Electrophobic Scalar Boson and Muonic Problems

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Muonic Problem

- Proton Radius Puzzle
- Lamb Shift in $2S_{1/2} - 2P_{3/2}$ in μH [1,2]

$$r_p = 0.84087(39) \text{ fm}$$

- CODATA 2014 from L.S. in H and $e-p$ scattering [3]

$$r_p = 0.8751(61) \text{ fm}$$

- More than 5σ away
- $e-p$ scattering? Nuclear theory? New physics?

[1] R. Pohl *et al*., Nature (London) **466**, 213 (2010).
[2] A. Antognini *et al*., Science **339**, 417 (2013).
[3] P. J. Mohr, D. B. Newell, and B. N. Taylor, arXiv:1507.07956.

Muonic Problem

- Muon Anomalous Magnetic Moment

$$a_\mu = \frac{(g-2)_\mu}{2}$$

- The measurement at BNL [1] differs from SM prediction [2,3] by more than 3σ away.
- $\Delta a_\mu = 287(80) \times 10^{-11}$

[1] T. Blum, A. Denig, I. Logashenko, E. de Rafael, B. Lee Roberts, T. Teubner, and G. Venanzoni, arXiv:1311.2198.
[2] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Eur. Phys. J. C **71**, 1515 (2011); **72**, 1874(E) (2012).
[3] K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, and T. Teubner, J. Phys. G **38**, 085003 (2011).

New Physics

- A Scalar Boson, ϕ, can solve both problems [1,2].
- Assume Yukawa Interaction $\mathcal{L} \supset e\epsilon_f \phi \overline{\psi}_f \psi_f$,
  where $\epsilon_f = \frac{g_f}{e}$, and $f = e, \mu, p, n$, etc.
- The classical potential between f_1 and f_2 by exchanging a scalar boson is

$$V_\phi(r) = -\epsilon_1 \epsilon_2 \alpha \frac{e^{-m_\phi r}}{r}.$$

[1] D. Tucker-Smith and I. Yavin, Phys. Rev. D **83**, 101702 (2011).
[2] E. Izaguirre, G. Krnjaic, and M. Pospelov, Phys. Lett. B **740**, 61 (2015).

New Physics

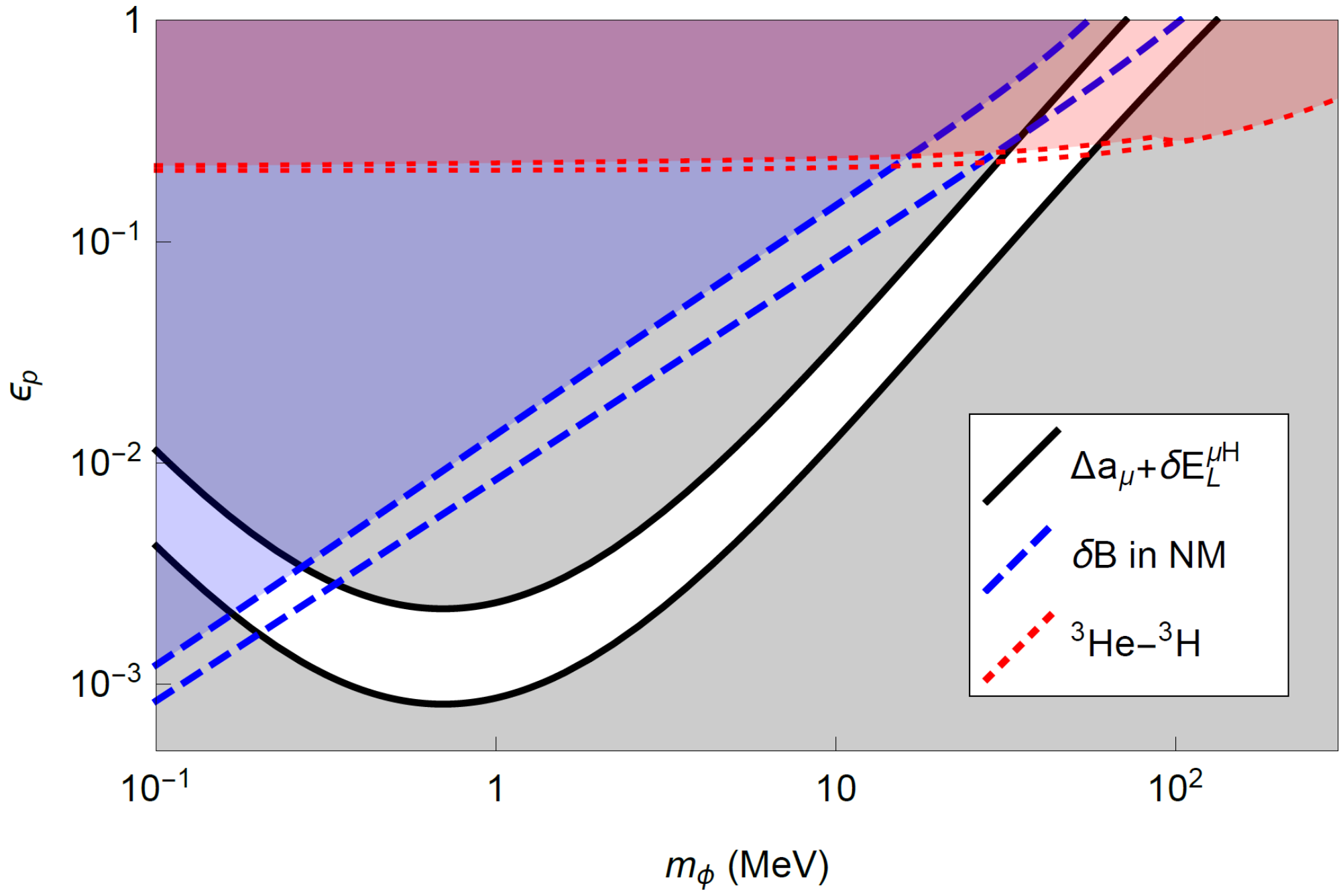
- Make no other *a priori* assumptions.
  ($\epsilon_\mu = \epsilon_p$ [1], $\epsilon_n = 0$ [1,2], mass-weighted [2], etc.)

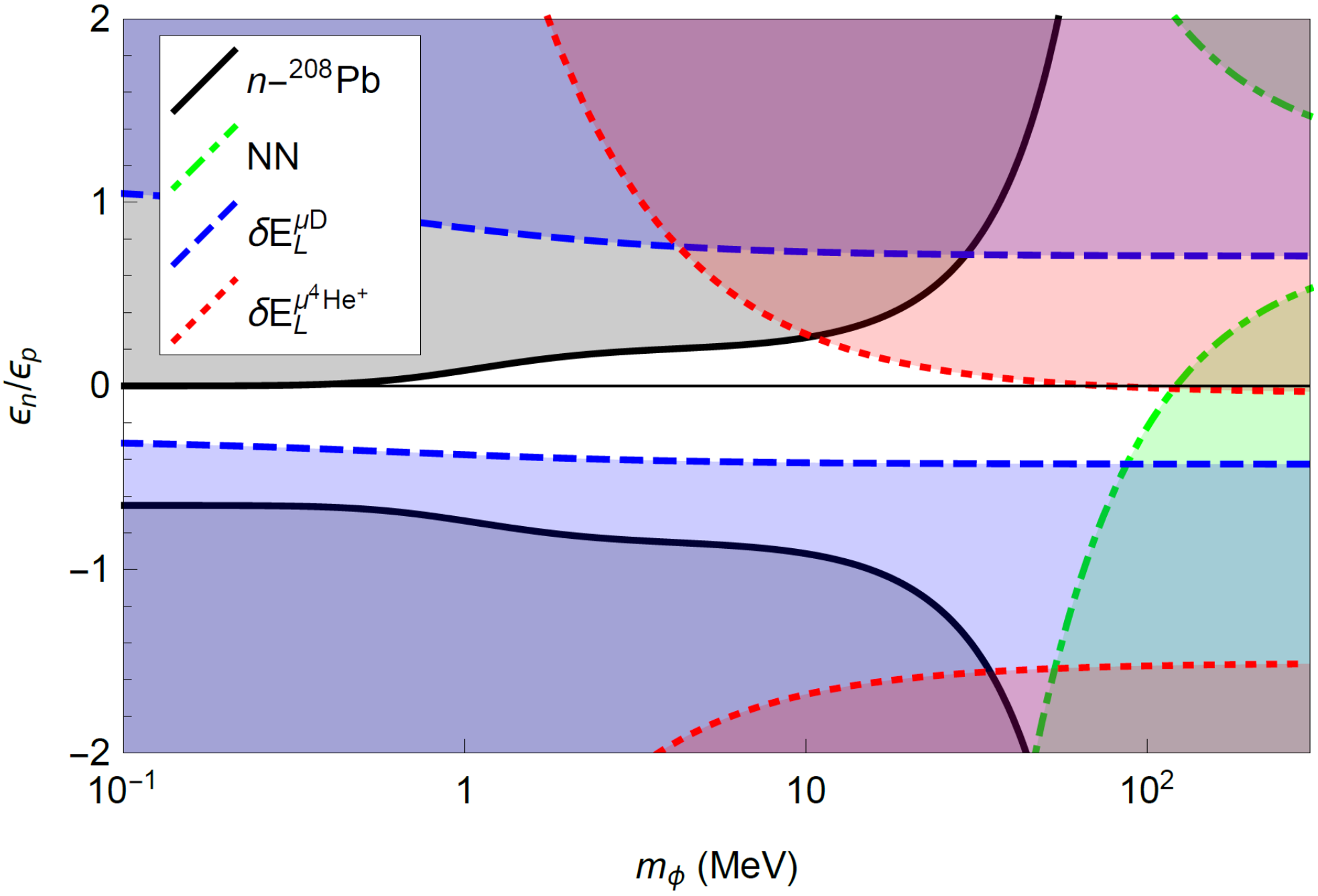
- $\epsilon_\mu \epsilon_p > 0$ (using Lamb Shift of $\mu\mathrm{H}$)
- Without lose of generality, we set $\epsilon_\mu > 0$ and $\epsilon_p > 0$.
- ϵ_e and ϵ_n are allowed to have either sign.

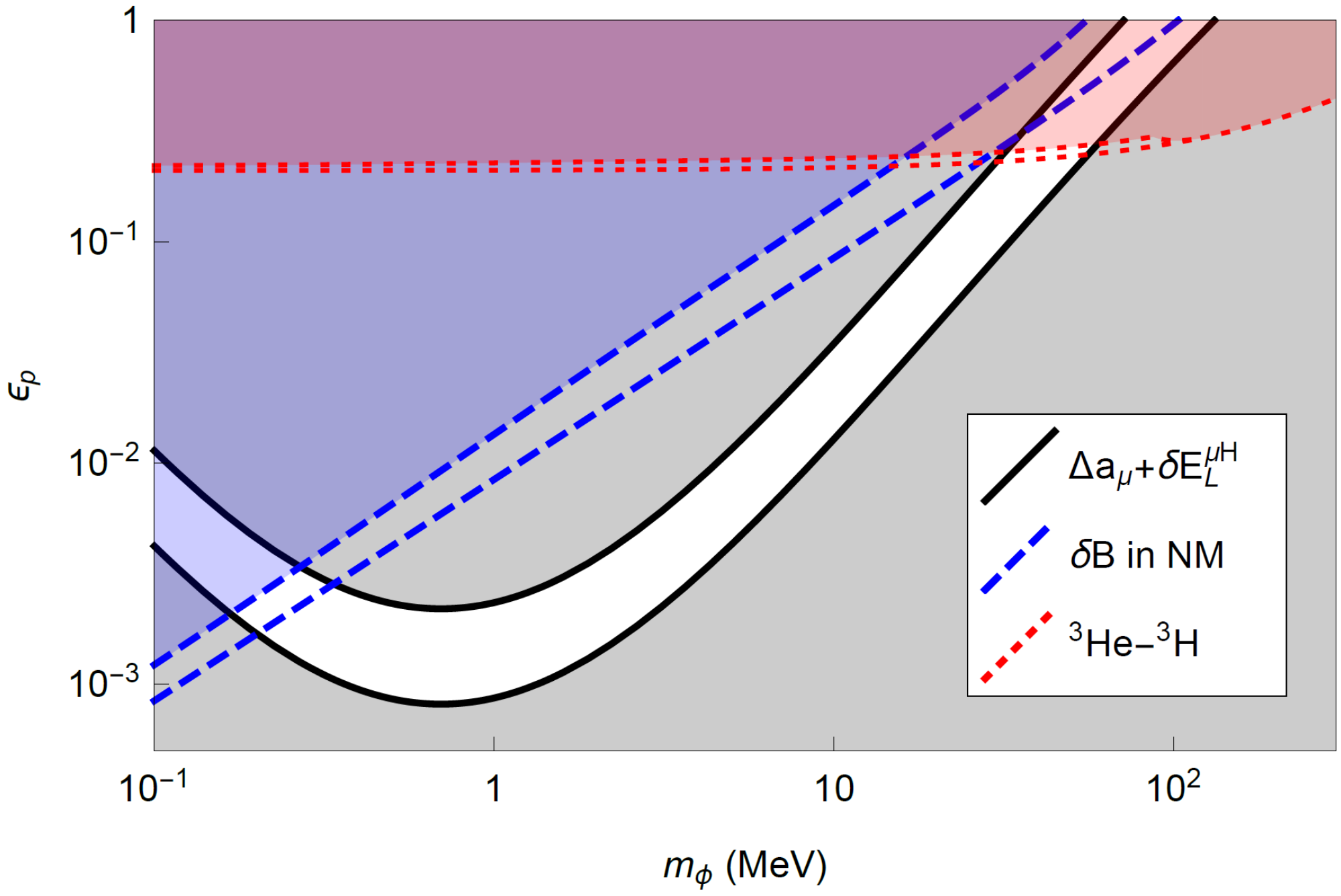
[1] D. Tucker-Smith and I. Yavin, Phys. Rev. D **83**, 101702 (2011).
[2] E. Izaguirre, G. Krnjaic, and M. Pospelov, Phys. Lett. B **740**, 61 (2015).

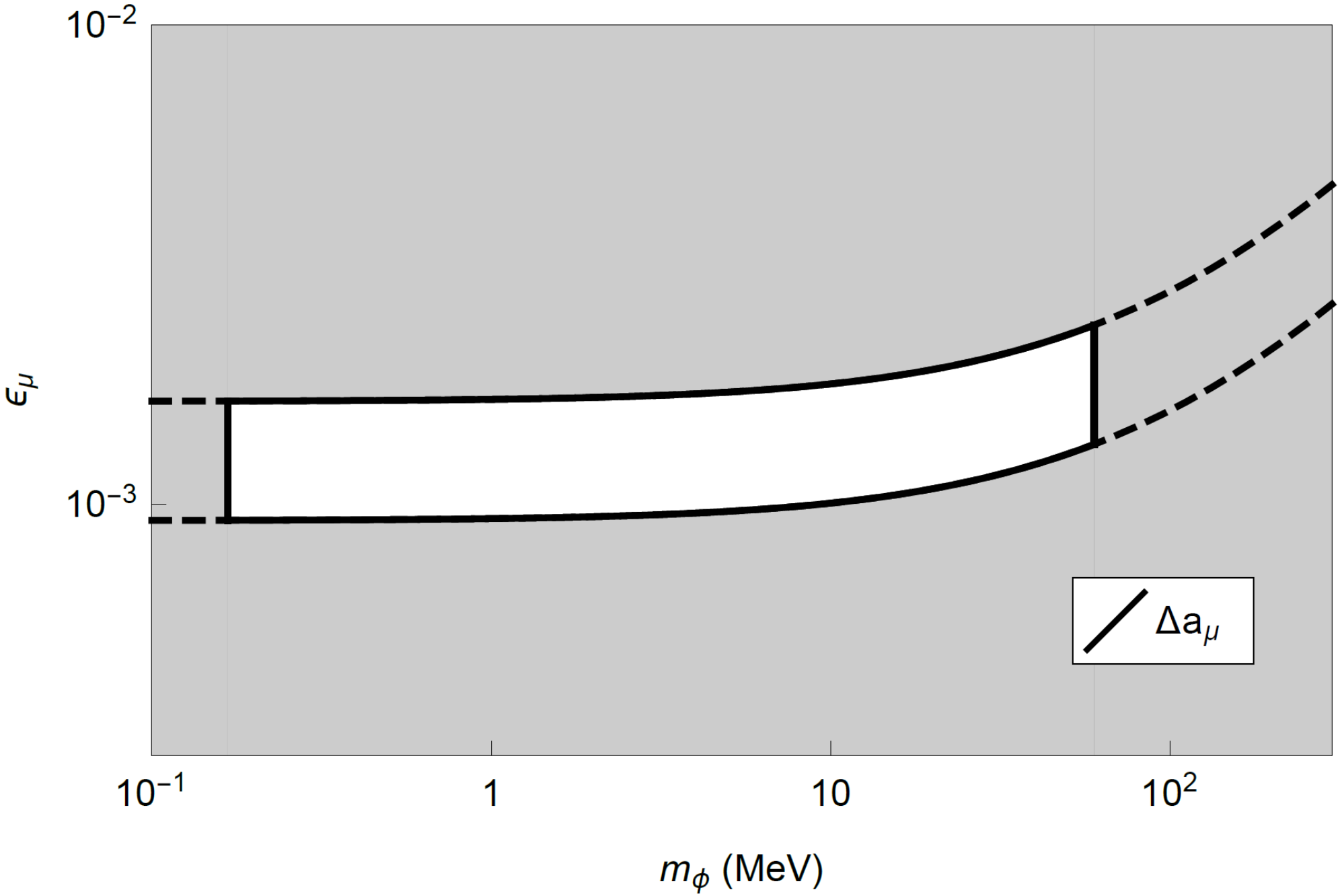
Muon and Nucleon Observables

- The Lamb shift using laser spectroscopy in muonic hydrogen, deuterium, and helium-4
- $(g-2)_{\mu}$
- Low energy scattering of neutron on $^{208}\mathrm{Pb}$
- The NN scattering length
- The binding energy per nucleon in nuclear matter
- The binding energy difference of $^{3}\mathrm{He}$ and $^{3}\mathrm{H}$


1
10^{-1}
10^{-2}
10^{-3}
ϵ_p
10^{-1}
1
10
10^2
m_ϕ (MeV)
$\Delta a_\mu + \delta E_L^{\mu H}$
δB in NM
$^3He - ^3H$

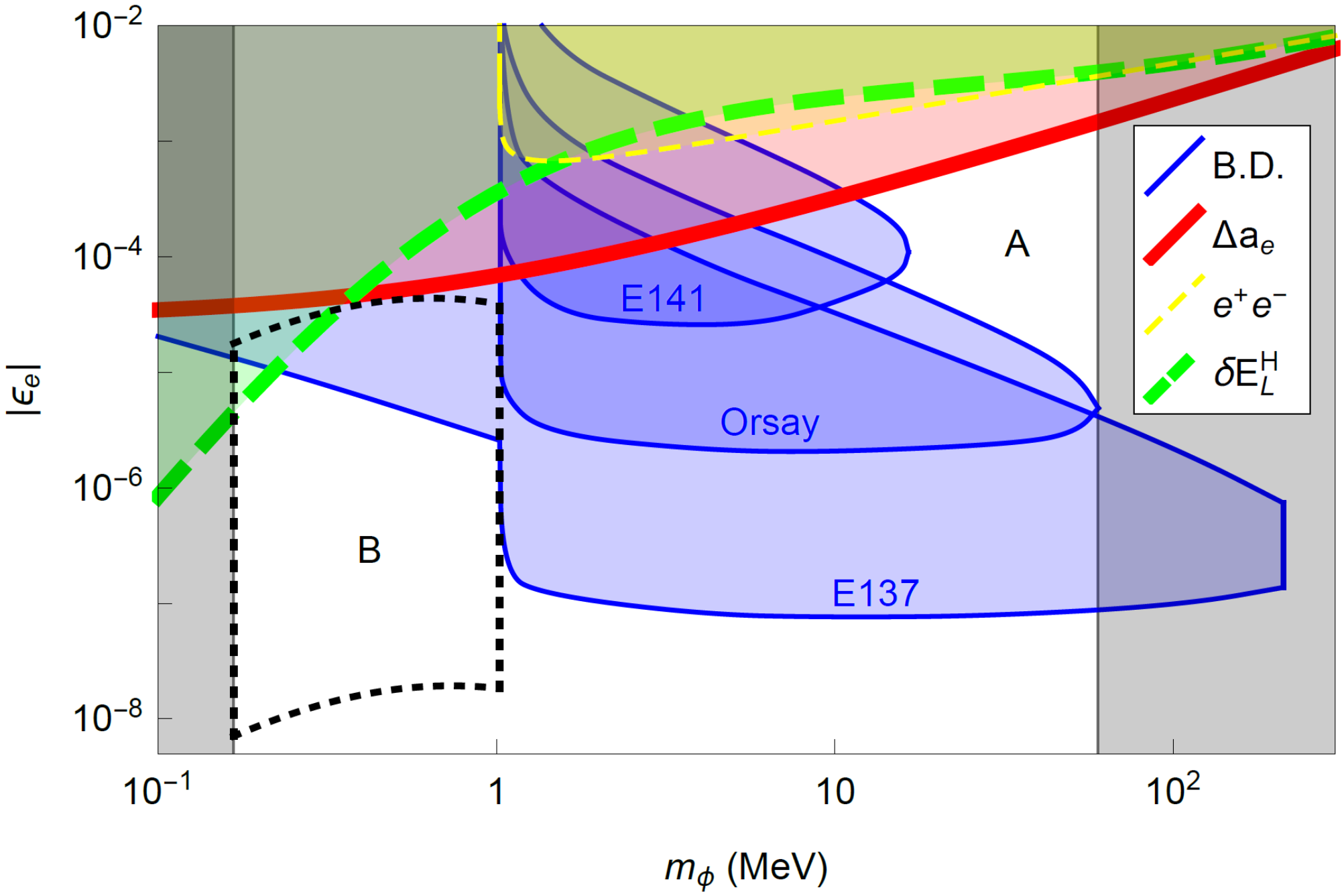

n–^{208}Pb
NN
$\delta E_L^{\mu D}$
$\delta E_L^{\mu\,^4He^+}$
2
1
0
−1
−2
ϵ_n/ϵ_p
10^{-1}
1
10
10^2
m_ϕ (MeV)


1
10^{-1}
10^{-2}
10^{-3}
ϵ_p
10^{-1}
1
10
10^2
m_ϕ (MeV)
$\Delta a_\mu + \delta E_L^{\mu H}$
δB in NM
$^3He - ^3H$


10^{-2}
10^{-3}
ϵ_μ
10^{-1}
1
10
10^2
m_ϕ (MeV)
Δa_μ

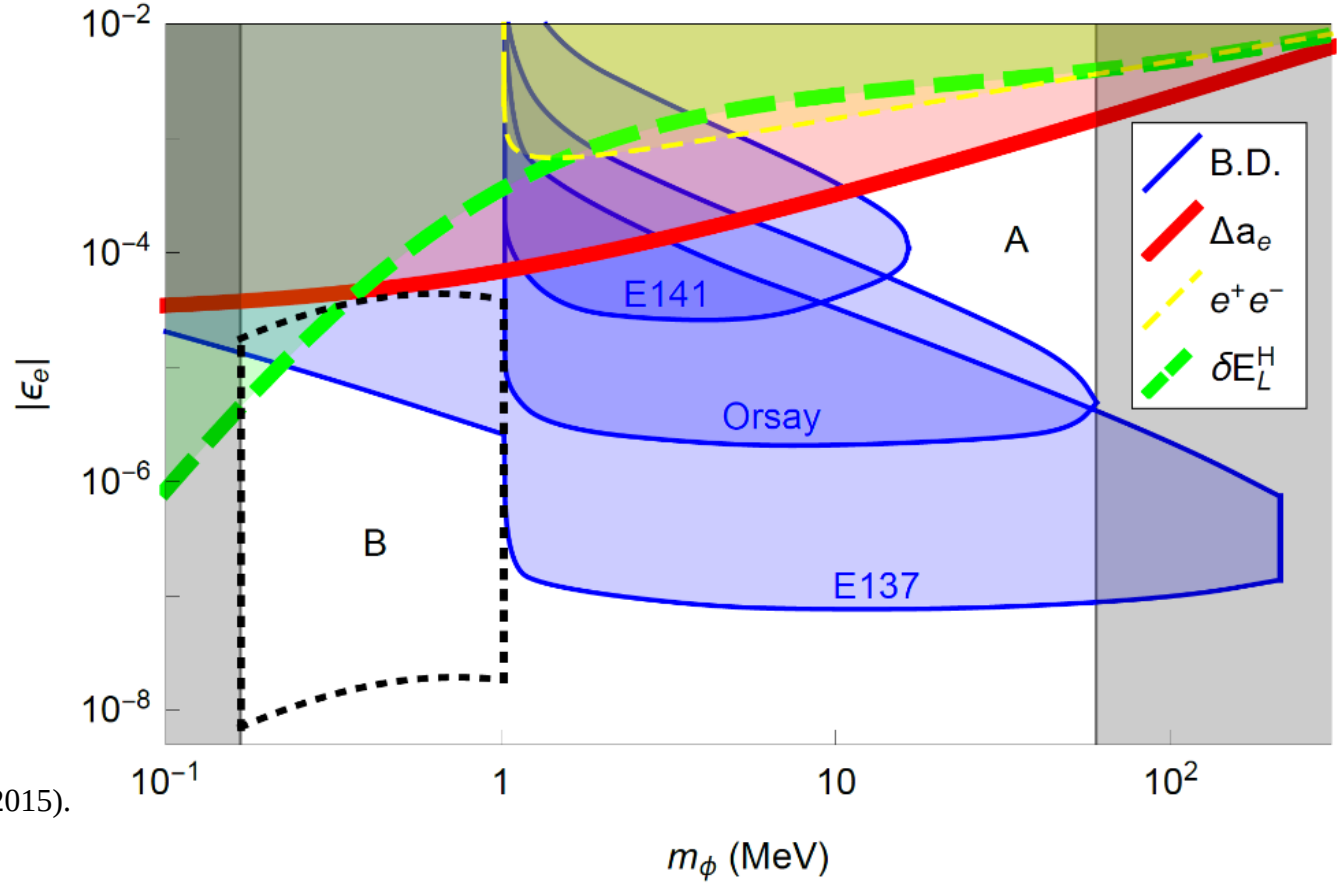
Electron Observables

- Electron Beam dump experiments, E137, E141, and Orsay.
- $(g-2)_e$
- Resonance in Bhabha Scattering
- The Lamb shift using laser spectroscopy in electronic hydrogen

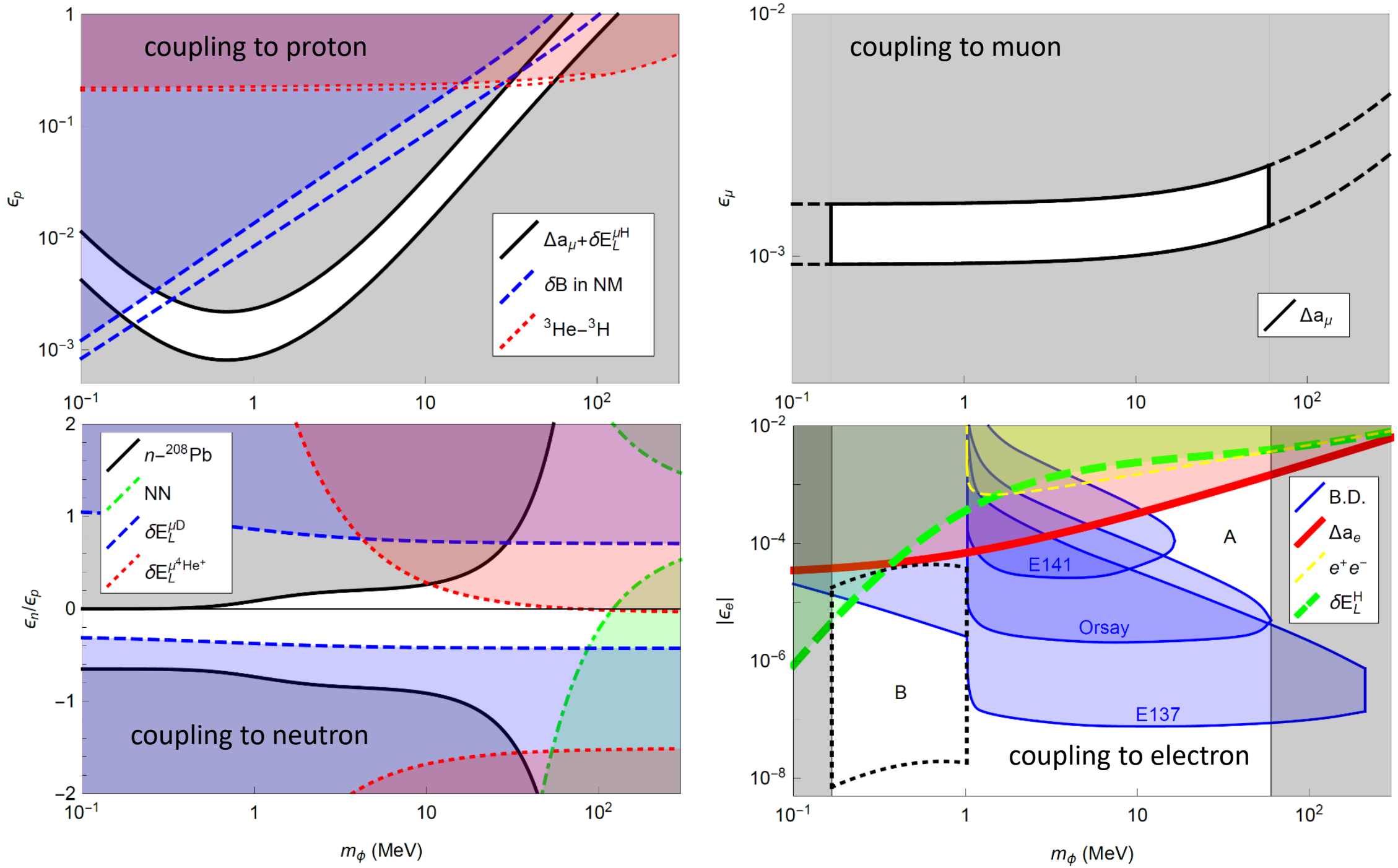

10^{-2}
10^{-4}
10^{-6}
10^{-8}
$|\epsilon_e|$
10^{-1}
1
10
10^2
m_ϕ (MeV)
B.D.
Δa_e
e^+e^-
δE_L^H
A
B
E141
Orsay
E137

Coupling to Electron ϵ_e

- A: APEX, HPS, DarkLight, VEPP-3, MAMI, MESA, etc.
- B: de-excitation of $^{16}O^*$ [1].
- A1 at MAMI and BaBar, Astronomical observables, Kaon decay, etc.
- mass-weighted $\epsilon_l \propto m_l^n$
- electrophobic



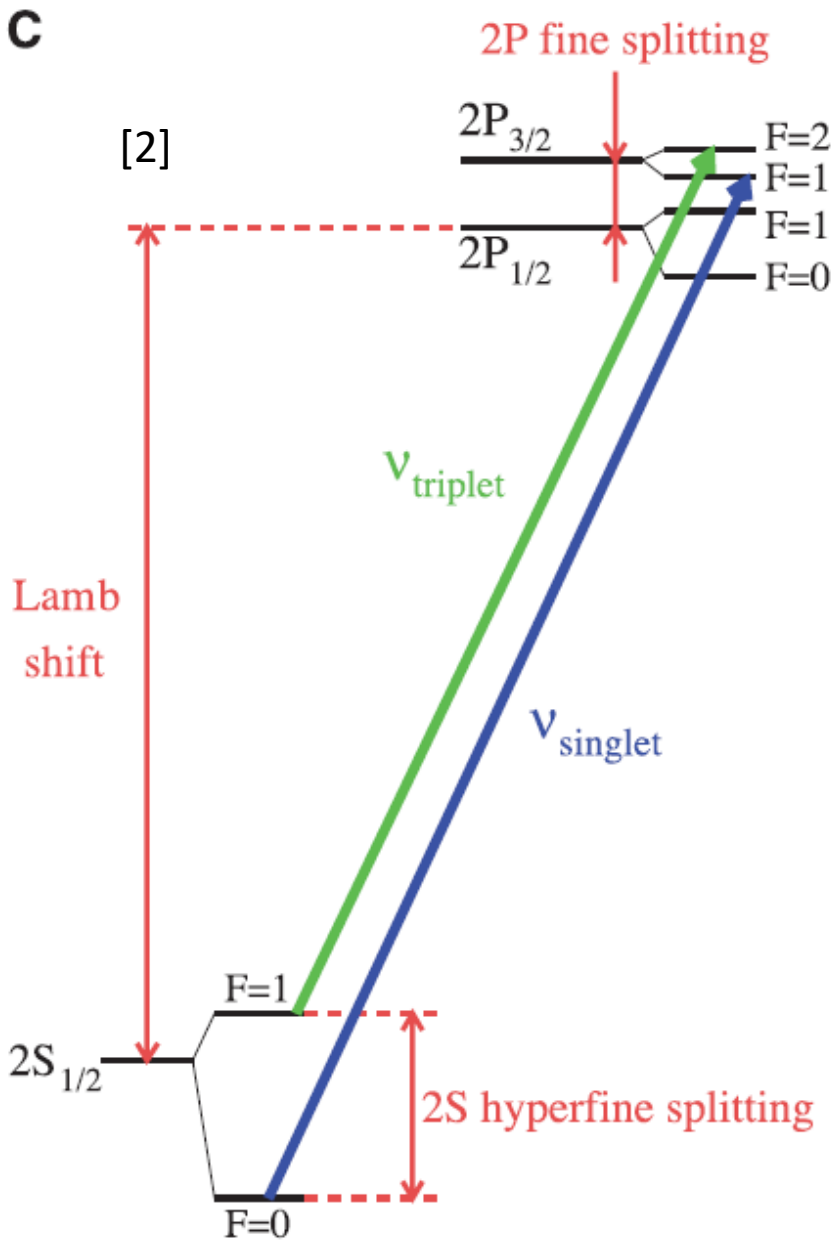
[1] E. Izaguirre, G. Krnjaic, and M. Pospelov, Phys. Lett. B **740**, 61 (2015).


coupling to proton
ϵ_p
$\Delta a_\mu + \delta E_L^{\mu H}$
δB in NM
^{3}He–^{3}H
coupling to muon
ϵ_μ
Δa_μ
n–^{208}Pb
NN
$\delta E_L^{\mu D}$
$\delta E_L^{\mu\, ^4He^+}$
ϵ_n/ϵ_p
coupling to neutron
m_ϕ (MeV)
B.D.
Δa_e
e^+e^-
δE_L^H
A
B
E141
Orsay
E137
$|\epsilon_e|$
coupling to electron
m_ϕ (MeV)

μH Lamb Shift

- $\delta E_L^{lN} = -\frac{\alpha}{2a_l}\epsilon_l\epsilon_N f(a_{lN}m_\phi)$
  (for lepton-nucleus)
  $f(x) = \frac{x^2}{(1+x)^4}$
  a_{lN} is the Bohr radius
- $\delta E_L^{\mu\mathrm{H}} = -0.307(56)\ \mathrm{meV}$
  [1-4]

[1] R. Pohl *et al.*, Nature (London) **466**, 213 (2010).
[2] A. Antognini *et al.*, Science **339**, 417 (2013).
[3] P. J. Mohr, D. B. Newell, and B. N. Taylor, arXiv:1507.07956.
[4] A. Antognini et al., EPJ Web Conf. **113**, 01006 (2016).



μD and $\mu^4\mathrm{He}^+$ Lamb Shift

- $\delta E_L^{lN} = -\frac{\alpha}{2a_l}\epsilon_l\epsilon_N f(a_{lN}m_\phi)$ (for lepton-nucleus)

  $f(x) = \frac{x^2}{(1+x)^4}$, a_{lN} is the Bohr radius
- $\delta E_L^{\mu\mathrm{D}} = -0.409(69)\mathrm{meV}$ [1,2]
- $\delta E_L^{\mu^4\mathrm{He}^+} = -1.4(1.5)\ \mathrm{meV}$ [3,4]

[1] R. Pohl *et al*., Science **353**, 669 (2016).
[2] J. J. Krauth, M. Diepold, B. Franke, A. Antognini, F. Kottmann, and R. Pohl, Ann. Phys. (Amsterdam) **366**, 168 (2016).
[3] A. Antognini et al., EPJ Web Conf. **113**, 01006 (2016).
[4] I. Sick, Phys. Rev. C **90**, 064002 (2014).

Low Energy Neutron Experiments

- Measuring total cross section of Scattering of neutron on $^{208}\mathrm{Pb}$
- In [1], it is assumed $g_p = g_n = g_N$,

$$\frac{g_N^2}{4\pi} \lesssim 8 \times 10^{-23} \left(\frac{m_\phi}{\mathrm{eV}}\right)^2 .$$

- Using the replacement

$$\frac{g_N^2}{4\pi} \to \alpha\epsilon_n \left(\frac{A-Z}{A}\epsilon_n + \frac{Z}{A}\epsilon_p\right)$$

[1] H. Leeb and J. Schmiedmayer, Phys. Rev. Lett. **68**, 1472 (1992).

NN scattering length

- $\Delta a = \bar{a} - a_{np}$, $\bar{a} = \frac{a_{pp}+a_{nn}}{2}$
- $\Delta a_{\mathrm{exp}} = 5.64(60)$ fm [1], $\Delta a_{\mathrm{th}} = 5.6(5)$ fm [2]
- $\Delta a_{\phi} = \bar{a} a_{np} M \int_0^{\infty} \Delta V \, \bar{u} u_{np} dr$
  $M = \frac{m_p+m_n}{2}$; $\Delta V = -\frac{1}{2}(\epsilon_p - \epsilon_n)^2 e^{-m_{\phi} r}$;
  $u(r)$ is the zero energy ${}^1S_0$ wave function,
  $u(r) \to (1 - r/a)$ as $a \to \infty$.
- $\Delta a_{\phi} < 1.6$ fm

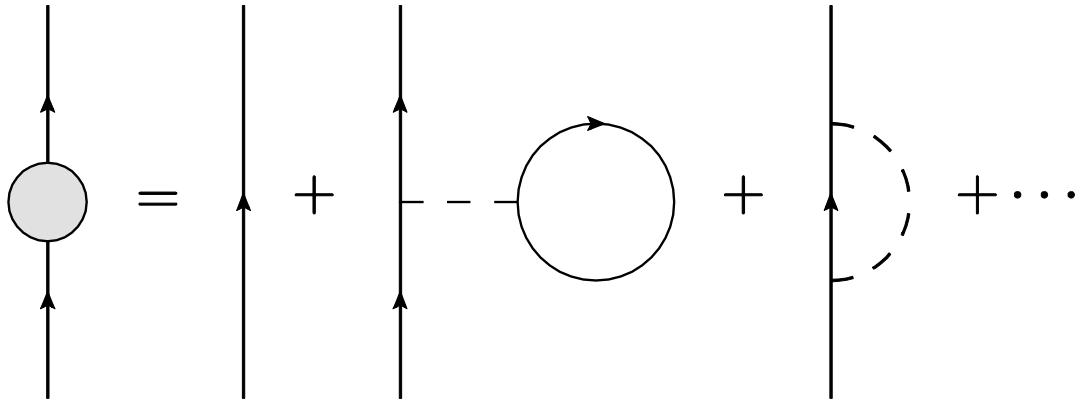
[1] R. Machleidt and I. Slaus, J. Phys. G **27**, R69 (2001).
[2] T. E. O. Ericson and G. A. Miller, Phys. Lett. **132B**, 32 (1983).

Nucleon B. E. in Nuclear Matter

- The volume term in the semiempirical mass formula
- Nucleon self-energy correction in $N = Z$ nuclear matter using Hartree approximation

  $\delta \mathrm{B}_N = \frac{1}{2m_\phi^2} g_N (g_p + g_n)\rho + \cdots$

  $\rho \sim 0.08\ \mathrm{fm}^{-3}$



- $\frac{\delta \mathrm{B}_p + \delta \mathrm{B}_n}{2} = \frac{1}{4m_\phi^2} (g_p + g_n)^2 \rho$
- $\frac{\delta \mathrm{B}_p + \delta \mathrm{B}_n}{2} < 1\ \mathrm{MeV}$

[1] R. D. Mattuck, *A Guide to Feynman Diagrams in the Many Body Problem*, 2nd ed. (Dover Science, New York, 1976).

B. E. difference of $^3\mathrm{He}$ and $^3\mathrm{H}$

- ${}^3_2\mathrm{He}$-${}^3_1\mathrm{H}$ binding energy difference (763.76 keV)
- Coulomb interaction: 693 keV
- Charge asymmetry of p and n: 68 keV [1-5]
- Contribution from scalar boson potential

$$\frac{2\alpha}{\sqrt{3}\pi}\int_0^\infty q^2 dq \frac{\epsilon_p^2-\epsilon_n^2}{q^2+m_\phi^2} F(q^2) < 30 \text{ keV [2,6-8]}$$

[1] J. L. Friar, Nucl. Phys. **A156**, 43 (1970).
[2] J. L. Friar and B. F. Gibson, Phys. Rev. C **18**, 908 (1978).
[3] S. A. Coon and R. C. Barrett, Phys. Rev. C **36**, 2189 (1987).
[4] G. A. Miller, B. M. K. Nefkens, and I. Slaus, Phys. Rep. **194**, 1 (1990).
[5] R. B. Wiringa, S. Pastore, S. C. Pieper, and G. A. Miller, Phys. Rev. C **88**, 044333 (2013).
[6] I. Sick, Prog. Part. Nucl. Phys. **47**, 245 (2001).
[7] F. P. Juster et al., Phys. Rev. Lett. **55**, 2261 (1985).
[8] J. S. Mccarthy, I. Sick, and R. R. Whitney, Phys. Rev. C **15**, 1396 (1977).

Electron Beam Dump Experiments

- Search for new particle [1-3]
- E137 (20 GeV, 30C) [4]
- E141 (9 GeV, 0.32 mC) [5]
- Orsay (1.6GeV, 3.2 mC) [6]

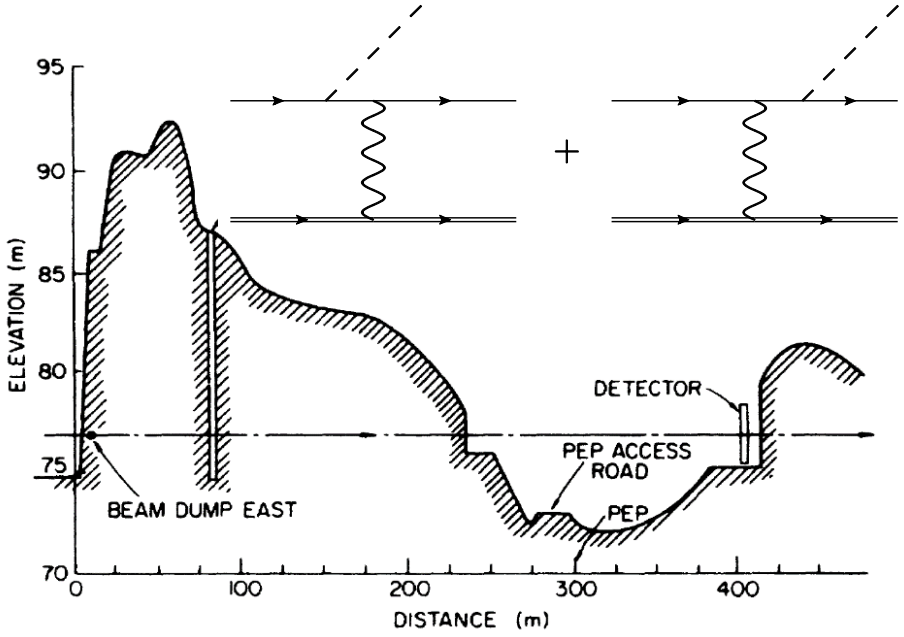
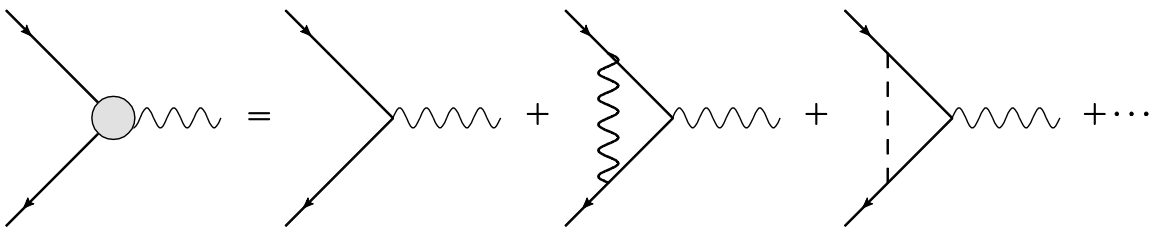


FIG. 2. Layout of SLAC experiment E137.

[1] J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. D **80**, 075018 (2009).
[2] R. Essig et al., arXiv:1311.0029.
[3] Y. S. Liu, D. McKeen and G. A. Miller, arXiv:1609.06781.
[4] J. D. Bjorken, S. Ecklund, W. R. Nelson, A. Abashian, C. Church, B. Lu, L.W. Mo, T. A. Nunamaker, and P. Rassmann, Phys. Rev. D **38**, 3375 (1988).
[5] E. M. Riordan et al., Phys. Rev. Lett. **59**, 755 (1987).
[6] M. Davier and H. Nguyen Ngoc, Phys. Lett. B **229**, 150 (1989).

$(g-2)_e$



- $\Delta a_l = \frac{\alpha}{2\pi}\epsilon_l^2 \xi\left(\frac{m_\phi}{m_l}\right), \xi(x) = \int_0^1 \frac{(1-z)^2(1+z)}{(1-z)^2+x^2 z} dz$
- The most accurate method to measure α
- The shift of $(g-2)_e$ by ϕ results in the measured α by $\Delta\alpha = 2\pi\Delta a_e$ [1].
- A measurement of α, which is not sensitive to ϕ, using ^{87}Rb atom [2] gives 0.66 ppb uncertainty.
- $\Delta a_e < 1.5 \times 10^{-12}$ (taking 2 S.D.)

[1] M. Pospelov, Phys. Rev. D **80**, 095002 (2009).
[2] R. Bouchendira, P. Clade, S. Guellati-Khelifa, F. Nez, and F. Biraben, Phys. Rev. Lett. **106**, 080801 (2011).

Resonance in Bhabha Scattering

- GSI group
- No resonance were found at 97% C.L. within the experimental sensitivity [1]

$$\int d\sqrt{s}\left(\frac{d\sigma}{d\Omega}\right)_{c.m.} < 0.5 \text{ b eV/sr.}$$

[1] H. Tsertos, C. Kozhuharov, P. Armbruster, P. Kienle, B. Krusche, and K. Schreckenbach, Phys. Rev. D **40**, 1397 (1989).

$e\mathrm{H}$ Lamb Shift

- $\delta E_L^{lN} = -\frac{\alpha}{2a_l}\epsilon_l\epsilon_N f(a_{lN}m_\phi)$ (for lepton-nucleus)

  $f(x) = \frac{x^2}{(1+x)^4}$, a_{lN} is the Bohr radius
- $\delta E_L^{e\mathrm{H}} < 14\ \mathrm{kHz}$ [1] $(5.8 \times 10^{-11}\ \mathrm{eV})$

[1] M. I. Eides, H. Grotch, and V. A. Shelyuto, Phys. Rep. **342**, 63 (2001).

Supernova 1987A [1]

- Cooling: produce ϕ to escape SN
  electron-positron annihilation [2,3]
  Nucleon-nucleon bremsstrahlung [4]
- Trapping: scatter ($e\phi \to e\phi$), decay [5]
- Absorption: $e\phi \to e\gamma$, $N\phi \to N\gamma$ [5]

[1] A. Burrows and J. M. Lattimer, Astrophys. J. **307**, 178 (1986).
[2] H. K. Dreiner, C. Hanhart, U. Langenfeld and D. R. Phillips, Phys. Rev. D **68**, 055004 (2003).
[3] H. K. Dreiner, J. F. Fortin, C. Hanhart and L. Ubaldi, Phys. Rev. D **89**, no. 10, 105015 (2014).
[4] E. Rrapaj and S. Reddy, arXiv:1511.09136.
[5] G. G. Raffelt, *Stars as laboratories for fundamental physics : The astrophysics of neutrinos, axions, and other weakly interacting particles*, Chicago, USA: Univ. Pr. (1996)