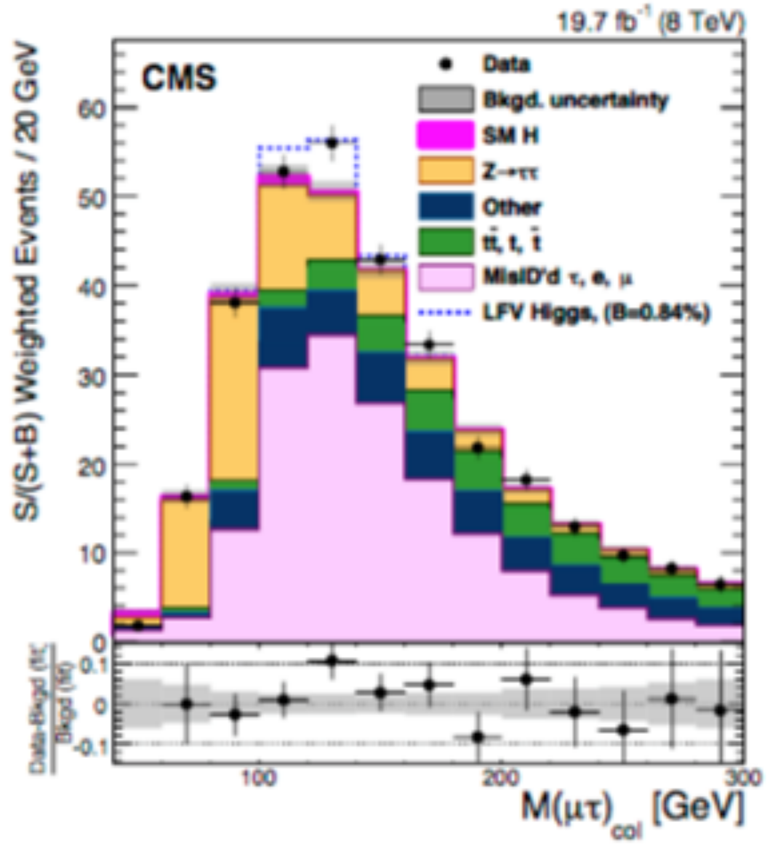
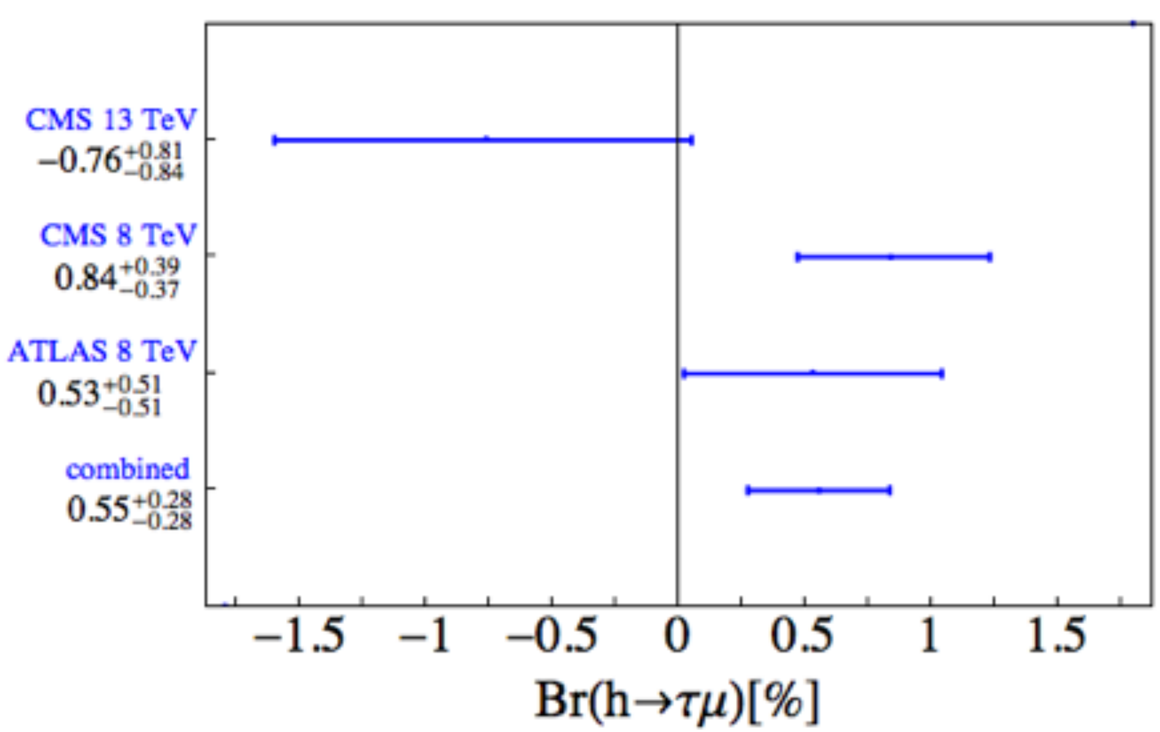
Lepton Flavor Violation and the Higgs boson

Michael Spannowsky

IPPP, Durham University

Since its 'Higgs days' lets focus on LFV Higgs interactions





Tremendous exp. and theo. developments

[Pilaftsis '92]

[Assamagan, Deandrea, Delsart '02]

[CMS-PAS-HIG-14-005]

[Arganda, Curiel, Herrero, Temes '04]

[Banerjee, Bhattacherjee, Mitra, MS '16]

[Diaz-Cruz, Ghosh, Dilip, Moretti '08]

[Chakraborty, Datta, Kundu '16]

[Kanemura, Shinya, Tsumura '09]

[Harnik, Kopp, Zupan '12]

[Arhrib, Cheng, Kong '12]

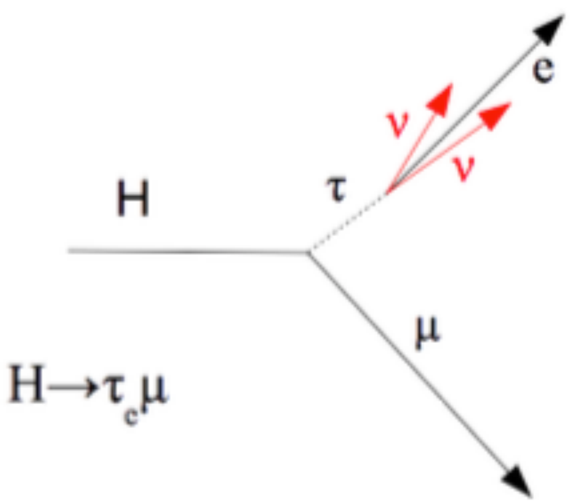
[Falkowski, Straub, Vicente '13]

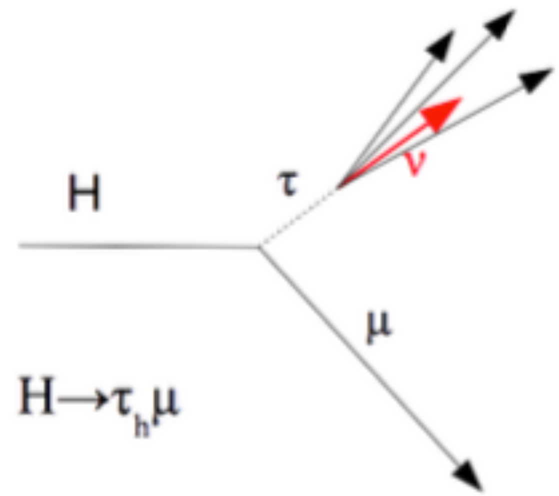
[Heeck, Holthausen, Rodejohann, Shimizu '15]

Many more

Prospects for future searches: $H \to \tau\mu$

Search for direct lepton flavor violation in $H \to \mu\tau_e$ and $H \to \mu\tau_h$:

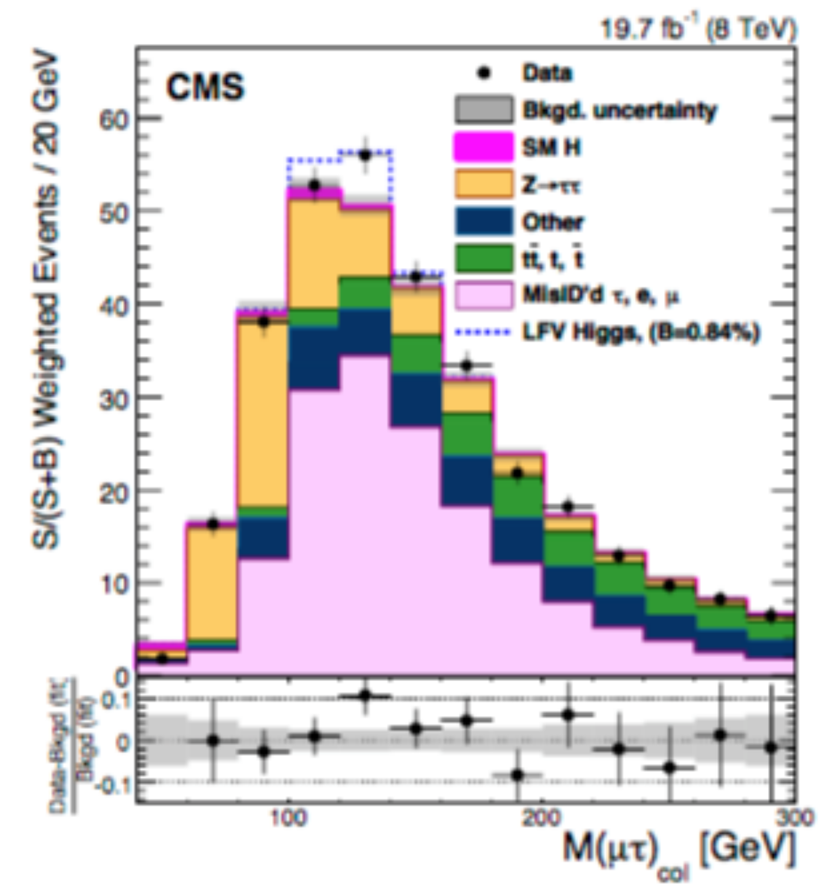




- each channel separated in 0, 1 and 2 jet categories (GF, VBF H-production)

- Small excess near mH = 125 GeV

  with significance of 2.4σ
- Best fit branching ratio $\mathrm{Br}(H \to \mu\tau) = 0.84^{+0.39}_{-0.37}\%$
- Constraint on BR at 95%CL $\mathrm{Br}(H \to \mu\tau) < 1.51(0.75)\%$
- Though excess not reproduced in 13 TeV (2015) data



ATLAS sees small excess in same range with 1.3σ 8 TeV data

Lepton sector of SM:

Interaction basis $Y^e \to V_L Y^e V_E = \lambda^e$

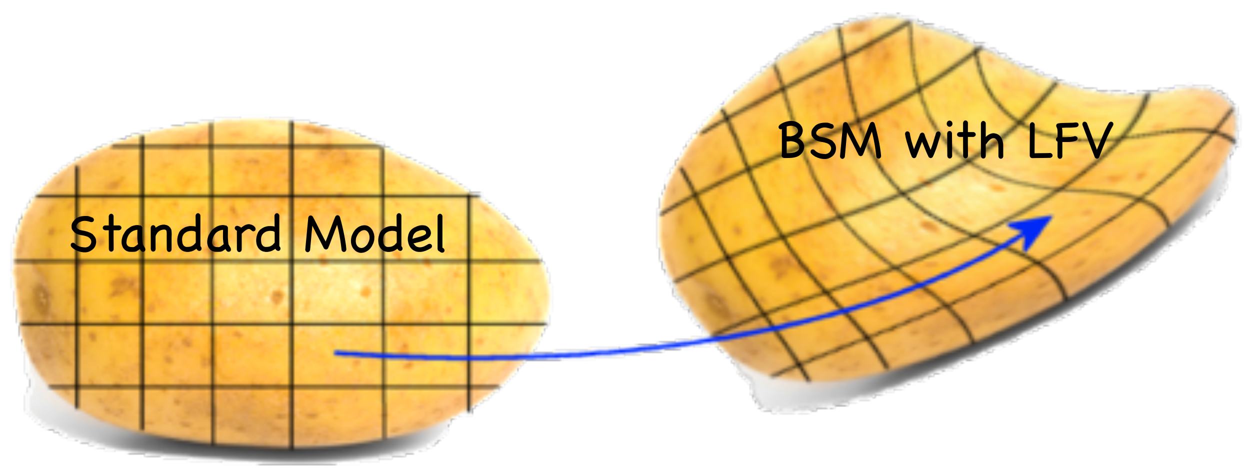
Matrix λ^e assumed to be diagonal and real $\lambda^e = \begin{pmatrix} \lambda_e & & \\ & \lambda_\mu & \\ & & \lambda_\tau \end{pmatrix}$

Yukawa inter. results in accid. symmetry $SU(3)_L \times SU(3)_E \to U(1)_e \times U(1)_\mu \times U(1)_\tau$

→ Lepton sector of SM, neither mixing nor CP violation

Boring! See Pedro's talk

To turn this around, observation of lepton flavor violation indicates new physics!



Need to deform SM for signal, but not too much!

Many models provide sources for LFV: (N)MSSM, Seesaw models, strongly coupled, ...

UV Models

inv. Seesaw models

Vector-like Quarks

RPV SUSY

2HDM

MSSM

EFT

$$\hat{\mathcal{O}}_{ij} = \frac{v^2}{\Lambda^2_{\rm NP}} \bar{f}_{L_i} f_{R_j} h$$

Measurements inferring $h \to e\mu, \mu\tau, \tau e$

EFT Language to communicate between separated scales

Ludwig Wittgenstein

Due to absence of new resonances and generically tight limits on LFV interactions EFT approach warranted:

$$\hat{O}_{ij} = \frac{v^2}{\Lambda_{\rm NP}^2} \bar{f}_{L_i} f_{R_j} h$$

The gauge invariant Lagrangian is extended by dim-6

$$\mathcal{L}_y = -\frac{\lambda_{ij}}{\Lambda^2} \bar{F}_L^i F_R^j H (H^\dagger) H) + \text{h.c.}$$

The limits of my language are the limits of my world

just 1 operator

results after EWSB in non-diagonal Higgs interactions

$$\mathcal{L}_y = -m_i \bar{f}_L^i f_R^i - Y_{ij} \bar{f}_L^i f_R^j h + \text{h.c.}$$

→ Eff. Yukawa

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\lambda_{ij}$$

Flavor violating Higgs decays $h \to e\mu, \mu\tau, \tau e$

Low energy limits on Higgs LFV interactions

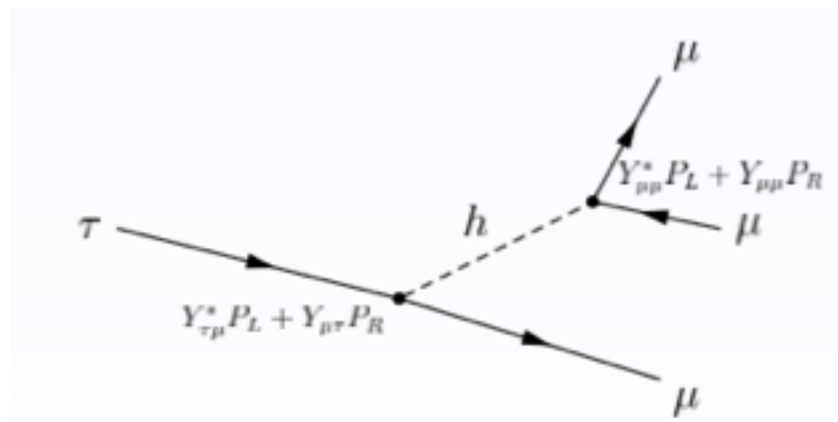
Limits fairly strong

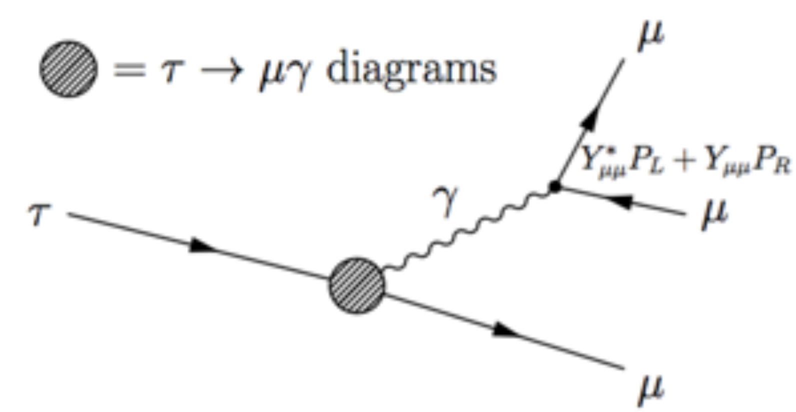
[Dassinger, Feldman, Mannel, Turcyk '07]

$\mu \to 3e$: $Y_{\mu e} < 2.19 \times 10^{-5}$

$\tau \to 3e$: $Y_{e\tau} < 0.085$

$\tau \to 3\mu$: $Y_{\mu\tau} < 0.176$





Same calculation as for scalar-mediated direct dark matter detection

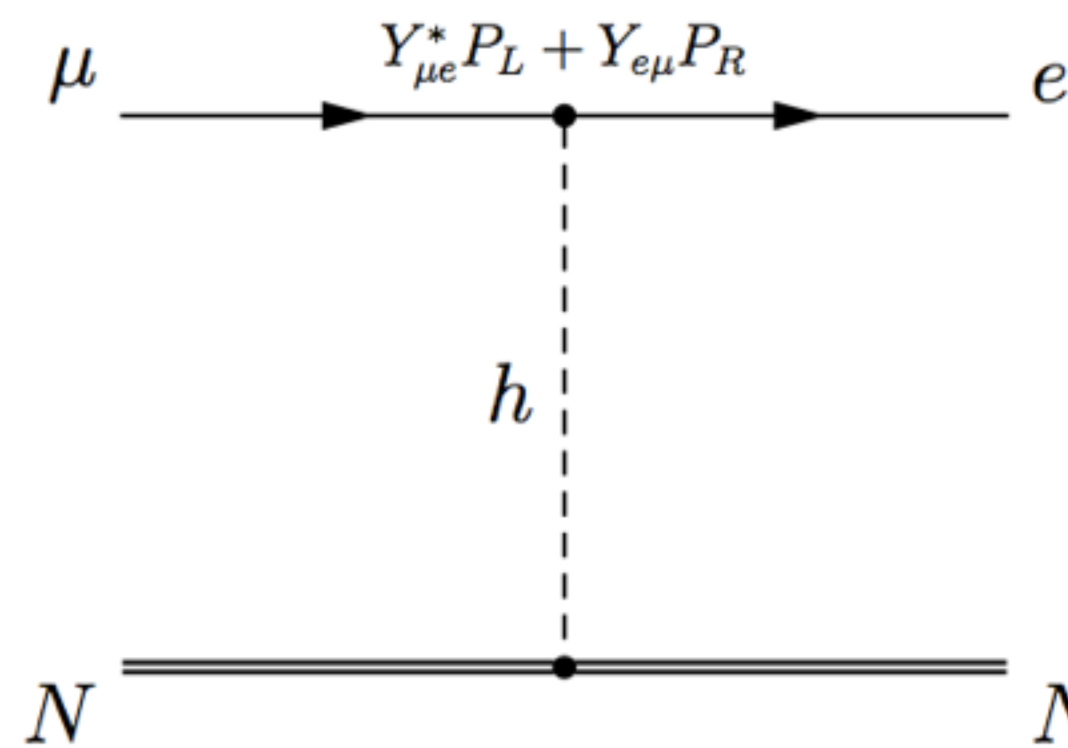
[Shifman, Vainshtein, Zakharov '78]

$$\mathcal{L}^h_{eff} \simeq -\frac{h}{v}\left(\sum_{q=u,d,s} y^h_q\, m_q\, \bar{q}\, q - \sum_{q=c,b,t} \frac{\alpha_s}{12\pi}\, y^h_q\, G^a_{\mu\nu} G^{\mu\nu}_a\right)$$

$$\langle N|\theta^\mu_\mu|N\rangle = m_N \langle N|\bar{\psi}_N \psi_N|N\rangle$$

$$\theta^\mu_\mu = -9\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s} m_q \bar{q} q$$

triangle anomaly

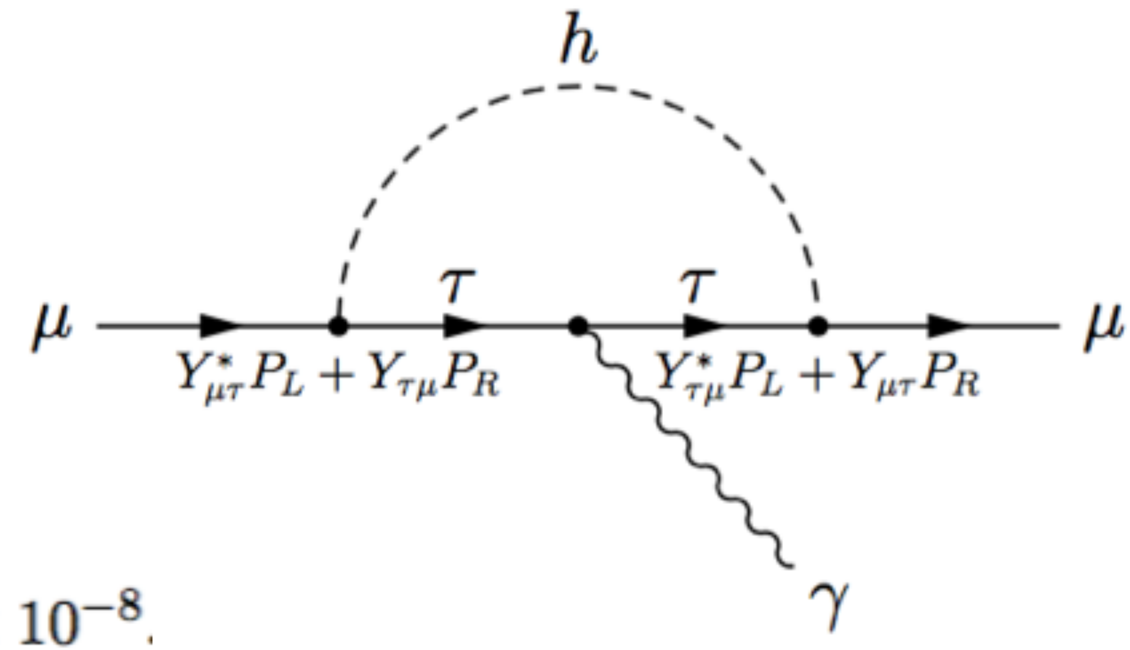


contribution to g-2 arises from

$$\mathcal{L}_{eff} = e\frac{m_{l_j}}{2}\bar{l}_i\sigma_{\mu\nu}F^{\mu\nu}(L_{ij}P_L + R_{ij}P_R)l_j$$

Muon $g-2$: $\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu}) < (2.7 \pm 0.75) \times 10^{-3}$

Electron $g-2$: $\mathrm{Re}(Y_{e\tau}Y_{\tau e}) < [-2.1, 2.9] \times 10^{-3}$



Complex phases constrained by EDMs

$$|\mathrm{Im}(Y_{e\tau}Y_{\tau e})| \lesssim 1.1 \times 10^{-8} \qquad |\mathrm{Im}(Y_{e\mu}Y_{\mu e})| \lesssim 9.8 \times 10^{-8}.$$

$\mathcal{L}_{\rm eff} = c_L Q_L + c_R Q_R$ with

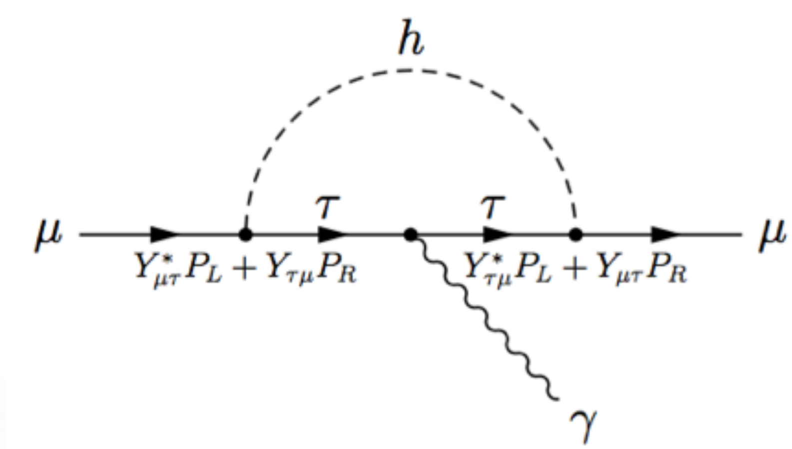
$$Q_{L/R} = \frac{e}{8\pi^2} m_\tau (\bar{\mu}\sigma^{\alpha\beta}P_{L/R}\tau)F^{\alpha\beta}$$

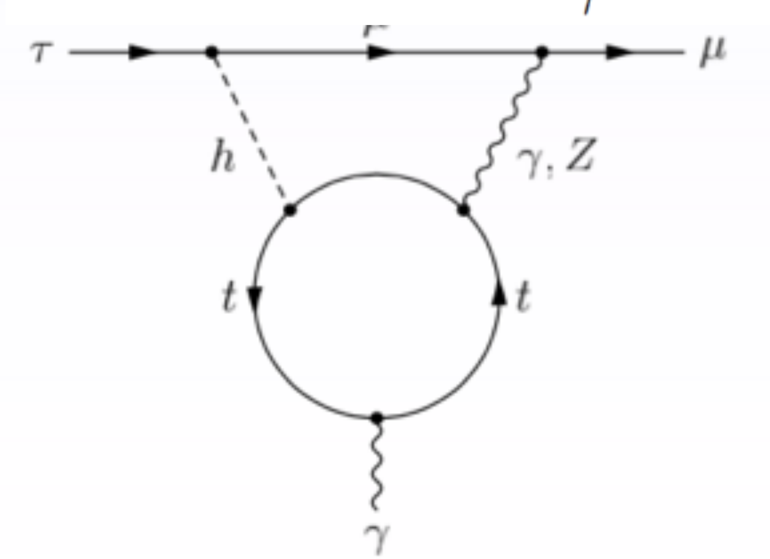
The Wilson coefficients at 1-Loop:

$$c_{L/R}^{1loop} \sim \frac{1}{3m_h^3} Y_{\tau\tau}Y_{\tau\mu}\left(-1 + \frac{3}{4}\log\frac{m_h^2}{m_\tau^2}\right)$$

2-loop contributions can be significant:

$$c_L^{2\rm loop} = Y_{\tau\mu}^*(-0.082\, Y_{tt} + 0.11)\frac{1}{(125\mathrm{GeV})^2}$$





Limits from direct searches

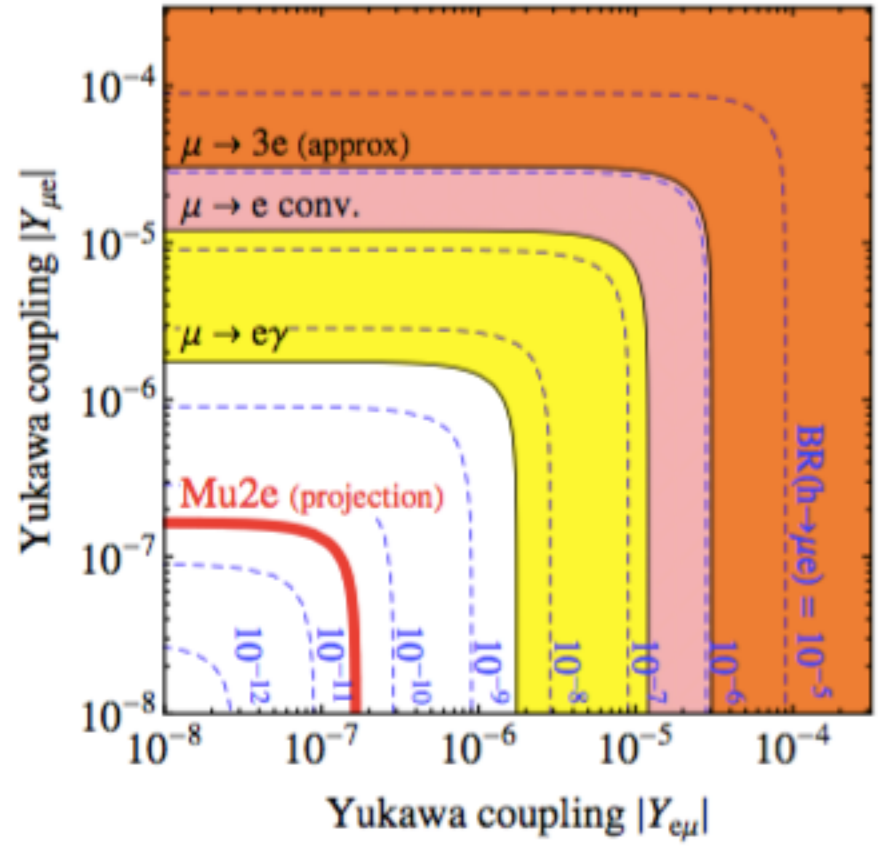
8 TeV searches

See Maria's talk

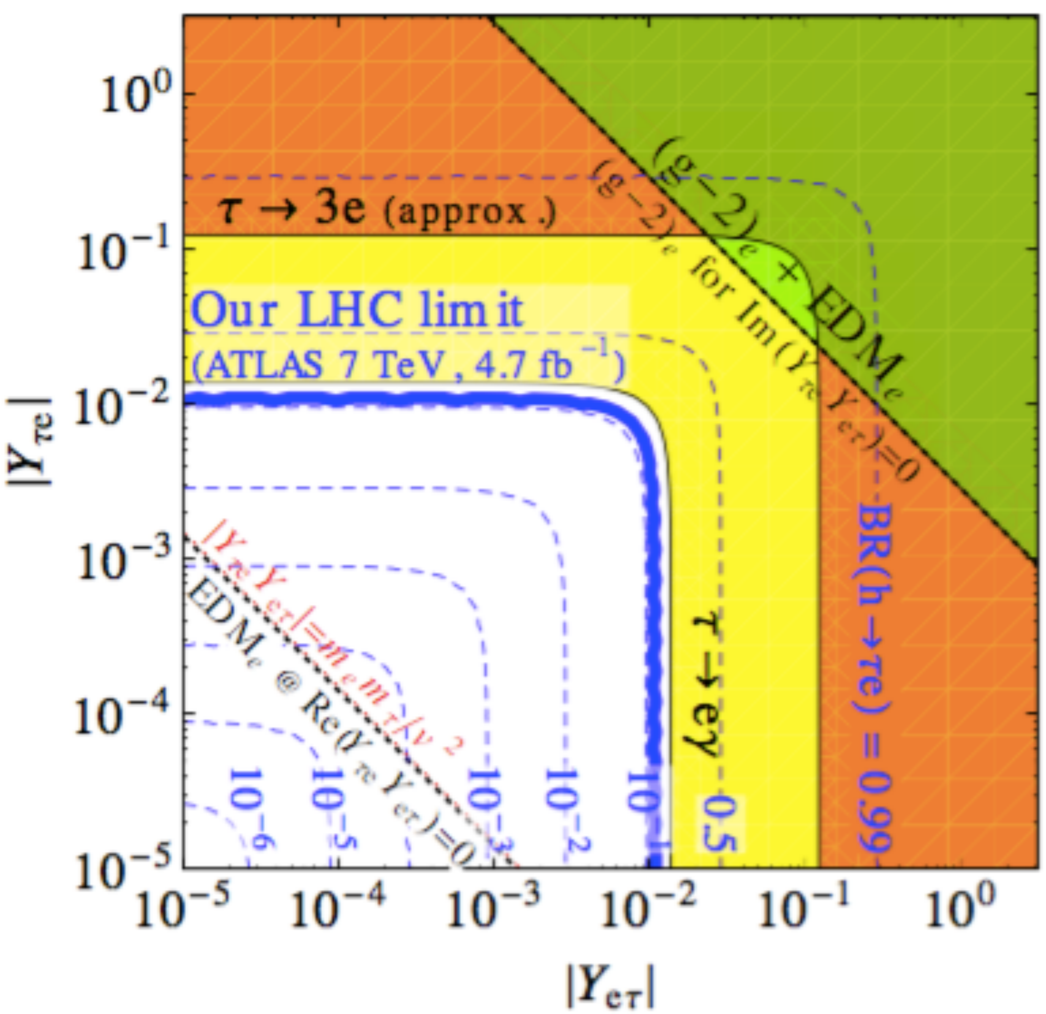
- CMS- $h \to \mu\tau \to Br(h \to \mu\tau) < 1.51\%$ at 95% C.L. 95% C.L
  ATLAS- $h \to \mu\tau \to Br(h \to \mu\tau) < 1.43\%$ at 95% C.L. 95% C.L
- CMS- $h \to e\mu \to Br(h \to e\mu) < 0.036\%$ at 95% C.L
- CMS- $h \to e\tau \to Br(h \to e\mu) < 0.69\%$ at 95% C.L
- ATLAS- $h \to e\tau \to Br(h \to e\mu) < 1.04\%$ at 95% C.L
- CMS $h \to ee \to Br(h \to ee) < 0.19\%$, $h \to \mu\mu \to Br(h \to \mu\mu) < 0.15\%$.

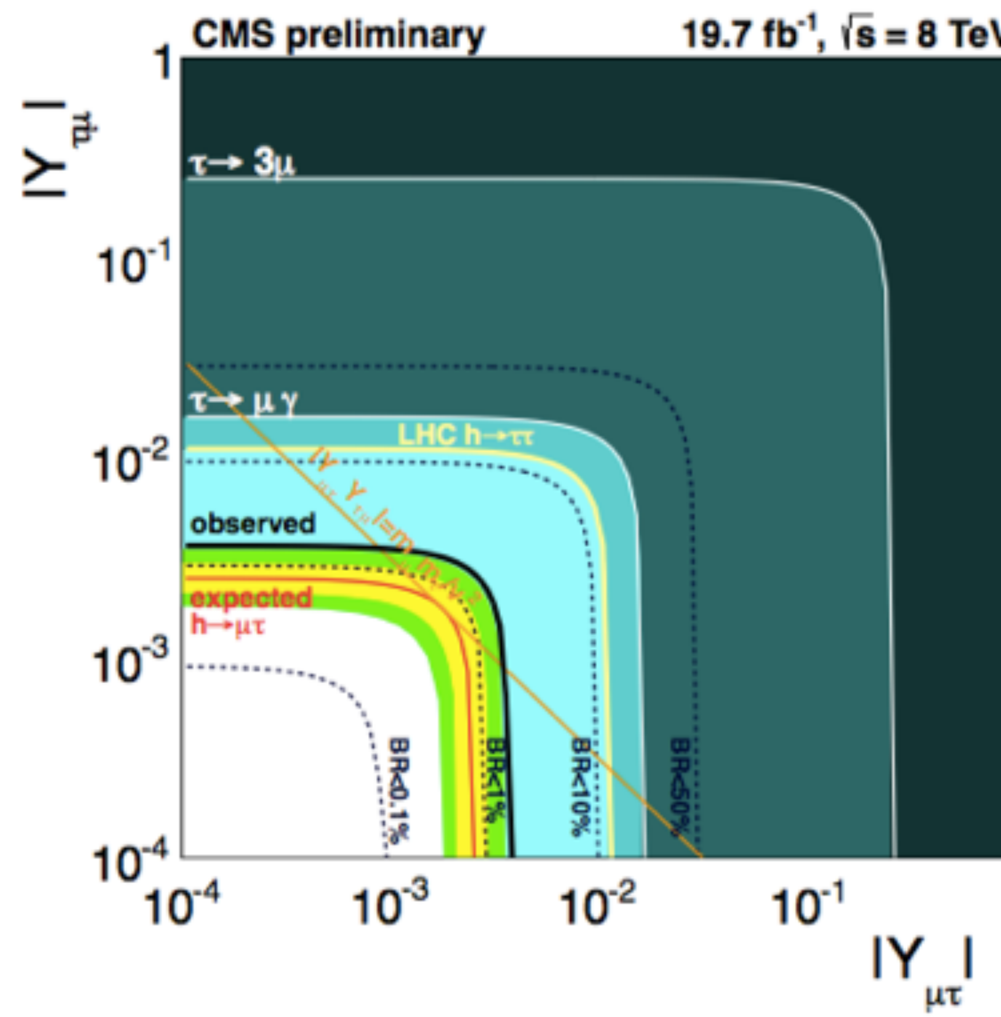
Searches	Experimental limit on branching ratios	Limits on Yukawas
$h \to \tau\mu$ (CMS)	1.51%	$Y_{\mu\tau} < 2.55 \times 10^{-3}$
	0.84%	$Y_{\mu\tau} = 1.87 \times 10^{-3}$
$h \to \tau\mu$ (ATLAS)	1.43%	$Y_{\mu\tau} < 2.45 \times 10^{-3}$
	0.77%	$Y_{\mu\tau} = 1.79 \times 10^{-3}$

Strongest constraint on $Y_{\mu\tau}$; come from direct searches



[Harnik, Kopp, Zupan '12]





[Banerjee, Bhattacherjee, Mitra, MS '16]

Summary

Direct

- $Y_{\mu\tau} < \mathcal{O}(10^{-3})$
- $Y_{e\mu} < \mathcal{O}(10^{-4})$
- $Y_{e\tau} < \mathcal{O}(10^{-3})$

Indirect

- $Y_{\mu\tau} < \mathcal{O}(10^{-2})$
- $Y_{e\mu} < \mathcal{O}(10^{-6})$
- $Y_{e\tau} < \mathcal{O}(10^{-3})$

Already now, collider searches provide strongest limit for $\mathrm{BR}(h \to \tau\mu)$

Searches	Experimental limit on branching ratios	Limits on Yukawas
$\tau \to \mu\gamma$	4.4×10^{-8} [70, 71]	$Y_{\mu\tau} < 0.011$
$\tau \to 3\mu$	2.1×10^{-8} [70, 71]	$Y_{\mu\tau} < 0.176$
Muon EDM	$-10 \times 10^{-20} e$ cm $< \lvert d_\mu \rvert < 8 \times 10^{-20} e$ cm [73]	$-0.8 \lesssim \lvert \mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu}) \rvert \lesssim 1.0$
Muon $g-2$	–	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu}) < (2.7 \pm 0.75) \times 10^{-3}$
$\tau \to \mu\gamma$ (f) (Belle-II/super KEKB)	10^{-9} [85]	$Y_{\mu\tau} < 0.0017$
$\tau \to e\gamma$	3.3×10^{-8} [70, 71]	$Y_{e\tau} < 0.0099$
$\tau \to 3e$	2.7×10^{-8} [70, 71]	$Y_{e\tau} < 0.085$
Electron $g-2$	–	$\mathrm{Re}(Y_{e\tau} Y_{\tau e}) < [-2.1, 2.9] \times 10^{-3}$
Electron EDM	$\lvert d_e \rvert \leq 0.105 \times 10^{-26}$ e cm	$\lvert \mathrm{Im}(Y_{e\tau} Y_{\tau e}) \rvert < 1.1 \times 10^{-8}$
$\tau \to e\gamma$ (f) (Belle-II/super KEKB)	10^{-9} [85]	$Y_{e\tau} < 0.00172$
$\mu \to e\gamma$	5.7×10^{-13} [70, 71]	$Y_{\mu e} < 1.24 \times 10^{-6}$
$\mu \to 3e$	1.0×10^{-12} [70, 71]	$Y_{\mu e} < 2.19 \times 10^{-5}$
Electron $g-2$	–	$\mathrm{Re}(Y_{e\mu} Y_{\mu e}) < [-0.019, 0.026]$
Electron EDM	$\lvert d_e \rvert \leq 0.105 \times 10^{-26}$ e cm	$\lvert \mathrm{Im}(Y_{e\mu} Y_{\mu e}) \rvert < 9.8 \times 10^{-8}$
$\mu \to e$ conversion	–	$Y_{\mu e} < 8.49 \times 10^{-6}$
$M - \bar{M}$ oscillations	–	$\lvert Y_{\mu e} + Y_{e\mu}^* \rvert < 0.079$
$\mu \to e\gamma$ (f) (MEG-II)	4×10^{-14} [84]	$Y_{\mu e} < 3.28 \times 10^{-7}$
$\mu \to e\gamma$	5.7×10^{-13}	$Y_{\mu\tau} Y_{e\tau} < 3.98 \times 10^{-8}$
$h \to \tau\mu$ (CMS)	1.51% [22]	$Y_{\mu\tau} < 2.55 \times 10^{-3}$
	0.84%	$Y_{\mu\tau} = 1.87 \times 10^{-3}$
$h \to \tau\mu$ (ATLAS)	1.43% [24]	$Y_{\mu\tau} < 2.45 \times 10^{-3}$
	0.77% [25]	$Y_{\mu\tau} = 1.79 \times 10^{-3}$
$h \to \tau\mu$ (CMS)+ $\mu \to e\gamma$	0.84%, 5.7×10^{-13}	$Y_{e\tau} < 2.13 \times 10^{-5}$
$h \to \tau\mu$ (ATLAS)+ $\mu \to e\gamma$	0.77%, 5.7×10^{-13}	$Y_{e\tau} < 2.23 \times 10^{-5}$
$h \to \tau e$ (CMS)	0.69% [23]	$Y_{e\tau} < 1.69 \times 10^{-3}$
$h \to \tau e$ (ATLAS)	1.04% [24]	$Y_{e\tau} < 2.08 \times 10^{-3}$
$h \to e\mu$ (CMS)	3.6×10^{-2}% [23]	$Y_{\mu e} < 3.85 \times 10^{-4}$

HL-LHC prospects for direct LFV Higgs decay searches:

[Banerjee, Bhattacherjee, Mitra, MS '16]

$H \to \tau\mu$

- Following CMS analysis in electron channel
- Assuming 10% systematics

channel	$\mathrm{BR}\ \%$ @ 95% CL
$e\mu + \not{E}_T$	0.025 (no syst)
	0.76 (10% syst)

$H \to e\tau$

- Allowing for all 3 tau decay modes
- Cut optimisation and MVA
- Most sensitive channel $e\mu + \not{E}_T$

channel	$\mathrm{BR}\ \%$ @ 95% CL
$e\mu + \not{E}_T$	0.028 (no syst)
	0.61 (10% syst)
$ee + \not{E}_T$	0.91 (10% syst)
$e\tau_{had} + \not{E}_T$	2.06 (10% syst)

$H \to \mu e$

- Rec. straightforward
- MET veto and rather small Higgs mass window $123\ \mathrm{GeV} < m_h < 127\ \mathrm{GeV}$

channel	$\mathrm{BR}\ \%$ @ 95% CL
$e\mu$	0.0193 (10% syst)

ILC prospects for direct LFV Higgs decay searches:

$H \to \tau\mu$

[Chakrborty, Datta, Kundu '16]

- Production WBF and HZ
- Best sensitivity in Z-> jets : $\mu\tau q\bar{q}$

different polarisations and lumis

BR limit ~ O(0.1)%

$H \to e\tau$

Due to limited production cross section limited sensitivity

- Production channels HZ and WBF
- Cut optimisation incl. ETmiss
- WBF important at 1 TeV
- Overall improvement at 1 TeV small

	$\mathrm{BR}\ \%$ @ 95% CL	
250 GeV 250 ifb	0.24	e+had tau
1 TeV 1000 ifb	0.63	$e\mu + \not{E}_T$
	0.22	all channels in quad

[Banerjee, Bhattacherjee, Mitra, MS '16]

Going beyond EFT to specific scenarios

UV theories can be matched onto EFT operators
or go beyond validity of EFT

Large LFV contributions (i.e. $\mathrm{Br}(H \to \mu\tau) = 0.84^{+0.39}_{-0.37}\%$)

challenging:

- MSSM $\mathrm{BR}(h \to \tau\mu) \lesssim 10^{-4}$
  [Arana-Catania et al '13]
- RPV SUSY $\mathrm{BR}(h \to \tau\mu) \lesssim 10^{-5}$
  [Arhrib et al '13]
- Vec-like leptons $\mathrm{BR}(h \to \tau\mu) \lesssim 10^{-5}$
  [Falkowski et al '14]
- Inverse Seesaw $\mathrm{BR}(h \to \tau\mu) \lesssim 10^{-5}$
  [Arganda et al '14]

but doable:

- 2HDM Type III $\mathrm{BR}(h \to \tau\mu) \lesssim 10^{-2}$
  [Davidson, Grenier '10]
  [Harnik et al '13]
  [Kopp, Nardecchia '14]
  [Aristizabal, Sierra, Vicente '14]
- SUSY inverse Seesaw $\mathrm{BR}(h \to \tau\mu) \lesssim 10^{-2}$
  [Arganda et al '16]

LFV in MSSM

[Alony, Nir, Stamou (Yesterday)]

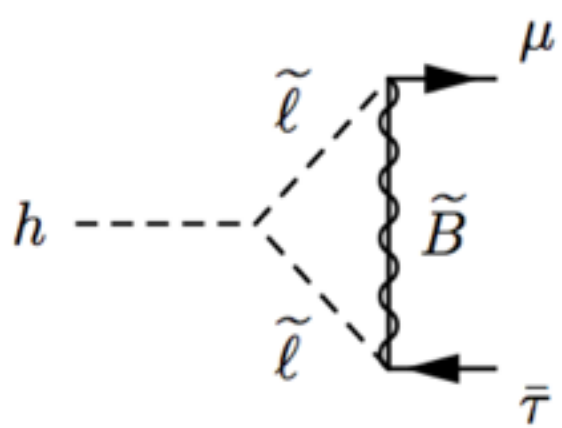
Introduce LFV soft-breaking terms

$$\mathcal{L}^{\rm LFV}_{\rm MSSM} = -\tilde{m}^2_{L_{ij}} \tilde{L}_i^\dagger \tilde{L}_j - \tilde{m}^2_{R_{ij}} \tilde{\bar{E}}_i^\dagger \tilde{\bar{E}}_j - (A^E_{ij} h_d \tilde{L}_i \tilde{\bar{E}}_j + {\rm h.c.})$$

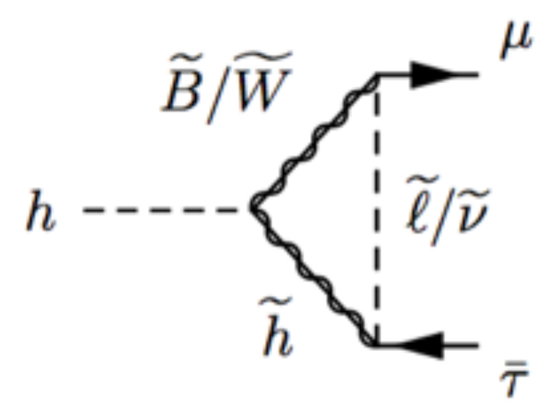
$$\tilde{\mathcal{M}}^2 = \begin{pmatrix} (\tilde{m}^2_L)_{\mu\mu} & (\tilde{m}^2_L)_{\mu\tau} & 0 \\ (\tilde{m}^2_L)^*_{\mu\tau} & (\tilde{m}^2_L)_{\tau\tau} & -m_\tau \mu t_\beta \\ 0 & -m_\tau \mu t_\beta & (\tilde{m}^2_R)_{\tau\tau} \end{pmatrix}$$

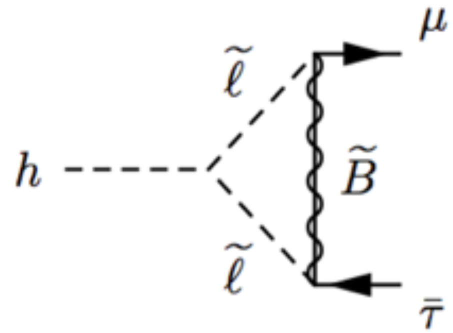
$$\tilde{\mathcal{M}}^2 = \begin{pmatrix} \tilde{m}^2_{\mu_L} & \frac{v_d A_{\mu\tau}}{\sqrt{2}} \\ \frac{v_d A_{\mu\tau}}{\sqrt{2}} & \tilde{m}^2_{\tau_R} \end{pmatrix}$$

LFV from M-terms

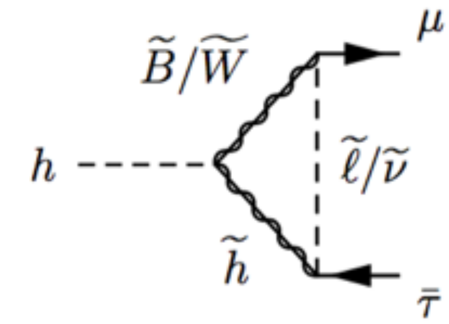


LFV from A-terms



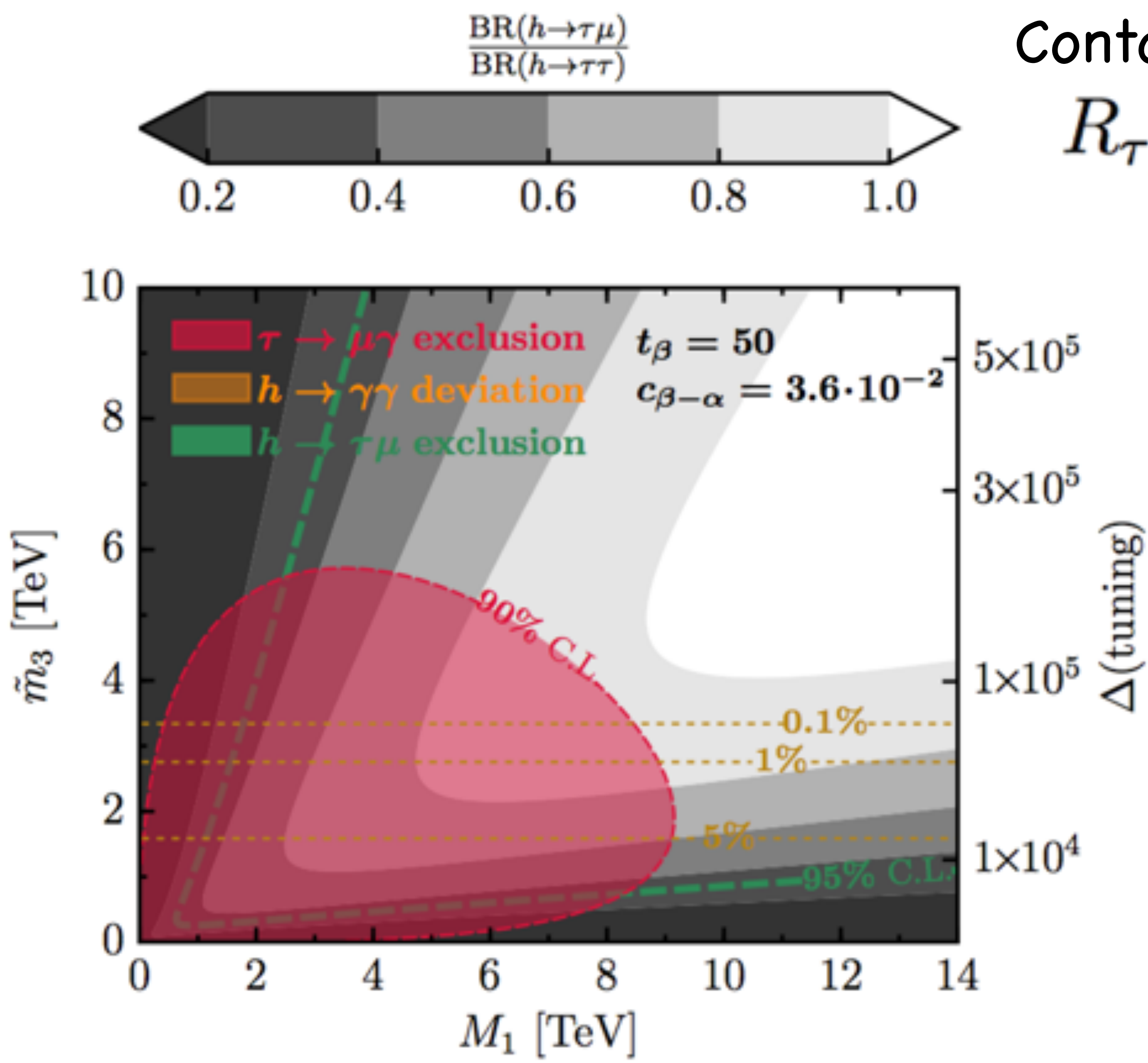


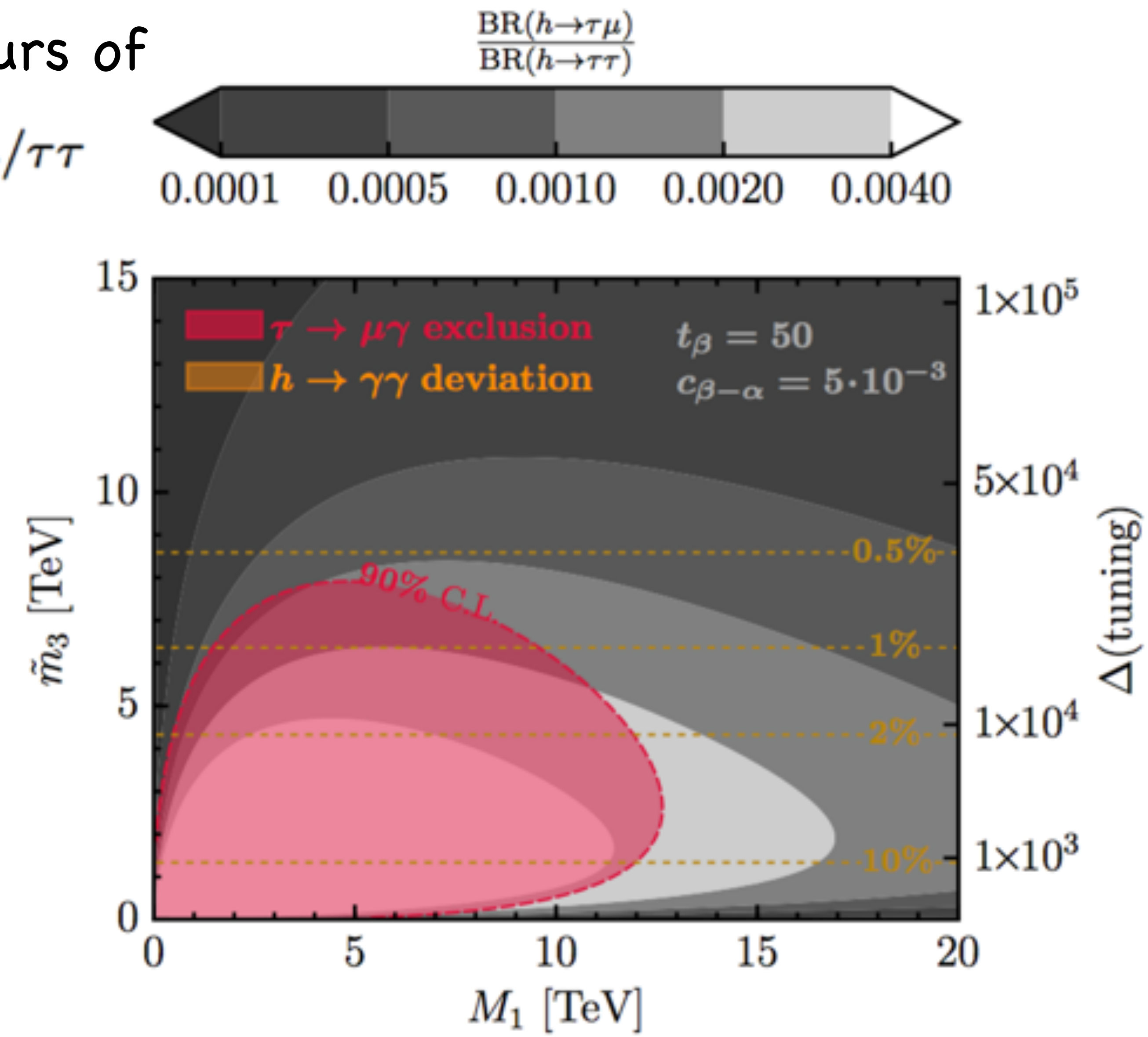
LFV from M-terms



LFV from A-terms

Contours of $R_{\tau\mu/\tau\tau}$





Very difficult to accommodate large LFV BR

Extend MSSM by Seesaw mechanism

Regular Seesaw mechanism

Introduce right-handed Neutrino $\{\nu_{L\ell}^C, N_{R\alpha}\}$

Define Majorana mass term $$-\mathcal{L}_M = \frac{1}{2}(M_N)_{\alpha\beta}\bar{N}_{R\alpha}^C N_{R\beta} + \text{H.c.}$$

From mass matrix $$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^{\mathsf{T}} & M_N \end{pmatrix}$$

obtain neutrino masses $$M_\nu \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}$$

ans LR mixings $$V_{\ell N_\alpha} \sim M_D M_N^{-1}$$

→ either large mixing or small masses

Inverse Seesaw mechanism

Introduce right-handed Neutrino and singlet fermion $\{(\nu_{L\ell})^C, N_{R\alpha}, (S_{L\rho})^C\}$ with $L(N_R) = +1 = -L(S_L)$

mass terms
$$-\mathcal{L}_Y = h_{l\alpha}\bar{L}_\ell\widetilde{\Phi}N_{R\alpha} + (M_S)_{\rho\alpha}\bar{S}_{L\rho}N_{R\alpha}$$
$$+\frac{1}{2}\left[(\mu_R)_{\alpha\beta}\bar{N}_{R\alpha}^C N_{R\beta} + (\mu_S)_{\rho\lambda}\bar{S}_{L\rho}S_{L\lambda}^C\right] + \text{H.c.}$$

Mass matrix $$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^{\mathsf{T}} & \mu_R & M_S^{\mathsf{T}} \\ \mathbf{0} & M_S & \mu_S \end{pmatrix}$$

Neutrino masses $$M_\nu = M_D M_S^{-1}\mu_S M_S^{-1^{\mathsf{T}}} M_D^{\mathsf{T}} + \mathcal{O}(\mu_S^3)$$

LR mixings $$V_{\ell N} \simeq \sqrt{\frac{M_\nu}{\mu_S}}$$

→ small μ_S lrg. active-sterile mixing and small masses

SM + inverse Seesaw doesnt cut it:

[Arganda, Herrero, Marcano, Weiland '14]

Global fit of Neutrino and Lepton data

$\sin^2\theta_{12} = 0.306^{+0.012}_{-0.012}$ $\sin^2\theta_{23} = 0.446^{+0.008}_{-0.008}$

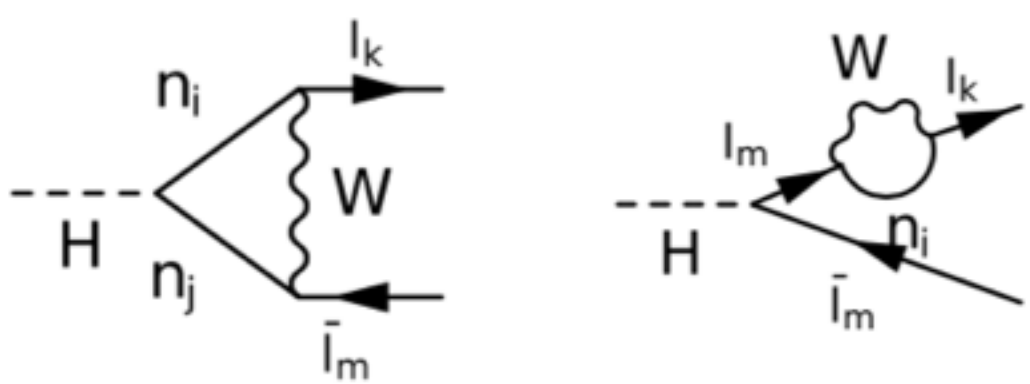
$\sin^2\theta_{13} = 0.0231^{+0.0019}_{-0.0019}$ $\frac{|Y_{ij}|^2}{4\pi} < 1.5$

$$\Delta m^2_{21} = 7.45^{+0.19}_{-0.16} \times 10^{-5}\ \mathrm{eV}^2$$

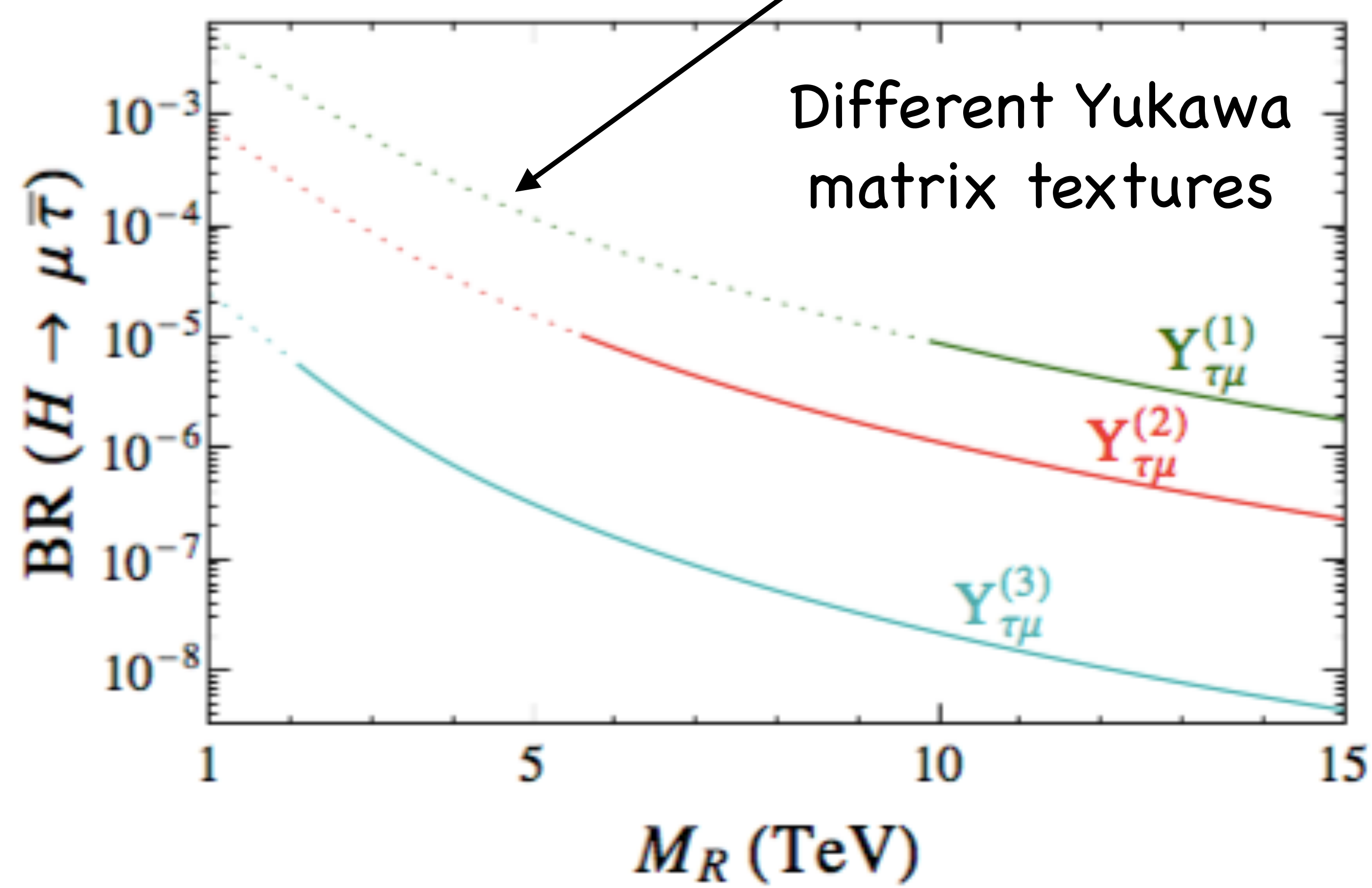
$$\Delta m^2_{31} = 2.417^{+0.014}_{-0.014} \times 10^{-3}\ \mathrm{eV}^2$$

$$\mathrm{BR}(\mu \to e\gamma) \leq 5.7 \times 10^{-13}$$
$$\mathrm{BR}(\tau \to e\gamma) \leq 3.3 \times 10^{-8}$$
$$\mathrm{BR}(\tau \to \mu\gamma) \leq 4.4 \times 10^{-8}$$

$H \to \mu\bar{\tau}$ only loop induced



violating $\mathrm{BR}(\tau \to \mu\gamma)$



Combine SUSY + inverse Seesaw = Boom

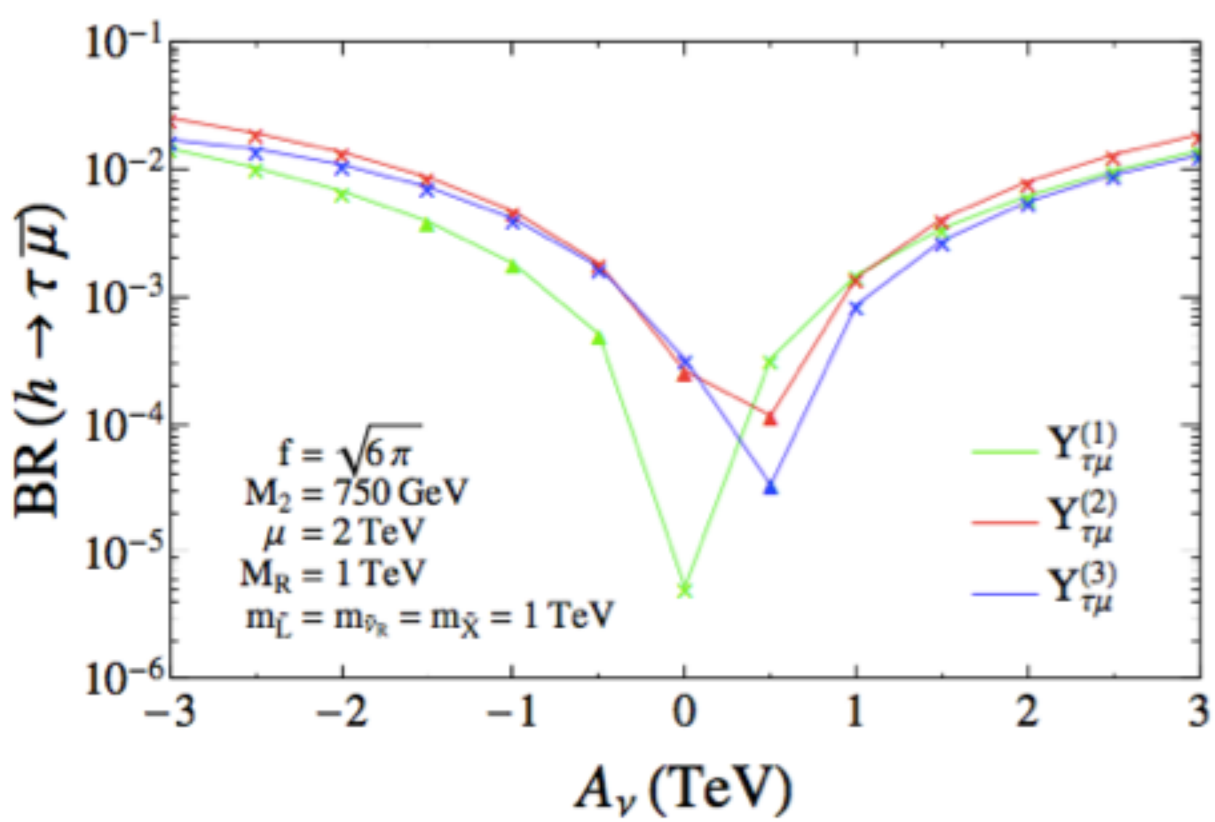
[Arganda, Herrero, Marcano, Weiland '16]

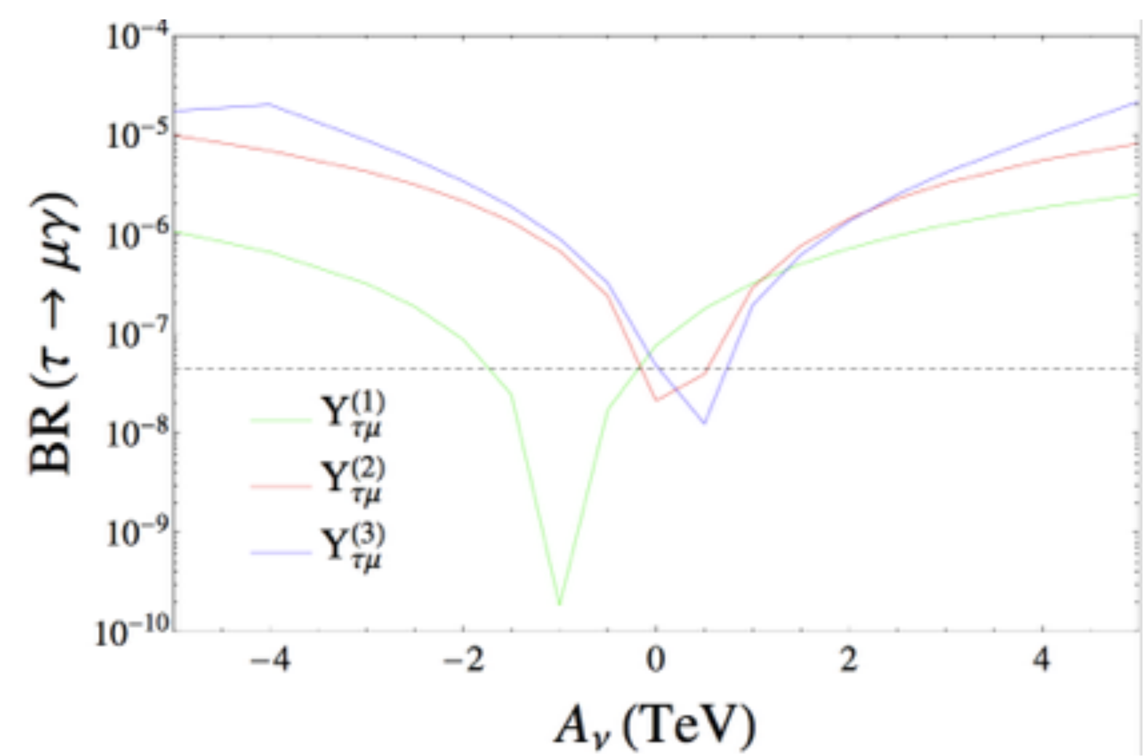
Extended soft terms

$$-\mathcal{L}_{\rm soft} = -\,\mathcal{L}_{\rm soft}^{\rm MSSM} + \widetilde{\nu}_R^T\, m^2_{\widetilde{\nu}_R}\, \widetilde{\nu}_R^* + \widetilde{X}^T m^2_{\widetilde{X}} \widetilde{X}^* \qquad (4)$$
$$+\, \widetilde{\nu}_R^\dagger (A_\nu Y_\nu) \widetilde{\nu}_L h_2^0 - \widetilde{\nu}_R^\dagger (A_\nu Y_\nu) \widetilde{e}_L h_2^+ + \text{h.c.}$$
$$+\, \widetilde{X}^\dagger (B_X \widetilde{\mu}_X) \widetilde{X}^* + \widetilde{\nu}_R^\dagger (B_R \widetilde{M}_R) \widetilde{X}^* + \text{h.c.}\,,$$

$\mathcal{L}_{\rm soft}^{\rm MSSM}$ assumed flavor diagonal,

except RGE induced $\delta_{ab} (\widetilde{L}^a)^\dagger m^2_{\widetilde{L}} \widetilde{L}^b$





→ In SUSY setup A-terms provide level to increase $\text{BR}(h \to \tau\mu)$

Honorary mentioning: 2HDM Type III

[Dorsner et al '15]

2HDM model with generic Yukawa coupling and MSSM-like scalar sector

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

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

$$x_u^k = (-\sin\alpha, -\cos\alpha, i\cos\beta)\ ,$$

$$x_d^k = (-\cos\alpha, \sin\alpha, i\sin\beta)\ .$$

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

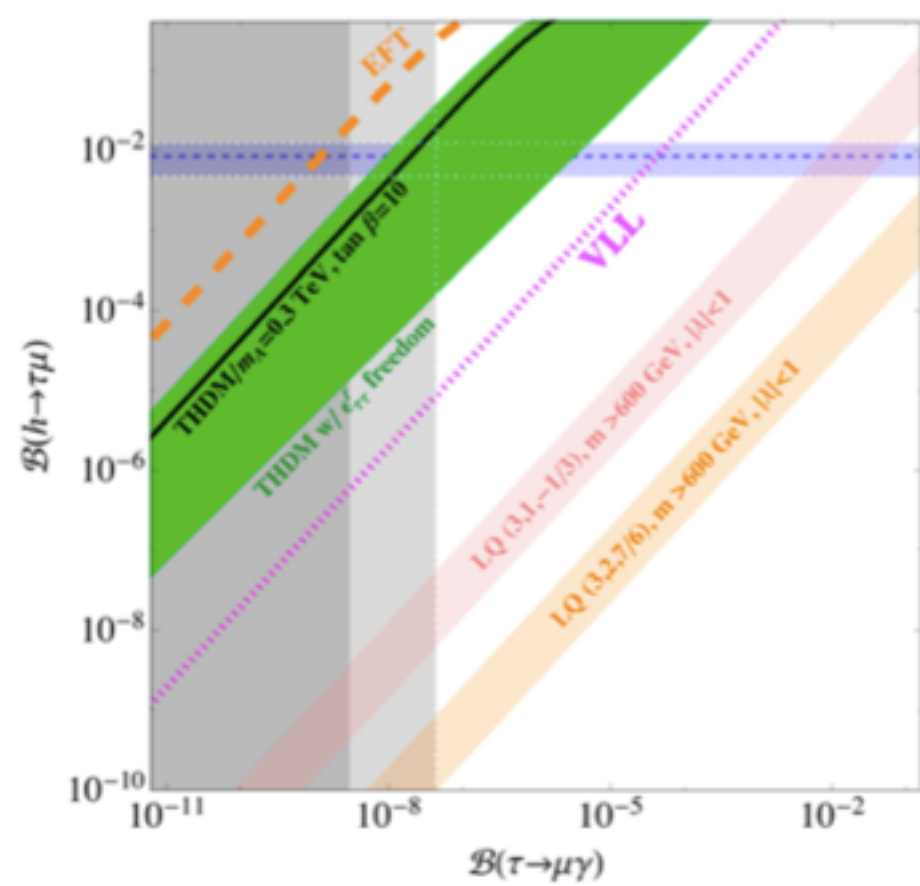
$$m_{H^\pm}^2 = m_A^2 + m_W^2 \quad m_H^2 = m_A^2 + m_Z^2 - m_h^2\,,$$

Tree-level LFV interactions allows to adjust

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

$\tau \to \mu\gamma$ $\quad$ $\mu^{\tau\tau} = 1.02^{+0.21}_{-0.20}$ $\quad$ $\tau^- \to \mu^-\mu^+\mu^-$

Higgs-tau decay



Freedom of Type III allows to accommodate signal and limits

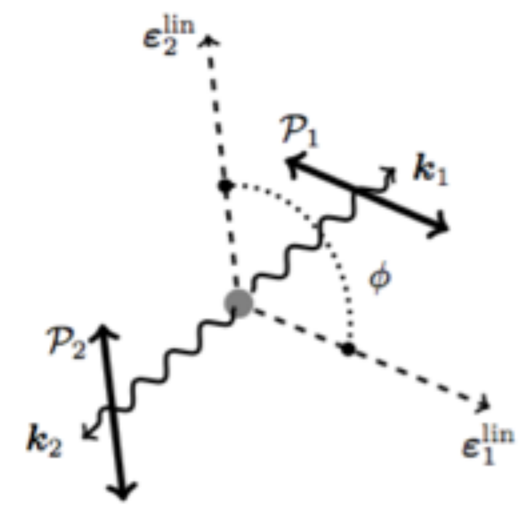
How about CP violation?

- CP violation important for matter-anti-matter asymmetry
- Lack of CP violation in SM requires us to look for new sources

[Harnik, Martin, Okui, Primulando, Yu '13]

One option, measure phase in angular distributions

$$|c_f|\frac{m_f}{v}\bar{f}(\cos\phi_f + i\gamma_5 \sin\phi_f) f h_{\rm phys}$$

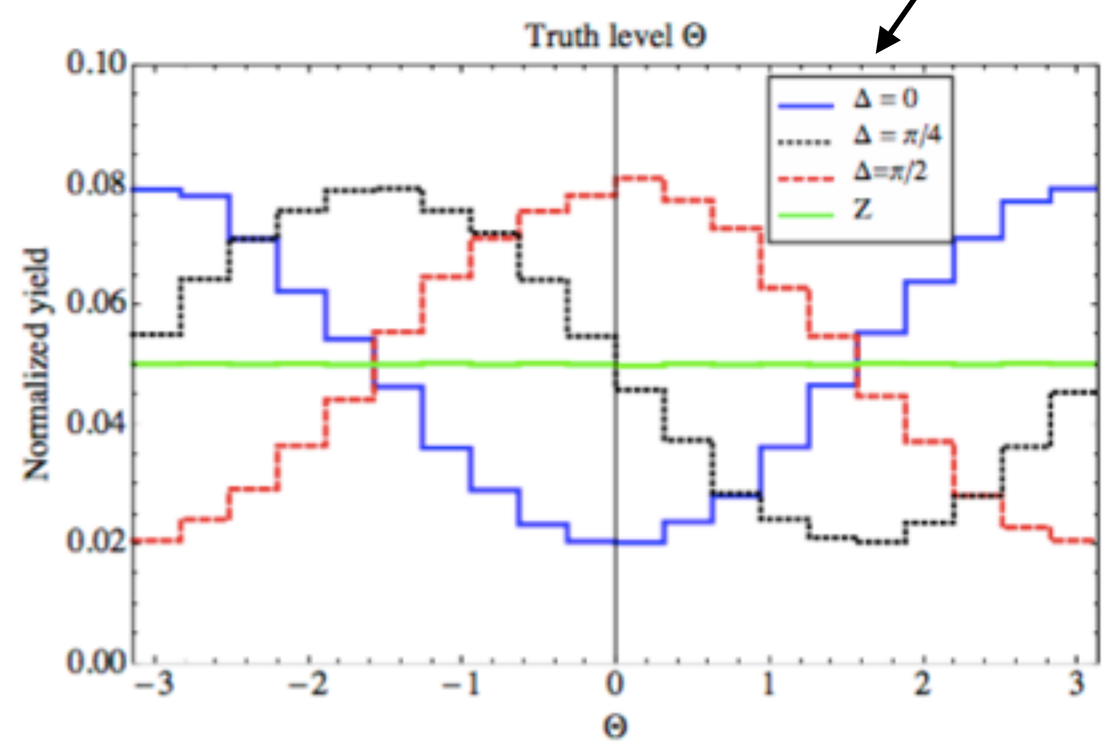


CP phase

phase in angular distributions of

$$\tau^\pm \to \rho^\pm(\pi^\pm\pi^0)\nu$$

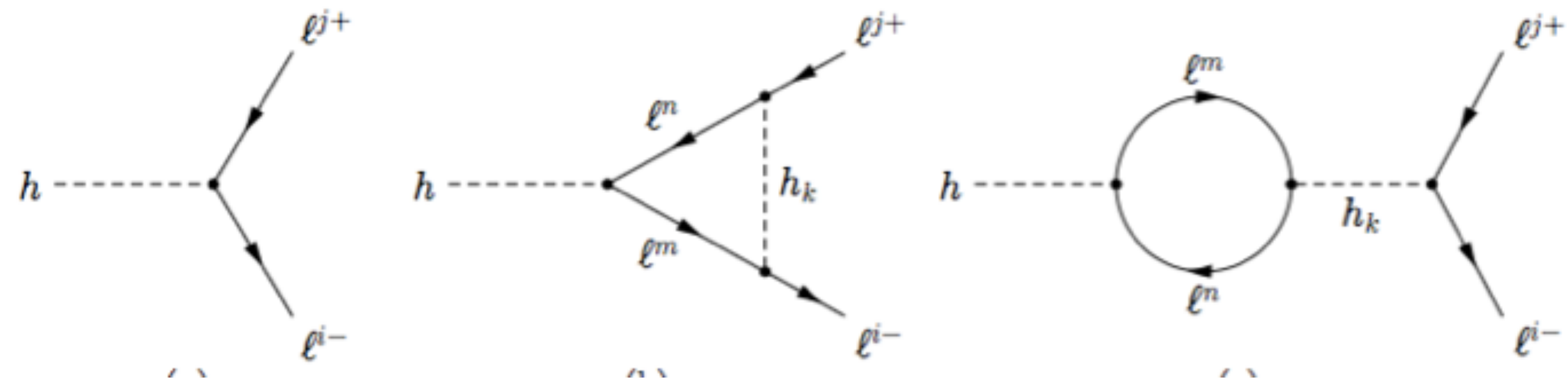
τ_h efficiency	50%	70%
3σ	$L = 550$ fb^{-1}	$L = 300$ fb^{-1}
5σ	$L = 1500$ fb^{-1}	$L = 700$ fb^{-1}
Accuracy$(L = 3$ ab$^{-1})$	11.5°	8.0°



Interference effects

[Kopp, Nardecchia '14]

Interference between tree and loop diagrams



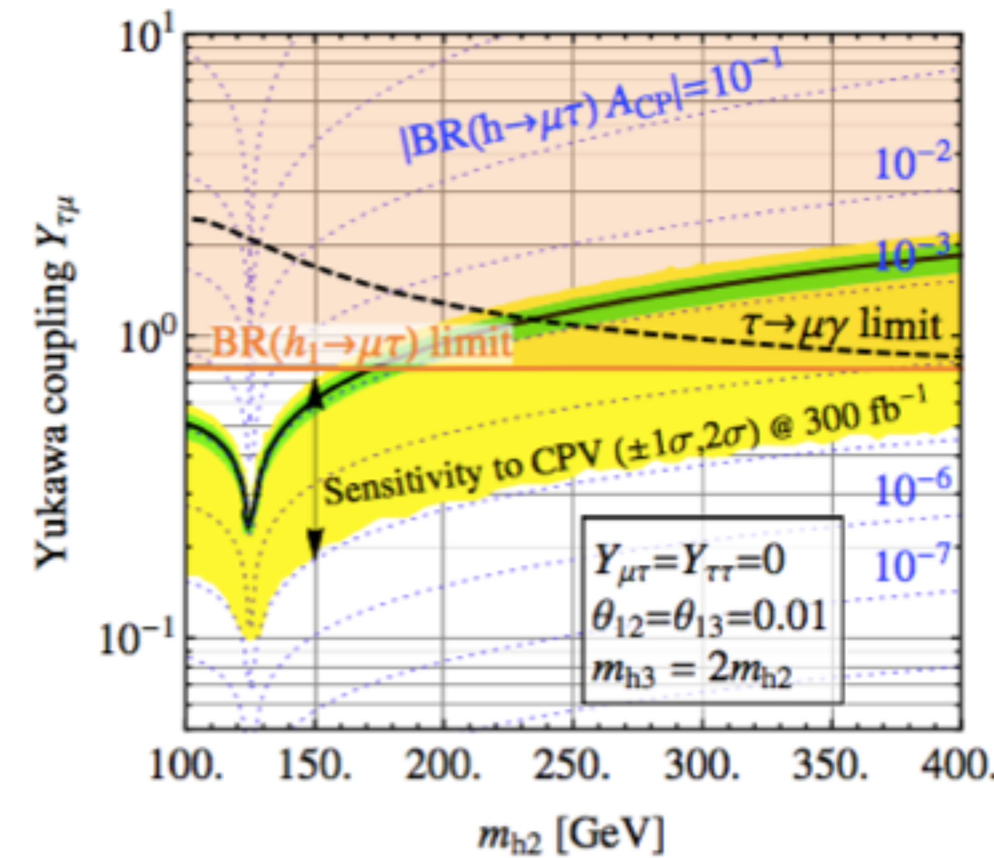
→ Asymmetry between $h \to \tau^+\mu^-$ and $h \to \tau^-\mu^+$

$$A_{CP}^{\mu\tau} = \frac{1-\log 2}{8\pi}\,\frac{\mathrm{Im}\left[Y^h_{\tau\tau}\left(Y^h_{e\mu}Y^{h*}_{e\tau}Y^{h*}_{\mu\tau} - Y^h_{\mu e}Y^{h*}_{\tau e}Y^{h*}_{\tau\mu}\right)\right]}{\left|Y^h_{\mu\tau}\right|^2 + \left|Y^h_{\tau\mu}\right|^2} + \frac{1}{8\pi}\,\frac{m_\tau^2}{m_h^2}\,\frac{\left|Y^h_{\mu\tau}\right|^2 - \left|Y^h_{\tau\mu}\right|^2}{\left|Y^h_{\mu\tau}\right|^2 + \left|Y^h_{\tau\mu}\right|^2}\mathrm{Im}\left[(Y^h_{\tau\tau})^2\right]$$

combination of all phases

300 ifb

However, enhancement possible in general Type-III 2HDM →



Summary

Golden Age of Lepton Flavor Violation:

- New sources of flavor and CP violation needed, e.g. for Leptogenesis
- Would be direct indication of physics beyond SM
- Highly sensitive low-energy experiments
- Many models where LHC provides best sensitivity
- Interesting searches for flavor violation, lepton nr violation, CP violation, ...