Lepton flavour violating Higgs decays involving taus

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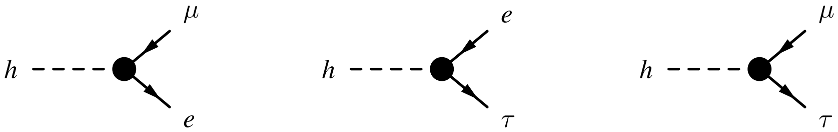
Charged lepton flavour violation (see Adrian's and Ana's talks)

- SM: no ν mass term, lepton number and lepton flavour are conserved
- Neutrino oscillations $=$ Neutral lepton flavour violation
  What about charged lepton flavour violation (cLFV) ?
- Ad-hoc SM extension (Dirac m_ν + U_{PMNS}): cLFV from loop processes
  $\Rightarrow$ negligible, e.g. Br$(\mu \to e\gamma) \sim 10^{-54}$ [Petcov, 1977]
- If cLFV observed:
  - Clear evidence of new Physics
  - Probe the origin of lepton mixing
  - Could tell us more about the origin of neutrino masses and mixing
- Searched for in numerous channels:

Radiative decays	$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]
3-body decays	$\mathrm{Br}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ [Belle, 2010]
Meson decays	$\mathrm{Br}(B^0 \to e\mu) < 1.0 \times 10^{-9}$ [LHCb, 2017]
Z decays	$\mathrm{Br}(Z^0 \to e\mu) < 7.5 \times 10^{-7}$ [ATLAS, 2014]
Neutrinoless muon conversion	$\mu^-, \mathrm{Au} \to e^-, \mathrm{Au} < 7 \times 10^{-13}$ [SINDRUM II, 2006]

Many sources of cLFV Higgs decays

- Higgs discovery allows to search for cLFV in the scalar sector



- Many models give rise to cLFV Higgs decays

Tree-level:

general 2HDM [Diaz-Cruz and Toscano, 2000; Han and Marfatia, 2001; Kanemura *et al.*, 2006; Dorsner *et al.*, 2015 ...]

3HDM [Campos *et al.*, 2015; Crivellin *et al.*, 2015; Merchand and Sher, 2017]

Warped extra-dim / Composite Higgs [Azatov *et al.*, 2009; de Lima *et al.*, 2015]

RPV SUSY [Arhrib *et al.*, 2013; Huang and Tang, 2015; ...]

Froggatt-Nielsen [Huitu *et al.*, 2016; Barradas-Guevara *et al.*, 2017; ...]

Loop induced:

low-scale seesaw models [Pilaftsis, 1992; Arganda, Herrero, Marcano and CW, 2015; Herrero-Garcia*et al.*, 2016; Thao *et al.*, 2017; ...]

MSSM [Diaz-Cruz, 2002; Brignole and Rossi, 2003; Arana-Catania *et al.*, 2013; Aloni *et al.*, 2016; Alvarado *et al.*, 2016; Gomez *et al.*, 2017;...]

SUSY seesaw Arganda *et al.*, 2005; Diaz-Cruz *et al.*, 2009, Arganda, Herrero, Marcano and CW, 2016...]

Leptoquarks [Dorsner *et al.*, 2015; de Medeiros Varzielas and Hiller, 2015; Cheung *et al.*, 2016 ...]

Vector-like fermions [Falkowski *et al.*, 2014; Dorsner *et al.*, 2015; Chen and Nomura, 2016 ...]

EFT as a generic description (see Adrian's talk)

- Effects of particles heavier than the process energy scale described by effective operators, e.g. for cLFV radiative decays

$$\hat{\mathcal{O}}^{\mathcal{D}} = \frac{C^{\mathcal{D}}}{\Lambda_{\text{NP}}^2} \bar{L} H \sigma^{\mu\nu} e_R B_{\mu\nu}$$

- For cLFV Higgs decays, dominant contribution from [Herrero-Garcia et al., 2016]

$$\hat{\mathcal{O}}^{\mathcal{Y}} = \frac{C^{\mathcal{Y}}}{\Lambda_{\text{NP}}^2} \bar{L} H e_R (H^\dagger H)$$

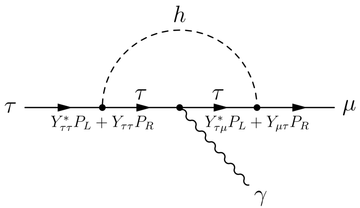
giving after EWSB non-diagonal Higgs interactions

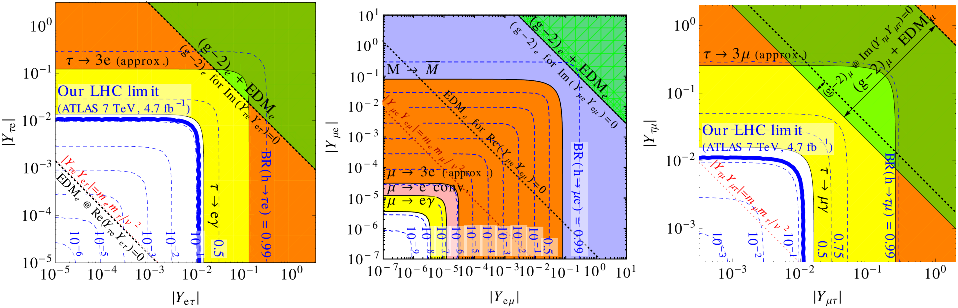
$$-\mathcal{L}^{\mathcal{Y}} = m_i \bar{\ell}_L^i \ell_R^j + Y_{ij} \ell_L^i \ell_R^j h + \text{h.c.} \quad \rightarrow \quad Y_{ij} = \frac{m_i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda_{\text{NP}}^2} C_{ij}^{\mathcal{Y}}$$

- cLFV Higgs decays governed by the effective Yukawa coupling Y_{ij}

Indirect constraints on Y_{ij}

- Y_{ij} contributes to [Harnik et al., 2013]
  -cLFV lepton decays
  -electron EDM
  -electron and muon g-2





- Good prospects for direct searches of cLFV Higgs decays into τ
  (See talks by Brian Le and Jian Wang for recent experimental results)

Future sensitivities

- Current upper limits at 95% C.L [Aad et al., 2017, Sirunyan et al., 2018]

	ATLAS	CMS
Br($h \to \tau\mu$)	1.41% (8 TeV)	0.25% (13 TeV)
Br($h \to \tau e$)	1.04% (8 TeV)	0.61% (13 TeV)

- HL-LHC sensitivities with $3\,\mathrm{ab}^{-1}$, 10% systematics, at 95% C.L [Banerjee et al., 2016]

	$e\mu + \not{E}_T$
Br($h \to \tau\mu$)	0.76%
Br($h \to \tau e$)	0.61%

- ILC sensitivities at 95% C.L, *HZ* and *VBF* production channels [Banerjee et al., 2016]

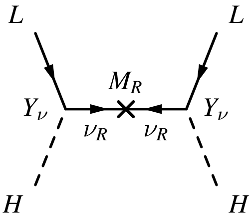
	250 GeV, 250 fb^{-1}	1 TeV, 1 ab^{-1}
Br($h \to \tau e$)	0.38%	0.22%

Expect similar results for $h \to \tau\mu$

- ILC sensitivity, assuming negligible background, *HZ* and *VBF* production channels, polarized beams (-0.8,0.3) [Chakraborty et al., 2016]:

	250 GeV, 1350 fb^{-1}
Br($h \to \tau\mu$)	0.0041%

2 examples based on low-scale seesaw models



- Taking $M_R \gg m_D$ gives the "vanilla" type 1 seesaw

$$\mathrm{m}_\nu = -m_D M_R^{-1} m_D^T \quad \text{, where } m_D = Y_\nu v$$

$$\mathrm{m}_\nu \sim 0.1\,\mathrm{eV} \Rightarrow \left| \begin{array}{l} Y_\nu \sim 1 \quad \text{and} \quad M_R \sim 10^{14}\,\mathrm{GeV} \\ Y_\nu \sim 10^{-6} \text{ and } M_R \sim 10^{2}\ \mathrm{GeV} \end{array} \right.$$

- m_ν suppressed by small active-sterile mixing m_D/M_R

- Problem: m_D/M_R also controls the heavy neutrinos phenomenology
  Solution: Cancellation in matrix product to get large m_D/M_R

- Theorem: $m_\nu = 0 \Leftrightarrow$ Conserved lepton number L
  [Kersten and Smirnov, 2007; Moffat, Pascoli, **CW**, 2017]
  Consequence: Large m_D/M_R in presence of nearly conserved L symmetry

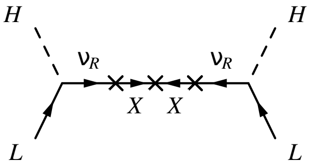
- Examples: the inverse seesaw and its SUSY realisation

An example: the inverse seesaw model

- Lower seesaw scale from approximately conserved lepton number
- Add fermionic gauge singlets ν_R $(L = +1)$ and X $(L = -1)$
  [Mohapatra and Valle, 1986, Bernabéu et al., 1987]

$$\mathcal{L}_{inverse} = -Y_\nu \overline{L}\tilde{\phi}\nu_R - M_R \overline{\nu_R^c} X - \frac{1}{2}\mu_X \overline{X^c} X + \text{h.c.}$$

with $m_D = Y_\nu \mathrm{v}\,, M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$



$$m_\nu \approx \frac{m_D^2}{M_R^2}\mu_X$$

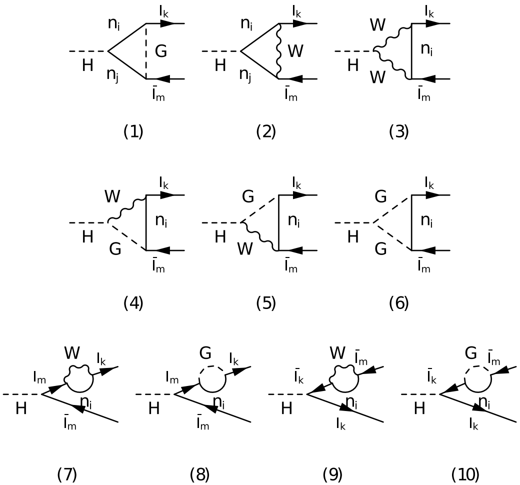
$$m_{N_1,N_2} \approx \mp M_R + \frac{\mu_X}{2}$$

2 scales: μ_X and M_R

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1\,\mathrm{TeV}$
  $\Rightarrow$ within reach of the LHC and low energy experiments

Diagrams for the ISS (PRD91(2015)015001)

- In the Feynman-'t Hooft gauge, same as type I seesaw [Arganda et al., 2005]:



- Formulas adapted from [Arganda et al., 2005]
- Diagrams 1, 8, 10 dominate at large M_R
- Enhancement from:
  -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale n_i

Most relevant constraints

- Neutrino data → Use specific parametrization (modified Casas-Ibarra (C-I) [Casas and Ibarra, 2001] or μ_X parametrization)

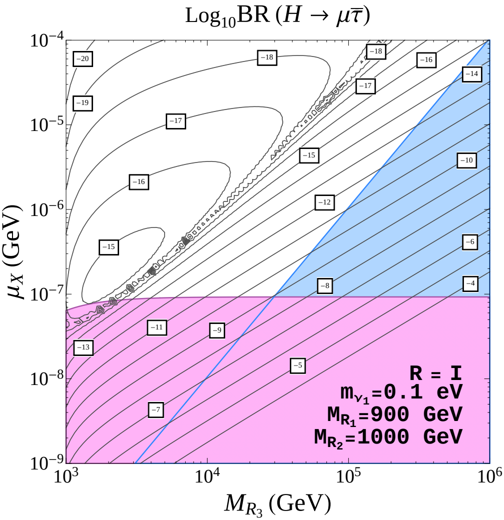
$$\mathrm{v}Y_\nu^T = V^\dagger \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3})\, R\, \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U_{PMNS}^\dagger$$
$$M = M_R \mu_X^{-1} M_R^T$$

or

$$\mu_X = M_R^T\, Y_\nu^{-1}\, U_{\mathrm{PMNS}}^* \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U_{\mathrm{PMNS}}^\dagger\, Y_\nu^{T^{-1}} M_R \mathrm{v}^2$$

- Charged lepton flavour violation → For example: $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]
- Lepton universality violation: less constraining than $\mu \to e\gamma$
- Electric dipole moment: 0 with real PMNS and mass matrices
- Invisible Higgs decays: $M_R > m_H$, does not apply
- Yukawa perturbativity: $|\frac{Y_\nu^2}{4\pi}| < 1.5$

Predictions using the modified C-I parametrization



- Grows with M_{R_3} and μ_X^{-1} due to Y_ν growth in C-I parametrization
- Different dependence on parameters for cLFV Higgs decays and cLFV radiative decays
- Similar behaviour with degenerate heavy neutrinos
- Excluded by $\mu \to e\gamma$
  Non-perturbative Y_ν
- $\mathrm{Br}(H \to \bar{\tau}\mu) \leqslant 10^{-9}$

Large cLFV Higgs decay rates from textures

- Possibility to evade the $\mu \to e\gamma$ constraint ?
- Approximate formulas for large Y_ν:

$$\mathrm{Br}^{\mathrm{approx}}_{\mu\to e\gamma} = 8\times 10^{-17}\mathrm{GeV}^{-4}\frac{m_\mu^5}{\Gamma_\mu}\left|\frac{\mathrm{v}^2}{2M_R^2}(Y_\nu Y_\nu^\dagger)_{12}\right|^2$$

$$\mathrm{Br}^{\mathrm{approx}}_{H\to\mu\bar{\tau}} = 10^{-7}\frac{\mathrm{v}^4}{M_R^4}\left|(Y_\nu Y_\nu^\dagger)_{23} - 5.7(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23}\right|^2$$

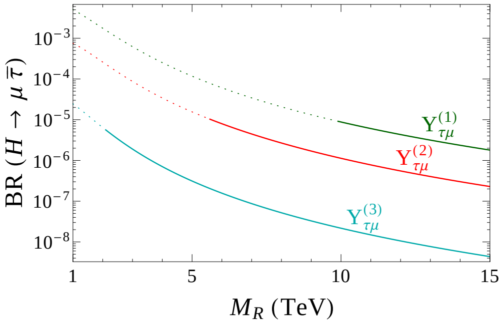
$$\underset{(Y_\nu Y_\nu^\dagger)_{12}=0}{=} 10^{-7}\frac{\mathrm{v}^4}{M_R^4}\left|1 - 5.7[(Y_\nu Y_\nu^\dagger)_{22} + (Y_\nu Y_\nu^\dagger)_{33}]\right|^2 \left|(Y_\nu Y_\nu^\dagger)_{23}\right|^2$$

→ Different dependence on the seesaw parameters

- Solution: Textures with $(Y_\nu Y_\nu^\dagger)_{12} = 0$ and $\frac{|Y_\nu^{ij}|^2}{4\pi} < 1.5$
- Examples:

$$Y_{\tau\mu}^{(1)} = f\begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix},\ Y_{\tau\mu}^{(2)} = f\begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix},\ Y_{\tau\mu}^{(3)} = f\begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$

Producing large $H \to \tau\mu$ rates



- Numerics done with the full one-loop formulas
- Dotted: excluded by $\tau \to \mu\gamma$
  Solid: allowed by cLFV, LUV, etc
- $\mathrm{Br}^{\max}(H \to \mu\bar{\tau}) \sim 10^{-5}$
- Same maximum branching ratio with hierarchical heavy N

- Similarly, $\mathrm{Br}^{\max}(H \to e\bar{\tau}) \sim 10^{-5}$ for $Y^{(i)}_{\tau e}$ (=$Y^{(i)}_{\tau\mu}$ with rows 1 and 2 exchanged)

- Out of LHC reach, $\mathrm{Br}^{\max}$ directly proportional to $\tau \to \left| \begin{array}{l} \mu\gamma \\ e\gamma \end{array} \right.$

  $\Rightarrow$ Observation at the LHC could exclude inverse seesaw

The supersymmetric inverse seesaw model

- MSSM extended by singlet chiral superfields $\widehat{N}$ and $\widehat{X}$ with $L = -1$ and $L = +1$
- Defined by the superpotential:

$$\mathcal{W} = W_{MSSM} + +Y_\nu \widehat{N}\widehat{L}\widehat{H}_u + M_R \widehat{N}\widehat{X} + \frac{1}{2}\mu_X \widehat{X}\widehat{X}$$

- New couplings, e.g.

$$A_{Y_\nu} Y_\nu \widetilde{N}\widetilde{L}H_u + \text{h.c.}$$

- Light right-handed sneutrinos:

$$M^2_{\widetilde{N}} = m^2_{\widetilde{N}} + M^2_R + Y_\nu Y_\nu^\dagger v_u^2 \sim (1\text{TeV})^2$$

$\Rightarrow$ Natural Yukawa couplings with a TeV new Physics scale

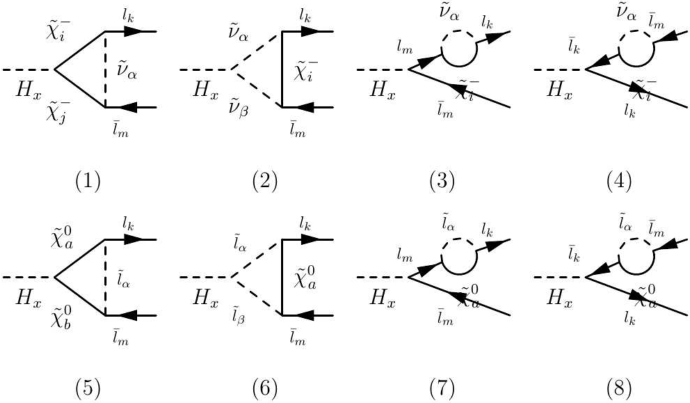
cLFV in supersymmetric seesaw models

- Typically in SUSY, cLFV through RGE-induced slepton mixing $(\Delta m^2_{\tilde{L}})_{ij}$
  [Borzumati and Masiero, 1986, Hisano et al., 1996, Hisano and Nomura, 1999]
  $\Rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto (Y^\dagger_\nu Y_\nu)_{ij} \ln \frac{M_{GUT}}{M_R}$
- Contribute to all cLFV observables
  → Dominant in most SUSY seesaw models
- Type I seesaw ($Y_\nu \sim 1$, $M_R \sim 10^{14}$GeV) → $(\Delta m^2_{\tilde{L}})_{ij} \propto 5$
- Inverse seesaw ($Y_\nu \sim 1$, $M_R \sim 1$TeV) → $(\Delta m^2_{\tilde{L}})_{ij} \propto 30$
  → one-loop $\widetilde{N}$-mediated processes are no longer suppressed
  [Deppisch and Valle, 2005, Hirsch et al., 2010, Abada et al., 2012, Ilakovac et al., 2012, Krauss et al., 2014, Abada et al., 2014]

cLFV Higgs decays from SUSY loops (PRD93(2016)055010)

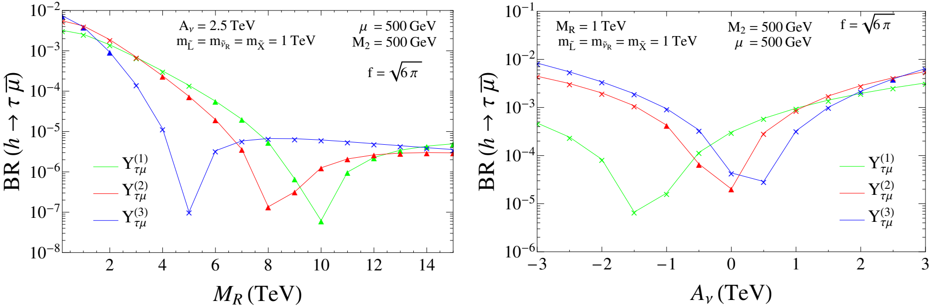
- In the Feynman-'t Hooft gauge, same as SUSY type I seesaw

  [Arganda et al., 2005]



- Formulas adapted from [Arganda et al., 2005]
- Enhancement from: -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale $\tilde{\nu}$

Results in SUSY ISS



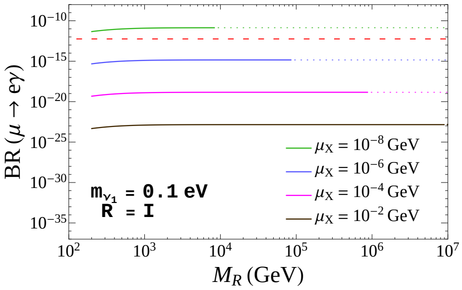
- M_R degenerate and real, $m_A = 800\,\text{GeV}$,
  squark parameters safe from LHC (direct searches, Higgs mass)
- ▲: allowed by cLFV radiative decays, $\times$: excluded
- At low M_R: dominated by chargino-sneutrino loops
  At large M_R / small f: dominated by neutralino-slepton loops
- Can adjust other parameters (A_ν, $m_{\tilde{\nu}_R}$) to reach $\text{Br}(h \to \tau\bar{\mu}) \sim 1\%$
  (Dips in BR($h \to \tau\bar{\mu}$) and BR($\tau \to \mu\gamma$) do not exactly coincide)

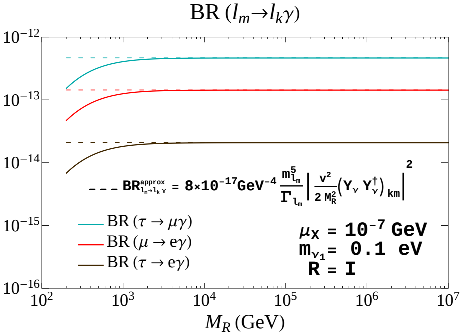
Conclusion

- Observation of cLFV would be a clear signal of new Physics
- cLFV Higgs decays: complementary to other cLFV searches
- LHC searches of cLFV Higgs decays already give the best constraints in the τ sector
- Many models are predicting rates within LHC reach, e.g. general 2HDM, SUSY seesaw, 3HDM, Froggatt-Nielsen, leptoquarks

Backup slides

Constraints: focus on $\mu \to e\gamma$

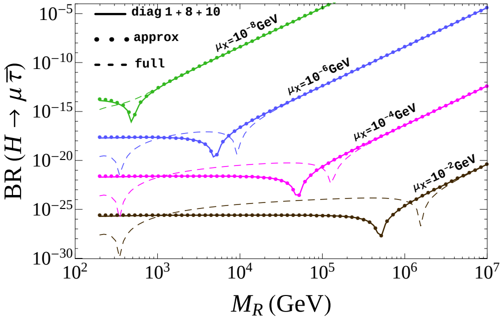




- M_R and μ_X real and degenerate, Casas-Ibarra (C-I) parametrization
- Constrains μ_X
- Perturbativity $\to \left|\frac{Y_\nu^2}{4\pi}\right| < 1.5$ (Dotted line = non-perturbative couplings)
- $\frac{v^2 (Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} \approx \frac{1}{\mu_X} \frac{(U_{\text{PMNS}} \Delta m^2 \ U^T_{\text{PMNS}})_{km}}{2 m_{\nu_1}}$

Dependence on ISS parameters: μ_X and M_R

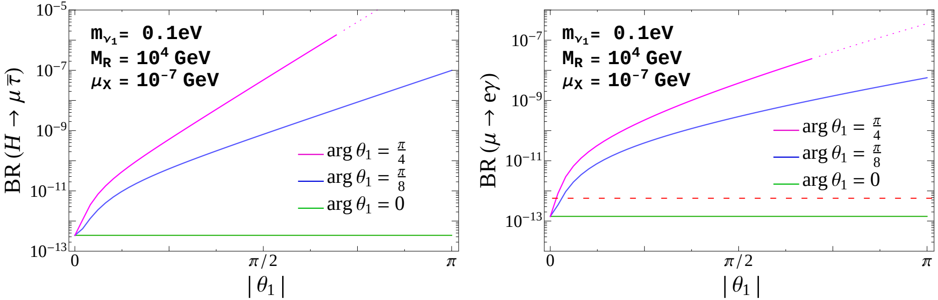
$$\mathrm{BR}^{\mathrm{approx}}_{H\to\mu\bar{\tau}} = 10^{-7}\left(v^4/M_R^4\right)\left|\left(Y_\nu Y_\nu^\dagger\right)_{23} - 5.7\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)_{23}\right|^2$$



- $R = \mathbb{1}$, M_R and μ_X degenerate and real, C-I parametrization
- Dips come from interferences between diagrams
- Can be understood using the mass insertion approximation

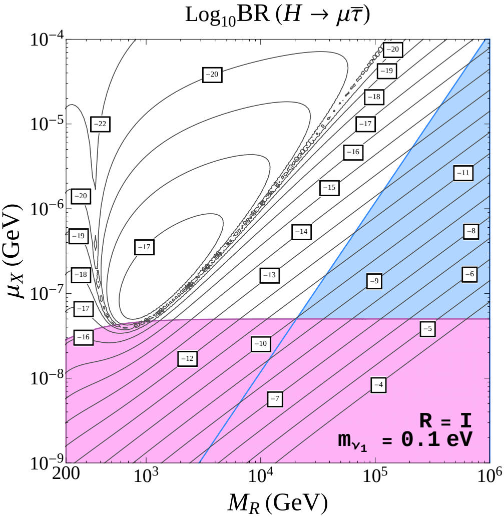
$$\frac{v^2 (Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} \approx \frac{1}{\mu_X}\frac{(U_{\mathrm{PMNS}}\Delta m^2\ U_{\mathrm{PMNS}}^T)_{km}}{2m_{\nu_1}} \quad \text{and} \quad \frac{v^2 (Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} = \frac{M_R^2 (U_{\mathrm{PMNS}}\Delta m^2\ U_{\mathrm{PMNS}}^T)_{km}}{v^2\mu_X^2}$$

Dependence on Casas-Ibarra parameters: R matrix



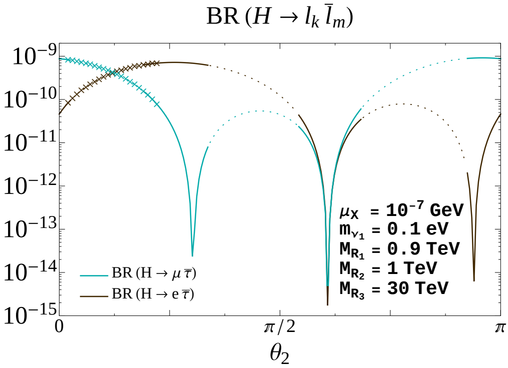
- M_R and μ_X degenerate and real
- Independent of R for real mixing angles
- Increase with complex angles, but increase limited by $\mu \to e\gamma$
  $\Rightarrow$ Complex R matrix doesn't change our results

Searching for maximal $\mathrm{Br}(H \to \bar{\tau}\mu)$



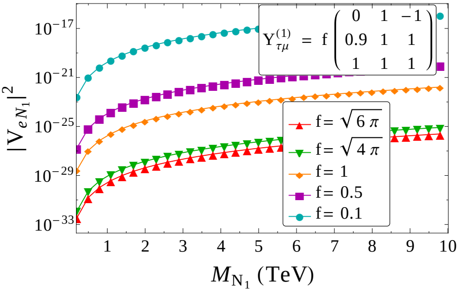
- M_R and μ_X degenerate and real
- Excluded by $\mu \to e\gamma$
  Non-perturbative Y_ν
- $\mathrm{Br}(H \to \bar{\tau}\mu) \leqslant 10^{-10}$
- End of the story ?

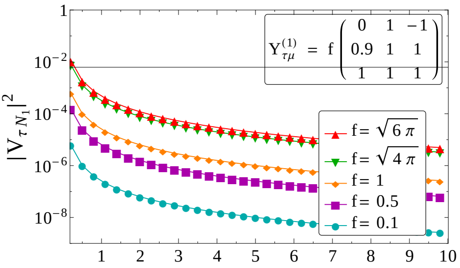
Impact of the R matrix for hierarchical N



- Contrary to degenerate case, R dependence
- Varying θ_1: Same conclusions as before
- Dotted = non-perturbative couplings
  Cross = Excluded by $\mu \to e\gamma$
- $\theta_2 \sim \pi/4$:
  $\mathrm{Br}(H \to e\bar{\tau}) > \mathrm{Br}(H \to \mu\bar{\tau})$
- Results quite insensitive to θ_3

Constraints from EWPO





- Active sterile mixing is controlled by $\theta \sim m_D M_R^{-1}$
- Large mixing → possible conflict with EWPO
- Limits taken from [del Aguila et al., 2008] at 90% C.L. :

$$|V_{eN}|^2 < 3.0 \times 10^{-3}$$
$$|V_{\mu N}|^2 < 3.2 \times 10^{-3}$$
$$|V_{\tau N}|^2 < 6.2 \times 10^{-3}$$