Charged Lepton Flavor Violation in General Two Higgs Doublet Model

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Based on **arXiv: 2003.03827 [PRD]**
arXiv: 2008.08469 [PRD]

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Motivation

Why Charged lepton flavor violation (cLFV) is interesting ?

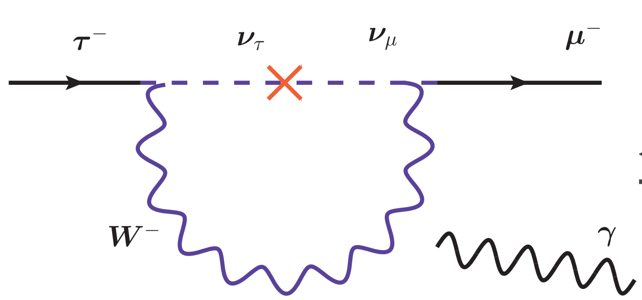
Unlike charge, color etc, the family number is not a symmetry of the $\mathscr{L}_{\rm SM}$.

Broken in quark sector— CKM. $b \to s\gamma$

Broken in neutral leptons— neutrino oscillations.

But, so-far, we have not seen flavor violation in charged leptons.
$\mu \to e\gamma, \tau \to \mu\gamma, \tau \to eee \ldots$

Highly suppressed due to
tiny neutrino masses and loop factor



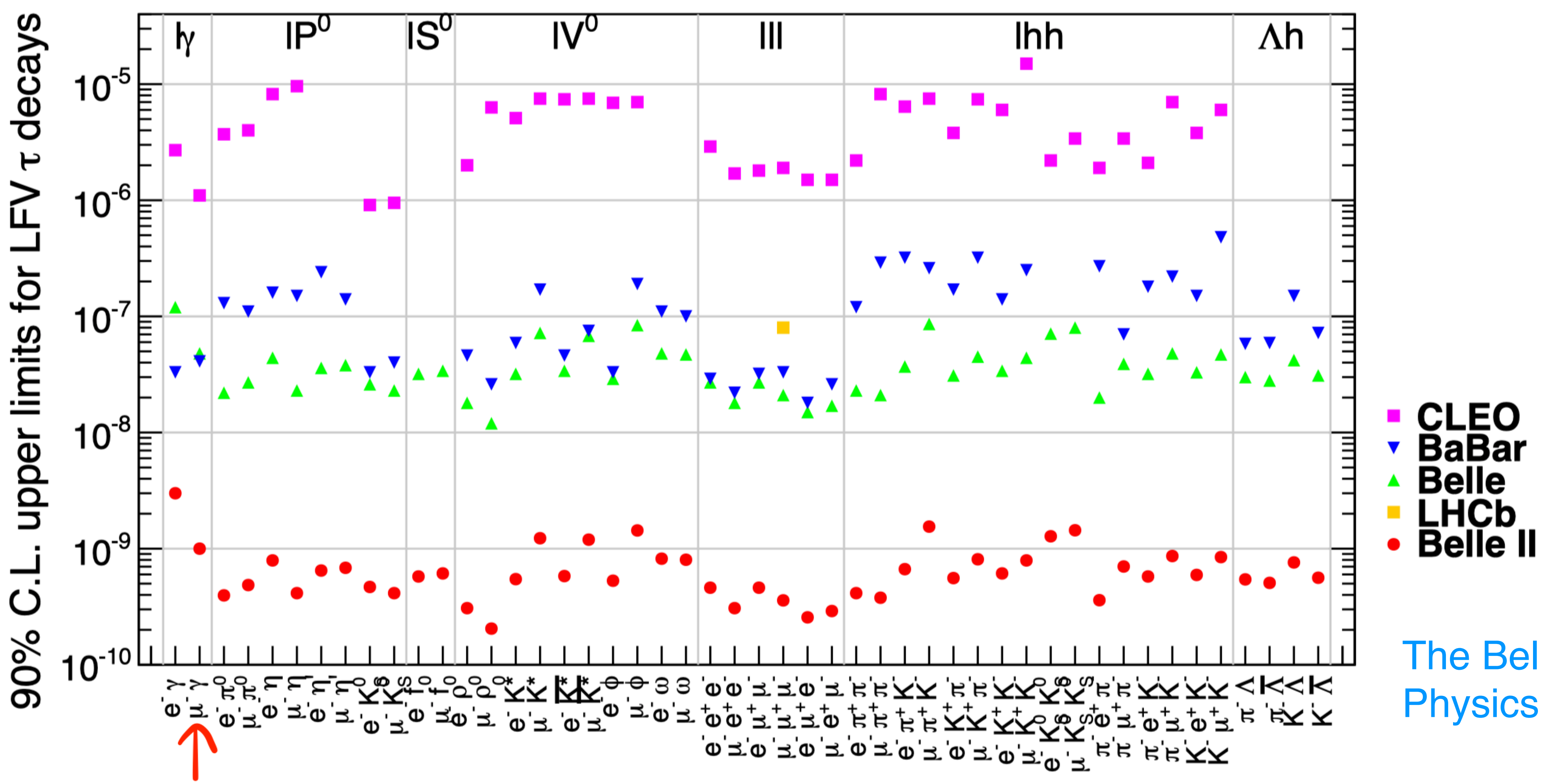
$\leq 10^{-53} \sim 10^{-49}$

zero SM background!

Discovery would be a clear sign of new physics!

ℓ-flavor violation: experimental data

μFV process	Current bound	Future sensitivity
$\mu \to e\gamma$	4.2×10^{-13} (MEG)	6×10^{-14} (MEG II)
$\mu \to 3e$	1.0×10^{-12} (SINDRUM)	$\sim 10^{-15}$–10^{-16} (Mu3e)
$\mu N \to eN$	7×10^{-13} (SINDRUM II)	$\sim 10^{-15}$–10^{-17} (COMET) 3×10^{-17}– (Mu2e) $\sim 10^{-18}$–10^{-19} (PRISM)
$\tau \to \mu\gamma$	4.4×10^{-8} (BaBar)	10^{-9} (Belle II)
$\tau \to 3\mu$	2.1×10^{-8} (Belle)	3.3×10^{-10} (Belle II)



The Belle II Physics Book, 2018

General Two-Higgs Doublet Model (g2HDM)

Formalism: Two Higgs doublets, Φ_1 and Φ_2, with $\langle \Phi_i \rangle = v_i/\sqrt{2}$.

$$-\mathcal{L}_Y^{\text{weak}} = \bar{Q}_L \left(\tilde{\Phi}_1 Y_1^U + \tilde{\Phi}_2 Y_2^U\right) U_R + \bar{Q}_L \left(\Phi_1 Y_1^D + \Phi_2 Y_2^D\right) D_R + \bar{L}_L \left(\Phi_1 Y_1^L + \Phi_2 Y_2^L\right) E_R + \mathrm{h.c.}$$

Lee, 1973;
for a review, see Branco et al, 2012

g2HDM : no additional Z_2 symmetry; both doublet couple to u-and d-type

Unitary transformation to fermion mass basis: not possible to diagonalize both Yukawa matrices simultaneously.

W.S. Hou, 1992, Davidson and Haber 2005
Mahmoudi and Stal, PRD (2010)

$$\mathcal{L}_Y^{\text{Phys.}} = -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \left[\left(\lambda_i^f \delta_{ij} s_\gamma + \rho_{ij}^f c_\gamma\right) h + \left(\lambda_i^f \delta_{ij} c_\gamma - \rho_{ij}^f s_\gamma\right) H - i \,\mathrm{sgn}\left(Q_f\right) \rho_{ij}^f A\right] R f_j - \bar{u}_i \left[\left(V\rho^d\right)_{ij} R - \left(\rho^{u\dagger} V\right)_{ij} L\right] d_j H^+ - \bar{\nu}_i \rho_{ij}^\ell R \ell_j H^+ + h.c.$$

λ^f are real and diagonal, $\lambda_i^f = \sqrt{2}\, m_i^f / v$

ρ^f ***("extra Yukawas")*** are in general non-diagonal and complex

Extra Yukawa in g2HDM

ρ_{ij}^{f} : source for flavor changing currents and CP violation

$$\rho^{\ell} = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix} \quad \rho^{u} = \begin{pmatrix} \rho_{uu} & \rho_{uc} & \rho_{ut} \\ \rho_{cu} & \rho_{cc} & \rho_{ct} \\ \rho_{tu} & \rho_{tc} & \rho_{tt} \end{pmatrix} \quad \rho^{d} = \begin{pmatrix} \rho_{dd} & \rho_{ds} & \rho_{db} \\ \rho_{sd} & \rho_{ss} & \rho_{sb} \\ \rho_{bd} & \rho_{bs} & \rho_{bb} \end{pmatrix}$$

Alignment ($c_\gamma \to 0$) without decoupling is possible in g2HDM

Hou and Kikuchi, EPJC (2017)

$$\mathscr{L}_Y = -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \Big[\Big(\lambda_i^f \delta_{ij} s_\gamma + \cancel{\rho_{ij}^f c_\gamma} \Big) h + \Big(\lambda_i^f \cancel{\delta_{ij} c_\gamma} - \rho_{ij}^f s_\gamma \Big) H - i\,\mathrm{sgn}\left(Q_f\right) \rho_{ij}^f A \Big] R f_j + h.c.$$

alignment limit $c_\gamma \to 0$

plus mass-mixing hierarchy

$$m_u \ll m_c \ll m_t$$
$$|V_{ub}|^2 \ll |V_{cb}|^2 \ll |V_{tb}|^2$$

our working assumption for $\rho_{\tau\mu}, \rho_{\tau\tau},$ and ρ_{tt} : $\rho_{32}^f, \rho_{33}^f = \mathcal{O}(\lambda_3^f)$

and $\max[c_\gamma] \sim 0.2$

Some motivations for study of *extra Yukawas*

Alignment plus fermion mass-mixing hierarchy can be an attractive substitute for natural flavor conservation's *overkill.*

Extra Yukawas are complex :

ρ_{tt} (or ρ_{tc}) can drive **baryon asymmetry of universe**

Fuyuto, Hou, Senaha, PLB (2018)
also, Fuyuto, Hou, Senaha, PRD (2020)
[connection with eEDM]

Mass-spectrum lies in sub-TeV range

ρ_{tt} **is naturally** $\mathcal{O}(1)$

promising signatures at LHC!

Kohda, Modak, Hou, PLB 776 (2018),
Kohda, Modak, Hou, PLB 786 (2018),
Ghosh, Hou, Modak, Phys.Rev.Lett (2020)

$$cg \to tA/tH \to tt\bar{t}$$

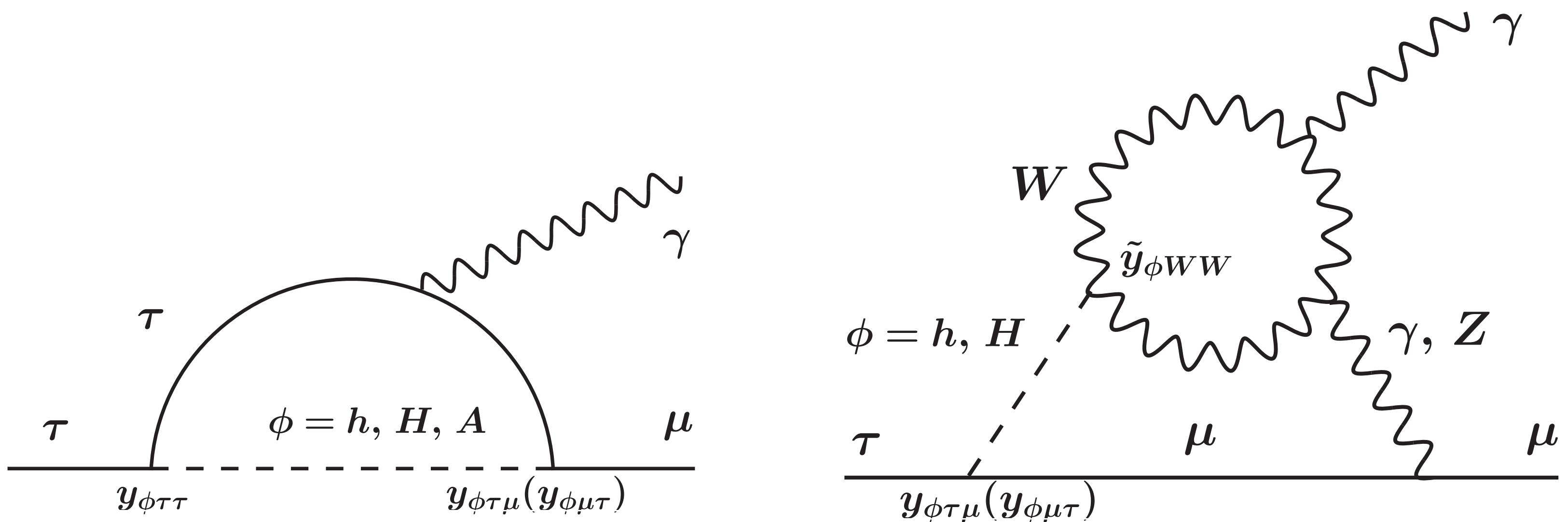
$$cg \to tA/tH \to tt\bar{c}$$

$$cg \to bH^+ \to bt\bar{b}$$

$\tau \to \mu\gamma$ in g2HDM

The g2HDM naturally contains Higgs LFV couplings, $\phi\ell\ell'$, inducing cLFV rates.

$$\frac{\mathscr{B}(\tau \to \mu\gamma)}{\mathscr{B}(\tau \to \mu\nu\bar{\nu})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_L|^2 + |A_R|^2\right)$$



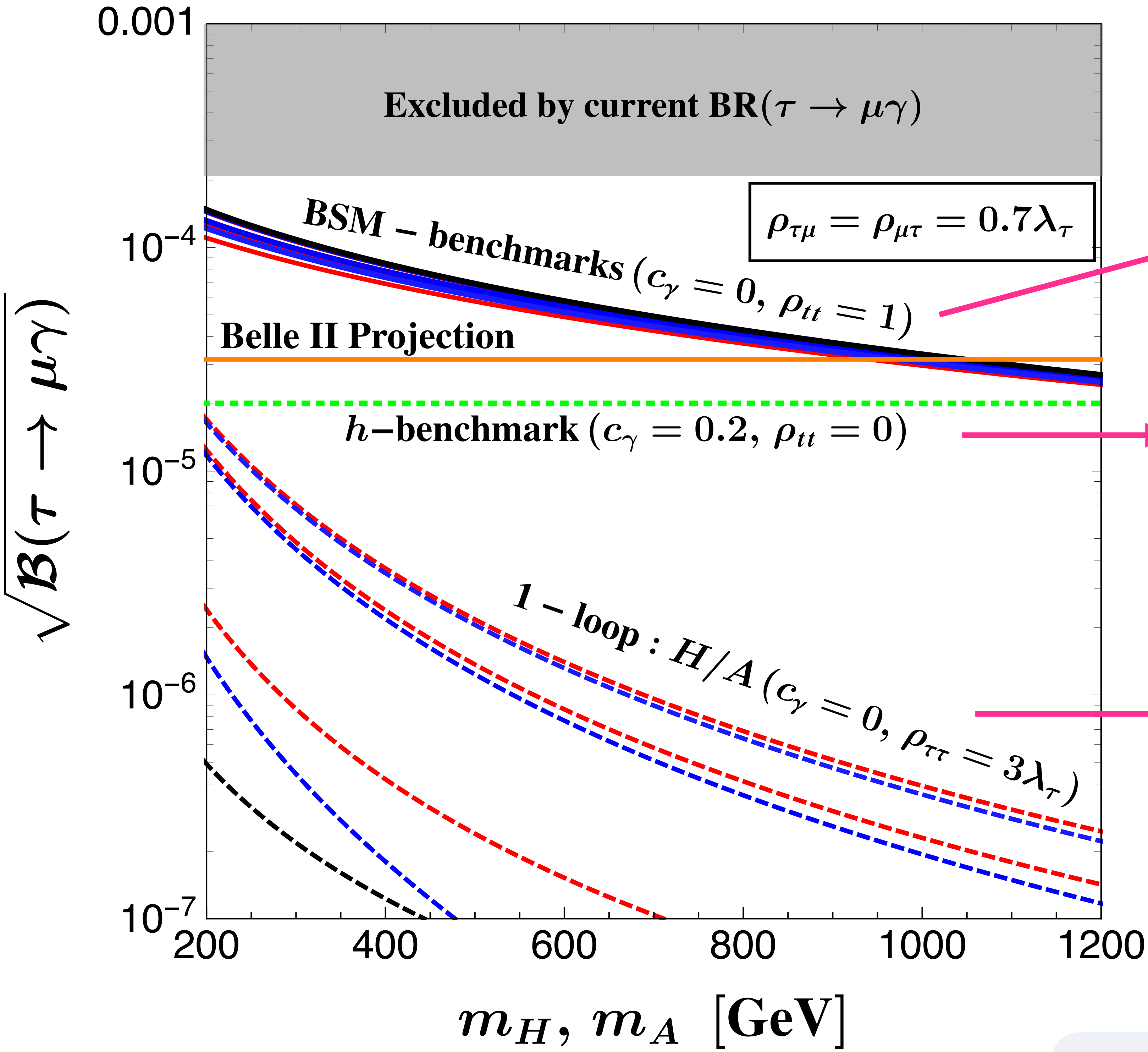
For 2-loop, see Chang, Hou, Keung, PRD'93

Few noteworthy points:

Cancellation between ***top*** 2-loop and ***W*** 2-loop contribution

Cancellation between ***CP-odd*** and ***CP-even*** contributions @1-loop

$\tau \to \mu\gamma$ in g2HDM



$\tau \to \mu\gamma$ is dominated by top 2-loop, natural choice $\rho_{tt} \sim \lambda_t$ sits just right between current bound and Belle II reach

Fixed by $h \to \tau\mu$ bound $|\rho_{\tau\mu} c_\gamma| \lesssim 0.14\lambda_\tau$. Fall below Belle II reach.

Mass splitting between H/A enhances contribution but not accessible to Belle II.

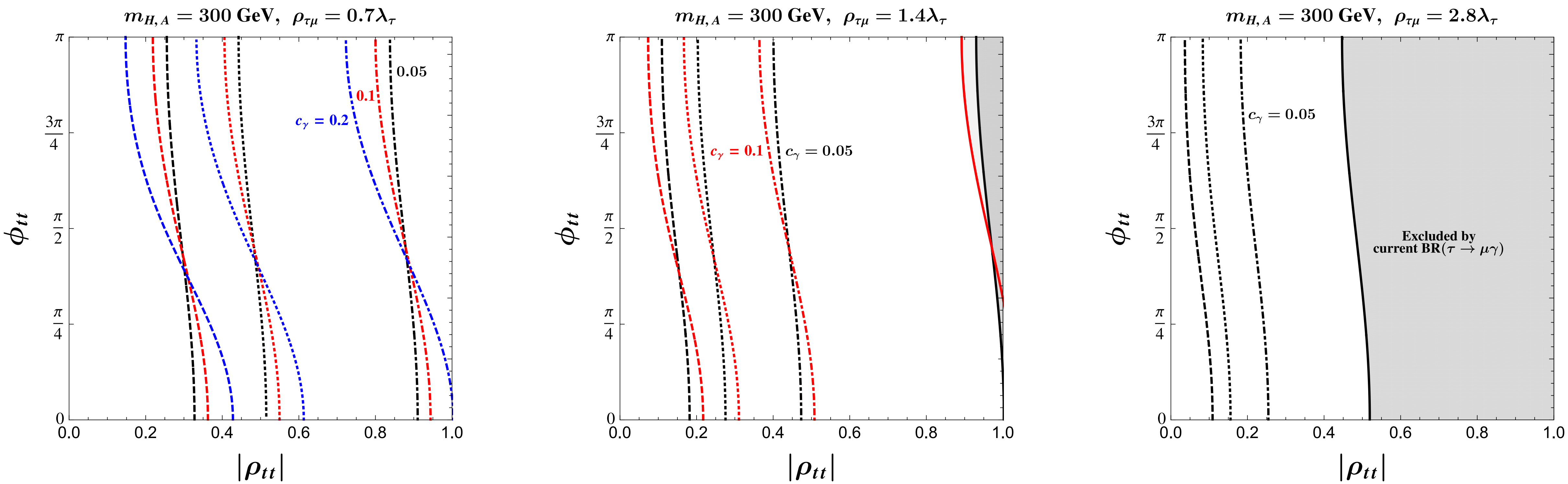
ρ_{tt} participation is necessary !!

Black: $m_H = m_A$

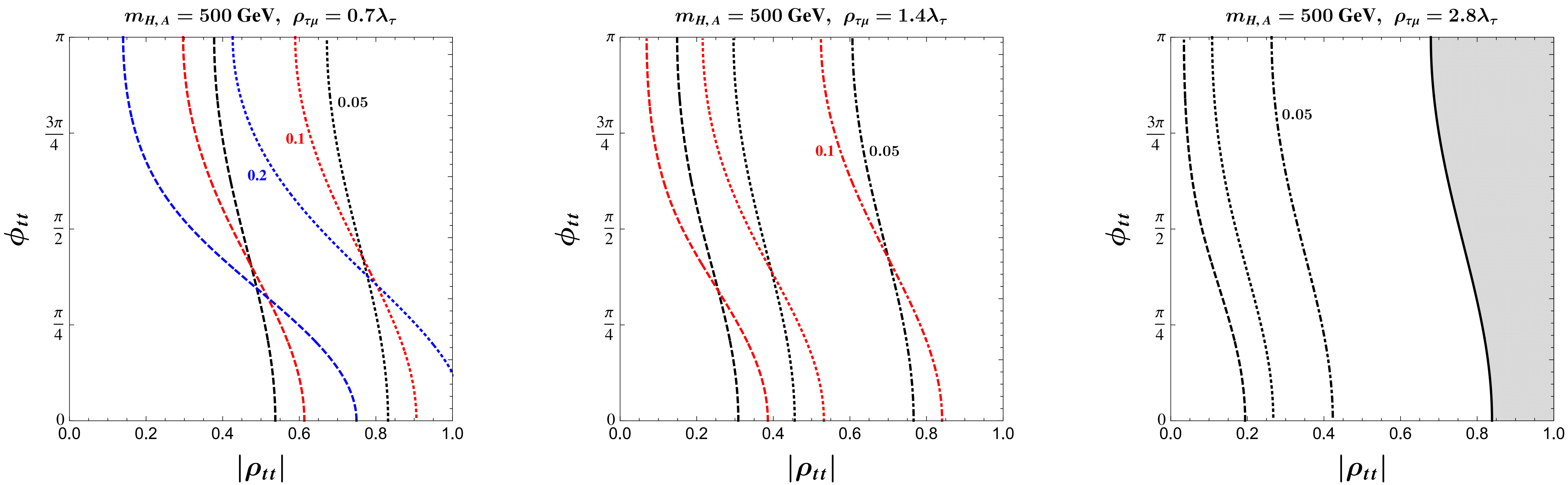
Red: variation due to m_H; **Blue:** for m_A with $|m_H - m_A| = 5, 100, 200$ GeV

Probing phase of ρ_{tt}

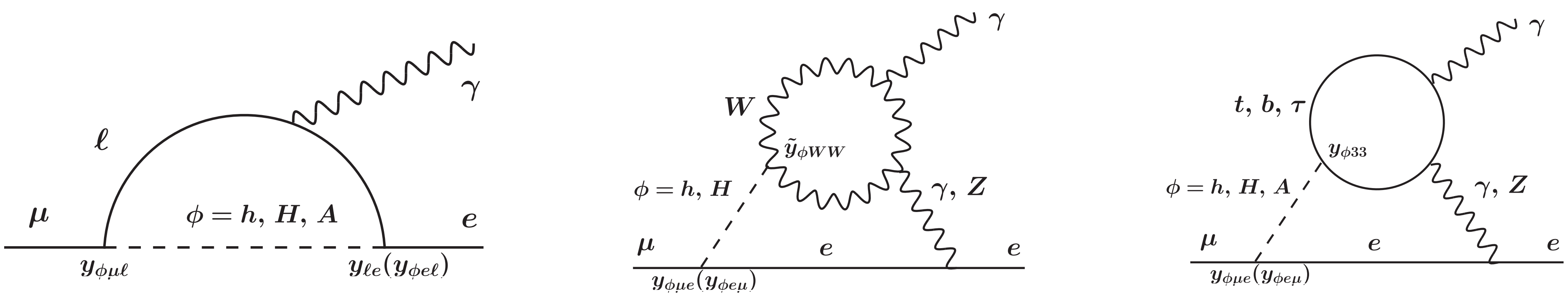
Curves are for 3, 10, 50 ab^{-1}

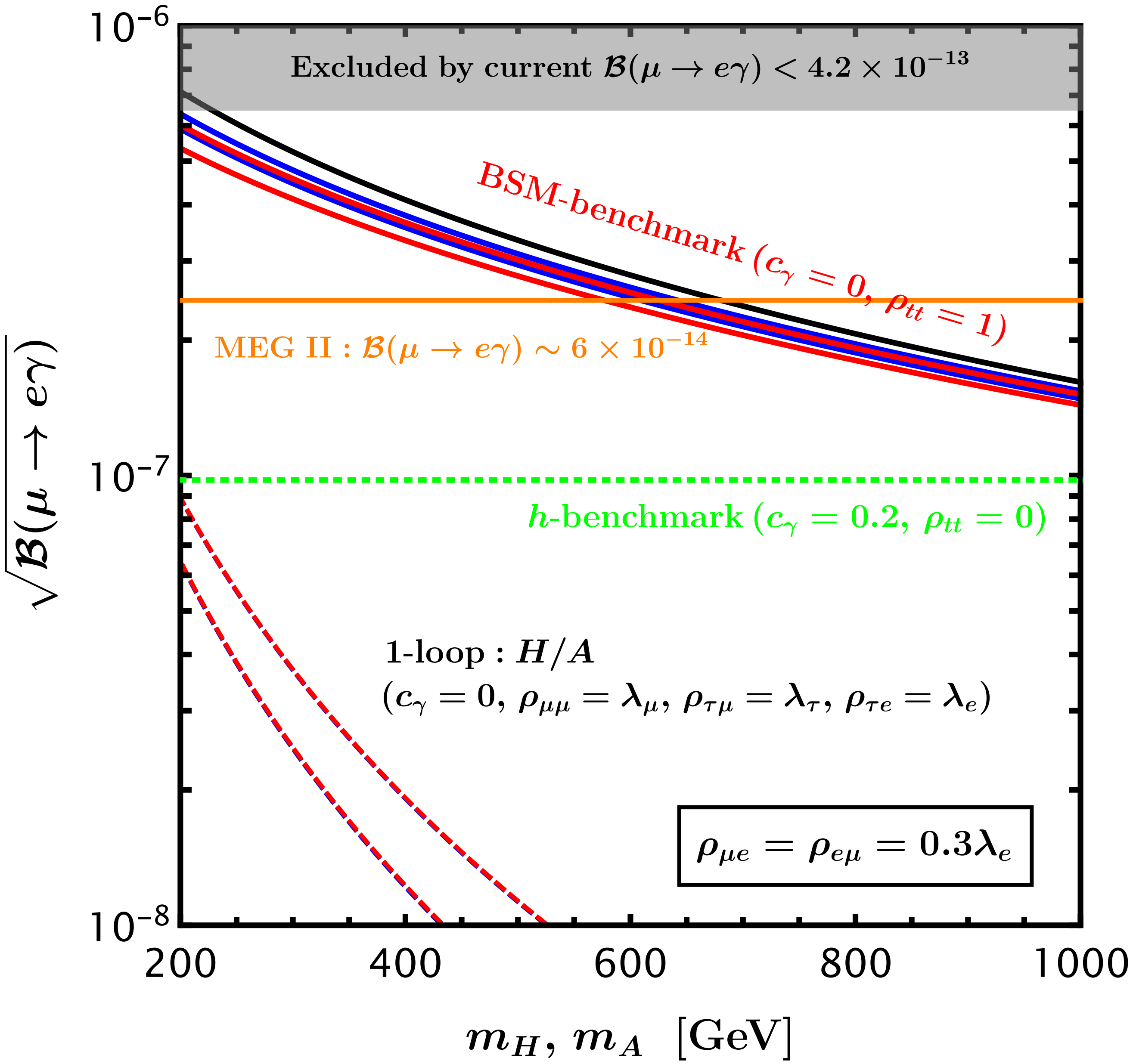


Large c_γ implies enhanced interference



$\mu \to e\gamma$ in g2HDM





Key takeaways:

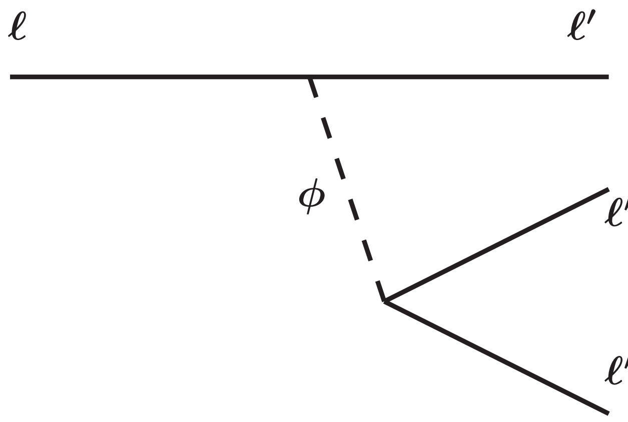
BSM-benchmark implies
$\rho_{\mu e} \leq \lambda_e/3$

h-benchmark standalone implies
$\rho_{\mu e} \leq 2\lambda_e$

$h \to \mu e$, unlike $h \to \tau\mu$ case, does not provide stringent bound

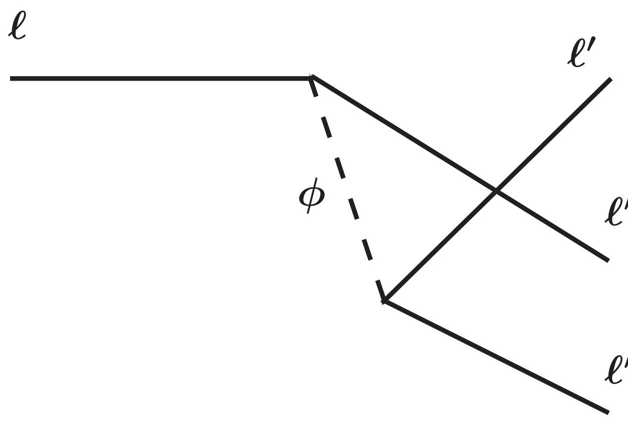
Leptonic decays : $\ell \to \ell'\ell'\ell'$

$\tau \to \mu\mu\mu,\ \mu \to eee$



There are contributions at tree-level itself

But highly **suppressed** in view of small $\rho_{\ell\ell'}$



But $\ell \to \ell'\gamma$ dipole can generate $\ell \to \ell'\ell'\ell'$:

$$\frac{\mathcal{B}(\ell \to 3\ell')}{\mathcal{B}(\ell \to \ell'\gamma)} \simeq \frac{\alpha}{3\pi}\left[\log\left(\frac{m_\ell^2}{m_{\ell'}^2}\right) - \frac{11}{4}\right]$$

~ 0.0063 for $\mu \to e$

~ 0.0023 for $\tau \to \mu$

$\mu - e$ Conversion in Nuclei

$$\mathscr{L}_{\text{eff}} = m_\mu \left(C_T^R \, \bar{e}\sigma_{\alpha\beta} L\mu + C_T^L \, \bar{e}\sigma_{\alpha\beta} R\mu \right) F^{\alpha\beta}$$

dipole term

$$+ \left(C_{qq}^{SR} \, \bar{e} L\mu + C_{qq}^{SL} \, \bar{e} R\mu \right) m_\mu m_q \bar{q} q$$

contact term

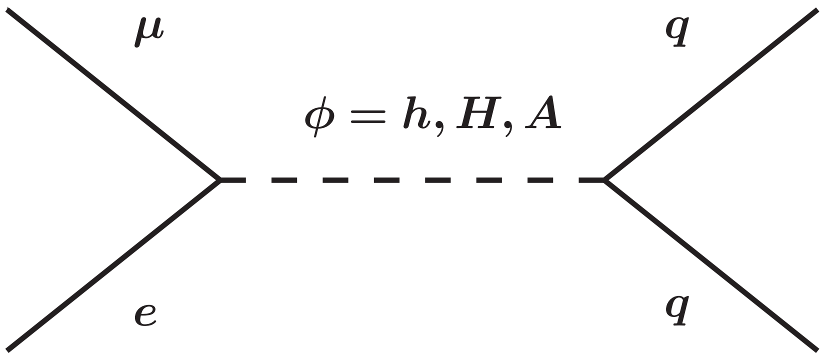
For a review, see
Kuno, Okada, hep-ph/9909265

$$\Gamma_{\mu\to e} = m_\mu^5 \left| \frac{1}{2} C_T^{L(R)} D + 2\left[m_\mu m_p \tilde{C}_p^{SL(R)} S^p + p \to n \right] \right|^2$$

contain information of
lepton-nucleons overlap

Kitano, Koine, Okada
hep-ph/0203110

g2HDM Wilson coefficients
modulated by quark content
of nucleon

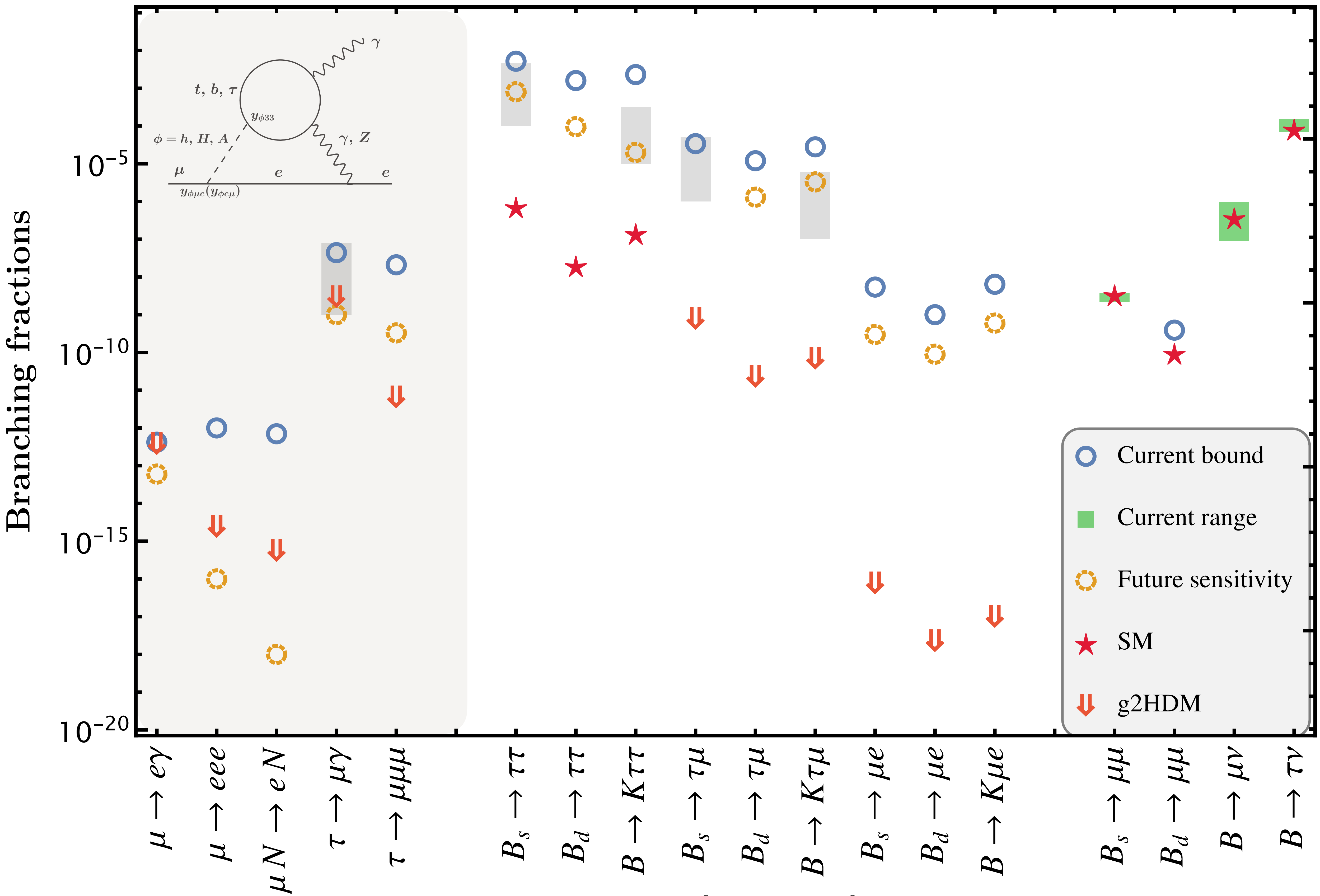


We use gold nuclei as target

Unlike $\mu \to e\gamma$, no cancellation between H and A contribution

Dipole dominates but **tree-level effects are important** as well

Short Summary



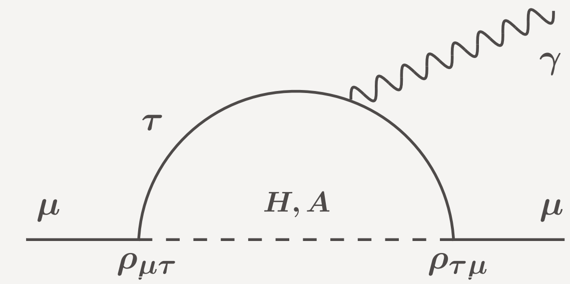
benchmark: $m_\phi = 300$ GeV, $\rho_{tt} = 0.4$, $\rho^\ell_{1j} = \lambda_e, \rho^\ell_{3j} = \lambda_\tau, \rho_{ii} = \lambda_i$

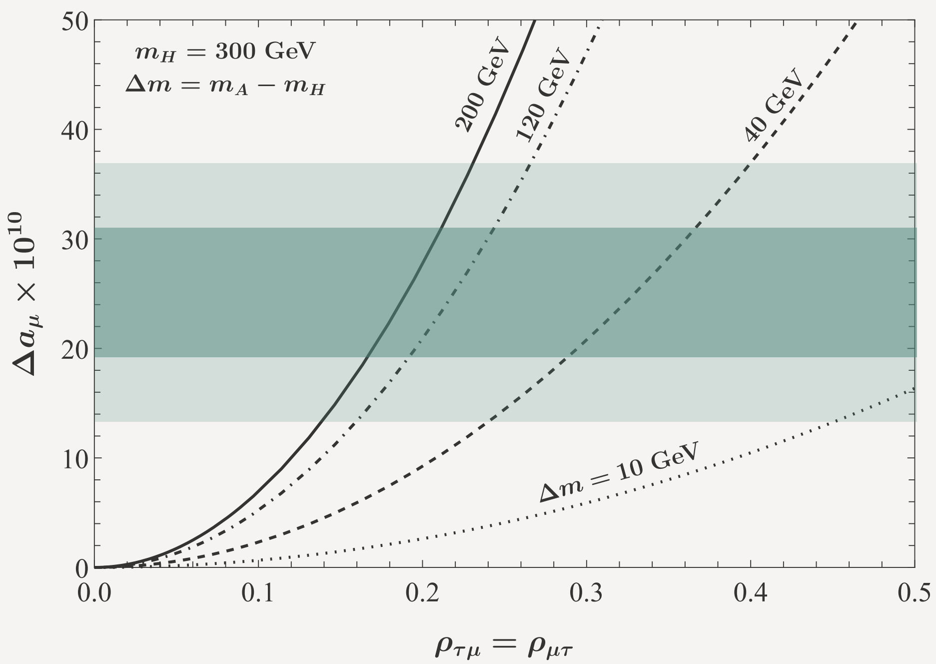
a digression…

Muon g-2: $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}$ $\sim 4.2\sigma$ tension

Fermilab Muon g-2 exp., 2104.03281, Aoyama et al, 2006.04822

Can be explained with large flavor-violating coupling $\rho_{\tau\mu}$





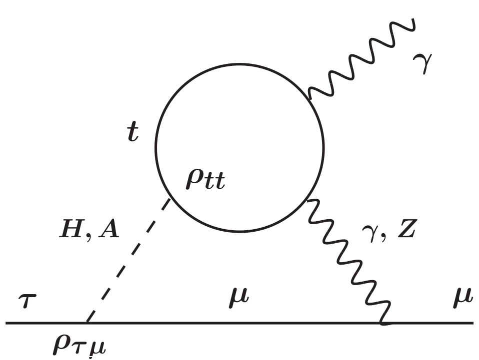
known mechanism, $\rho_{\tau\mu} \sim 20\,\lambda_\tau$

with $c_\gamma \to 0$, $m_A - m_H \neq 0$

$\tau \to \mu\gamma$: large $\rho_{\tau\mu}$ $\to$ small ρ_{tt}

collider searches $\phi \to \tau\mu$ provide better probes

CMS JHEP 03, 103 (2020)



Muon (g-2): 2-loop with top coupling

in conflict with collider search $\phi \to \mu\mu$

CMS, PLB 798 (2019)
ATLAS, JHEP 07, 117 (2019)

WS Hou, R. Jain, C. Kao, GK, T. Modak, *in preparation*

Summary

We have explored cLFV phenomena in g2HDM.

Alignment plus mass-mixing hierarchy can explain why extra Yukawa effects are *well-hidden.*

Two-loop mechanism induced by ρ_{tt} , naturally $\mathcal{O}(1)$, can enhance cLFV processes easily.

There are potential prospects for $\tau \to \mu\gamma$ discovery at Belle-II, while $\mu \to e\gamma$ and $\mu N - eN$ are <u>also promising</u>.

Within g2HDM with our assumptions for extra Yukawa, LFV B-decays are unlikely to reach current sensitivity

Back-up

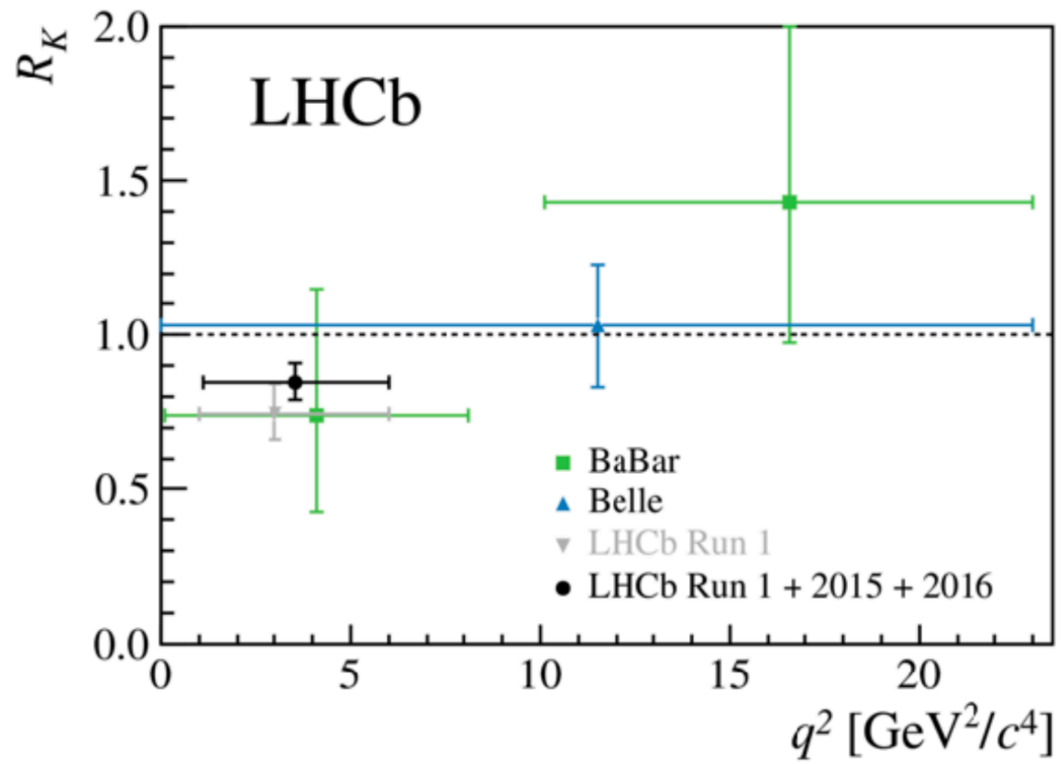
Scalar Potential

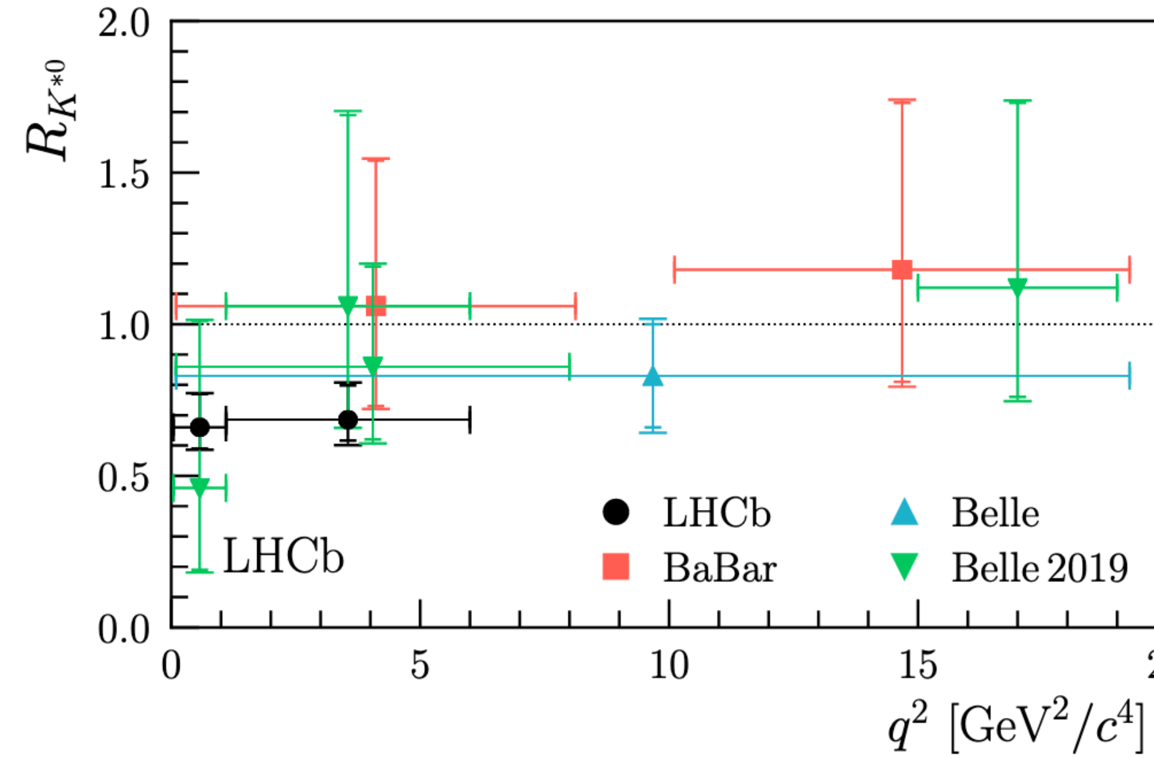
$$
\begin{aligned}
V(\Phi, \Phi') = {} & \mu_{11}^2 |\Phi|^2 + \mu_{22}^2 \left|\Phi'\right|^2 - \left(\mu_{12}^2 \Phi^\dagger \Phi' + \mathrm{h.c.}\right) \\
& + \frac{\eta_1}{2} |\Phi|^4 + \frac{\eta_2}{2} \left|\Phi'\right|^4 + \eta_3 |\Phi|^2 \left|\Phi'\right|^2 + \eta_4 \left|\Phi^\dagger \Phi'\right|^2 \\
& + \left\{ \frac{\eta_5}{2} \left(\Phi^\dagger \Phi'\right)^2 + \left[\eta_6 |\Phi|^2 + \eta_7 \left|\Phi'\right|^2\right] \Phi^\dagger \Phi' + \mathrm{h.c.} \right\}.
\end{aligned}
$$

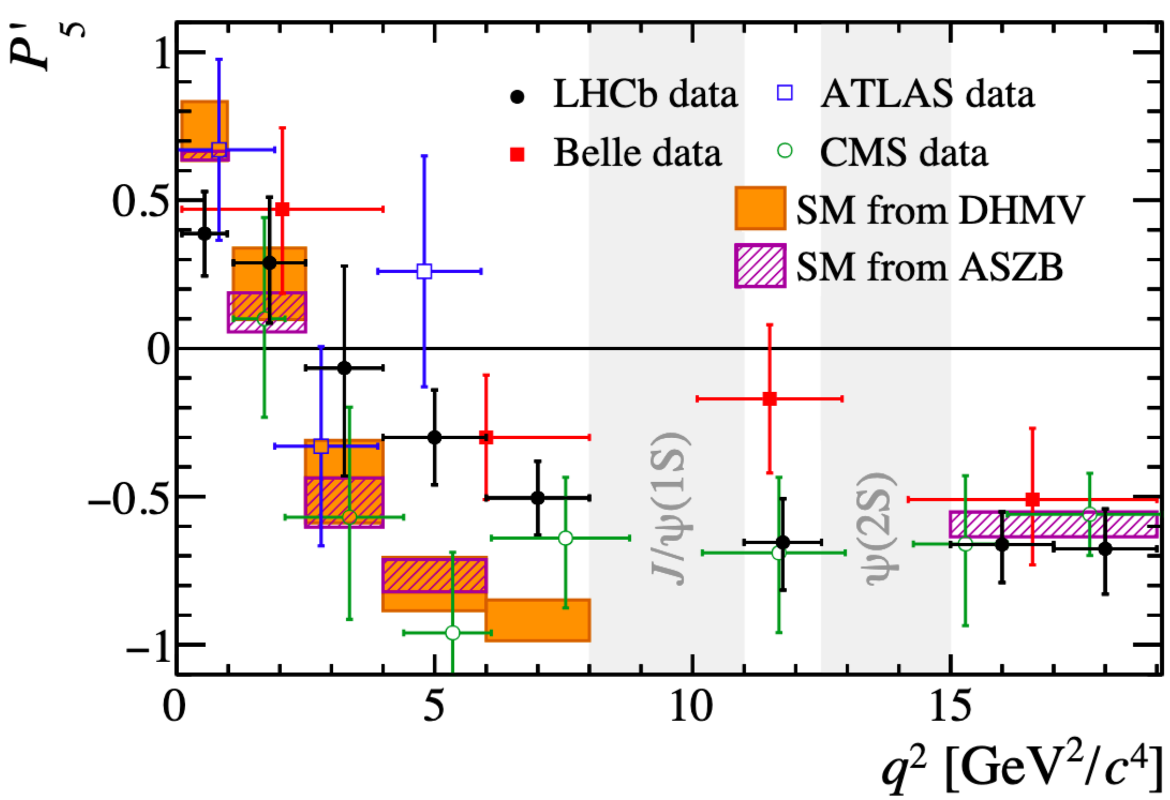
Relation between scalar masses and potential parameters

$$
\begin{aligned}
m_{H+}^2 &= \mu_{22}^2 + \frac{v^2}{2}\eta_3\,, \\
m_A^2 - m_{H+}^2 &= -\frac{v^2}{2}\left(\eta_5 - \eta_4\right)\,, \\
m_H^2 + m_h^2 - m_A^2 &= +\,v^2\left(\eta_1 + \eta_5\right)\,, \\
\left(m_H^2 - m_h^2\right)^2 &= \left[m_A^2 + \left(\eta_5 - \eta_1\right)v^2\right]^2 + 4\eta_6^2 v^4\,, \\
\sin(2\gamma) &= -\frac{2\eta_6 v^2}{m_H^2 - m_h^2}\,.
\end{aligned}
$$

$b \to s\ell\ell$ anomalies







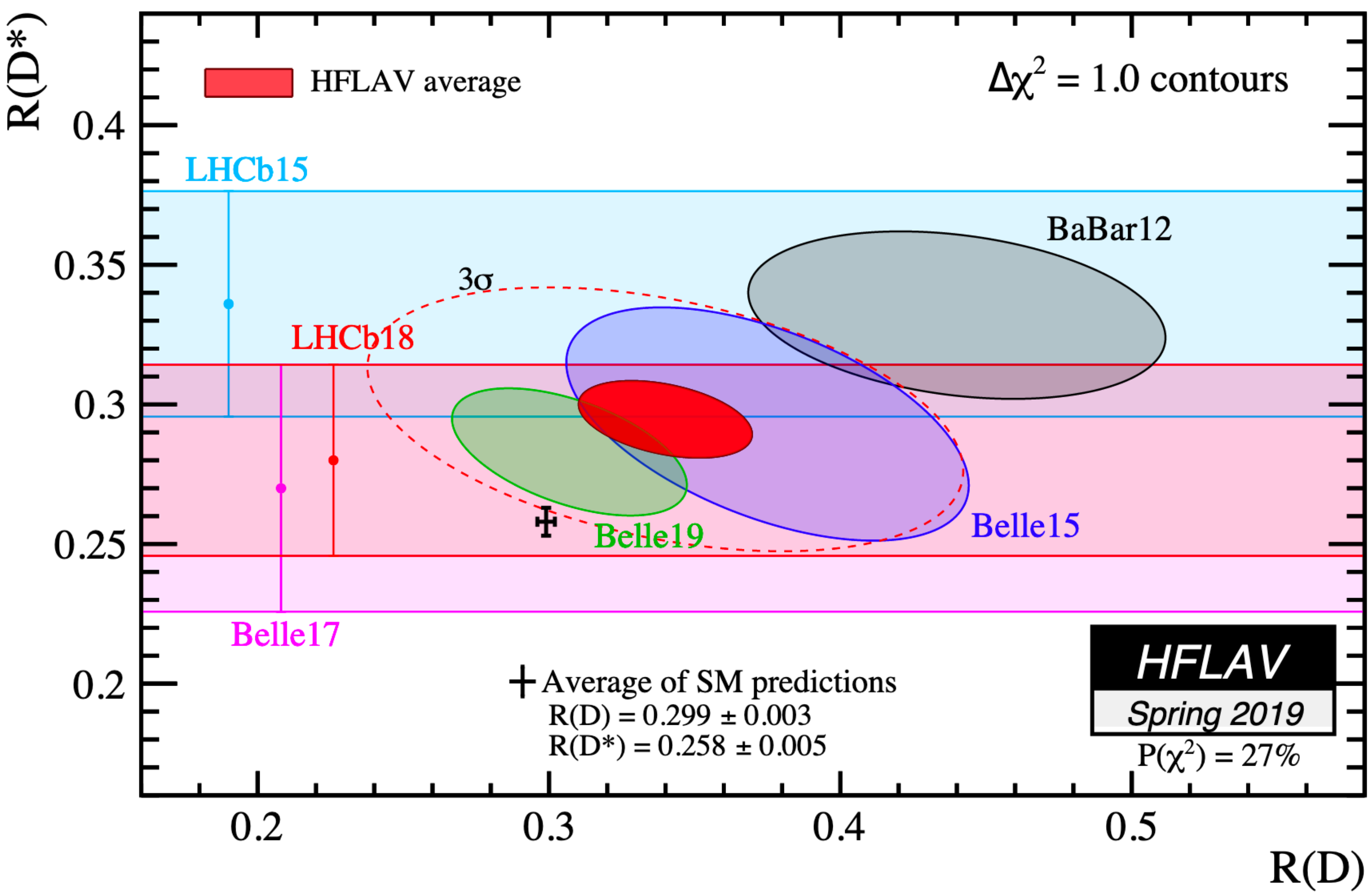
Lepton flavor universality violation

$$R_H = \frac{\mathscr{B}(B \to H\mu\mu)}{\mathscr{B}(B \to Hee)}, \qquad H = K, K^*$$

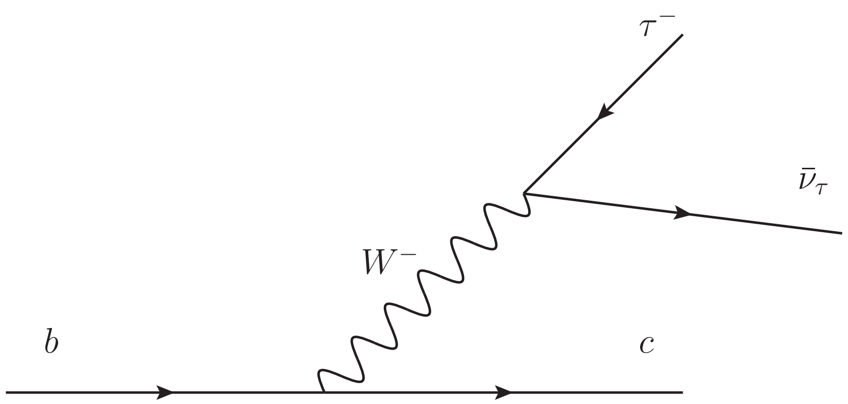
$\simeq 1 + \mathcal{O}(10^{-2})$ in the SM

P'_5 anomaly in $B \to K^*\mu\mu$ angular distribution

$b \to c\ell\nu$ anomalies



$$R_{D^{(*)}} = \frac{\mathrm{BR}\left(\bar{B} \to D^{(*)}\tau\bar{\nu}\right)}{\mathrm{BR}\left(\bar{B} \to D^{(*)}\ell\bar{\nu}\right)}$$



$$R^{\mathrm{Exp}}_{D^{(*)}} > R^{\mathrm{SM}}_{D^{(*)}}$$

Also, ~2σ deviation in $B_c^+ \to J/\psi\tau^+\nu$

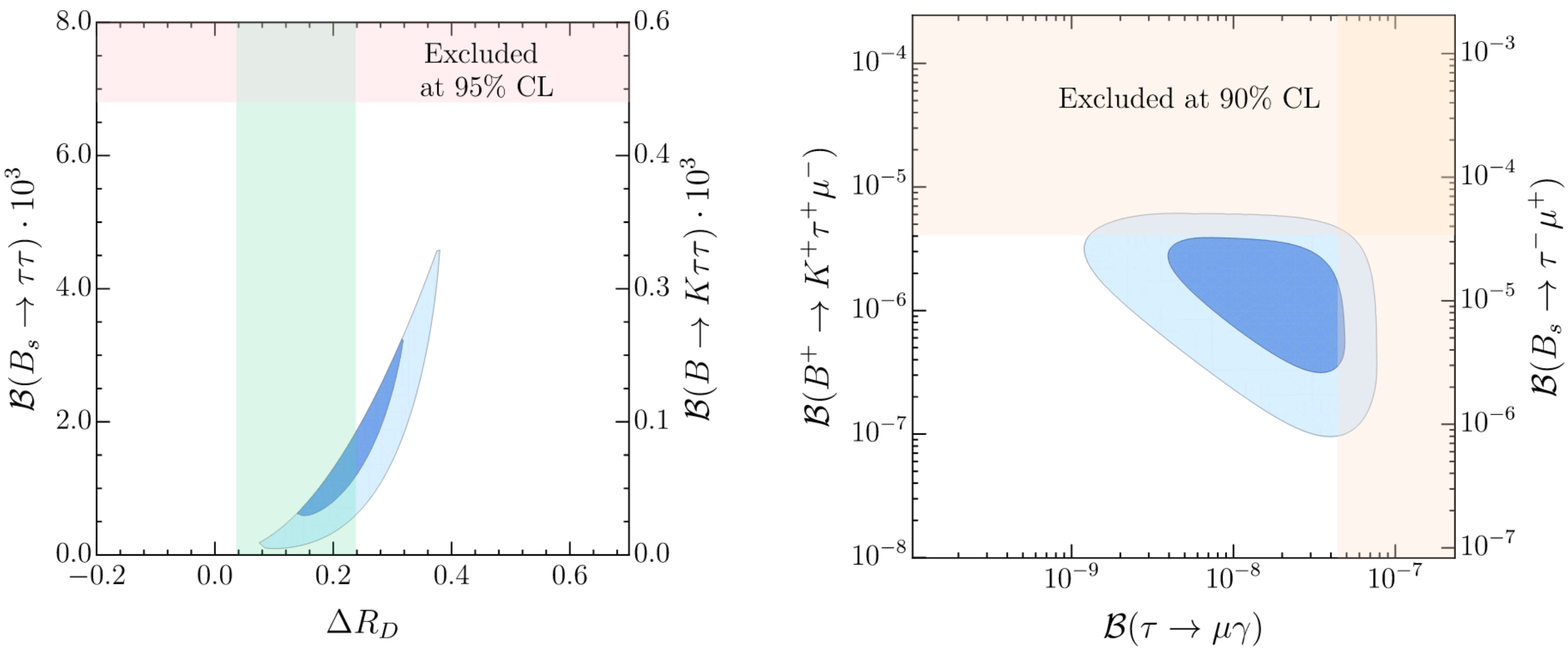
$R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ LHCb, PRL 120, 121801 (2018)

Lepton Flavor Violating signatures

Charged current anomalies prefers NP model favouring 3rd generation leptons; general prediction of large rates for $b \to s(d)\tau\tau$ modes

Popular NP models (eg. leptoquark models) also predict large rates for LFV B-decay such as $B_s \to \tau\mu$, $B \to K(K^*)\tau\mu$

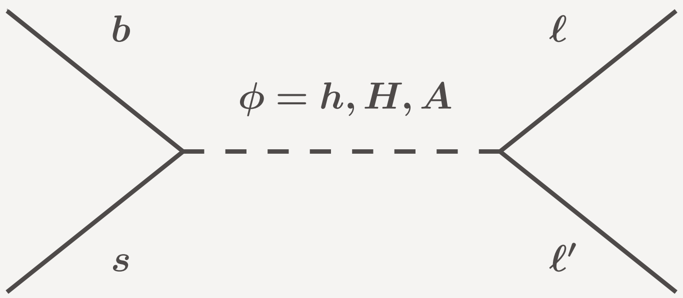
For example, see Cornella et al, *JHEP* 07 (2019) 168
Bordone et al , *JHEP* 10 (2018) 148



Current exp. bounds and future prospects

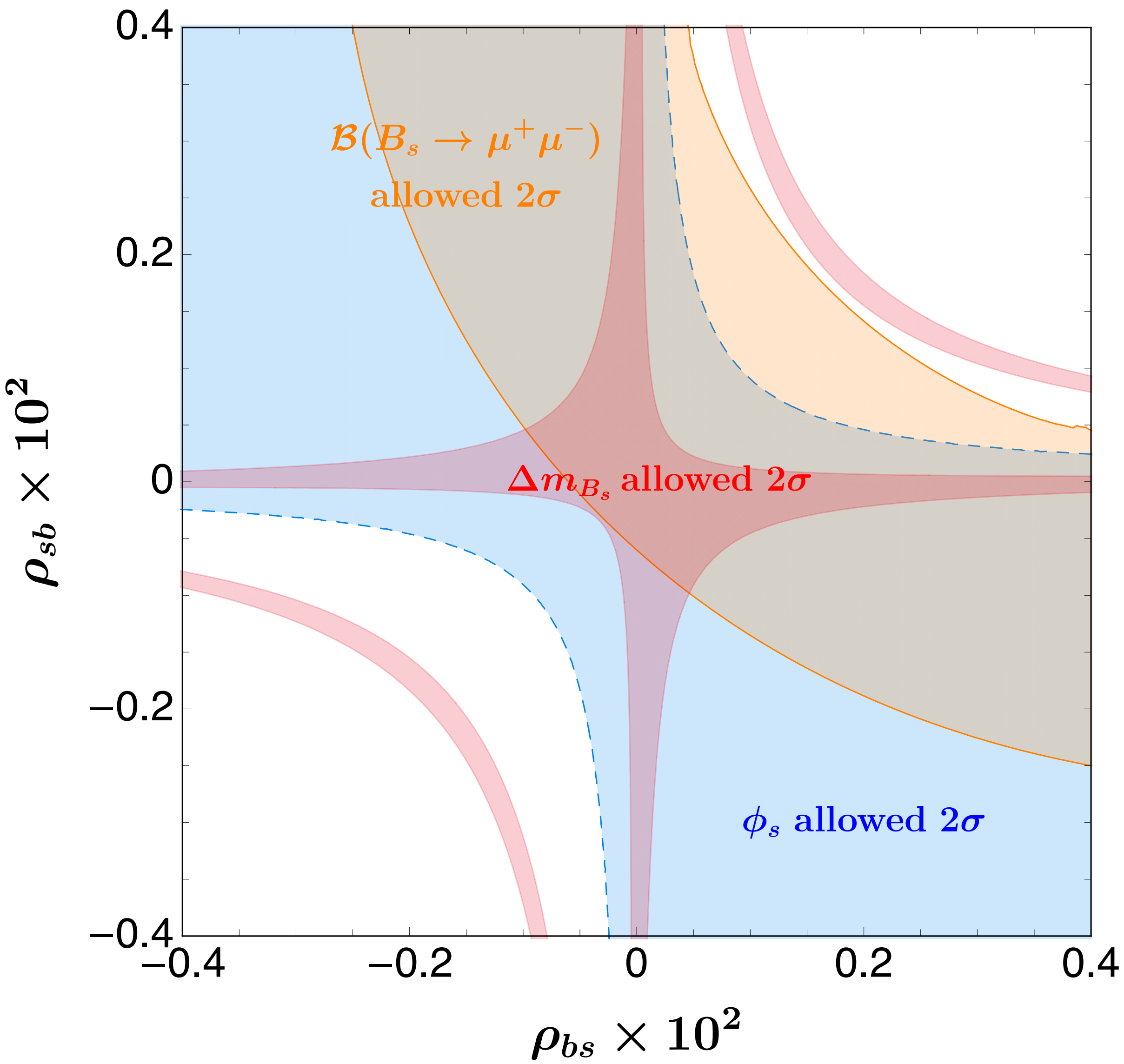
Decay Mode	Current bound	Future sensitivity
$B_s \to \tau\tau$	5.2×10^{-3} (LHCb)	$\sim 8 \times 10^{-4}$ (Belle II, $5\,\mathrm{ab}^{-1}$)
		$\sim 5 \times 10^{-4}$ (LHCb Phase II)
$B_d \to \tau\tau$	1.6×10^{-3} (LHCb)	$\sim 1 \times 10^{-4}$ (Belle II)
$B \to K\tau\tau$	2.3×10^{-3} (BaBar)	$\sim 2 \times 10^{-5}$ (Belle II)
$B_s \to \tau\mu$	3.4×10^{-5} (LHCb)	[Not yet publicized]
$B_d \to \tau\mu$	1.2×10^{-5} (LHCb)	1.3×10^{-6} (Belle II))
		3×10^{-6} (LHCb Phase II)
$B \to K\tau\mu$	2.8×10^{-5} (BaBar)	$\sim 3 \times 10^{-6}$ (Belle II)
	3.9×10^{-5} (LHCb)	[LHCb competitive]
$B_s \to \mu e$	5.4×10^{-9} (LHCb)	3×10^{-10} (LHCb Phase II)
$B_d \to \mu e$	1.0×10^{-9} (LHCb)	9×10^{-11} (LHCb Phase II)
$B \to K\mu e$	6.4×10^{-9} (LHCb)	$\sim 6 \times 10^{-10}$ (LHCb Phase II)
$B_s \to \mu\mu$	$(3.0 \pm 0.4) \times 10^{-9}$ (PDG)	$\sim 4.4\%$ (LHCb (300 fb^{-1}))
$B_d \to \mu\mu$	$(1.1^{+1.4}_{-1.3}) \times 10^{-10}$	$\sim 9.4\%$ (LHCb (300 fb^{-1}))
$B \to \tau\nu$	$(1.1 \pm 0.2) \times 10^{-4}$ (PDG)	$\sim 5\%$ (Belle II)
$B \to \mu\nu$	$(5.3 \pm 2.2) \times 10^{-7}$ (Belle)	$\sim 7\%$ (stat) (Belle II)

$B_s \to (K, K^*)\ell\ell'$ decays

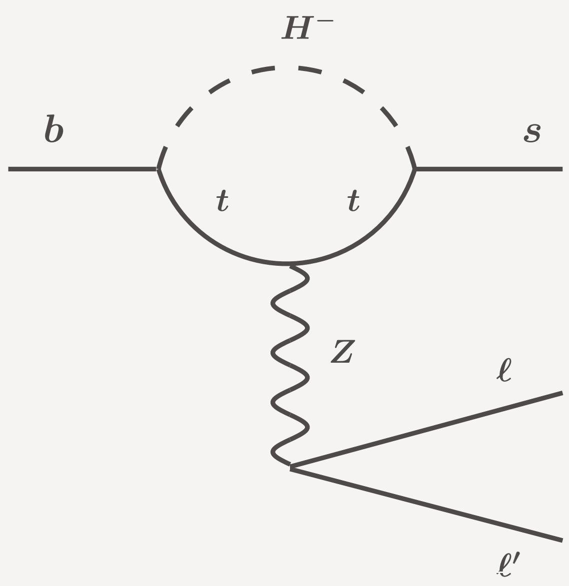


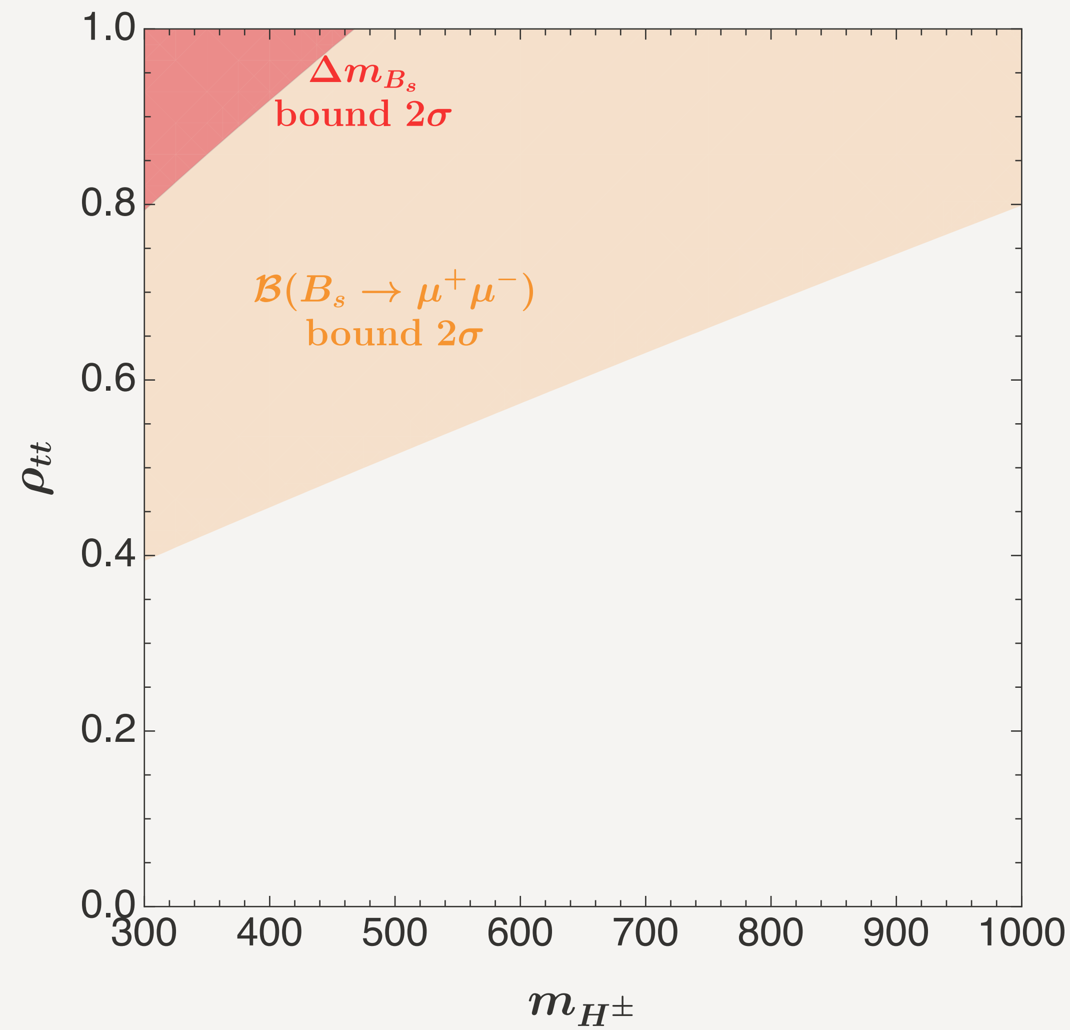
- involves ρ_{bs}, ρ_{sb}, and $\rho_{\ell\ell'}$

strong bounds from $B_s - \bar{B}_s$ mixing

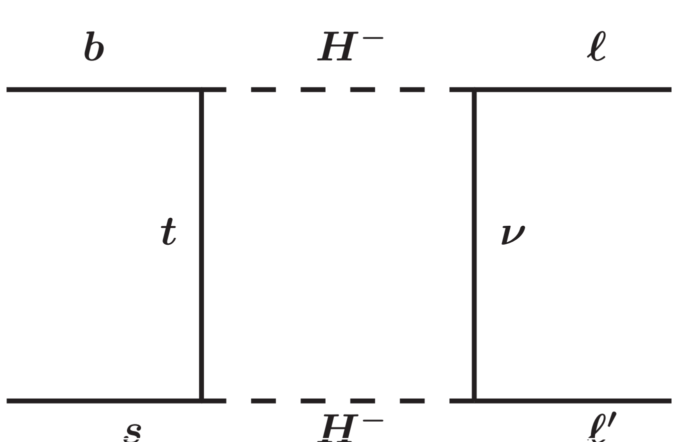


$B_s \to (K, K^*)\ell\ell'$ decays





- depends on up-type extra Yukawas
- puts stringent bounds on ρ_{tt}
- only **flavor conserved contribution**



- suppressed contribution due to small $\rho_{\ell\ell'}$

(Higgs penguins not shown)

$B_{s,d} - \bar{B}_{s,d}$ mixing