Exploring New Physics with μ's (and muse).

Roni Harnik,
Fermilab

Preliminaries

* Who am I?
* Who are you?
* Whats the goal here?

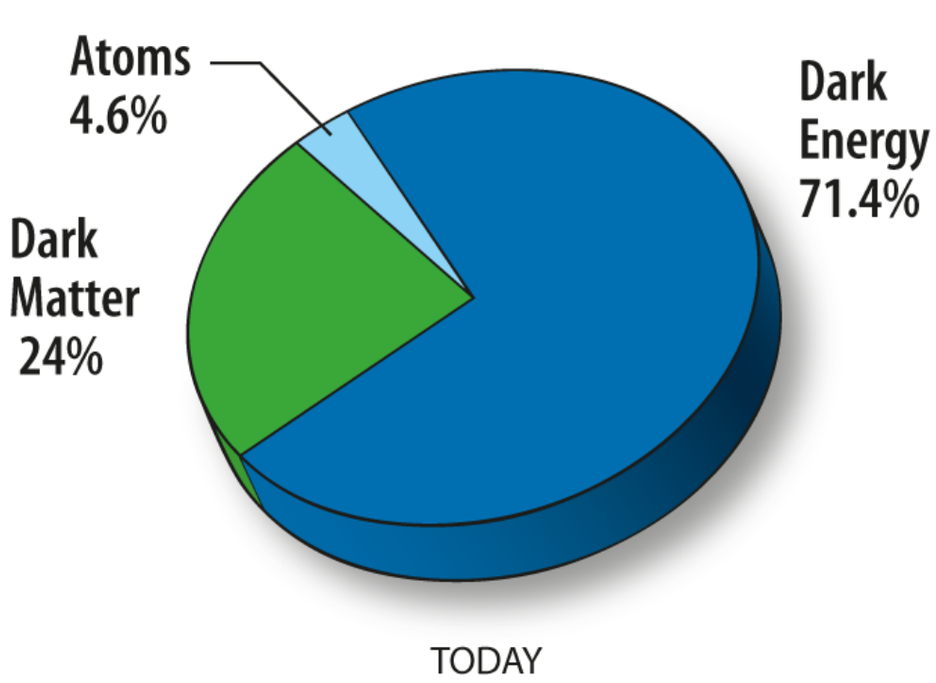
* Please ask questions.
* I'll jump between slides and blackboard.

Particle Physics: the Goal

* We look at the world around us.
  We are curious!
* What are the laws of physics at short distances?
* What are the laws of nature at large distance?

Standard model of Cosmology

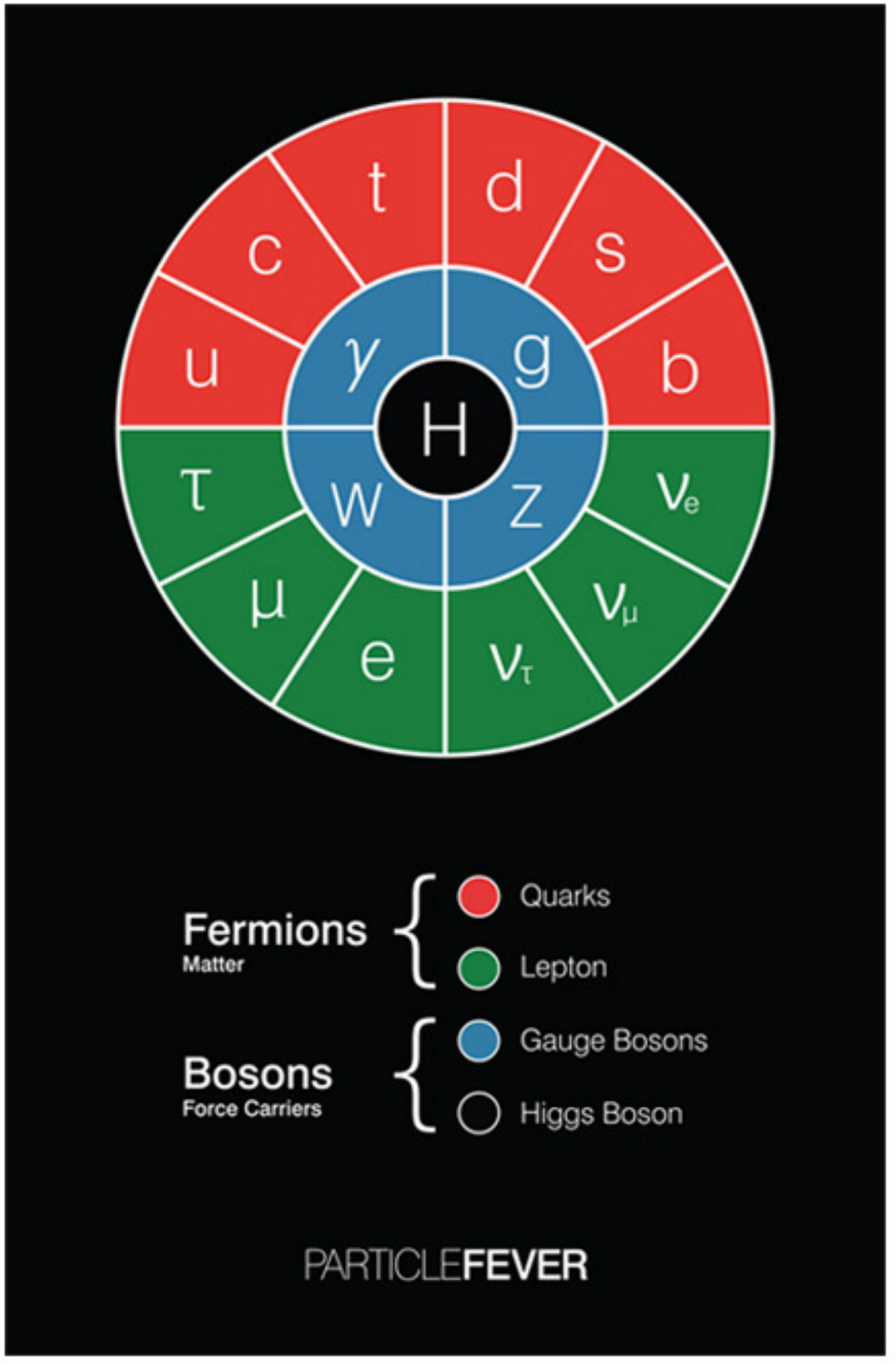
* We live in an expanding Universe.
* On large scales its flat, homogeneous, isortopic.
* Its contents by energy density:



* A successful model!

Standard model

* A collection of elementary particles and interactions that explain all short distance phenomena we know of.
* Not bad!!
* So what are we so curious about?



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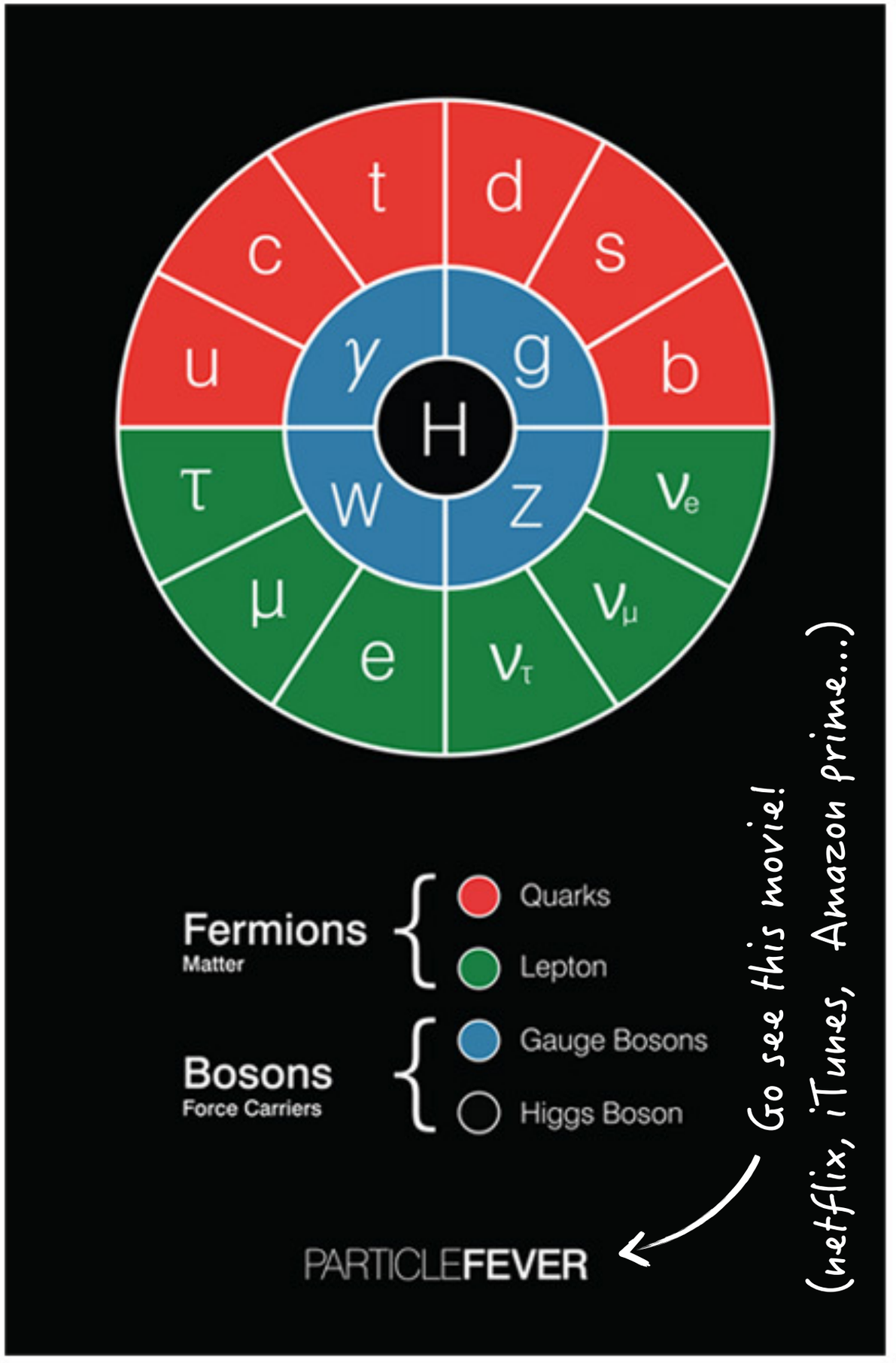

A Curiosity List:

(Partial! In no particular order.)

* Is there any physics beyond the standard model?
* What sets the strength of the weak force? Is it fine-tuned?
* Is the world supersymmetric?
* Is there a Higgs boson?
* What is Dark Matter?
* Is there a dark sector? Dark Forces?
* What is Dark Energy?
* Can the Cosmological constant be natural or is it tuned?
* Are we part of a Universe or a Multiverse?
* What's with the 3 families of fermions?
* What sets the size of particle masses?
* Why is there more matter than anti-matter?
* Are neutrinos their own anti-particles?
* Are there sterile Neutrinos?
* Do neutrinos interact in a non standard way?
* Where is CP violated? neutrinos?
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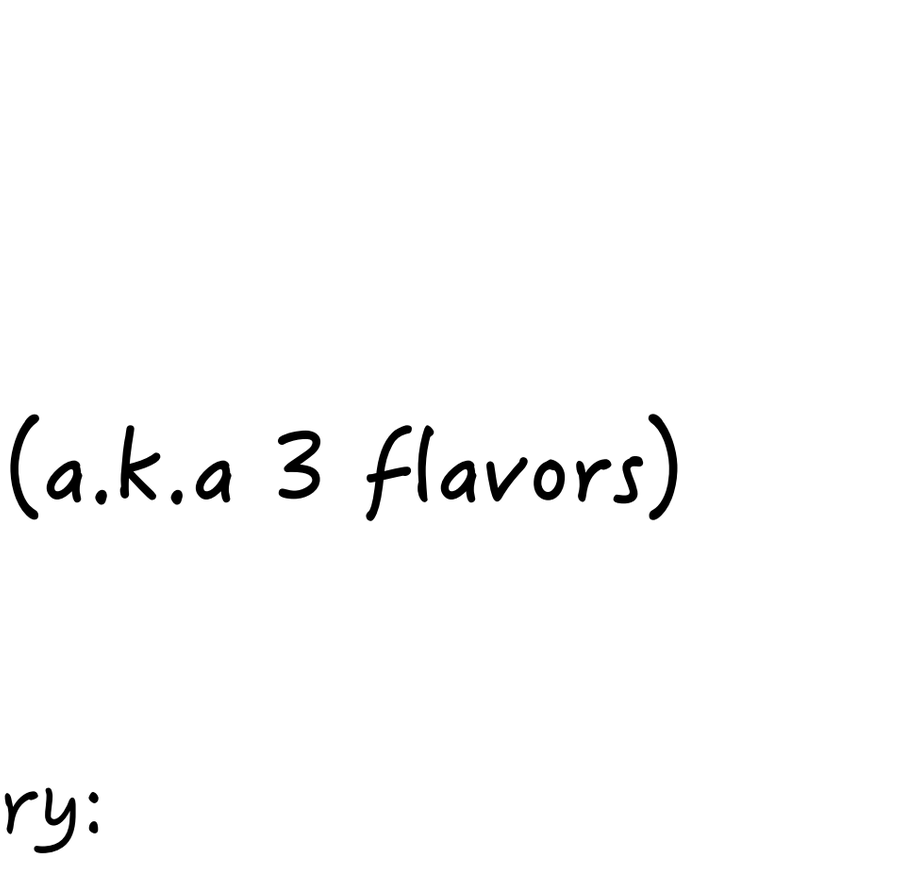
Flavor

* What's with the 3 families (a.k.a 3 flavors) of fermions?
* This question has a long history:



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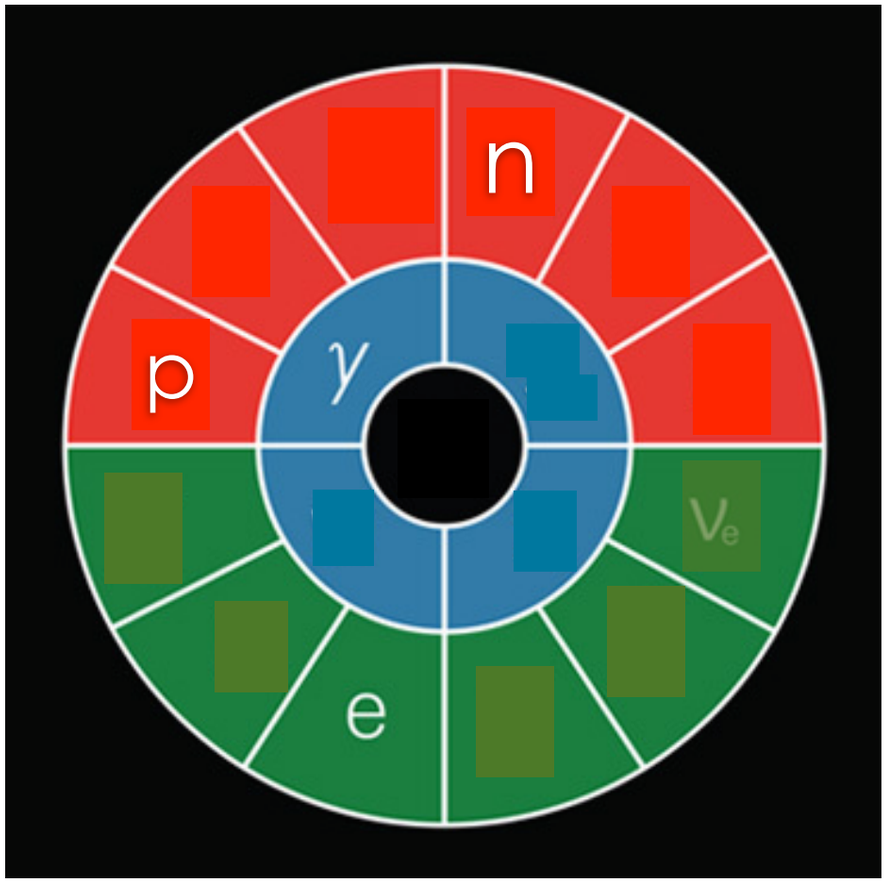

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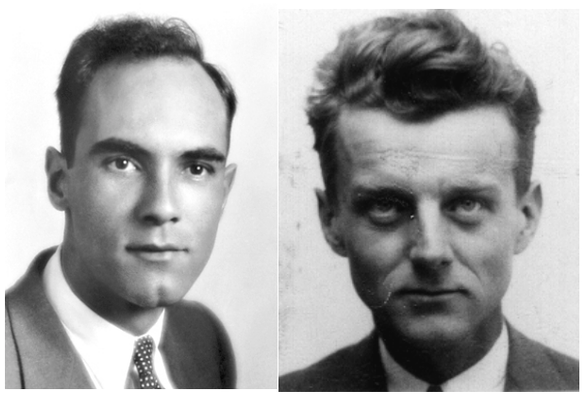
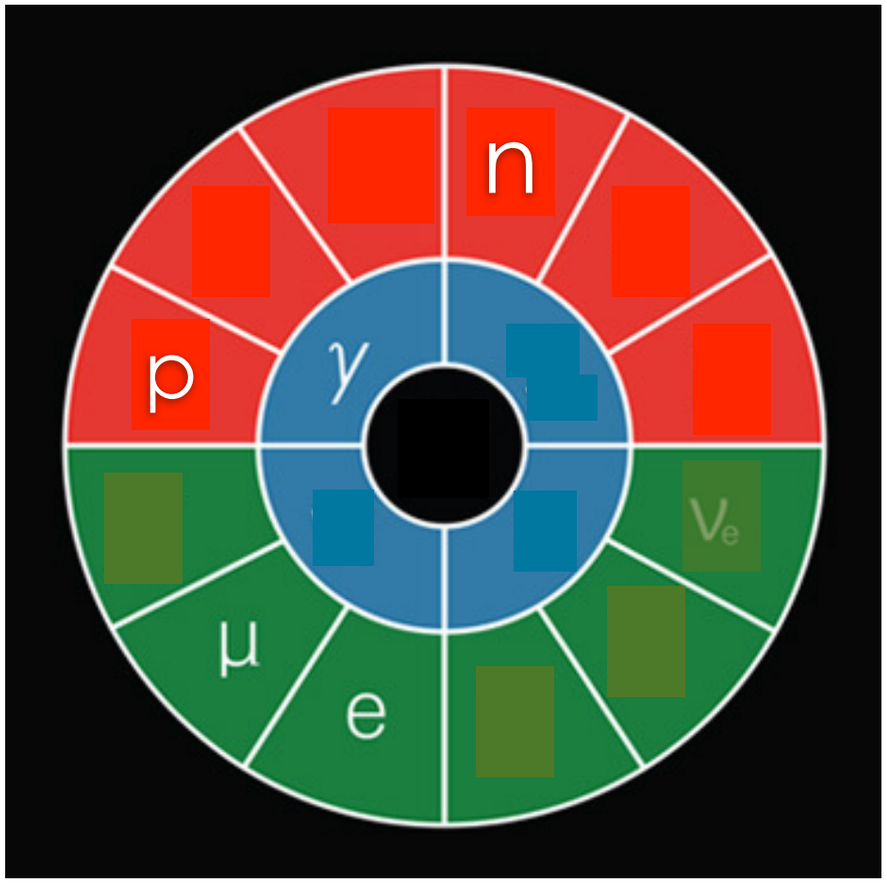


1936: Anderson and Neddermeyer discover the muon.



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@RabiNMR

Follow

The muon: who ordered that !?

Reply Retweet Favorite More

1:23 AM - 20 Jun 1937 · Embed this Tweet

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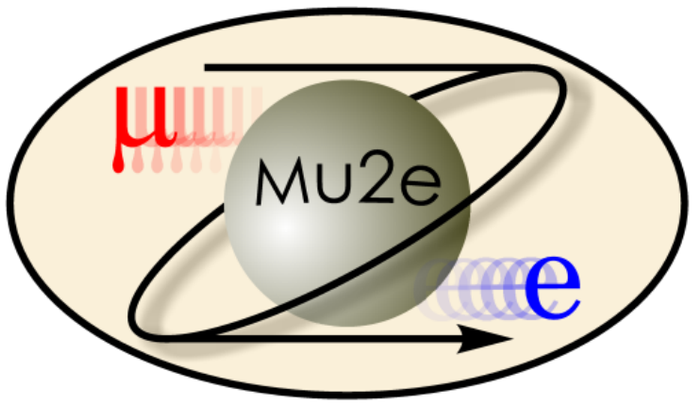
Rabi's question was
posed over 70 years ago.
It is still unanswered!

What's with the three flavors?
How are they related?
How do they interact with one another?

This, and the hope of finding new physics motivates us to **study the muon and its connection to other flavors as best we can.**

Examining μ

* I will tell you about to aspects of the muon properties that we explore here at Fermilab:
  - Flavor violation. Does $\mu \rightarrow e$?. (μ2e)



  - Detailed EM properties of the muon (g-2).

Searches for Flavor Violation

Flavor Violation

* In quantum mechanics I can multiply the wavefunction by a phase, $\psi \rightarrow e^{i\phi}\psi$.

* This is a **symmetry**.

* In QFT, symmetries are deeply connected to conservation laws:

symmetry: $\psi_{electron} \rightarrow e^{i\phi}\psi_{electron}$

$\Updownarrow$

"electron number" is conserved.

Emmy Neother

Flavor Symmetry

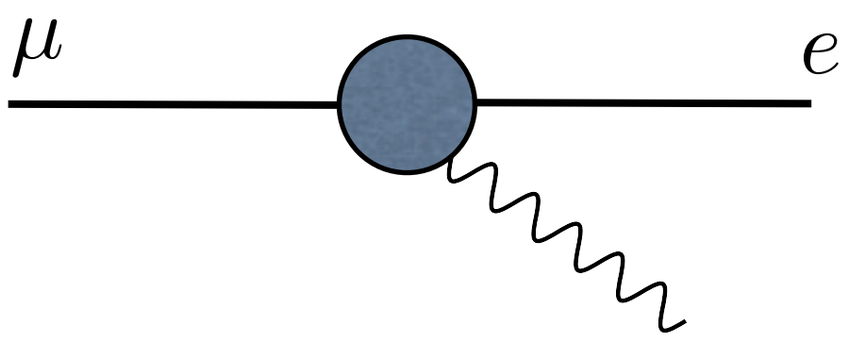
* Pre-1998: In the SM, every lepton flavor has its own symmetry.

$\psi_e \longrightarrow e^{i\phi}\psi_e$ e-number is conserved.

$\psi_\mu \longrightarrow e^{i\phi}\psi_\mu$ $\Longleftrightarrow$ μ-number is conserved.

$\psi_\tau \longrightarrow e^{i\phi}\psi_\tau$ τ-number is conserved.

(aka "Lepton flvor number")



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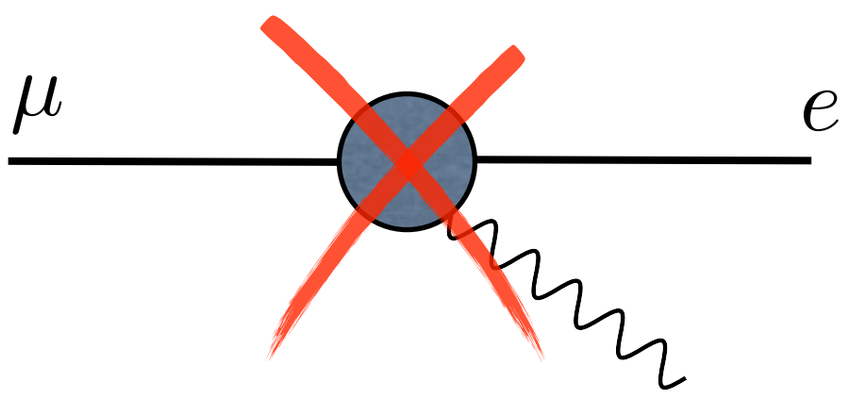
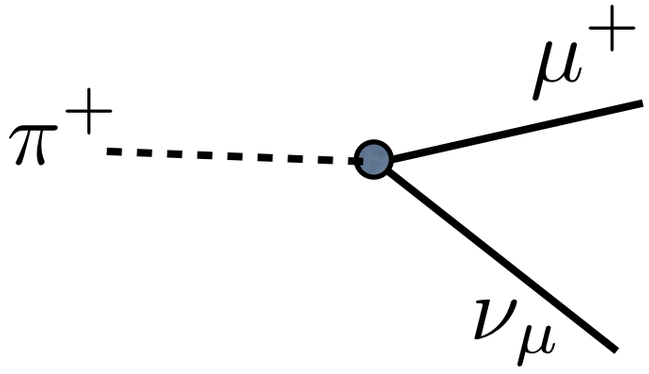


Flavor Violation

* In 1998 we learnt that neutrinos have mass.
* More presicely, we learnt that neutrinos can change flavor.
* Their flavor symmetry is broken.
* What does that have to do with e, μ, and τ?

CLFV was Observed!



Neutrino Experiments

(for more on neutrino oscillations: upcoming lectures in winter).

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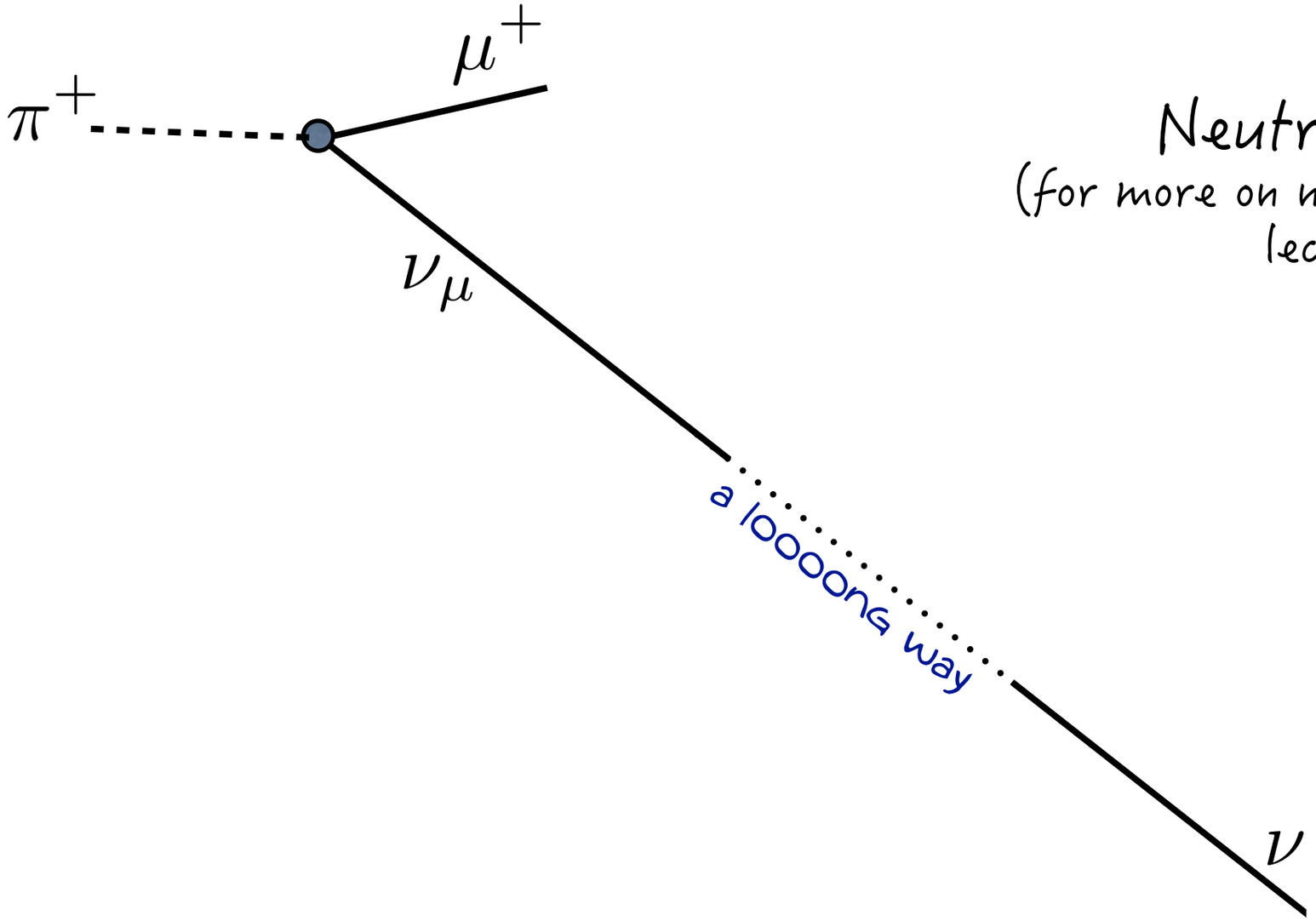

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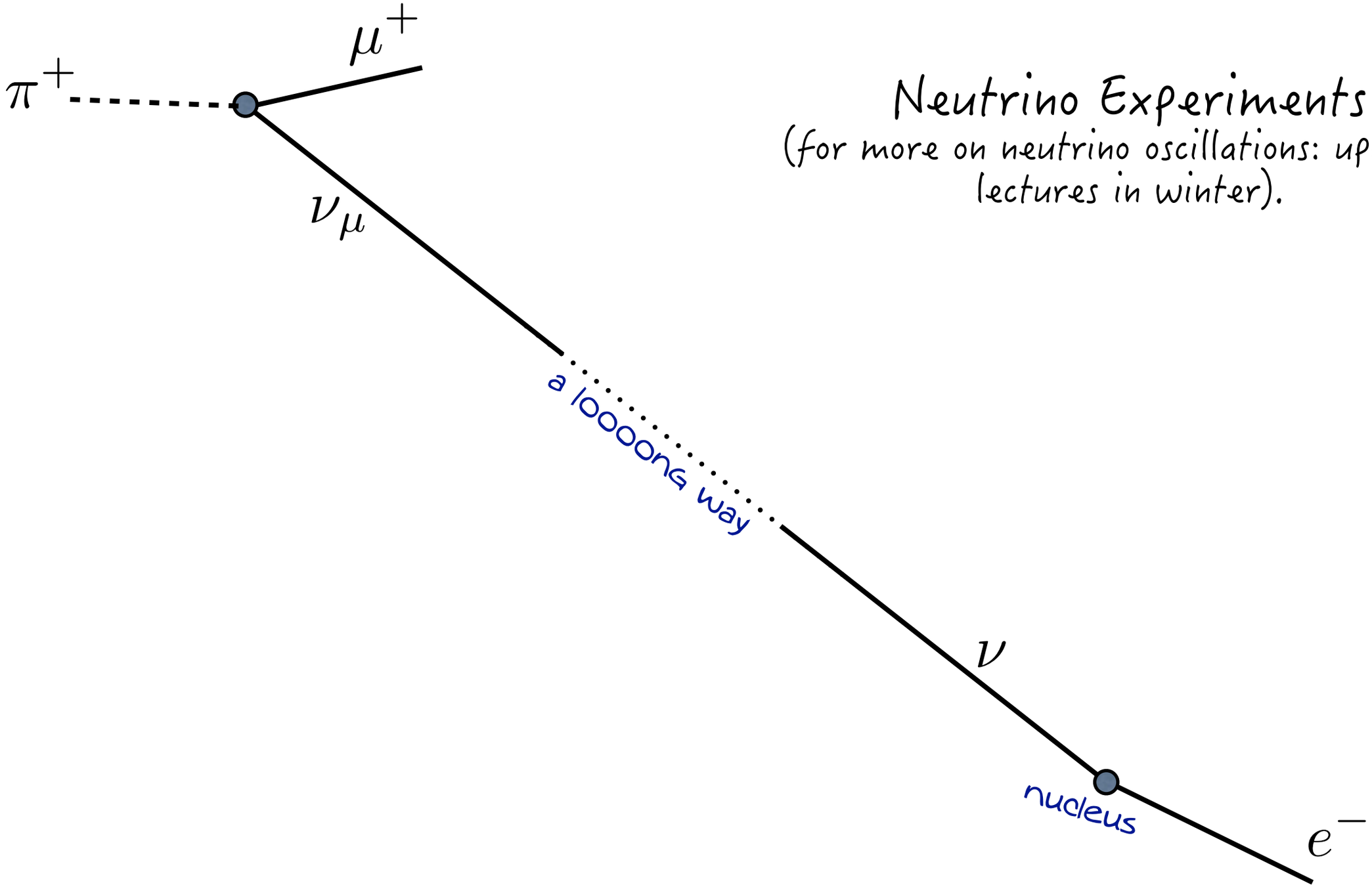

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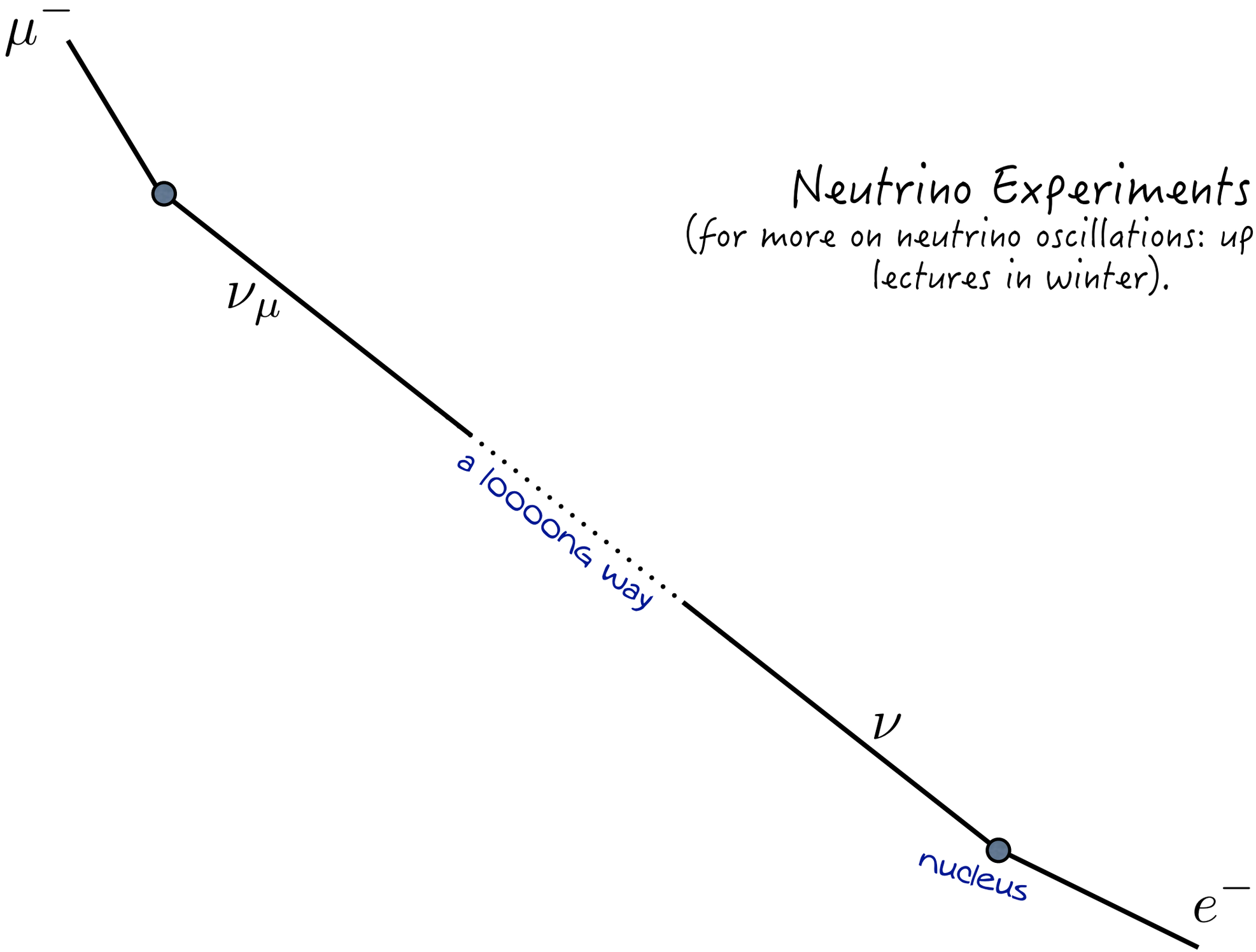

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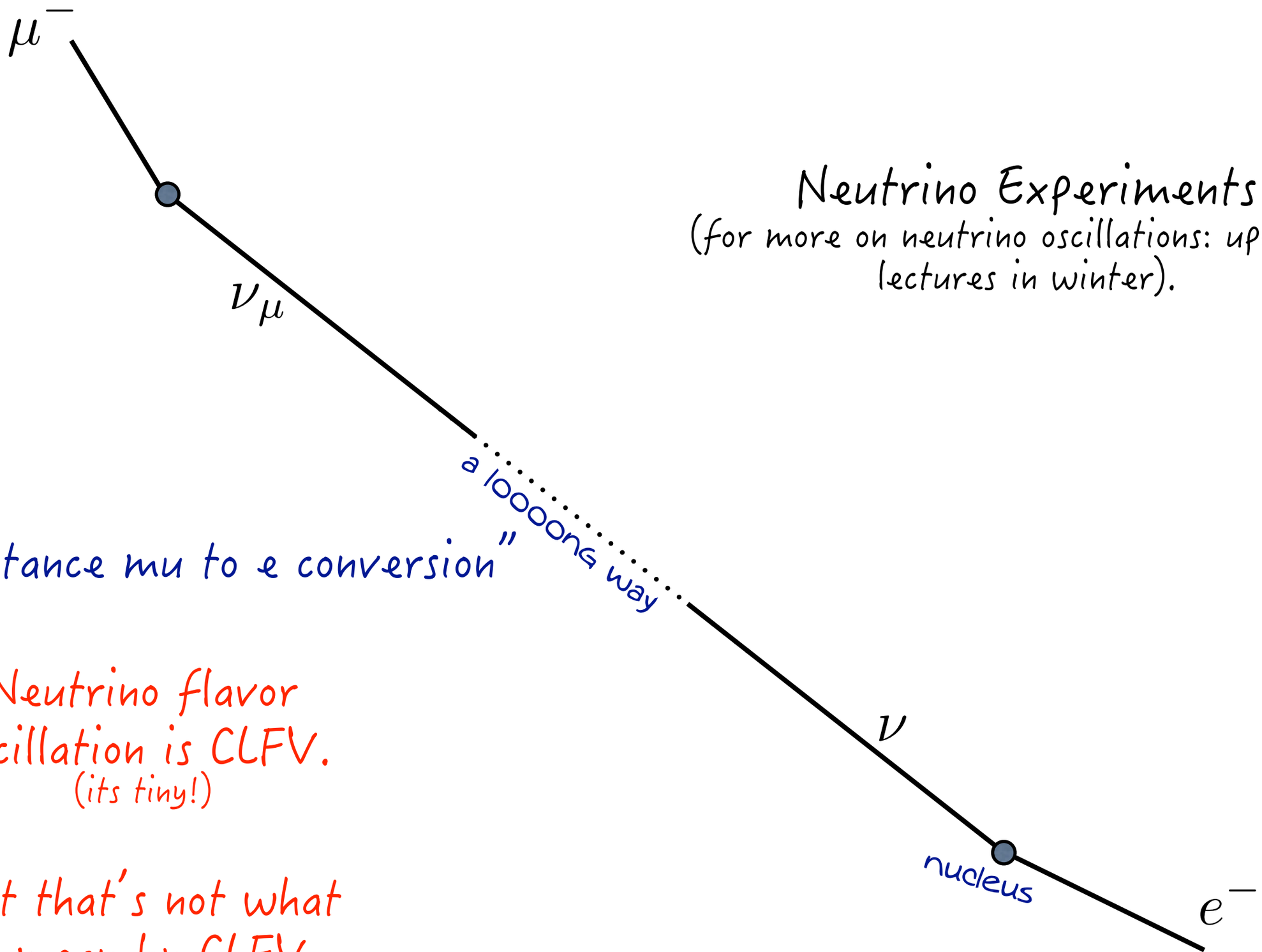

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"long distance mu to e conversion"

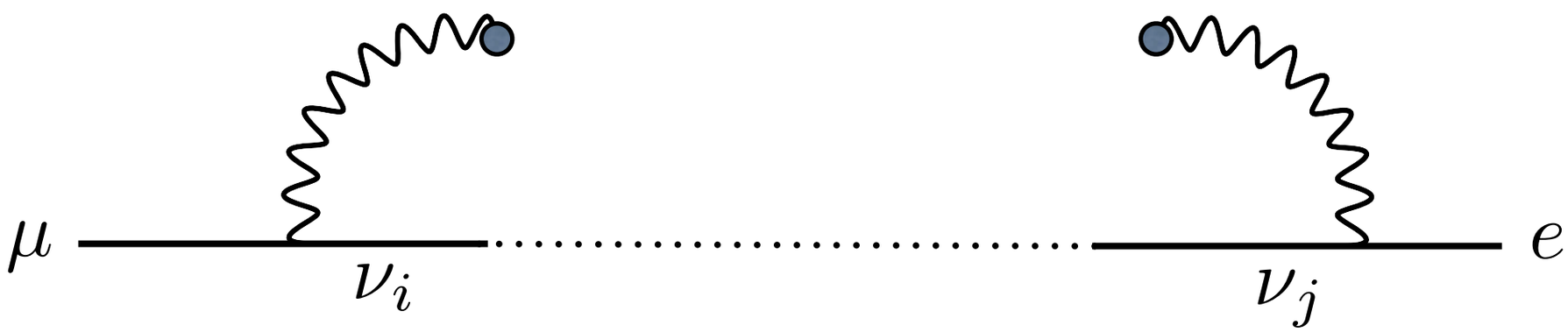
Neutrino flavor oscillation is CLFV.
(its tiny!)

But that's not what we mean by CLFV...

CLFV in the SM

* We are searching for CLFV at short distances.

* Neutrino masses induce this too:



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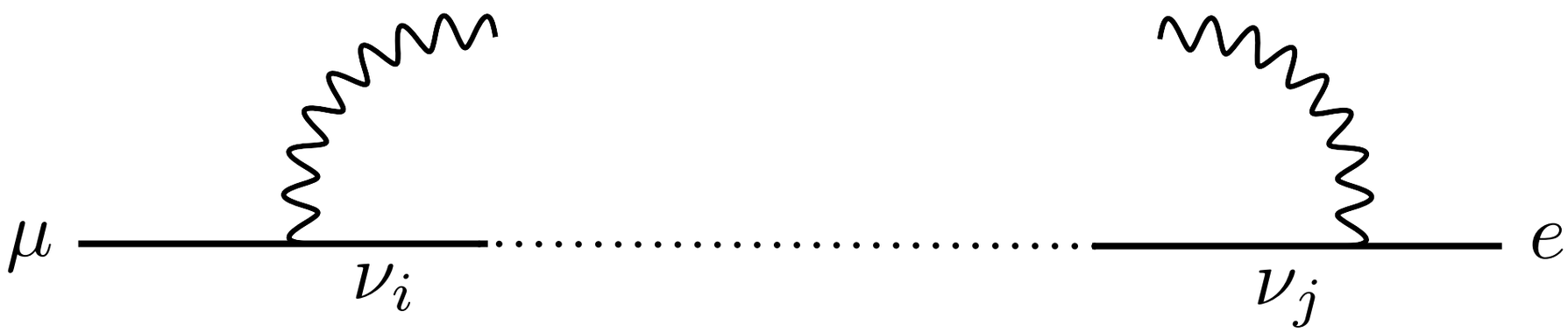

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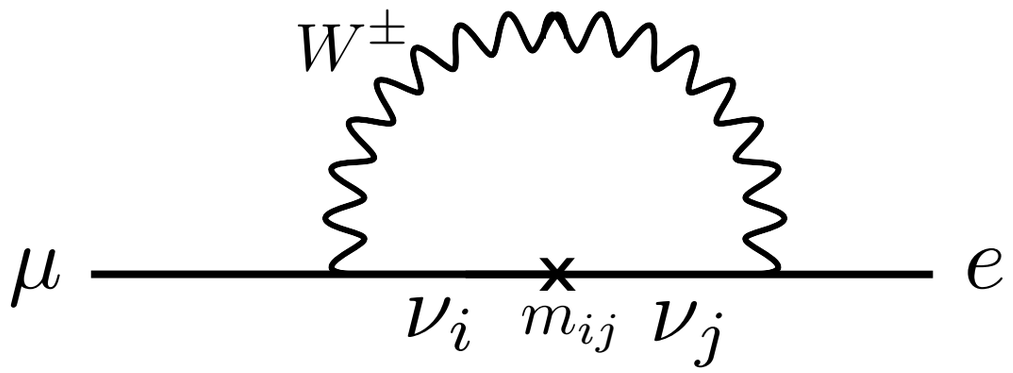

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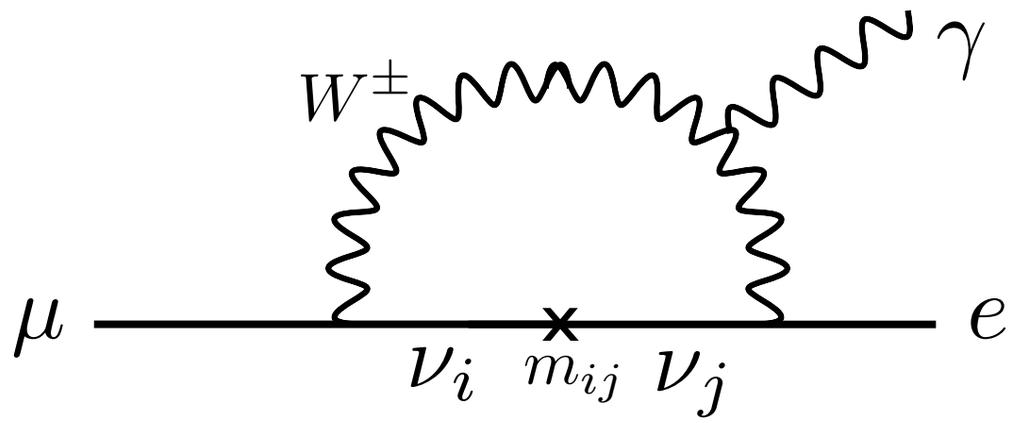


CLFV in the SM

* For the record, the branching ration is:

$$\mathrm{BR}(\mu \to e\gamma)_{\mathrm{SM}} \sim \frac{3\alpha}{32\pi}\left(\frac{\Delta m^2_\nu}{m^2_W}\right)^2 \sim 10^{-54}$$

* **Bad news:** we will never observe this.

* **Good news:** we will never observe this.
  No backgrounds* in the search for BSM!

*Except for the difficult experimental BG's which I am not qualified to talk about.

New Physics

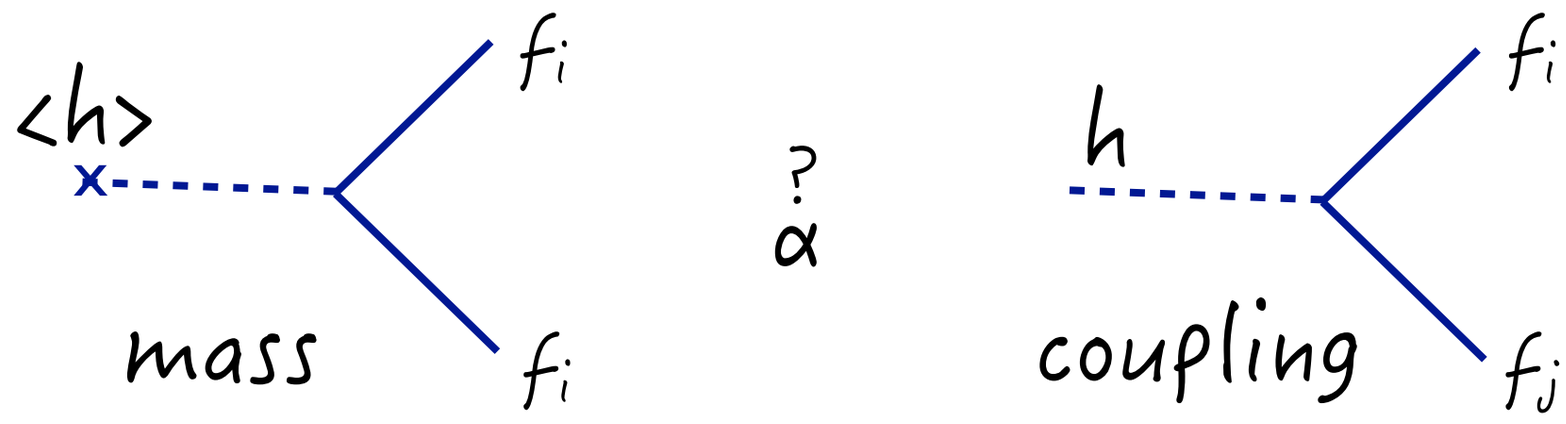
* What new physics can contribute to $\mu \rightarrow e$ transitions at observable levels?

* New Heavy particles! A low energy process can be sensitive to high mass particles (via uncertainty principle).
  - Higgs
  - Supersymmetry
  - Extra dimensions

* Details on to the blackboard....

FV Higgs

* The Higgs is the source of mass in the SM.
* Is it the **only** source of mass?
* If there is another, the two sources can be mis-aligned in flavor space.
* Can lead to flavor violating Higgs interactions.



Higgs couplings to μe

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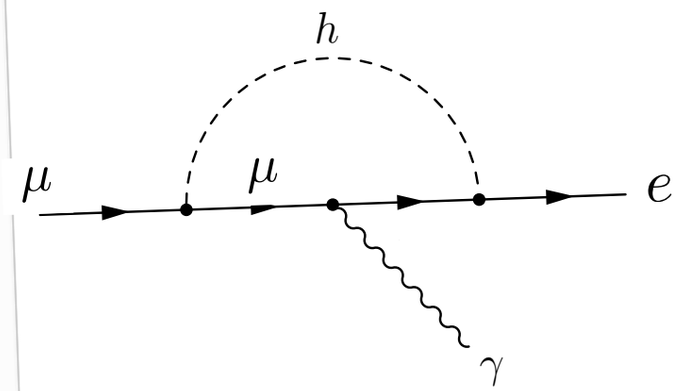
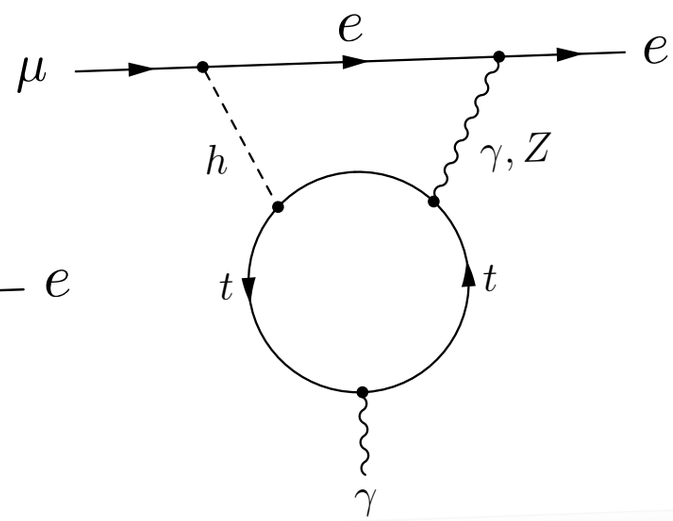
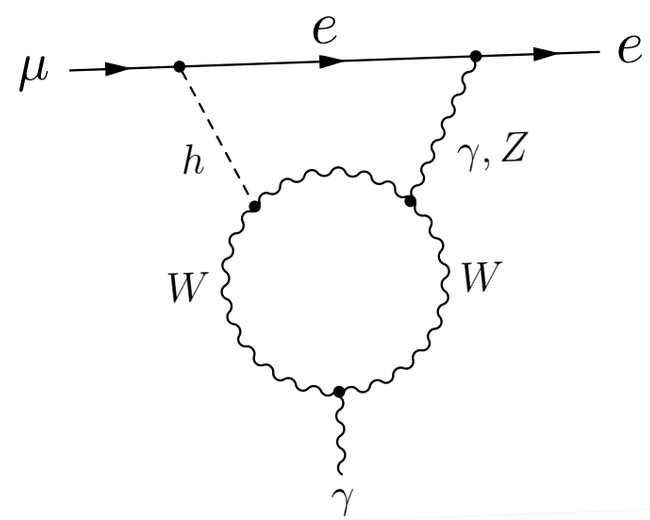
mu to e gamma & mu to 3e (at 1 and 2-loop):







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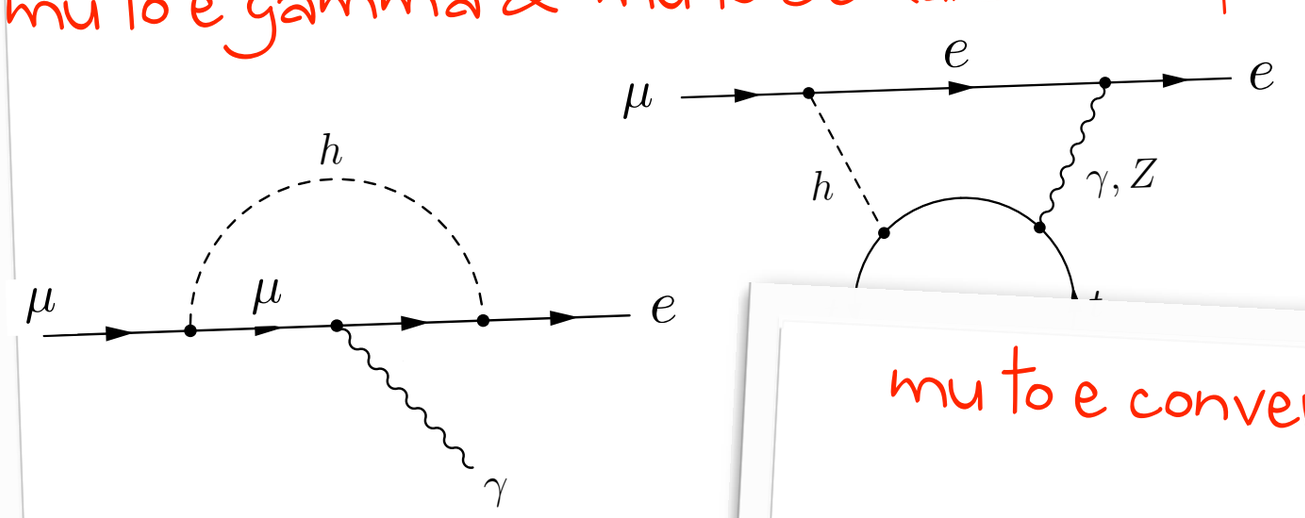
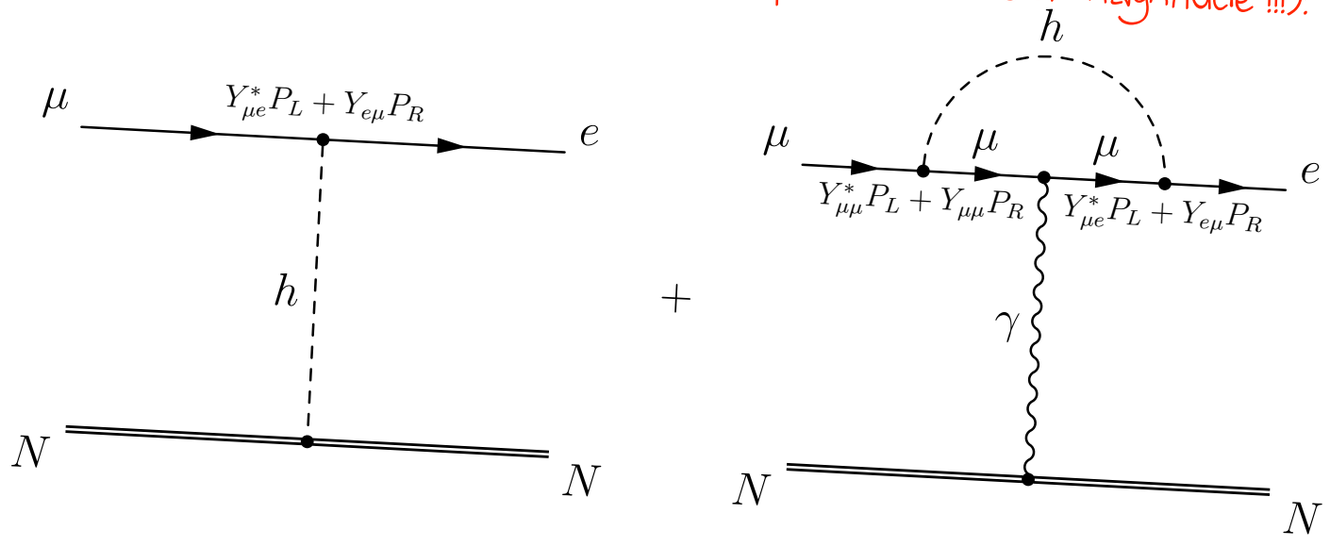


mu to e conversion (will improve 4 orders of magnitude !!!):



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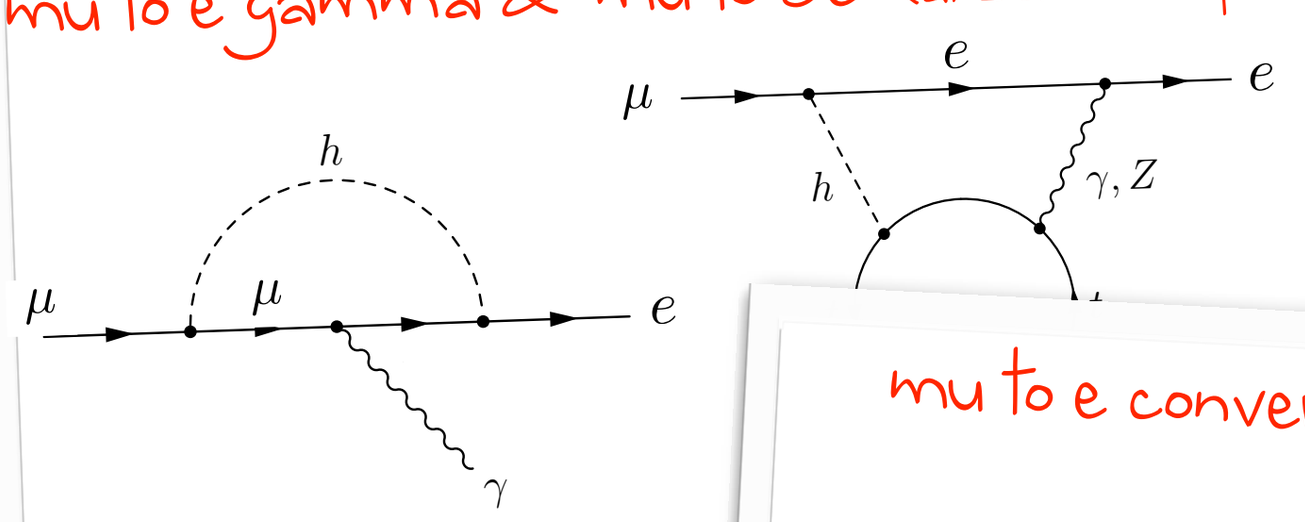

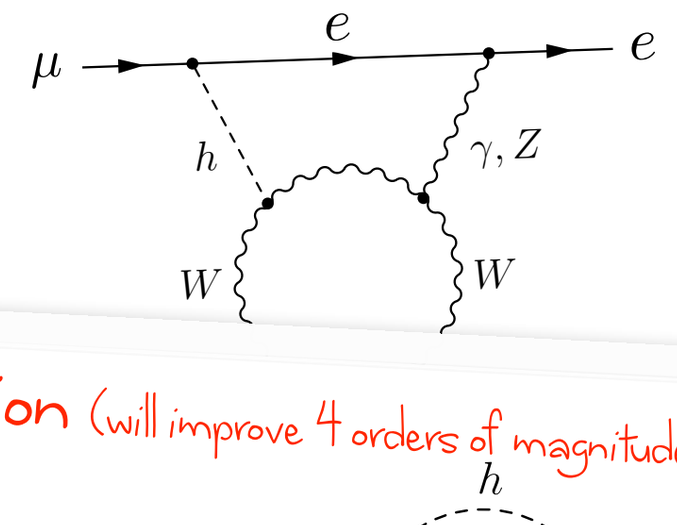

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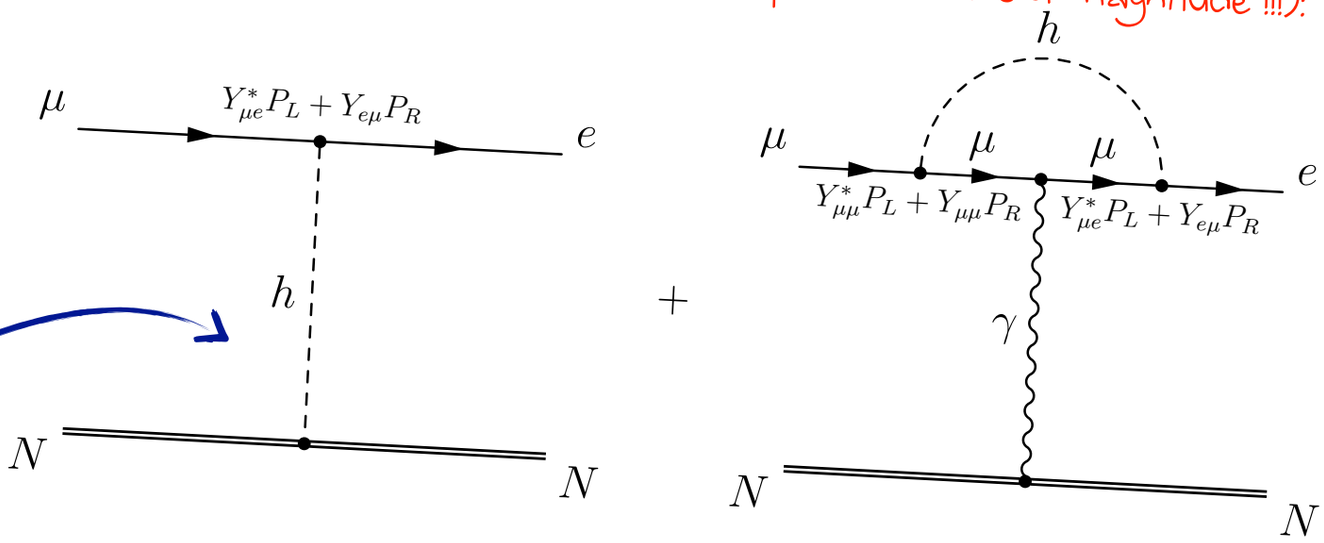


Which operator?

Higgs couplings to μe

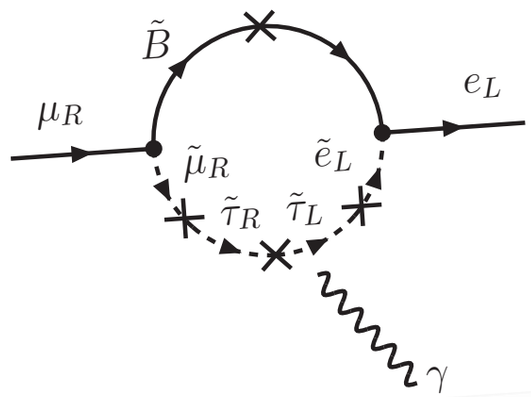
Outside of LHC reach.

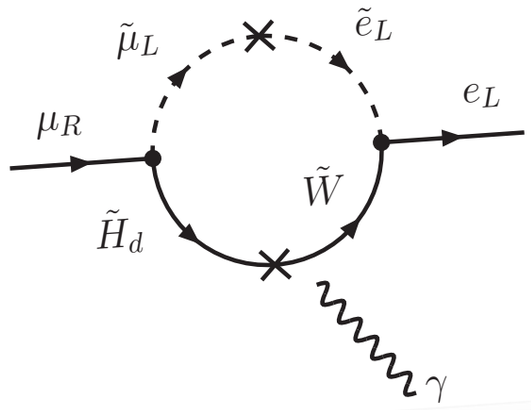
Probing "natural" models.

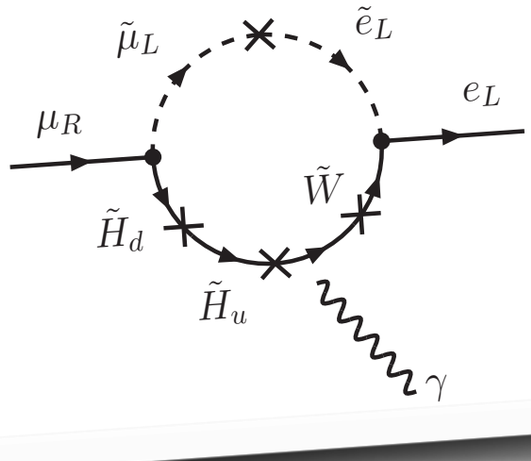
Supersymmetry

* Flavor violation processes:

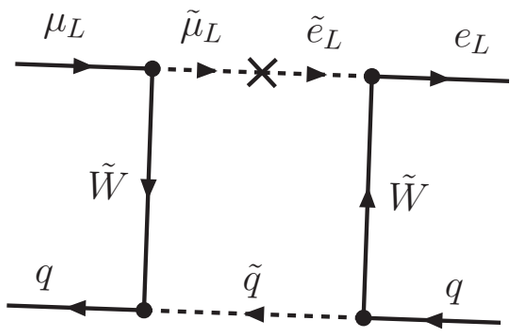
mu to e gamma:

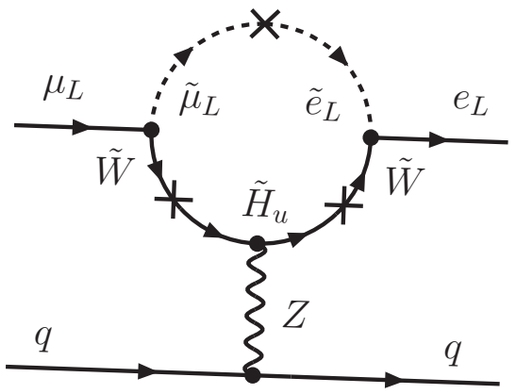


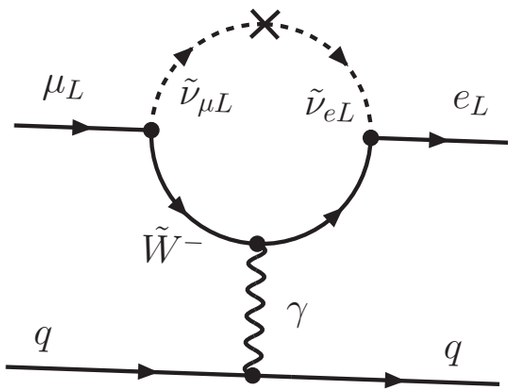




mu to e conversion and mu to 3e:







Experiments

* Current and future searches:
  - $\mu \rightarrow e\,\gamma$
  - $\mu + N \rightarrow e + N$ ($\mu \rightarrow e$ conversion)
* Fermilab's future μ2e experiment will improve the limit by 4 (!) orders of magnitude.

Precision tests of muon E&M properties.

Magnetic Dipole Moment

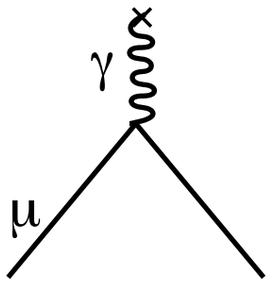
* Elementary spin 1/2 particles have a magnetic dipole moment:

$$H \propto \mu \cdot B$$

* Dirac: classically, the electron's mag. moment is $g=2$ (in units of Bohr Magnetons, $e/2m_e$).

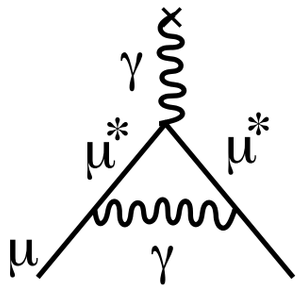
* QED: quantum correction cause mag moment to deviate from 2.

g-2



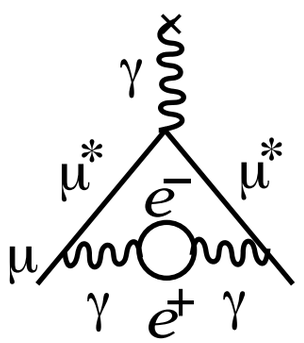
Dirac

(a)



Schwinger

(b)



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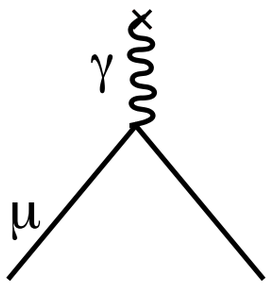

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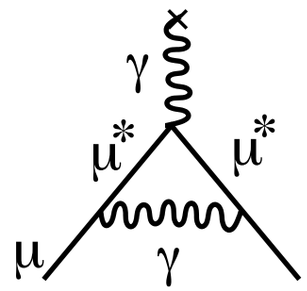
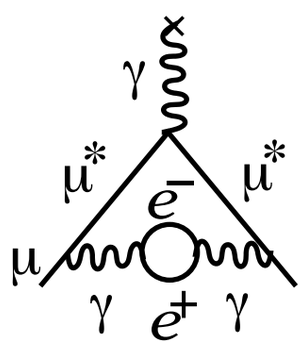
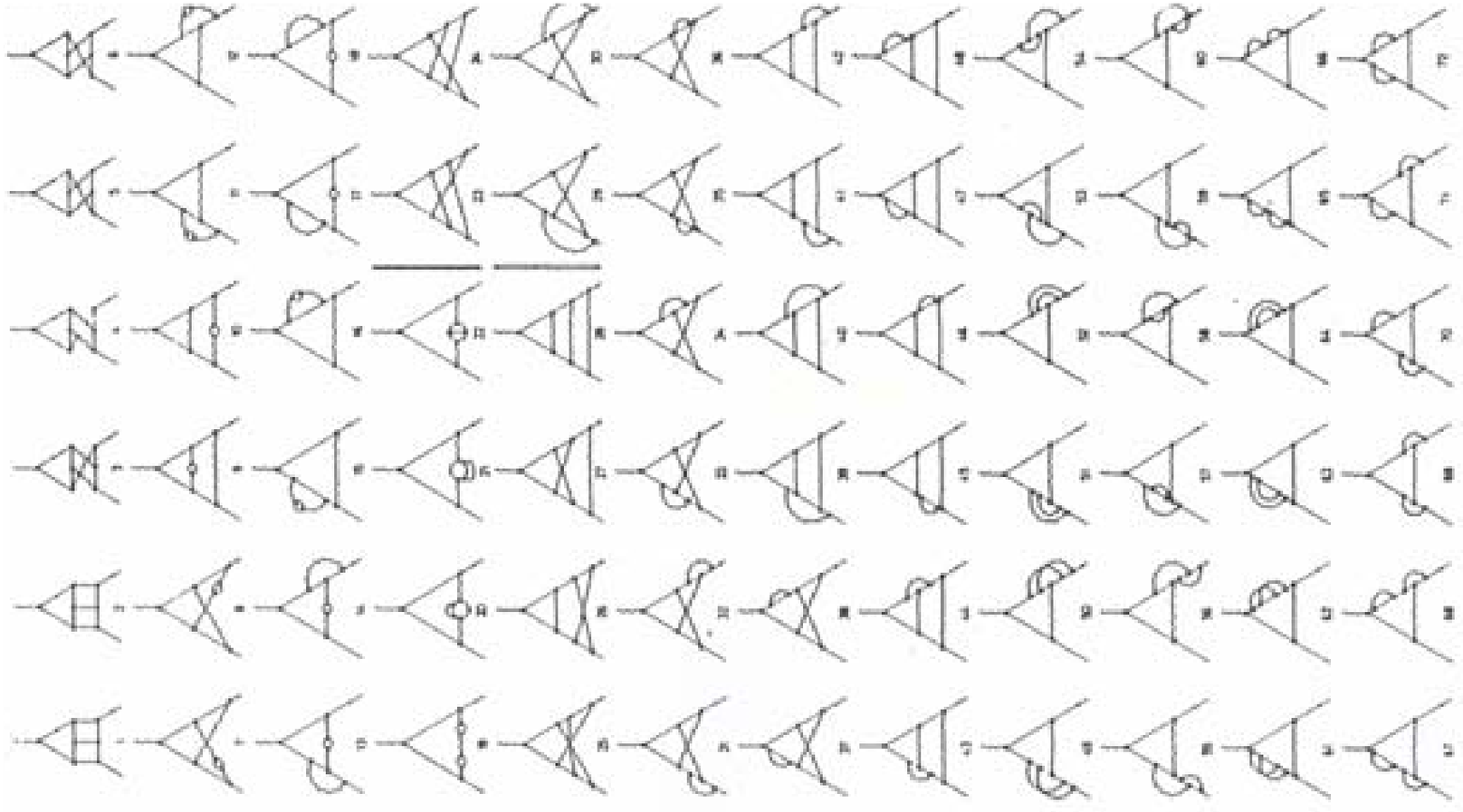


Schwinger

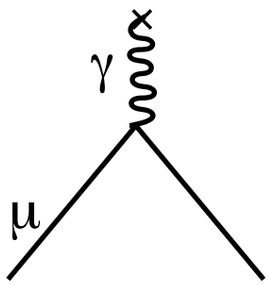
(b)



(c)



g-2



Dirac

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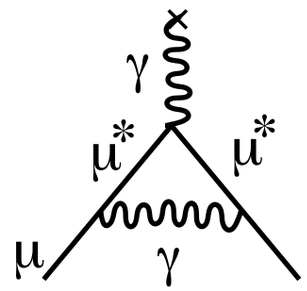

Schwinger

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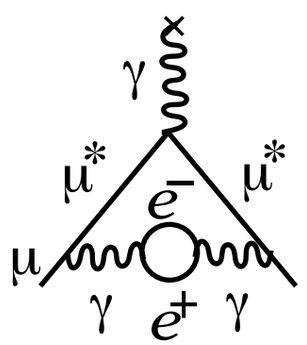

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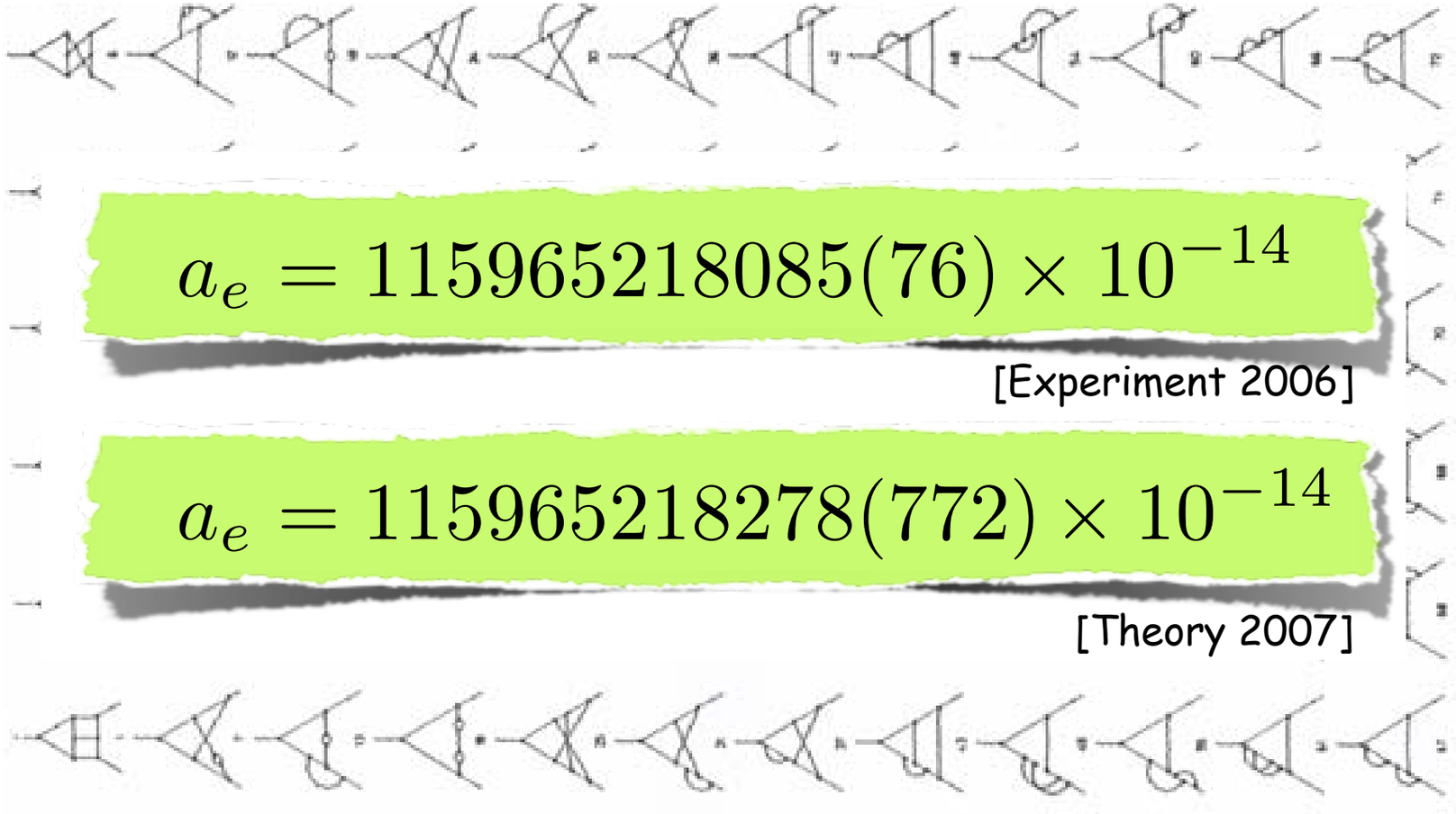


$$a_e = 115965218085(76) \times 10^{-14}$$

[Experiment 2006]

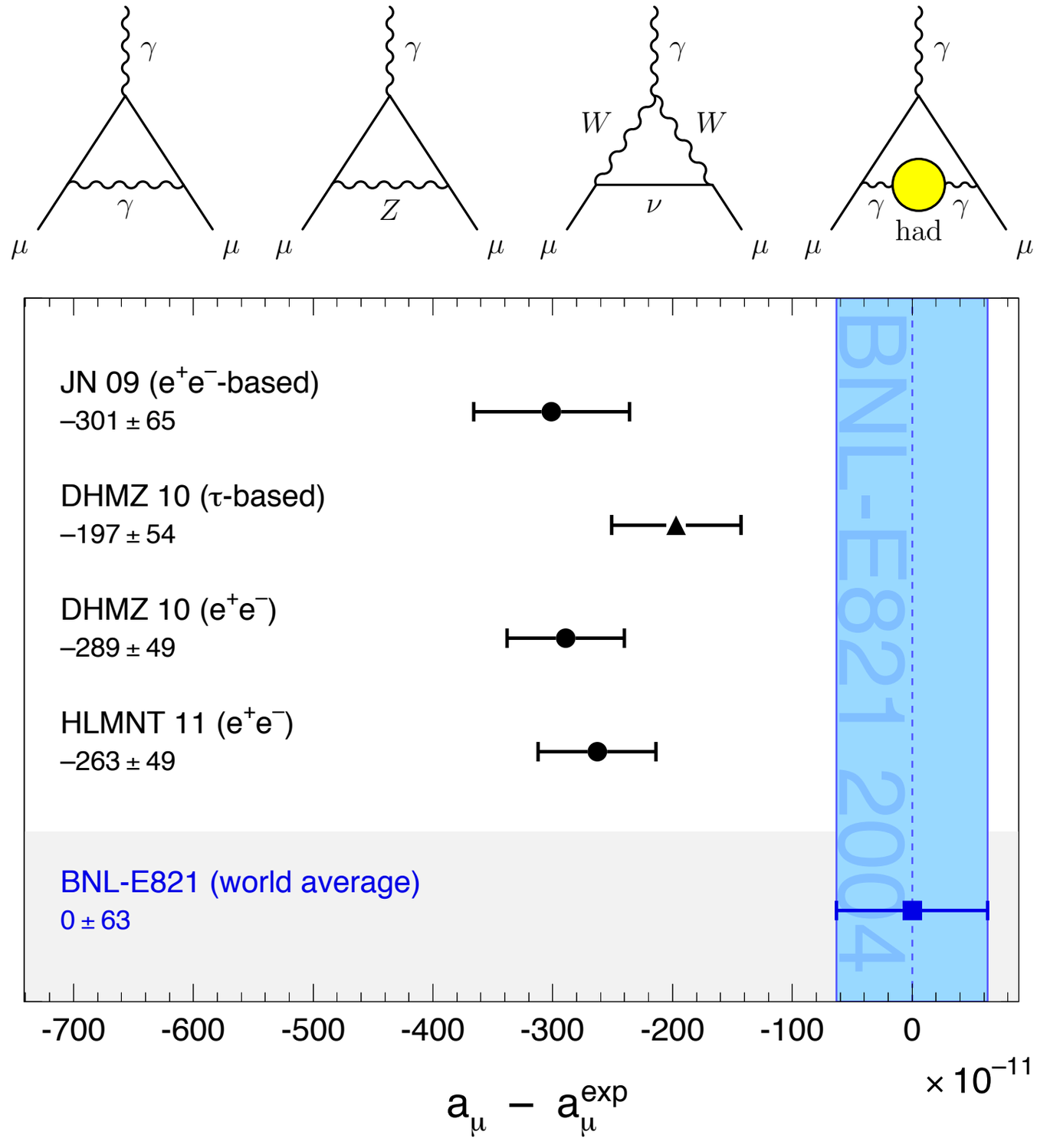
$$a_e = 115965218278(772) \times 10^{-14}$$

[Theory 2007]

muon g-2

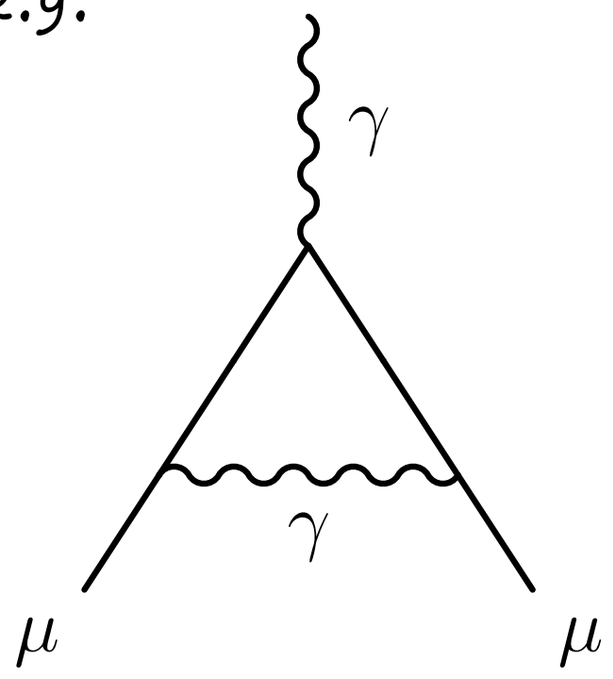
* The situation w/ muon g-2 is intriguing:

Fermilab's muon g-2 experiment will reduce the uncertainty by a factor of a few!



muon g-2

* The discrepancy can be a result of:
  - Un-controlled uncertainty of theoretical SM g-2 due to strong interactions (lattice QCD will hopefully resolve this).
  - New Physics! e.g.



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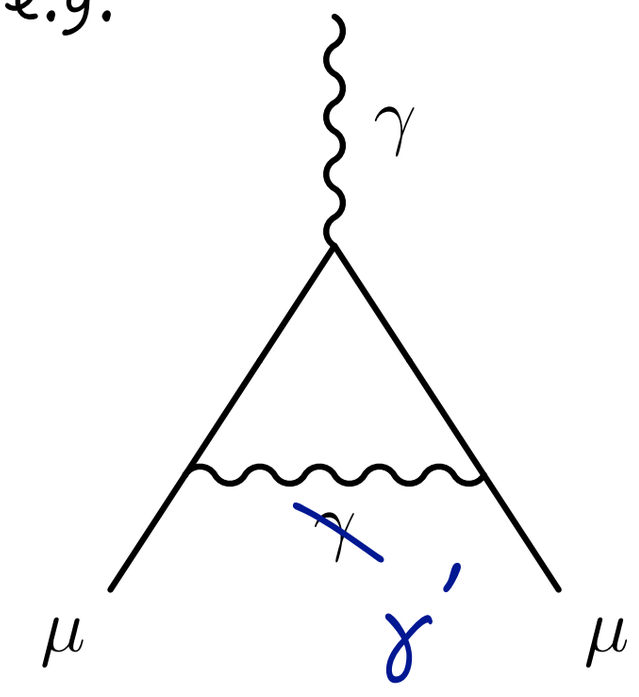

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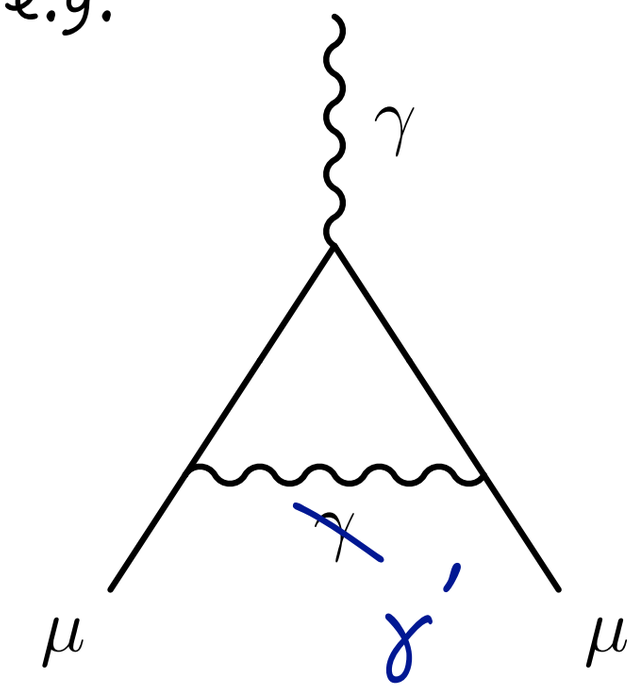

a new (massive) photon.

A New Photons

* Such a new photon could come from:
  - A new dark E&M force (maybe connected to dark matter?)
  - An extra dimension.

* Another (famous) possibility: supersymmetry.

* More specifics on the whiteboard...

Conclusions:

* We are curious!
* For example: who ordered the muon?
  what makes it different from the electron?
* Upcoming experiments at Fermilab's muon campus can unveil new physics and shel light on some deep questions!

Deleted Scenes

$\mu \to e\gamma$ $\tau \to e\gamma$ $\tau \to \mu\gamma$

$\mu \to 3e$ $\mu + N \to e + N$

Higgs FV-
A more technical story.

Can We violate this?
Can we have FV Higgs couplings?

In the mass basis, could we have

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

?

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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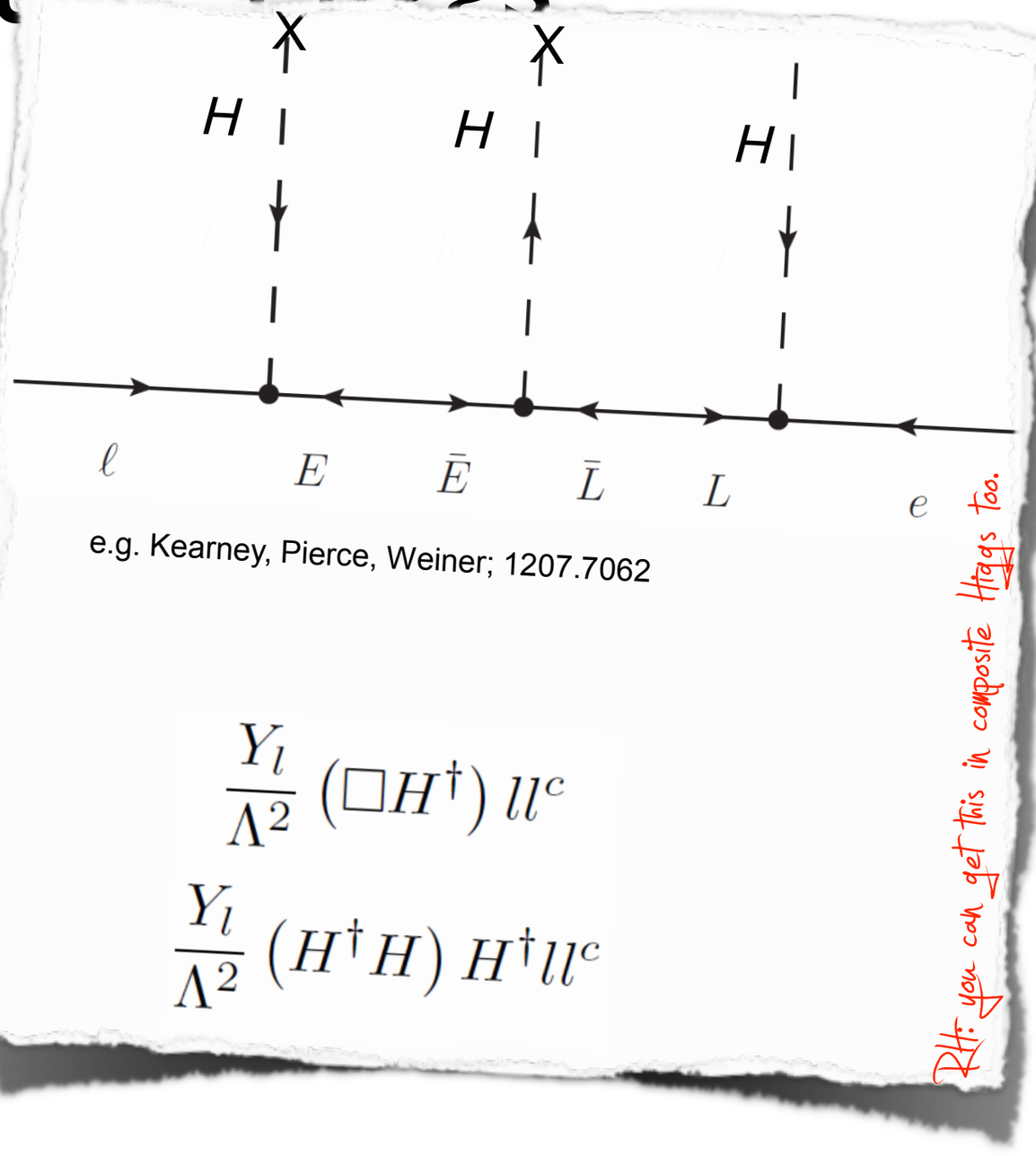

e.g. Kearney, Pierce, Weiner; 1207.7062

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

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

RH: you can get this in composite Higgs too.

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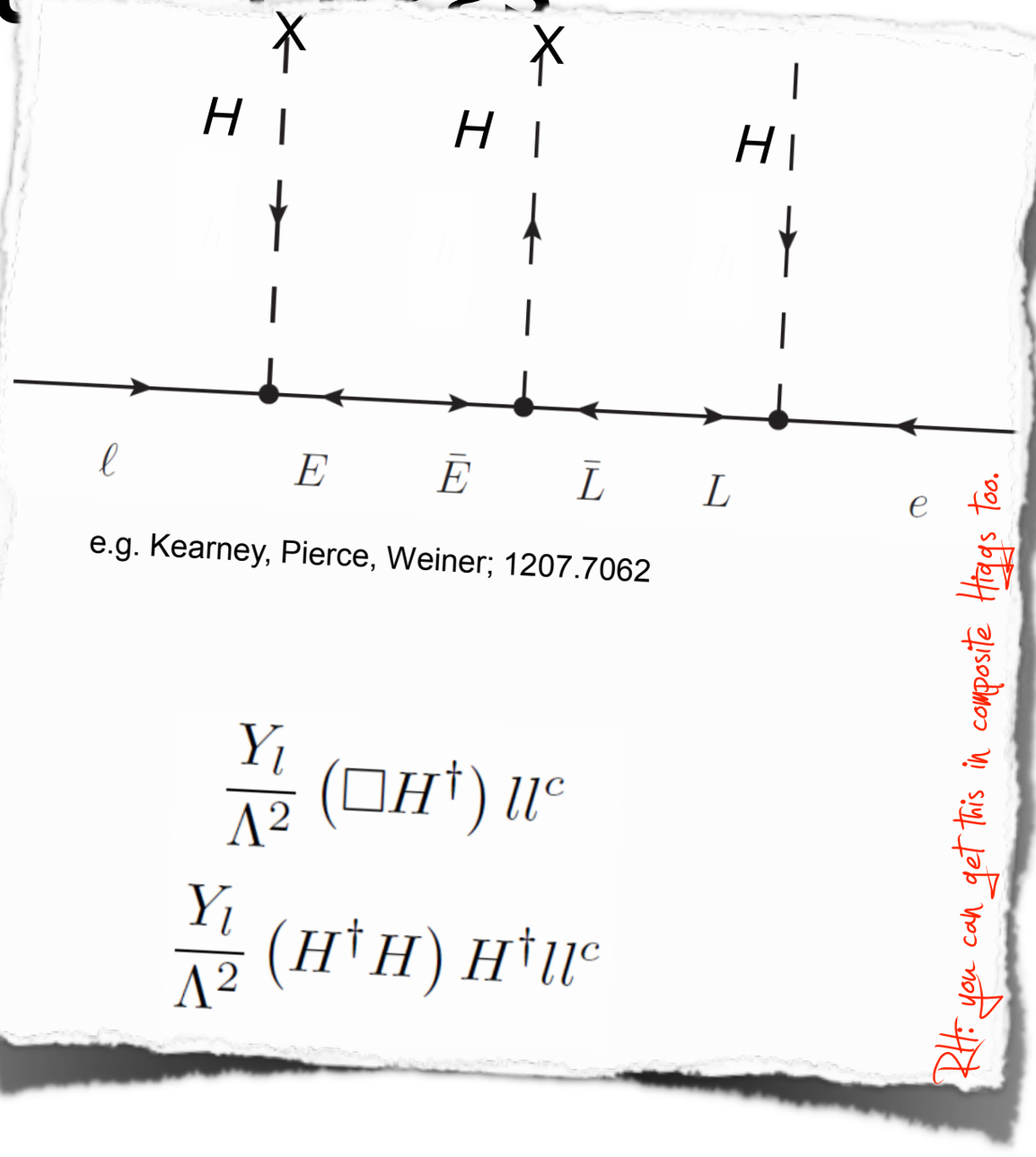

$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2}$$

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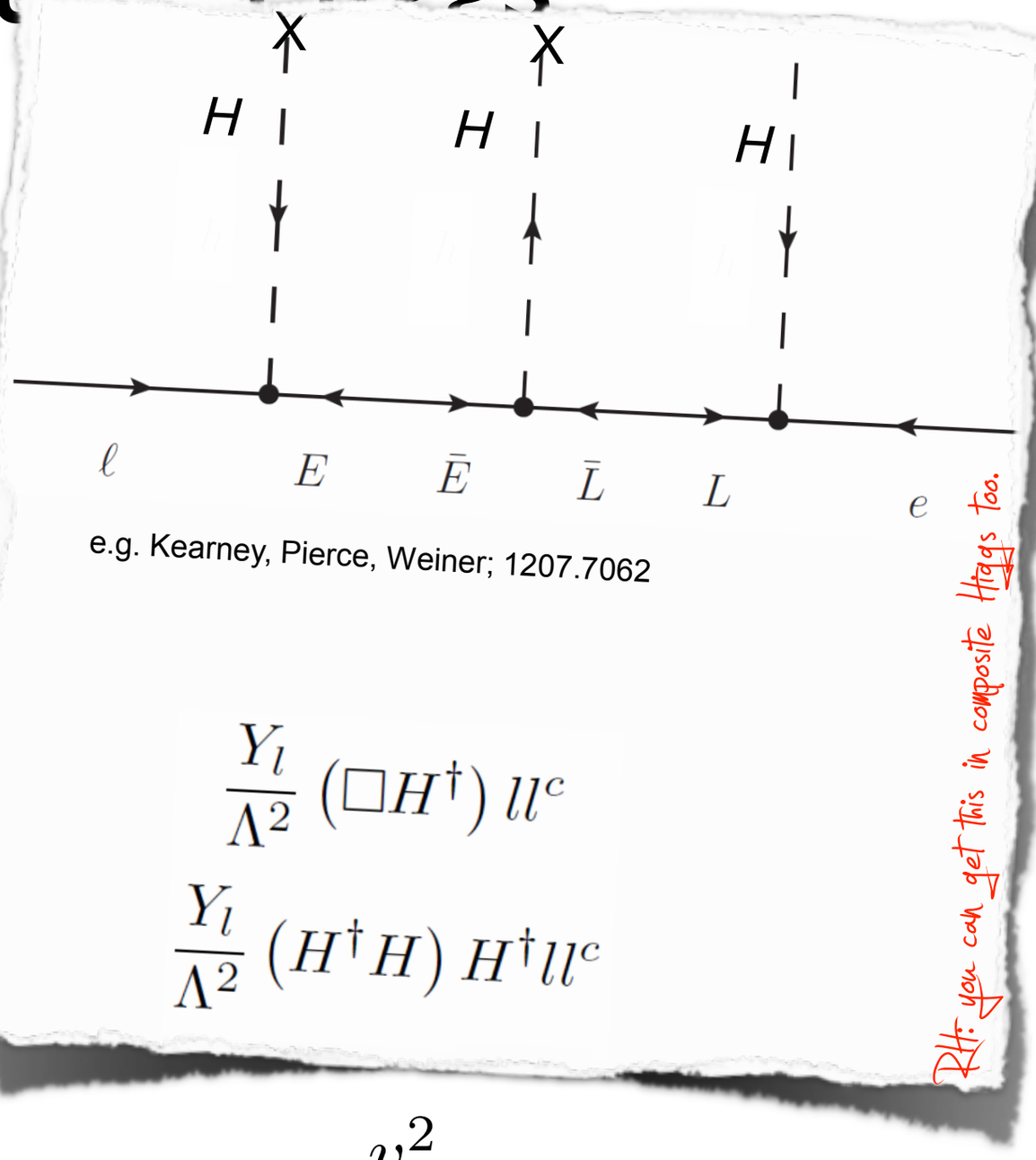

$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2} \quad \Rightarrow \quad m_f = (\lambda_f + \frac{v^2}{\Lambda^2})v, \quad y_f = \lambda_f + \frac{3v^2}{\Lambda^2}$$

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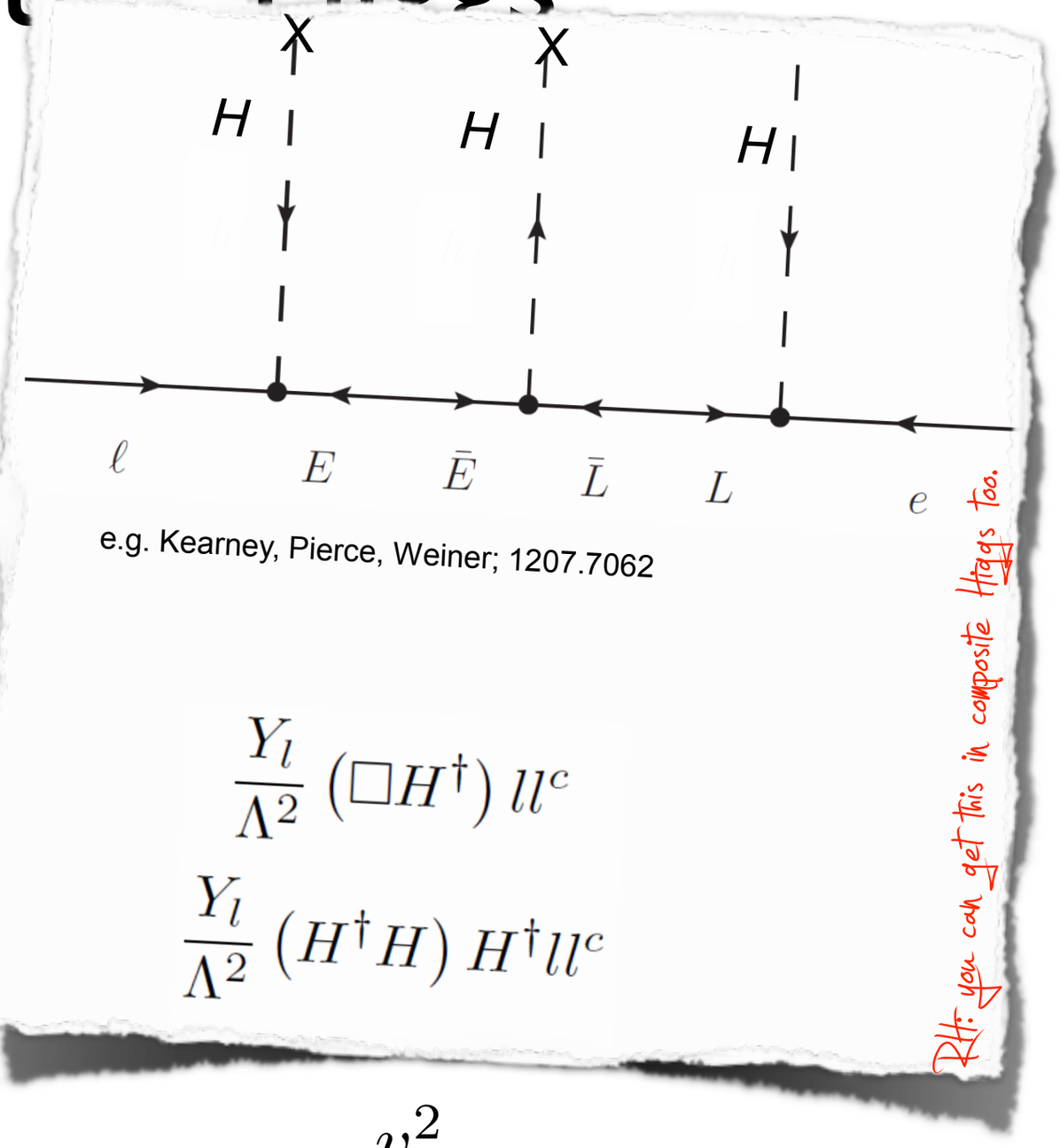

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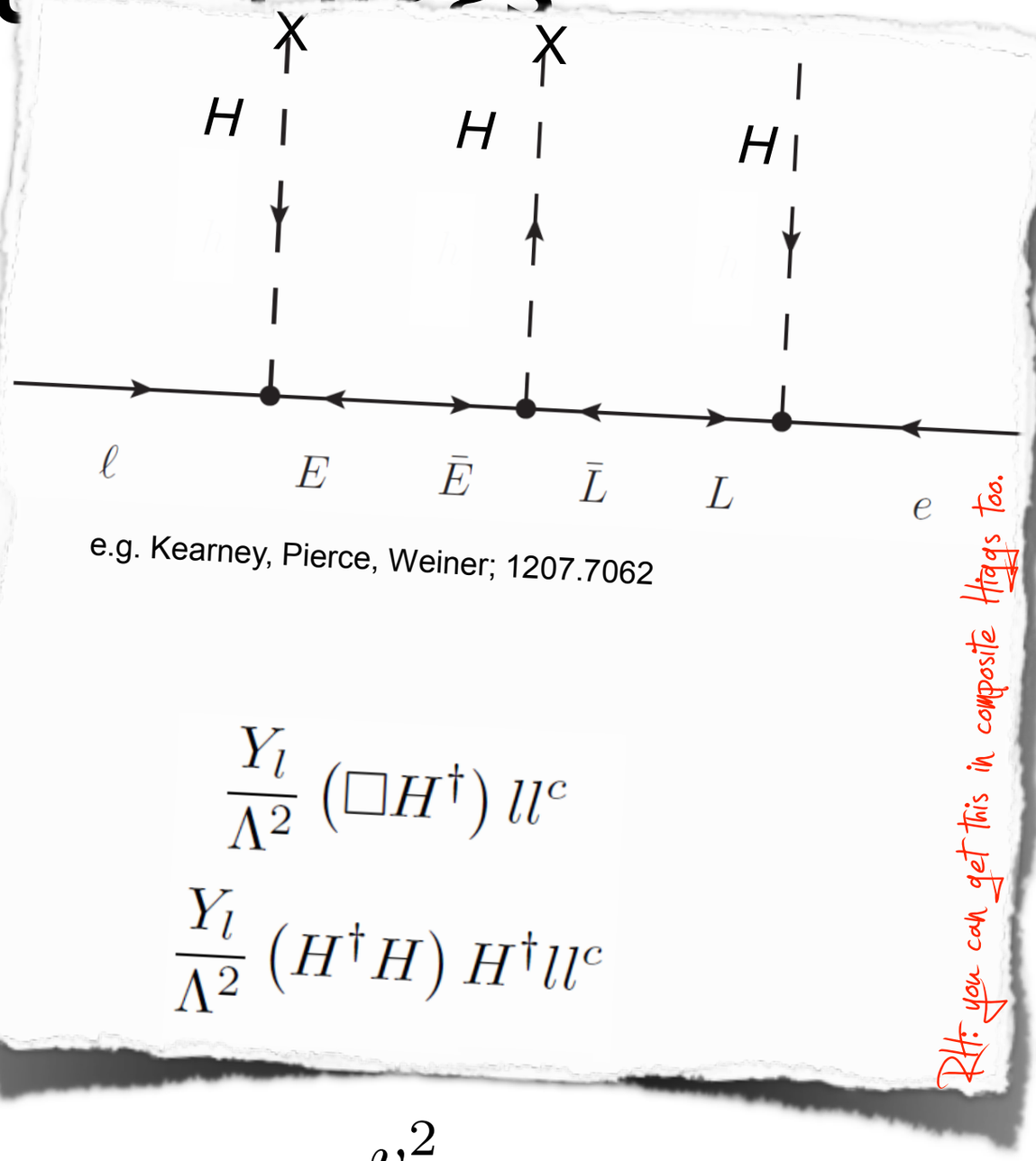

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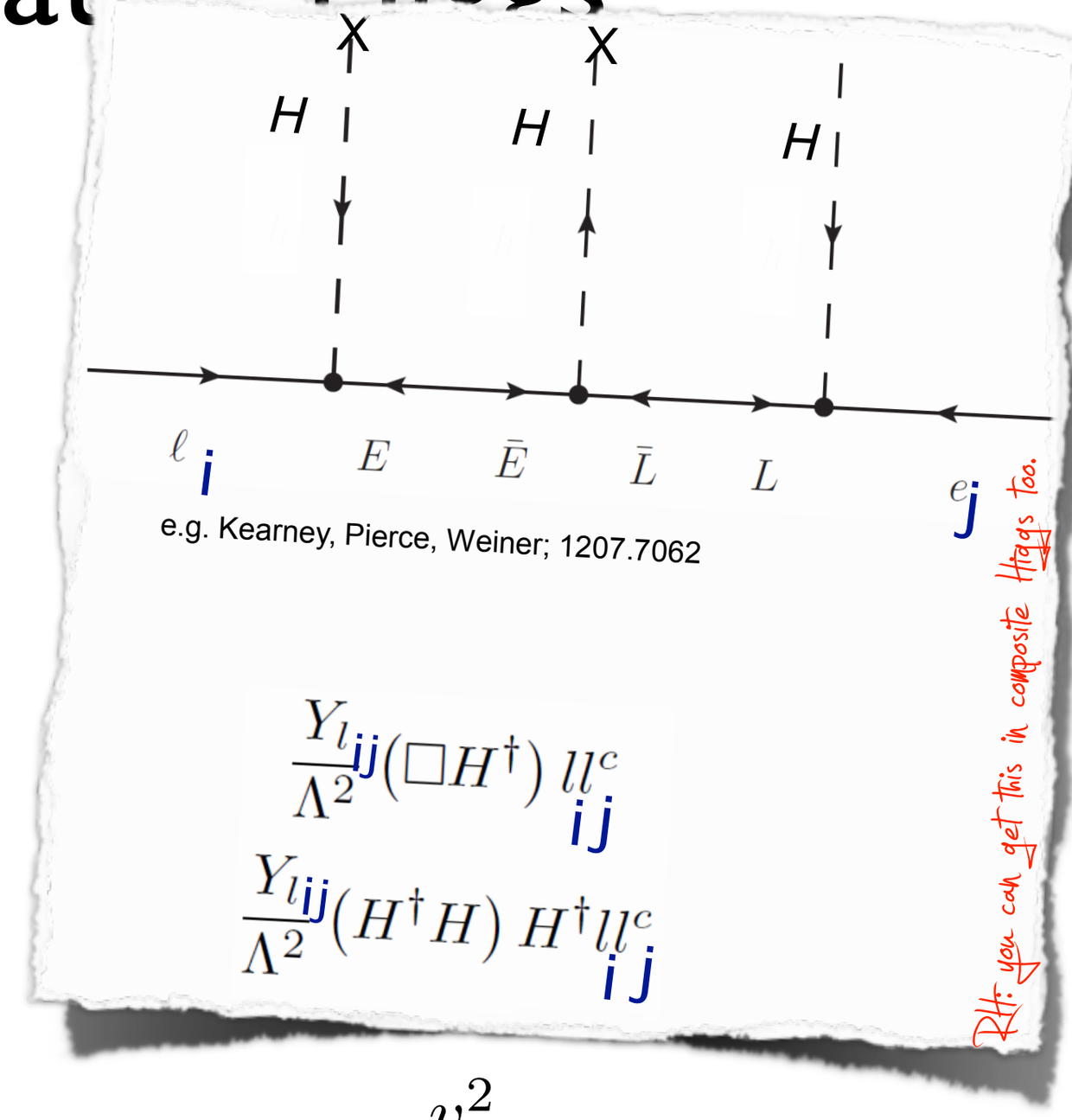

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Flavor Violating Higgs

* Writing it a bit more neatly, we get:

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

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

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

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

An arbitrary matrix! (sort of)

"Natural" FV

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

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

* 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.

Leptonic Flavor Violation

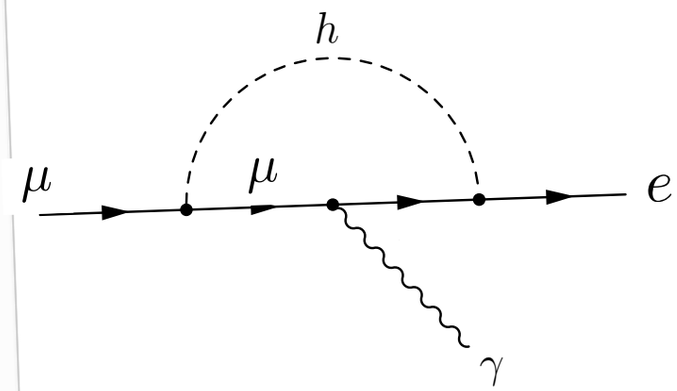
$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

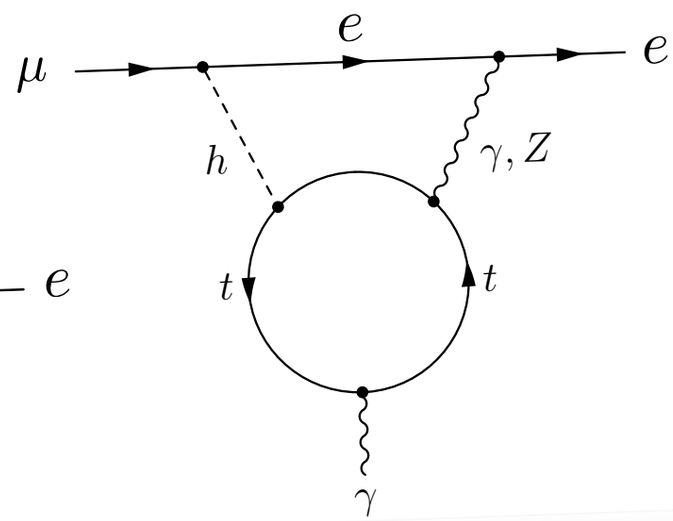
Which experiments constrain the Y_{ij}'s?

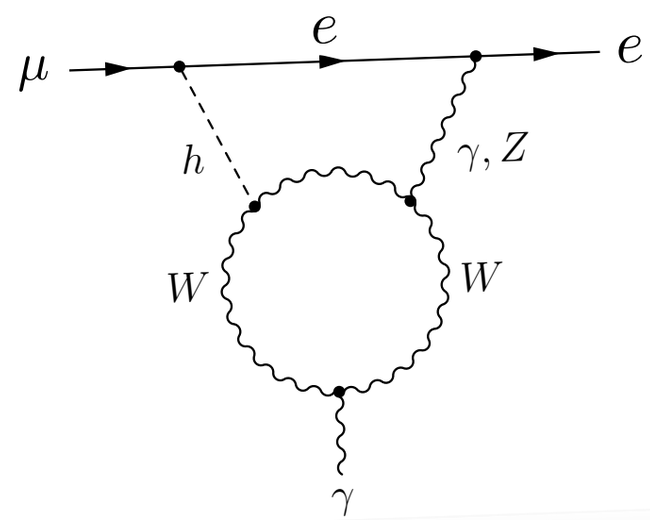
Higgs couplings to μe

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

mu to e gamma & mu to 3e (at 1 and 2-loop):







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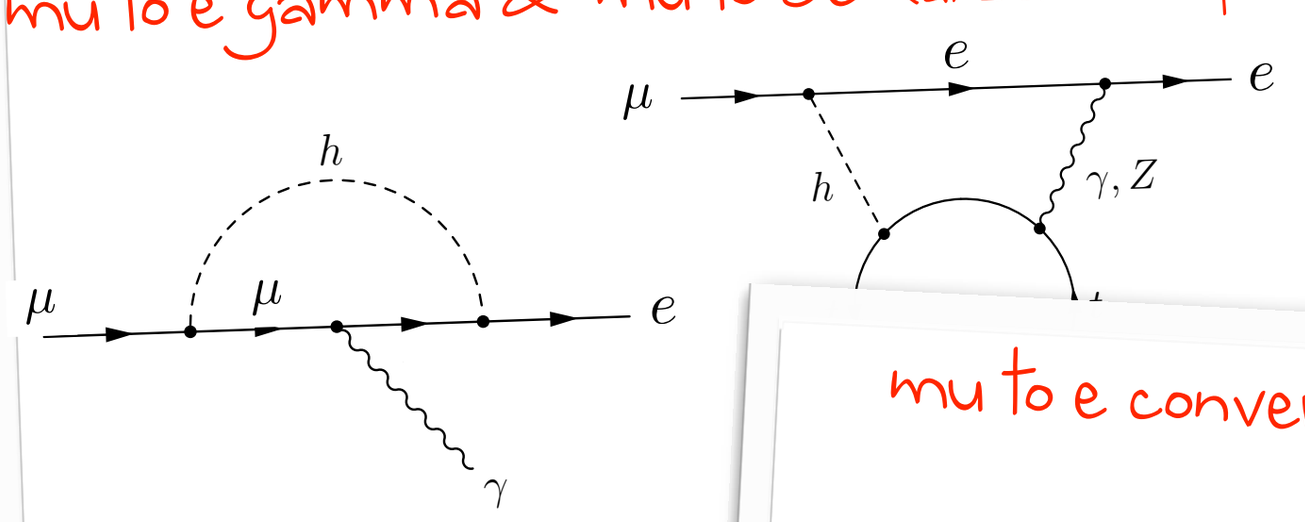
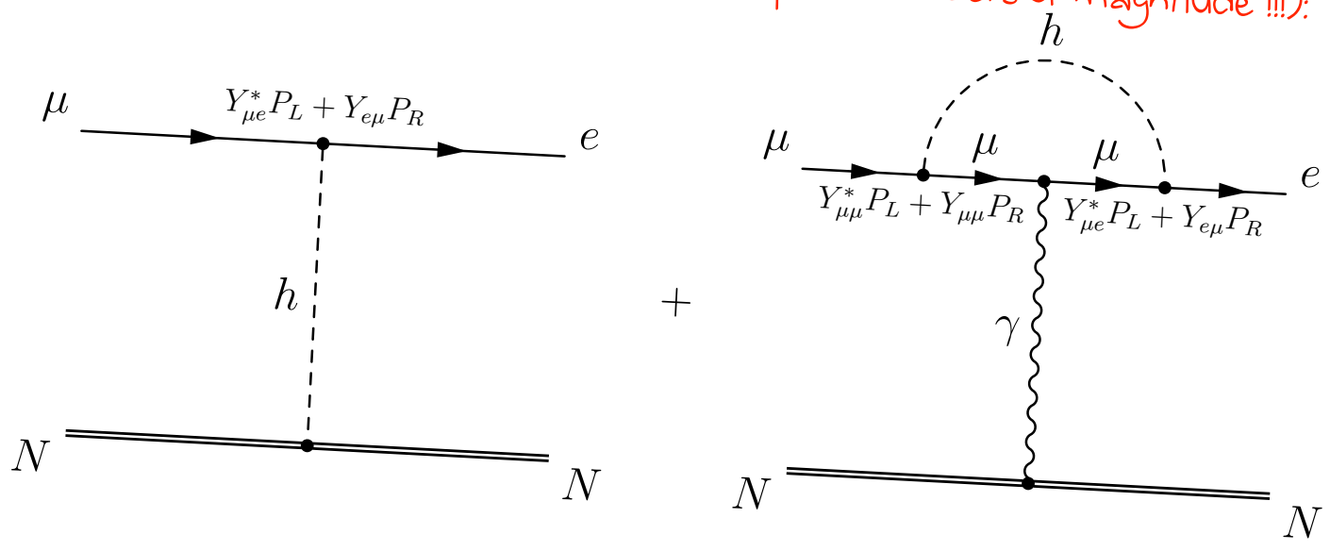


mu to e conversion (will improve 4 orders of magnitude !!!):



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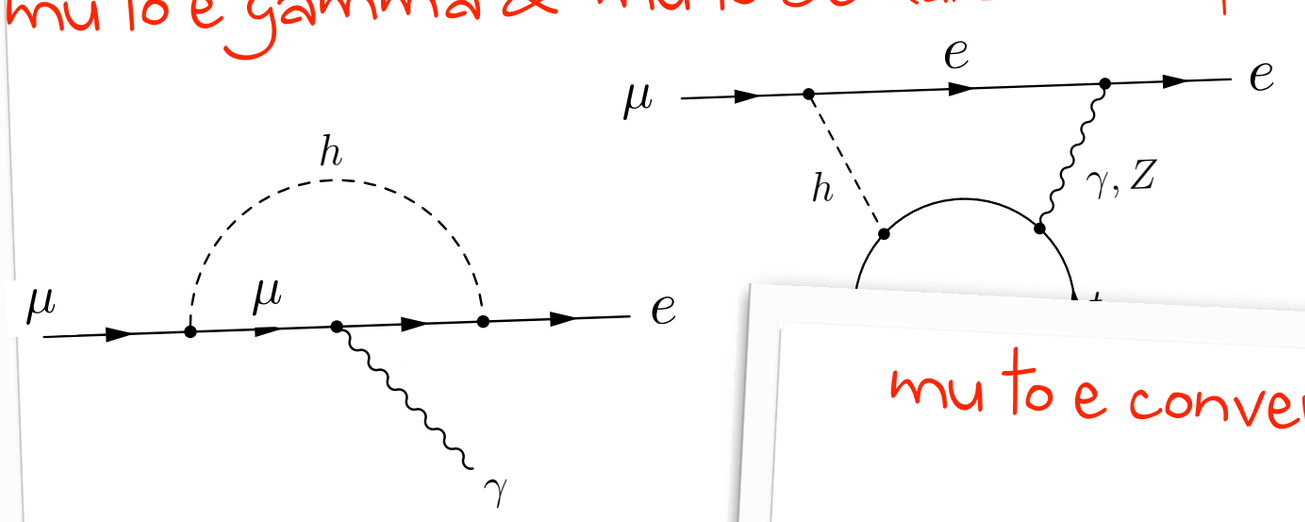

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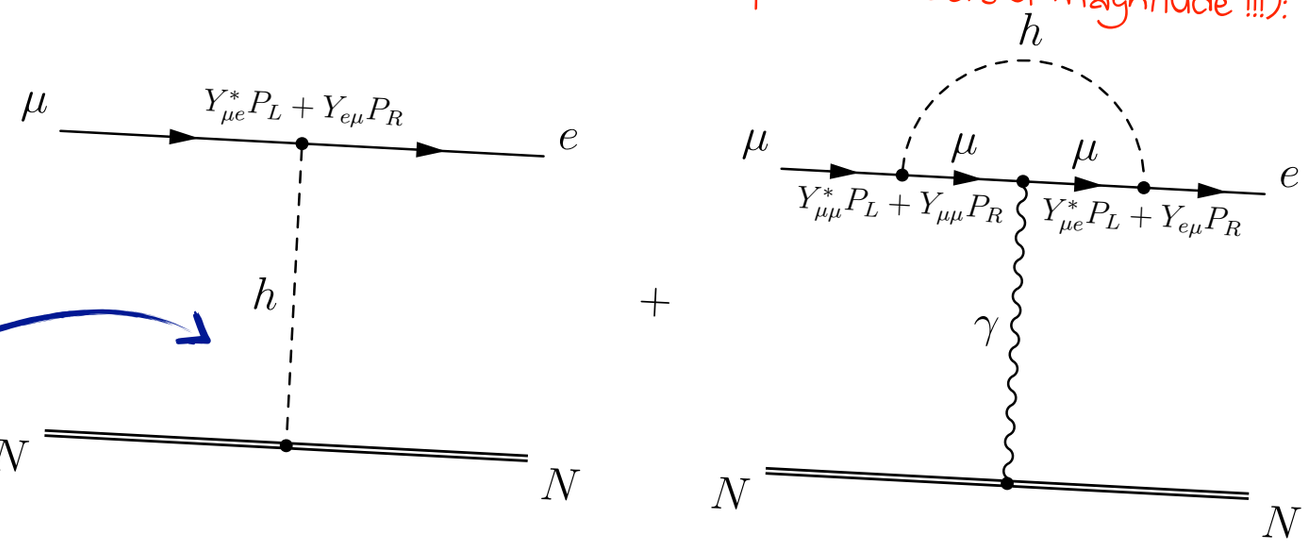
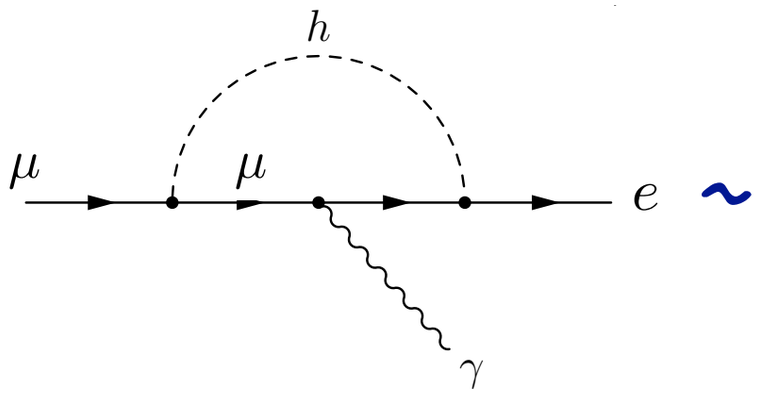


Which operator?

Higgs couplings to μe

* Lets practice more. we are aiming for:

$$H (\bar{\mu}_R \sigma^{\mu\nu} e_L) F_{\mu\nu}$$



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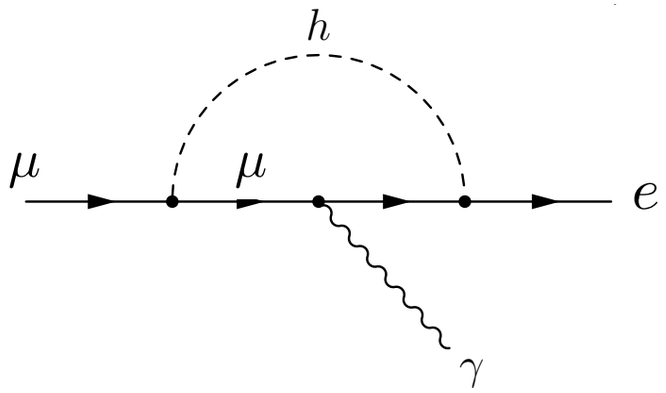

$$\sim \frac{1}{16\pi^2}$$

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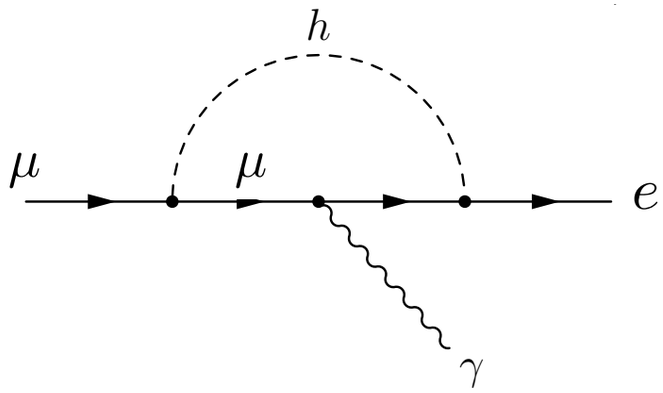

$$\sim \frac{e}{16\pi^2}$$

Higgs couplings to μe

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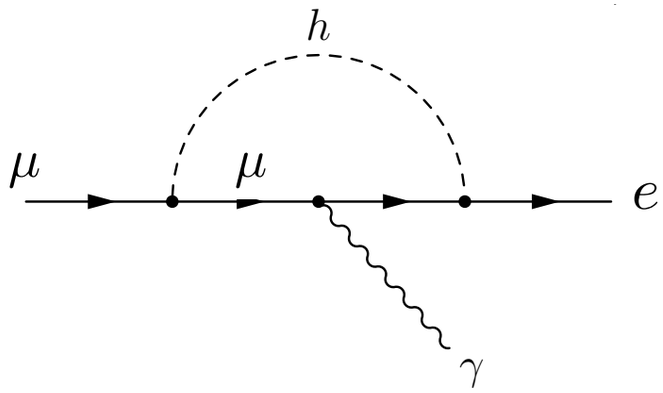

$$\sim \frac{e}{16\pi^2} m_\mu$$

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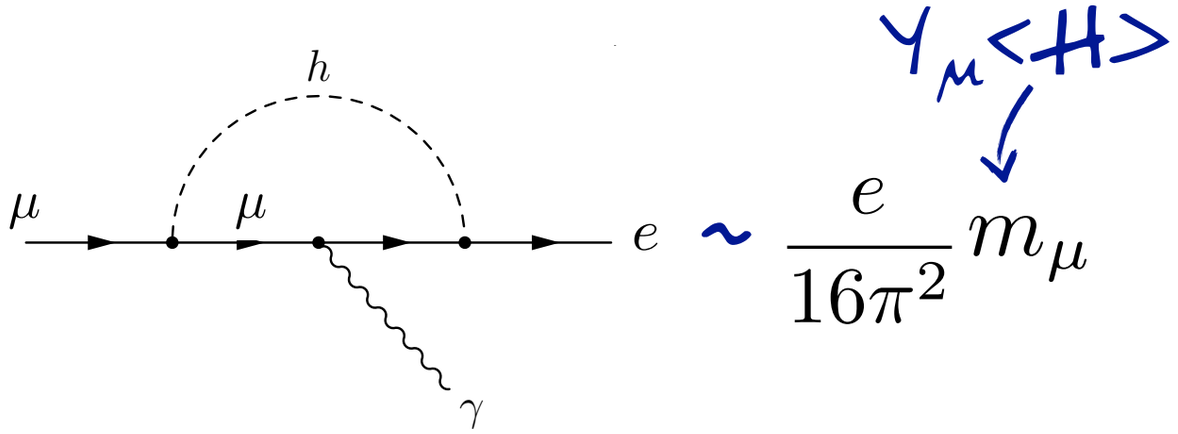

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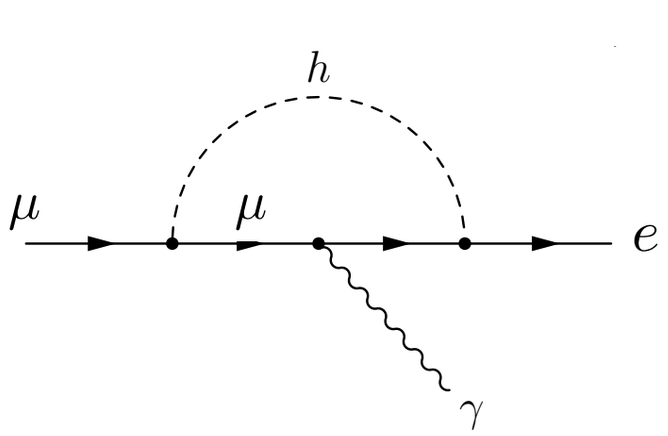

$$\sim \frac{e}{16\pi^2} m_\mu \frac{1}{m_h^2}$$

$Y_\mu \langle H \rangle$

Higgs couplings to μe

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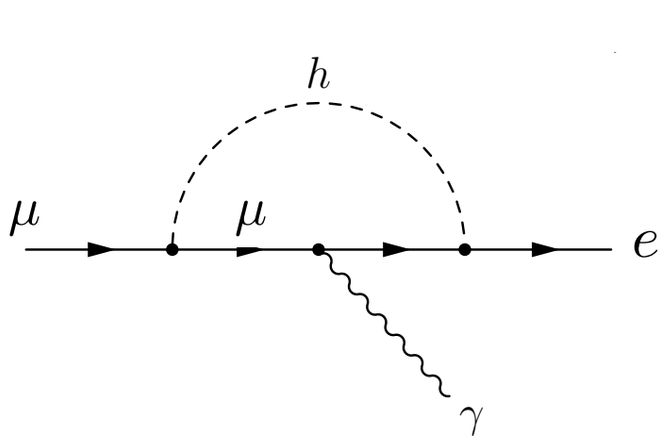

$$\sim \frac{e}{16\pi^2} m_\mu \frac{1}{m_h^2} Y^*_{\mu\mu} Y_{\mu e}$$

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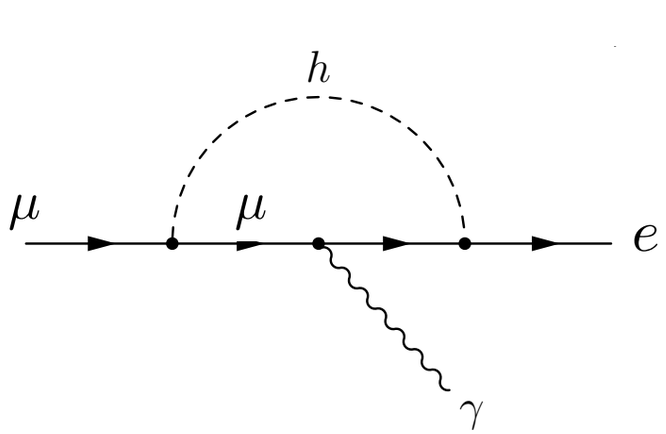

$$\sim \frac{e}{16\pi^2} m_\mu \frac{1}{m_h^2} Y^*_{\mu\mu} Y_{\mu e} \log \dots$$

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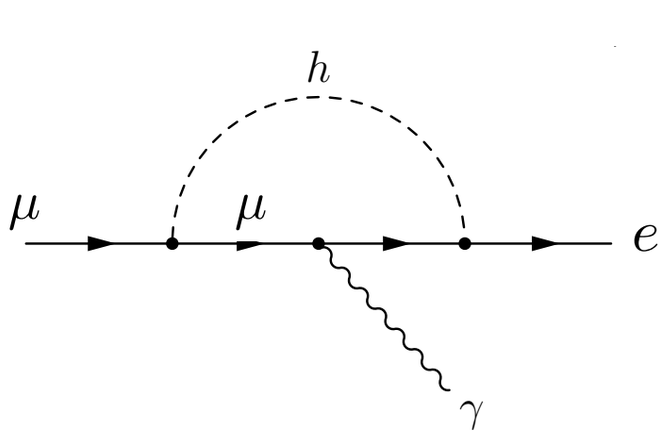

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$Y_\mu \langle H \rangle$

* The notation is $\mathcal{L}_{\mu\to e\gamma} = C_L \frac{e}{8\pi^2} m_\mu (\bar{\mu}_R \sigma^{\mu\nu} e_L) F_{\mu\nu}$

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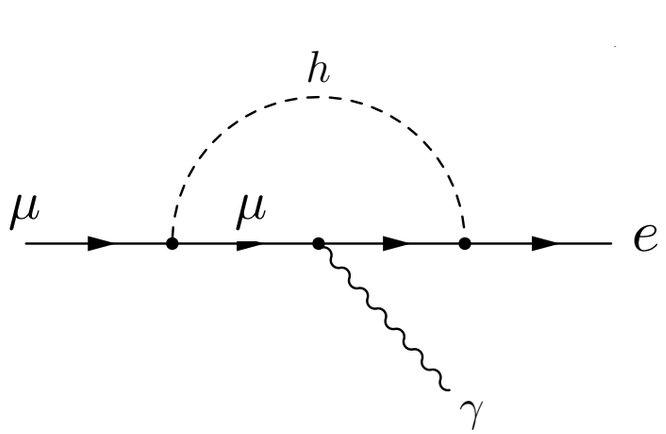


$\sim$ $Y_\mu \langle H \rangle$

$$\frac{e}{16\pi^2} m_\mu \frac{1}{m_h^2} Y^*_{\mu\mu} Y_{\mu e} \log \ldots$$

* The notation is $\mathcal{L}_{\mu\to e\gamma} = C_L \frac{e}{8\pi^2} m_\mu (\bar{\mu}_R \sigma^{\mu\nu} e_L) F_{\mu\nu}$

* The real answer is (pages of algebra)-

$$c_L^{1\text{loop}} \simeq \frac{1}{12 m_h^2} Y_{\tau\tau} Y^*_{\tau\mu} \left(-4 + 3 \log \frac{m_h^2}{m_\tau^2} \right)$$

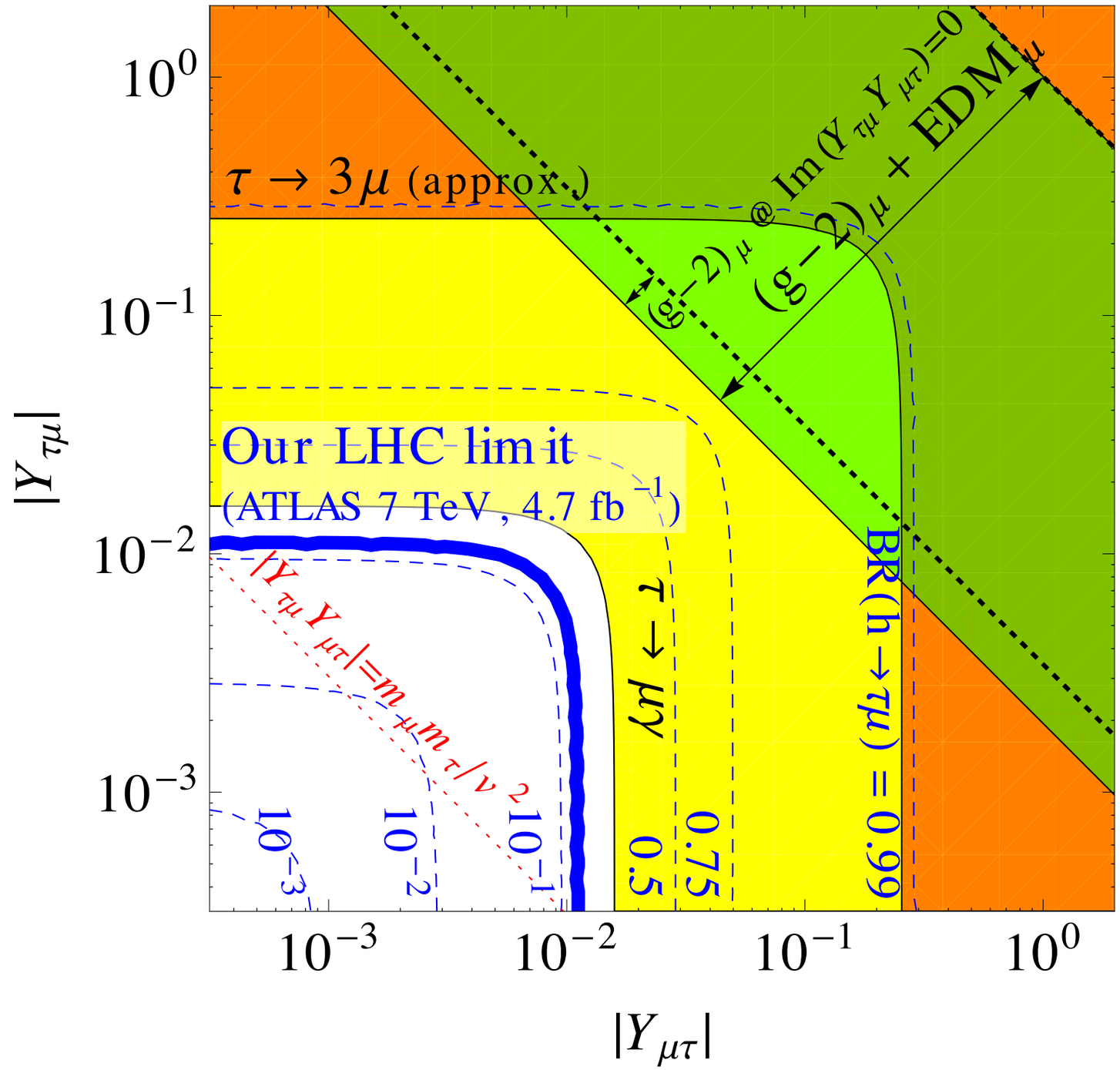
(swap tau with mu and mu with e)

Higgs couplings to μe

Outside of
LHC reach.

Probing
"natural" models.

Higgs couplings to $\tau\mu$



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

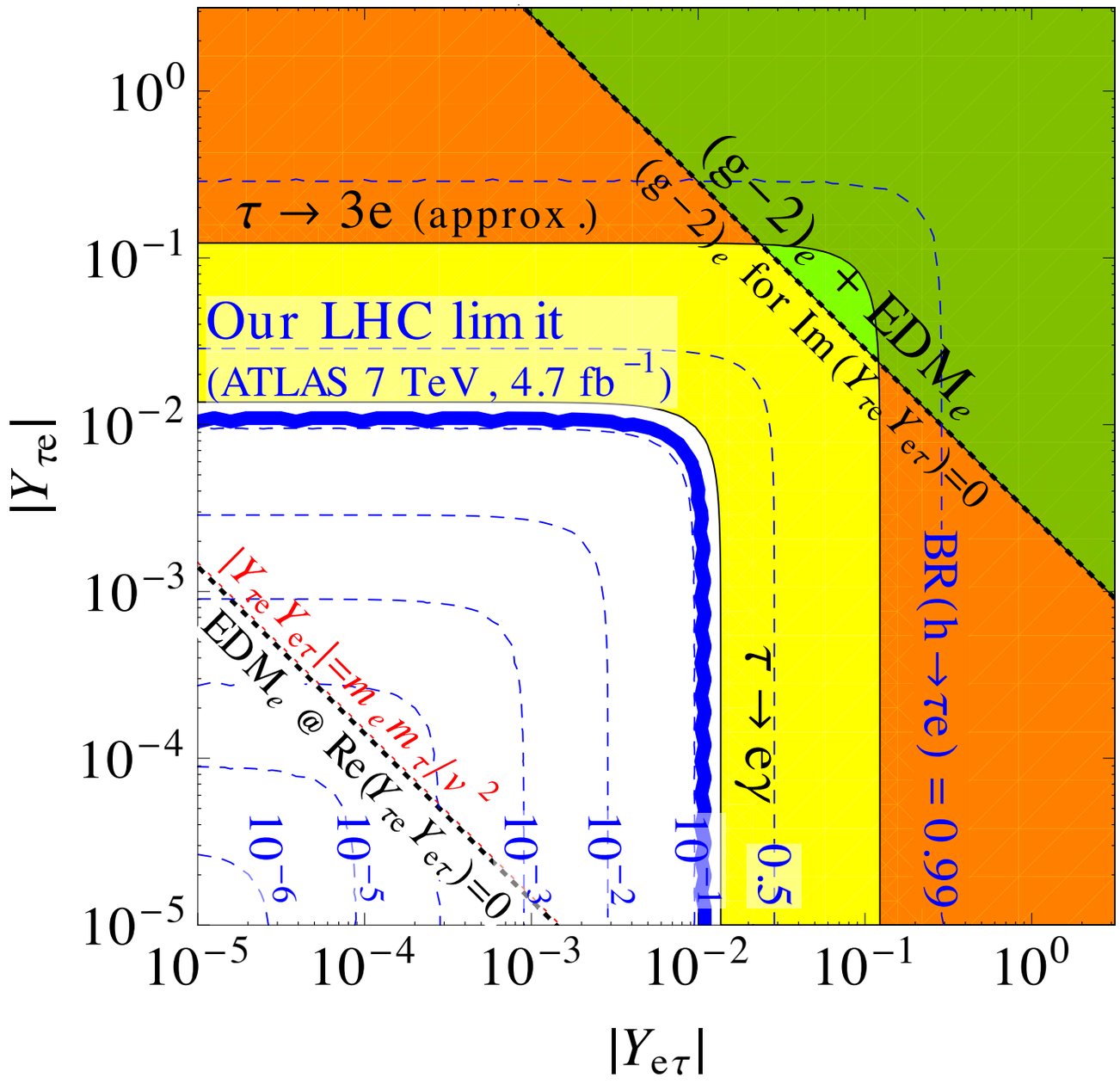
(currently just a theorist's re-interpretation)

"natural models" are within reach.

RH, Kopp, Zupan 1209.1397

Higgs couplings to τe

* τe is similar to $\tau\mu$.... but:



Higgs couplings to τe

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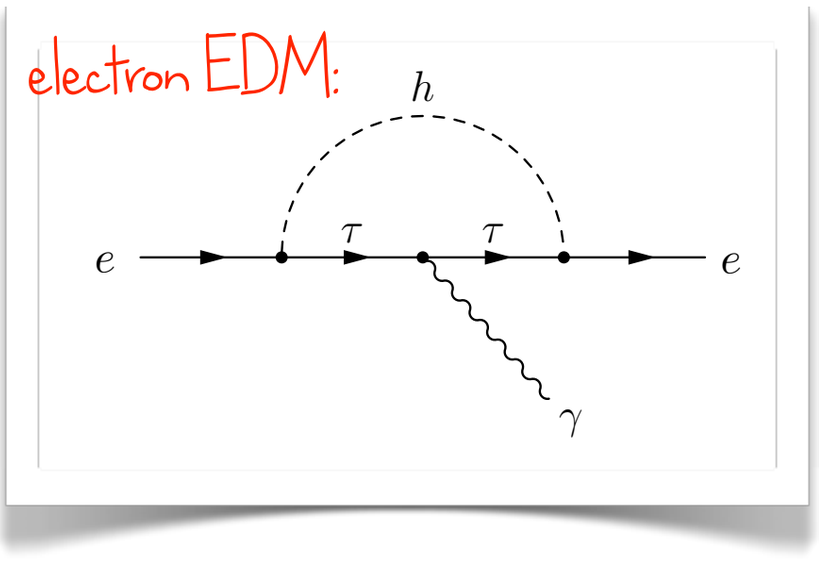
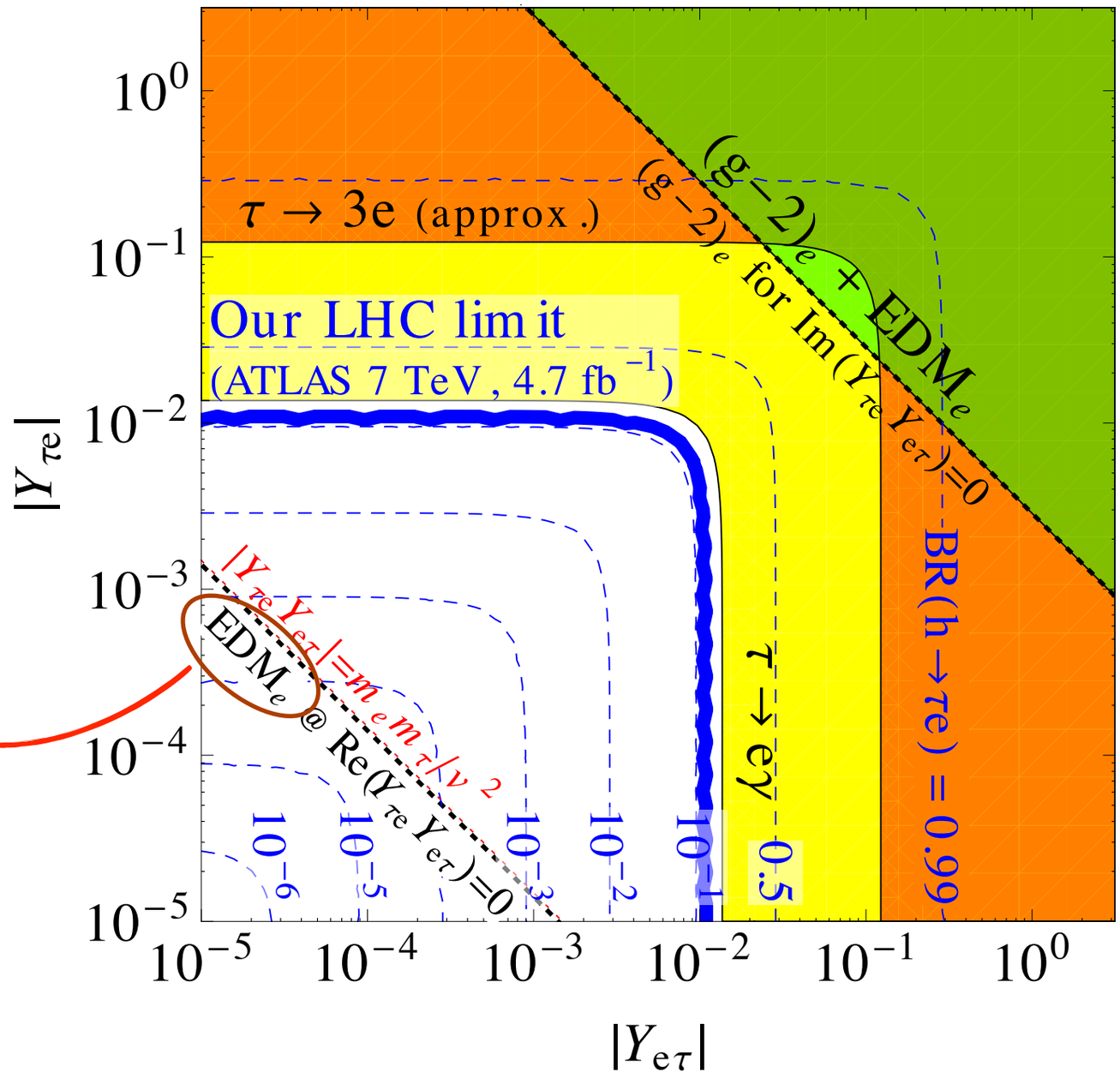
Electron EDM is interesting here!





Higgs Summary:

Flavor violation:

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

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

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

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

*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!

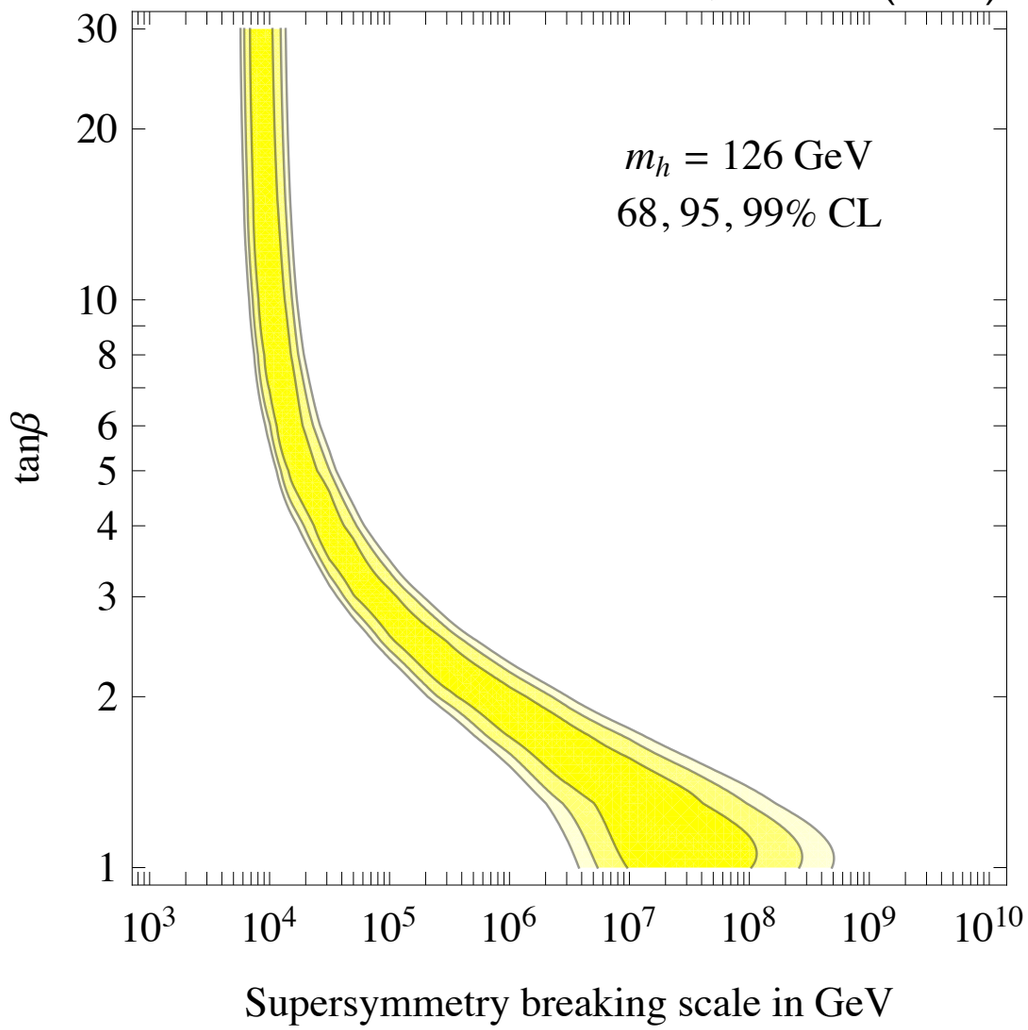
Almost all channels are sensitive at well motivated levels!

Split 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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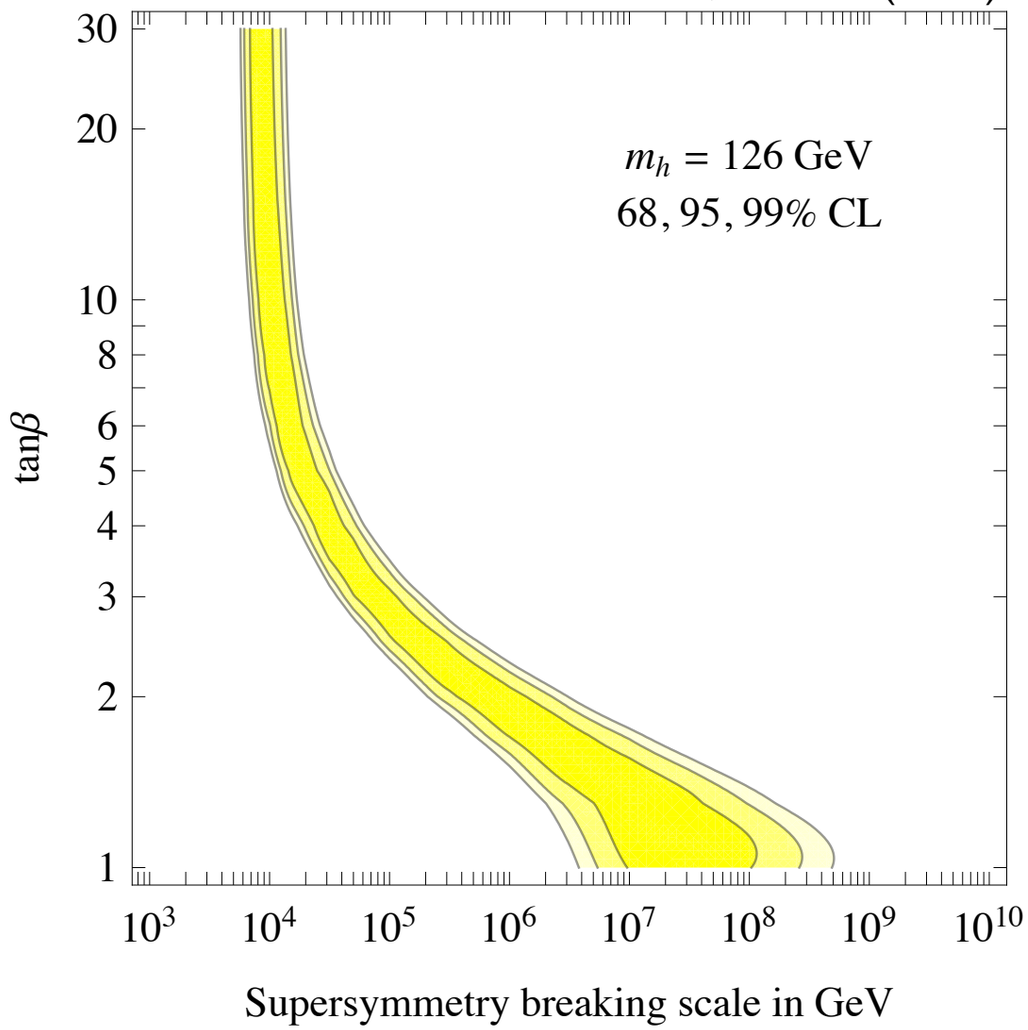

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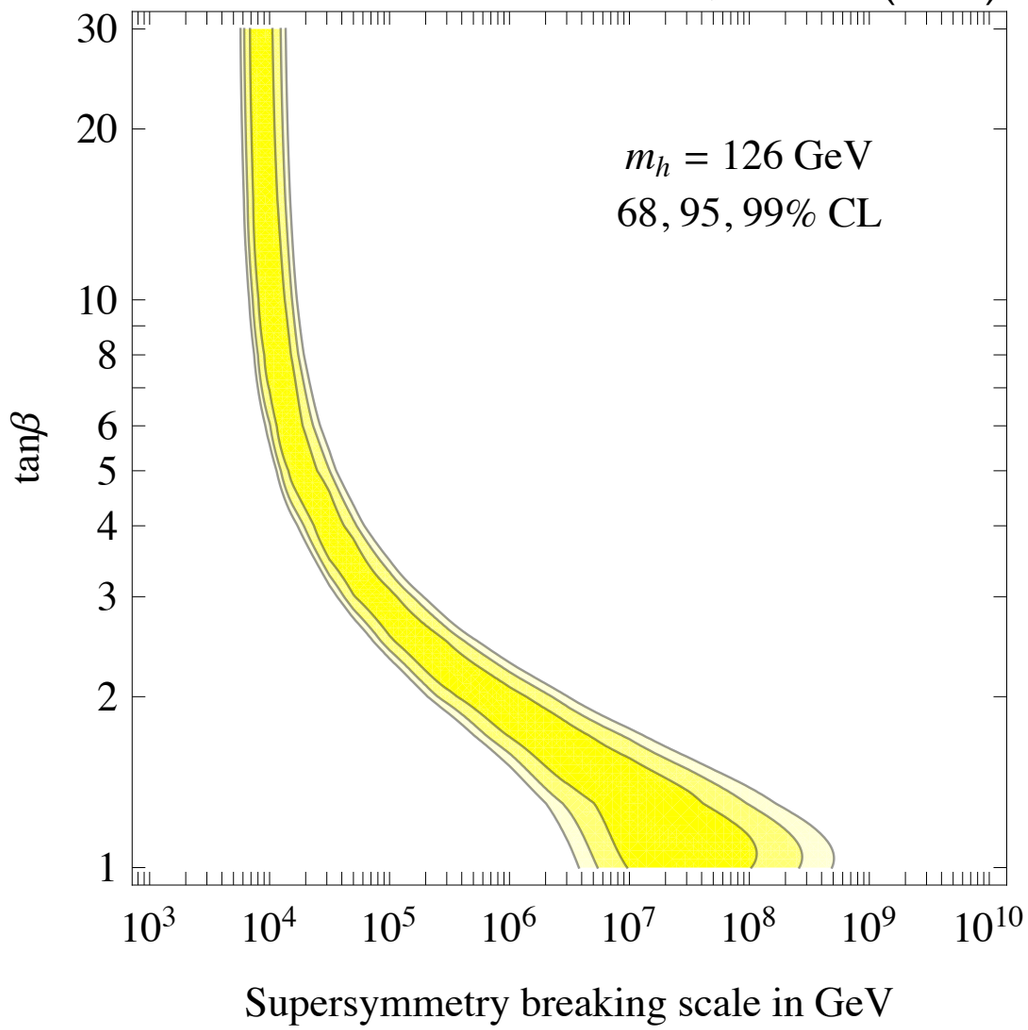
Goal: try to reach O(PeV) with as many probes as possible.

Giudice, Strumia (2012)



The Spectrum

* Lepton superpatners at 100-1000 TeV.

* Gauginos at a few TeV

Assume large FV at the high scale.
Can we probe it?

The Spectrum

* Lepton superpatners at 100-1000 TeV.

Higgsinos can be either here or here.

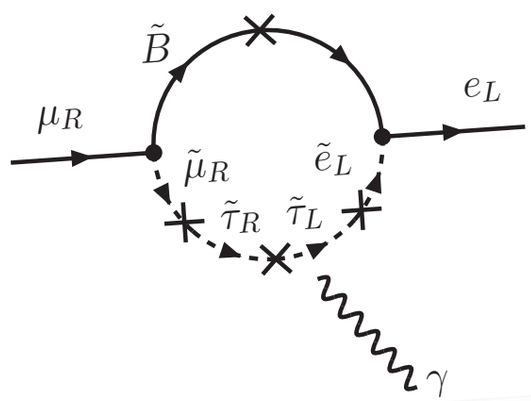
* Gauginos at a few TeV

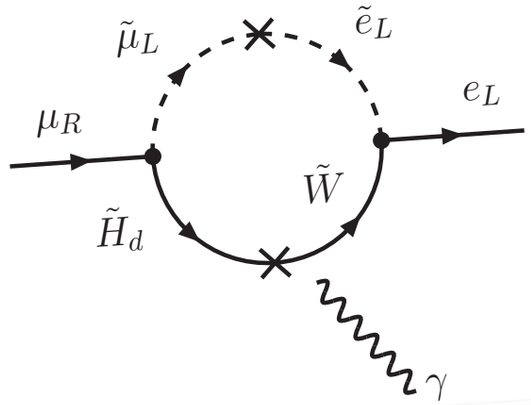
Assume large FV at the high scale.
Can we probe it?

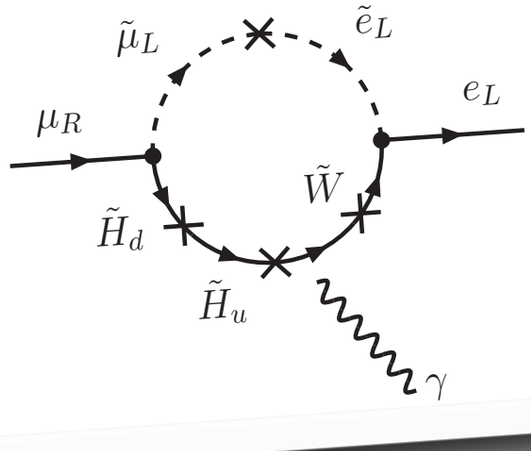
LFV form PeV Sleptons

* Flavor violation processes:

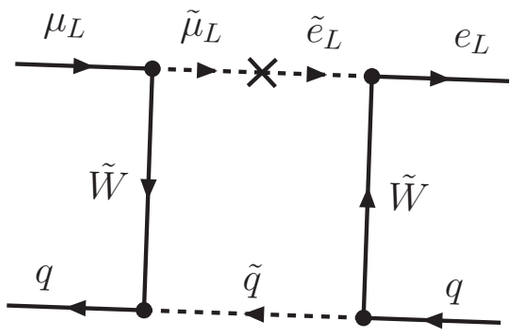
mu to e gamma:

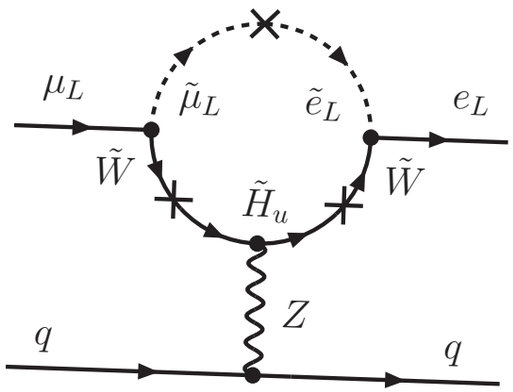


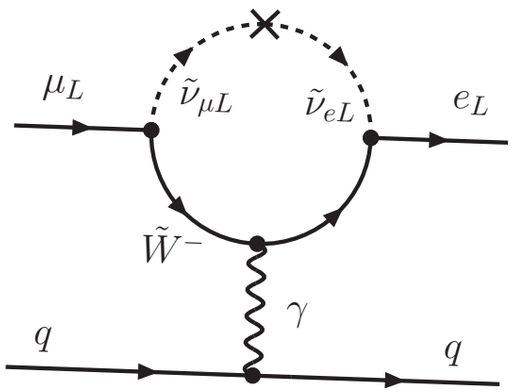




mu to e conversion and mu to 3e:

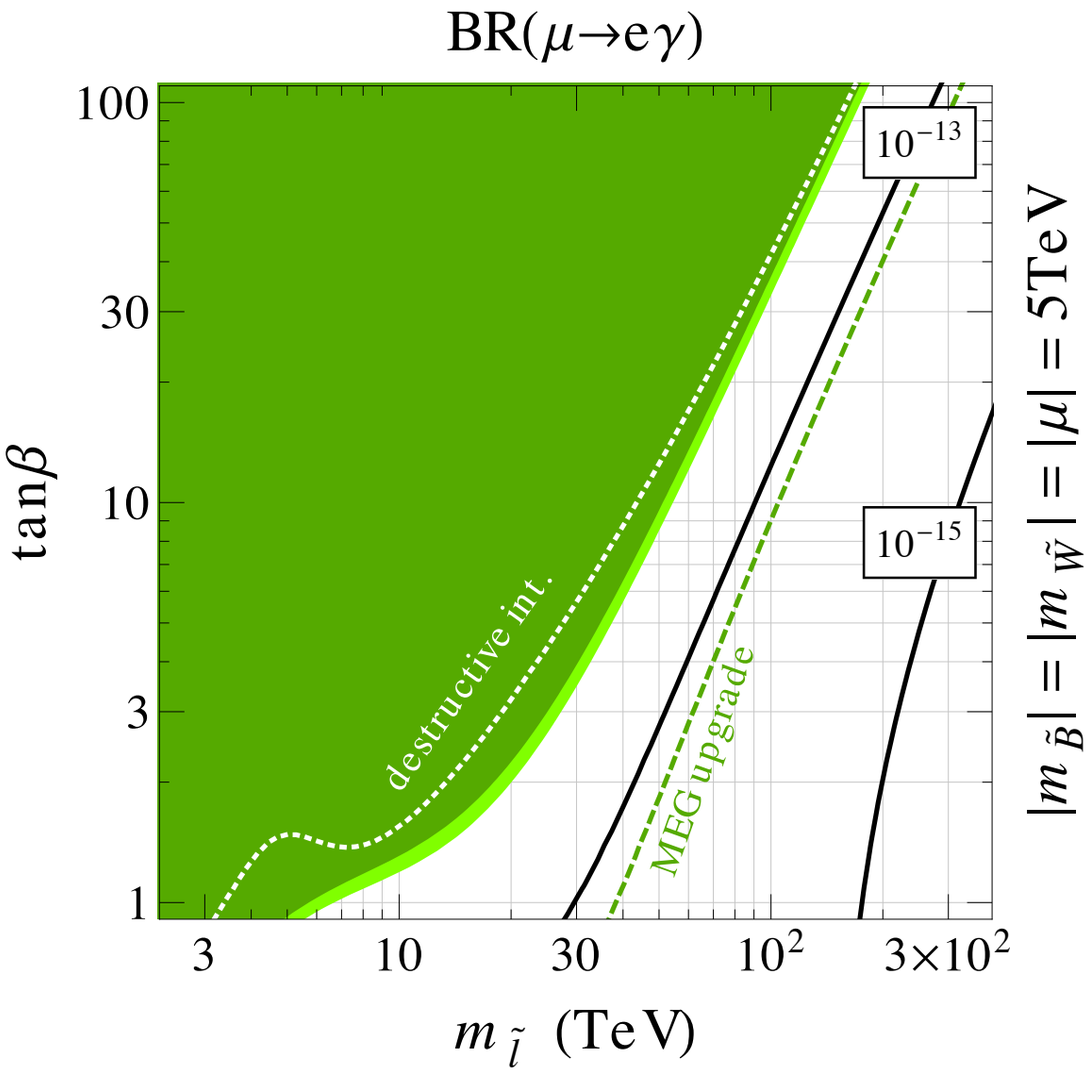


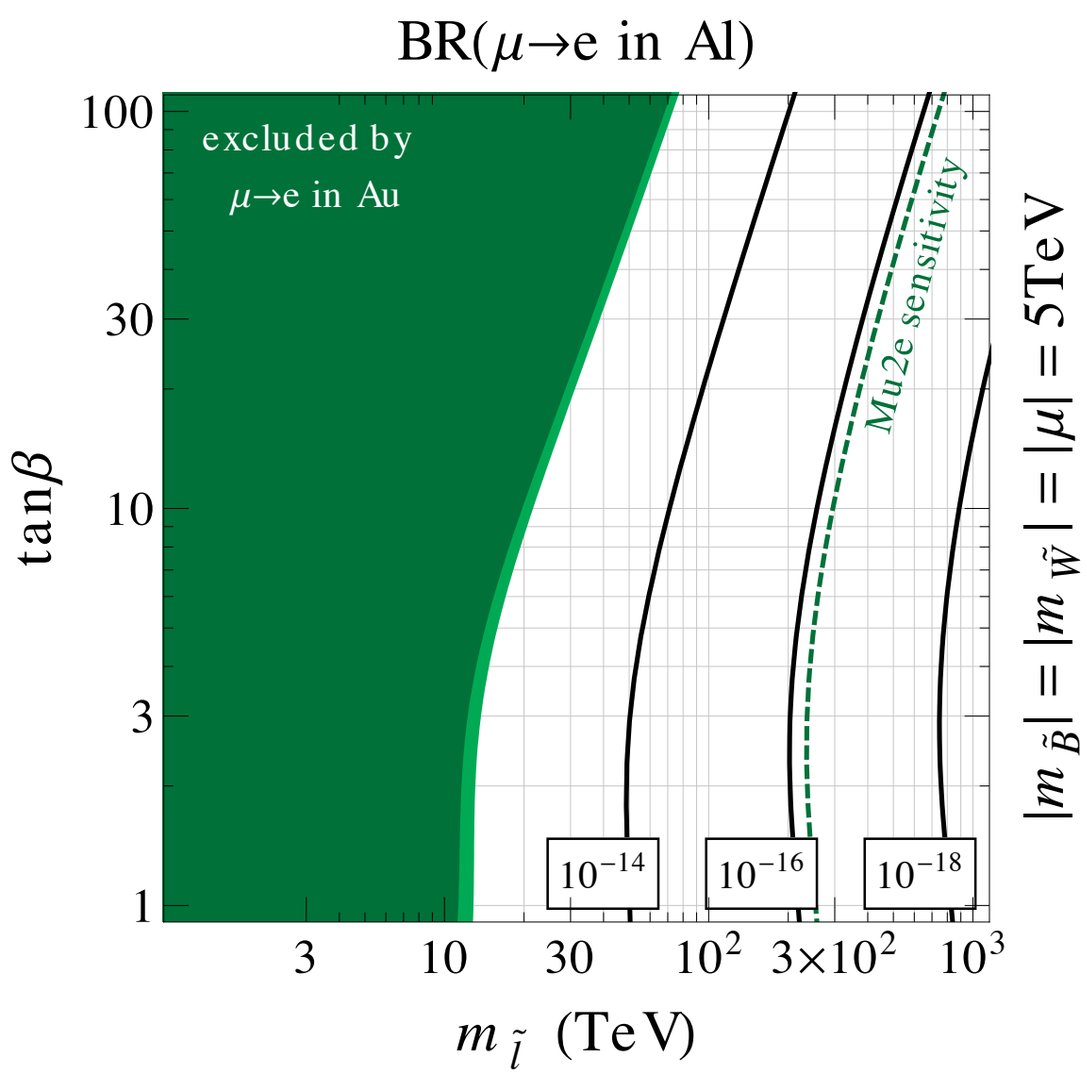




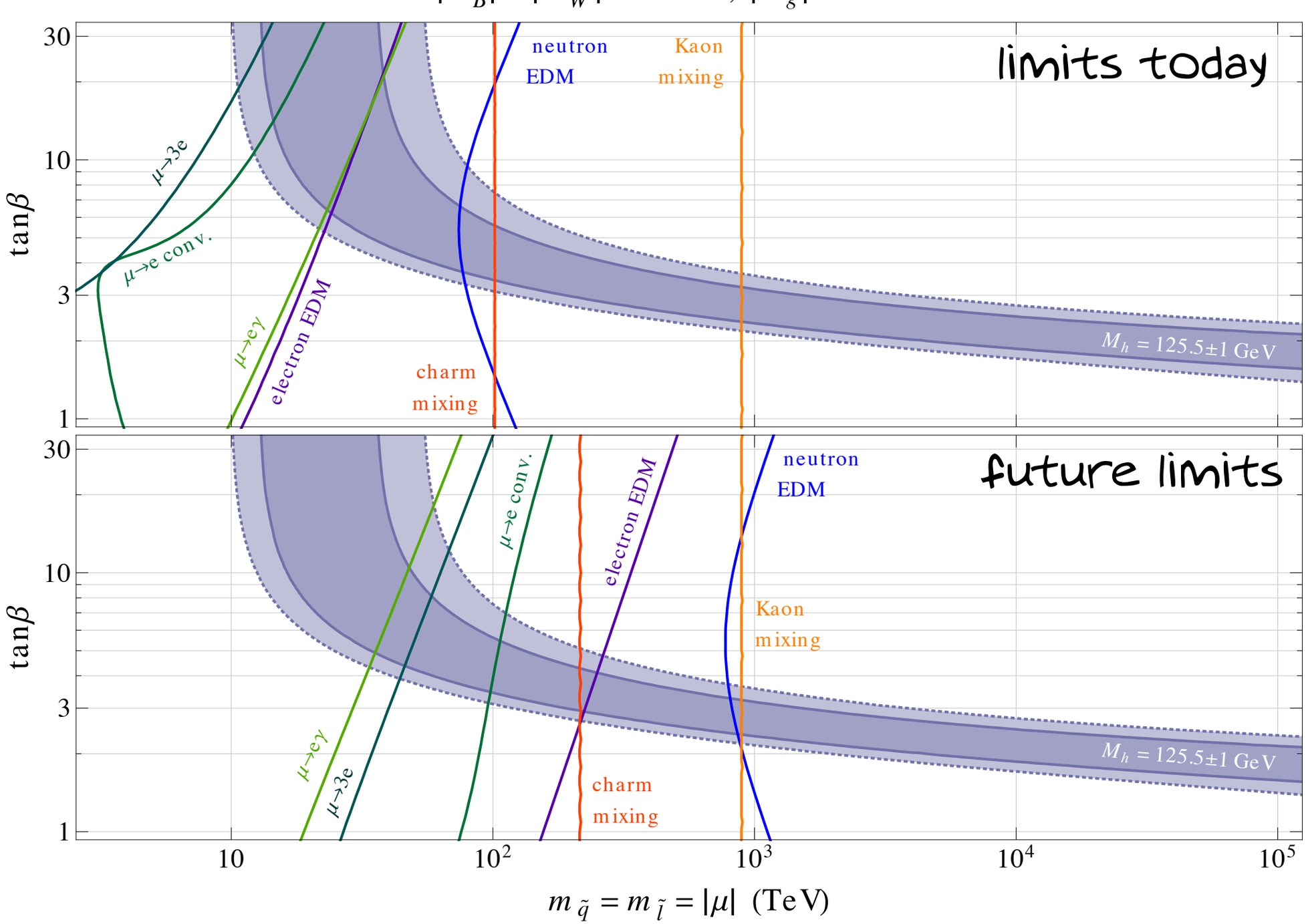
LFV form PeV Sleptons

* LFV is sensitive to sleptons 100's of TeV!





Other Probes



LFV is not alone!

Conclusions

- What's the deal with flavor? we still don't know!
- CLFV is a sensitive probe of many NP scenarios. (EFT's are a simple way to parametrize them).
- For the LHC, new physics probed by LFV is often:
  - either too heavy (as in Split SUSY).
  - or too weakly couples (as for the Higgs).
- The mu2e experiment will move the limit by four orders of magnitude! A decade in NP scale!

Isidor I. Rabi
@RabiNMR

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The muon: who ordered that !?

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