Light Scalar and Lepton Anomalous Magnetic Moments

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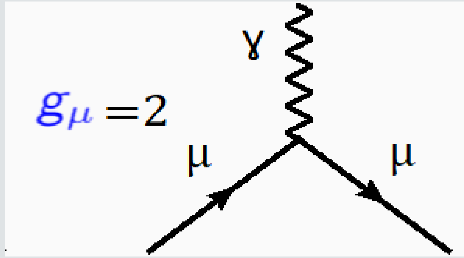
Based on: *Phys.Rev.D* 101 (2020) 11, 115037 (in collaboration with Sudip Jana and Shaikh Saad)

Oklahoma State University

Muon Magnetic Moment

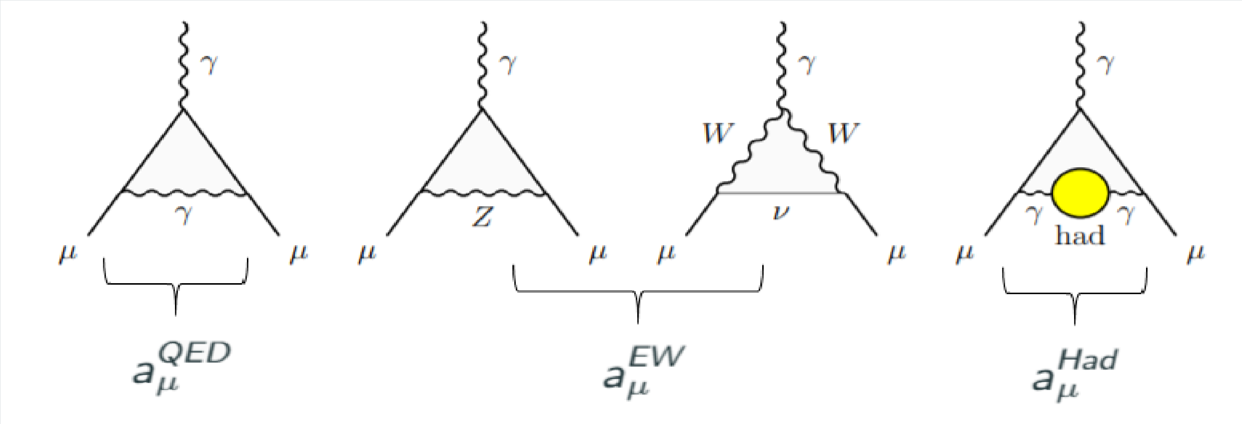
- Magnetic moment of Leptons: $$\vec{\mu}_B = g_\mu \frac{e}{2m_\mu}\vec{S}$$

- Lande' g- factor:



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

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

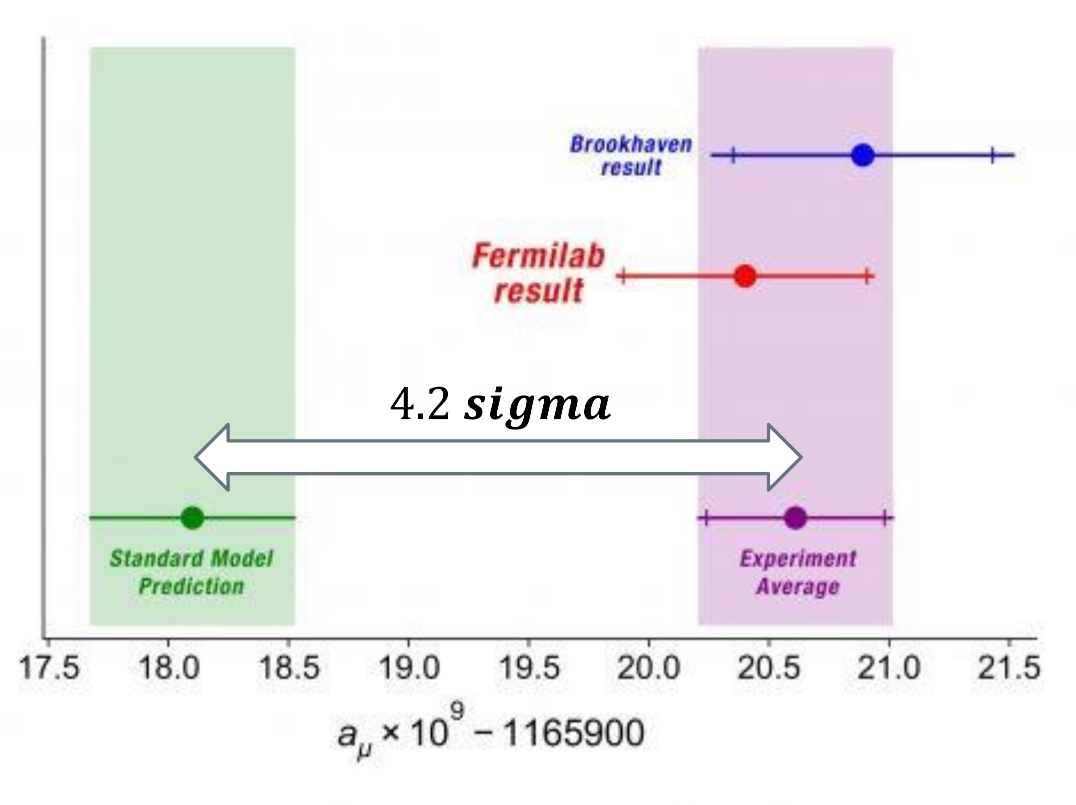


$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

Current Status of muon (g-2)

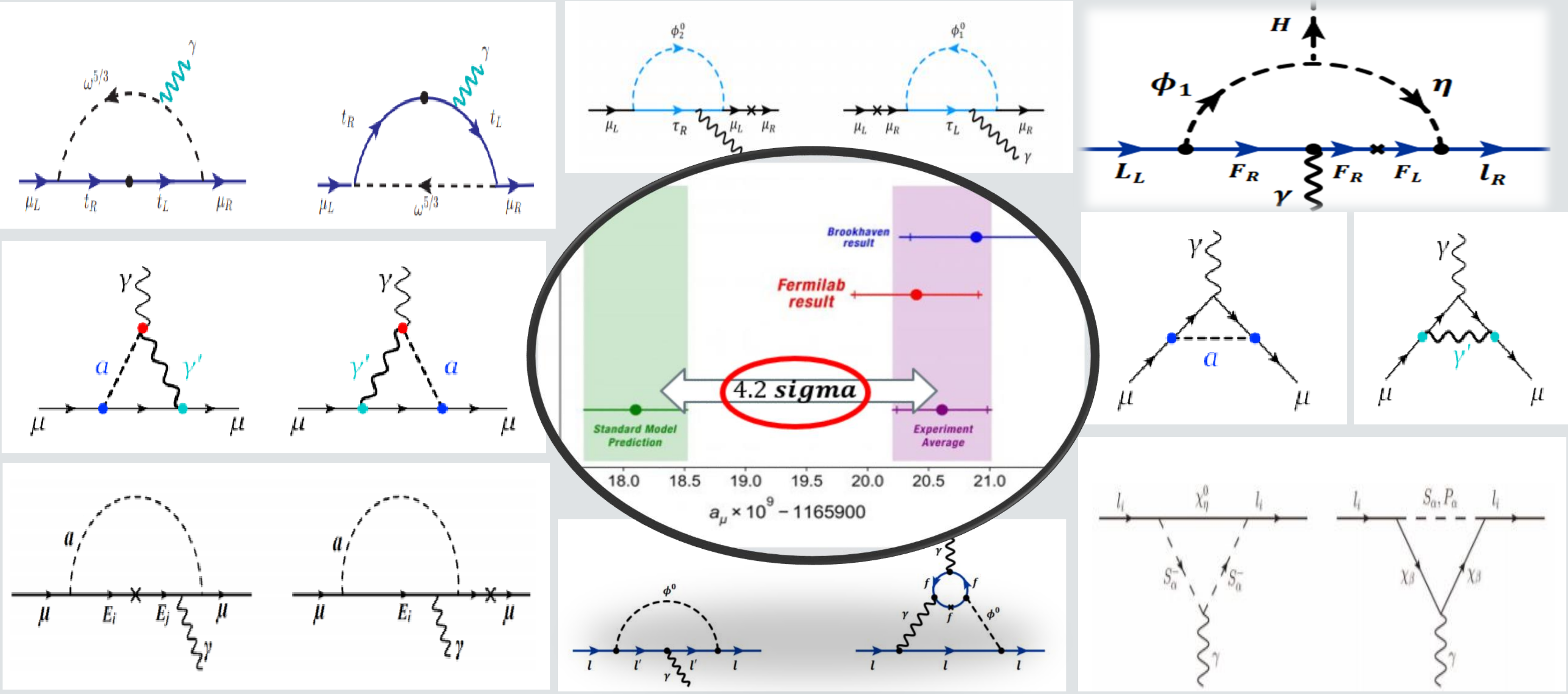
$$10^{11} a_\mu = \begin{cases} 116591810(43)\ \mathbf{SM} \\ 116592040(54)\ \mathbf{Exp} \end{cases}$$

$$\Delta a_\mu = a_\mu{}^{exp} - a_\mu{}^{SM} = 251(59) \times 10^{-11}$$



Fermilab Muon g-2 Collaboration, B. Abi *et al.* (2021)

Possible Explanations in different contexts..



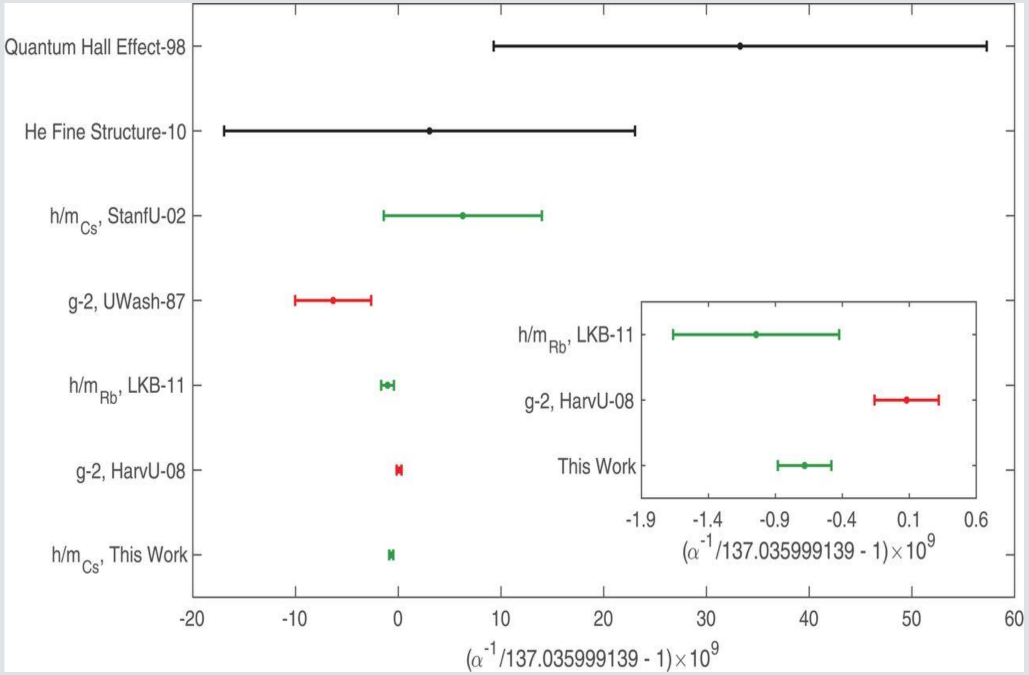
Current Status of electron (g-2)

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

$$10^{12} a_e = \begin{cases} 1159652181.61(23) \ \textbf{SM} \\ 1159652180.73(28) \ \textbf{Exp} \end{cases}$$

$$\Delta a_e = a_e^{exp} - a_e^{SM} = -87(36) \times 10^{-14}$$

2.4 σ



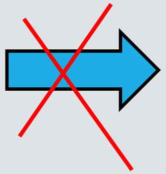
R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Mueller (2018)

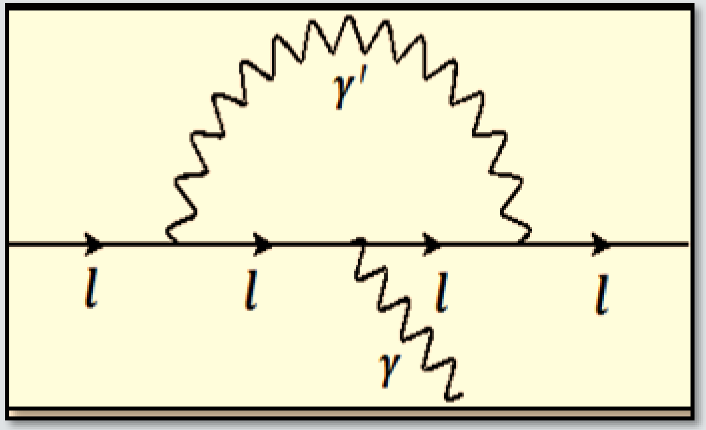
Challenges

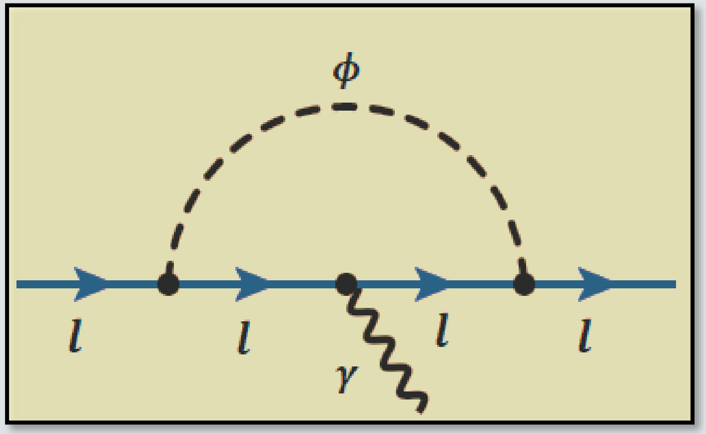
A simultaneous explanation of these two anomalies is challenging

➢ Opposite Sign:

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

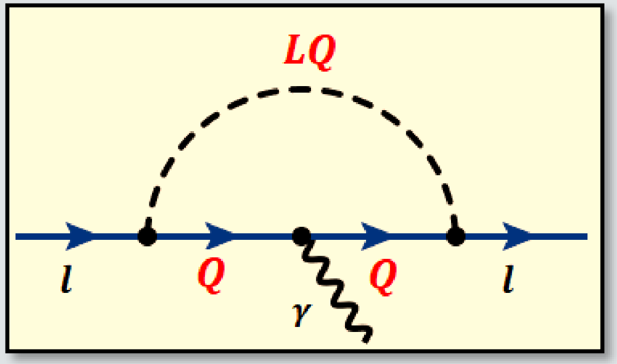






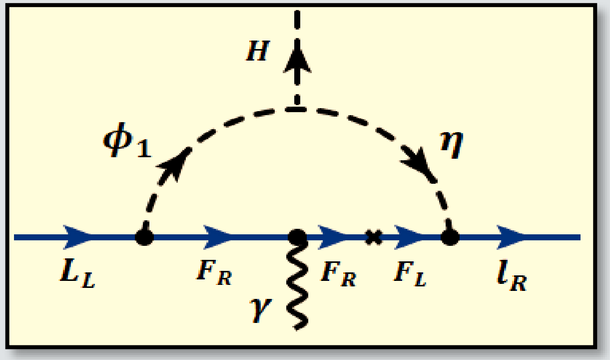
Possible Explanations

- With Lepto-quarks:



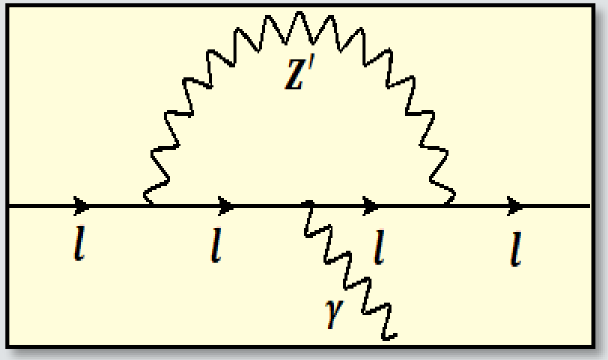
I. Dorsner, S. Fajfer,S. Saad (2020)
I. Bigaran, and R. R. Volkas (2020)

- With additional Fermions and Scalars:



K.F.Chen,,C.W.Chiang, and K.Yagyu (2020)
S. Jana, VPK, S. Saad, W. Rodejohann (2020)

- With light **Z'**:



A. Bodas, R. Coy, and S. King (2021)

Possible Explanations

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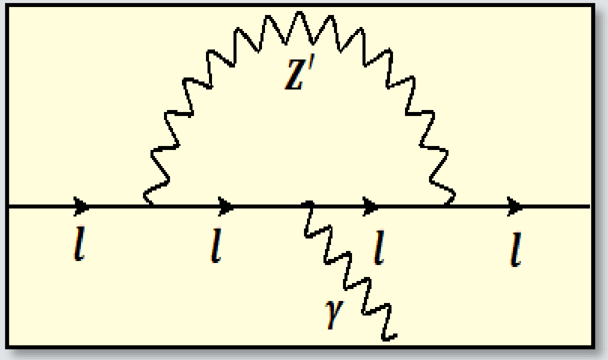

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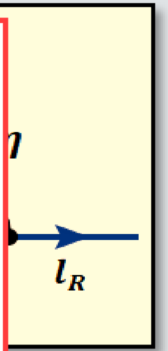
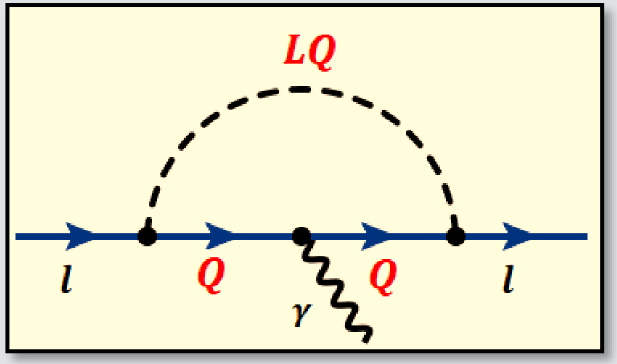


Is it possible to resolve these two anomalies in a more minimal setup?

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

S. Jana, VPK, S. Saad, W. Rodejohann (2020)

❑ With Lepto-quarks:



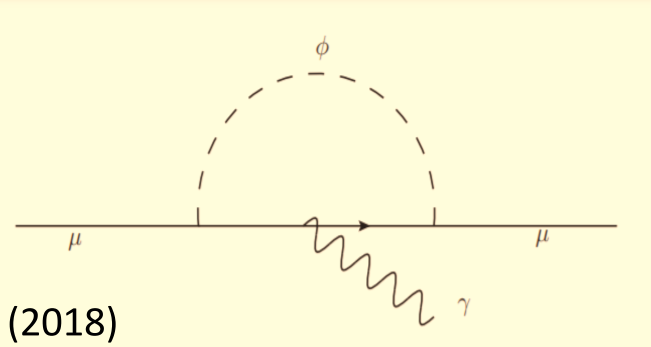
I. Dorsner, S. Fajfer,S. Saad (2020)
I. Bigaran, and R. R. Volkas (2020)

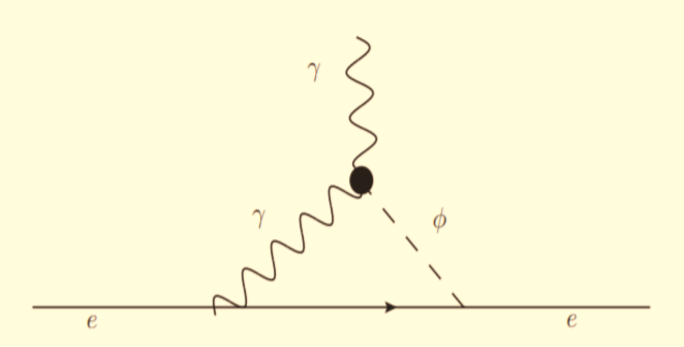
Light Scalar

- A light neutral scalar that has coupling with the charged leptons can possibly resolve these two anomalies simultaneously.

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

- Muon AMM can be explained via a one-loop contribution, whereas the electron AMM via a two-loop Barr-Zee diagram.

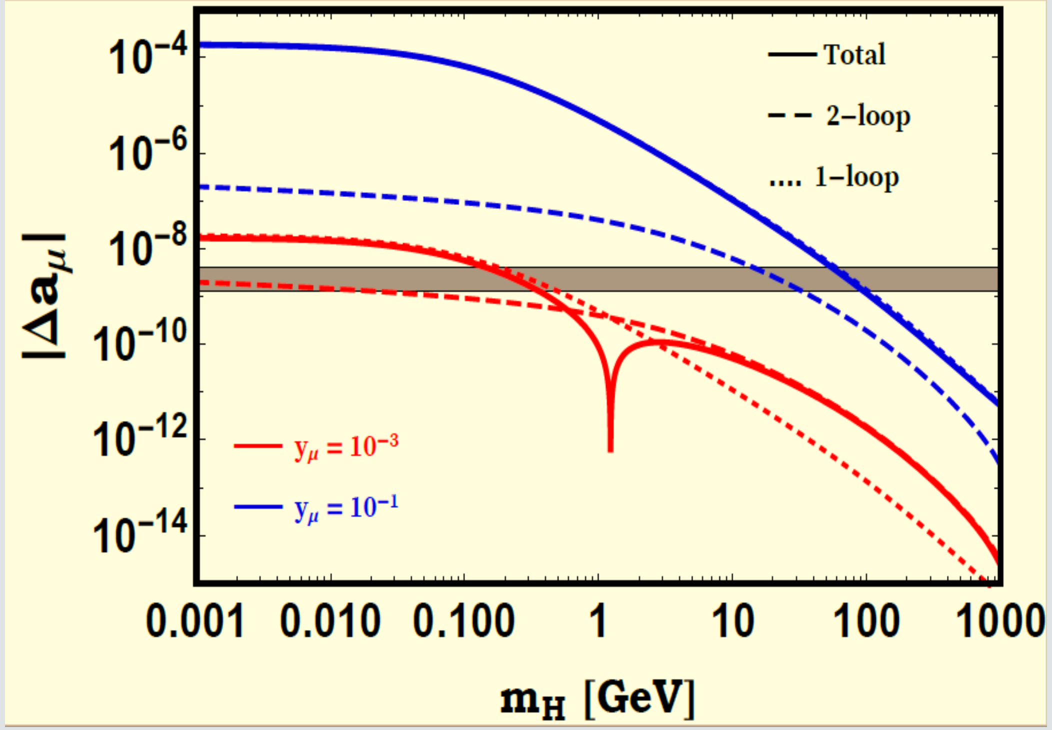


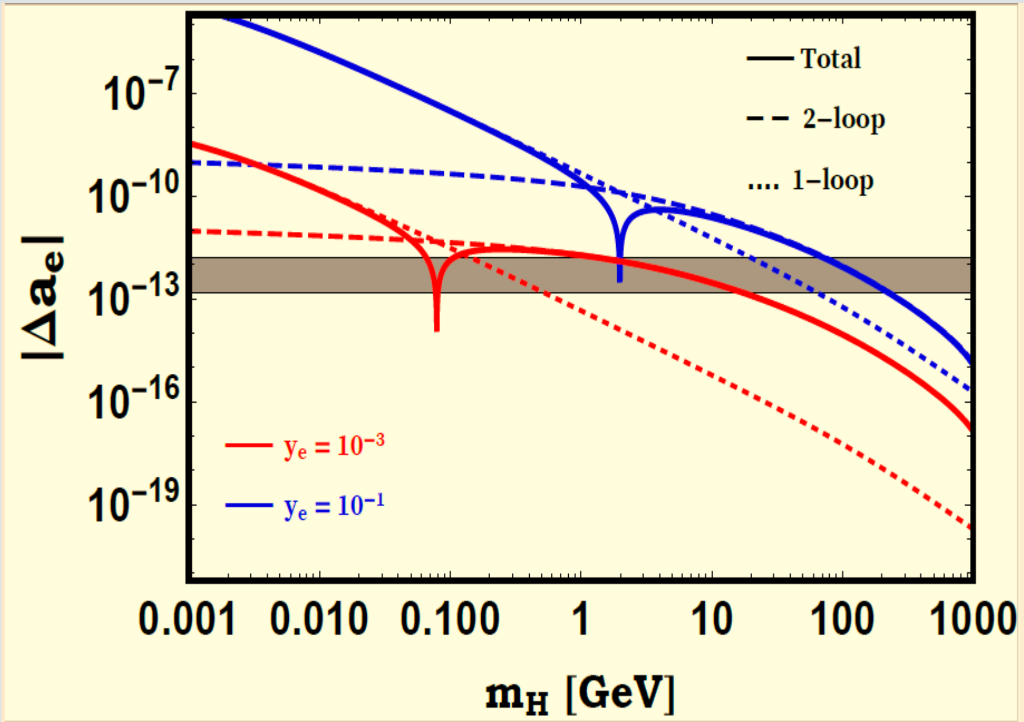


H. Davoudiasl, W. J. Marciano (2018)
S. Jana, VPK, S. Saad (2020)

Light Scalar

However, such a light scalar also leads to a two-loop contribution to muon AMM and a one-loop contribution to electron AMM.





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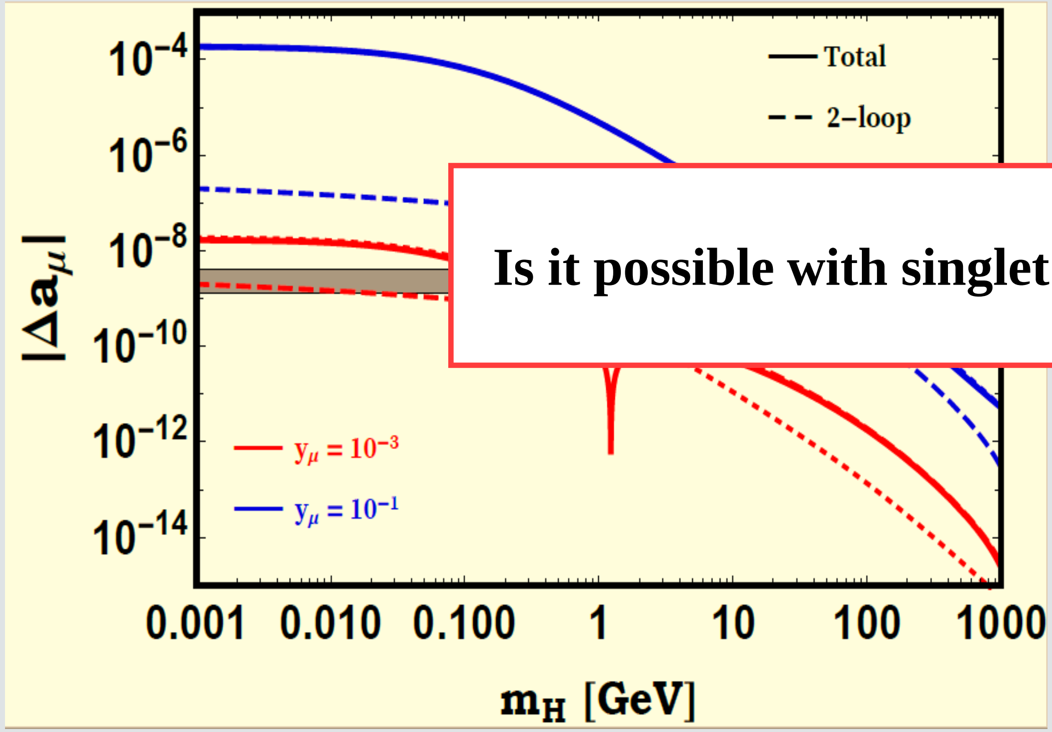

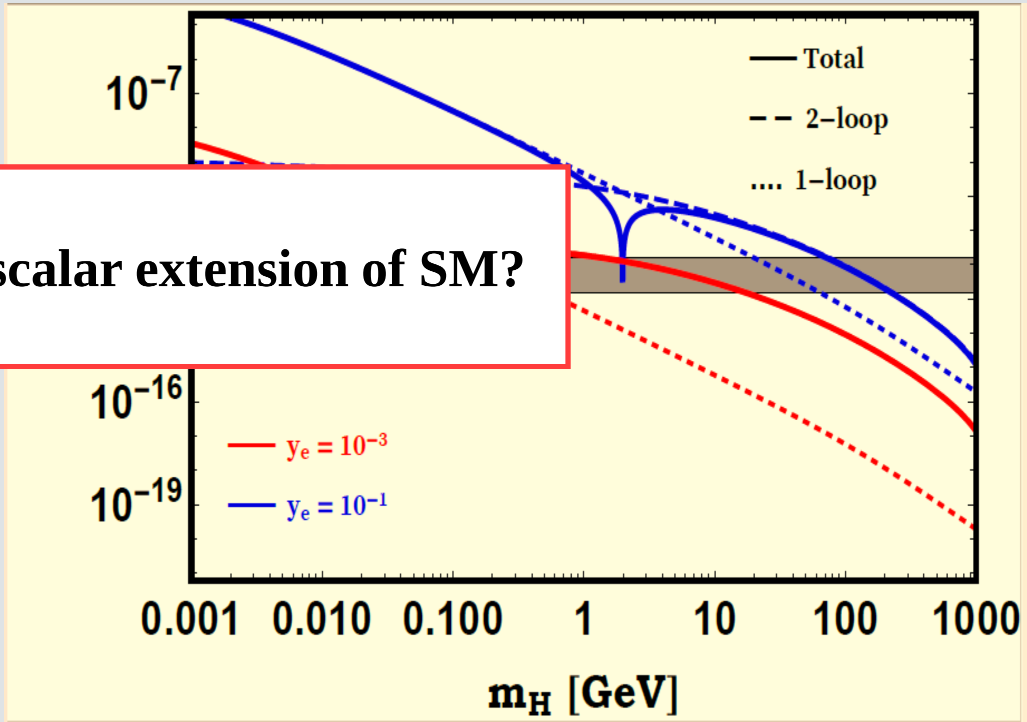

Is it possible with singlet scalar extension of SM?

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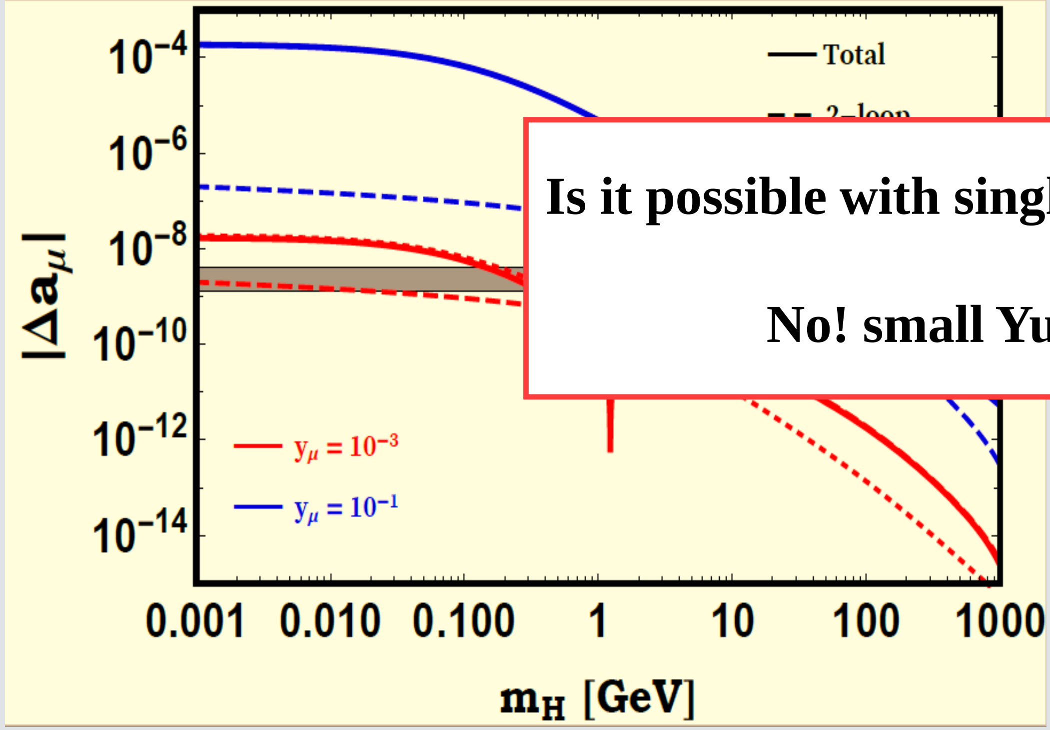
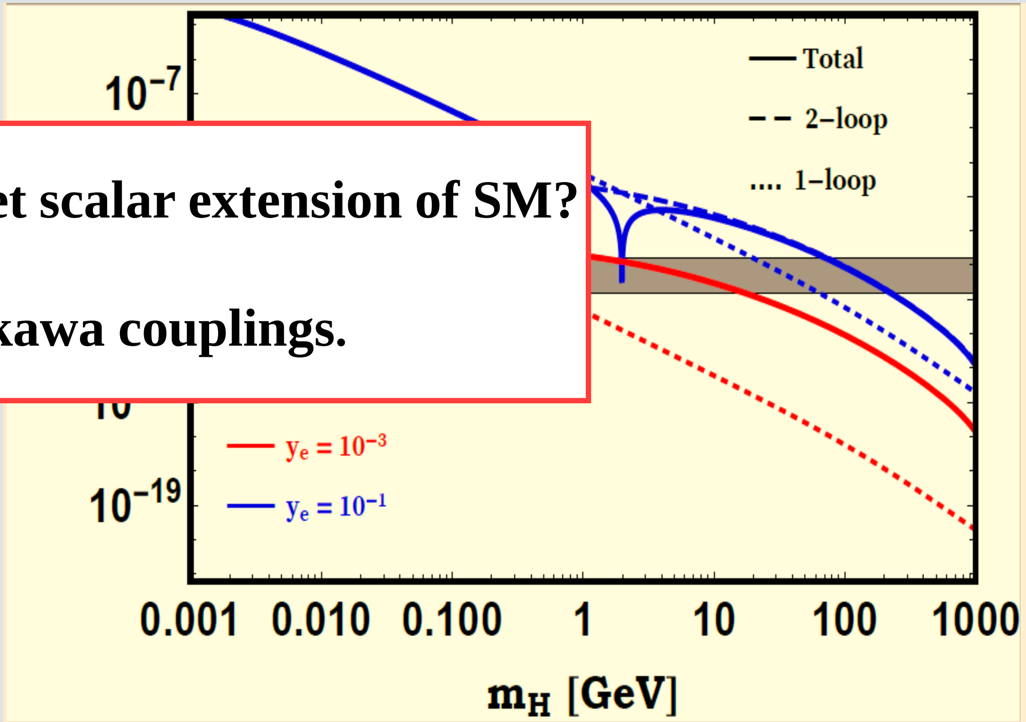


Is it possible with singlet scalar extension of SM?

No! small Yukawa couplings.



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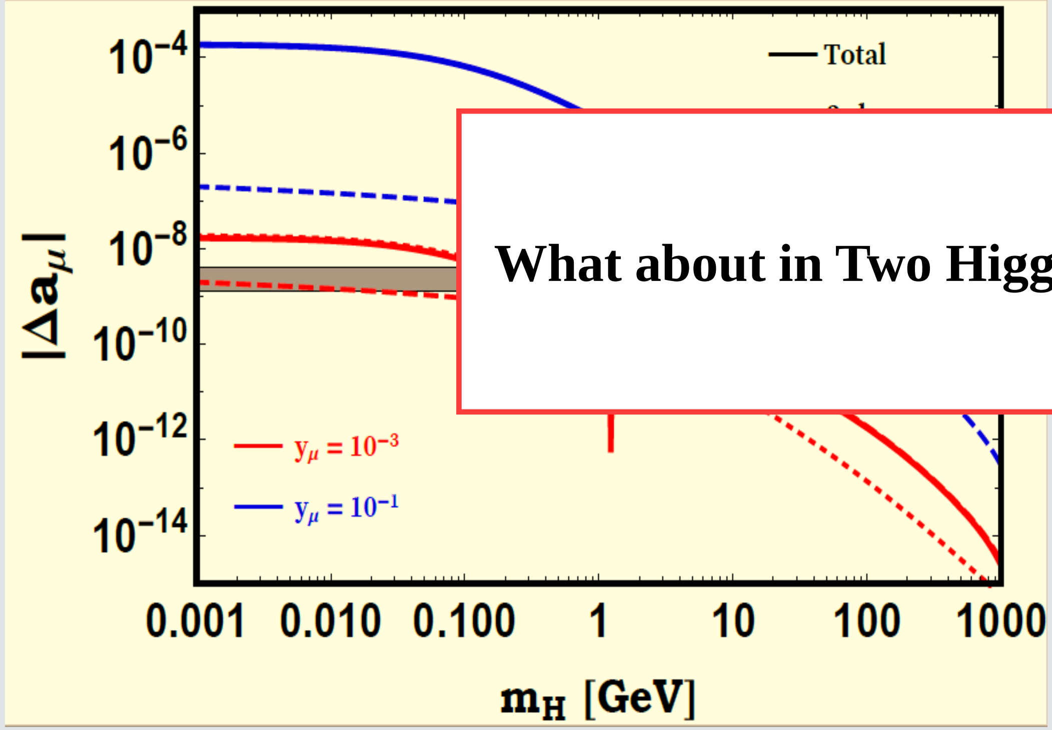
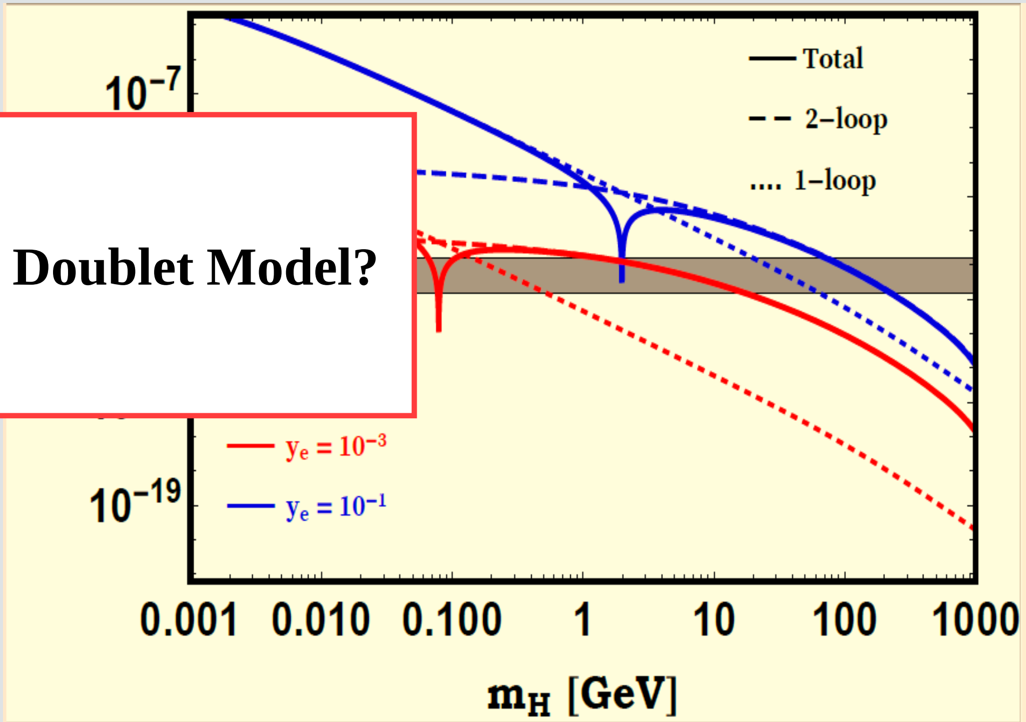




What about in Two Higgs Doublet Model?

Light Scalar: 2HDM

Scalar Sector:

$$\begin{aligned}\mathcal{V} &= M_{11}^2 H_1^\dagger H_1 + M_{22}^2 H_2^\dagger H_2 - [M_{12}^2 H_1^\dagger H_2 + \text{h.c.}] \\ &+\tfrac{1}{2}\Lambda_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2}\Lambda_2 (H_2^\dagger H_2)^2 + \Lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \Lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &+ \left\{ \tfrac{1}{2}\Lambda_5 (H_1^\dagger H_2)^2 + \left[\Lambda_6 \,(H_1^\dagger H_1) + \Lambda_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \text{h.c.} \right\} .\end{aligned}$$

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

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

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

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

Light Scalar: 2HDM

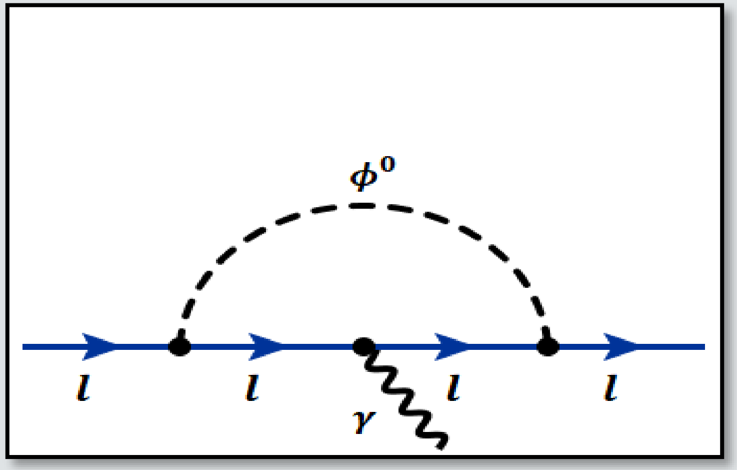
Yukawa Sector:

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

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

Light Scalar: from 2HDM

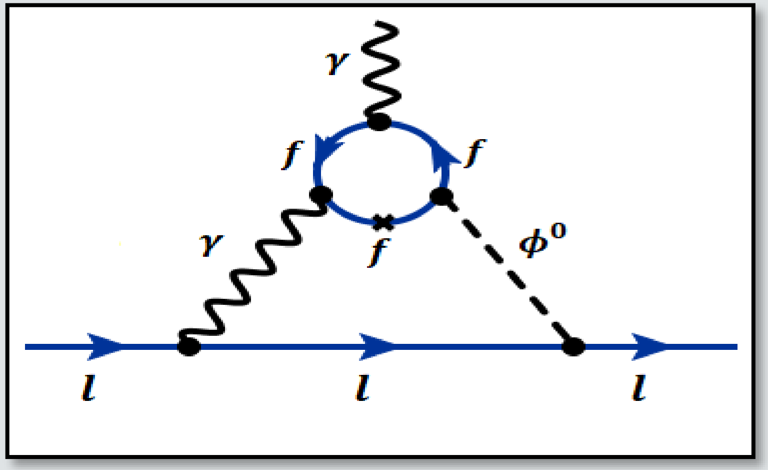
Muon AMM



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

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

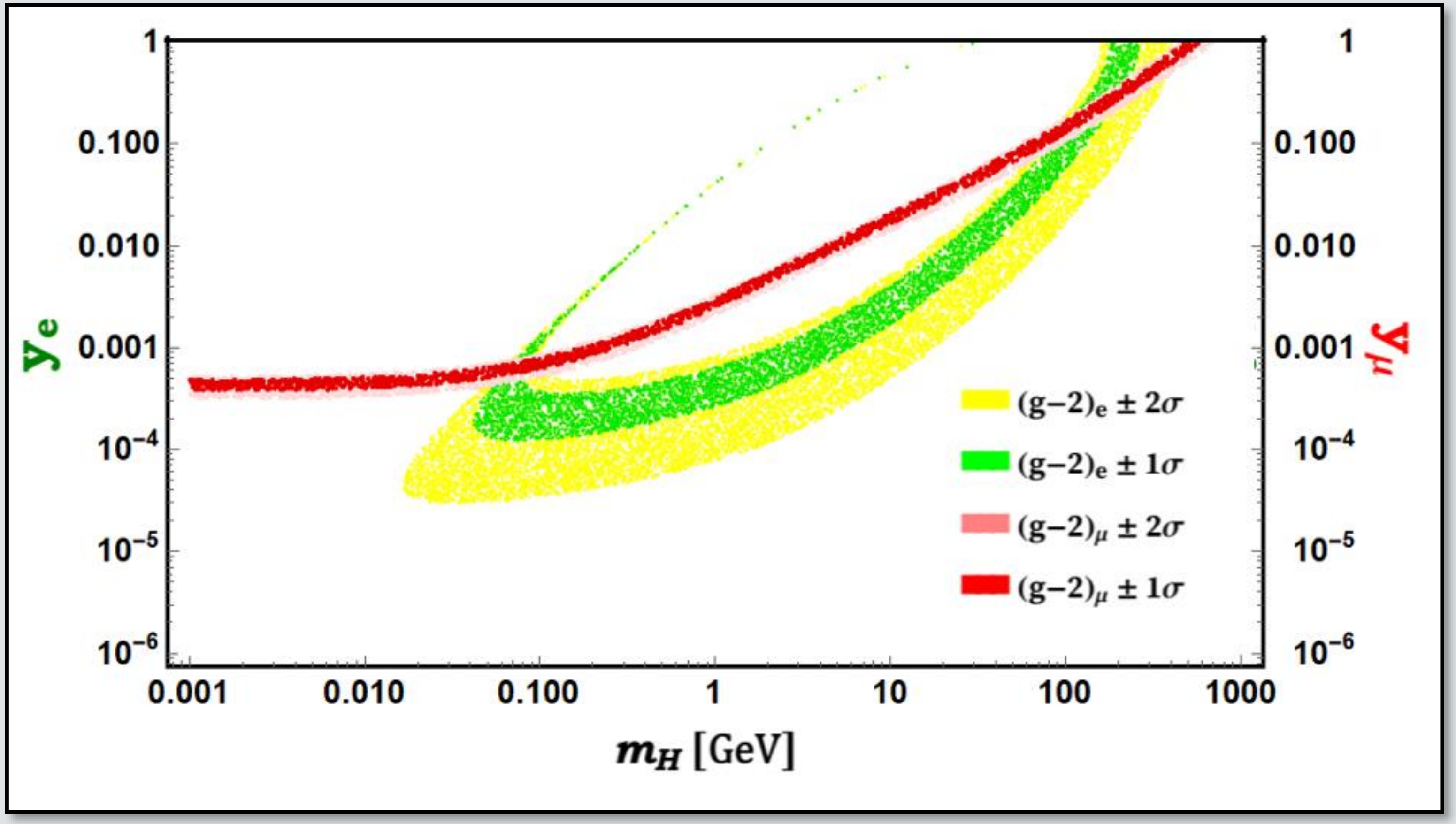
Electron AMM



$$\Delta a^H_{2,\ell} = \frac{\alpha}{8\pi^3} m_\ell Y_\ell^H \sum_f \frac{N_f^c Q_f^2 Y_f^H}{m_f} F_H\left[\frac{m_f^2}{m_H^2}\right],$$

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

Light Scalar: from 2HDM



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

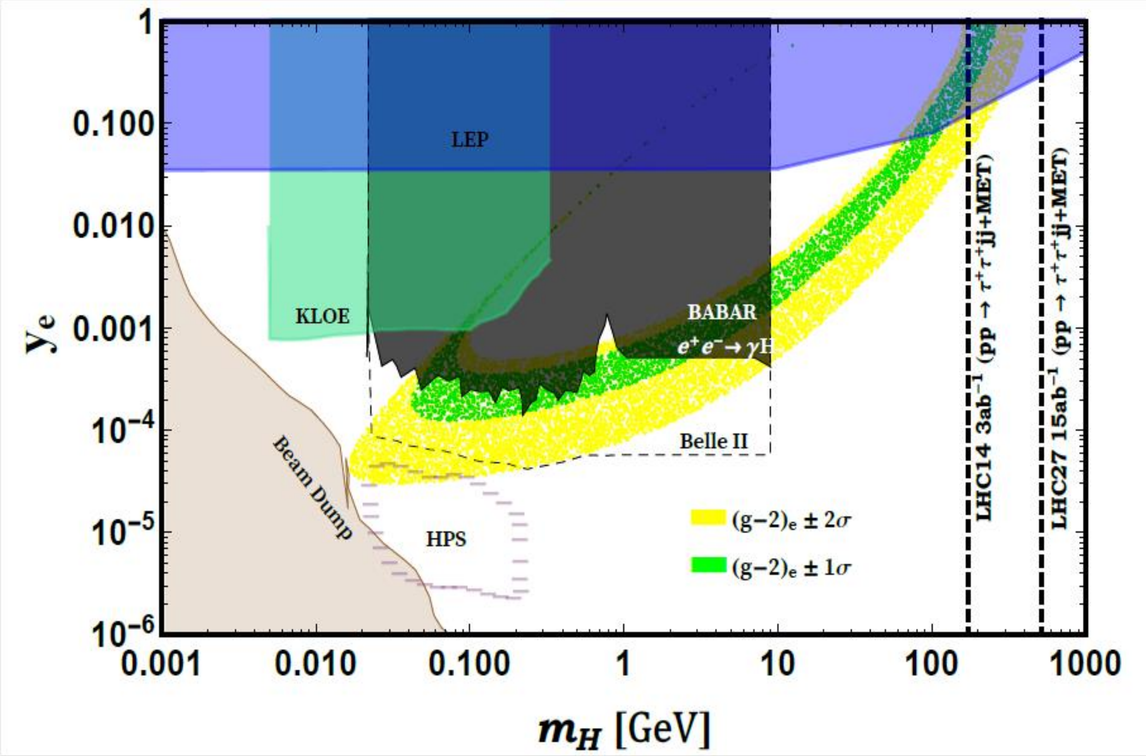
S. Jana, VPK, S. Saad (2020)

Other Constraints

- Fixed Target Experiments: Electron beam dump experiments put a severe constraint on the light scalar that has coupling with electrons.

- Dark Photon Searches: **KLOE** collaboration and **BaBar** collaboration searches for the dark photons A_d through the process: $e^+e^- \to \gamma A_d$, with $A_d \to e^+e^-$

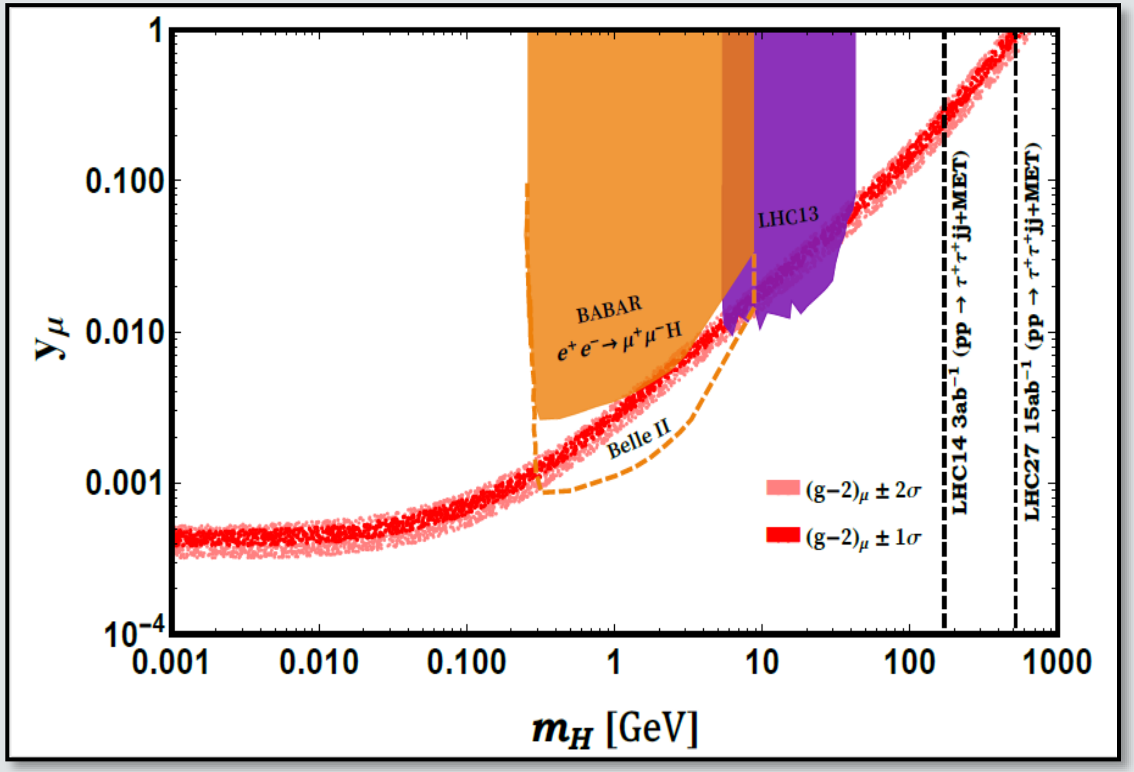
- LEP experiments: $e^-e^+ \to f\bar{f}$ process constrained by the LEP experiments, which can be used to constrain the masses of the neutral scalar and its corresponding coupling with charged fermions.



Other Constraints

- 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 $\mathrm{H}\,\mu^+\mu^-$ coupling via $e^+e^- \to \mu^+\mu^- H$ process.

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

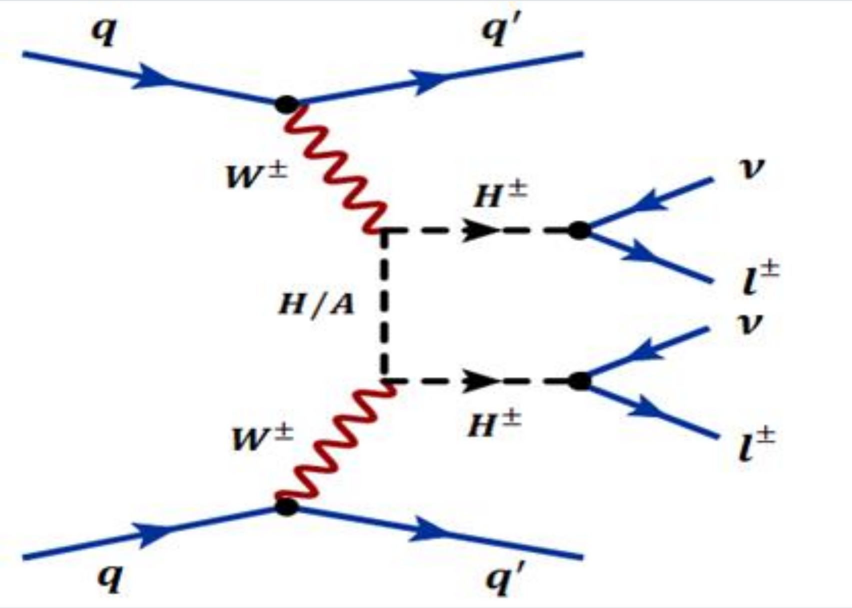


LHC Prospects

The most promising signal of the model is $pp \to \tau^- \tau^+ jj + E_T$ 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. Correspondingly, our scenario will fail to explain the lepton AMMs

At the HL-LHC with an integrated luminosity of $3\ \mathrm{ab}^{-1}$, the charged scalars of mass up to 282 GeV can be probed.



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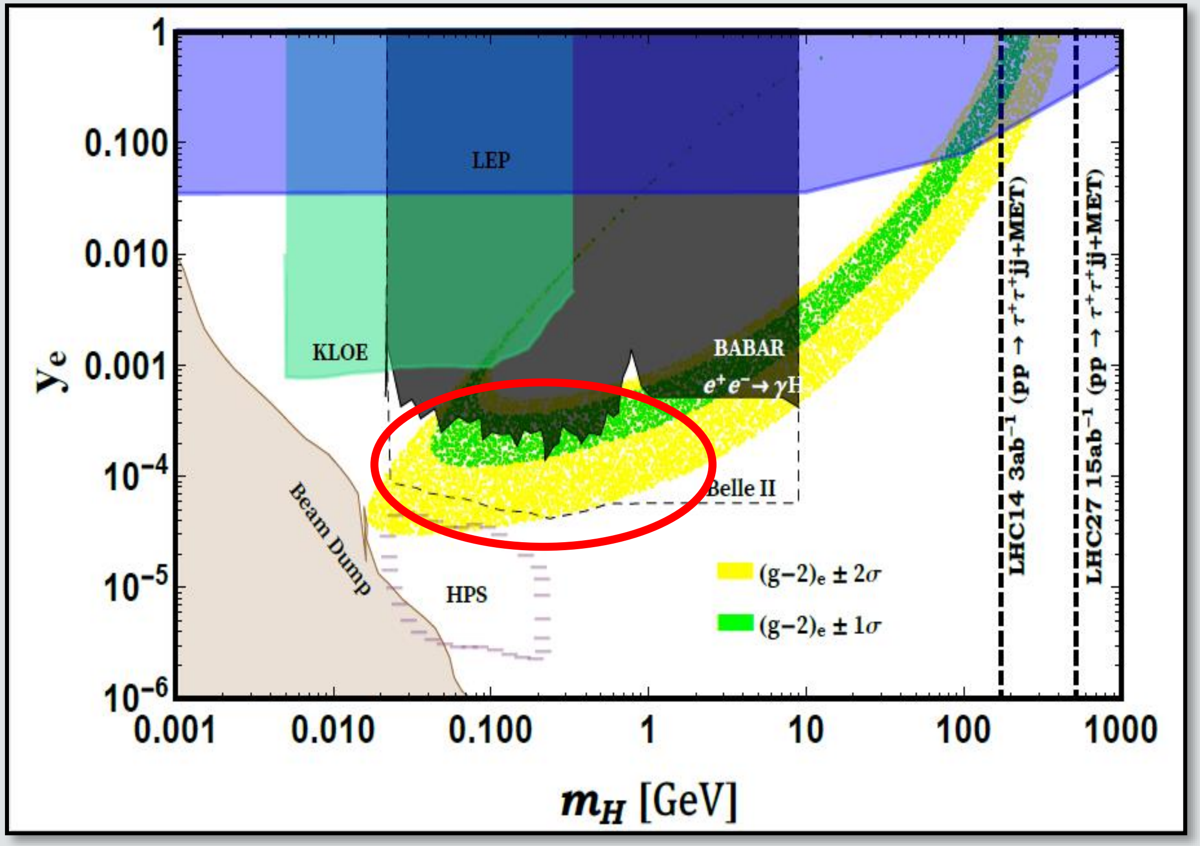
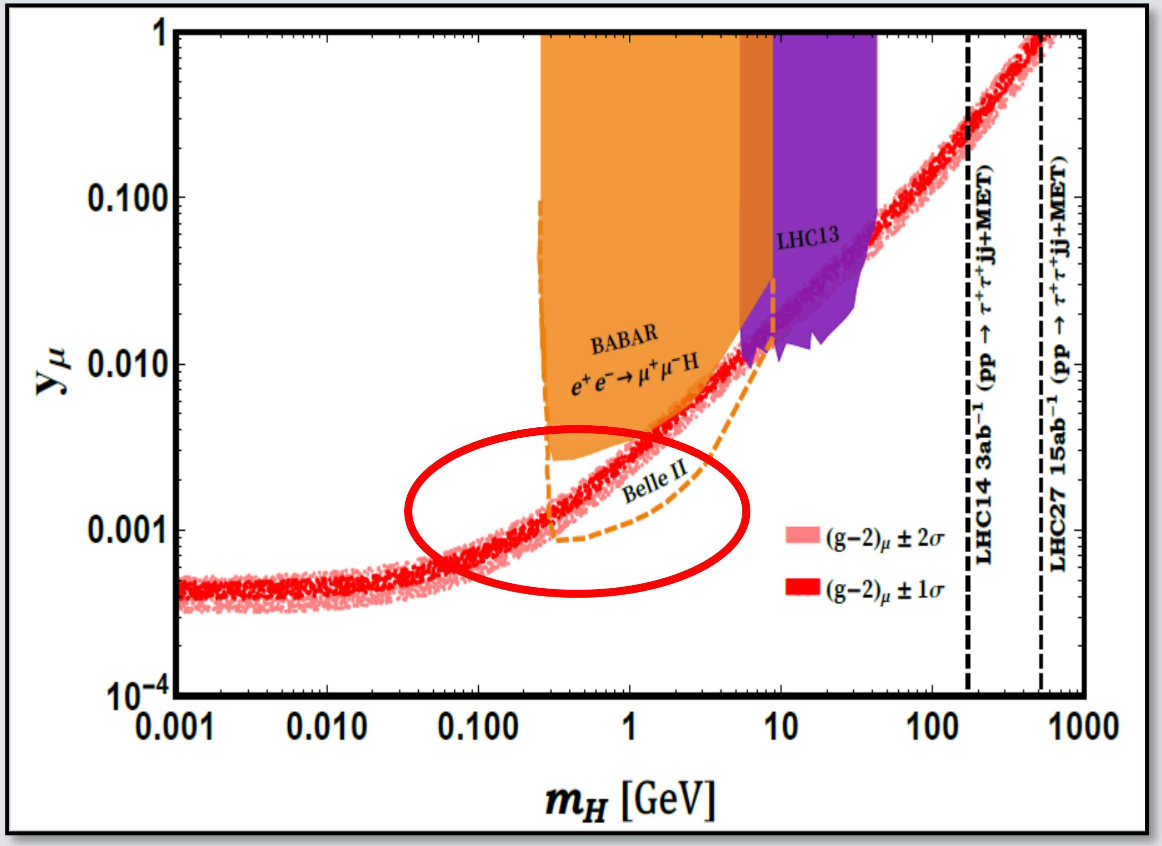
Muon Anomalous Magnetic Moment and Electron Anomalous Magnetic Moment





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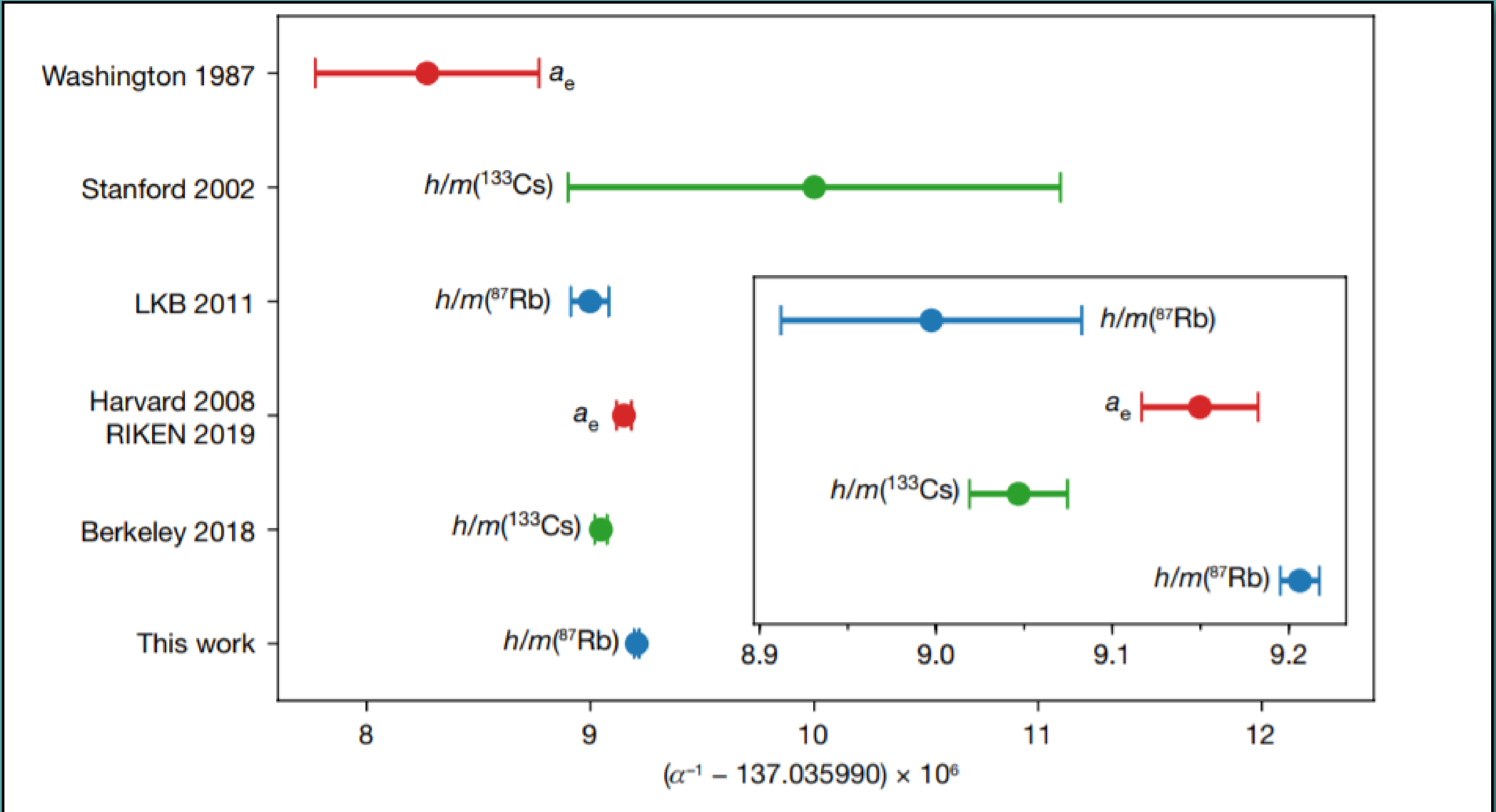
Conclusions

We have proposed a novel scenario that can explain the anomalies related to the lepton anomalous magnetic moments.

We have shown that a light scalar of mass $\boldsymbol{\mathcal{O}(10)\ MeV} - \boldsymbol{\mathcal{O}(1)\ GeV}$ can contribute simultaneously to both electron and muon AMM with correct sign and magnitude needed to explain these anomalies.

We analyze possible ways to probe new-physics signals at colliders and find that this scenario can be tested at the LHC by looking at the novel process is $\boldsymbol{pp \to \tau^- \tau^+ jj + E_T}$ via same-sign pair production of charged Higgs bosons.

Thank You !



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

Morel, L., Yao, Z., Cladé, P. *et al.* *Nature* **588,** 61–65 (2020)

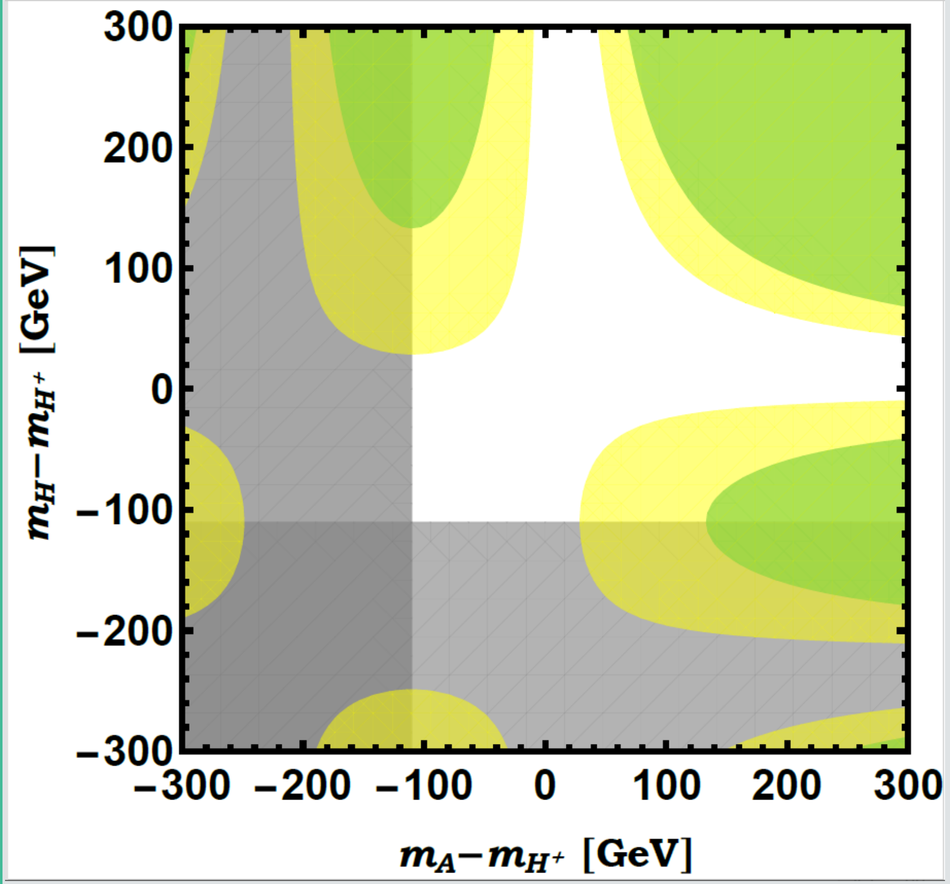
Electroweak Precision Constraints

- T parameter in the alignment of 2HDM

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

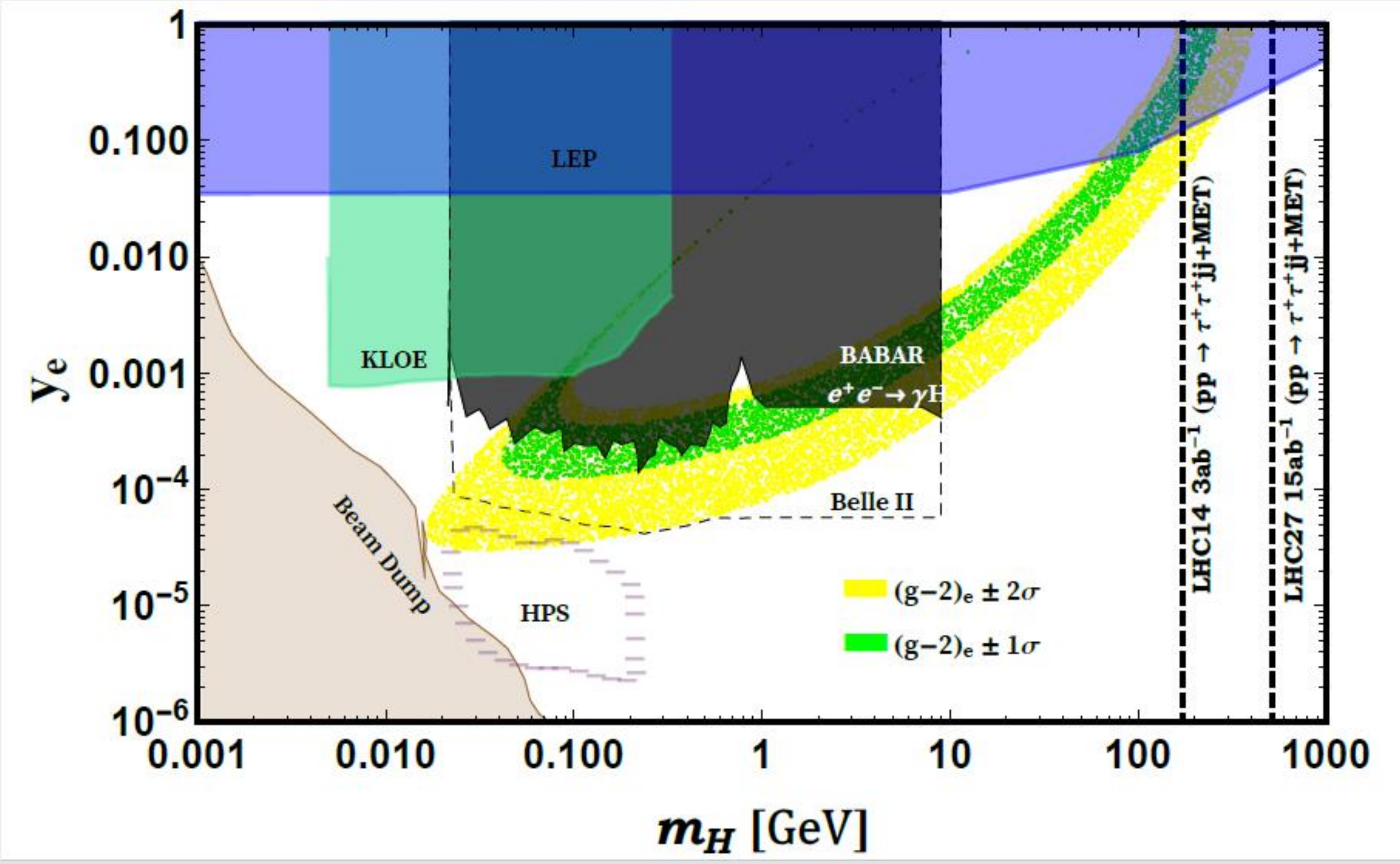
$$\mathcal{F}(m_1^2, m_2^2) \equiv \frac{1}{2}(m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2} \ln\left(\frac{m_1^2}{m_2^2}\right).$$

- Our scenario, $m_H^2 \ll m_{H+}^2 \approx m_A^2 \sim \mathcal{O}(110)\ GeV$ 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 $e + N \to e + N + H$ process.
- For a scalar of mass $m_H < 2m_\mu$, 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.



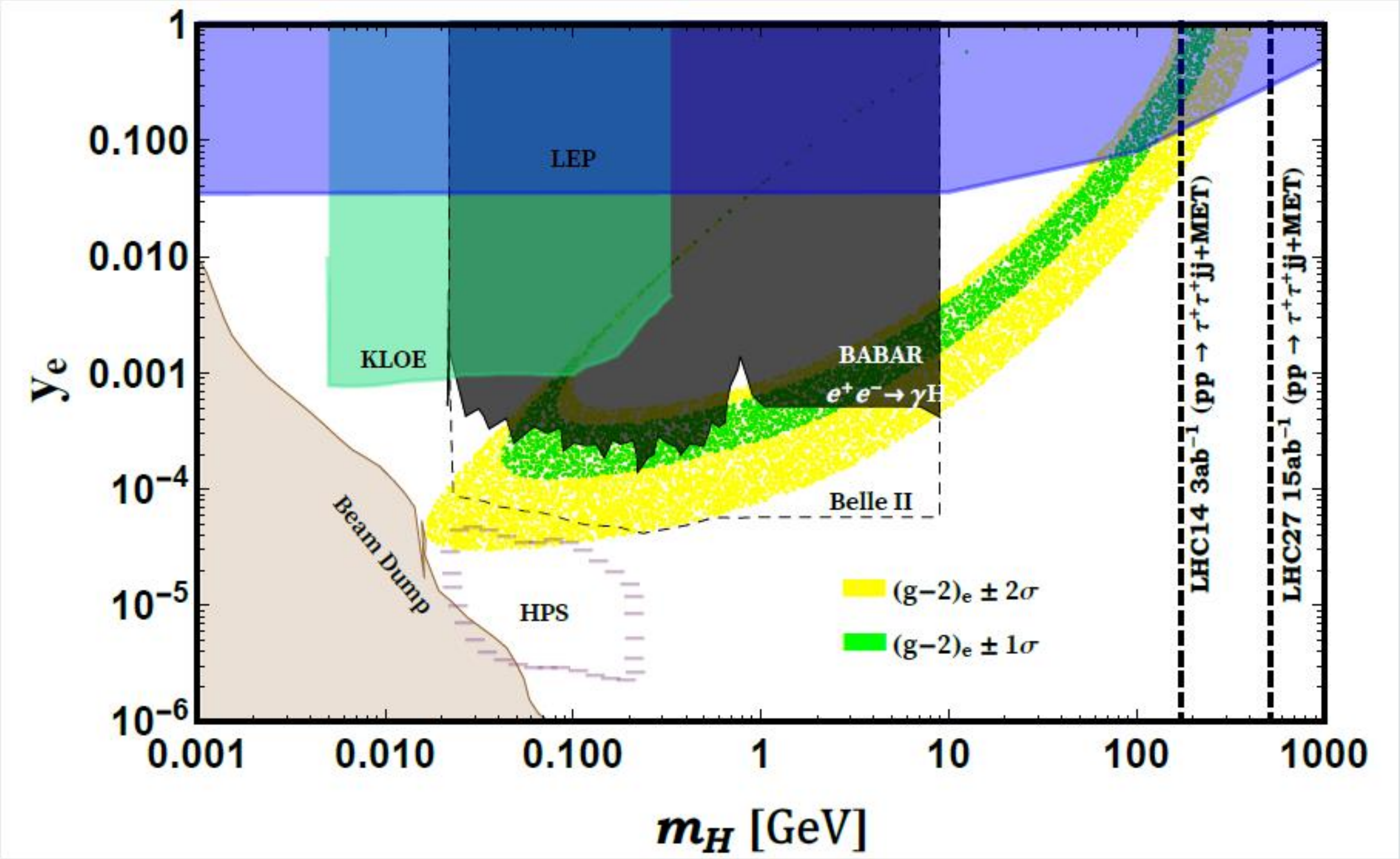
S. Jana, VPK, S. Saad (2020)

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 A_d through the process: $e^+e^- \to \gamma A_d$, with $A_d \to e^+e^-$.

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



Dark-photon Searches

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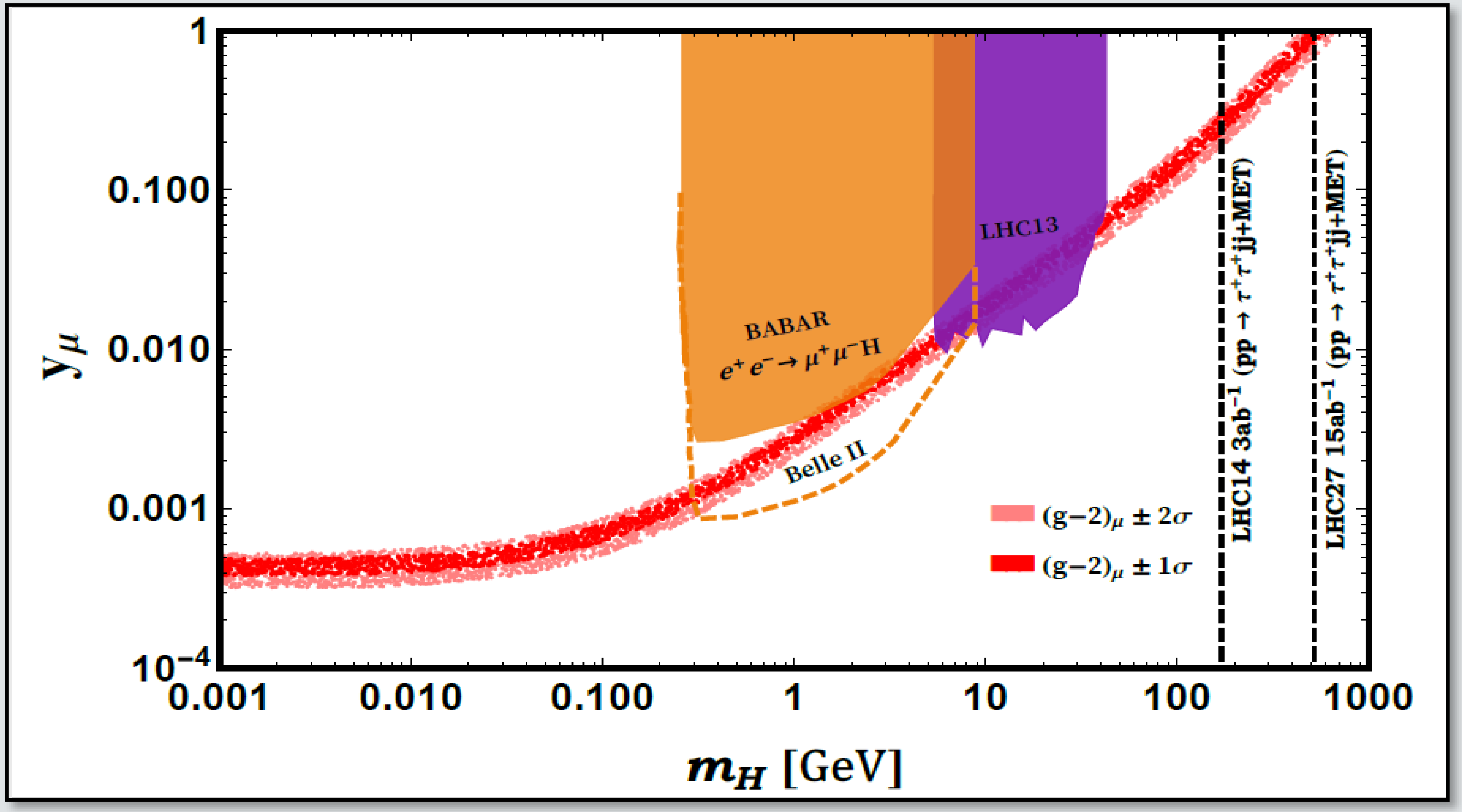
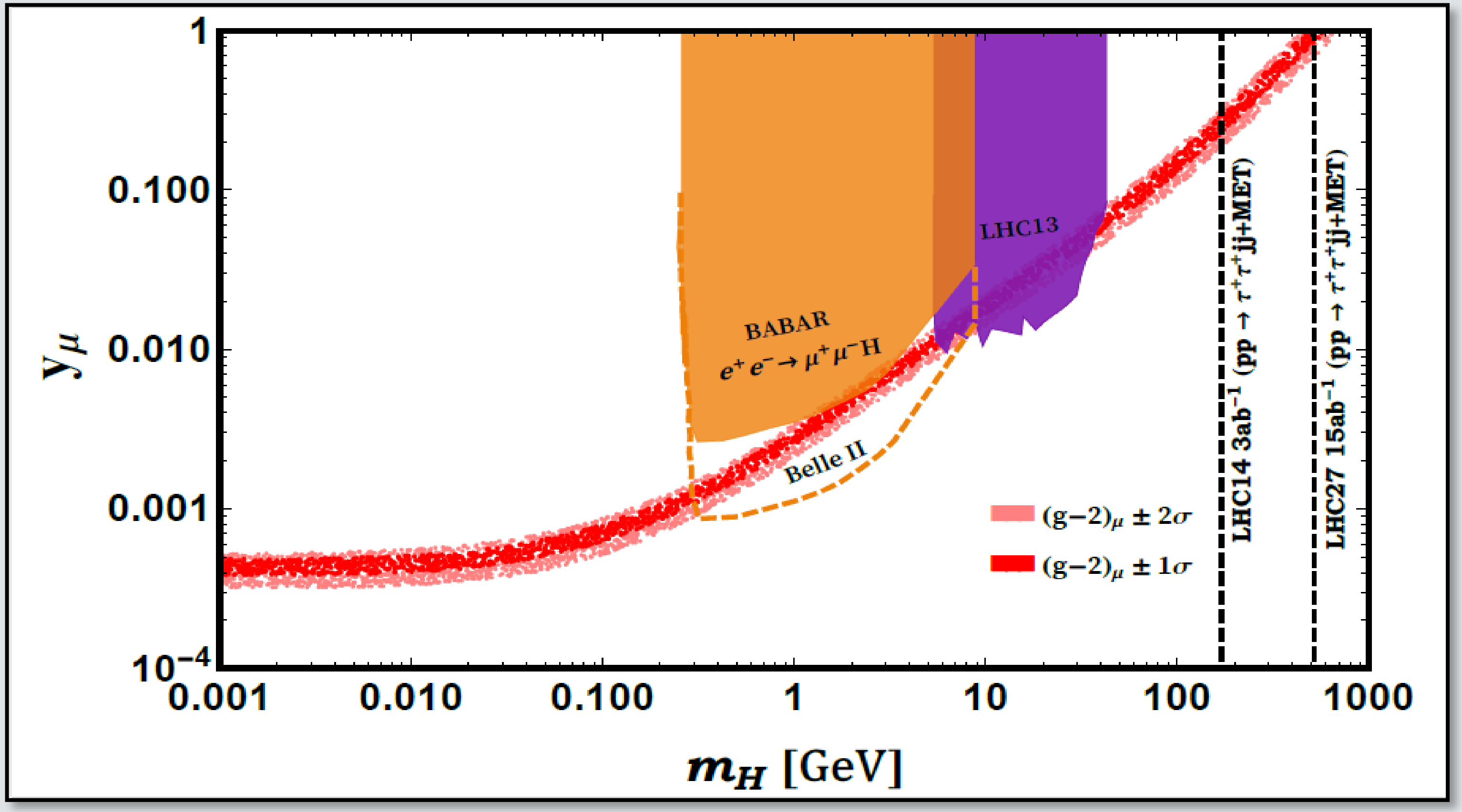


Rare Z-decay constraints

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

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



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.