) = \begin{cases} \exp[-iqa^2BN_xn_y] & (n_x = N_x - 1) \\ 1 & (\text{otherwise}) \end{cases}$$

$$u_y(n_x, n_y, n_z, n_\tau) = \exp[iqa^2Bn_x]$$

$$u_z(n_x, n_y, n_z, n_\tau) = u_t(n_x, n_y, n_z, n_\tau) = 1$$

No sign problem !

Quantization of the magnetic field

$$\begin{aligned} q_u &= 2/3 \, e \\ q_d &= -1/3 \, e \\ q_s &= -1/3 \, e \end{aligned} \longrightarrow eB = \frac{6\pi N_b}{N_x N_y} a^{-2}$$

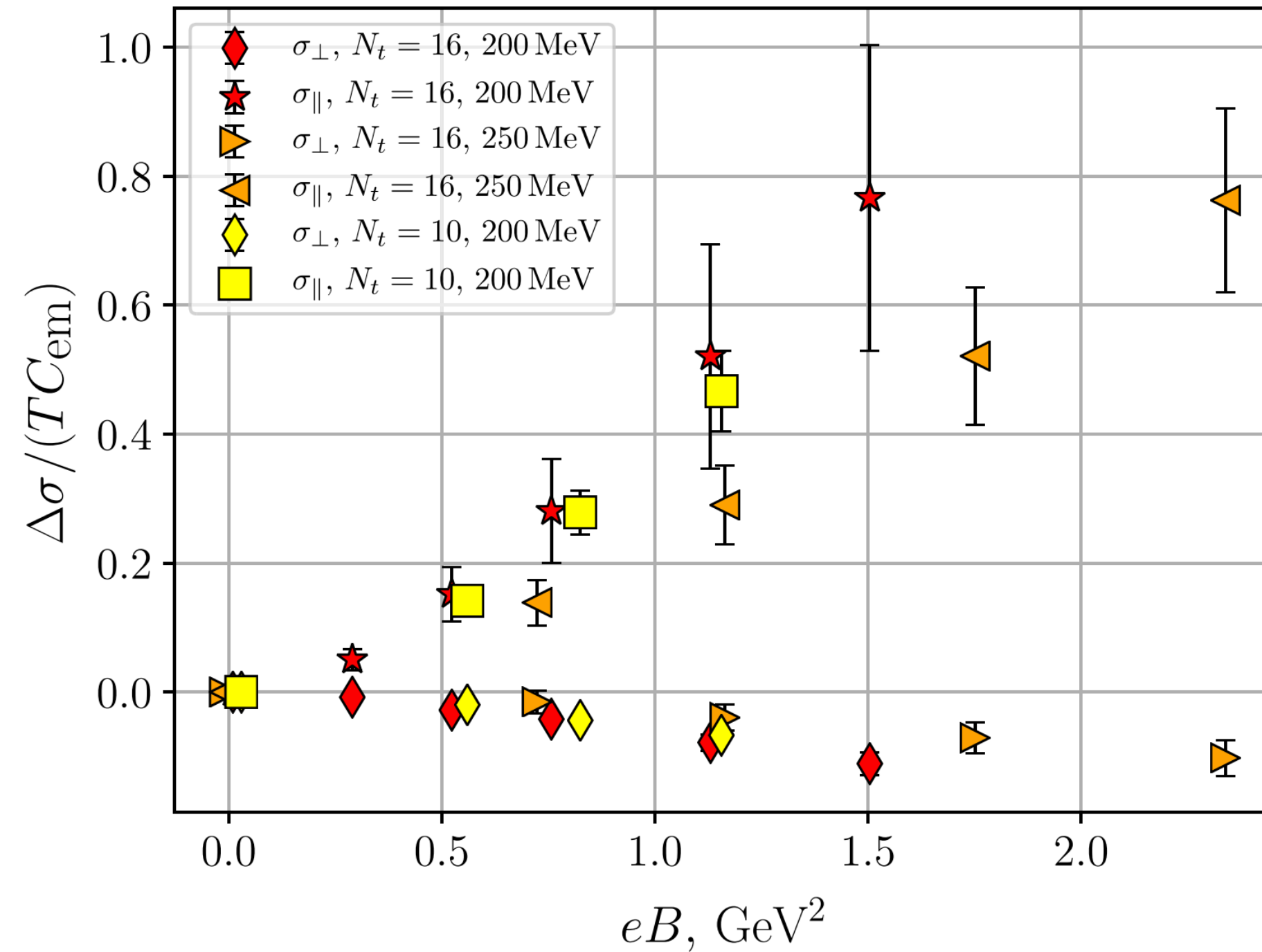
a is changed to get the targeted T , $T = \frac{1}{aN_\tau}$

- Statistics($eB \neq 0$): $N_\tau=8$: ~ 40000 (N_{rv} : 603)
 $N_\tau=12$: ~ 5000 (N_{rv} : 102 $\sim$ 705)
 $N_\tau=16$: ~ 3000 (N_{rv} : 603)

Landau gauge
G.S. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S.D. Katz,
S. Krieg et al., JHEP 02 (2012) 044.

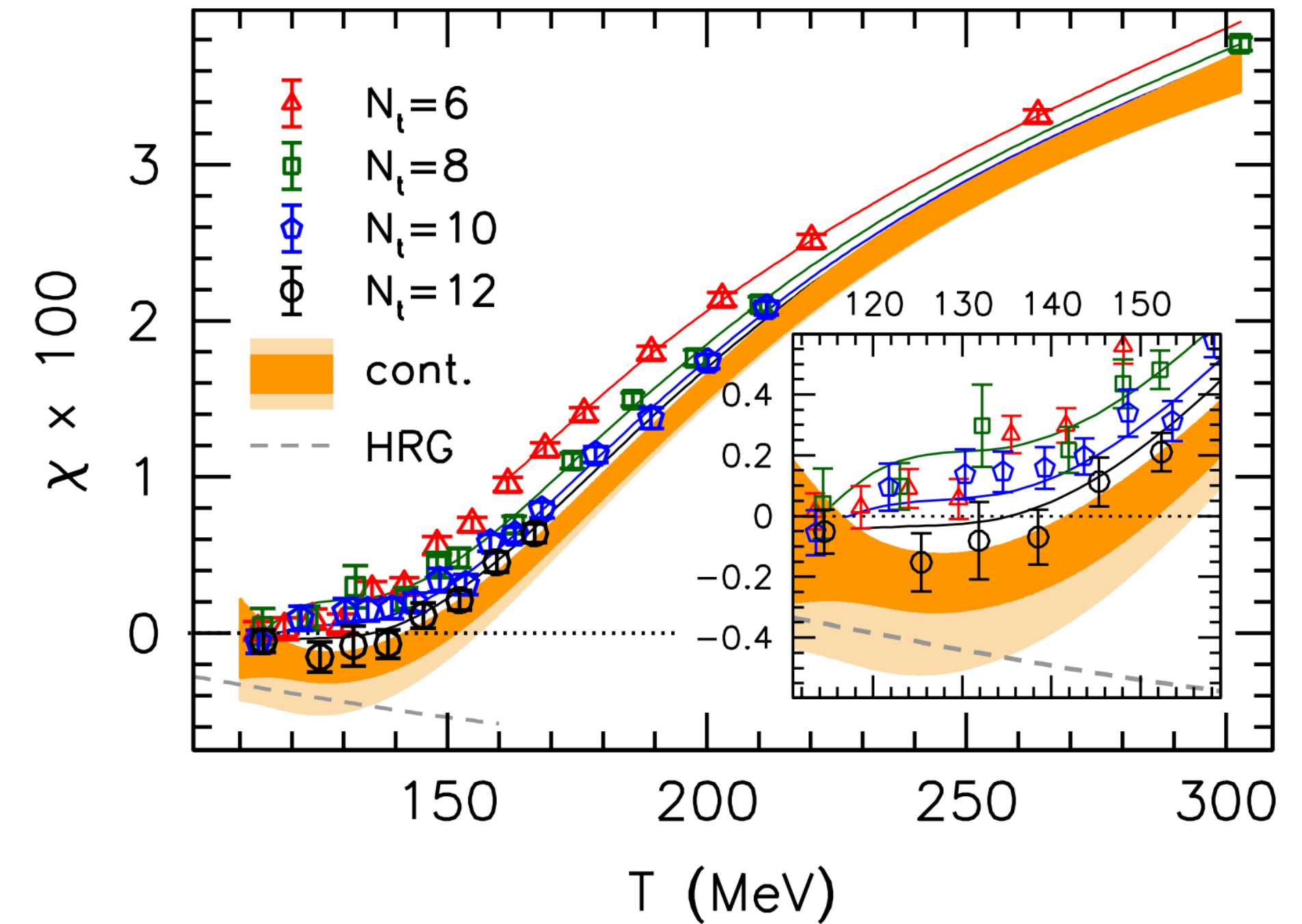
Electromagnetic conductivity and type of magnetism of QGP

Electromagnetic conductivities at non-zero magnetic fields



N. Astrakhantsev et al., PRD 102 (2020) 054516

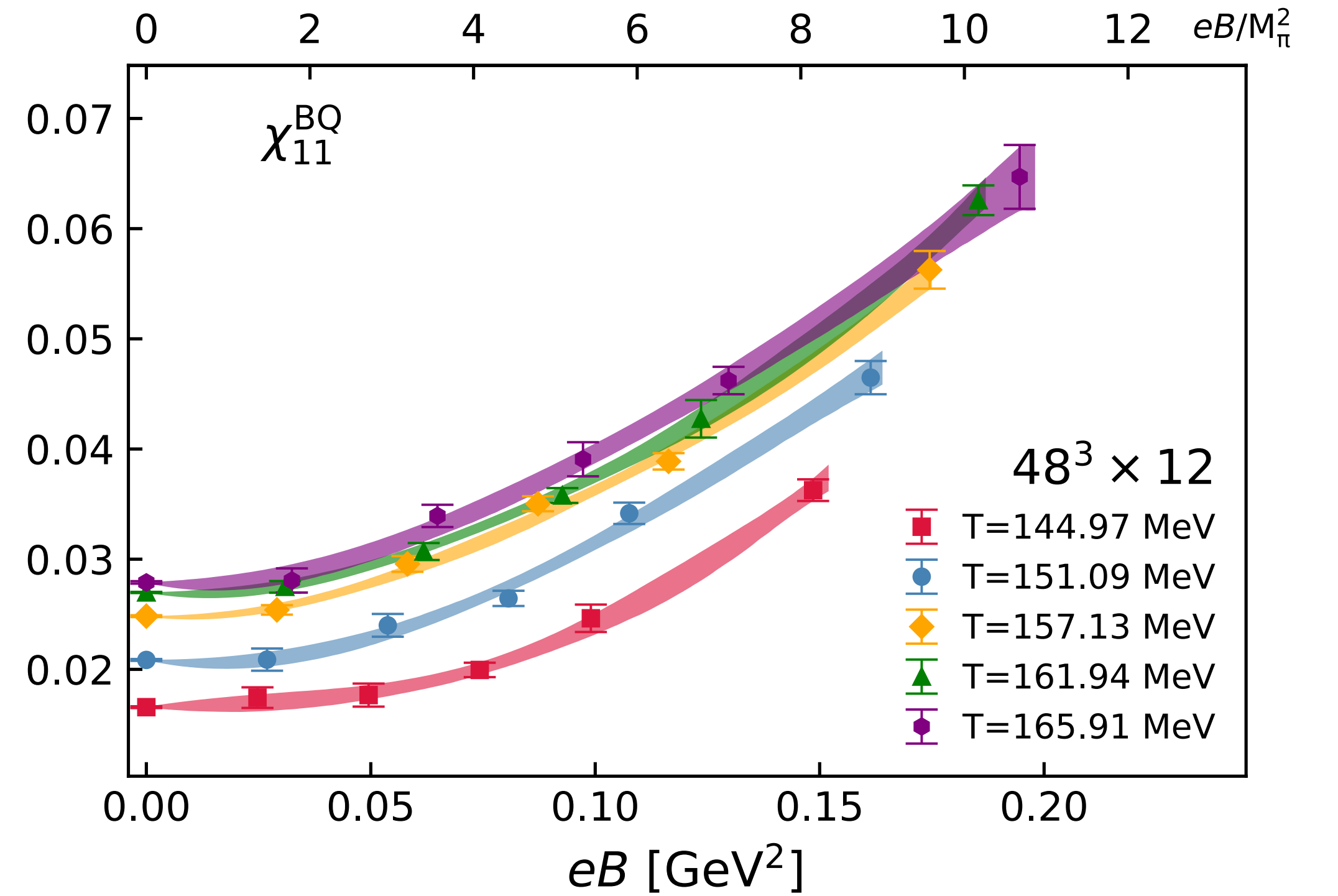
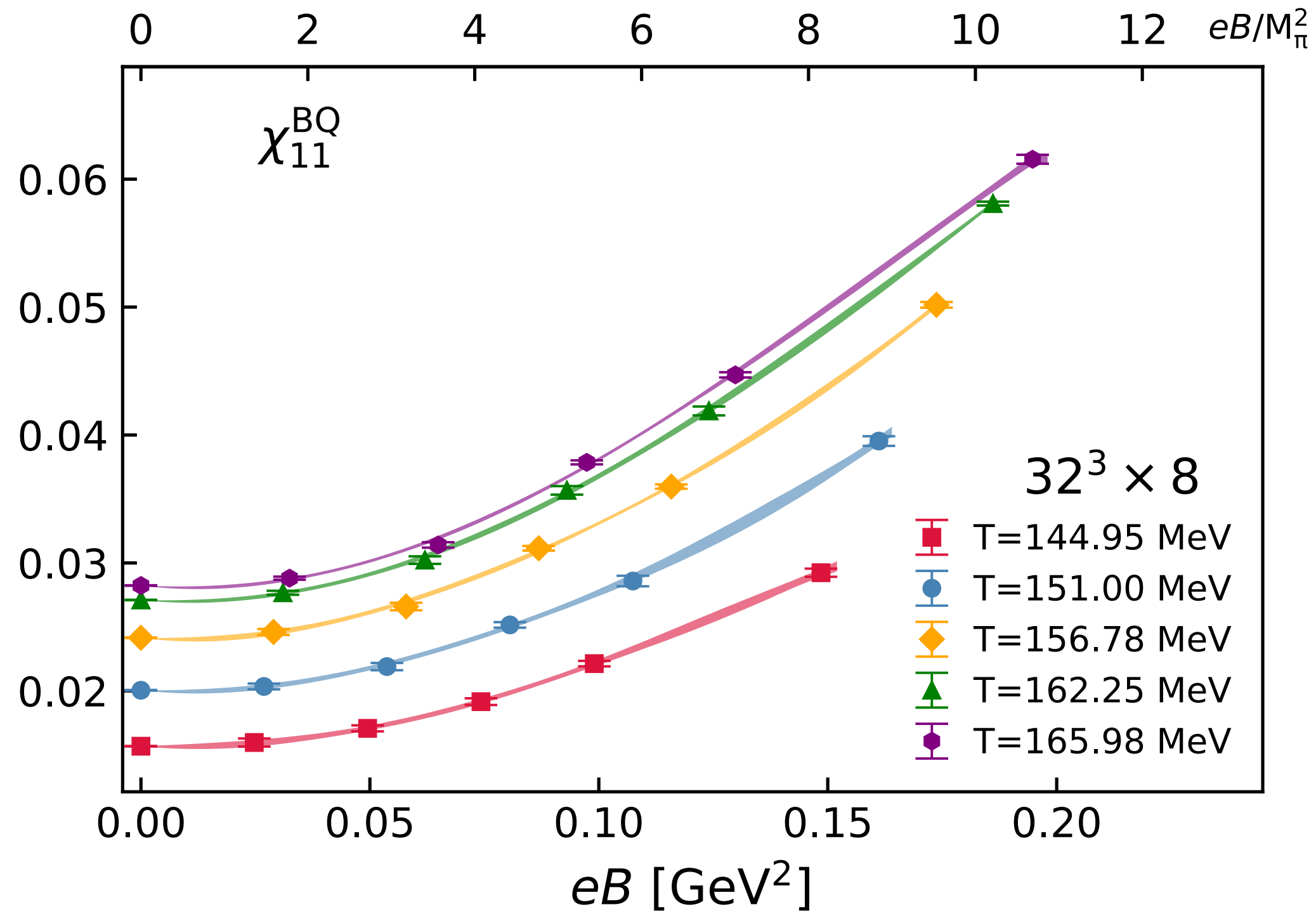
Magnetic susceptibility at non-zero magnetic fields



G. Bali et al., JHEP 07 (2020) 183

The magnetic field could live **longer** in the evolution of HICs than in the vacuum.

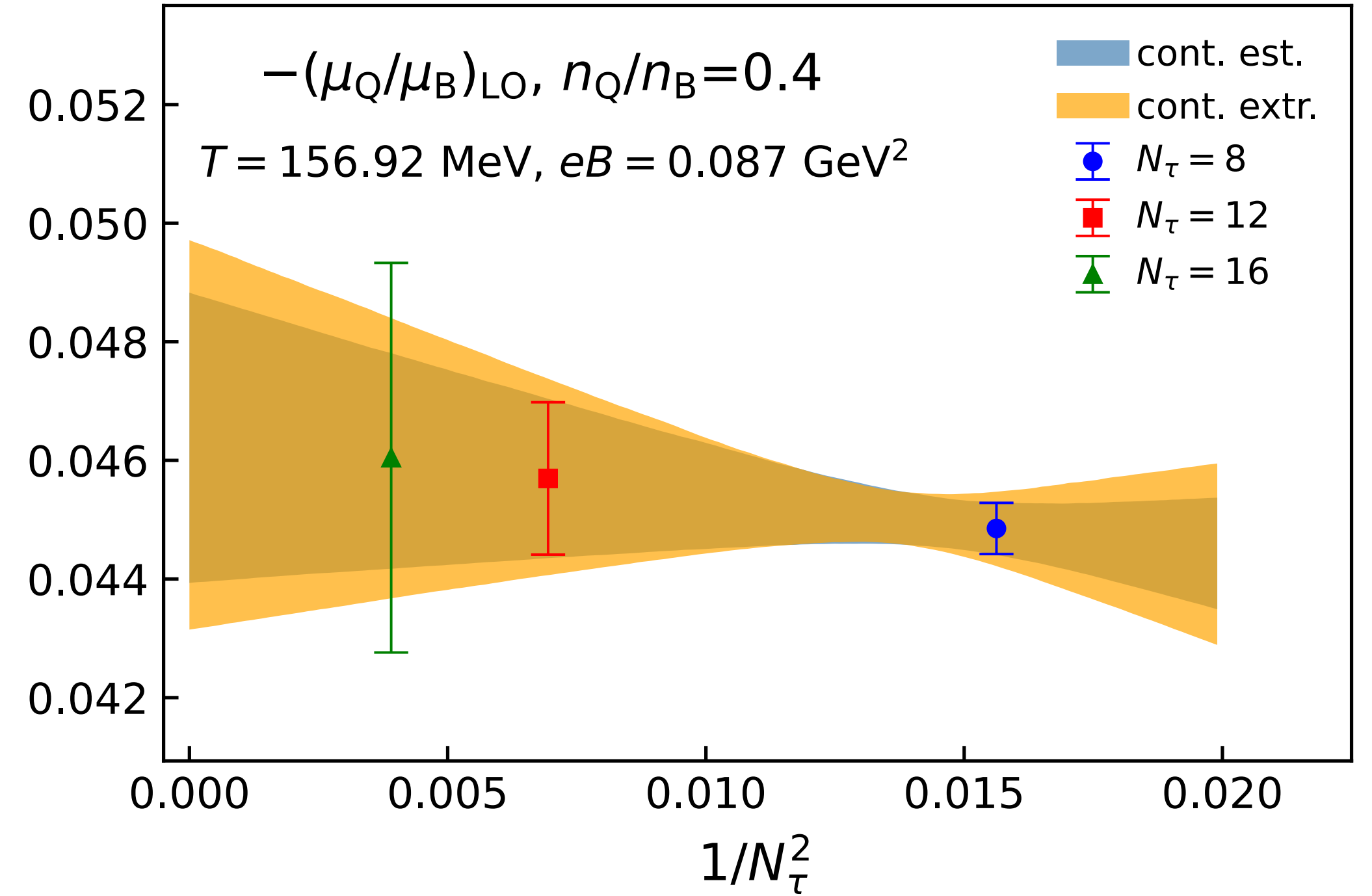
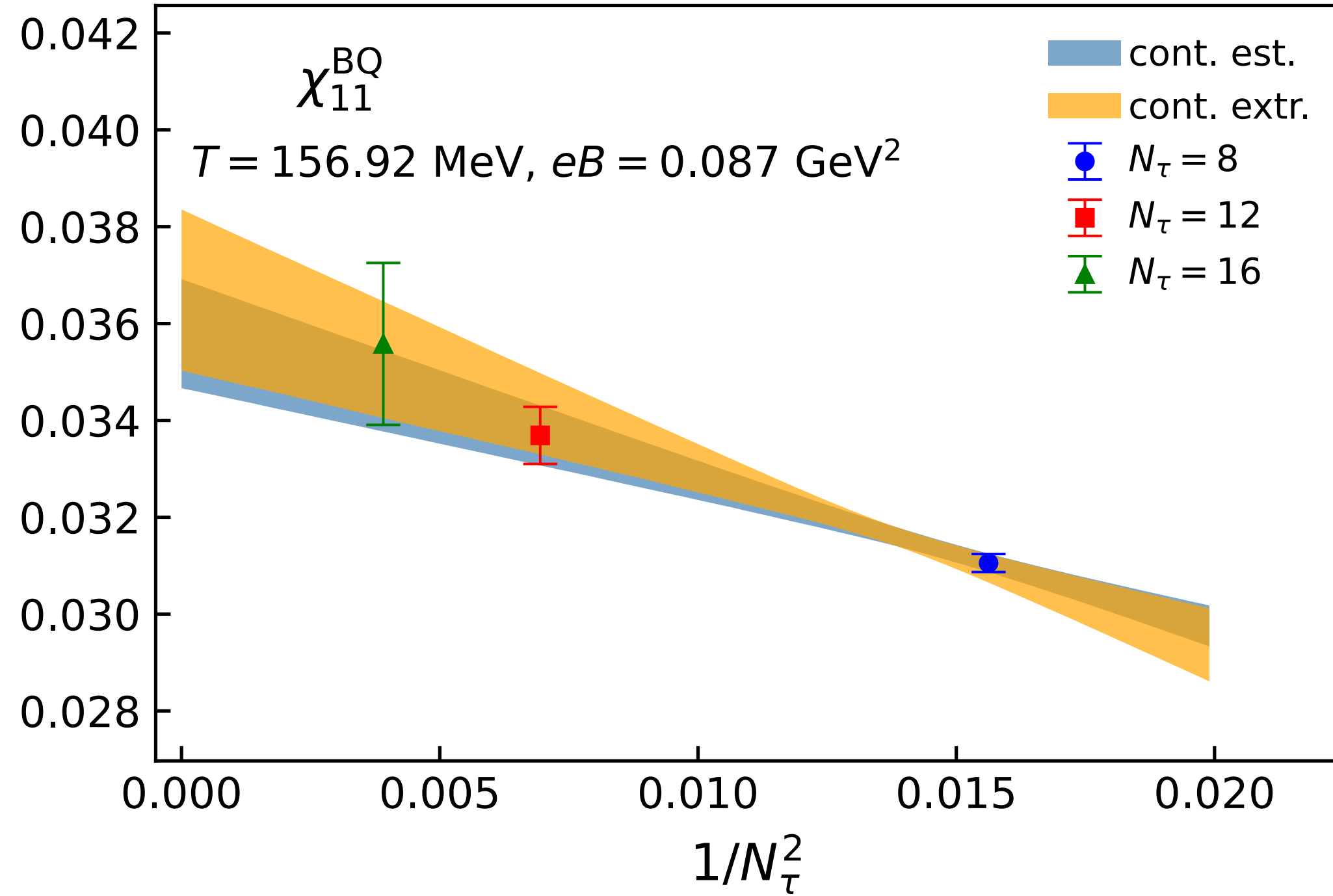
Lattice data on $N_\tau = 8$ and 12 lattices



H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li, Phys. Rev. Lett. 132, 201903 (2024)

The zero magnetic field data comes from D. Bollweg et al., Phys. Rev. D 104, 074512 (2021)

Continuum estimate and extrapolation

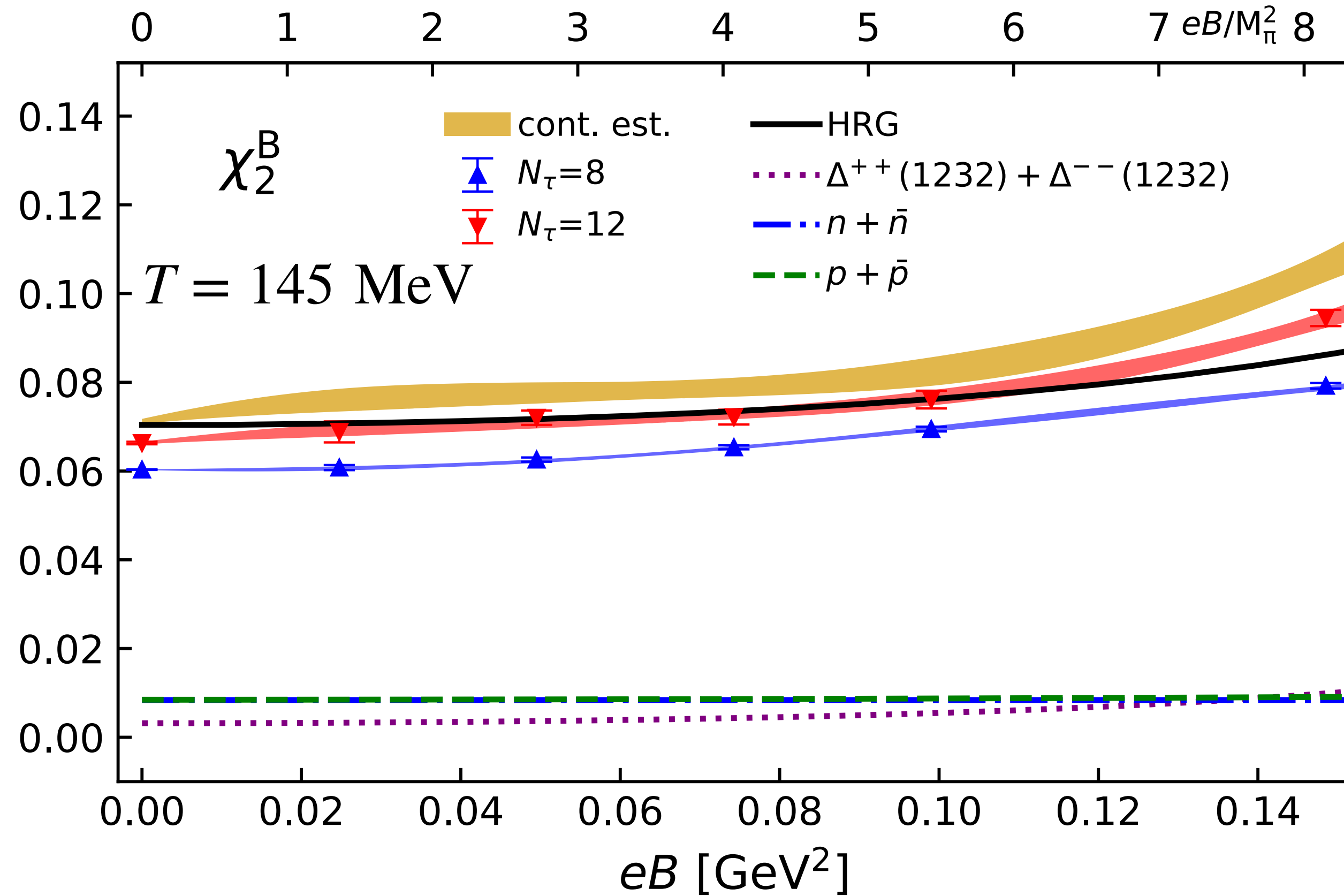


H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, Phys. Rev. Lett. 132, 201903 (2024)

$$\mathcal{O}(T, eB, N_\tau) = \mathcal{O}(T, eB) + \frac{c}{N_\tau^2} \begin{cases} \text{Continuum estimate} \\ \text{Continuum extrapolation} \end{cases} \quad \begin{matrix} \text{obtained from } N_\tau = 8 \text{ and } 12 \\ N_\tau = 8, 12, \text{ and } 16 \end{matrix}$$

Continuum estimate and continuum extrapolation are consistent within uncertainty

Baryon number fluctuations at $T = 145$ MeV



H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, Phys. Rev. Lett. 132, 201903 (2024)

❖ χ_2^B increases $\sim 45\%$ at $eB \sim 8M_\pi^2$

❖ Hadron Resonance Gas model (HRG):
Pressure arising from charged hadrons
($eB \neq 0$):

$$\frac{p_c^{M/B}}{T^4} = \frac{|q_i| B}{2\pi^2 T^3} \sum_{s_z = -s_i}^{s_i} \sum_{l=0}^{\infty} \epsilon_0 \sum_{n=1}^{\infty} (\pm 1)^{n+1} \frac{e^{n\mu_i/T}}{n} K_1 \left(\frac{n\epsilon_0}{T} \right)$$

❖ χ_2^B receives contributions also from
neutral baryons

H.-T. Ding et al., Eur. Phys. J. A 57 (2021) 6, 202

Proxy in experiment

◆ Conserved charges susceptibilities in experiment:

$$\chi_\alpha^2 = \frac{1}{VT^3} \kappa_\alpha^2, \quad \chi_{\alpha,\beta}^{1,1} = \frac{1}{VT^3} \kappa_{\alpha,\beta}^{1,1}$$

the second-order cumulants(κ) are the variance or covariance(σ) of the net-multiplicity N :

$$\kappa_\alpha^2 = \sigma_\alpha^2 = \langle (\delta N_\alpha - \langle \delta N_\alpha \rangle)^2 \rangle$$

$$\kappa_{\alpha,\beta}^{1,1} = \sigma_{\alpha,\beta}^{1,1} = \langle (\delta N_\alpha - \langle \delta N_\alpha \rangle)(\delta N_\beta - \langle \delta N_\beta \rangle) \rangle$$

with $\delta N_\alpha = N_{\alpha^+} - N_{\alpha^-}$ and $\alpha, \beta = p, Q^{PID}, k$

- p : a proxy for the net-baryon
- k : a proxy for the net-strangeness
- Q^{PID} : identified π, k and p

STAR, Phys.Rev.C 100 (2019) 1, 014902

$$\sigma_{Q^{PID},p}^{1,1} = \sigma_p^2 + \sigma_{p,\pi}^{1,1} + \sigma_{p,K}^{1,1}$$

$$\sigma_p^2 = \sum_R \left(P_{R \rightarrow \tilde{p}} \right) \left(P_{R \rightarrow \tilde{p}} \right) \frac{\partial^2 p_R / T^4}{\partial \hat{\mu}_R^2}$$

$$\sigma_{p,\pi}^{1,1} = \sum_R \left(P_{R \rightarrow \tilde{p}} \right) \left(P_{R \rightarrow \tilde{\pi}^+} \right) \frac{\partial^2 p_R / T^4}{\partial \hat{\mu}_R^2}$$

$$\sigma_{p,K}^{1,1} = \sum_R \left(P_{R \rightarrow \tilde{p}} \right) \left(P_{R \rightarrow \tilde{K}^+} \right) \frac{\partial^2 p_R / T^4}{\partial \hat{\mu}_R^2}$$

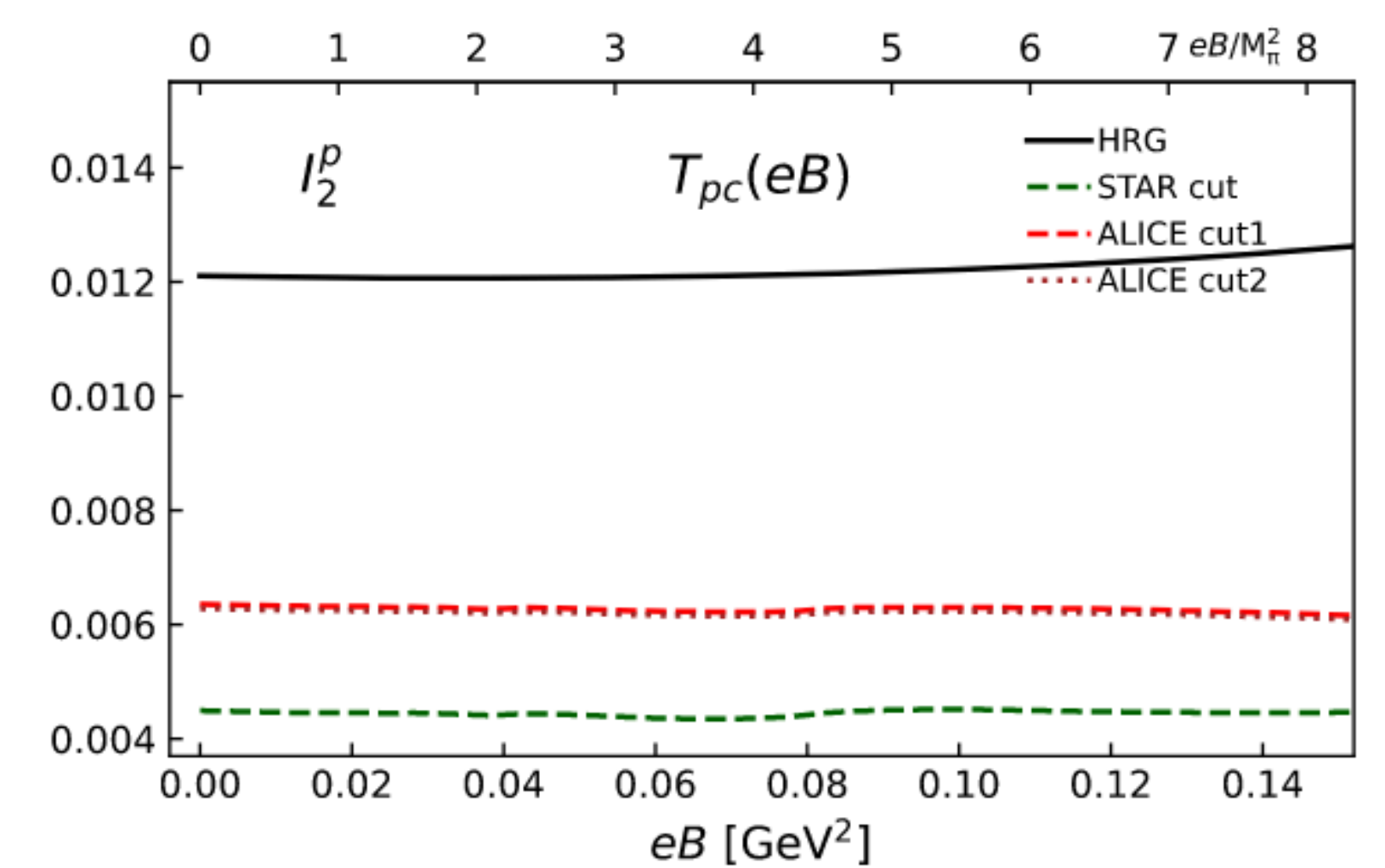
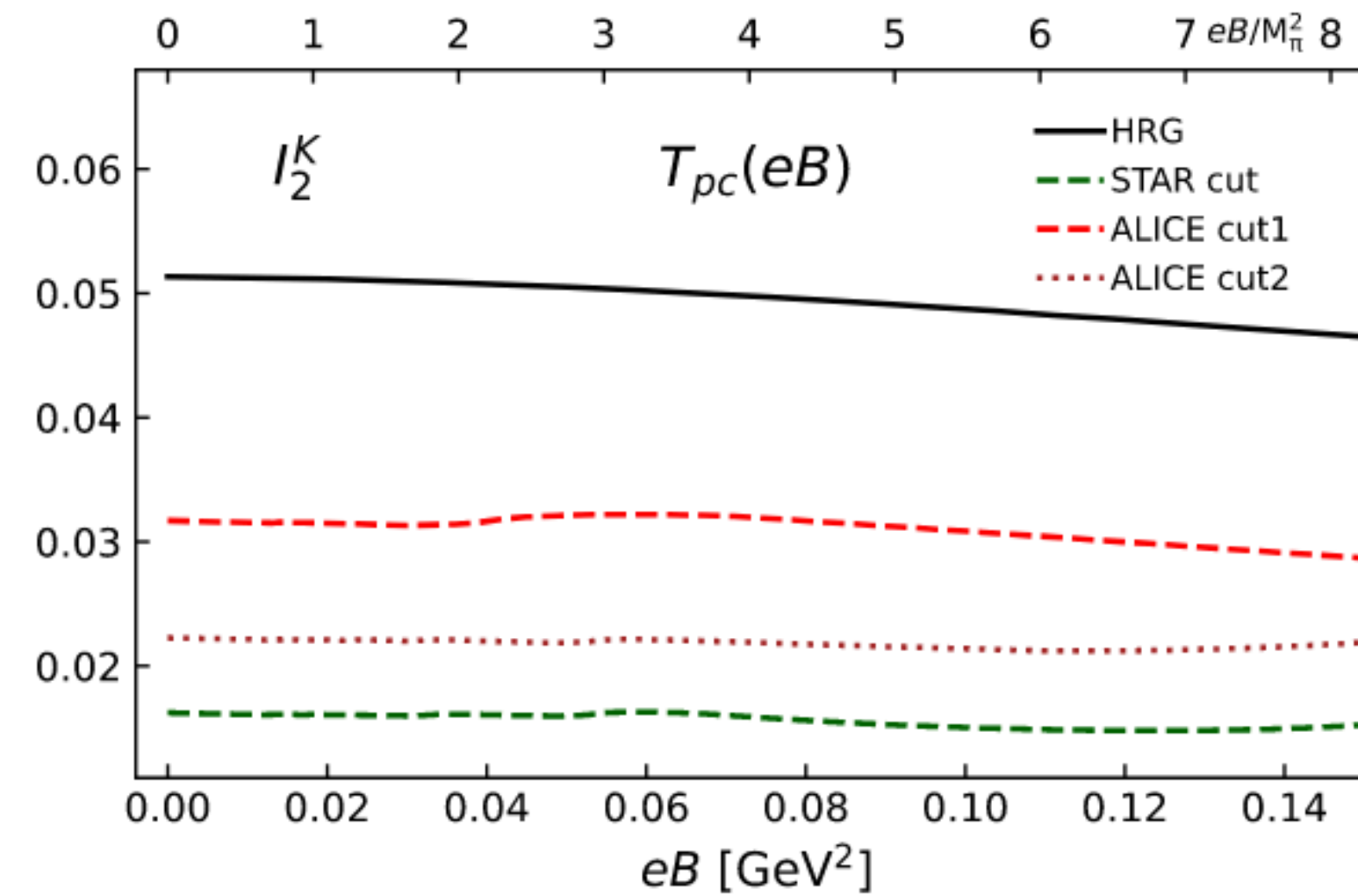
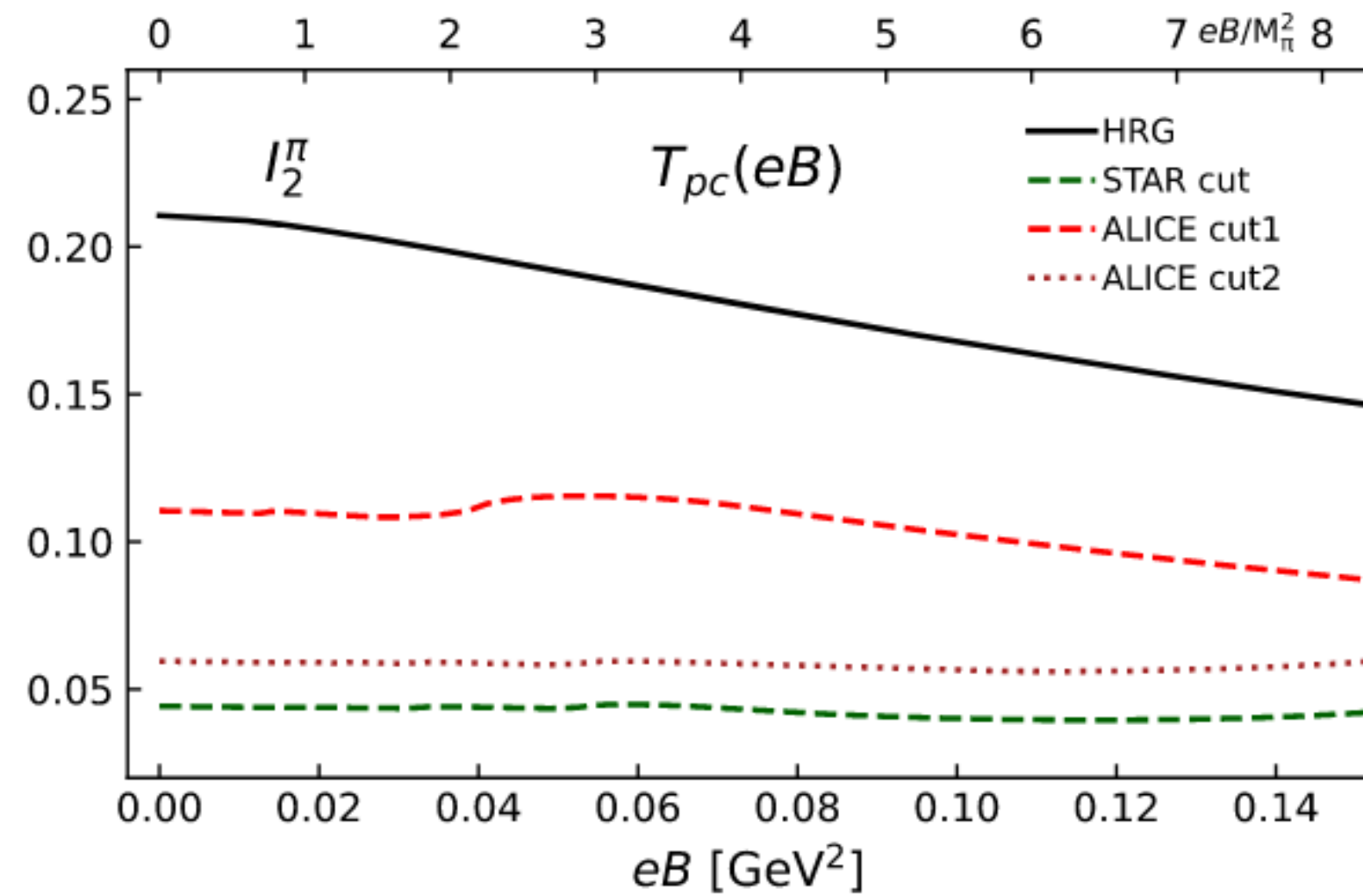
$$\text{where } P_{R \rightarrow i} = \sum_\alpha N_{R \rightarrow i}^\alpha n_{i,\alpha}^R$$

$n_{i,\alpha}^R$: numbers of i produced by R in decay channel α

$N_{R \rightarrow i}^\alpha$: Branching ratio of channel α

Phase space integral for π , K and p

$$I_2^i = \frac{\partial^2 p_i / T^4}{\partial \mu_i^2} \text{ with different kinematic cuts. } i \in \{\pi, K, p\}$$



$$R_{\text{STAR}}^{\text{cut}} : |\eta| < 0.5,$$

$$R_{\text{ALICE}}^{\text{cut1}} : |\eta| < 0.8,$$

$$R_{\text{ALICE}}^{\text{cut2}} : |\eta| < 0.8,$$

$$\pi^\pm, K^\pm \text{ and } p(\bar{p}) : 0.4 < p_T < 1.6 \text{ GeV}/c$$

$$\pi^\pm \text{ and } K^\pm : 0.2 < p_T < 2 \text{ GeV}/c$$

$$\pi^\pm, K^\pm \text{ and } p(\bar{p}) : 0.4 < p_T < 1.6 \text{ GeV}/c$$

$$p(\bar{p}) : 0.4 < p_T < 2 \text{ GeV}/c$$

H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)