

Muon ($g - 2$) and Light Leptophilic Boson at the ILC

Tanmoy Mondal

Korea Institute for Advanced Study
Seoul , South Korea

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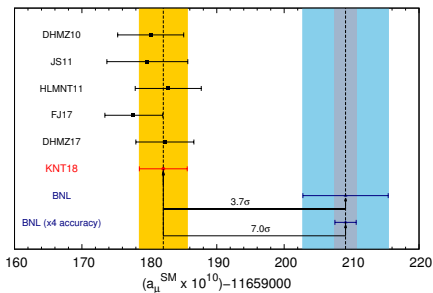
March 18th, 2021

PLB 802 (2020) 135190

arXiv:210x.yyyyy

- This talk is about light lepto-philic scalars
- Motivated by muon ($g - 2$) anomaly and dark matter
- A natural framework is **2HDM + scalar or pseudoscalar**
- I will show which mass-coupling range is allowed and how to explore such region

- This talk is about light lepto-philic scalars
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$$\Delta a_\mu = (2.79 \pm 0.76) \times 10^{-9} \quad 2006.04822$$

New result on April 7, 2021

2HDM type-X + Scalar

$$V_{Portal} \sim A_{12}(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1)s + A_{11} \Phi_1^\dagger \Phi_1 s + A_{22} \Phi_2^\dagger \Phi_2 s$$

- Mixing among the CP even scalars:

$$\begin{pmatrix} \Phi_1^{0R} \\ \Phi_2^{0R} \\ s \end{pmatrix} = \begin{pmatrix} -s_\alpha & c_\alpha & s\theta_1 \\ c_\alpha & s_\alpha & s\theta_2 \\ -s\theta_1 & -s\theta_2 & 1 \end{pmatrix} \begin{pmatrix} h_{125} \\ \Phi \\ H \end{pmatrix}$$

The Yukawa Lagrangian in mass eigenstates:

$$\mathcal{L} \supset -\frac{s\theta_2}{\sin\beta} \sum_q \frac{m_q}{v} \bar{q}qH - \frac{s\theta_1}{\cos\beta} \sum_\ell \frac{m_\ell}{v} \bar{\ell}\ell H$$

- $\tan\beta \gg 1 \implies H$ is leptophilic

2HDM type-X + Pseudoscalar

 $V_{\text{Portal}} \sim$

$$i B_{12}(\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1)P + (\lambda_{P1}\Phi_1^\dagger \Phi_1 + \lambda_{P2}\Phi_2^\dagger \Phi_2 + \lambda_{P12}(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1))P^2$$

- After EWSB, $\Phi_{1,2}$ mixes to generate Goldstone of Z and A_0
- Mixing among the CP odd scalars:

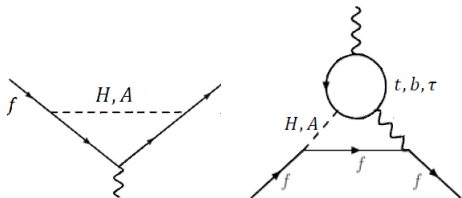
$$\begin{pmatrix} A_0 \\ P \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix}, \quad \text{Mixing angle : } \tan 2\theta = \frac{2B_{12}v}{m_A^2 - m_a^2}$$

The Yukawa Lagrangian in mass eigenstates:

$$\mathcal{L} \supset - \left[\sum_{u(d)} \frac{m_q}{v} \frac{1(-1)}{\tan \beta} i \bar{q} \gamma^5 q - \sum_\ell \frac{m_\ell}{v} \tan \beta i \bar{\ell} \gamma^5 \ell \right] (\cos \theta A - \sin \theta a)$$

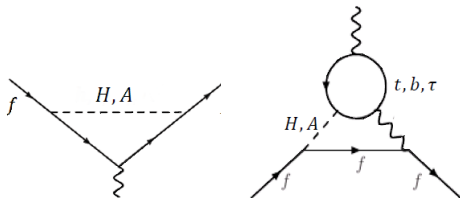
- $\tan \beta \gg 1$ and $\sin \theta \sim \mathcal{O}(0.1 - 1) \implies a$ is leptophilic

Scalar or Pseudoscalar Solutions to $(g - 2)_\mu$



- One loop contribution :
H is + ve & A is - ve
- Two loop contribution :
H is - ve & A is + ve

Scalar or Pseudoscalar Solutions to $(g - 2)_\mu$

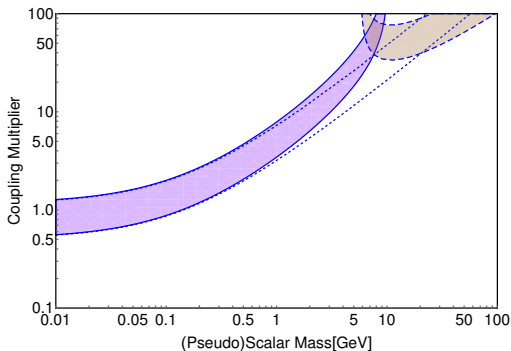


- One loop contribution :
H is +ve & A is -ve
- Two loop contribution :
H is -ve & A is +ve

Leptophilic Interactions

$$\mathcal{L}_S = -\xi_H \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} H \bar{\ell} \ell$$

$$\mathcal{L}_A = -\xi_A \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} A \bar{\ell} i \gamma^5 \ell$$



- Strong constraint on light scalar comes from beam dump experiments.
- Limit from B and K decay (CHRAM, E949, NA62, LHCb)

$$\xi_H^q \lesssim \text{few} \times 10^{-4}$$

- Leptophilic scalars can evade hadronic constraints easily.
- Limit on leptophilic scalars come from BABAR:

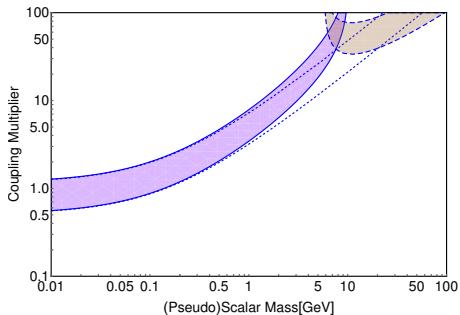
$$e^+e^- \rightarrow \tau^+\tau^-H, \quad H \rightarrow e^+e^- \text{ or } \mu^+\mu^-$$

PRL 125 (2020) 18, 181801

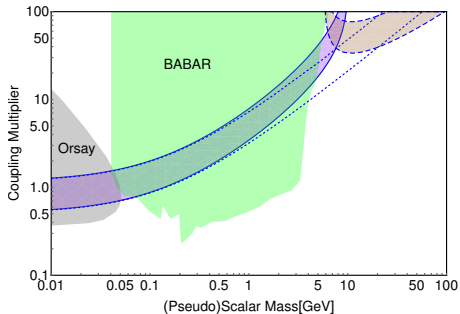
- Also bremsstrahlung of light scalar at electron beam dump experiments, like Orsay, E137

Scalar or Pseudoscalar Solutions to $(g - 2)_\mu$

imagine the impossible

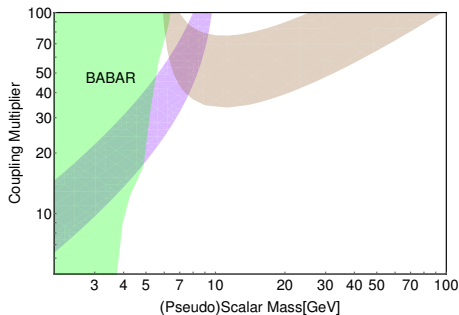
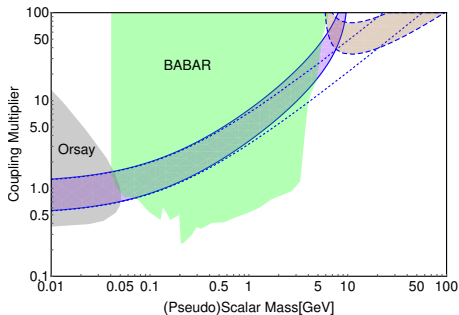


Scalar or Pseudoscalar Solutions to $(g - 2)_\mu$

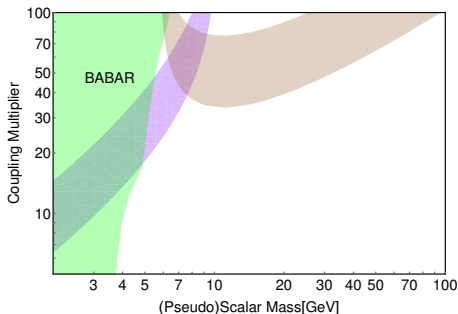
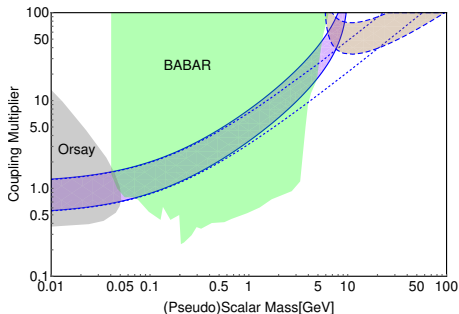


Scalar or Pseudoscalar Solutions to $(g - 2)_\mu$

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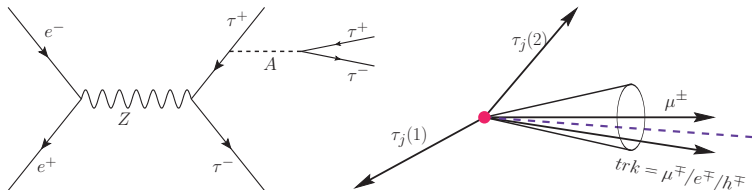
Scalar or Pseudoscalar Solutions to $(g - 2)_\mu$



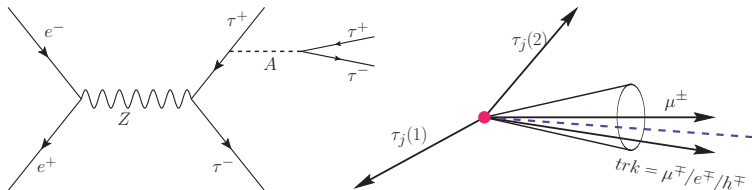
- Mass of the light scalar or pseudo scalar has to be $\gtrsim 5$ GeV
- **Q. How much LHC or ILC can explore ?**
- Unlike $U(1)_{L_\mu - L_\tau}$ search via $Z \rightarrow 4\mu$, here all the signals are tau rich.
- Lepton collider is necessary to look for leptophilic scalars.

- Yukawa production : $Z \rightarrow \tau\tau \rightarrow \tau\tau A \rightarrow 4\tau$
- Equivalent to ttH searches at LHC. Independent probe of Yukawa.
- Based on mass of A different signal topology is possible.
- **When A is relatively heavy :**
 - We can see 4 separated tau leptons.
 - It is possible to reconstruct mass of A using collinear approximation.
 - Use reconstructed invariant mass to minimize background.
- **When A is light :**
 - A will be boosted and taus coming from boosted A will merge.
 - Four distinguished tau lepton search is not feasible.
 - Utilize the large one-prong BR of tau to look $A \rightarrow \tau_\mu \tau_{\text{one-prong}}$ decay

Signal topology



Signal topology



Signal selection

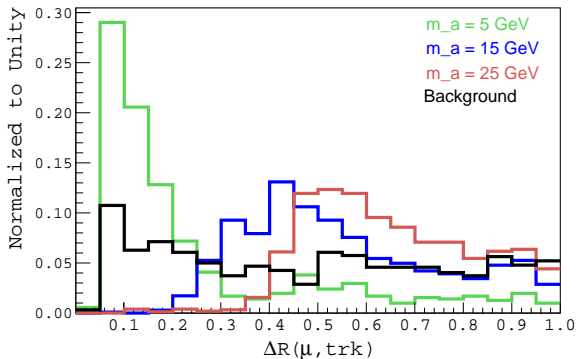
- Two τ -tagged jets with $E(\tau_j) \geq 20$ GeV & $|\eta(\tau_j)| \leq 2.3$
- One muon $E(\mu^\pm) \geq 20$ GeV & $|\eta(\mu^\pm)| \leq 2.3$
- One high p_T OS charged track(trk) with $\Delta R(\mu^\pm, trk^\mp) < 0.8$
- Tau tagged jets and μ^\pm should be well separated from each other.

Background

- $e^+e^- \rightarrow Z(\gamma^*) Z(\gamma^*) \rightarrow 2\tau 2\mu$
- $e^+e^- \rightarrow Z(\gamma^*) Z(\gamma^*) \rightarrow 4\tau$
- $e^+e^- \rightarrow Z h_{125} \rightarrow 4\tau/2\mu 2\tau$

Background

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ILC search of relatively heavy (pseudo)scalar

- MadGraph_aMC@NLO \rightarrow PYTHIA8 \rightarrow Delphes3 + ILD card
- Signal : 3 τ -tagged jets + X (= τ -jet/untagged jet/lepton)
- Jets and leptons should have minimum energy of 20 GeV and should be in the central region with $|\eta| < 2.3$ i.e. $\cos\theta < 0.98$.

Collinear approximation : Reconstruction of the taus

- Energy momentum equations are,

$$\begin{aligned}\vec{p}(\tau_1) + \vec{p}(\tau_2) + \vec{p}(\tau_3) + \vec{p}(\tau_4) &= \vec{0}, \\ E(\tau_1) + E(\tau_2) + E(\tau_3) + E(\tau_4) &= \sqrt{s}.\end{aligned}$$

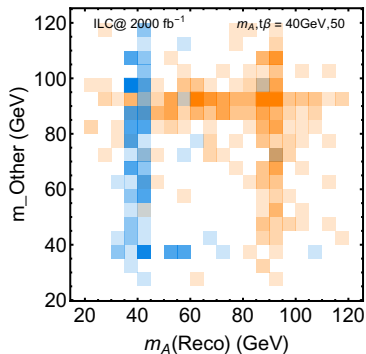
- Assumption: The missing energy in the decay of a tau lepton is collinear to the visible part of the decay.
- Visible part of the tau decay take z_i fraction of the tau momentum :

$$p^\mu(j_i) = z_i p^\mu(\tau_i)$$

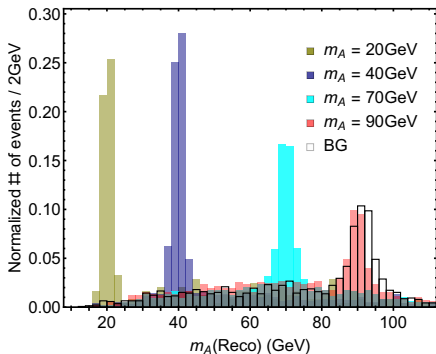
- Solve for z_i where we should have $0 < z_i < 1$. However to account for the detector resolution etc we assume 10% relaxation in the upper limit of z_i .

Reconstruction of the pseudoscalar

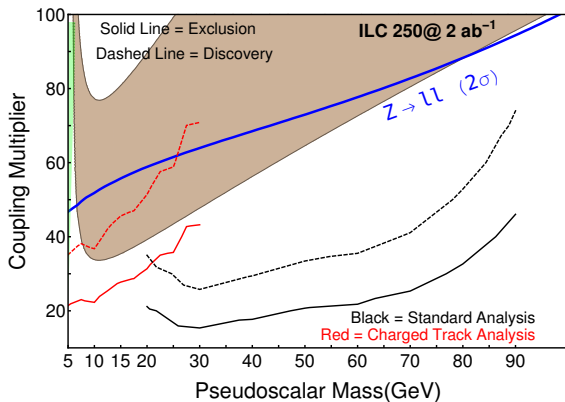
- Discard the most energetic tau \rightarrow Choose OS tau pair with highest p_T .



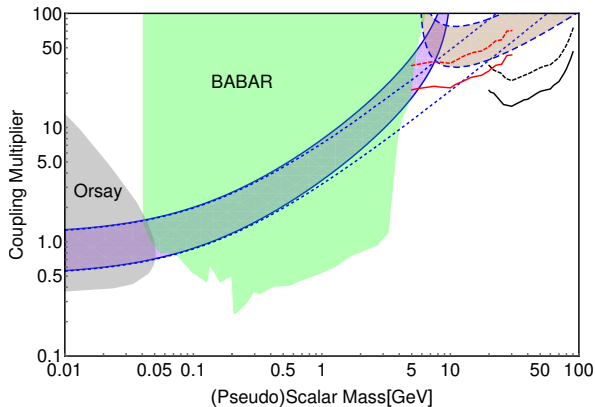
$m_A = 40$ GeV



- Background : Dominantly $e^+e^- \rightarrow Z(\gamma^*) Z(\gamma^*) \rightarrow 4\tau$.



The big picture



- Light leptophilic scalars can explain muon $g - 2$ and/or dark matter
- Possible UV complete model : 2HDM + Scalar or Pseudoscalar
- Light scalar explanation of $g - 2$ requires $m_H \leq 10$ GeV.
- BABAR and electron beam dump experiments ruled out m_H up to 5 GeV.
- For light pseudoscalar, lepton universality is a strong constraint
- ILC 'Higgs factory' can explore the leptophilic scenario where BABAR stops.
- Almost all the parameter space will be explored.

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Thank You

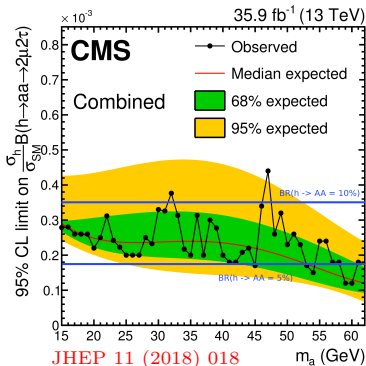
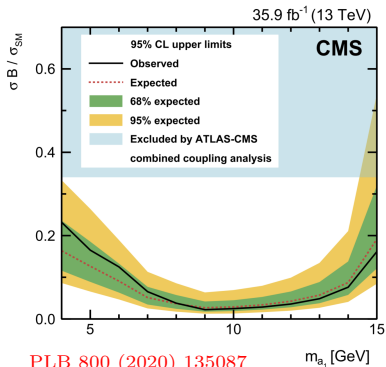
BACK UP

- Higgs decay to aa

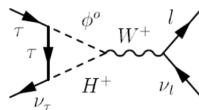
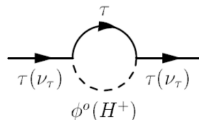
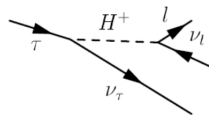
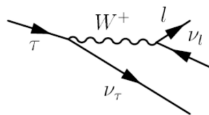
$$\lambda_{haa} v \simeq \begin{cases} \cos^2 \theta (v^2 (\lambda_{P1} \cos^2 \beta + \lambda_{P2} \sin^2 \beta + \lambda_{P12} \sin 2\beta) - m_A^2 \sin^2 \theta) \\ \cos^2 \theta ((\lambda_{P2} \sin^2 \beta - \lambda_{P1} \cos^2 \beta) v^2 + m_A^2 \cos 2\beta \sin^2 \theta) \end{cases}$$

- Quartic couplings makes this parameter free
- At the LHC only feasible channel is via Higgs decay:

$$pp \rightarrow h_{125} \rightarrow HH/AA \rightarrow 4\tau/2\tau 2\mu/4\mu$$



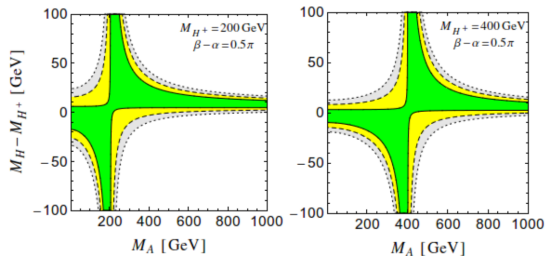
- Muon $g - 2$
- **Lepton universality**
- EWPD
- Higgs signal strength
- $B_s \rightarrow \mu^+ \mu^-$ or $B_s \rightarrow X_s \gamma$



Limits coming from :

$$\frac{\Gamma(\tau \rightarrow \mu \nu \nu)}{\Gamma(\tau \rightarrow e \nu \nu)} \quad \text{or} \quad \frac{\Gamma(\tau \rightarrow e \nu \nu)}{\Gamma(\mu \rightarrow e \nu \nu)} \quad \text{etc}$$

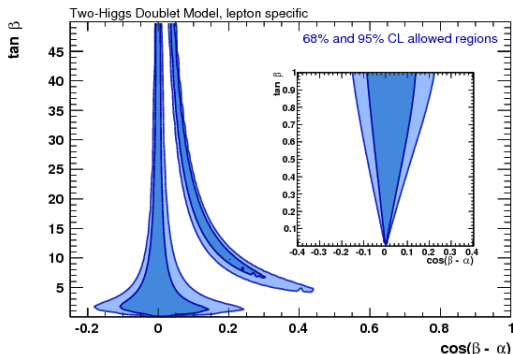
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Charged Higgs mass should be close to H or A .

2HDM-X : Allowed parameter space

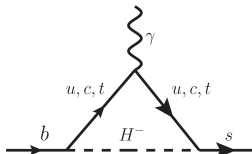
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GFitter : 1803.01853.

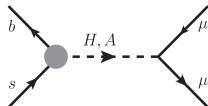
2HDM-X : Allowed parameter space

- Muon $g - 2$
- Lepton universality
- EWPD
- Higgs signal strength
- Higgs invisible decay width
- $B_s \rightarrow \mu^+ \mu^-$ or
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$$\frac{m_t}{t_\beta} P_L - \frac{m_b}{t_\beta} P_R \quad (X, I)$$

$$\frac{m_t}{t_\beta} P_L + m_b t_\beta P_R \quad (II, Y)$$

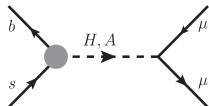
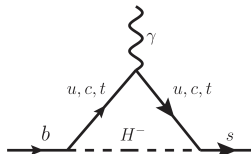


For type X : ~ 1

For type II : $(\tan \beta)^2$

2HDM-X : Allowed parameter space

- Muon $g - 2$
- Lepton universality



- EWPD
- Higgs signal strength
- Higgs invisible decay width
- $B_s \rightarrow \mu^+ \mu^-$ or $B_s \rightarrow X_s \gamma$

$$\frac{m_t}{t_\beta} P_L - \frac{m_b}{t_\beta} P_R \quad (X, I)$$

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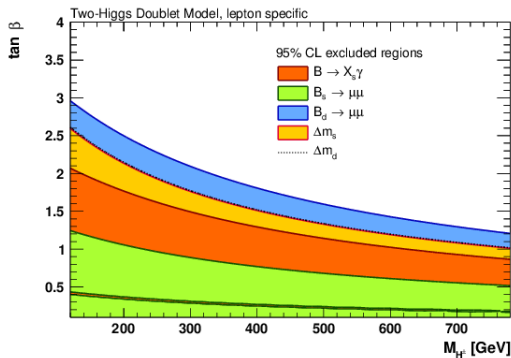
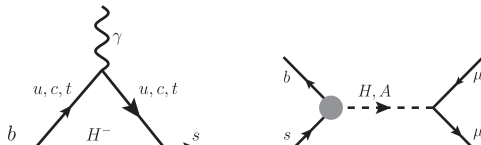
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For type II : $(\tan \beta)^2$

- $b \rightarrow s \gamma : m_{H^\pm} > 580 \text{ GeV}$. [BELLE, 1608.02344](#)
- $BR(B_s \rightarrow \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
[LHCb, 1703.05747](#)
- Limit on type-II 2HDM : $\tan \beta < 7$ for $m_A < 70 \text{ GeV}$

2HDM-X : Allowed parameter space

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GFitter : 1803.01853.