# Leptophilic Spin-0 Particles at the ILC

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`PLB 802 (2020) 135190`

`ArXiv:210x.yyyyy`

# Introduction

- 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

# Introduction

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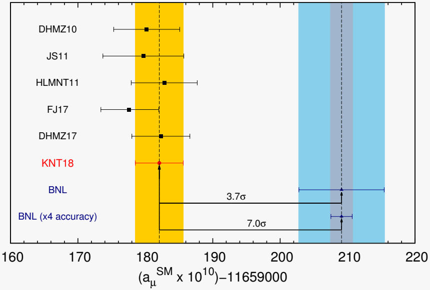
- A natural framework is 2HDM + scalar or pseudoscalar
- I will show which mass-coupling range is allowed and how to explore such region



$$\Delta a_\mu = (2.79 \pm 0.76) \times 10^{-9}$$ `2006.04822`

`New result on April 7, 2021`

# A Framework for Light Leptophilic Scalars

## 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:**

$$\mathcal{L} \supset -\frac{s_{\theta 2}}{\sin\beta}\sum_q \frac{m_q}{v}\bar{q}qH - \frac{s_{\theta 1}}{\cos\beta}\sum_\ell \frac{m_\ell}{v}\bar{\ell}\ell H$$

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

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PRD93, 035006 (2016), PRD 95, 075003 (2017), · · ·

# A Framework for Light Leptophilic Pseudoscalars

## 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:

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

**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 $\sin\theta \sim \mathcal{O}(0.1-1) \Longrightarrow a$ is leptophilic

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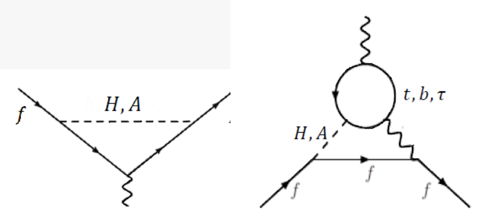
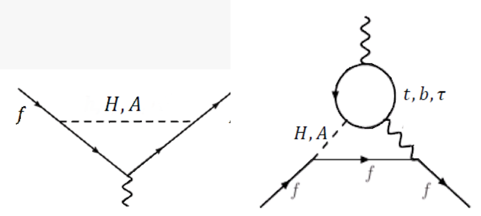
PRD 90, 055021 (2014), JHEP 05 (2017) 138, $\cdots$

# 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 $(g-2)_\mu$

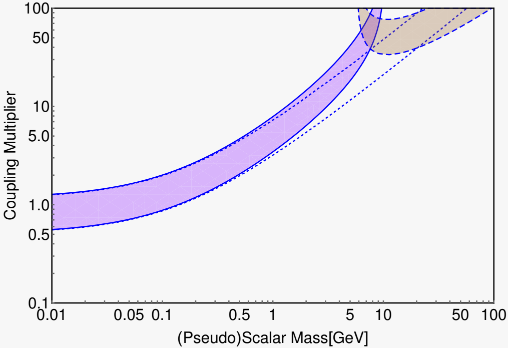


- One loop contribution : H is + ve & A is - ve
- Two loop contribution : H is - ve & A is + ve

**Leptophilic Interactions**

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

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



# Experimental Constraints

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

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

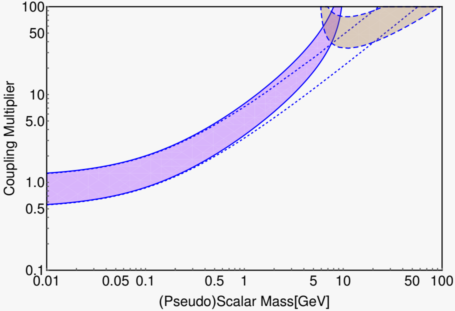
- Leptophilic scalars can evade hadronic constraints easily.
- Limit on leptophilic scalars come from BABAR:

$$e^+e^- \to \tau^+\tau^- H \;, \qquad H \to e^+e^- \;\; \text{or} \;\; \mu^+\mu^-$$

`PRL 125 (2020) 18, 181801`

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

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



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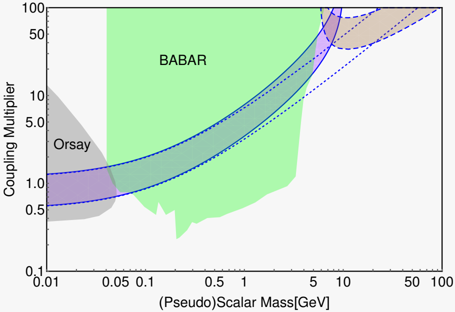

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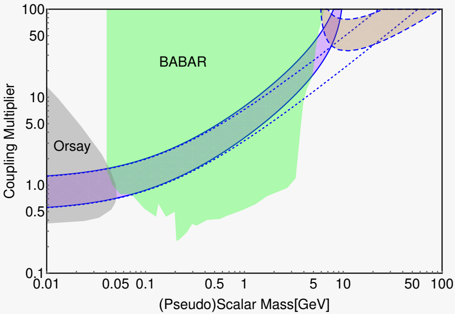
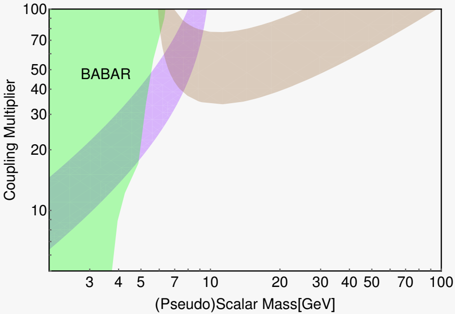
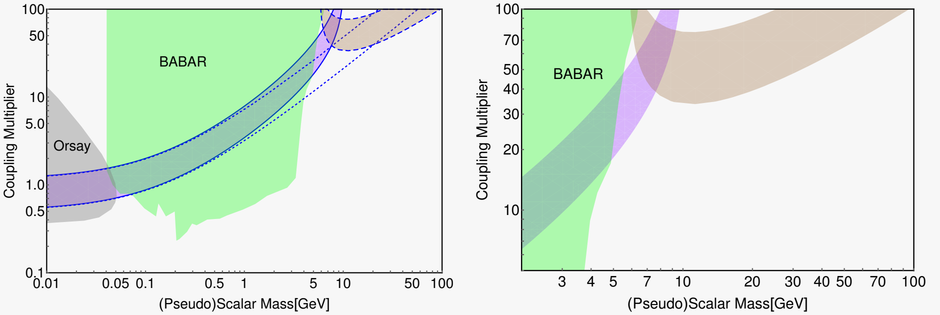




# Scalar or Pseudoscalar Solutions to $(g-2)_\mu$



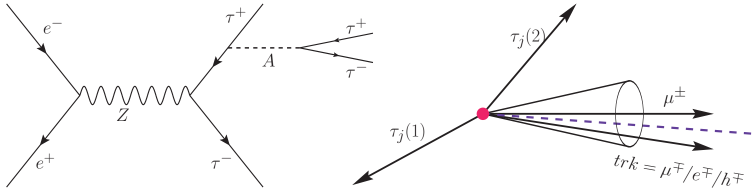
- Mass of the light scalar or pseudo scalar has to be $\gtrsim 5$ GeV
- Q. How much LHC or ILC can explore ?
- Unlike $U(1)_{L_\mu - L_\tau}$ search via $Z \to 4\mu$, here all the signals are tau rich.
- Lepton collider is necessary to look for leptophilic scalars.

# Search at lepton collider

- Yukawa production : $Z \to \tau\tau \to \tau\tau A \to 4\tau$
- 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 minmize 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 $A \to \tau_\mu \tau_{\text{one-prong}}$ decay

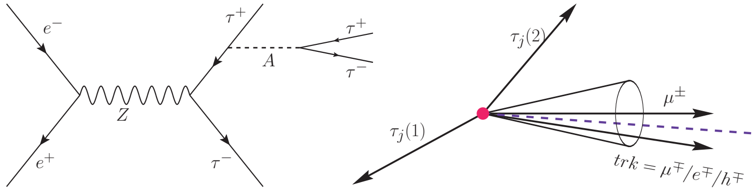
# ILC search of light (pseudo)scalar

## Signal topology



# ILC search of light (pseudo)scalar

## Signal topology



### Signal selection

- Two $\tau$-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 $\mu^\pm$ should be well separated from each other.

# ILC search of light (pseudo)scalar

## Background

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

# ILC search of light (pseudo)scalar

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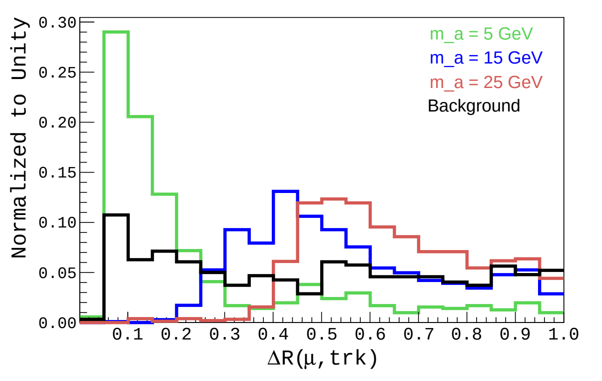


# ILC search of relatively heavy (pseudo)scalar

- `MadGraph_aMC@NLO` → `PYTHIA8` → `Delphes3 + ILD card`
- Signal : 3 $\tau$-tagged jets + X (= $\tau$-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 :

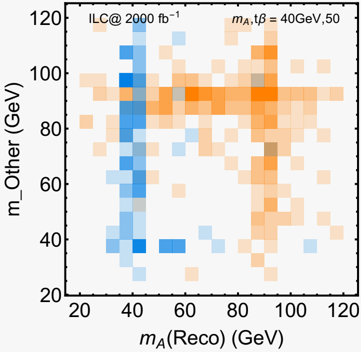
$$p^\mu(j_i) = z_i \ p^\mu(\tau_i)$$

- 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 $z_i$.

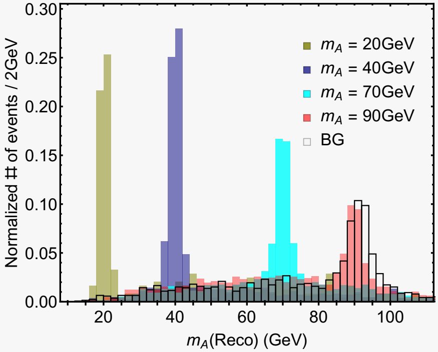
# ILC search of relatively heavy (pseudo)scalar

## Reconstruction of the pseudoscalar

- Discard the most energetic tau → Choose OS tau pair with highest $p_T$.

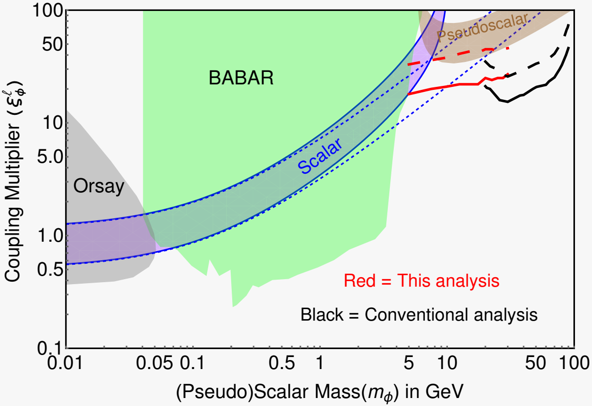


$m_A = 40$ GeV



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

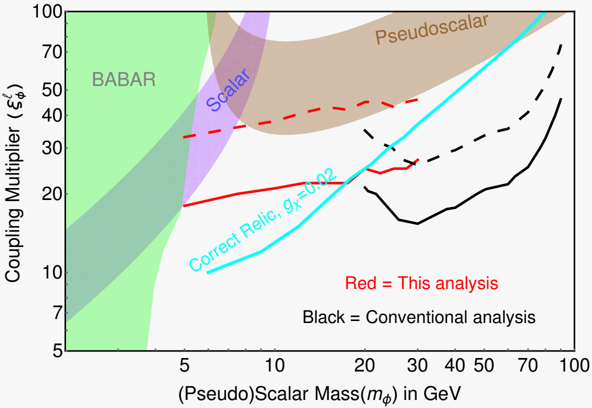
## The big picture



# Results

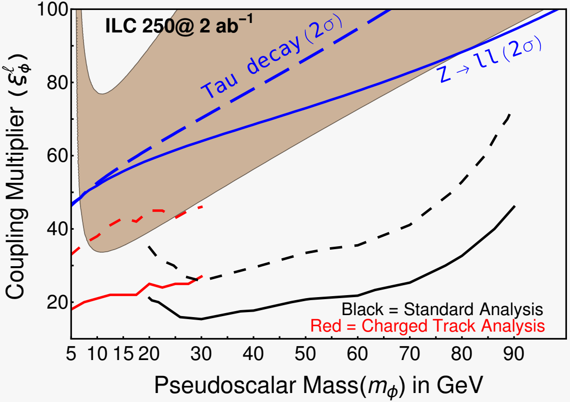
imagine the impossible

## The big picture



# Results

Additional constraints may come from UV completion



# Conclusion

- 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 universlity 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

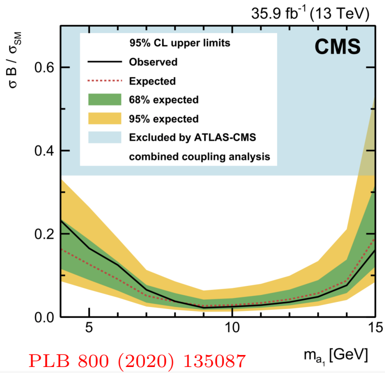
# LHC search

- Higgs decay to $aa$

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

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

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



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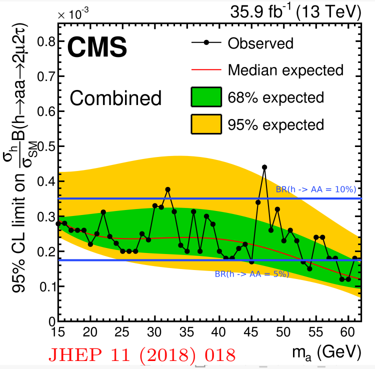
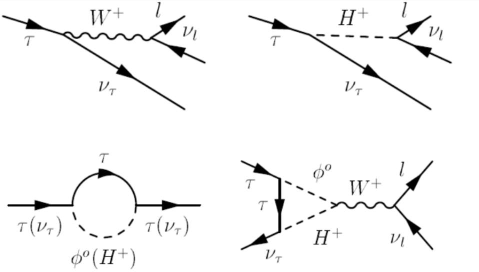


JHEP 11 (2018) 018

# 2HDM-X : Allowed parameter space

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



Limits coming from :

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

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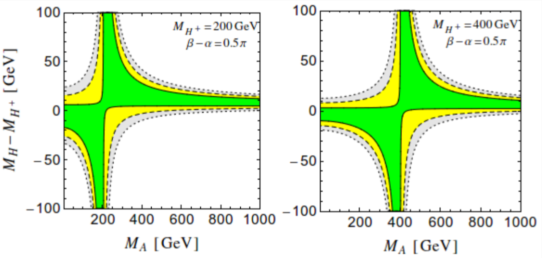

Charged Higgs mass should be close to $H$ or $A$.

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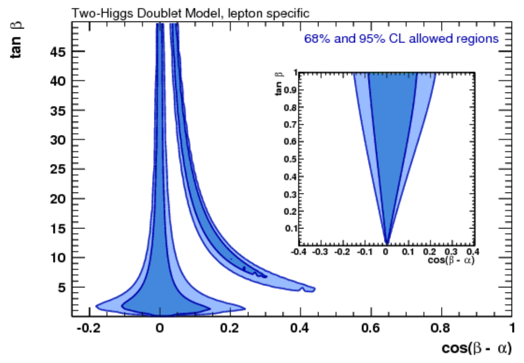

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# 2HDM-X : Allowed parameter space

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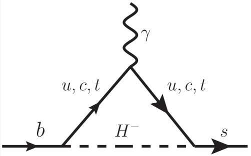
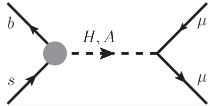


$$\frac{m_t}{t_\beta} P_L - \frac{m_b}{t_\beta} P_R \qquad (X, I)$$

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



For type X : $\sim 1$
For type II : $(\tan\beta)^2$

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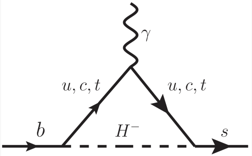

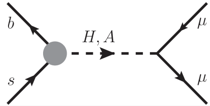

$$\frac{m_t}{t_\beta}P_L - \frac{m_b}{t_\beta}P_R \quad (X, I)$$

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

For type X : $\sim 1$
For type II : $(\tan\beta)^2$

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

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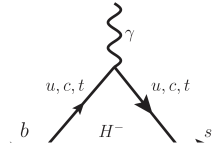

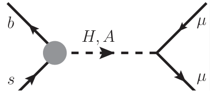

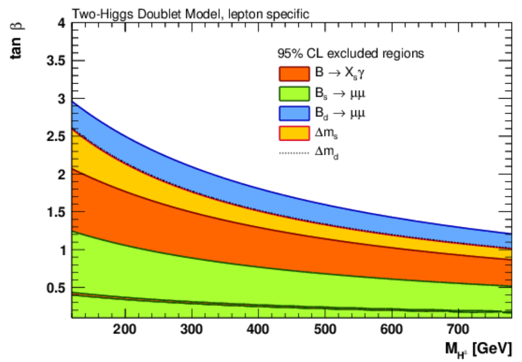

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