New Physics in Lepton Flavor Violating Higgs Decays

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SCALARS 2015

03-07 December 2015
Warsaw, Poland

Outline

- Motivation
  - establish connection with LFV observables;
  - to search for viable scenarios;
- Model independent approach;
- Extended scalar sector;
- Extended fermion sector;
- Summary.

(In collaboration with I. Doršner, A.Grelljo, J.F.Kamenik, N. Košnik and I. Nišandžić , arXiv: 1502.077)

Lepton flavour violating Higgs decays

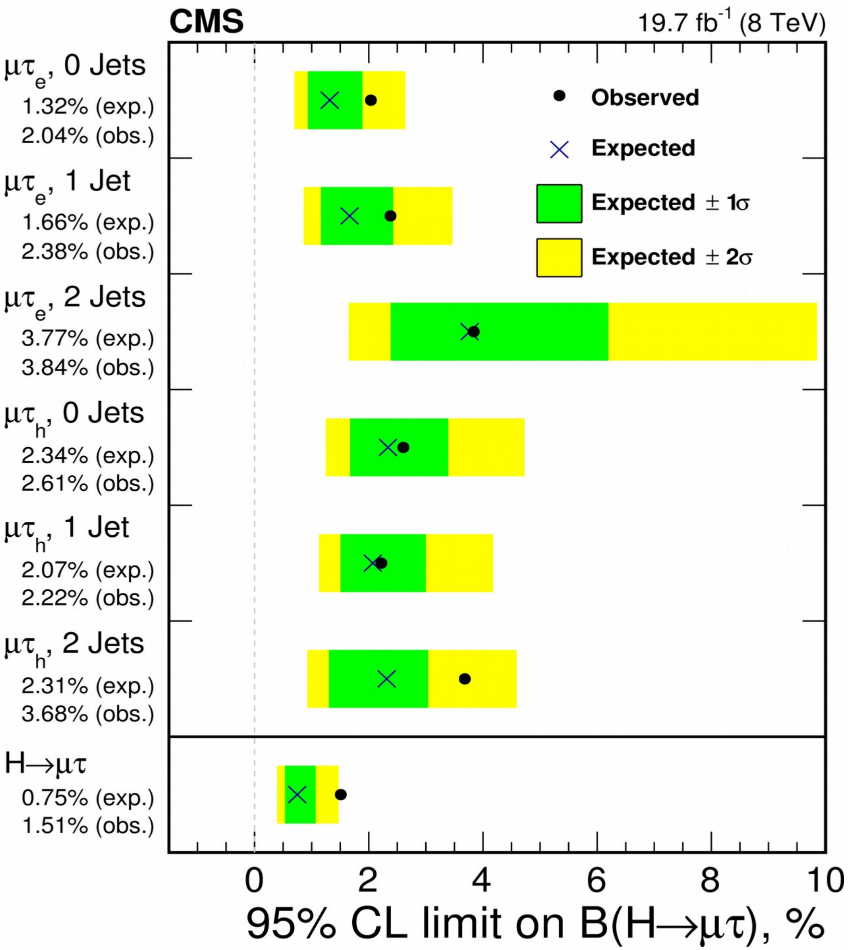
CMS result 2014:

$$BR(H \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$

2.4σ excess

ATLAS result 2015:

$$BR(H \to \tau\mu) = (0.77 \pm 0.62)\%$$



ATLAS arXiv:1508.03372

	SR1	SR2	Combined
Expected limit on $\mathrm{Br}(H \to \mu\tau)$ [%]	$1.60^{+0.64}_{-0.45}$	$1.75^{+0.71}_{-0.49}$	$1.24^{+0.50}_{-0.35}$
Observed limit on $\mathrm{Br}(H \to \mu\tau)$ [%]	1.55	3.51	1.85
Best fit $\mathrm{Br}(H \to \mu\tau)$ [%]	$-0.07^{+0.81}_{-0.86}$	$1.94^{+0.92}_{-0.89}$	0.77 ± 0.62

Naive average of ATLAS+CMS: B = 0.8 ± 0.3

from Landsberg @ SCALAR 2015

Model Independent approach

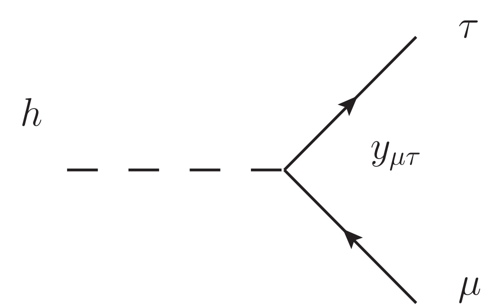
Assumption: SM contains all relevant degrees of freedom at energies few hundred GeV .

General parametrization of Higgs couplings to charged leptons after electroweak symmetry breaking:

$$\mathcal{L}_{Y_\ell}^{\mathrm{eff.}} = -m_i \delta_{ij} \bar{\ell}_L^i \ell_R^j - \boxed{y_{ij}} \left(\bar{\ell}_L^i \ell_R^j\right) h + \ldots + \mathrm{h.c.}$$

$$y_{ij}^{SM} = \delta_{ij} \frac{m_i}{v}$$

source of LFV

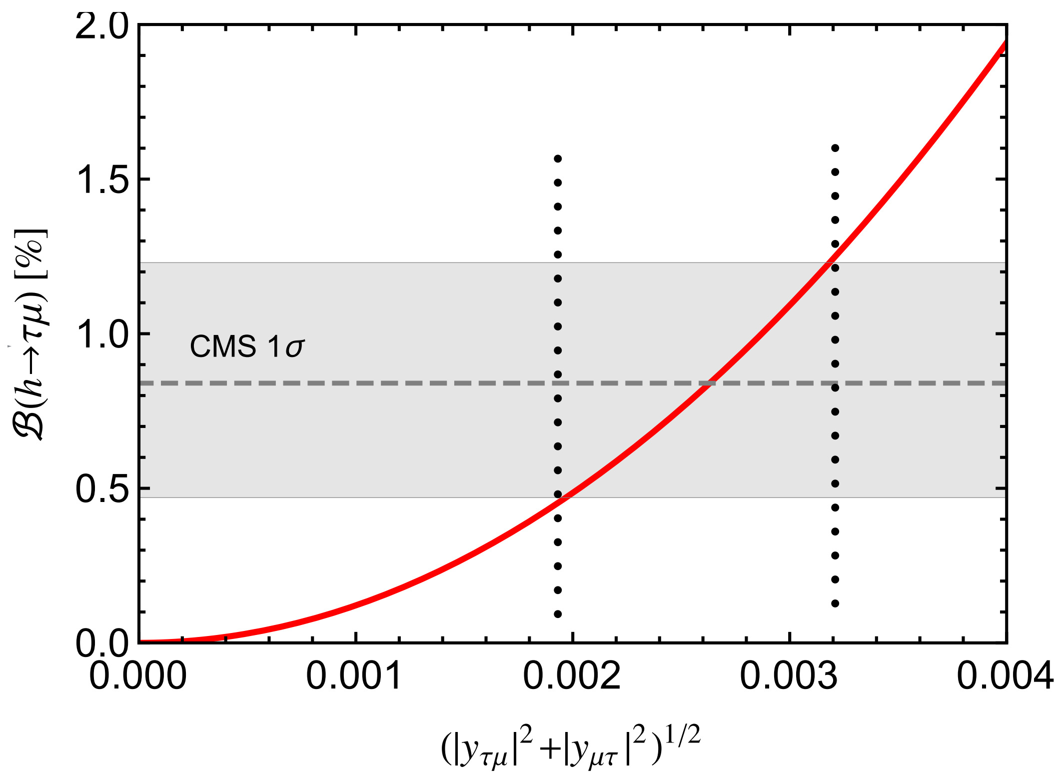


$$\mathcal{B}(h \to \tau\mu) = \frac{m_h}{8\pi\Gamma_h} \left(|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2\right)$$

$$\Gamma_h = \Gamma_h^{\mathrm{SM}} / [1 - \mathcal{B}(h \to \tau\mu)]$$

Experimentally measured $H \to \mu\tau$ event does not depend only on $y_{\tau\mu}$, $y_{\mu\tau}$ couplings, but also on couplings contributing to total Higgs decay width and production cross section.

If NP enters only in $H \to \tau\mu$



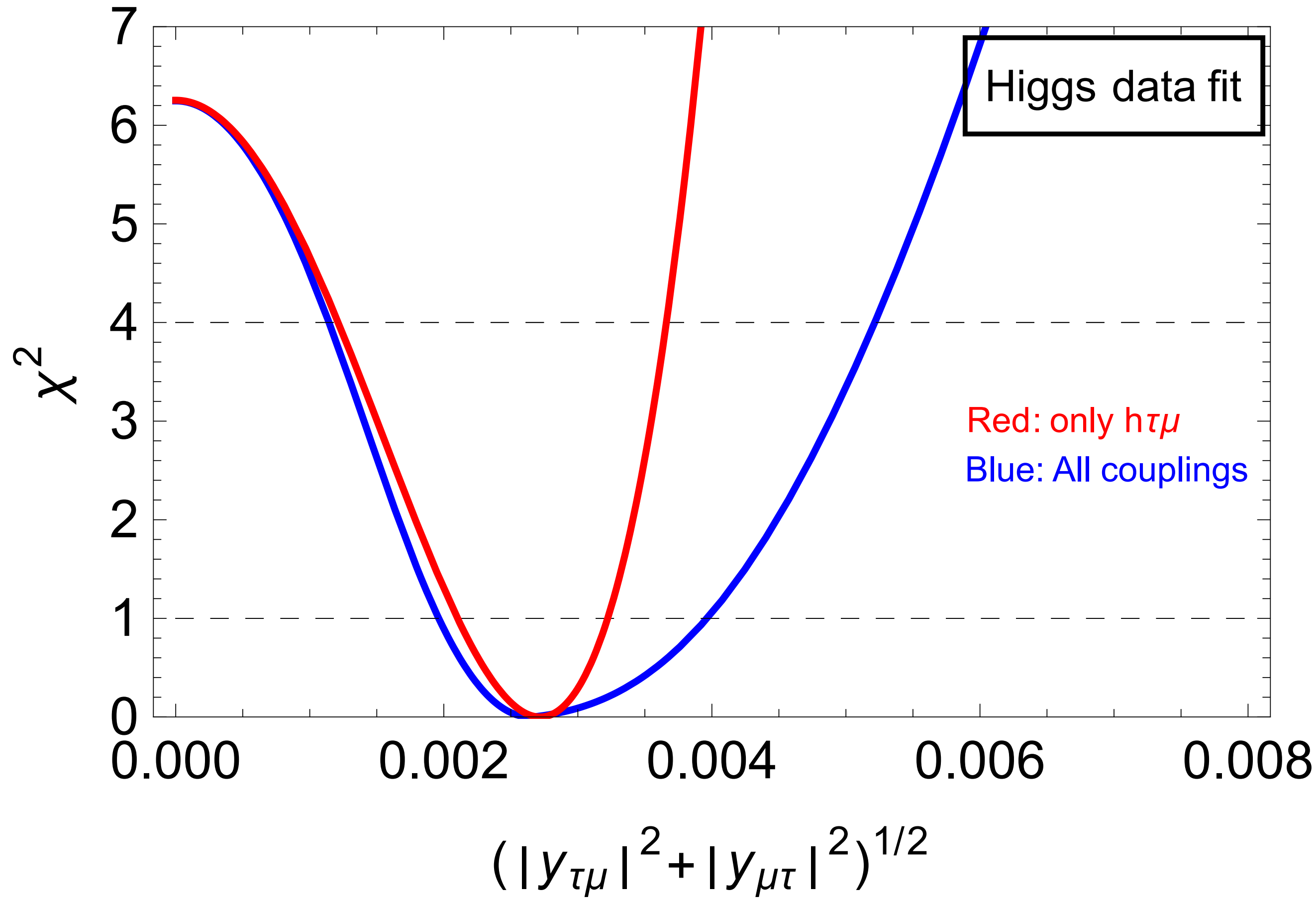
$$0.0019(0.0008) < \sqrt{|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2} < 0.0032(0.0036) \text{ at } 68\% \ (95\%) \text{ C.L.}$$

Testing robustness of the lower bound on LFV Yukawa couplings allowing for non-SM production and total decay rate

$$N_{h\to\tau\mu} \sim \sigma_h \frac{\Gamma_{h\to\tau\mu}}{\Gamma_h}$$

Decay channel	Production mode	Signal strength
		CMS
$h \to b\bar{b}$	VH	1.0 ± 0.5
	VBF	0.7 ± 1.4
	ttH	1.0 ± 2.0
$h \to WW^*$	ggF+ttH	0.76 ± 0.23
	VBF+VH	0.74 ± 0.62
$h \to ZZ^*$	ggF+ttH	0.90 ± 0.45
	VBF+VH	1.7 ± 2.3
$h \to \gamma\gamma$	ggF+ttH	0.50 ± 0.41
	VBF+VH	1.64 ± 0.88
$h \to \tau\tau$	0-jet	0.34 ± 1.09
	1-jet	1.07 ± 0.46
	2-jet (VBF-tag)	0.94 ± 0.41
	VH-tag	-0.33 ± 1.02
$\mathcal{B}(h \to \tau\mu)$ [%]	0-jet	0.77 ± 0.55
	1-jet	0.59 ± 0.62
	2-jet	1.1 ± 0.80
$h \to$ invisible	VBF+VH	0.14 ± 0.22
$h \to Z\gamma$	inclusive	0.0 ± 4.8
$h \to \mu\mu$	inclusive	2.9 ± 2.8

Decay channel	Production mode	Signal strength
		ATLAS
$h \to b\bar{b}$	VH	0.2 ± 0.65
$h \to ZZ^*$	ggF+ttH	1.8 ± 0.65
	VBF+VH	-0.2 ± 3.7
$h \to WW^*$	ggF+ttH	0.82 ± 0.37
	VBF+VH	1.74 ± 0.80
$h \to \gamma\gamma$	ggF+ttH	1.61 ± 0.41
	VBF+VH	1.87 ± 0.80
$h \to \tau\tau$	ggF+ttH	1.5 ± 1.6
	VBF+VH	1.7 ± 0.84
$h \to$ invisible	VH	0.13 ± 0.31
$h \to Z\gamma$	inclusive	2.0 ± 4.6
$h \to \mu\mu$	inclusive	1.6 ± 4.2



robust lower bound!

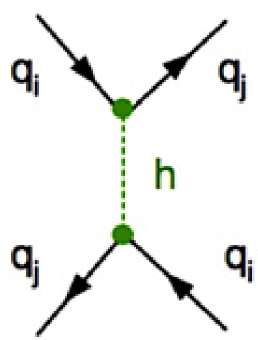
$$0.0017(0.0007) < \sqrt{|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2} < 0.0036(0.0047) \text{ at } 68\% \ (95\%) \text{ C.L}$$

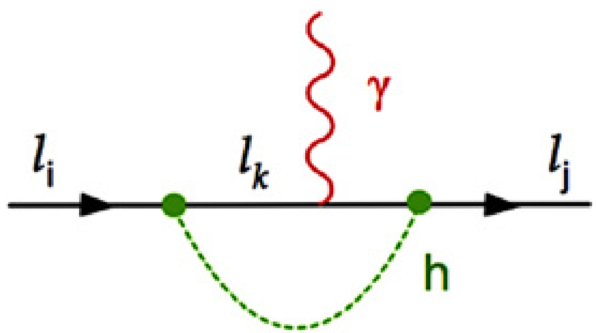
Main goal of our study: to interpret these bounds in terms of NP!

Flavor violating Higgs decays

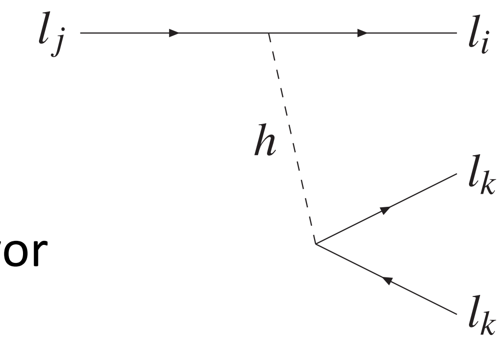
$$\mathcal{L}_{\rm eff} = \sum_{i,j=d,s,b\ (i\neq j)} c_{ij}\bar{d}^i_L d^j_R h + \sum_{i,j=u,c,t\ (i\neq j)} c_{ij}\bar{u}^i_L u^j_R h + \sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\bar{\ell}^i_L \ell^j_R h + \text{H.c.}$$

Harnik, Kopp, Zupan, 1209.1397;
Goudelis, Lebedeev, Park, 1111.1715;
Blankenburg, Ellis, Isidori, 1202.5704.





In the quark sector strong bounds come from ΔF=2 sector.



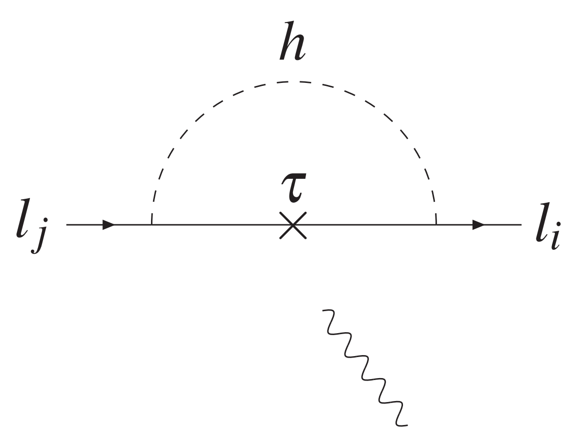
In the lepton sector no analog of ΔF=2 transitions.

Higgs coupling to tree level decays of charged: lepton flavor violating (LFV) decays and μ-e conversion in nuclei;

One-loop induced amplitudes:

a) Logarithmically divergent corrections to the lepton masses;
b) Finite contributions to the anomalous magnetic moments and the electric dipole moments of charged leptons;
c) Finite contributions to LFV processes

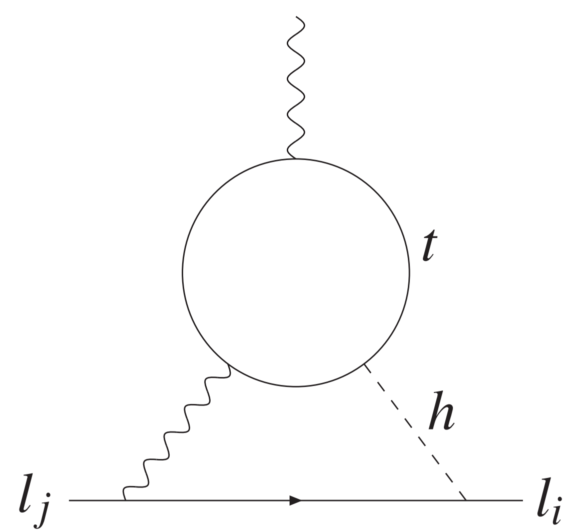
$$l_i \to l_j \gamma$$



Eff. couplings	Bound	Constraint
$\lvert c_{e\tau}c_{\tau e}\rvert$ ($\lvert c_{e\mu}c_{\mu e}\rvert$)	1.1×10^{-2} (1.8×10^{-1})	$\lvert\delta m_e\rvert < m_e$
$\lvert\mathrm{Re}(c_{e\tau}c_{\tau e})\rvert$ ($\lvert\mathrm{Re}(c_{e\mu}c_{\mu e})\rvert$)	0.6×10^{-3} (0.6×10^{-2})	$\lvert\delta a_e\rvert < 6\times10^{-12}$
$\lvert\mathrm{Im}(c_{e\tau}c_{\tau e})\rvert$ ($\lvert\mathrm{Im}(c_{e\mu}c_{\mu e})\rvert$)	0.8×10^{-8} (0.8×10^{-7})	$\lvert d_e\rvert < 1.6\times10^{-27}\,e\,\mathrm{cm}$
$\lvert c_{\mu\tau}c_{\tau\mu}\rvert$	2	$\lvert\delta m_\mu\rvert < m_\mu$
$\lvert\mathrm{Re}(c_{\mu\tau}c_{\tau\mu})\rvert$	2×10^{-3}	$\lvert\delta a_\mu\rvert < 4\times10^{-9}$
$\lvert\mathrm{Im}(c_{\mu\tau}c_{\tau\mu})\rvert$	0.6	$\lvert d_\mu\rvert < 1.2\times10^{-19}\,e\,\mathrm{cm}$
$\lvert c_{e\tau}c_{\tau\mu}\rvert$, $\lvert c_{\tau e}c_{\mu\tau}\rvert$	1.7×10^{-7}	$\mathcal{B}(\mu\to e\gamma) < 2.4\times10^{-12}$
$\lvert c_{\mu\tau}\rvert^2$, $\lvert c_{\tau\mu}\rvert^2$	0.9×10^{-2} [*]	$\mathcal{B}(\tau\to\mu\gamma) < 4.4\times10^{-8}$
$\lvert c_{e\tau}\rvert^2$, $\lvert c_{\tau e}\rvert^2$	0.6×10^{-2} [*]	$\mathcal{B}(\tau\to e\gamma) < 3.3\times10^{-8}$

Blankenburg, Ellis, Isidori, 1202.5704

Interesting: Barr-Zee two-loops, with top-quark in the loop, can be important (Davidson, Granier, 1001.0434, Goudelis, Lebedevs, Park, 1111.1715).



Effective Lagrangian approach

Integrating out heavy Higgses, fermions, scalars, keeping terms up to dimension 6:

(Harnik, Kopp, Zupan, 1209.1397)

$$\mathcal{L}_{Y_\ell} = -\lambda^{\alpha}_{ij}\bar{L}_i H_\alpha E_j - \lambda'^{\alpha\beta\gamma}_{ij}\frac{1}{\Lambda^2}\bar{L}_i H_\alpha E_j (H^\dagger_\beta H_\gamma) + \text{h.c.}$$

multiple Higgses $H_\alpha = (h^+_\alpha, v_\alpha + x_\alpha h + \ldots)^T$

Electroweak precision tests constrain $\sum_\alpha v_\alpha^2 \sim v^2/2$ $\sum_\alpha |x_\alpha|^2 \sim 1/2$

Dimension 6 creates mismatch between masses and Yukawa matrices:

$$y_{ij} = \frac{m_i}{v}\delta_{ij} + \epsilon_{ij} \qquad \frac{m}{v} = V_L\left(\lambda^\alpha \bar{v}_\alpha + \lambda'^{\alpha\beta\gamma}\frac{v^2}{\Lambda^2}\bar{v}_\alpha\bar{v}_\beta\bar{v}_\gamma\right)V_R^\dagger$$

$$\boxed{\epsilon = V_L \left[\lambda^{\alpha}\bar{v}_{\alpha}\left(\frac{x_{\alpha}}{\bar{v}_{\alpha}} - 1\right) + \lambda'^{\alpha\beta\gamma}\frac{v^2}{\Lambda^2}\bar{v}_{\alpha}\bar{v}_{\beta}\bar{v}_{\gamma}\left(\frac{x_{\alpha}}{\bar{v}_{\alpha}} + \frac{x_{\beta}}{\bar{v}_{\beta}} + \frac{x_{\gamma}}{\bar{v}_{\gamma}} - 1\right)\right] V_R^{\dagger}}$$

Two possible sources of non-vanishing $y_{\tau\mu}$ and $y_{\mu\tau}$ ($\bar{v}_{\alpha} = v_{\alpha}/v$)

a) If $x_{\alpha} \neq \bar{v}_{\alpha}$, first term isdifferent then 0 (NP possible bellow NP scale Two Higgs doublet model!)

In single Higgs theory, first term vanishes ($v_1 = v/\sqrt{2}$, $x_1 = 1/\sqrt{2}$)

b) If the first term vanishes, then LFV Higgs decay is due to second term.

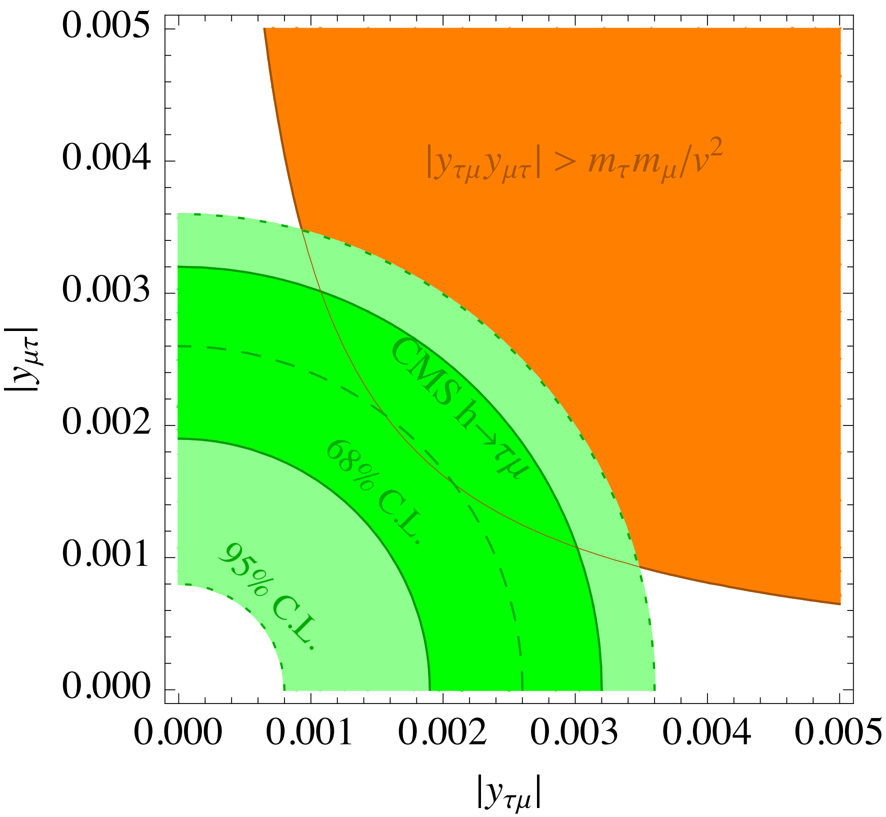
If only one Higgs, CMS result can be interpreted as giving bound on the NP scale

$$\boxed{\Lambda \simeq 4\ \mathrm{TeV}\left[\left(\frac{0.84\%}{\mathcal{B}(h\to\tau\mu)}\right)\left(|V_L\lambda'^{111}V_R^{\dagger}|^2_{\tau\mu} + |V_L\lambda'^{111}V_R^{\dagger}|^2_{\mu\tau}\right)\right]^{1/4}}$$

Hierarchy between τ and μ mass (Cheng- Sher anzatz)

$$\sqrt{|y_{\tau\mu}y_{\mu\tau}|} \lesssim \frac{\sqrt{m_\mu m_\tau}}{v} = 0.0018$$

(Cheng, Sher, PRD 35 ,3484, Branco et al, PR 516,1)



One more model independent constraints:
Operator of dim-6 will mix with the SM.
In single Higgs setup λ' will mix under charged lepton renormalisation!
Small effect - according to:
Jenkins et al., 1308.2627,
Jenkins et al.,1310.4838.

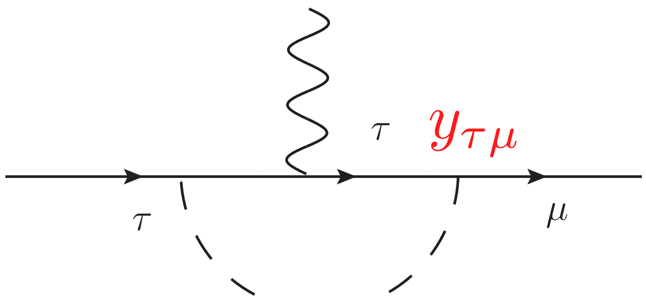
Constraints from τ radiative lepton flavor violating decays

Important for phenomenology: UV finite one and two-loop contributions to radiative LFV decays, anomalous muon magnetic moments, lepton dipole moments. The stringent constraint comes from τ LFV decays.

$$\mathcal{L}_{\text{eff.}} = c_L \mathcal{Q}_{L\gamma} + c_R \mathcal{Q}_{R\gamma} + \text{h.c.}$$

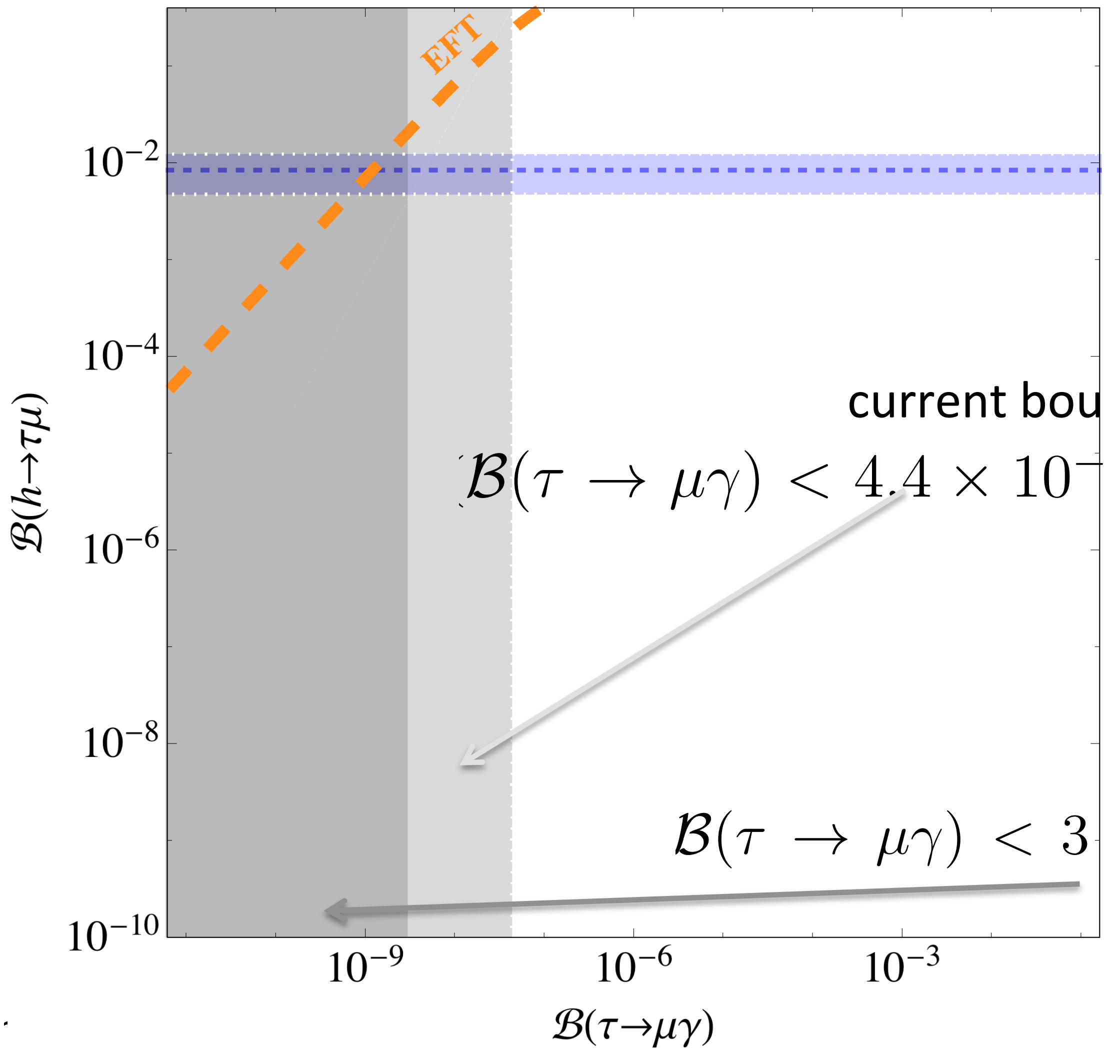
$$\mathcal{Q}_{L,R\gamma} = (e/8\pi^2) m_\tau (\bar{\mu}\sigma^{\alpha\beta} P_{L,R}\tau) F_{\alpha\beta}$$

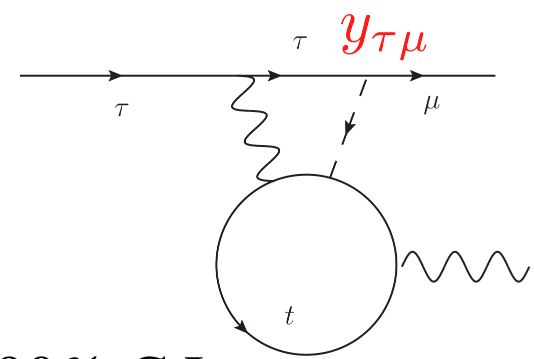
Harnik, Kopp, Zupan, 1209.1397;
Goudelis, Lebedeev, Park, 1111.1715;
Blankenburg, Ellis, Isidori, 1202.5704.



$$c_L^{(1-\text{loop})} \simeq \frac{1}{m_h^2} y^*_{\tau\mu} y_{\tau\tau} \left(-\frac{1}{3} + \frac{1}{4} \log \frac{m_h^2}{m_\tau^2} \right) \qquad c_R^{(1-\text{loop})} \simeq \frac{1}{m_h^2} y_{\mu\tau} y_{\tau\tau} \left(-\frac{1}{3} + \frac{1}{4} \log \frac{m_h^2}{m_\tau^2} \right)$$

$$c_L^{(2-\mathrm{loop})} \simeq \frac{1}{(125\,\mathrm{GeV})^2} y^*_{\tau\mu}(0.11 - 0.082 y_{tt}) \qquad c_R^{(2-\mathrm{loop})} \simeq \frac{1}{(125\,\mathrm{GeV})^2} y_{\mu\tau}(0.11 - 0.082 y_{tt})$$





current bound

$$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \text{ @ } 90\% \text{ C.L.}$$

comparable one- loop and Barr Zee contribution

$$\mathcal{B}(\tau \to \mu\gamma) < 3 \times 10^{-9} \text{ @ } 90\% \text{ C.L.}$$

projected bound for Bele II

Comment on LFV Higgs decay and τ radiative decay:

$L \sim (3,1),\ E \sim (1,3)$ under $\mathcal{G}_\ell \equiv SU(3)_L \times SU(3)_E \in \mathcal{G}_F$

$\bar{L}HE(H^\dagger H)$ dim-6 part of the Lagrangian transforms the same way as

$\bar{L}H(\sigma \cdot B)E$ and $\bar{L}\tau^a H(\sigma \cdot W_a)E$

If $\bar{L}HE(H^\dagger H)$ is generated at loop level, then in the loops are necessarily charged particles.

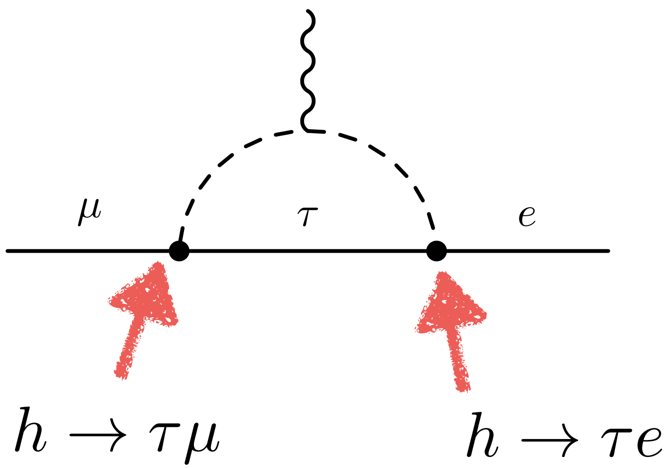
Therefore:

$$\boxed{c_{L,R} \sim 8\pi y_{\tau\mu,\mu\tau}/v m_\tau}$$

It implies that for $\mathcal{B}(h \to \tau\mu)$ ~ % level that $\mathcal{B}(\tau \to \mu\gamma)$ can be an order of magnitude bigger!

It means that an accidental cancellation should occur in the amplitude of the radiative decays (of the order 10^{-3})!

Additional correlation: $\mu \to e\gamma$ and μ – e conversion



assumption: $h_{\tau e}$ coupling is nonzero!

$$\mu \to e\gamma$$

$$\mu N \to eN$$

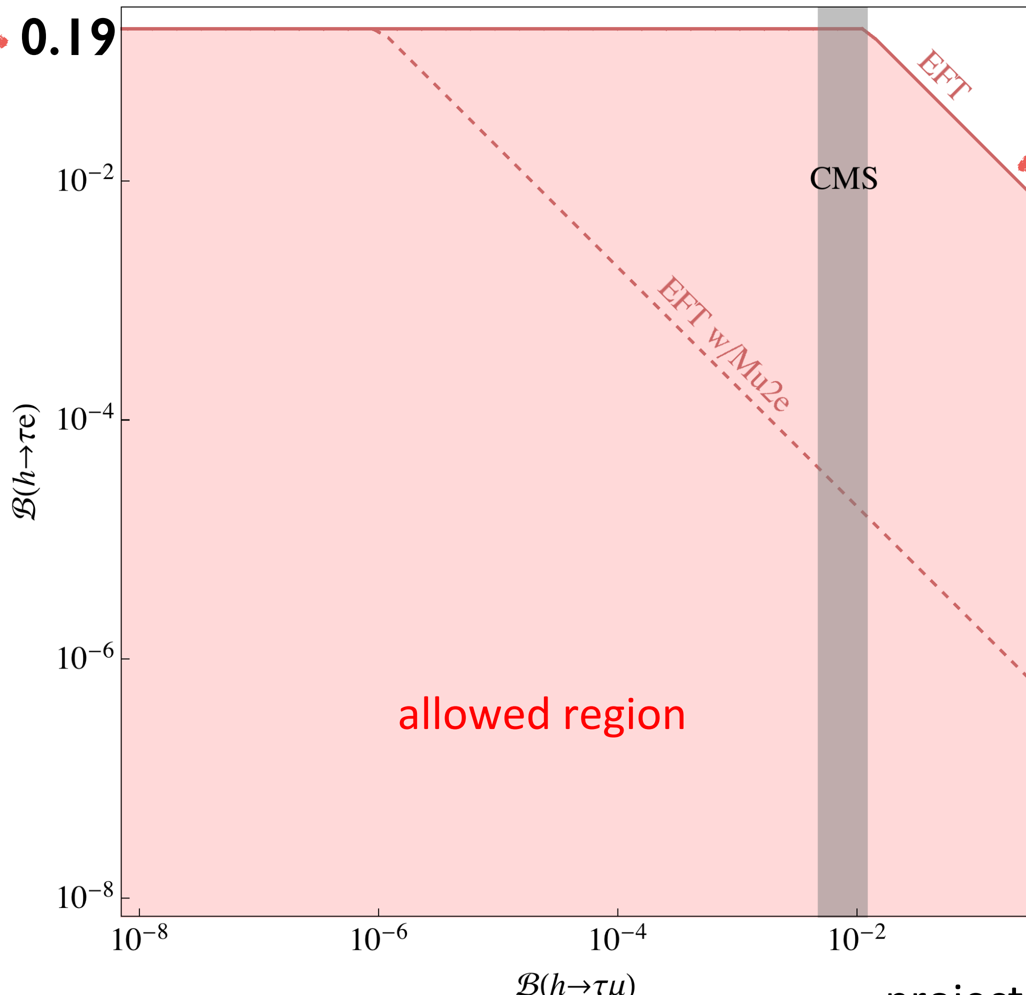
$$\mathcal{B}(\mu \to e\gamma) \simeq 185 \left(|y_{\mu\tau} y_{\tau e}|^2 + |y_{\tau\mu} y_{e\tau}|^2\right)$$

$$\mathcal{B}(\mu \to e)_{\mathrm{Au}} \simeq 4.67 \times 10^{-4} \left(|y_{e\tau} y_{\mu\tau}|^2 + |y_{\tau e} y_{\tau\mu}|^2\right)$$

$$\mathcal{B}(h \to \tau\mu) \times \mathcal{B}(h \to \tau e) = 7.95 \times 10^{-10} \left[\frac{\mathcal{B}(\mu \to e\gamma)}{10^{-13}}\right] + 3.15 \times 10^{-4} \left[\frac{\mathcal{B}(\mu \to e)_{\mathrm{Au}}}{10^{-13}}\right]$$

$\tau \to e\gamma$
$< 3.3\times10^{-8}$

0.19



BaBar, PRL104,021802, (2010)

SINDRUM II, μ e conversion on Au; EPJC 47,337 (2006)

projected Mu2e limit on μe < 6 x 10^{-17}

From symmetry point of view, LFV Higgs interactions:

$$L \sim (3,1),\ E \sim (1,3) \text{ under } \mathcal{G}_\ell \equiv SU(3)_L \times SU(3)_E \in \mathcal{G}_F.$$

In SM (without neutrino masses) Yukawa matrix $\lambda \sim (3,\bar{3})$ is the only source of $\mathcal{G}_\ell$ breaking.

At tree level there are only possibilities:

1) Extend scalar sector:
   - 2HDM type III;
   - Scalar leptoquarks;

2) Extend fermion sector: vector-like leptons;

3) LQ + vector-like up-quark (?).

Two Higgs Doublet Model-Type III

Framework

(e.g. Branco et al, PR 516,1;
Crivellin et al, PRD87, 094031)

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} , \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

5 physical scalar states:
H, H^0, $H^\pm$, A

$$\left\{\begin{aligned} H_u^0 &= \frac{1}{\sqrt{2}} \left(H^0 \sin\alpha + h^0 \cos\alpha + iA^0 \cos\beta\right) \\ H_d^0 &= \frac{1}{\sqrt{2}} \left(H^0 \cos\alpha - h^0 \sin\alpha + iA^0 \sin\beta\right) \\ H_u^1 &= H^+ \cos\beta \\ H_u^2 &= H^- \sin\beta \end{aligned}\right.$$

2 parametrers:
tanβ, m_A

$$\tan\beta = \frac{v_u}{v_d}, \quad \tan 2\alpha = \tan 2\beta \frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2} ,$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2 \quad m_H^2 = m_A^2 + m_Z^2 - m_h^2$$

Couplings to flavors

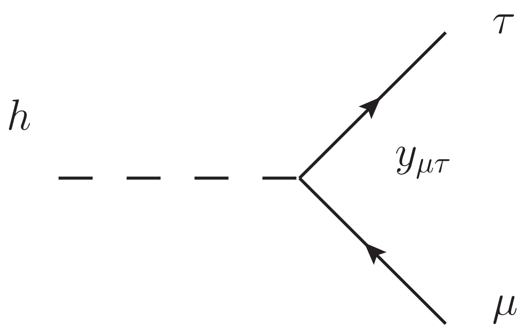
- No restriction on Higgs couplings to fermions;
- Tree level Higgs couplings:
  - charged and FCN transition in the quark sector (K, D, B, mixing and rare decays)
  - lepton flavor violation

$$\mathcal{L} = \frac{y_{fi}^{H_k}}{\sqrt{2}} H_k \bar{\ell}_{L,f} \ell_{R,i} + \frac{y_{fi}^{H^+}}{\sqrt{2}} H^+ \bar{\nu}_{L,f} \ell_{R,i} + \text{h.c.}$$

$$\boxed{y_{fi}^{H_k} = x_d^k \frac{m_{\ell_i}}{v_d} \delta_{fi} - \epsilon_{fi}^{\ell} \left(x_d^k \tan\beta - x_u^{k*} \right)}$$

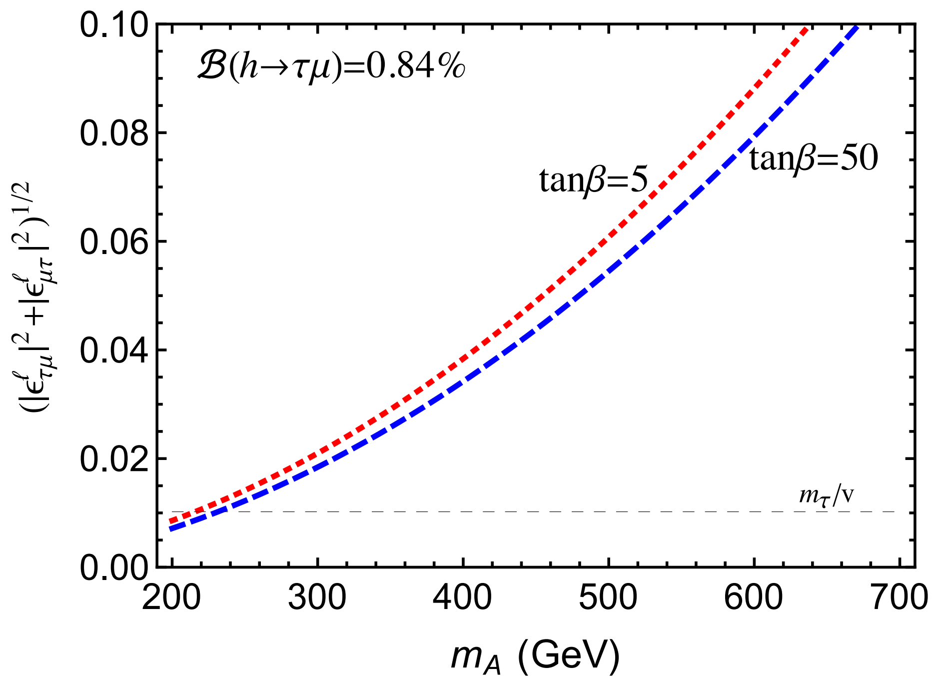
$$y_{fi}^{H^\pm} = \sqrt{2} \sum_{j=1}^{3} \sin\beta \, V_{fj}^{\text{PMNS}} \left(\frac{m_{\ell_i}}{v_d} \delta_{ji} - \epsilon_{ji}^{\ell} \tan\beta \right)$$

$H \to \mu\tau$



$$y_{\mu\tau\,(\tau\mu)} = \frac{\epsilon^{\ell}_{\mu\tau\,(\tau\mu)}}{\sqrt{2}} (\sin\alpha \tan\beta + \cos\alpha)$$

$$\mathcal{B}(h \to \tau\mu) = \frac{m_h}{16\pi\Gamma_h} (\sin\alpha \tan\beta + \cos\alpha)^2 \left(|\epsilon^{\ell}_{\mu\tau}|^2 + |\epsilon^{\ell}_{\tau\mu}|^2\right)$$

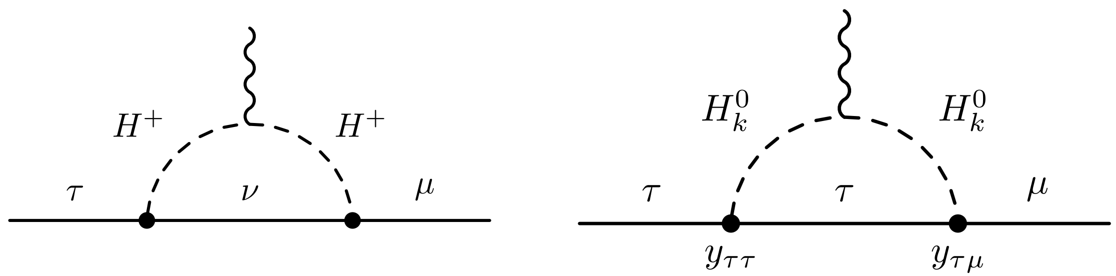


small dependence on large tan β

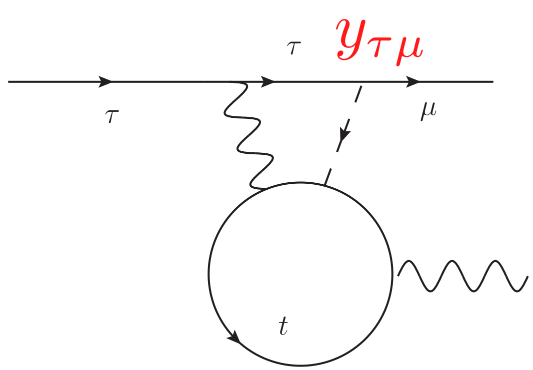
$$\sin\alpha \tan\beta + \cos\alpha \simeq -\frac{2m_Z^2}{m_A^2}$$

For large tan β, effect decouples
(large m_A).

Constraints from $\tau \to \mu\gamma$

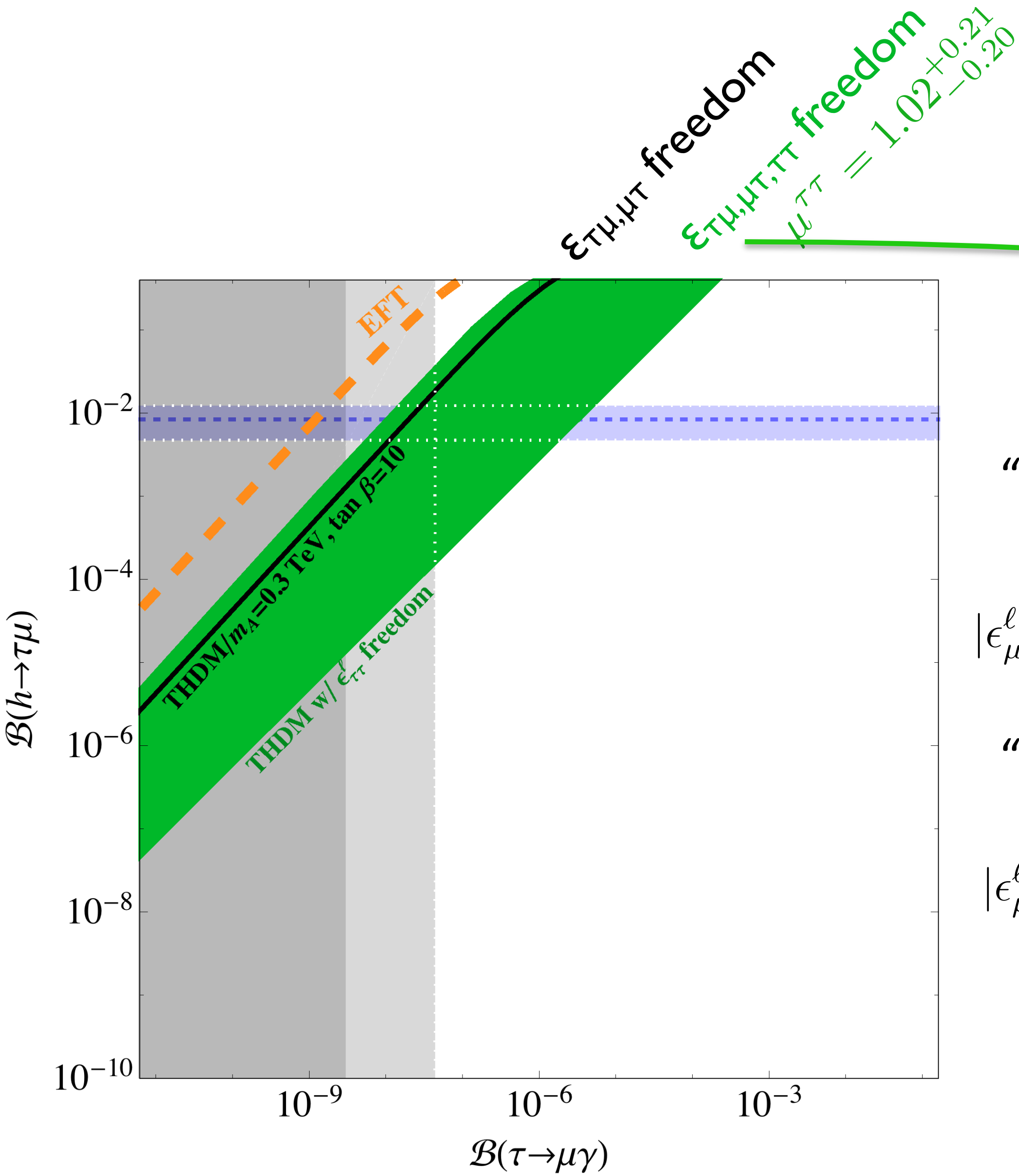


At one loop level amplitude is proportional to product of small Yukawa and LFV coupling.



Barr-Zee contribution dominant!

Chang et al., PRD48, 217



$\epsilon^\ell_{\tau\tau}$ from ATLAS + CMS data

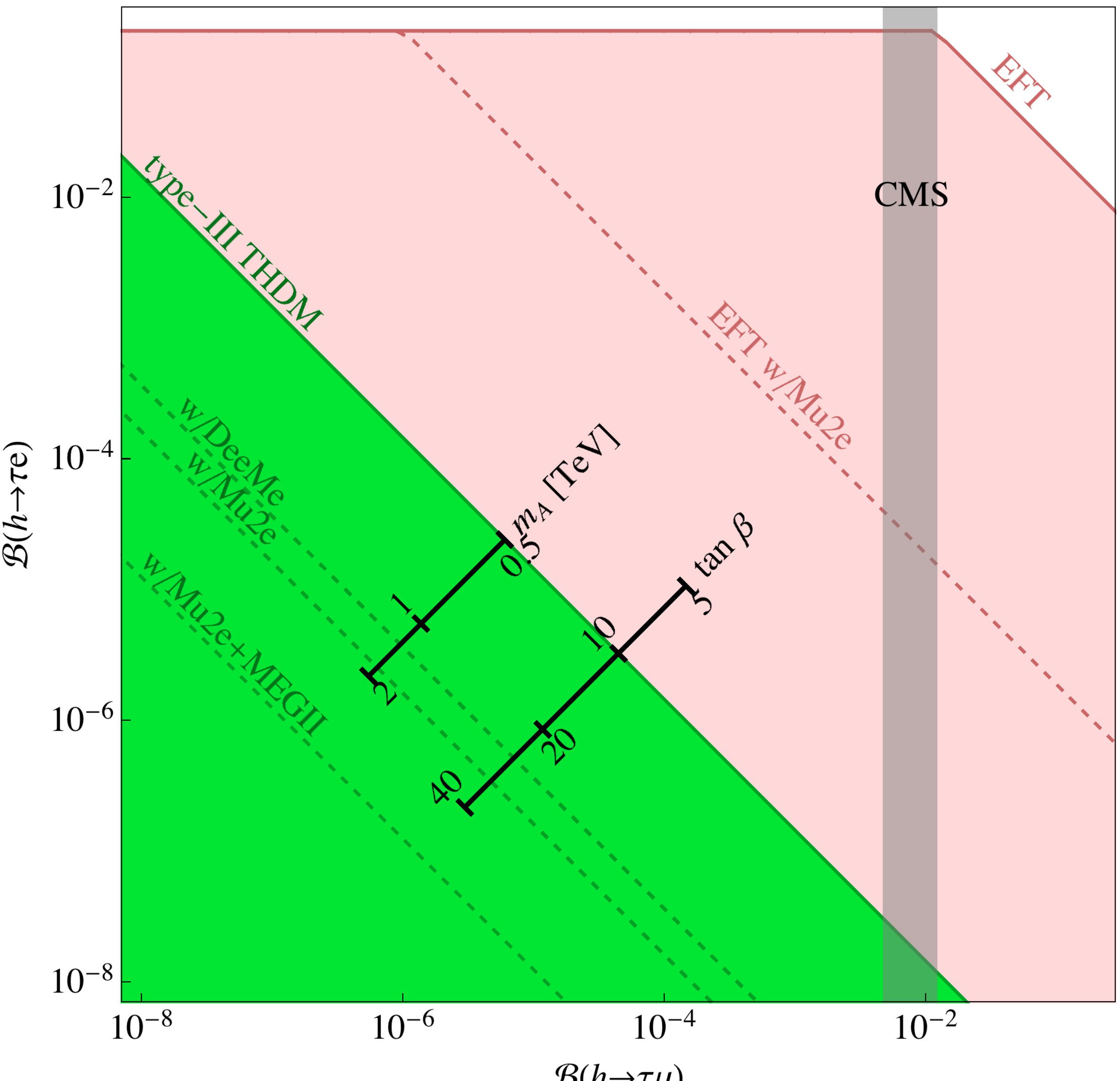
"naturalness" condition fulfilled:

$$|\epsilon^\ell_{\mu\tau}\epsilon^\ell_{\tau\mu}| < \frac{m_\mu m_\tau}{v^2/2}(\sin\alpha\tan\beta + \cos\alpha)^{-2}$$

"perturbativity" condition fulfilled:

$$|\epsilon^\ell_{\mu\tau,\tau\mu}| < \sqrt{4\pi}\,\sqrt{2}|\sin\alpha\tan\beta + \cos\alpha|^{-1}$$

works up to m_A~ 0.5 TeV



$$\mathcal{B}(h \to \tau e) < 6 \times 10^{-6}$$

(taking central value of $h \to \tau\mu$)

From SINDRUMII μ - e conversion on AU EPJC47,337;
and MEG 1303.0754

$$\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

Extended fermionic sector: vector-like leptons

Vector-like fermions appear in some GUT or in scenarios with compositeness

$$SU(3)_c \times SU(2)_L \times U(1)_Y \quad \begin{array}{l} (1,2)_{1/2} \oplus (1,2)_{-1/2} \\ (1,1)_1 \oplus (1,1)_{-1} \end{array}$$

either weak doublet (L) or singlet (E)

Higgs couplings to VL are directly related to Z boson couplings
(SF, Greljo, Kamenik, Mustac, arXiv:1304.4219)

$$\mathcal{L}^Z_{\mathrm{LFV}} = \frac{g}{2c_W}\left(X_{ij}\bar{\ell}^i_L\gamma^\mu\ell^j_L - Y_{ij}\bar{\ell}^i_R\gamma^\mu\ell^j_R\right)Z_\mu$$

$X_{\tau\mu,\mu\tau}, Y_{\tau\mu,\mu\tau} \lesssim 10^{-3}$ from $\tau \to \mu\mu\mu$

too small contribution to $H \to \tau\mu$

Direct couplings to the Higgs by mixing with heavy vector-like leptons

$$-\mathcal{L}_{VLL} = \lambda_\Psi \bar{\Psi}^E H (1-\gamma_5)\Psi^L + \tilde{\lambda}_\Psi \bar{\Psi}^E H (1+\gamma_5)\Psi^L$$

$$+ M_\Psi \left(\underbrace{\lambda_e \bar{E}\Psi^E + \lambda_l \bar{L}\Psi^L}_{\text{mixing terms}} + \underbrace{C_L \bar{\Psi}^L \Psi^L + C_R \bar{\Psi}^E \Psi^E}_{\text{Dirac mass terms}} \right) + \text{h.c.}$$

Flavor off-diagonal Higgs coupling

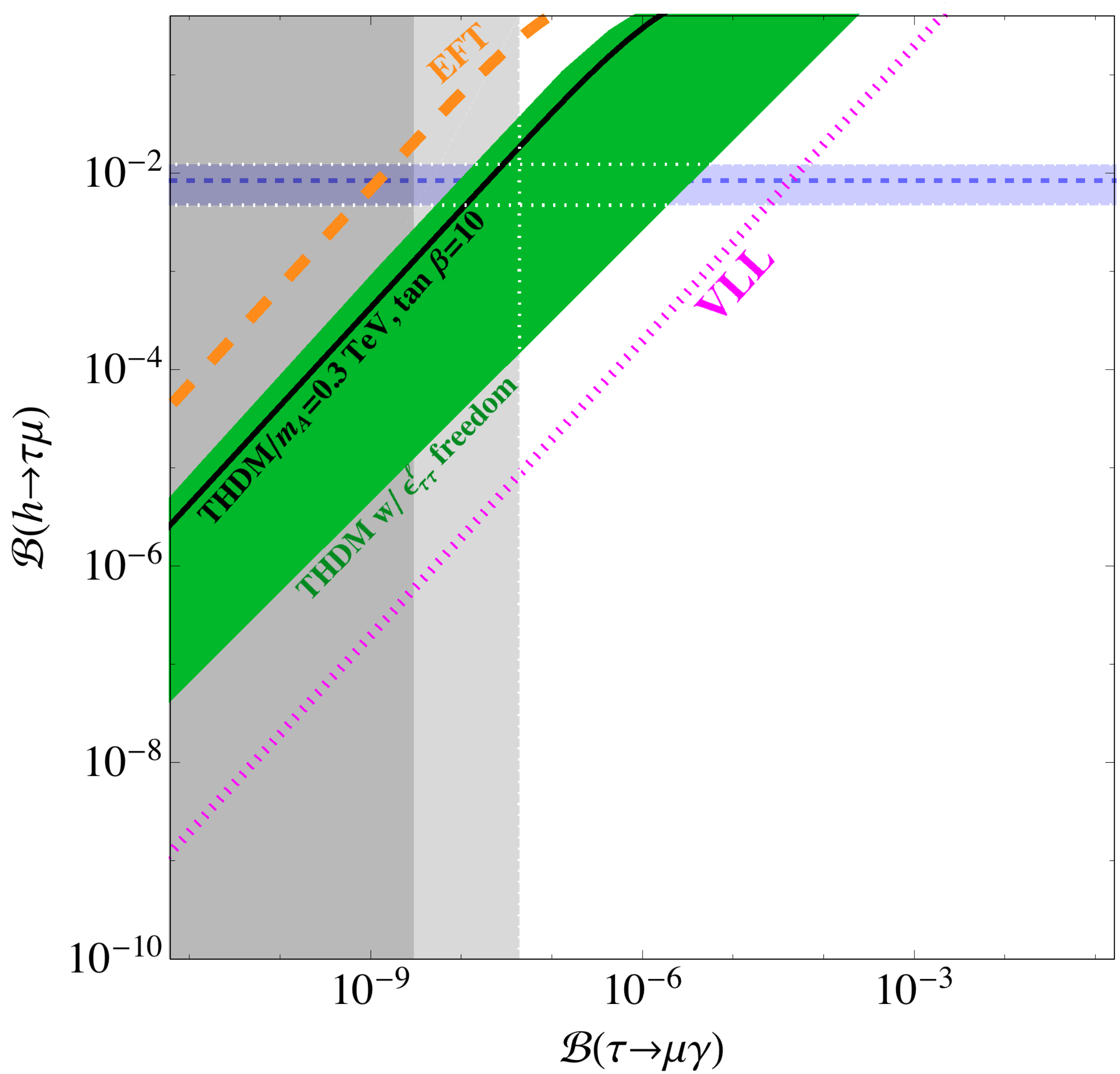
$$\epsilon = \frac{8v^2}{M_\Psi^2} \lambda_l C_L^{-1} \lambda_\Psi C_R^{-1} \tilde{\lambda}_\Psi C_L^{-1} \lambda_\Psi C_R^{-1} \lambda_e$$

Falkowski, Straub, Vicente,
1312.5329
SM leptons get masses only through mixing with VLL

tree level

$$\frac{\mathcal{B}(h \to \tau\mu)}{\mathcal{B}(\tau \to \mu\gamma)} = \frac{4\pi}{3\alpha} \frac{\mathcal{B}(h \to \tau^+\tau^-)_{\mathrm{SM}}}{\mathcal{B}(\tau \to \mu\bar{\nu}\nu)_{\mathrm{SM}}} \approx 2 \times 10^2$$

one-loop



EFT
THDM/m_A=0.3 TeV, tan β=10
THDM w/ $\epsilon^{\ell}_{\tau\tau}$ freedom
VLL
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-9}
10^{-6}
10^{-3}
$\mathcal{B}(h\to\tau\mu)$
$\mathcal{B}(\tau\to\mu\gamma)$

Scalar Leptoquarks

In B physics there are three puzzles:

1) $R_{D^{(*)}} = \dfrac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$ 3.5σ

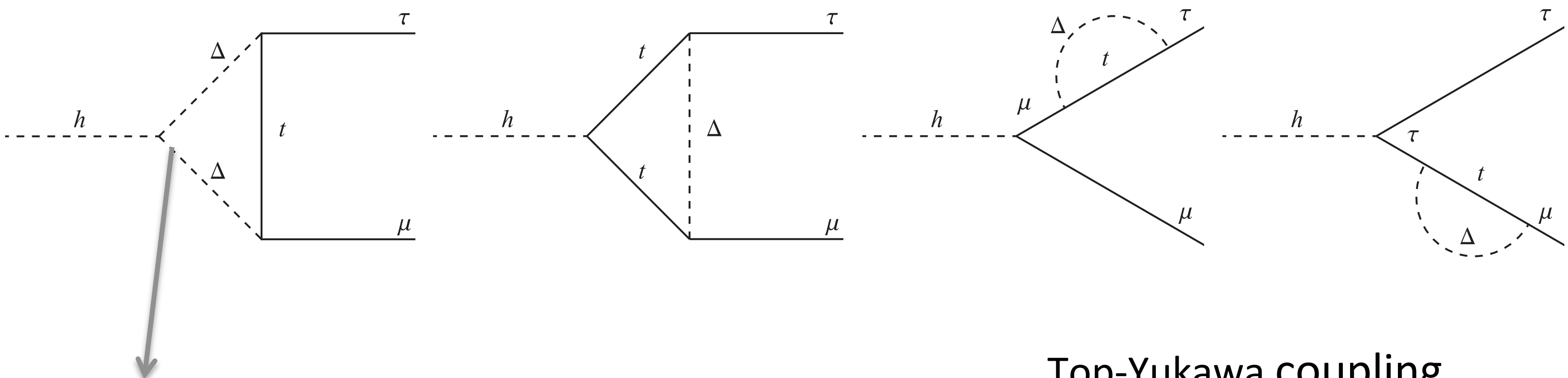
charged current

2) P_5' in $B \to K^* \mu^+ \mu^-$ 3σ

FCNC

3) $R_K = \dfrac{\Gamma(B \to K \mu\mu)}{\Gamma(B \to K ee)}$ in the dilepton invariant mass bin $1 \text{ GeV}^2 \leq q^2 \leq 6 \text{ GeV}^2$ 2.6σ

e.g. Bauer, Neubert. arXiv:1511.01900
Bečirević, SF, Košnik. arXiv:1503.09024
Hiller,Schmaltz. arXiv:1411.4773
Freytsis, Ligeti,. Ruderman.arXiv:1506.08896
Doršner, SF, Košnik, Nišandžić. arXiv:1306.6493
Dorsner,SF, Kosnik. arXiv:1204.0674



Top-Yukawa coupling

"Higgs portal" coupling

$$\mathcal{L} \ni -\lambda H^\dagger H \Delta^\dagger \Delta$$

- Loop induced LFV;
- Need top-quark mass chiral enhancement: non-chiral LQ!
- $\tau \to \mu\gamma$ enhanced in the same way as $H \to \tau\mu$

(3,1, 1/3) leptoquark

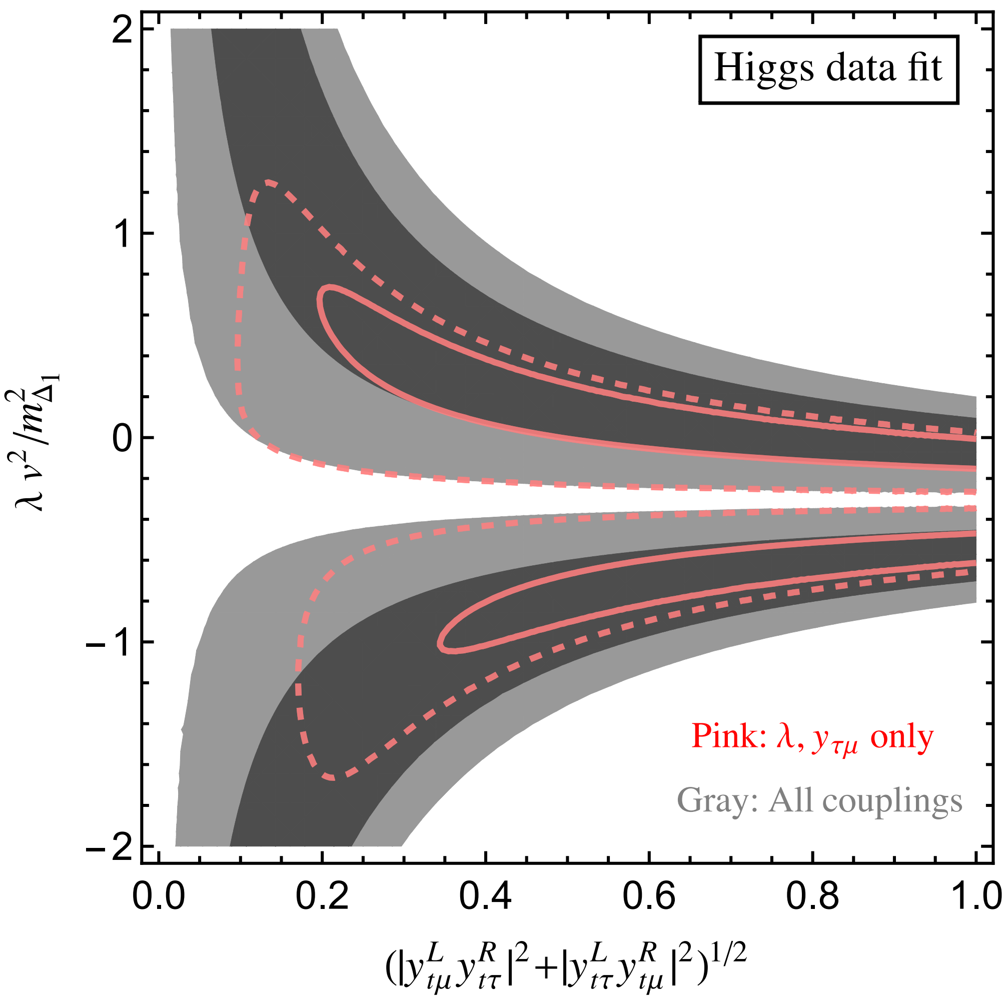
Δ_1 used recently by Bauer &Neubert, arXiv:1511.01900for B anomalies!
Can couple to diquarks and destabilize proton.

$$\mathcal{L}_{\Delta_1} = y^L_{ij}\bar{u}^i_L \ell^{C\,j}_L \Delta_1 - (V^\dagger_{\rm CKM} y^L_{ij} V_{\rm PMNS})\bar{d}^i_L \nu^{C\,j}_L \Delta_1 + y^R_{ij}\bar{u}^i_R \ell^{C\,j}_R \Delta_1 + \text{h.c.}$$

$$\boxed{\mathcal{B}(\tau \to \mu\gamma) = \frac{\alpha m_\tau^3}{2^{12}\pi^4\Gamma_\tau}\,\frac{m_t^2}{m_{\Delta_1}^4}\,h_1(x_t)^2\,\left(\left|y^L_{t\mu}y^R_{t\tau}\right|^2 + \left|y^L_{t\tau}y^R_{t\mu}\right|^2\right)}$$

Constraints come from (g-2) $_\mu$, $\mathcal{B}(Z \to b\bar{b})$.

Portal coupling has an effect on $H \to \gamma\gamma$ and $gg \to H$



$$\frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma}} = |\hat{c}_\gamma|^2$$

$$\hat{c}_\gamma = 1 - 0.025\frac{\lambda v^2}{m^2_\Delta} d(r_\Delta) \sum_i Q^2_{\Delta^i}$$

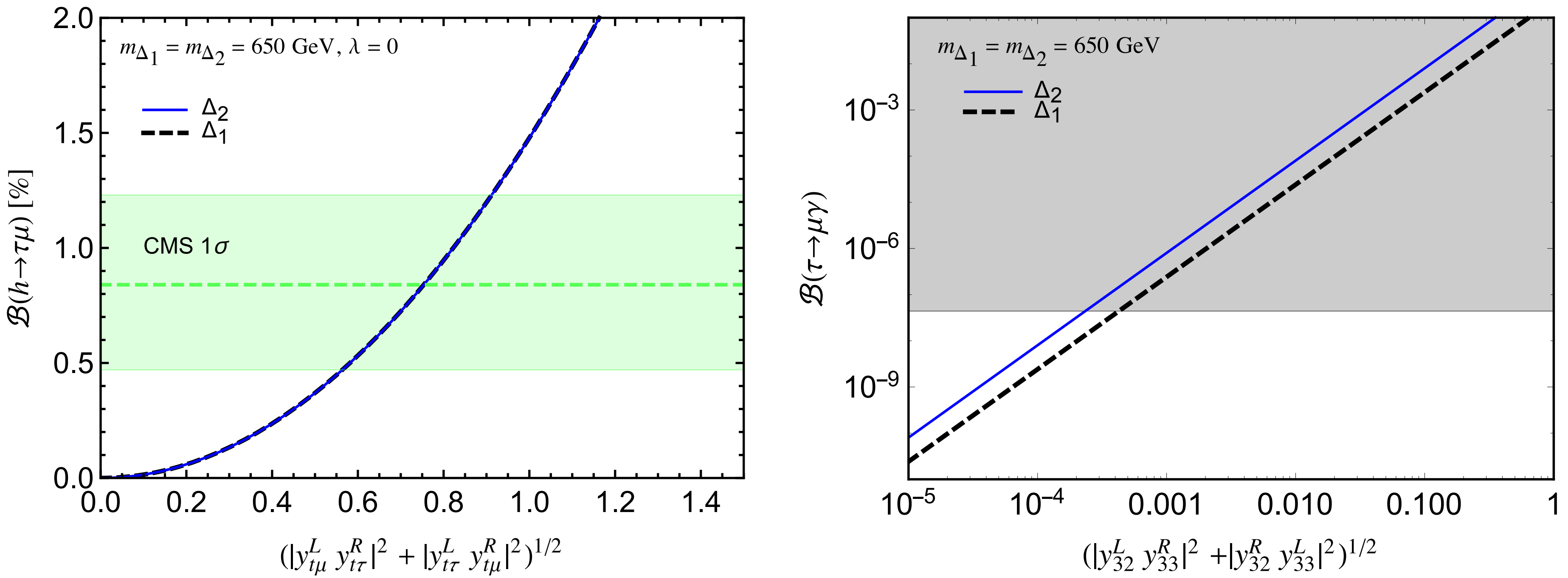
(3,2,7/6) Leptoquark

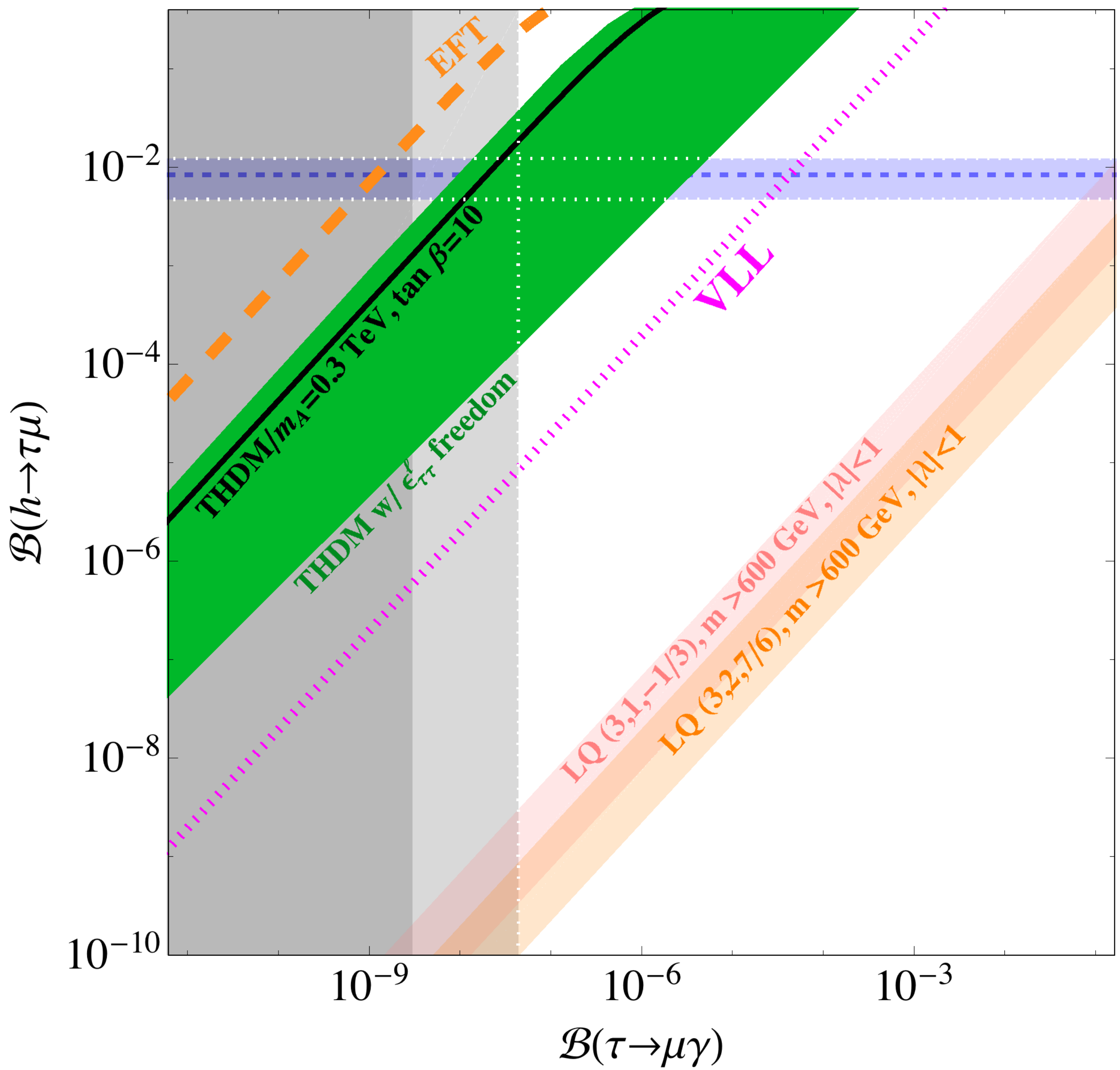
Good candidate to explain $R_{D(*)}$ anomaly (Doršner, SF, Košnik, arXiv:1306.6493), cannot destabilize proton;

$$\mathcal{L}_{\Delta_2} = y^L_{ij}\bar{\ell}^i_R d^j_L \Delta_2^{2/3\,*} + (y^L V^\dagger_{\mathrm{CKM}})_{ij}\bar{\ell}^i_R u^j_L \Delta_2^{5/3\,*}$$

$$+ (y^R V_{\mathrm{PMNS}})_{ij}\bar{u}^i_R \nu^j_L \Delta_2^{2/3} - y^R_{ij}\bar{u}^i_R \ell^j_L \Delta_2^{5/3} + \mathrm{h.c.}$$

$$\mathcal{B}(\tau\to\mu\gamma) = \frac{\alpha m_\tau^3}{2^{12}\pi^4\Gamma_\tau}\frac{m_t^2}{m_\Delta^4}\, h_2(x_t)^2\ \left(|y^R_{t\tau}y^L_{\mu t}|^2 + |y^R_{t\mu}y^L_{\tau t}|^2\right)$$


$m_{\Delta_1} = m_{\Delta_2} = 650$ GeV, $\lambda = 0$
Δ_2
Δ_1
CMS 1σ
$\mathcal{B}(h \to \tau\mu)$ [%]
$(|y^L_{t\mu}\, y^R_{t\tau}|^2 + |y^L_{t\tau}\, y^R_{t\mu}|^2)^{1/2}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.5
1.5
2.0
$m_{\Delta_1} = m_{\Delta_2} = 650$ GeV
Δ_2
Δ_1
$\mathcal{B}(\tau \to \mu\gamma)$
10^{-3}
10^{-6}
10^{-9}
10^{-5}
10^{-4}
0.001
0.010
0.100
1
$(|y^L_{32}\, y^R_{33}|^2 + |y^R_{32}\, y^L_{33}|^2)^{1/2}$



EFT
THDM/m_A=0.3 TeV, tan β=10
THDM w/ $\epsilon^{\ell}_{\tau\tau}$ freedom
VLL
LQ (3,1,−1/3), m>600 GeV, |λ|<1
LQ (3,2,7/6), m>600 GeV, |λ|<1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$\mathcal{B}(h\to\tau\mu)$
10^{-9}
10^{-6}
10^{-3}
$\mathcal{B}(\tau\to\mu\gamma)$

Fine-tuning solution

LQ (3,1-1/3) and vector-like top partner T_L' and T_R' (3,1,2/3)

$$-\mathcal{L} \supset y_t \bar{q}'_{3L} \tilde{H} t'_R + y_T \bar{q}'_{3L} \tilde{H} T'_R + M_T \bar{T}'_L T'_R + \text{h.c.}$$

$$m_t \approx y_t v/\sqrt{2}\,, \quad m_T \approx M_T\,,$$

$$\sin\theta_L \approx \frac{m_t y_T}{m_T y_t}\,, \quad \sin\theta_R \approx \frac{m_t}{m_T}\sin\theta_L$$

LHC lower bound on $m_{T,}$ electroweak observable (ρ parameter) constrain ϑ_L

$$\left.\begin{aligned} m_T &= 700\ \text{GeV} \\ \sin\theta_L &= 0.2 \end{aligned}\right\}$$

$$\mathcal{L} \supset y^L_{3j} \bar{q}'^a_{3L} \Delta_1 \epsilon^{ab} L^{C\,j,b} + y^R_{3j} \bar{t}'_R \Delta_1 E^{C\,j} + x^R_{3j} \bar{T}'_R \Delta_1 E^{C\,j} + \text{h.c.}$$

After rotating to the mass-basis

$$\mathcal{L} \supset y^L_{3j} (\cos\theta_L \bar{t}_L + \sin\theta_L \bar{T}_L) \ell^{C\,j}_L \Delta_1 + y^R_{3j} (\cos\theta_R \bar{t}_R + \sin\theta_R \bar{T}_R) \ell^{C\,j}_R \Delta_1$$

$$+ x^R_{3j} (\cos\theta_R \bar{T}_R - \sin\theta_R \bar{t}_R) \ell^{C\,j}_R \Delta_1 + \text{h.c.}$$

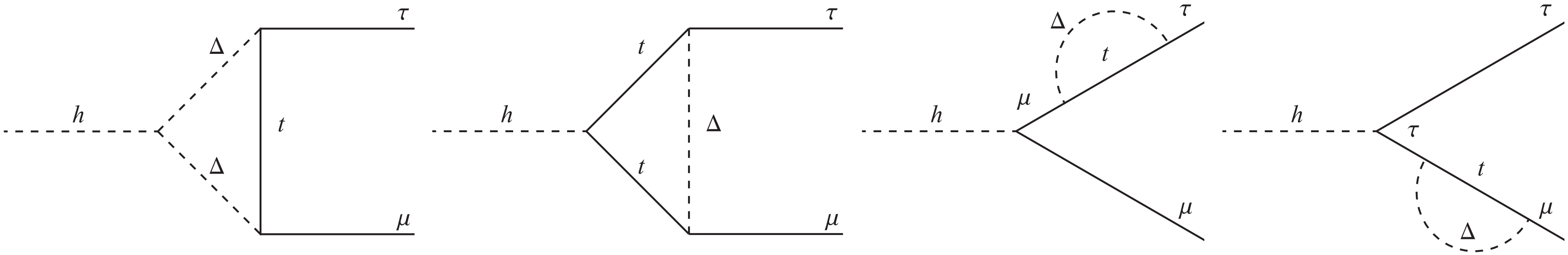
$$\boxed{\mathcal{B}(\tau \to \mu\gamma) = \frac{\alpha_{\rm EM} m_\tau^3 |y^L_{33}|^2}{2^{12}\pi^4 \Gamma_\tau m^4_{\Delta_1}} \left| y^{R*}_{32}\, m_t h_1(m_t^2/m^2_{\Delta_1}) + x^{R*}_{32} \sin\theta_L\, m_T h_1(m_T^2/m^2_{\Delta_1}) \right|^2}$$

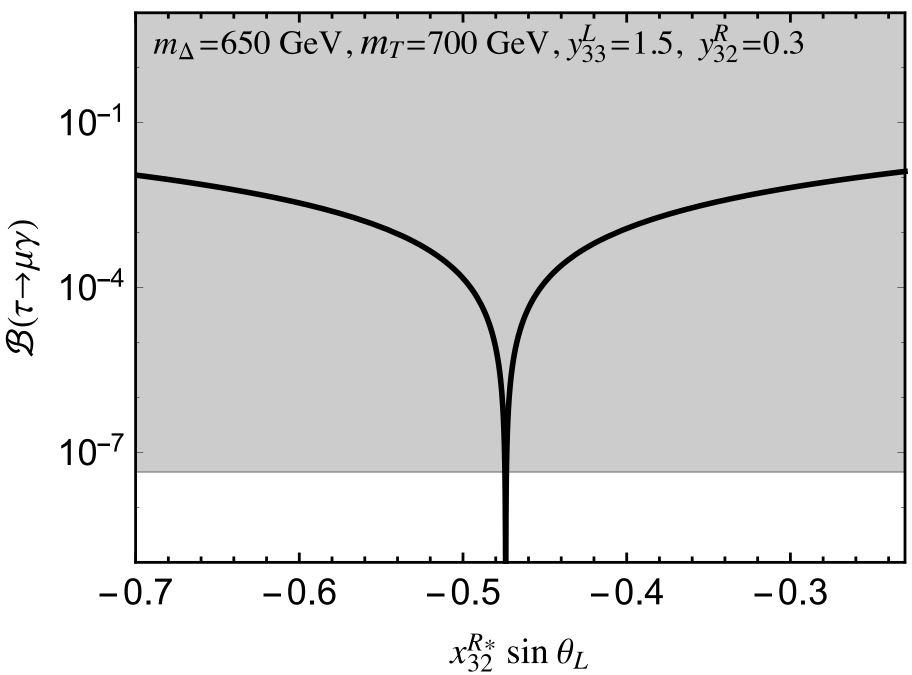
Numerical benchmark point $\quad y_{\tau\mu} \approx \frac{N_c}{16\pi^2} \frac{m_t}{v} \left(0.26 y^R_{32} + 0.43\, x^R_{32} \sin\theta_L\right) y^{L*}_{33}$

$$\left.\begin{aligned} m_{\Delta_1} &= 650\,\text{GeV} \\ m_T &= 700\,\text{GeV} \end{aligned}\right\}$$

cancellation in the rate for $\tau \to \mu\gamma$

$$y^R_{32} = -0.63\, x^R_{32} \sin\theta_L$$





T, t , Δ_1 are running in the loops (4 vertex + 4 legs) result is finite.

$$y^R_{32} y^{L*}_{33} = 0.47$$

best fit point for the $h \to \tau\mu$ excess.

For $m_T > m_\Delta, T \to \Delta\ell$ signature for LHC.

Summary

- Signal on $\mathcal{B}(H \to \tau\mu)$ implies lower bound on Higgs LFV couplings;
- This bound is robust even after allowing for a deviation of other Higgs couplings

- From Higgs effective Lagrangian approach: Belle II should observe $\tau \to \mu\gamma$
- Future μe conversion measurements lead to

$$\mathcal{B}(H \to \tau\mu)\mathcal{B}(H \to e\tau) < 10^{-7}$$

- Specific models are restrictive on $\mathcal{B}(\tau \to \mu\gamma)$.

1. Vector-like leptons (Leptoquarks) with loop induced $H \to \tau\mu$ imply too large $\mathcal{B}(\tau \to \mu\gamma)$;

2. Two Higgs doublet model is testable in $\mathcal{B}(\tau \to \mu\gamma)$ at Belle II;

3. Two Higgs doublet model is further testable by μe conversion. Correlation $\mathcal{B}(H \to \tau\mu)\mathcal{B}(H \to e\tau) < 10^{-10}$

Thanks!

ATLAS and CMS results on Higgs decay modes