ENFPC 2015

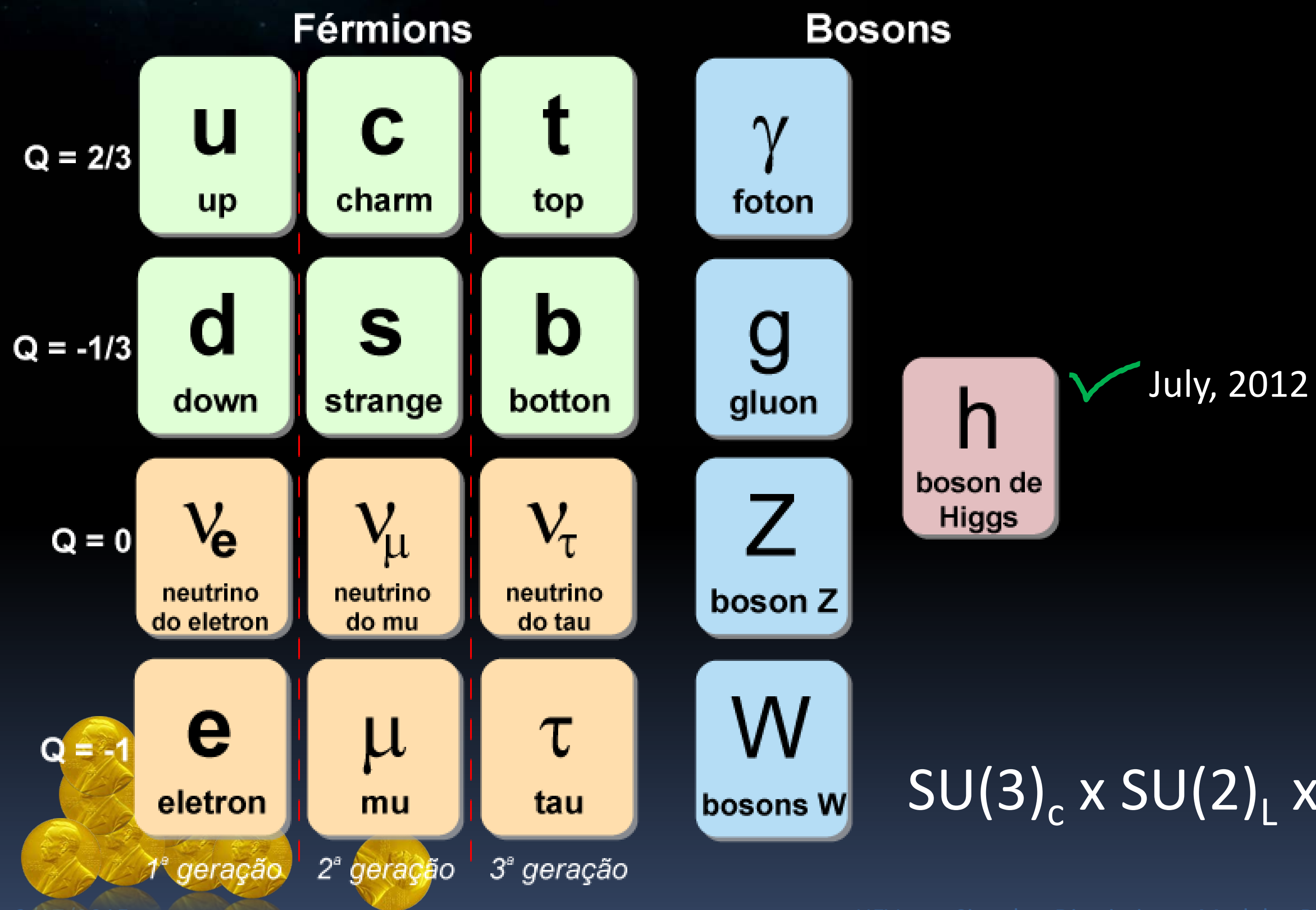
Higgs Flavor Violation as a Signal to Discriminate Models

Ricardo D'Elia Matheus

IFT - Instituto de Física Teórica - UNESP

The Standard Model

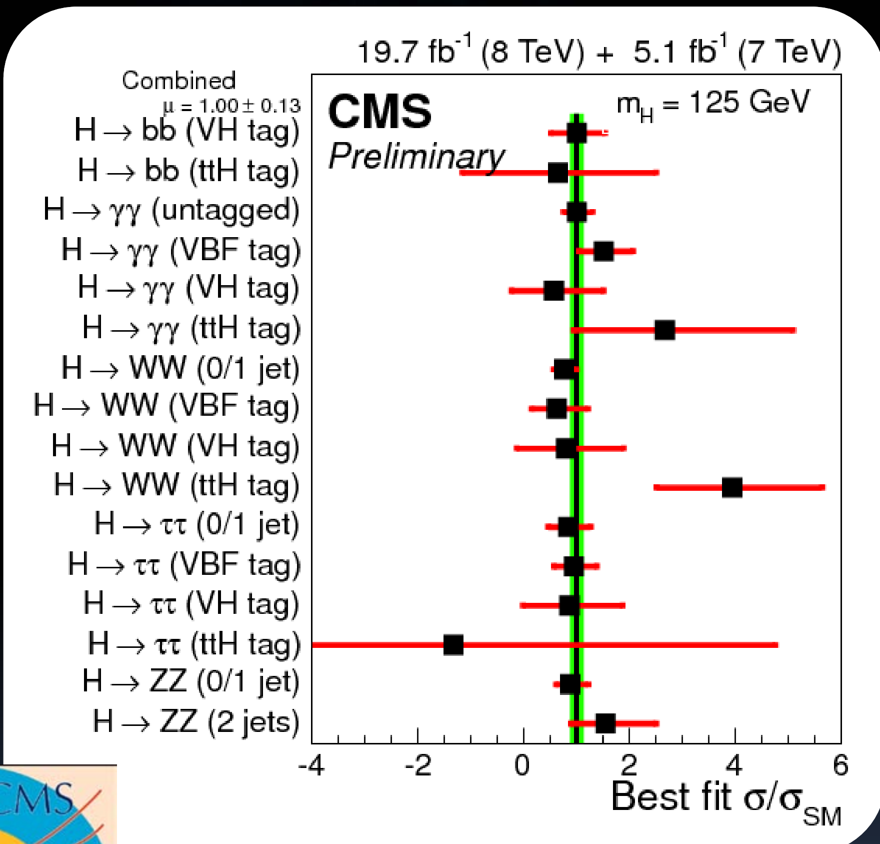
A story of success

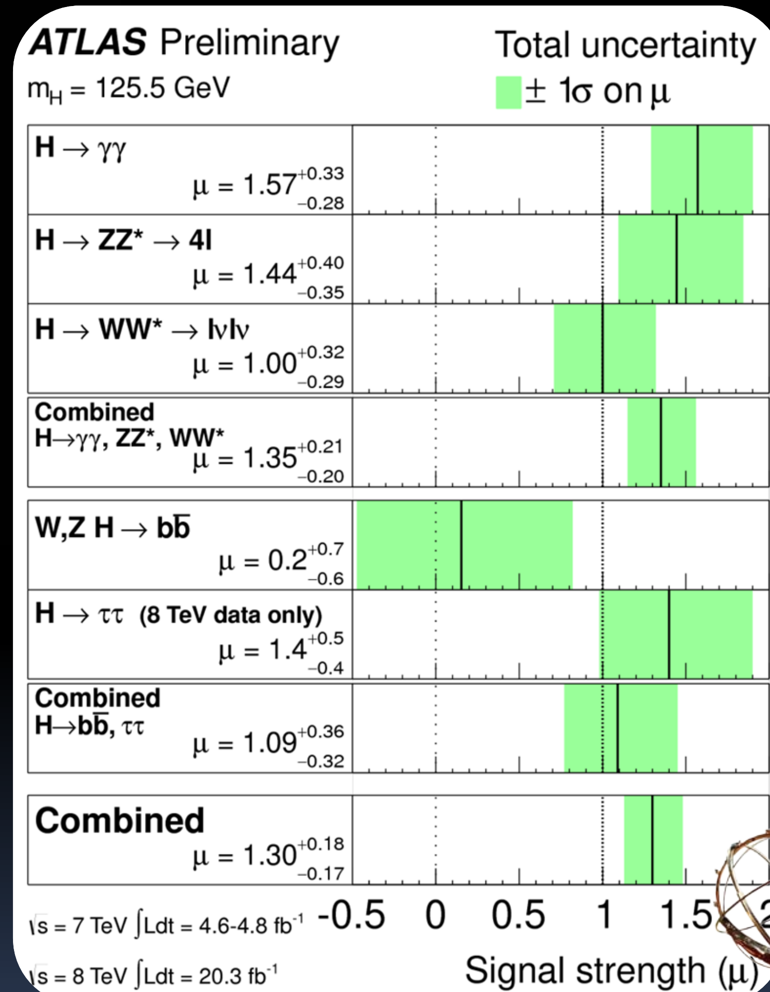


$$SU(3)_c \times SU(2)_L \times U(1)_y$$

The Standard Model

A story of success





The Standard Model

Are we done?

What about…

- …fermion masses?

$$\mathcal{L}_H = m_d \bar{d}_L d_R + h.c.$$ $$m_d = \frac{Y_d v}{\sqrt{2}}$$ $$v \approx 246 \text{ GeV}$$

$$Y_e \sim 10^{-5}$$ $$Y_u \approx Y_d \sim 10^{-3}$$ $$Y_t \sim 1$$

No idea of how!

Are neutrinos also getting mass the same way?

- …dark matter?

- …CP violation? (big enough to deal with Bariogenesis)

The Standard Model

Are we done?

What about…

- …quantum corrections (to the Higgs mass)?

$$\Lambda \sim 10^{18}\ \text{GeV}\quad (M_p)$$

$$m_h \sim \sqrt{-\mu^2 + 10^{34}\ \text{GeV}}$$ **= 125 GeV**

Set by quantum gravity

Set by EW scale physics

How can these two numbers be SO similar?

A more NATURAL situation would be having both to be set at the EW scale:

$$\Lambda \sim 10^{3}\ \text{GeV}$$

$$m_h \sim \sqrt{-\mu^2 + 10^{4}\ \text{GeV}}$$

But that means NEW PHYSICS at the TeV scale

Physics Beyond the SM (BSM)

In most cases there is a DECOUPLING LIMIT where, by making the scale Λ associated with the new physics very big, one gets:

- A theory increasingly SIMILAR to the SM. New physics effects DECREASE with INCREASING Λ.

  Precision measurements
  Agreement with SM
  → Pushes Λ away!

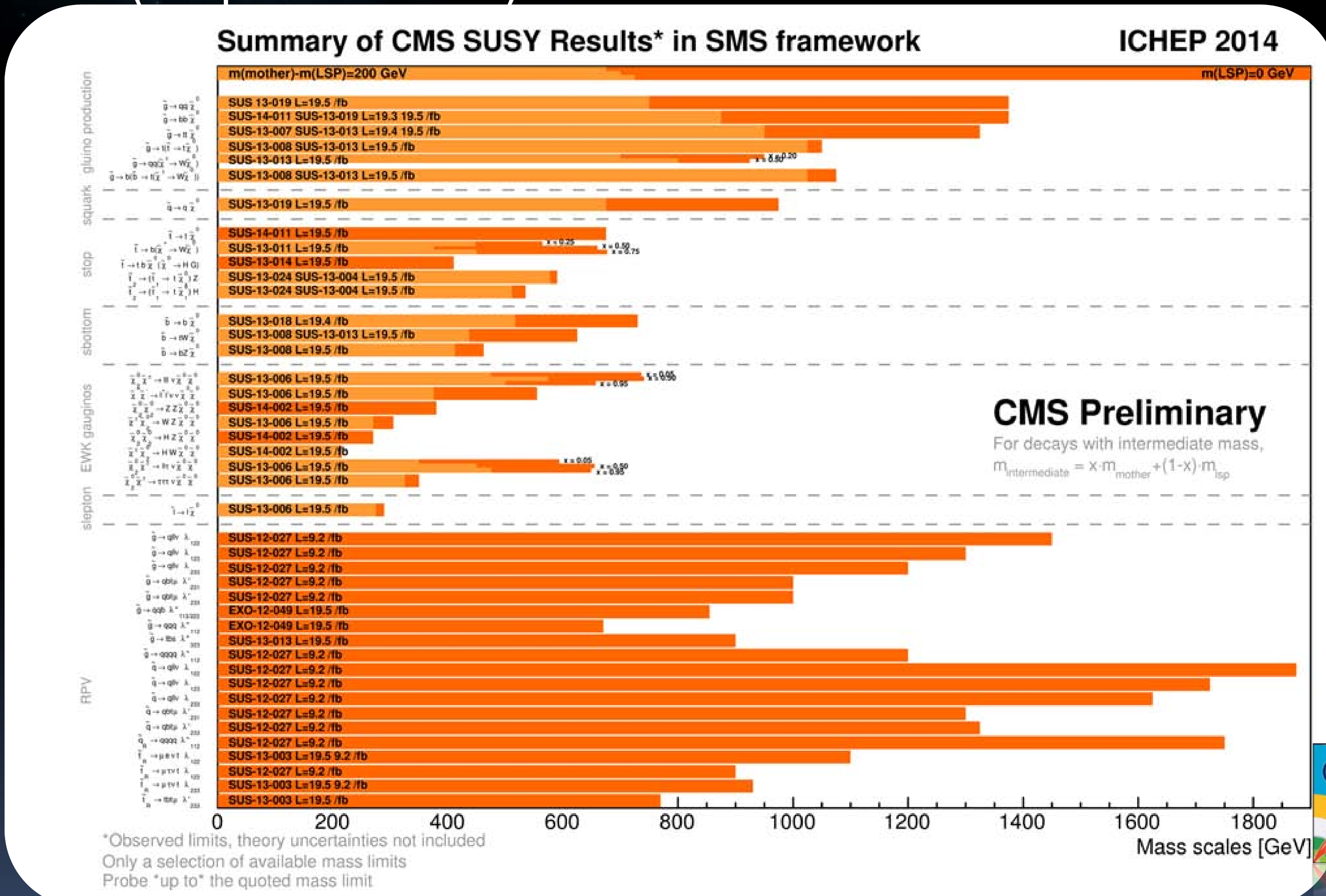
- A re-introduction of the hierarchy problem

e.g.:

The cancelling is only good if $m_t \simeq m_{\tilde{t}}$

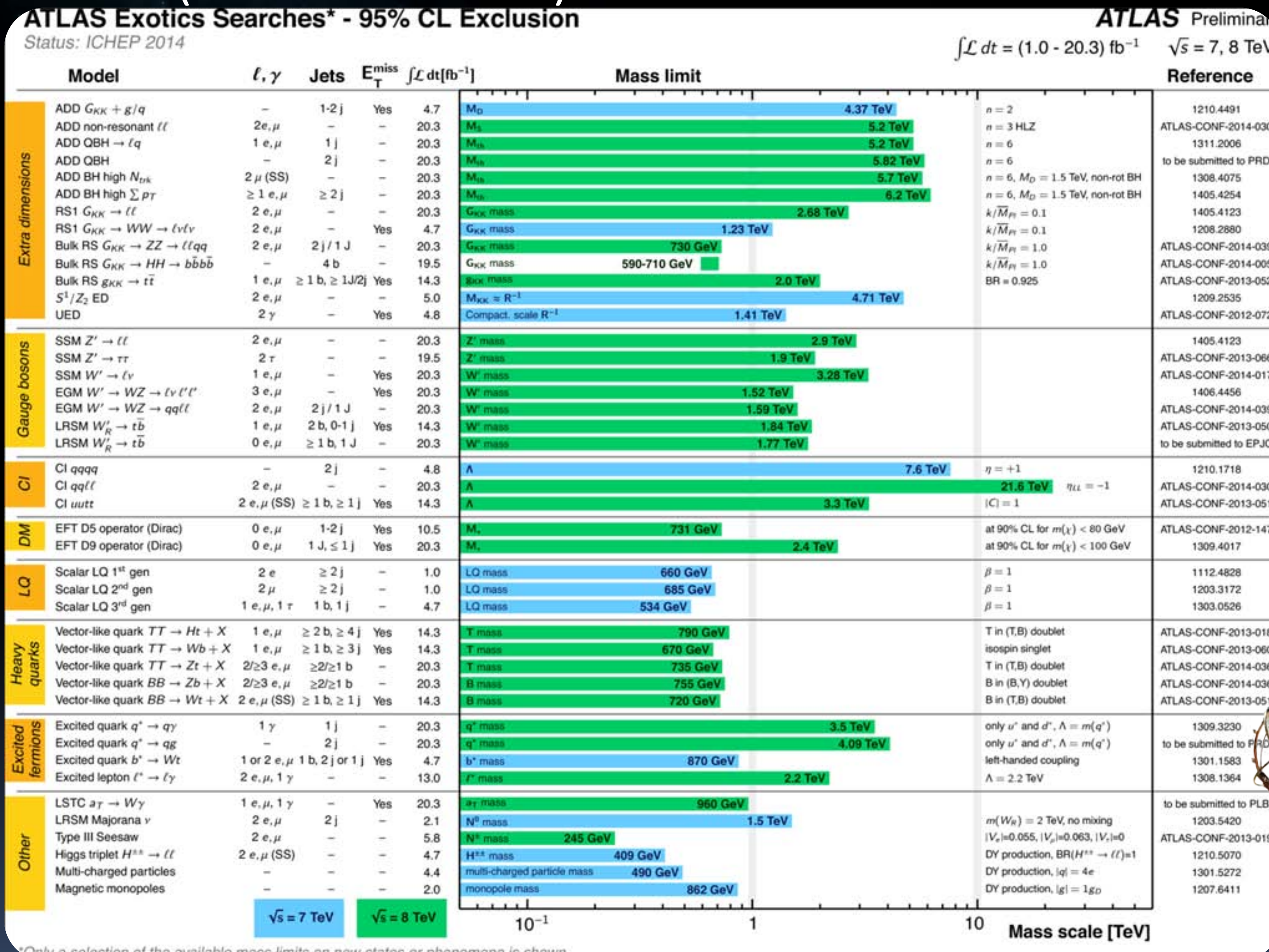
The search for BSM signals

SUSY (simplified model)



The search for BSM signals

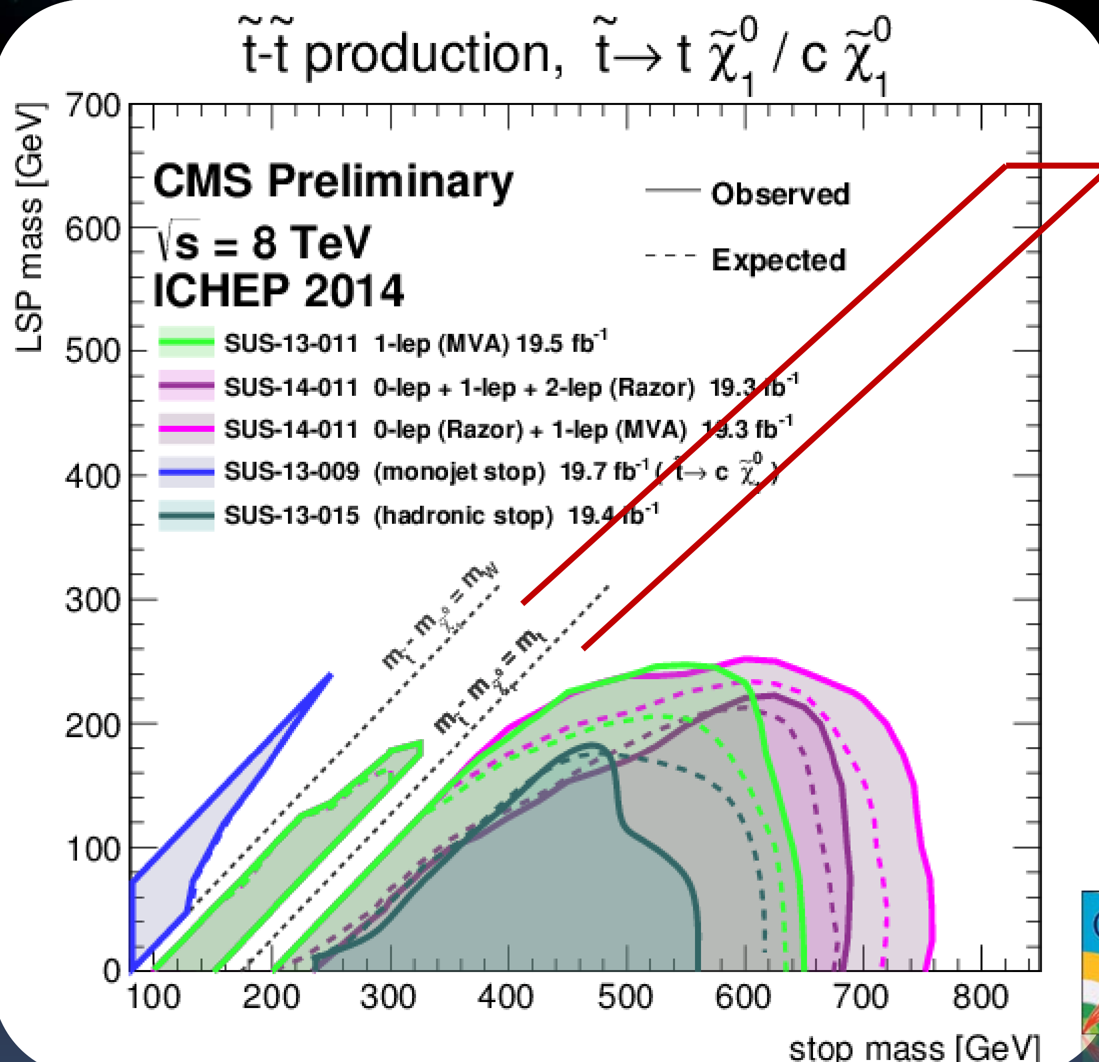
Exotics (a.k.a. non-SUSY)



Many of these limits can be directly used to restrict composite model resonances in specific models

The search for BSM signals

SUSY (simplified model)

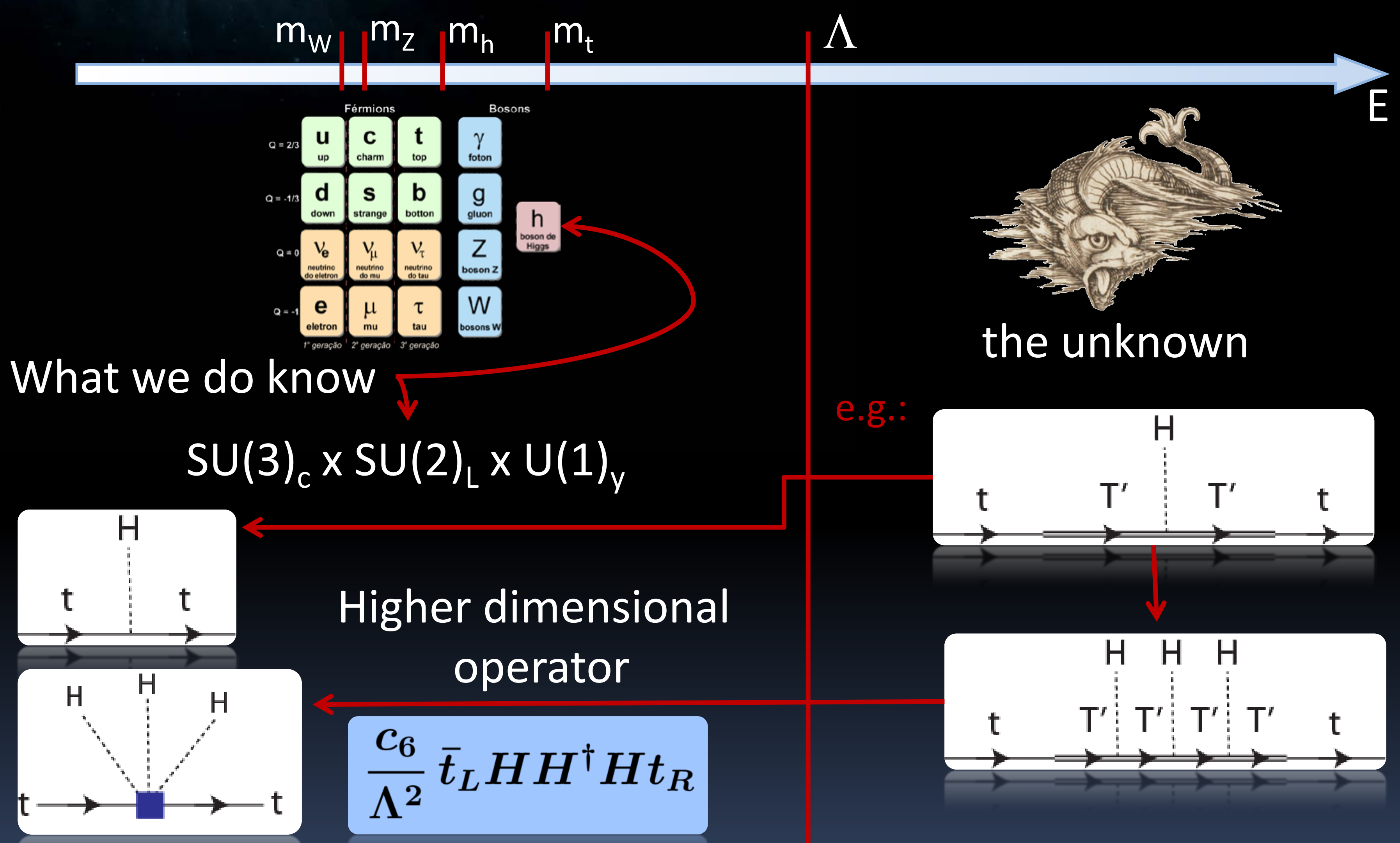


The devil in the details

Mass range exclusions don't apply uniformly on the model's parameter space and are not effective to all models

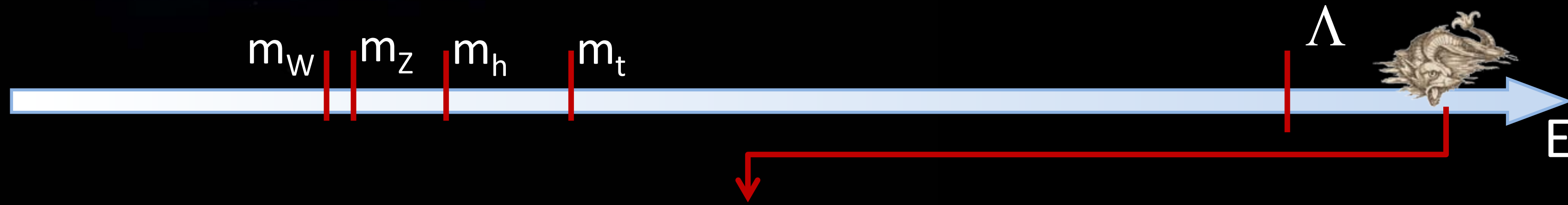
Crafty theorists can hide light particles away!

Effective Field Theories



Effective Field Theories

We can then approach the problem in the following way:



Unknown UV can generate all Higher Dimensional Operators that…

- Are built only of known fields (no new particles below Λ)
- Are invariant under $SU(3)_c \times SU(2)_L \times U(1)_y$
- Conserve barion and lepton numbers

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

59 dimension 6 operators (baring flavor and Hermitian conj.)
1 dimension 5 operator (Majorana Mass for neutrinos)

Lepton Flavor Violation

$$-\left[\lambda_{ij}(\bar{f}_L^i f_R^j)H + h.c.\right]$$ Dim 4

$$-\frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H)$$ Dim 6

$$\sqrt{2}m = V_L\left[\lambda + \frac{v^2}{2\Lambda^2}\lambda'\right]V_R^\dagger v$$

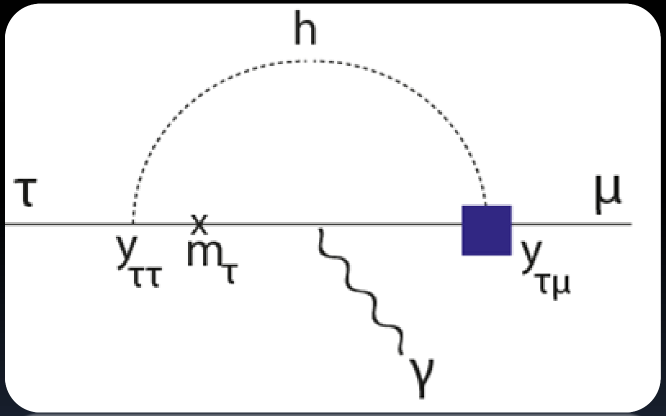
$$\sqrt{2}Y = V_L\left[\lambda + 3\frac{v^2}{2\Lambda^2}\lambda'\right]V_R^\dagger$$

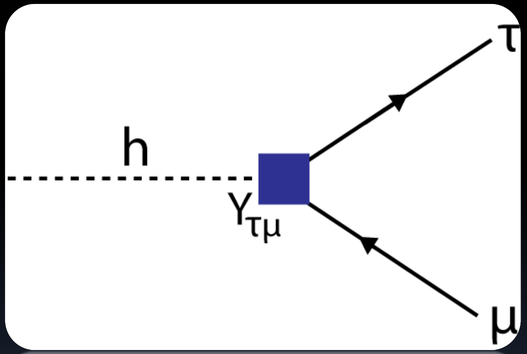
The mass and interaction matrices are not diagonal at the same time!

Lepton Flavor Violation

In the mass basis we have: $$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

Contributes to a lot of flavor violating processes, e.g.:





Lepton Flavor Violation

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 4.6 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y_{e\mu}^*\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau}Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau}Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu}Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau}Y_{e\tau}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

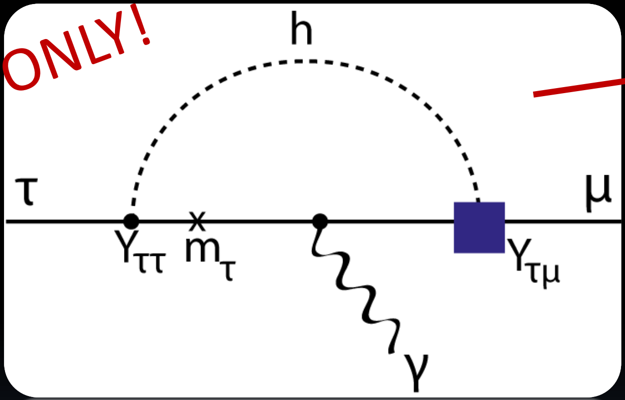
Bounds from flavor violating processes

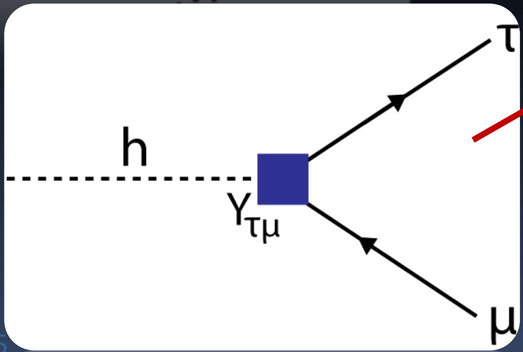
arXiv:1209.1397

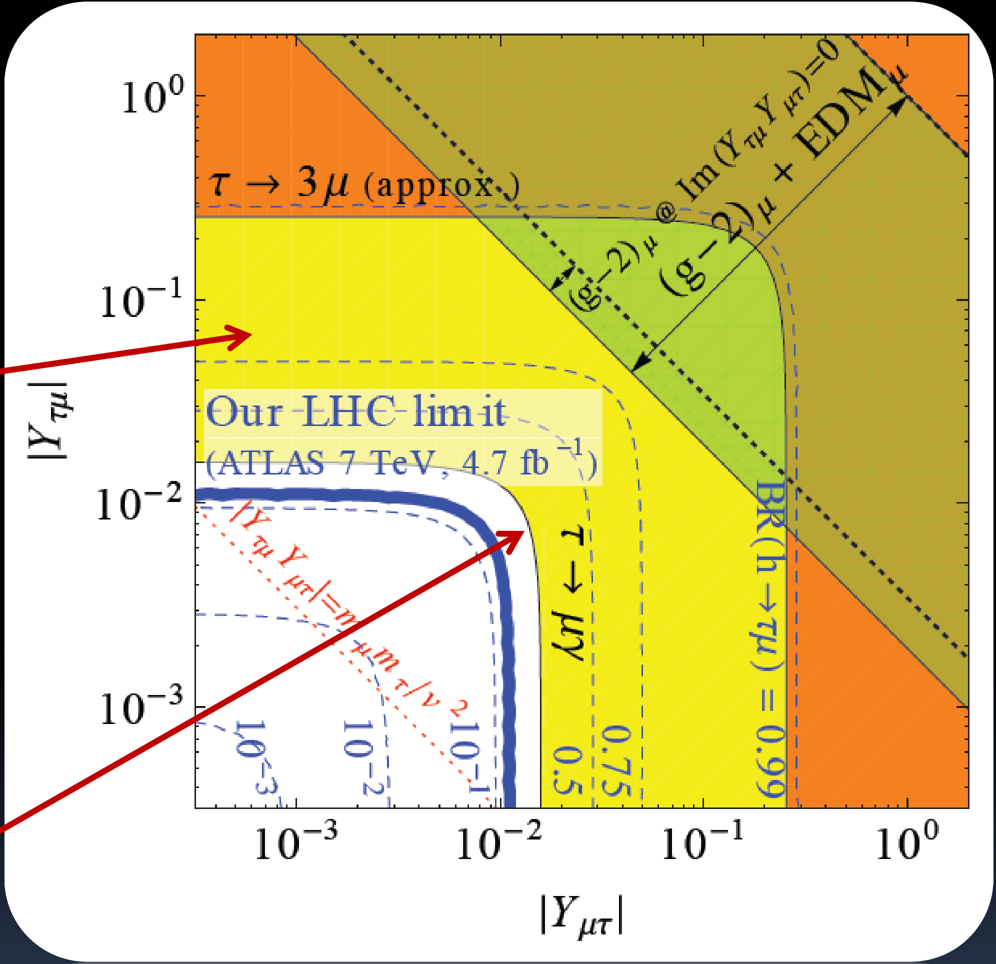
Lepton Flavor Violation

R. Harnik et al., arXiv:1209.1397

One can than use the allowed size of $y_{\mu\tau}$ to look for flavor violating Higgs decays:







Lepton Flavor Violation

One can than use the allowed size of $y_{\mu\tau}$ to look for flavor violating Higgs decays:

2.5σ excess

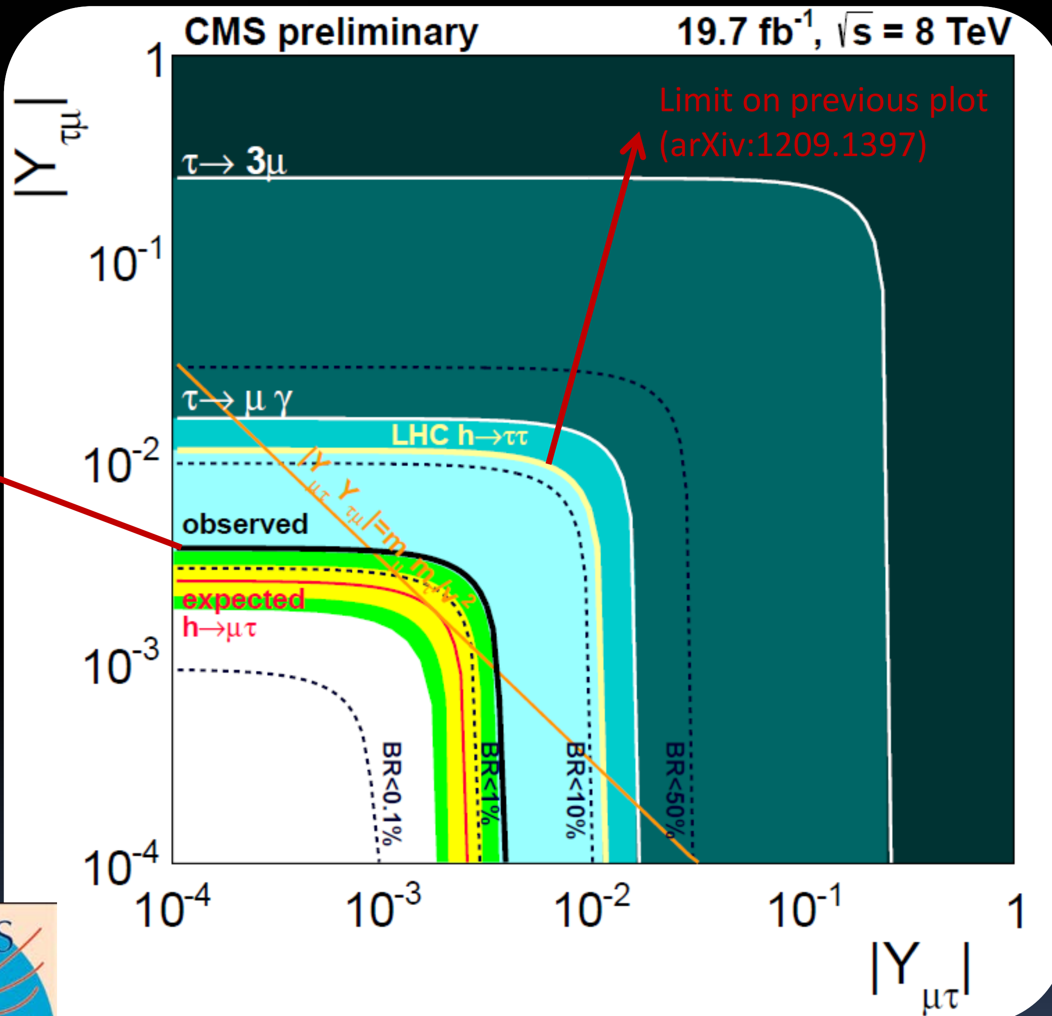
$$\mathrm{BR}(h \to \tau\mu) < 1.57\%$$

or

$$\mathrm{BR}(h \to \tau\mu) = (0.89^{+0.40}_{-0.37})\ \%$$

Atlas recently released similar results (arXiv:1508.03372)

CMS-PAS-HIG-14-005



Lepton Flavor Violation

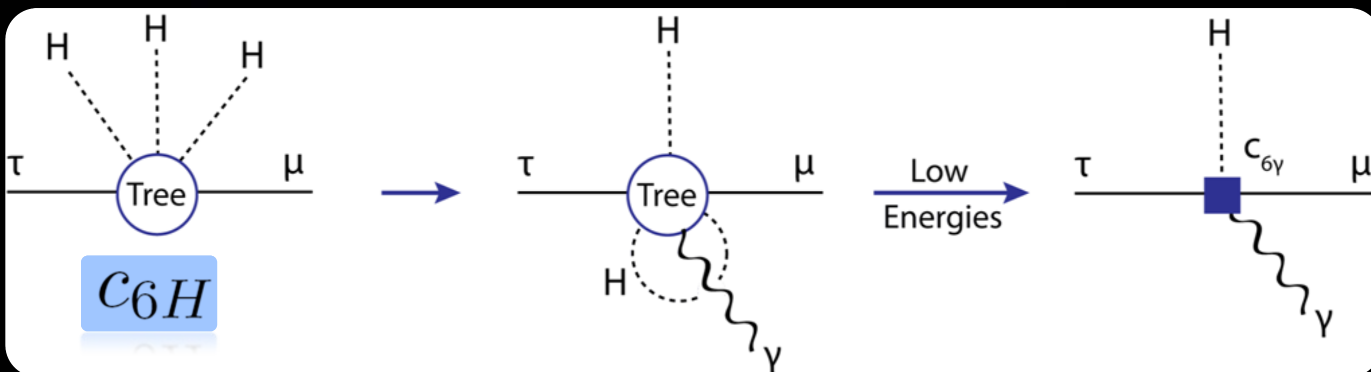
On the LFV case, we found out that most UV theories also generate one or both of the dipole operators:

$$\frac{c_{6H}}{\Lambda^2}\bar{L}HH^\dagger HE + \mathrm{h.c}$$

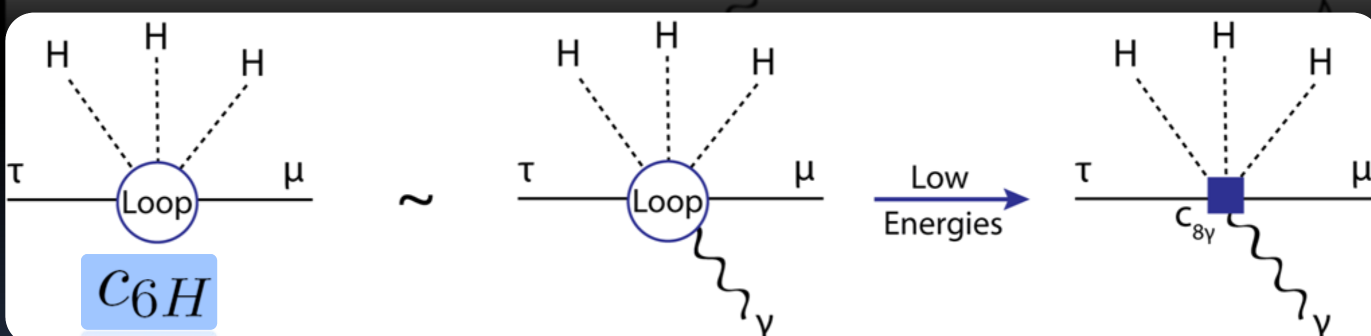
$$e\frac{c_{6\gamma}}{\Lambda^2}\bar{L}H\sigma_{\alpha\beta}EF^{\alpha\beta} + e\frac{c_{8\gamma}}{\Lambda^4}\bar{L}HH^\dagger H\sigma_{\alpha\beta}EF^{\alpha\beta} + \mathrm{h.c}$$

Lepton Flavor Violation

On the LFV case, we found out that most UV theories also generate one or both of the dipole operators:



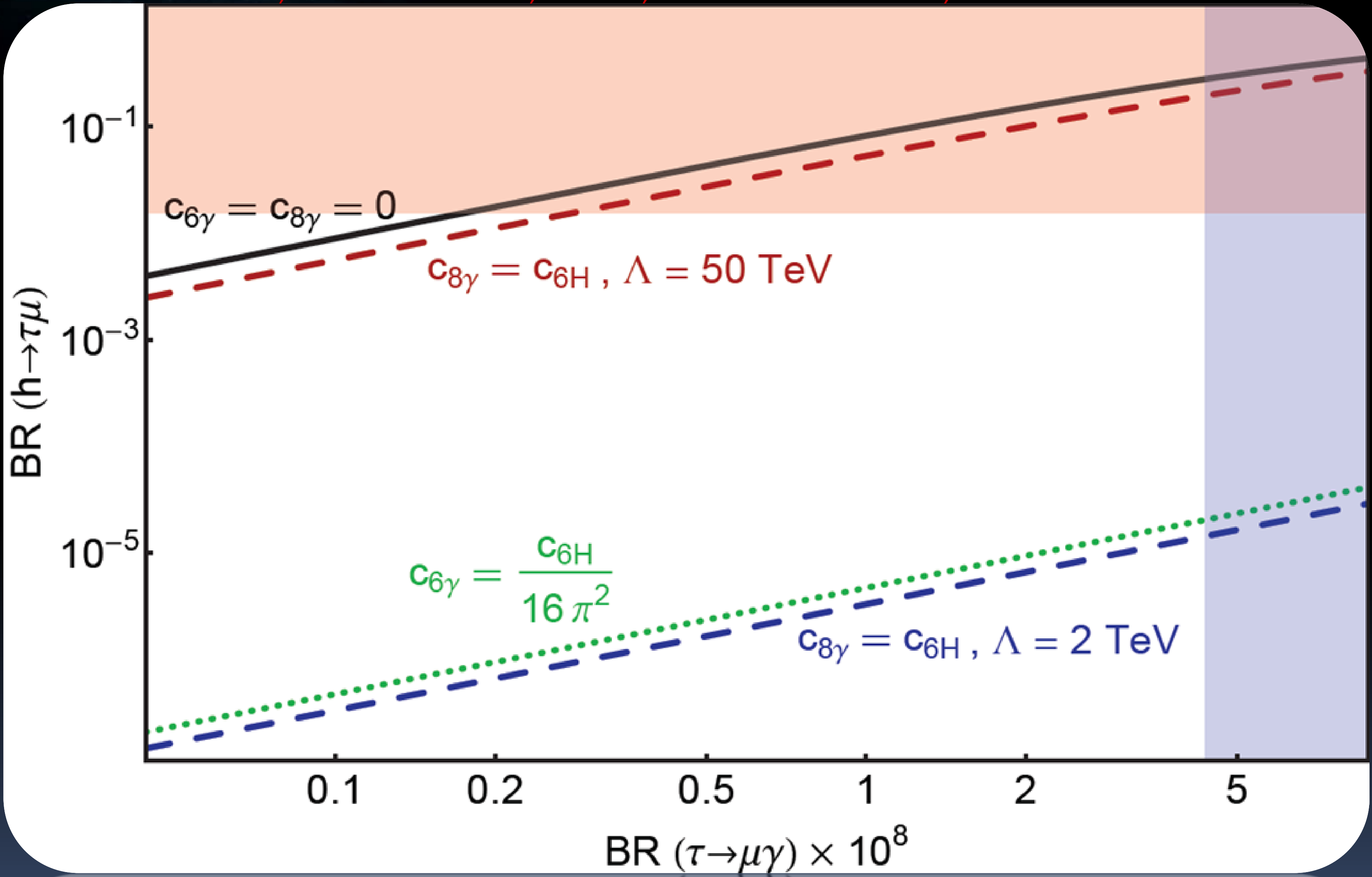
$$c_{6\gamma} \sim \frac{c_{6H}}{16\pi^2}$$



$$c_{8\gamma} \sim c_{6H}$$

Lepton Flavor Violation

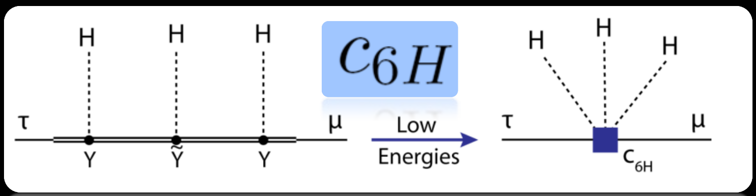
Leonardo de Lima, Camila S. Machado, R. D. M., Leônidas A. F. do Prado, arXiv:1501.06923

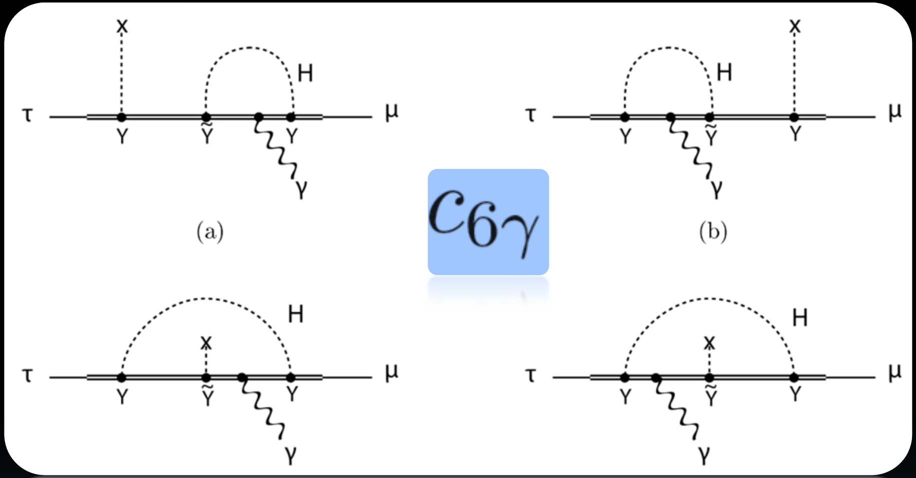


Simple UV models

Composite Sector (vector like heavy leptons):

$$\mathcal{L} = M\lambda_l \bar{L}_L \Psi_R + M\lambda_e \bar{E}_R \tilde{\Psi}_L - M c_l \bar{\Psi}\Psi - M c_e \bar{\tilde{\Psi}}\tilde{\Psi} + Y\bar{\Psi}_L H \tilde{\Psi}_R + \tilde{Y}\bar{\Psi}_R H \tilde{\Psi}_L + \text{h.c.}$$





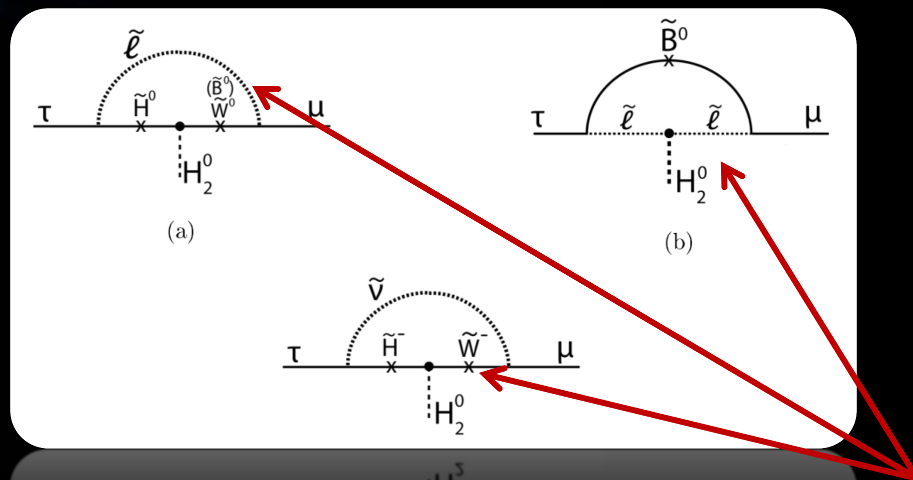
-0.6

$$c_{6\gamma} = -\frac{11}{18(4\pi)^2} c_{6H}$$

NOT responsible for $\text{BR}(h \to \tau\mu) = (0.89^{+0.40}_{-0.37})\ \%$

Simple UV models

SUSY (MSSM): at large tan(β) = v_2/v_1, LFV is dominated by:

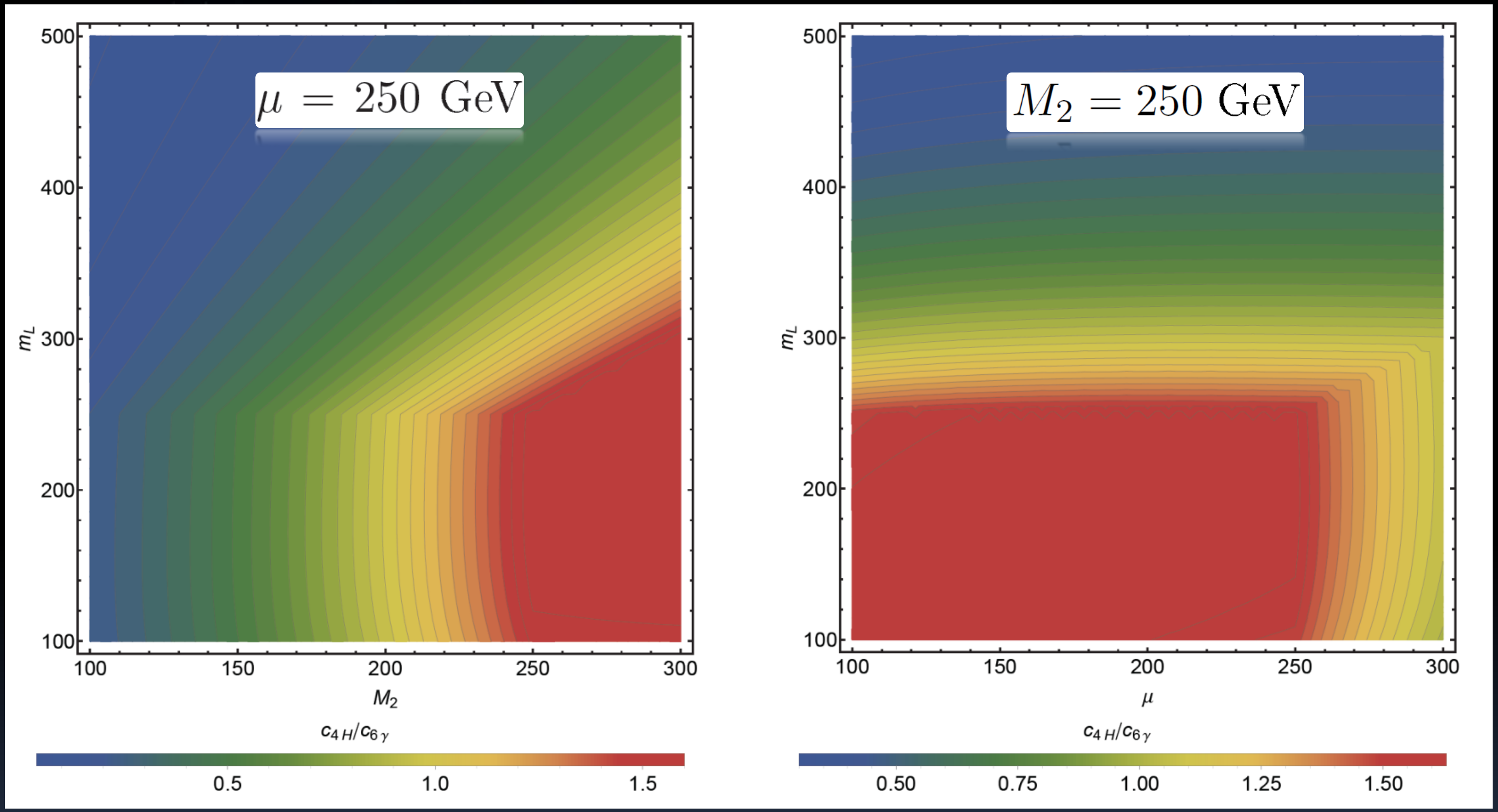


Interplay between c_{4H} and $c_{6\gamma}$ (very similar to c_{6H} vs $c_{8\gamma}$):

(a) →
$$\frac{c_{6\gamma}}{\Lambda^2} = c_{4H} \frac{2\cos\beta\sin\beta}{\cos(\alpha-\beta)} \frac{\left(I_2(M_2,\mu,\tilde{m}_{L2}^2) - \tilde{m}_{L2} \leftrightarrow \tilde{m}_{L3}\right)}{\left(I_1(M_2,\mu,\tilde{m}_{L2}) - \tilde{m}_{L2} \leftrightarrow \tilde{m}_{L3}\right)}$$

Simple UV models

SUSY (MSSM): at large tan(β) = v_2/v_1, LFV is dominated by:



$\tan\beta = 40$

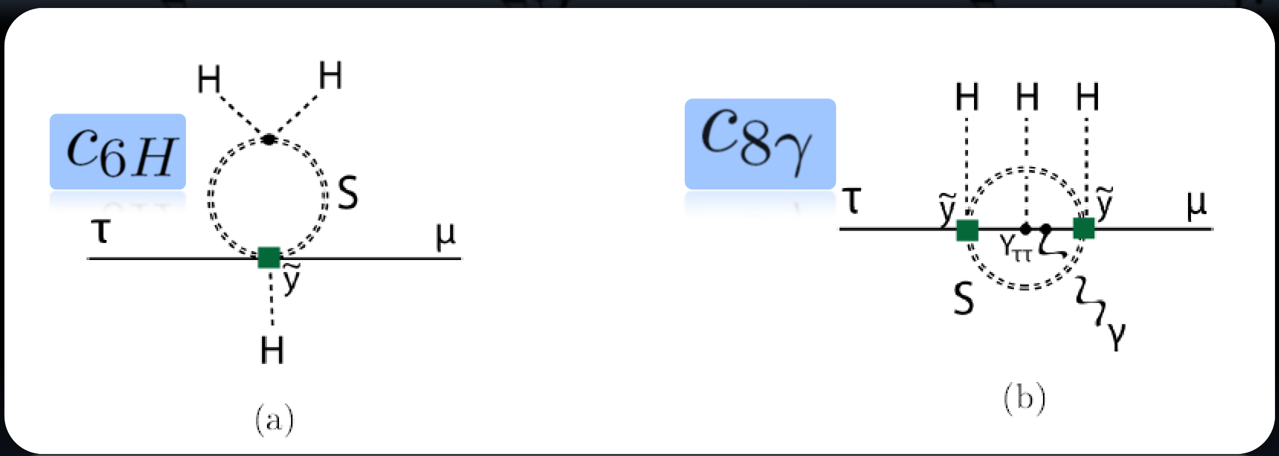
$M_A = 200$ GeV

NOT responsible for $\mathrm{BR}(h \to \tau\mu) = (0.89^{+0.40}_{-0.37})\,\%$

Simple UV models

Higgs portal:

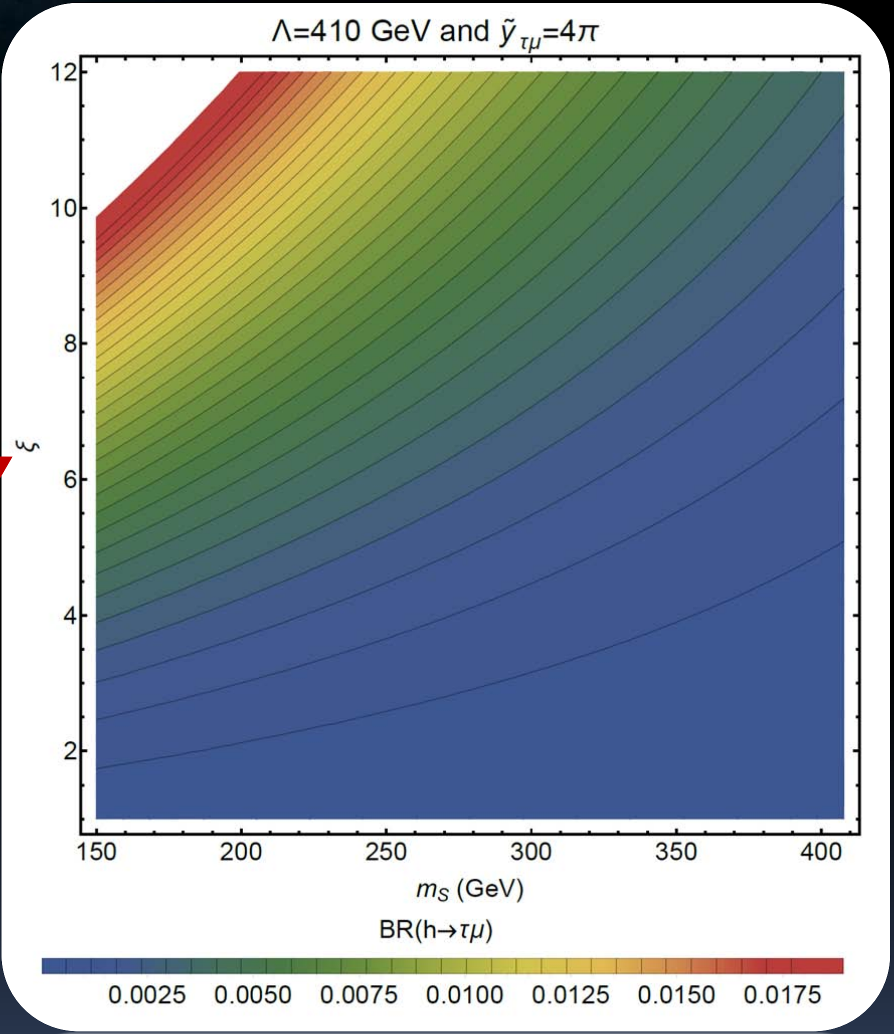
$$\mathcal{L}_{SH} = \frac{\xi}{2} S^2 H^\dagger H - \frac{\tilde{y}}{2\Lambda^2} S^2 \bar{L} H E - \frac{m_{S_0}^2}{2} S^2 + \frac{\lambda_S}{4!} S^4$$



$C_{8\gamma}$ is loop suppressed in relation to c_{6H} ($c_{6\gamma}$ even more!)

Simple UV models

Higgs portal:



MAYBE responsible for

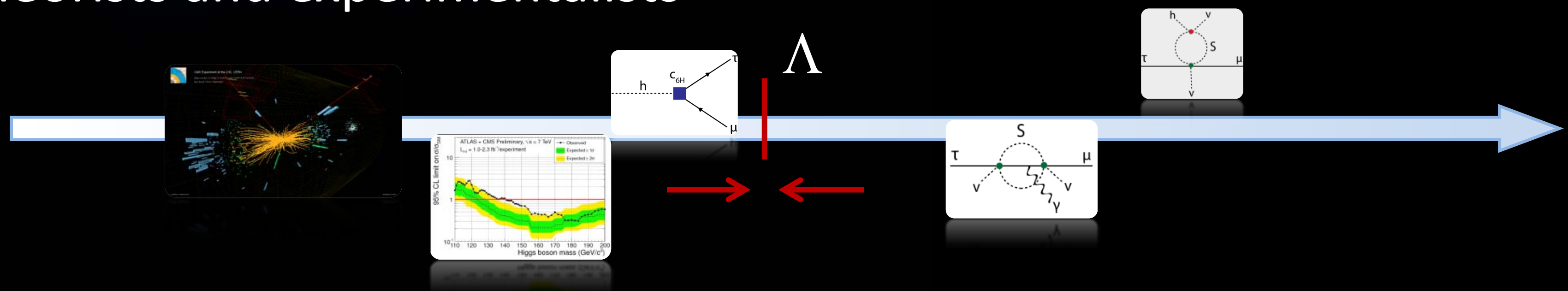
$\mathrm{BR}(h \to \tau\mu) = \left(0.89^{+0.40}_{-0.37}\right)\%$

This is not DM!

$\xi \leq 3 \times 10^{-4}(m_S/1\ \mathrm{GeV})$

Conclusions

• Model independent searches! EFTs are a good meeting point for theorists and experimentalists



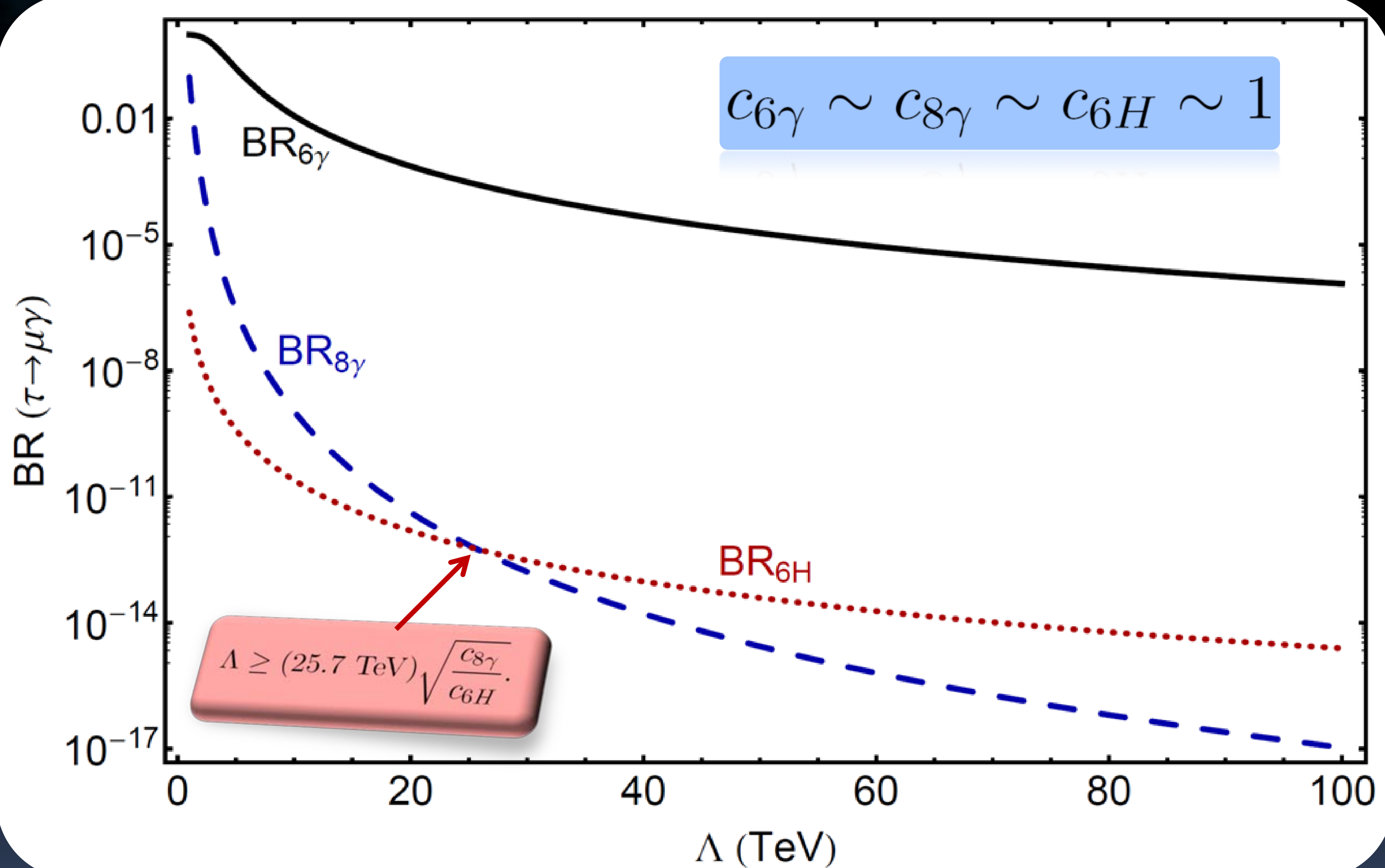
• LFV: possible sign in CMS and ATLAS. UV models generally generate dipole operators ($c_{6\gamma}$ and $c_{8\gamma}$) correlated to the dimension 6 FV operator (c_{6H}), and these heavily restrict Higgs FV decays.

• Composite Fermions and MSSM (at large tan(β)) are disfavored by this signal. Higgs Portal model is favored (also 2HDM* and 2HDM-like SUSY)

* 2HDMs may have FV at tree level through dimension 4 operators, important even in the decoupling limit.

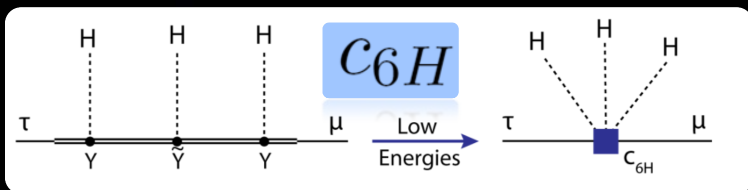
Thank You!

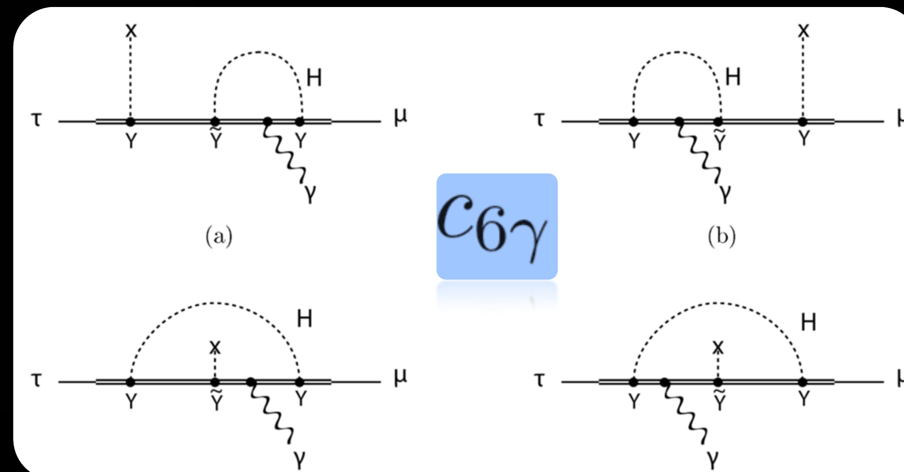
$\tau \rightarrow \mu \gamma$



Composite (extra)

$$\mathcal{L} = M\lambda_l \bar{L}_L \Psi_R + M\lambda_e \bar{E}_R \tilde{\Psi}_L - M c_l \bar{\Psi}\Psi - M c_e \bar{\tilde{\Psi}}\tilde{\Psi} + Y\bar{\Psi}_L H \tilde{\Psi}_R + \tilde{Y}\bar{\Psi}_R H \tilde{\Psi}_L + \text{h.c.}$$





$$i\mathcal{M}_{6H} = \frac{v^3}{2\sqrt{2}}\frac{1}{M^2}\bar{u}_L(p)\lambda_l Y\tilde{Y}Y\lambda_e u_R(p)$$

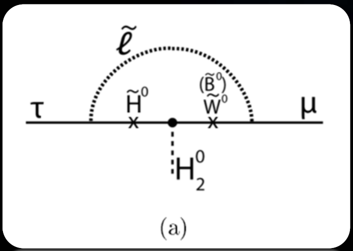
$$i\mathcal{M}_{6\gamma} = i\frac{ve}{(4\pi)^2\sqrt{2}}\frac{\lambda_l Y\tilde{Y}Y\lambda_e}{M^2}\bar{u}(p')(1+\gamma^5)u(p)p^\mu\epsilon_\mu(q)\left[\left(\frac{11}{9} - \frac{19}{9}\left(\frac{m_h}{M}\right)^2\right)\right] + \ldots,$$

$$c_{6H} = \lambda_l Y\tilde{Y}Y\lambda_e$$

$$c_{6\gamma} = -\frac{11}{18(4\pi)^2}c_{6H}$$

MSSM (extra)

SUSY (MSSM): at large tan(β) = v_2/v_1, LFV is dominated by:



$$c_{4H} = y_\tau \mu M_2 \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta} \frac{g^2}{32\pi^2} \sin\theta_L \cos\theta_L \left(I_1(M_2, \mu, \tilde{m}_{L2}) - \tilde{m}_{L2} \leftrightarrow \tilde{m}_{L3}\right)$$

$$I_1(m_1, m_2, m_3) = -\int_0^1 dx \int_0^{1-x} dy \frac{1}{m_1^2 x + m_2^2 y + (1-x-y) m_3^2}$$

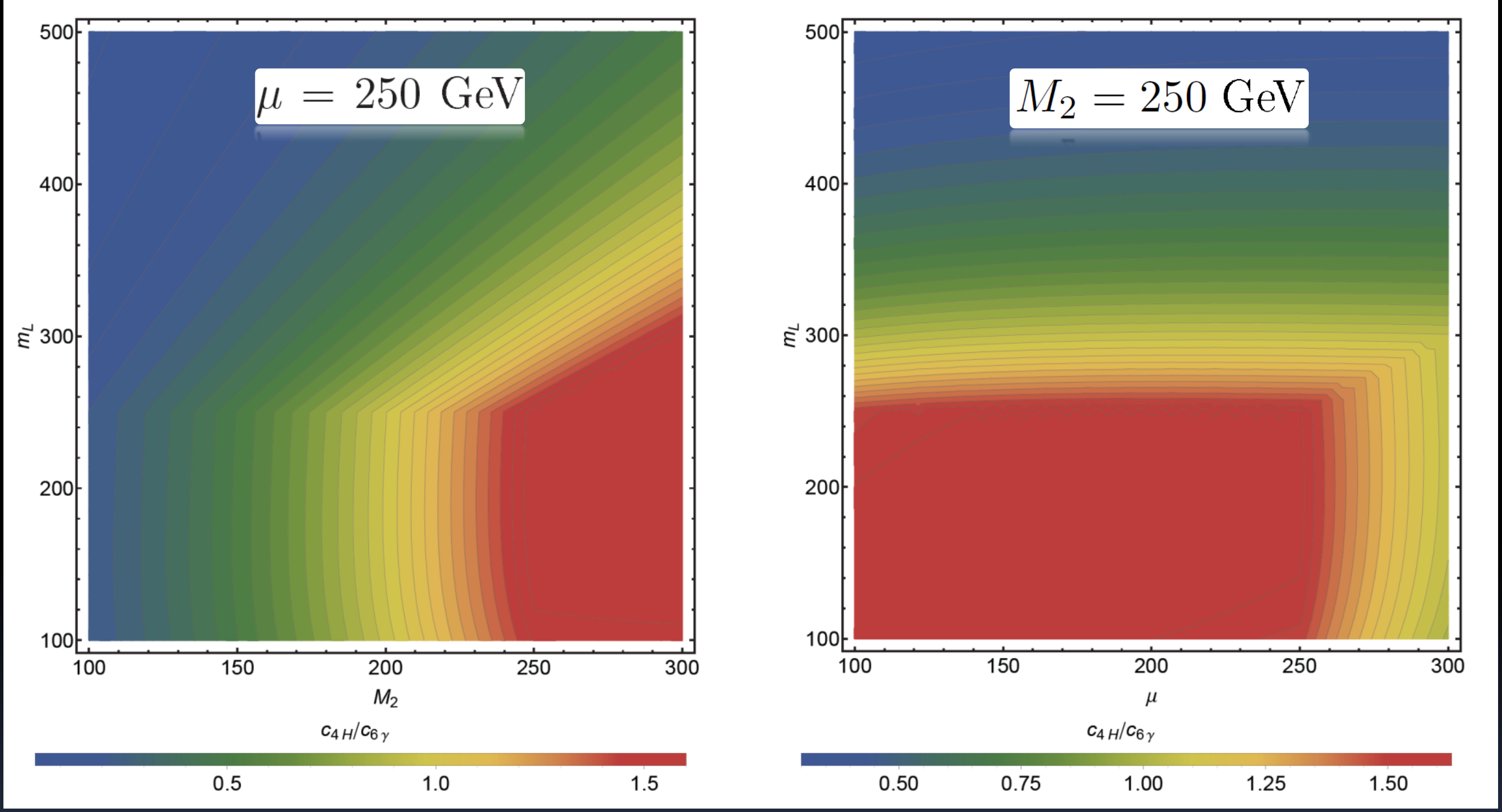
Add a photon

$$\frac{c_{6\gamma}}{\Lambda^2} = c_{4H} \frac{2\cos\beta\sin\beta}{\cos(\alpha-\beta)} \frac{\left(I_2(M_2, \mu, \tilde{m}_{L2}^2) - \tilde{m}_{L2} \leftrightarrow \tilde{m}_{L3}\right)}{\left(I_1(M_2, \mu, \tilde{m}_{L2}) - \tilde{m}_{L2} \leftrightarrow \tilde{m}_{L3}\right)}$$

$$I_2(m_1, m_2, m_3) = -\int_0^1 dx \int_0^{1-x} dy \frac{x+y-(x+y)^2}{(m_1^2 x + m_2^2 y + (1-x-y) m_3^2)^2}$$

Simple UV models

SUSY (MSSM): at large $\tan(\beta) = v_2/v_1$, LFV is dominated by:



$\tan\beta = 40$

$M_A = 200$ GeV

NOT responsible for $\mathrm{BR}(h \to \tau\mu) = (0.89^{+0.40}_{-0.37})\ \%$