Flavor anomalies and collider search within a general two Higgs doublet model (G2HDM)

Syuhei Iguro

NAGOYA UNIVERSITY

Based on

- 1907.09845 Syuhei Iguro, Y. Omura, M. Takeuchi.
- **PhysRevD.99.075013** Syuhei Iguro, Y. Omura, M. Takeuchi.

Today's menu

- Flavor anomalies: muon g-2 and RD,RD*

- Model: G2HDM

- Result: LHC search and constraint

What we do:

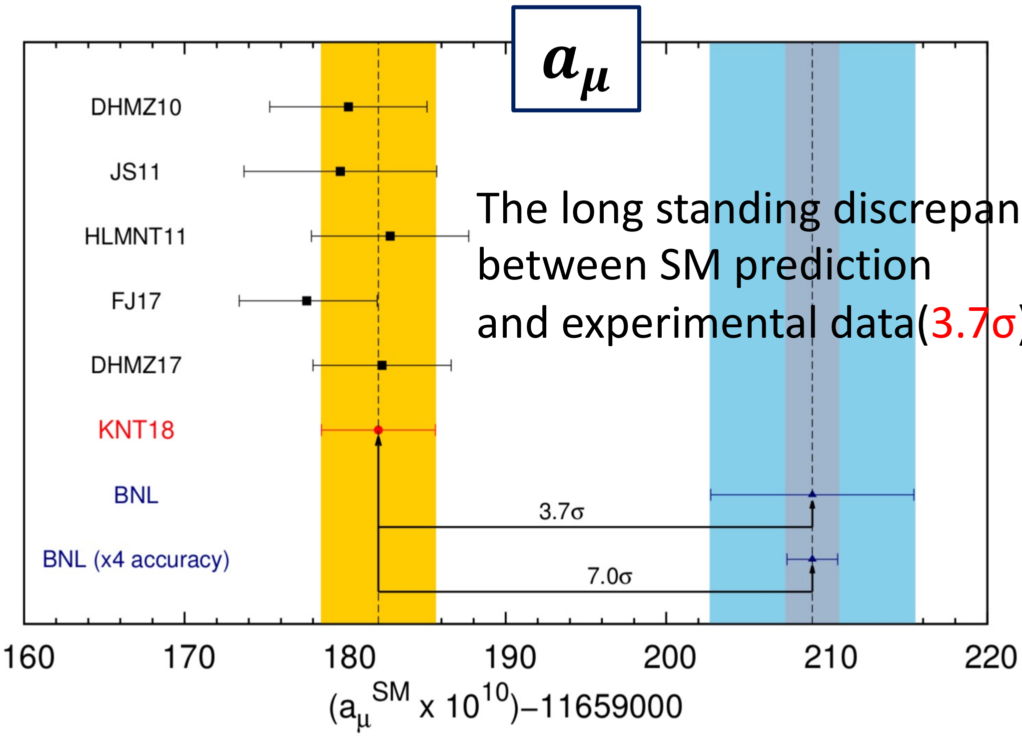
We discuss on collider physics for scenarios that can explain those anomalies with additional scalars

Muon g-2 anomaly >3σ discrepancy

Magnetic dipole moment $\mu = g(\frac{e}{2m_\mu})s$

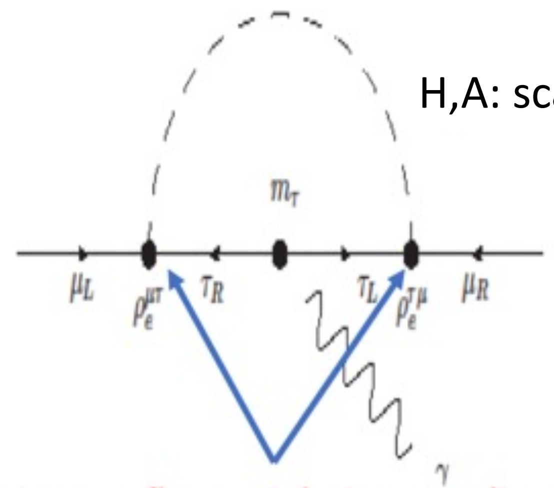
This g is exactly 2 in tree level. Higher order quantum correction changes g from 2.

$a_\mu = \frac{g-2}{2}$ is muon anomalous magnetic moment.



The long standing discrepancy between SM prediction and experimental data(3.7σ).

Alexander,et al:180202996



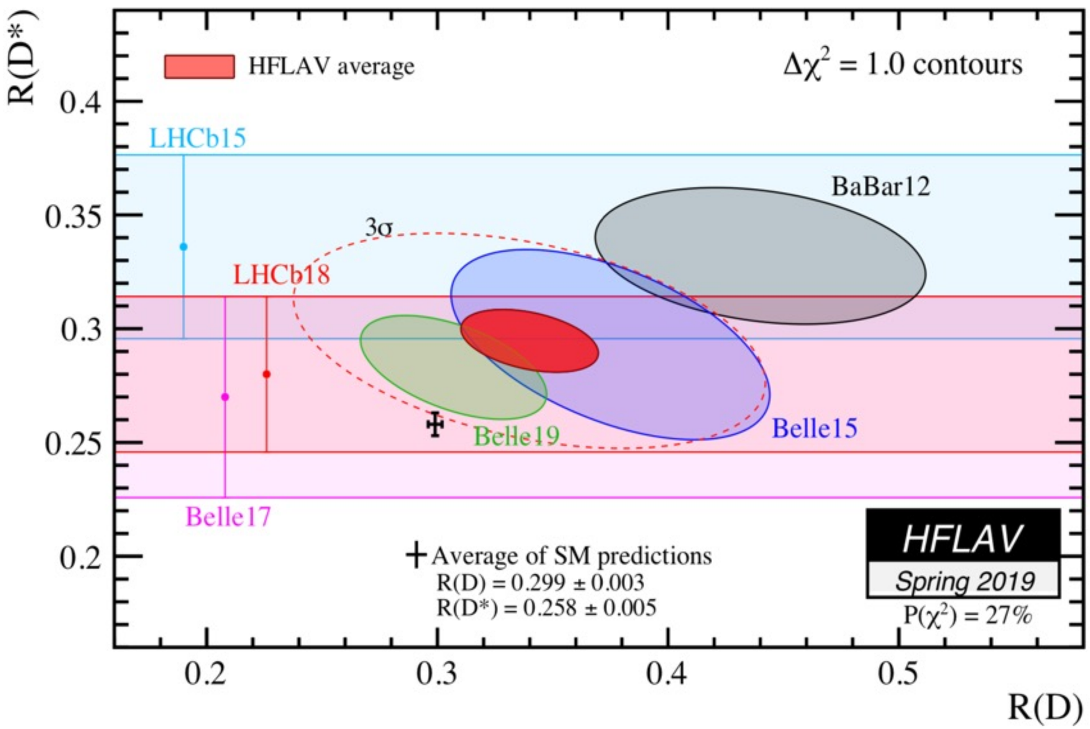
H,A: scalars

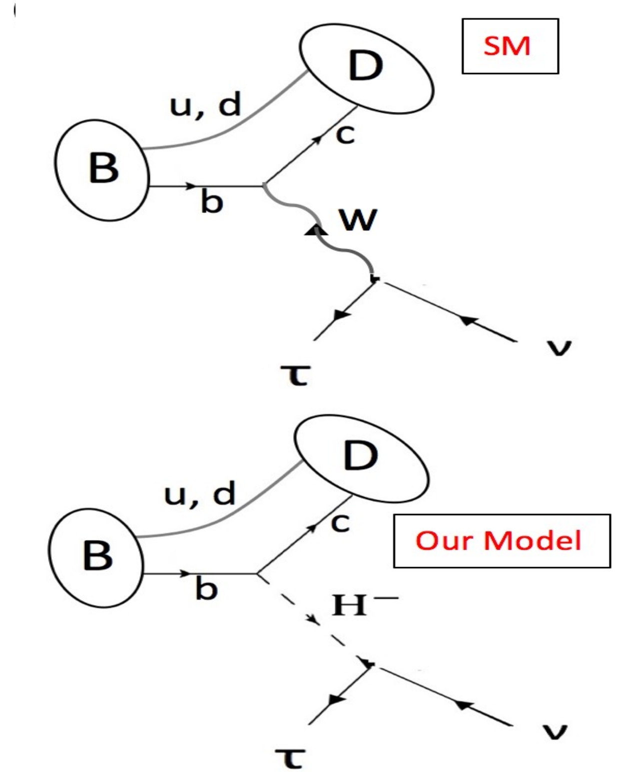
μ-τ Lepton flavor violating coupling generates τ mass enhancement

Omura, Senaha, Tobe: **JHEP 1505 (2015) 028**

$\mathbf{R(D^{(*)})}$ anomaly >3σ discrepancy

$$R(D^{(*)}) \equiv \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}l\nu)}, l = \mu, e$$





Taking ratio of BRs makes SM prediction more accurate
by cancelling large uncertainties in Vcb and meson form factors.

Phys.Rev. D86 (2012) 054014 A. Crivellin et al.
Nucl.Phys. B925 (2017) 560-606 Syuhei Iguro, K. Tobe(KMI,Nagoya-U).

Our Model

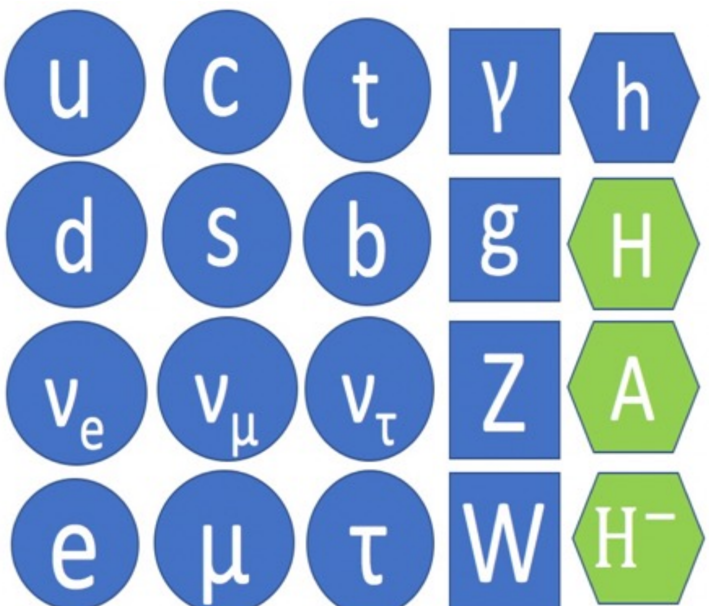
In the alignment limit: H_1-> H_1(SM)

Particle set in G2HDM

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\Phi_1+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\Phi_2+iA}{\sqrt{2}} \end{pmatrix}$$

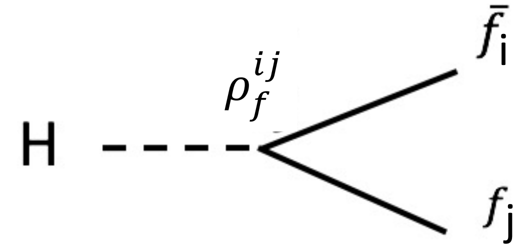
G^+,G: N-G boson, H^+ :charged Higgs,

A : CP odd Higgs



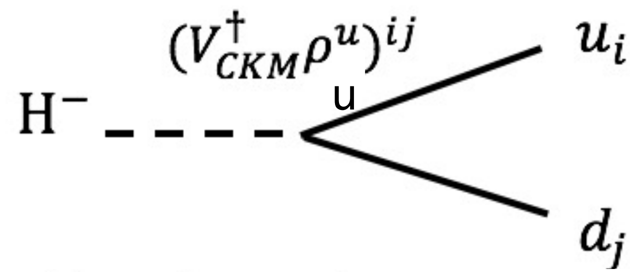
Neutral Scalar

$$\frac{1}{\sqrt{2}}\rho_f^{ij} H \bar{f}_L^i f_R^j \quad (f = u, d, e, \nu)$$



Charged Scalar

$$(V_{CKM}\rho_d)^{ij} H^- \overline{u_L^i} d_R^j + (V_{CKM}^\dagger \rho_u)^{ij} H^- \overline{d_L^i} u_R^j$$



e.g. Stringent bounds come from

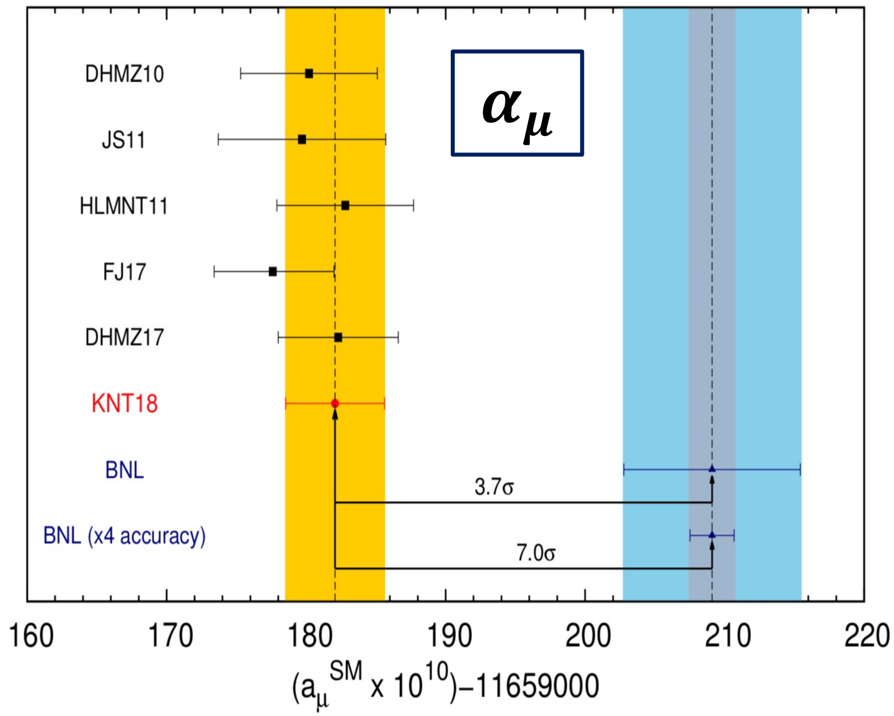
- meson mixing
- $b \to s\gamma$
- $B \to \tau\nu$ .....

$\rho_d^{ij} << 1,$

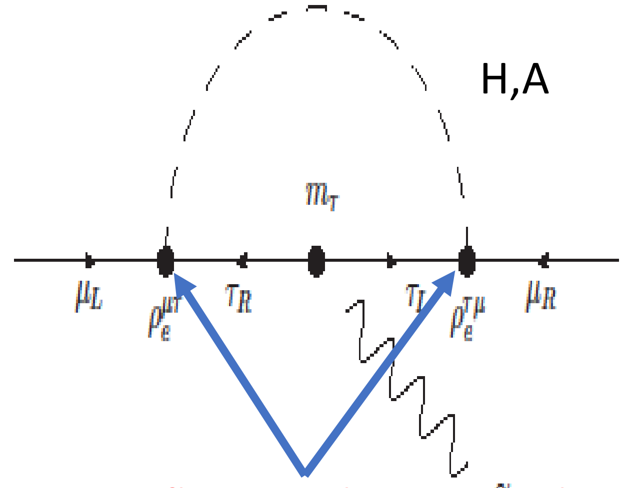
ρ_u^{ij} other than ρ_u^{tc}, ρ_u^{ct} , ρ_u^{tt} should be small

muon g-2 anomaly >3σ discrepancy

can be explained in G2HDM

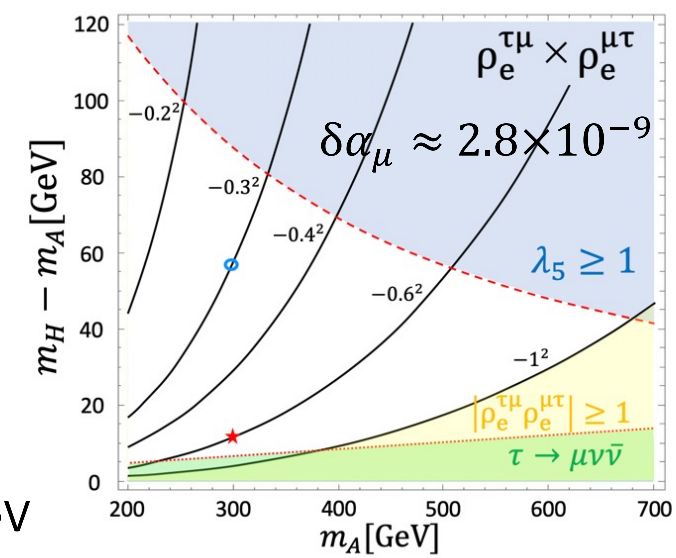


Alexander,et al:1802.02996



μ-τ Lepton flavor violating coupling generates τ mass enhancement

Omura, Senaha, Tobe: **JHEP 1505 (2015) 028**



1907.09845 Syuhei Iguro, Y. Omura, M. Takeuchi.

$$\delta a_\mu \approx \frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{16\pi^2}\left(\frac{\log\frac{m_H^2}{m_\tau^2}-\frac{3}{2}}{m_H^2}-\frac{\log\frac{m_A^2}{m_\tau^2}-\frac{3}{2}}{m_A^2}\right)$$

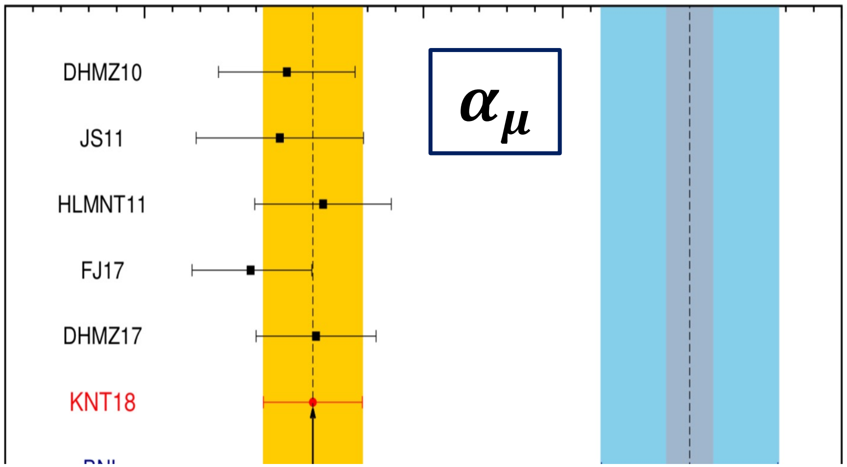
$$\approx 2.6\left(\frac{\rho_e^{\mu\tau}\rho_e^{\tau\mu}}{-0.034}\right)\times10^{-9} \text{ for } (m_A, m_H) = (200,250)\text{ GeV}$$

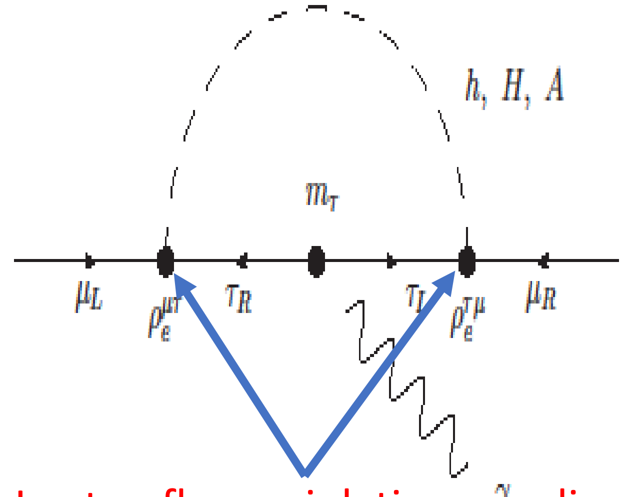
$m_A - m_H \neq 0$ is needed

Anomalies to try to explain

muon g-2 anomaly >3σ discrepancy

can be explained in G2HDM





μ-τ Lepton flavor violating coupling generates τ mass enhancement

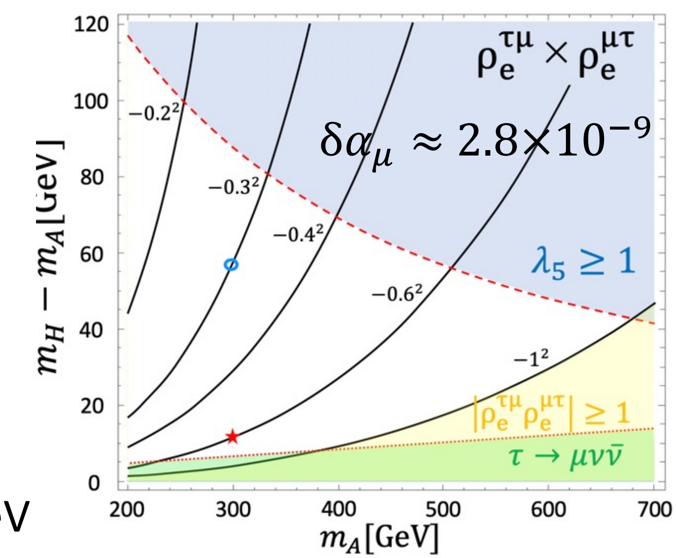
Omura, Senaha, Tobe: **JHEP 1505 (2015) 028**

If only $\rho_e^{\mu\tau}, \rho_e^{\tau\mu}$ are nonzero, it looks hard to test this scenario in a proton collider (LHC).

$$\delta a_\mu \approx \frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{16\pi^2}\left(\frac{\log\frac{m_H^2}{m_\tau^2}-\frac{3}{2}}{m_H^2}-\frac{\log\frac{m_A^2}{m_\tau^2}-\frac{3}{2}}{m_A^2}\right)$$

$\approx 2.6\,\left(\frac{\rho_e^{\mu\tau}\rho_e^{\tau\mu}}{-0.034}\right)\times 10^{-9}$ for $(m_A, m_H) = (200, 250)$ GeV

$m_A - m_H \neq 0$ is needed

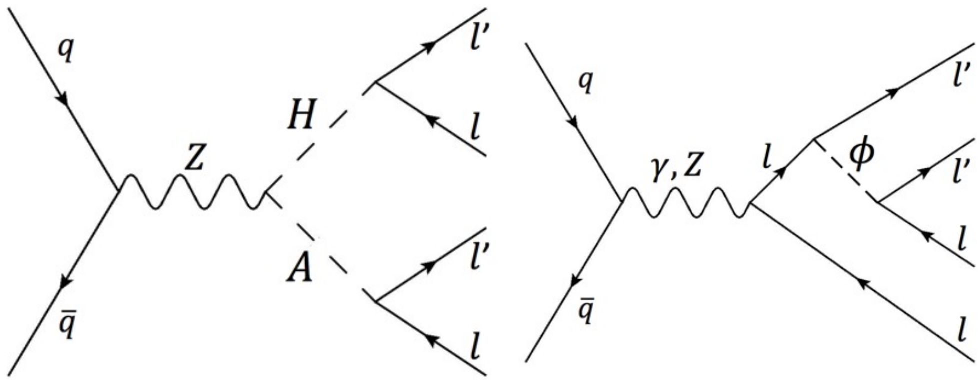


SI_19

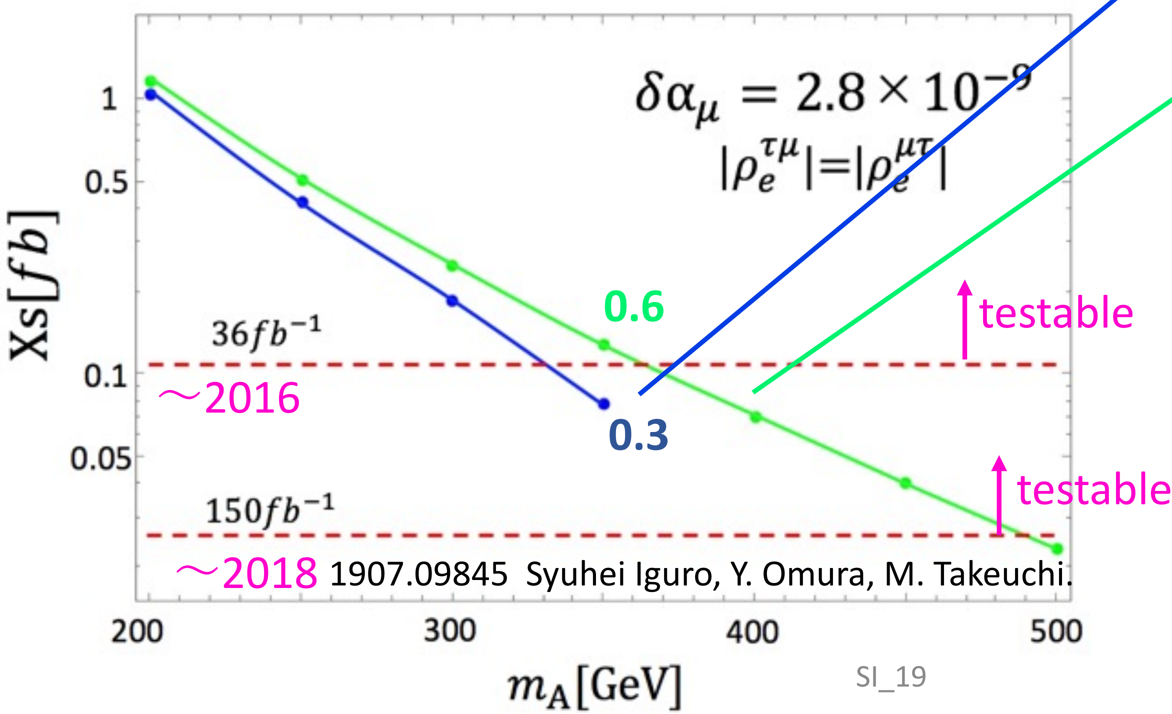
1907.09845 Syuhei Iguro, Y. Omura, M. Takeuchi.

Proposal for a $\mu\mu\bar{\tau}\bar{\tau}$ search **Small SMBG**

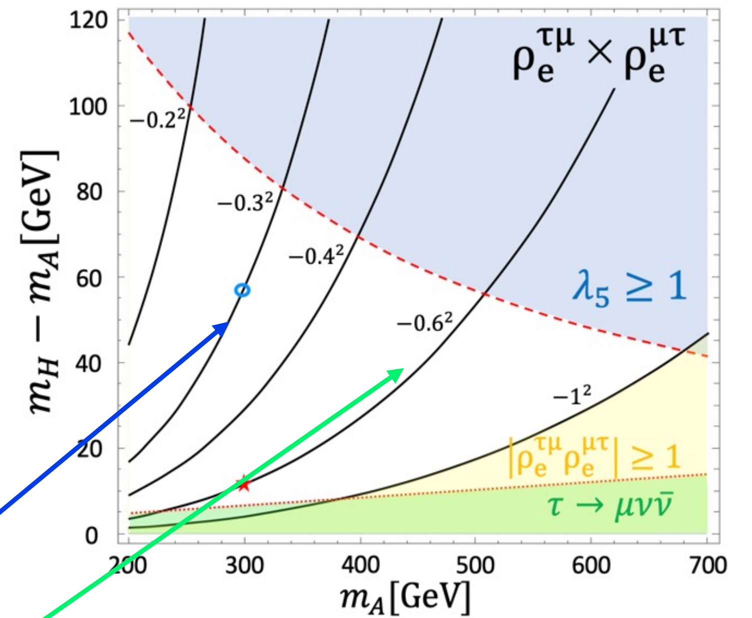
production mode



A,H is charged under $SU(2)_L$



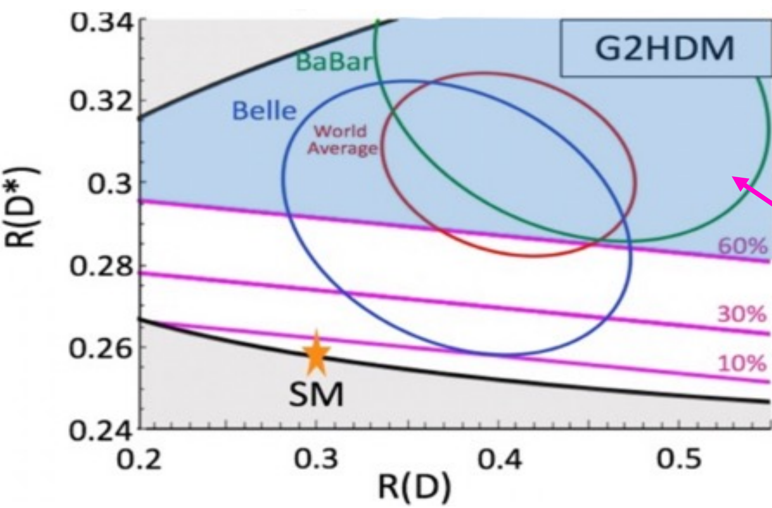
1907.09845 Syuhei Iguro, Y. Omura, M. Takeuchi.



$\mu\mu\bar{\tau}\bar{\tau}$ mode can test the scenario in near future!

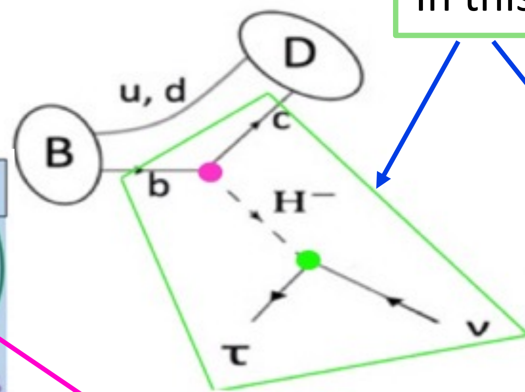
$R(D^{(*)})$ and collider search

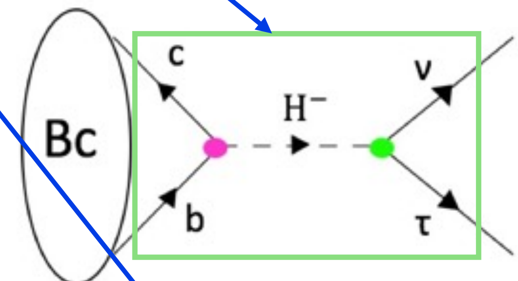
G2HDM can explain the updated $R(D^{(*)})$ within 1σ!

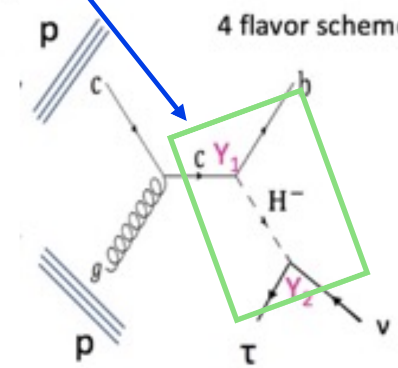


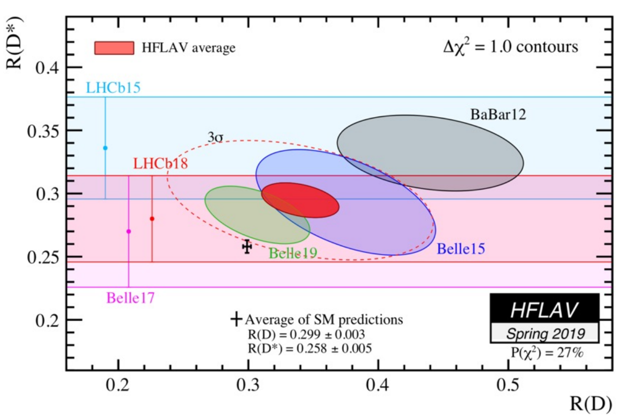
Previous constraint from BR(Bc->τν)

Same interactions In this box

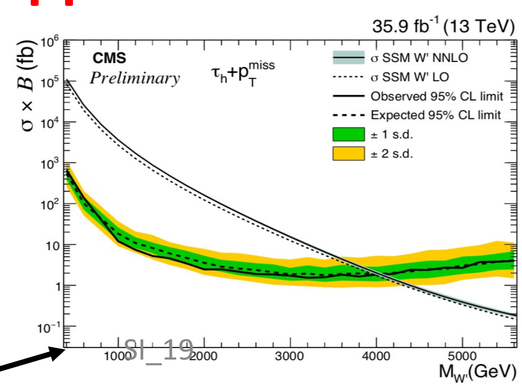








We applied W'->τν search to H^- scenario



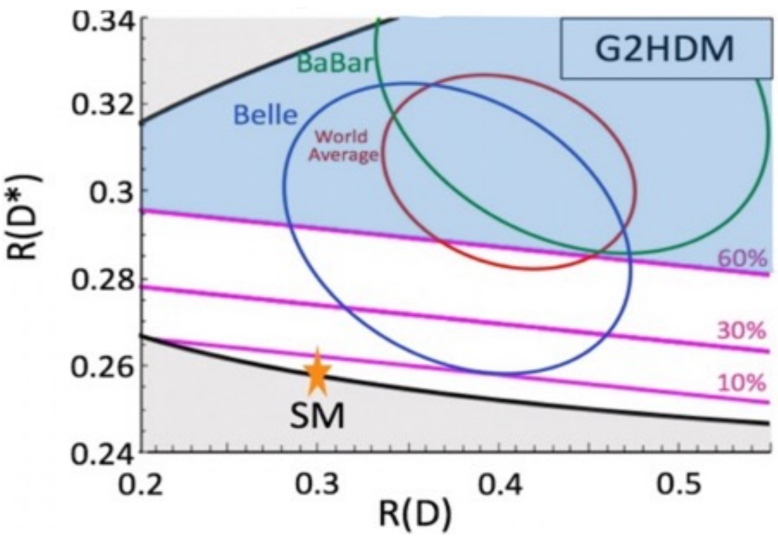
400GeV

pp->W'->τν search

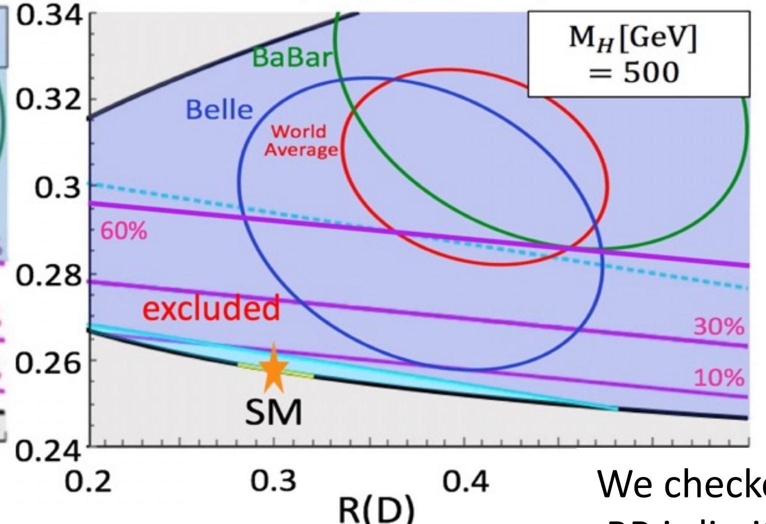
They look for a τν resonance heavier than 400GeV

SI_19

$\tau\,\nu$ resonance gives the most stringent constraint.



PhysRevD.99.075013 Syuhei Iguro, Yuji Omura, Michihisa Takeuchi

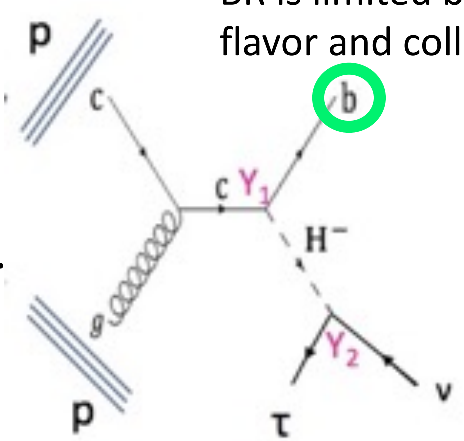


Constraint for m_{H^-} >400GeV

We checked that diluting BR is limited because of flavor and collider constraints.

Additional b-tagging will improves sensitivity

Nucl.Phys. B925 (2017) 560-606 Syuhei Iguro, K. Tobe.



Summary

G2HDM can explain anomalies in muon g-2 and RD, RD*. We found that those scenarios are testable at LHC in near future.

Thank you!

Back ups start from the next

Acknowledgement

My trip here is supported by Toyoaki scholarship foundation (affiliate foundation to TOYOTA company).
Many thanks for collaborators!

G2HDM

We take so called Higgs base : a doublet acquires VEV

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\Phi_1+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\Phi_2+iA}{\sqrt{2}} \end{pmatrix}$$

G^+,G: N-G boson, H^+ :charged Higgs, A : CP odd Higgs

Linear transformation to mass base of CP even scalars

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\beta\alpha} & \sin\theta_{\beta\alpha} \\ -\sin\theta_{\beta\alpha} & \cos\theta_{\beta\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

Yukawa terms

$$\begin{aligned} \mathcal{L}_y = & -\textstyle\sum_{f=u,d,e}\sum_{\Phi=h,H,A} y^f_{\Phi ij}\overline{f_{Li}}\,\Phi f_{Rj} + \text{h.c.} \\ & -\overline{\nu_{Li}}(V^\dagger_{MNS}\rho_e)^{ij}H^+ e_{Rj} + \text{h.c.} \\ & -\bar{u}_i(V_{CKM}\rho_d P_R - \rho_u^\dagger V_{CKM} P_L)^{ij} H^+ d_j + \text{h.c.}, \end{aligned}$$

$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha}, \quad y^f_{Aij} = \begin{cases} -\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = u \\ +\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = d, e, \end{cases} \quad y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

Simultaneous explanation can be ?

JHEP 1805 (2018) 173 Syuhei Iguro, Y. Omura

- $R(D^{(*)})$=$BR(B \to D^{(*)}\tau\nu)/BR(B \to D^{(*)}l\nu)$
- muon g-2 Omura, Senaha, Tobe: **JHEP 1505 (2015) 028**
- P'_5 : angular observable in $B \to K^*\mu\mu$
- $R(K^{(*)})$=$BR(B \to K^{(*)}\mu\mu)/BR(B \to K^{(*)}ee)$

	$R(K^{(*)})$	P_5'	$R(D)$	$R(D^*)$	δa_μ
(B) $\rho_e \neq 0,\ \rho_\nu = 0$					
ρ_u^{tt}	×	×	×	×	○
ρ_u^{tc}	×	○	○	×	×
ρ_u^{ct}	×	×	×	×	○

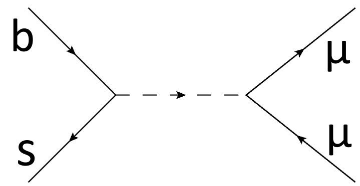
○: within 1σ

or X X O X O

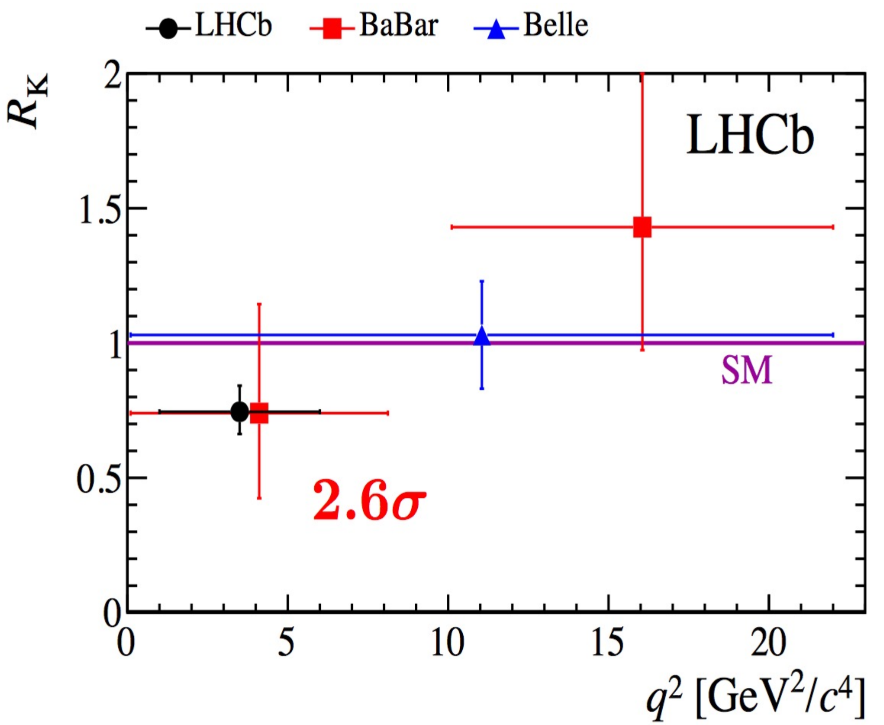
ε' / ε is difficult
1905.11778 Syuhei Iguro, Y. Omura

$R(K), P'_5$ anomalies

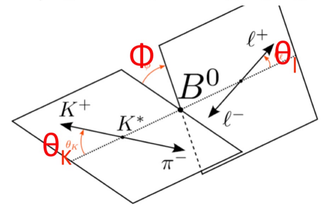
b→s quark transition



$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

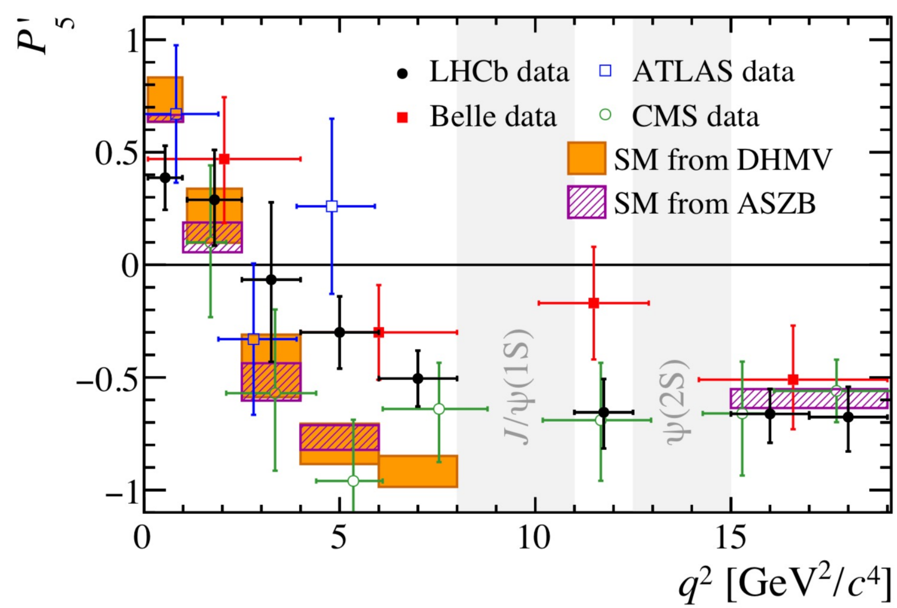


$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell - F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi + S_5\sin2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi + S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$



Optimized observable

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}},$$



Talk by C. Langenbruch (RWTH)@ Moriond EW 2018

Result1

- (blue box) R(D): $\rho_u^{tc}\rho_e^{\mu\tau}$ is large
- (magenta box) P'$_5$: ρ_u^{tc} is large
- (green box) muon g-2: $\rho_e^{\tau\mu}\rho_e^{\mu\tau}$ is large

$$\rho_u^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_u^{ct} \\ 0 & \boxed{\rho_u^{tc}} & \rho_u^{tt} \end{pmatrix}, \quad \rho_e^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \boxed{\rho_e^{\mu\tau}} \\ 0 & \boxed{\rho_e^{\tau\mu}} & \boxed{\rho_e^{\tau\tau}} \end{pmatrix}$$

(cyan box) Combination of $\rho_u^{tc}\rho_e^{\tau\mu}$ enhances Br($B \to D^{(*)}\mu\nu$) and breaks Lepton Flavor Universality in $B \to D^{(*)}e\nu$ and $B \to D^{(*)}\mu\nu$

$$R_{D^*l} \equiv \frac{Br(B\to D^* e\nu)}{Br(B\to D^*\mu\nu)} = 1.04 \pm 0.05$$ Belle 1702.01521

One can evade the constraint by taking $\rho_u^{tc} \ll 1$ or $\rho_e^{\tau\mu} \ll 1$.

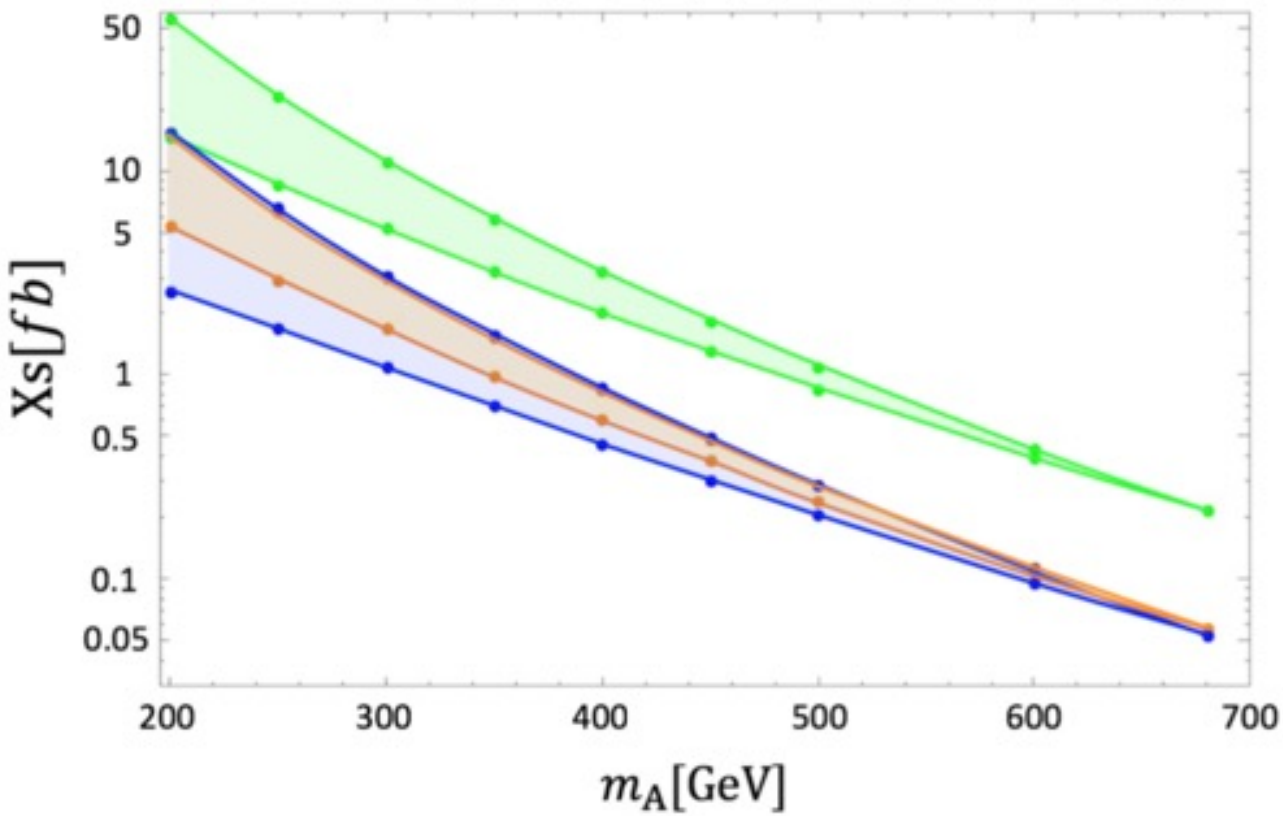


Figure 3: The pair-production cross sections for $\phi H^{\pm}$ ($AH^{\pm}$ and $HH^{\pm}$ are summed, green hatched), $H^{-}H^{+}$ (blue hatched), and HA (orange hatched) at the LHC with $\sqrt{s} = 13$ TeV as functions of m_A. In the each process, the upper line is given by assuming $|\rho_e^{\mu\tau}| = |\rho_e^{\tau\mu}| = 1$, that corresponds to the minimum Δ_{H-A}, while the lower line is obtained by $\lambda_5 = 1$.