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Neutral Meson properties in hot and magnetized quark matter

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Universidade Federal de Santa Maria SEDES SAPIENTIÆ 1960

FAPERGS

XXXII International Workshop on High Energy Physics
"**Hot problems of Strong Interactions**"

Outline

- Motivation
- Thermo-magnetic effects on the coupling constants - 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 non 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).

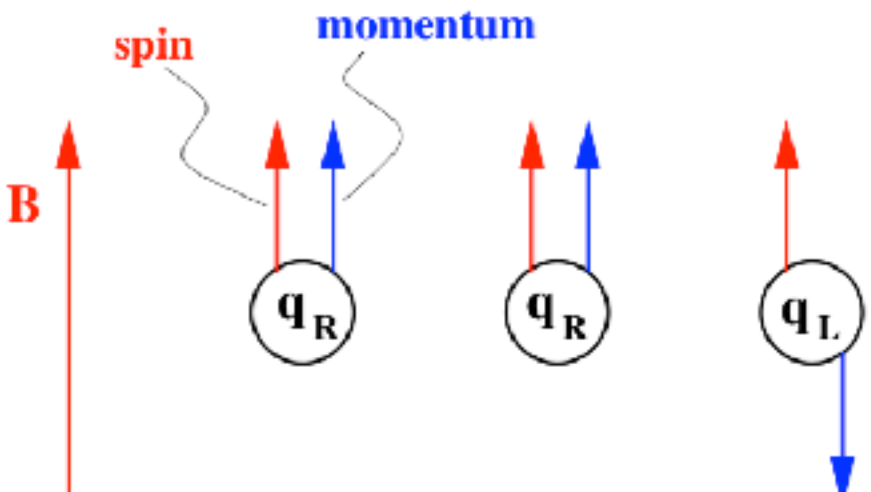
heavy-ion collisions:

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

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

- Chiral magnetic effect

D.E. Kharzeev, L.D. McLerran, H.J. Warringa NPA 803, 227 (2008)



$$J = \frac{e^2 N_c}{2\pi^2}\mu_5 B$$

⇒ electric current parallel to B


NATURE PHYSICS | LETTER

Chiral magnetic effect in $ZrTe_5$

Qiang Li, Dmitri E. Kharzeev, Cheng Zhang, Yuan Huang, I. Pletikosić, A. V. Fedorov, R. D. Zhong, J. A. Schneeloch, G. D. Gu & T. Valla

Affiliations | Contributions Corresponding authors

Nature Physics (2016) | doi:10.1038/nphys3648

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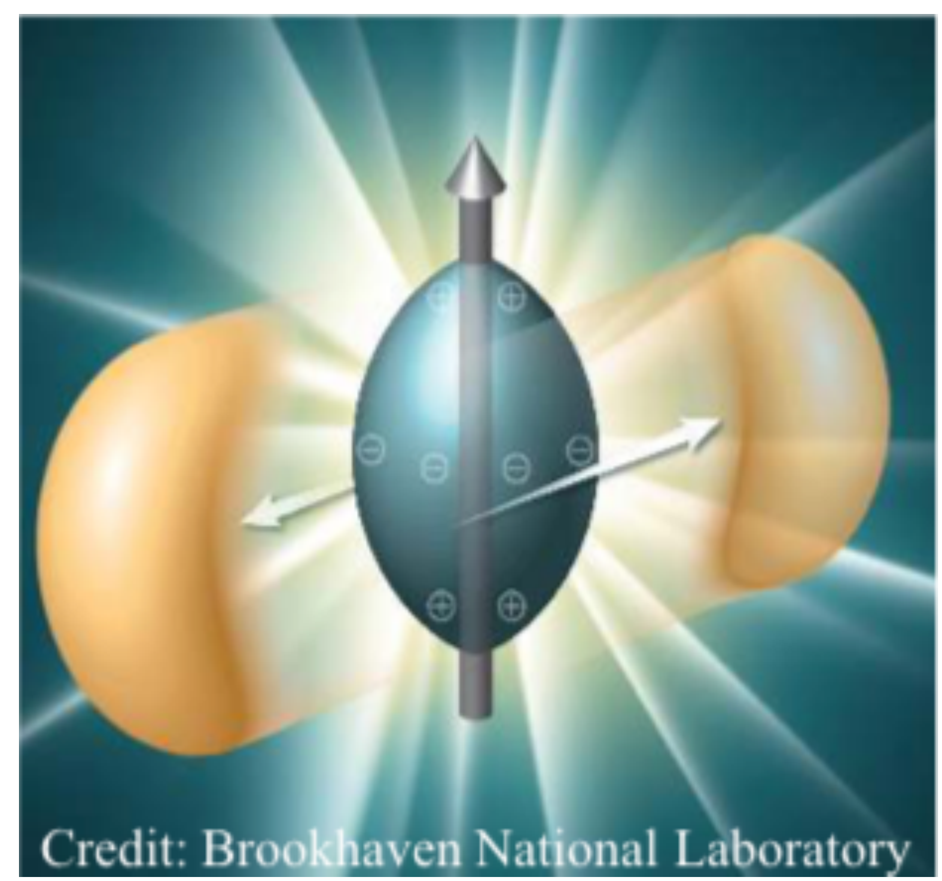


Motivation

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

magnetars:

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

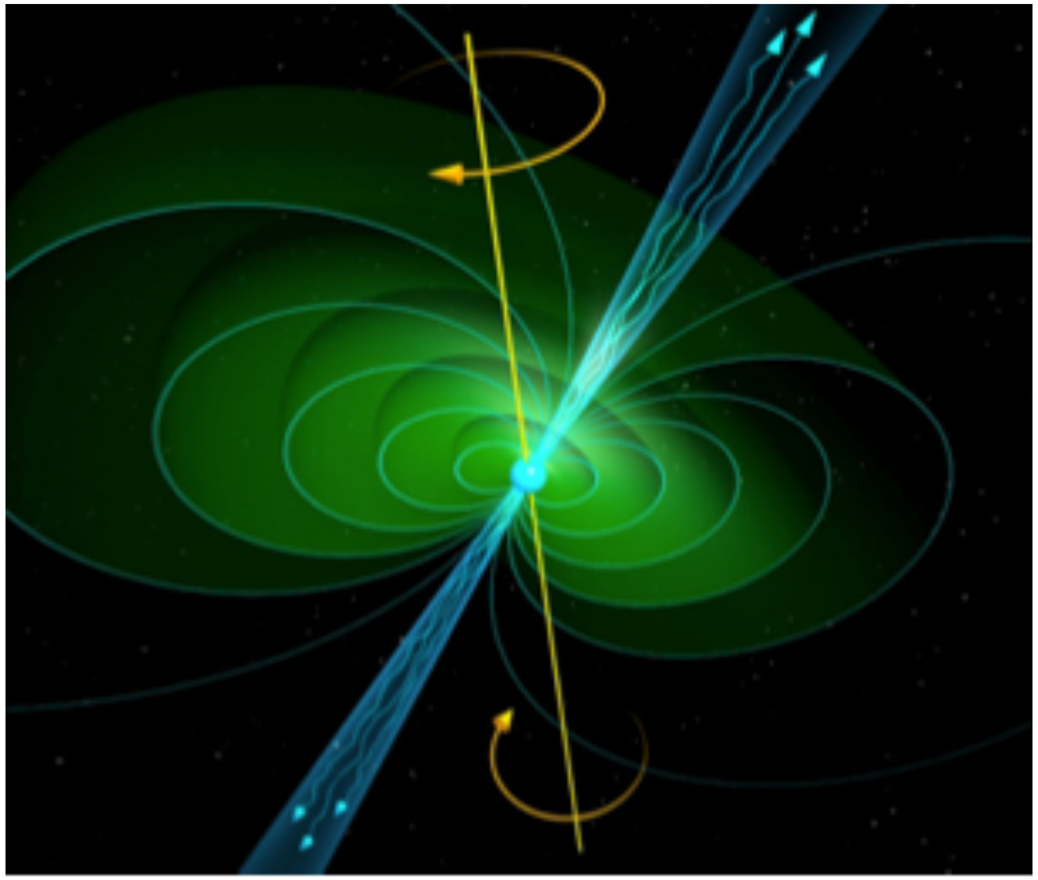
Duncan, Thompson, Astrophys.J. 392, L9 (1992)

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).

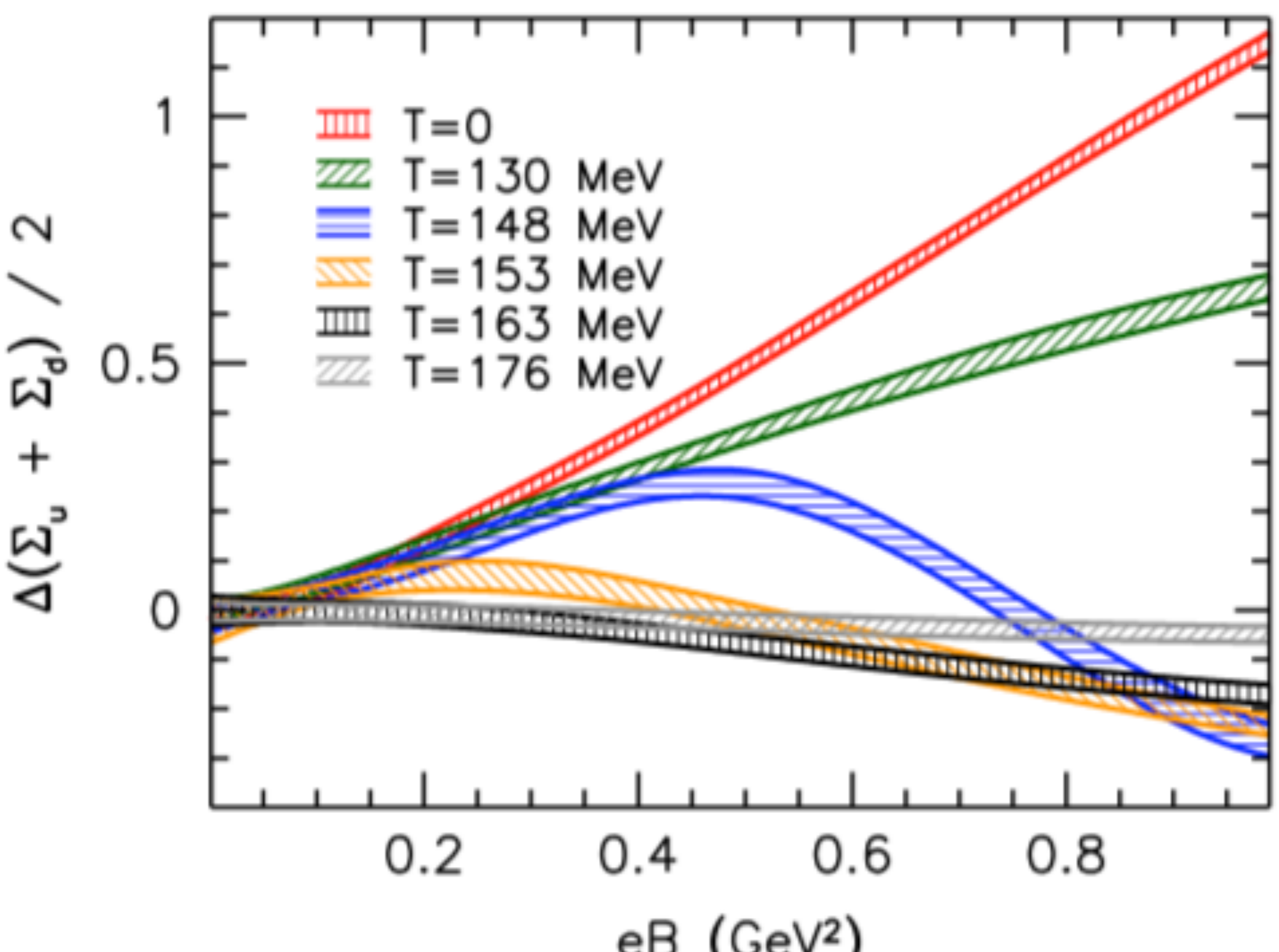
D. Grasso and H.R. Rubinstein, Phys. Rep. 348, 163 (2001).

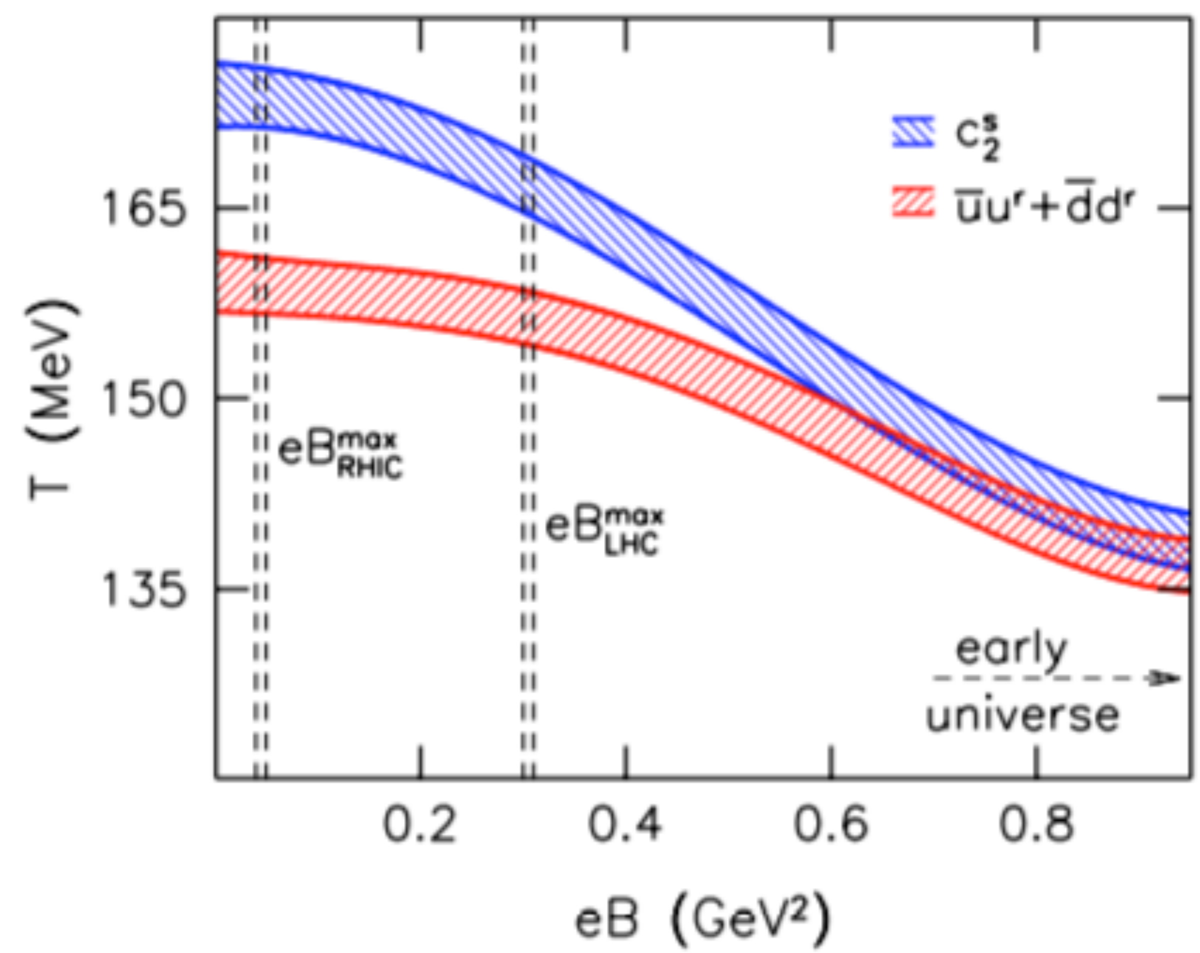
Effect on QCD phase transitions?

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

IMC mini-review
Aritra Bandyopadhyay, R.L.S. Farias,
e-Print: 2003.11054 [hep-ph]

MC and IMC





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

SU(2) Nambu—Jona-Lasinio model (NJL)

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

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

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

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

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

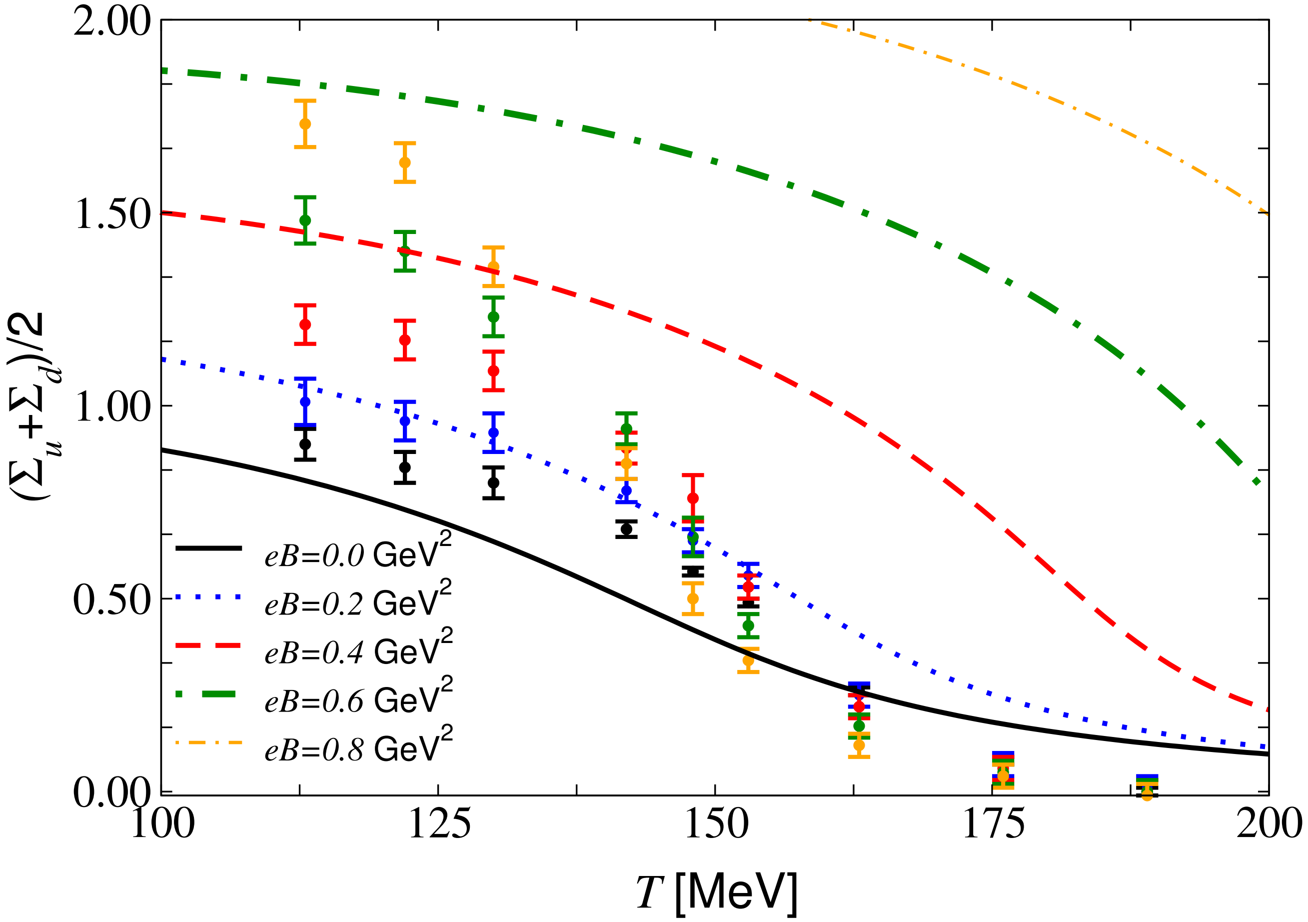
$$\alpha_k = 2 - \delta_{k0}$$

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

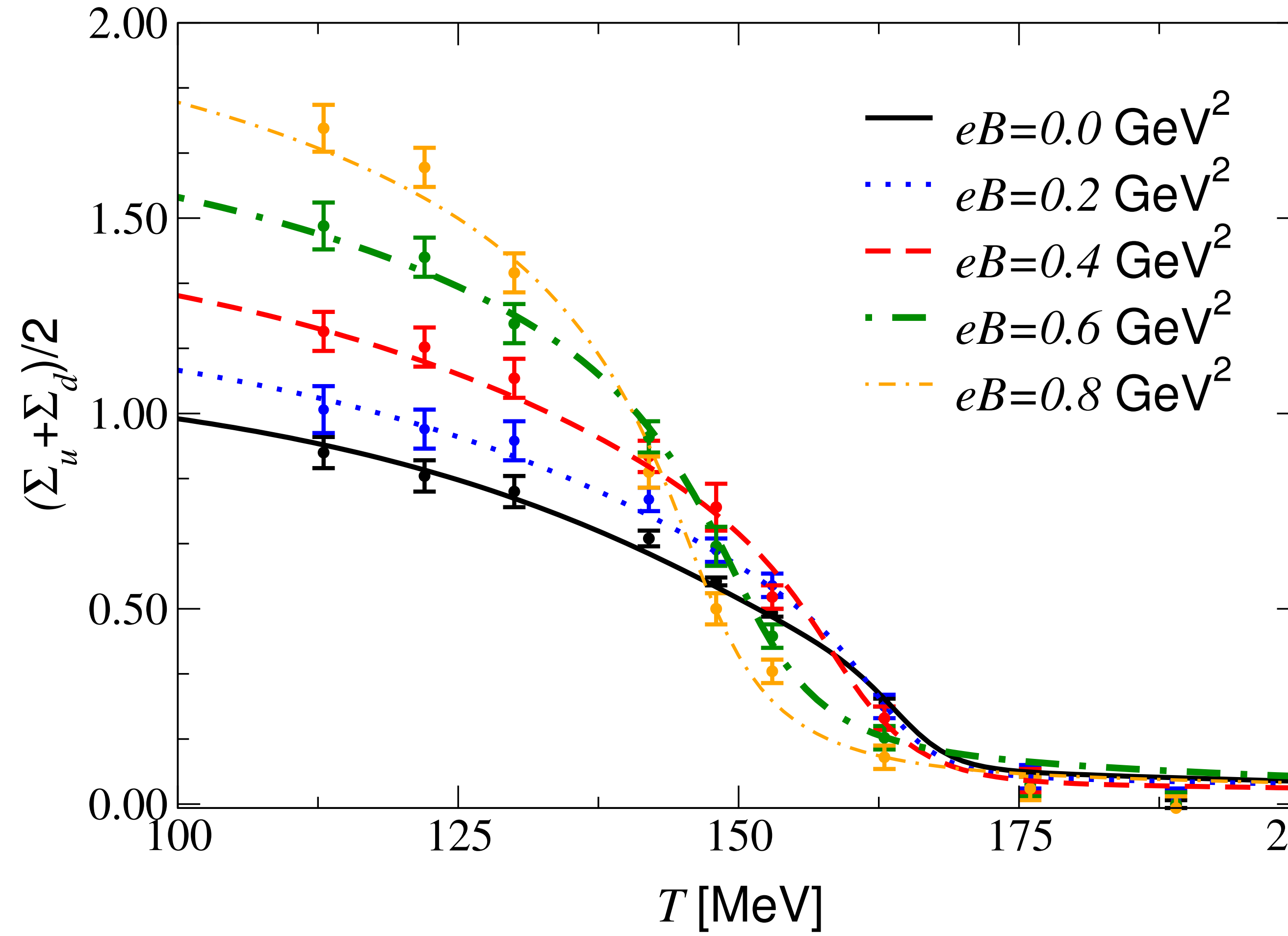
And the gap equation: $\partial\mathcal{F}/\partial M = 0 \longrightarrow \infty$

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

G(0,0)



G(B,T)



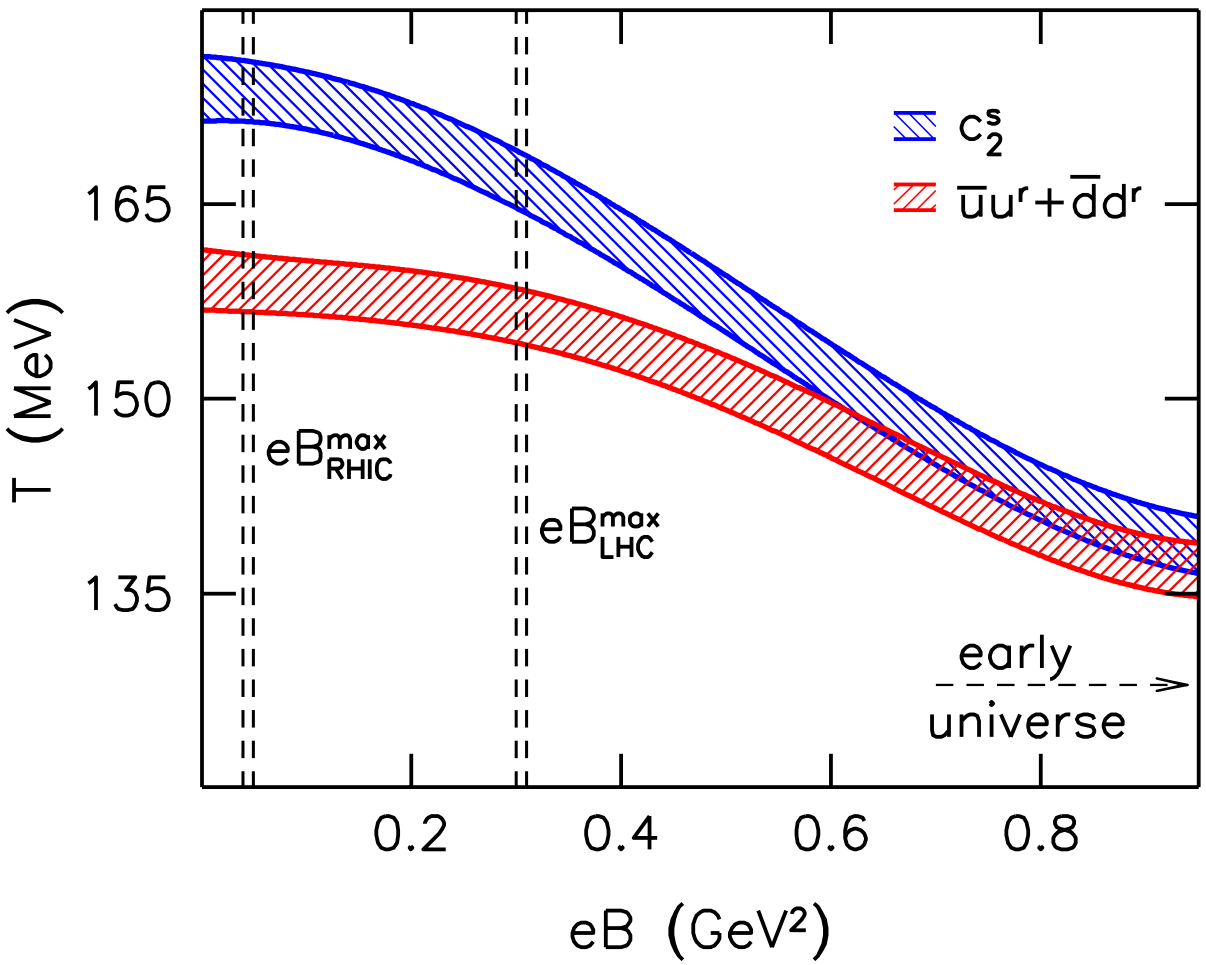
$$\Sigma_f(B,T) = \frac{2m_f}{m_\pi^2 f_\pi^2}\left[\langle\bar{\psi}_f\psi_f\rangle - \langle\bar{\psi}_f\psi_f\rangle_0\right] + 1$$

R. L. S. Farias, Phys. Rev. C 90, 025203 (2014)

Farias at all, Eur. Phys. J. A (2017) 53: 101

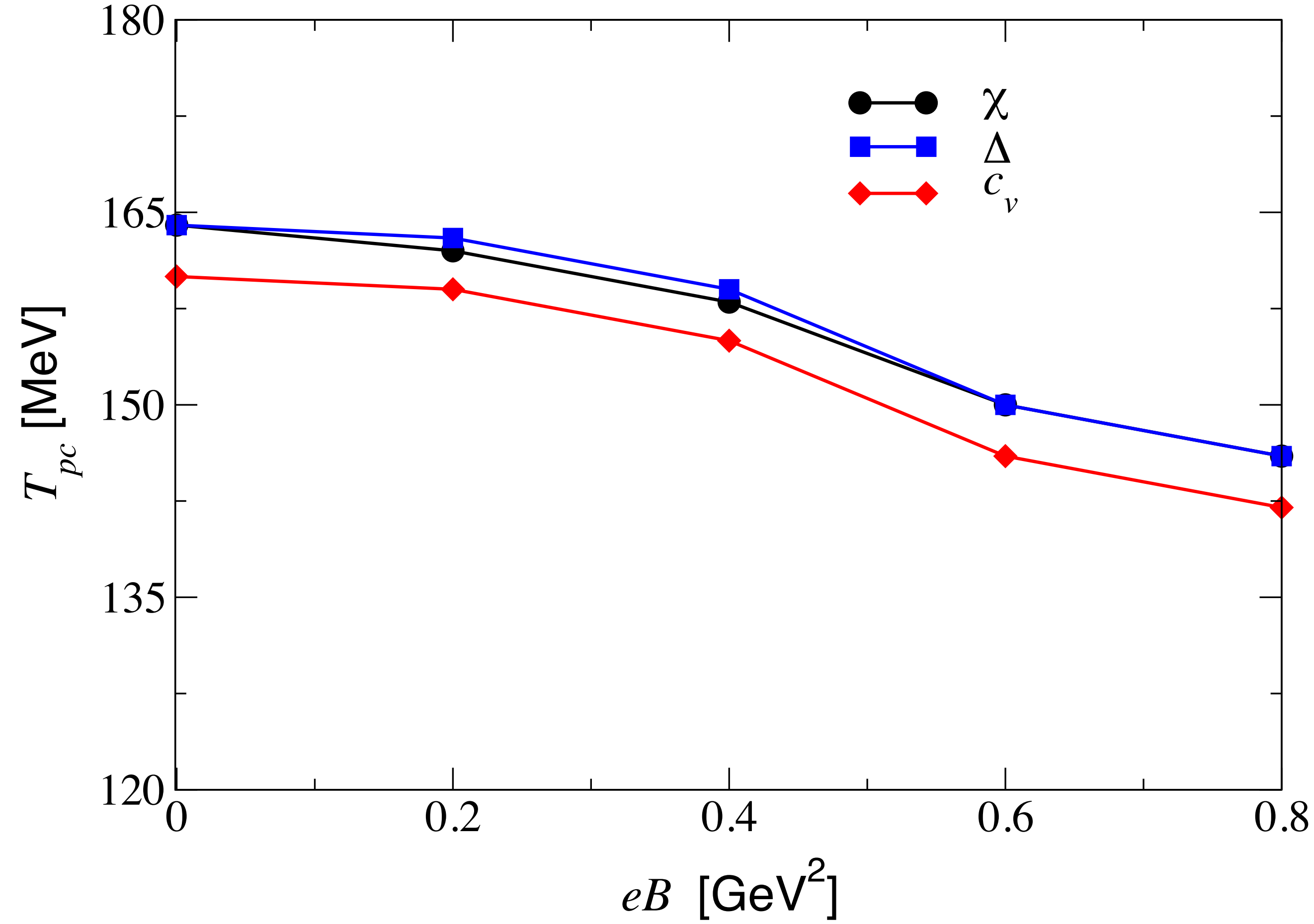
T_{pc} lattice X NJL

Lattice



JHEP 1207 (2012) 056

G(B,T)



Farias at all, Eur. Phys. J. A (2017) 53: 101

G(B,T) **Thermo-magnetic effects!**

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, **Phys. Rev. D 014010 (2016)**

- ✓...

MFIR - Magnetic Field Independent Regularization

$$\frac{\partial \mathcal{F}}{\partial M} = \frac{M - m_0}{2G} - 2MN_c \sum_f \frac{|q_f|B}{2\pi}$$

$$\times \sum_{k=0}^{\infty} \alpha_k \int_{-\infty}^{\infty} \frac{dp_4}{2\pi} \int_{-\infty}^{\infty} \frac{dp_3}{2\pi} \frac{1}{p_4^2 + p_3^2 + 2k|q_f|B + M^2}$$

We add and subtract the B=0 contribution

$$I_1 = 4 \int \frac{dp^4}{(2\pi)^4} \frac{1}{p^2 + M^2}$$

$$\frac{\partial \mathcal{F}}{\partial M} = \frac{M - m_0}{2G} - 2MN_c \left[I_1 + \sum_f I_f \right]$$

MFIR

$$I_f = \int_{-\infty}^{\infty} \frac{dp_4}{2\pi} \int_{-\infty}^{\infty} \frac{dp_3}{2\pi} \left[\frac{|q_f|B}{2\pi} \sum_{k=0} \alpha_k \frac{1}{p_3^2 + p_4^2 + 2k|q_f|B + M^2} \right.$$
$$\left. -2 \int_{-\infty}^{\infty} \frac{dp_1}{2\pi} \int_{-\infty}^{\infty} \frac{dp_2}{2\pi} \frac{1}{p_1^2 + p_2^2 + p_3^2 + p_4^2 + M^2} \right]$$

$$I_f = \frac{M^2}{8\pi^2} \eta(x_f)$$

Where: $\eta(x) = \frac{\ln \Gamma(x)}{x} - \frac{\ln 2\pi}{2x} + 1 - \left(1 - \frac{1}{2x}\right) \ln x$

$$\frac{\partial \mathcal{F}}{\partial M} = \frac{M - m_0}{2G} - 2MN_c I_1 + \frac{Nc}{4\pi^2} M^3 \sum_f \eta(x_f)$$

$$x_f = M^2/(2|q_f|B)$$

$I_1 \to \infty$

Noncovariant Regularizations

Form factors: $$\sum_{k=0}^{\infty}\int_{-\infty}^{\infty}\frac{dp_3}{2\pi}\rightarrow\sum_{k=0}^{\infty}\int_{-\infty}^{\infty}\frac{dp_3}{2\pi}\,U_\Lambda(p_3^2+2k|q_f|B)$$

✓ Lorenztian: $$U_\Lambda^{(LorN)}(x)=\left[1+\left(\frac{x}{\Lambda^2}\right)^N\right]^{-1}$$

✓ Wood-Saxon: $$U_\Lambda^{(WS\alpha)}(x)=\left[1+\exp\left(\frac{x/\Lambda^2-1}{\alpha}\right)\right]^{-1}$$

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

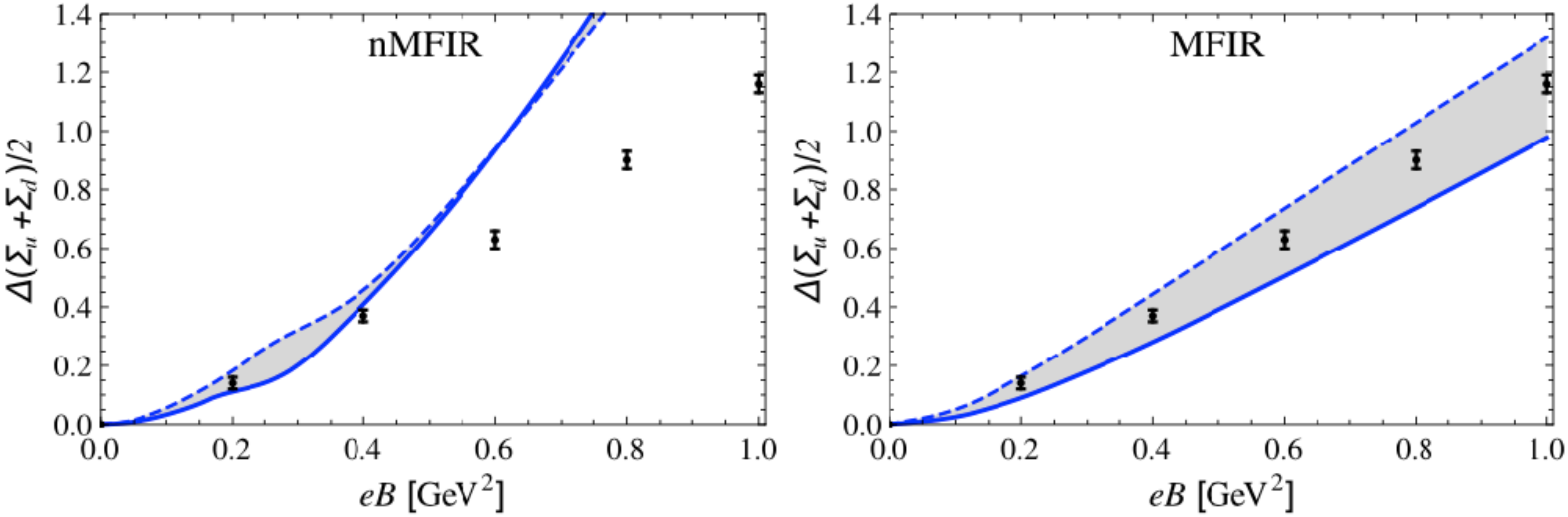
✓ 3D sharp cutoff

S.S. Avancini, R. L. S. Farias, N. Scoccola, W.R. Tavares, PRD 99, 116002 (2019)

Lorentzian Form Factor

$$U_\Lambda^{(Lor N)}(x) = \left[1 + \left(\frac{x}{\Lambda^2}\right)^N\right]^{-1}$$

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

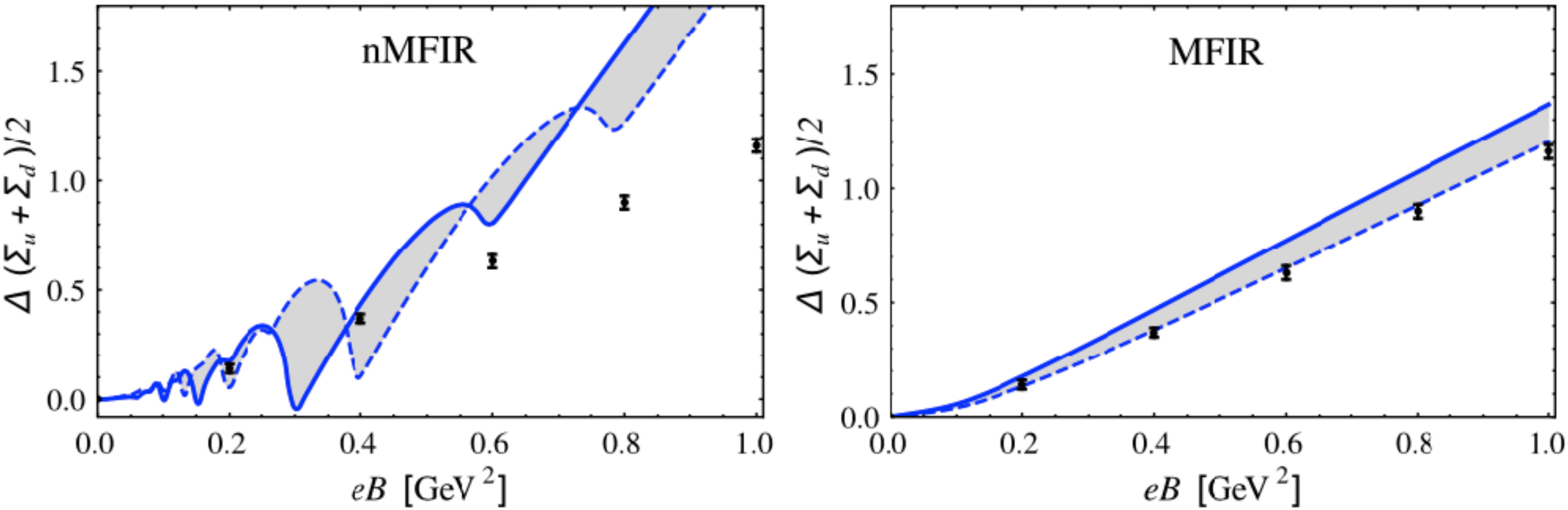


S.S. Avancini, R. L. S. Farias, N. Scoccola, W.R. Tavares, PRD 99, 116002 (2019)

Fermi-Dirac Form Factor

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

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

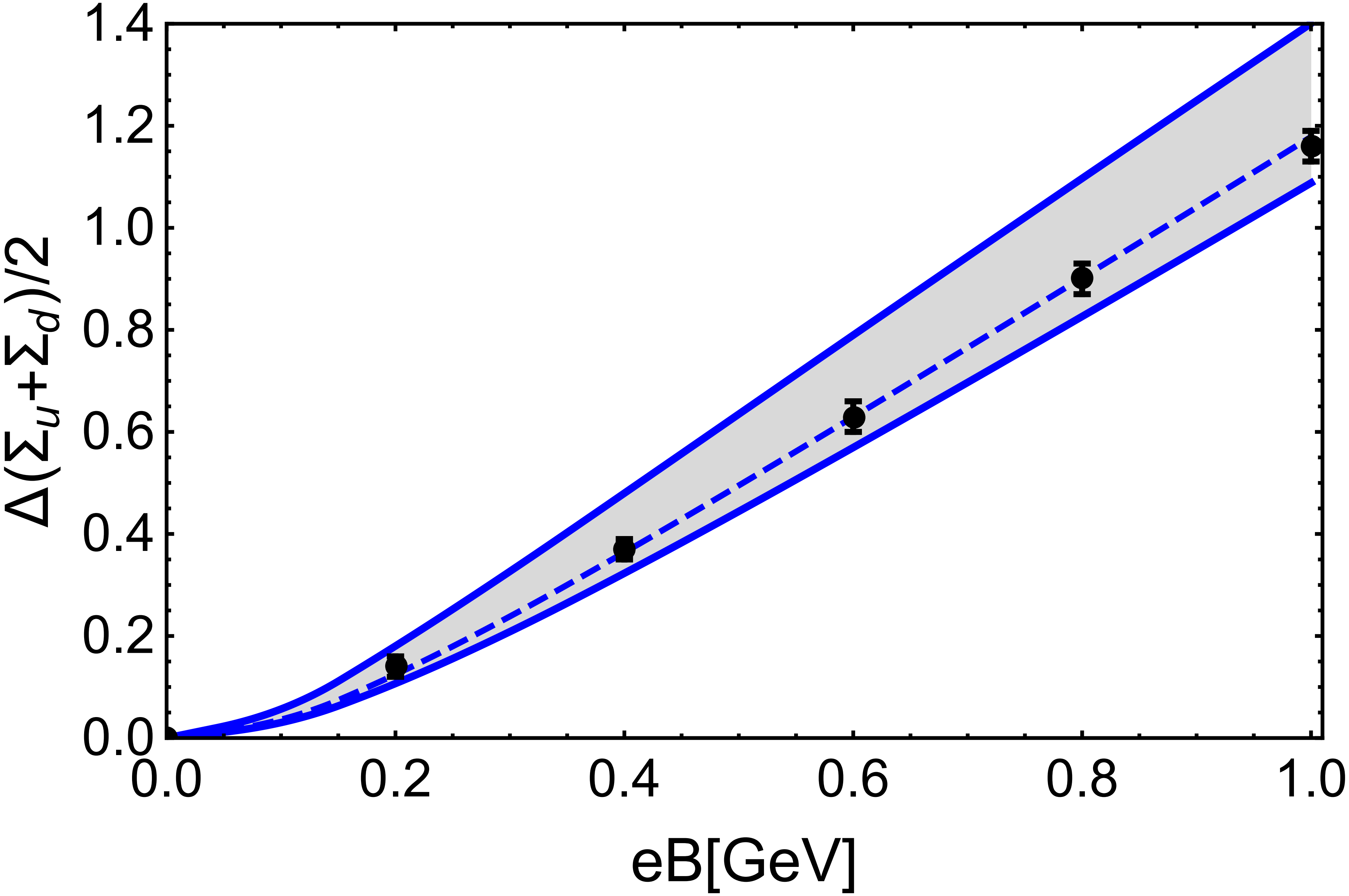


S.S. Avancini, R. L. S. Farias, N. Scoccola, W.R. Tavares, PRD 99, 116002 (2019)

Cutoff 3D + MFIR

$$241\,\mathrm{MeV} < -\bar{\Phi}_0^{1/3} < 260\,\mathrm{MeV}$$

$$I_1^{3D} \quad = \quad \frac{\Lambda^2}{2\pi^2}\left[\sqrt{1+M_\Lambda^2} + M_\Lambda^2 \ln \frac{M_\Lambda}{1+\sqrt{1+M_\Lambda^2}}\right]$$



Covariant Regularizations:

- ✓ 4D sharp cutoff
- ✓ Proper time
- ✓ Pauli-Villars

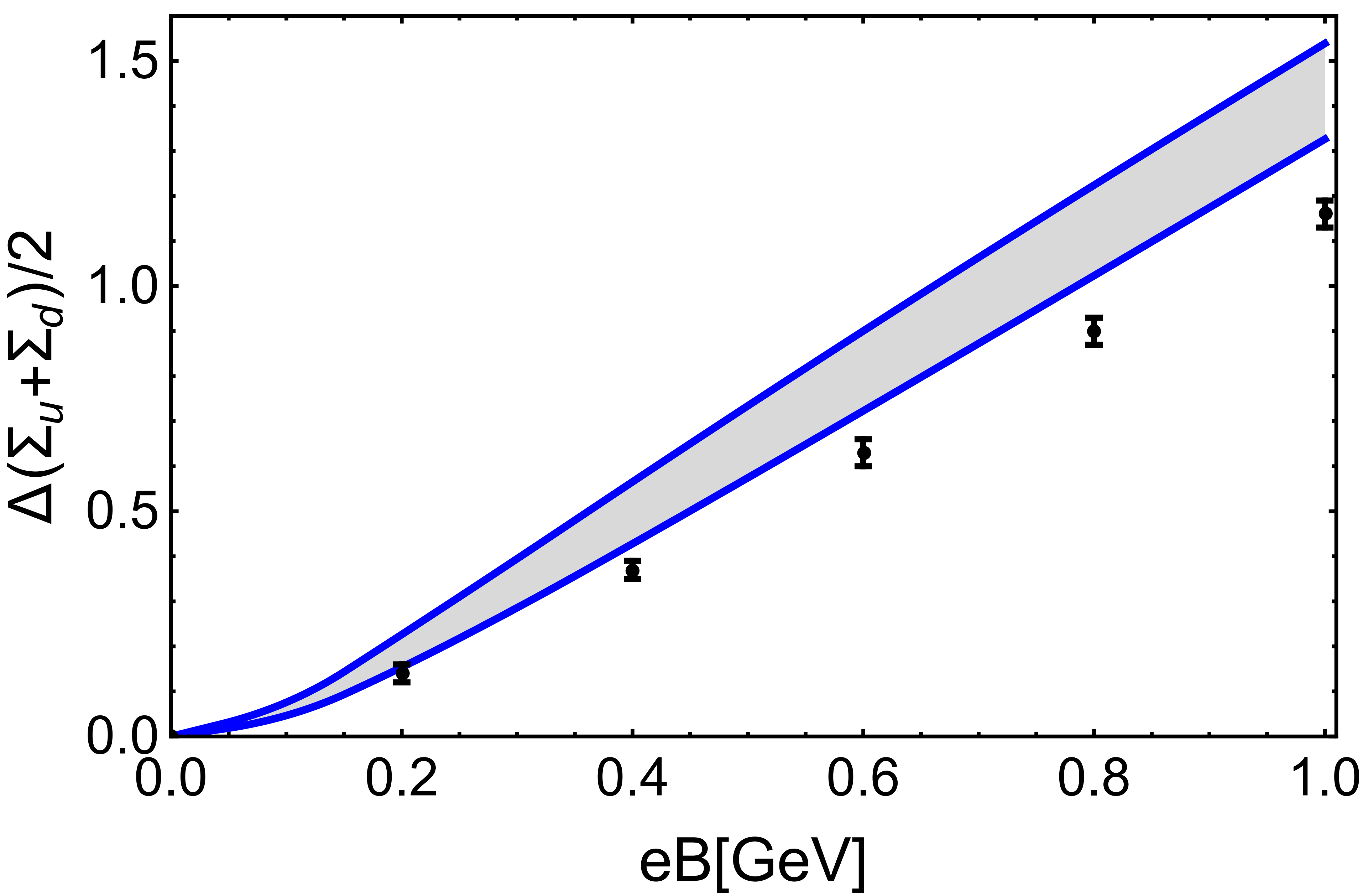
$$\mathcal{F} = \frac{(M - m_c)^2}{4G} - N_c \sum_f \frac{|q_f|B}{2\pi} \sum_{k=0}^{\infty} \alpha_k \int_{-\infty}^{\infty} \frac{dp_3}{2\pi} \int_{-\infty}^{\infty} \frac{dp_4}{2\pi} \ln\left[p_4^2 + p_3^2 + 2k|q_f|B + M^2\right]$$

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

S.S. Avancini, R. L. S. Farias, N. Scoccola, W.R. Tavares, PRD 99, 116002 (2019)

Cutoff 4D + MFIR

$$245\,\mathrm{MeV} < -\bar{\Phi}_0^{1/3} < 260\,\mathrm{MeV} \qquad I_1^{4D} = \frac{\Lambda^2}{4\pi^2}\left[1 + M_\Lambda^2 \ln \frac{M_\Lambda^2}{1+M_\Lambda^2}\right]$$



$$M_\Lambda = \frac{M}{\Lambda}$$

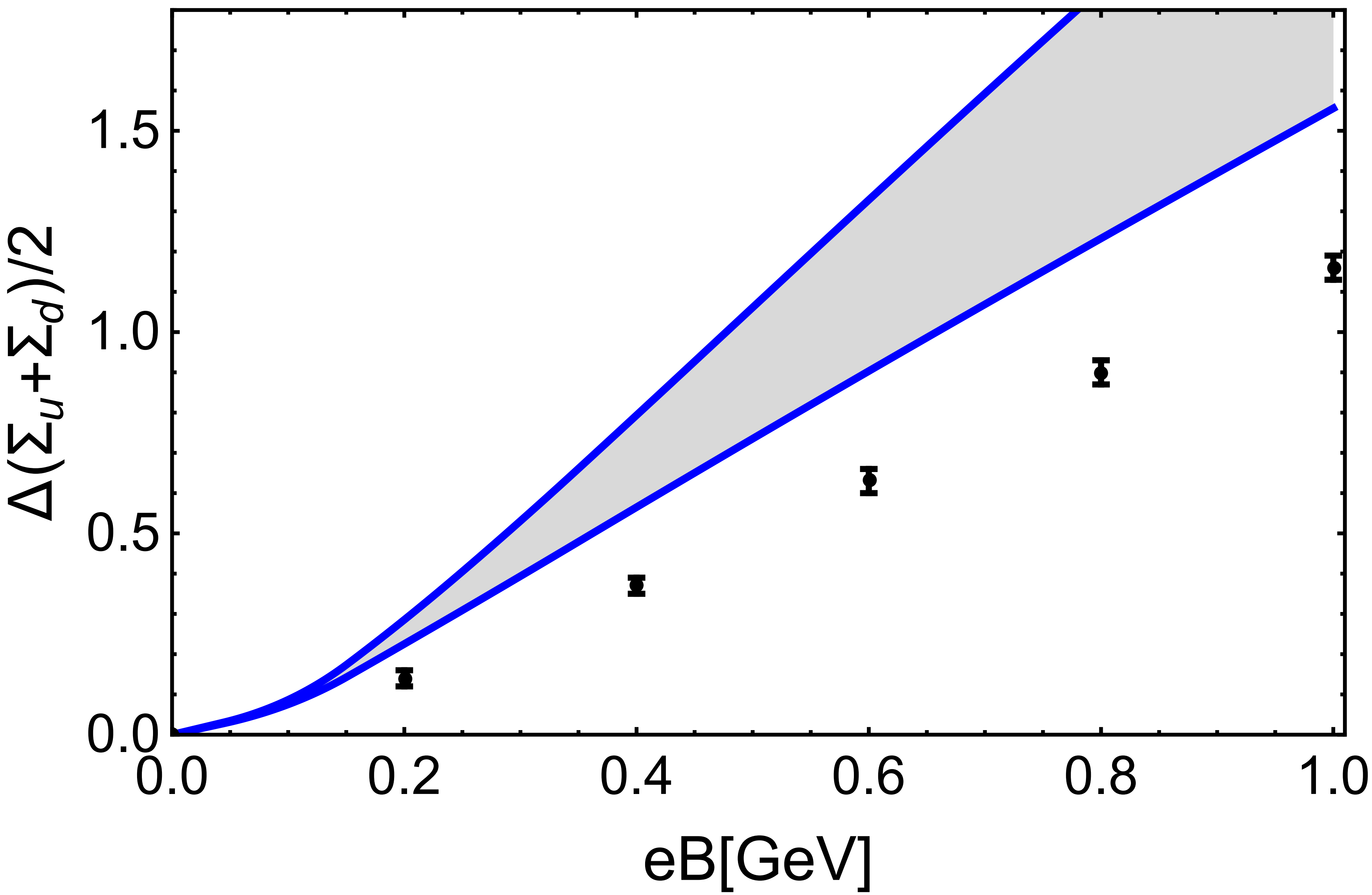
Proper Time + MFIR

$$220\,\mathrm{MeV} < -\bar{\Phi}_0^{1/3} < 260\,\mathrm{MeV}$$

$$\frac{1}{p^2+M^2} = \int_0^\infty e^{-\tau(p^2+M^2)}d\tau$$

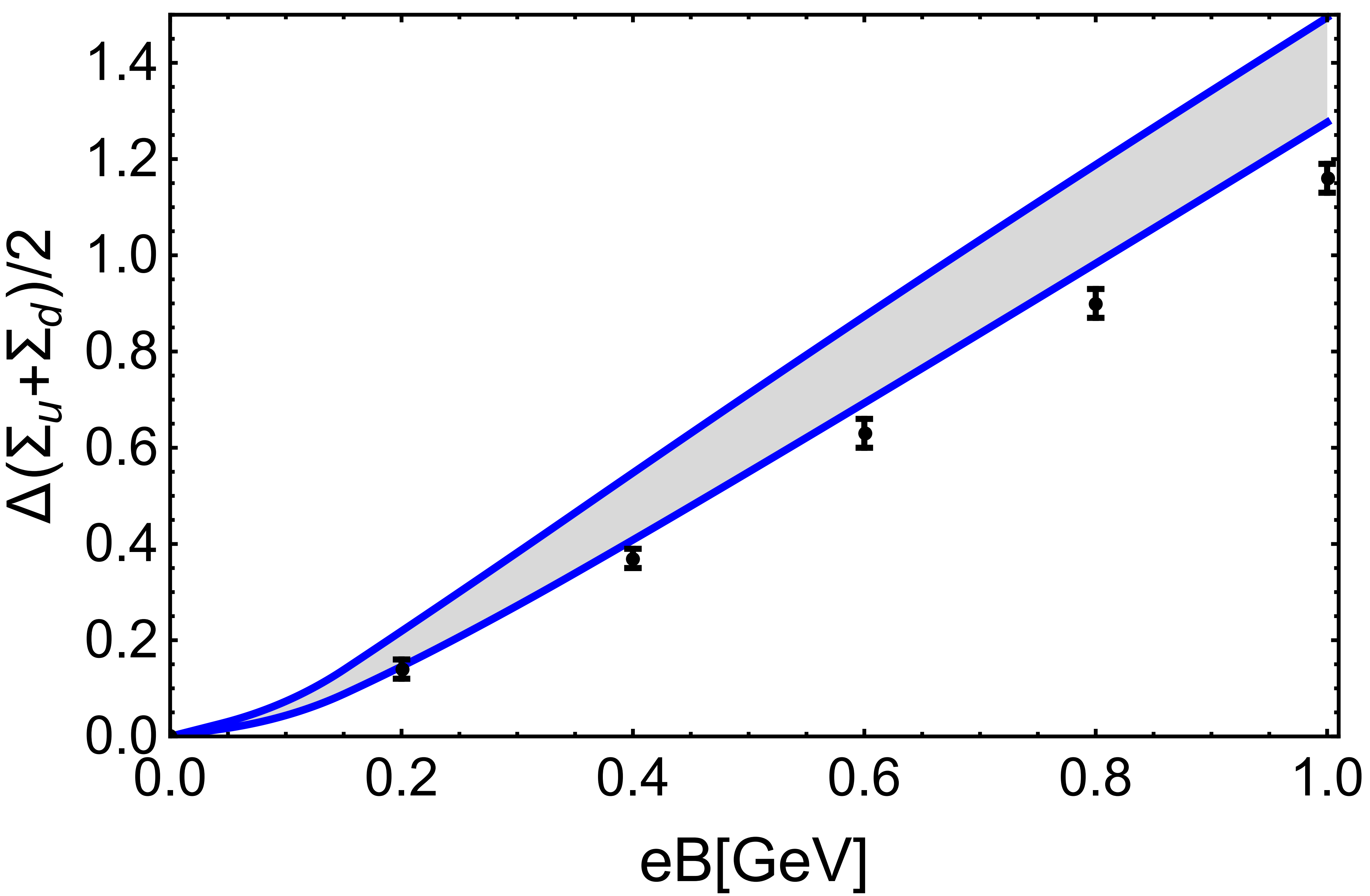
$$I_1^{PT} = \frac{\Lambda^2}{4\pi^2}E_2\left(M_\Lambda^2\right)$$

$$E_n(x) = \int_1^\infty d\tau\tau^{-n}e^{-\tau x}$$



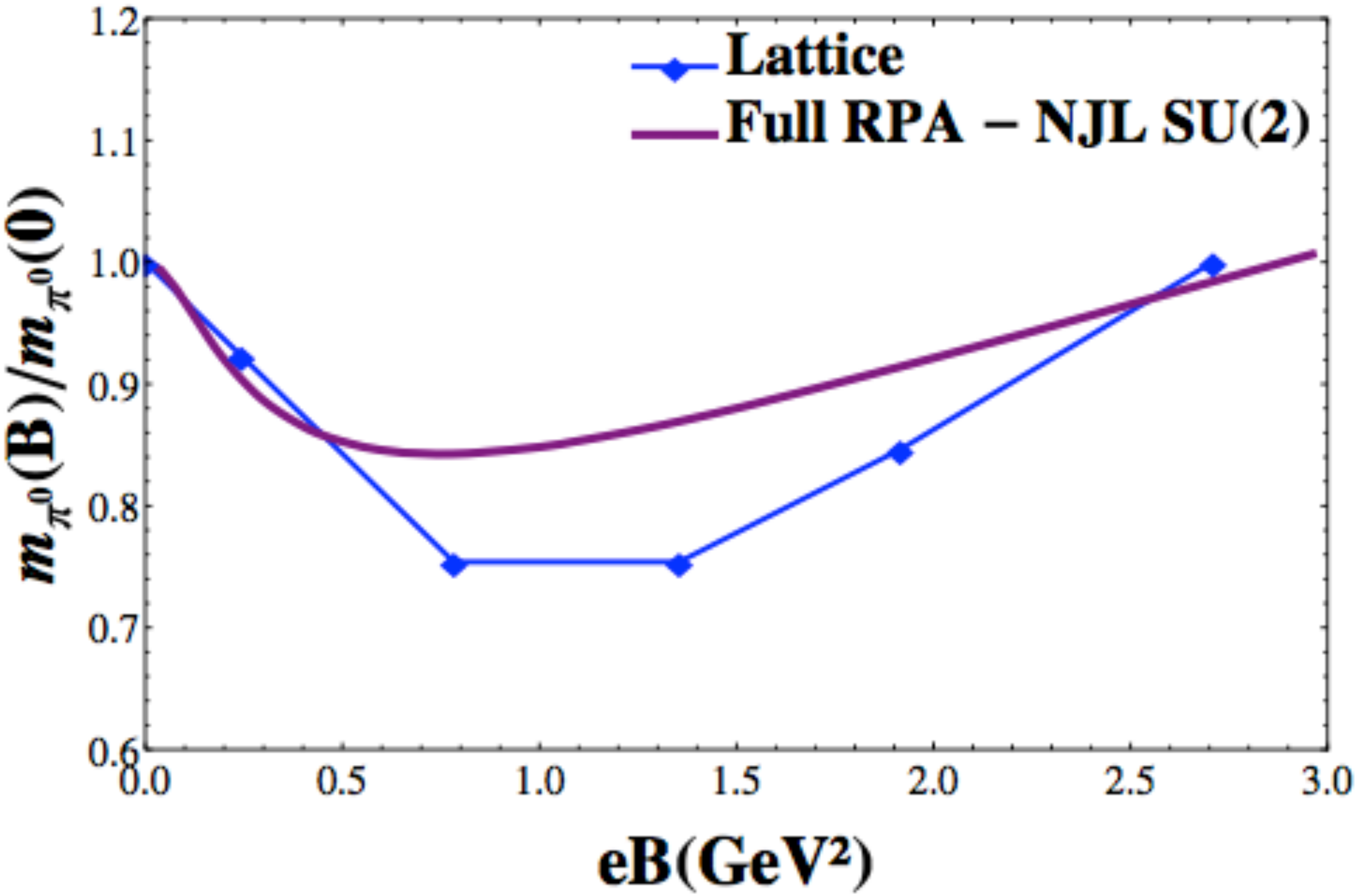
Pauli-Villars + MFIR

$$220\,\mathrm{MeV} < -\bar{\Phi}_0^{1/3} < 260\,\mathrm{MeV}$$



Meson masses

Lattice Results (2013)



Y. Hidaka and A. Yamamoto,

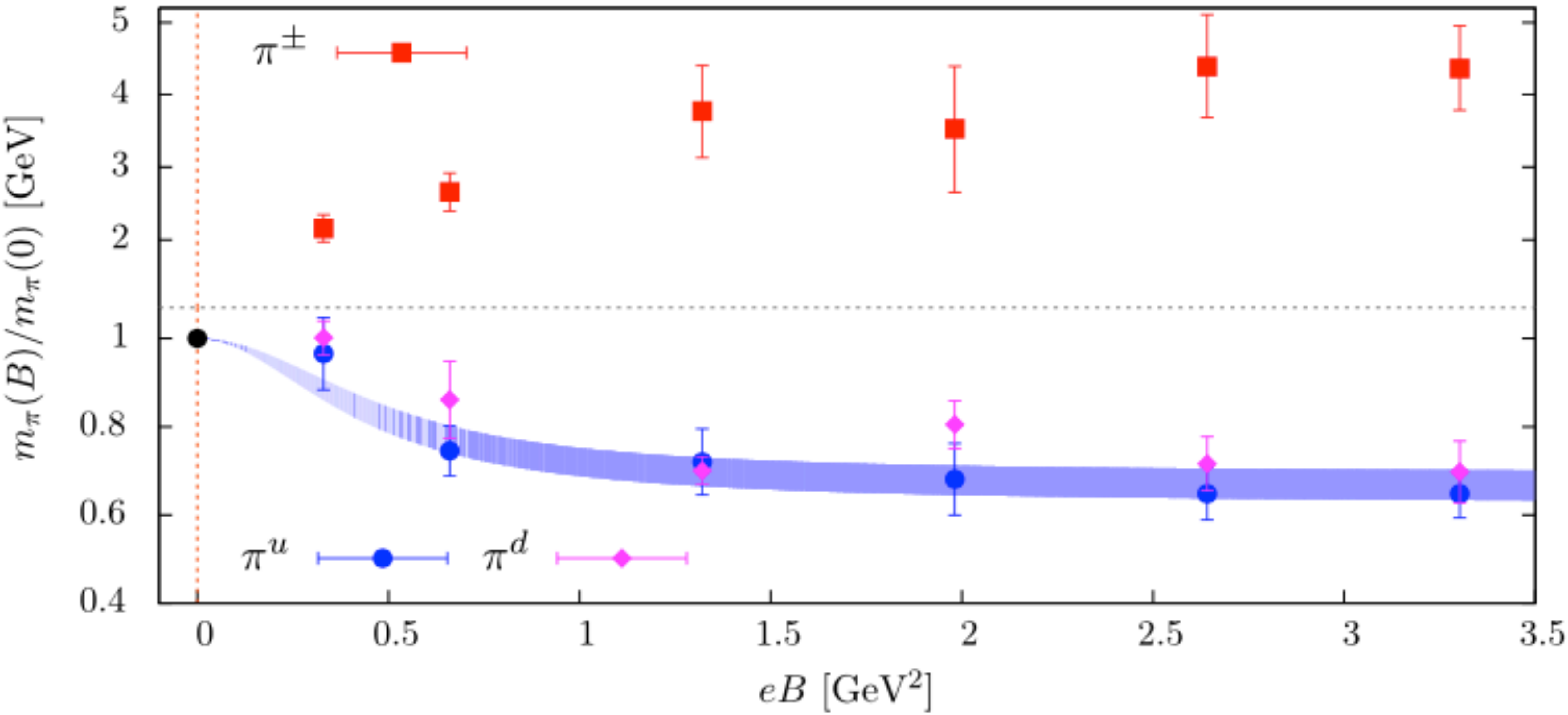
Phys. Rev. D 87, 094502 (2013)

NJL + MFIR

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

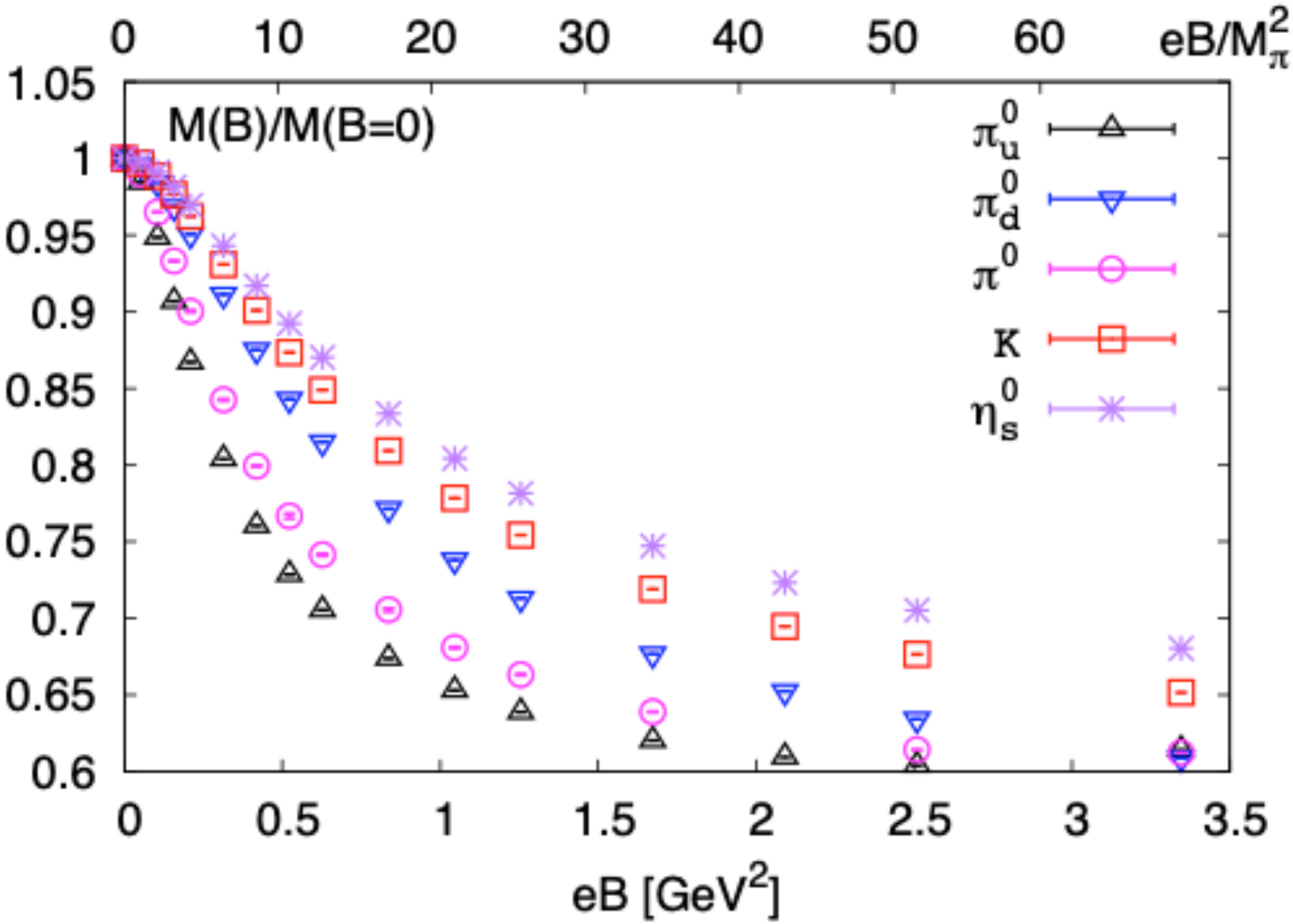
Phys.Rev D 93, 014010 (2016)

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, e-Print:2008.00493 [hep-lat].

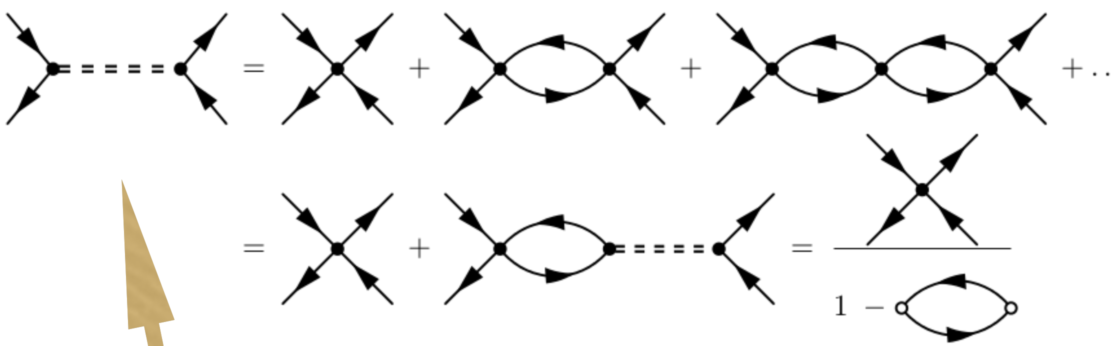
NJL - Meson properties at finite B

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:



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

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

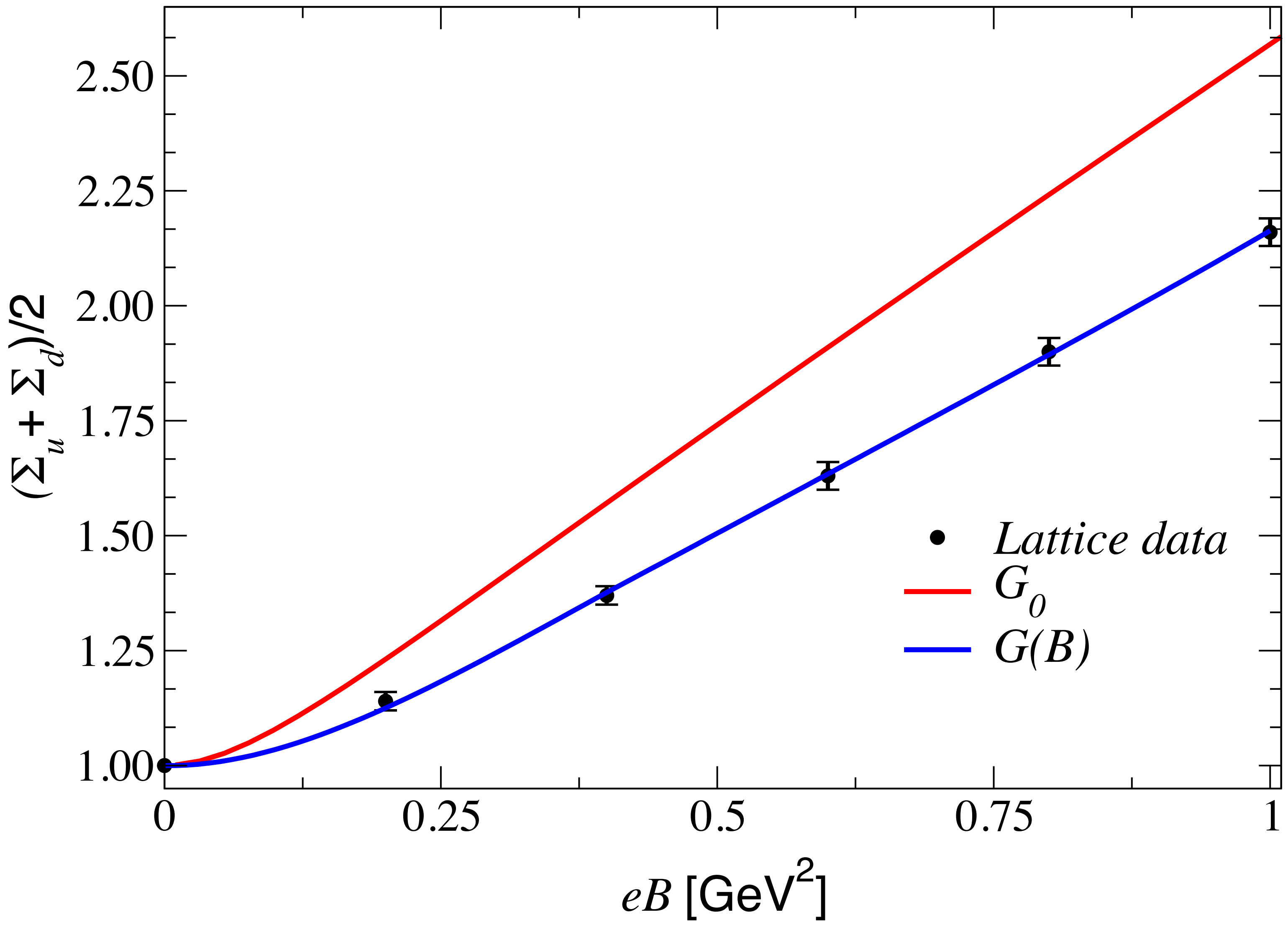
$$\mathcal{L}_{\pi qq} = ig_{\pi qq}\overline{\psi}\gamma_5 \vec{\tau}\cdot\vec{\pi}\psi$$

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

✓ Magnetic Field Independent Regularization (MFIR)

Field dependent coupling G(B,T=0)

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

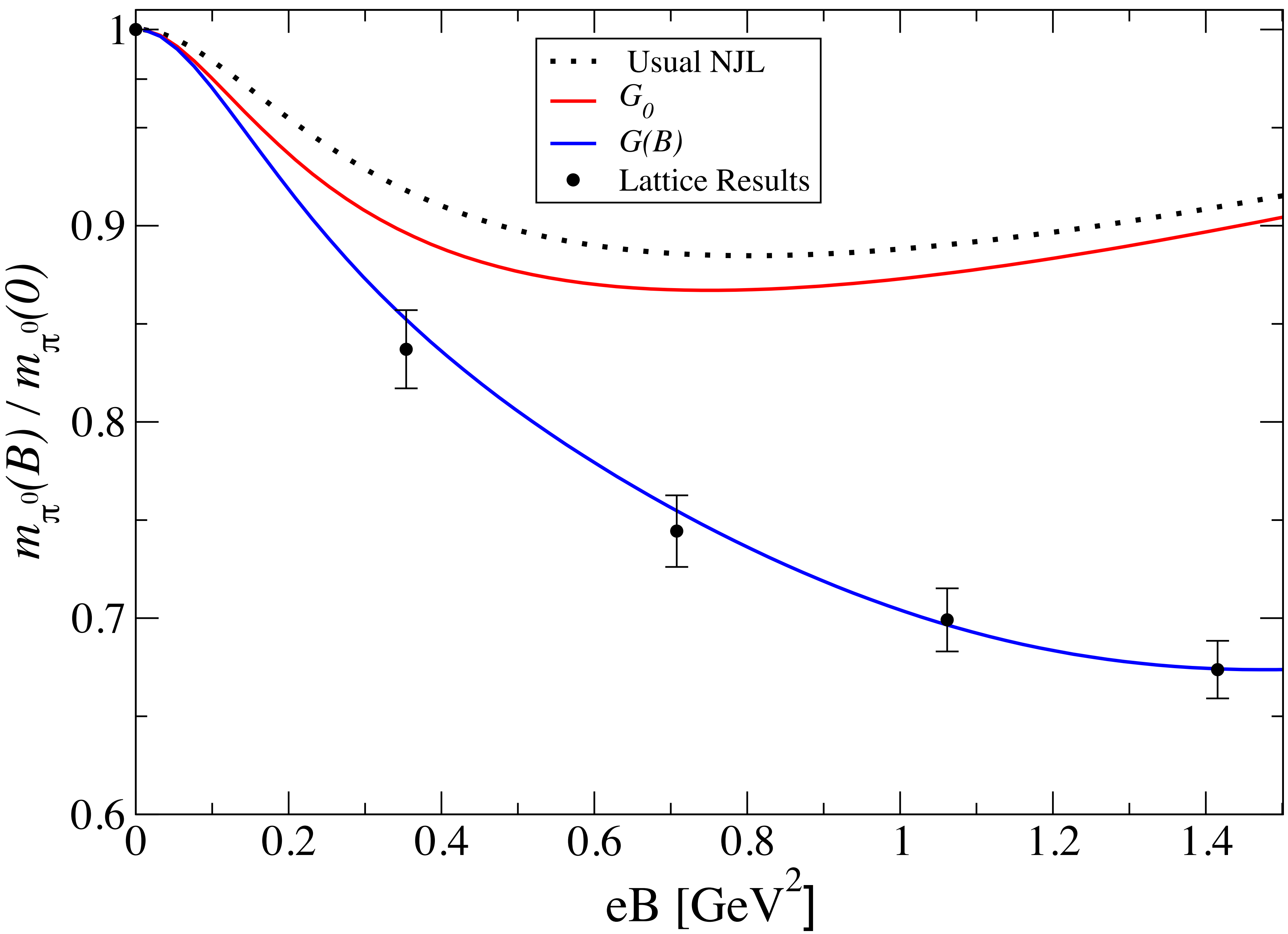


$$G(eB) = \alpha + \beta\, e^{-\gamma\,(eB)^2}$$

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

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

Meson masses at finite B



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

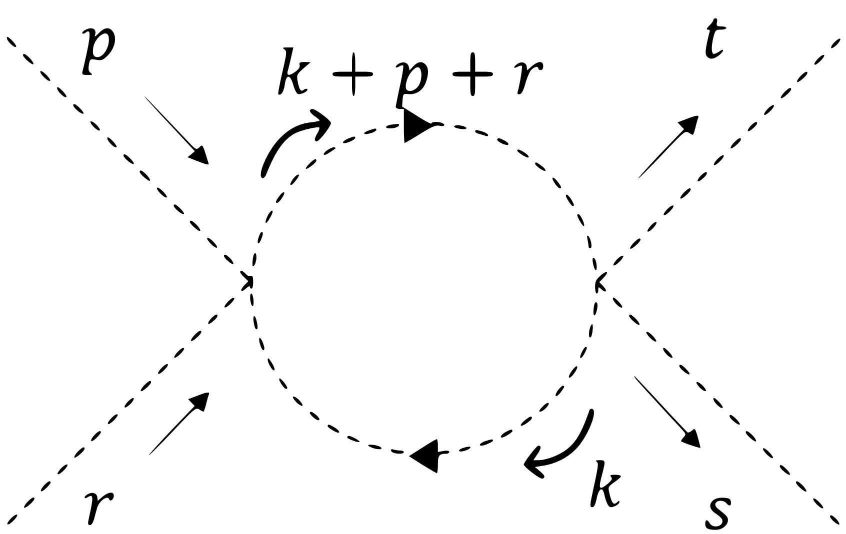
Lattice data: G. Bali, B.B. Brandt, G. Endrodi, B. Glaessle, arXiv:1510.03899 [hep-lat]

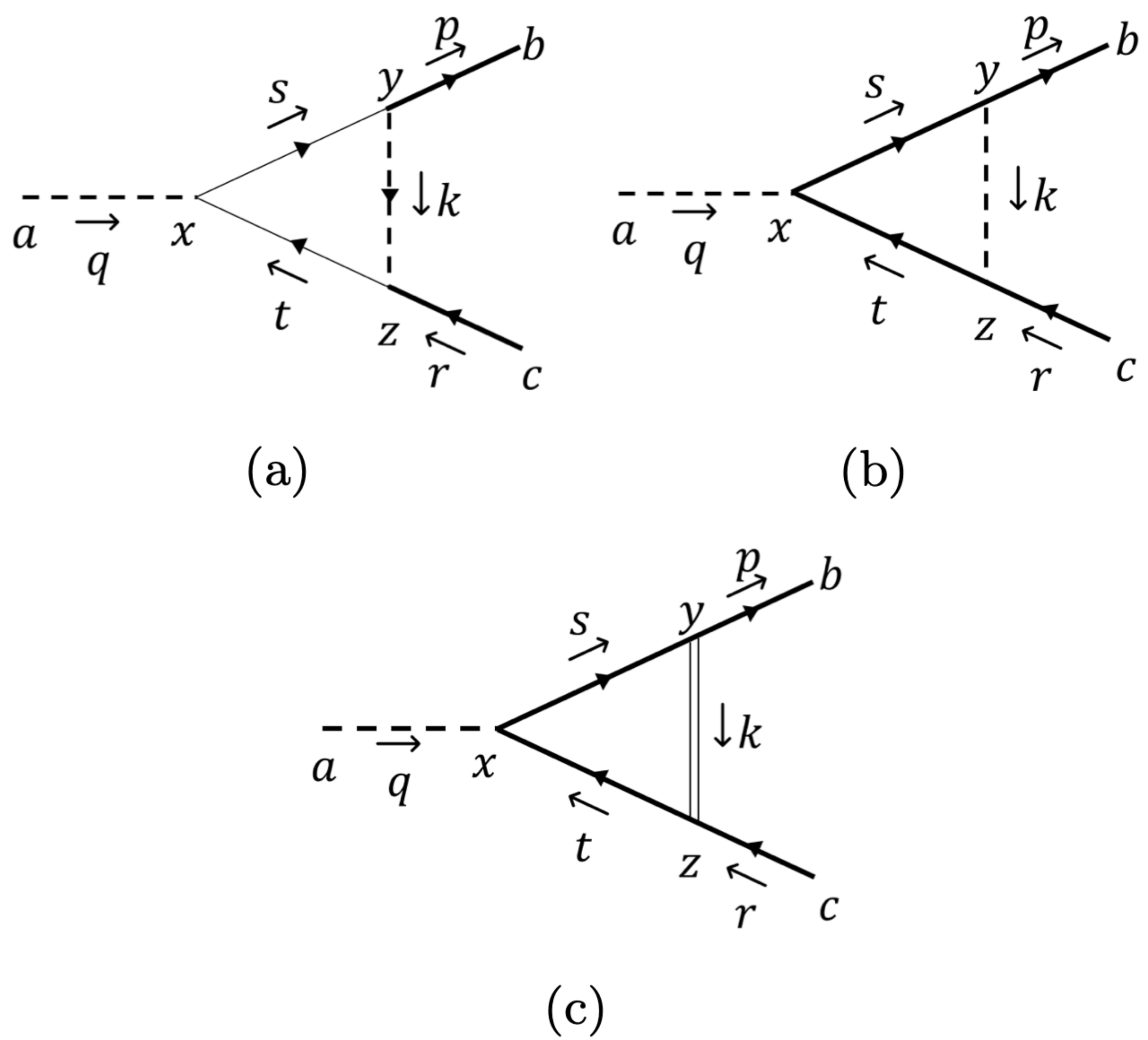
Linear Sigma model with quarks - LSMq

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

- 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.

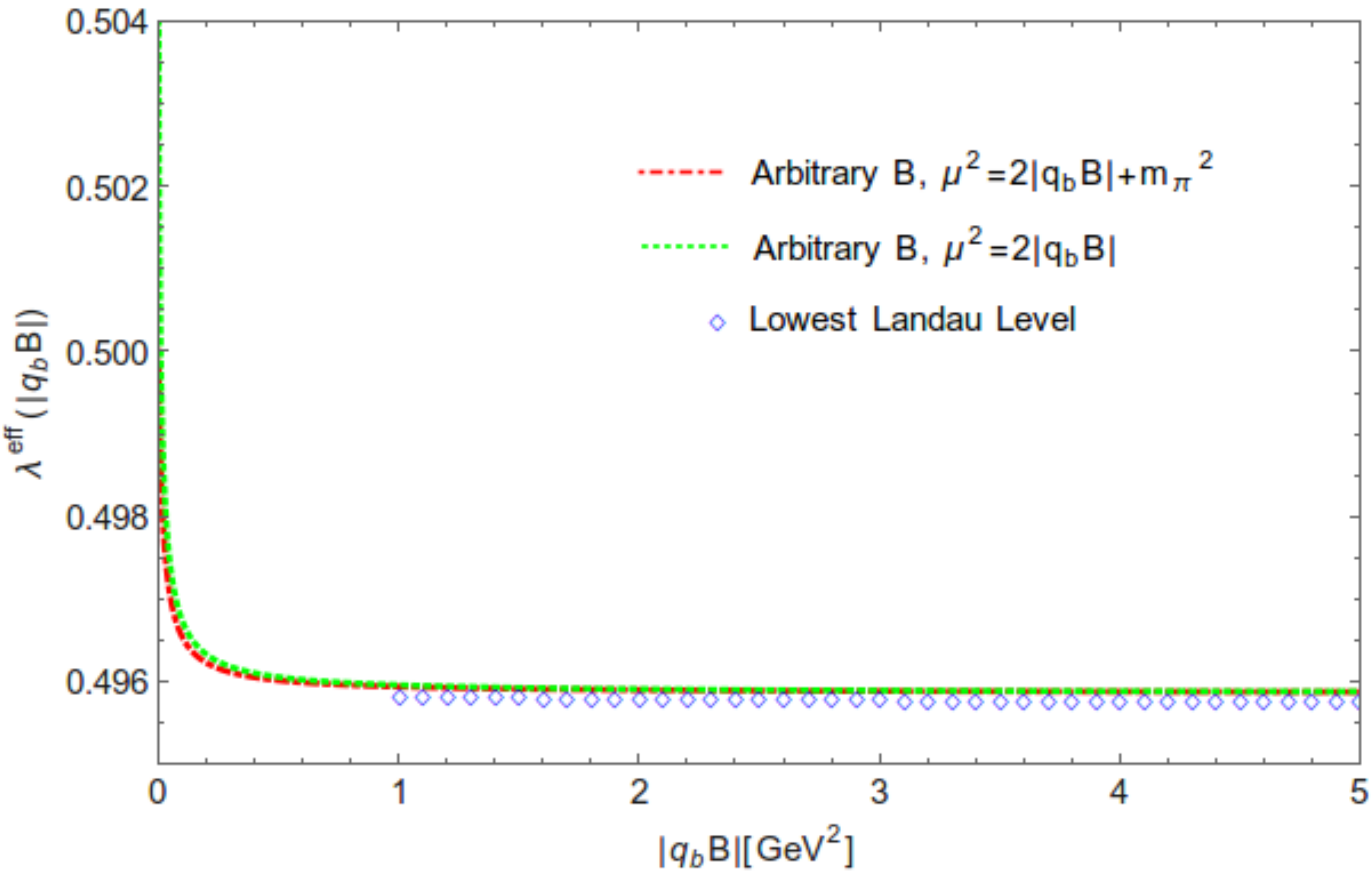
Magnetic corrections to the boson self-coupling and boson-fermion coupling in the LSMq





arXiv:2009.13740 [hep-ph], A.Ayala, J.L.Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora

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



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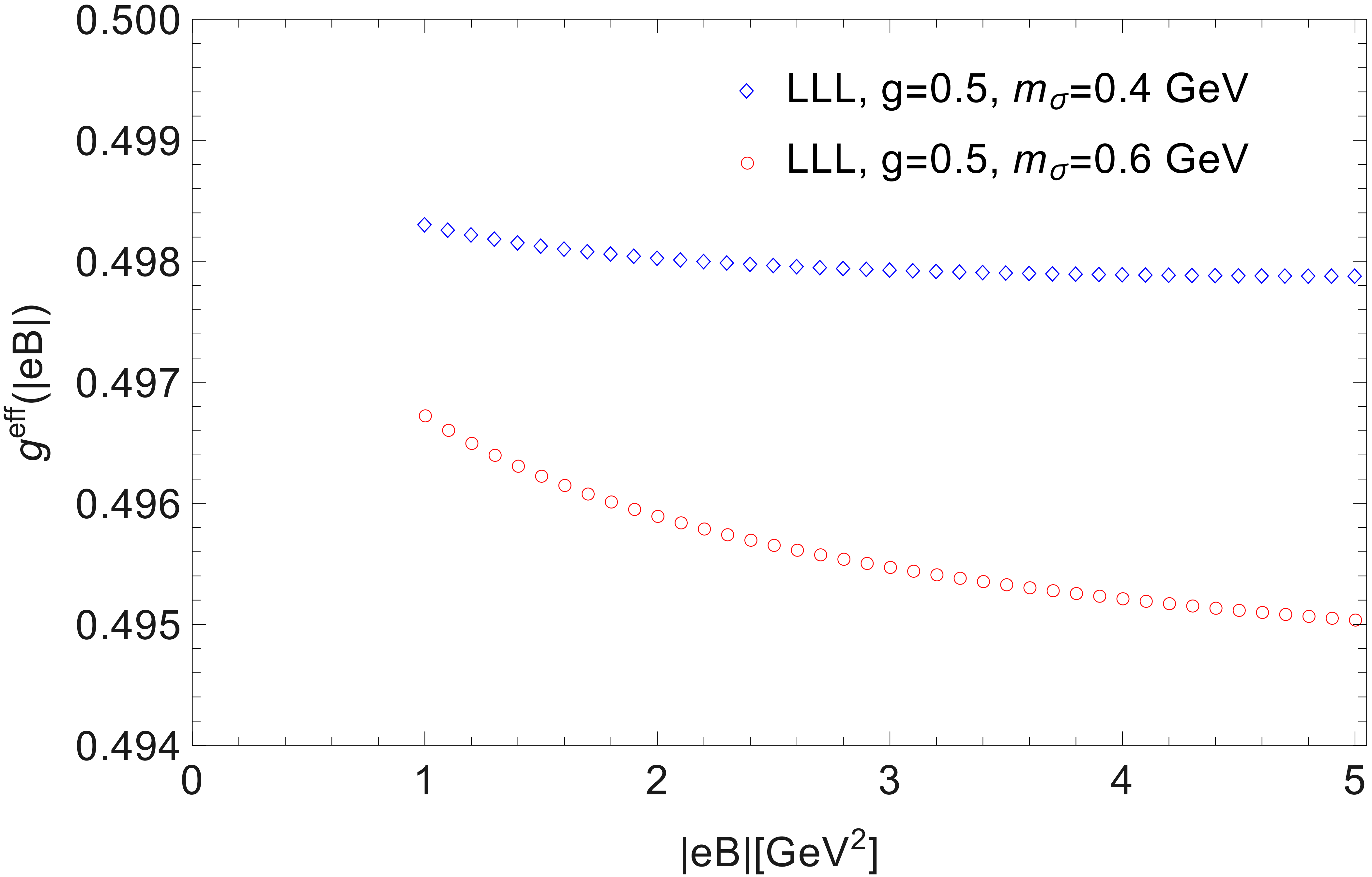
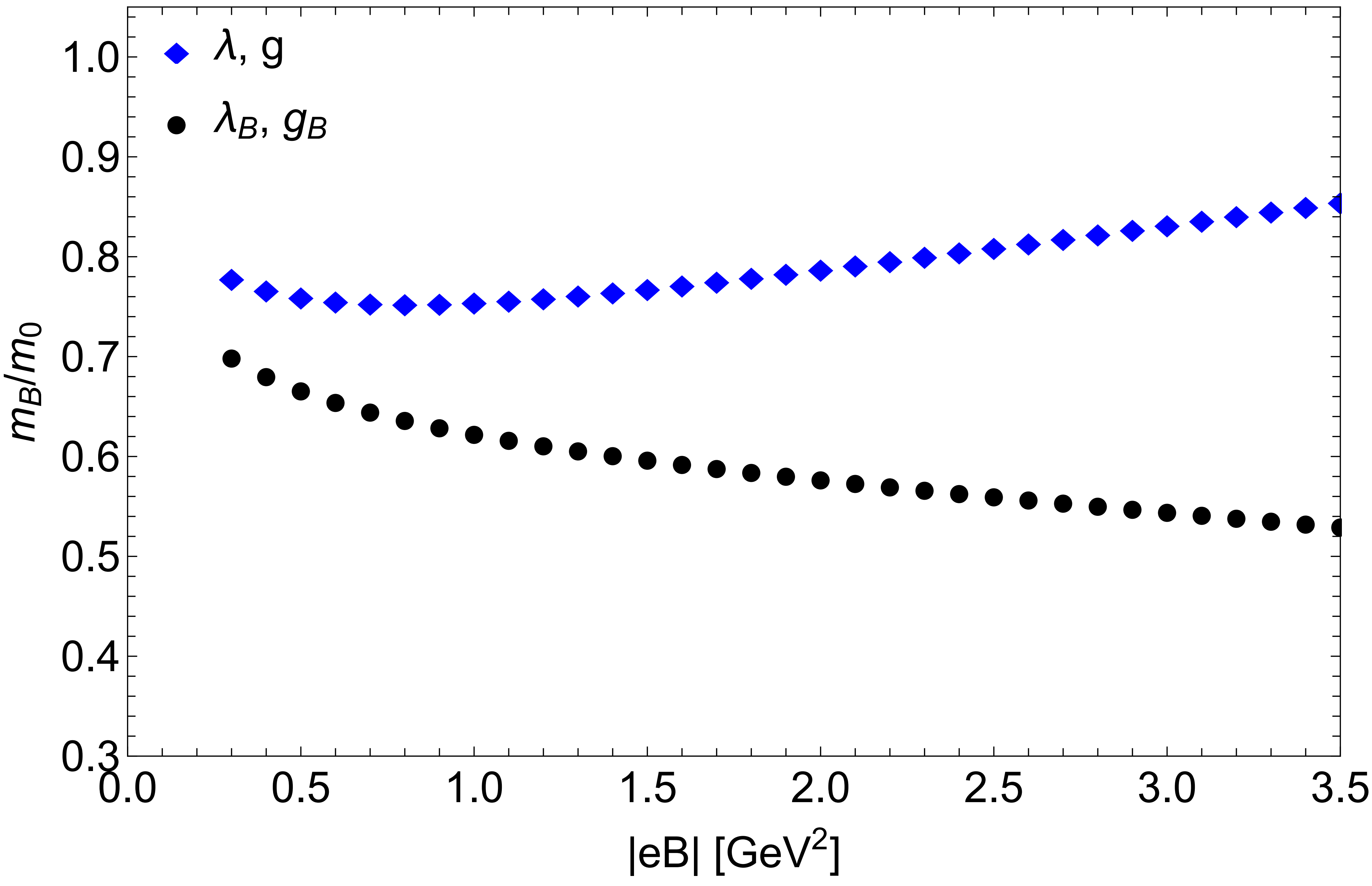


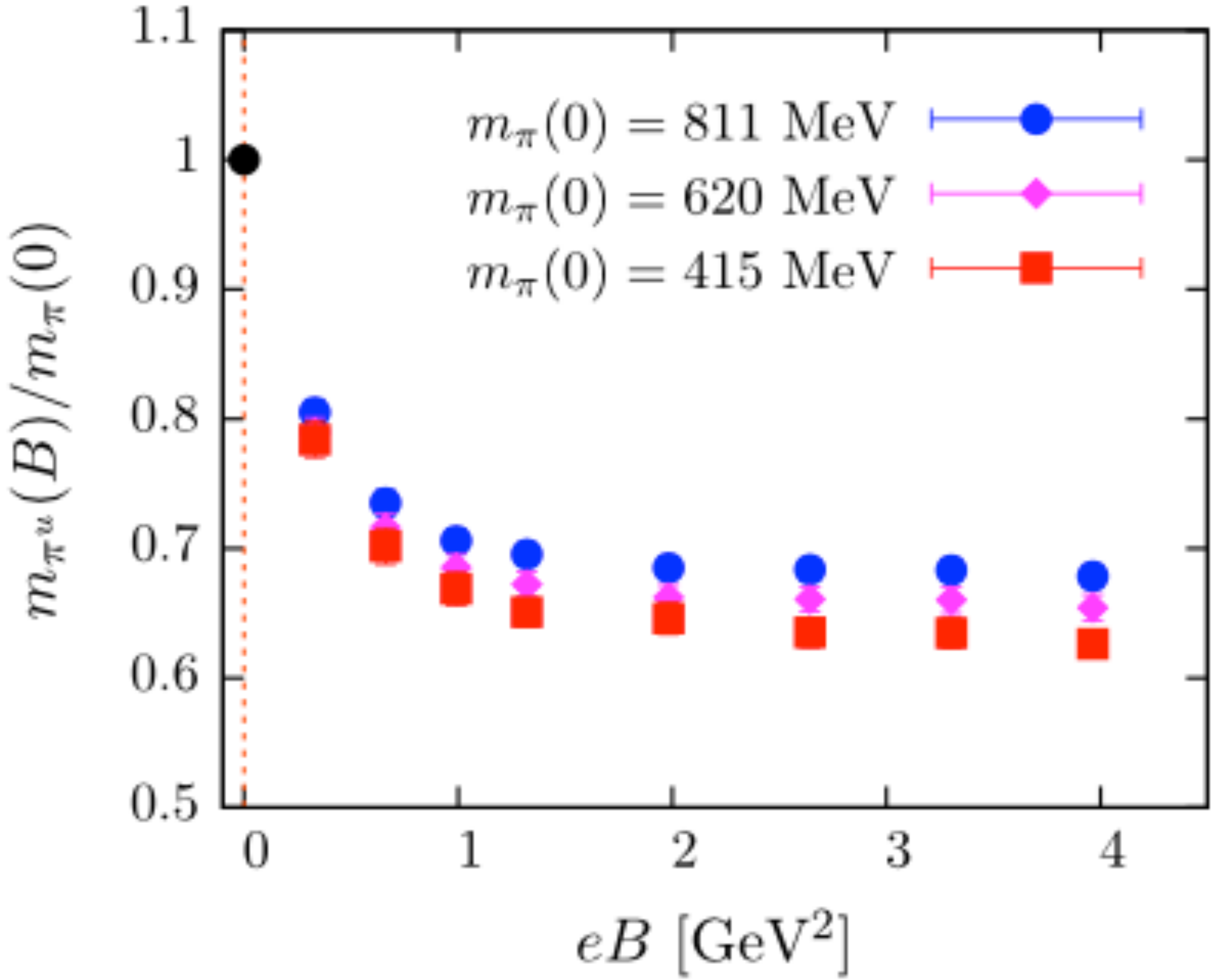
arXiv:2009.13740 [hep-ph], A.Ayala, J.L.Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora

Neutral pion mass X eB



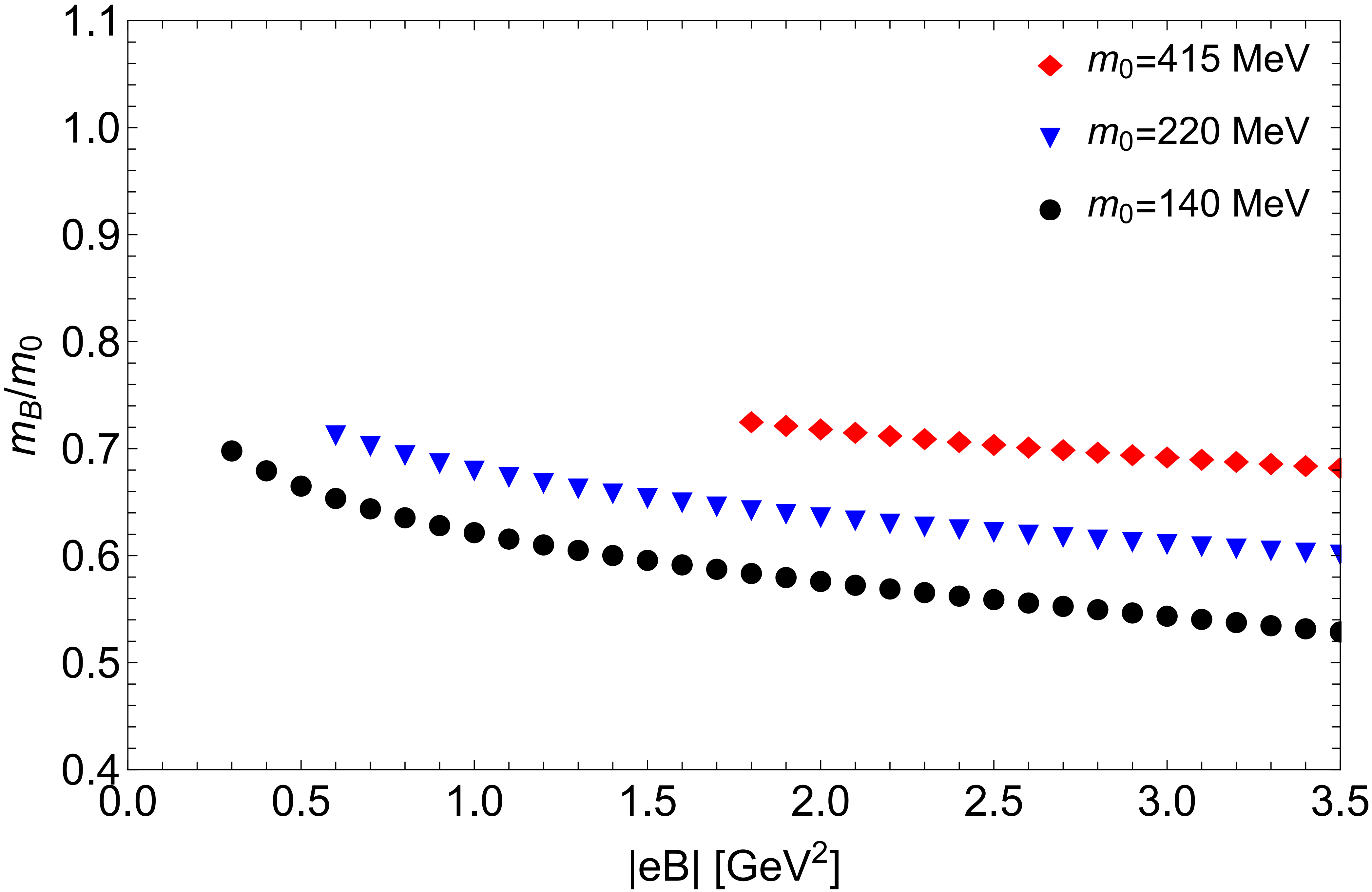
Tomorrow on arxivs, A. Ayala, J.L. Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora

Lattice



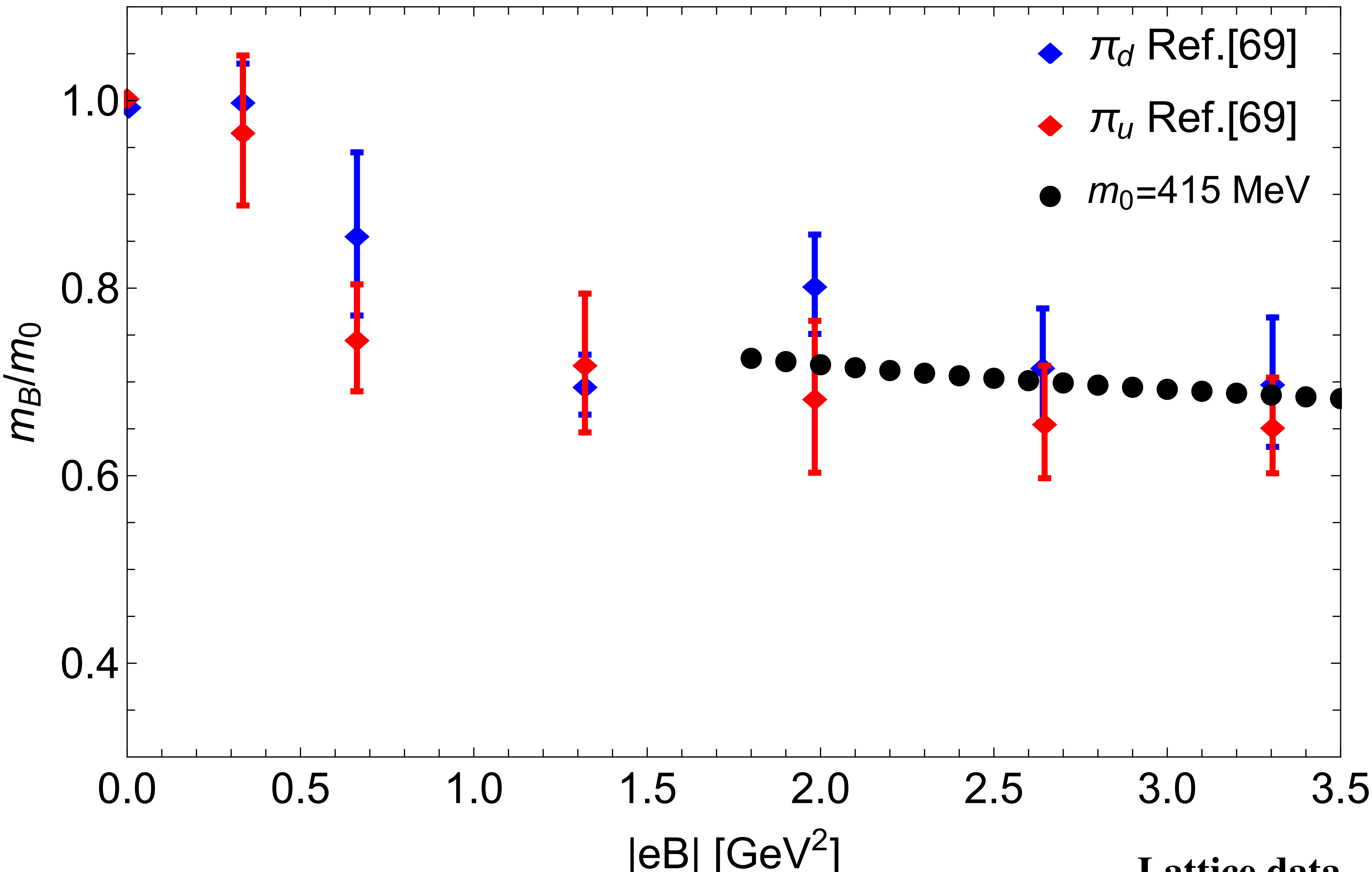
G.S. Bali, B.B. Brandt, G.Endrodi and B.Glaessle, Phys. Rev D 97, 034505 (2018)

LSMq strong field



Tomorrow on arxivs, A. Ayala, J.L. Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora

LSMq strong field

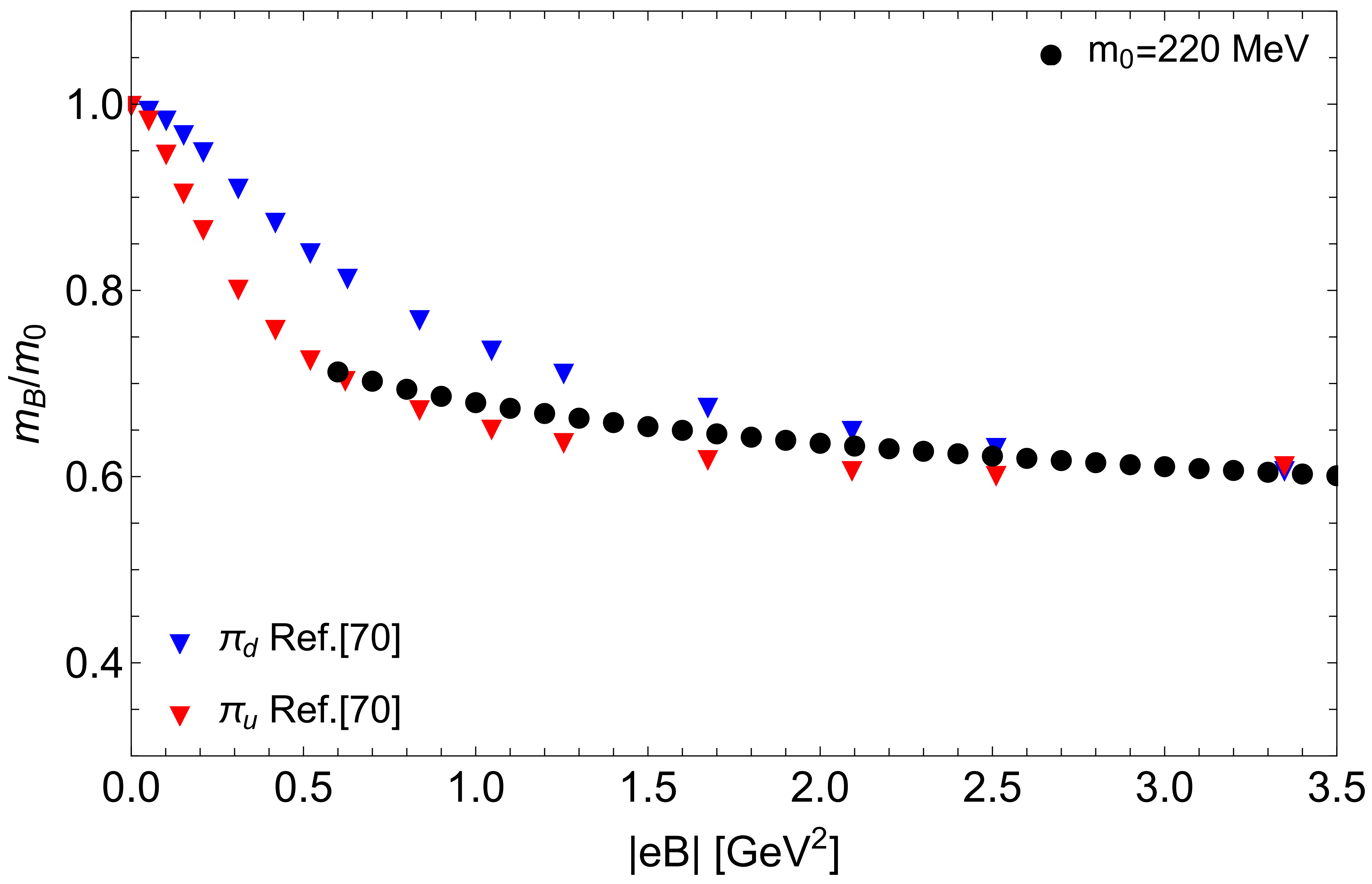


Lattice data

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

Tomorrow on arxivs, A. Ayala, J.L. Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora

LSMq strong field



Lattice data

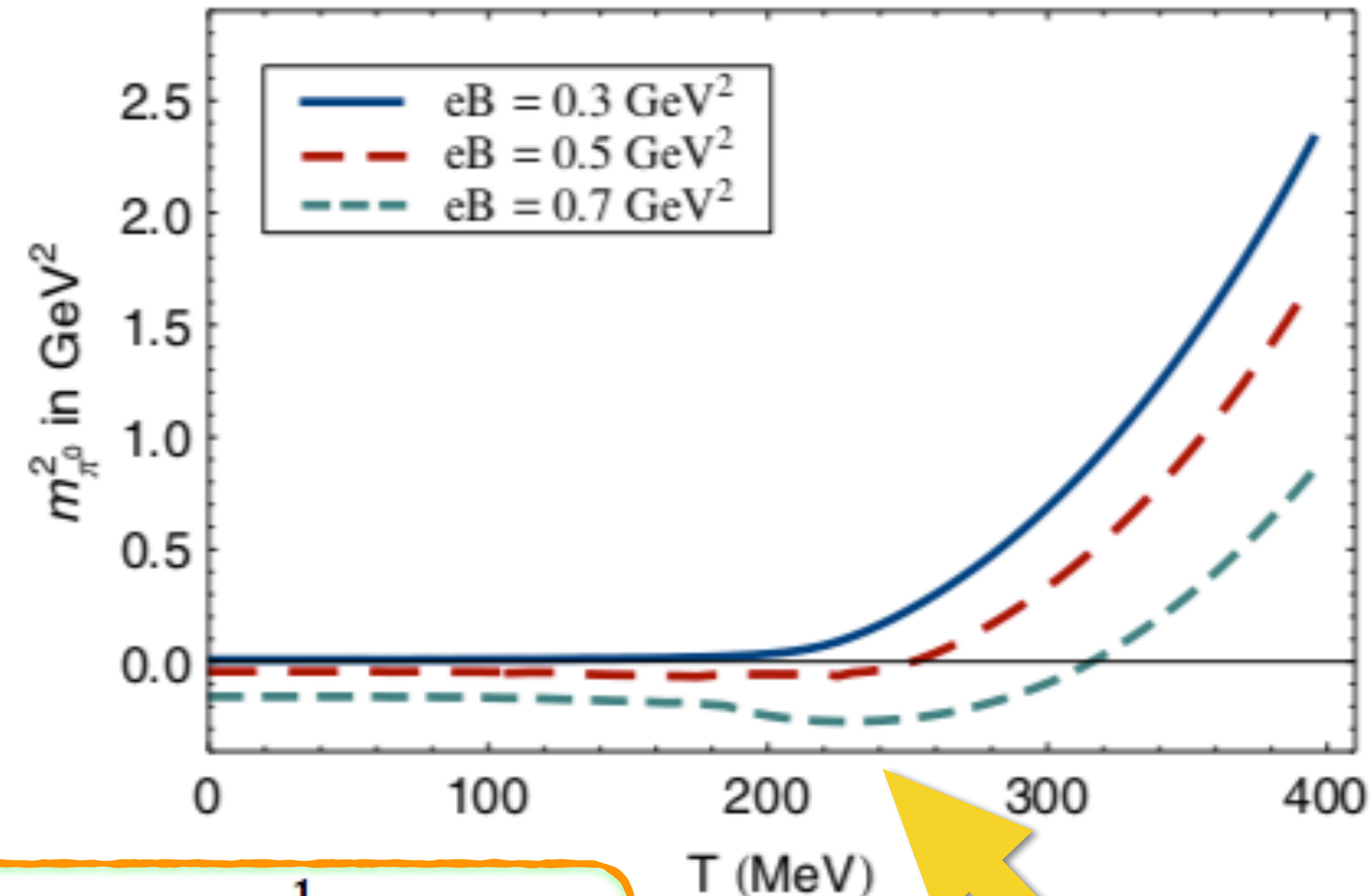
Tomorrow on arxivs, A. Ayala, J.L. Hernández, L. A. Hernández, R.L. S. Farias, R. Zamora

H.-T. Ding, S.-T. Li, A. Tomiya, X.-D. Wang and Y. Zhang, e-Print:2008.00493 [hep-lat].

Meson masses + T + B using NJL

Neutral pion mass + B + T

SU(2) NJL
+ B +T

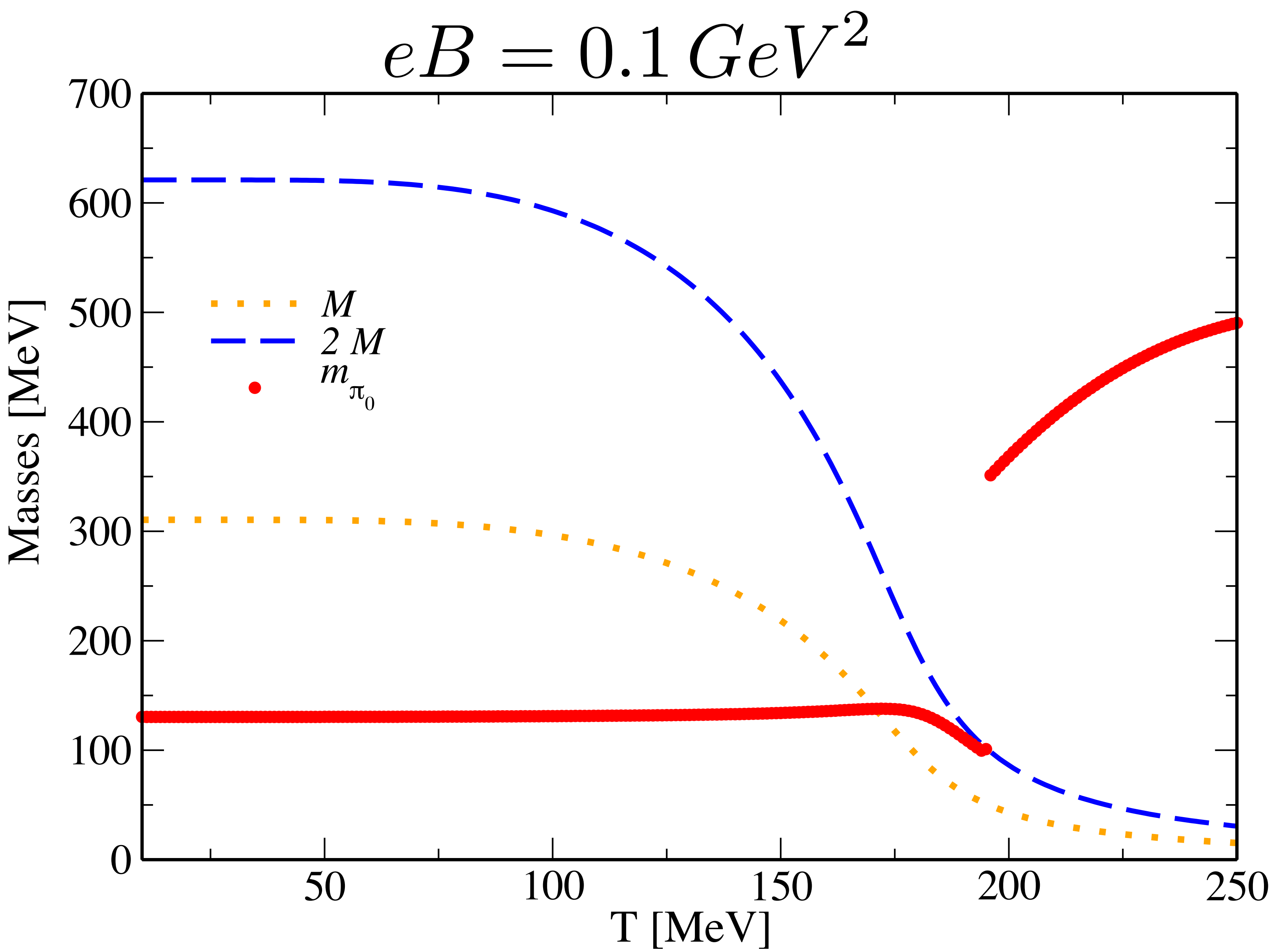


$$f_\Lambda = \frac{1}{1+\exp\left(\frac{|\mathbf{p}|-\Lambda}{A}\right)}, \qquad f^p_{\Lambda,B} = \frac{1}{1+\exp\left(\frac{\sqrt{p_3^2+2|qeB|p}-\Lambda}{A}\right)}$$

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

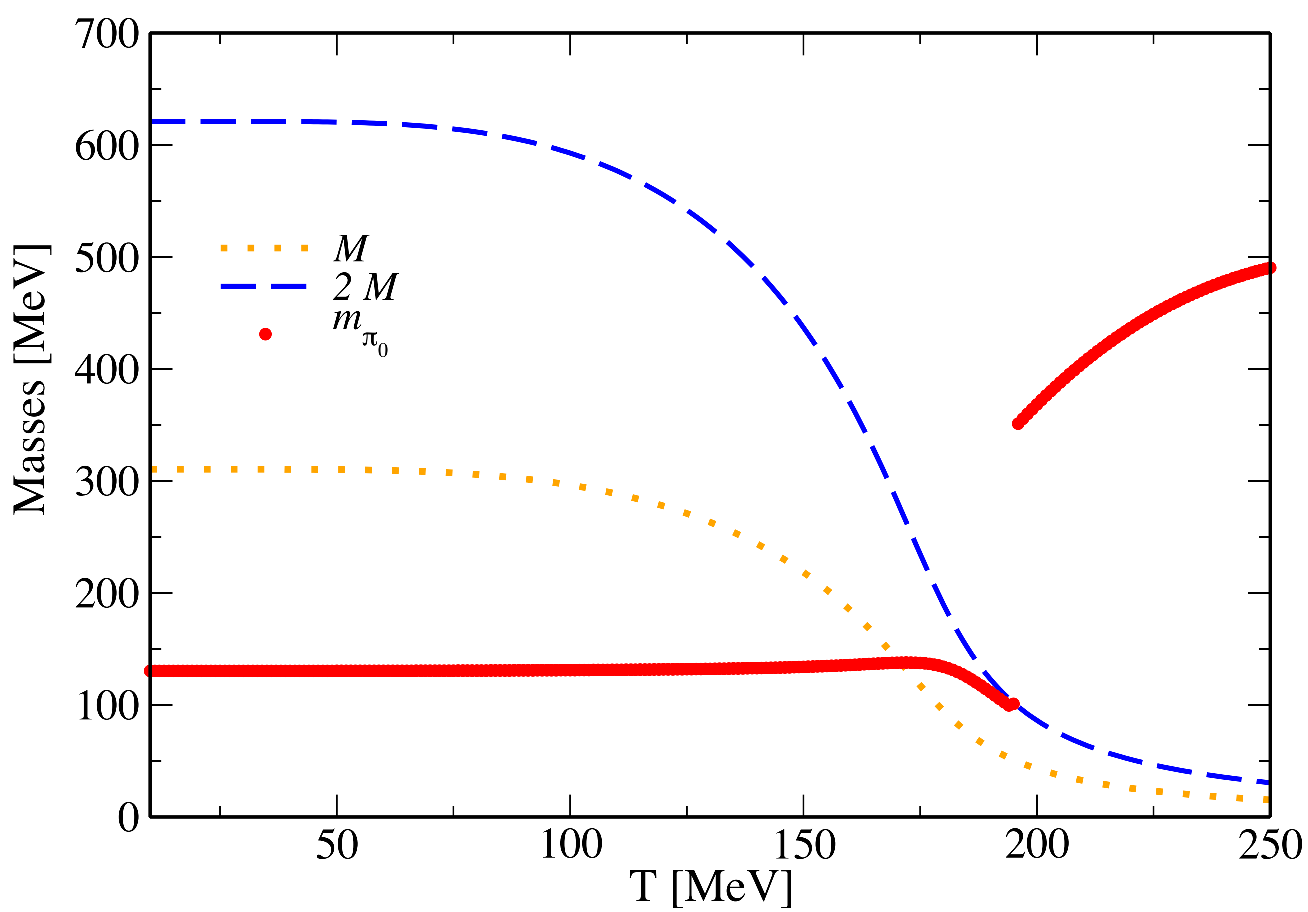
No Tachyonic Instabilities

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

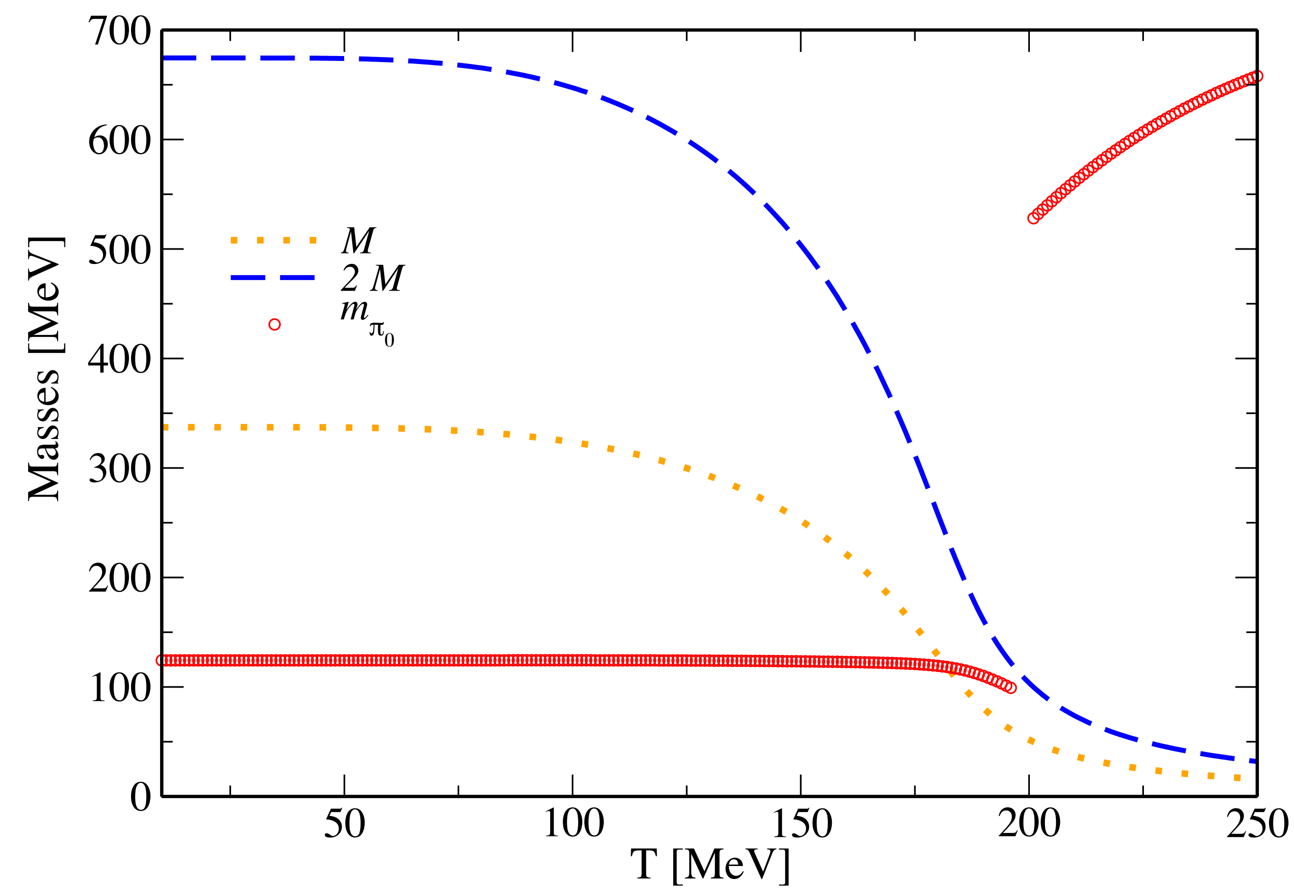
Neutral pion mass X eB

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!