The Flavor of the Higgs

Roni Harnik,
Fermilab

Results drawn from:
Blankenburg, Ellis, Isidori 1202.5704
RH, Kopp, Zupan 1209.1397
Brod, Haisch, Zupan 1310.1385
RH, Martin, Okui, Primulando, Yu 1308.1094

Plan:

* FV and CPV Higgs.
  - Models
  - Reasonable size of FV.
* Constraints:
  - Lepton flavor.
  - Quark flavor.
  - CP phases.

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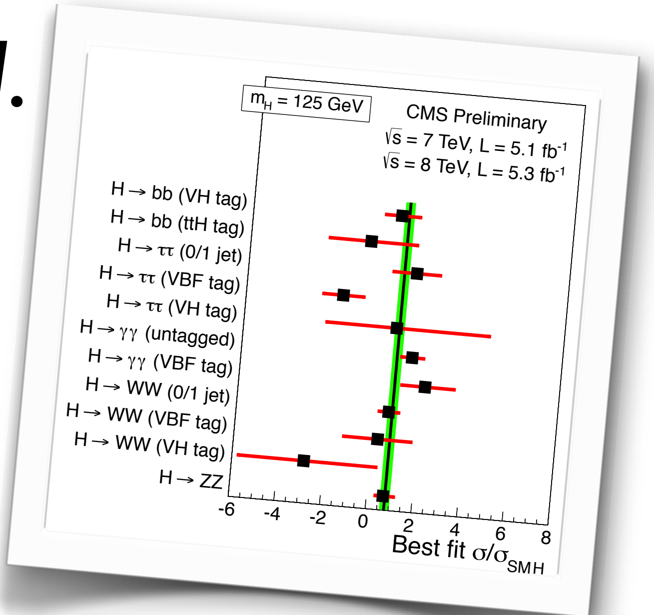
will come from a variety of experiments. Both low and high energy.

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

* The Higgs boson can have more general couplings. the mass basis we could have:

$$\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij} (\bar{f}^i_L f^j_R) h + h.c. + \cdots$$

But didn't I just tell you that the Higgs is automatically aligned with flavor?

How do we get FV and CPV Higgs?

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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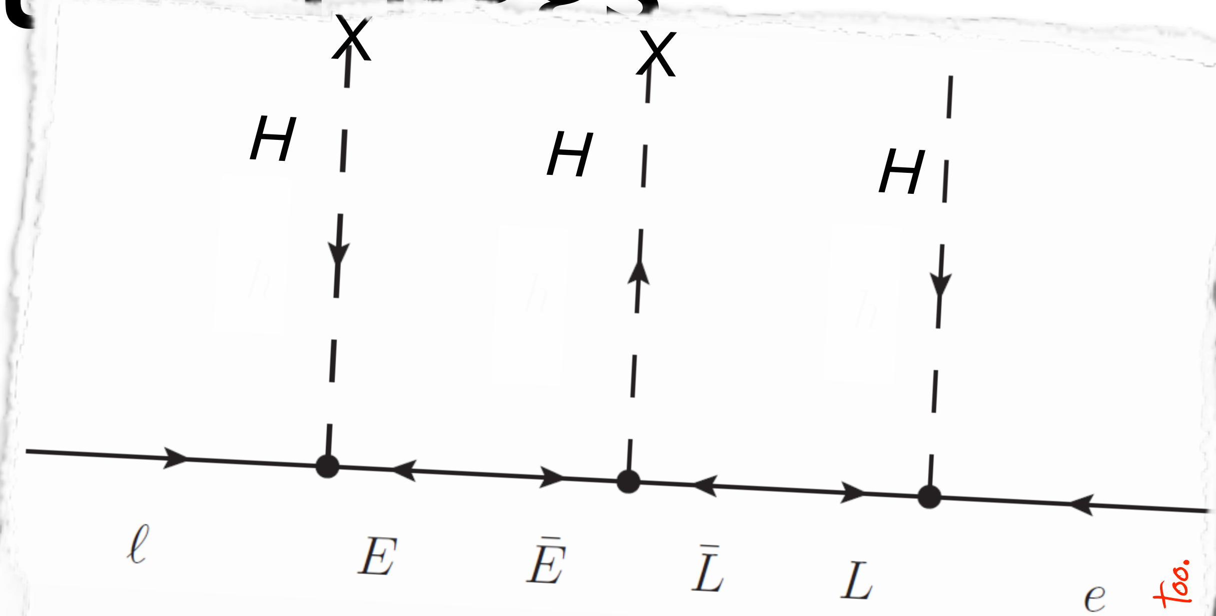

e.g. Kearney, Pierce, Weiner; 1207.7062

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

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

PH: you can get this in composite Higgs too.

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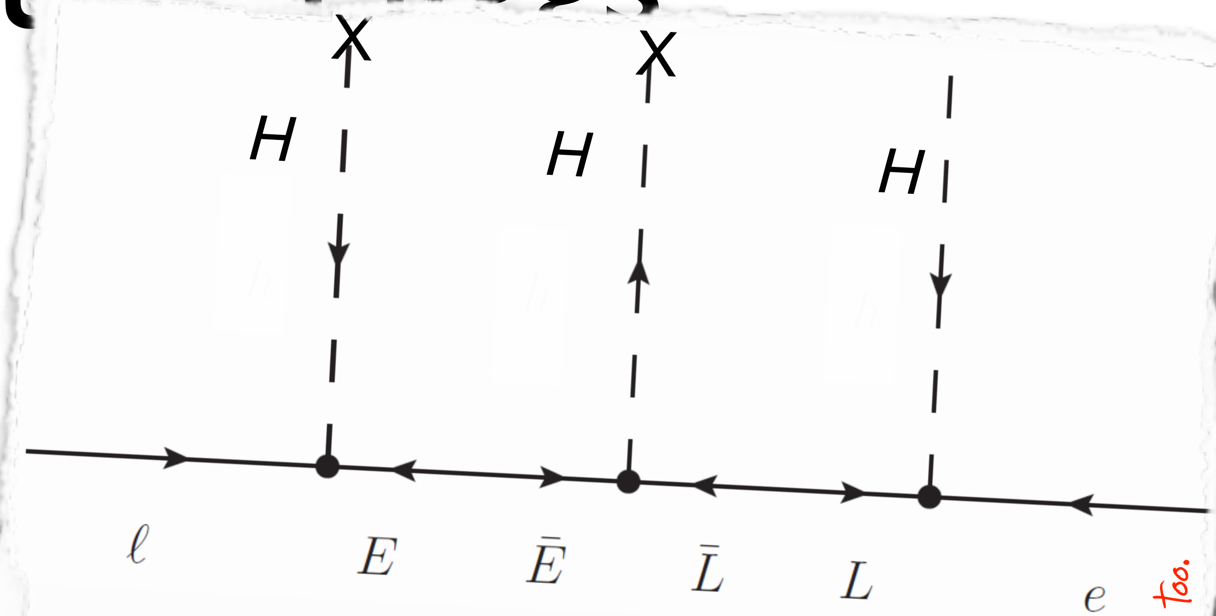

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$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2}$$

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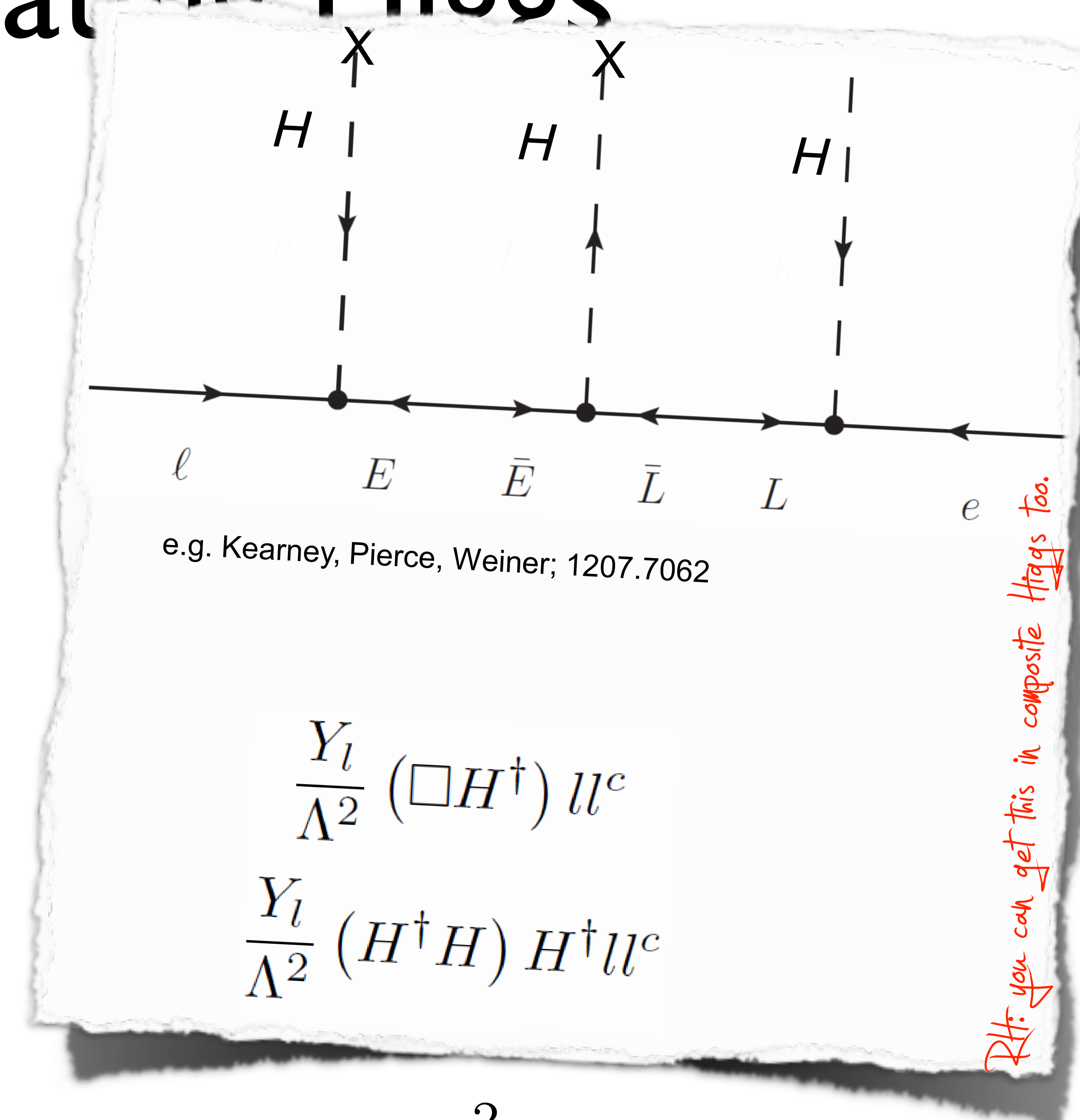

$$\mathcal{L} = \lambda_f H \bar{f} f + \frac{(H^\dagger H) H \bar{f} f}{\Lambda^2}$$

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

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

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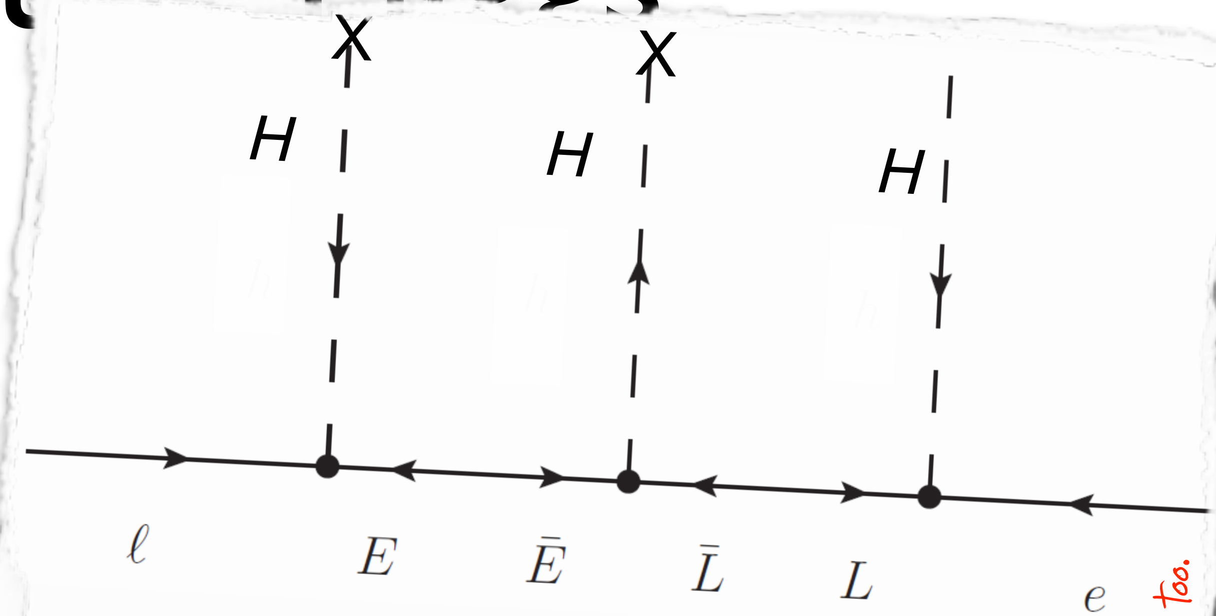

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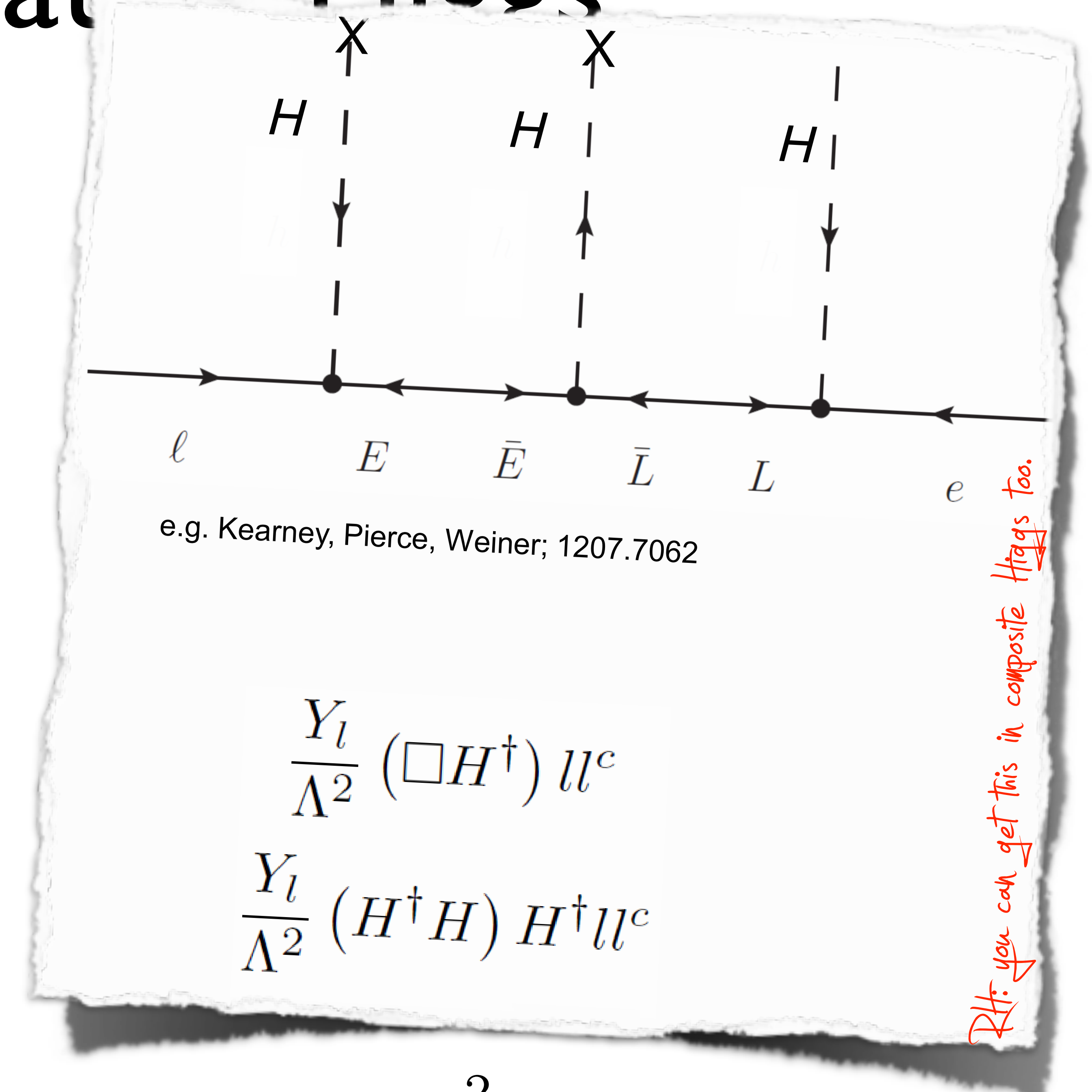

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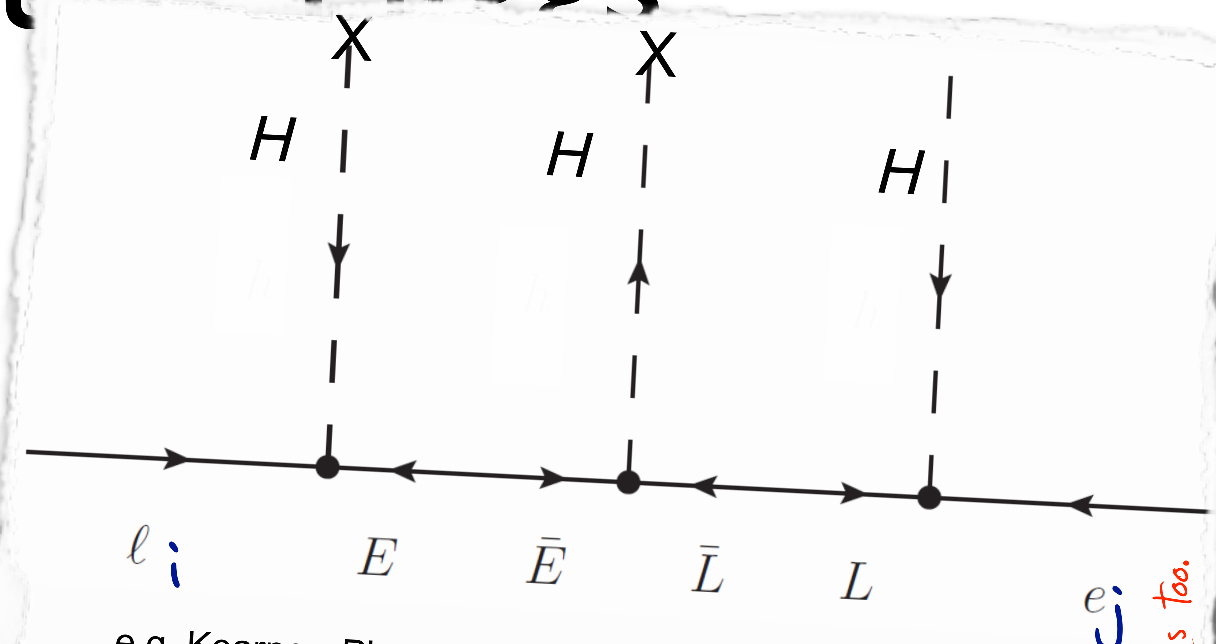

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$$\frac{Y_{l\,ij}}{\Lambda^2}(\Box H^\dagger)\, l_i l^c_j$$

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BTW: you can get this in composite Higgs too.

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

Flavor Violating Higgs

* Writing it a bit more neatly, we get:

$$Y^{ij} H f_L^i f_R^j + \hat{Y}^{ij} \frac{|H|^2}{\Lambda^2} H f_L^i f_R^j$$

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

or

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

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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

$$Y_{ij} \lesssim \frac{\sqrt{m_i m_j}}{v}$$

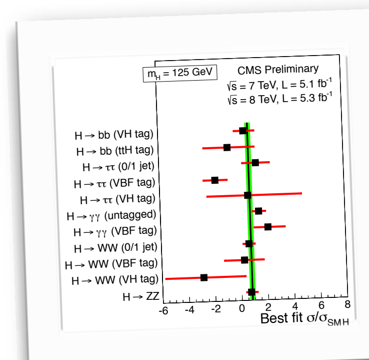
I’ll call these "natural" models*.

*In this era of data, considerations of fine-tuning are not of huge importance...

But we’ll keep it in the back of our mind.

With NP Yukawa couplings can be:

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

So, in addition to these 

,

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

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

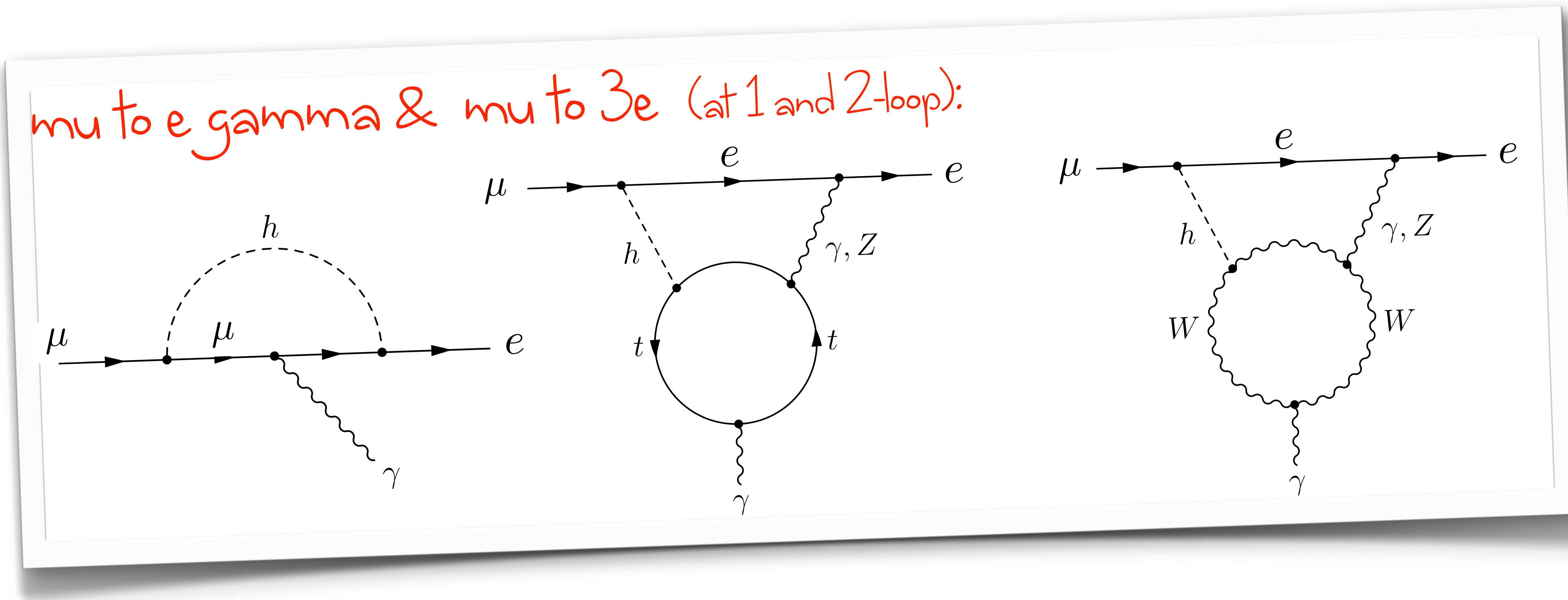
Leptonic Flavor Violation

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

Which experiments constrain the Y_{ij}'s?

Higgs couplings to μe

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



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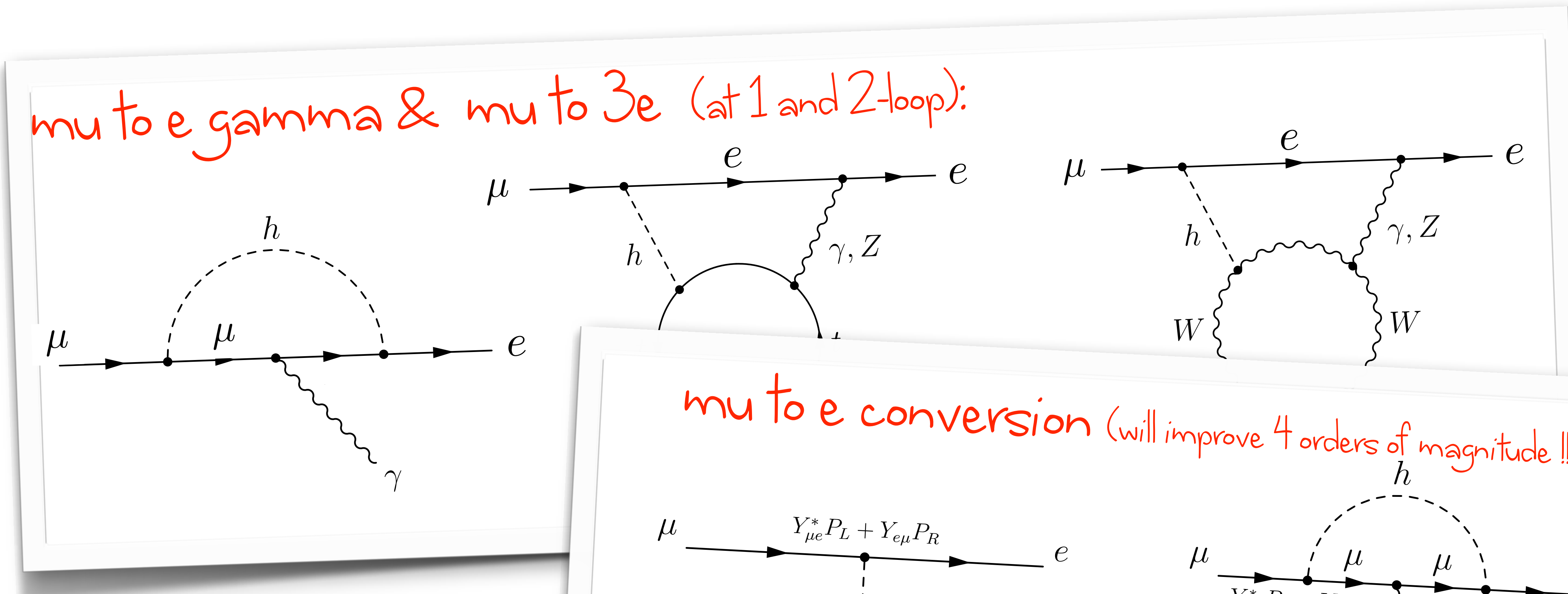

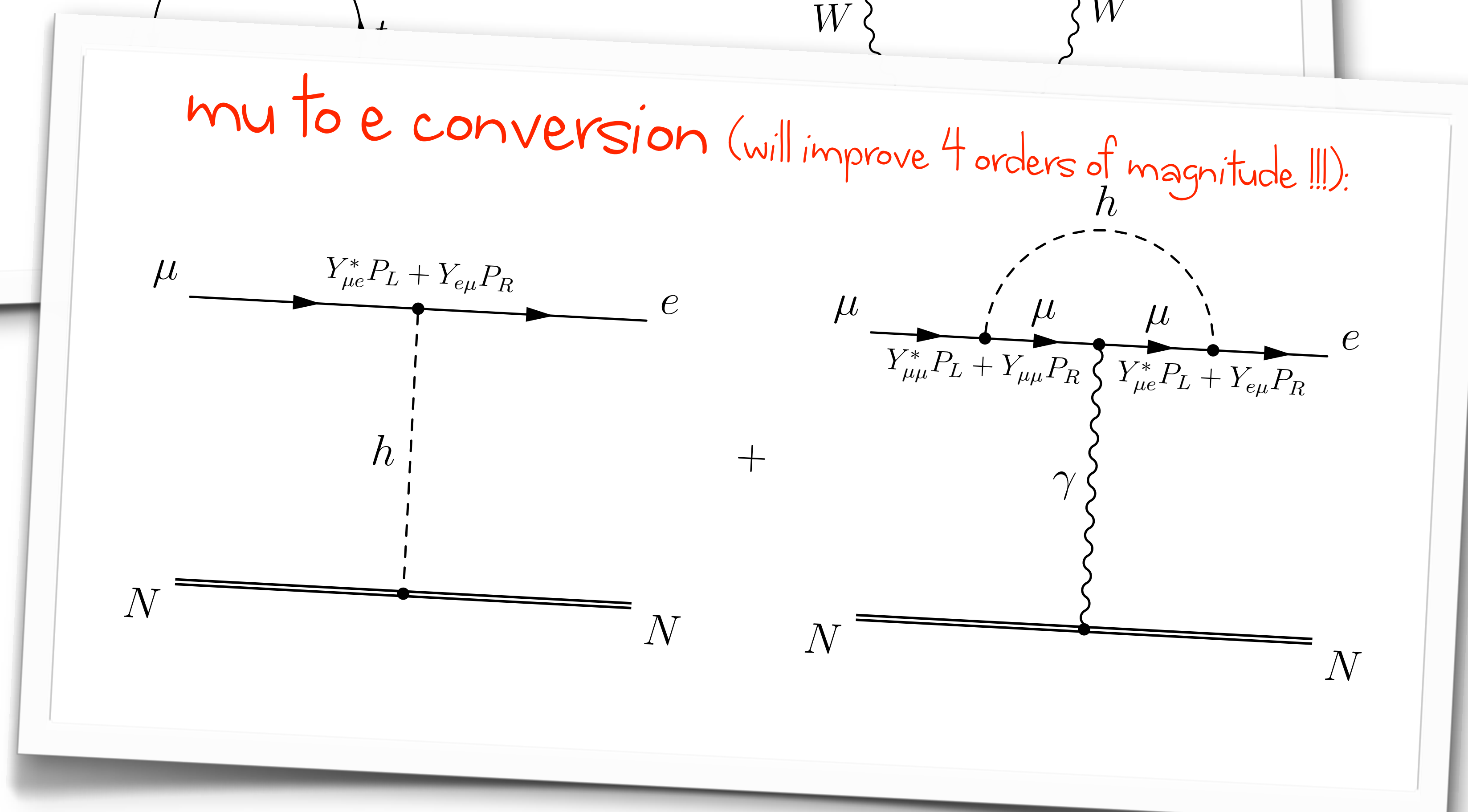

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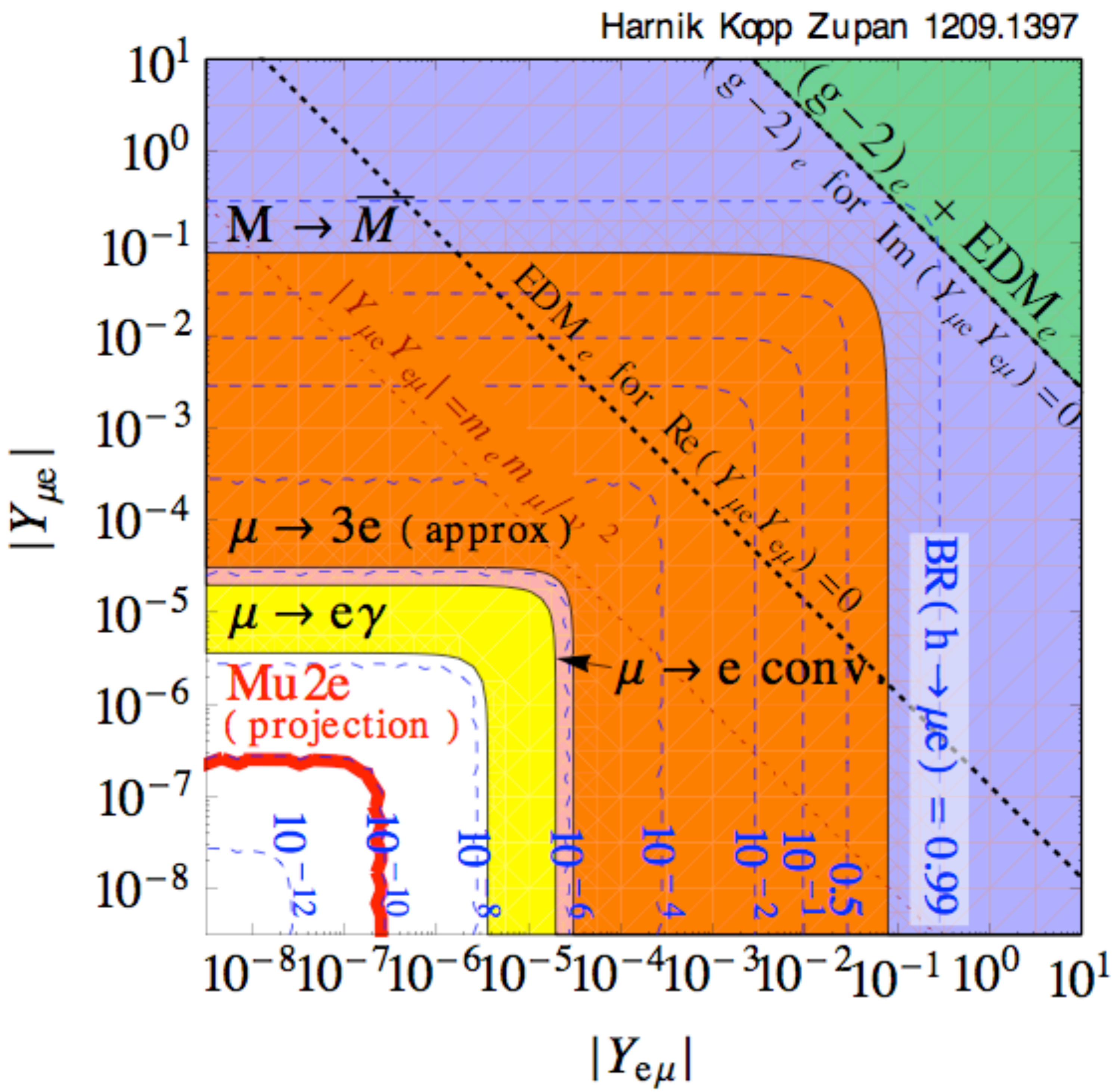
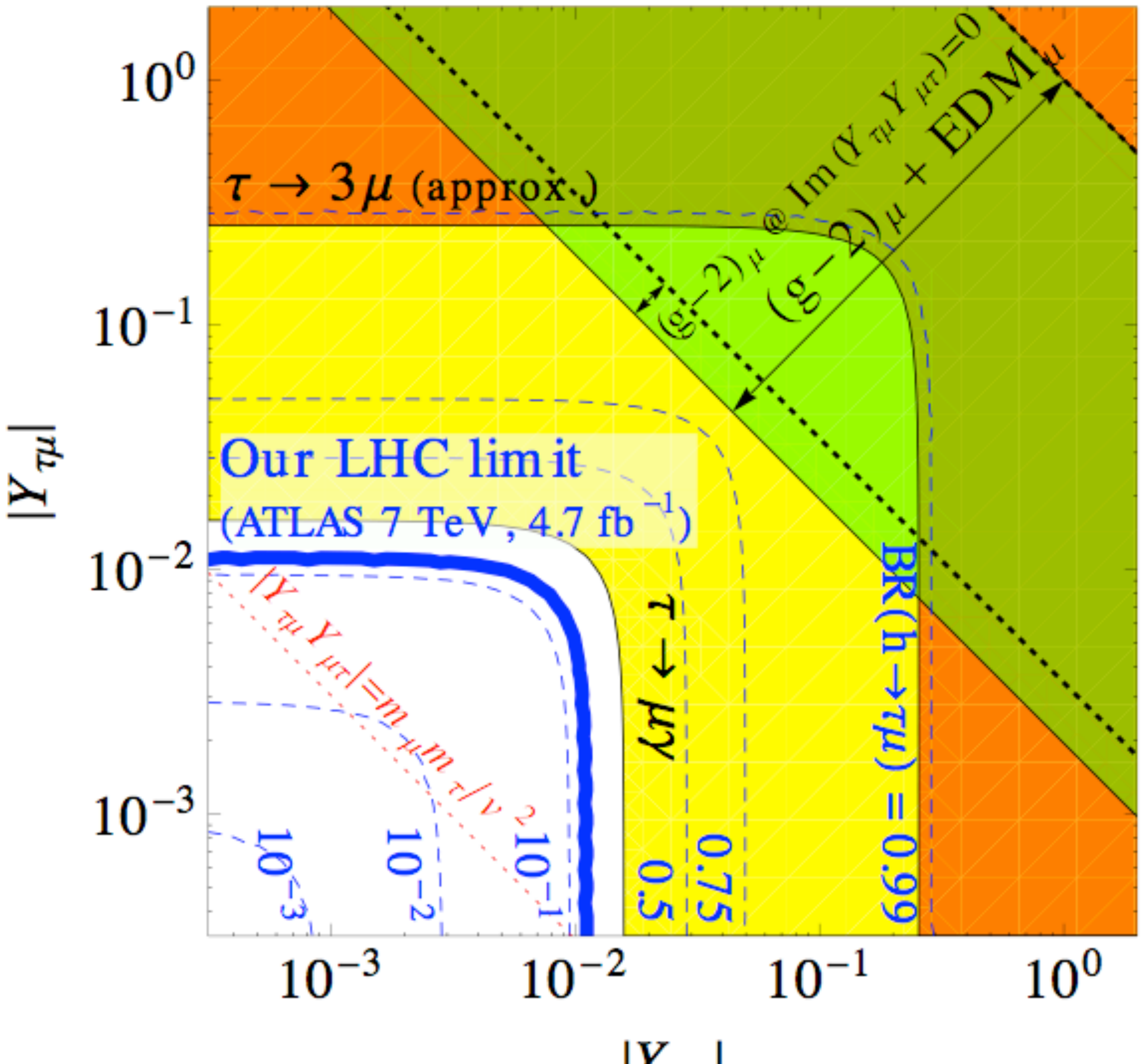


Outside of LHC reach.

Probing "natural" models.

Higgs couplings to $\tau\mu$



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

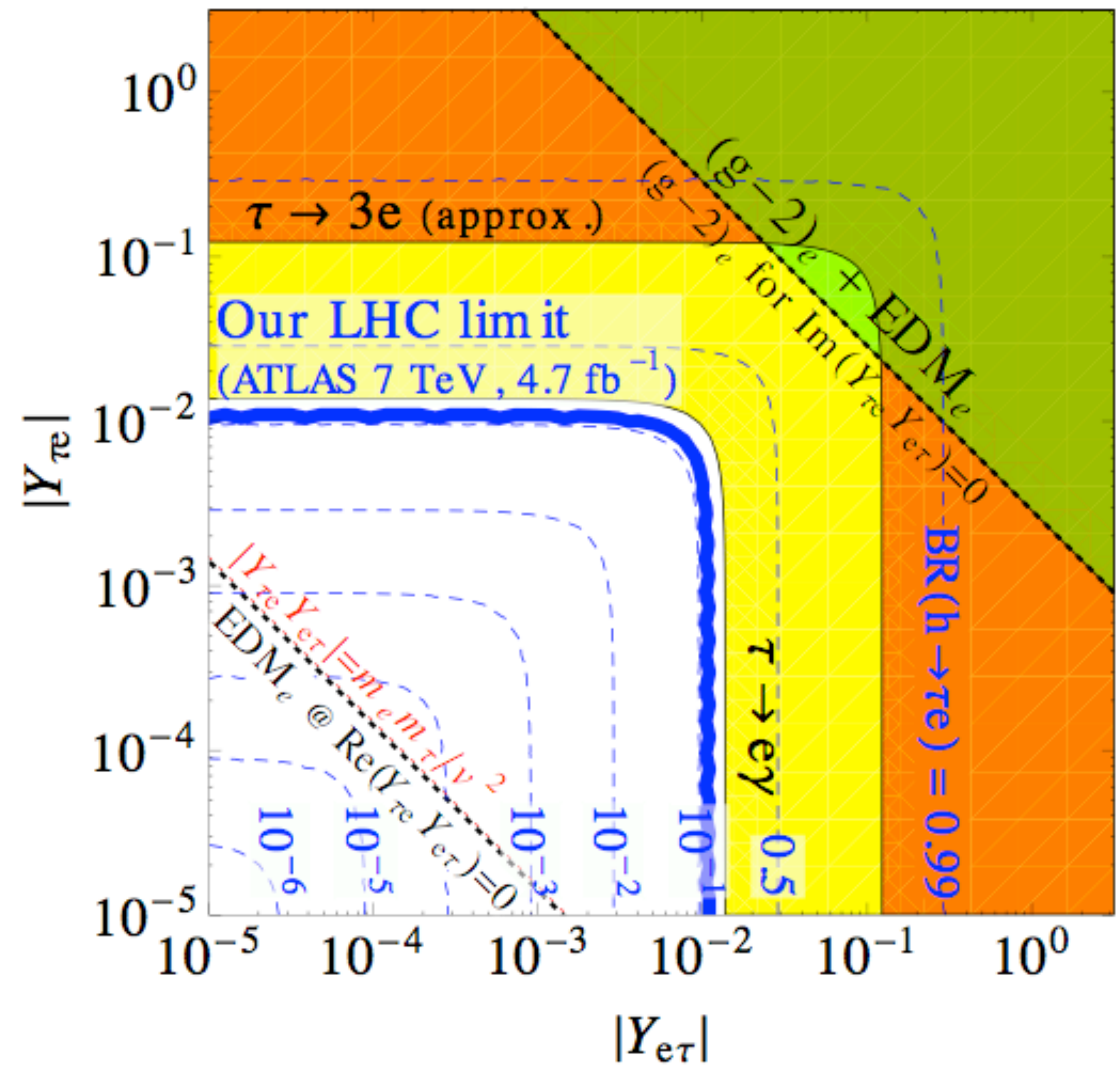
(currently just a theorist's re-interpretation)

"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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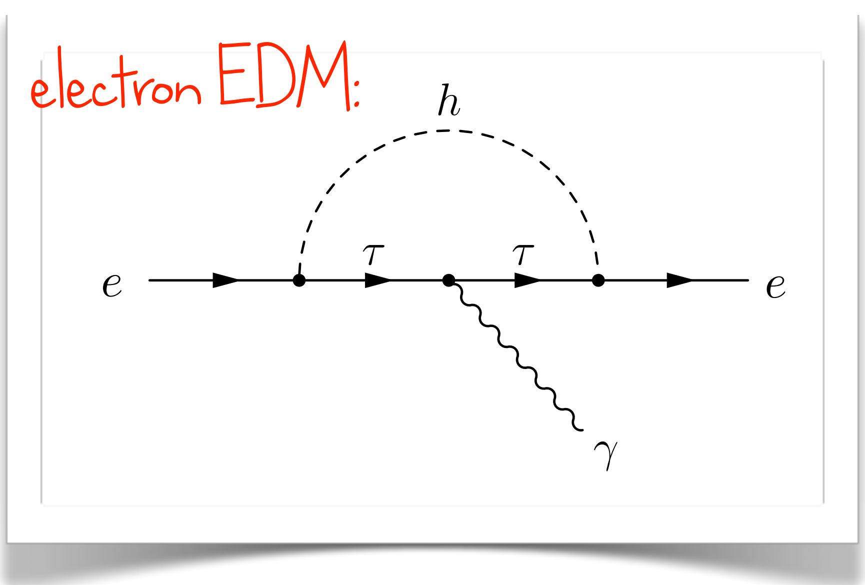
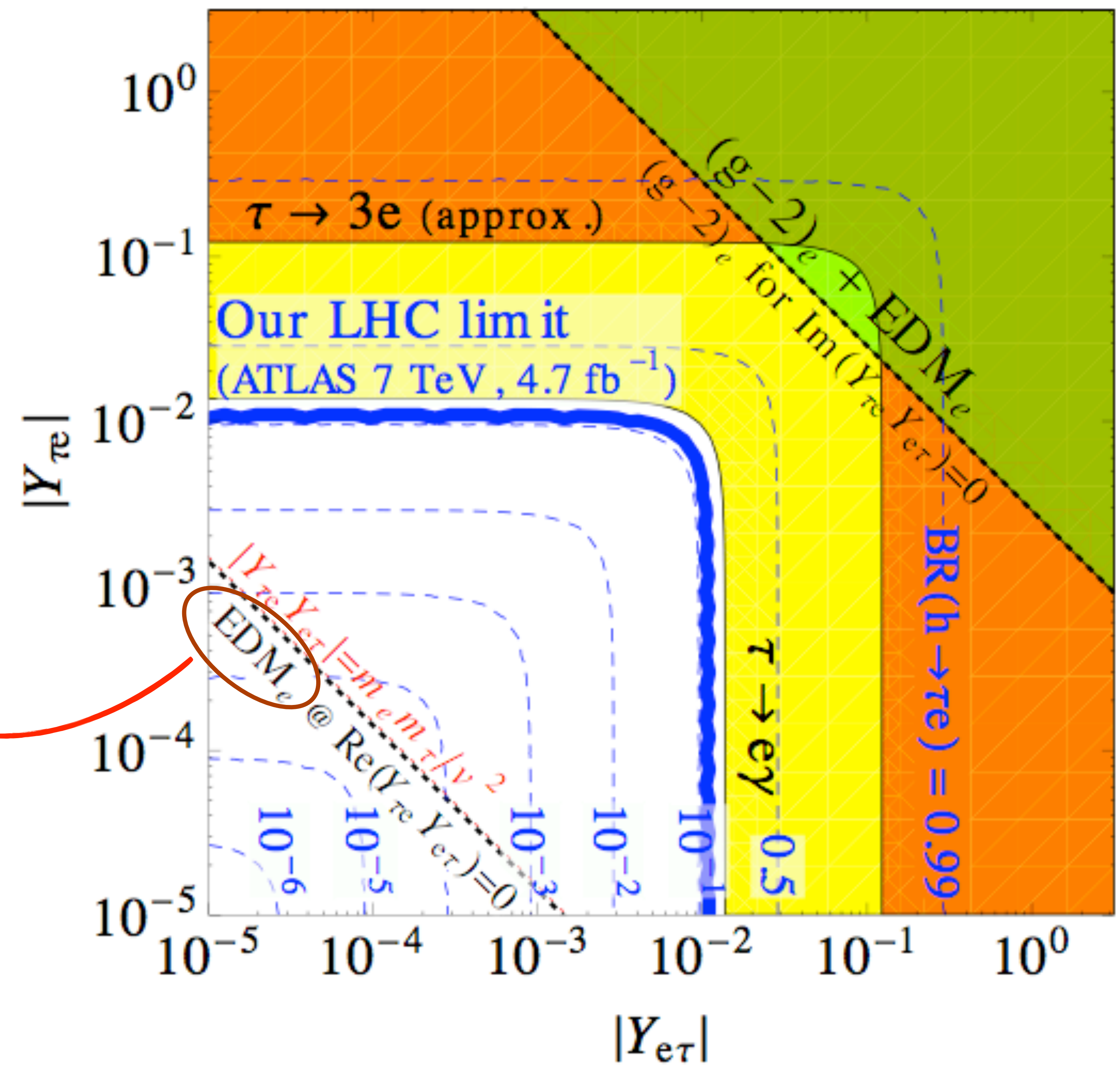
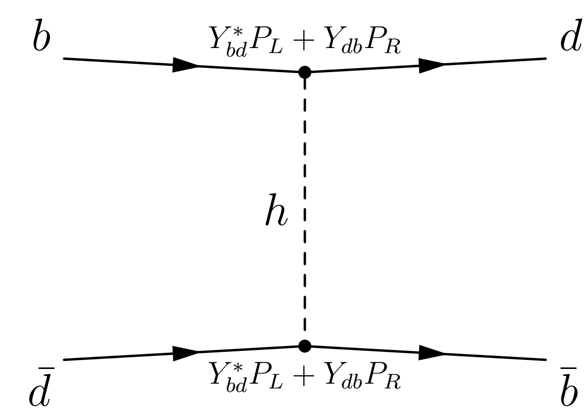
Electron EDM is interesting here!





Quark Flavor Violation

Meson Mixing



* Meson mixing's powerful:

Technique	Coupling	Constraint	$m_i m_j/v^2$
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$	5×10^{-8}
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$	
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$	3×10^{-7}
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$	
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$	7×10^{-6}
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$	
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!

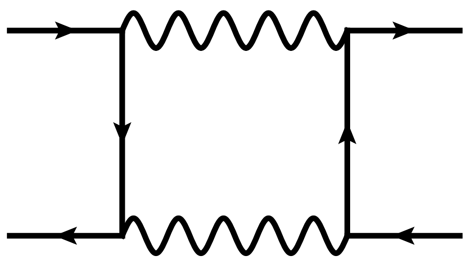
"What about $B_s \to \tau\mu$?"

"And $B_s \to \mu\mu$?"

Lets do a back of the envelope estimate:

$B_s \to \mu\mu$:

In the SM, $BR_{(B_s \to \mu\mu)} \sim 3 \times 10^{-9}$



$$\sim \frac{1}{16\pi^2} G_F g^2 V_{tb} V_{ts}^* \frac{m_\mu}{m_B}$$

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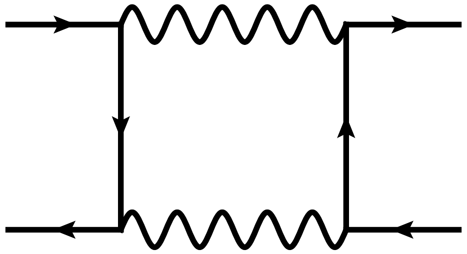

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I'm not a box.
I'm really a fish.

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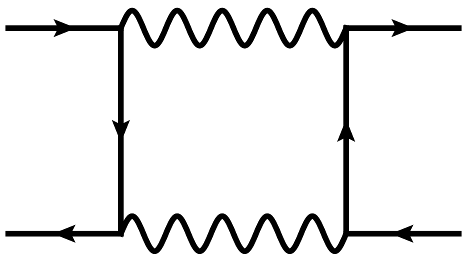

$$\sim \frac{1}{16\pi^2} \, G_F \, g^2 V_{tb} V_{ts}^* \frac{m_\mu}{m_B}$$

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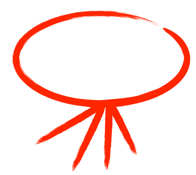

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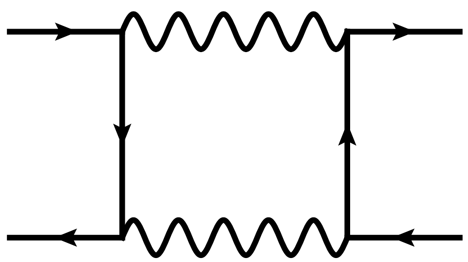

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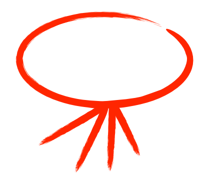

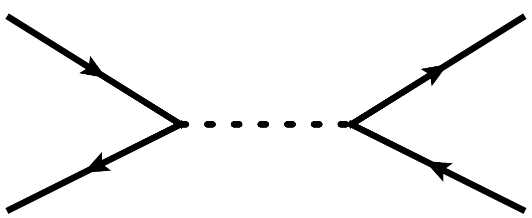

$$\sim \frac{1}{m_h^2}\, Y_{bs} Y_{\mu\mu}^*$$

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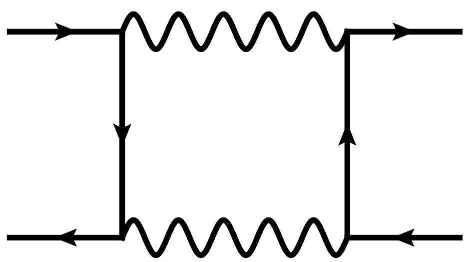

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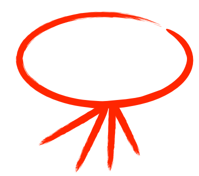

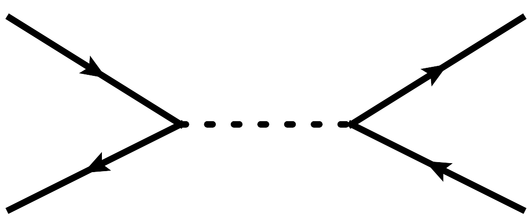

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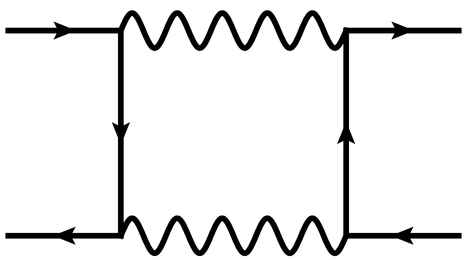

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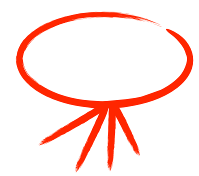
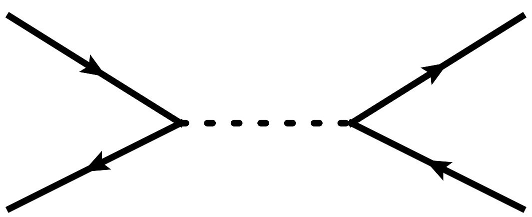




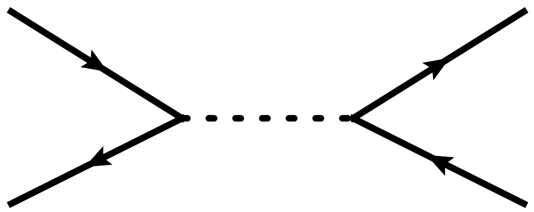
$$\sim \frac{1}{m_h^2} Y_{bs} Y_{\mu\mu}^*$$

(after plugging in 1303.3820)

$$Y_{bs} \lesssim \frac{\lambda^2 G_F g^2 m_h^2 v}{16\pi^2 m_B} \sim 3 \times 10^{-3}$$

not as strong as mixing...

$B_s \to \tau\mu$:

 $\sim \dfrac{1}{m_h^2} Y_{bs} Y^*_{\tau\mu}$

use the limts: $Y_{Bs} < 5 \times 10^{-4}$ and $Y_{\tau\mu} < 10^{-2}$

↓ algebra + 1303.3820

$BR(B_s \to \tau\mu) \sim 5 \times 10^{-8}$

Beyond reach...

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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neutron EDM	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$	7×10^{-6}

- Improvements:

$t + (h \to \gamma\gamma)$: $Y_{tj} < 0.17$ (!)
(ATLAS-CONF-2013-081)

lepton + multi-b + met: $Y_{tj} < 10^{-3}$ (!)
(Atwood, Gupta, Soni 1305.2427)

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D^0 oscillations	$\lvert Y_{ut}Y_{ct}\rvert,\ \lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$	
	$\lvert Y_{tu}Y_{ct}\rvert,\ \lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$	2x10-4
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$	
neutron EDM	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$	7x10-6

* Improvements:

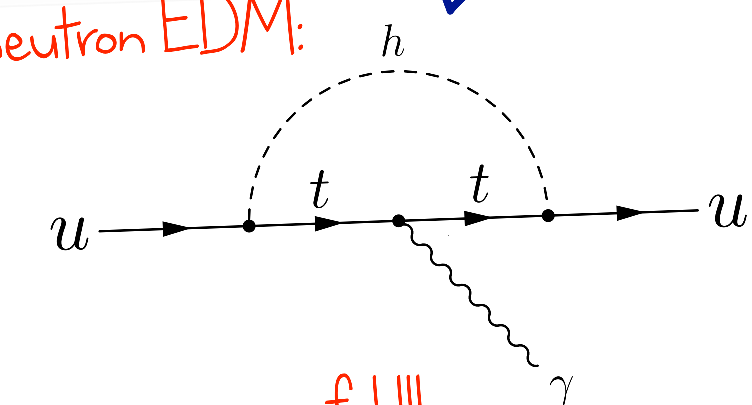
t + (h -> γγ) : Y_{tj}<0.17 (!)

(ATLAS-CONF-2013-081)

lepton + multi-B + met: Y_{tj}<10-3 (!)

(Atwood, Gupta, Soni 1305.2427)

neutron EDM:



powerful !!!

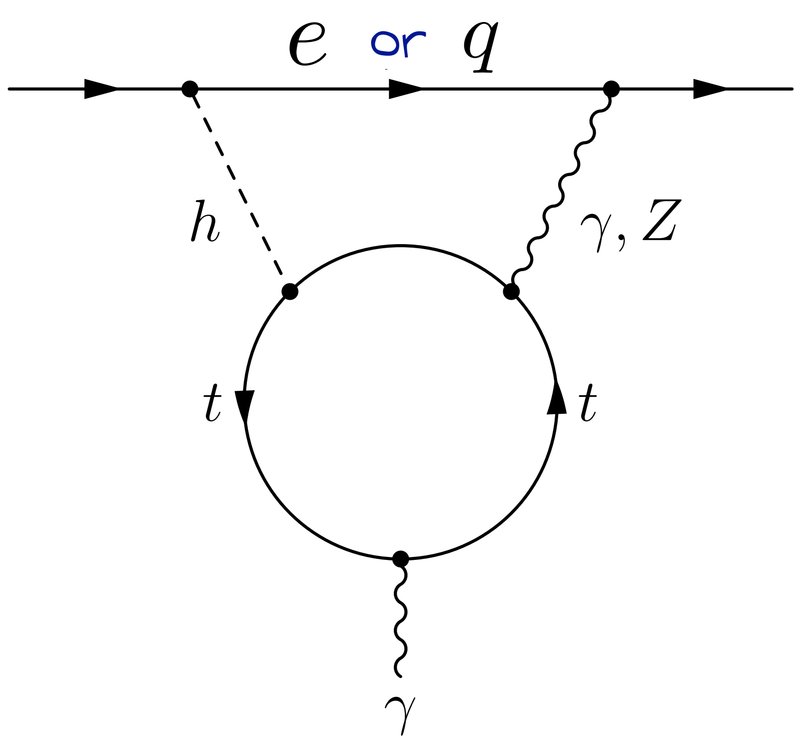
Flavor diagonal phases

Assume diagonal Yukawas with $|Y_i| = \frac{m_i}{v}$.

What are the constraints on
the phases of the Y_i's?

Two Loop EDM

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



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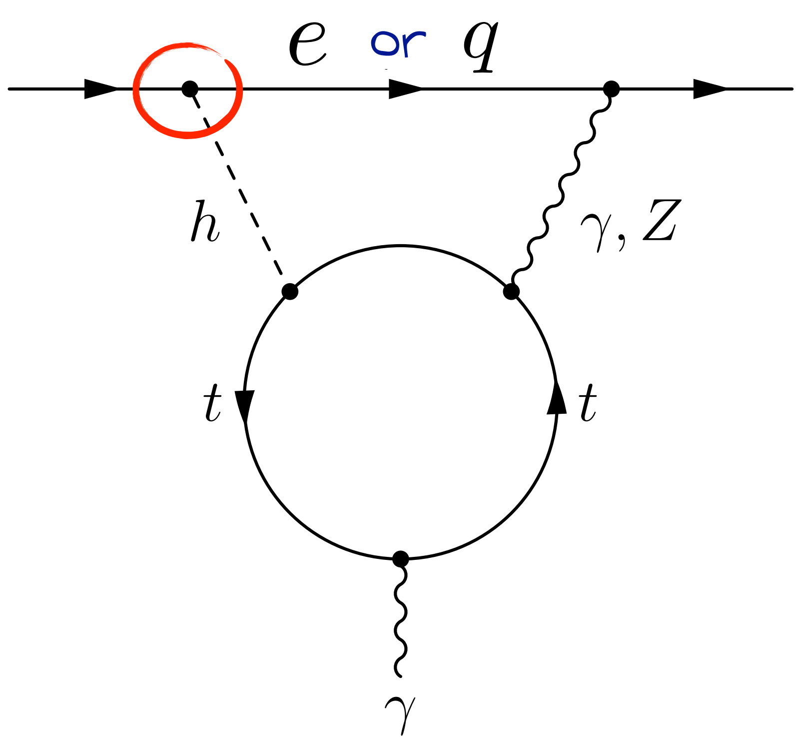
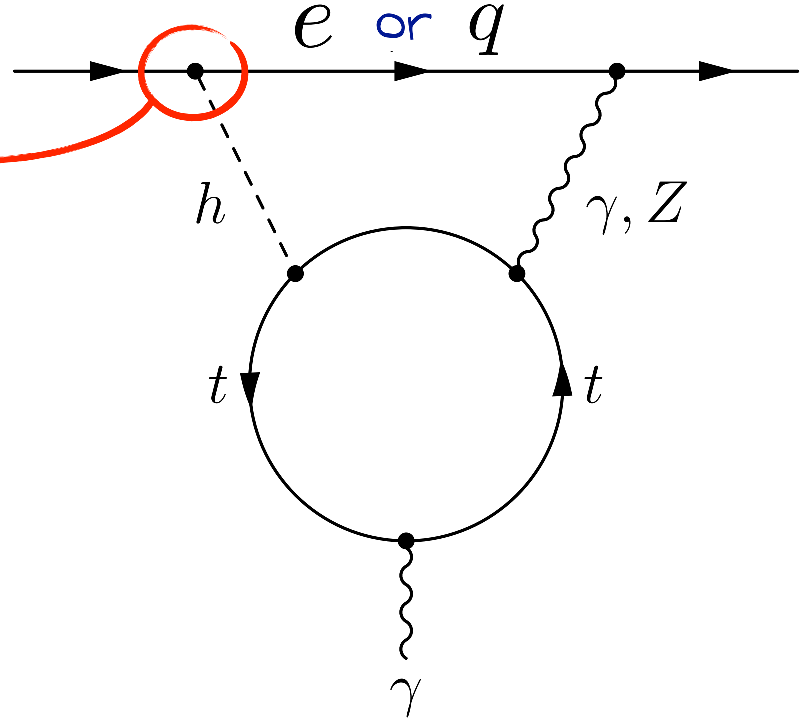


Two Loop EDM

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

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

from e and n EDM's



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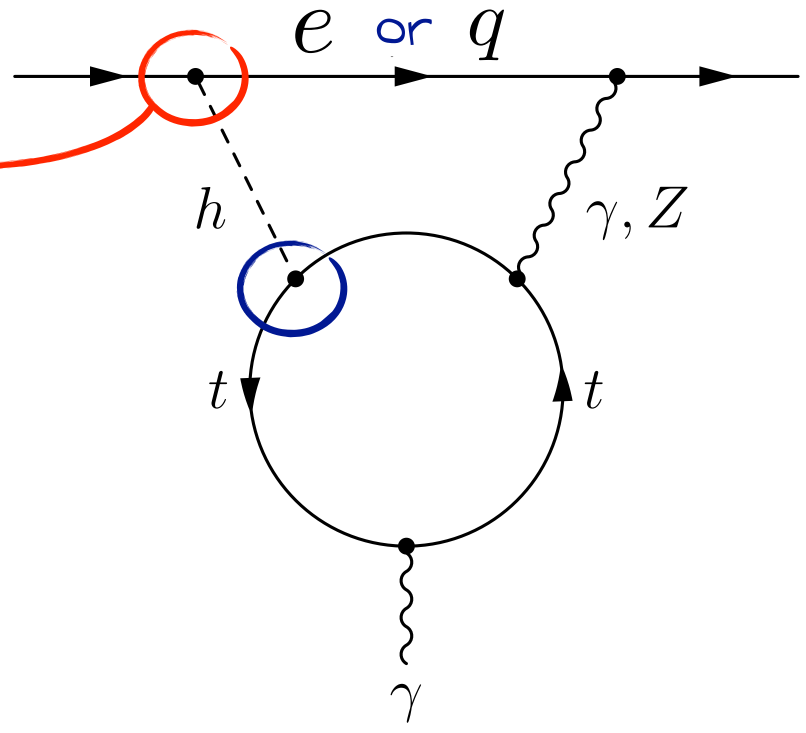

Two Loop EDM

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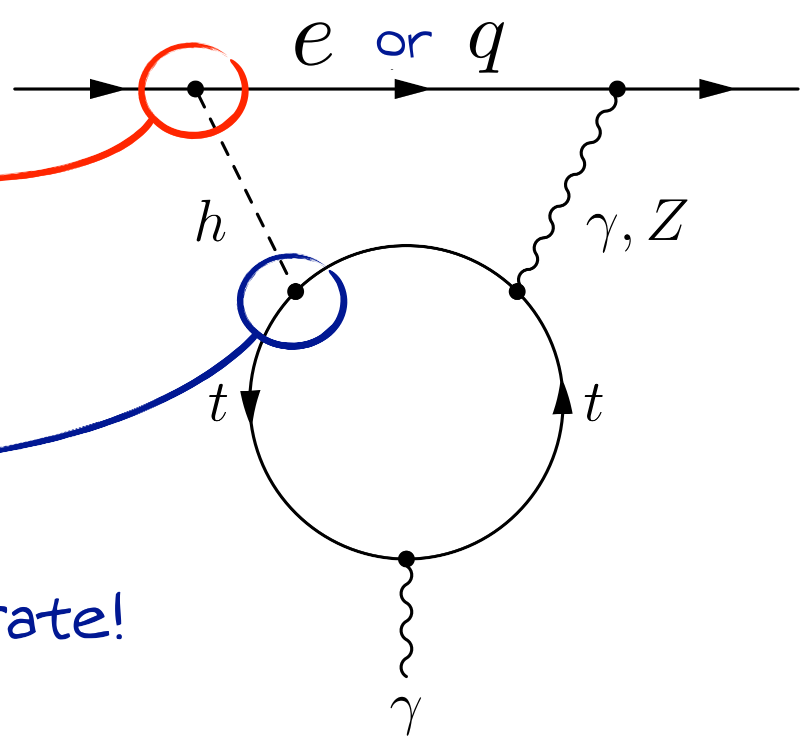
$$\phi_t \lesssim 0.05$$

from e and n EDM's

Interplay with LHC Higgs production rate!

Brod, Haisch, Zupan (in prep.)



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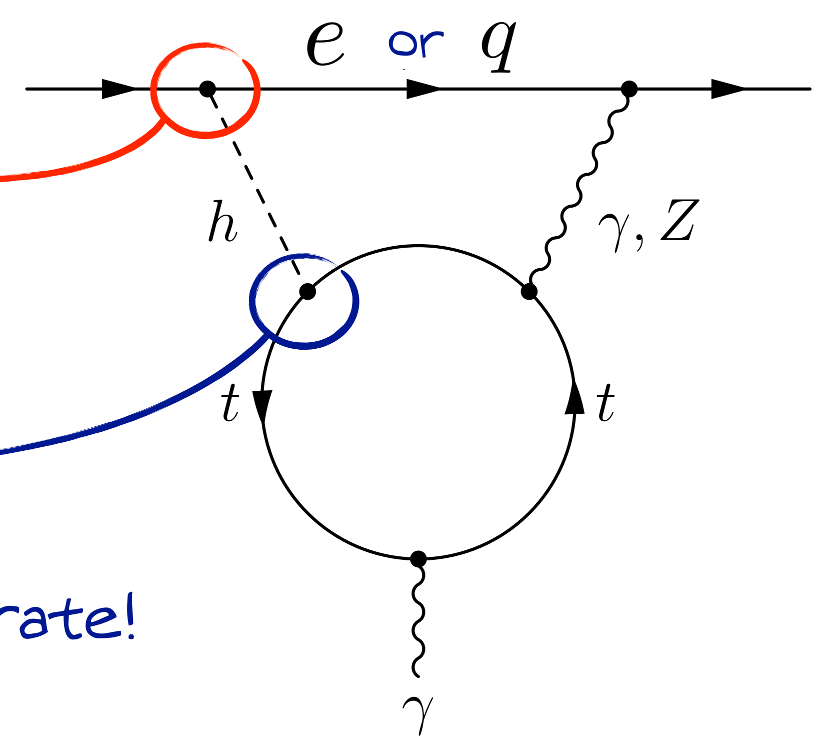

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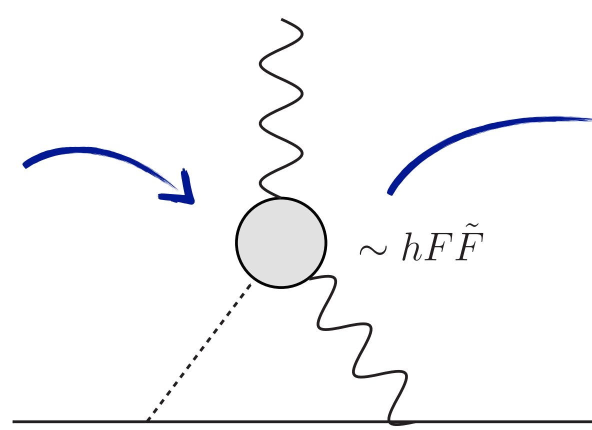
* Also sensitive to CPV in $h\gamma\gamma$ from NP:

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



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

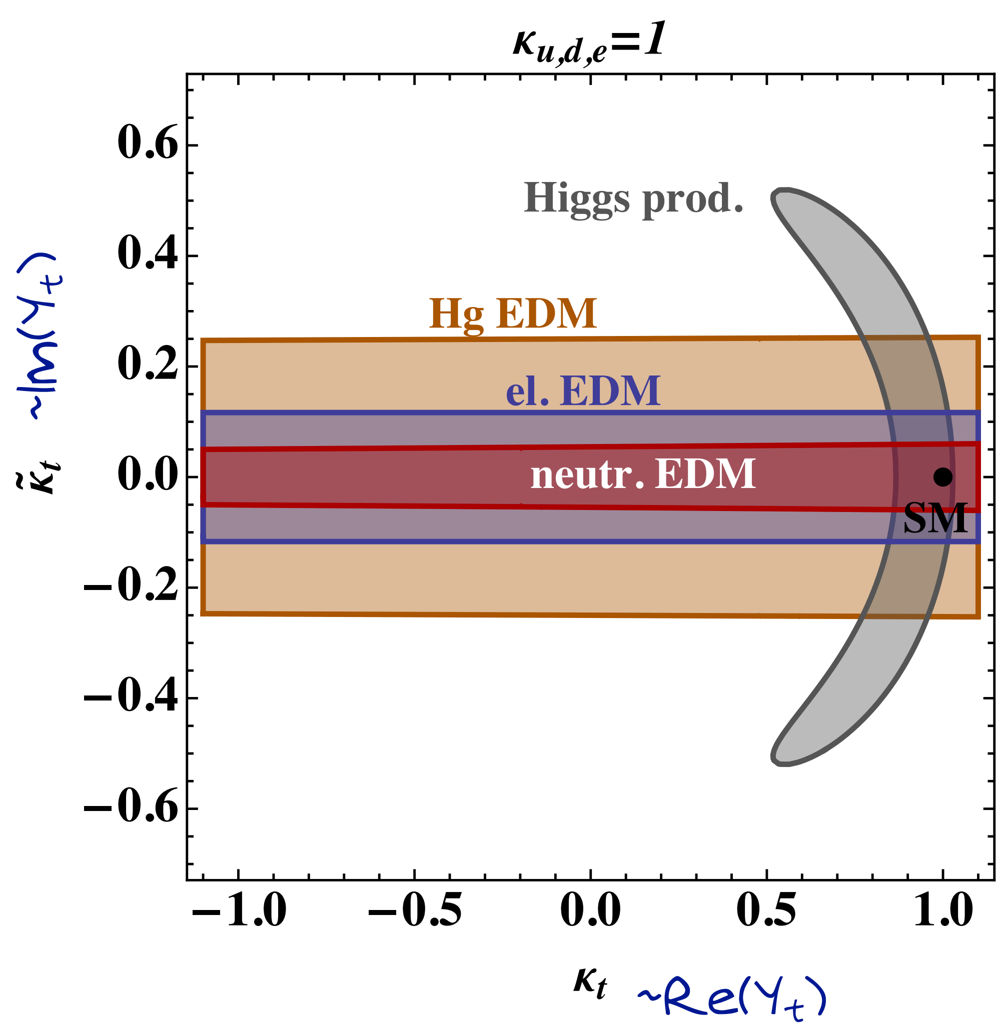
McKeen, Pospelov, Ritz (1208.4597)

Brod, Haisch, Zupan (1310.1385)

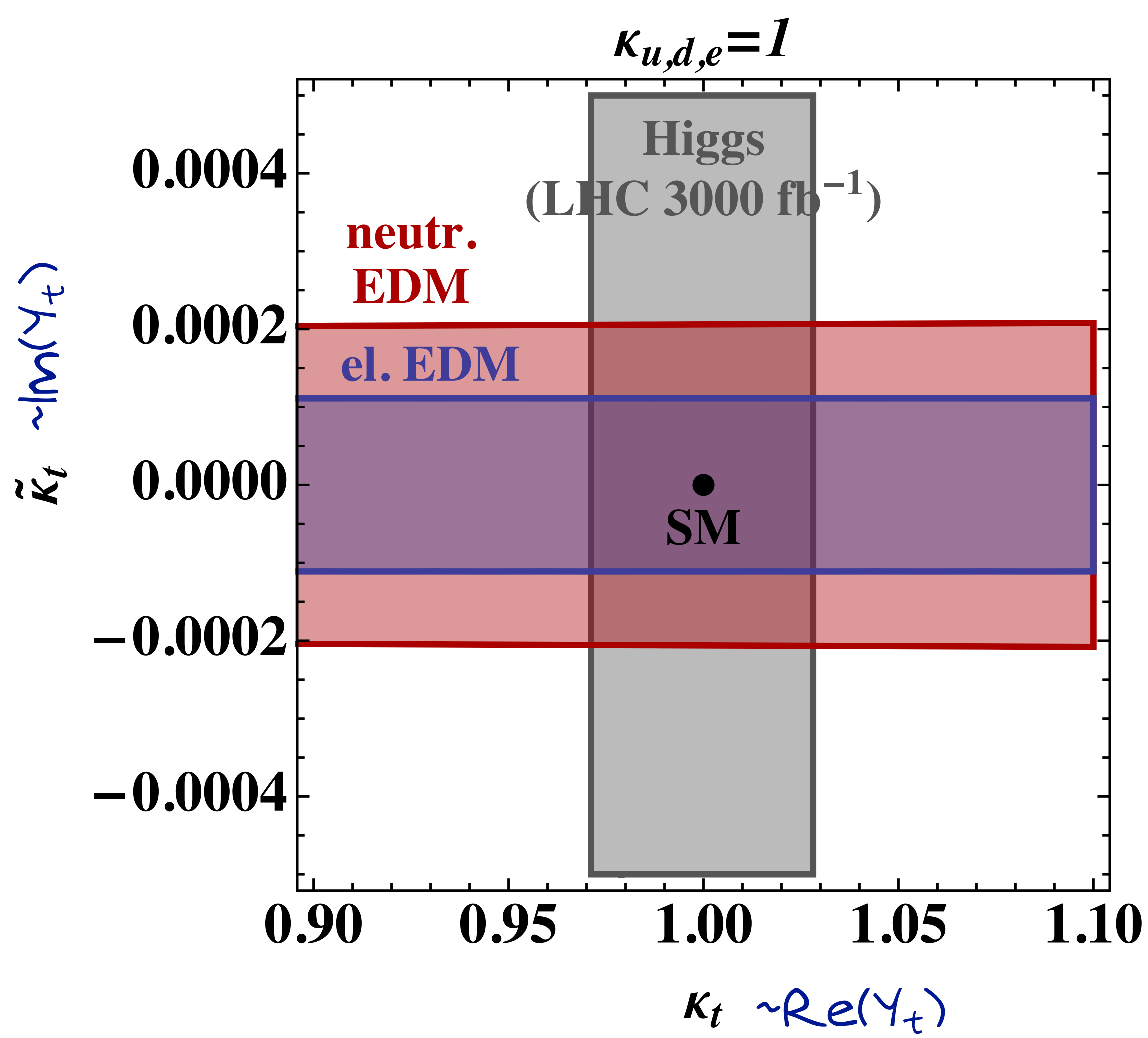
LHC & EDMS

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

Today:



In the future:



τ phase

* The tau phase is currently unconstrained!
* Can be probed by:
  - Hadronic tau polarization in Higgs decay.
  - Electron EDM.

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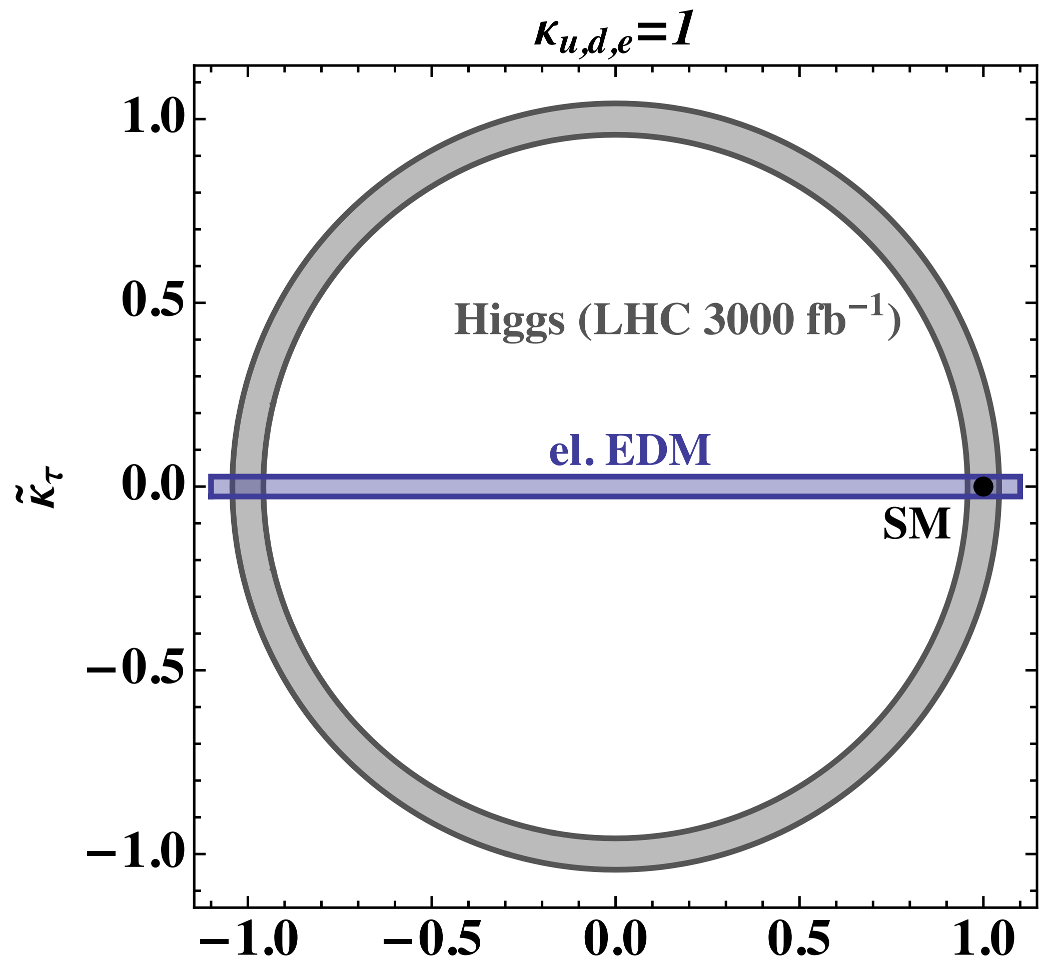
Future e EDMs:
high sensitivity!

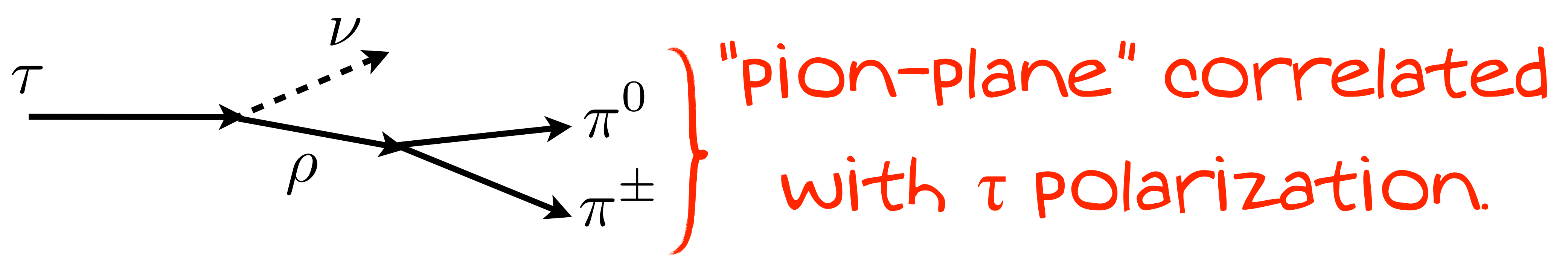


Brod, Haisch, Zupan 1310.1385

RH, Martin, Okui, Primulando, Yu 1308.1094

τ phase at Colliders

- A challenging measurement.
- Requires hadroinc "tau-substructure" (LHCb ?).

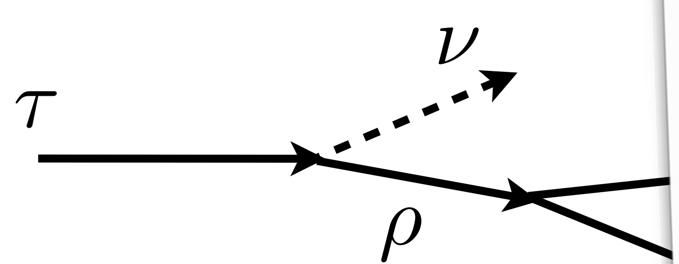


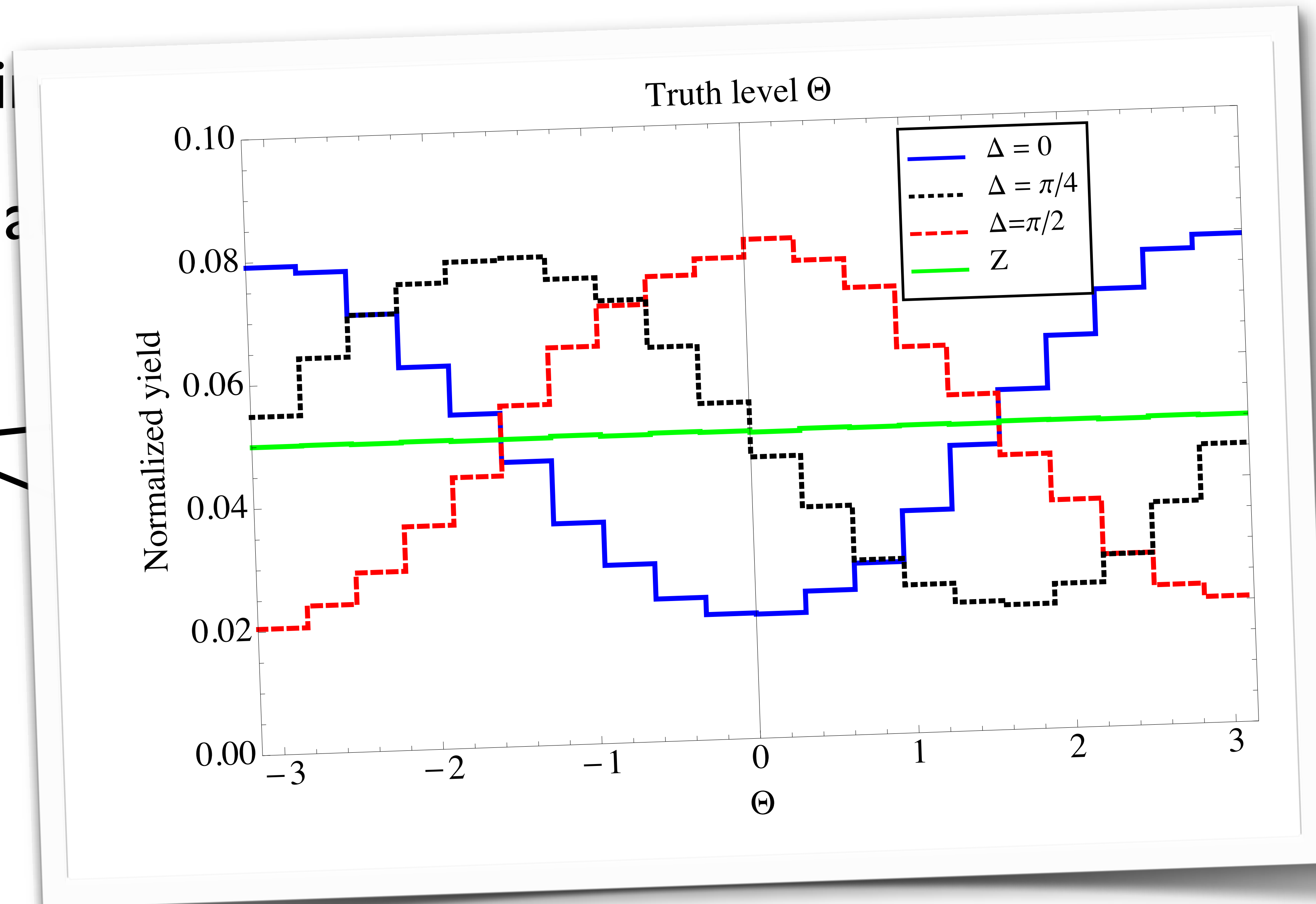
θ: the relative azimuthal angle between reconstructed polarizations

RH, Martin, Okui, Primulando, Yu 1308.1094

τ phase at Colliders

- A challengi
- Requires ha





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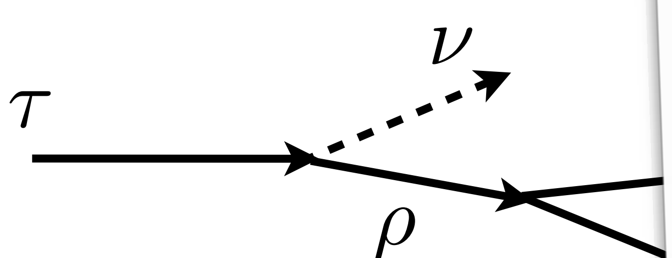

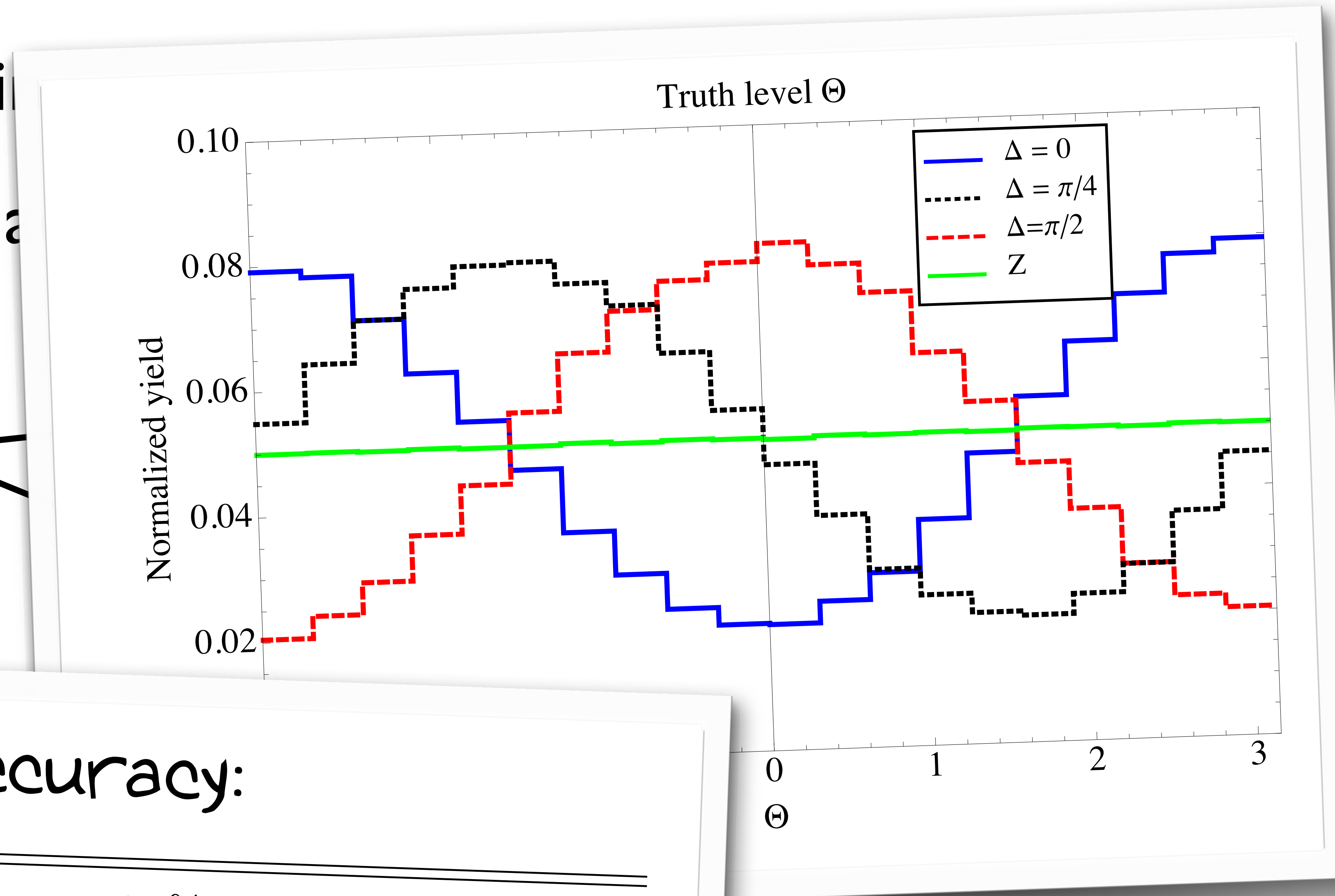

thal angle

polarizations

Promising accuracy:

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

W phase

* Up-down asymmetry is sensitive to CPV in Higgs coupling to W.

The paper I discovered very late last night....

Delanuey, Perez, de Sandes, Skiba
1308.4930

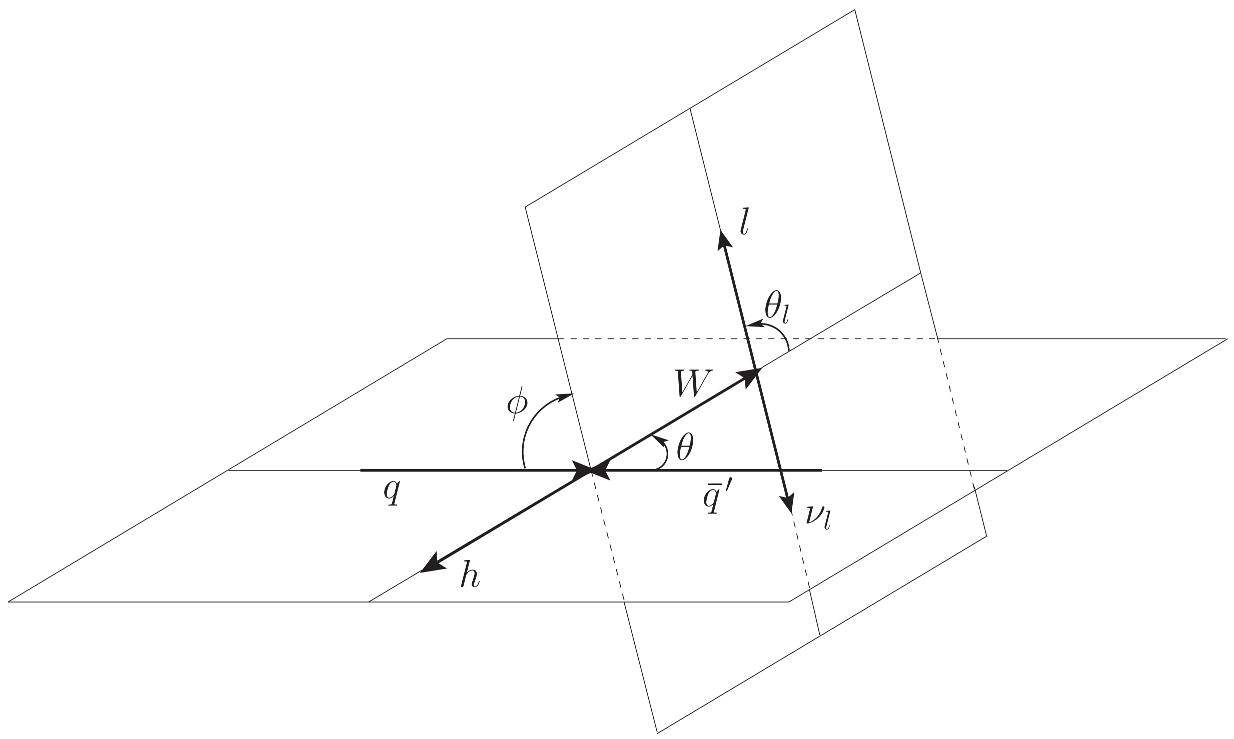

FIG. 1: Definition of the production and decay angles. The W and h directions are drawn in the $q\bar{q}'$ center-of-mass frame, while the leptons are drawn in their parent W rest frame. ϕ is the angle between the production plane and the W decay plane.

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
W/Z	LHC

Multiple probes!

Many experiments!

Almost all channels are sensitive at well motivated levels!

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b-d	B-B ✓

d-quarks	Probe
c-u	D-D ✓
t-u	

The Higgs can violate flavor and CP.
A large variety of measurements and future opportunities!

e	e-EDM
u,d	nEDM
γ	eEDM

Phase	Probe
t	EDMs
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Multiple probes!
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Almost all channels are sensitive at well motivated levels!

Deleted Scenes:

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	$\lvert \mathrm{Im}(Y_{e\tau} Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	$< 1.6 \times 10^{-2}$
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	< 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...

Top Flavor Violation

* But, top decays are interesting: