SCOUTING FOR NEW PHYSICS (USING CHARGED LEPTONS)

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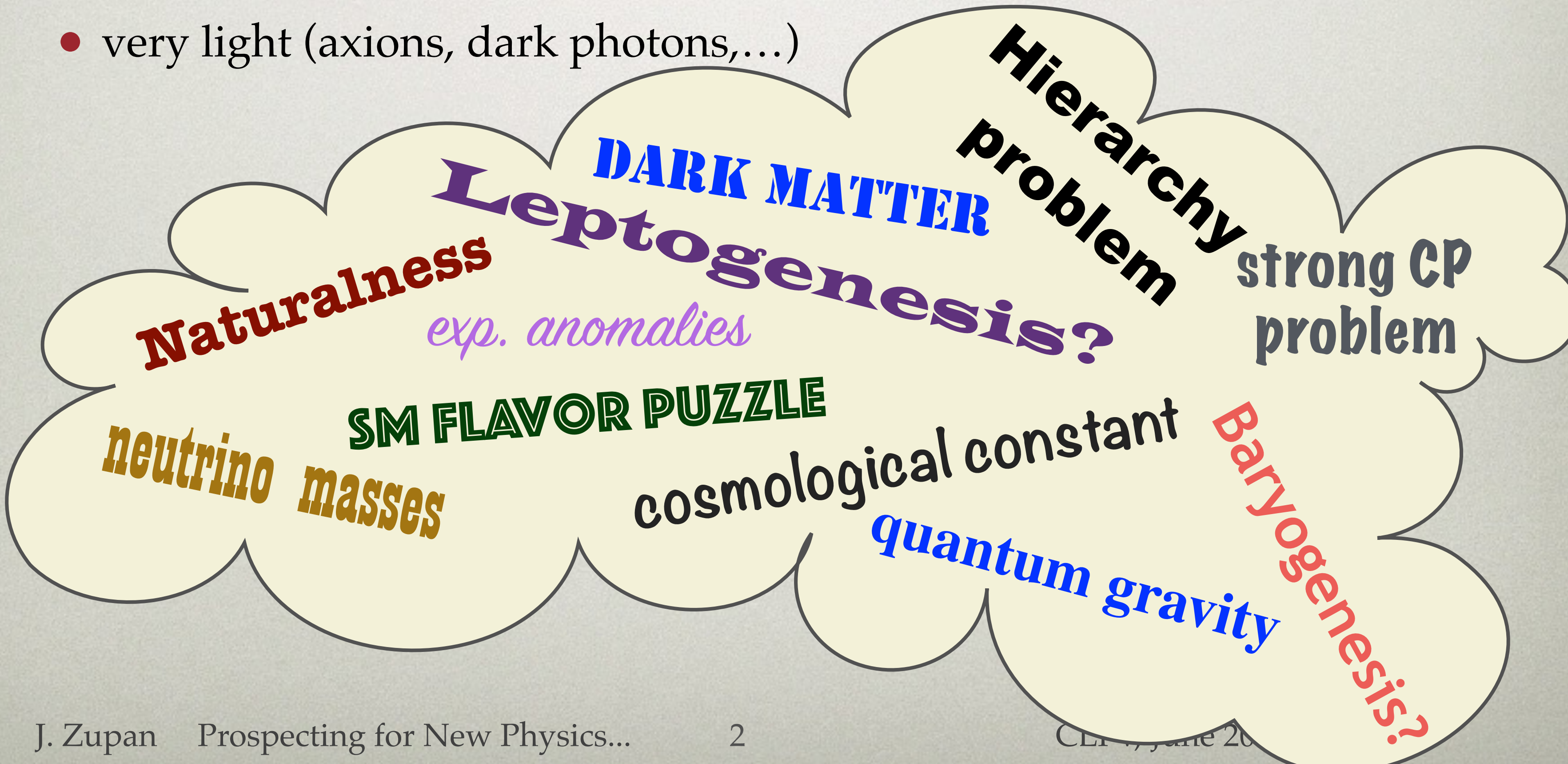
CLFV, Charlottesville, VA, June 20 2016

WHY NEW PHYSICS?

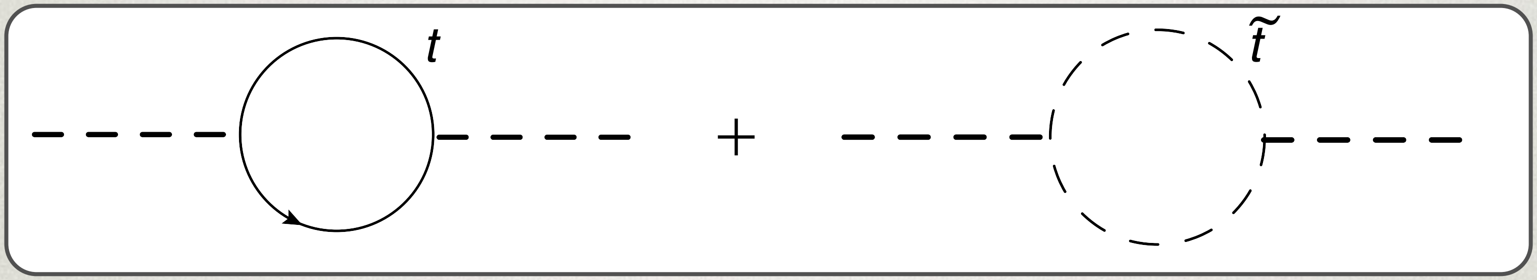
- many of the questions in particle physics may require new physics
- NP can be at very different scales
  - weak scale (WIMPS, weak scale SUSY…)
  - GUT scale (right handed neutrinos, extra gauge bosons,…)
  - very light (axions, dark photons,…)



WHICH SCALE?

- for the Higgs mass we had unitarity bounds, $m_h \lesssim 1TeV$
  - no such precise statement about the next scale
- naturalness/hierarchy problem an important guidance
  - but not bullet proof
- cLFV probes of new physics
  - can probe high scales
  - if new particles are discovered, complementary information to high p_T searches

NATURALNESS



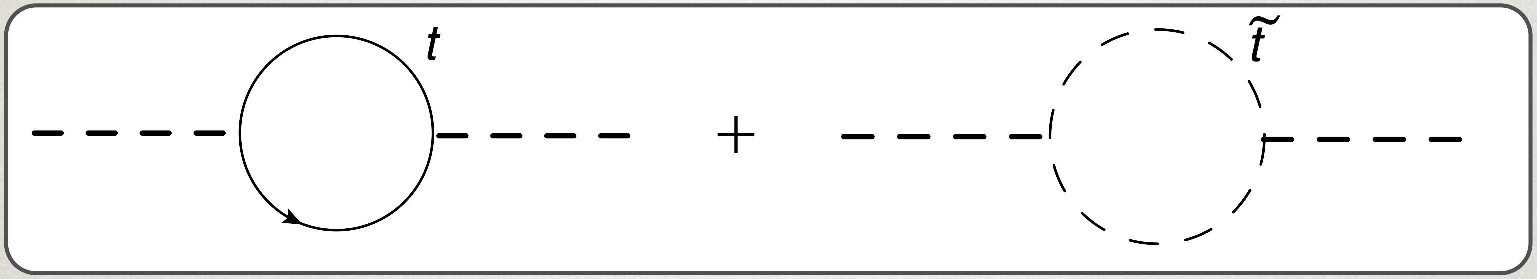
- the naturalness problem
  - large M_{Pl} - weak scale hierarchy
  - what sequesters m_h from M_{Pl}?
- the problem with naturalness
  - how much fine-tunning is too much?

radiative corrections → 100000000000000000000000000000000.00TeV²

bare mass → -99999999999999999999999999999999.99TeV²

=(0.1TeV)²

NATURALNESS



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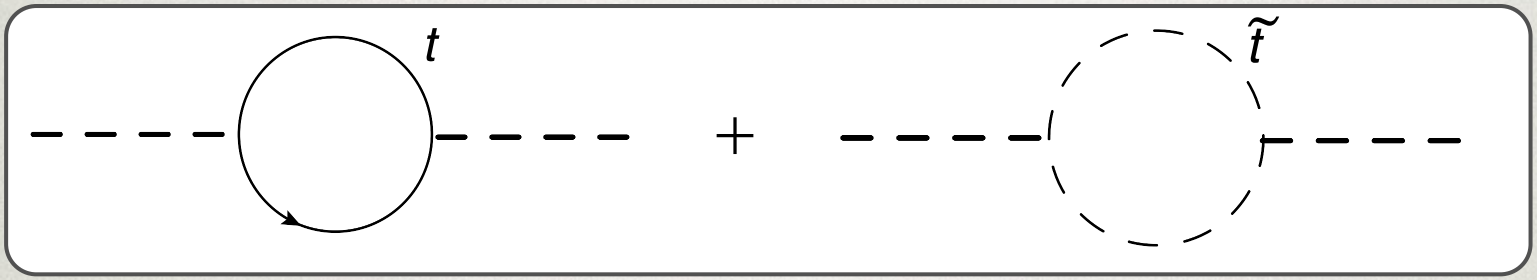
radiative corrections → 1.00TeV^2

bare mass → $-.99\text{TeV}^2$

$=(0.1\text{TeV})^2$

NATURALNESS



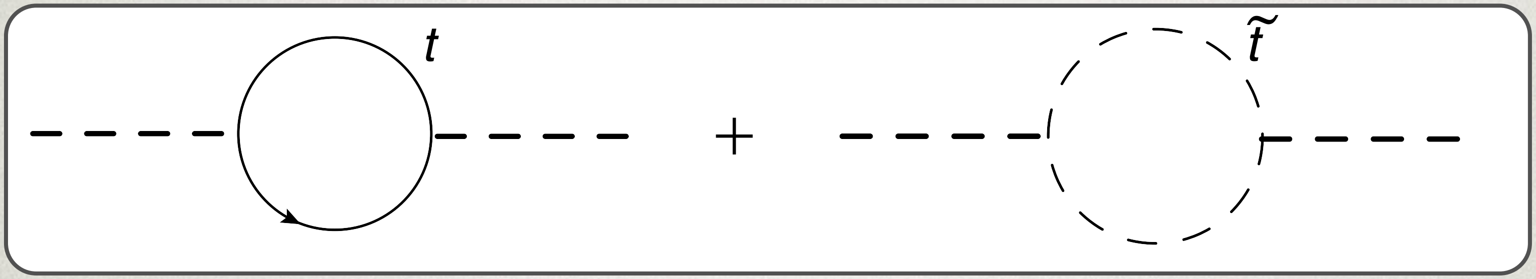
- the naturalness problem
  - large M_{Pl} - weak scale hierarchy
  - what sequesters m_h from M_{Pl}?
- the problem with naturalness
  - how much fine-tunning is too much?

radiative corrections → 100.00TeV^2

bare mass → -99.99TeV^2

$=(0.1\text{TeV})^2$

NATURALNESS



- the naturalness problem
  - large M_{Pl} - weak scale hierarchy
  - what sequesters m_h from M_{Pl}?
- the problem with naturalness
  - how much fine-tunning is too much?

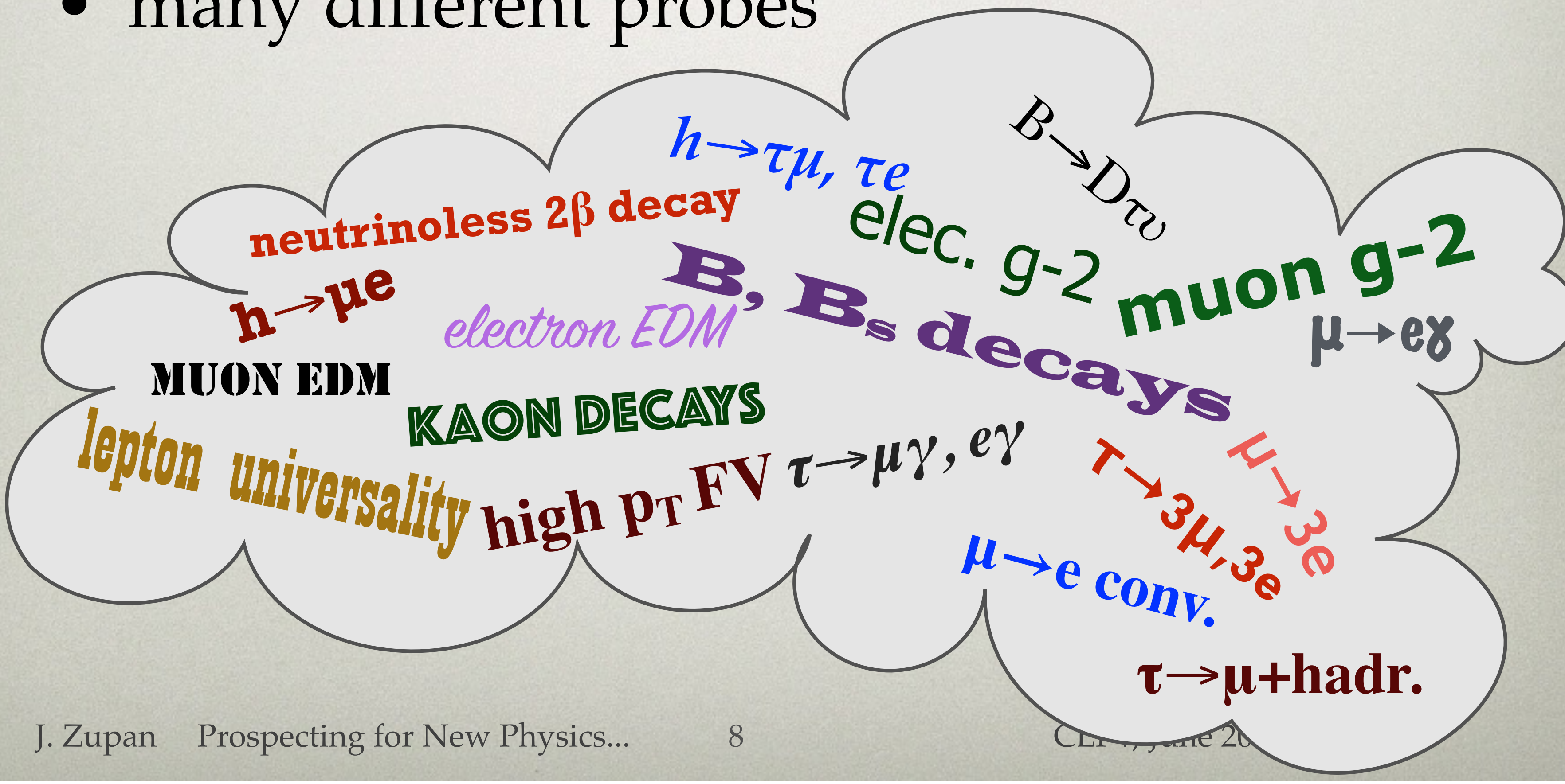
radiative corrections: $10000.00\,\text{TeV}^2$

bare mass: $-9999.99\,\text{TeV}^2$

$=(0.1\,\text{TeV})^2$

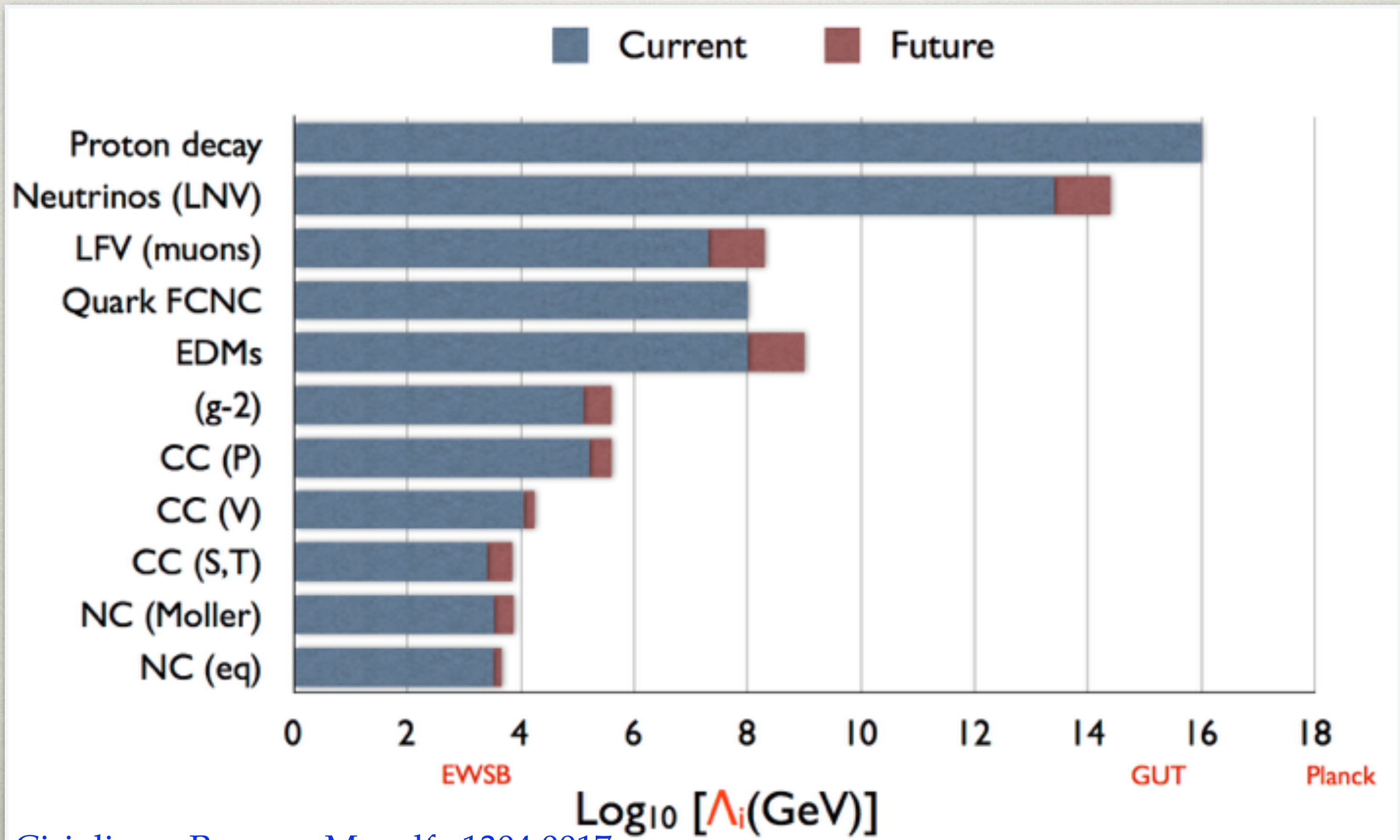
WHY CHARGED LEPTONS?

- theoretically simpler than hadrons
- can make very precise measurements
- many different probes



SENSITIVITY

- cLFV very high reach in NP scale
  - depends on the chiral/Lorentz structure of NP operators
  - several low eng. measrm.nts ⇒ nontrivial info. about NP

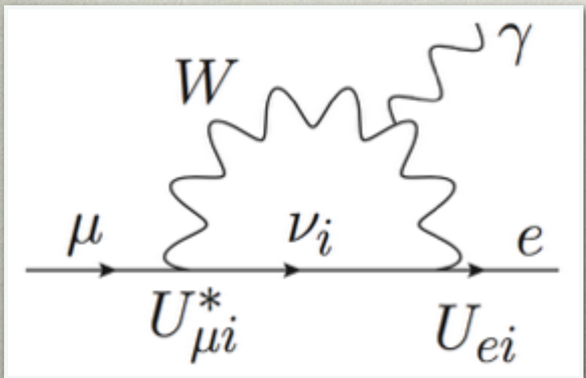


J. Zupa Cirigliano, Ramsey-Musolf, 1304.0017

WHY SO SENSITIVE?

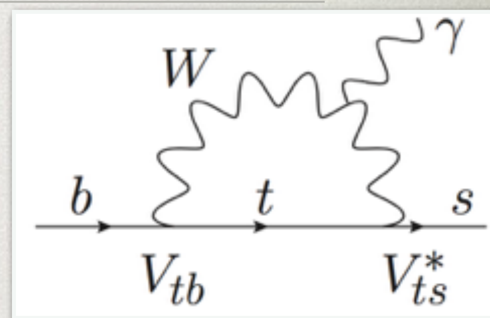
- the flavor structure in the SM is special
    - gauge invariance ⇒ lepton universality in couplings to Z, γ
    - GIM cancellation leads to very suppressed FCNCs in the νSM
- LFV established in neutrino oscillations ⇒ cLFV generated at least at loop level
    - due to GIM mechanism vanishingly small

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W}\right|^2 \sim 10^{-54}$$



PMNS unitary, $U_{\mu i}{}^* U_{ei} = 0$
⇒ the piece indep. of m_ν cancels

CHARGED LEPTONS VS. QUARKS



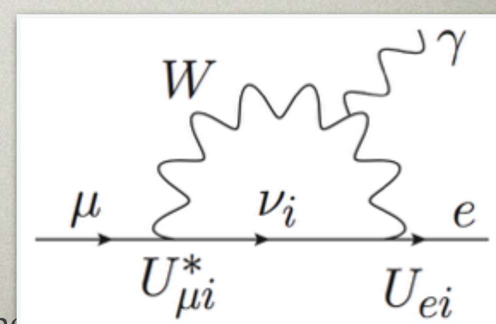
- compare with quarks
  - GIM mechanism less effective
  - not a zero theory ("SM background" free) search

$$\mathrm{Br}(b \to s\gamma) \simeq \frac{6\alpha}{\pi}\left|\frac{V_{ts}^* V_{tb}}{V_{cb}} f(m_t/m_W, \alpha_S)\right|^2 \to_{\text{NNLO QCD}} (3.36 \pm 0.23) \times 10^{-4}$$

Asatrian et al., 1503.01789

- for cFLV as soon as signal found it means NP
  - i.e. NP beyond νSM (=SM+ dim5 op. for neutrino masses)

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{m_W^2}\right|^2 \sim 10^{-54}$$



CHARGED LEPTONS AND NEUTRINOS

- if neutrinos Majorana, their masses from dim 5 Weinberg operator

$$C_{ij}\,\frac{(HL_i)(HL_j)}{\Lambda}$$

- requires new particles that couple to leptons
  - in general new sources of flavor violation beyond PMNS
  - can enhance cFLV to observable levels

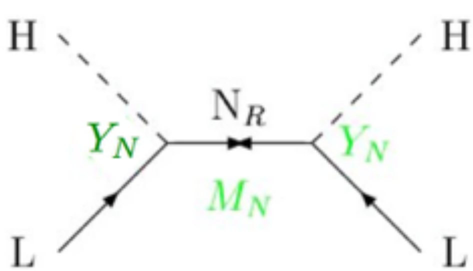
SEE SAW MODELS

- 3 tree level see-saw models to generate Majorana neutrino masses

Right-handed singlet: (type-I seesaw)

$$N_{R_i}$$

$$\mathcal{L} \ni -Y_{N_{ij}} \bar{N}_i L_j H - \frac{m_{N_i}}{2} \overline{N_i^c} N_i + h.c.$$

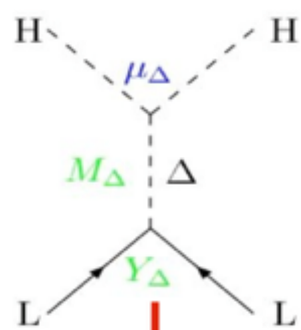


$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Scalar triplet: (type-II seesaw)

$$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$$

$$\mathcal{L} \ni -Y_\Delta \Delta L_i L_j - \mu_\Delta \Delta H H + h.c.$$

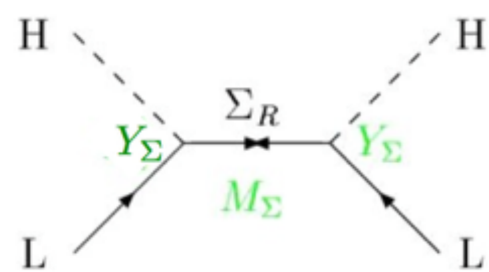


$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Fermion triplet: (type-III seesaw)

$$\Sigma_i \equiv (\Sigma_i^{+}, \Sigma_i^{0}, \Sigma_i^{-})$$

$$\mathcal{L} \ni -Y_{\Sigma_{ij}} \bar{\Sigma}_i L_j H - \frac{m_{\Sigma_i}}{2} \overline{\Sigma_i^c} \Sigma_i + h.c.$$



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Hambye, talk at 1st CLFV, Lecce, 2013

DISTINGUISHING SEE-SAW MODELS

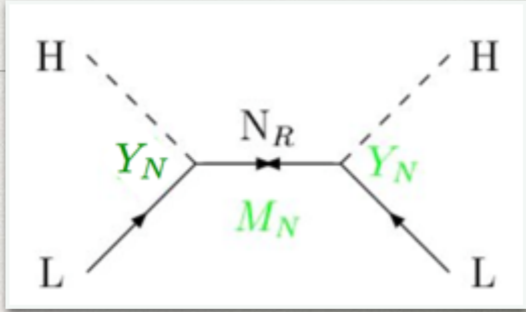
- all three see-saw models lead to the same Weinberg operator

$$C_{ij}\frac{(HL_i)(HL_j)}{\Lambda}$$

  - impossible to distinguish the models from neutrino oscillation data alone
- need extra input
  - production of extra states at the LHC if scale low enough
  - from cLFV processes also for high scales, if Yukawas large enough
- note: different combinations of FV couplings enter the cFLV processes and the Weinberg operator

Chu, Dhen, Hambye, 1107.1589;
Alonso, Dhen, Gavela, Hambye, 1209.2679;

TYPE I SEE-SAW



- for instance in type I see saw (with quasi-degenerate N_i)

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

$$\Gamma(\mu \to e\gamma) \propto \frac{1}{m_N^4} \sum_{N_i} \left| Y_{N_{ie}} Y^\dagger_{N_{i\mu}} \right|^2$$

- using (approximate) symmetries possible to have large cLFV and small neutrino masses

- for quasi-degenerate N_i to a good extend the product of Yukawas cancel in ratios of cLFV processes

$$\frac{R^N_{\mu\to e}}{\Gamma(\mu \to e\gamma)} = \left(\frac{b^N + b'^N \log[m_N^2/m_W^2]}{c \ + c' \ \log[m_N^2/m_W^2]}\right)^2$$

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to eee)} = \left(\frac{c + c' \log[m_N^2/m_W^2]}{d + d' \log[m_N^2/m_W^2]}\right)^2$$

- can probe scale of m_N from $\mu \to e$ conversion

Chu, Dhen, Hambye, 1107.1589;
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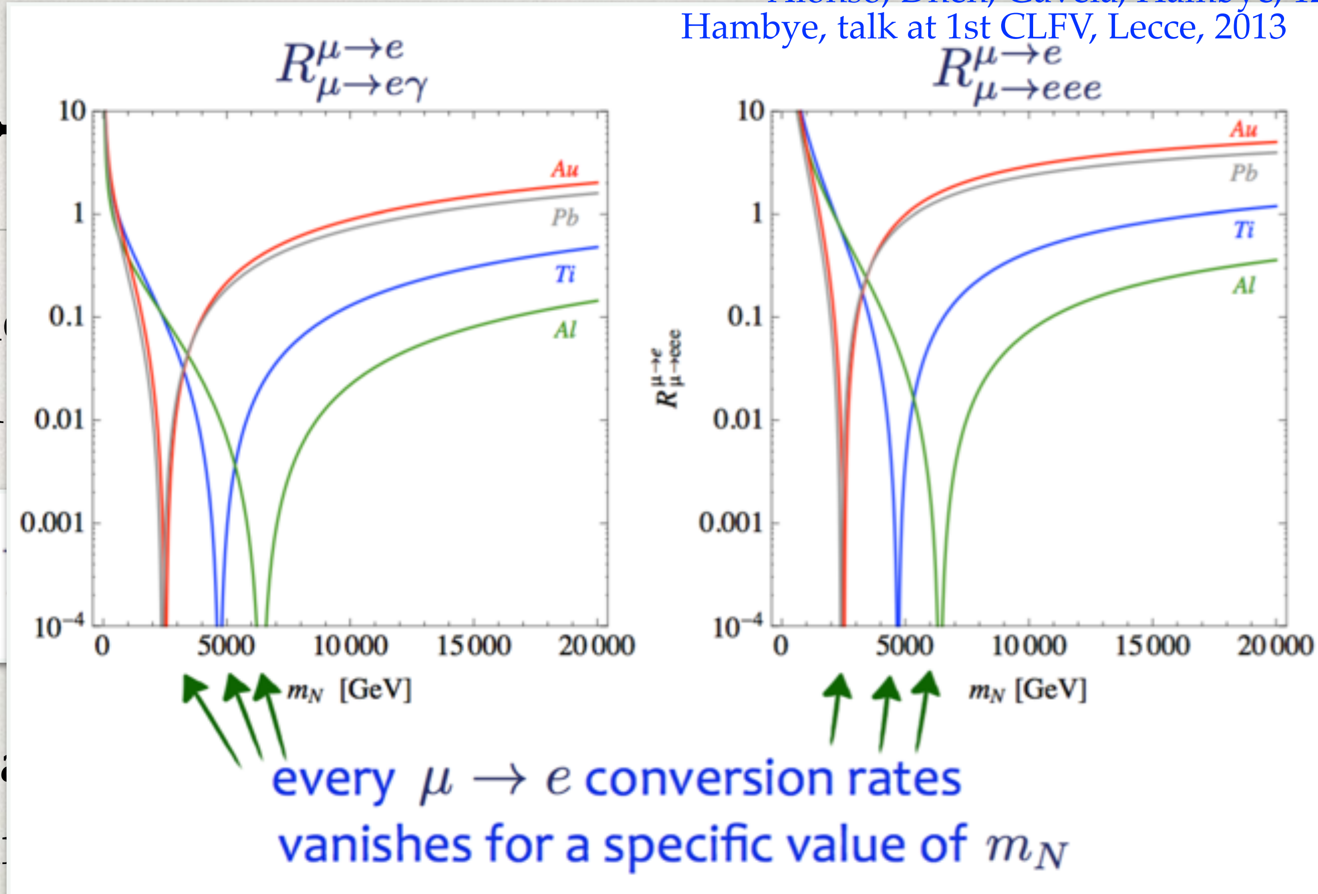
Hambye, talk at 1st CLFV, Lecce, 2013



- for instan…
(with qua…

$$m_\nu = Y_N^T \frac{1}{M_N} \ldots$$

  - using (… cLFV a…

- for quasi-degenerate N_i to a good extend the product of Yukawas cancel in ratios of cLFV processes

$$\frac{R^N_{\mu\to e}}{\Gamma(\mu \to e\gamma)} = \left(\frac{b^N + b'^N \log[m_N^2/m_W^2]}{c \ + c' \ \log[m_N^2/m_W^2]}\right)^2$$

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- can probe scale of m_N from $\mu \to e$ conversion

SINGLING OUT THE RIGHT NEW PHYSICS MODEL

- more generally, the pattern of observed cLFV processes can point to which NP

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$	$0.06\ldots2.2$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$	$0.03\ldots1.3$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2$	~ 5	$0.3\ldots0.5$	$1.5\ldots2.3$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$	$1.4\ldots1.7$
$\frac{R(\mu Ti\to eTi)}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

Buras, Duling, Feldmann, Heidsieck, Promberger, 1006.5356

EXAMINING THE HIGGS

- another case in point : flavor properties of the Higgs

HIGGS

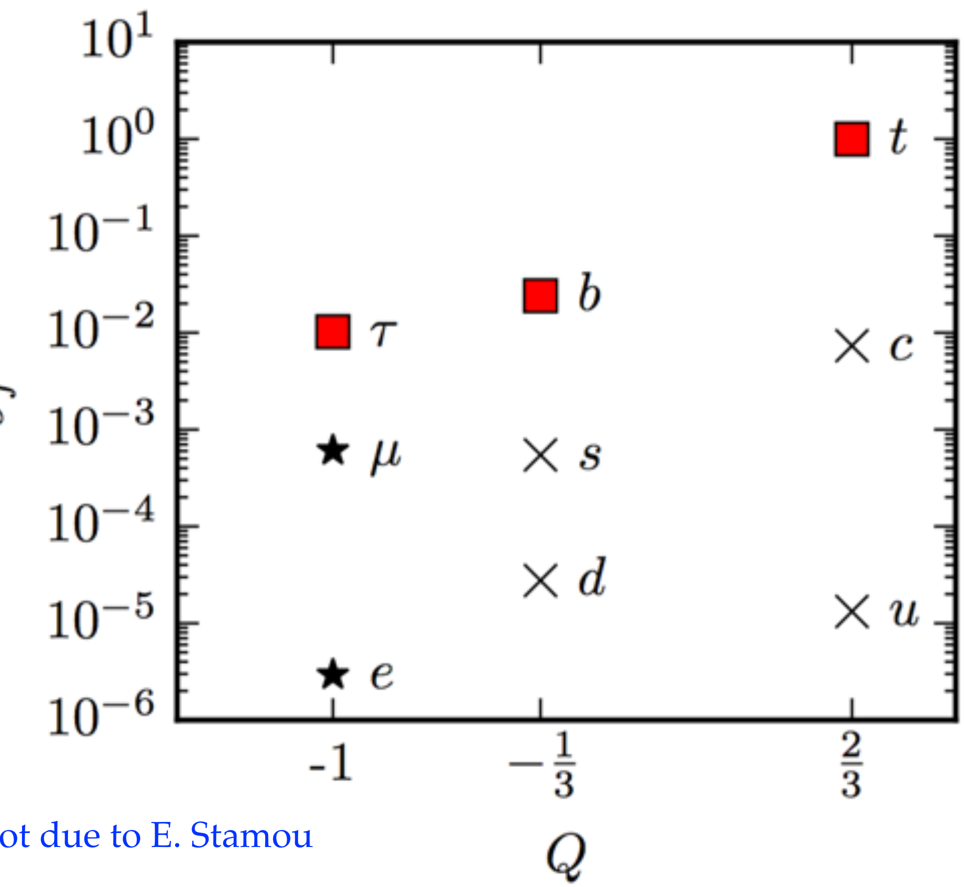
- two main questions about the Higgs
  - responsible for electroweak symmetry breaking?
    - from couplings to $Z, W \Rightarrow$ predominant source of EWSB
  - does it give the dominant contrib. to quark and lepton masses?
    - here precision low eng. measurements with charged leptons very important

HIGGS = NONTRIVIAL FLAVOR STRUCTURE

- generation of masses in the SM through the Higgs mechanism
- implies Higgs has hierarchical couplings to fermions
- in the SM

$$y_f = \sqrt{2} m_f / v$$

- can it be modified by NP?
- how well have we tested this?

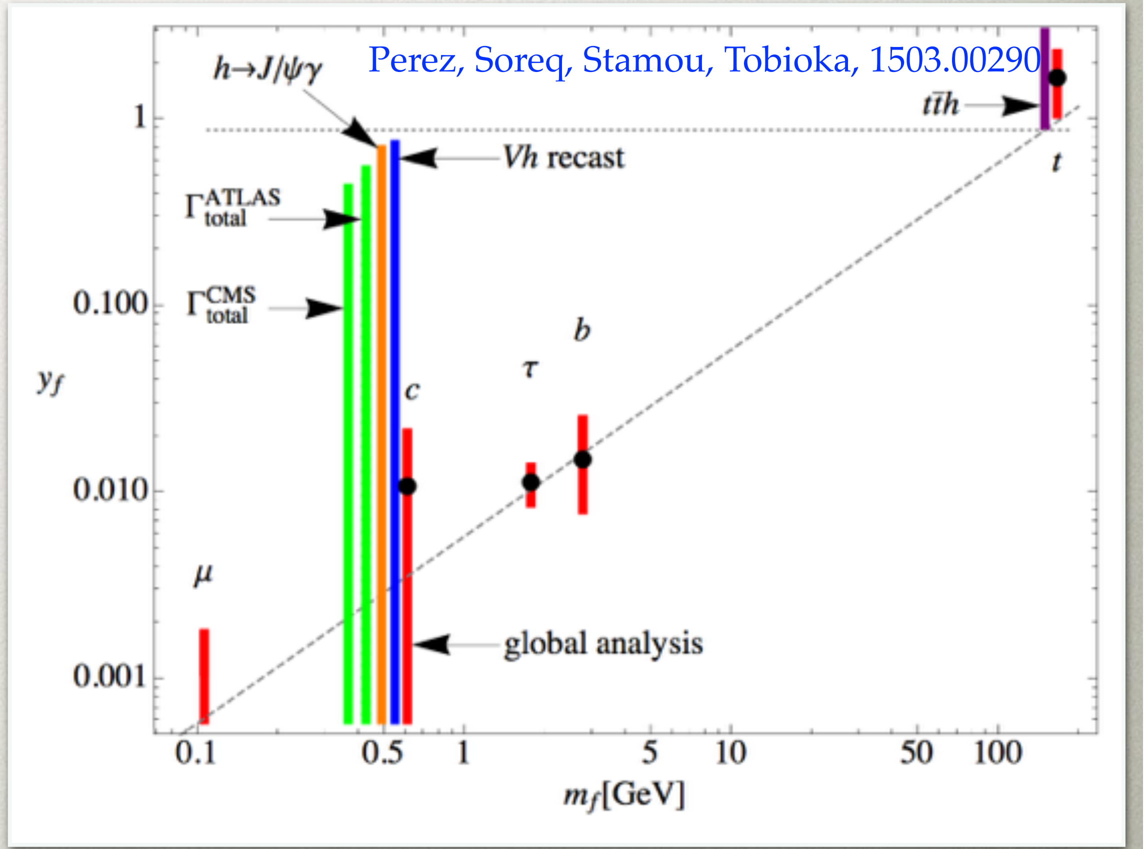


plot due to E. Stamou

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433

- how well have we tested the flavor of the Higgs? $y_f^{\rm SM} = \sqrt{2} m_f / v$
- several questions
  - proportionality? $y_{ii} \propto m_i$
  - factor of proportionality? $y_{ii}/m_i = \sqrt{2}/v$
  - diagonality? $y_{ij} = 0, \quad i \neq j$
  - reality? (CP conserving?) $\arg(y_{ij}) = 0$



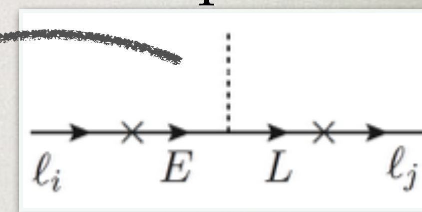
HOW LARGE?

- two important questions
  - how large are Y_{ij} assuming EFT?
  - how large can Y_{ij} be in reasonable models?

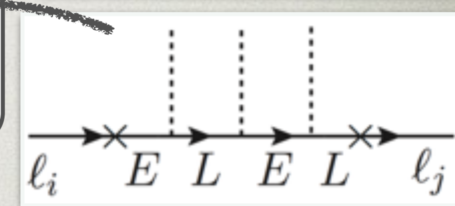
CPV and FV Higgs couplings to SM fermions

- if SM an EFT, the Yukawas get corrected by higher dim. ops

$$\mathcal{L}_{SM} = -\left[\lambda_{ij}(\bar{f}_L^i f_R^j)H + h.c.\right]$$



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



  - decouples mass terms from yukawas

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

  - can lead to flavor violating Higgs decays
  - can lead to CPV Higgs decays

- different models lead to different patterns of flavor diagonal and flavor violating Yukawas

SUMMARY OF MODELS

- an example: higgs couplings to 2nd&3rd gen. charged leptons

adapted from Dery, Efrati, Hochberg, Nir, 1302.3229 and extended;
see also Bishara, Brod, Uttayarat, JZ, 1504.04022

Model	$\hat{\mu}_{\tau\tau}$	$(\hat{\mu}_{\mu\mu}/\hat{\mu}_{\tau\tau})/(m_\mu^2/m_\tau^2)$	$\hat{\mu}_{\mu\tau}/\hat{\mu}_{\tau\tau}$
SM	1	1	0
NFC	$(V_{h\ell}^* v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert^2 v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(\hat{\mu}_{\mu\mu}/\hat{\mu}_{\tau\tau})$
RS (i)	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)\sqrt{m_\tau/m_\mu}$
RS (ii)	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$
PGB (1 rep.)	$1-v^2/f^2$	1	0

EXPERIMENTAL CONSTRAINTS

- what are present experimental constraints?
- right now can address
  - are diagonal Yukawas hierarchical?
  - are they CP violating?
  - are there FV Yukawas?
- the notation

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

- focus on charged leptons

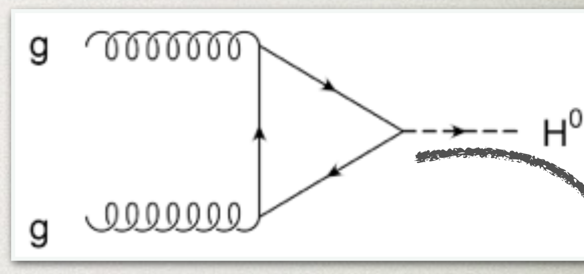
HIERARCHICAL YUKAWAS?

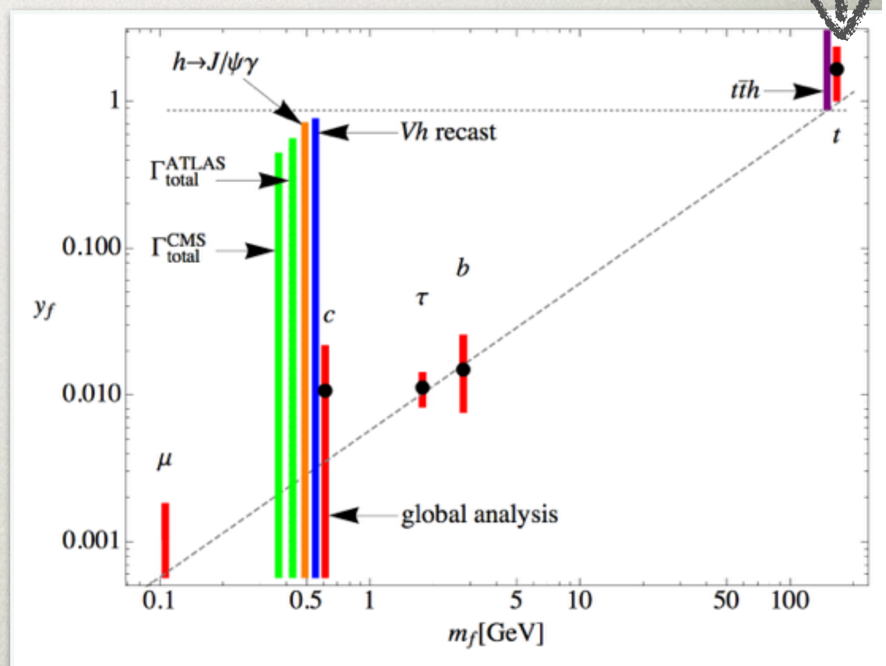
- proportionality for 3rd generation?

$$y_{ii} \propto m_i$$

  - top quark yukawa most precise indirectly through loops
  - Y_b and Y_τ could still be equal
- hierarchical among generations?
  - i.e., are 1st and 2nd generation Yukawas smaller than 3rd gen.?
  - only established for leptons

$$Y_e, Y_\mu \ll Y_\tau$$



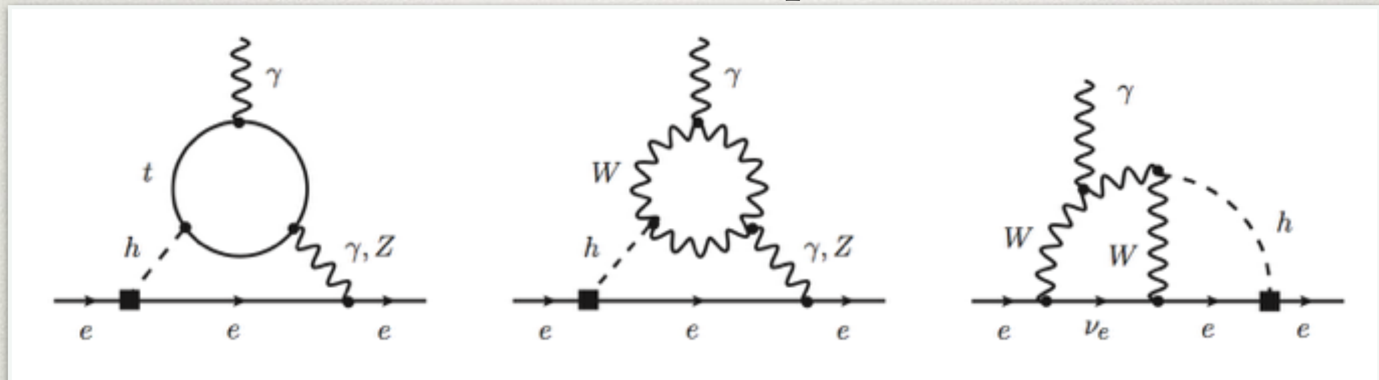


CPV electron Yukawa?

- $\tilde{\kappa}_e \neq 0$ induces electron EDM

Altmannshofer, Brod, Schmaltz, 1503.04830

- dominant contributions at 2-loop



- experimental bound

ACME coll., 1310.7534

$$\left|\frac{d_e}{e}\right|_{\rm exp} < 8.7 \times 10^{-29}\ {\rm cm} \quad @\ 90\%\ {\rm C.L.}\,,$$

$$|\tilde{\kappa}_e| < 1.7 \times 10^{-2}$$

  - for $c_0 = i \Rightarrow M > 1000\ TeV$

$$g_{eeh} = y_e + \frac{3c_0}{2}\frac{v^2}{M^2} = \frac{\sqrt{2}m_e}{v} + c_0\frac{v^2}{M^2}\,.$$

- compare with

CMS-HIG-13-007

$$\mathrm{Br}(h \to e^+e^-) < 0.0019 \quad @\ 95\%\ {\rm C.L.}\,.$$

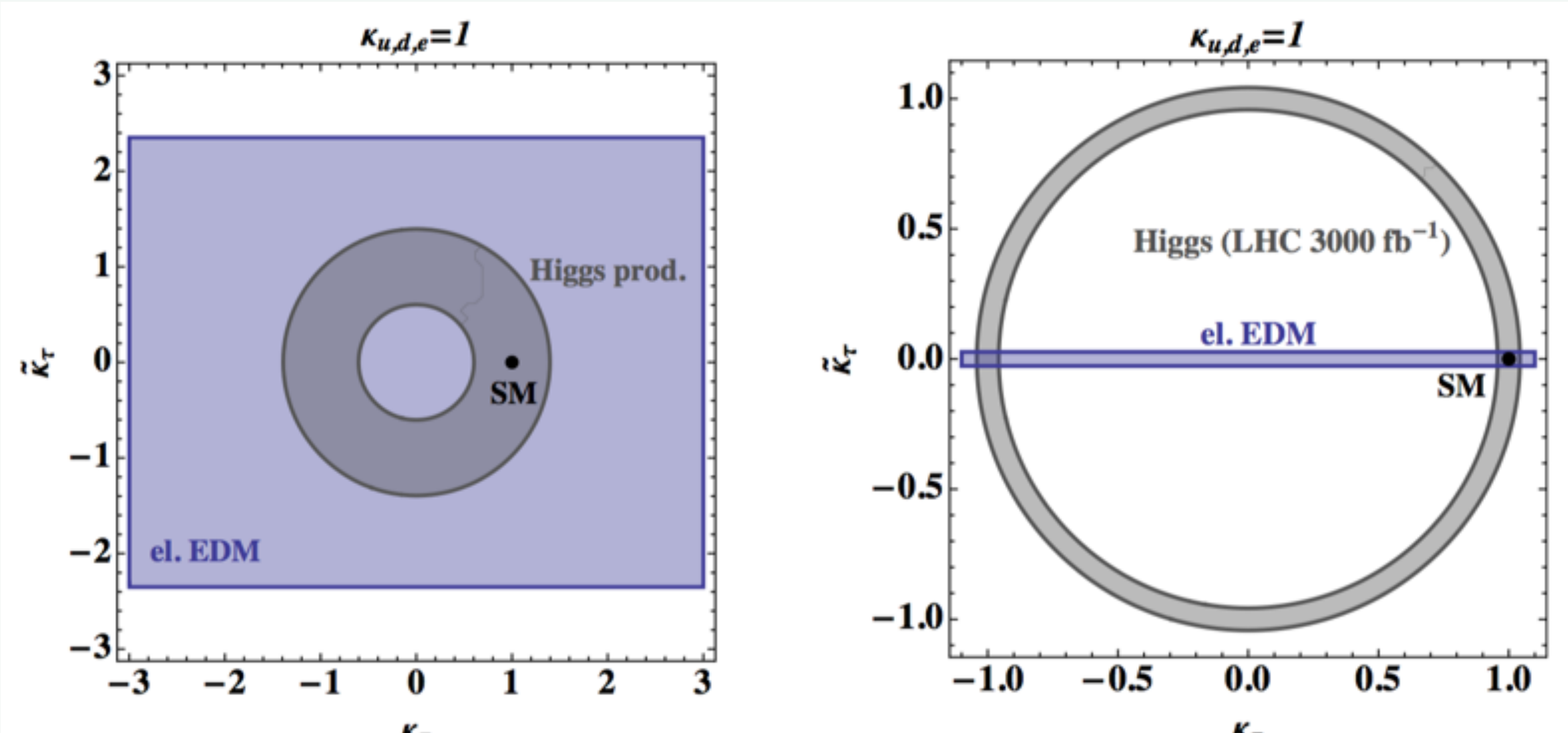
$$\sqrt{|\kappa_e|^2 + |\tilde{\kappa}_e|^2} < 611$$

CPV coupling to τ

- impressive improvement in el. EDM is projected
    - 3 orders of magnitude
- in the plot no direct CPV measnt. at the LHC is assumed

Harnik, Martin, Okui, Primulando, Yu, 1308.1094

- - $O(0.2)$ measrmnt. on $\tilde{\kappa}_\tau$ maybe possible (at LHC 3 ab^{-1})



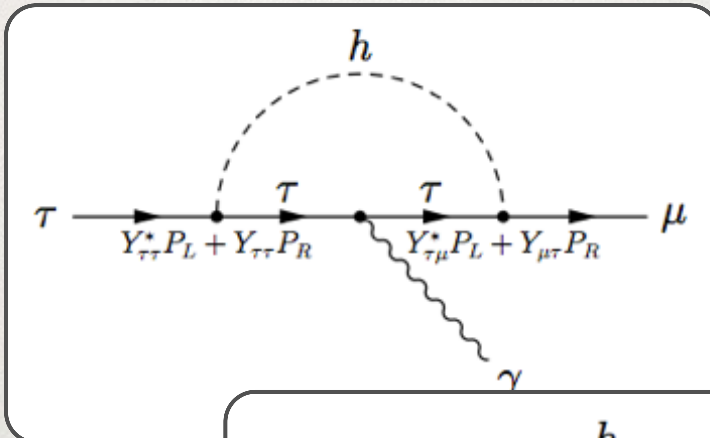
Brod, Haisch, JZ, 1310.1385

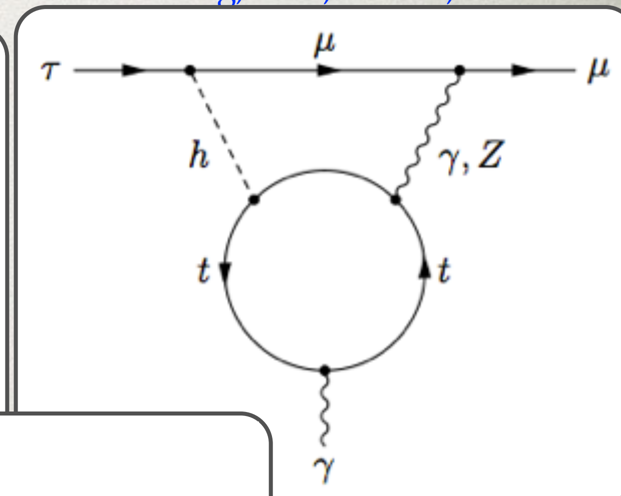
$h \to \tau\mu$

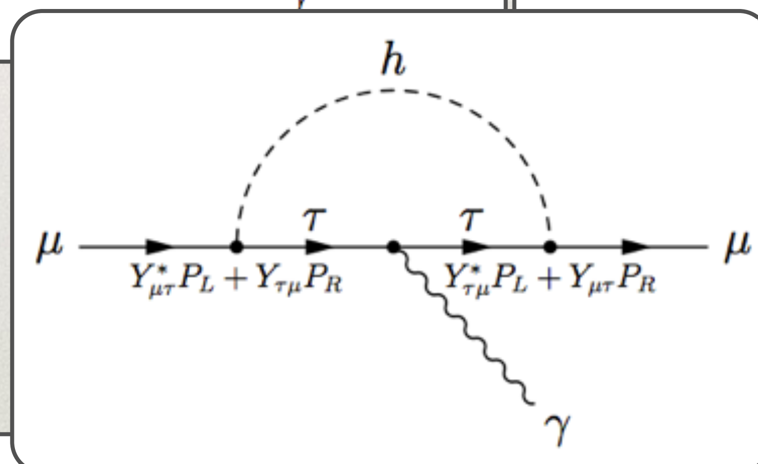
Harnik, Kopp, JZ, 1209.1397

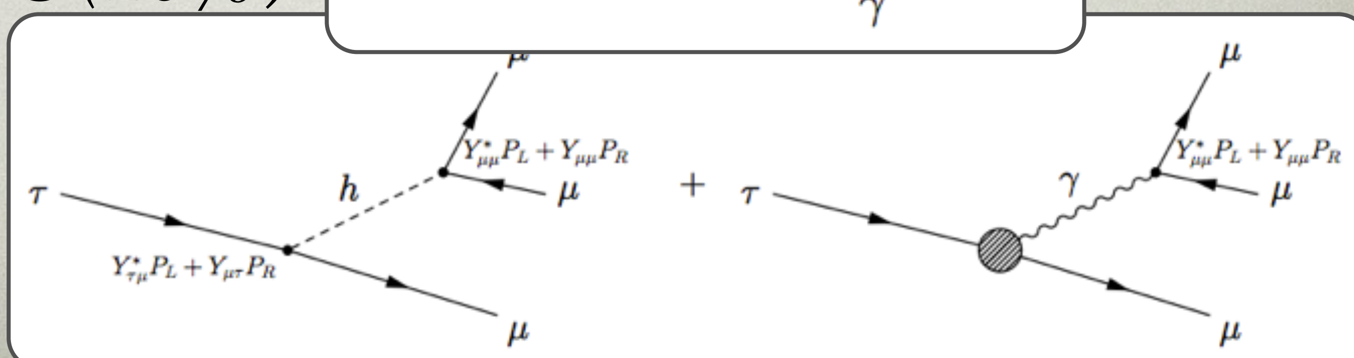
see also Blankenburg, Ellis, Isidori, 1202.5704

- bounds from
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$
  - muon *g*-2
  - muon EDM
- $Br(h \to \tau\mu) \sim O(10\%)$ allowed









$h \to \tau\mu$

Harnik, Kopp, JZ, 1209.1397

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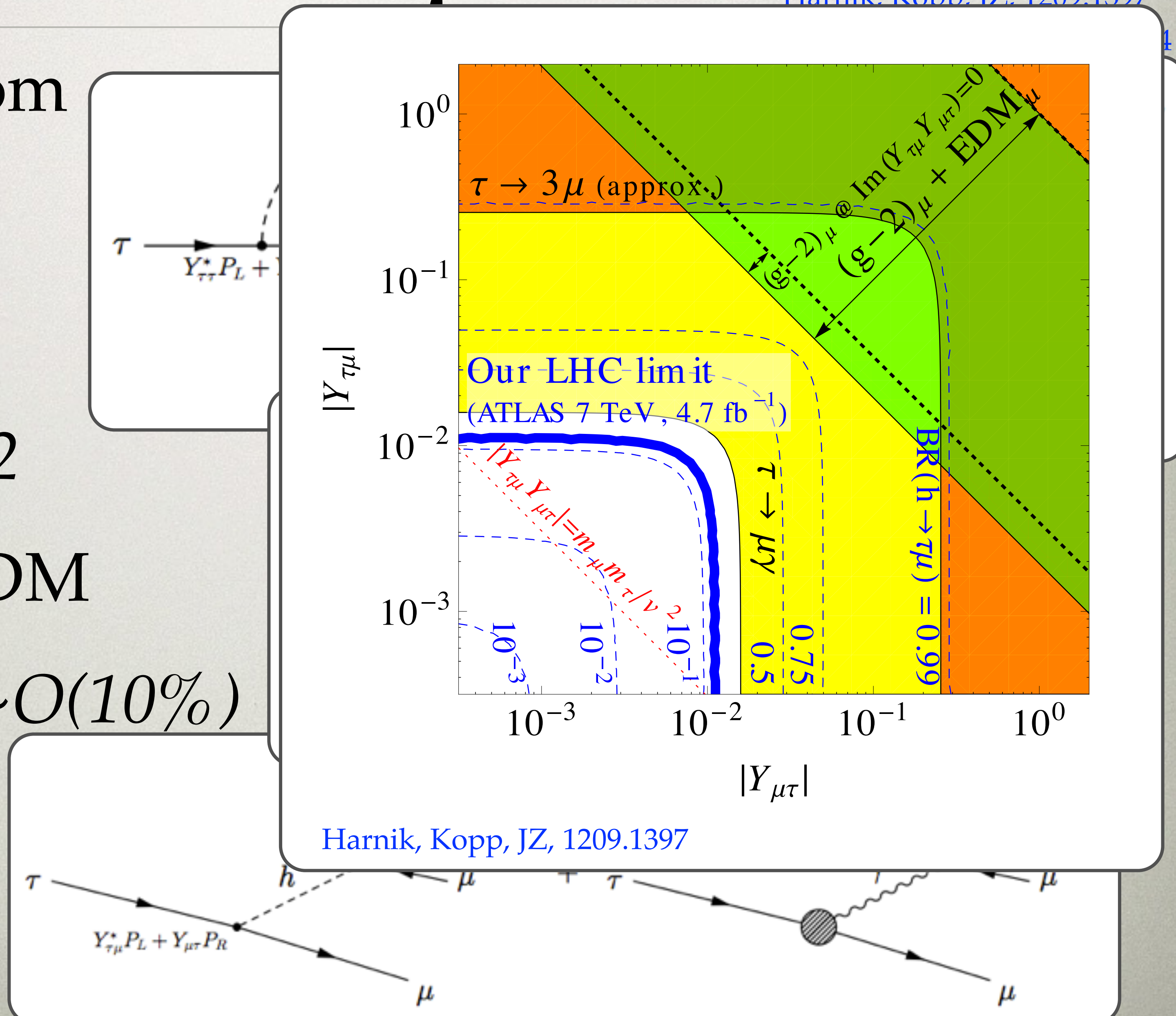

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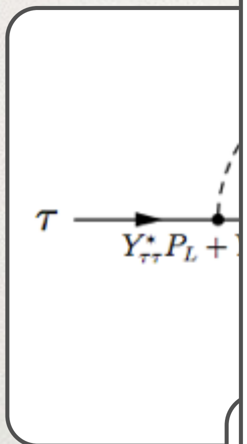
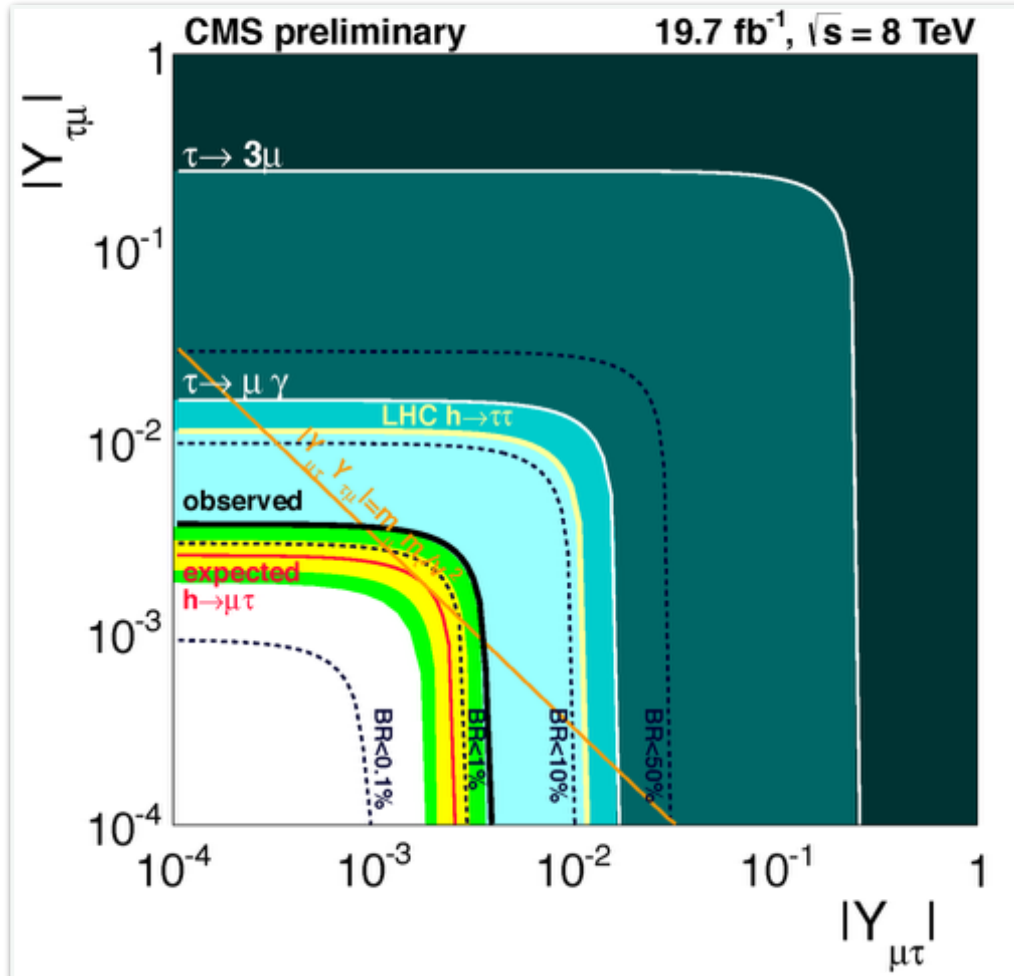
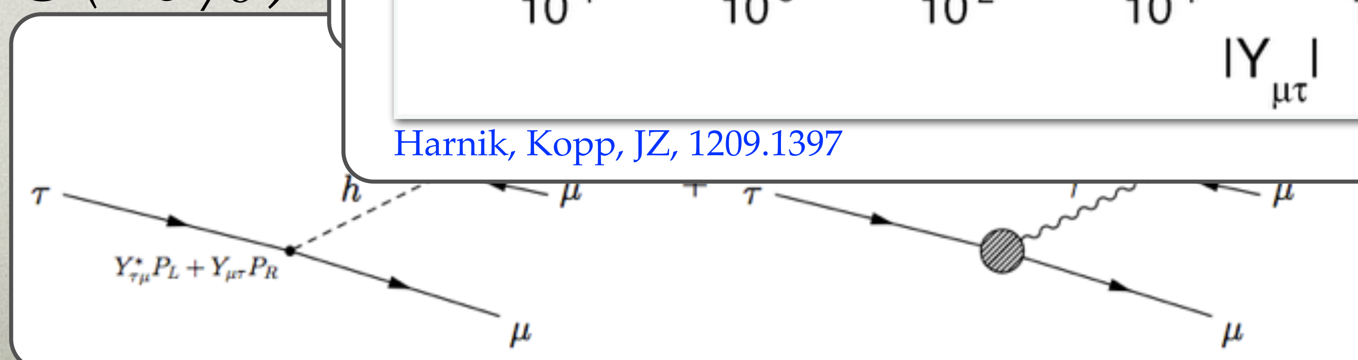
- *Br*($h \to \tau\mu$)~*O*(10%) allowed



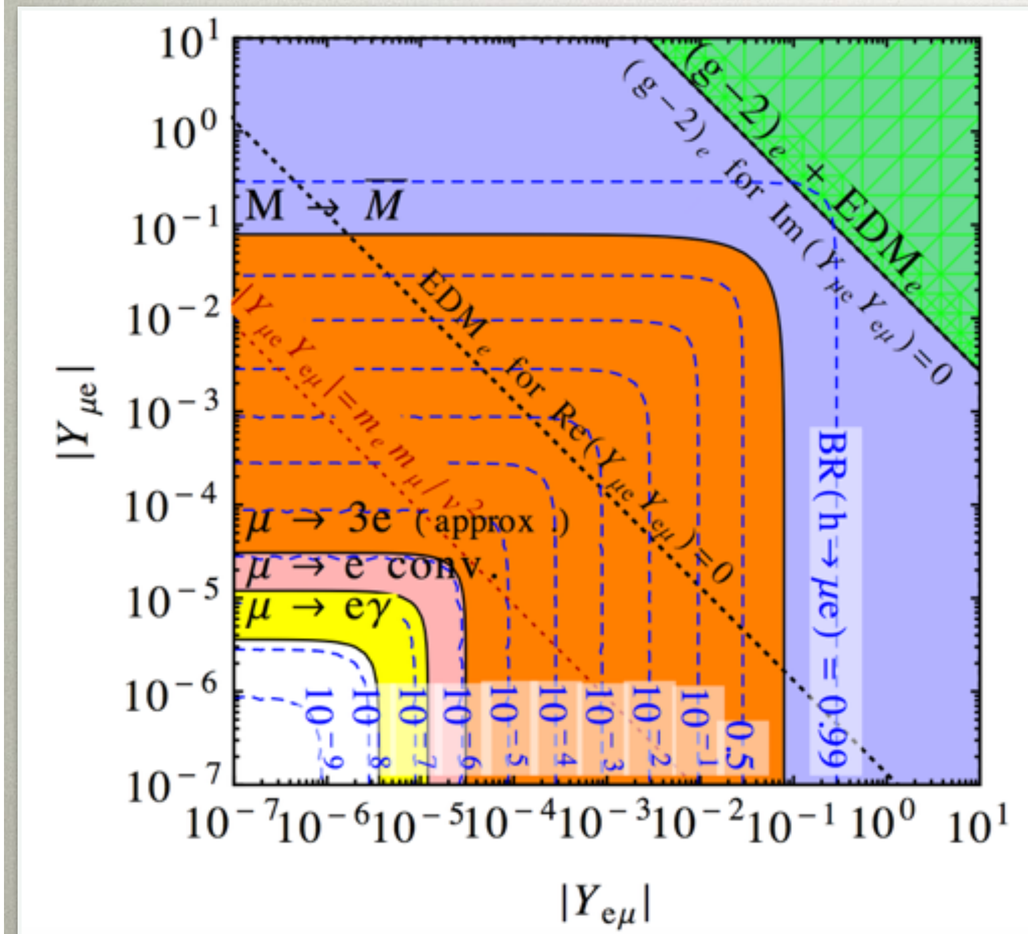


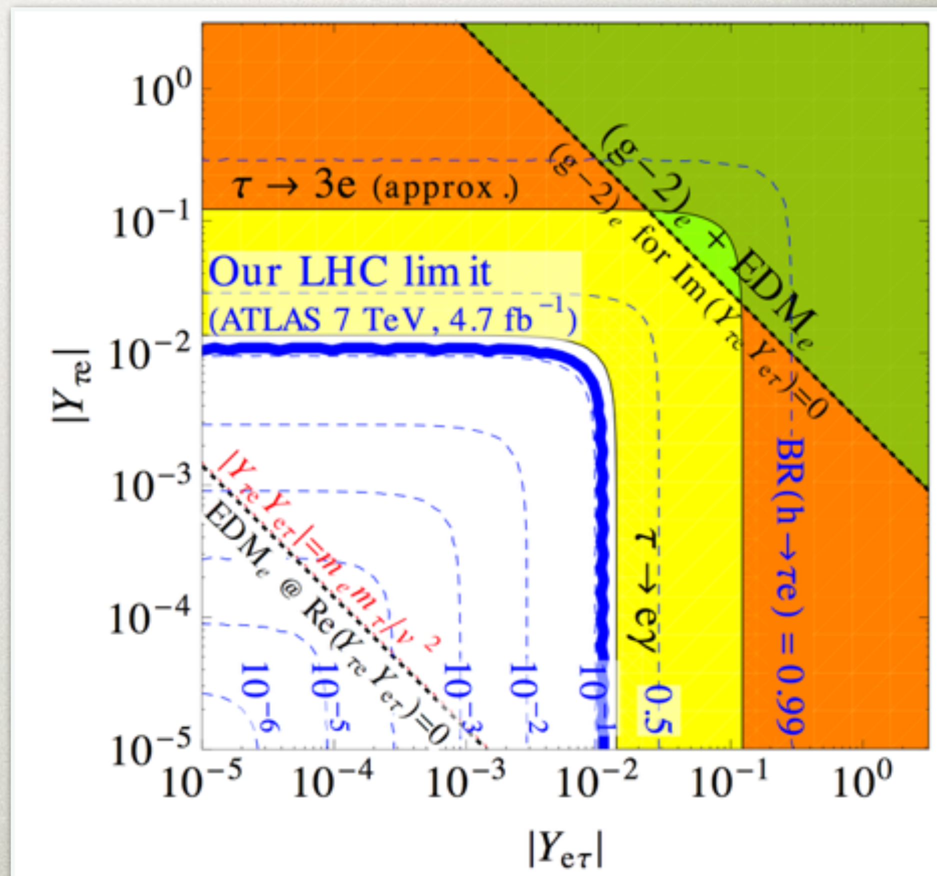
Harnik, Kopp, JZ, 1209.1397



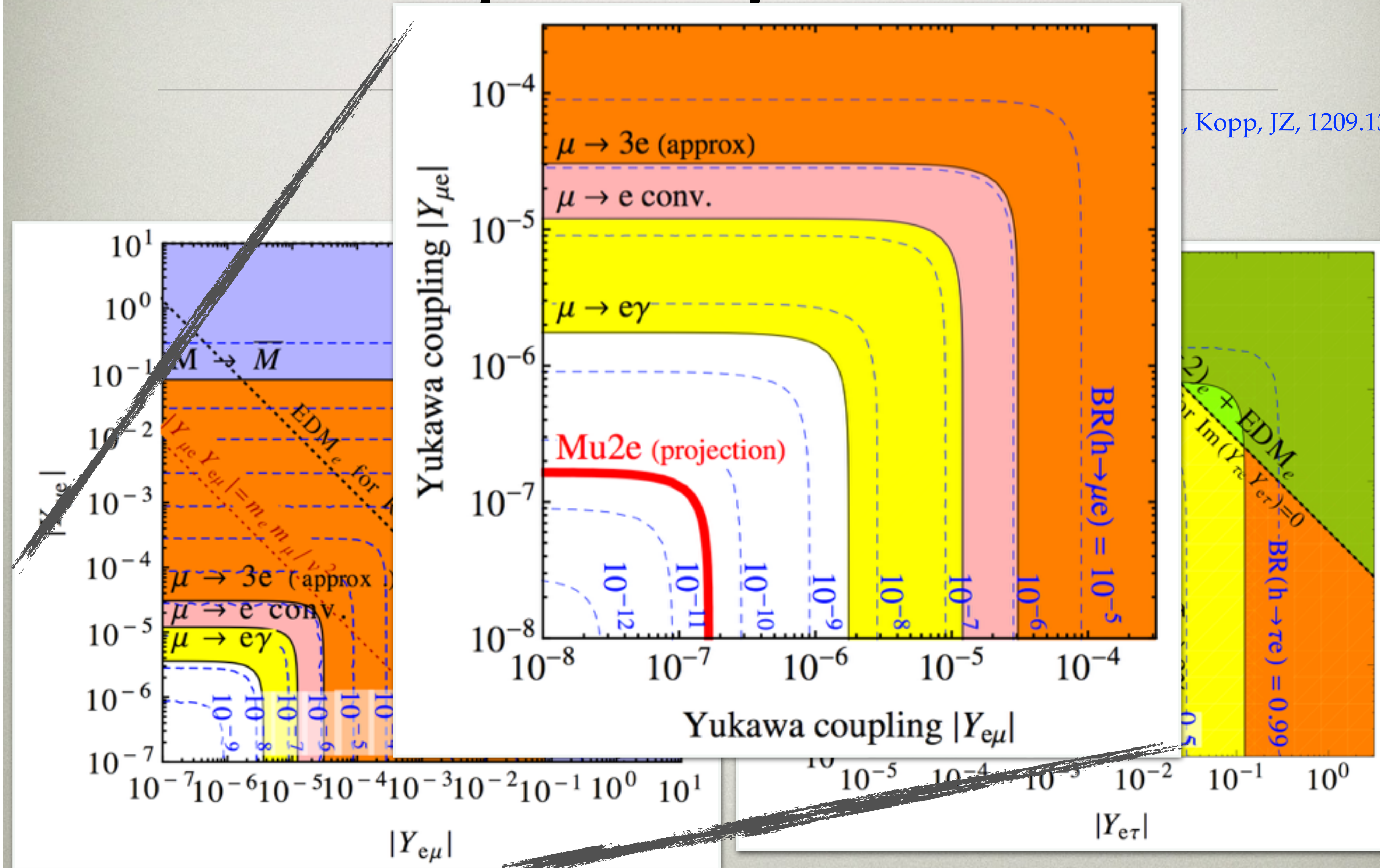
$h \to \tau e$, $h \to \mu e$

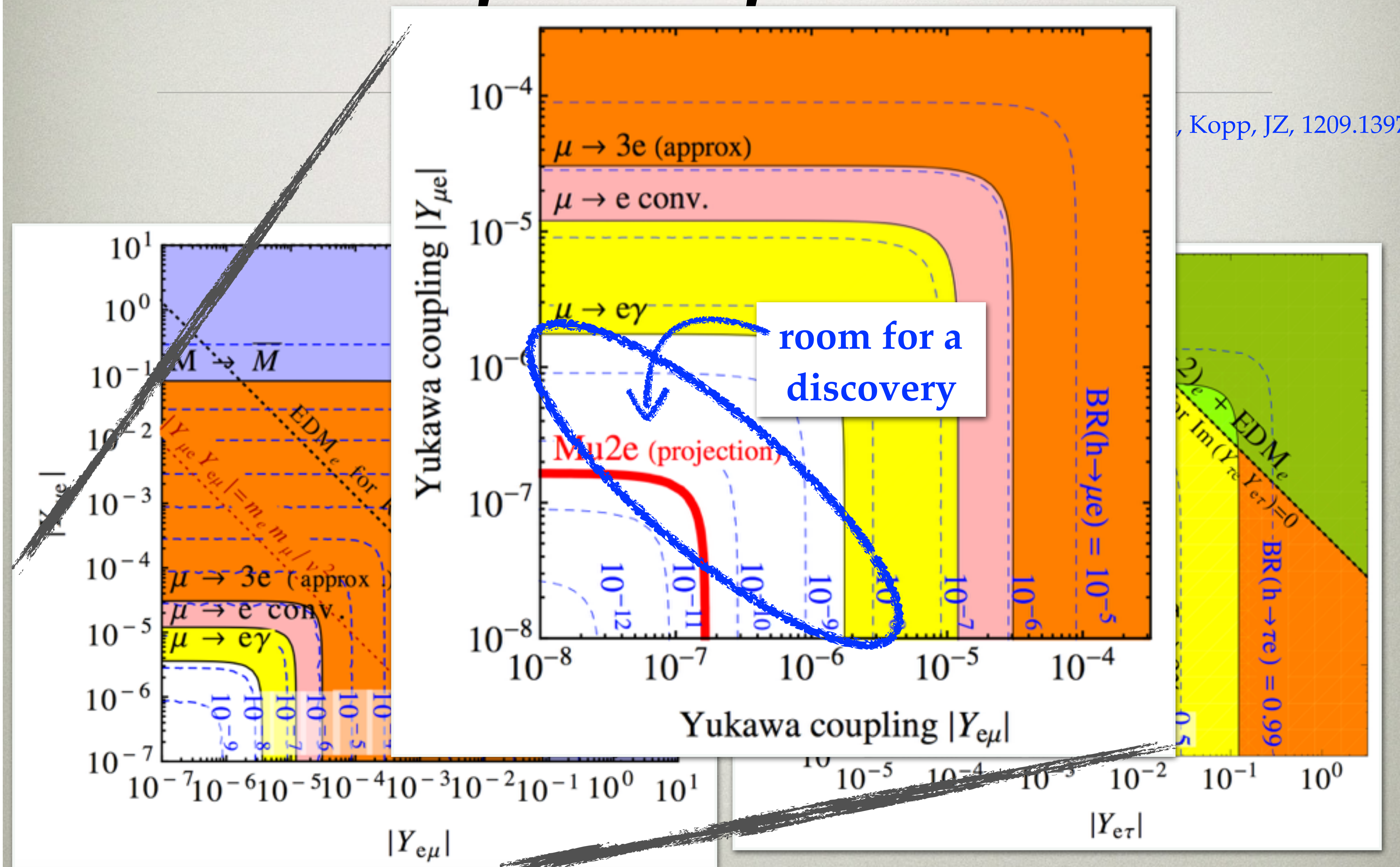
Harnik, Kopp, JZ, 1209.1397





, Kopp, JZ, 1209.1397





, Kopp, JZ, 1209.1397
room for a discovery
Mu2e (projection)
μ → 3e (approx)
μ → e conv.
μ → eγ
BR(h→μe) = 10^-5
Yukawa coupling |Y_μe|
Yukawa coupling |Y_eμ|
EDM_e
BR(h→τe) = 0.99
|Y_eτ|
|Y_eμ|

FLAVOR VIOLATING HIGGS DECAYS?

ATLAS, 1508.03372, 1604.07730
CMS-HIG-14-005

- CMS [ATLAS] at 8 TeV observes hint of a signal at 2.4 [1]σ

$$\mathrm{BR}(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\,\%\ [(0.53 \pm 0.51)\,\%]$$

talk by María Cepeda at Higgs Tasting,
May 2016, Benasque, Spain

- first 13 TeV analysis (CMS)

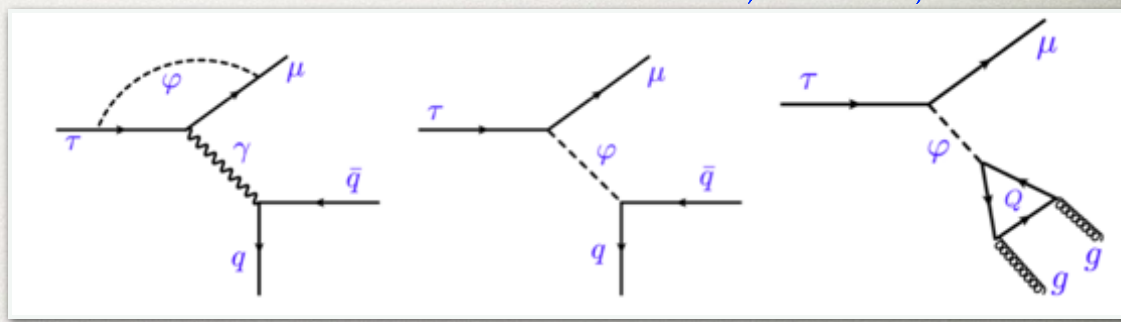
$$\mathrm{BR}(H \to \mu\tau) = (-0.76^{+0.81}_{-0.84})\,\%$$

  - does not exclude 8TeV
  - a hint of a signal?

$\tau \to \mu\pi\pi$

reinterpreting Celis, Cirigliano, Passemar, 1309.3564;
see also Petrov, Zhuridov, 1308.6561

- hadronic tau decays $\tau \to \mu\pi^+\pi^-, \tau \to \mu\pi^0\pi^0$
  - sensitive to both $Y_{\tau\mu}, Y_{\mu\tau}$ and light quark yukawas $Y_{u,d,s}$
  - $Y_{u,d,s}$ poorly bounded $\sim O(Y_b)$

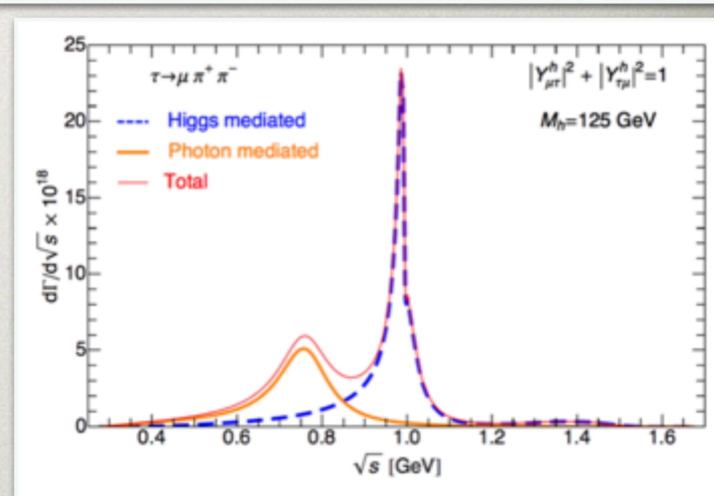


- for $Y_{u,d,s}$ at their SM values then

$$Br(\tau \to \mu\pi^+\pi^-) < 1.6 \times 10^{-11}, Br(\tau \to \mu\pi^0\pi^0) < 4.6 \times 10^{-12}$$
$$Br(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-10}, Br(\tau \to e\pi^0\pi^0) < 6.9 \times 10^{-11}$$

- for $Y_{u,d,s}$ at their present upper bounds

$$Br(\tau \to \mu\pi^+\pi^-) < 3.0 \times 10^{-8}, Br(\tau \to \mu\pi^0\pi^0) < 1.5 \times 10^{-8}$$
$$Br(\tau \to e\pi^+\pi^-) < 4.3 \times 10^{-7}, Br(\tau \to e\pi^0\pi^0) < 2.1 \times 10^{-7}$$



- $Br(\tau \to \mu\pi^+\pi^-)$ below present exp. limit, if discovered would (among other things) imply upper limit on $Y_{u,d}$
- similarly pseudoscalar Higgses can be bounded from $\tau \to \mu\pi(\eta,\eta')$, $\tau \to e\pi(\eta,\eta')$
  - can saturate present experimental limits

CORRELATED BOUNDS

- $\mu\to e\gamma$ and $\mu\to e$ conversion constrain also the products of off-diagonal tau Yukawas
  - setting $Y_{\mu e}$ and $Y_{e\mu}$ to zero one has

$$\mathcal{B}(\mu\to e\gamma)\simeq \mathcal{B}_0^{\mu\to e\gamma}\left(|y_{\mu\tau}y_{\tau e}|^2+|y_{\tau\mu}y_{e\tau}|^2\right)\,,\qquad \mathcal{B}_0^{\mu\to e\gamma}=185\,.$$

$$\mathcal{B}(\mu\to e)_{\rm Au}=\mathcal{B}_0^{\mu e}\left(|y_{e\tau}y_{\mu\tau}|^2+|y_{\tau e}y_{\tau\mu}|^2\right)\,,\qquad \mathcal{B}_0^{\mu e}=4.67\times 10^{-4}\,,$$

- one then has a constraint on FV Higgs decay Br's

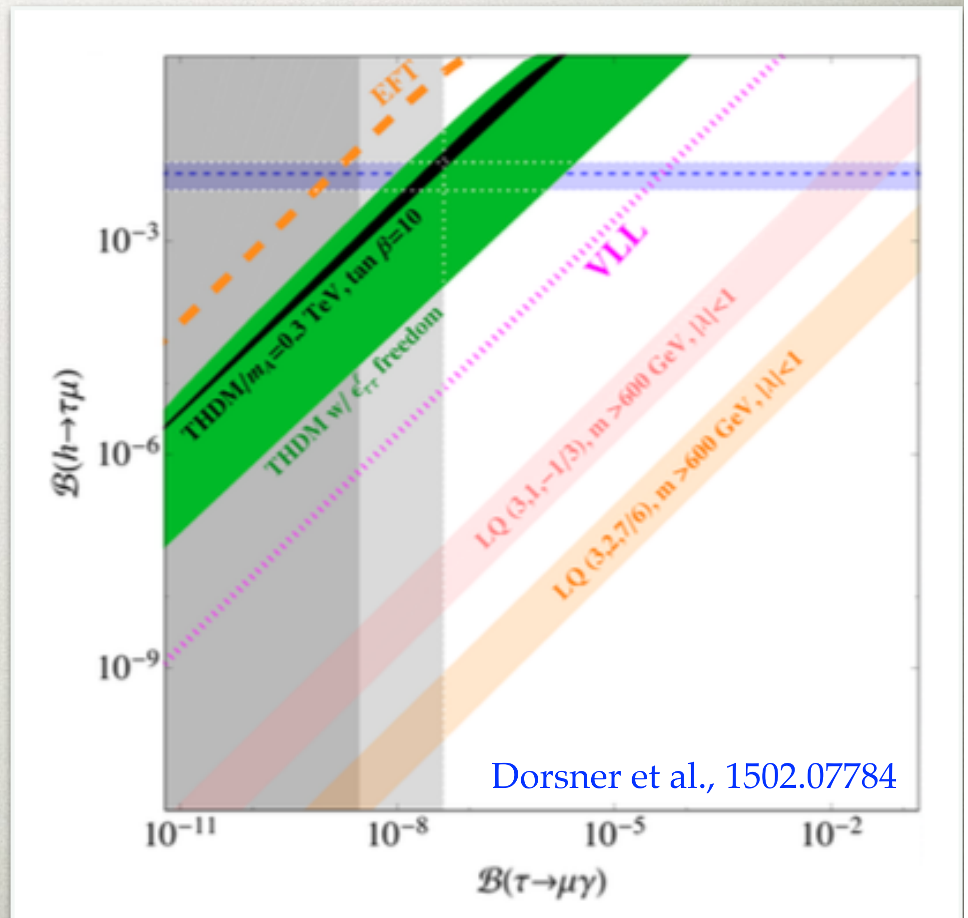
Dorsner, Fajfer, Greljo, Kamenik, Kosnik, Nisandzic, 1502.07784

$$\mathcal{B}(h\to\tau\mu)\times\mathcal{B}(h\to\tau e)=7.95\times10^{-10}\left[\frac{\mathcal{B}(\mu\to e\gamma)}{10^{-13}}\right]+3.15\times10^{-4}\left[\frac{\mathcal{B}(\mu\to e)_{\rm Au}}{10^{-13}}\right]$$

- $\Rightarrow$ if $Br(h\to\tau\mu)$ is at the CMS central value, then $Br(h\to\tau e)<25\%$
  - improving $\mu\to e$ conversion can have a big effect

LARGE FV HIGGS DECAYS?

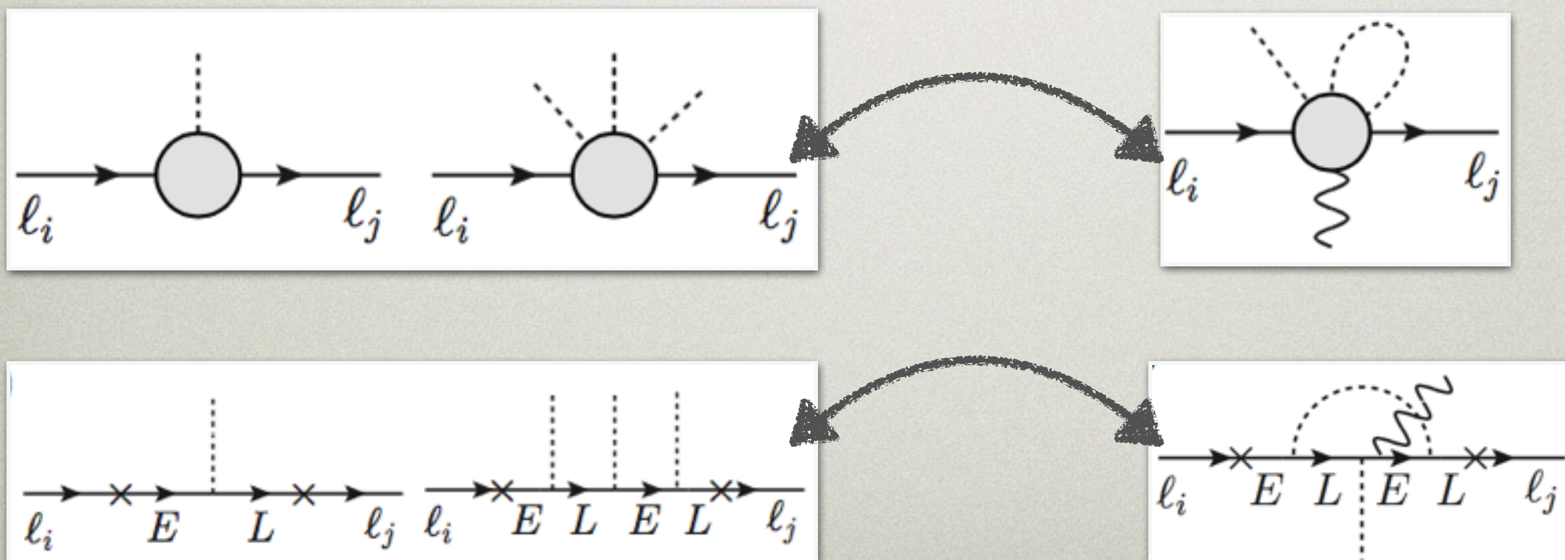
- Can one have large flavor violating Higgs decays in reasonable NP models?
- What is so special about type III 2HDM?



LARGE FV

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

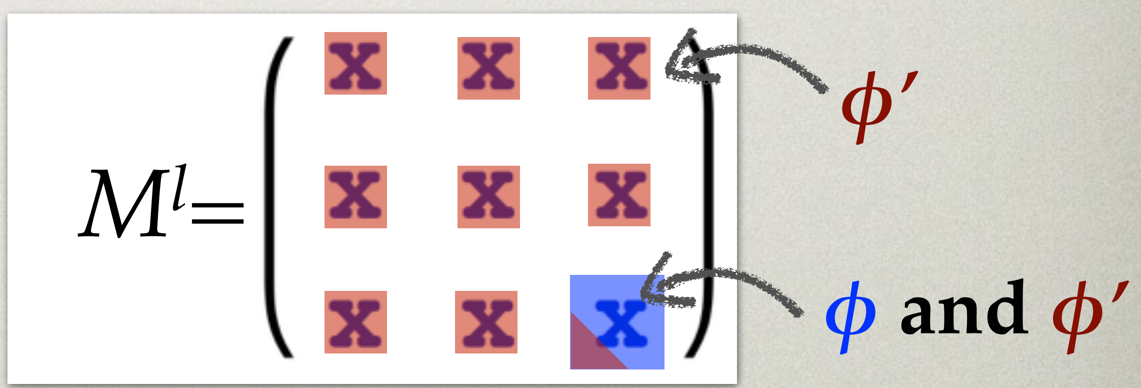
- a generic obstacle to large $h \to \tau\mu$ is the bound on $\tau \to \mu\gamma$
  - improvement on $Br(\tau \to \mu\gamma)$ can have a big impact
- same diagrams that generate fermion masses (higgs yukawas) also give $\tau \to \mu\gamma$



LARGE FV

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

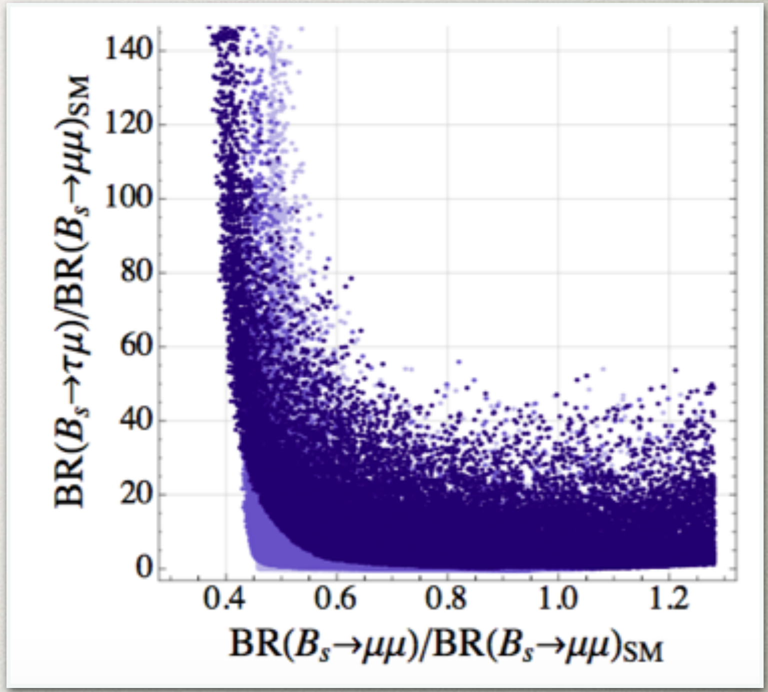
- a viable set of models
  - decouple fermion mass generation from $\tau \to \mu\gamma$
  - possible if new source of EWSB
  - for instance if our higgs only responsible for tau mass
  - e.g. in 2HDM



  - but could also be other sources of mass (TC,..)

PHENOMENOLOGICAL IMPLICATIONS

Altmannshofer, Gori, Kagan, Silvestrini, JZ, to appear

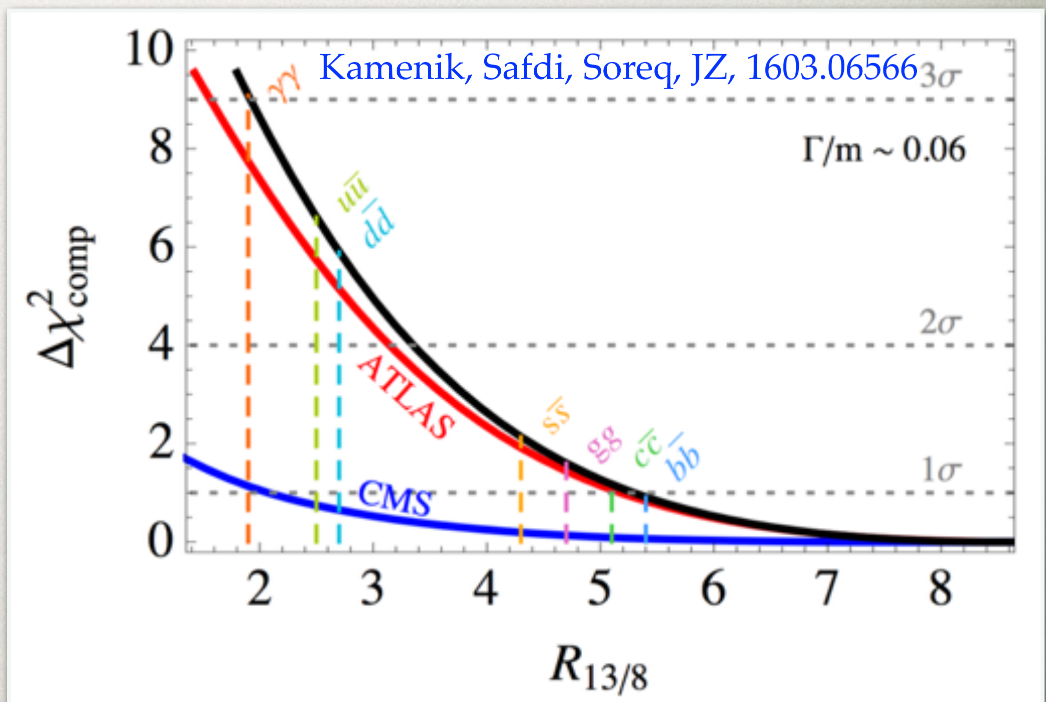


- $B_s\to\mu\mu$ can be modified by *O(1)*
- sizable $B_s\to\tau\mu$, $B\to K\tau\mu$, $B\to K^*\tau\mu$
- anomalies could be seen in B_s mixing, $\tau\to\mu\gamma$, $b\to s\gamma$
- leptonic heavy Higgs *(H)* decays to $\mu\mu$ dominate over $\tau\tau$
  - opposite to Type-II 2HDMs
  - lower bound on $H\to\tau\mu$

Efrati, Kamenik, Nir, work in progress

750 GeV

- other NP states can have nontrivial flavor interactions
- e.g. 750 GeV di-photon
- right now preference for couplings to heavy quarks of gluons
- flavor violating decays of S severely constrained

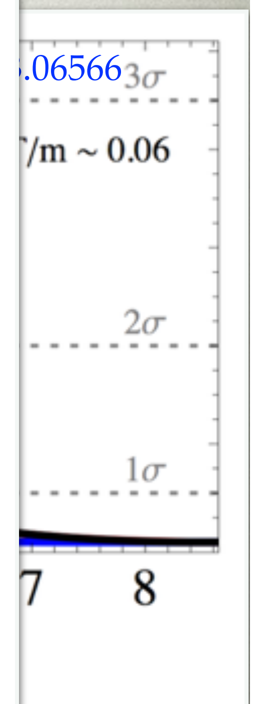


750 GeV

- other NP states can have nontrivial flavor interac
- e.g. 75
- right r for cou quarks
- flavor of S se

Goertz, Kamenik, Katz, Nardecchia, 1512.08500

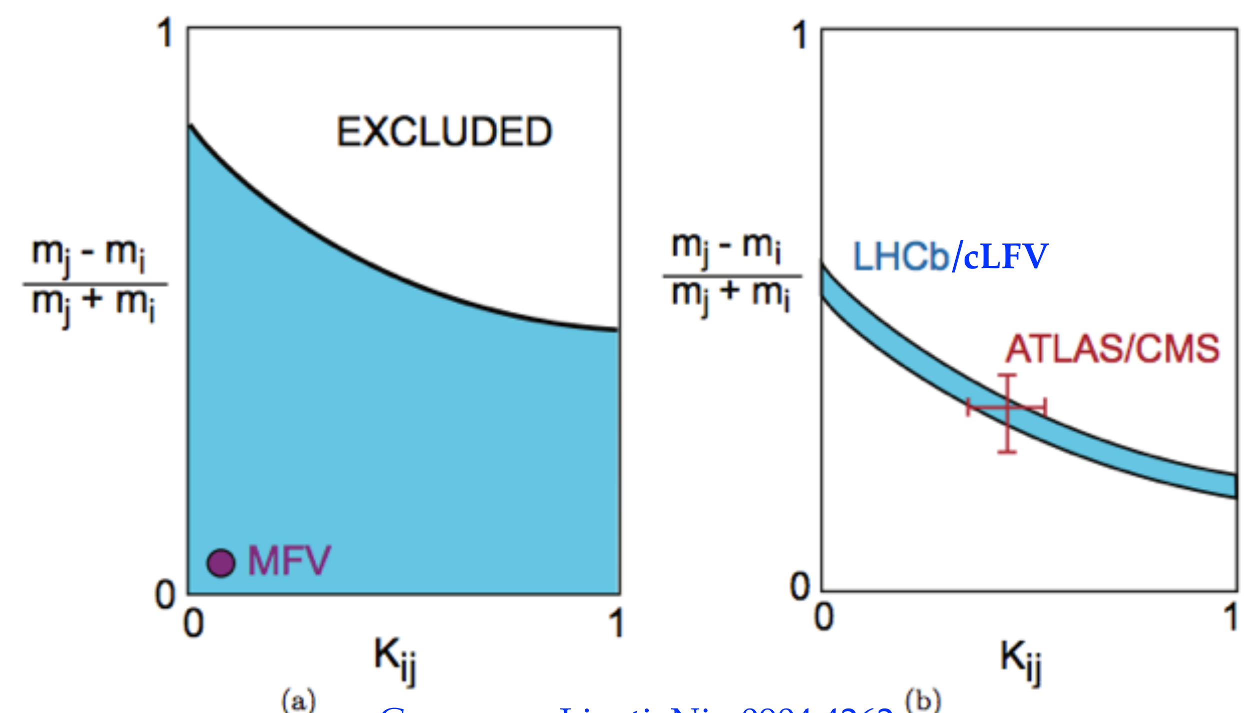
Bound on $Y_{f,f'}$	Observable	$\Gamma(S \to f f')/M$
$\lvert\mathrm{Im}(Y_{ee})\rvert \lesssim 6 \times 10^{-8}$	d_e	$\lesssim 1 \times 10^{-16}$
$\lvert\mathrm{Im}(Y_{dd})\rvert \lesssim 2 \times 10^{-4}$	d_N, d_{Hg}	$\lesssim 5 \times 10^{-9}$
$\lvert\mathrm{Im}(Y_{uu})\rvert \lesssim 3 \times 10^{-4}$	d_N, d_{Hg}	$\lesssim 1 \times 10^{-8}$
$\lvert\mathrm{Im}(Y_{cc})\rvert \lesssim 0.3$	d_N, d_{Hg}	$\lesssim 0.01$
$\lvert Y_{e\mu}\rvert, \lvert Y_{\mu e}\rvert \lesssim 1 \times 10^{-5}$	$\mathcal{B}(\mu \to e\gamma)$	$\lesssim 4 \times 10^{-12}$
$\lvert Y_{e\tau}\rvert, \lvert Y_{\tau e}\rvert \lesssim 0.05$	$\mathcal{B}(\tau \to e\gamma)$	$\lesssim 1 \times 10^{-4}$
$\lvert Y_{\mu\tau}\rvert, \lvert Y_{\tau\mu}\rvert \lesssim 0.06$	$\mathcal{B}(\tau \to \mu\gamma)$	$\lesssim 1 \times 10^{-4}$
$\sqrt{\mathrm{Re}[(Y_{sd})^2]}, \sqrt{\mathrm{Re}[(Y_{ds})^2]} < 1.0 \times 10^{-4}$	Δm_K	$< 1.2 \times 10^{-9}$
$\sqrt{\mathrm{Im}[(Y_{sd})^2]}, \sqrt{\mathrm{Im}[(Y_{ds})^2]} < 7.2 \times 10^{-6}$	ϵ_K	$< 6.2 \times 10^{-12}$
$\lvert(Y_{cu})\rvert, \lvert(Y_{uc})\rvert < 3.0 \times 10^{-4}$	x_D	$< 1.1 \times 10^{-8}$
$\lvert(Y_{bd})\rvert, \lvert(Y_{db})\rvert < 6.4 \times 10^{-4}$	Δm_d	$< 4.9 \times 10^{-8}$
$\lvert(Y_{bs})\rvert, \lvert(Y_{sb})\rvert < 5.7 \times 10^{-3}$	Δm_s	$< 3.9 \times 10^{-6}$



TAKE HOME MESSAGE #1

- there is complementarity between cLFV and high p_T searches for New Physics
  - they measure orthogonal properties

see also Galon, Shadmi, 1108.2220

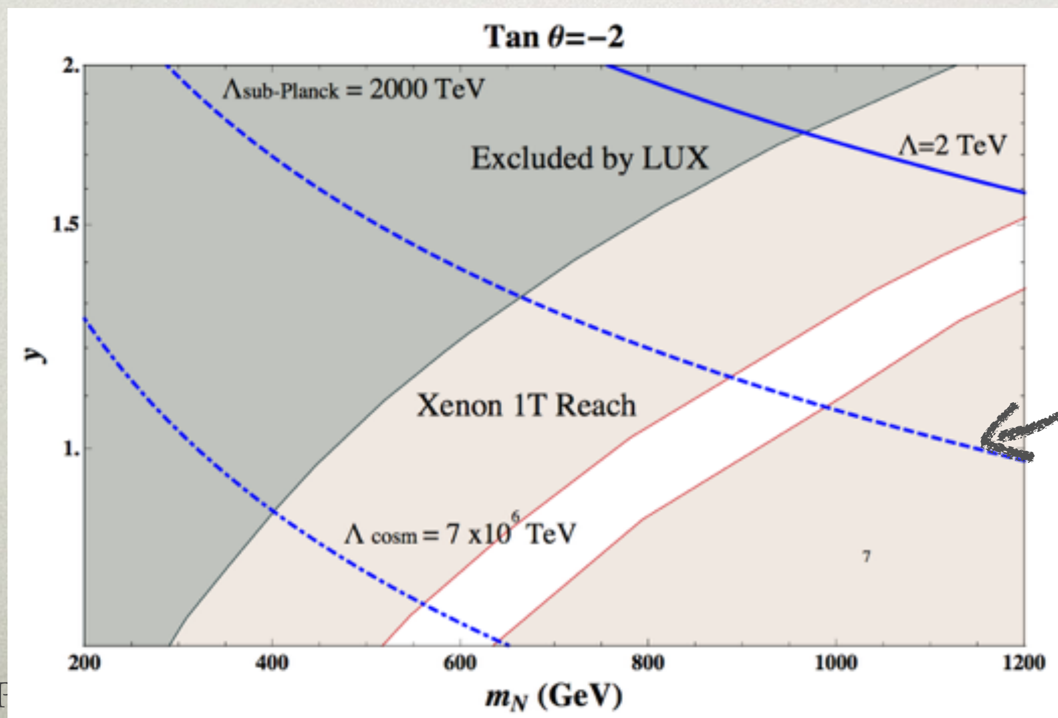


Grossman, Ligeti, Nir, 0904.4262

TAKE HOME MESSAGE #2

- cLFV signals could come from unexpected NP corners
- example: relaxion mechanism to make EW scale technically natural through cosmological evolution
  - some concrete realizations require extra Z_2 odd charged leptons
  - if any mixing with SM leptons ⇒ cLFV

Gupta et al., 1509.00047

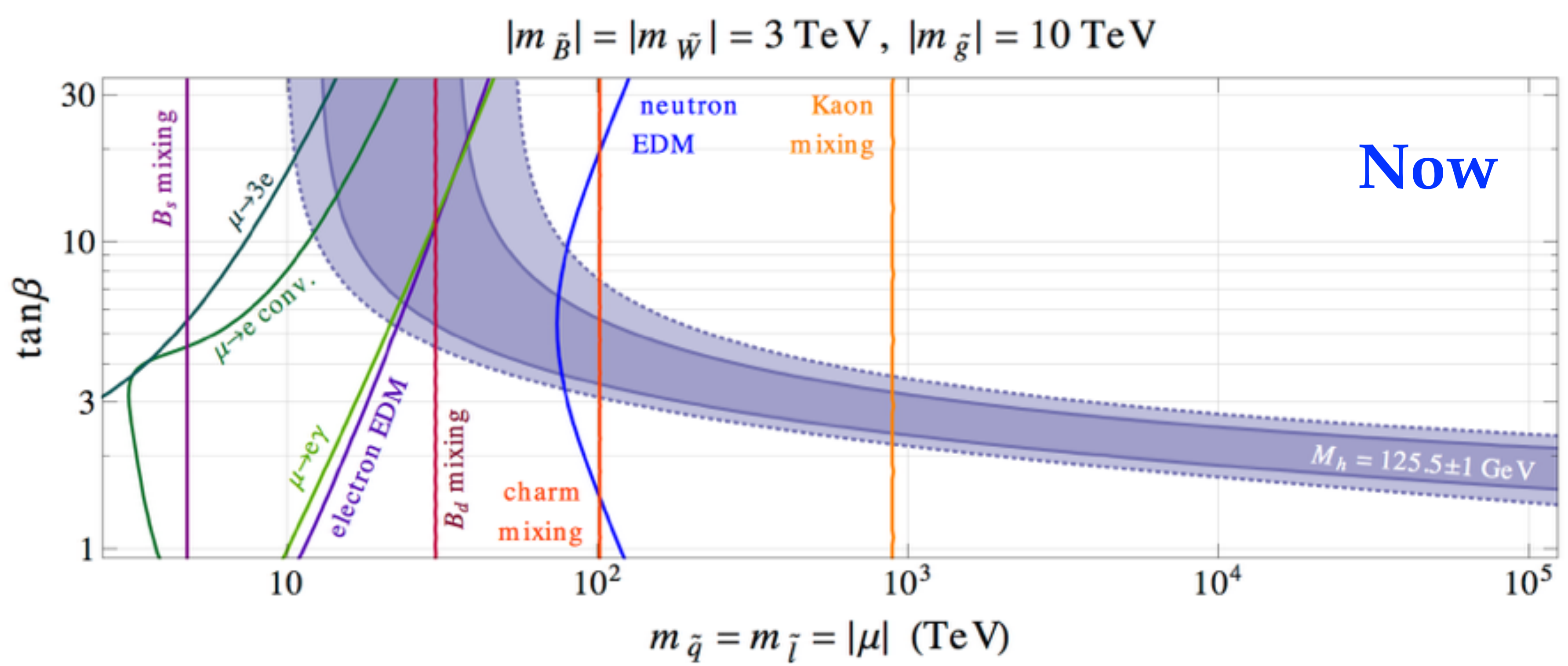


large couplings,
low mass scale

TAKE HOME MESSAGE #3

- cLFV can probe high scale
- examples mini-split SUSY
- *O(1-10TeV)* gauginos at LHC or future collider; PeV sfermions from low energy precision probes

see also McKeen, Pospelov, Ritz, 1303.1172

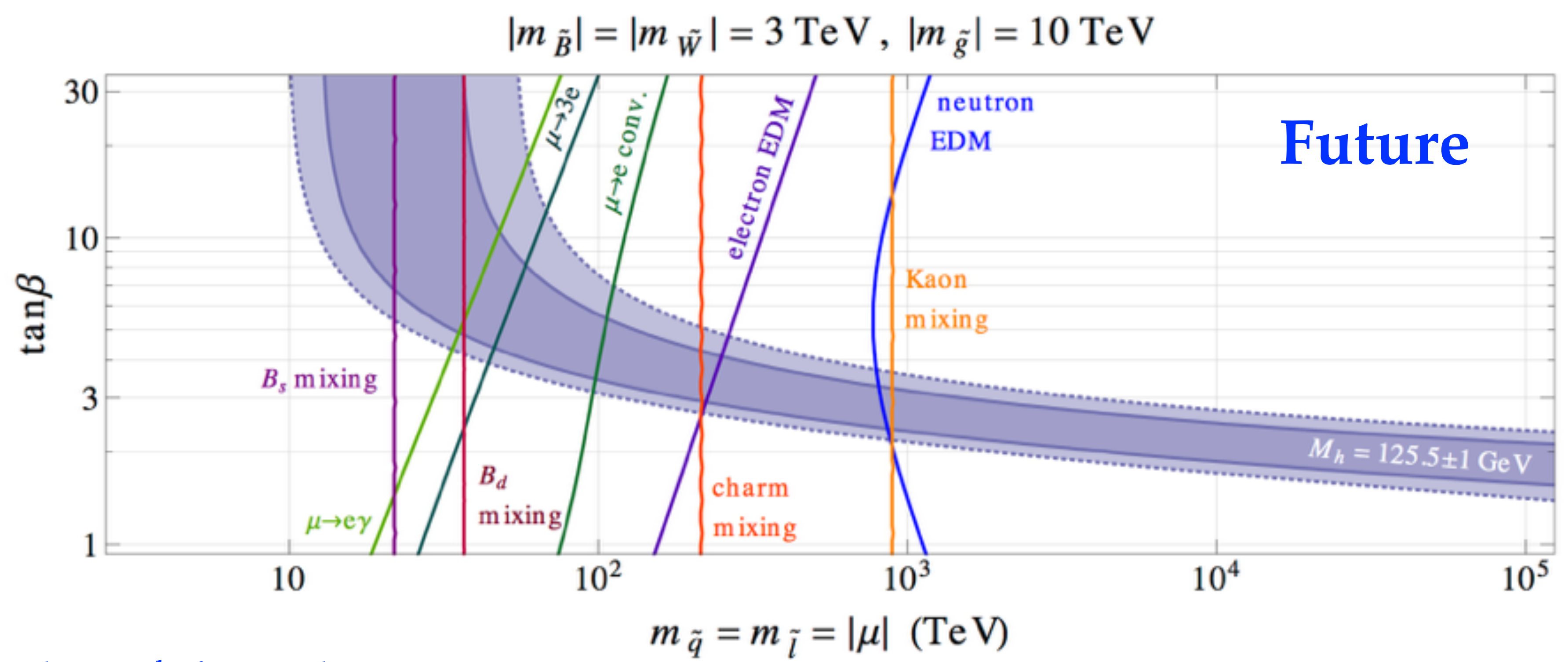


Altmannshofer,Harnik, JZ, 1308.3653

TAKE HOME MESSAGE #3

- and will improve dramatically in the future

see also McKeen, Pospelov, Ritz, 1303.1172



Altmannshofer,Harnik, JZ, 1308.3653

CONCLUSIONS

- cLFV searches are an indispensable part of particle physicist's toolkit
- shown examples where cLFV probe see-saw models, Higgs Yukawas, PeV SUSY, 750 GeV scalar..
  - the discovery may well be in an unexpected corner of NP model space

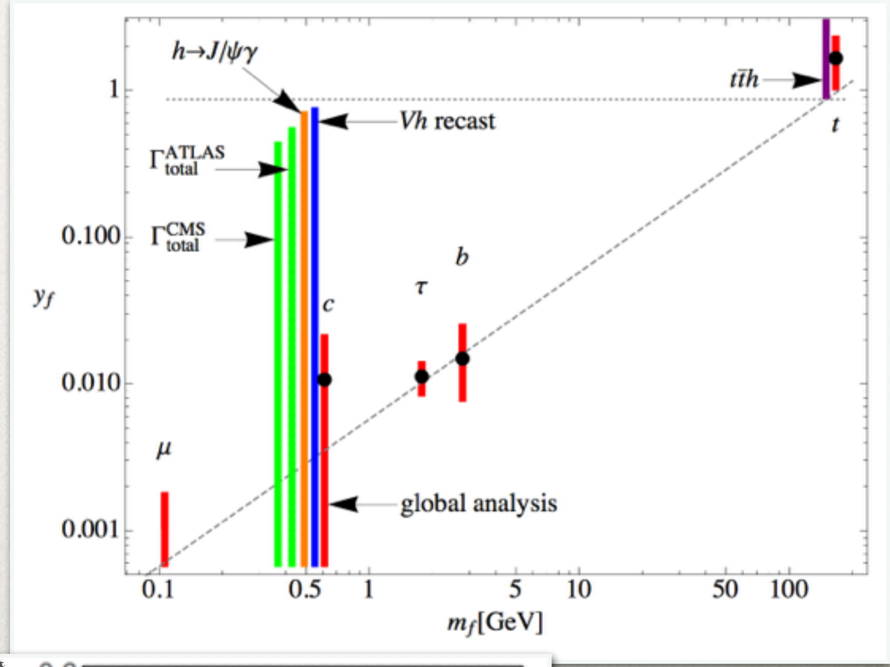
BACKUP SLIDES

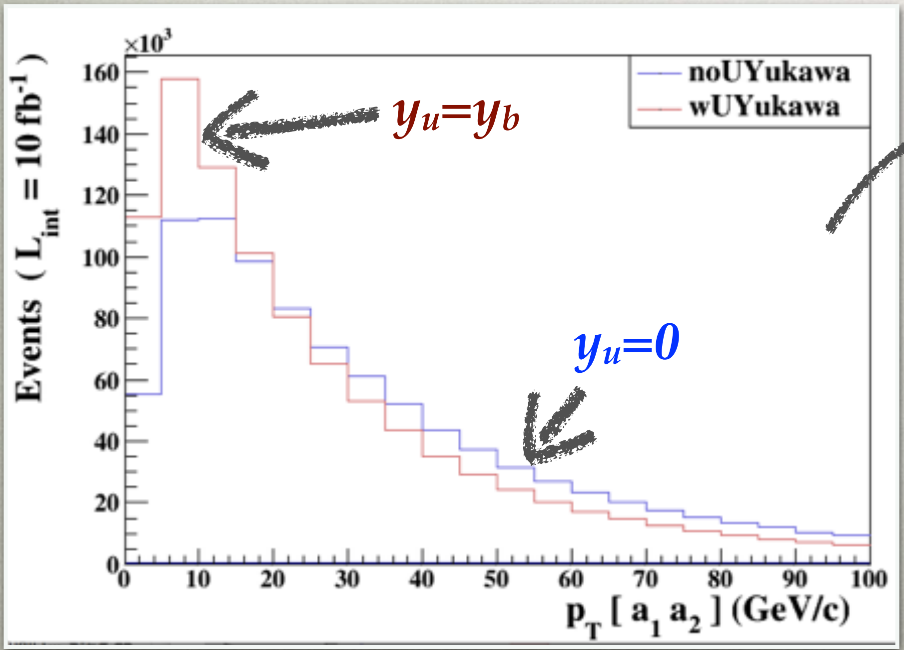
FOR LIGHT QUARK YUKAWA COUPLINGS

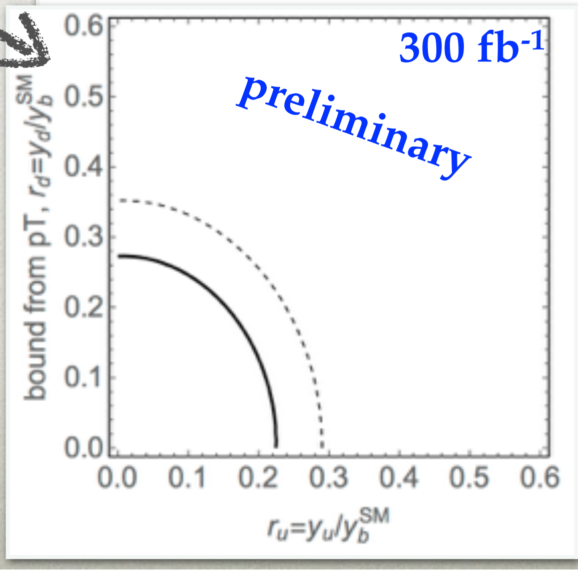
- several indirect probes of 1[st] and 2[nd] generation Higgs yukawas
  - using charm tagging for $h \to c\bar{c}$ inclusive decays
    Perez, Soreq, Stamou, Tobioka, 1503.00290
  - exclusive decays: $h \to \Upsilon\gamma$ (y_b), $h \to J/\psi\gamma$ (y_c), $h \to \phi\gamma$ (y_s)
    Bodwin, Petriello, Stoynev, Velasco, 1306.5770
    Konig, Neubert, 1505.03870
    Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
  - potentially isotopic shift measurements
    Delaunay, Ozeri, Perez, Soreq, 1601.05087

HIGGS FLAVOR NON-UNIVERSALITY

- for up-quarks and charged leptons the non-universality established
  - how about down quarks?
- possible from p_T and η distribution of h





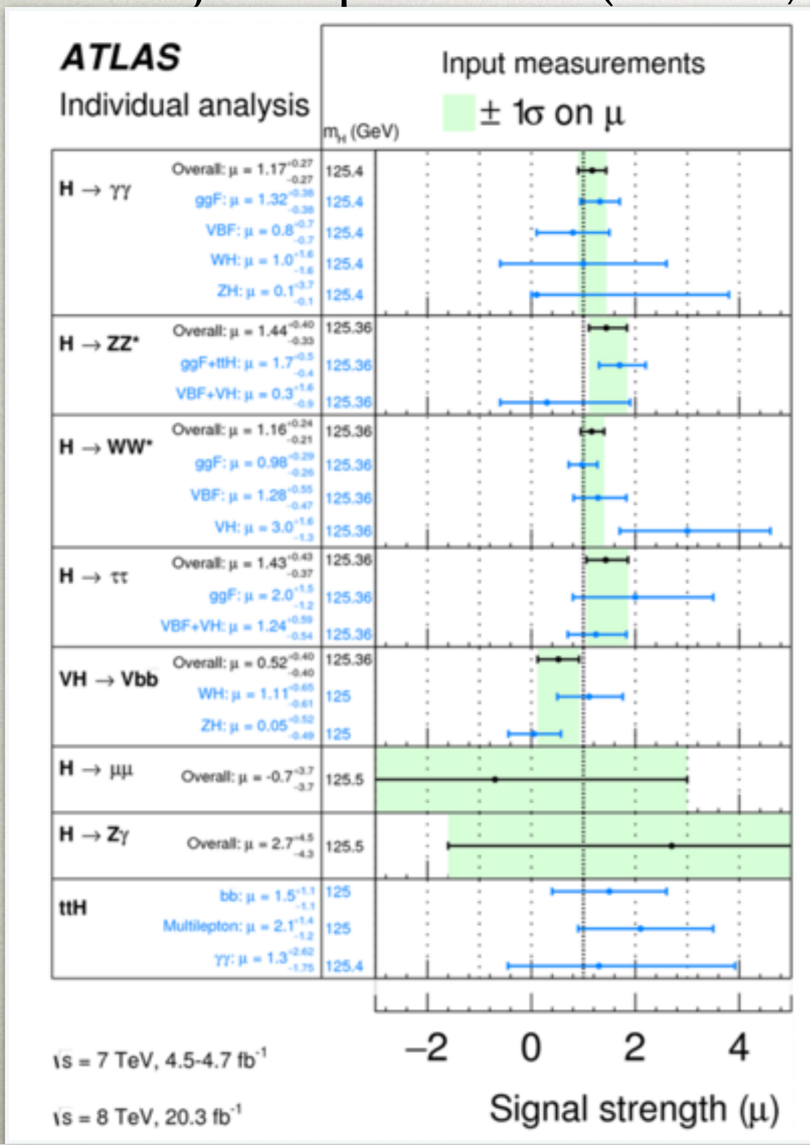


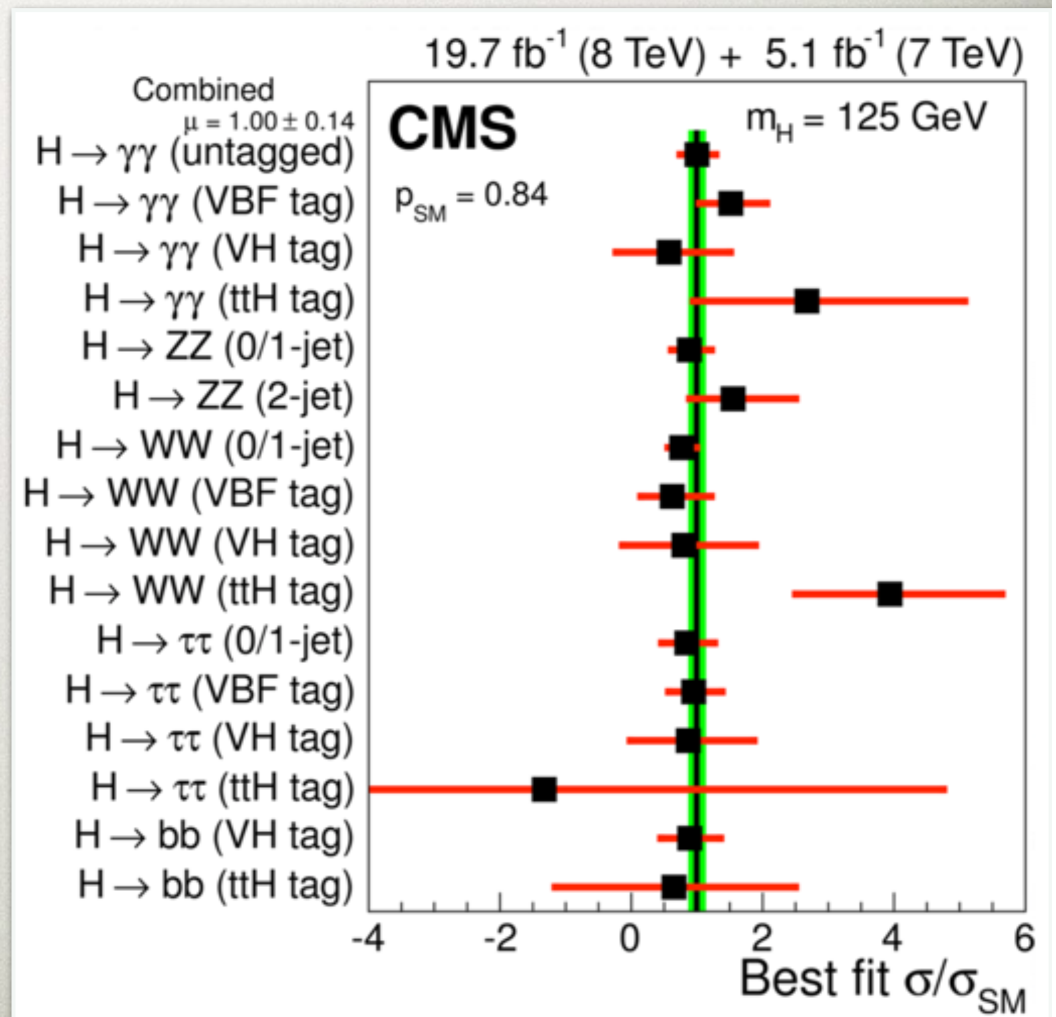
Soreq, Zhu, JZ,
work in progress

MEASUREMENTS

talk by M. Pieri at LHCP2015

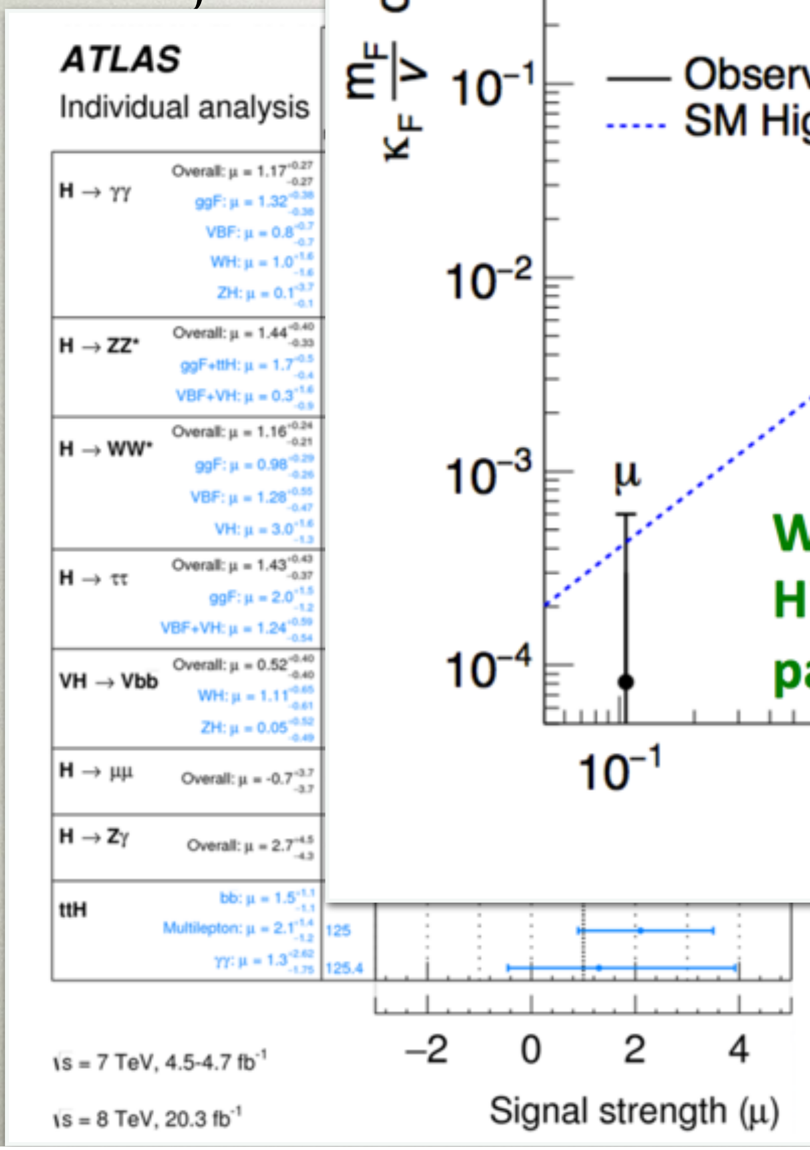
- $J^P = 0^+$ preferred (at 97.8% C.L. over 0^-)

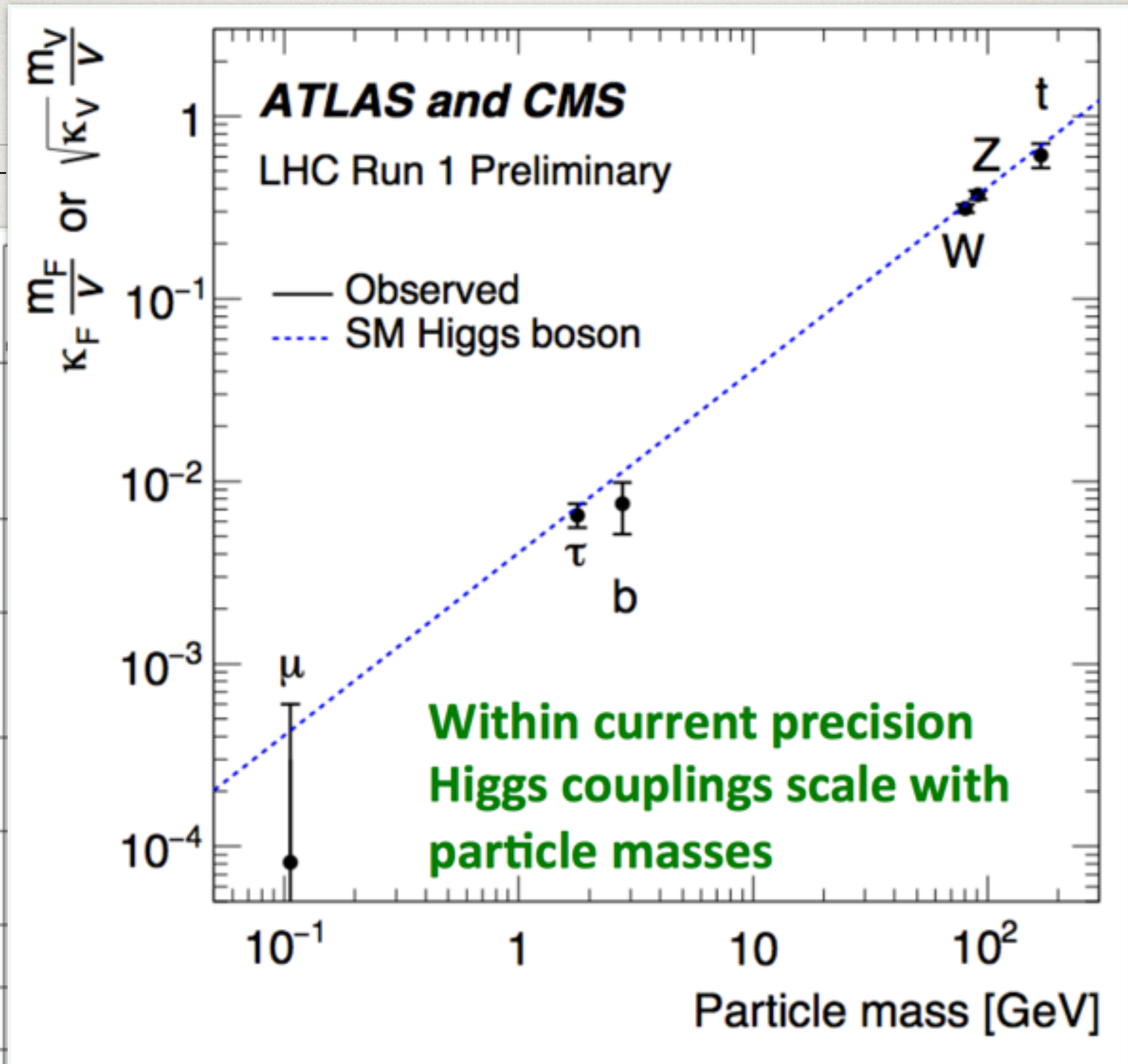


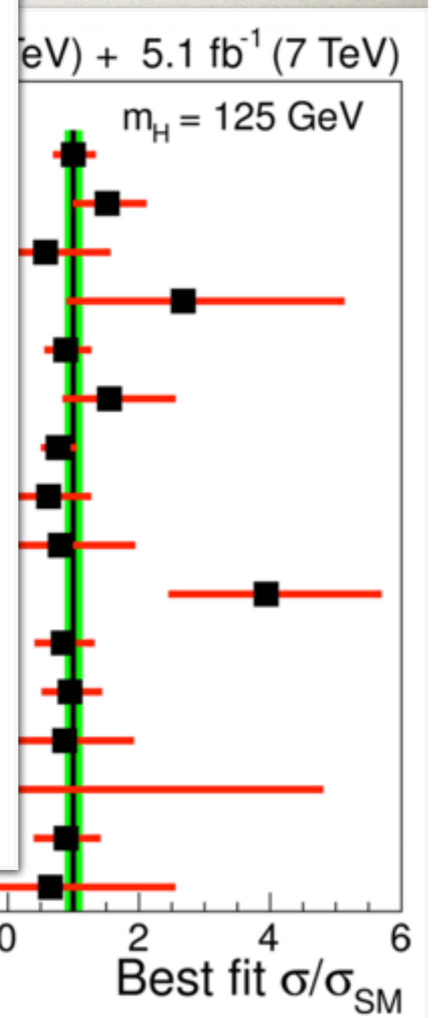


M. Pieri at LHCP2015

• $J^P=0^+$





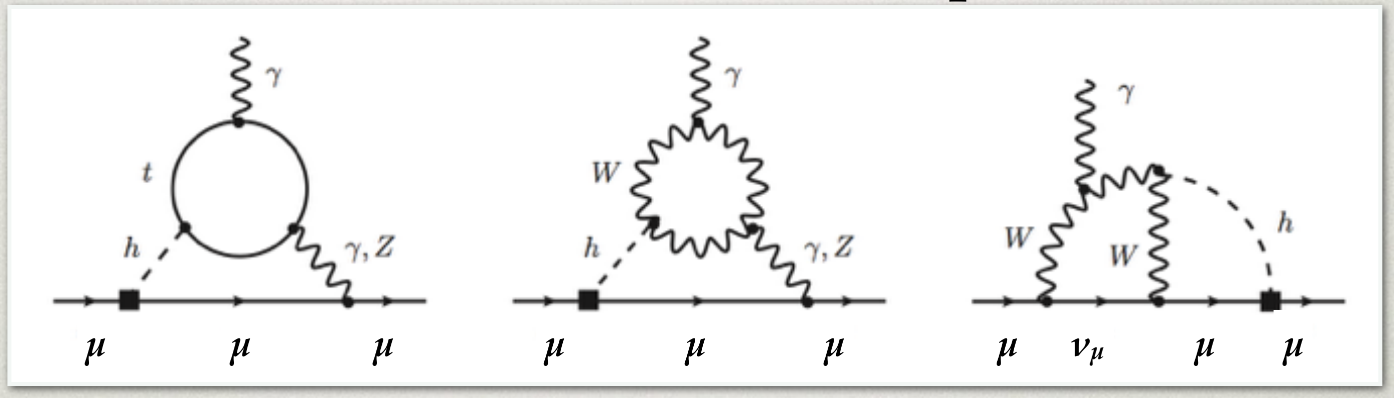


3;

MUON YUKAWA

thanks to J. Brod

- similarly, $\tilde{\kappa}_\mu \neq 0$ induces muon EDM
  - dominant contributions at 2-loop



- experimental bound Muon (g-2) Collaboration, 0811.1207

$$|d_\mu| < 1.9 \times 10^{-19} \; e{\cdot}\mathrm{cm} \; (95\% \; \mathrm{C.L.}).$$

$$|\tilde{\kappa}_\mu| < 1.8 \times 10^5$$

- compare with CMS-HIG-13-007; ATLAS 1406.7663

$$Br(h \to \mu^+\mu^-) < 1.5 \times 10^{-3}$$

$$\sqrt{|\kappa_\mu|^2 + |\tilde{\kappa}_\mu|^2} < 7.0$$