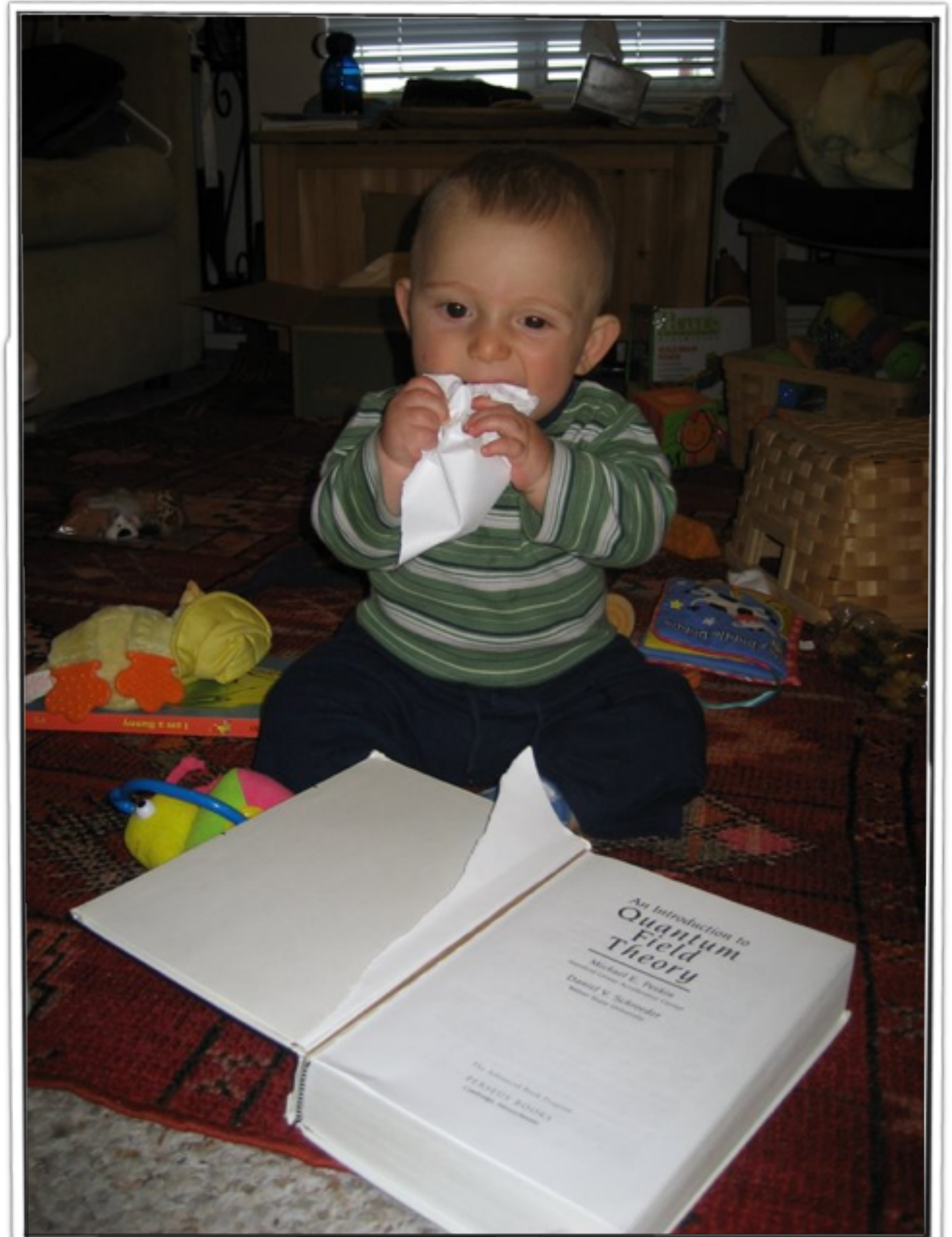
Low Energy Probes of the Higgs

Roni Harnik,
Fermilab



(my son, Lotem, 2008)

Metaphor:

$\simeq$ Our Field

 is driven by curiosity and a desire to explore the world around him.

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He has several tools for exploration:

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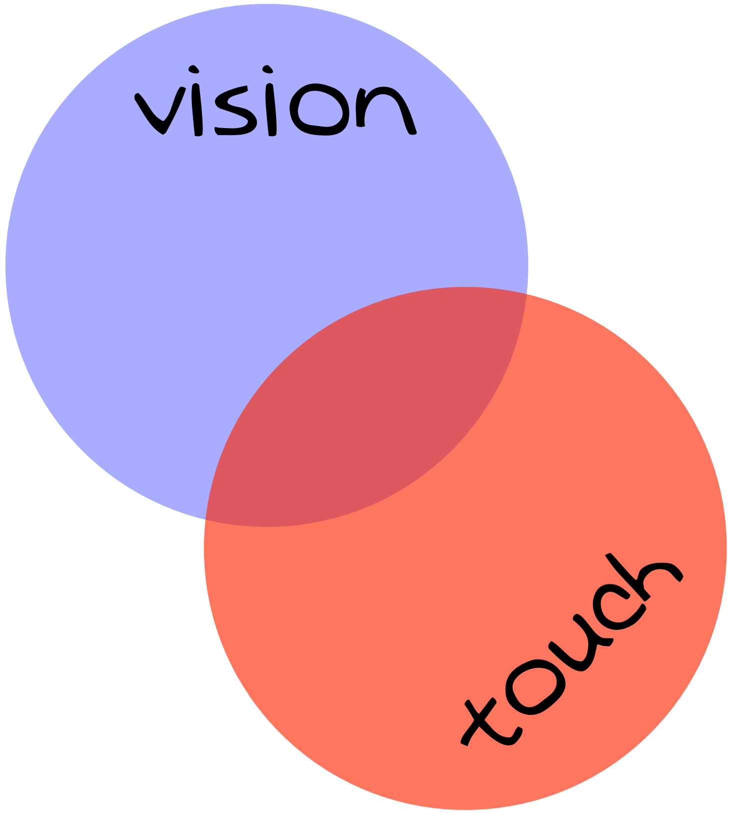

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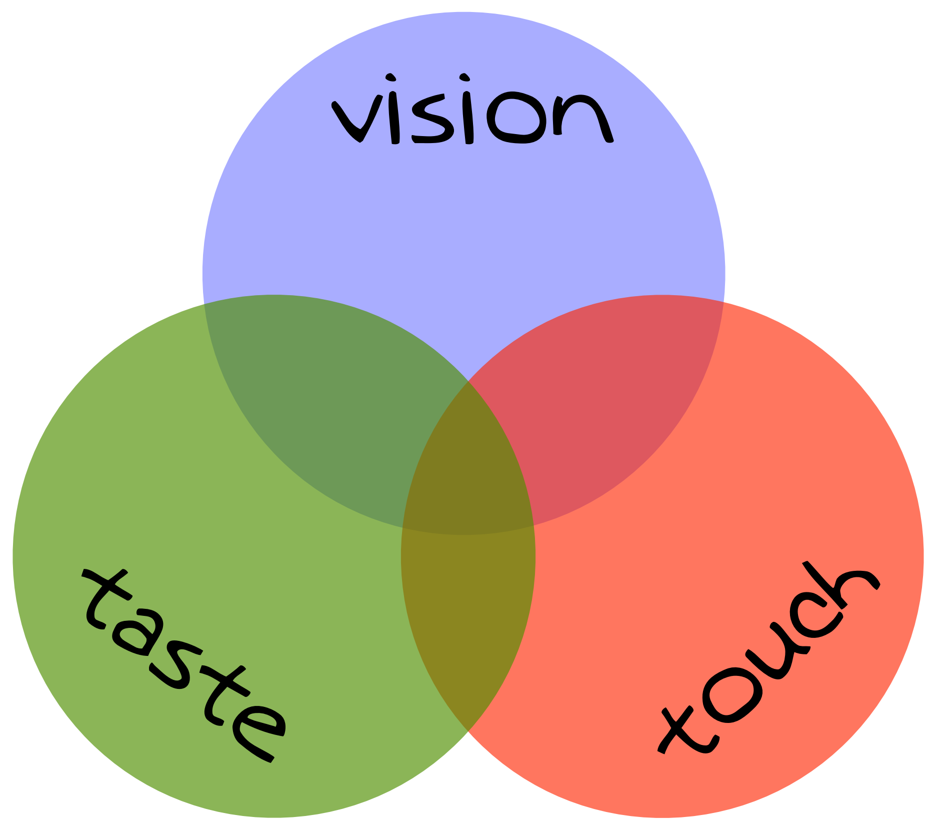

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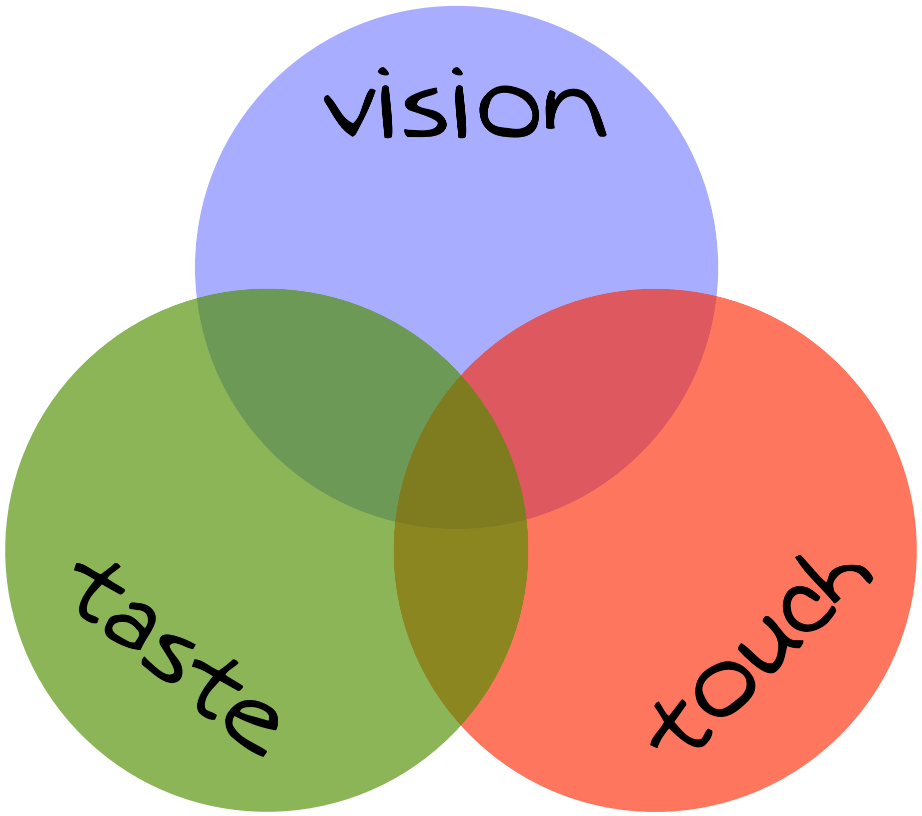


But he does <u>not</u> categorize them this way....

His instinct tells him: use them all!

Learning from this:
Lets use all of our tools to explore the

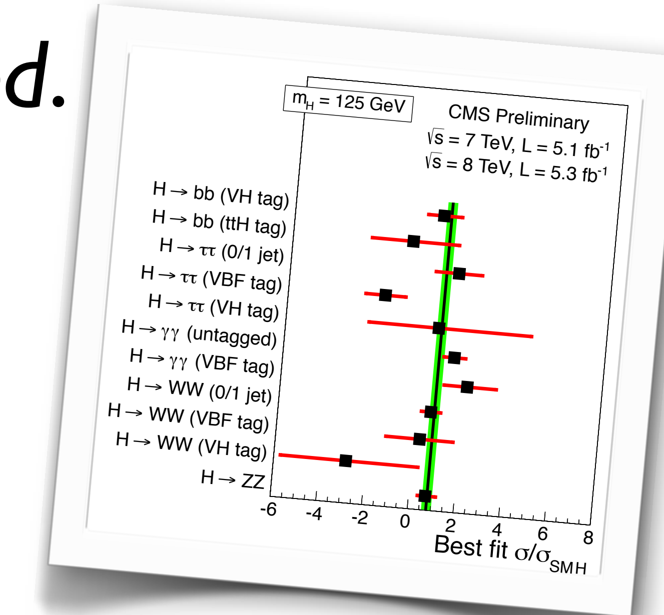
Higgs

(As you will see,
the multi-sensory
approach will be useful).

Blankenburg, Ellis, Isidori 1202.5704
RH, Kopp, Zupan 1209.1397

Higgs Couplings: SM

* The Higgs couplings in the SM are *determined.*
  Thats why they are so important to measure!



* Yukawa couplings:

$$\mathcal{L} \supset y_i h f_L^i f_R^i + \text{h.c.} \qquad \text{with} \qquad y_i = \frac{m_i}{v}$$

In the SM Yukawa couplings are:

* Flavor diagonal.
* Real (CP is conserved).

Higgs Couplings: New Physics

* Fermions can get a mass from several sources. For example:

2 doublet model: $$Y_1^{ij} H_1 f_L^i f_R^j + Y_2^{ij} H_2 f_L^i f_R^j$$

- or -

Higher dim. op: $$Y^{ij} H f_L^i f_R^j + \hat{Y}^{ij} \frac{|H|^2}{\Lambda^2} H f_L^i f_R^j$$

Two sources can be misaligned in flavor and/or in phase.

Higgs Couplings: New Physics

* The Higgs boson then has more general couplings:

$$\mathcal{L} \supset Y_{ij}\, h f_L^i f_R^j + \text{h.c.}$$

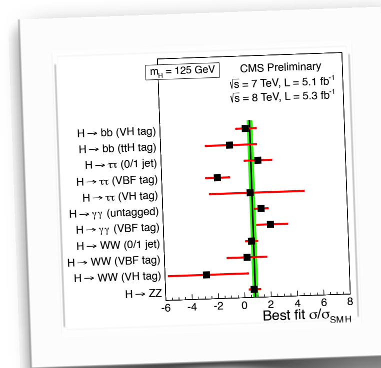
With NP Yukawa couplings can be:

* Flavor off-diagonal*.
* complex (CP violating).
* Both.

* To avoid tuning we expect $Y_{ij} \lesssim \frac{\sqrt{m_i m_j}}{v}$,

but phases can be of order one.

lets call couplings that satisfy this "natural"

So, in addition to these 

,

there are a lot more couplings the Higgs can have, and that <u>we should probe</u>.

Low energy experiments are crucial to test many of these couplings.

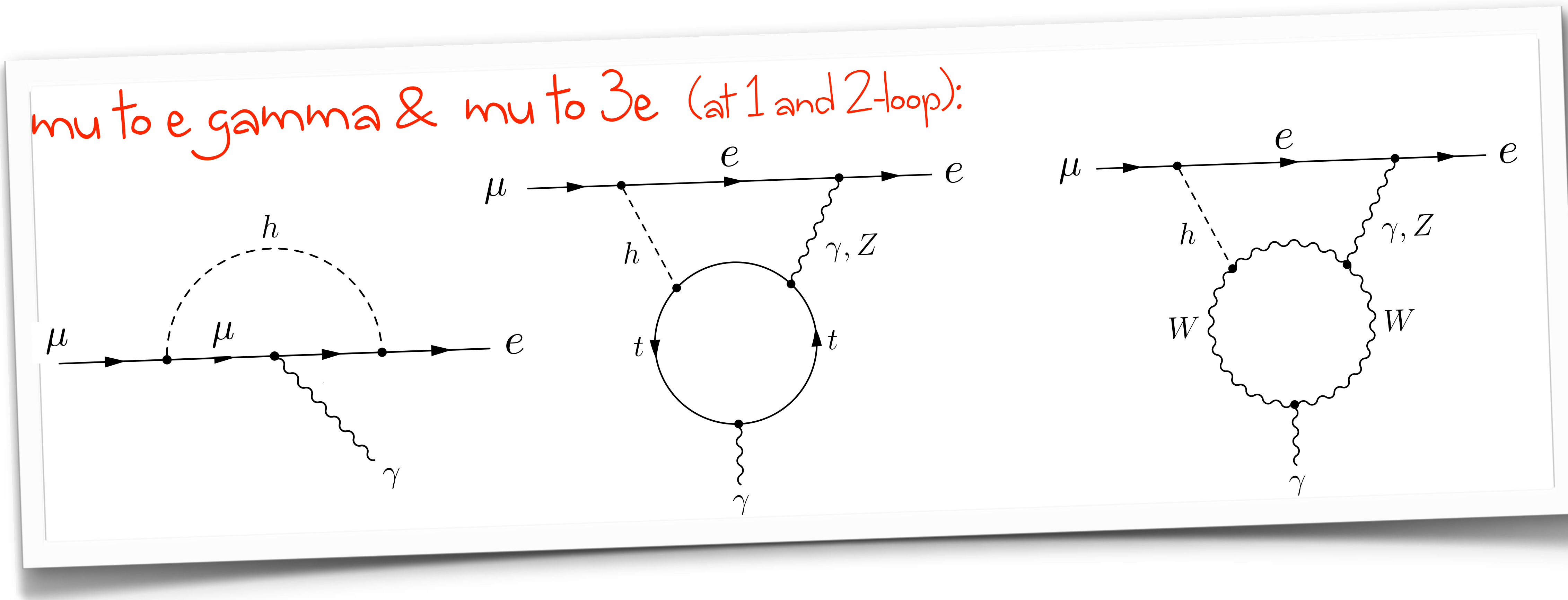
Leptonic Flavor Violation

$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

Which experiments constrain the Y_{ij}'s?

Higgs couplings to μe

* Higgs coupling to μe is constrained, e.g. by:



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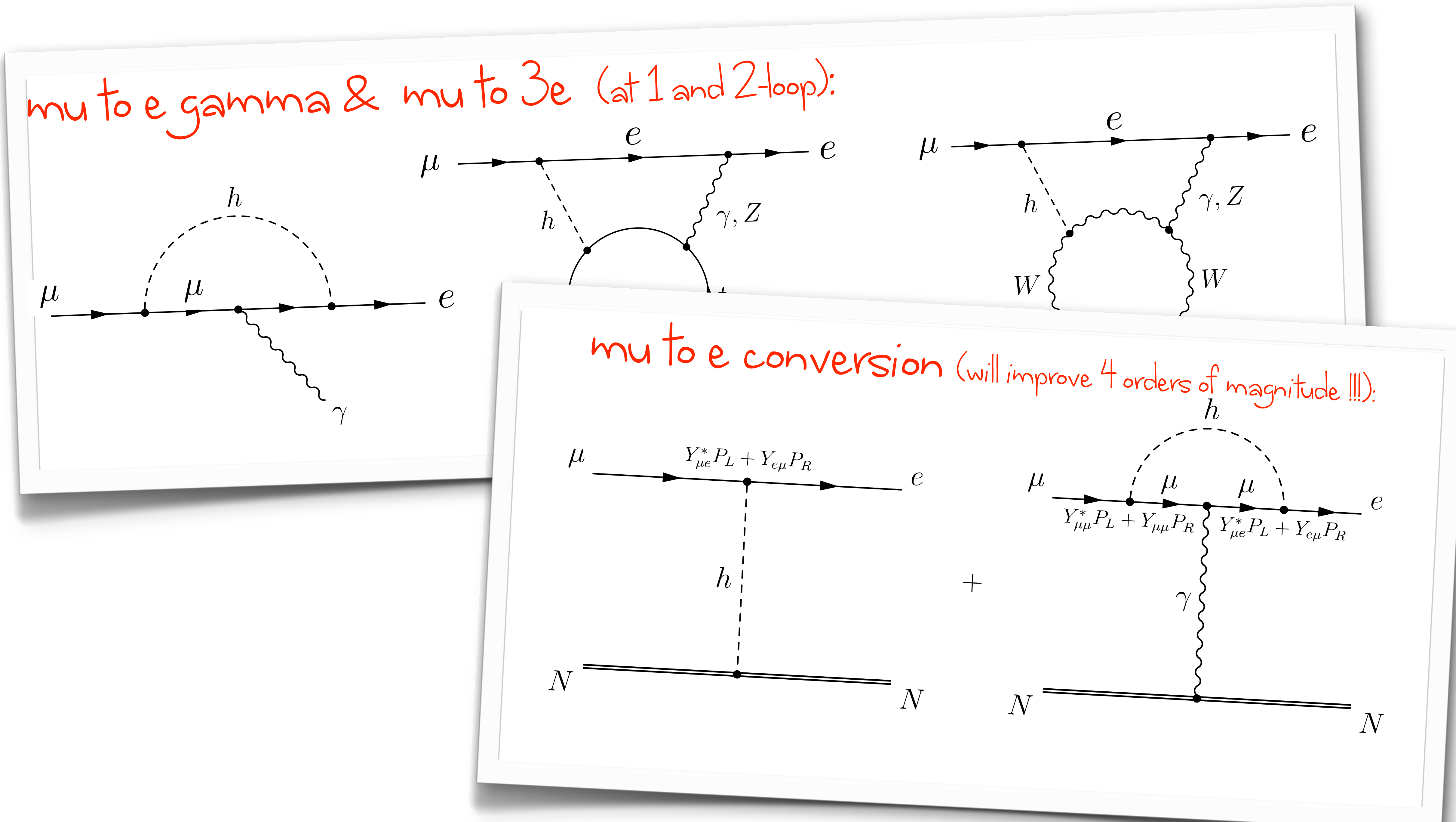
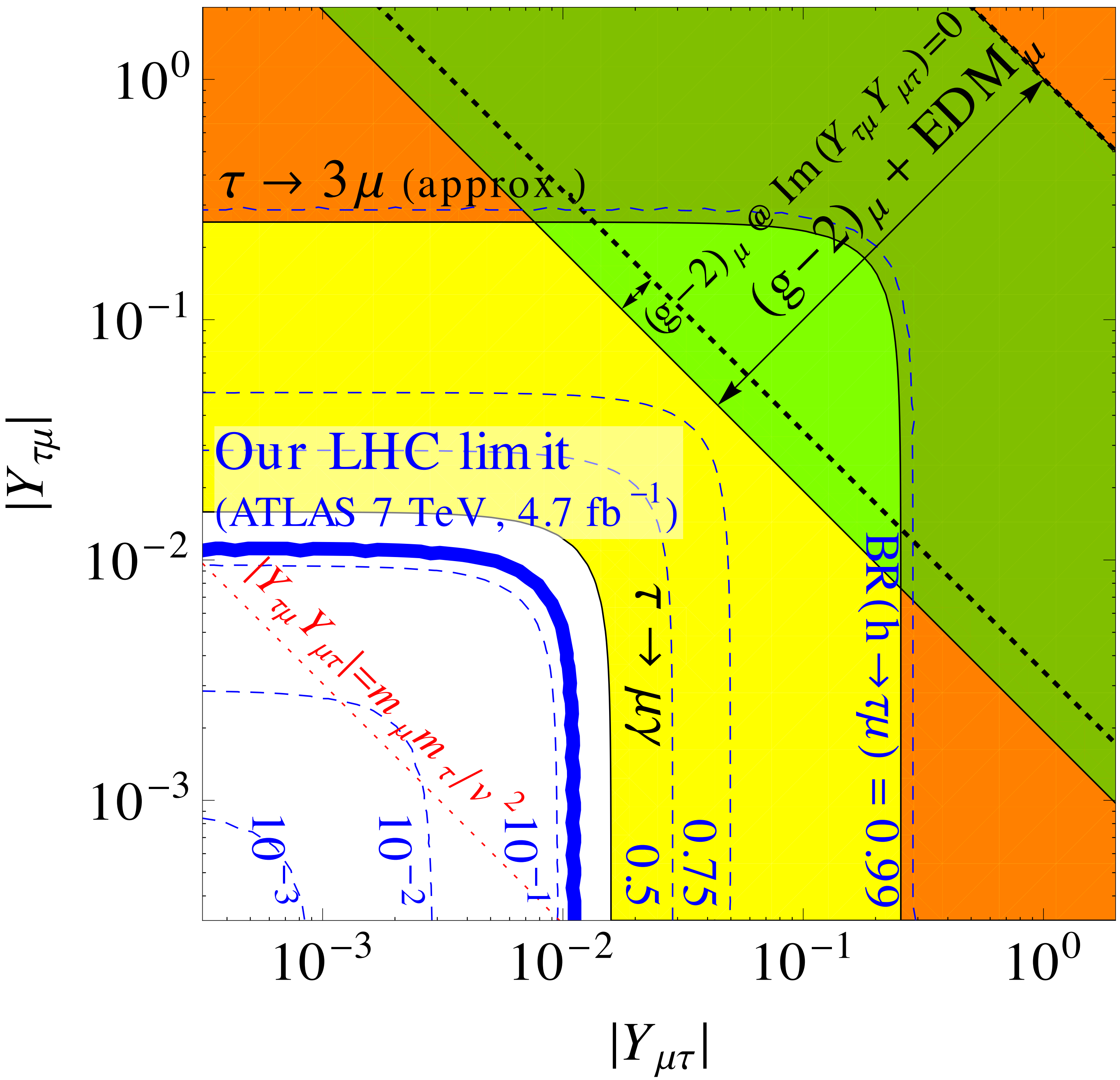


Higgs couplings to μe

Outside of
LHC reach.

Probing
"natural" models.

Higgs couplings to $\tau\mu$



LHC $h \to \tau\mu$ gives dominant bound.

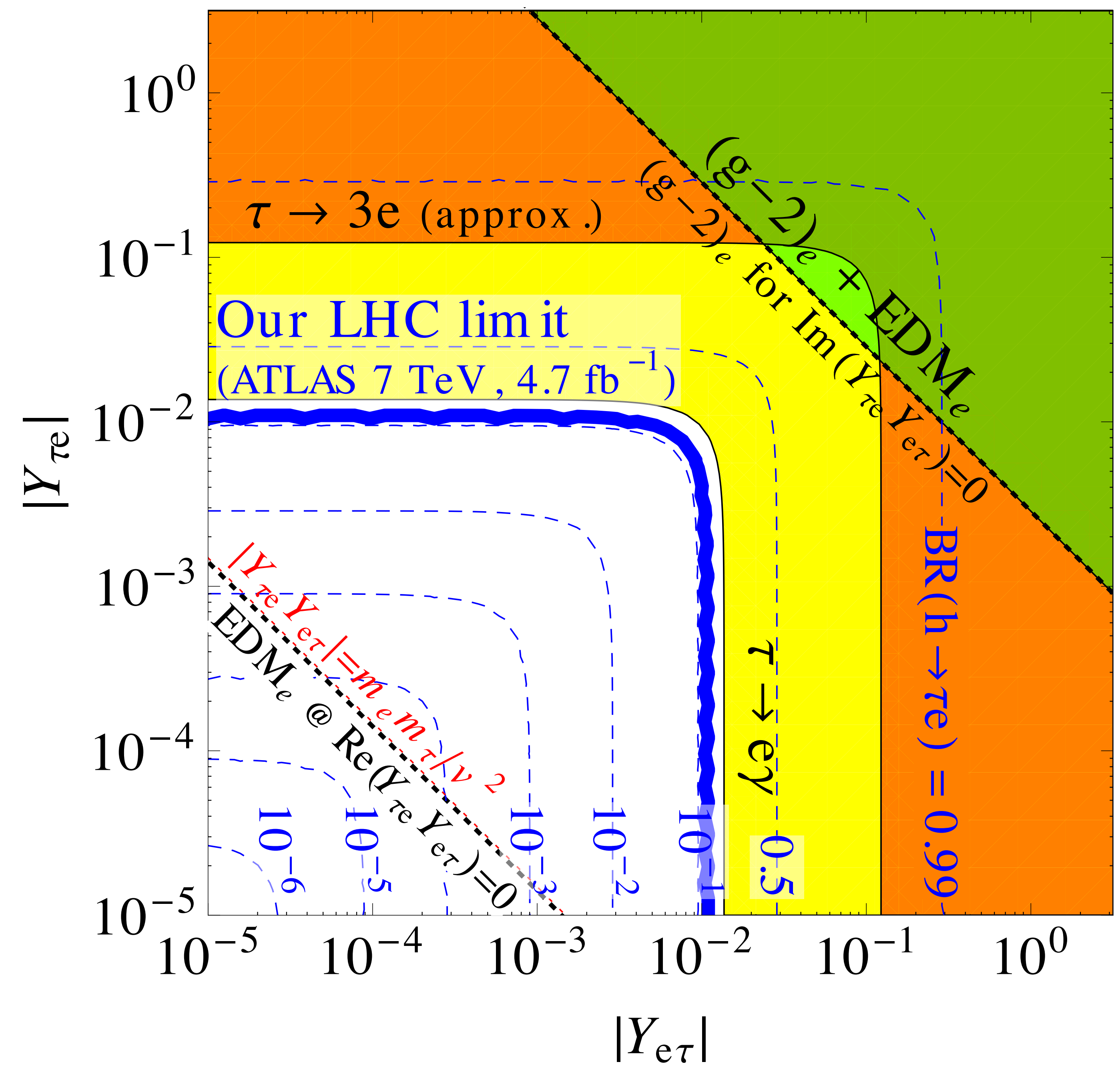
(currently just a theorist's re-interpretation)

"natural models" are within reach.

RH, Kopp, Zupan 1209.1397

Higgs couplings to τe

* τe is similar to $\tau\mu$.... but:



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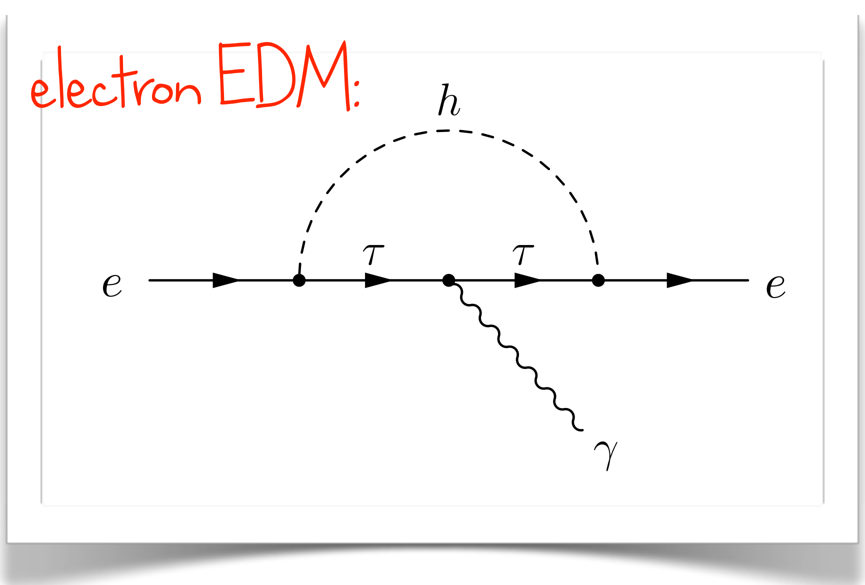
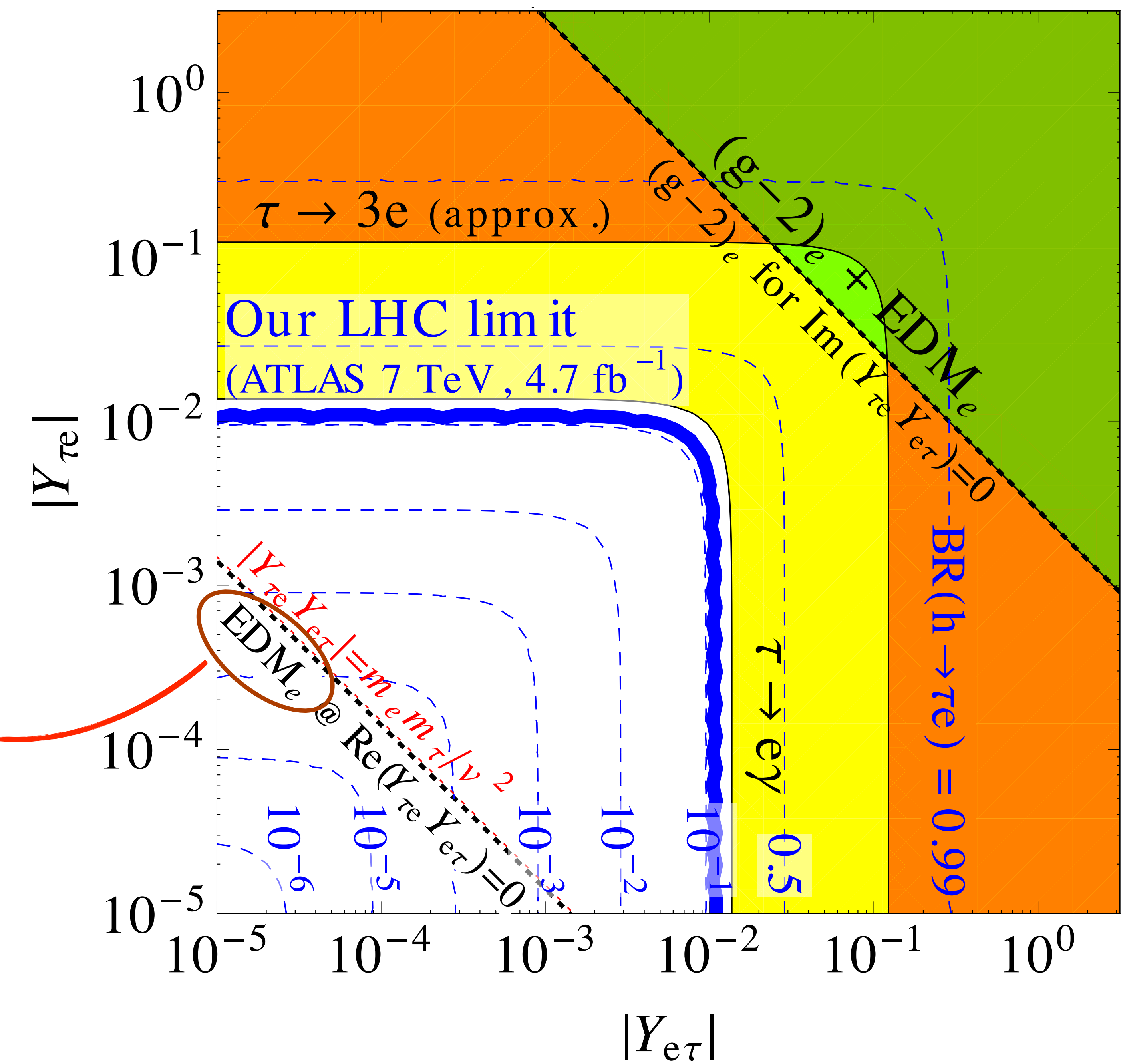
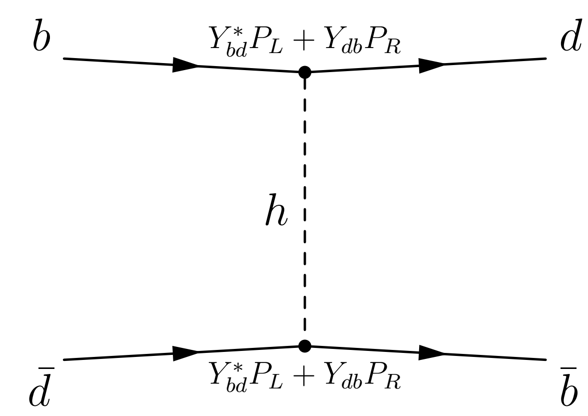
Electron EDM is interesting here!





Quark Flavor Violation

Meson Mixing



* Meson mixing's powerful:

Technique	Coupling	Constraint	$m_i m_j / v^2$
D^0 oscillations [48]	$\|Y_{uc}\|^2$, $\|Y_{cu}\|^2$	$< 5.0 \times 10^{-9}$	5×10^{-8}
	$\|Y_{uc}Y_{cu}\|$	$< 7.5 \times 10^{-10}$	
B_d^0 oscillations [48]	$\|Y_{db}\|^2$, $\|Y_{bd}\|^2$	$< 2.3 \times 10^{-8}$	3×10^{-7}
	$\|Y_{db}Y_{bd}\|$	$< 3.3 \times 10^{-9}$	
B_s^0 oscillations [48]	$\|Y_{sb}\|^2$, $\|Y_{bs}\|^2$	$< 1.8 \times 10^{-6}$	7×10^{-6}
	$\|Y_{sb}Y_{bs}\|$	$< 2.5 \times 10^{-7}$	
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$	8×10^{-9}
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$	
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$	
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$	

"Natural" models are constrained!

FV Couplings with top

* A variety of techniques:

Technique	Coupling	Constraint	$m_i m_j / v^2$
$t \to hj$ [Craig et al. 1207.6794]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34	3×10^{-3}
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34	7×10^{-6}
D^0 oscillations	$\lvert Y_{ut}Y_{ct}\rvert,\ \lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$	
	$\lvert Y_{tu}Y_{ct}\rvert,\ \lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$	2×10^{-4}
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$	
neutron EDM	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$	7×10^{-6}

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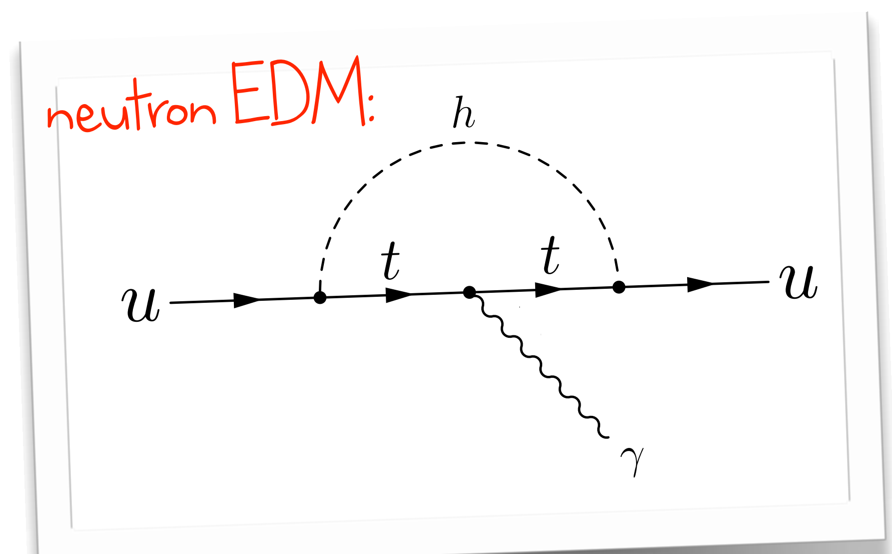
The neutron EDM is powerful!

(Probing "natural" models).



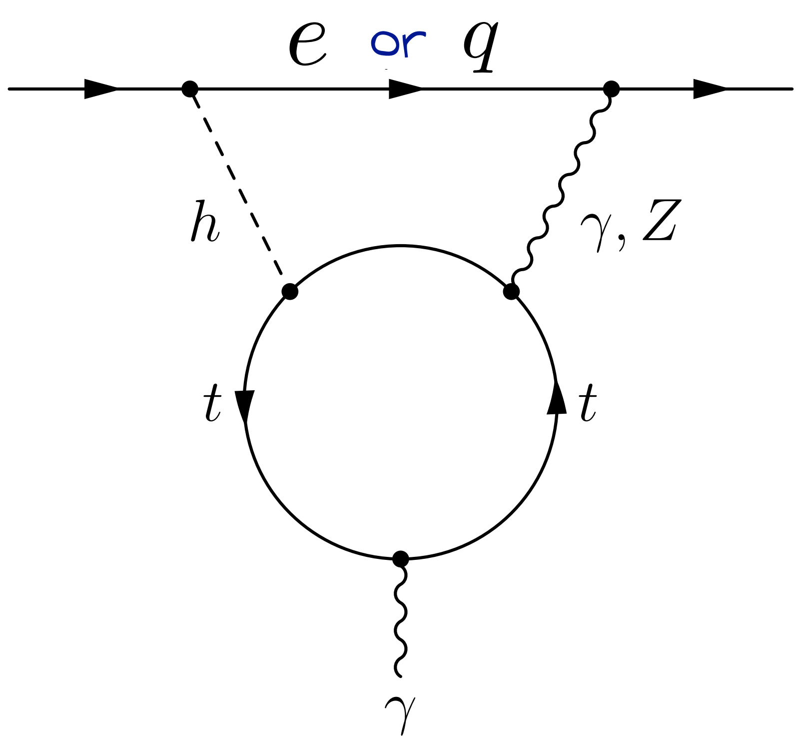
Flavor diagonal phases

<u>Assume</u> diagonal Yukawas with $|Y_i| = \frac{m_i}{v}$.

What are the constraints on
the <u>phases</u> of the Y_i's?

Two Loop EDM

* Electron or neutron EDM at 2-loops (Barr-Zee):



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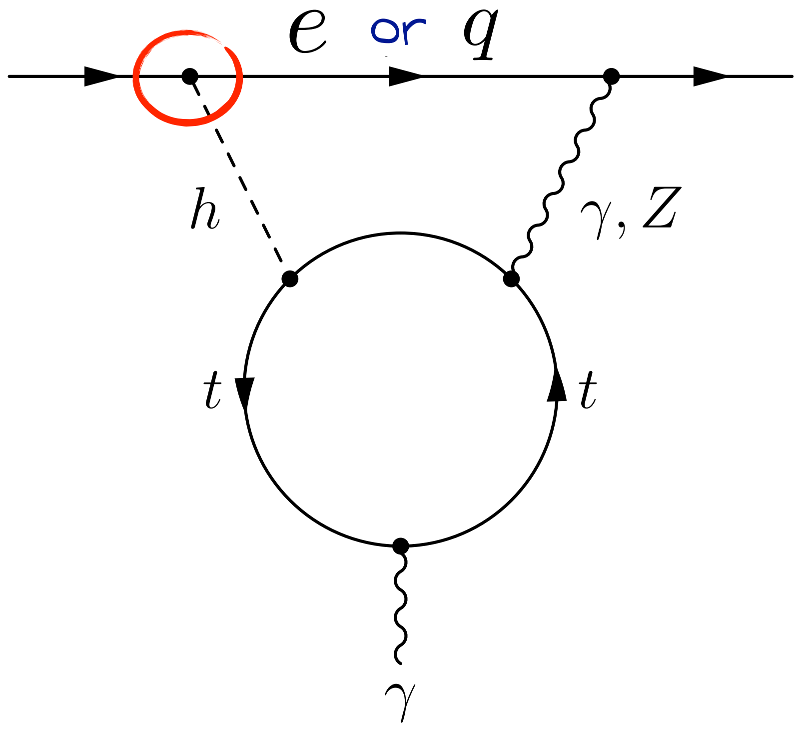

Two Loop EDM

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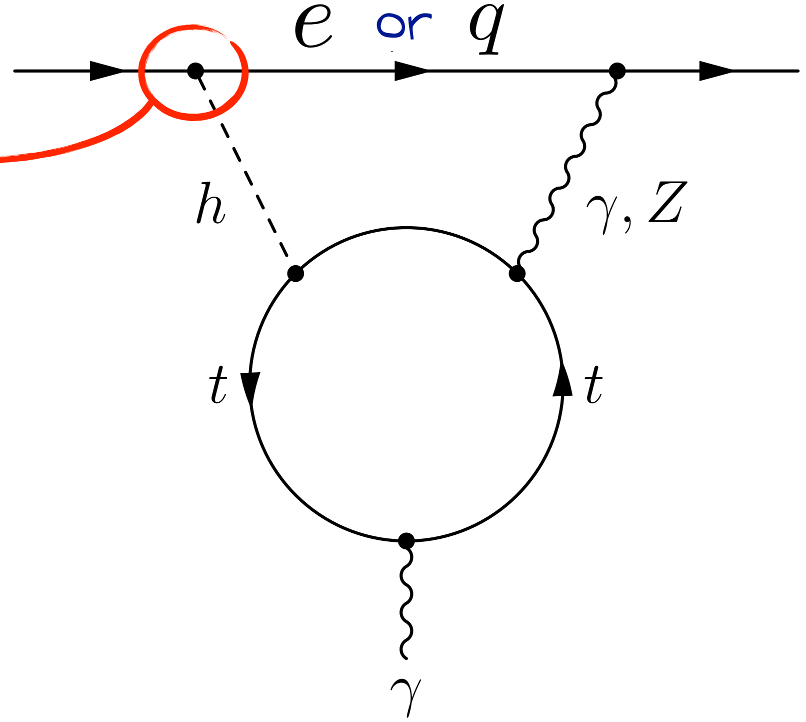
$$\phi_e, \phi_q \lesssim 0.1$$

from e and n EDM's



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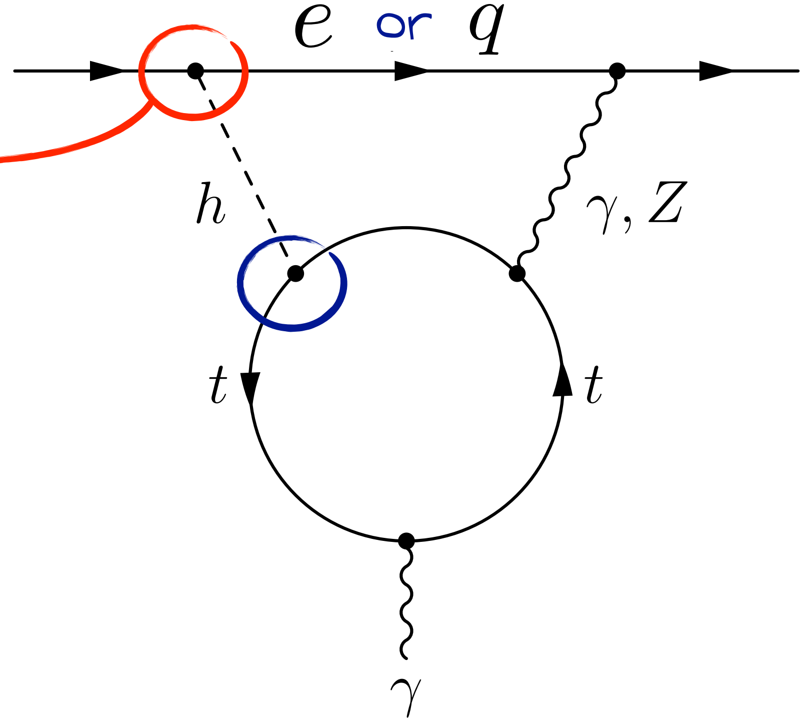

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$$\phi_t \lesssim 0.05$$

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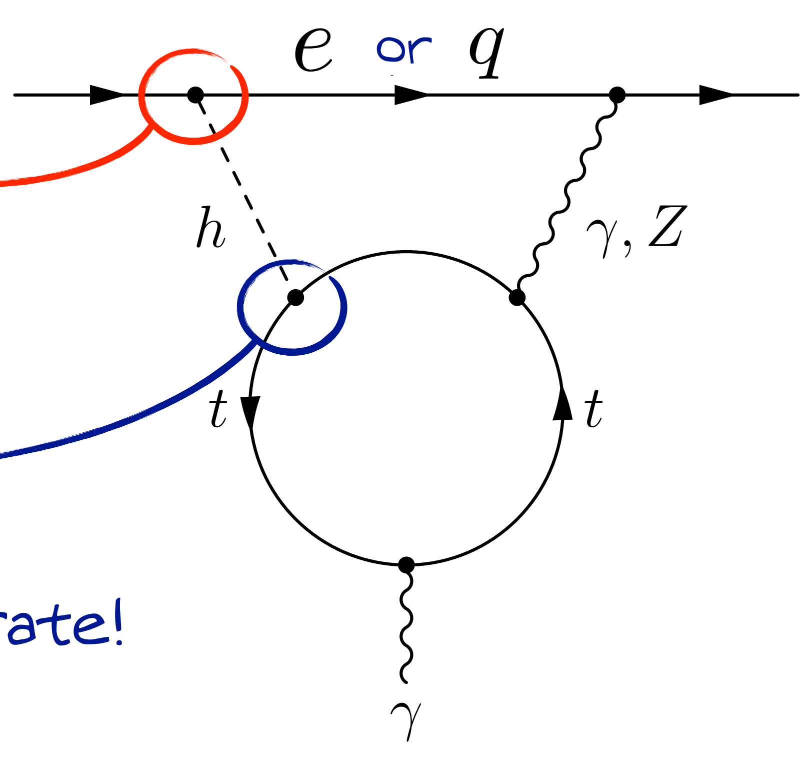
Interplay with LHC Higgs production rate!

Brod, Haisch, Zupan (in prep.)



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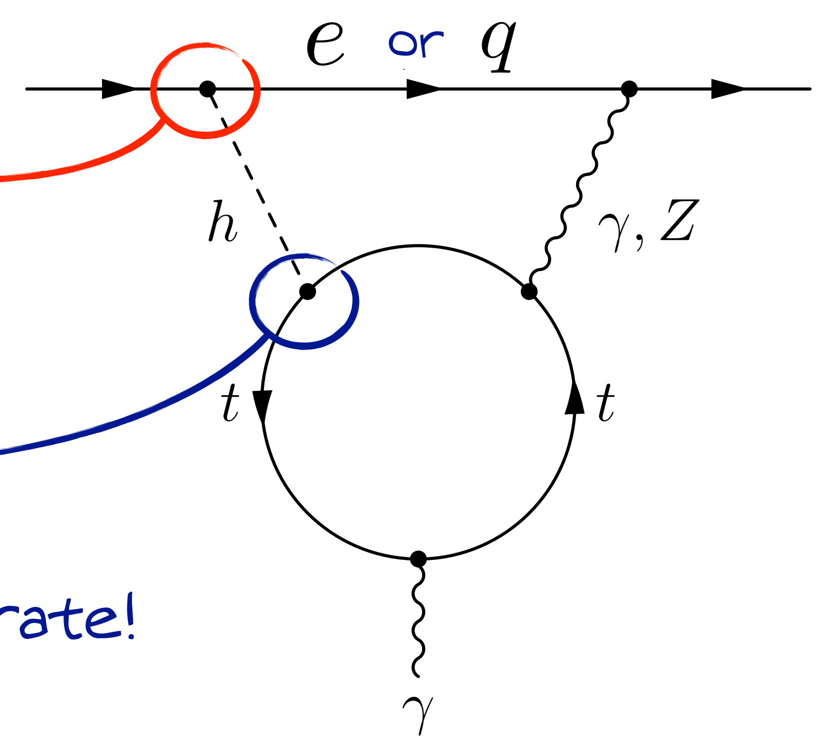
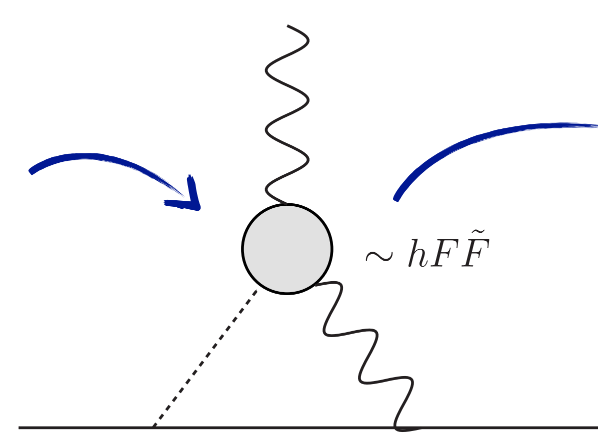


* Also sensitive to CPV in $h\gamma\gamma$ from NP:

$$c_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} + \tilde{c}_\gamma \frac{\alpha}{2\pi v} h F_{\mu\nu} \tilde{F}^{\mu\nu}$$



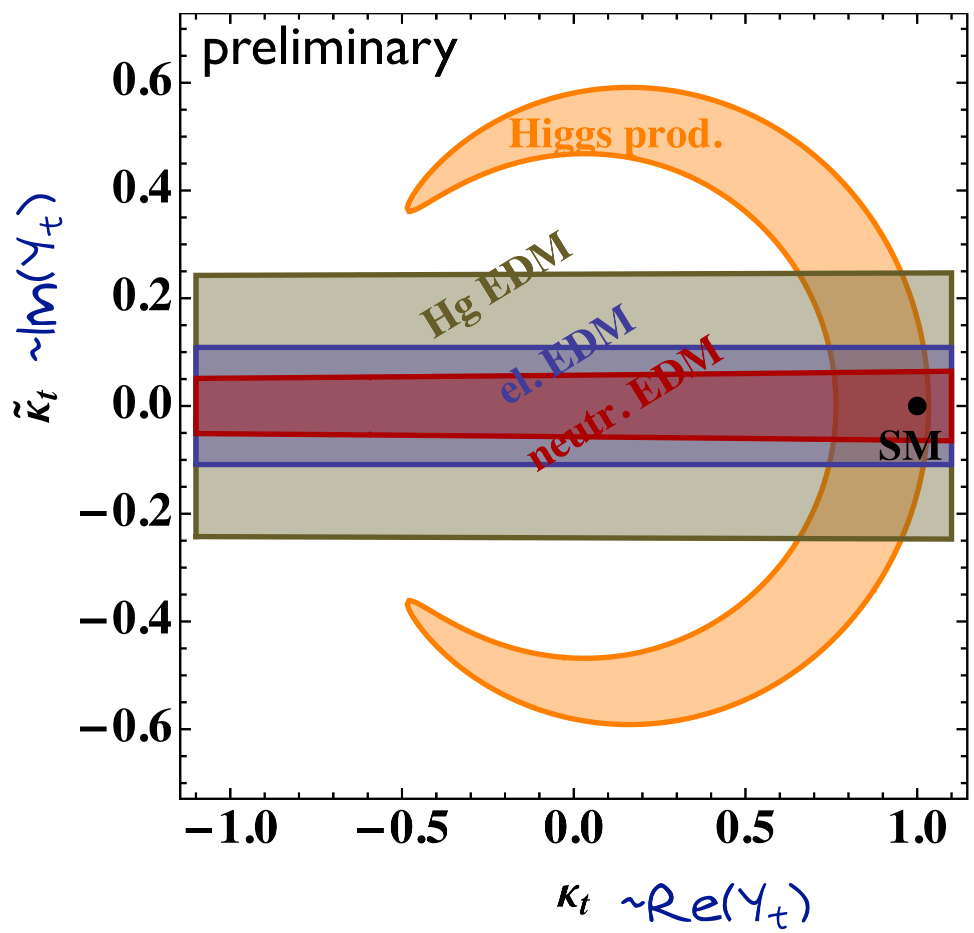
$$\phi_\gamma \lesssim 0.01 - 0.1$$

McKeen, Pospelov, Ritz
(1208.4597)

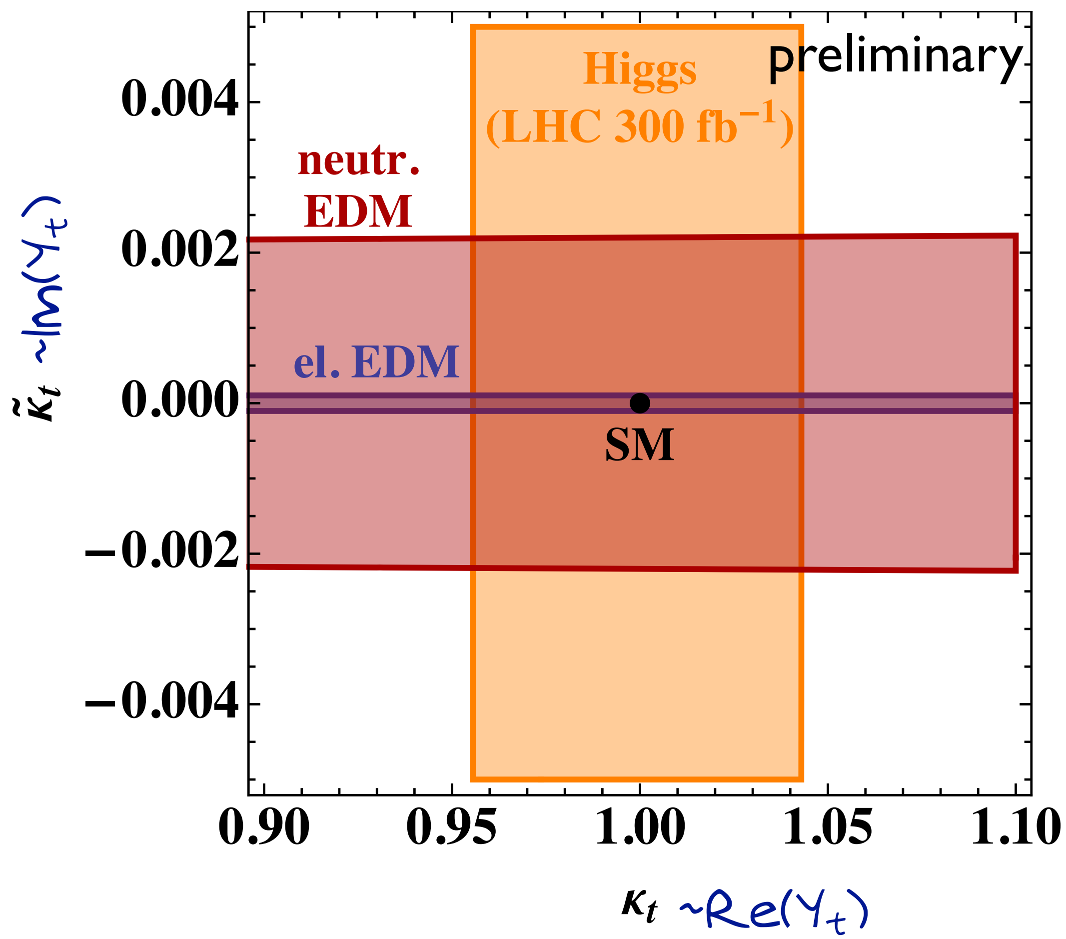
LHC & EDMS

* Top couplings are probed both by the LHC (gluon fusion) and by EDM experiments. Interpley

Today:



In the future:



Brod, Haisch, Zupan (in prep.)

Summary:

Flavor violation:

✓ =sensitive at the level of $Y_{ij} \lesssim \frac{\sqrt{m_i m_j}}{v}$.

Leptons	Probe
μ-e	muons ✓
τ-e	eEDM* ✓
τ-μ	LHC ✓

d-quarks	Probe
s-d	K-K ✓
b-d	B-B ✓
b-s	B_s-B_s ✓

d-quarks	Probe
c-u	D-D ✓
t-u	nEDM* ✓
t-c	LHC / D-D ✓?

*LHC, if CP is conserved.

CP violation:

Phase	Probe
e	e-EDM
u,d	nEDM
γ	eEDM

Phase	Probe
t	EDMs
τ	LHC / Higgs factory
Z	LHC

Multiple probes across frontiers!

Almost all channels are sensitive at well motivated levels!

Conclusions

* Probing the Higgs requires many sensory tools!
  - LHC
  - Higgs Factory
  - A strong program of precision & rare processes.
* A deviation from the SM could show up in any of these.

Deleted Scenes:

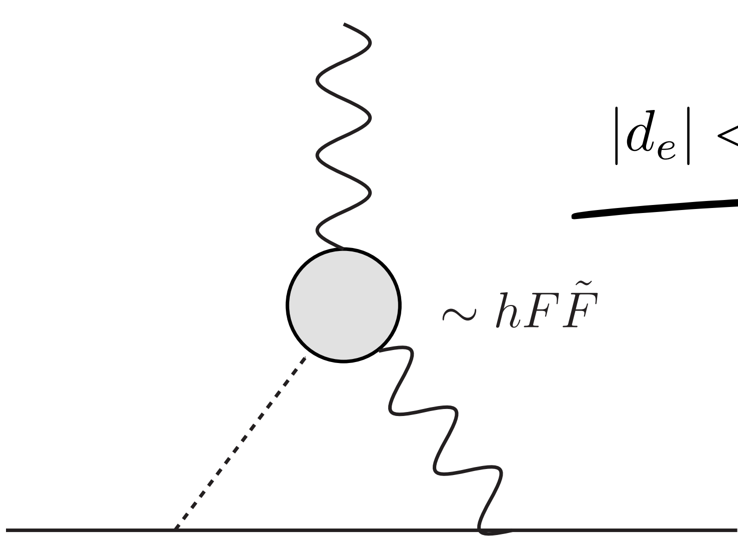
Higgs and EDM's

* Higgs couplings to photons can violate CP:

$$c_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} + \tilde{c}_\gamma \frac{\alpha}{2\pi v} h F_{\mu\nu} \tilde{F}^{\mu\nu}$$

* A potential explanation to an enhanced di-photon branching ratio....?

* But, it contributes to the electron EDM:

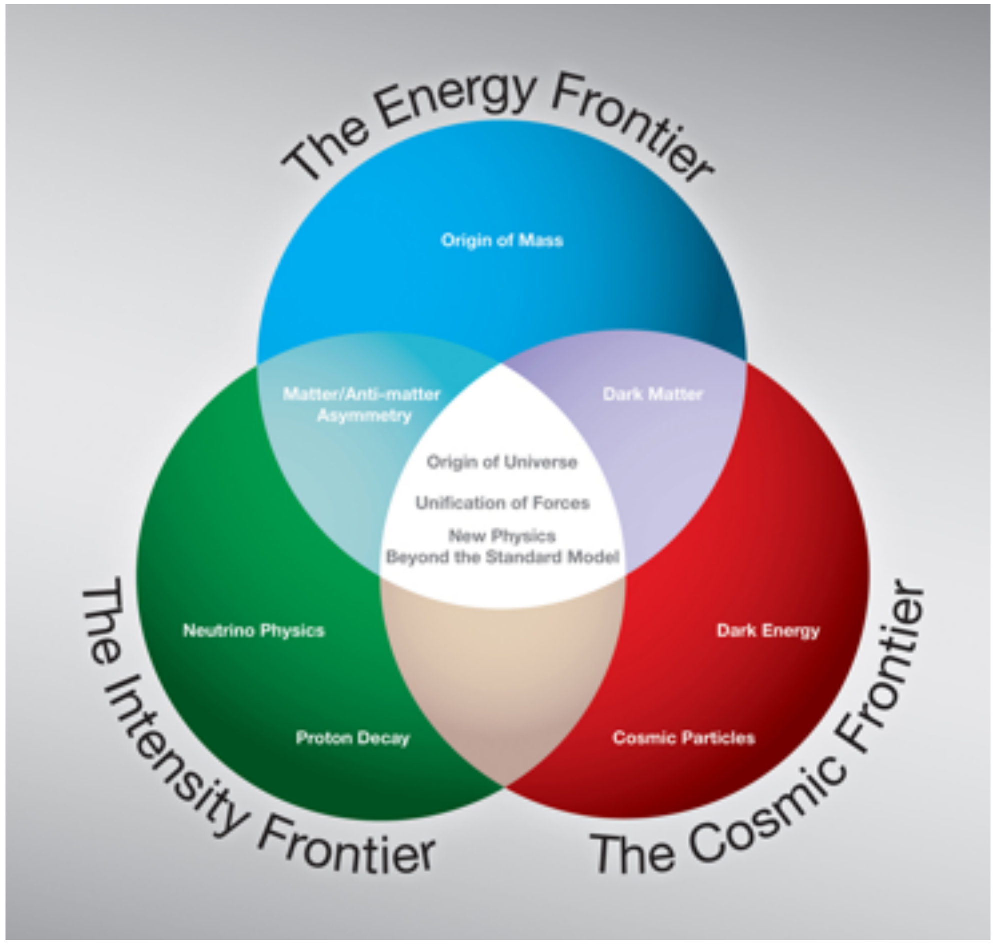


$|d_e| < 1.05 \times 10^{-27} e$ cm

$$\Delta \mathrm{BR}_{\gamma\gamma} < 1.6 \times 10^{-4}$$

McKeen, Pospelov, Ritz (1208.4597)

Frontiers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Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
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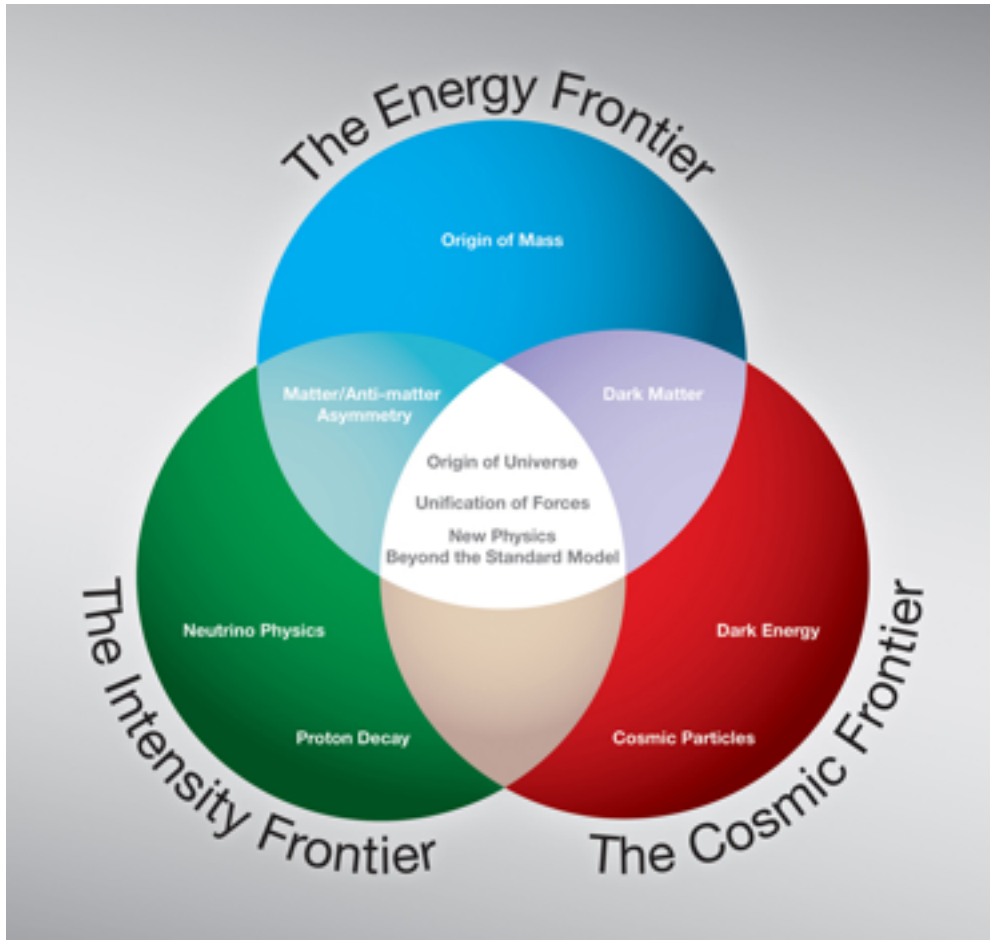
Frontiers



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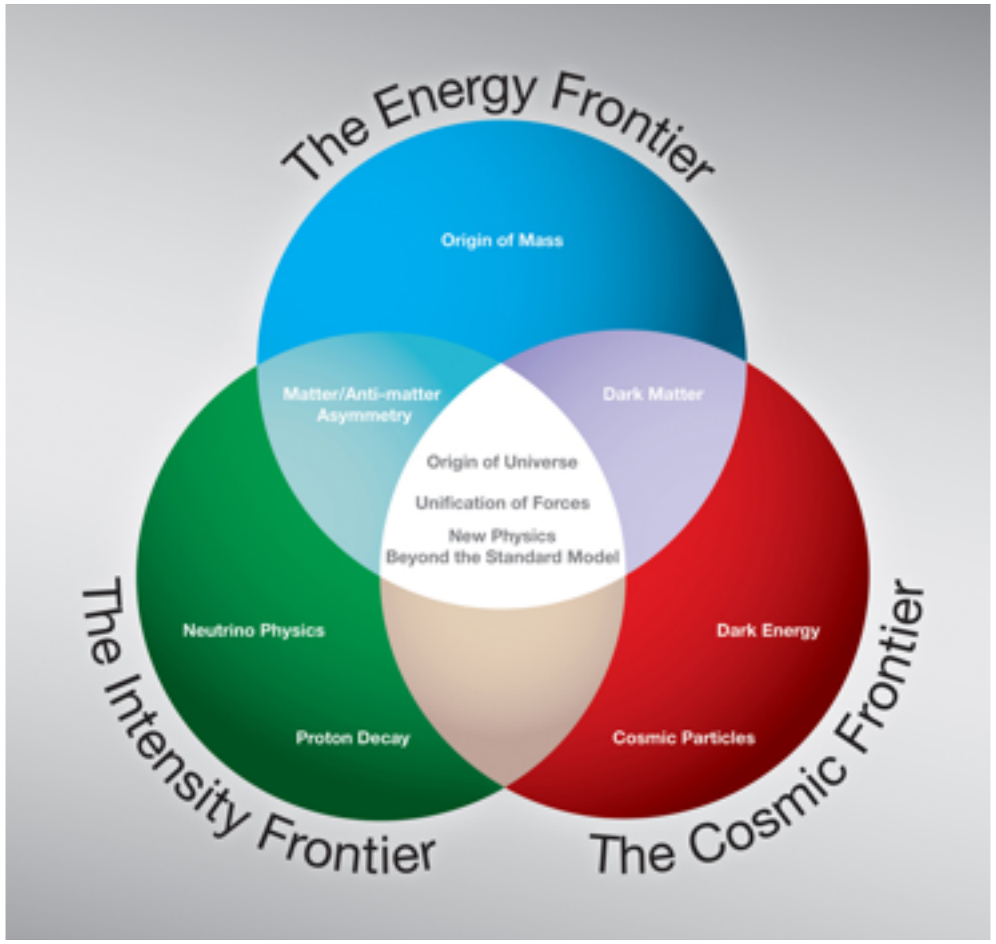
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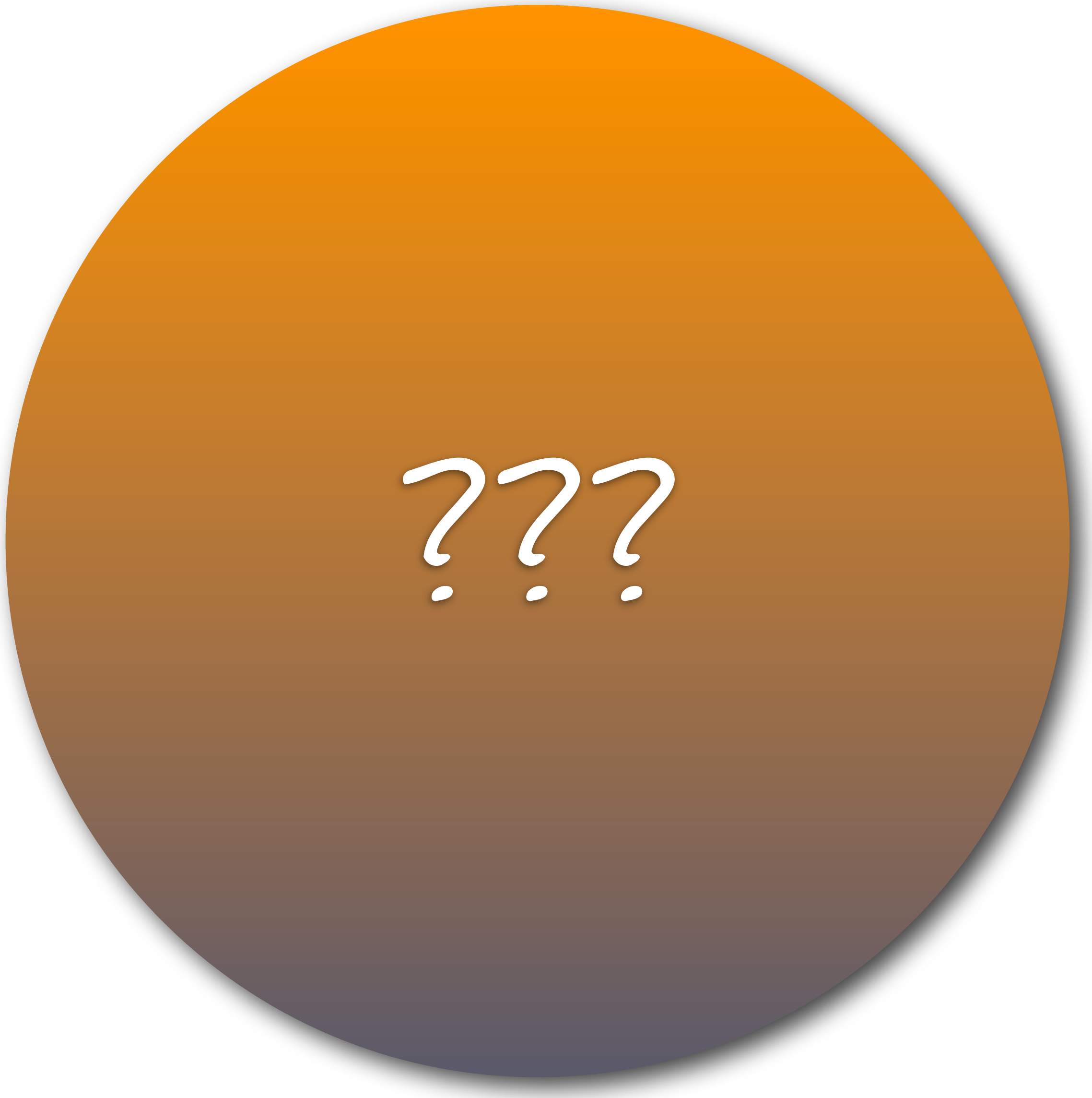
Frontiers

The Curiosity Frontier



Flavor Violating Higgs

* UV Recipe for FV Higgs:

1. Rip a page from a paper that modifies Higgs couplings.

2. Sprinkle flavor indices all over the place.

3. Re-diagonalize mass matrix.

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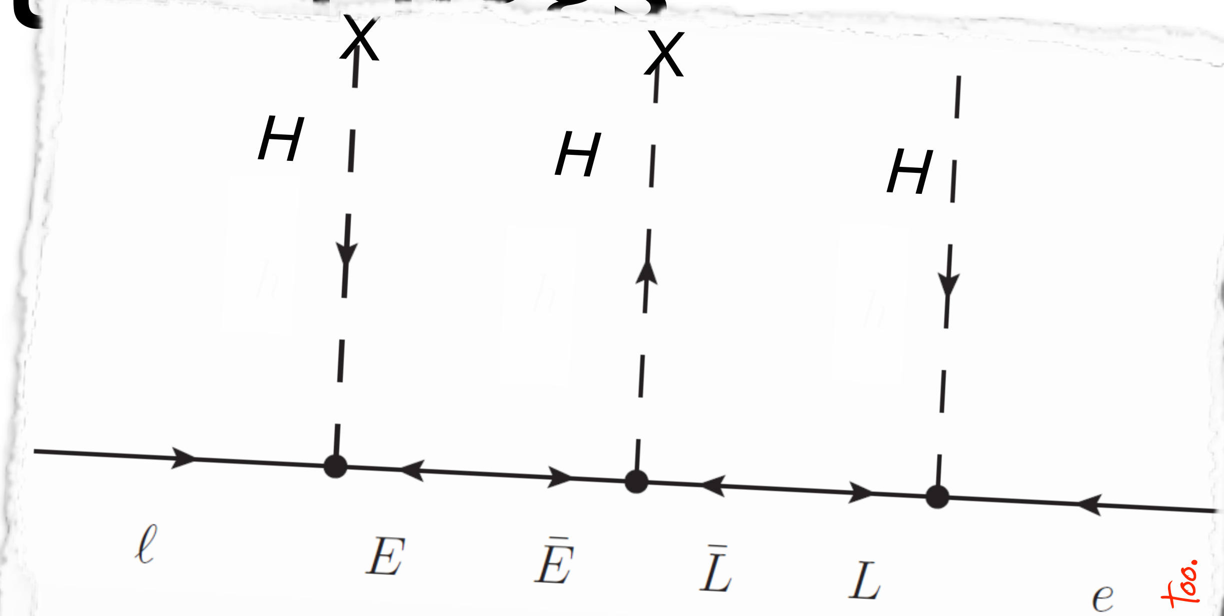

e.g. Kearney, Pierce, Weiner; 1207.7062

$$\frac{Y_l}{\Lambda^2}\left(\Box H^\dagger\right) l l^c$$

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PH: you can get this in composite Higgs too.

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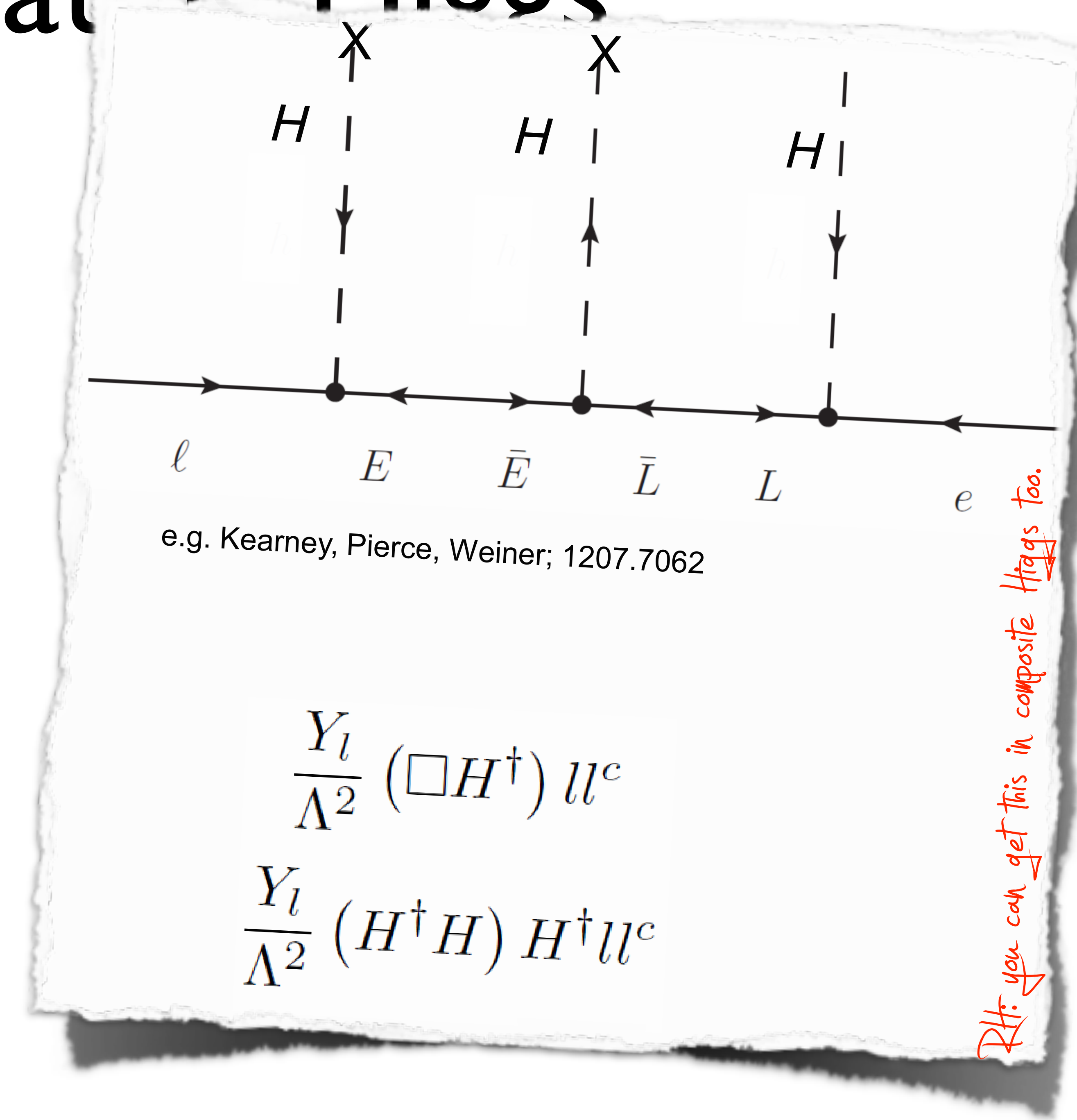

$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2}$$

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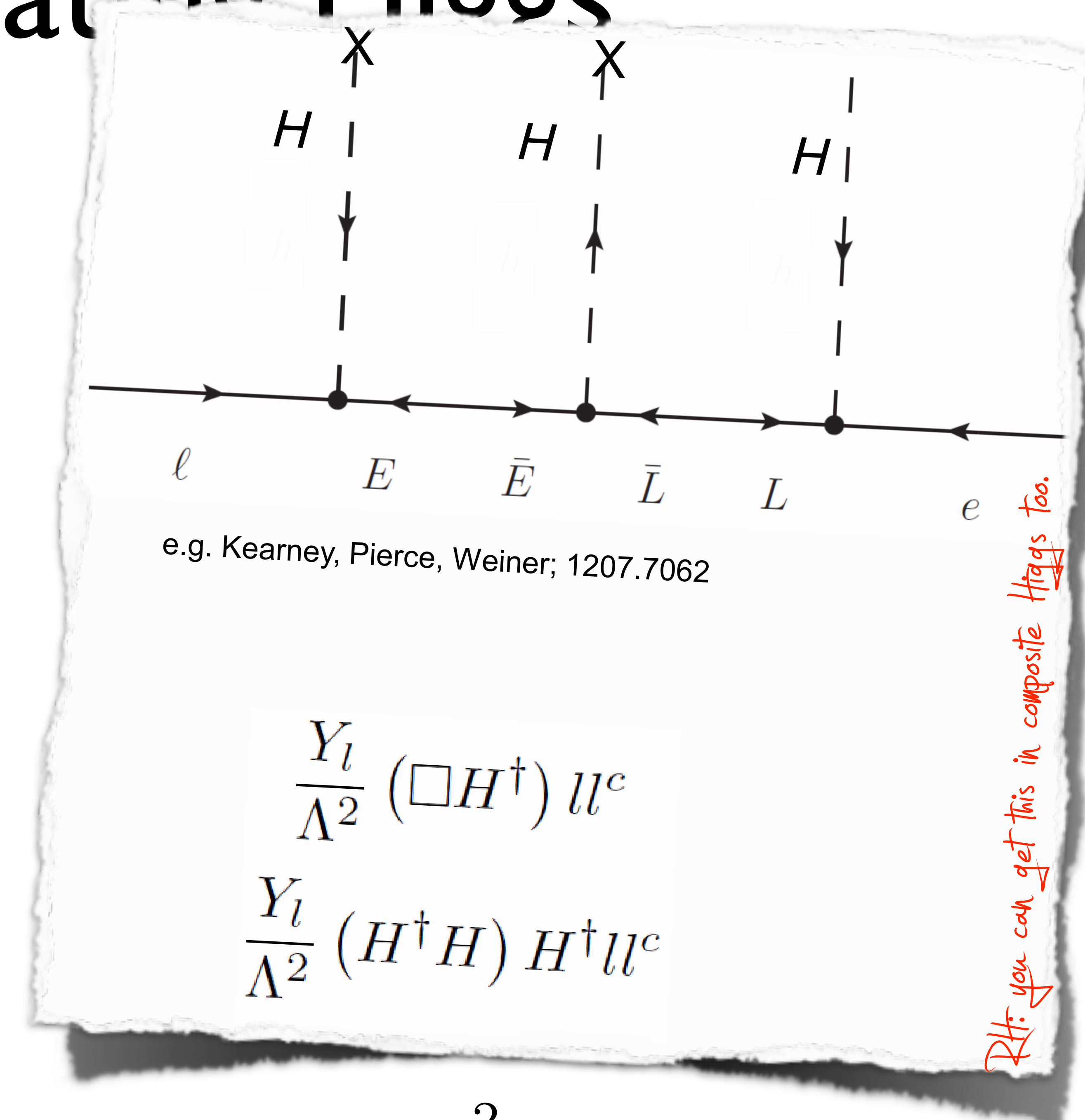

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$$y_f = \lambda_f + \frac{3v^2}{\Lambda^2}$$

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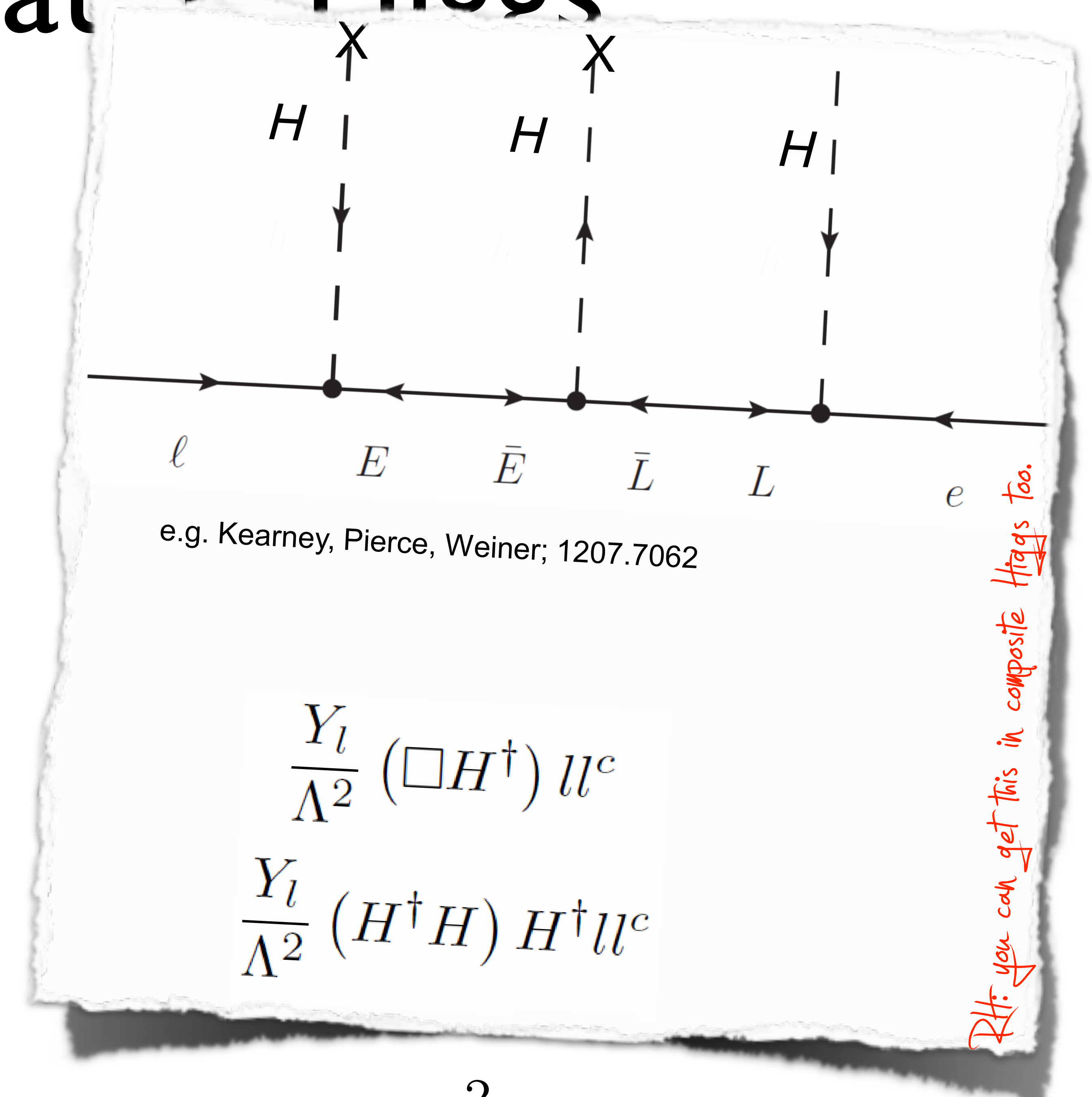

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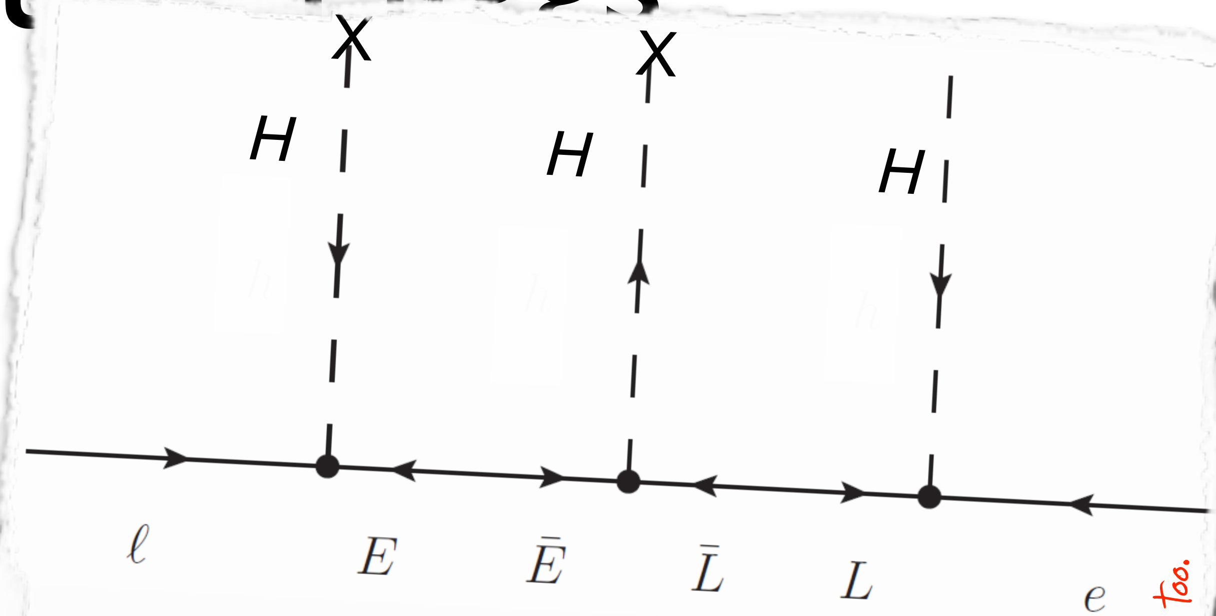

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$$m_f = (\lambda_f + \frac{v^2}{\Lambda^2})v$$

$$y_f = \lambda_f + \frac{3v^2}{\Lambda^2}$$

$$y_f \neq \frac{m_f}{v}$$

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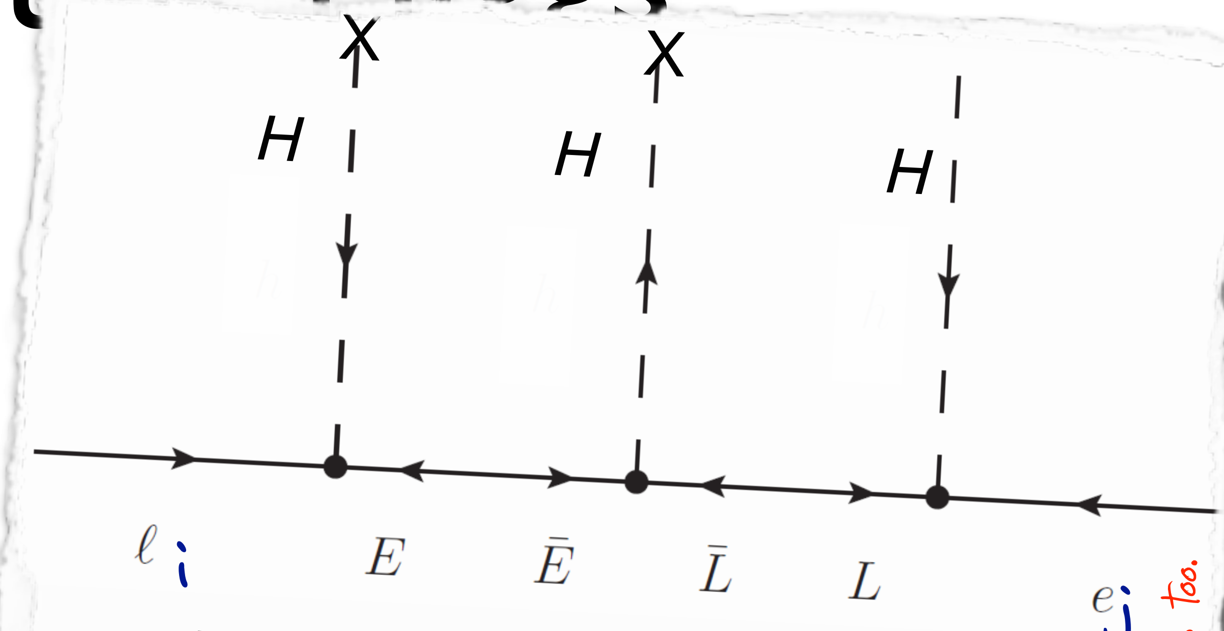

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$$\frac{Y_{l\,ij}}{\Lambda^2}(\Box H^\dagger)\, l_i l^c_j$$

$$\frac{Y_{l\,ij}}{\Lambda^2}(H^\dagger H)\, H^\dagger l_i l^c_j$$

BTW: you can get this in composite Higgs too.

$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2}$$

$$m_f = (\lambda_f + \frac{v^2}{\Lambda^2}) v$$

$$y_f = \lambda_f + \frac{3v^2}{\Lambda^2} \quad \rightarrow \quad y_f \neq \frac{m_f}{v}$$

Flavor Violating Higgs

* Writing it a bit more neatly, we get:

$$\mathcal{L}_{SM} = \bar{f}_L^j i\not{D} f_L^j + \bar{f}_R^j i\not{D} f_R^j - \left[\lambda_{ij}(\bar{f}_L^i f_R^j)H + h.c.\right]$$
$$+ D_\mu H^\dagger D^\mu H - \lambda_H\left(H^\dagger H - \tfrac{v^2}{2}\right)^2$$

$$\Delta\mathcal{L}_Y = -\frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H) + h.c. + \cdots$$

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

or $$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

An arbitrary matrix! (sort of)

“Natural” FV

* FV that’s too large comes at a tuning price:

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

* Requiring no cancelation in the determinant

$$|Y_{\tau\mu}Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}$$

(same for any pair of fermions)

In an era of data, considerations of fine tuning are not of huge importance...
But we’ll keep it in the back of our mind.

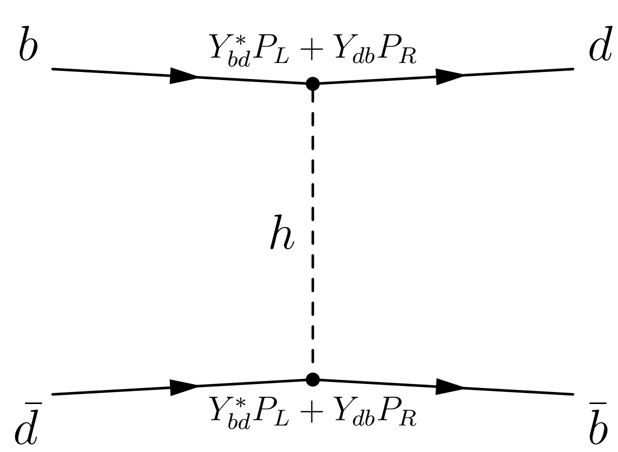
LFV Summary

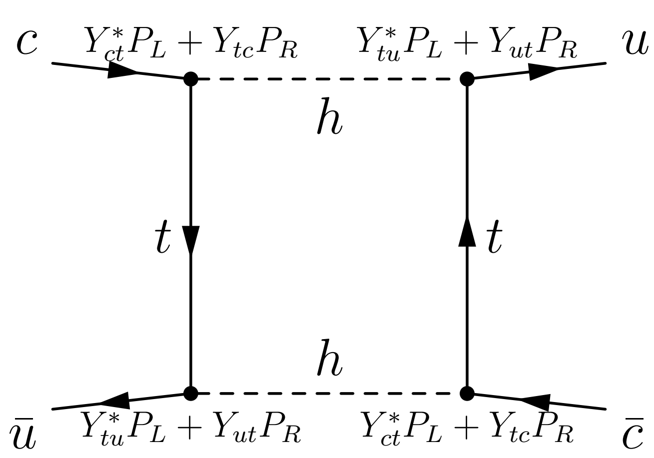
Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	< 0.31
electron $g-2$	$\mathrm{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu} Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ 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
$\tau \to e\mu\mu$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.66
electron $g-2$	$\mathrm{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau} Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	$< 1.6 \times 10^{-2}$
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	< 0.52
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu} Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau} Y_{e\tau}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

many processes to consider...

Meson Mixing

* Meson mixing's powerful.

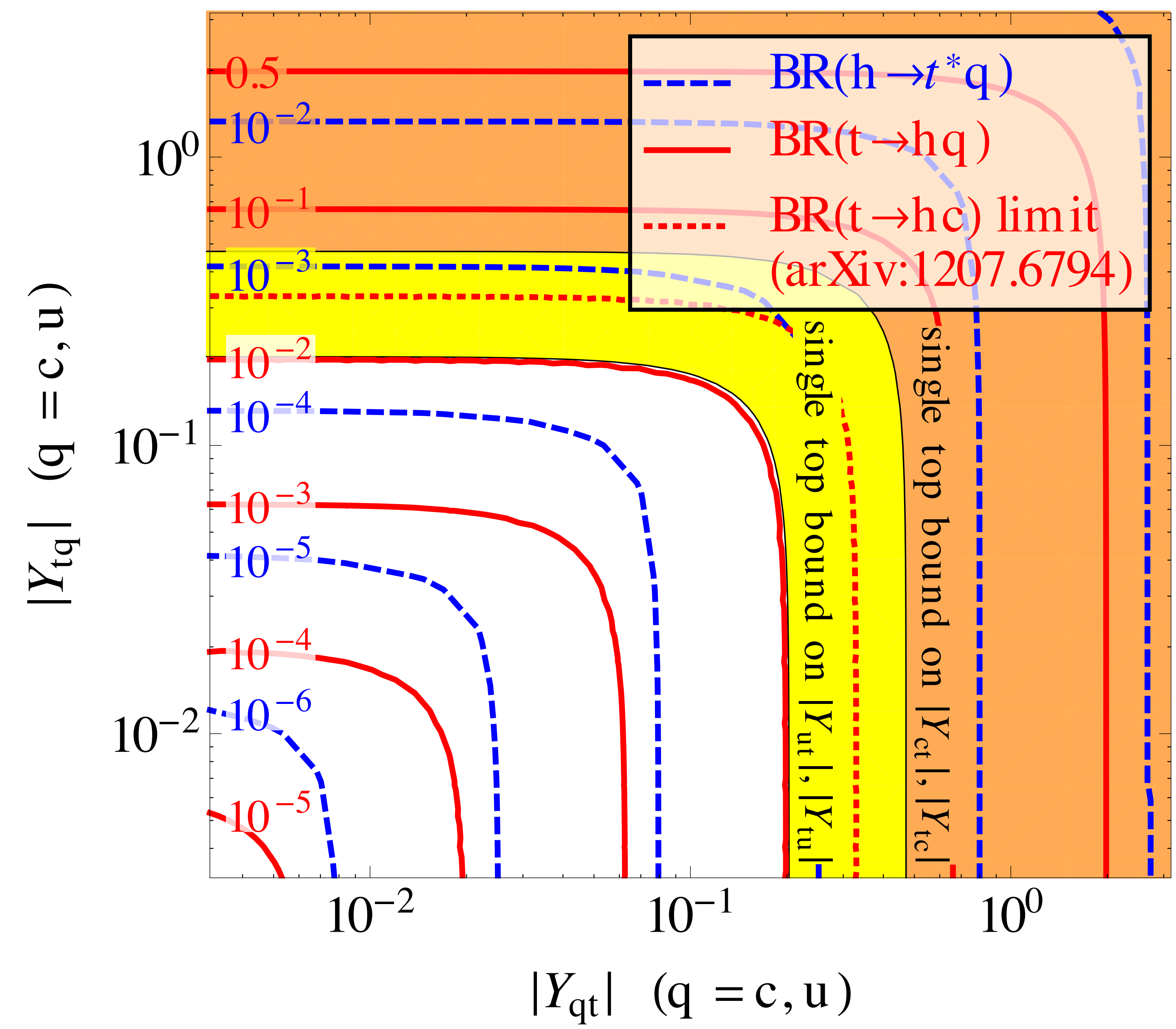




Technique	Coupling	Constraint
D^0 oscillations [39]	$\lvert Y_{uc}\rvert^2,\ \lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [39]	$\lvert Y_{db}\rvert^2,\ \lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [39]	$\lvert Y_{sb}\rvert^2,\ \lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [39]	$\mathrm{Re}(Y_{ds}^2),\ \mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2),\ \mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^*Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^*Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [40]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.54
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.23
$t \to hj$ [41]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [39]	$\lvert Y_{ut}Y_{ct}\rvert,\ \lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert,\ \lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [29]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

Top Flavor Violation

* But, top decays are interesting:



Back to the Curiosity List...

How much of it can intensity experiments shed light on?

Curiosity List (incomplete)

* Is there any physics beyond the standard model?
* What sets the EW scale? Is it natural?
* Is the world supersymmetric?
* Is it the Higgs boson?
* What is Dark Matter?
* Is there a dark sector?
* What is Dark Energy?
* Can the CC be natural?
* Are we part of a Universe or a Multiverse?
* What sets the fermion masses?
* Why is there more matter than anti-matter?
* Are neutrinos their own anti-particles?
* Are there sterile Neutrinos?
* Do neutrino interact in a non standard way?
* What solves strong CP?
* Is there an axion? Is it Dark matter?
* How many space-time dimensions do we live in?
* Do the forces unify?
* Is CP violated Beyond CKM? where? LBNE EDMs QFV
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Curiosity List (incomplete)

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Not too Shabby!