Light Scalar and Lepton Anomalous Magnetic Moments

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Based on: *Phys.Rev.D* 101 (2020) 11, 115037 (in Collaboration with Sudip Jana and Shaikh Saad)

❖ Outline

❖ Leptons AMM ⟶ New Physics Beyond SM

- Long standing tension in the measurement muon anomalous magnetic moment (AMM) and the corresponding SM prediction.

- This discrepancy has survived over decades even after improving the theoretical calculations within the SM and performing accurate experimental measurements.

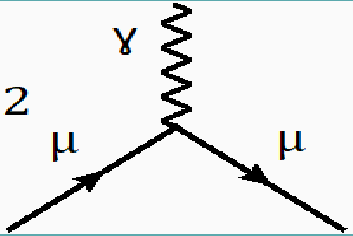
- On the other hand, the recent precise determination of the electron AMM also shows deviations from the experimental value.

- These two anomalies strongly point towards physics beyond the SM.

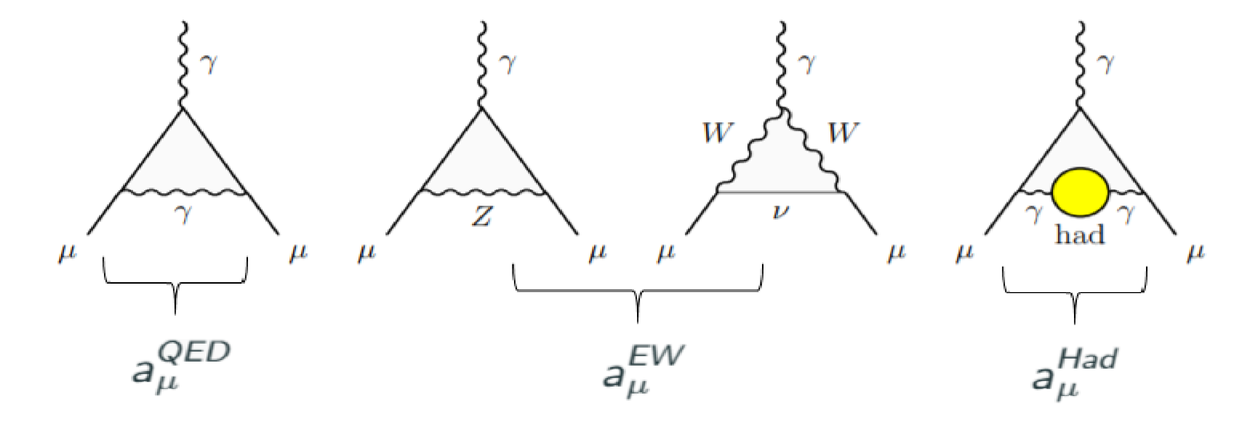
❖ Muon Magnetic Moment

- Muon magnetic moment : $\vec{\mu}_B = g_\mu \frac{e}{2m_\mu}\vec{S}$

- Lande' g-factor : $g_\mu = 2$



- Due to quantum corrections, $(g-2)_\mu \neq 0$.



- Anomalous Magnetic Moment: $$a_\mu = \frac{(g-2)_\mu}{2}$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

❖ Current Status

- Muon AMM:

$$10^{11} a_\mu = \begin{cases} 116591810(43) & \text{SM} \\ 116592089(63) & \text{exp} \end{cases}$$

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❑ Electron AMM:

➢ Recent improved determination of the fine structure constant, leads to a negative discrepancy between the measured AMM and the SM prediction.

$$10^{12} a_e = \begin{cases} 1159652181.61(23) & \text{SM} \\ 1159652180.73(28) & \text{exp} \end{cases}$$

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New Physics !

- If the reason behind these anomalies is because of some NP, then there are many challenges for a simultaneous explanation of these anomalies.
  - Opposite Sign:

$$\Delta a_\mu = (2.79 \pm 0.76) \times 10^{-9}$$
$$\Delta a_e = -(8.7 \pm 3.6) \times 10^{-13}$$

  - Discrepancies are larger in magnitude than the lepton mass scaling.

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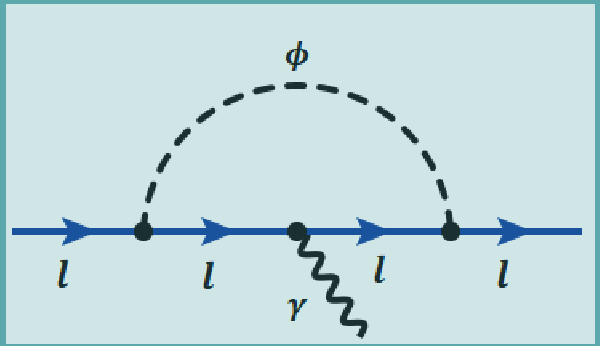
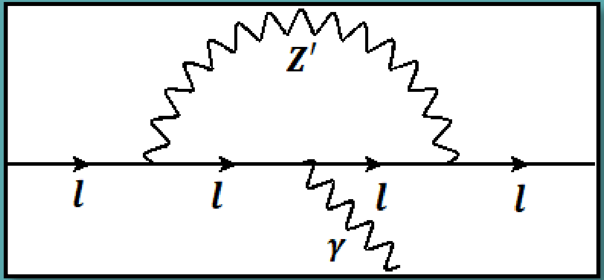


Same sign, not possible

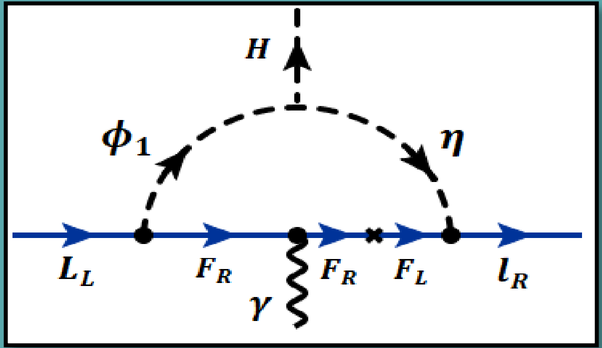
Possible Explanations

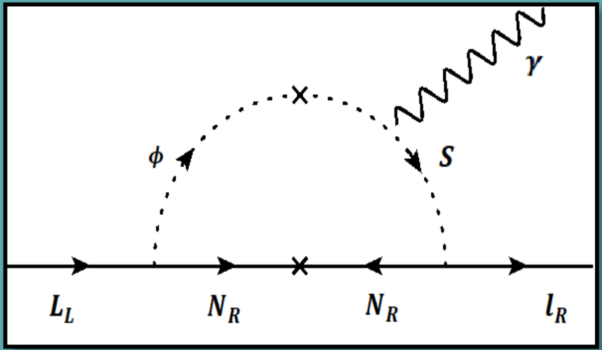
- ❑ With light Z`:



⇨ Needed gauge extension

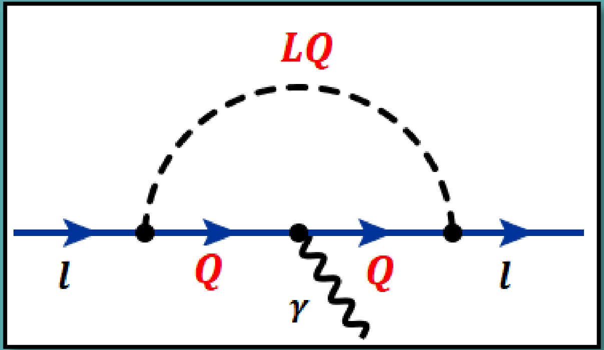
- ❑ With additional Fermions and Scalars:





K.F.Chen,C.W.Chiang,K.Yagyu arXiv: 2006.07929
S. Jana, VPK, S. Saad, W. Rodejohann
arXiv: 2008.02377

- ❑ With additional Scalars only:
  - ❑ Colored Scalars (Lepto-quarks):



I. Dorsner, S. Fajfer,S. Saad arXiv: 2006.11624
I. Bigaran, R. R. Volkas arXiv: 2002.12544

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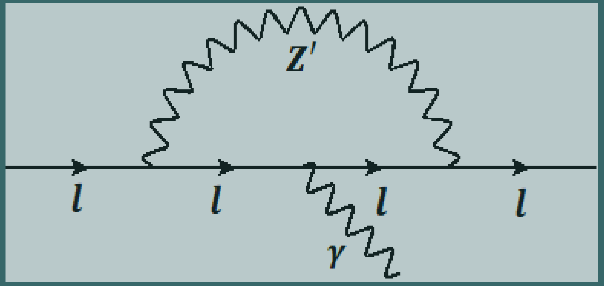

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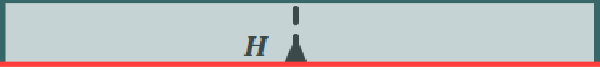

Q. Is there is any more minimal setups to explain these two anomalies simultaneously?

- With additional Scalars only:
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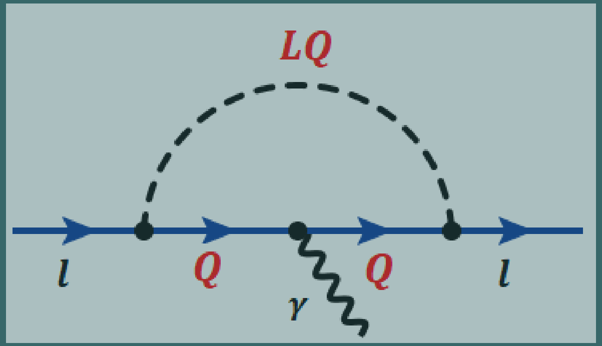

Possible Explanations

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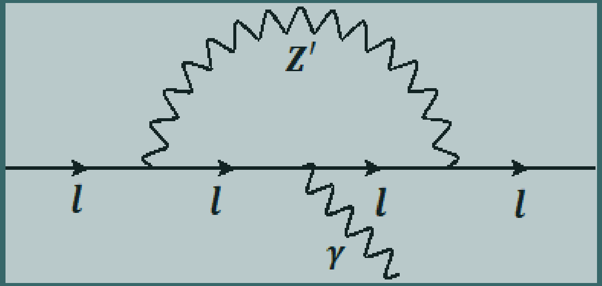

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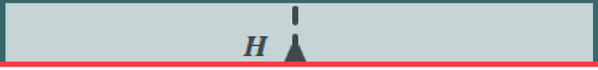

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Without any
1. gauge extension
2. BSM fermions
3. Colored scalars

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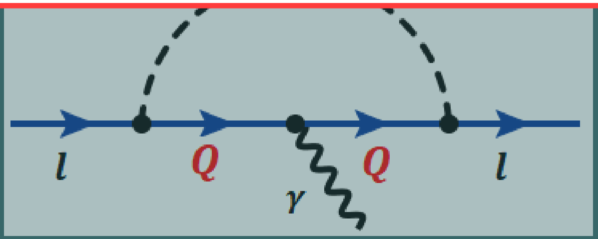


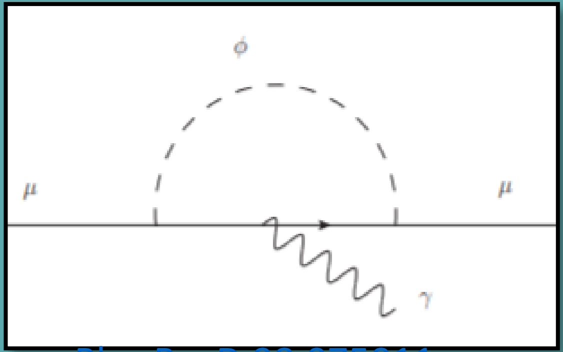
❖ Light Scalar

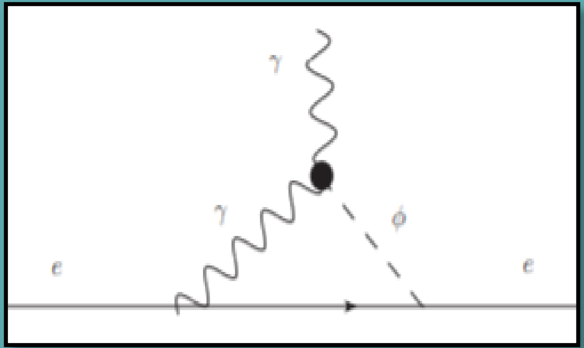
- ❑ Light scalar which has coupling with leptons can possibly explain the lepton AMM.

- ❑ Consider the effective Lagrangian for a real scalar $\boldsymbol{\phi}$

$$\mathcal{L}_\phi = -\frac{1}{2} m_\phi^2 \phi^2 - \sum_f \lambda_f \phi \bar{f} f - \frac{\kappa_\gamma}{4} \phi F_{\mu\nu} F^{\mu\nu},$$

- ❑ Muon AMM can be explained via one-loop contribution, where as electron AMM via Barr-Zee diagram





H. Davoudiasl, W. J. Marciano PhysRevD.98.075011
S. Jana, VPK, S. Saad PhysRevD.101.115037

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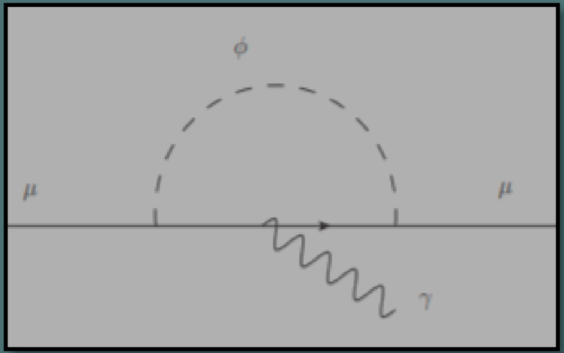
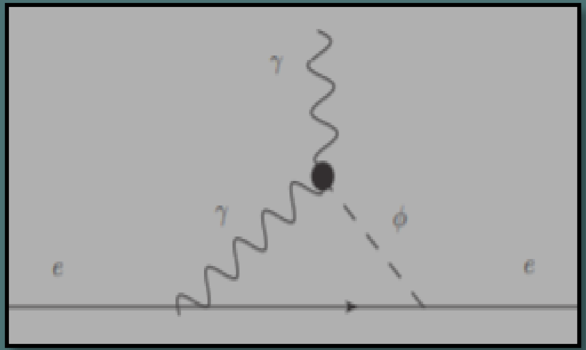
Is it possible with singlet scalar extension of SM?





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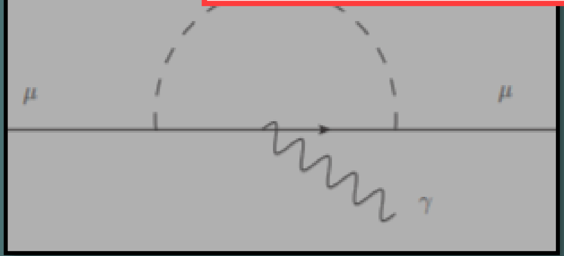
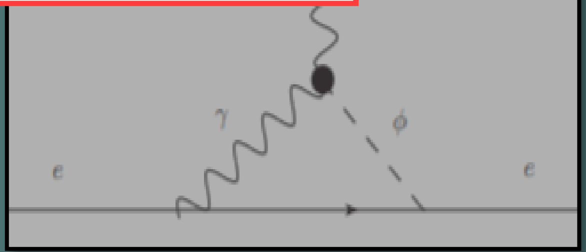
No! Small couplings.





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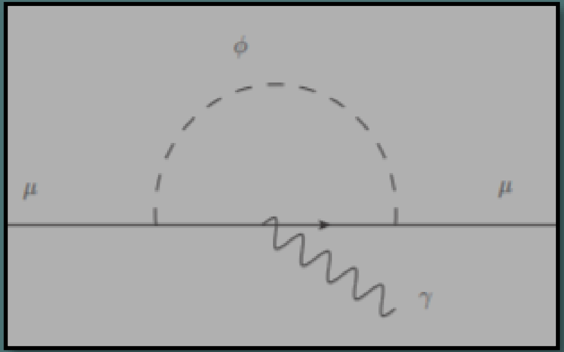
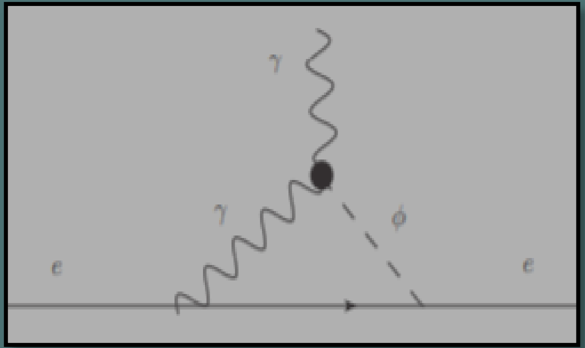
What about in Two Higgs Doublet Model?

- ❑ Muon AMM can be explained vi MM via Barr-Zee diagram





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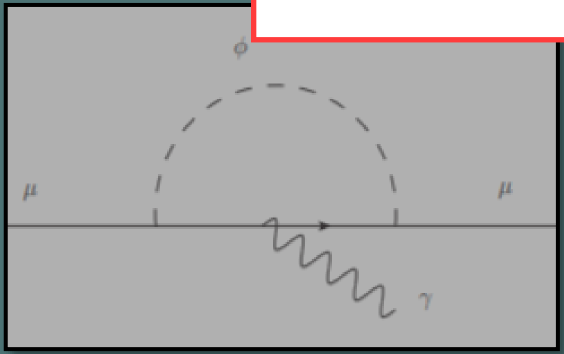
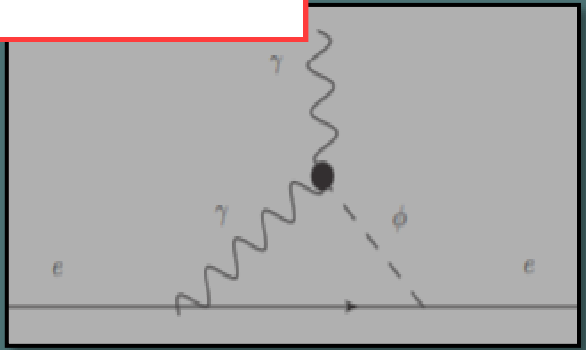
What about in Two Higgs Doublet Model?

Yes!





❖ Light Scalar from 2HDM

- Scalar Sector:

$$
\begin{aligned}
V = &\, m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - \{m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\} \\
&+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\
&+ \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \text{h.c.} \right\} \\
&+ \left\{ [\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\}.
\end{aligned}
$$

$$
H_1 = \begin{pmatrix} G^+ \\ \frac{v + H_1^0 + iG^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{H_2^0 + iA^0}{\sqrt{2}} \end{pmatrix}.
$$

$$
\begin{aligned}
h &= \cos(\alpha - \beta)\, H_1^0 + \sin(\alpha - \beta)\, H_2^0, \\
H &= -\sin(\alpha - \beta)\, H_1^0 + \cos(\alpha - \beta)\, H_2^0.
\end{aligned}
$$

- Alignment Limit: $\boldsymbol{\alpha \approx \beta}$, SM higgs decouples from the other CP-even higgs.

❖ Light Scalar from 2HDM

- Scalar Sector:

$$V = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - \{m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\} + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \text{h.c.}\right\} + \left\{\left[\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \text{h.c.}\right\}.$$

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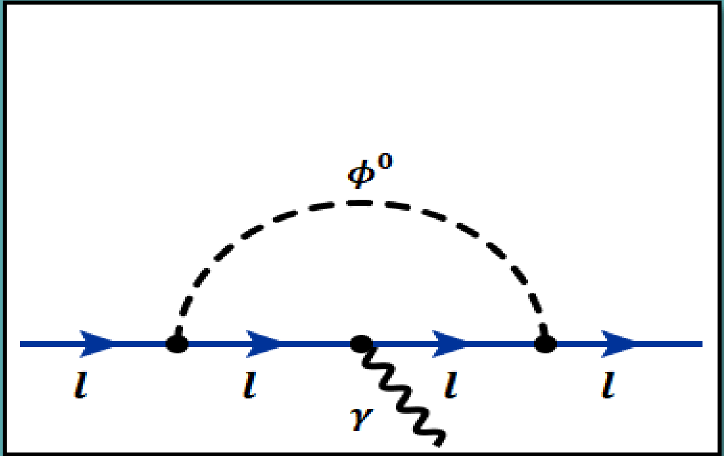
- Yukawa Sector:

$$-\mathcal{L}_Y \supset \left[Y_{\ell,ij} H^0 + i\, Y_{\ell,ij} A^0\right] \bar{\ell}_{Li} \ell_{Rj} + Y_{\ell,ij} \bar{\nu}_{Li} \ell_{Rj} H^+ \sqrt{2} + h.c.,$$

- For $\boldsymbol{Y_l}$, we assume a diagonal texture $\boldsymbol{Y_l = diag(y_e, y_\mu, y_\tau)}$.

❖ Light Scalar from 2HDM

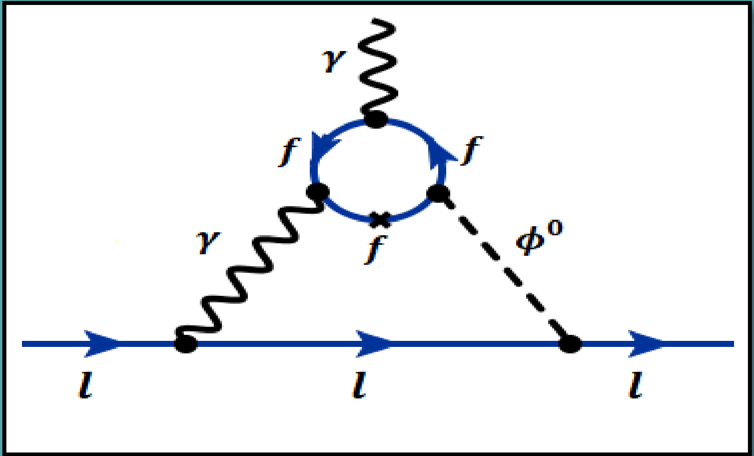
Muon AMM



$$\Delta a^H_{1,\ell} = \frac{-1}{8\pi^2} Q_\ell \left(Y^{\phi^0}_\ell\right)^2 \int_0^1 dx \frac{x^2(1-x+1)}{x^2+z_H^2(1-x)},$$

$$z_H = \frac{m_H}{m_\ell}$$

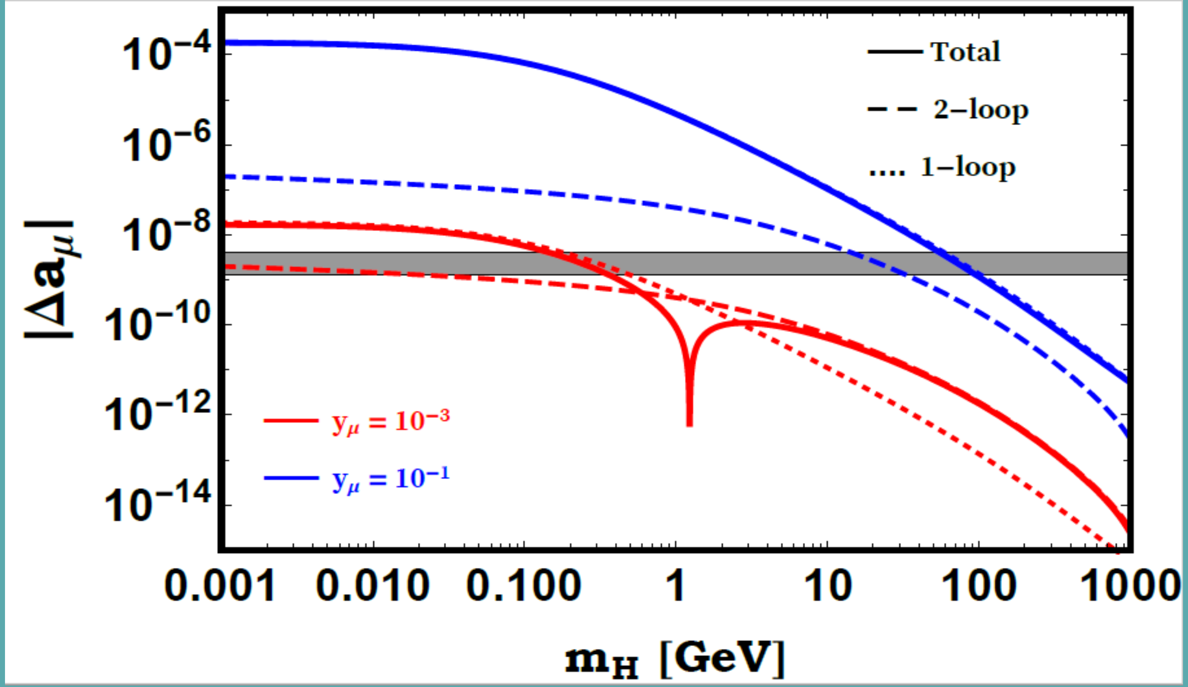
Electron AMM

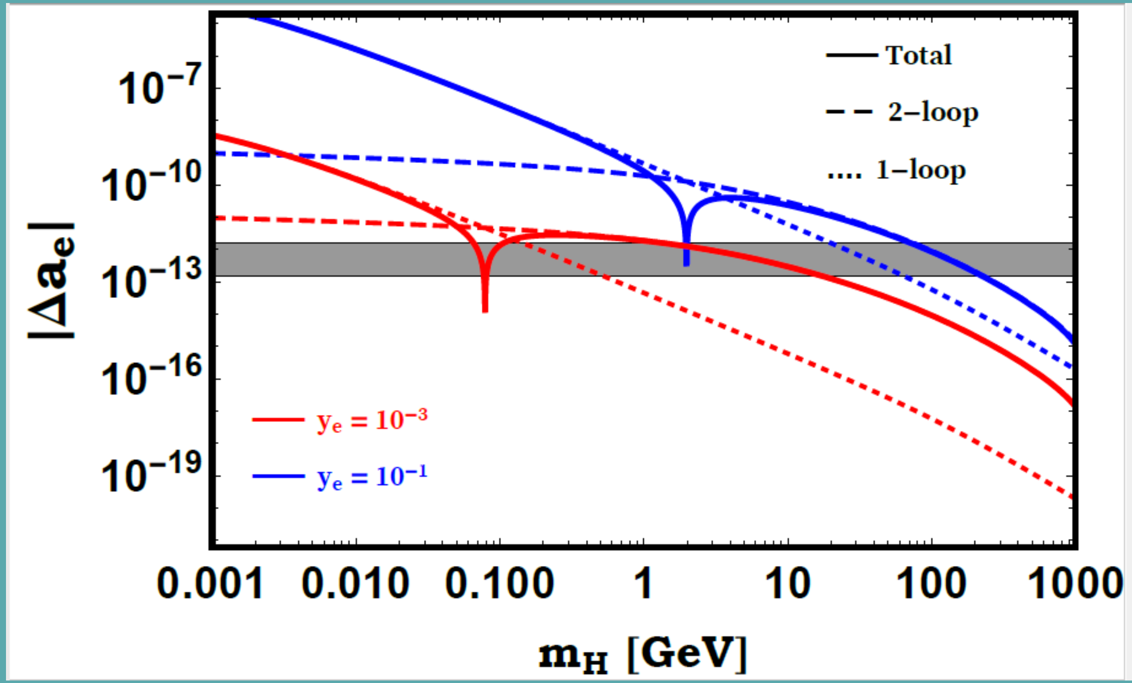


$$\Delta a^H_{2,\ell} = \frac{\alpha}{8\pi^3} m_\ell Y^H_\ell \sum_f \frac{N^c_f Q^2_f Y^H_f}{m_f} F_H\left[\frac{m_f^2}{m_H^2}\right],$$

$$F_H[z_H] = z_H \int_0^1 dx \frac{2x(1-x)-1}{x(1-x)-z_H} \ln \frac{x(1-x)}{z_H}.$$

❖ Light Scalar from 2HDM





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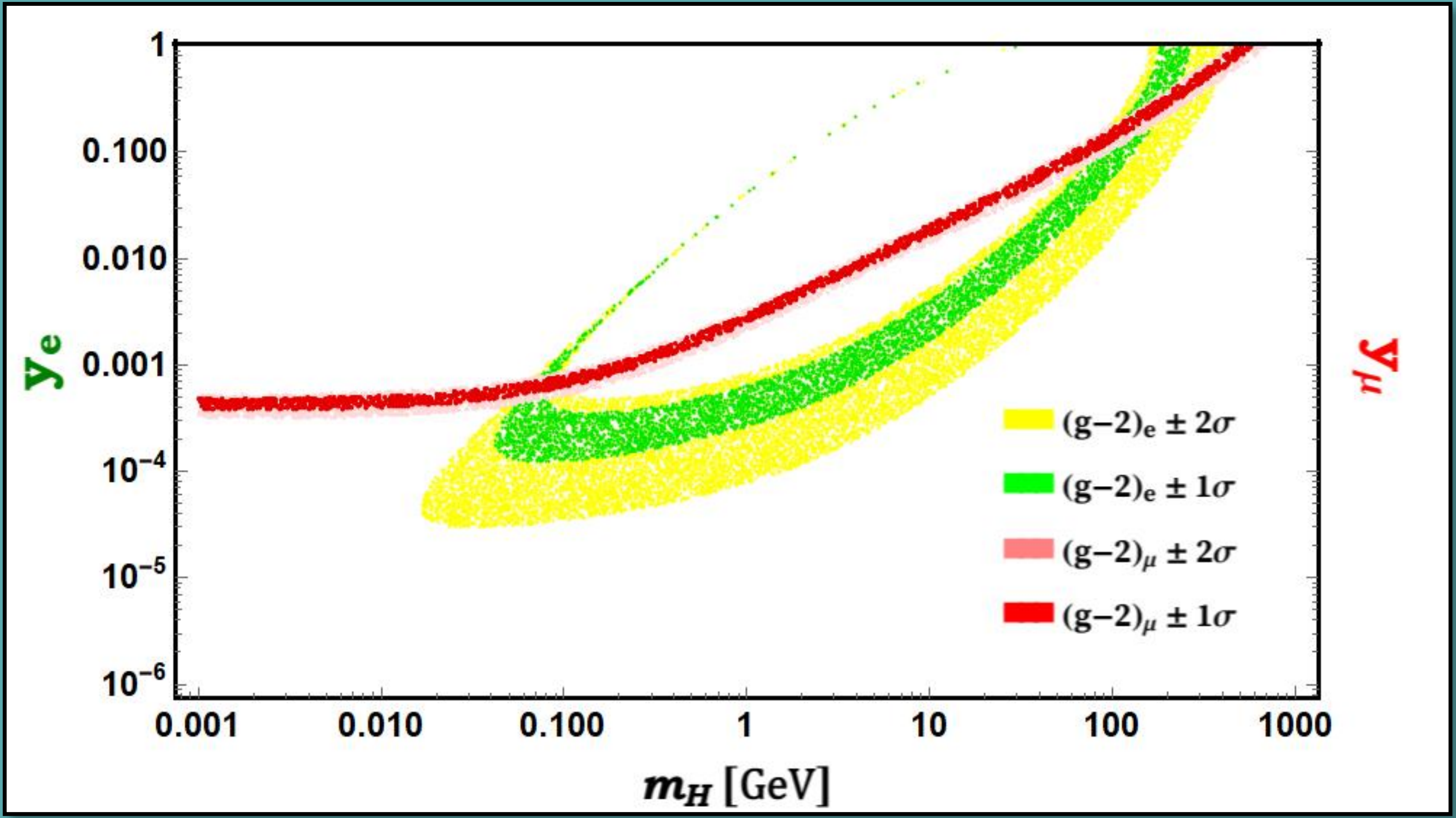


Setting $\boldsymbol{m_H^2 \ll m_{H+}^2 \approx m_A^2 \sim \mathcal{O}(110)\ GeV}$

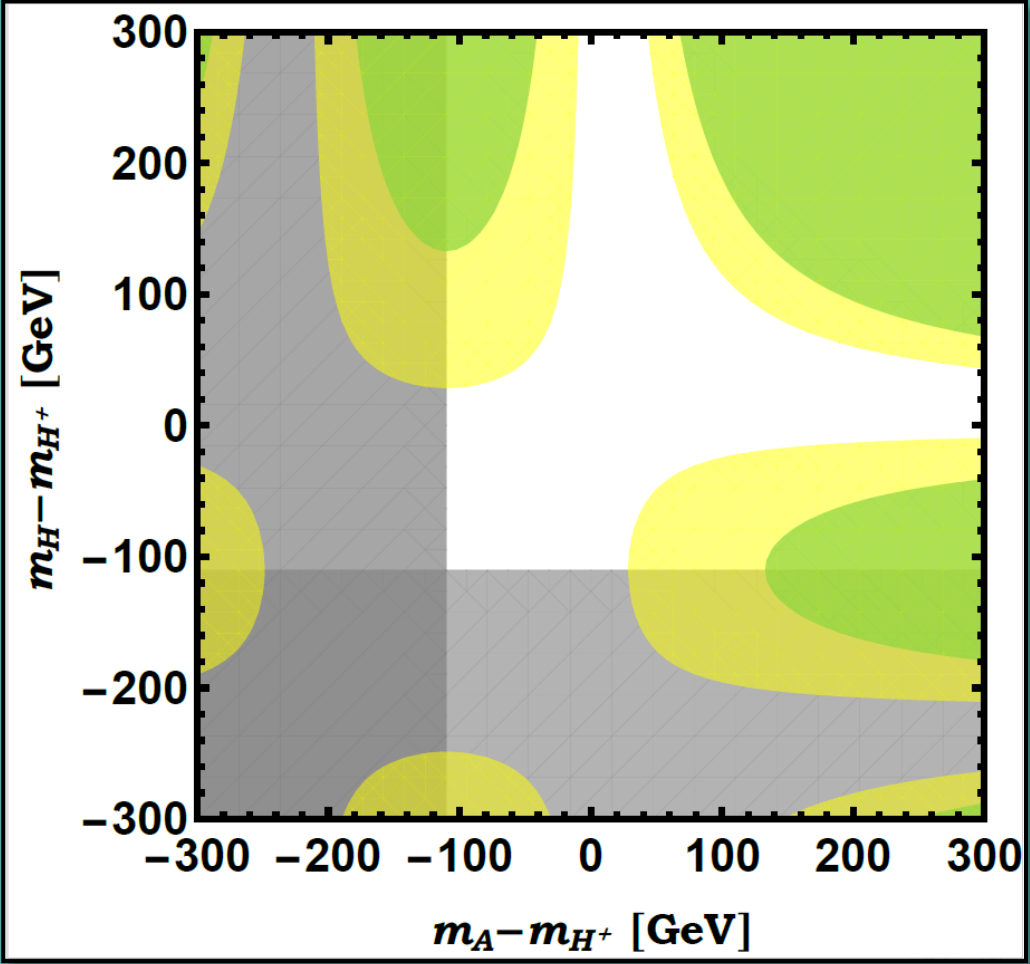
❖ Electroweak Precision Constraints

- T parameter in the alignment of 2HDM

$$T = \frac{1}{16\pi s_W^2 M_W^2}\left\{\mathcal{F}(m_{H^+}^2, m_H^2) + \mathcal{F}(m_{H^+}^2, m_A^2) - \mathcal{F}(m_H^2, m_A^2)\right\},$$

$$\mathcal{F}(m_1^2, m_2^2) \equiv \frac{1}{2}(m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\left(\frac{m_1^2}{m_2^2}\right).$$

- Our scenario, $\boldsymbol{m_H^2 \ll m_{H+}^2 \approx m_A^2 \sim \mathcal{O}(110)\ GeV}$ is well consistent with the EW precision constraints.



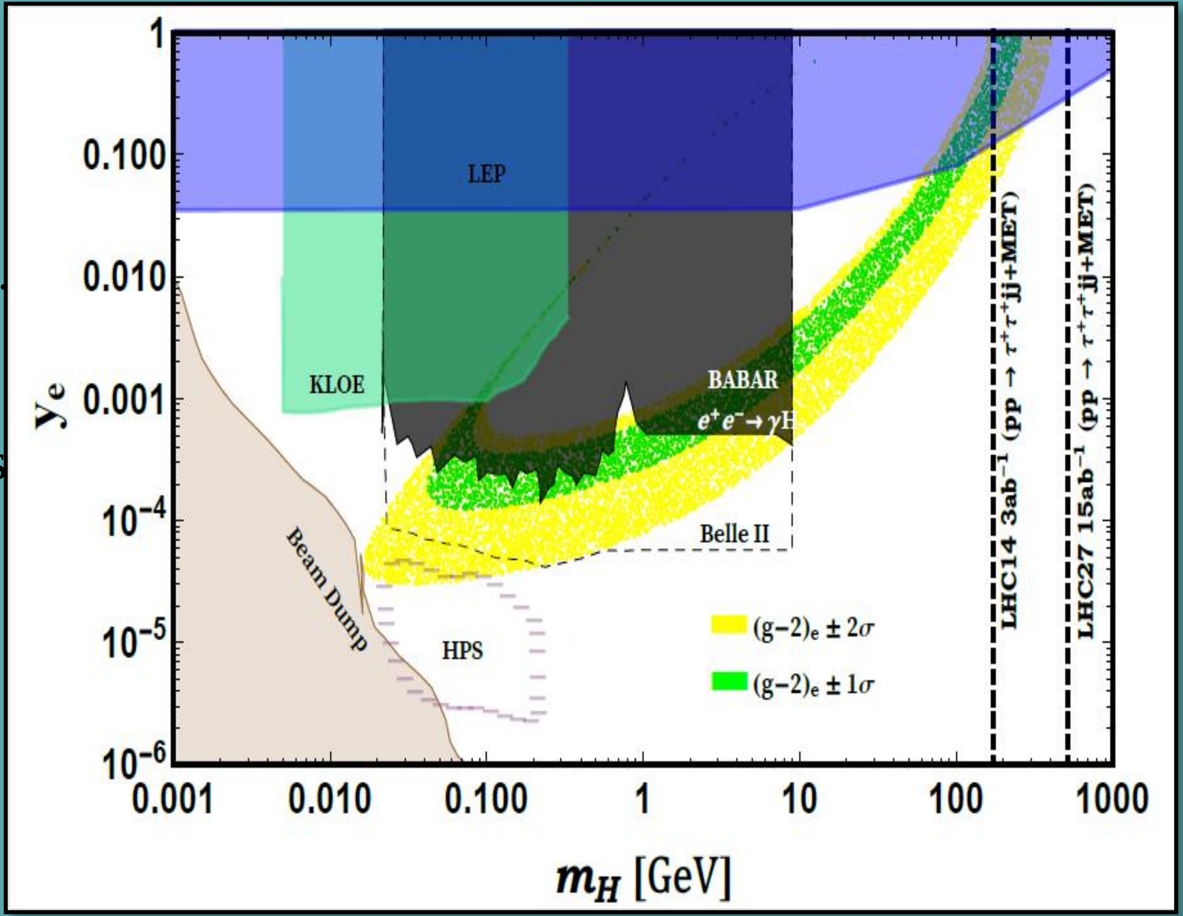
❖ Fixed Target Experiments

- Electron beam-dump experiments can probe light scalars that have coupling with the electrons.

- Light Scalars are produced via $\boldsymbol{e} + \boldsymbol{N} \rightarrow \boldsymbol{e} + \boldsymbol{N} + \boldsymbol{H}$ process.

- For a scalar of mass $\boldsymbol{m_H} < \boldsymbol{2m_\mu}$, after traveling macroscopic distances, it would decay back to electron pairs.

- Lack of such events constrain the mass of scalar and its corresponding coupling with the electron.



❖ Dark Photon Searches

- There are several experiments that search for the presence of dark-photons and their null observations can be translated to provide stringent constraints on the allowed parameter space of light scalars.

- **KLOE** collaboration and **BaBar** collaboration searches for the dark photons $\boldsymbol{A_d}$ through the process: $\boldsymbol{e^+e^- \to \gamma A_d}$, with $\boldsymbol{A_d \to e^+e^-}$.

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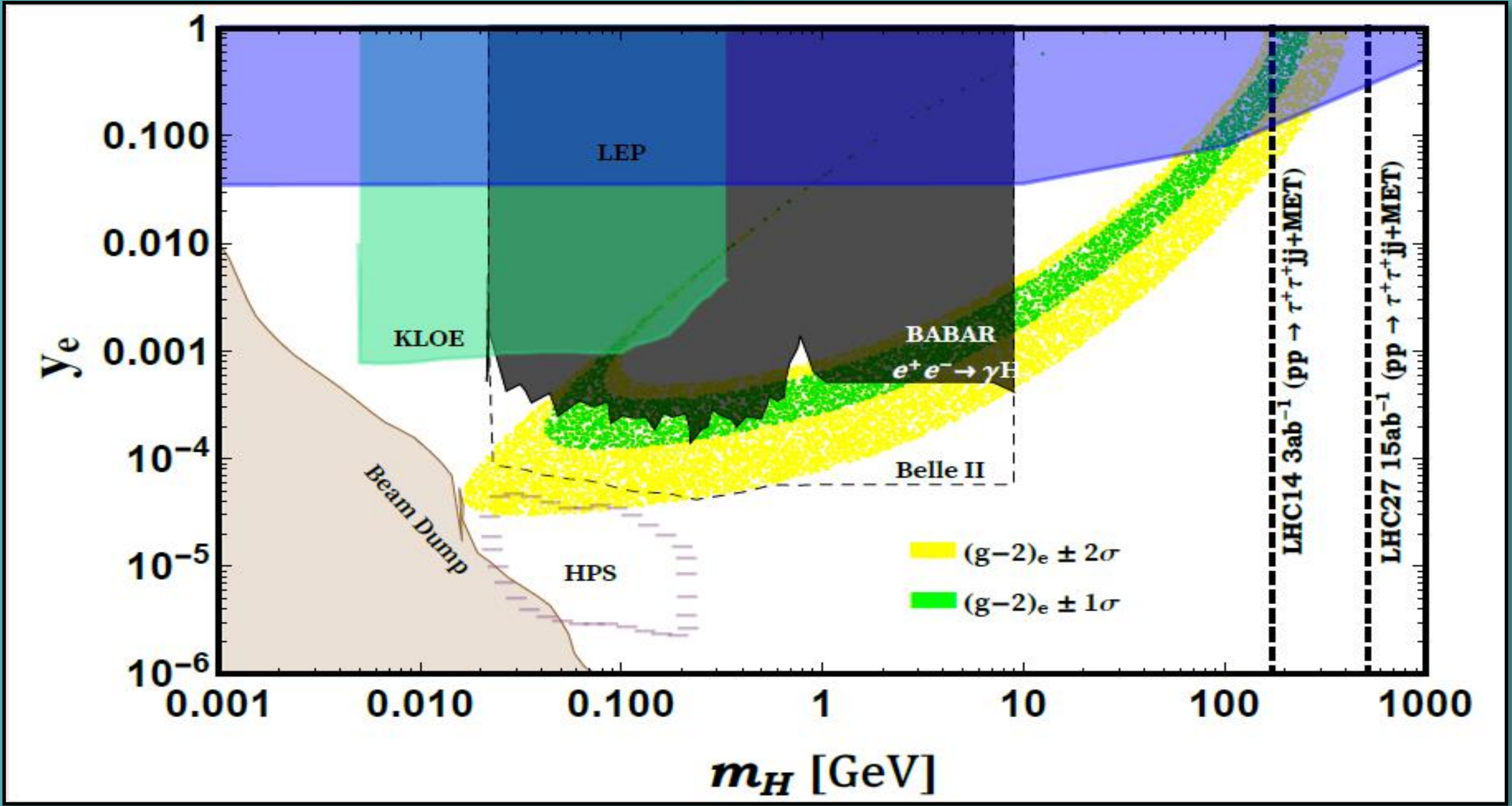
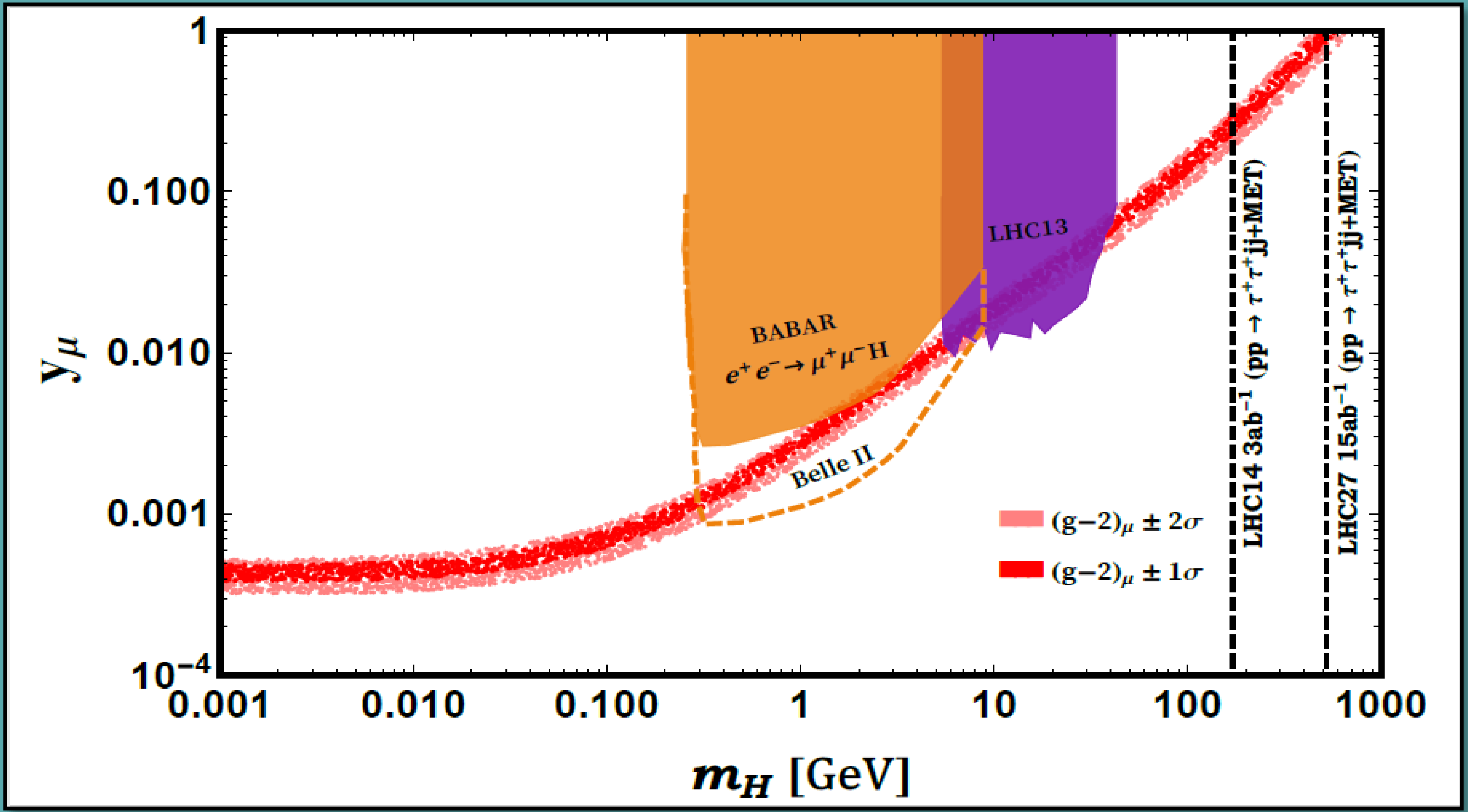
❖ Dark Photon Searches



❖ Dark Photon Searches

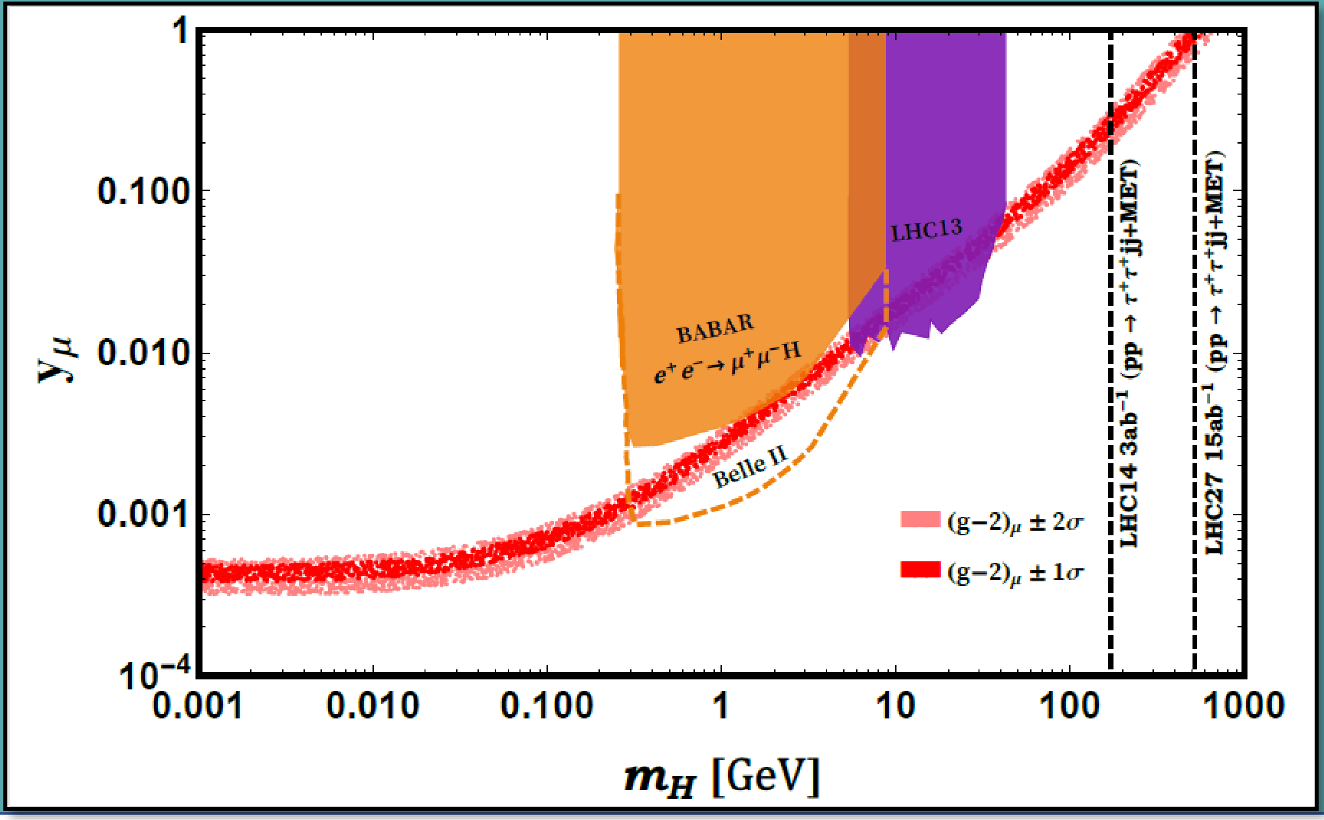
- For a scalar mass $m_H > 200\ MeV$, the dark-boson searches at the BaBar can be used to impose limits on H $\mu^+\mu^-$ coupling via $e^+e^- \rightarrow \mu^+\mu^- H$ process.



❖ Rare Z-decay Constraints

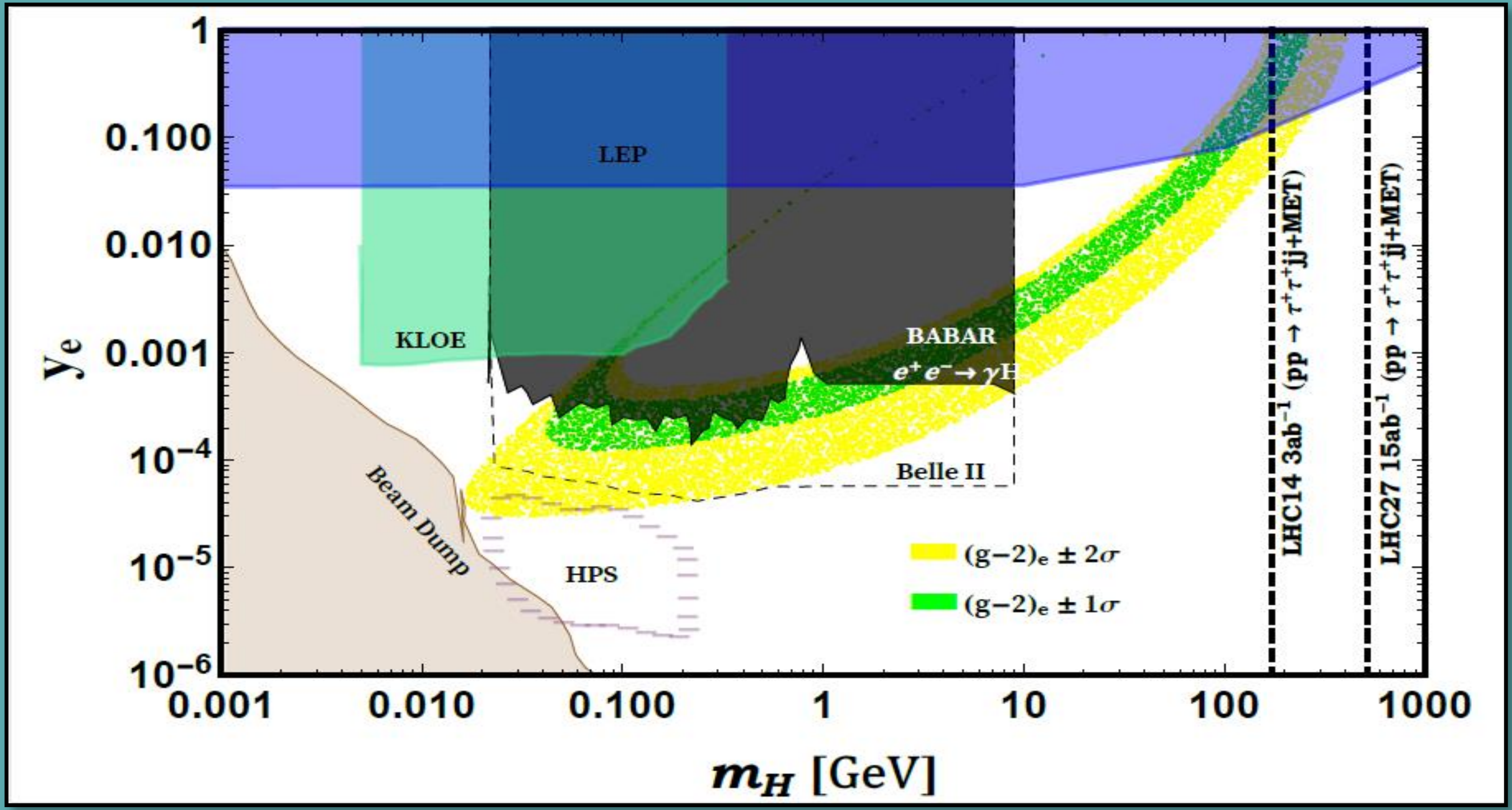
- Rare Z-decay constraints:– Exotic Z decay of the type $Z \to 4\mu$ has been searched by both the ATLAS and the CMS collaborations.

- The LHC results can be interpreted as constraints on the process $Z \to \mu^+\mu^- H$, with $H \to \mu^+\mu^-$.

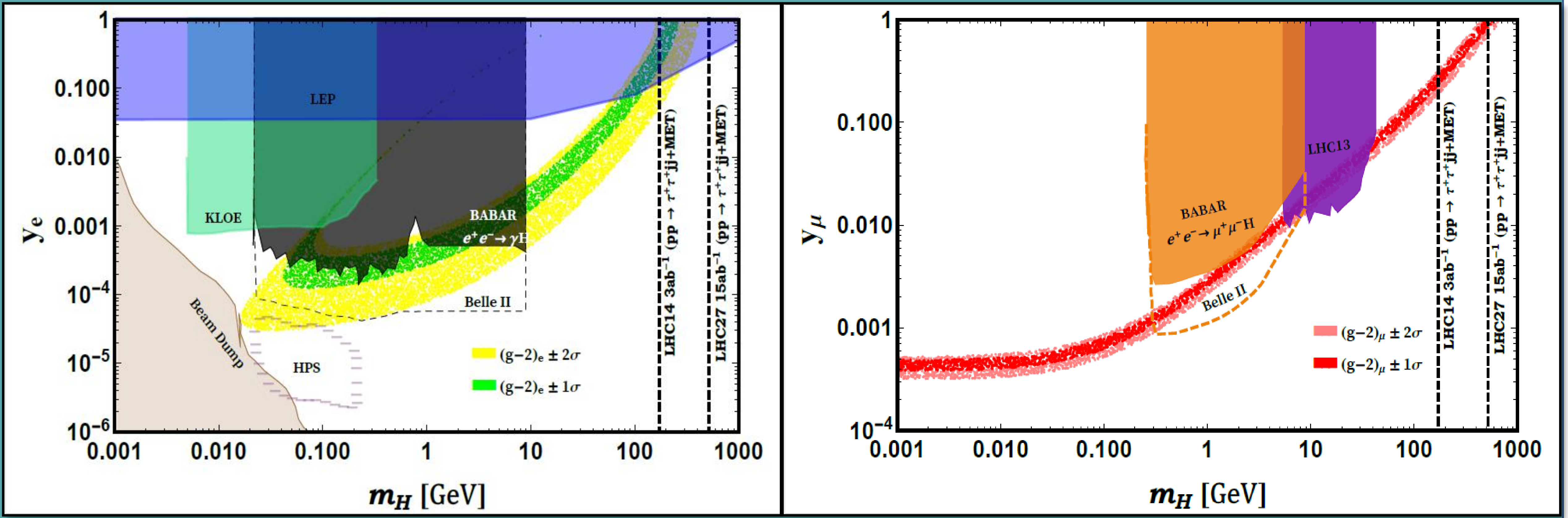


❖ LEP Constraints

- $e^+e^- \to f\bar{f}$ process constrained by the LEP experiments, which can be used to constrain the masses of the neutral scalar and its corresponding coupling with charged fermions.



❖ Conclusions



❖ Conclusions

- Despite the numerous tight constraints, the CP-even scalar H can remain light and live in $\mathcal{O}(10)\ MeV\ -\ \mathcal{O}(1)\ GeV$ mass range and contribute simultaneously to both electron and muon AMM with correct sign and magnitude.

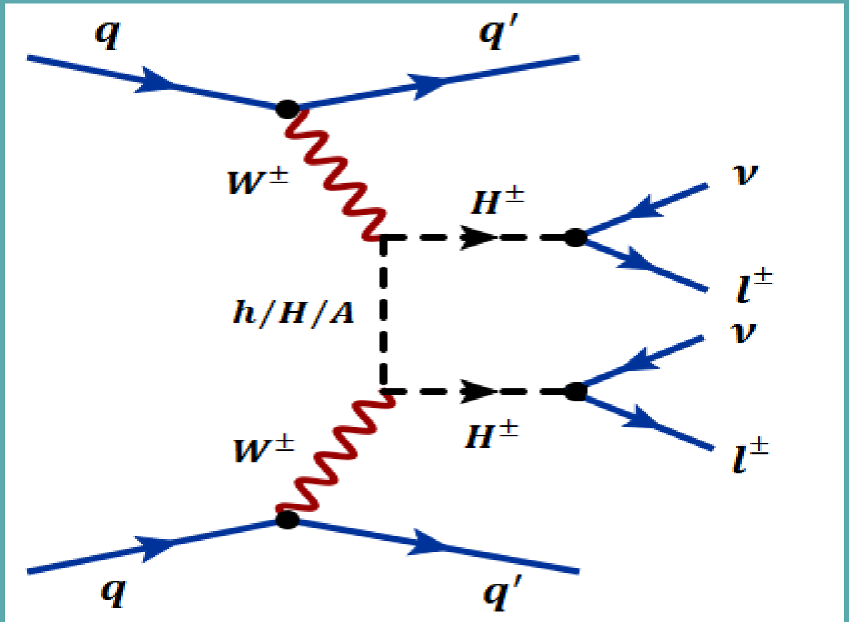
- In the lower mass regime $m_H < \mathcal{O}(10)\ MeV$, it is incapable of explaining the electron AMM correctly (even though it can explain the muon AMM).

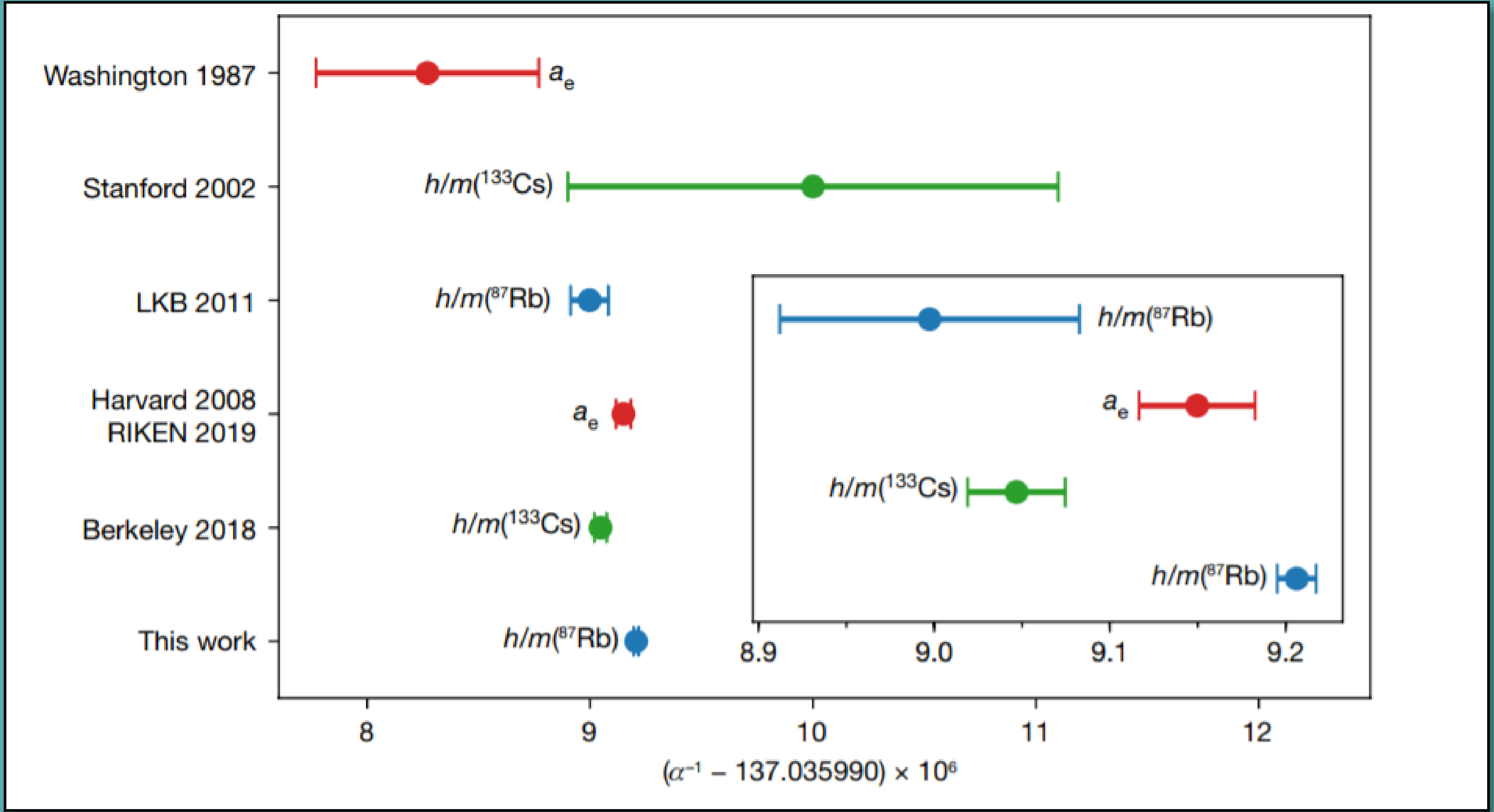
- For $m_H > \mathcal{O}(1)\ GeV$, even though a concurrent explanation of both electron and muon AMM is possible, , however, various experimental constraints kill most of this portion of the parameter space.


Thank you!

❖ Future Implication at Collider

- ❑ Same-sign charged lepton signature via vector-boson fusion process at the LHC.
- ❑ If the mass splitting between the CP-even and CP-odd neutral scalars is turned off, then the amplitude for this process will be exactly zero.





$$\Delta a_e^{\mathrm{Rb}} \equiv a_e^{\exp\,(\mathrm{Rb})} - a_e^{\mathrm{SM}} = (4.8 \pm 3.0) \times 10^{-13}\,.$$

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