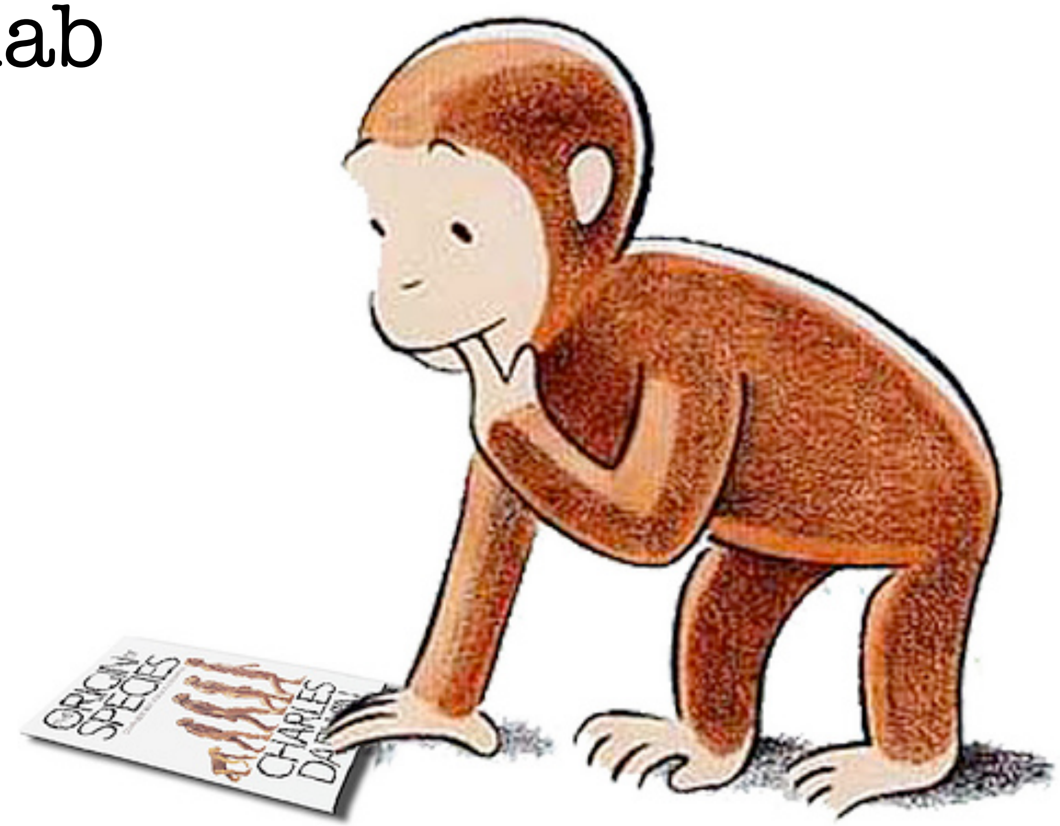
# The Curiosity Frontier

Roni Harnik,
Fermilab



# Why Are We Here?

* **We are curious**.
* We are like kids that have many many questions.
* We receive great pleasure from finding things out.

What are we curious about?

# A Curiosity List:

(Partial! In no particular order.)

* Is there any physics beyond the standard model?
* What sets the EW scale? Is it natural?
* Is the world supersymmetric?
* Is there a Higgs boson?
* What is Dark Matter?
* Is there a dark sector?
* What is Dark Energy?
* Can the CC be natural?
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Note!

These questions do not belong to any frontier.

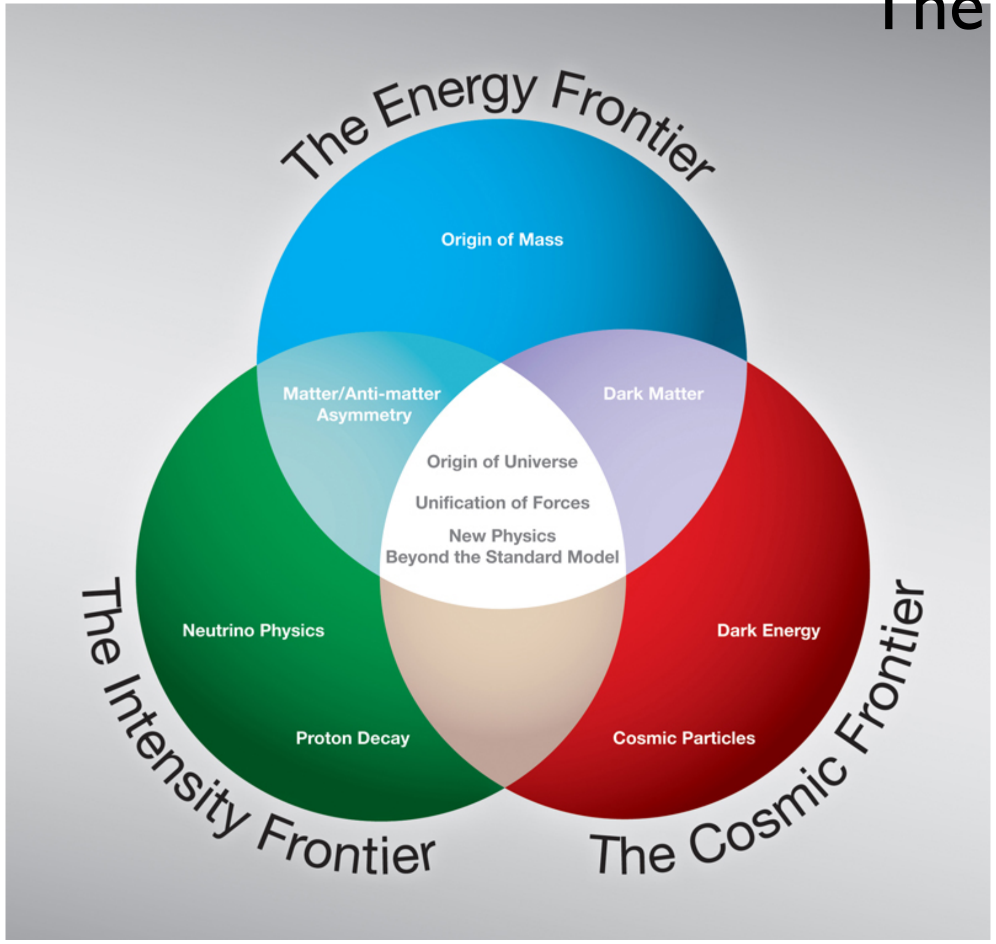
They are questions that drive our field.

# Frontier-ology

* The more technical reason we're here is - we want to know how to best answer these questions.
* We have a bunch of experimental tools that can (hopefully) answer them.
* At some point (for practical purposes) the **tools** we use were divided into 3 groups, or frontiers.
* The questions, and the physicist that are curious about them, do not fall into these groups.

# Frontiers

The Curiosity Frontier



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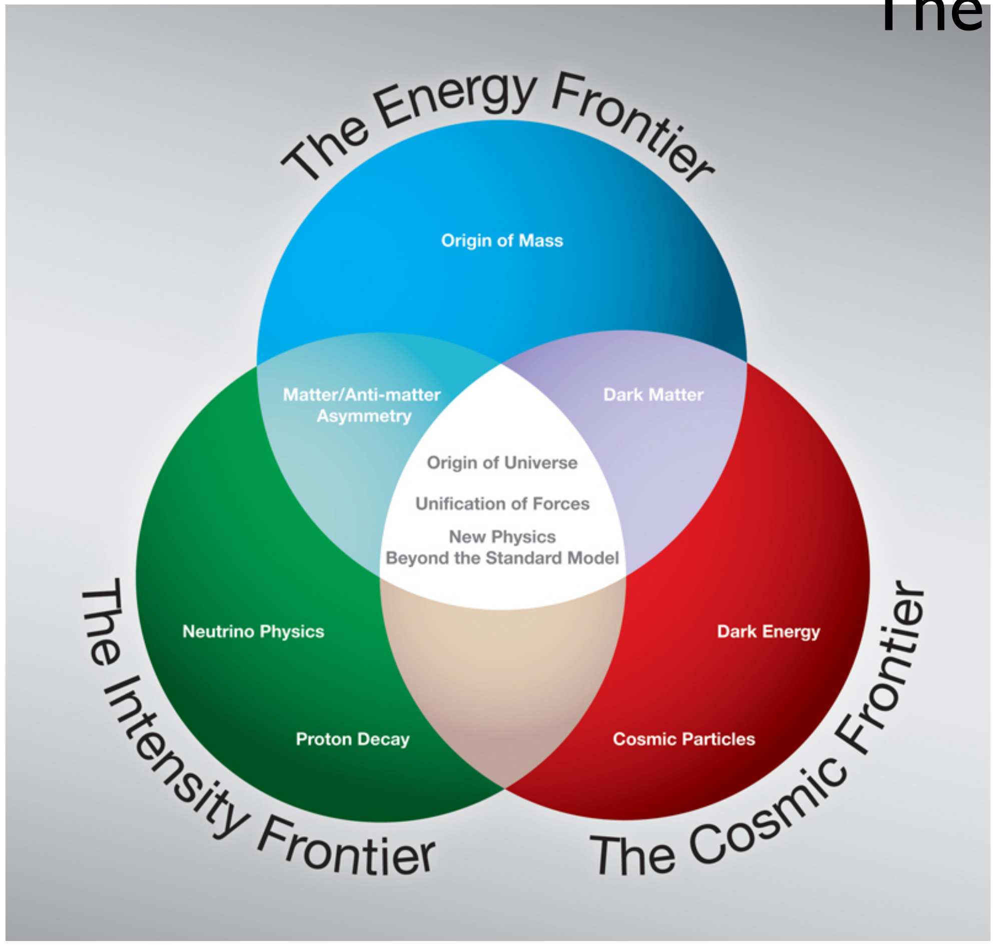


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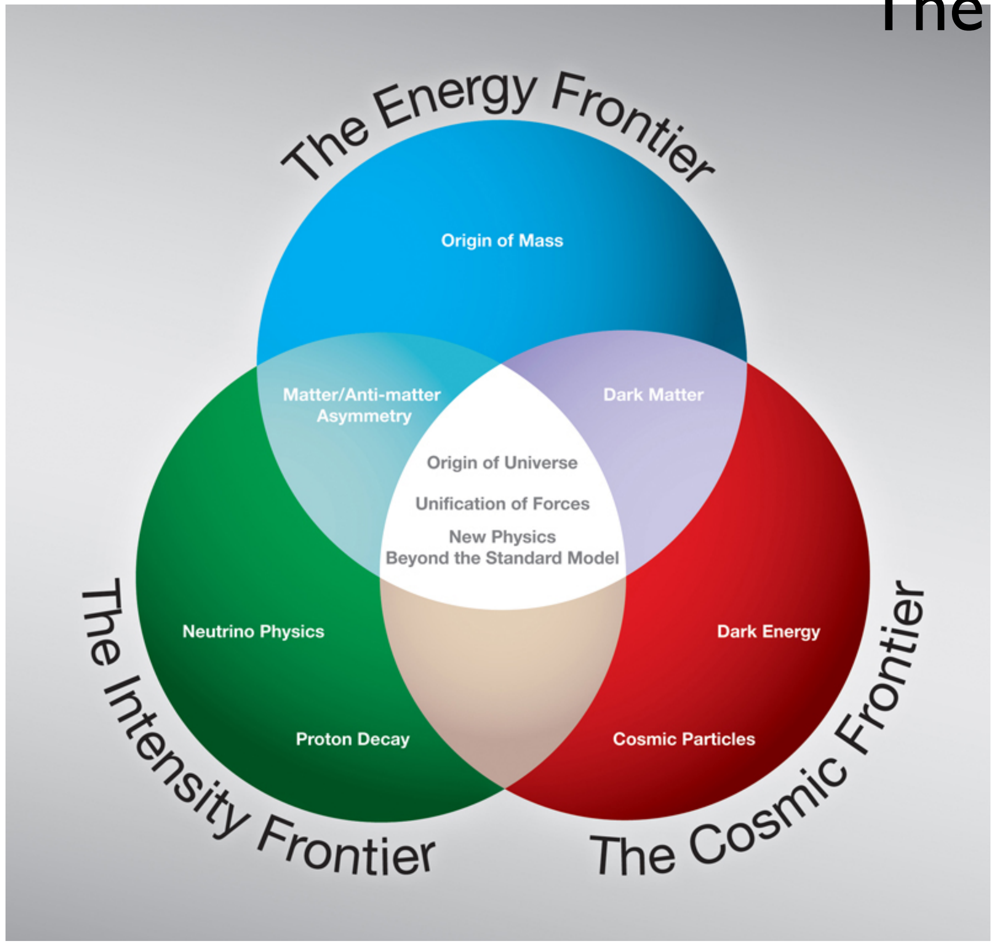


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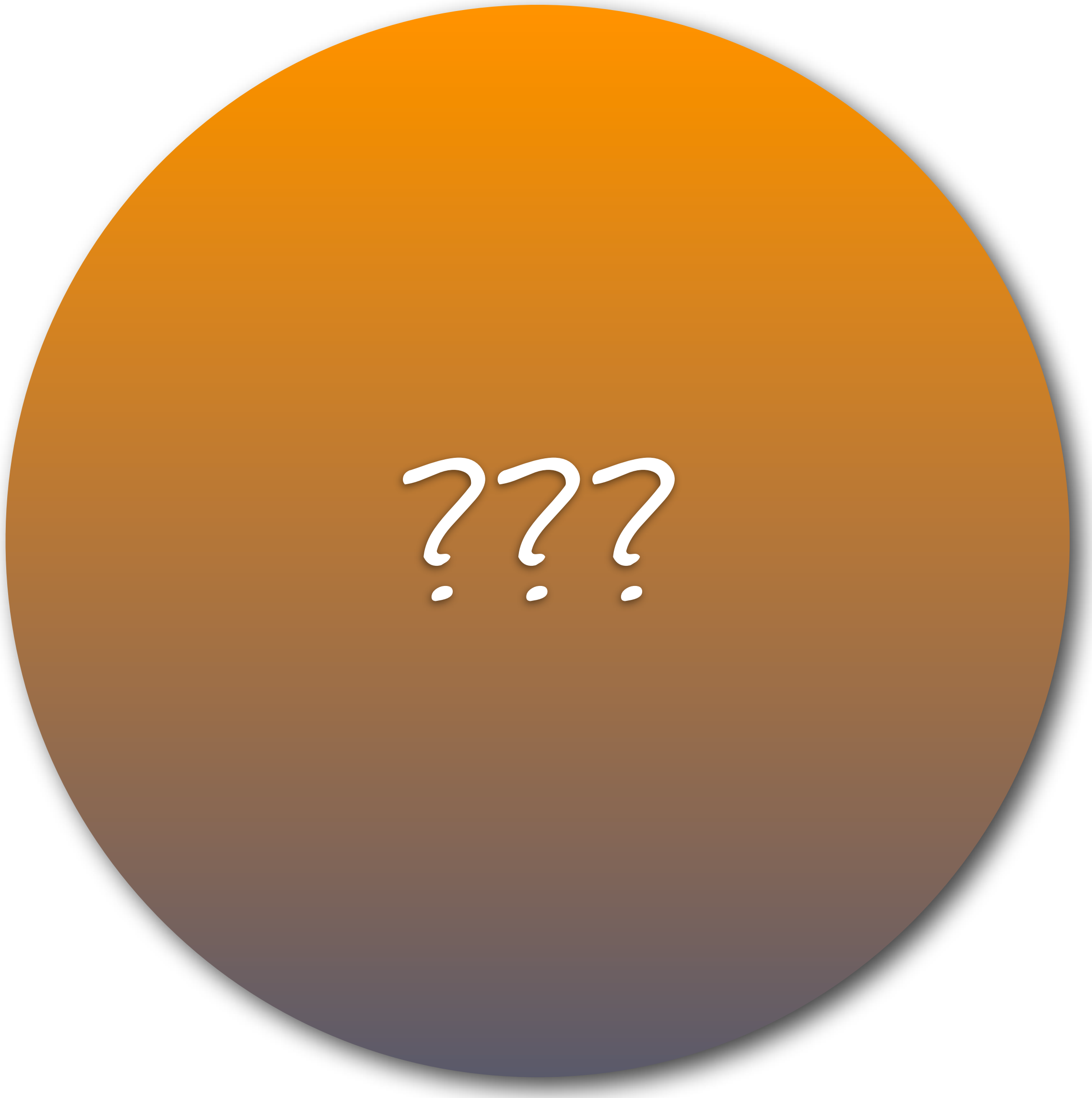

# Curiosity

- What drives the field is our **childish curiosity**. How does Nature work?
- So lets think like children!
- If a child is curious about something she goes at it **with all her senses**. **All her tools**. **All "frontiers"**.

usually done simultaneously!

Speaking of child-like curiosity...
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Goody! a present!!!...
What is it?? oh boy!

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So, how does a child approach this?
lets dissect her actions in slow motion.

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"Theory"

The theorist springs into action:

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wow! mommy! what is it?!

I bet it a bike! I asked for a bike...

maybe its a bus! or a doll?

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# 2. Observe:

"Cosmic"

Cosmic frontier type observation:

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# 2.Observe:

"Cosmic"

Cosmic frontier type observation:

Wow! cool wrapping paper!

looks very homogeneous,

but Its too small to be a bike....

## 3. Open the box:

"Energy"

Answer the question *directly*. Head on.

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Though it does not give a definitive answer, sometimes the giveaway clue come from *indirect* observation:

"Intensity"

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Though it does not give a definitive answer, sometimes the giveaway clue come from *indirect* observation:

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hmmm, its not that heavy... but it feels sort of hard...

lets shake it a bit and listen...

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**Do Intensity Frontier experiments help satisfy our curiosity?**

**of course!**
**Here are examples.**

# Higgs

Is it the SM Higgs boson?

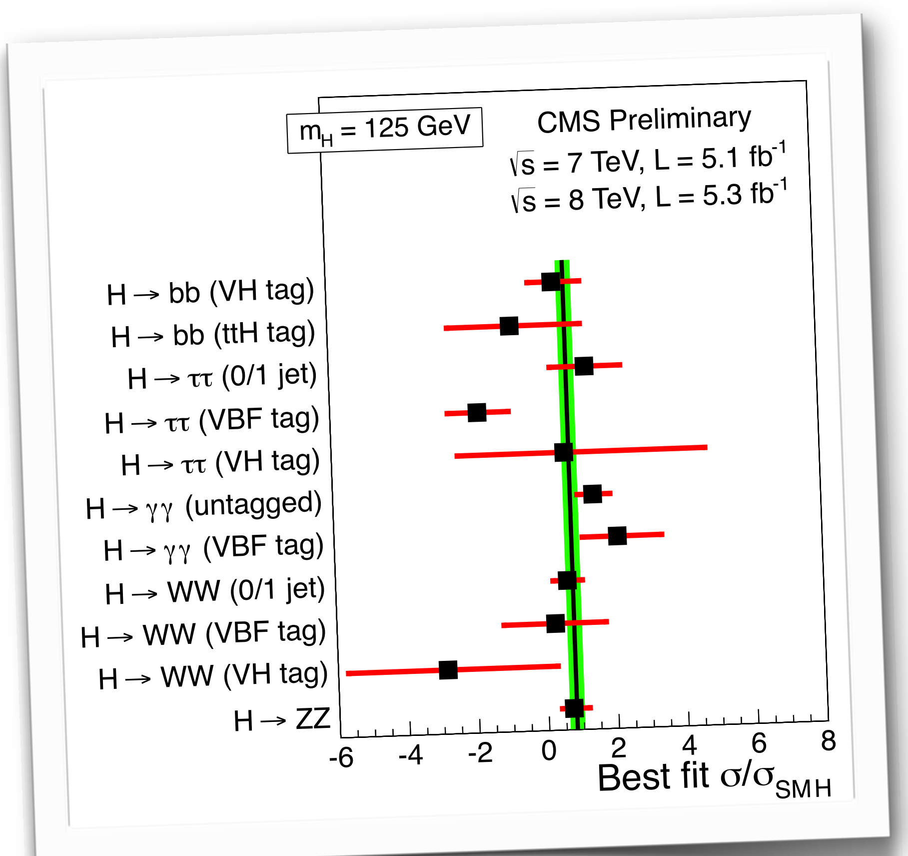
Note:

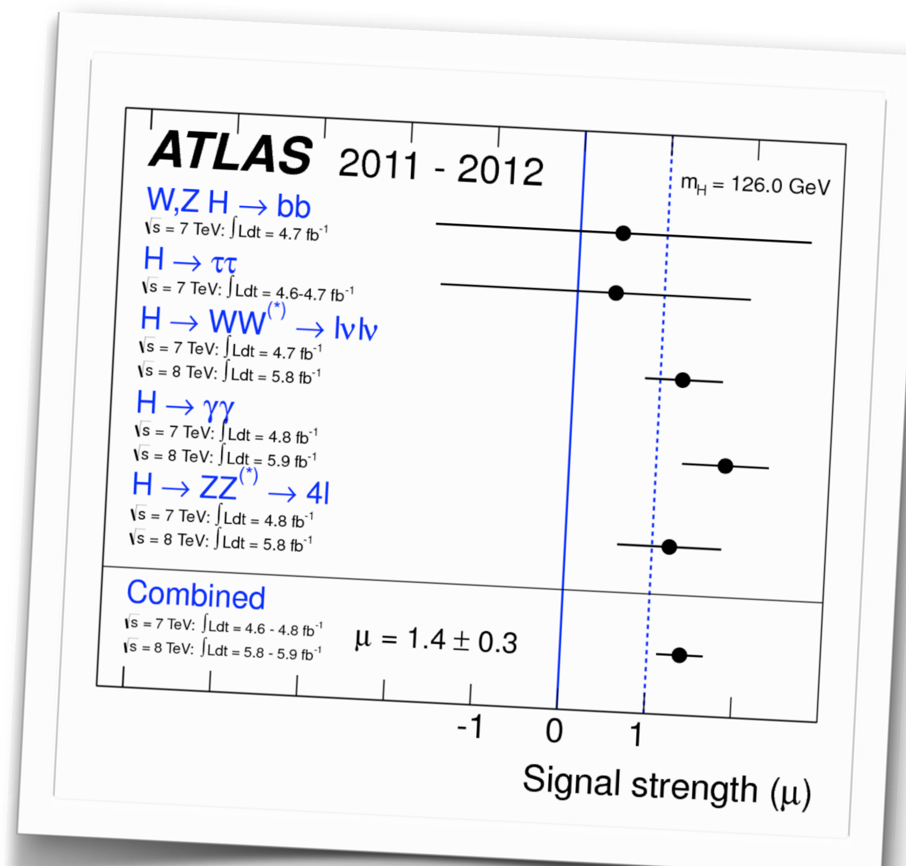
Stereotypically, the Higgs is in the "energy frontier".

But recall, the questions do not get divided.

# Higgs

* A timely topic.
* Probing Higgs couplings is a pressing goal.
* A remarkable opportunity to look for NP.




**How about non-SM Higgs coupling?**

# Higgs & Flavor Violation

* *In the presence of new physics,* Yukawa couplings can violate flavor:

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots$$

* Any fermion bilinear is possible:
(UV models are easy to come by)

$$\boxed{\begin{array}{ccc} \tau\mu & \tau e & \mu e \\ tc & tu & \ldots \end{array}}$$

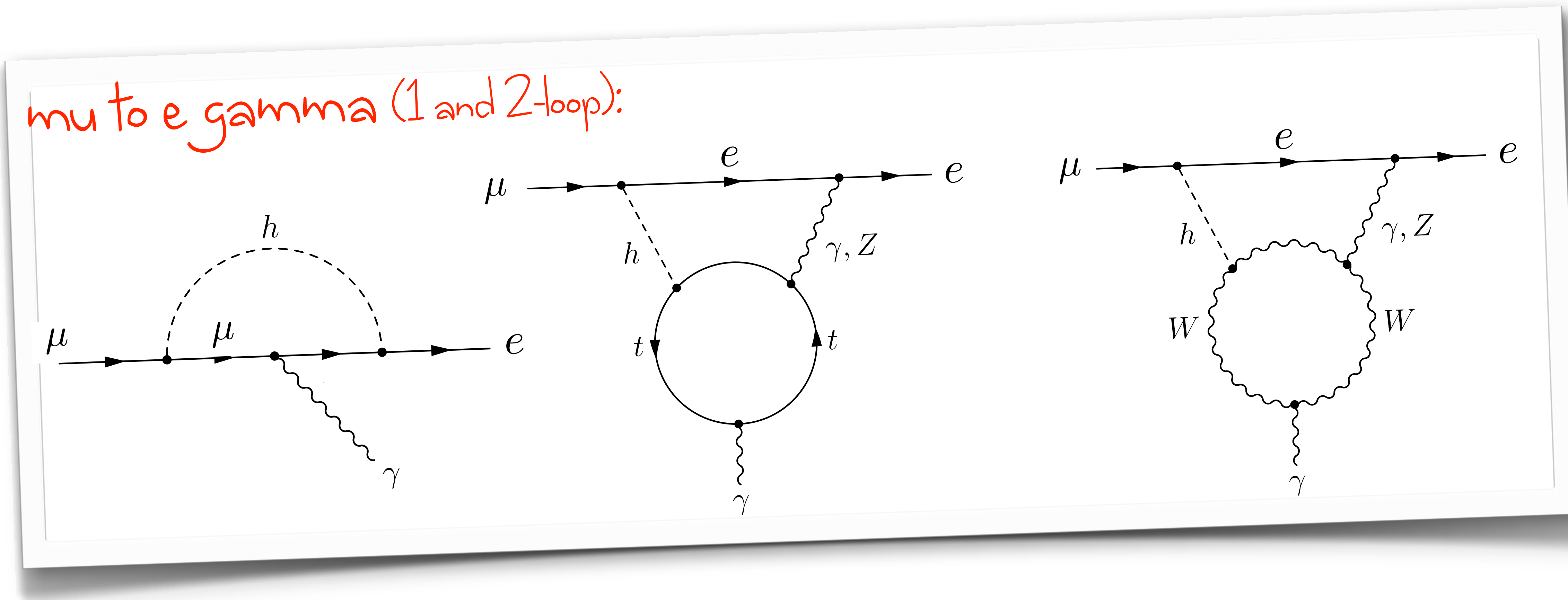
* How large can FV be?
Very roughly-

$$|Y_{ij}Y_{ji}| \lesssim \frac{m_i m_j}{v^2}$$

Anything below this is "natural".

# Higgs couplings to $\mu e$

* Higgs coupling to $\mu e$ is constrained, e.g. by:



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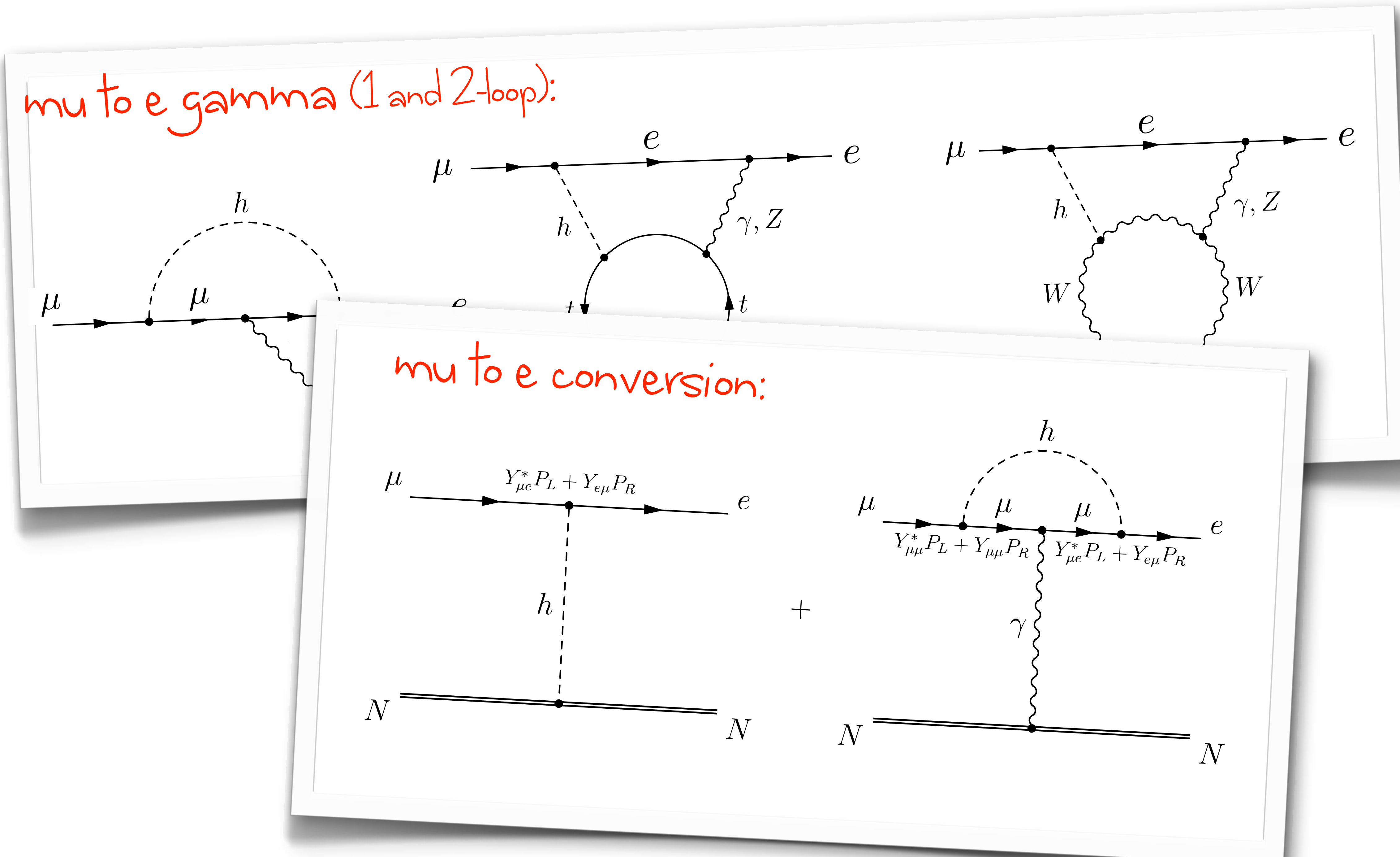


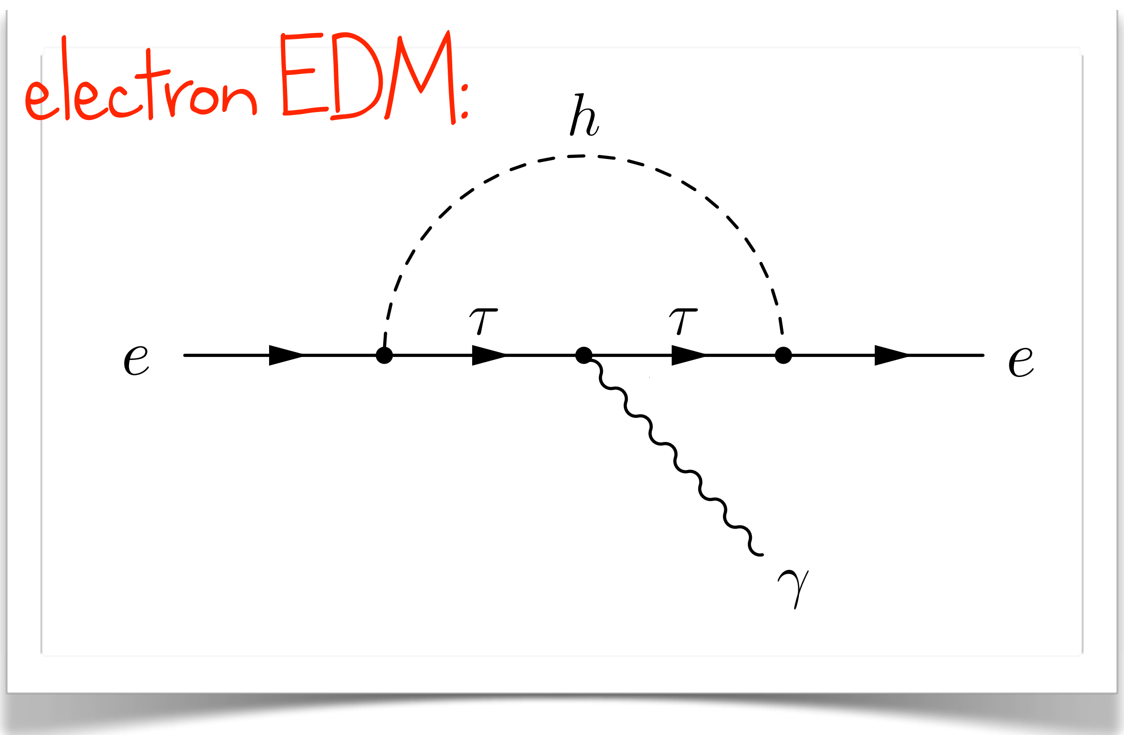
# Higgs couplings to $\mu e$

Outside of
LHC reach.

Probing
"natural" models.

# Higgs and EDM's

- EDM searches also constrain FV & CPV couplings.
- Consider Higgs couplings to e-tau:




$$|\mathrm{Im}(Y_{e\tau}Y_{e\tau})| < 1.1 \times 10^{-8}$$

starting to probe "natural" models.

Note:
We get a similar bound on top-up-Higgs couplings from the neutron EDM.

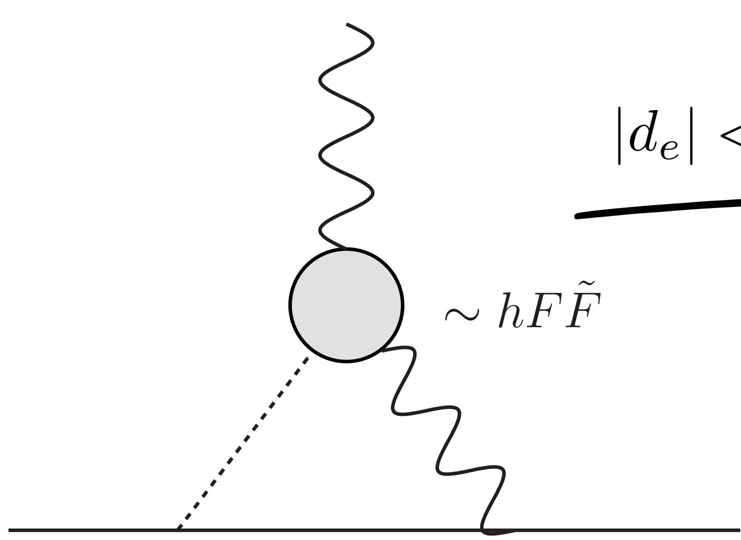
# Higgs and EDM's

- 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:




$$|d_e| < 1.05 \times 10^{-27} e \text{ cm} \longrightarrow \Delta \mathrm{BR}_{\gamma\gamma} < 1.6 \times 10^{-4}$$

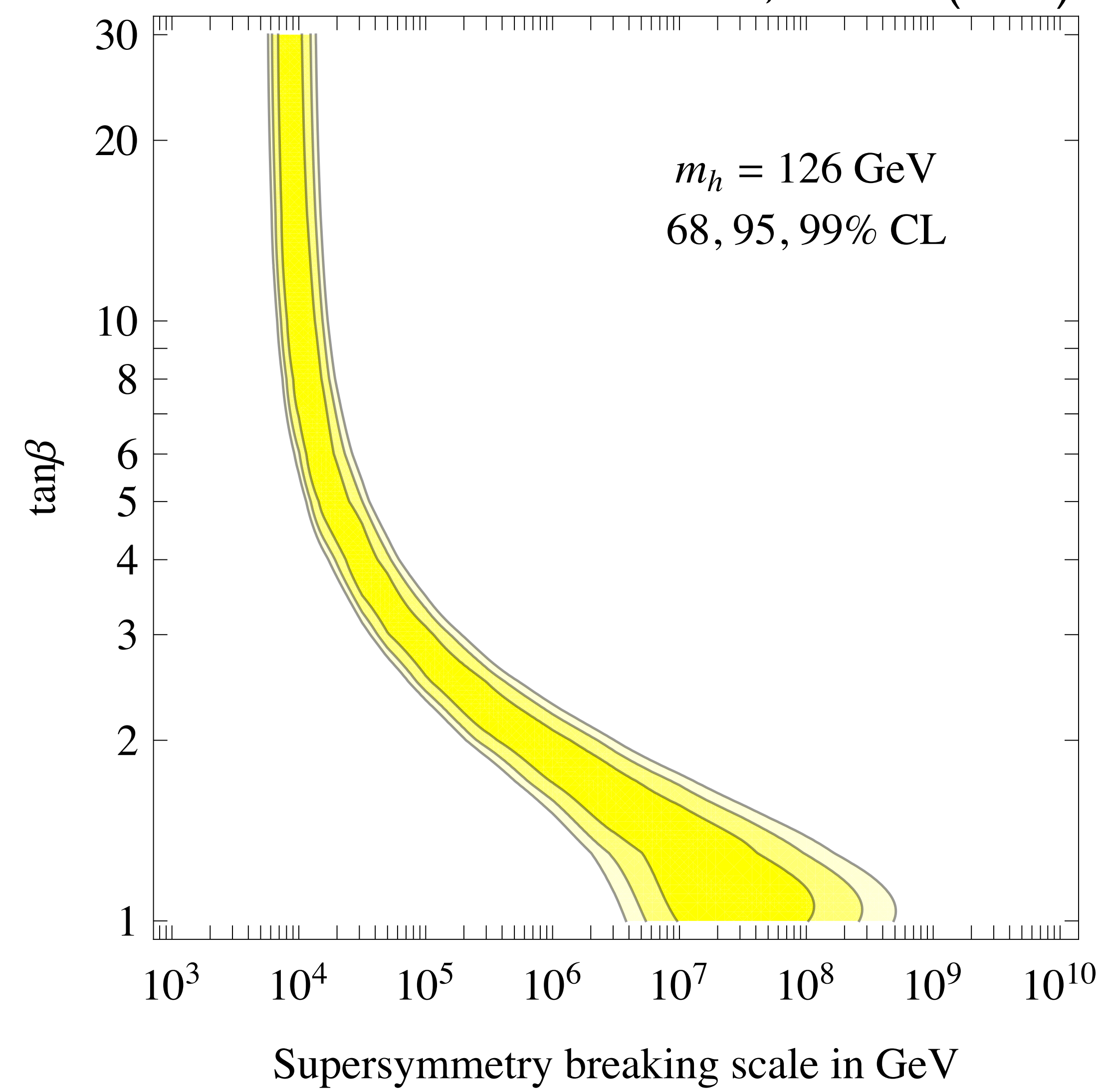
McKeen, Pospelov, Ritz (1208.4597)

# High Scale SUSY

# Split SUSY

* SUSY has a "missing superpartner problem".
* Maybe SUSY addresses most, *but not all* of the tuning.
* The Higgs mass provides a hint:

Giudice, Strumia (2012)



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SUSY at such high scales is likely to include flavor and CP violation.

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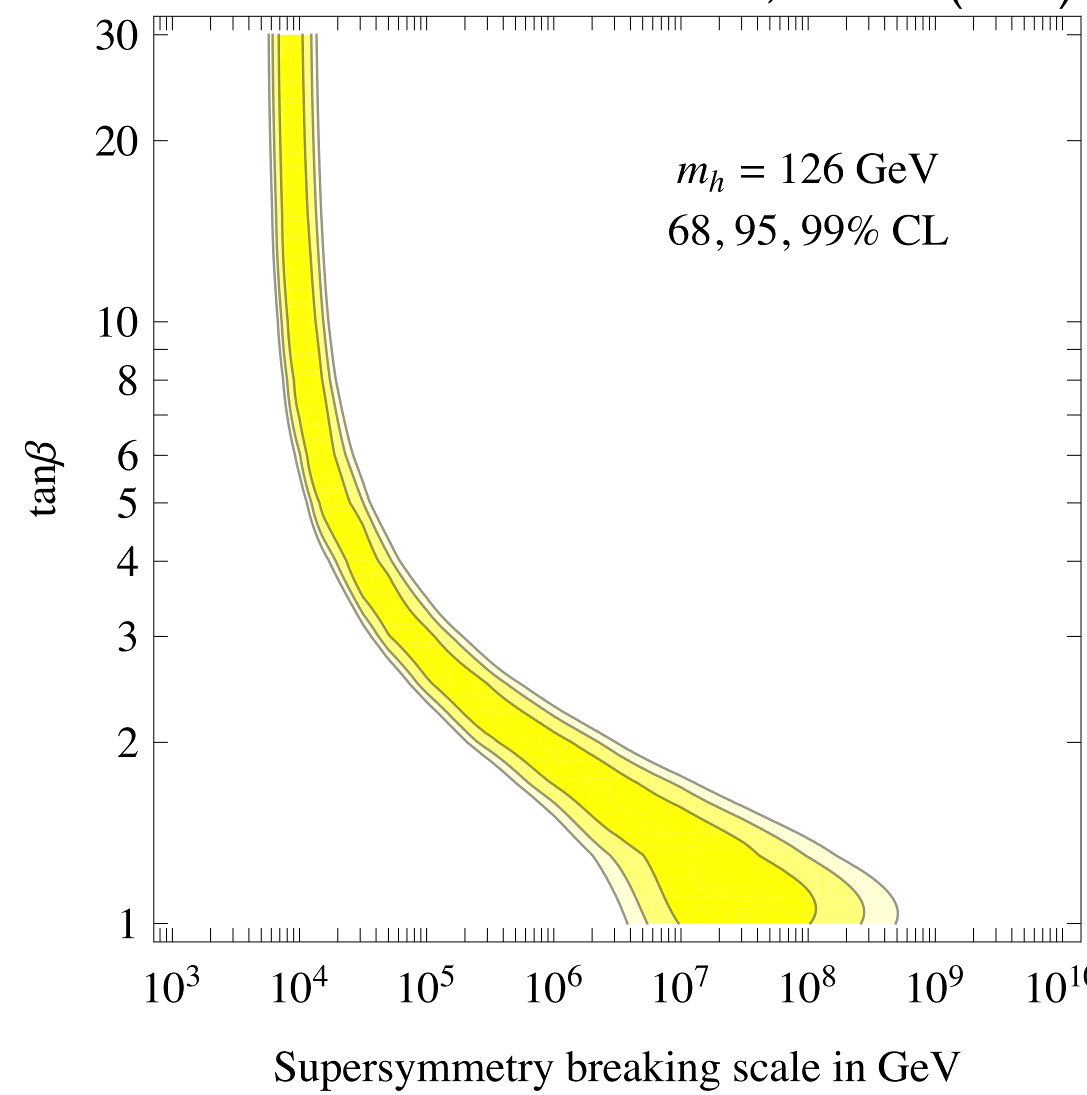

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Goal: try to reach O(PeV) with as many probes as possible.

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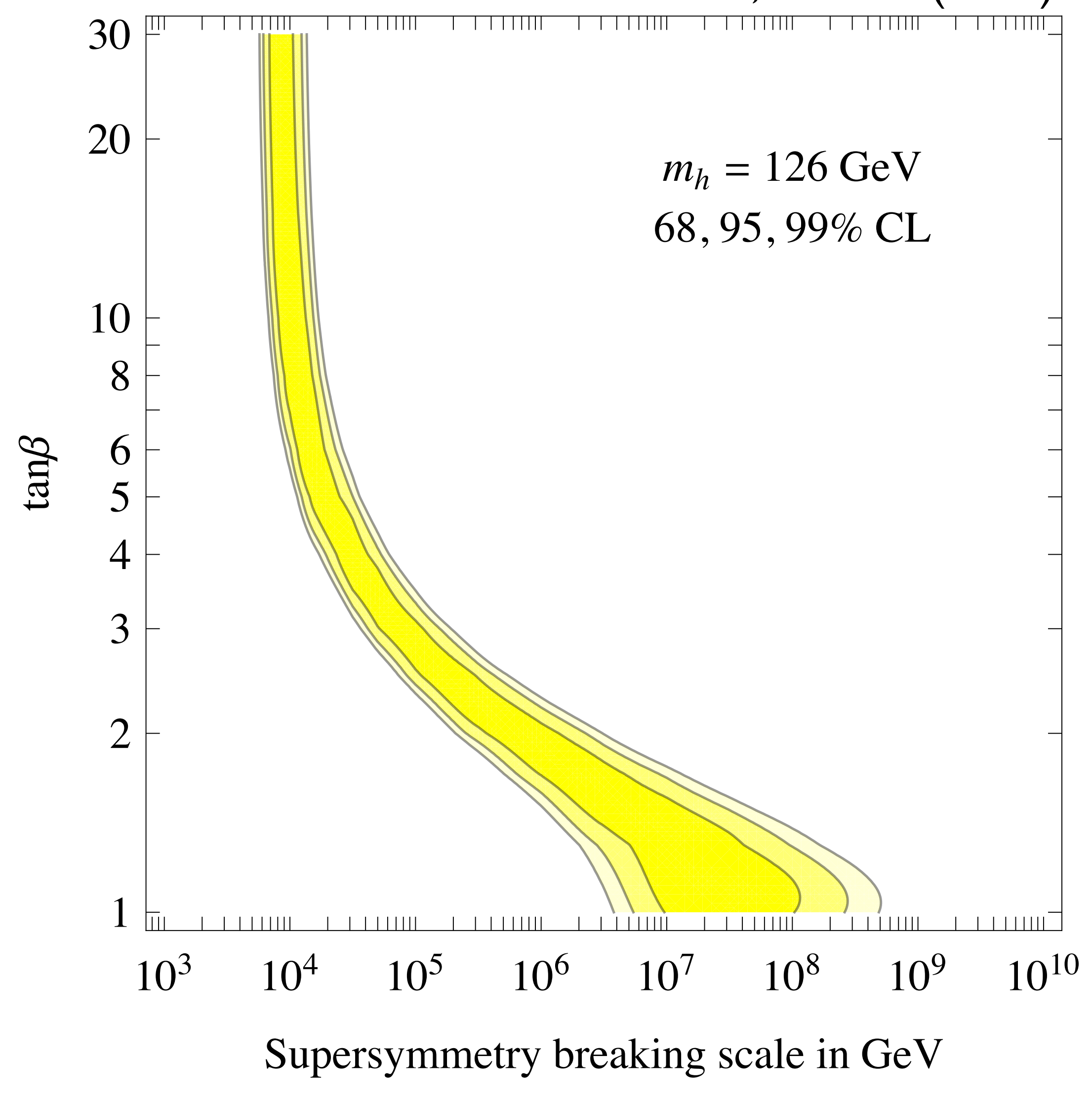
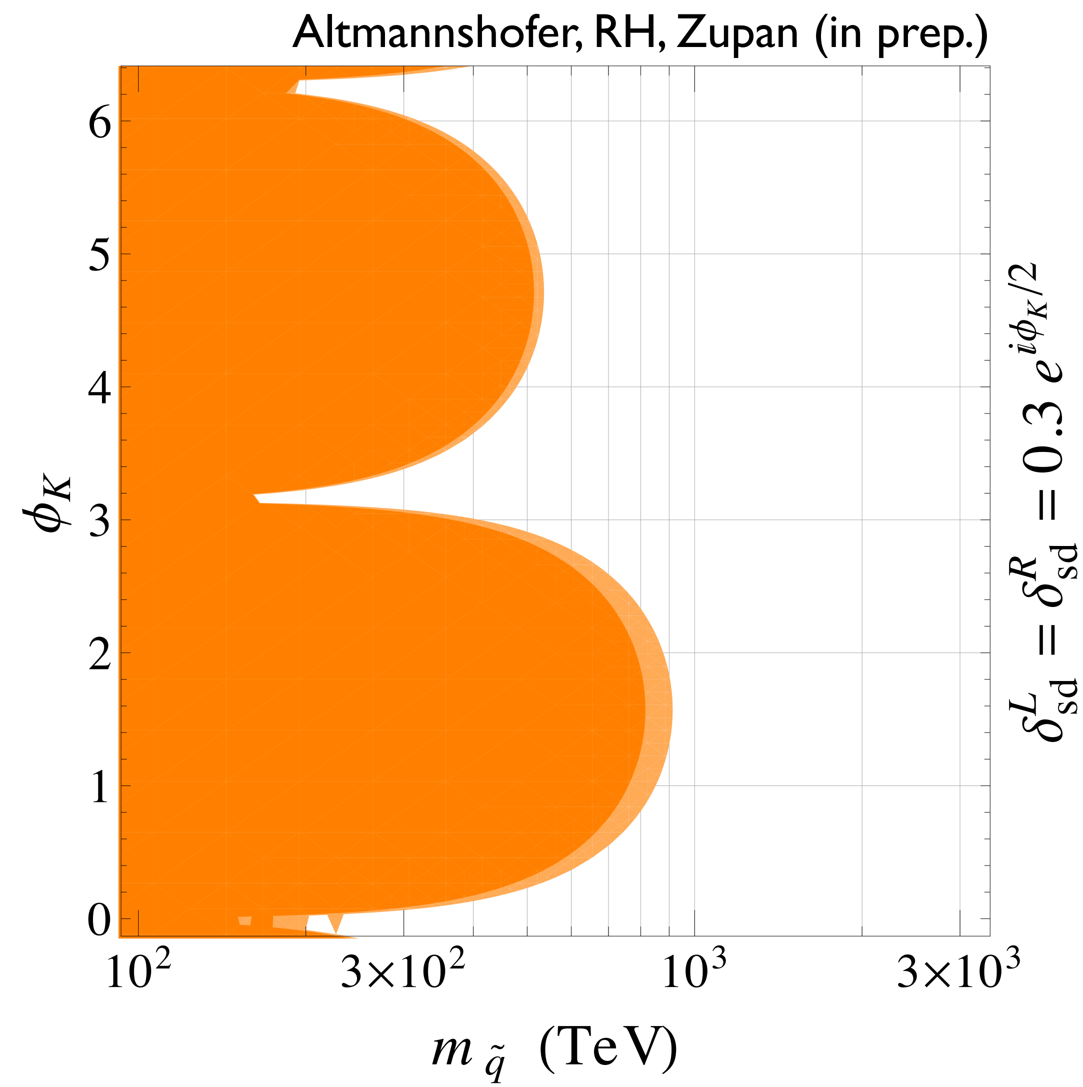


# Meson Mixing

* K mixing is probing the 100-1000 TeV. Particularly if CPV phase is of O(1).



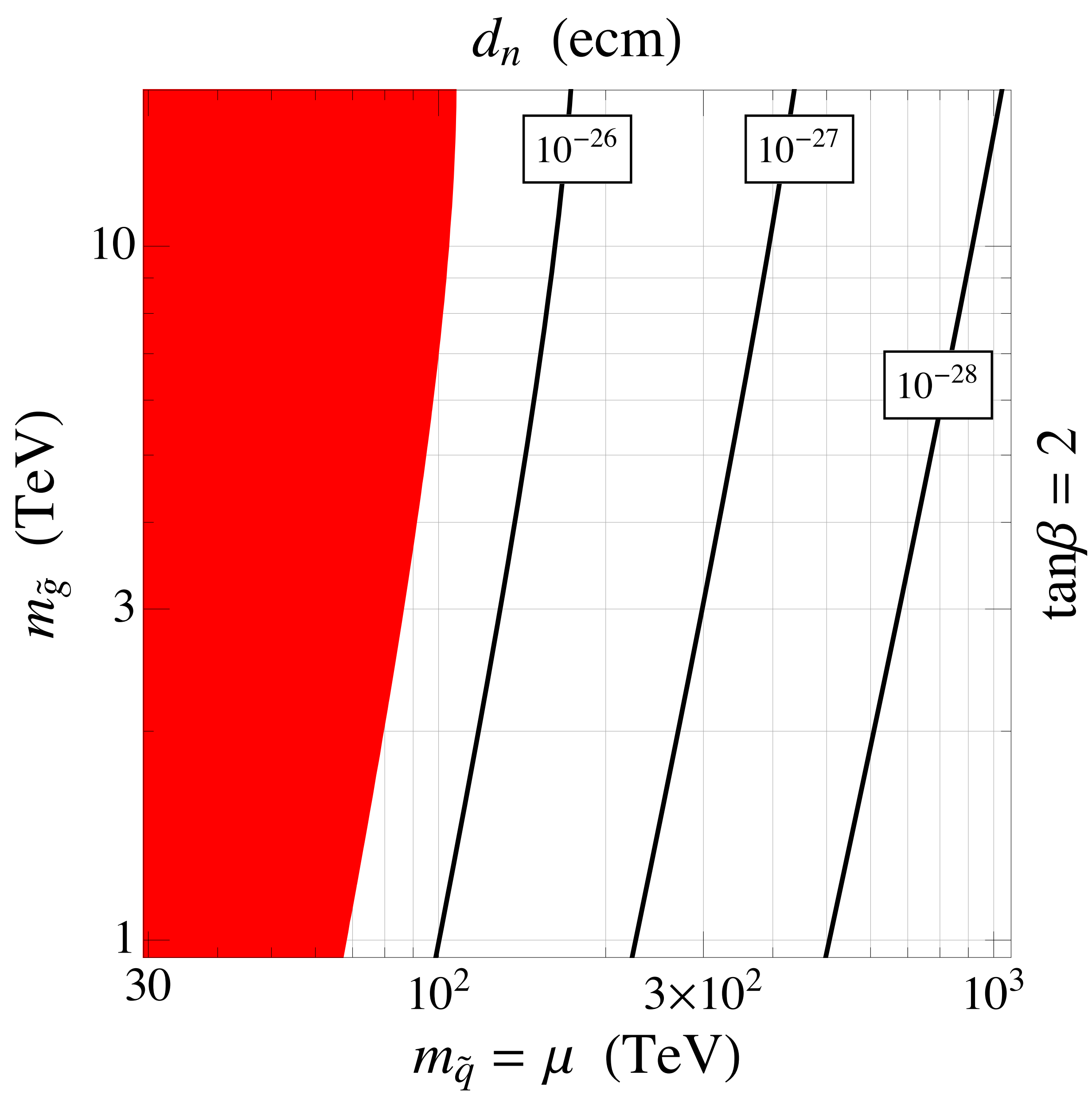

* CPV in D decays is also promising (~100 TeV in the coming years).

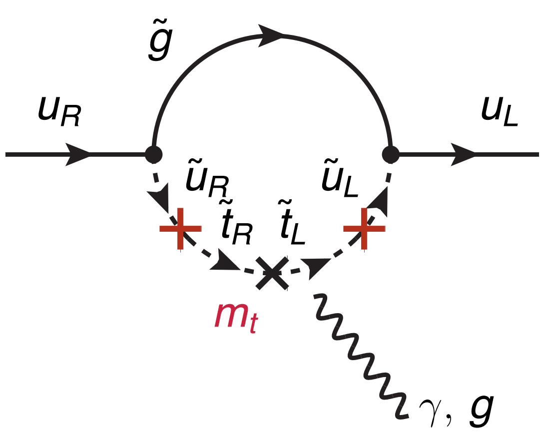
Altmannshofer, RH, Zupan (in prep.)

see also McKeen, Pospelov, Ritz (2013)

# EDM's

* Combination of FV and CPV leads to enhanced nucleon EDM.




precise limit is model dependent, But 1000 TeV is with reach!

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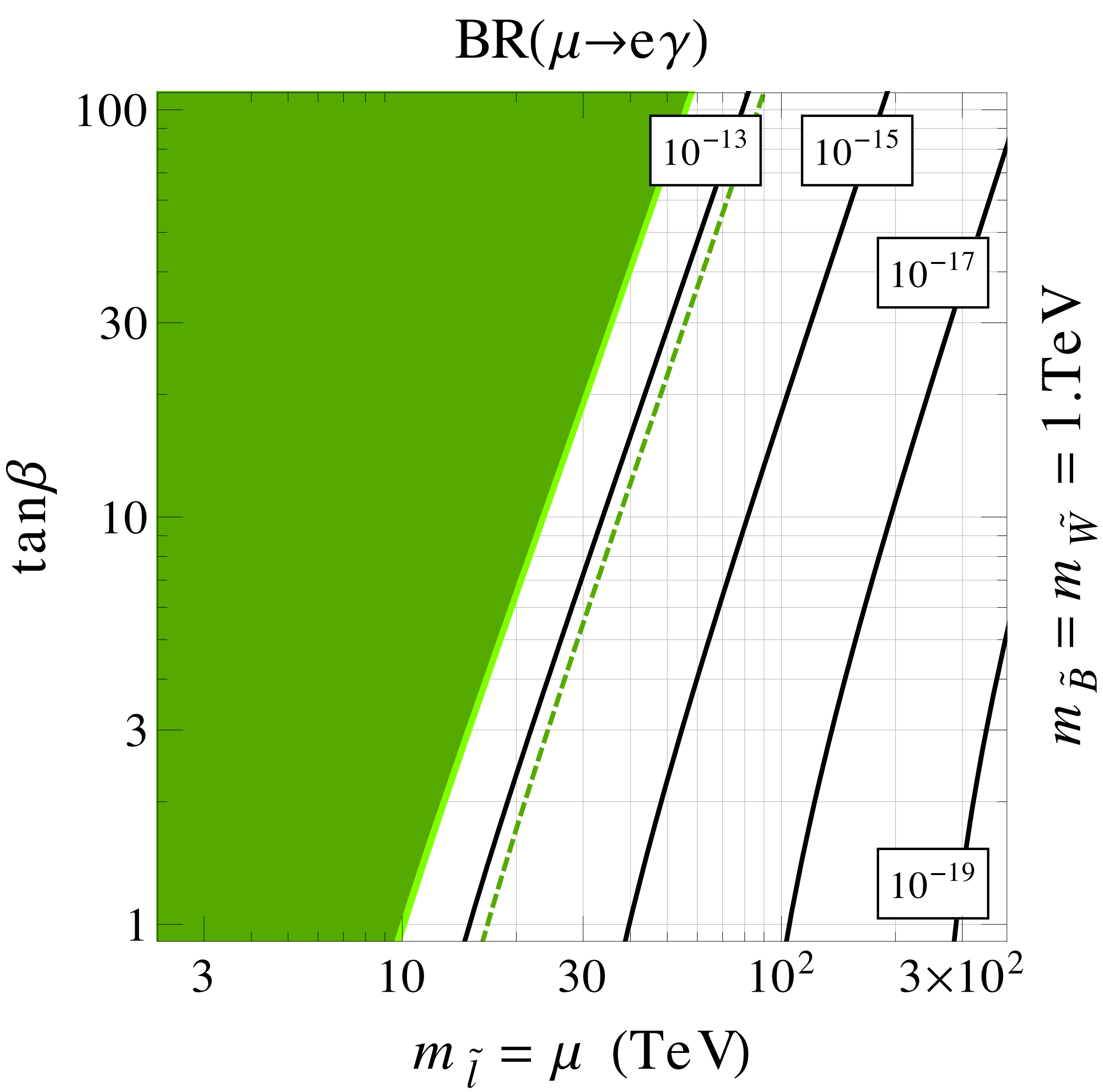
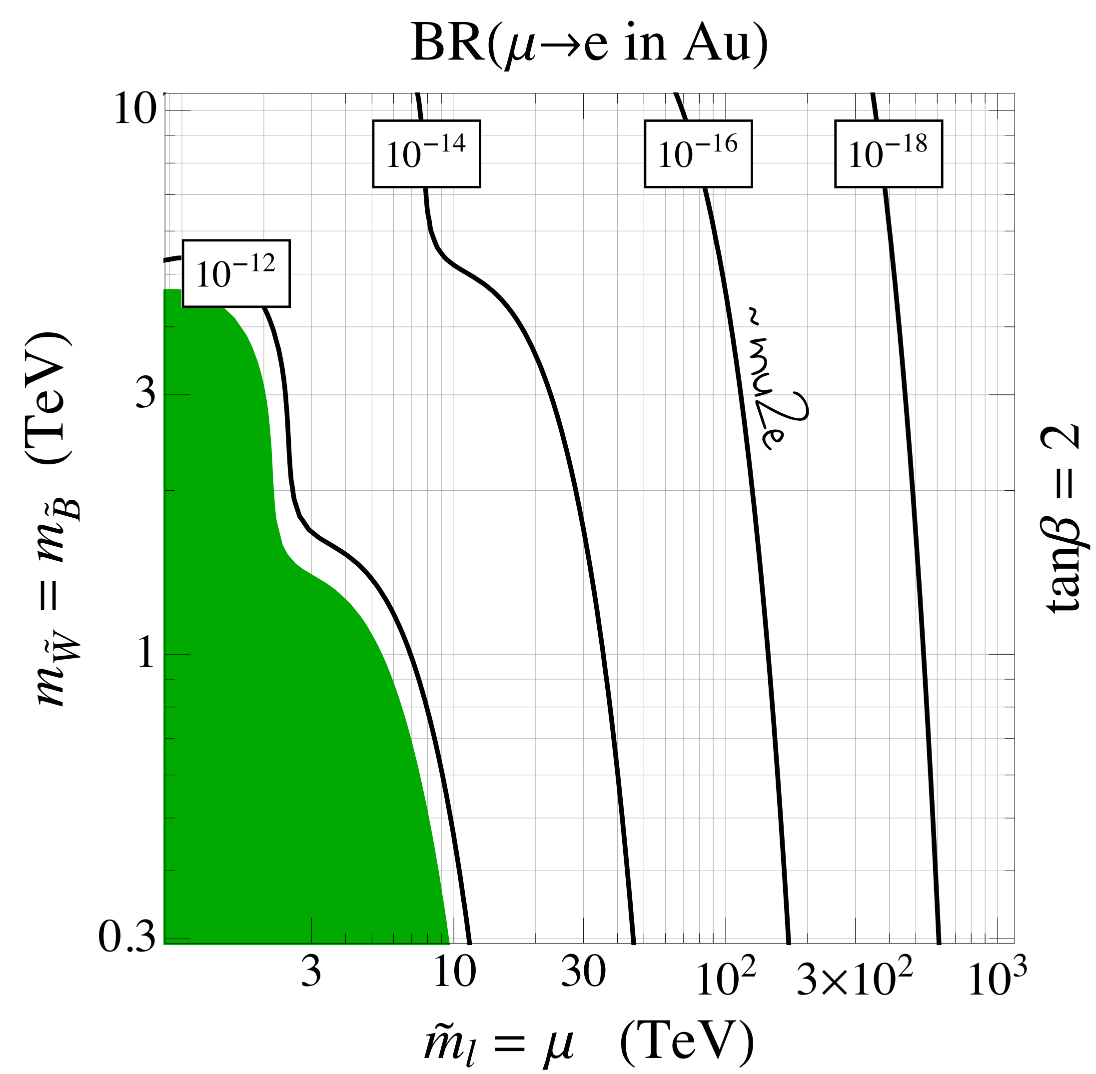
# LFV

- Sleptons may be lighter than squarks.
- μ→eγ and μ2e are *complementary* (in tanβ and ino masses).



# Back to the Curiosity List...

How much of it can intensity experiments shed light on?

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Not too Shabby!

# To Conclude

* **We are driven by curiosity.**
* To satisfy our yearning to find things out we should use *all* of our tools.
* **The Intensity frontier is an important tool.**
* **Learn from our kids- explore the world with all of our senses simultaneosly.**

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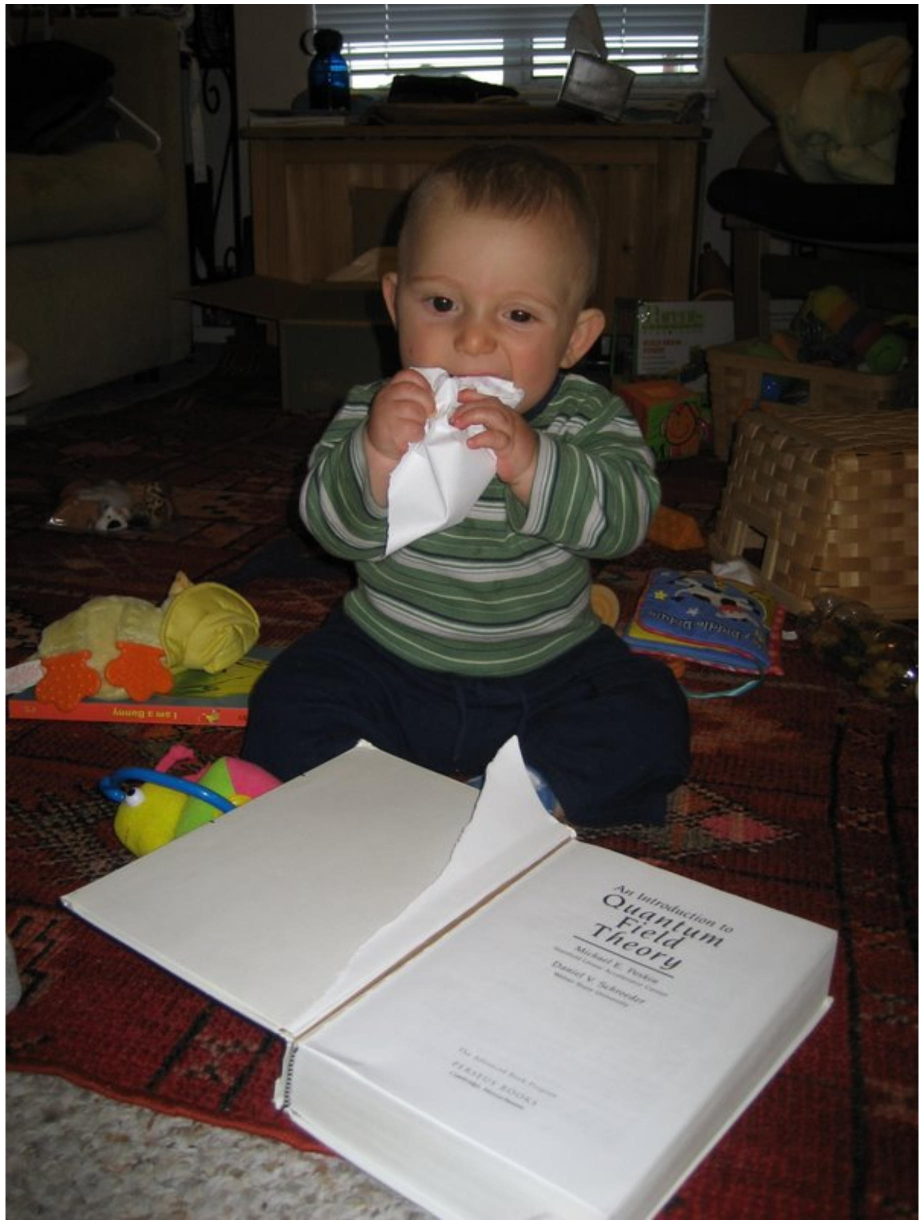

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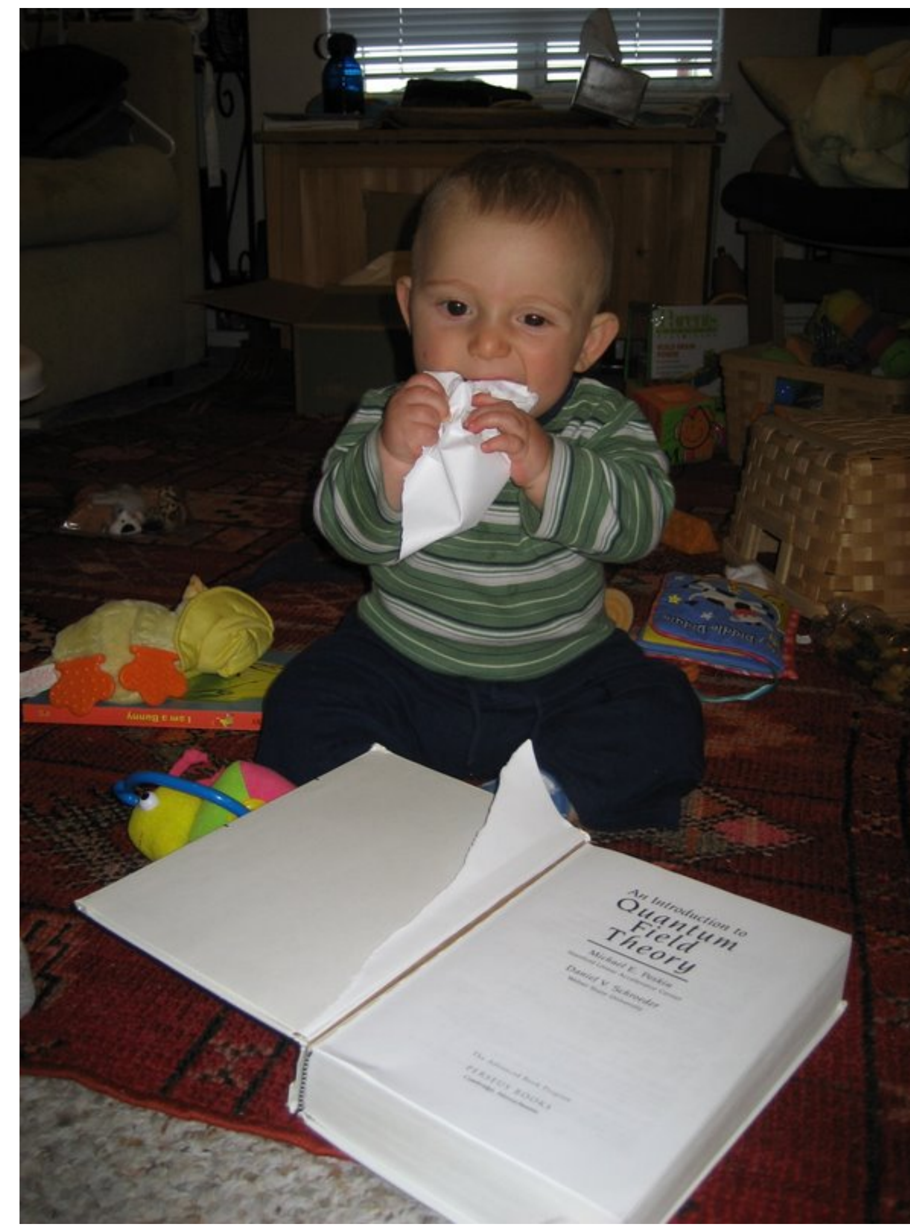
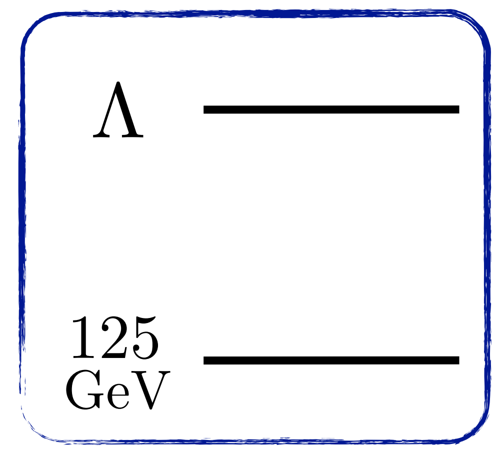



(Yes, that's my son eating Peskin).

# Deleted scenes




*Recipe:*

NP for modified Higgs Couplings + Flavor Violation = Flavor Violating Higgs decays

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.87 \pm 0.63 \pm 0.49) \times 10^{-9}$$

# 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.

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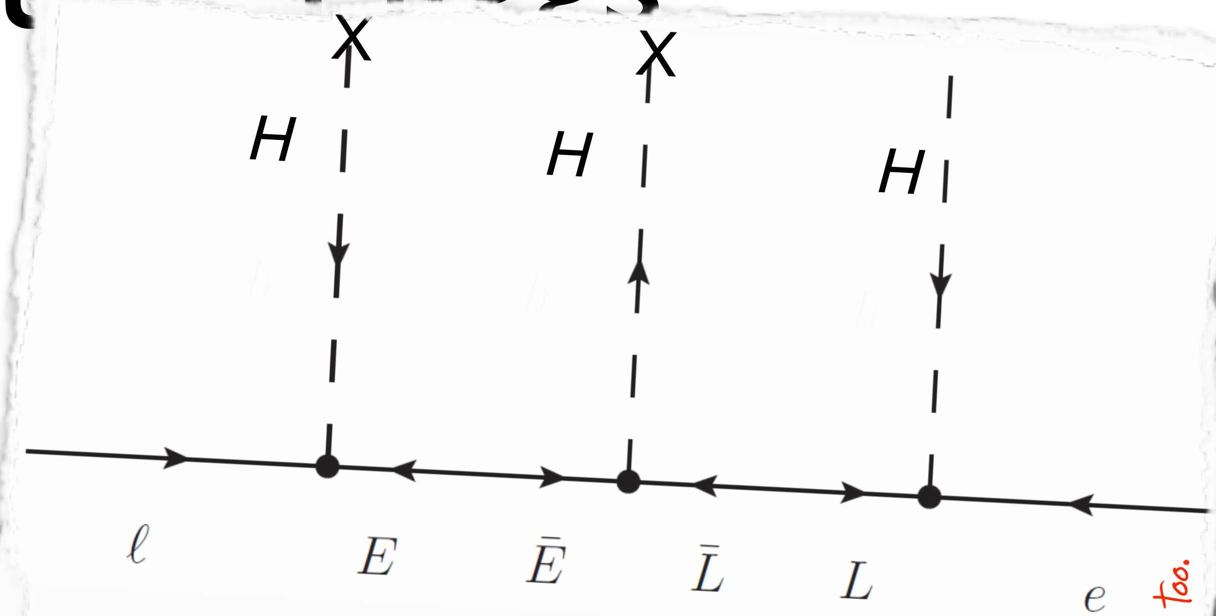


e.g. Kearney, Pierce, Weiner; 1207.7062

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

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PH: you can get this in composite Higgs too.

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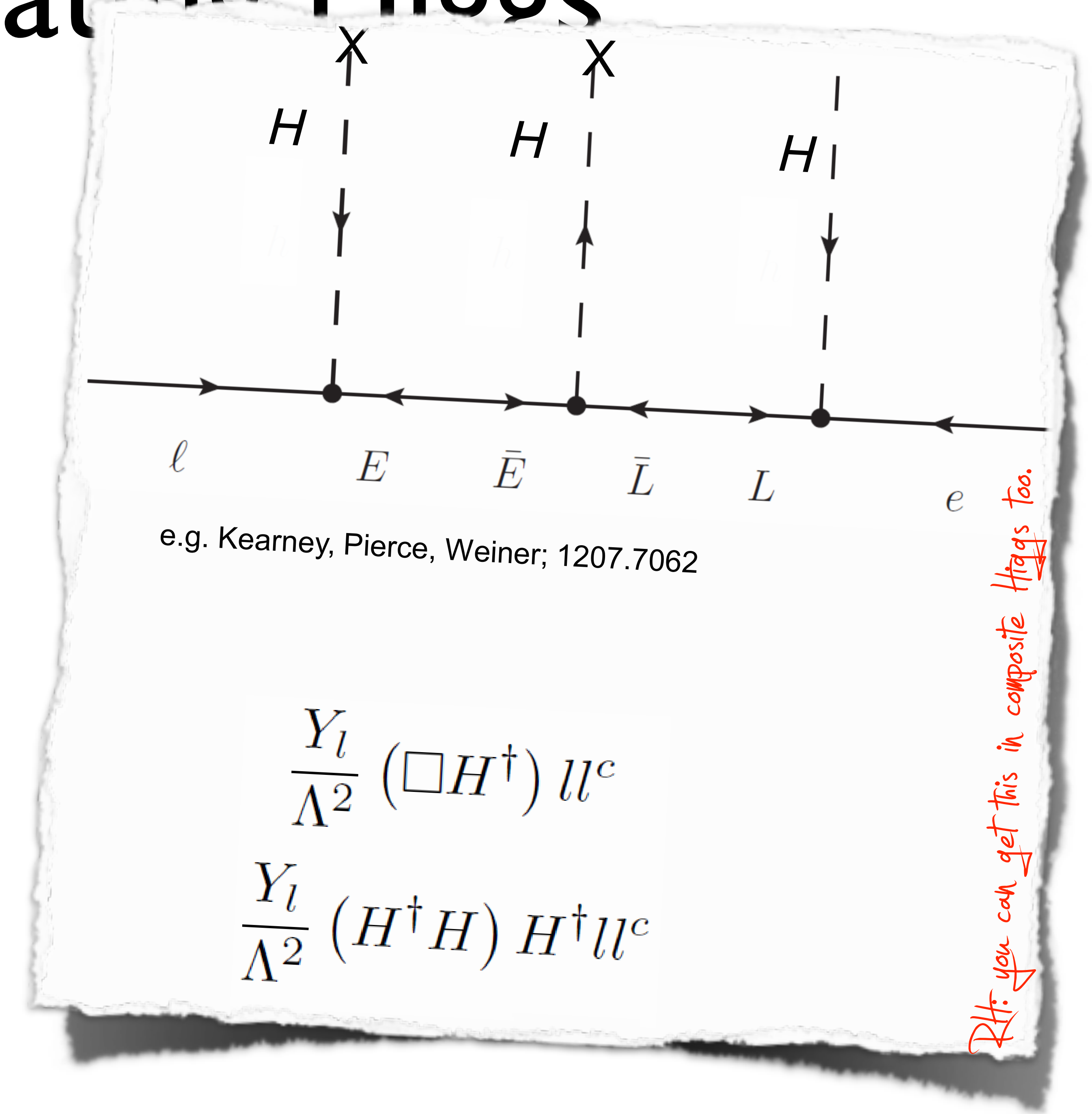


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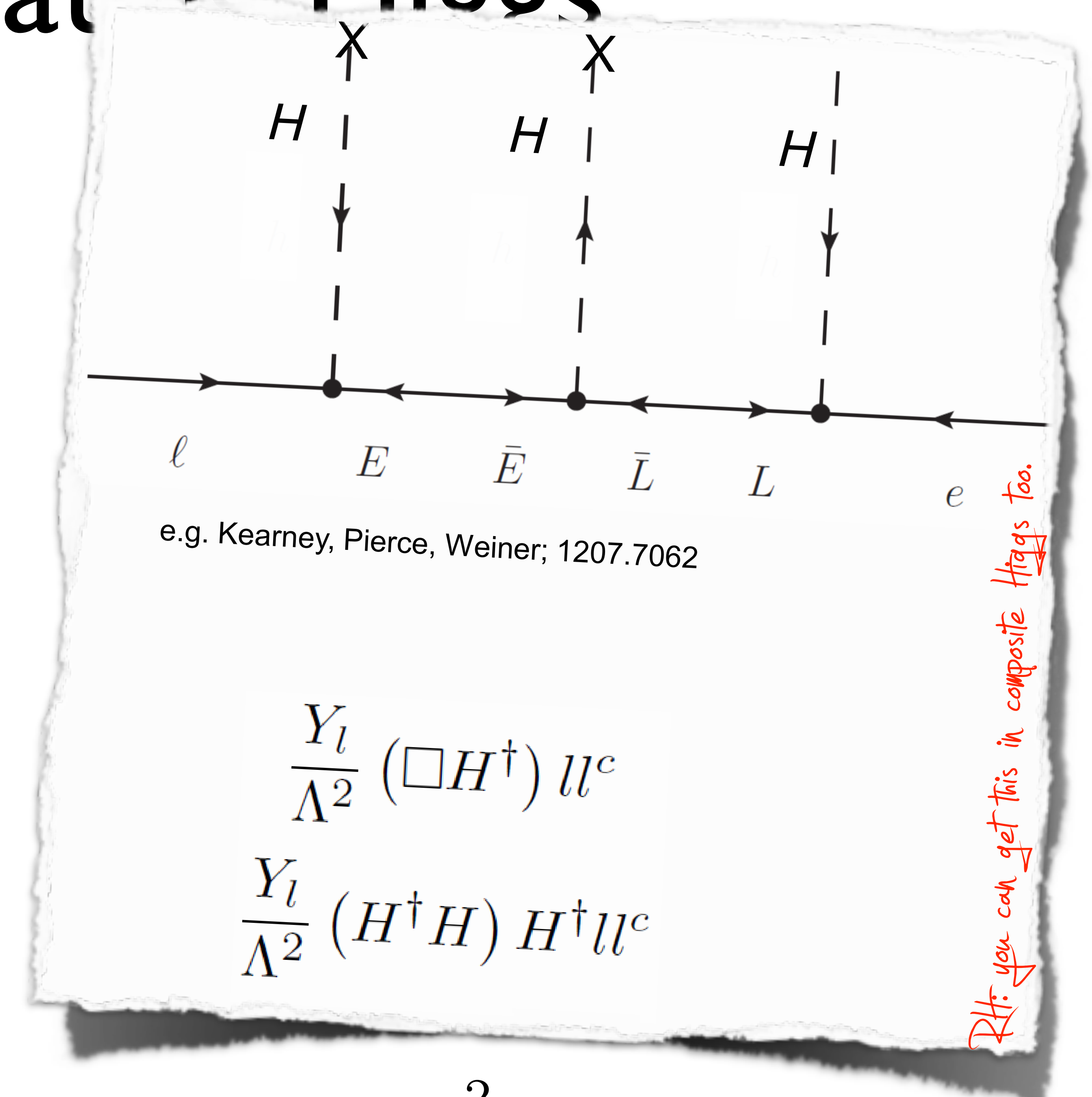


$$m_f = (\lambda_f + \frac{v^2}{\Lambda^2})v$$

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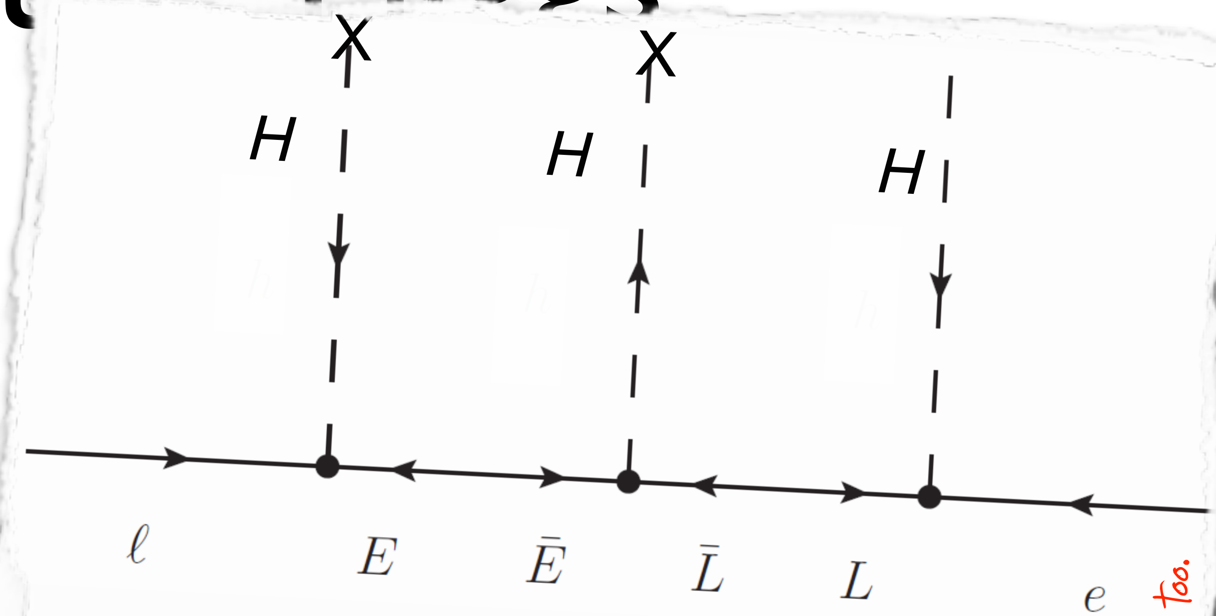


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RH: you can get this in composite Higgs too.

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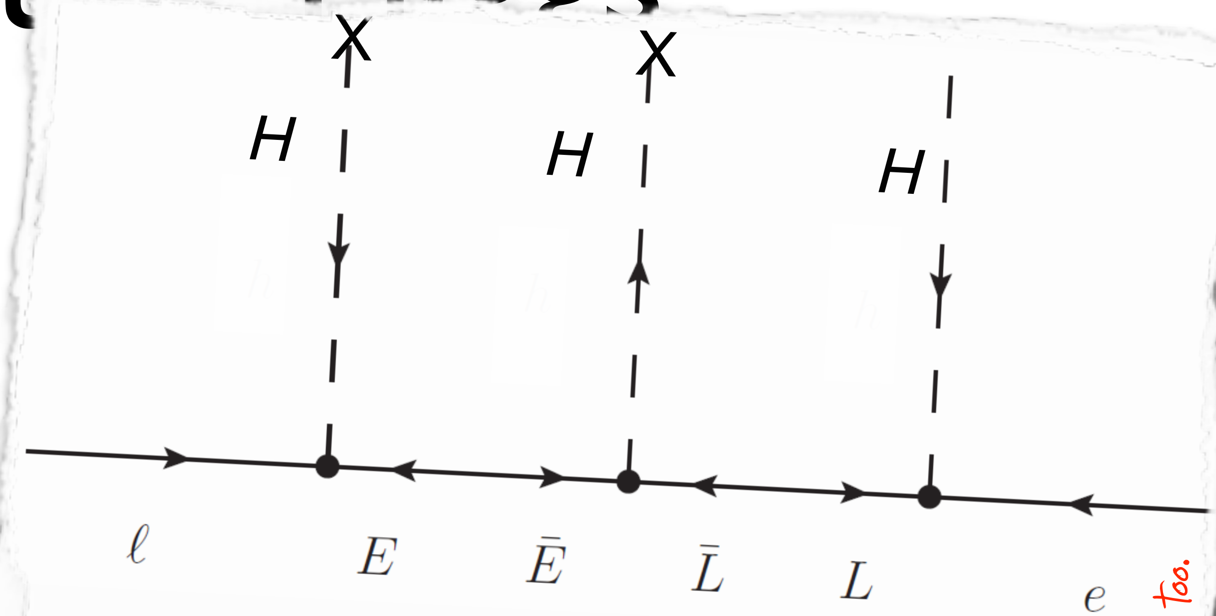


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$$m_f = (\lambda_f + \frac{v^2}{\Lambda^2}) v$$

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

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

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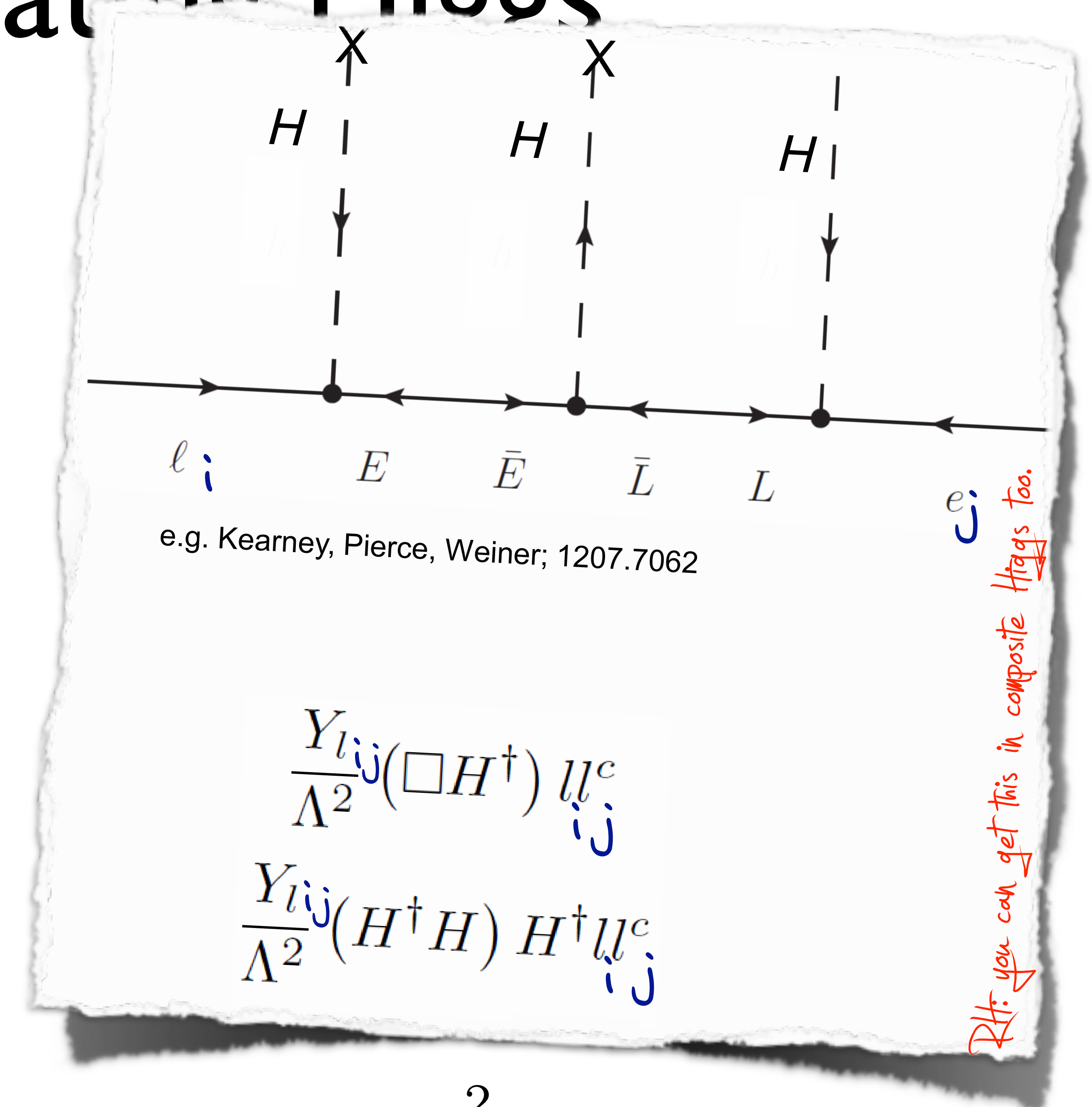



$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2}$$

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

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

# Flavor Violating Higgs

* Writing it a bit more neatly, we get:

$$\mathcal{L}_{SM} = \bar{f}^j_L i \not{D} f^j_L + \bar{f}^j_R i \not{D} f^j_R - \left[\lambda_{ij} (\bar{f}^i_L f^j_R) H + h.c.\right]$$

$$+ D_\mu H^\dagger D^\mu H - \lambda_H \left( H^\dagger H - \tfrac{v^2}{2} \right)^2$$

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

# Flavor Violating Higgs

* Writing it a bit more neatly, we get:

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

$$+ D_\mu H^\dagger D^\mu H - \lambda_H \left(H^\dagger H - \tfrac{v^2}{2}\right)^2$$

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

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

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

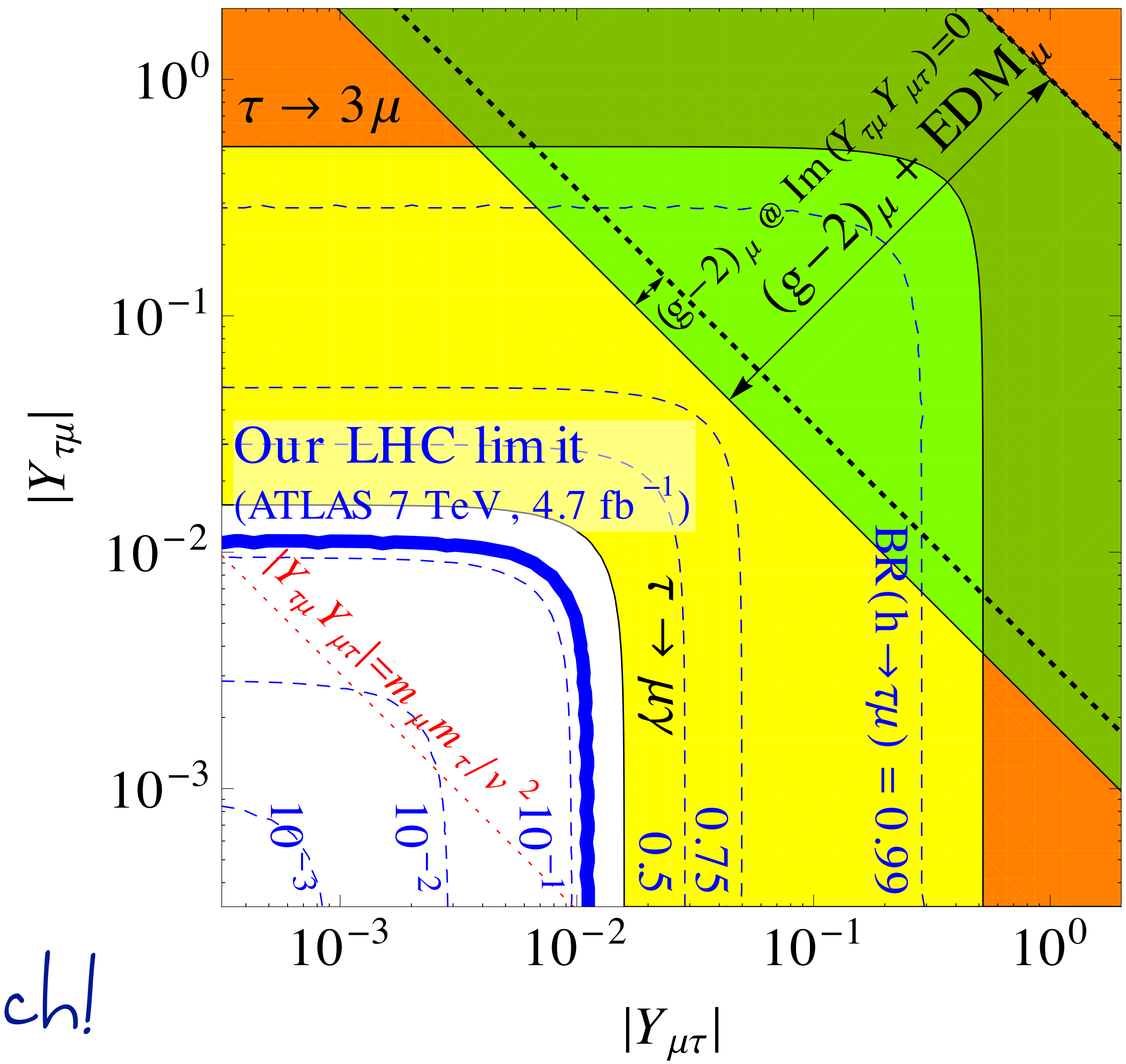
$$|Y_{\tau\mu}Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}$$

(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

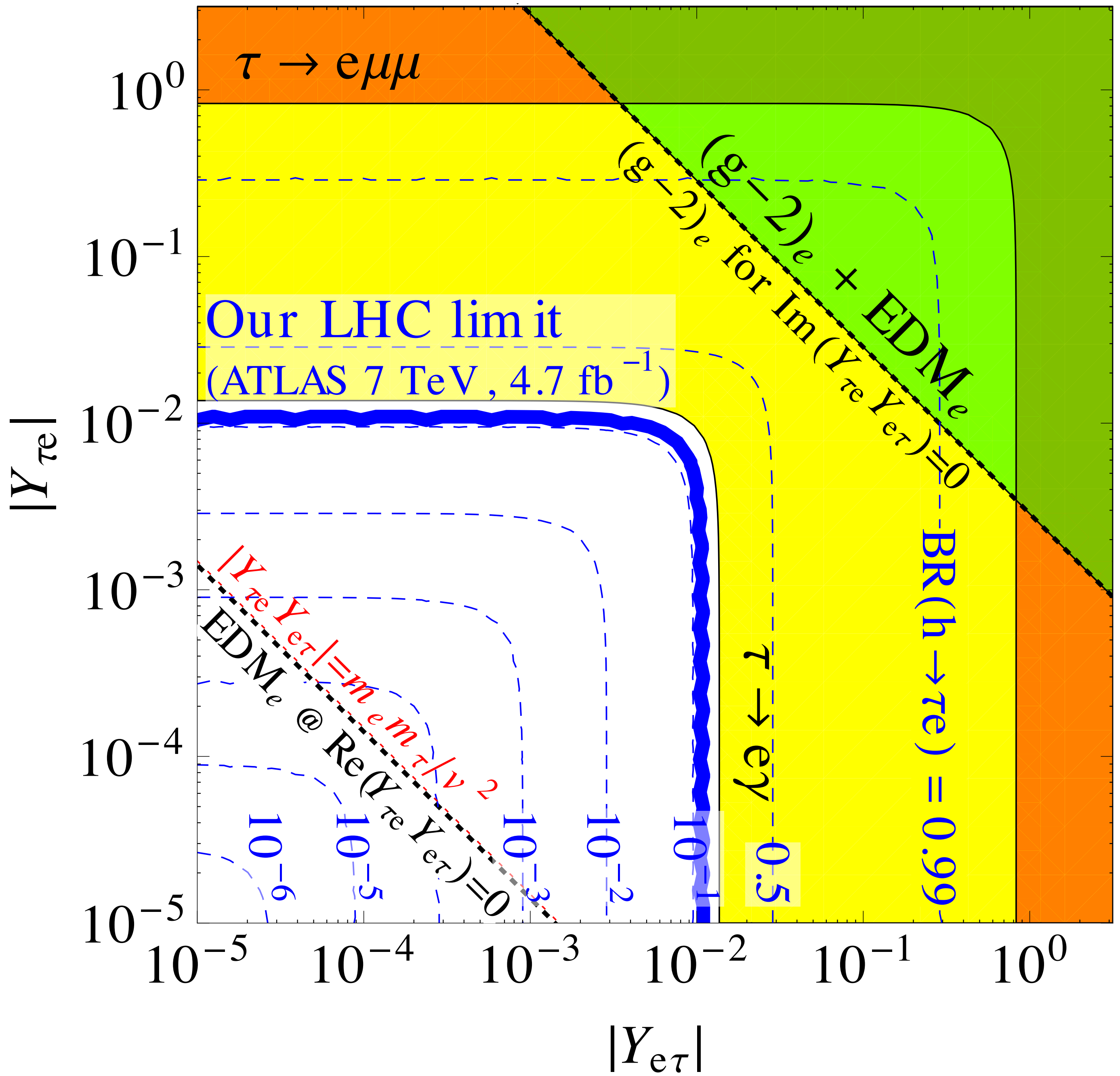
* $\tau$-$\mu$ is wide open. **Opportunity for LHC!**




"natural" FV is within reach!

# LFV Summary

* Same for $\tau$-$e$ . **Opportunity for LHC!**



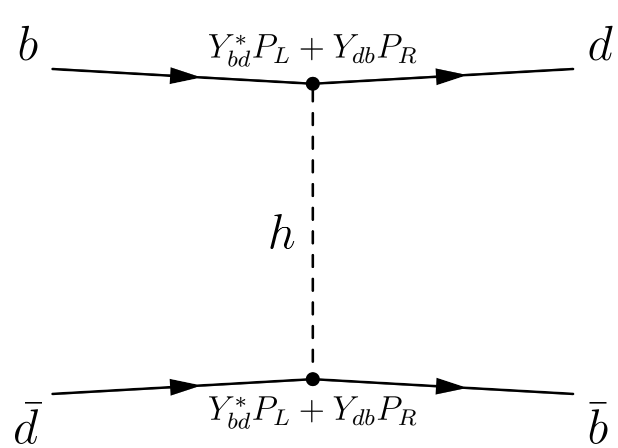
# LFV Summary

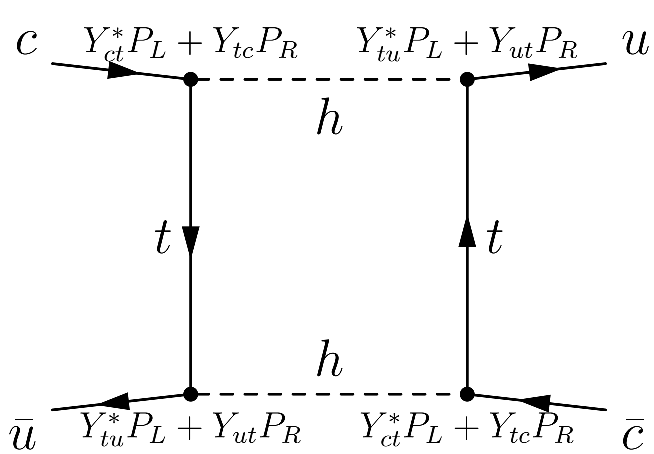
| Channel | Coupling | Bound |
|---|---|---|
| $\mu \to e\gamma$ | $\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$ | $< 3.6 \times 10^{-6}$ |
| $\mu \to 3e$ | $\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$ | $< 0.31$ |
| electron $g-2$ | $\mathrm{Re}(Y_{e\mu}Y_{\mu e})$ | $-0.019 \ldots 0.026$ |
| 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] | $\lvert Y_{uc}\rvert^2,\ \lvert Y_{cu}\rvert^2$ | $< 5.0 \times 10^{-9}$ |
| | $\lvert Y_{uc}Y_{cu}\rvert$ | $< 7.5 \times 10^{-10}$ |
| $B^0_d$ oscillations [39] | $\lvert Y_{db}\rvert^2,\ \lvert Y_{bd}\rvert^2$ | $< 2.3 \times 10^{-8}$ |
| | $\lvert Y_{db}Y_{bd}\rvert$ | $< 3.3 \times 10^{-9}$ |
| $B^0_s$ 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] | $\mathrm{Re}(Y^2_{ds}),\ \mathrm{Re}(Y^2_{sd})$ | $[-5.9 \ldots 5.6] \times 10^{-10}$ |
| | $\mathrm{Im}(Y^2_{ds}),\ \mathrm{Im}(Y^2_{sd})$ | $[-2.9 \ldots 1.6] \times 10^{-12}$ |
| | $\mathrm{Re}(Y^*_{ds}Y_{sd})$ | $[-5.6 \ldots 5.6] \times 10^{-11}$ |
| | $\mathrm{Im}(Y^*_{ds}Y_{sd})$ | $[-1.4 \ldots 2.8] \times 10^{-13}$ |
| single-top production [40] | $\sqrt{\lvert Y^2_{tc}\rvert + \lvert Y_{ct}\rvert^2}$ | $< 0.54$ |
| | $\sqrt{\lvert Y^2_{tu}\rvert + \lvert Y_{ut}\rvert^2}$ | $< 0.23$ |
| $t \to hj$ [41] | $\sqrt{\lvert Y^2_{tc}\rvert + \lvert Y_{ct}\rvert^2}$ | $< 0.34$ |
| | $\sqrt{\lvert Y^2_{tu}\rvert + \lvert Y_{ut}\rvert^2}$ | $< 0.34$ |
| $D^0$ 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: