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Mesonic excitations of magnetized and hot quark matter within effective models of QCD

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FAPERGS

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Outline

- Motivation
- Thermo-magnetic effects on the coupling constants in NJL model - IMC
- The importance of implementing a proper regularization procedure in order to treat thermo and magnetic contributions within non renormalizable theories
- Neutral meson pole mass in a magnetized and thermal medium within the SU(2) NJL model
- Neutral meson pole mass in a magnetized medium within the Linear Sigma model with quarks
- Conclusions and perspectives

Strong magnetic fields may be produced in off-central heavy ion collisions

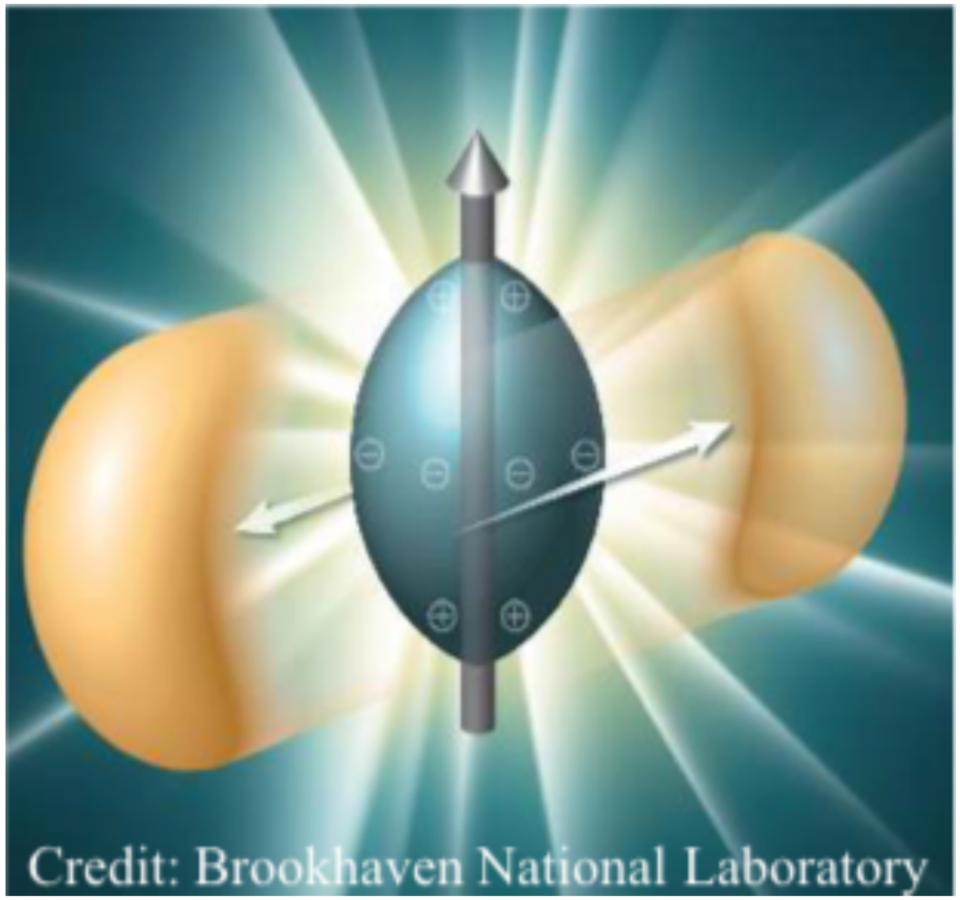
K. Fukushima, D. E. Kharzeev, and H. J. Warringa, Phys. Rev. D 78, 074033 (2008). D. E. Kharzeev and H. J. Warringa, Phys. Rev. D 80, 0304028 (2009). D. E. Kharzeev, Nucl. Phys. A 830, 543c (2009).

heavy-ion collisions:

temporarily $B \lesssim 10^{19}\,\mathrm{G}$

Skokov, Illarionov, Toneev, Int. J. Mod. Phys. A 24, 5925 (2009)

- Chiral magnetic effect
- Effects in EoS
- Anisotropies



Neutron Stars

- Strong magnetic fields are also present in magnetars: C. Kouveliotou et al., Nature 393, 235 (1998).

magnetars:

at surface $B \lesssim 10^{15}\,\mathrm{G}$

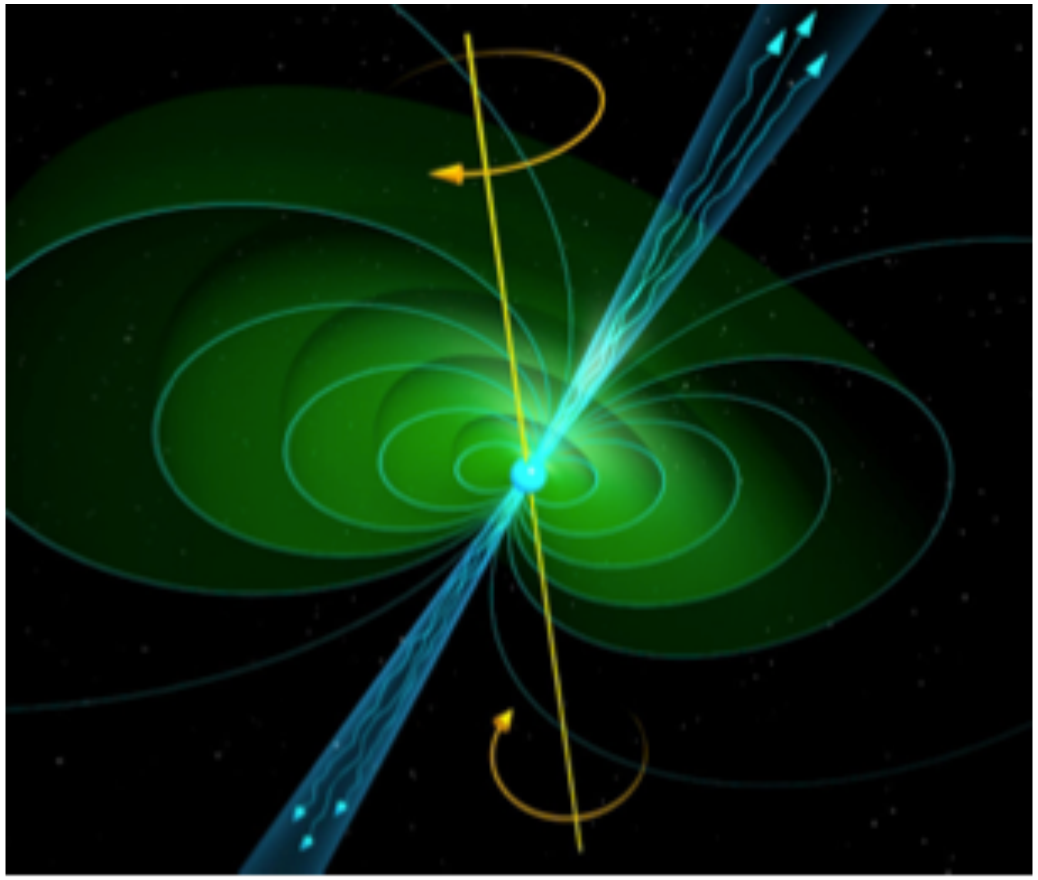
Duncan, Thompson, Astrophys.J. 392, L9 (1992)

larger in the interior,

$B \sim 10^{18-20}\,\mathrm{G}$?

Lai, Shapiro, Astrophys.J. 383, 745 (1991)

E. J. Ferrer *et al.*, PRC 82, 065802 (2010)

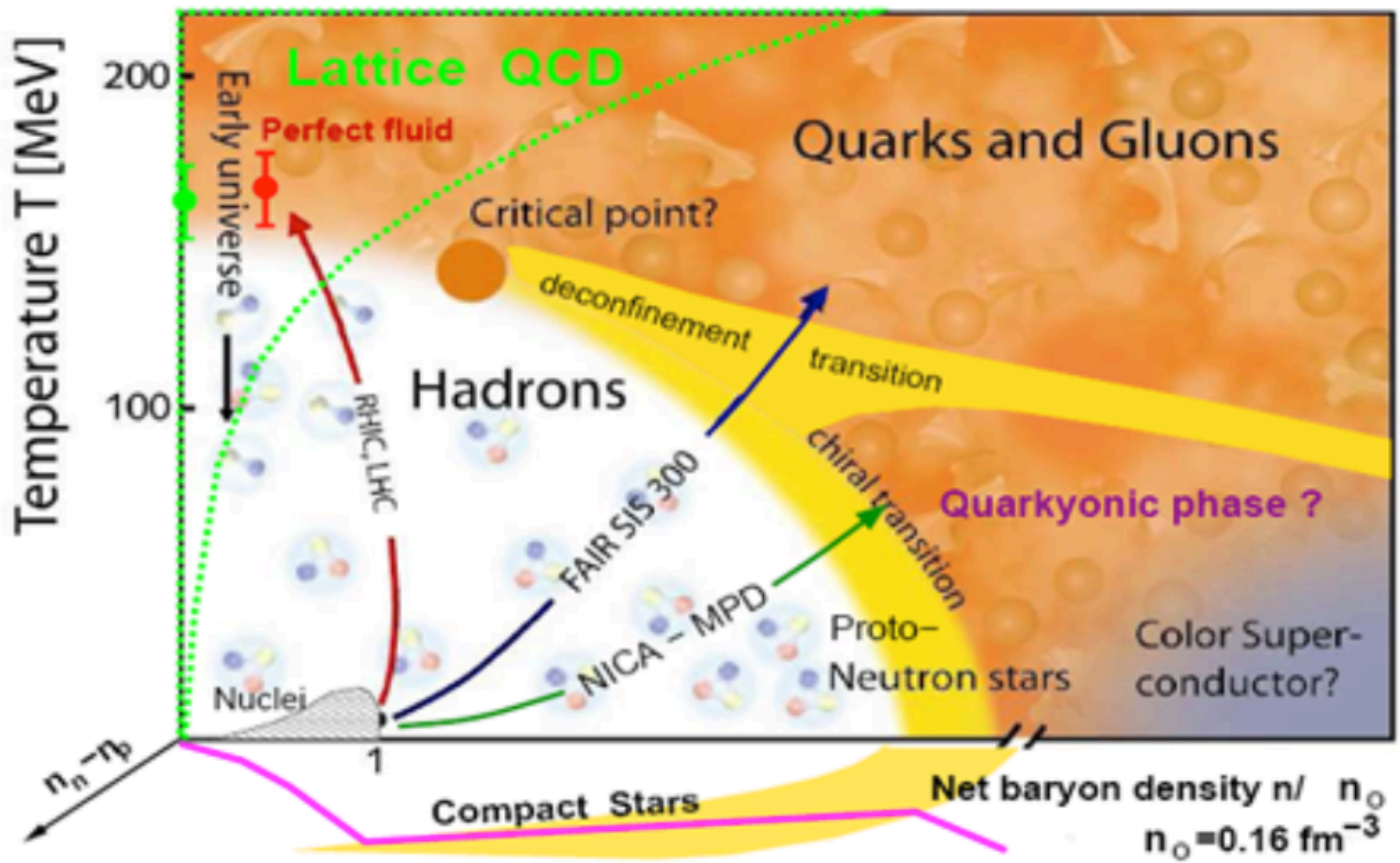


A. K. Harding, D. Lai, Rept. Prog. Phys. 69, 2631 (2006)

- and might have played an important role in the physics of the early universe. T. Vaschapati, Phys. Lett. B 265, 258 (1991).

D. Grasso and H.R. Rubinstein, Phys. Rep. 348, 163 (2001).

B effects in QCD Phase Diagram



NICA - Nuclotron-based
Ion Collider fAcility

FAIR - Facility for Antiproton and
Ion Research

Lattice Results: Sign Problem

- fermion determinant is complex

$$[\det\, M(\mu)]^* = \det\, M(-\mu^*) \in \mathbb{C}$$

- no positive weight in path integral

$$Z = \int \mathcal{D}U\, e^{-S_{YM}}\, \det\, M(\mu)$$

- standard lattice methods base on importance sampling cannot be used!

To make progress

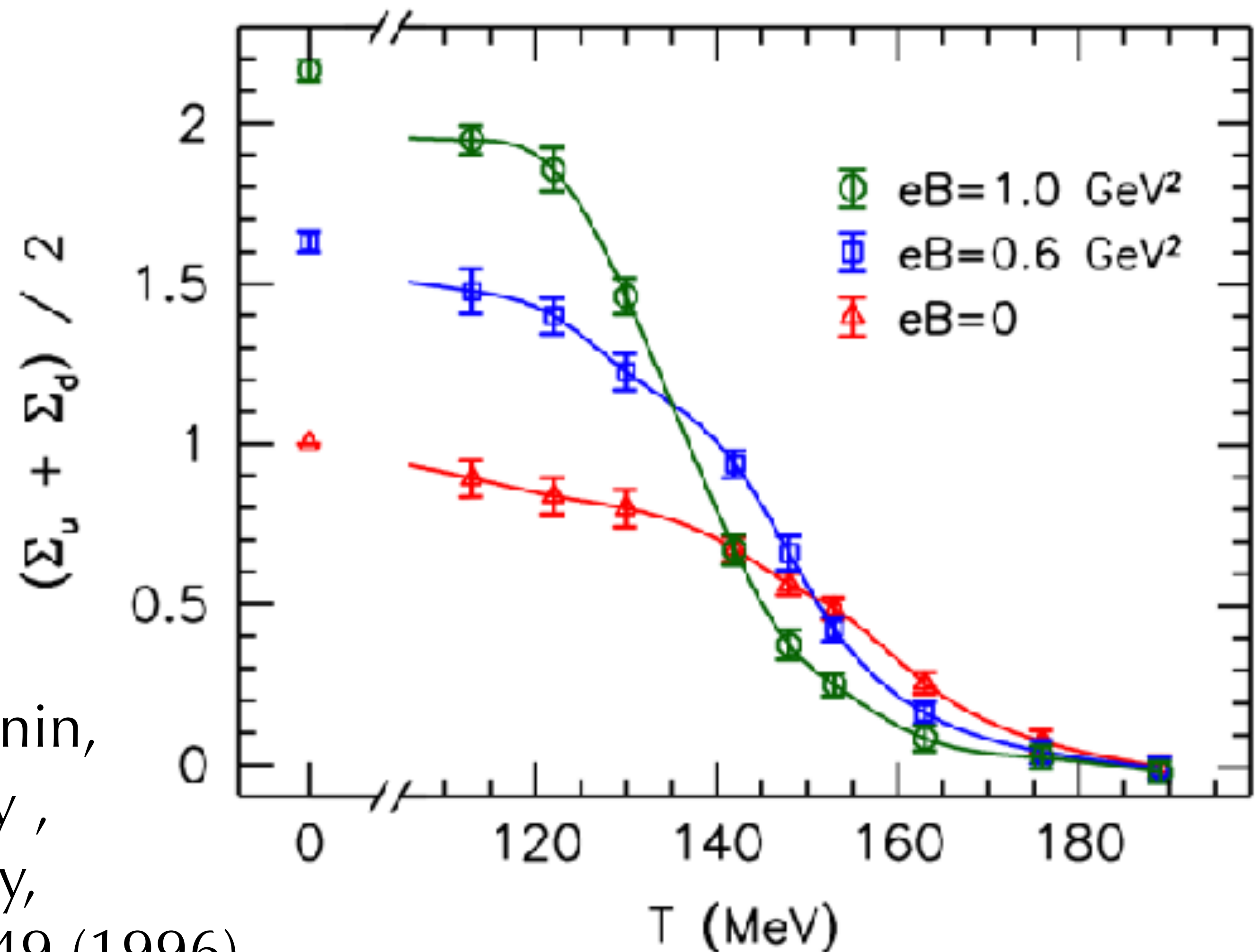
- We use Quantum Field Theory (in medium)
- DSE (beyond RL truncation…)
- Holographic models
- EOS + susceptibilities calculated on the lattice + Taylor series (limitations…)
- Effective models (just a few degrees of freedom): NJL/PNJL, Linear σ model, MIT,…

QCD at finite T and B :
NO
Sign Problem!

There is hope that lattice simulations of QCD with B can be used as a benchmark platform for comparing different effective models used in the literature.

B Effects on QCD phase transitions?

$$\Lambda_{QCD}^2 \sim (200\,\mathrm{MeV})^2 \sim 2 \times 10^{18}\,\mathrm{G}$$

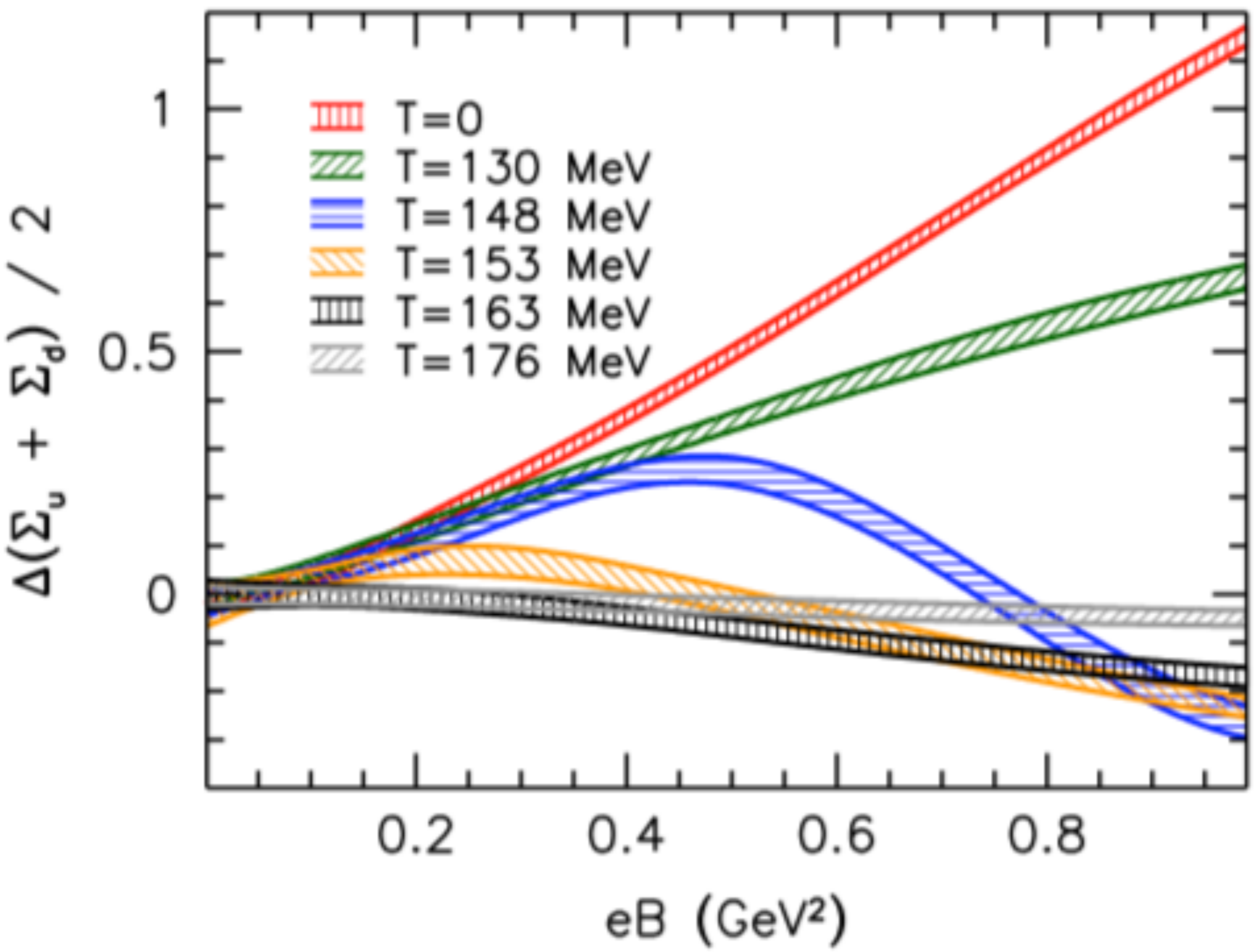


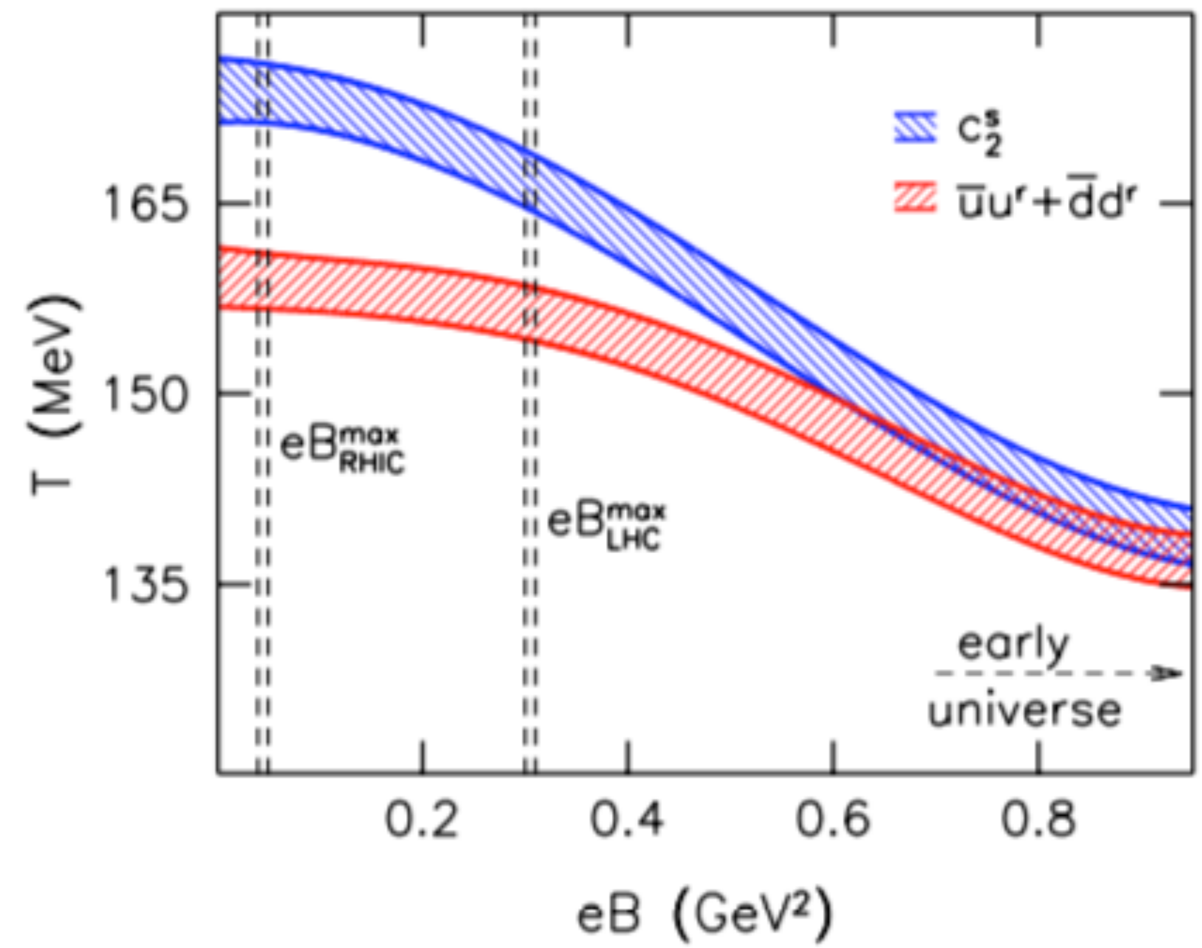
IMC: Bali, Bruckmann, Endrodi, Fodor, Katz et al. *JHEP* 02 (2012) 044 *Phys.Rev.D* 86 (2012) 071502

MC: V.P. Gusynin, V.A. Miransky , I.A. Shovkovy, *Nucl. Phys. B* **462** 249 (1996)

B Effects on QCD phase transitions?

MC and IMC



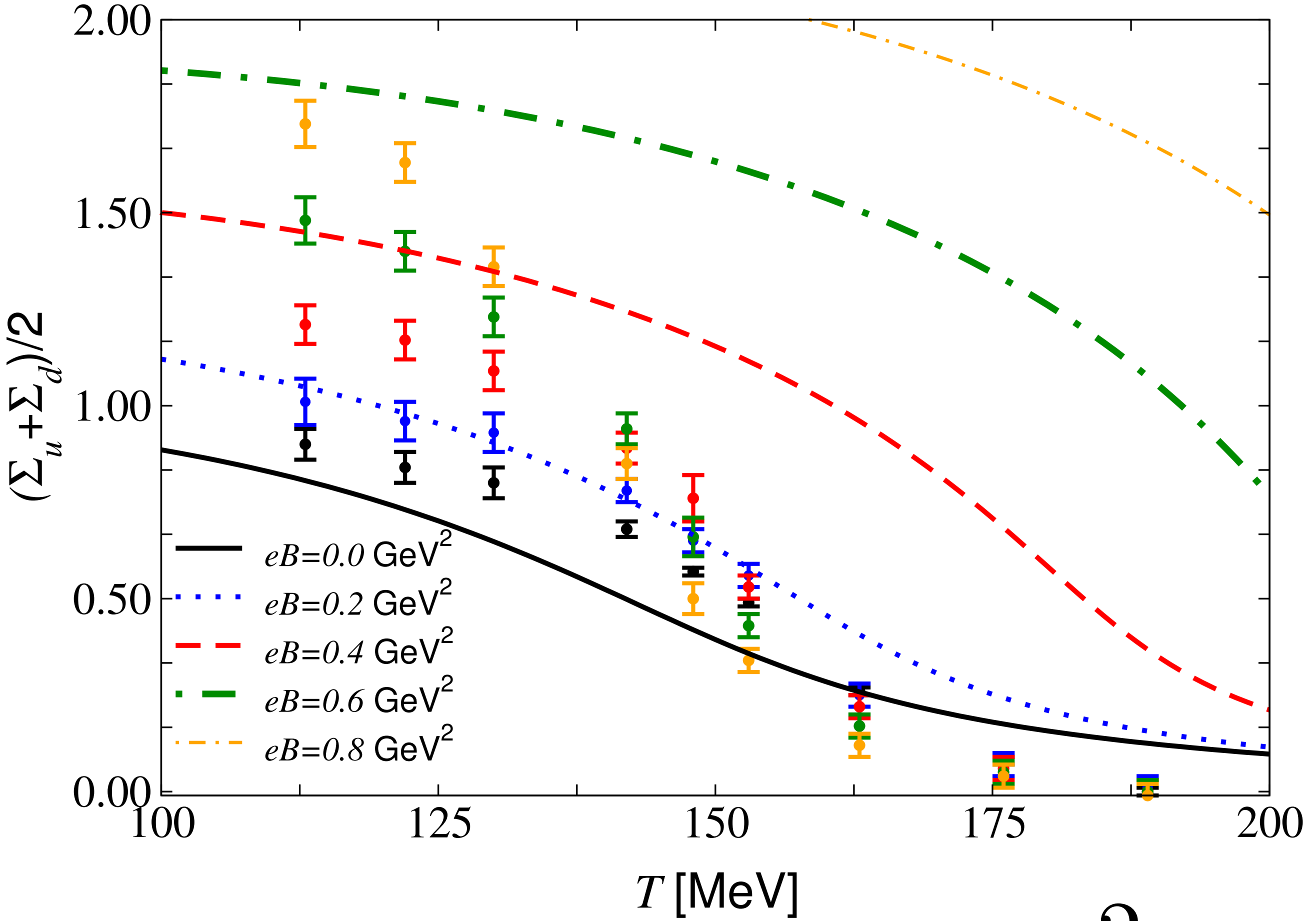


Failure of ALL effective models in providing inverse magnetic catalysis!

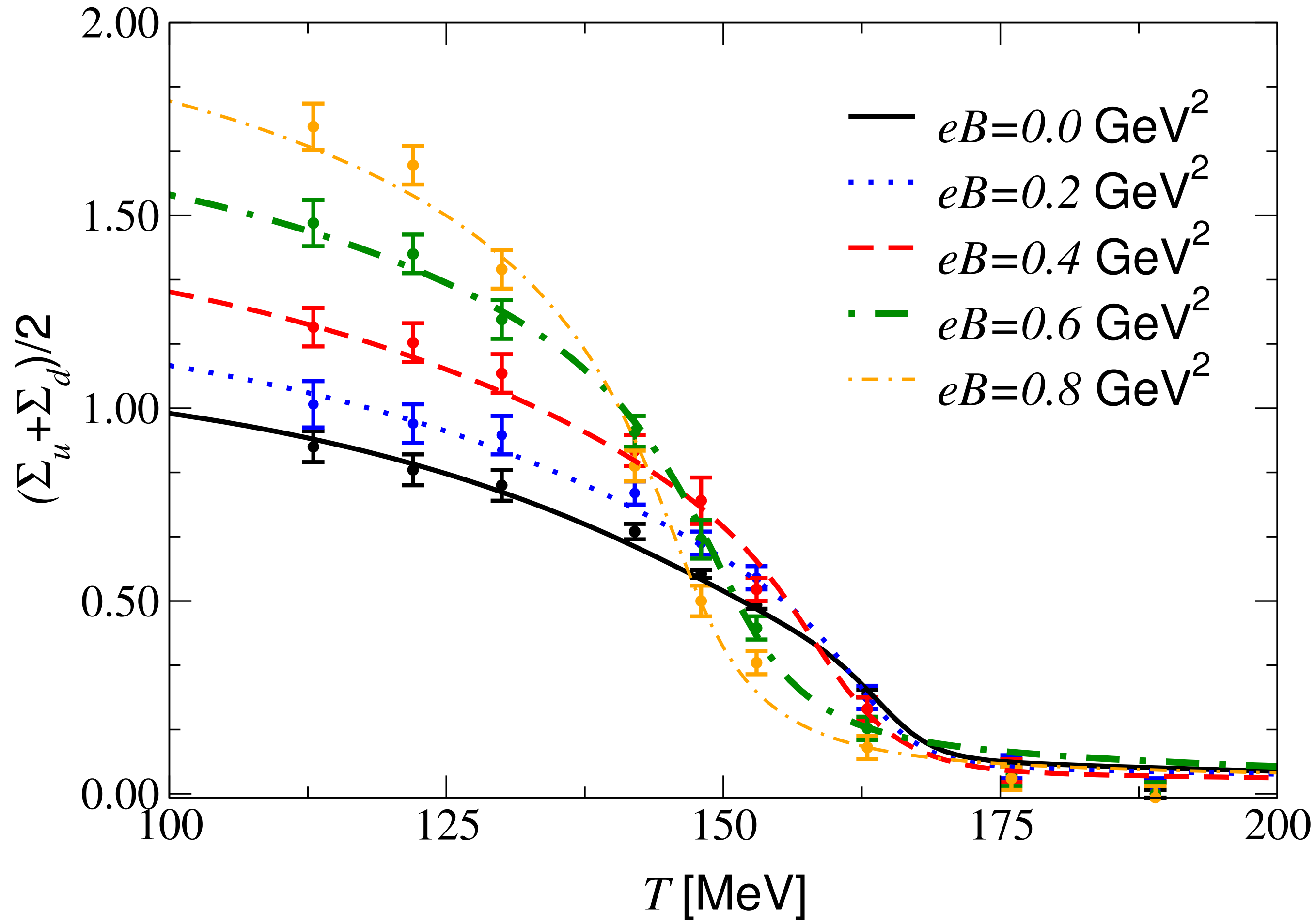
G. S. Bali et al., JHEP **1202**, 044 (2012)

SU(2) NJL + Thermo-Magnetic effects G(B,T)

G(0,0)



G(B,T)



$$\Sigma_f(B,T) = \frac{2m_f}{m_\pi^2 f_\pi^2}\left[\langle\bar{\psi}_f\psi_f\rangle - \langle\bar{\psi}_f\psi_f\rangle_0\right] + 1$$

RLSF, K.P. Gomes, M.B.Pinto, G. Krein, Phys. Rev. C **90**, 025203 (2014).

RLSF, V.S. Timoteo, S.S.Avancini,M.B.Pinto and G.Krein Eur. Phys. J. A (2017) **53**: 101

Thermo-Magnetic effects G(B,T)

$$G(B,T) = c(B)\left[1 - \frac{1}{1+e^{\beta(B)[T_a(B)-T]}}\right] + s(B)$$

eB [GeV^2]	c [GeV^{-2}]	T_a [MeV]	s [GeV^{-2}]	β [MeV^{-1}]
0.0	0.9000	168.000	3.73110	0.40000
0.2	1.2256	167.922	3.2621	0.34117
0.4	1.7693	169.176	2.2942	0.22988
0.6	0.7412	155.609	2.8638	0.14401
0.8	1.2887	157.816	1.8040	0.11506

SU(2) **RLSF**, V.S. Timoteo, S.S.Avancini,M.B.Pinto and G.Krein Eur. Phys. J. A (2017) **53**: 101

SU(3) **RLSF**, W. Tavares, S.S.Avancini, V.S. Timoteo, G.Krein and M.B. Pinto, e-Print: 2104.11117 [hep-ph]

B Effects on QCD phase transitions?

Inverse magnetic catalysis: how much do we know about?
A. Bandyopadhyay, R.L.S. Farias, *Eur. Phys. J. ST* 230 (2021) 3, 719-728,
B. e-Print: 2003.11054 [hep-ph]

Possible explanations for IMC:

- Competition of B effects on sea and valence quarks, F. Bruckmann, G. Endrodi, T. G. Kovacs, *JHEP* 04 (2013) 112

- Inclusion of plasma screening effects that capture the physics of collective, long-wave modes, and thus describe a prime property of plasmas near transition lines, namely, long distance correlations. e-Print: 2104.05854 [hep-ph]

IMC $\neq$ Tc decreasing with eB

SU(2) Nambu—Jona-Lasinio model (NJL)

$$\mathcal{L}_{NJL} = \bar{\psi}\,(\not{D} - m)\,\psi + G\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2\right] - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$D^\mu = (i\partial^\mu - QA^\mu)$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

Q=diag(q_u= $2e/3$, q_d=-$e/3$)

good **chiral** physics, pions,…
BUT no confinement

✓ **strong magnetic field background that is constant and homogeneous!**

G, Λ and m_c → m_π, f_π and $\langle\bar{\psi}\psi\rangle$

natural units: $1\mathrm{GeV}^2 \approx 5.34 \times 10^{19}\,\mathrm{G}$ and $e = \sqrt{\frac{4\pi}{137}}$

Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122**, 345 (1961)

NJL at finite B

At B=0 $$\mathcal{F} = \frac{(M-m_c)^2}{4G} - N_c \sum_{f,s} \int \frac{d^4p}{(2\pi)^4} \ln\left[p^2 + M^2\right]$$

By using the replacement $\vec{p}^{\,2} \to p_3^2 + 2k|q_f|B$

$$\int \frac{d^4p}{(2\pi)^4} \to \int_{-\infty}^{\infty} \frac{dp_3}{2\pi} \int_{-\infty}^{\infty} \frac{dp_4}{2\pi} \sum_{k=0}^{\infty} \alpha_k$$

$$\alpha_k = 2 - \delta_{k0}$$

$$\begin{aligned}\mathcal{F} &= \frac{(M-m_c)^2}{4G} \\ &- N_c \sum_f \frac{|q_f|B}{2\pi} \sum_{k=0}^{\infty} \alpha_k \int_{-\infty}^{\infty} \frac{dp_3}{2\pi} \int_{-\infty}^{\infty} \frac{dp_4}{2\pi} \ln\left[p_4^2 + p_3^2 + 2k|q_f|B + M^2\right]\end{aligned}$$

And the gap equation: $\partial\mathcal{F}/\partial M = 0 \longrightarrow \infty$

We need a regularization procedure!

Which procedure/method is more appropriate?

Is there any criteria?

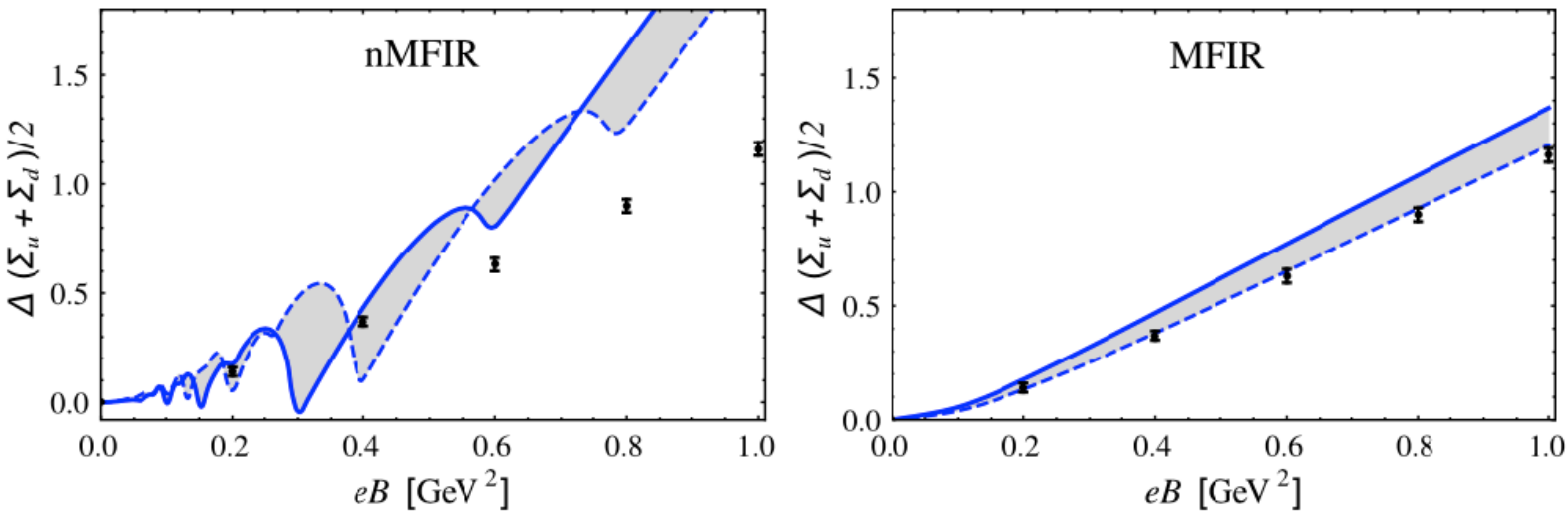
MFIR - Magnetic Field Independent Regularization

- ✓ D. Ebert and K.G. Klimenko, Nucl. Phys. **A728**, 203 (2003).
- ✓ D. P. Menezes, M. B. Pinto, S. S. Avancini, A. P. Martínez, and C. Providência, Phys. Rev. C **79**, 035807 (2009).
- ✓ P. G. Allen, A. G. Grunfeld, and N. N. Scoccola, Phys. Rev. D **92**, 074041 (2015).
- ✓ D.C.Duarte, P.G.Allen, R.L.S.Farias, P.H.A.Manso,R.O.Ramos,and N. N. Scoccola, Phys. Rev. D **93**, 025017 (2016).
- ✓ S. S. Avancini, W. R. Tavares, and M. B. Pinto, Phys. Rev. D **93**, 014010 (2016).
- ✓...

Fermi-Dirac Form Factor

$$U_{\Lambda}^{\mathrm{FD}}(x) = \frac{1}{2}\left[1 - \tanh\left(\frac{\frac{x}{\Lambda} - 1}{\alpha}\right)\right]$$

$$245\,\mathrm{MeV} < -\bar{\Phi}_0^{1/3} < 260\,\mathrm{MeV}$$

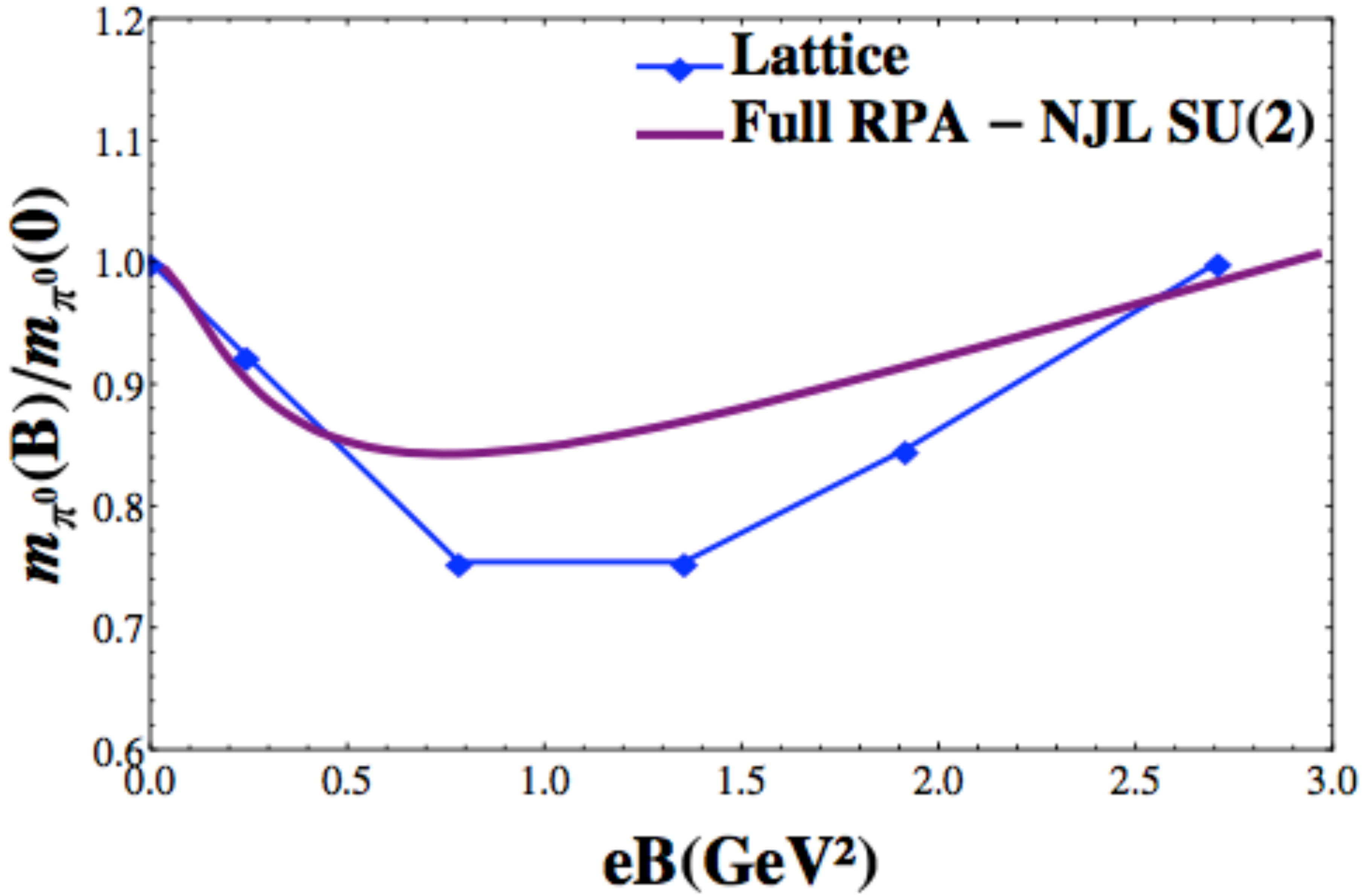


Lattice data: G. S. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S. D. Katz and A. Schafer, Phys. Rev. D **86**, 071502(R) (2012)

RLSF, S.S. Avancini, N. Scoccola, W.R. Tavares, PRD **99**, 116002 (2019).

Meson masses

Lattice Results (2013)



NJL + MFIR

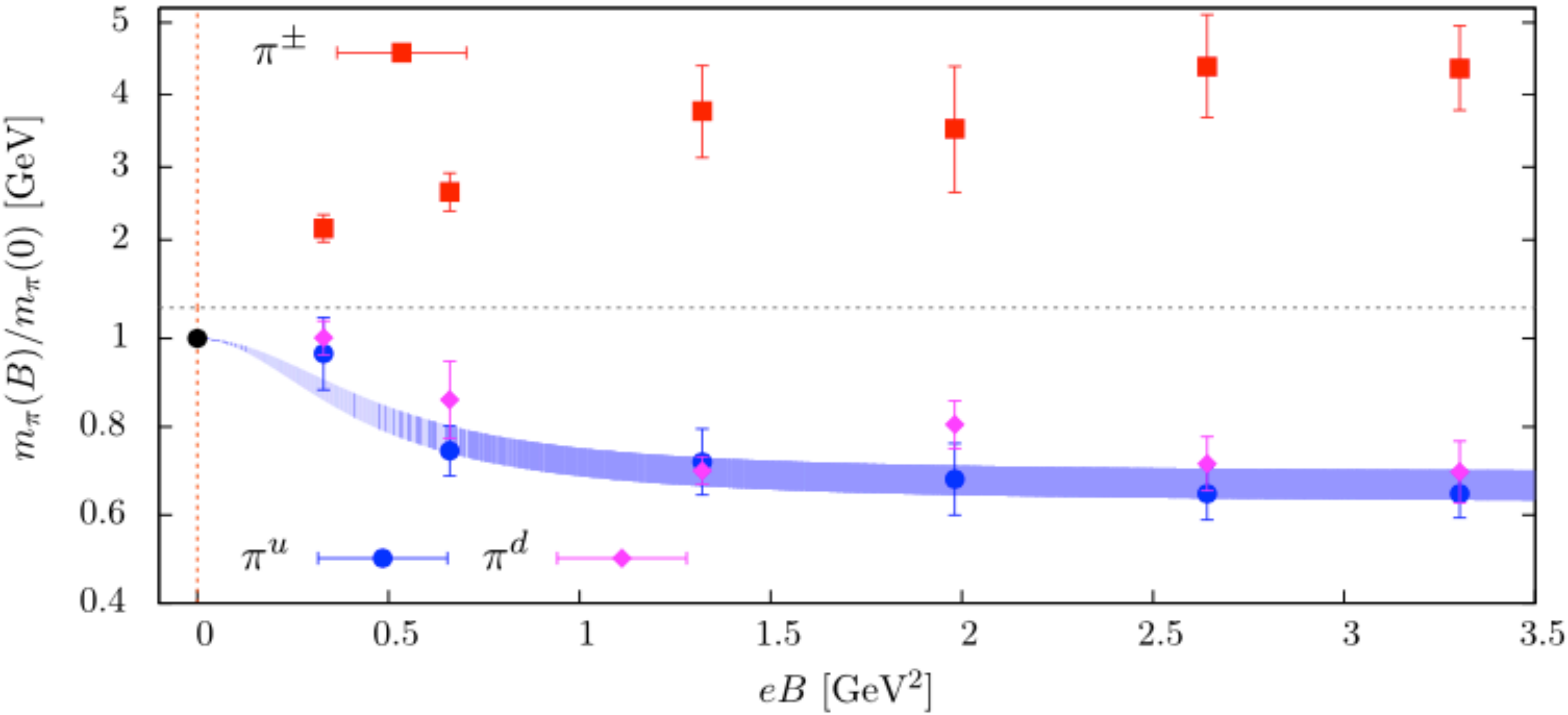
Y. Hidaka and A. Yamamoto,

Phys. Rev. D 87, 094502 (2013)

S.S. Avancini, W. R. Tavares, M.B. Pinto,

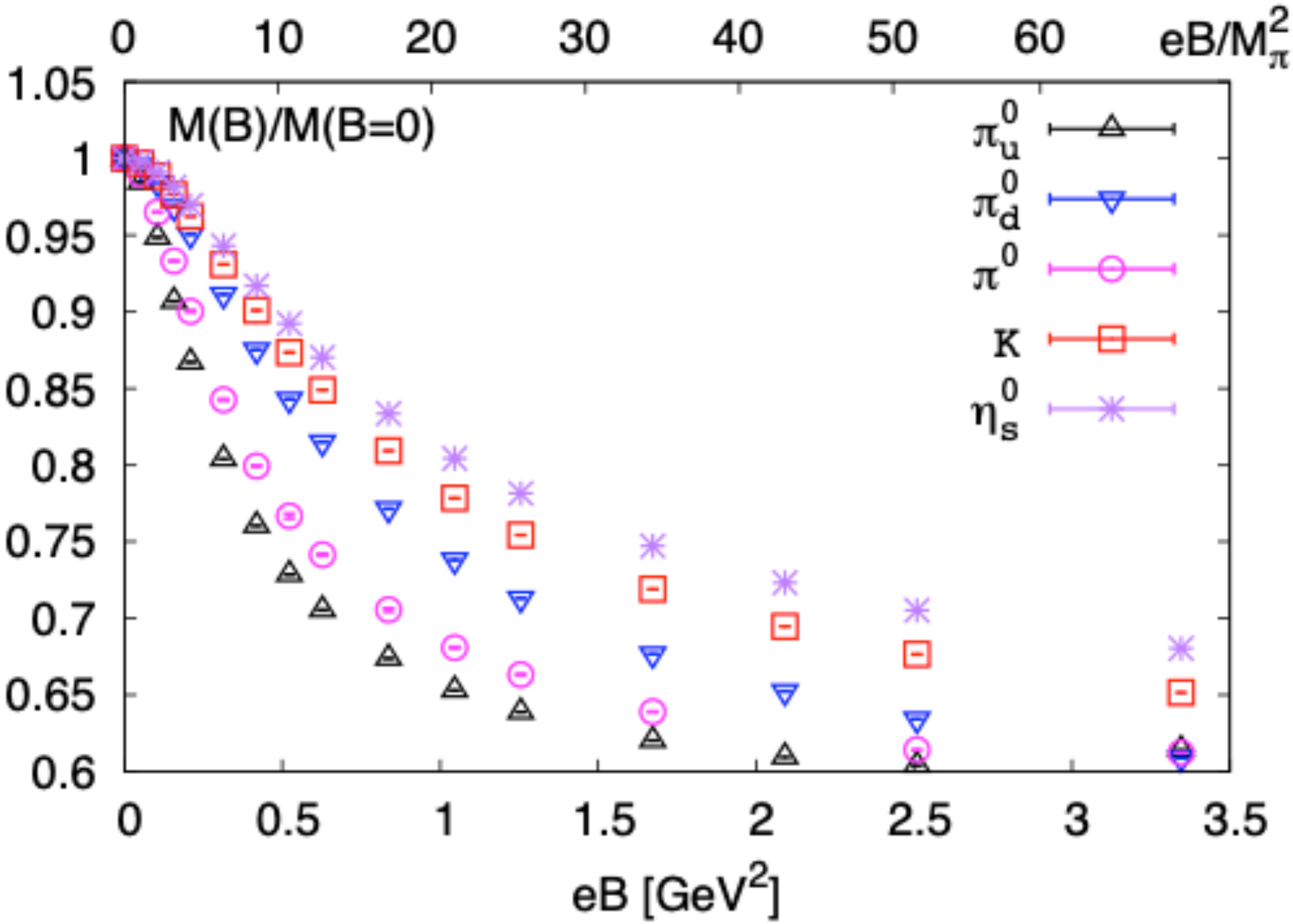
Phys.Rev D 93, 014010 (2016)

Lattice Results (2018)



G.S. Bali, B.B. Brandt, G.Endrodi and B.Glaessle, Phys. Rev D 97, 034505 (2018)

Lattice Results (2020)



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

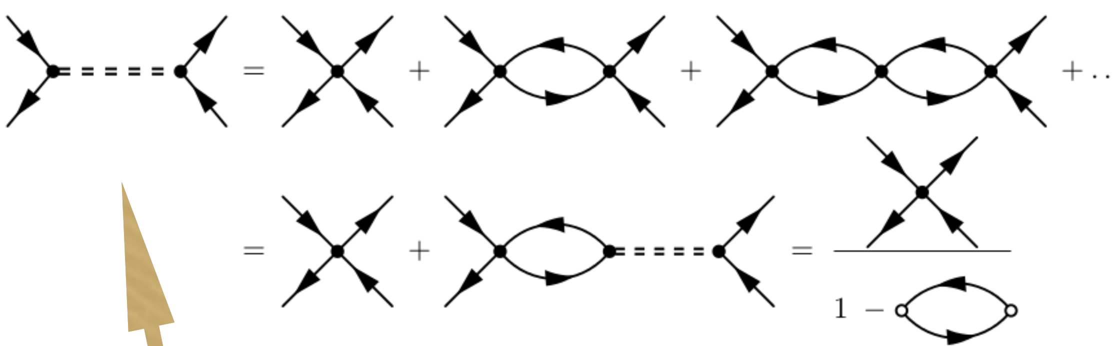
NJL - Meson properties at finite B

T matrix for the scattering of pairs of quarks, $q_1\, q_2 \rightarrow q_1'\, q_2'$

can be calculated -> solving the Bethe-Salpeter equation in the ladder or random phase approximation (RPA)

$$m_{\pi_0}(B, T=0)$$

only pionic degrees of freedom:



$$(ig_{\pi^0 qq})^2 iD_{\pi^0}(k^2) = \frac{2iG}{1-2G\Pi_{ps}(k^2)}$$

$$D_{\pi^0}(k^2) = \frac{1}{k^2 - m^2_{\pi^0}}$$

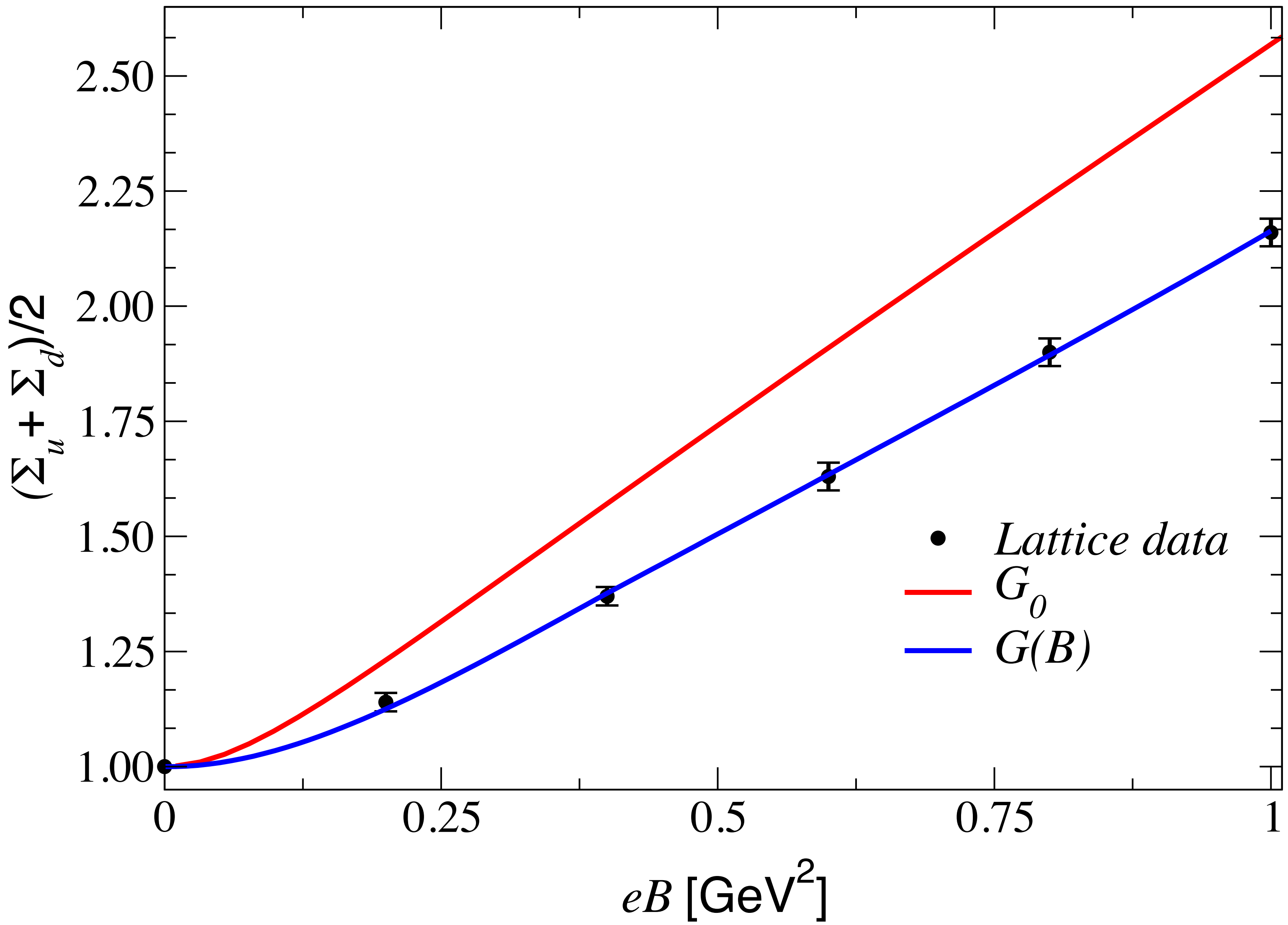
$$\mathcal{L}_{\pi qq} = ig_{\pi qq}\overline{\psi}\gamma_5\vec{\tau}\cdot\vec{\pi}\psi$$

$$1 - 2G\Pi_{ps}(k^2)|_{k^2=m^2_{\pi^0}} = 0$$

✓ Magnetic Field Independent Regularization (MFIR)

Field dependent coupling G(B,T=0)

$$\Sigma_f(B) = \frac{2m}{m_\pi^2 f_\pi^2}\left[\langle\bar{\psi}_f\psi_f\rangle_B - \langle\bar{\psi}_f\psi_f\rangle_{00}\right] + 1$$



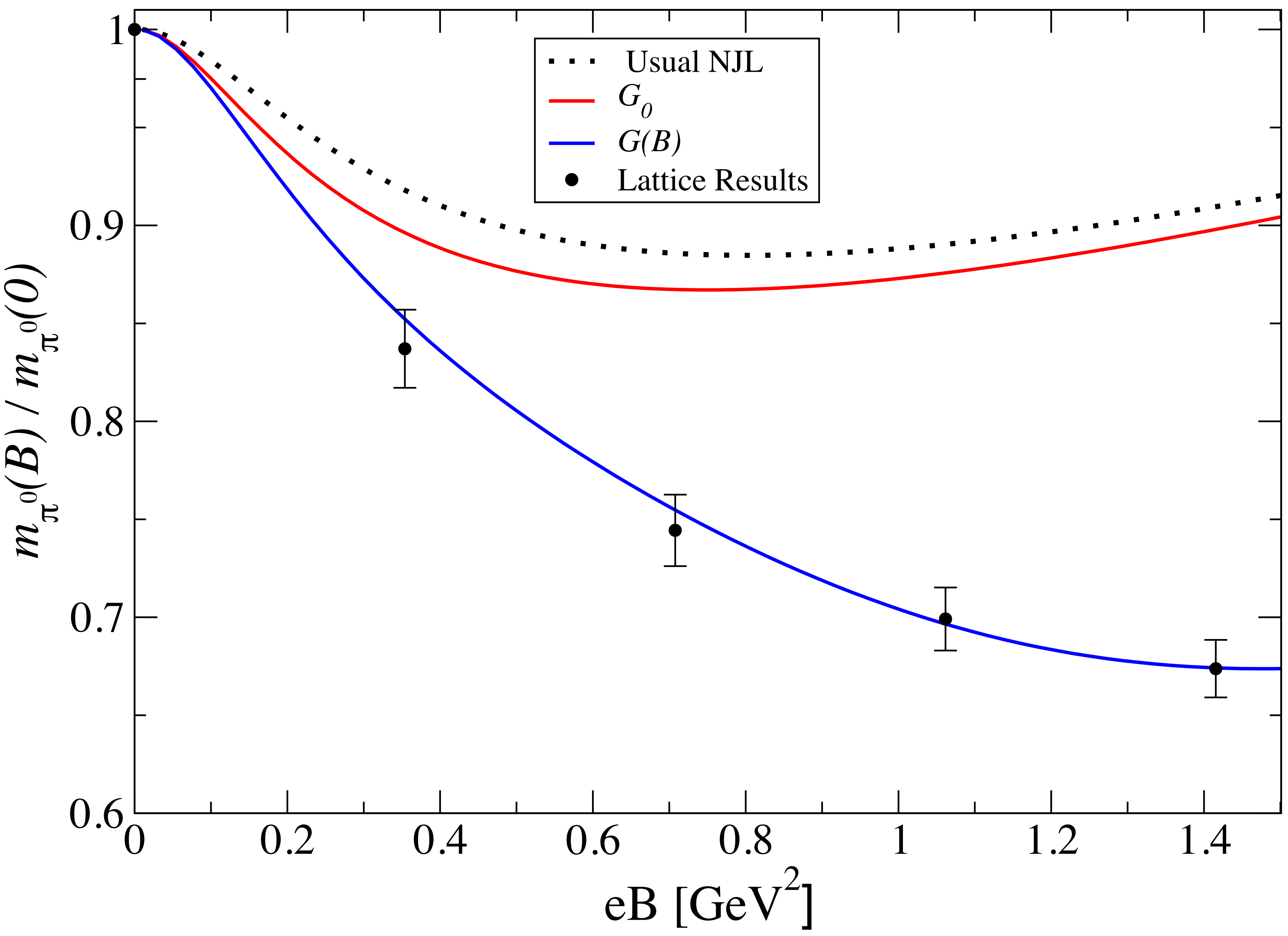
$$G(eB) = \alpha + \beta\, e^{-\gamma\,(eB)^2}$$

$$\alpha = 1.44373\ \mathrm{GeV}^{-2}$$
$$\beta = 3.06\ \mathrm{GeV}^{-2}$$
$$\gamma = 1.31\ \mathrm{GeV}^{-4}$$

lattice results: Phys. Rev. D 86, 071502(R) (2012)

G(B) in Farias at all, Phys. Lett. B 767 (2017) 247–252

Meson masses at finite B



Farias at all, Phys. Lett. B 767 (2017) 247–252

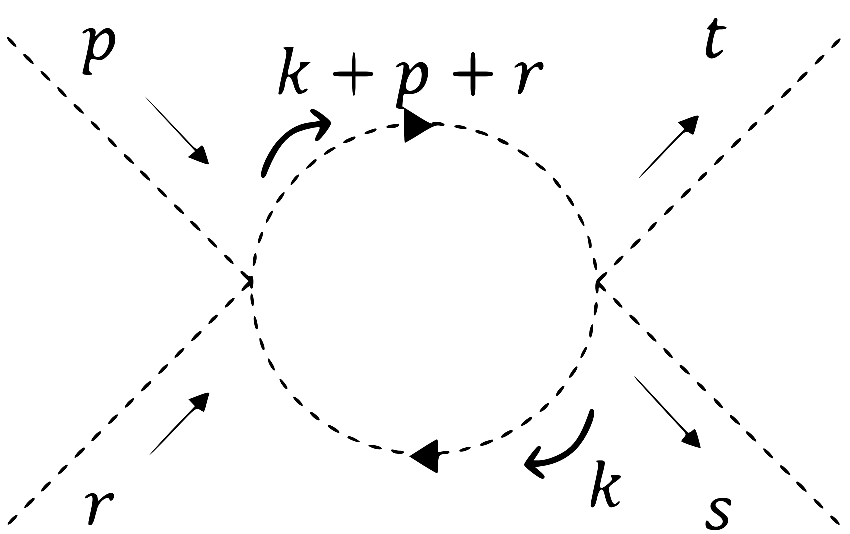
Lattice data: G. Bali, B.B. Brandt, G. Endrodi, B. Glaessle, arXiv:1510.03899 [hep-lat]

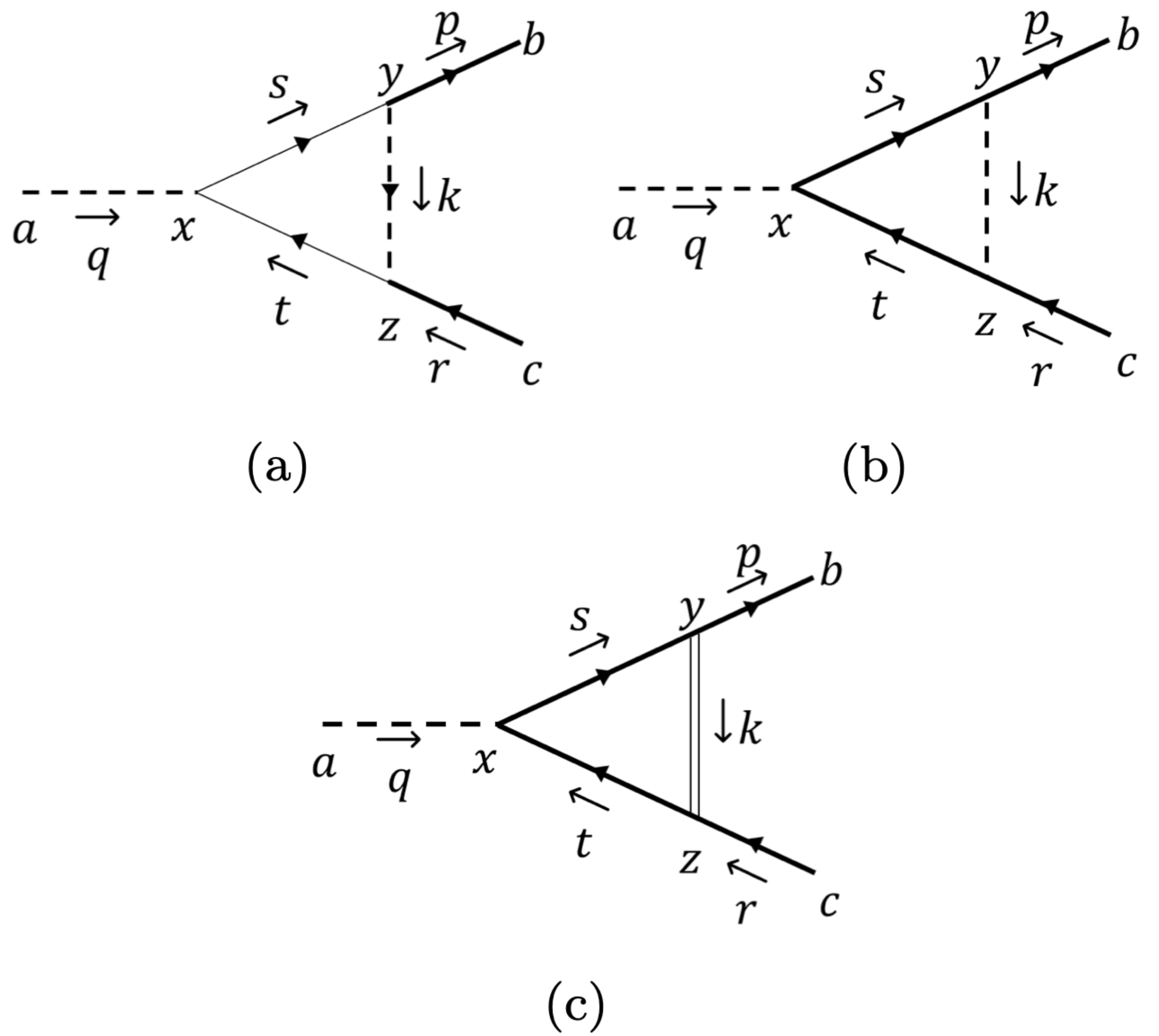
Linear Sigma model with quarks - LSMq

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 + \frac{a^2}{2}(\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 \\
&+ i\bar{\psi}\gamma^\mu \partial_\mu \psi - ig\gamma^5 \bar{\psi}\vec{\tau}\cdot\vec{\pi}\psi - g\bar{\psi}\psi\sigma
\end{aligned}
$$

- Pions are described by an isospin triplet, $\vec{\pi} = (\pi_1, \pi_2, \pi_3)$;
- Two species of quarks are represented by an $SU(2)$ isospin doublet, ψ;
- The σ scalar is included by means of an isospin singlet;
- λ is the boson self-coupling;
- g is the fermion-boson coupling;
- $a^2 > 0$ is the mass parameter.

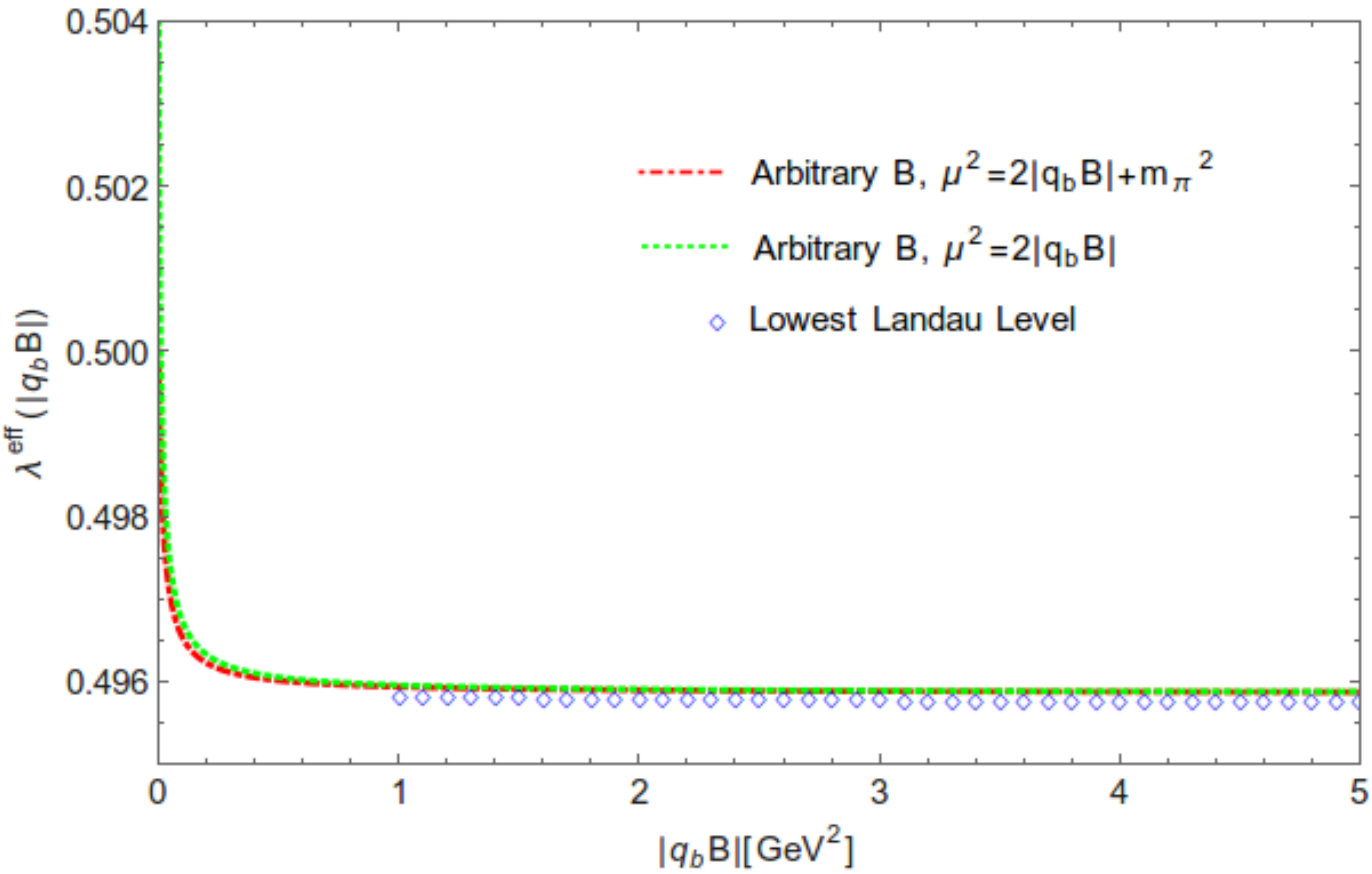
Magnetic corrections to the boson self-coupling and boson-fermion coupling in the LSMq





A.Ayala, J.L.Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora, *Phys.Rev.D* 102 (2020) 11, 114038, arXiv:2009.13740 [hep-ph],

Magnetic corrections to the boson self-coupling and boson-fermion coupling in the LSMq



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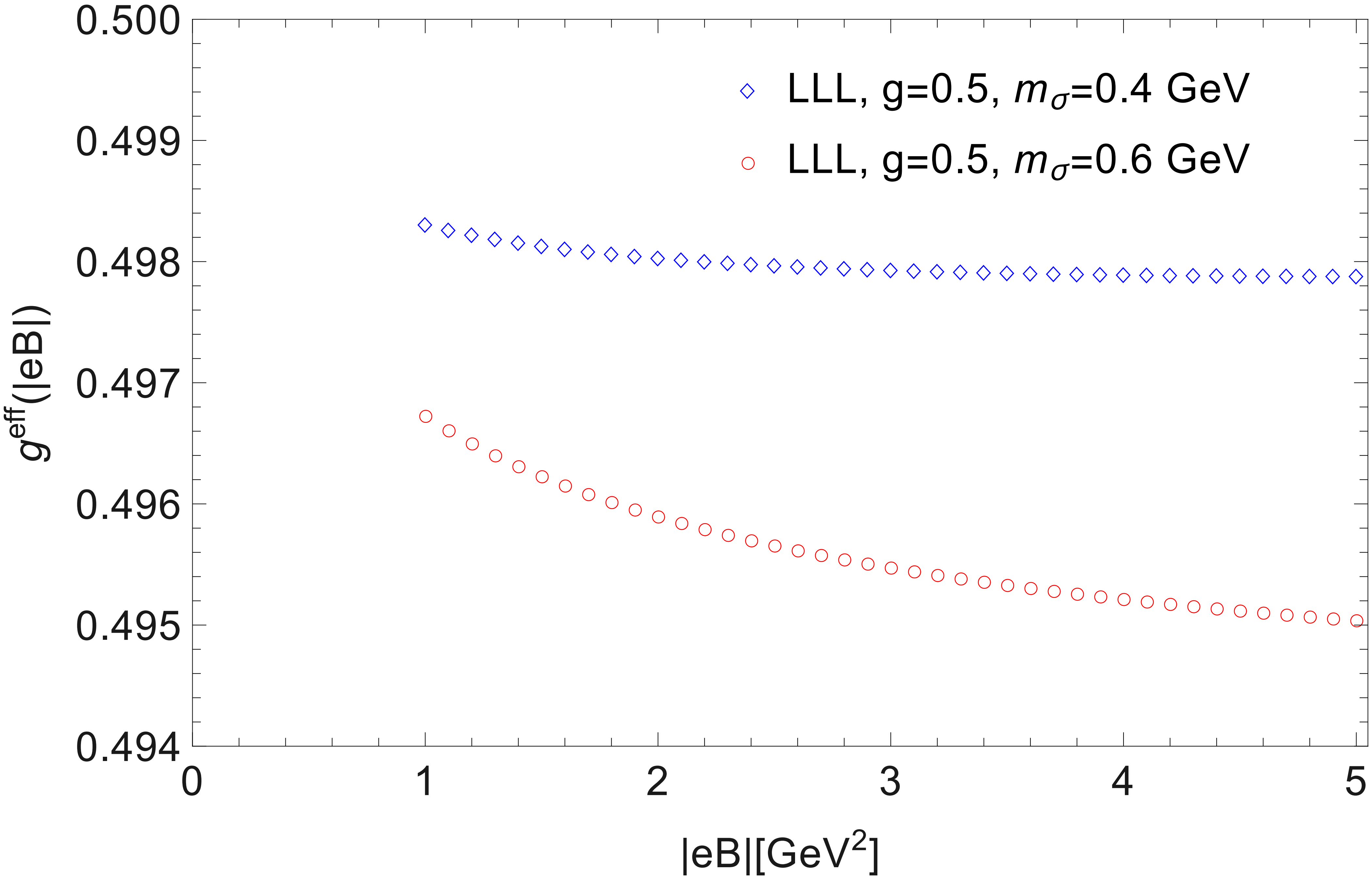
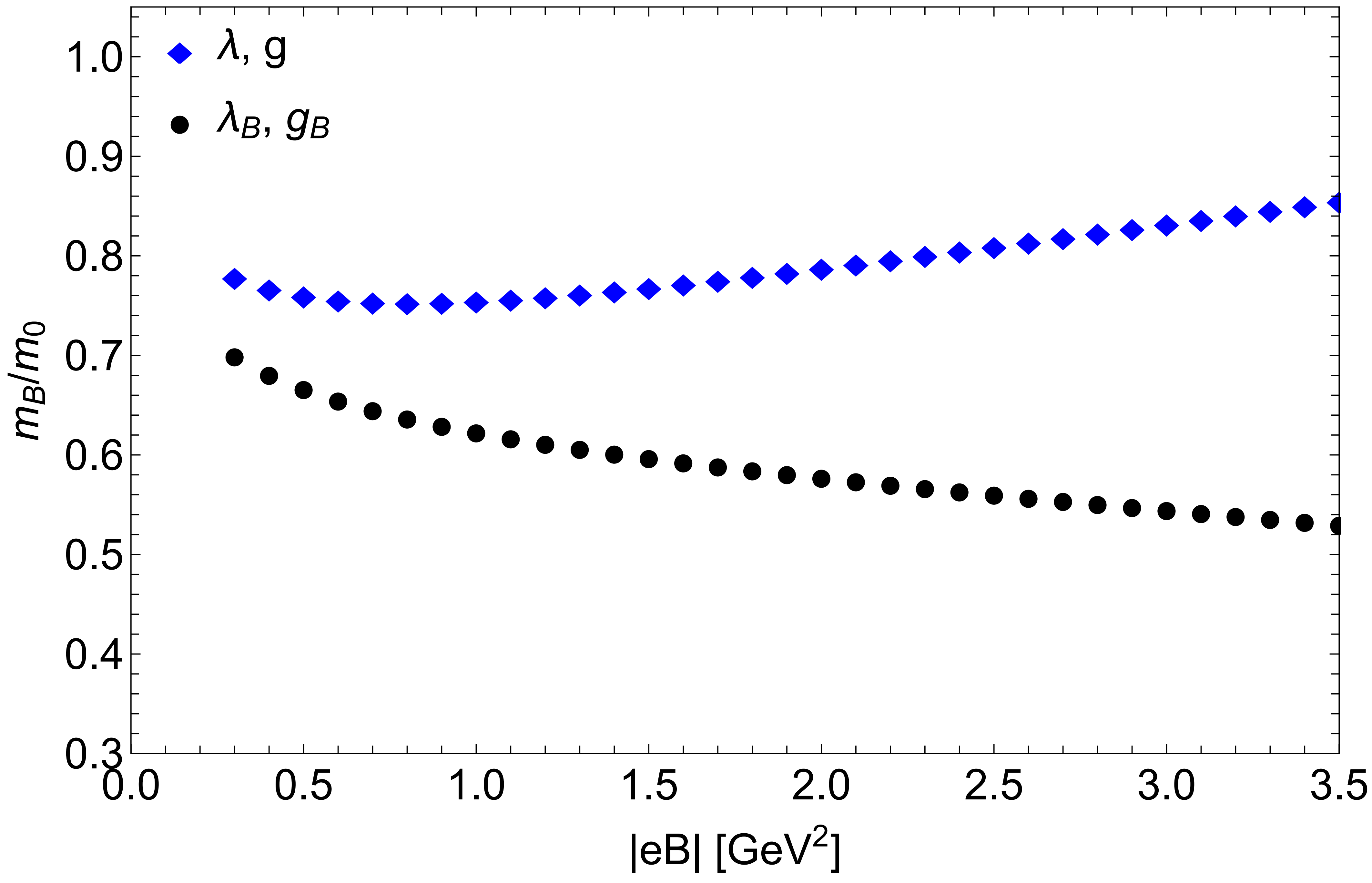


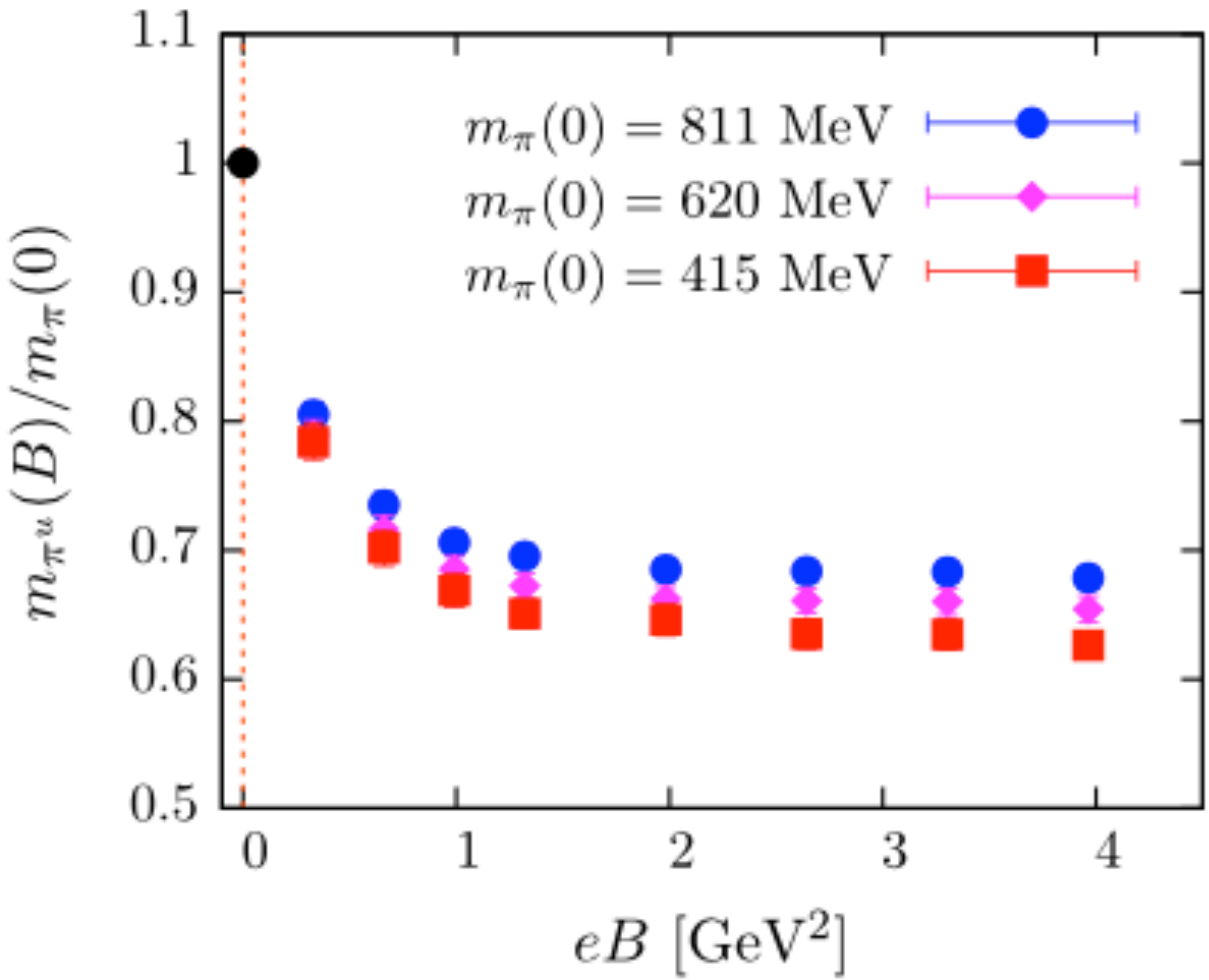
A.Ayala, J.L.Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora, *Phys.Rev.D* 102 (2020) 11, 114038, arXiv:2009.13740 [hep-ph],

Neutral pion mass X eB



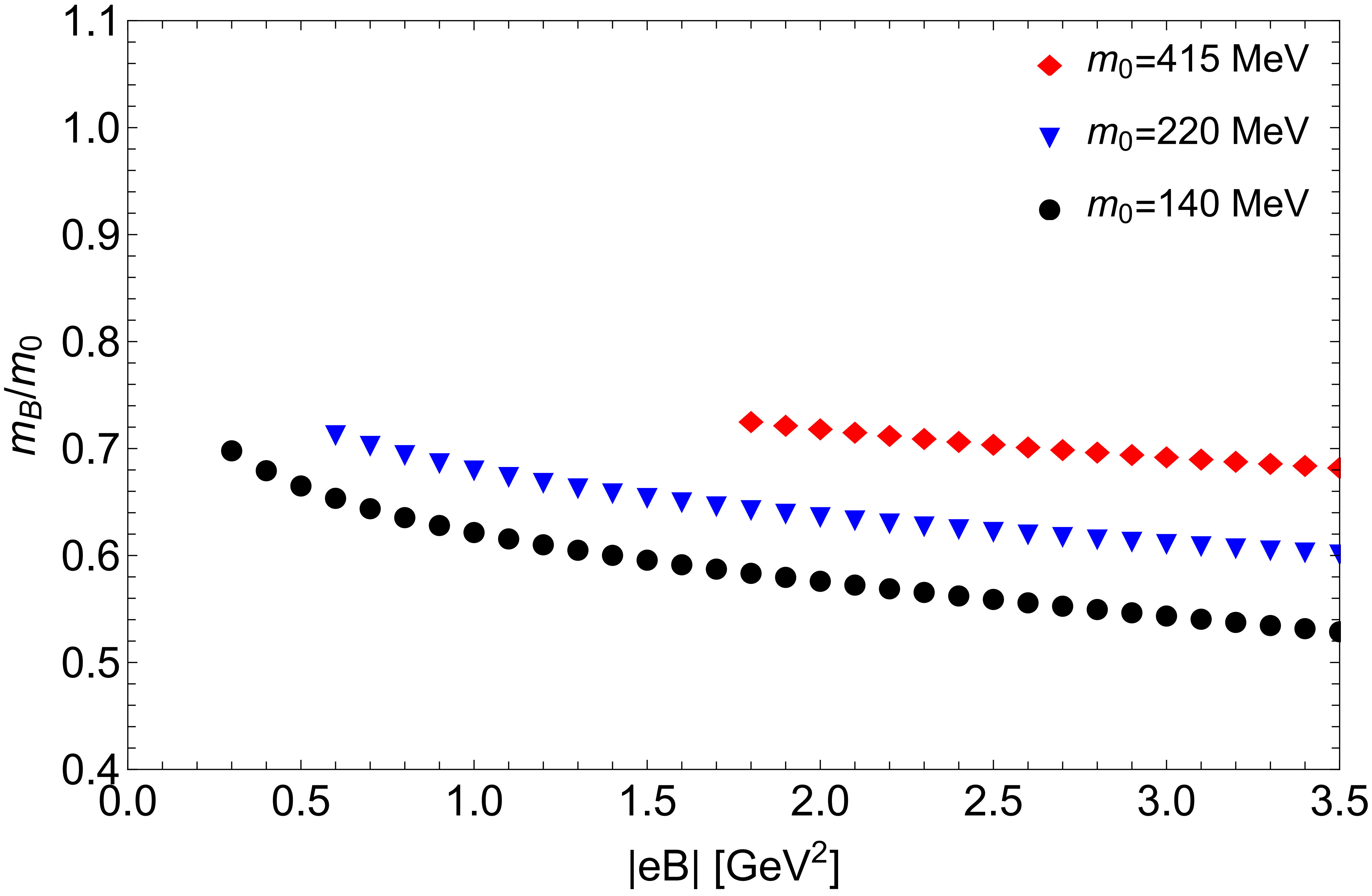
A. Ayala, J.L. Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora, *Phys.Rev.D* 103 (2021) 5, 054038, e-Print: 2011.03673 [hep-ph].

Lattice



G.S. Bali, B.B. Brandt, G.Endrodi and B.Glaessle, Phys. Rev D 97, 034505 (2018)

LSMq strong field



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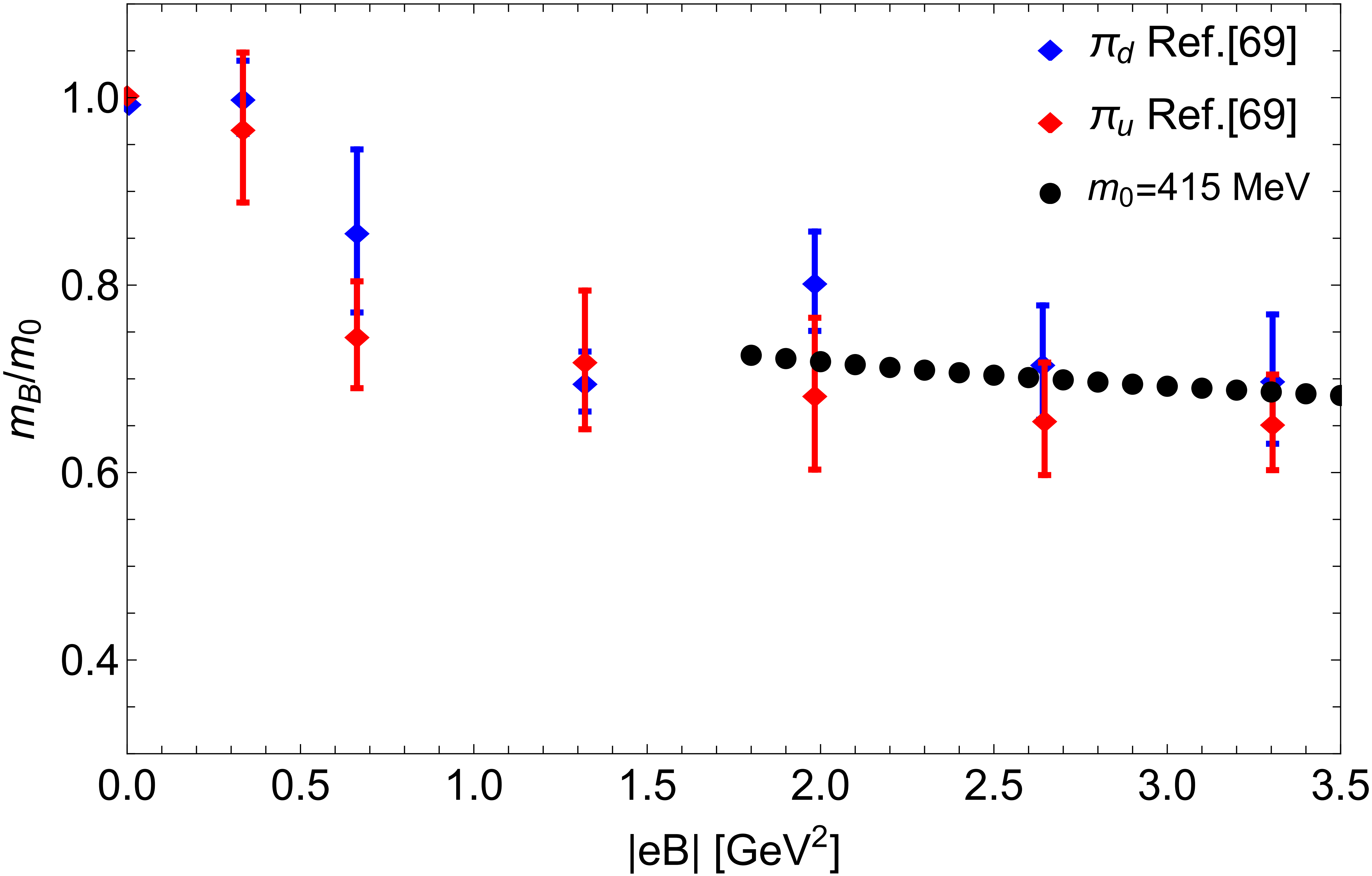
LSMq strong field



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Lattice data

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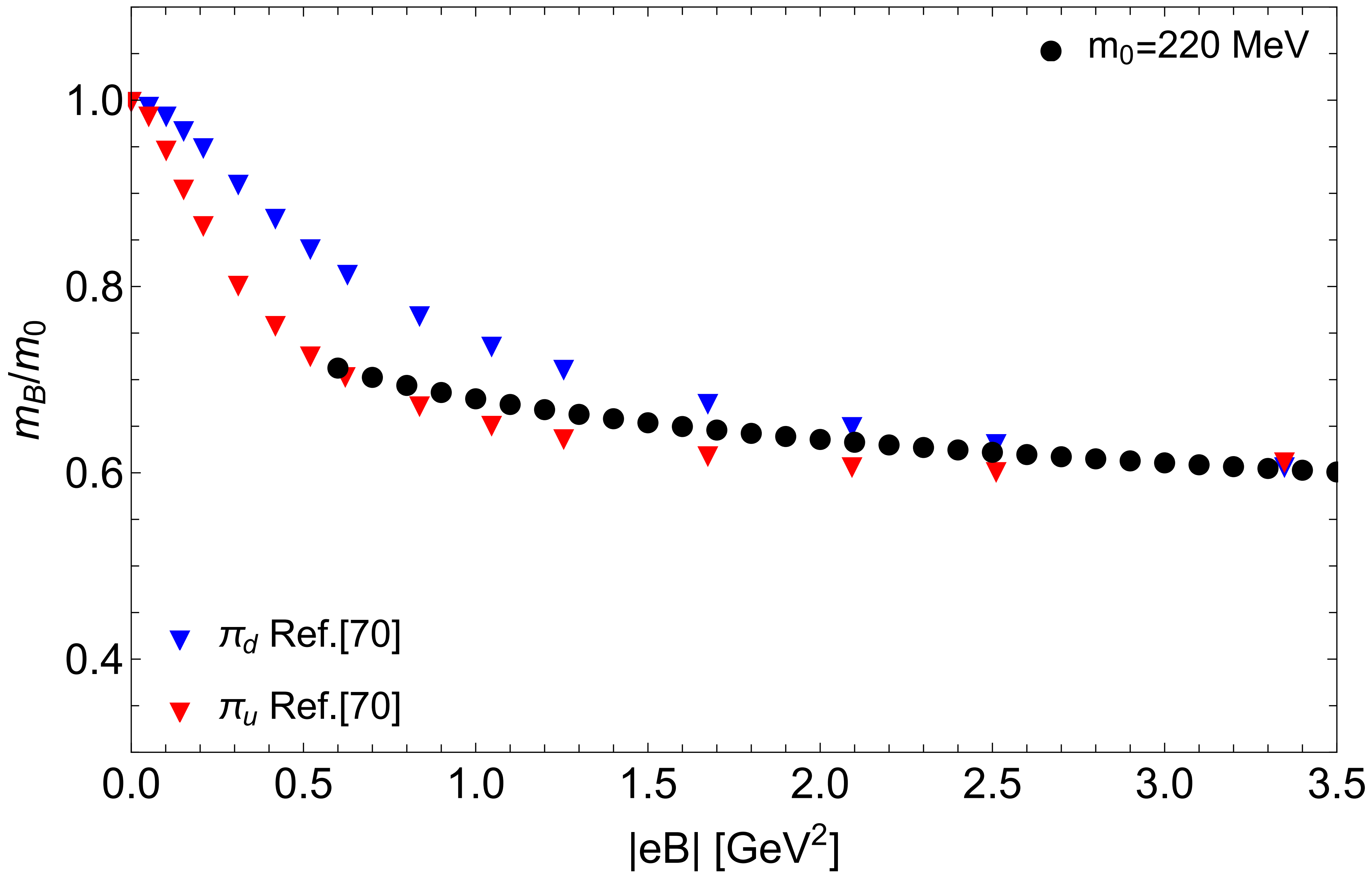
LSMq strong field



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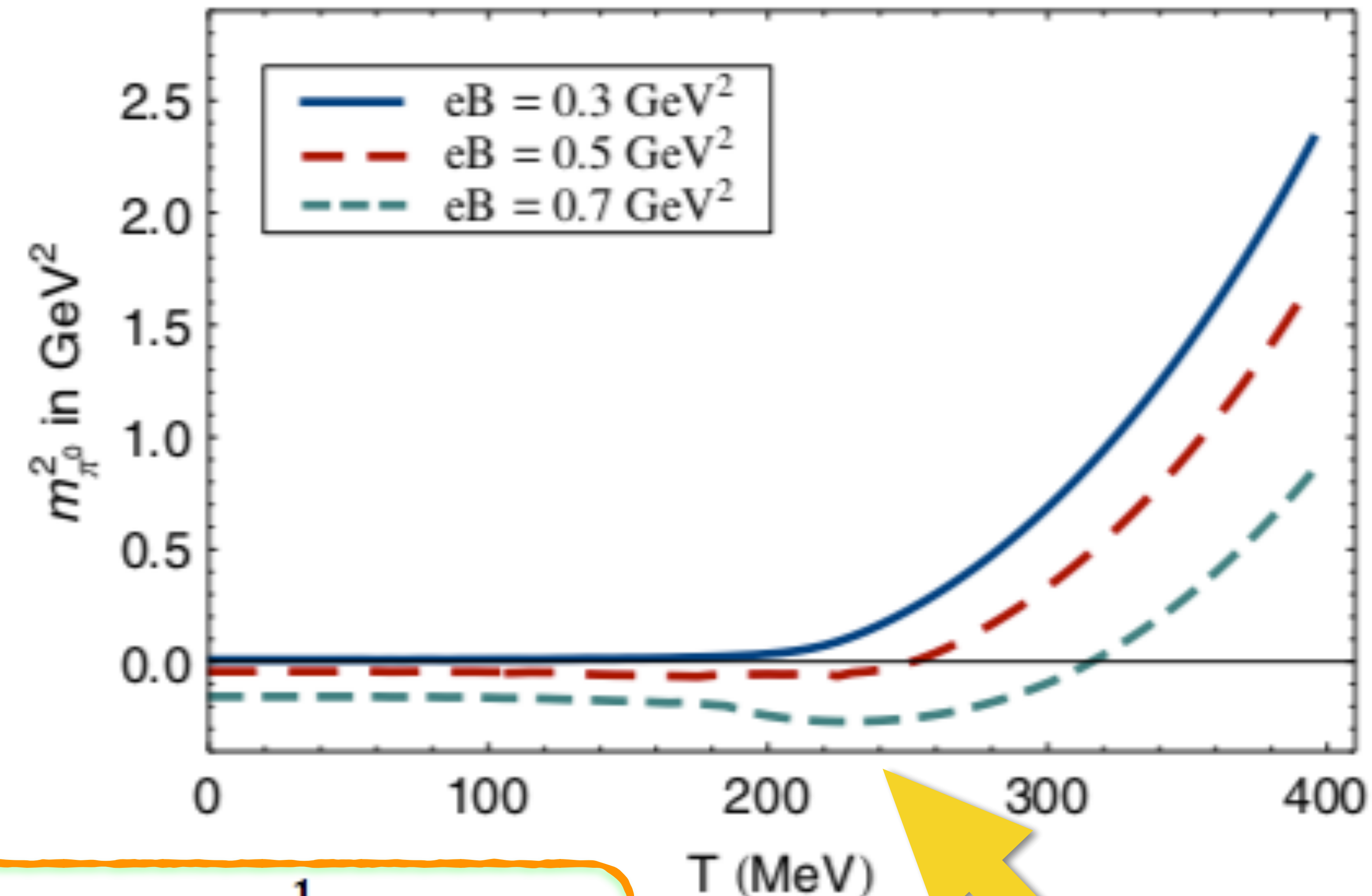
Lattice data

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

Meson masses + T + B using NJL

Neutral pion mass + B + T

SU(2) NJL
+ B +T

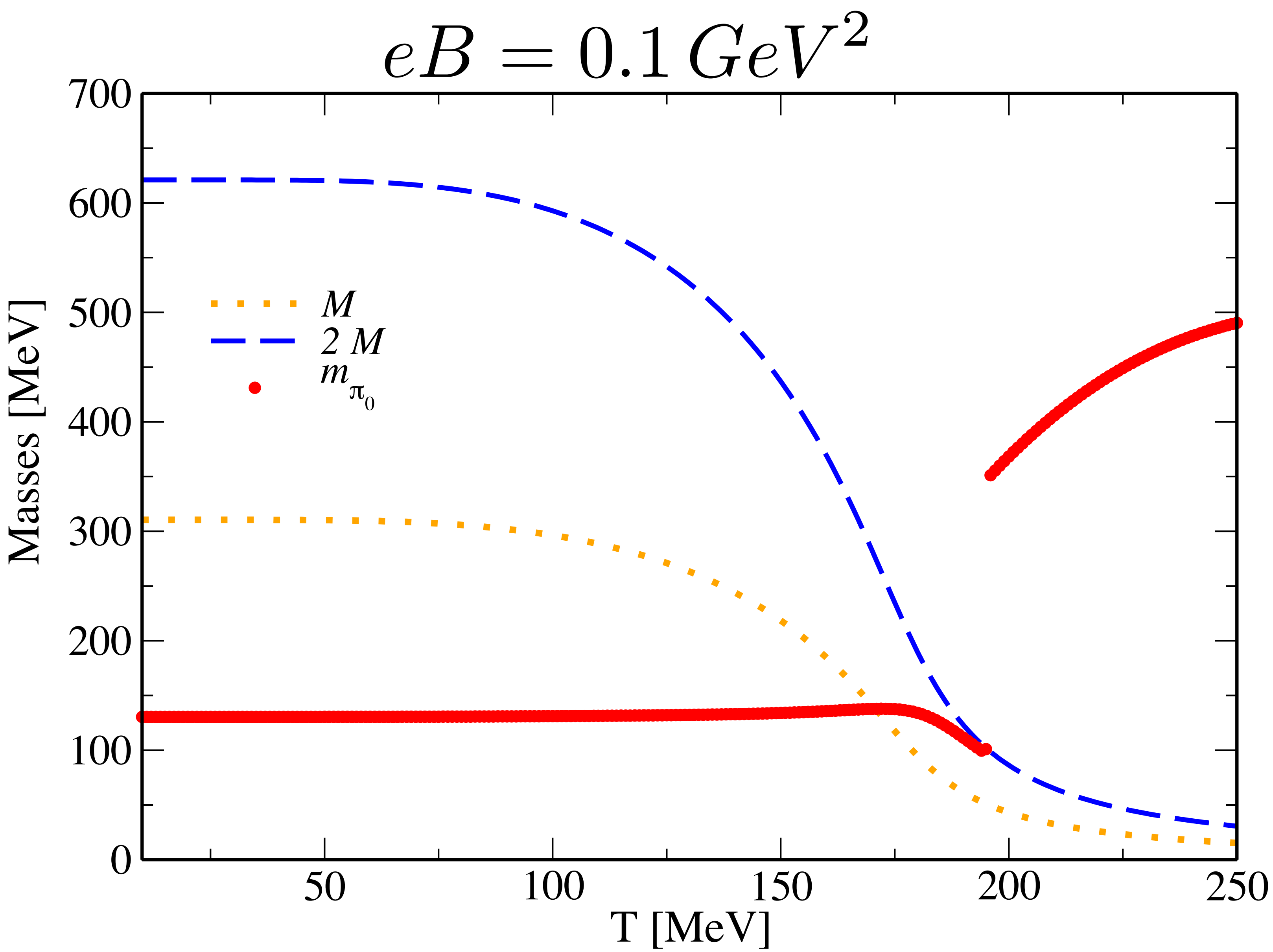


$$f_\Lambda = \frac{1}{1+\exp\left(\frac{|\mathbf{p}|-\Lambda}{A}\right)}, \qquad f^p_{\Lambda,B} = \frac{1}{1+\exp\left(\frac{\sqrt{p_3^2+2|qeB|p}-\Lambda}{A}\right)}$$

Tachyonic Instabilities

PRD 86, 085042 (2012)

Neutral pion mass X eB + MFIR



More energetic resonances that we obtain as we increase the magnetic field

dimensional reduction

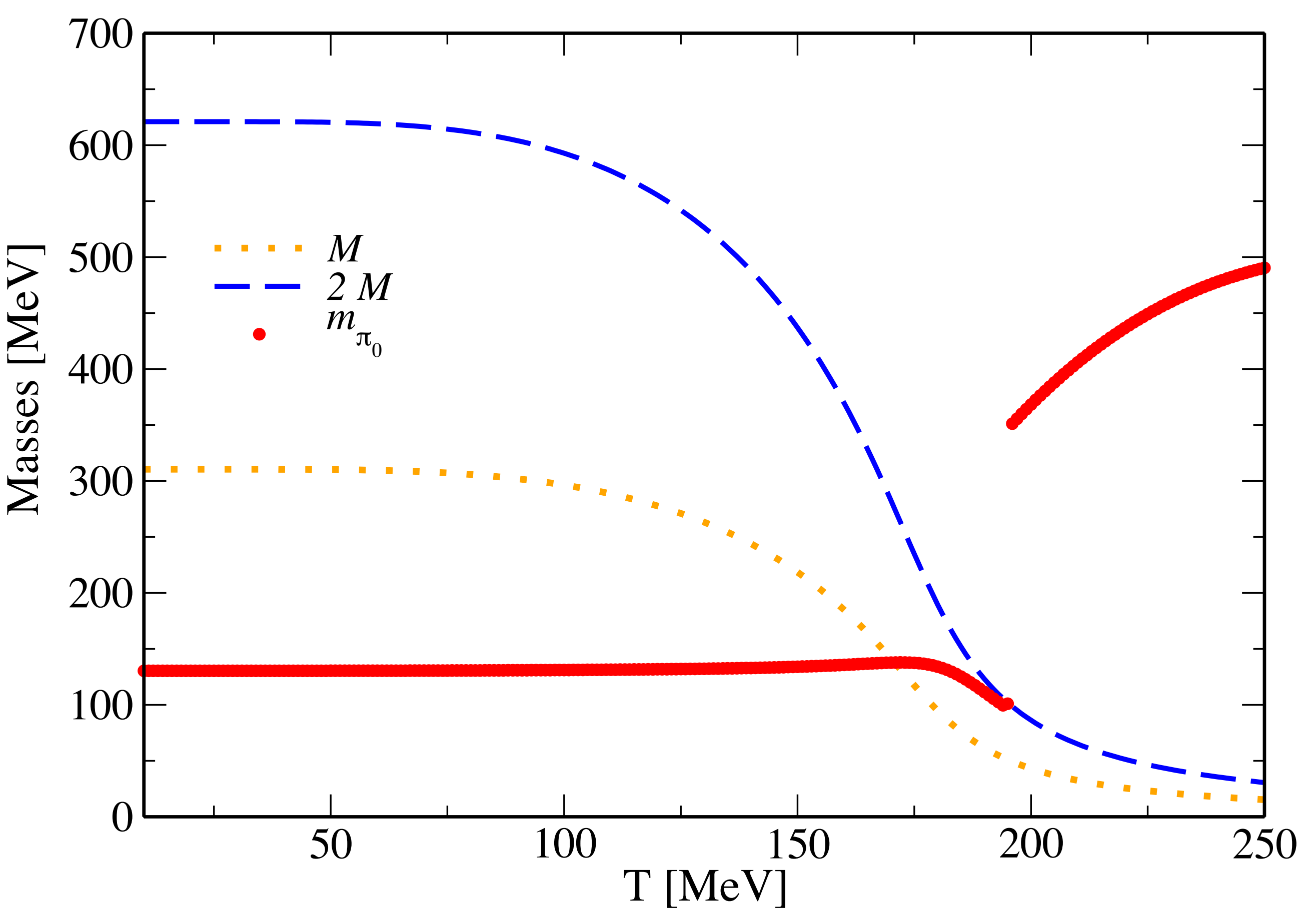
No Tachyonic Instabilities

S.S. Avancini, R.L.S. Farias, W.R. Tavares, *Phys. Rev. D* 99, 056009 (2019)

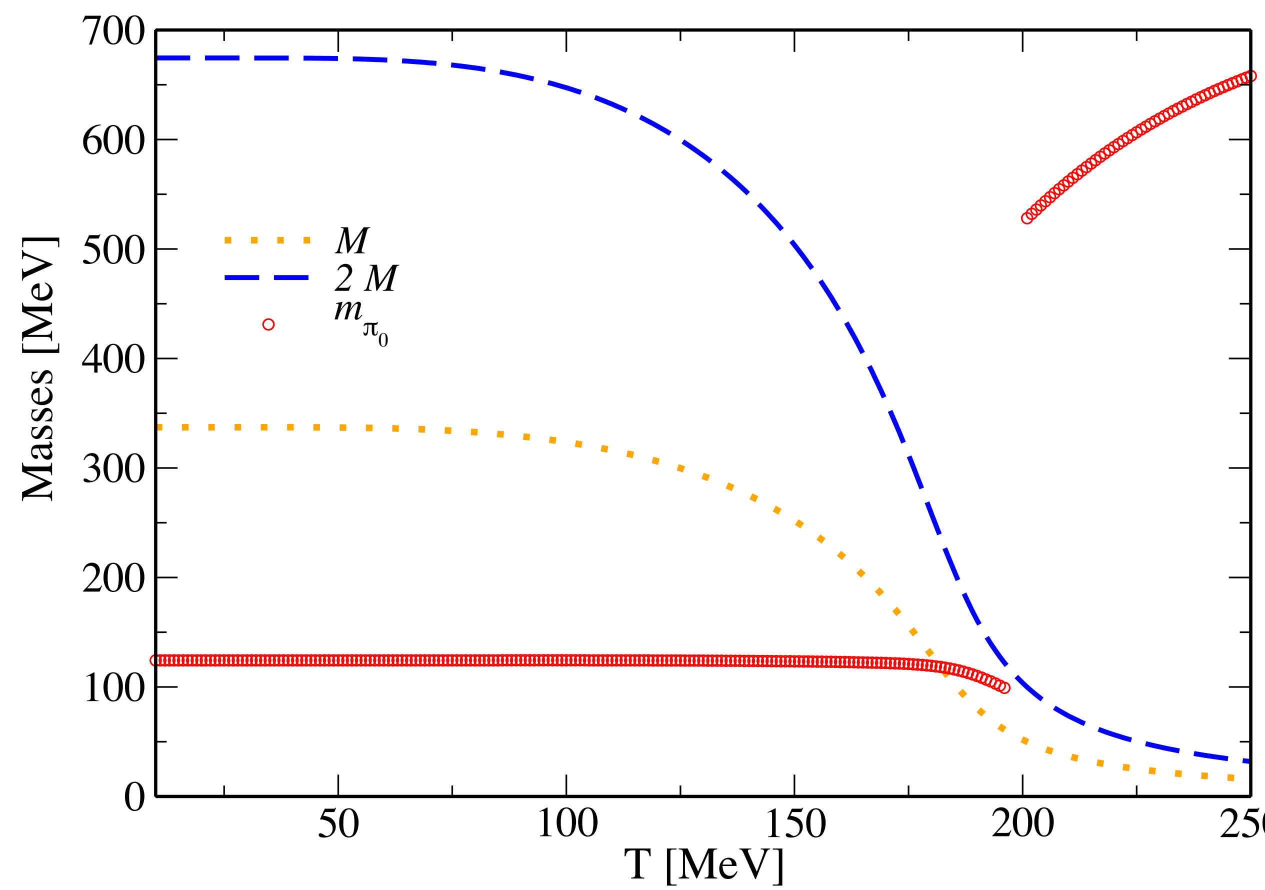
Neutral pion mass X eB

No Tachyonic Instabilities!!!

$eB = 0.1\,GeV^2$



$eB = 0.2\,GeV^2$



T Mott increase with B using MFIR approach!

S.S. Avancini, R.L.S. Farias, W.R. Tavares, *Phys. Rev. D* 99, 056009 (2019)

Conclusions

✓ We use results from lattice simulations of QCD in the presence of intense magnetic fields as a benchmark platform for comparing different regularization procedures used in the literature for the NJL type models MFIR X nMFIR

✓ **MFIR scheme avoid some unphysical results**, and this choice of regularization provide to us some different results from most of the regularizations prescriptions of the current literature.

✓ At T=0 meson masses evaluate using NJL and LSMq are in agreement with lattice when their coupling constants depend on B;

Conclusions

- ✓ Mott dissociation temperature is catalyzed with the increase of B

- ✓ The dramatic result is the **more energetic resonances** that we obtain as we increase the magnetic field. The π_0 meson at the Mott dissociation temperature jumps to a resonance in a degenerate state with the σ meson.

- ✓ This is a direct result from the **dimensional reduction** of the system at strong magnetic fields that enforces the system to go to another state, since we have less states to the creation of the thermal $q - \bar{q}$ excitation.

Perspectives

- ✓ Inclusion of ***thermo***-magnetic effects in LSMq
- ✓ Charged mesons: NJL and LSMq

Thank you for your attention!