Nuclear Science Computing Center at CCNU

Baryon Electric Charge Correlation as a Magnetometer of QCD

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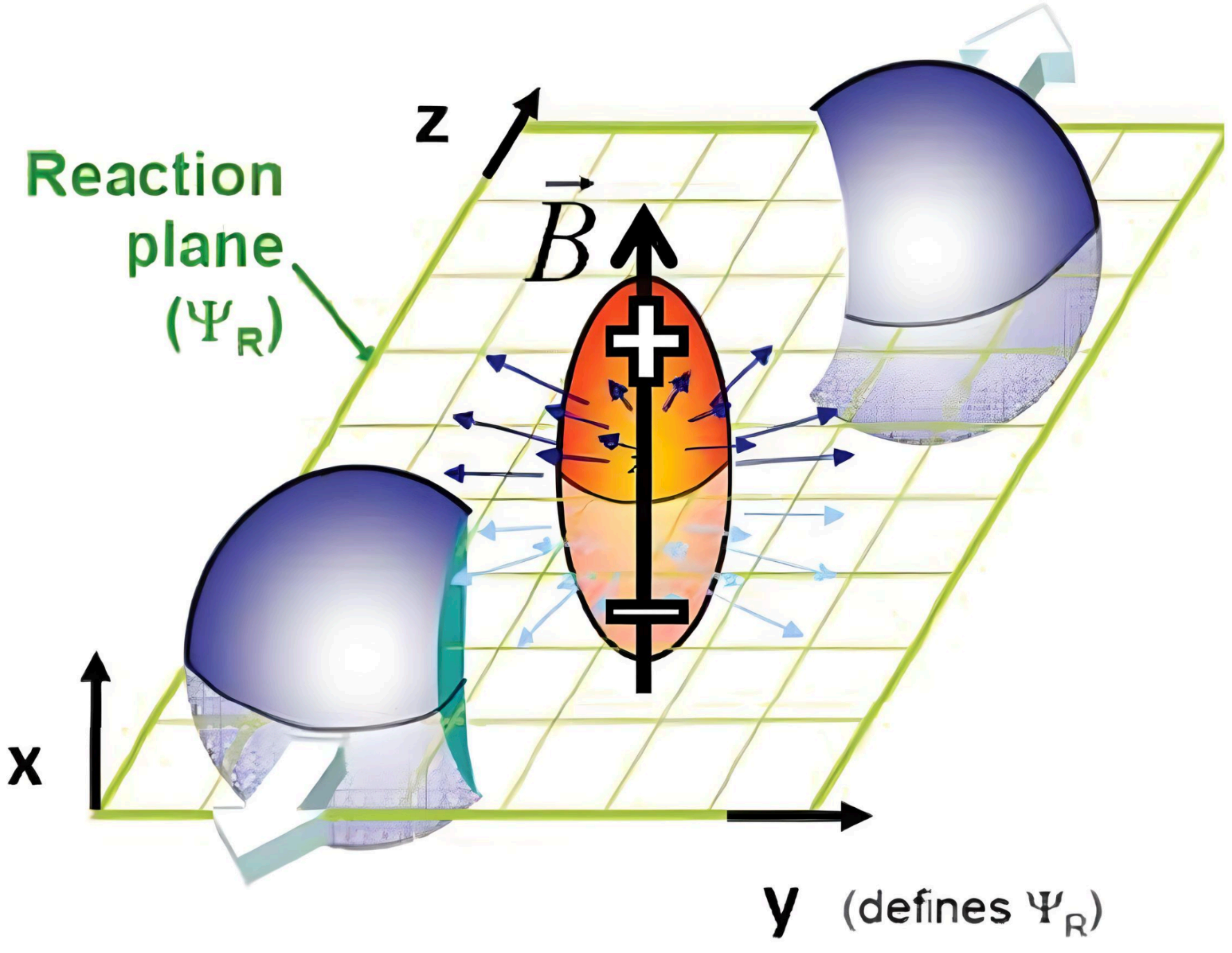
Based on *Phys. Rev. Lett.* **132**, 201903 (2024) and *Phys.Rev.D* **111**, 114522 (2025)

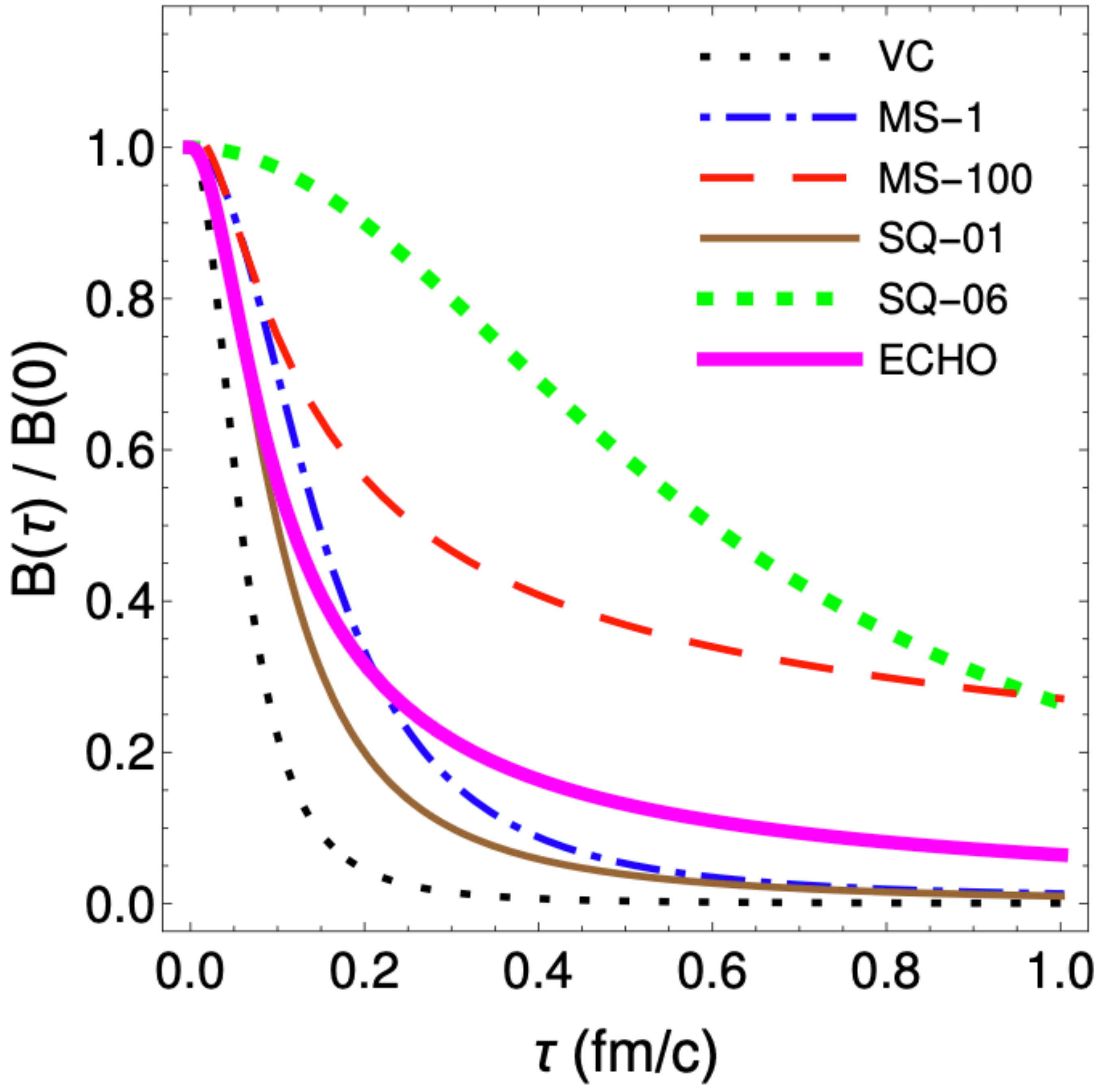
In collaboration with H.-T. Ding, A. Kumar and S.-T. Li

第五届中国格点量子色动力学研讨会,
2025年10月 9 - 12日@ 广东惠州

Strong magnetic fields in heavy-ion collisions



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



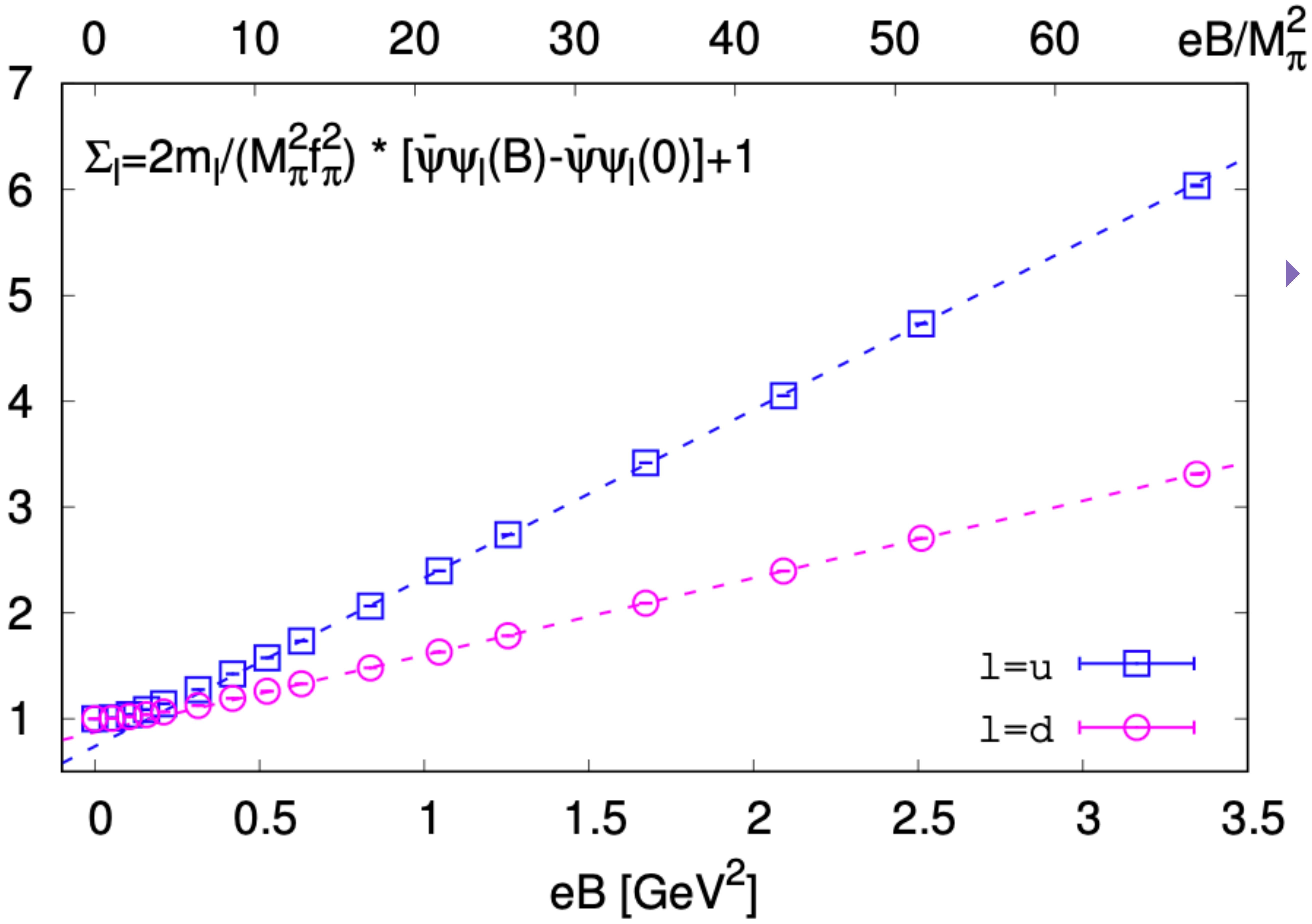
A. Huang et al. Phys.Lett.B 777 (2018) 177-183

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

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



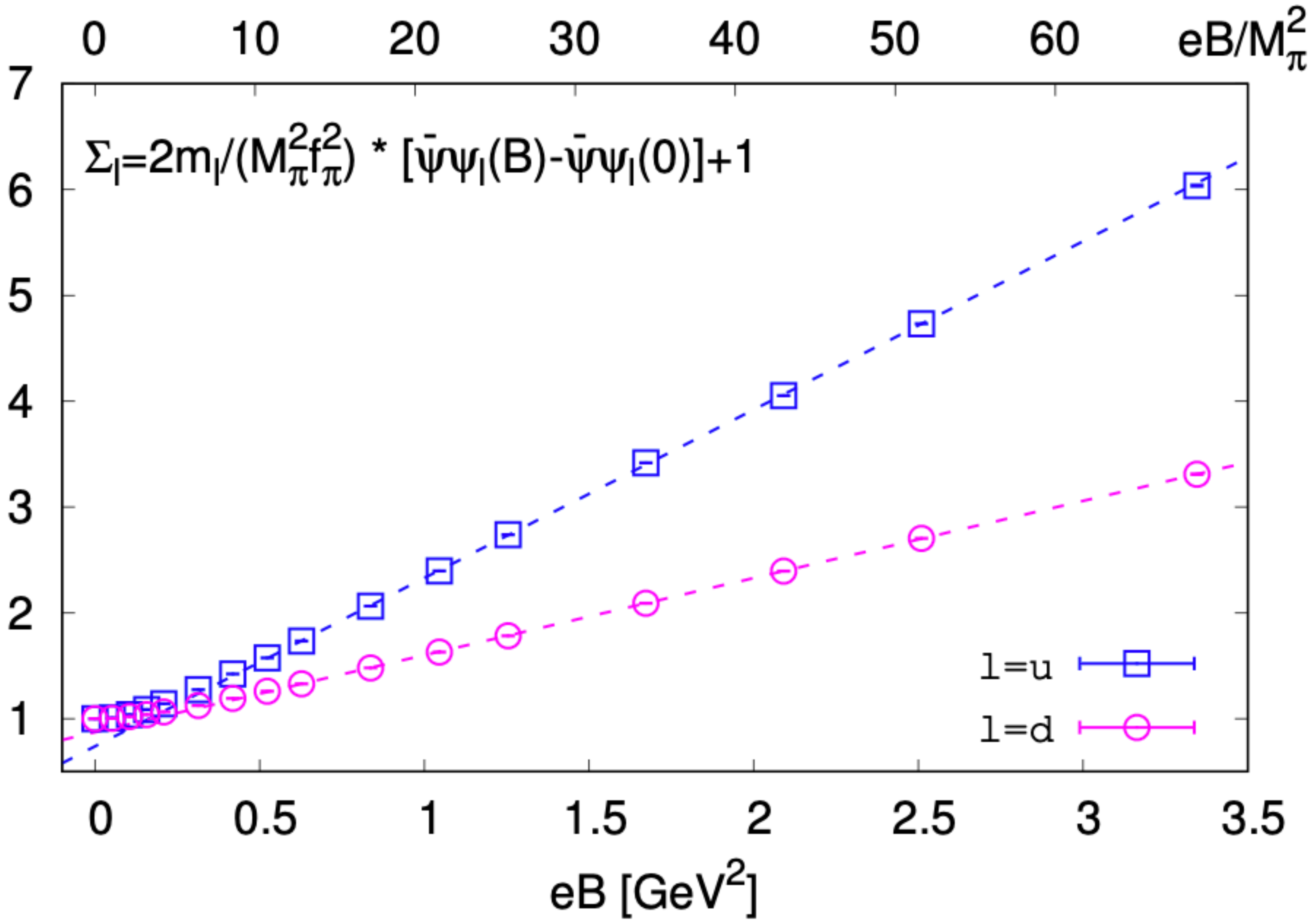
H.-T.Ding, S.-T. Li, A. Tomiya, X.-D. Wang and Y. Zhang, Phys.Rev.D 104, 014505 (2021)

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

- Sign of isospin symmetry breaking:

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

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



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

A clear effect but Not accessible in HIC experiments!

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

Taylor expansion of the QCD pressure:

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

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

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

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

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

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

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

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

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)*

Lattice Setup

- 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 : $(144\ \text{MeV},\ 166\ \text{MeV})$, i.e. $(0.9T_{pc},\ 1.1T_{pc})$
- eB window: $eB \lesssim 8M_\pi^2 \sim 0.15\ \text{GeV}^2$

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

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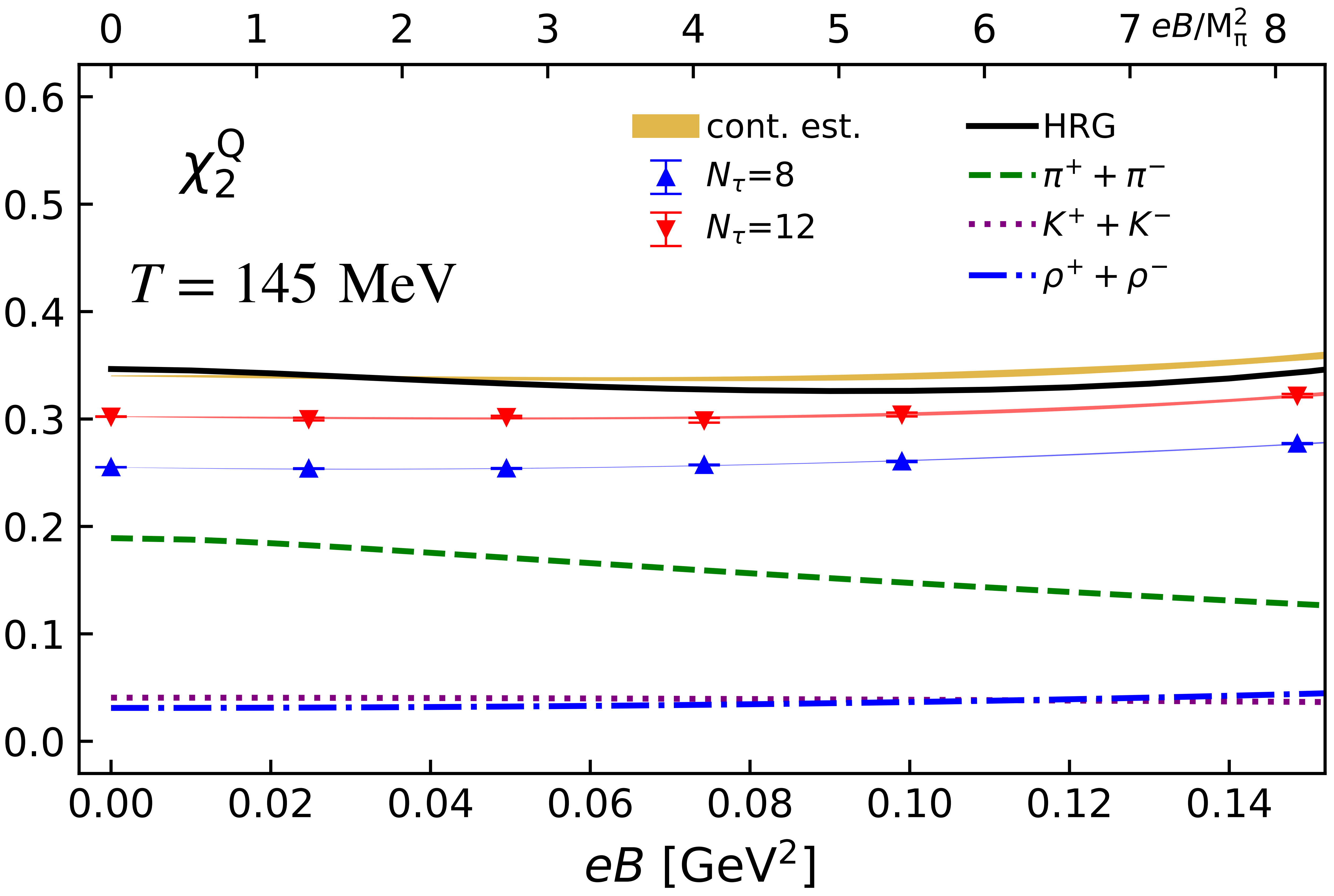


H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, Phys. Rev. Lett. 132, 201903 (2024)

- χ_2^Q almost independent of eB
- Hadron Resonance Gas model (HRG): Pressure arising from charged hadrons ($eB \neq 0$):

$$\frac{p_i^{M/B}}{T^4} = \frac{|q_i|\,B}{2\pi^2 T^3} \sum_{s_z=-s_i}^{s_i} \sum_{l=0}^{\infty} \varepsilon_0 \sum_{n=1}^{\infty} (\pm 1)^{n+1} \frac{e^{n\mu_i/T}}{n} K_1\left(\frac{n\varepsilon_0}{T}\right)$$

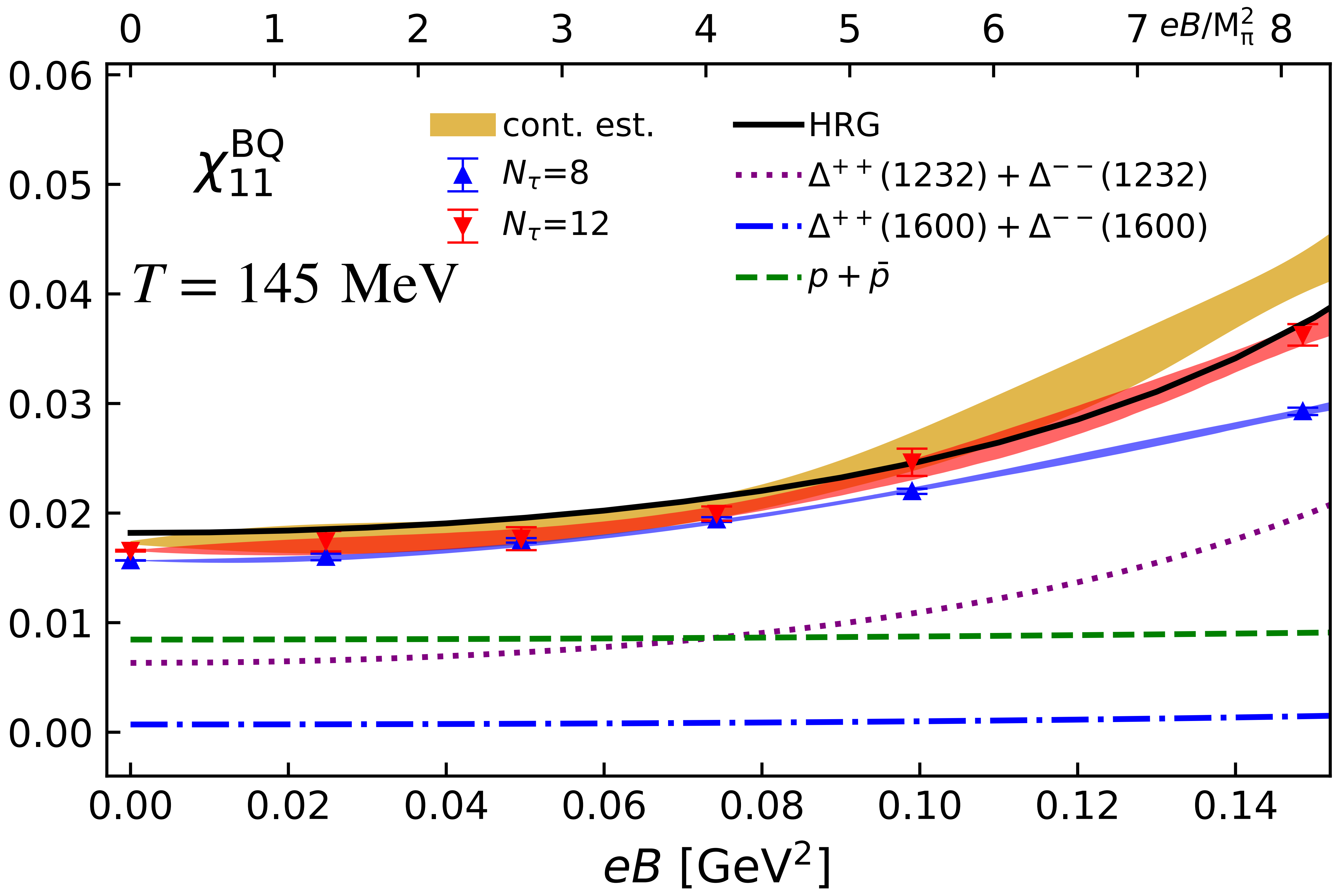
Quantized energy level:

$$\varepsilon_0 = \sqrt{m_i^2 + 2\,|q_i|\,B\boxed{\left(l + 1/2 - s_z\right)}}$$

$(l + 1/2 - s_z) > 0 : \varepsilon_0$ increases
$(l + 1/2 - s_z) < 0 : \varepsilon_0$ decreases
with eB

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

Baryon electric charge correlation at $T = 145\ \mathrm{MeV}$



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

$$\Delta^{++}(1232) \to p + \pi^+$$

Proxy construction based on the HRG

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

HRG: Fluctuations expressed in terms of stable hadronic states:

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

net- B : $\boxed{\tilde{p}} + \tilde{n} + \tilde{\Lambda} + \tilde{\Sigma}^+ + \tilde{\Sigma}^- + \tilde{\Xi}^0 + \tilde{\Xi}^- + \tilde{\Omega}^-$

net- Q : $\boxed{\tilde{\pi}^+ + \tilde{K}^+ + \tilde{p}} + \tilde{\Sigma}^+ - \tilde{\Sigma}^- - \tilde{\Xi}^- - \tilde{\Omega}^-$

net- S : $\boxed{\tilde{K}^+} + \tilde{K}^0 - \tilde{\Lambda} - \tilde{\Sigma}^+ - \tilde{\Sigma}^- - 2\tilde{\Xi}^0 - 2\tilde{\Xi}^- - 3\tilde{\Omega}^-$

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)

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

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

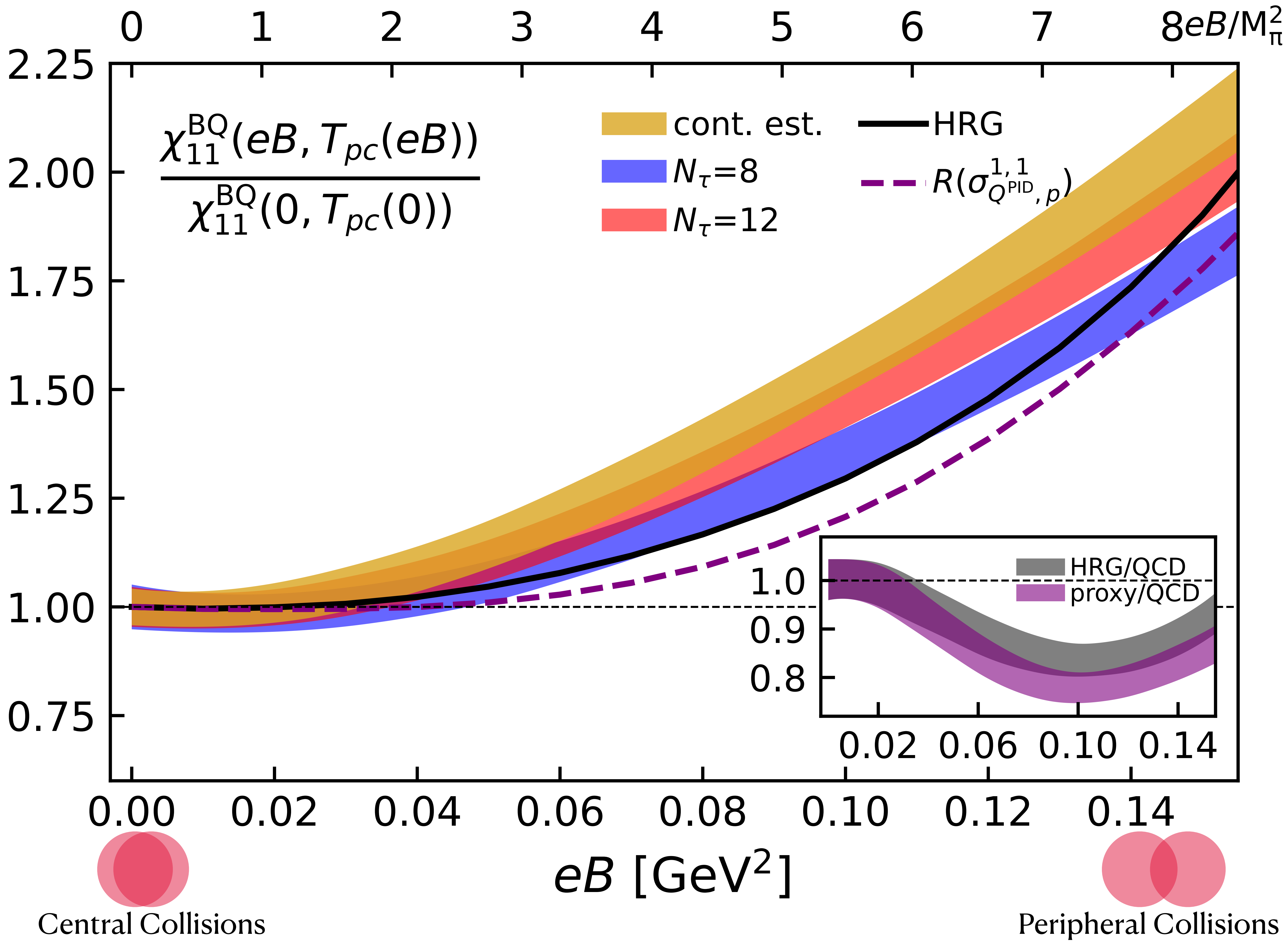
net-B $\to \tilde{p}$: $\omega_{R\to\tilde{p}}$

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

Where $\omega_{R\to\tilde{i}}$ 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!

Proxy for $R(\chi_{11}^{BQ})$ 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 $eB \simeq 8M_\pi^2$, $R(\chi_{11}^{BQ}) \sim$ **2.1**

$$\chi_{11}^{BQ} \to \sigma^{1,1}_{Q^{PID},p}$$

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

net- B : $\tilde{p}$

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

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

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

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

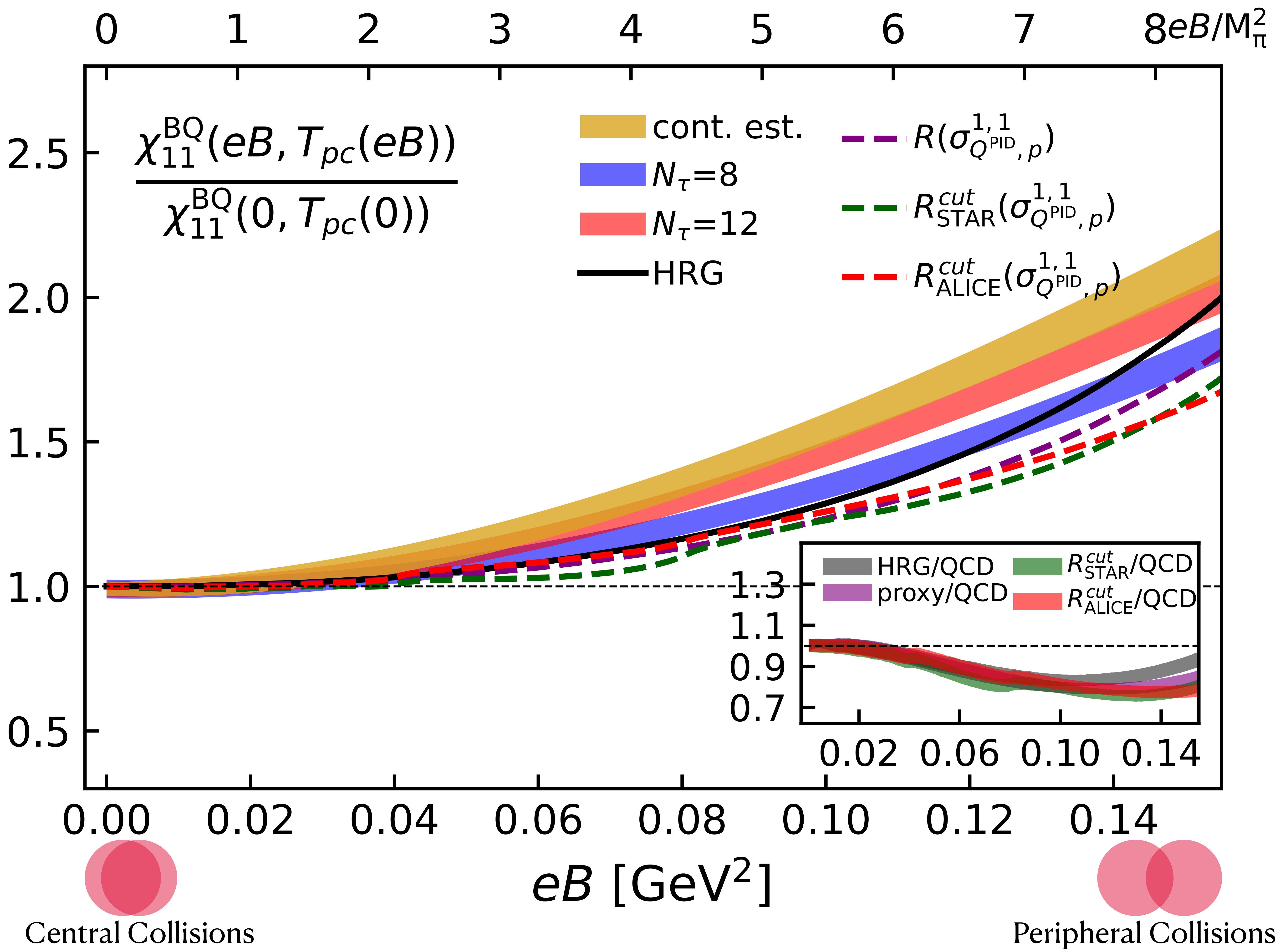
$R^{cut}_{\mathrm{STAR}}: |\eta| < 0.5,$

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

$R^{cut}_{\mathrm{ALICE}}: |\eta| < 0.8,$

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

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

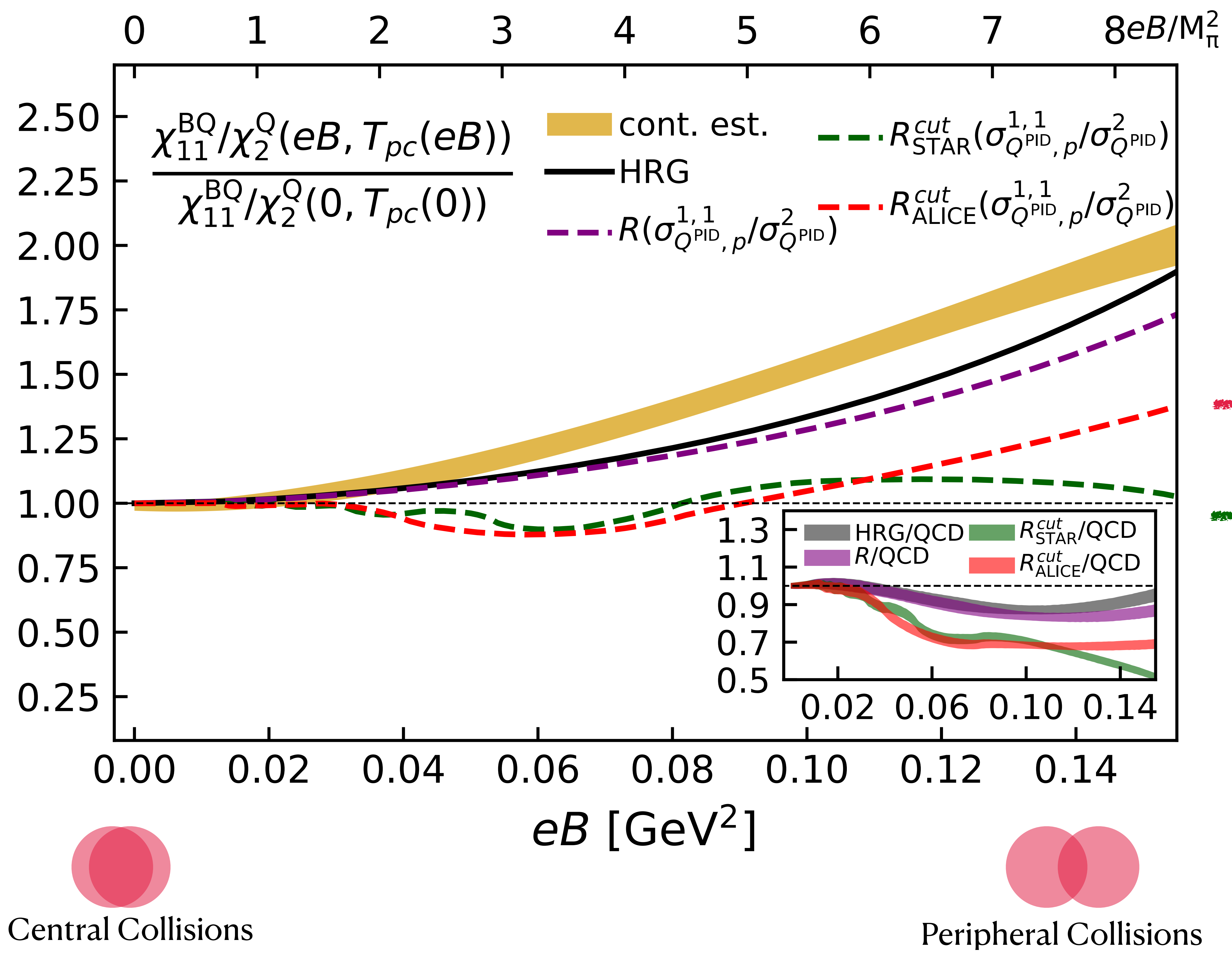


H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)

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

ALICE collaboration, arXiv:2503.18743

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



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

- R_{cp}−like observables:

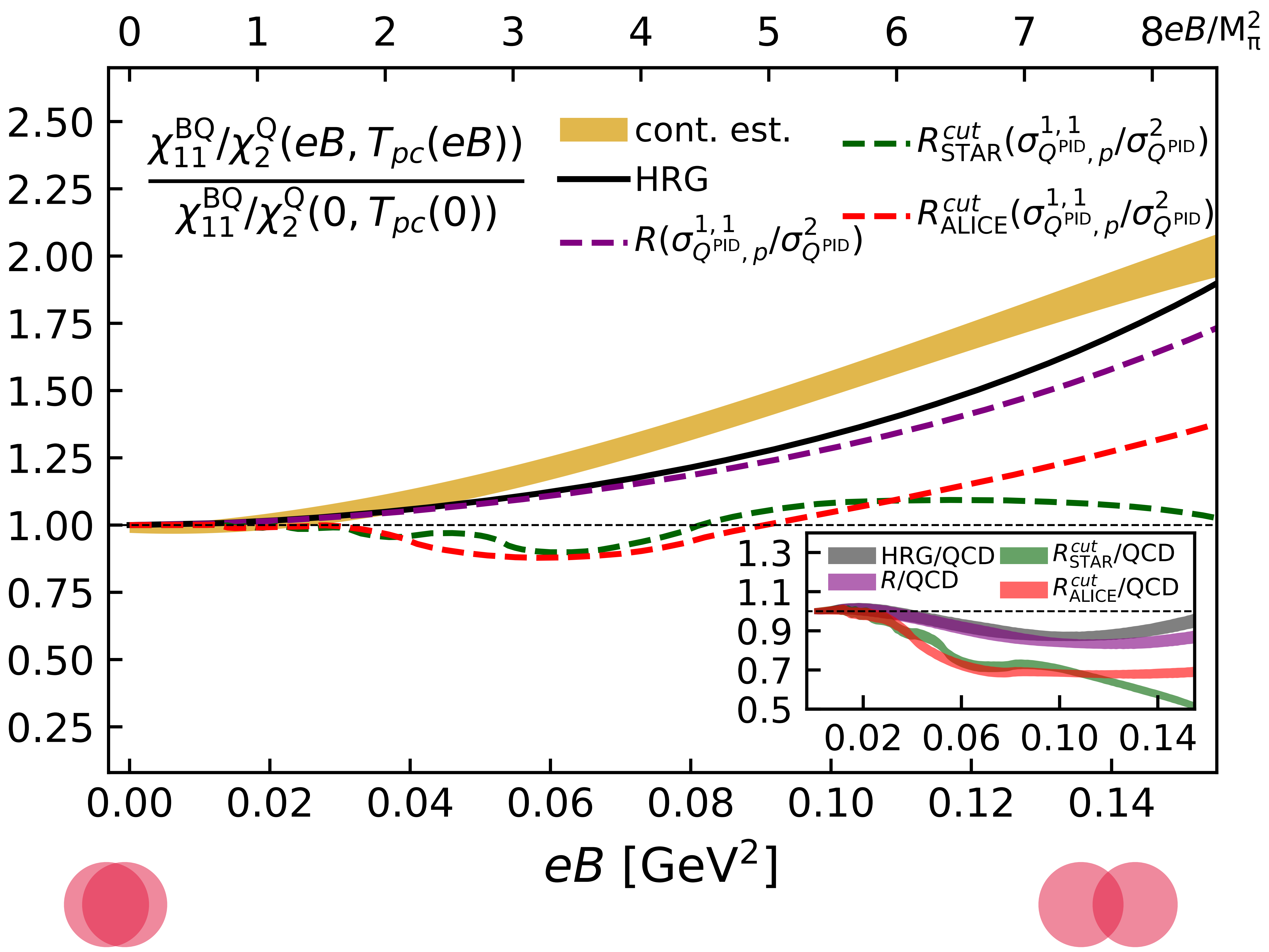
$$R(\mathcal{O}) \equiv \frac{\mathcal{O}(eB, T_{pc}(eB))}{\mathcal{O}(eB=0, T_{pc}(0))}$$

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

ALICE cut: ~25% enhancement

No clear dependence on eB

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

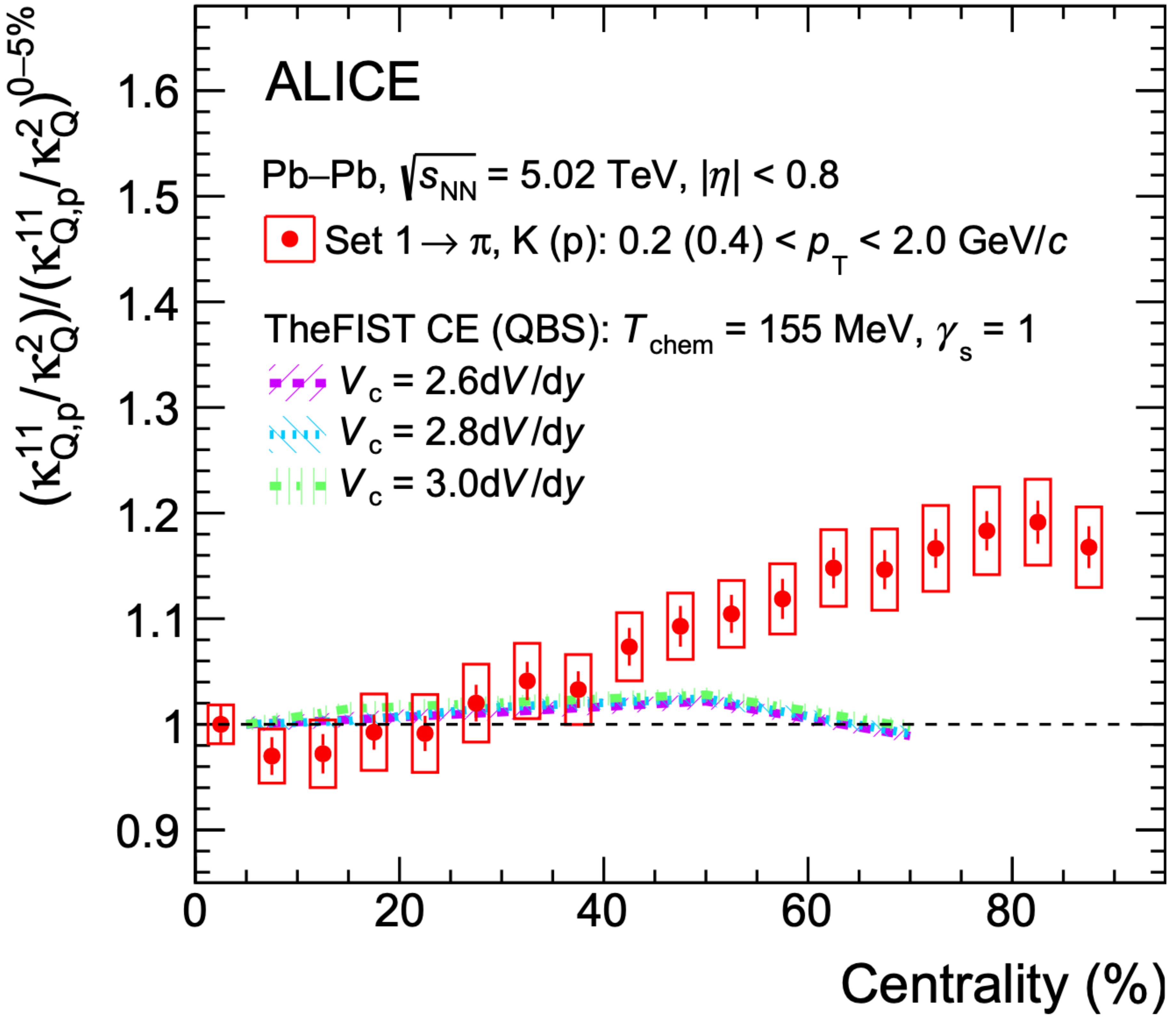


Central Collisions

Peripheral Collisions

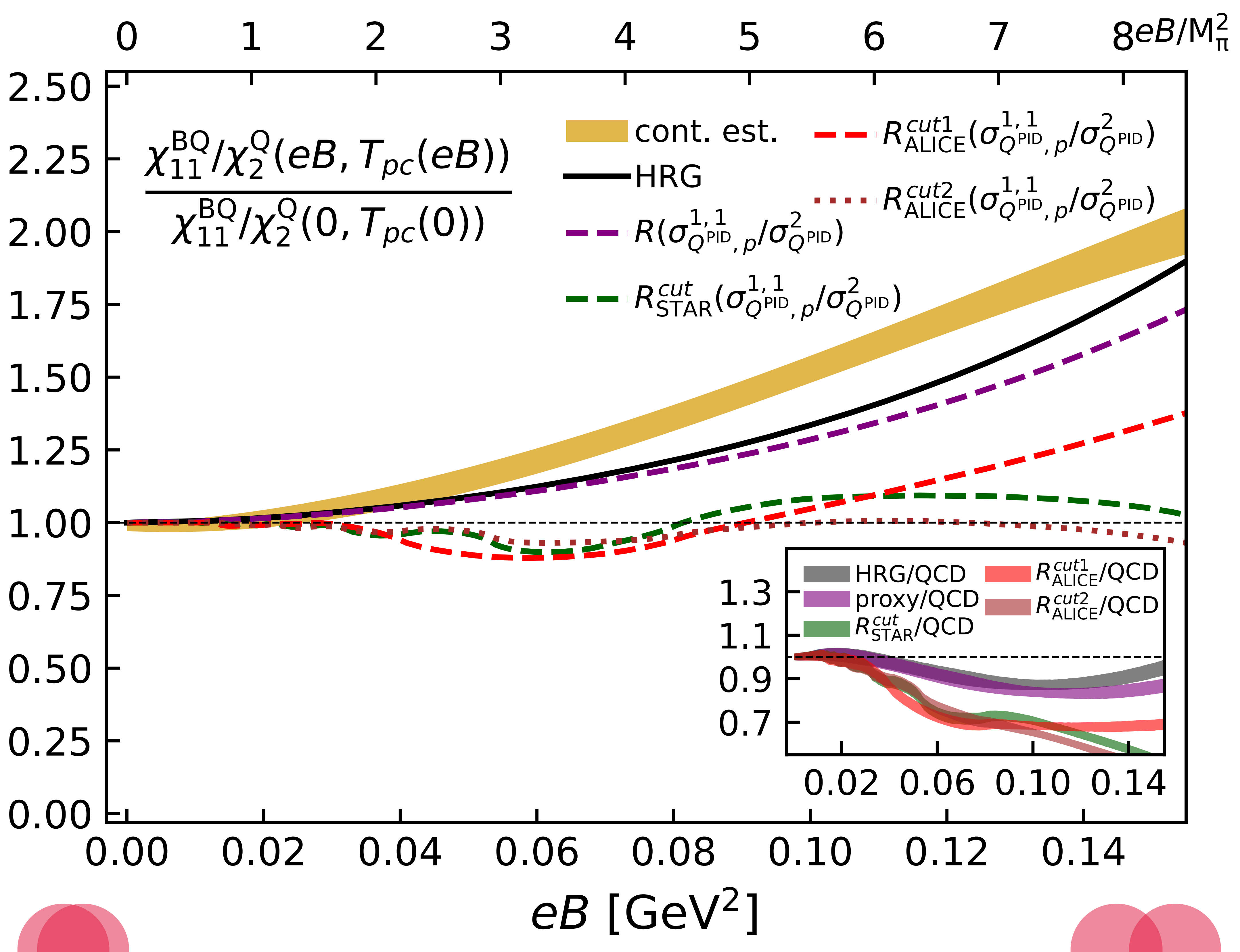
H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)

Proxy for $R(\chi^{BQ}_{11}/\chi^{Q}_{2})$ from ALICE



ALICE collaboration, JHEP 08 (2025) 210

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

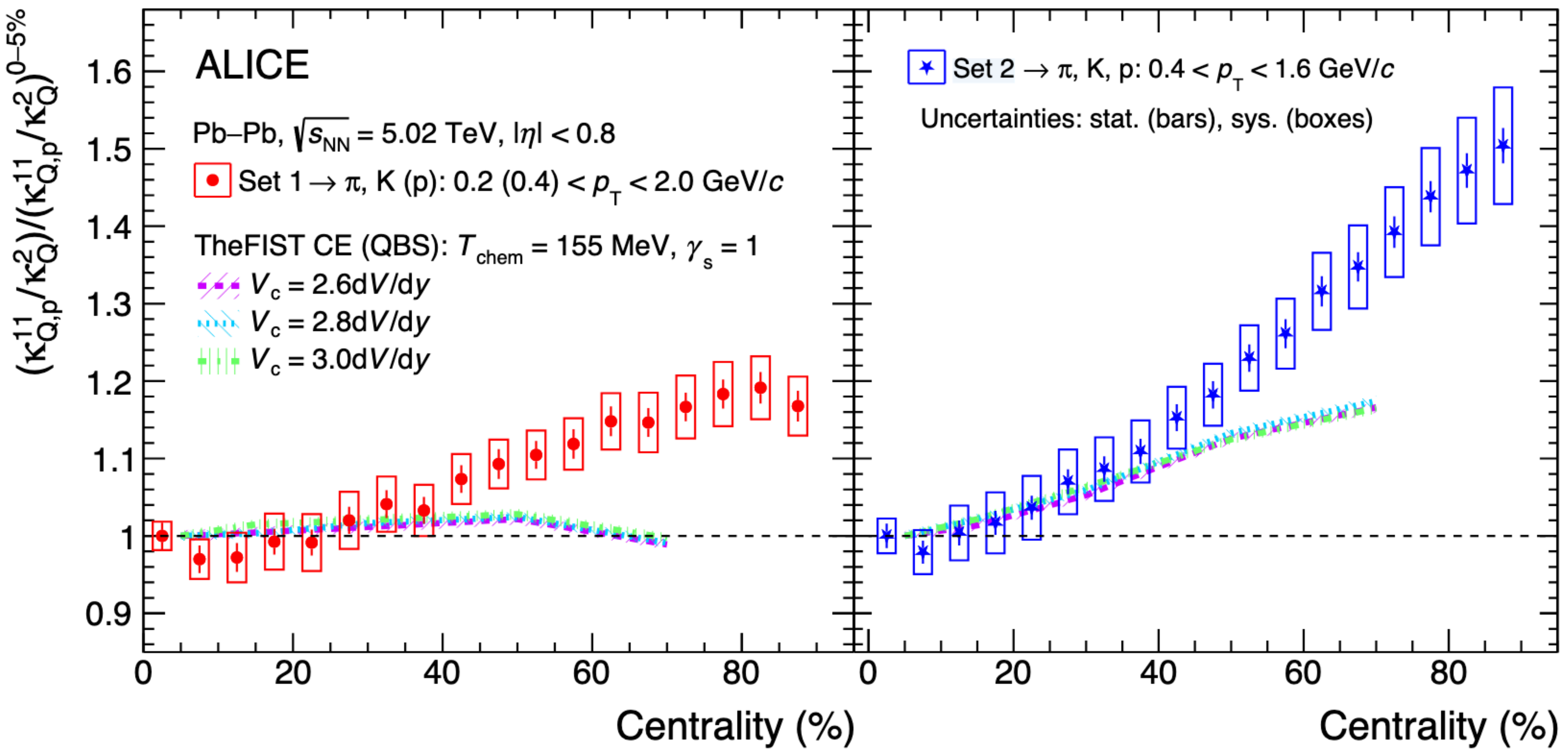


Central Collisions

Peripheral Collisions

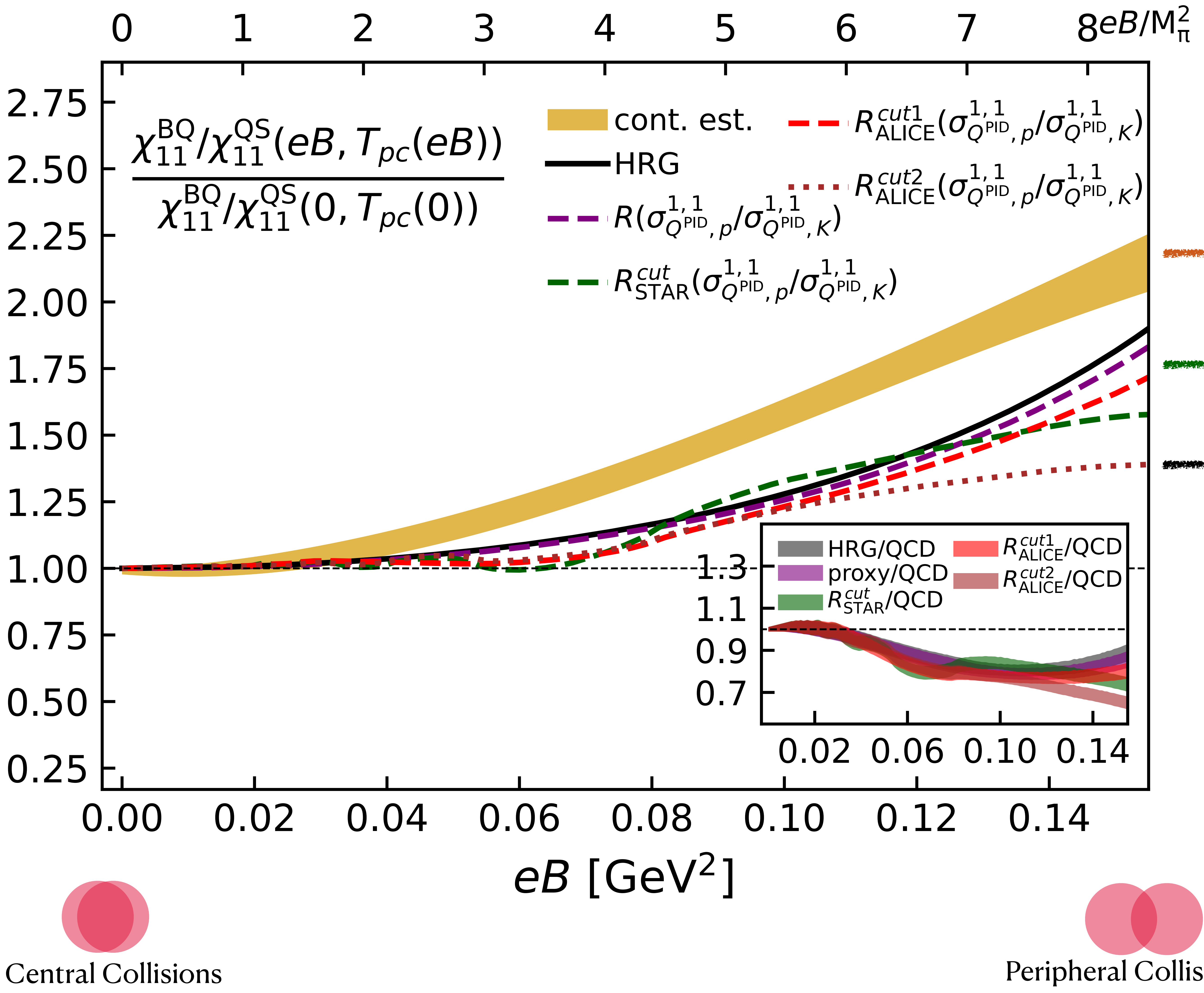
H.-T. Ding, J.-B. Gu, A. Kumar and S.-T. Li, Phys.Rev.D 111, 114522 (2025)

Proxy for $R(\chi^{BQ}_{11}/\chi^{Q}_{2})$ from ALICE



ALICE collaboration, JHEP 08 (2025) 210

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



~ 2.1

$\sim 1.5 - 1.75$

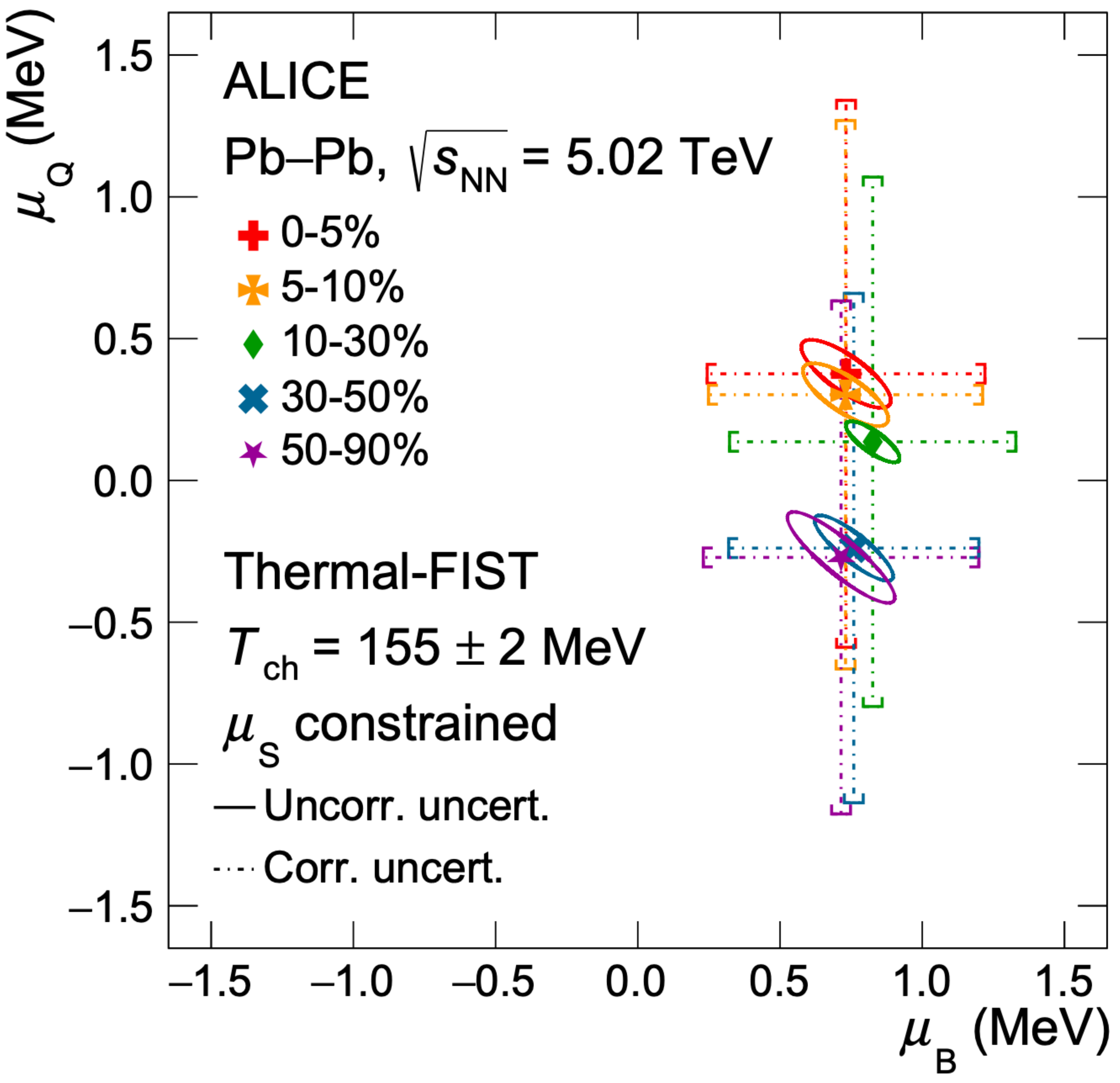
~ 1.3

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

- Weaker dependence on the kinematic cuts
- More effective probe!

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

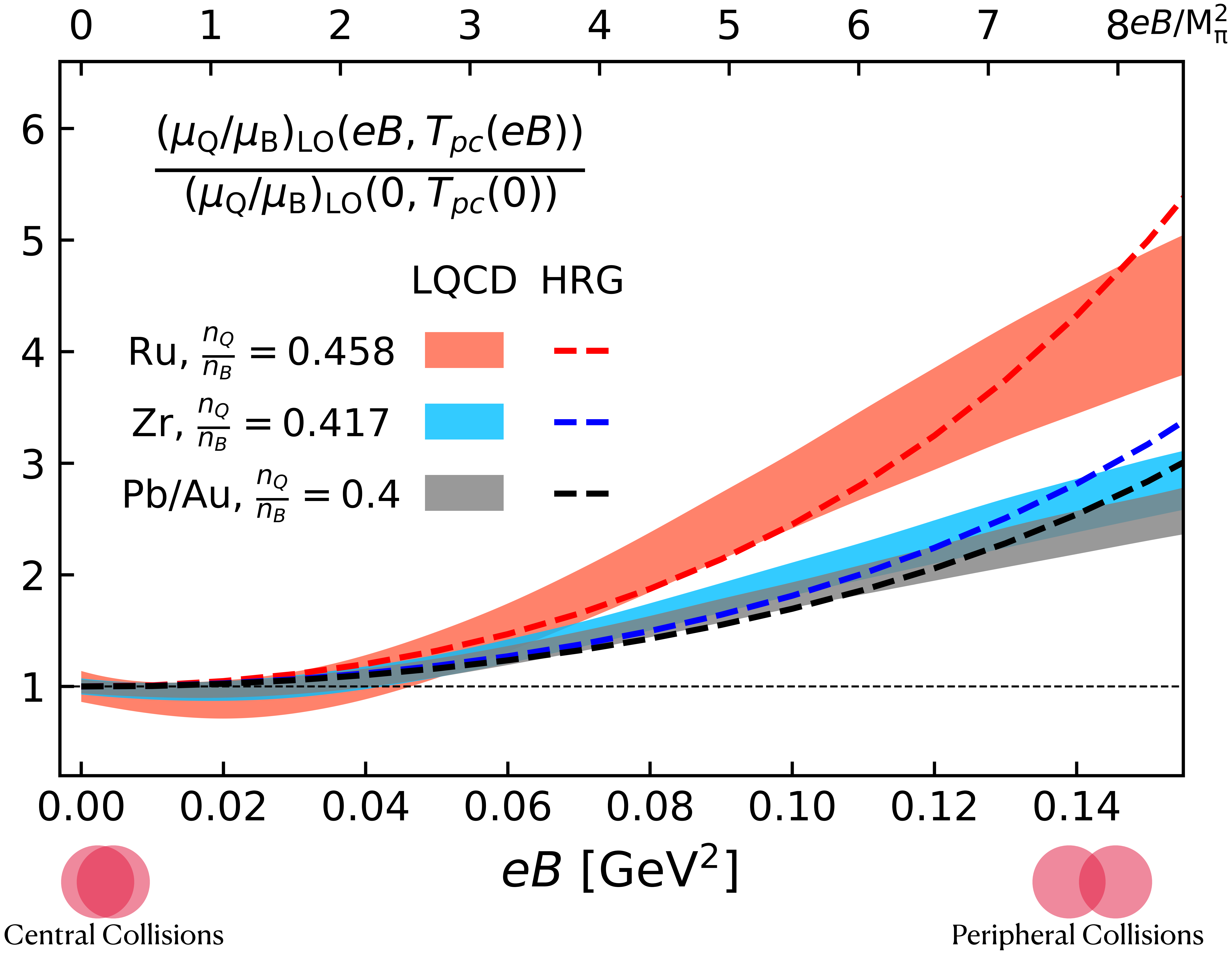
- μ_Q/μ_B also can be obtained from fluctuations of B, Q, S

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

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

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

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



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

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

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

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

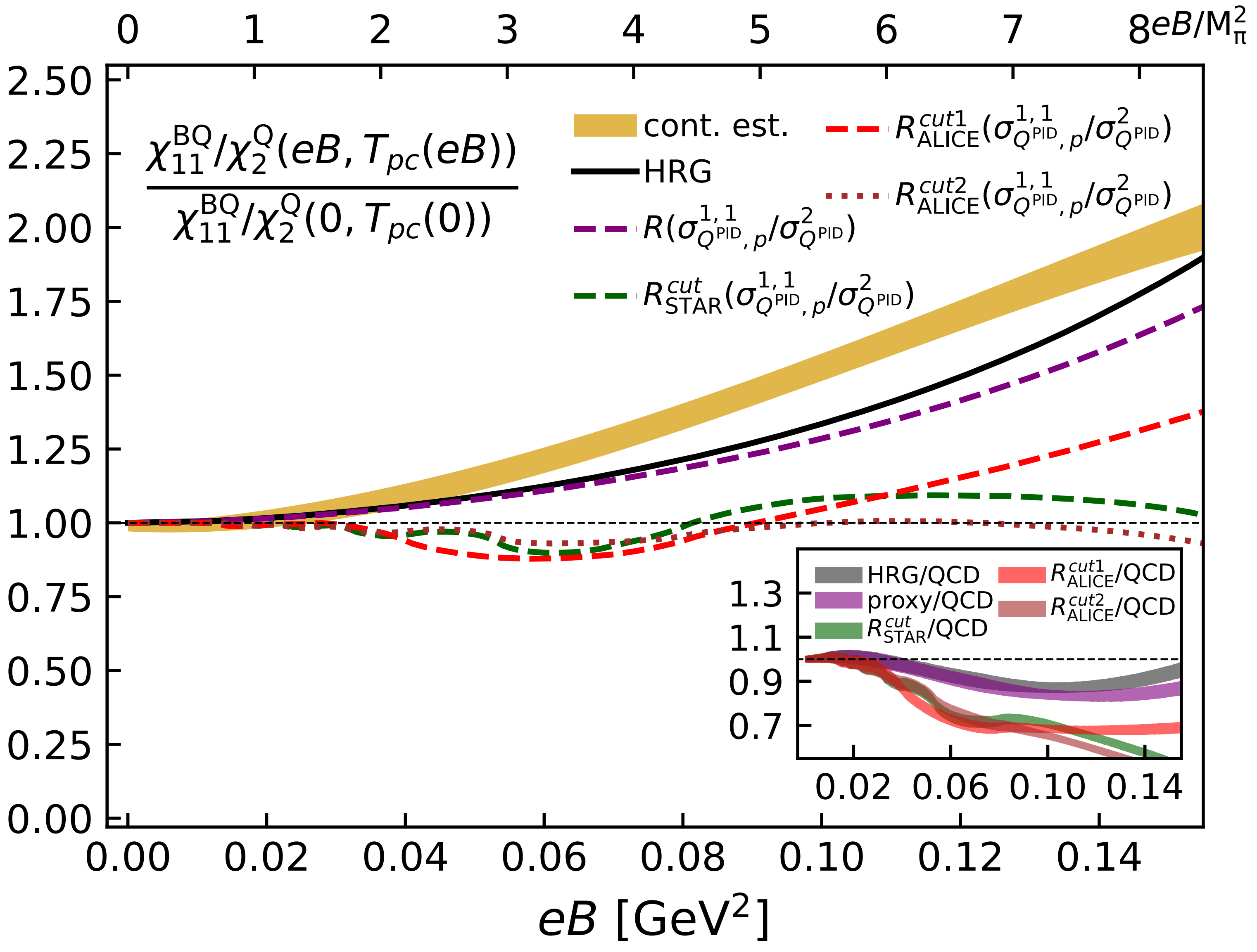
$${}^{208}_{82}\text{Pb} + {}^{208}_{82}\text{Pb} : \text{r} = 0.4$$

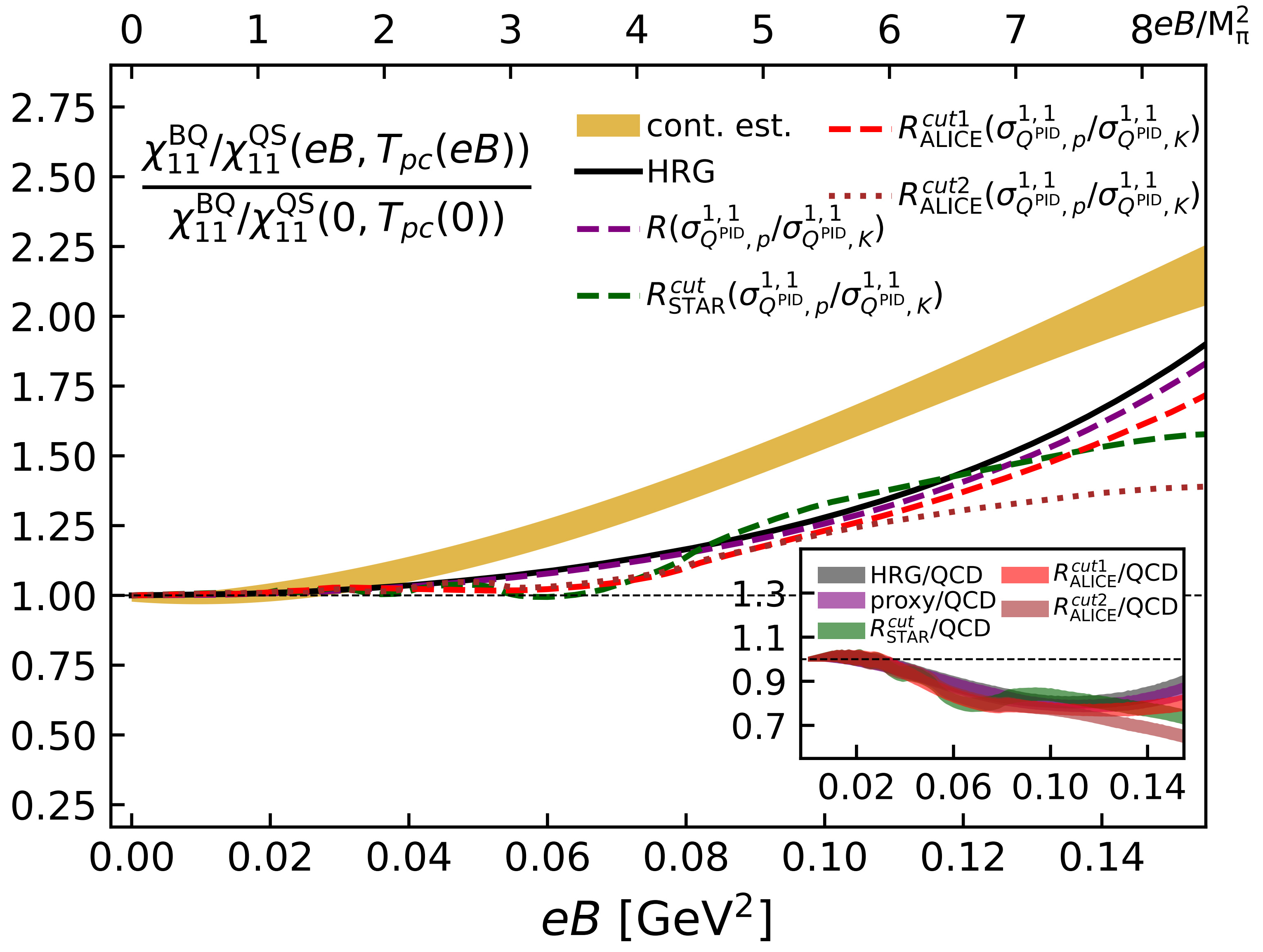
- At $eB \simeq 8M_\pi^2$,

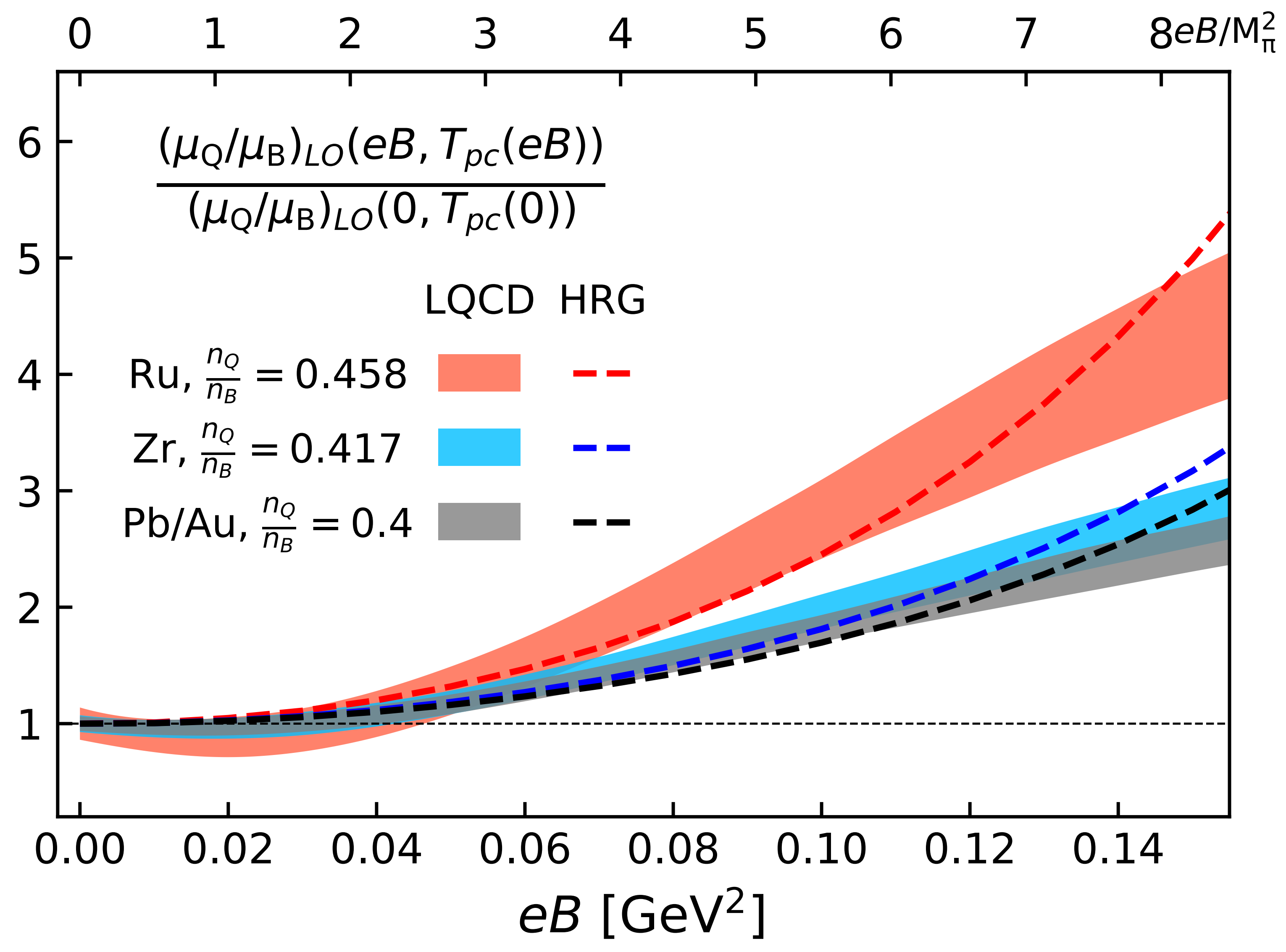
  Ratio of $(\mu_Q/\mu_B)_{LO}$ for Pb, Au, Zr ~2.4

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

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







Thank you!

Backup

Lattice QCD in strong magnetic fields

B pointing along the z direction

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

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

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

No sign problem !

Quantization of the magnetic field

$$q_u = 2/3\ e$$
$$q_d = -1/3\ e$$
$$q_s = -1/3\ e$$

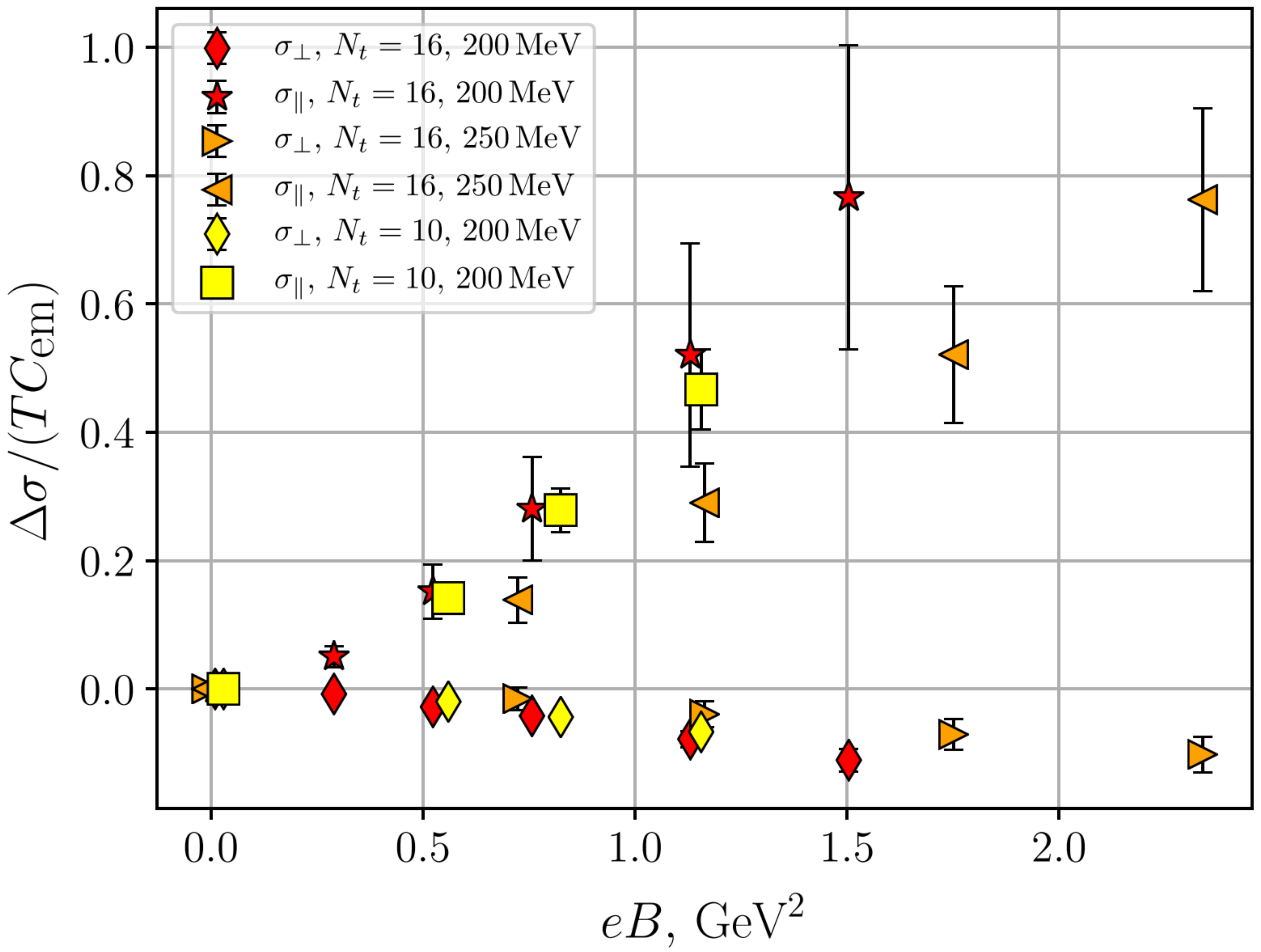
$$\longrightarrow \quad eB = \frac{6\pi N_b}{N_xN_y}a^{-2}$$

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

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

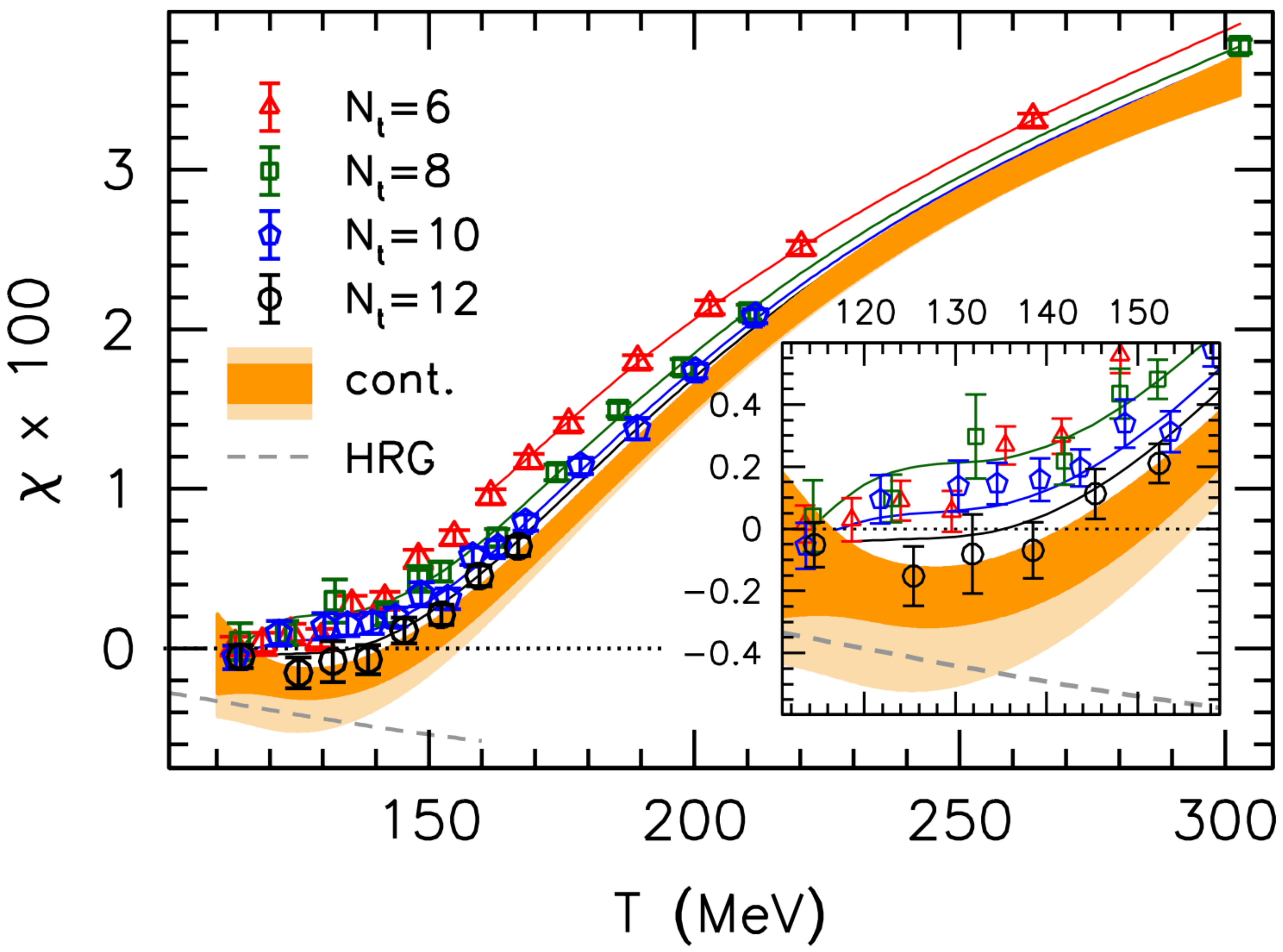
Landau gauge
G.S. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S.D. Katz, S. Krieg et al., JHEP 02 (2012) 044.

Electromagnetic conductivities at non-zero magnetic fields



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

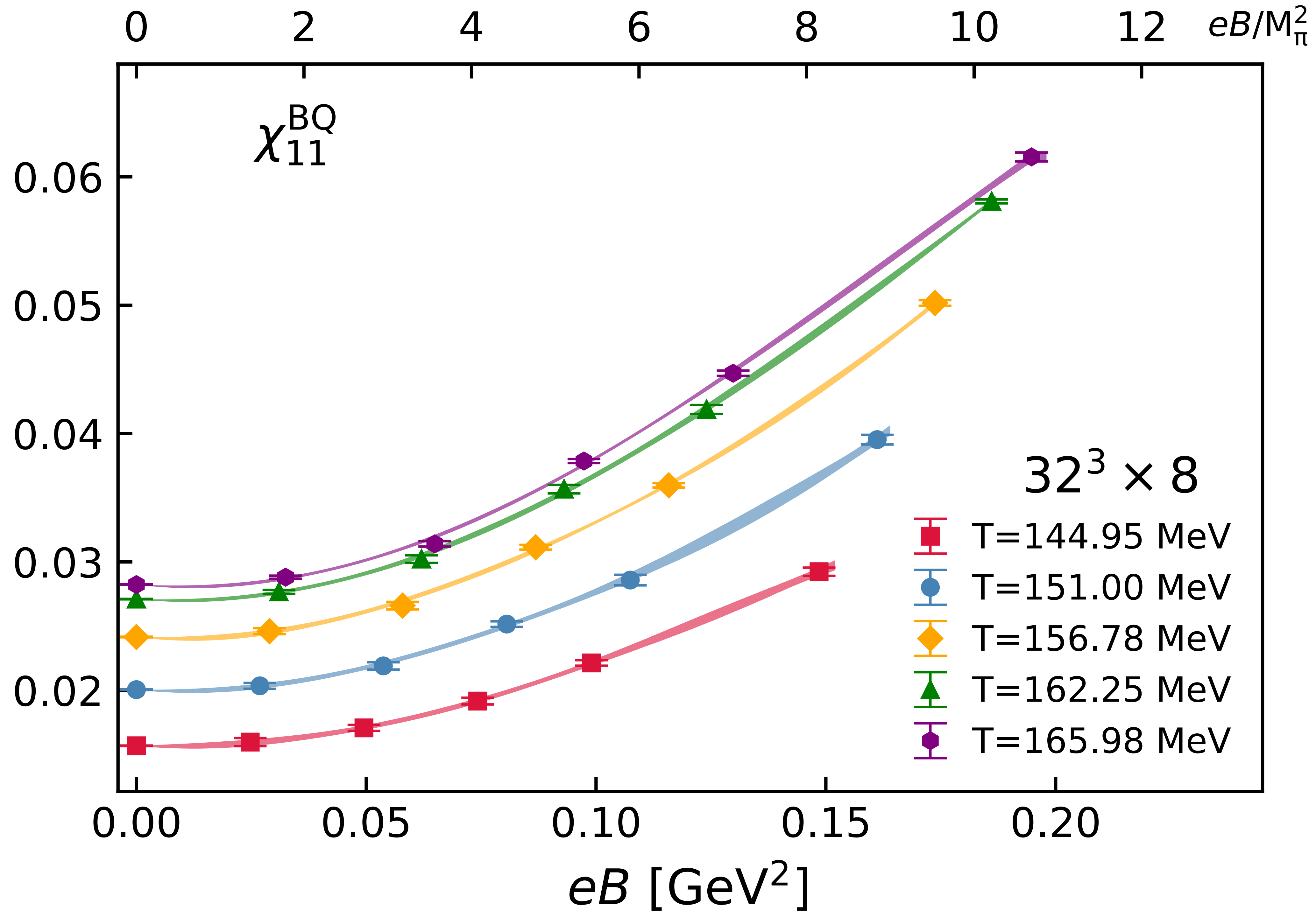
Magnetic susceptibility at non-zero magnetic fields

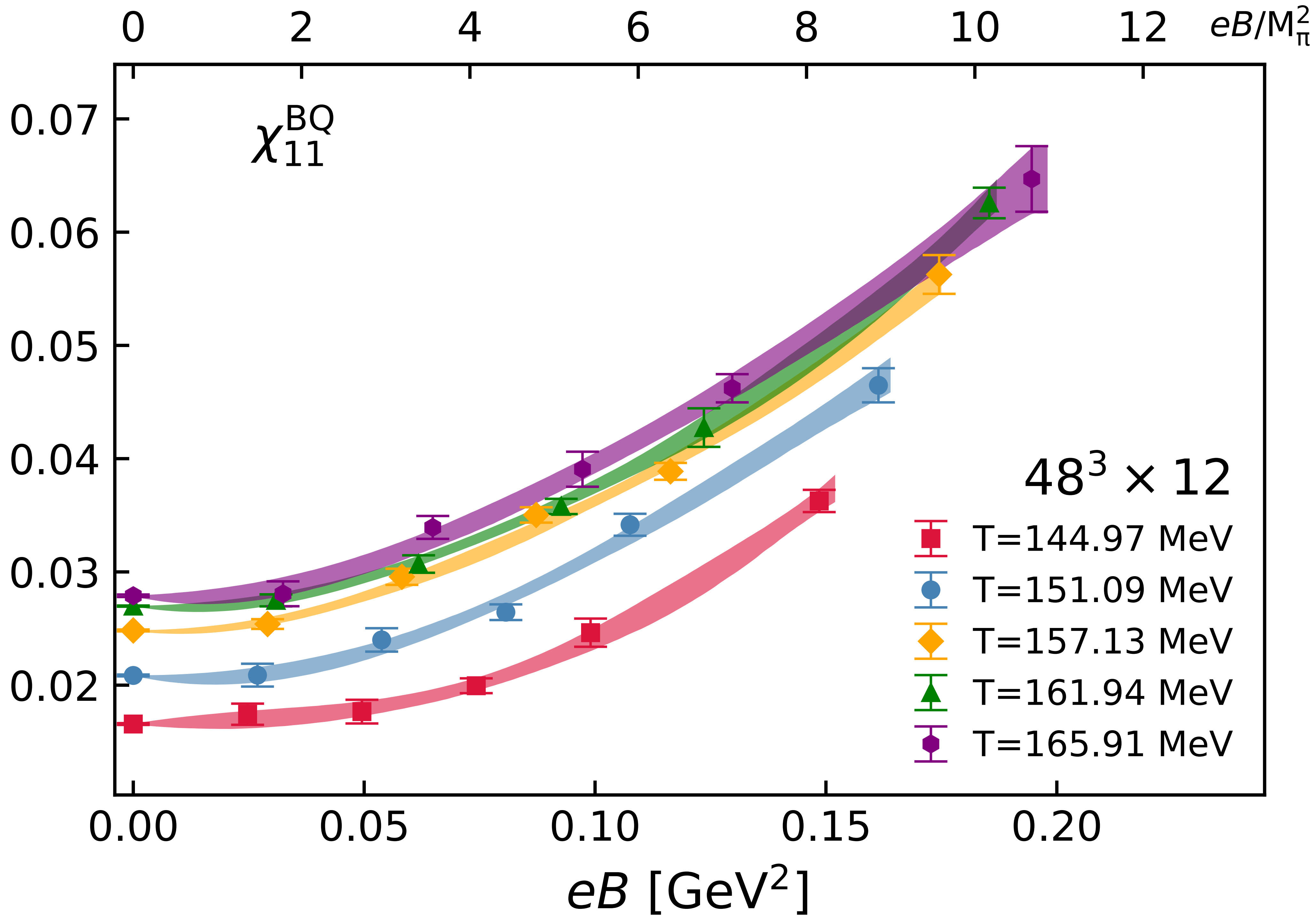


G. Bali et al., JHEP 07 (2020) 183

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

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

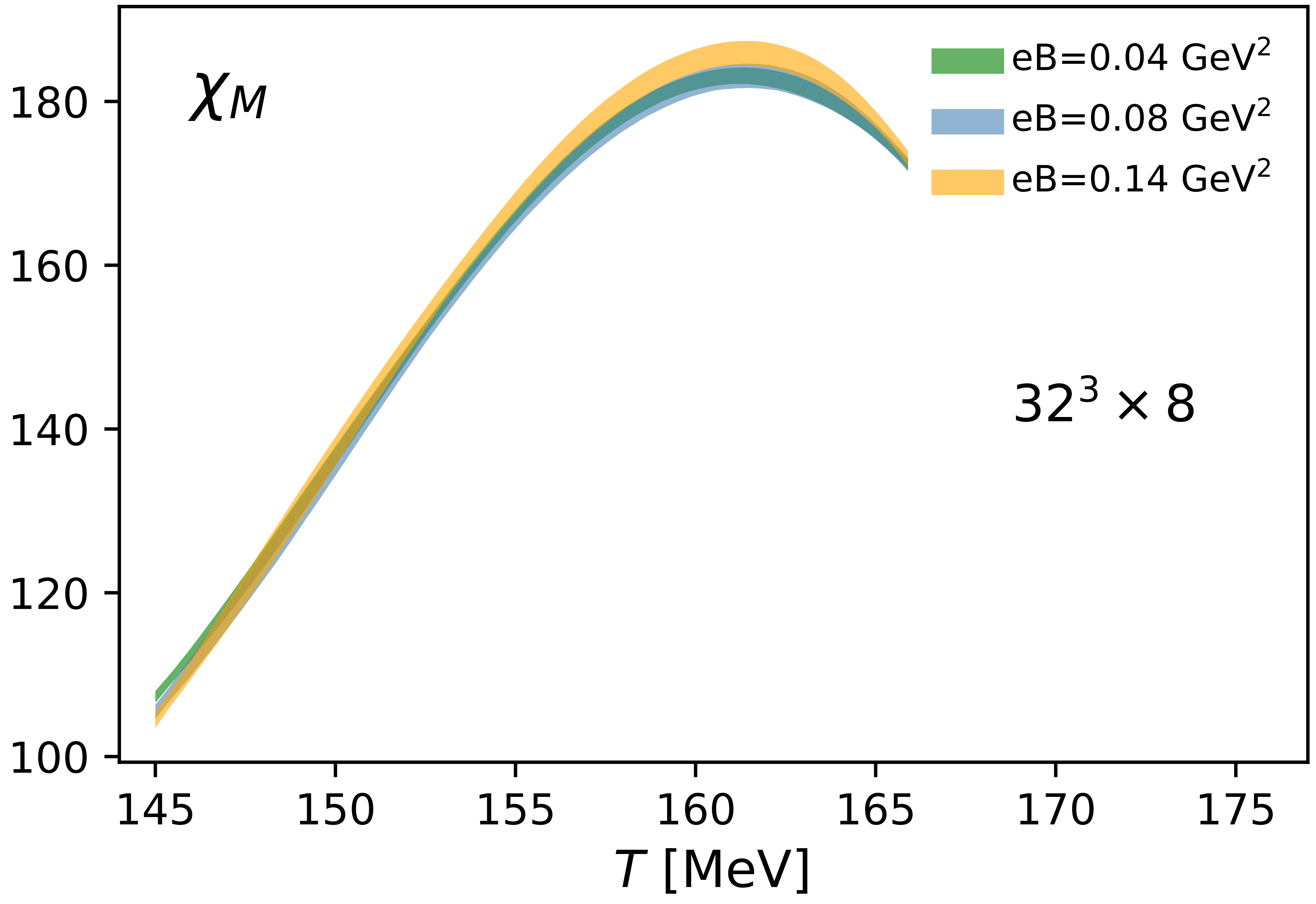




H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li, Phys. Rev. Lett. 132, 201903 (2024)

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

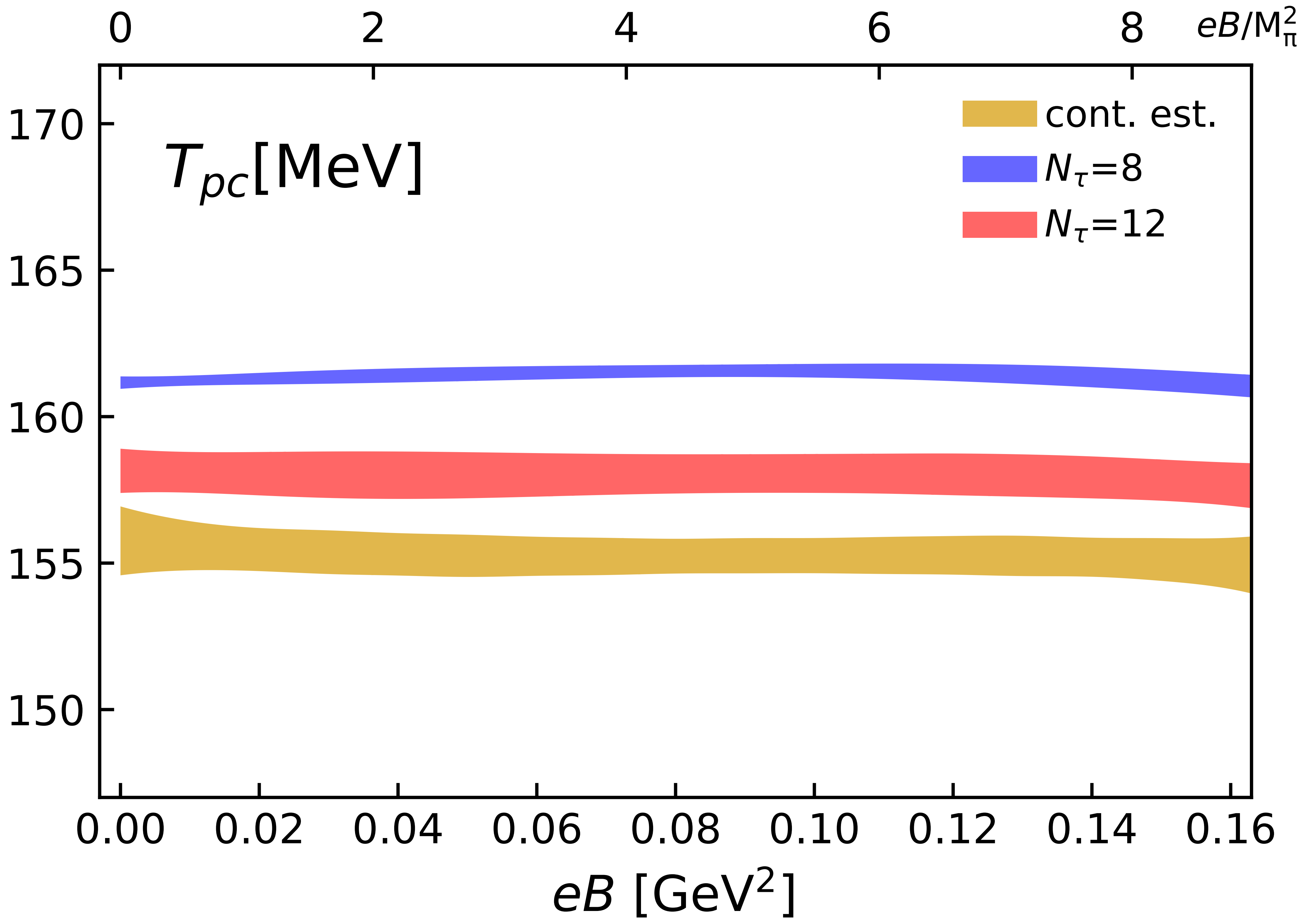
QCD transition temperature in nonzero magnetic field



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

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

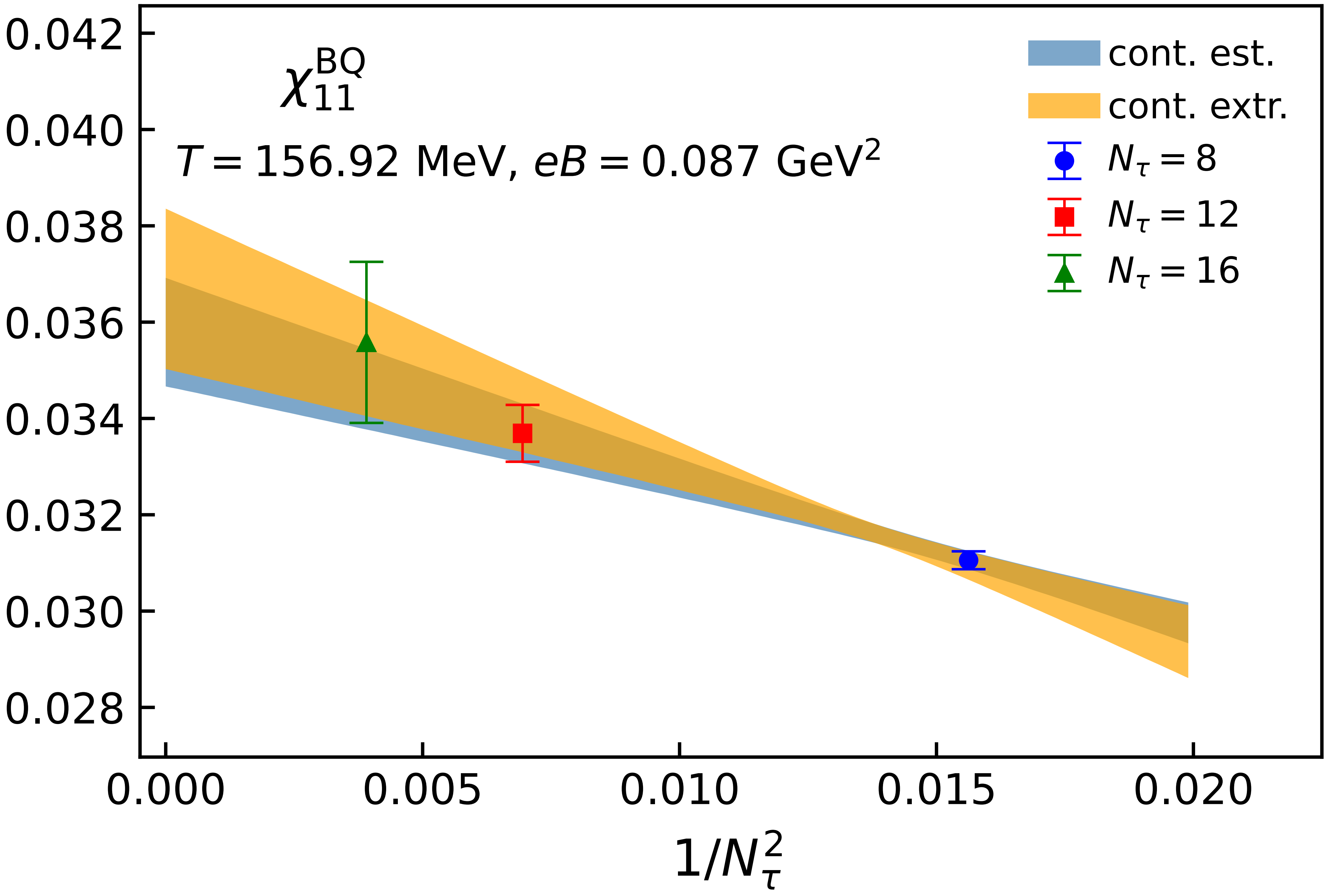
H.-T. Ding et al., Phys. Rev. Lett. 123, 062002 (2019)

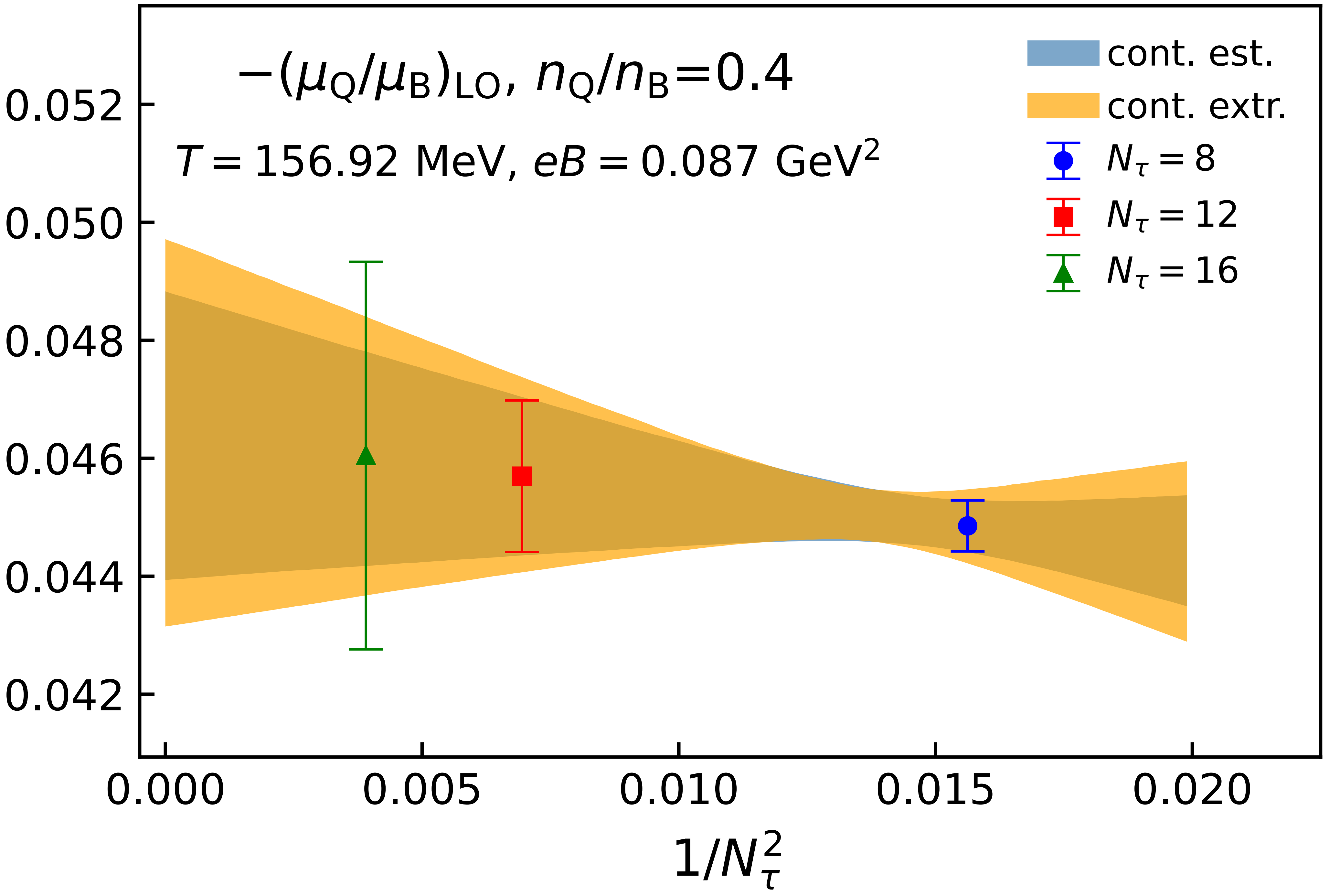


T_{pc} almost independent of eB at $eB \lesssim 0.16$ GeV^2

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

Continuum estimate and extrapolation





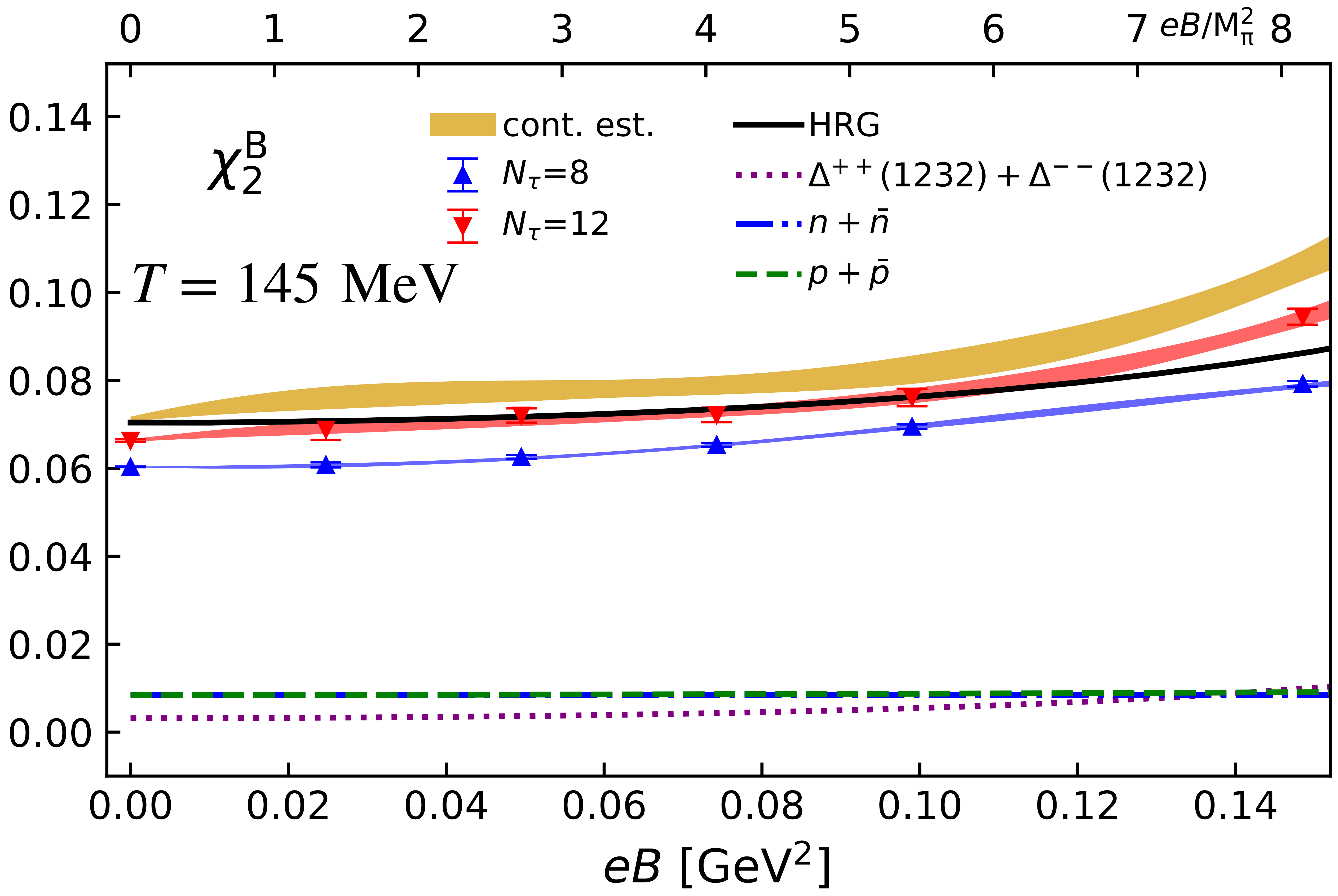
H.-T. Ding, J.-B. Gu, A. Kumar, S.-T. Li and J.-H. Liu, Phys. Rev. Lett. 132, 201903 (2024)

$$\mathcal{O}\left(T, eB, N_\tau\right) = \mathcal{O}(T, eB) + \frac{c}{N_\tau^2}$$

$\begin{cases} \text{Continuum estimate} \\ \text{Continuum extrapolation} \end{cases}$ obtained from $\begin{matrix} N_\tau = 8 \text{ and } 12 \\ N_\tau = 8,\ 12, \text{ and } 16 \end{matrix}$

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

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

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

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

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

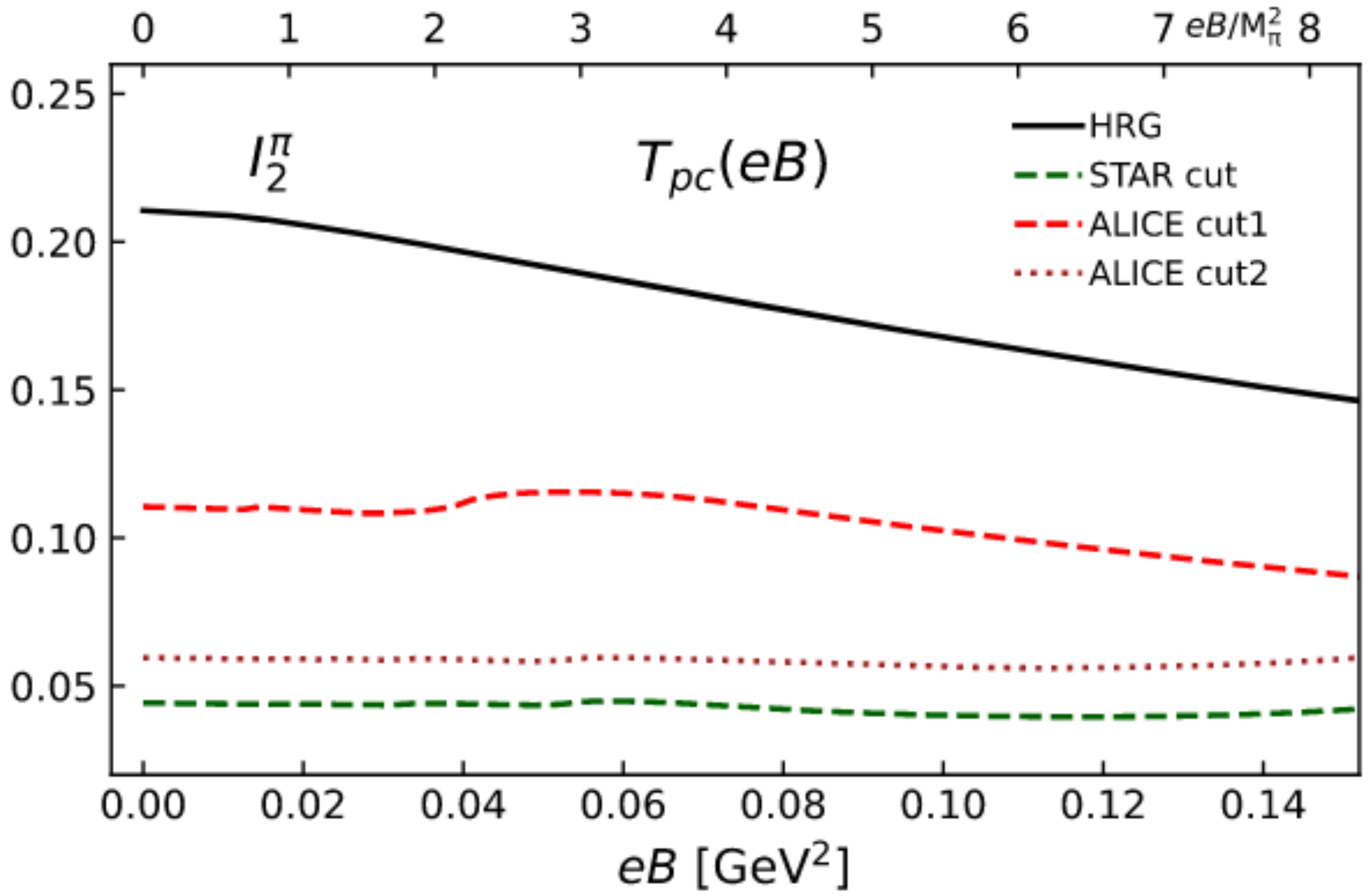
where $P_{R\to i} = \sum_\alpha \mathrm{N}_{R\to i}^\alpha n_{i,\alpha}^R$

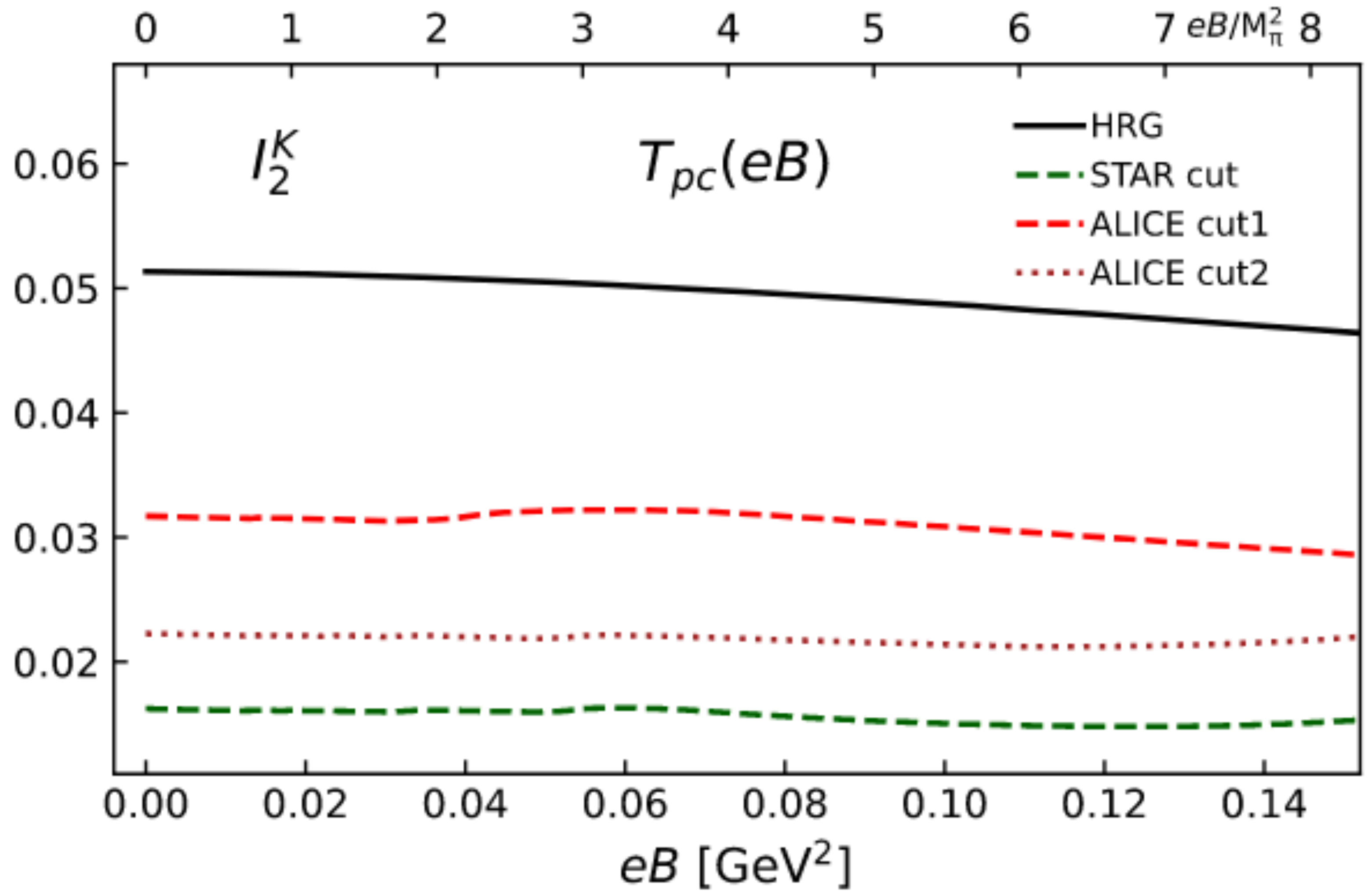
$n_{i,\alpha}^R$: numbers of i produced by R in decay channel α

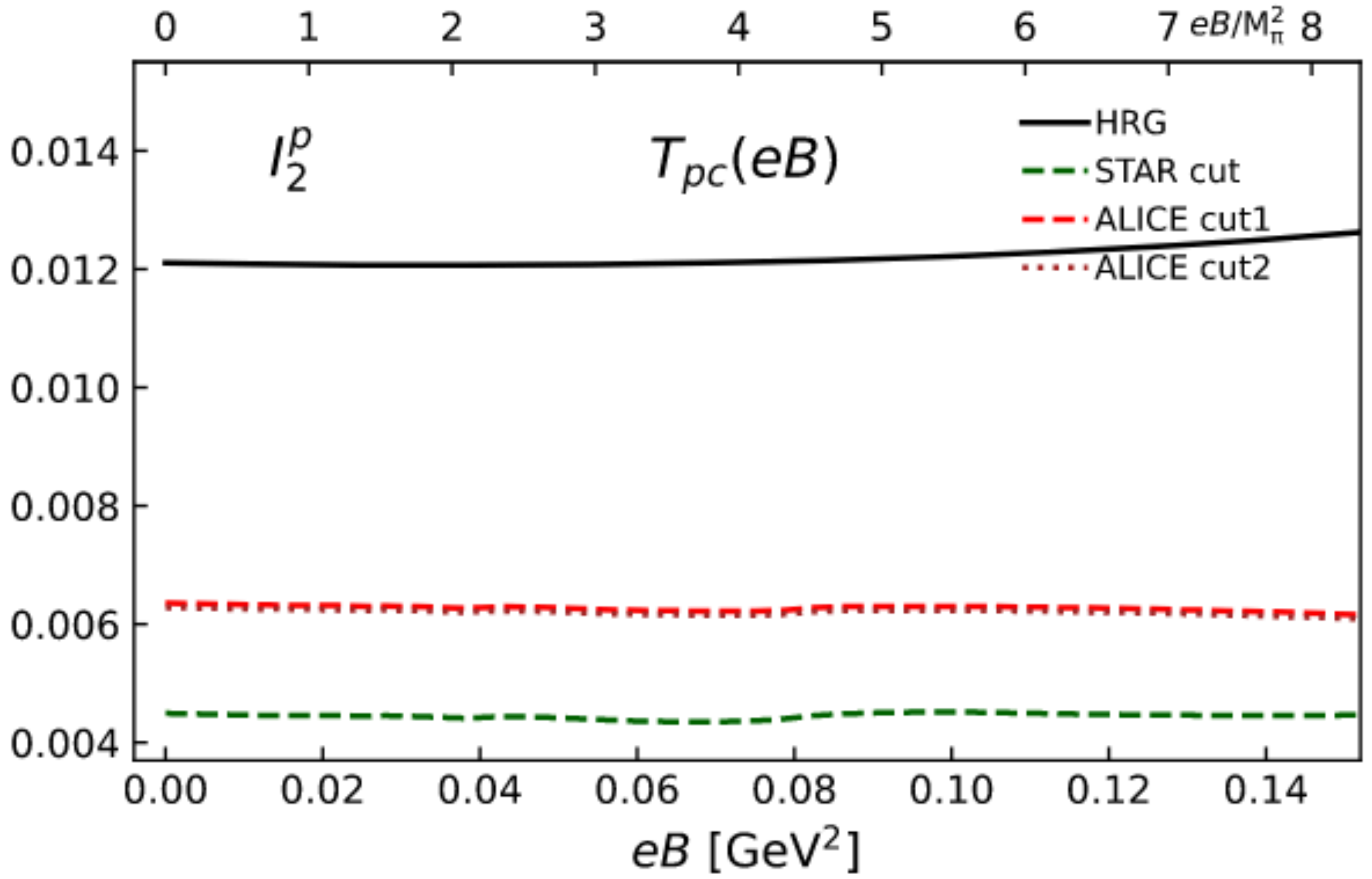
$\mathrm{N}_{R\to i}^\alpha$: Branching ratio of channel α

Phase space integral for π, K and p

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







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

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

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

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

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

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

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

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