HIGGS AND FLAVOR
(WITH FOCUS ON FCNCs)

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THE MAIN MESSAGE

- fermion masses break EW symmetry

$$\mathscr{L} \supset - m_f \bar{f}_L f_R$$

  - in the SM due to Higgs

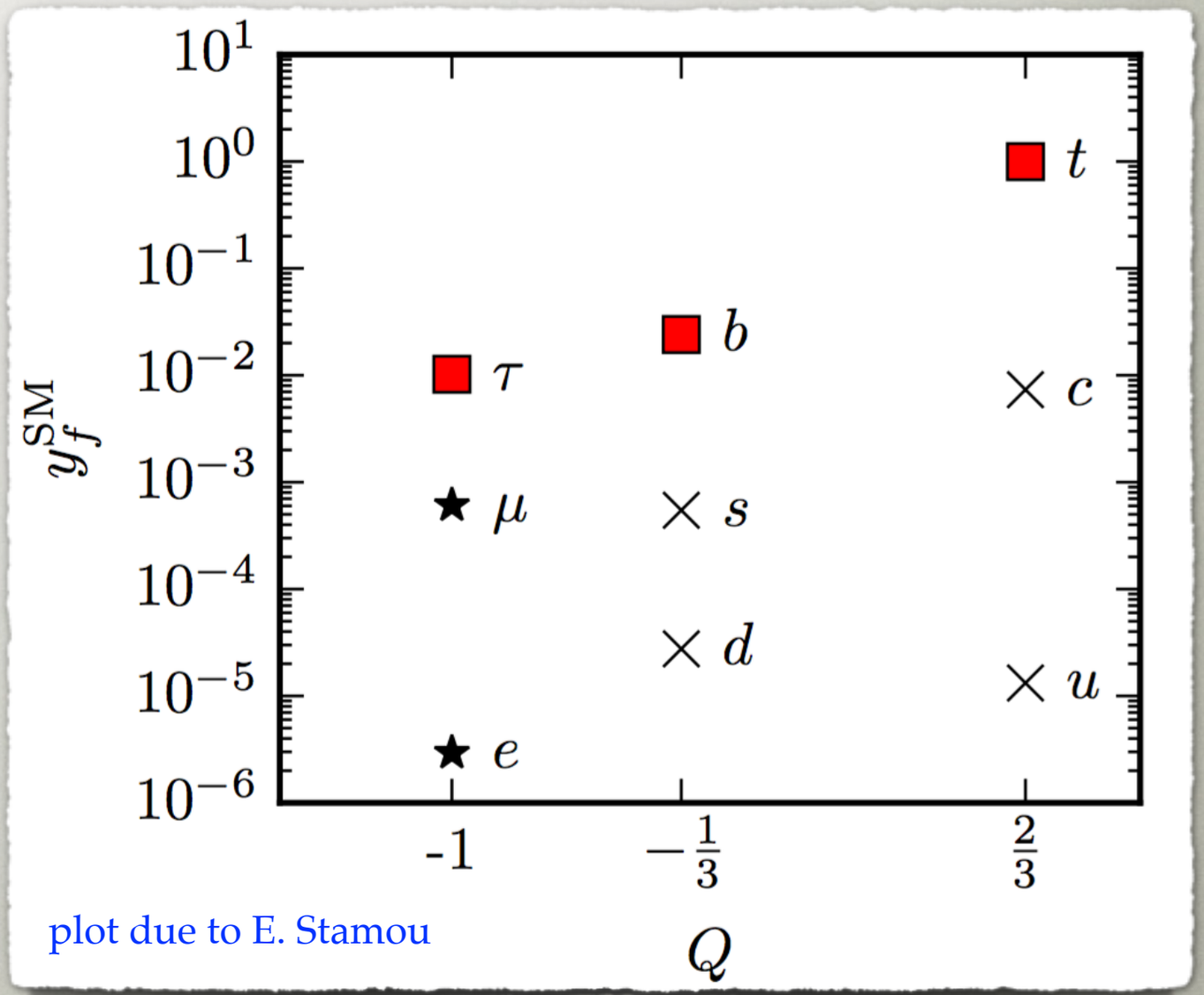
- 1st, 2nd gen. small fermion masses
  - could easily be due to new physics/new EWSB source
  - generically lead to FV Higgs Yukawas
  - small couplings ⇒ precision⇒FCC

HIGGS = NONTRIVIAL FLAVOR STRUCTURE

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

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

- we want to test this



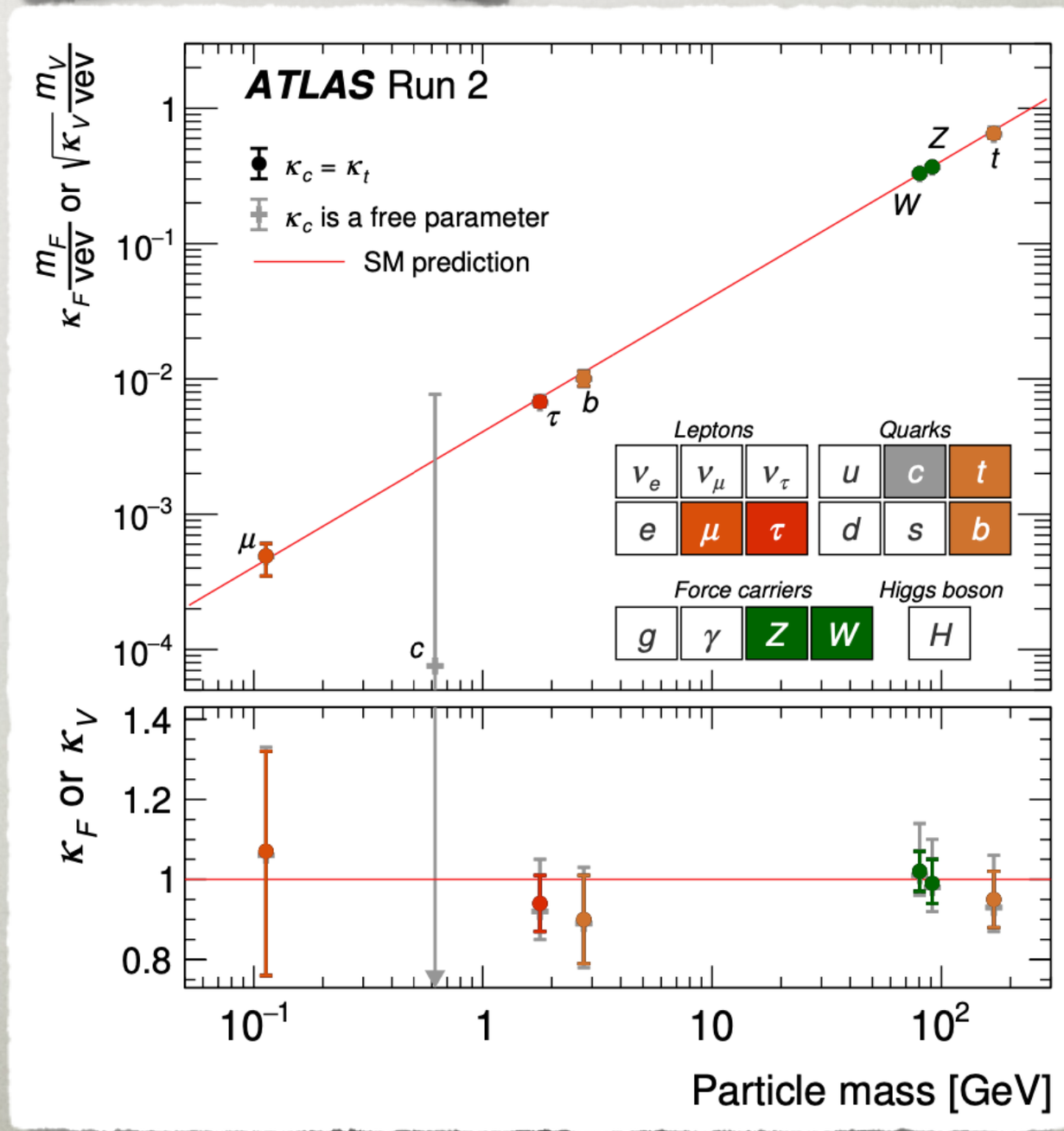
plot due to E. Stamou

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433; JZ 1903.05062

- 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
  $\mathrm{Im}(y_{ij}) = 0$

$$y_f^{\rm SM} = \sqrt{2} m_f / v$$



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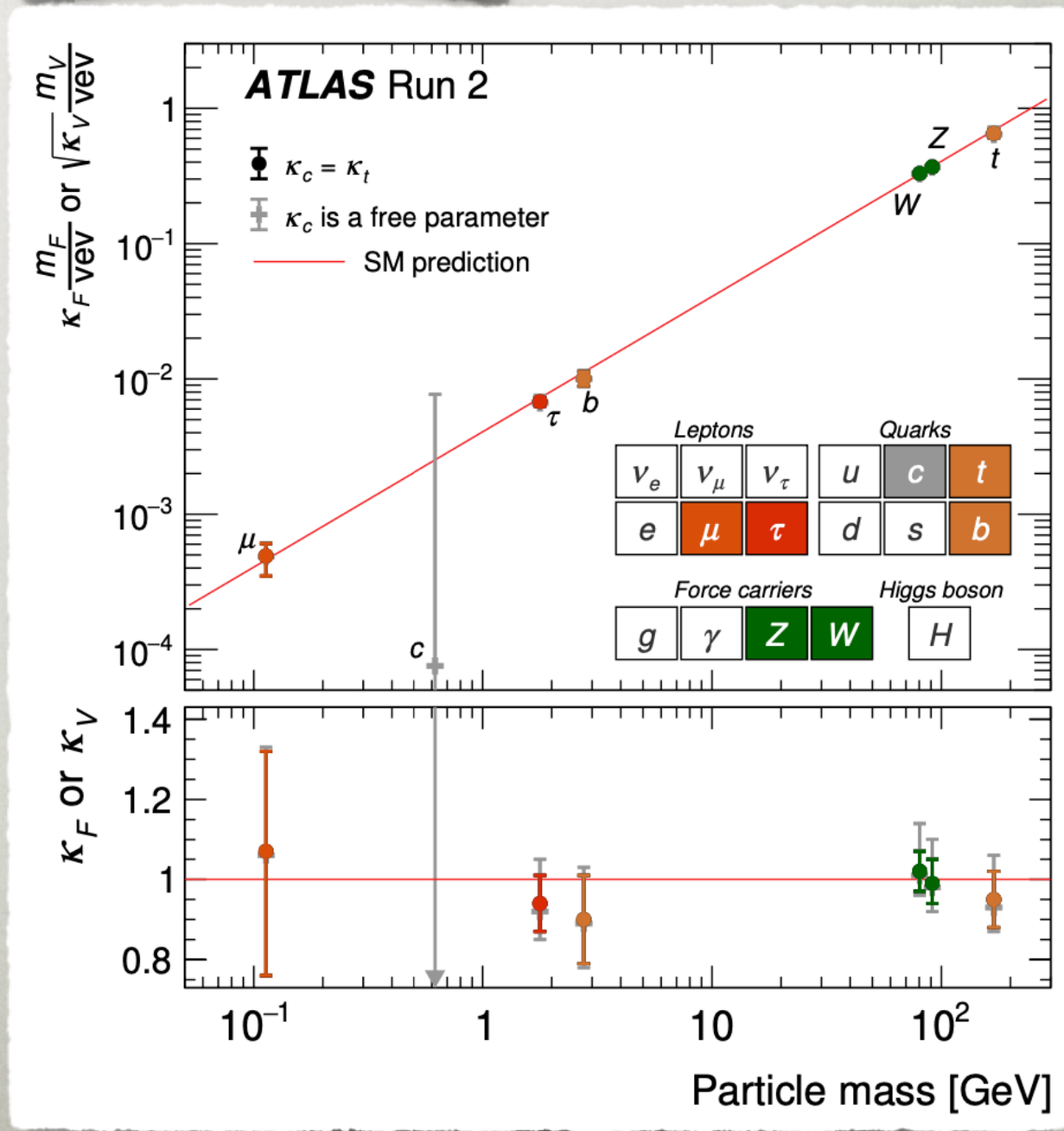

NEW PHYSICS CORRECTIONS TO HIGGS COUPLINGS

- in SMEFT, the Yukawas get corrected by higher dim. ops

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

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

  - there could be other sources of EWSB

- NP in general misaligns mass and Yukawa matrices

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

$$m = \left(\lambda + \frac{v^2}{2\Lambda^2}\lambda'\right)\frac{v}{\sqrt{2}}$$

$$Y = \left(\lambda + 3\frac{v^2}{2\Lambda^2}\lambda'\right)\frac{1}{\sqrt{2}}$$

$$m = v\begin{pmatrix} * + *' & * + *' & * + *' \\ * + *' & * + *' & * + *' \\ * + *' & * + *' & * + *' \end{pmatrix}$$

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CPV and FV higgs couplings to SM fermions

$$m = v \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix} \qquad Y = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

- NP contribs in general lead to Harnik, Kopp, JZ, 1209.1397
  - flavor violating Higgs decays Blackenburg, Ellis, Isidori, 1202.5704
  - CPV Higgs decays
- different models lead to different patterns of flavor diagonal and flavor violating Yukawas
- note: large Yukawas for light fermions require significant tuning in contributions to fermion masses

CPV and FV higgs

Bishara et al, 1504.04022

Model	$\kappa_{ct(tc)}/\kappa_t$	$\kappa_{ut(tu)}/\kappa_t$	$\kappa_{uc(cu)}/\kappa_t$
GL & GL2	$\epsilon(\epsilon^2)$	$\epsilon(\epsilon^2)$	ϵ^3
MFV	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{cb}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(c)}}{v_W}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(u)}}{v_W}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^*\right)}{\Lambda^2}\frac{\sqrt{2}m_{c(u)}}{v_W}$
RS	$\sim \lambda^{(-)2}\frac{m_{t(c)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)3}\frac{m_{t(u)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)1}\frac{m_{c(u)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$
pNGB	$\mathcal{O}(y_*^2\frac{m_t}{v_W}\frac{\lambda_{L(R),2}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_t}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_c}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),2}m_W^2}{M_*^2})$

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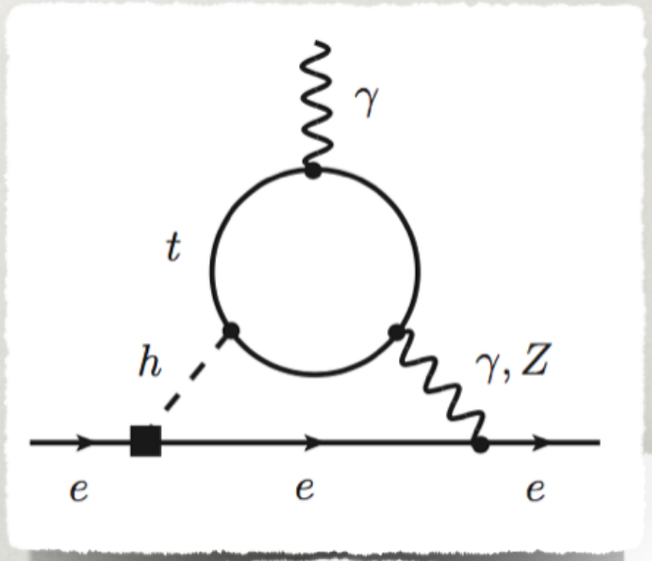
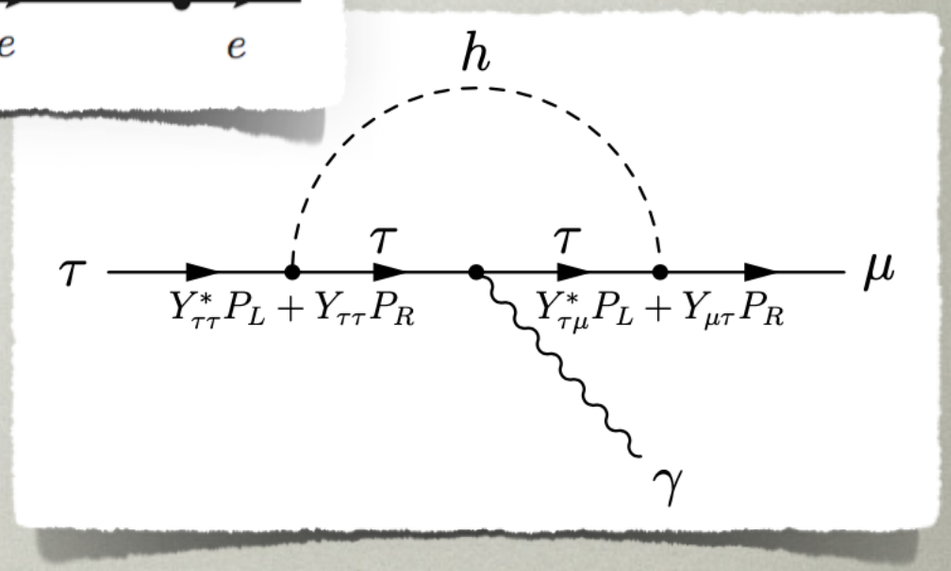
OTHER CONSTRAINTS

- both CPV and FV Higgs couplings face severe indirect constraints
  - CPV from EDM
  - FV from low energy FCNC processes
    - wide open for HL-LHC & FCC: $h \to \tau\mu, \tau e$ and $t \to hc, hu$





CP violating

Higgs Yukawas

EDM CONSTRAINTS

Brod et al, 2203.03736

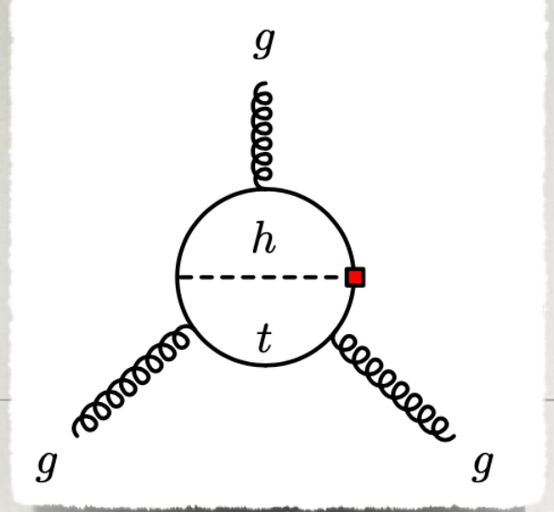
- CPV dim. 6 ops contribute to EDMs through loops

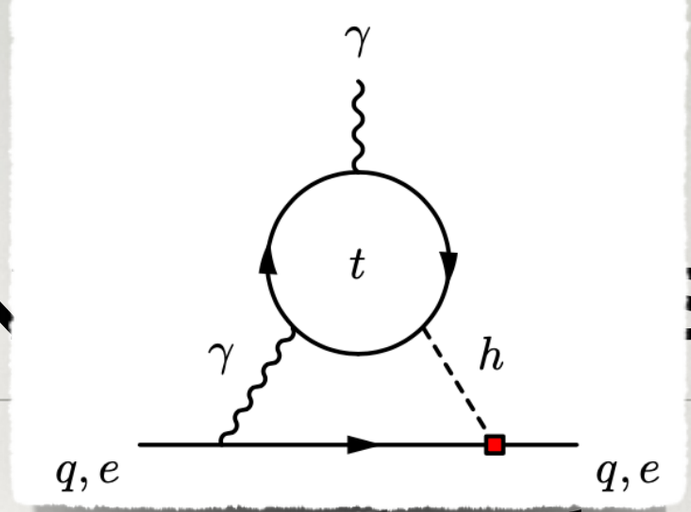
$$\mathscr{L}_h = -\sum_{f=u,d,\ell} \frac{h}{\sqrt{2}} \bar{f}_L \left(y_f^{\rm SM} - \frac{v^2}{\Lambda^2} C_{fH} \right) f_R + \text{h.c.},$$

$$C_{fH,ij} = C_{fH+,ij} + iC_{fH-,ij}$$

  - 2-loop electroweak mixing⇒large logs⇒ leading log QCD resummation

- if single flavor dominates ⇒ in general stringent constraints
  - two extreme cases: top and muon
- if more than one flavor important
  - cancellations in EDMs possible but not in LHC constr.
  - the parameter space for CPV couplings opens up ⇒FCC





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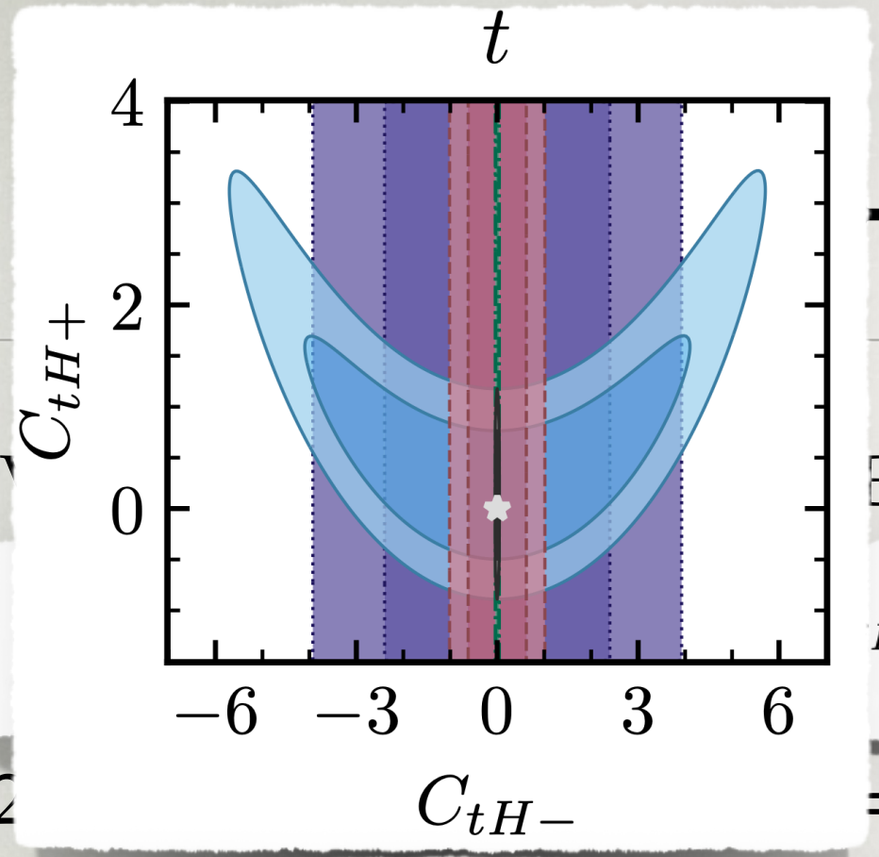

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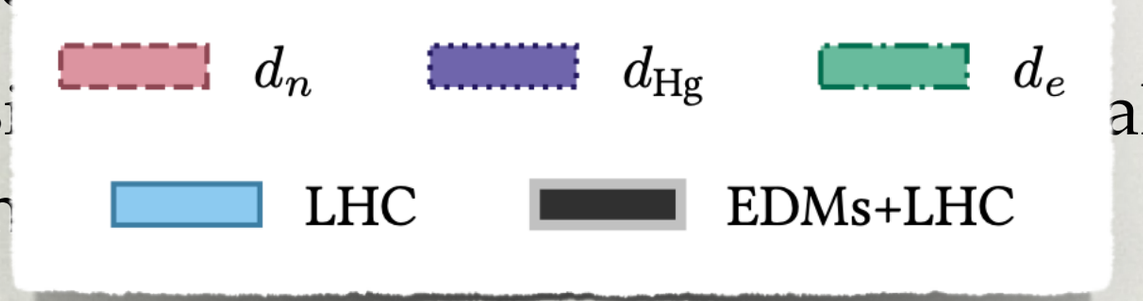

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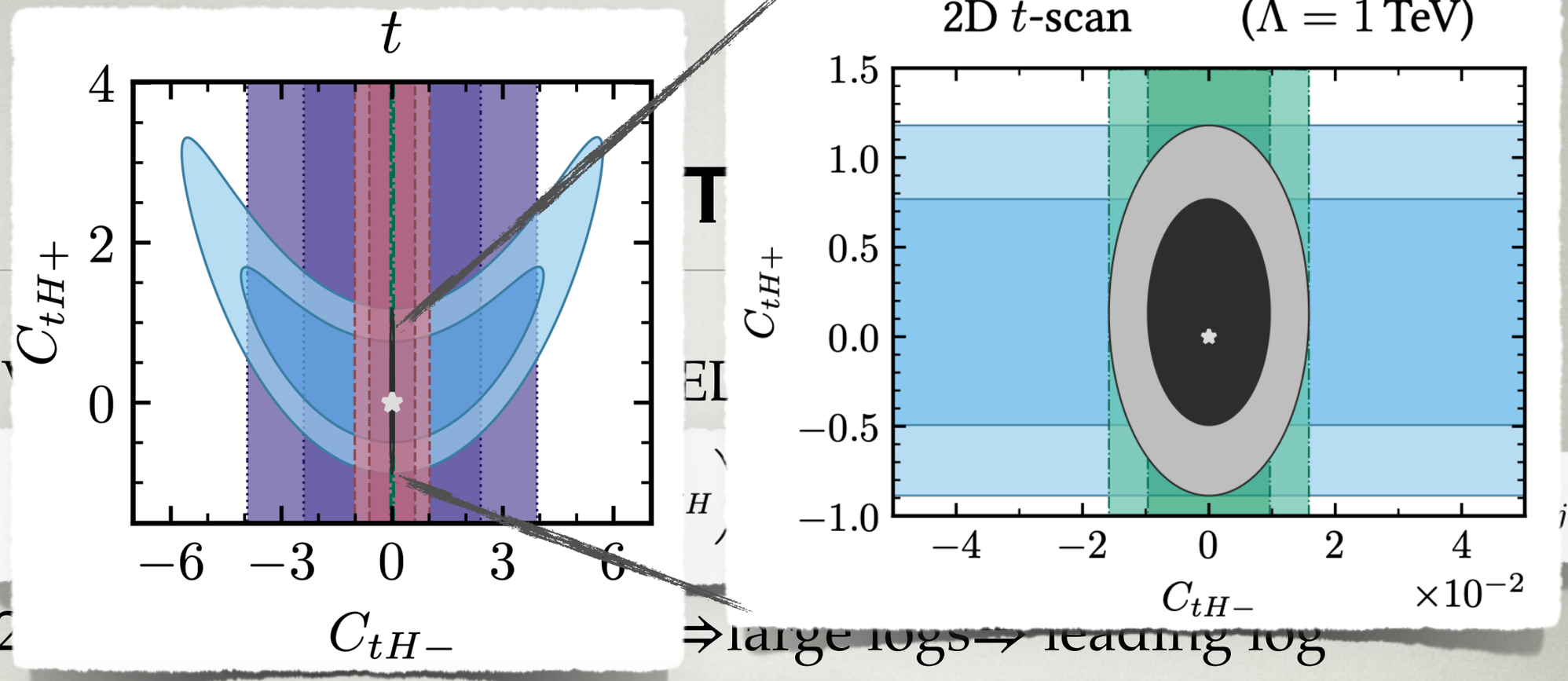

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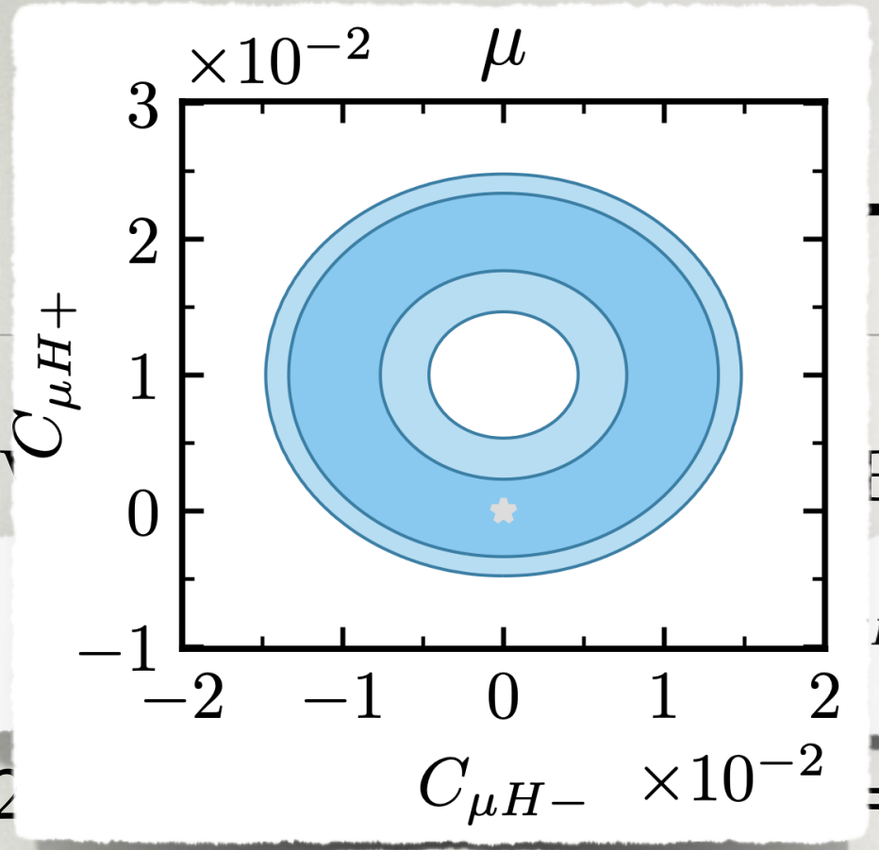

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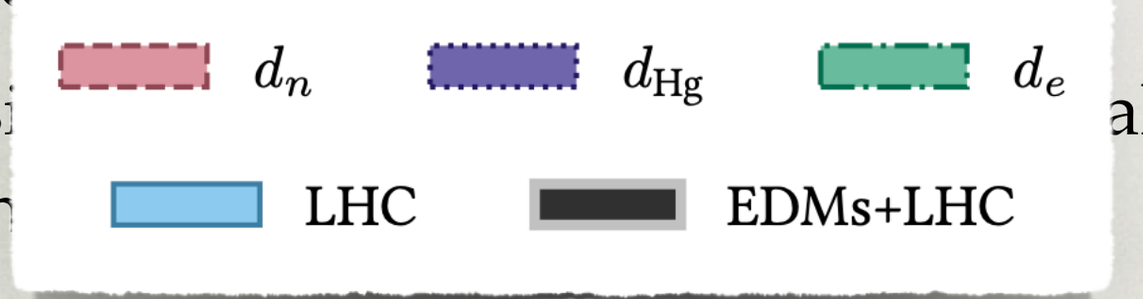

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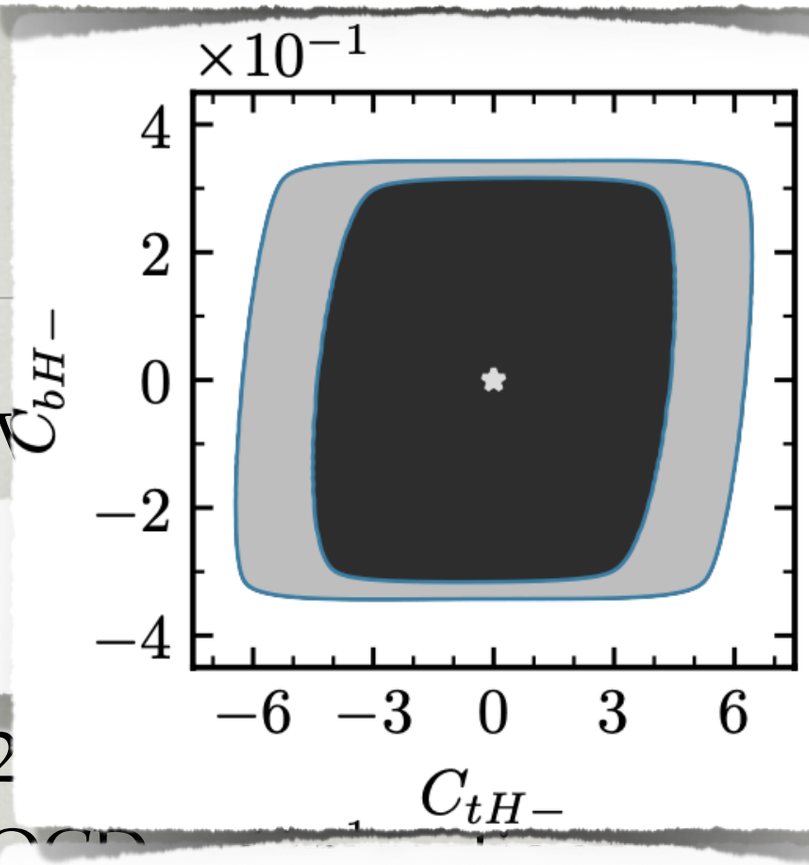
4D t, b LHC scan $(\Lambda = 1\,\text{TeV})$



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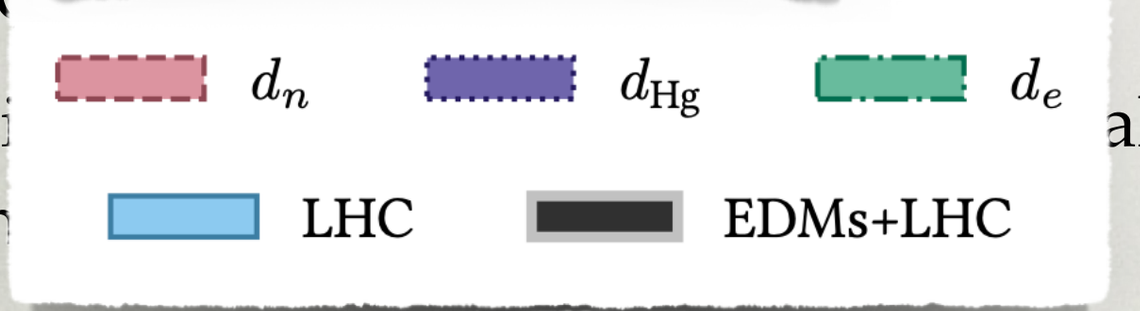
QCD



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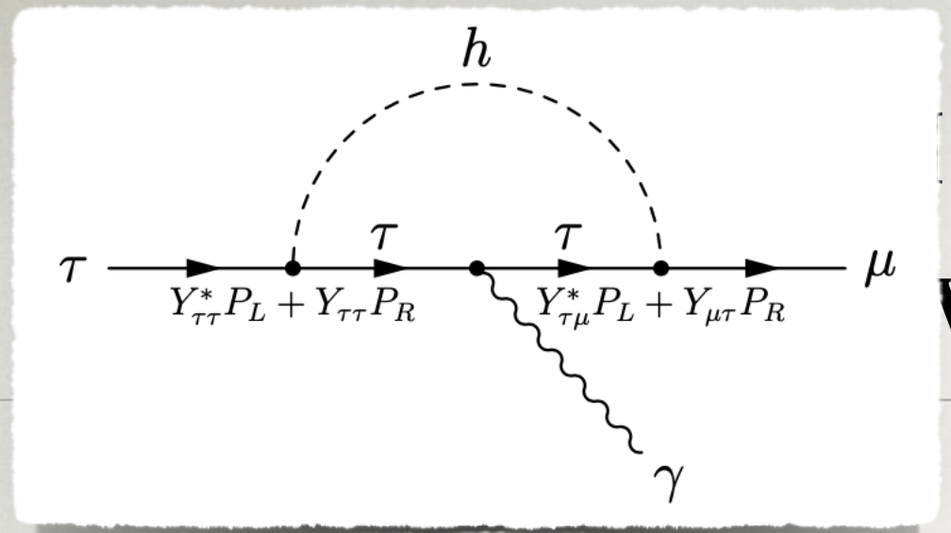
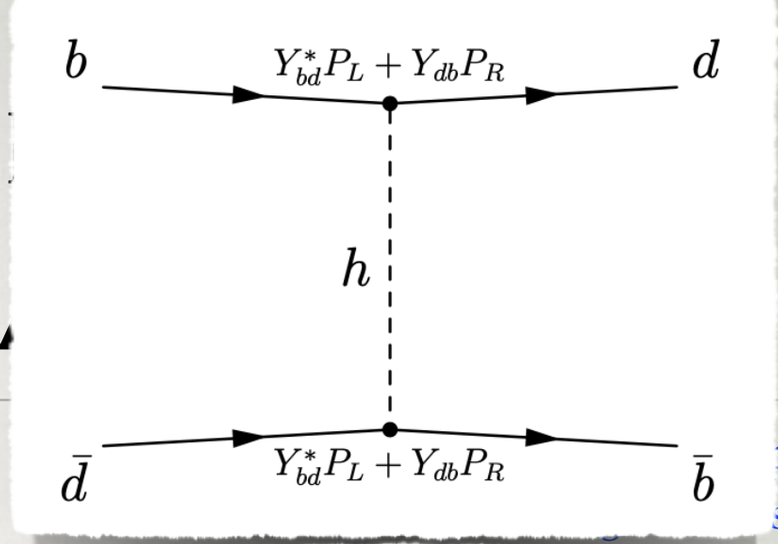
Flavor violating Higgs Yukawas

FLAVOR VIOLATING YUKAWAS

Harnik, Kopp, JZ, 1209.1397
Blackenburg, Ellis, Isidori, 1202.5704

- FV Yukawas induce other FCNCs
  - D,B,B_s,K mixing ⇒ tightly constrain FV quark Yukawas (apart from top)
    - Y_{tq} Yukawas from LHC, HL-LHC, FCC
  - $\mu \to e\gamma, \mu \to 3e, \ldots$ ⇒ stringent constraints on $Y_{\mu e}$, less on $Y_{\tau e}, Y_{\tau\mu}$
- "model independent" ⇒ not easy to suppress in concrete models





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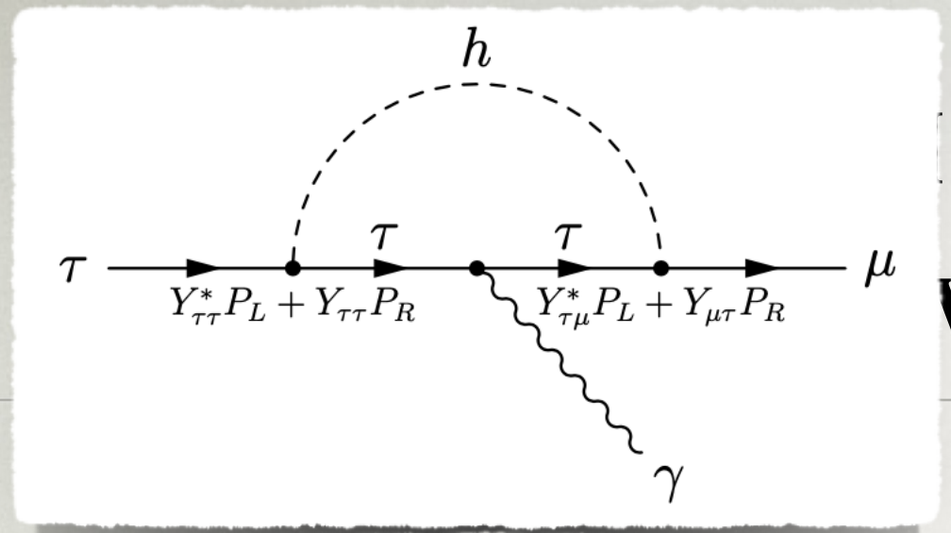

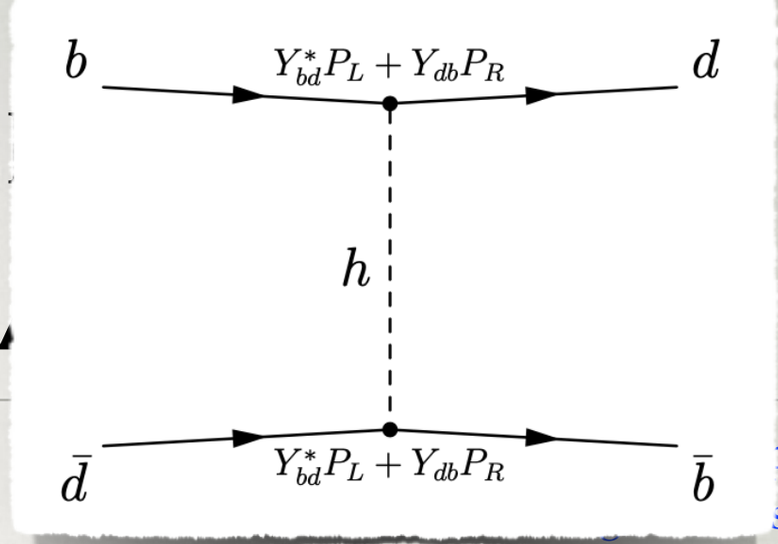

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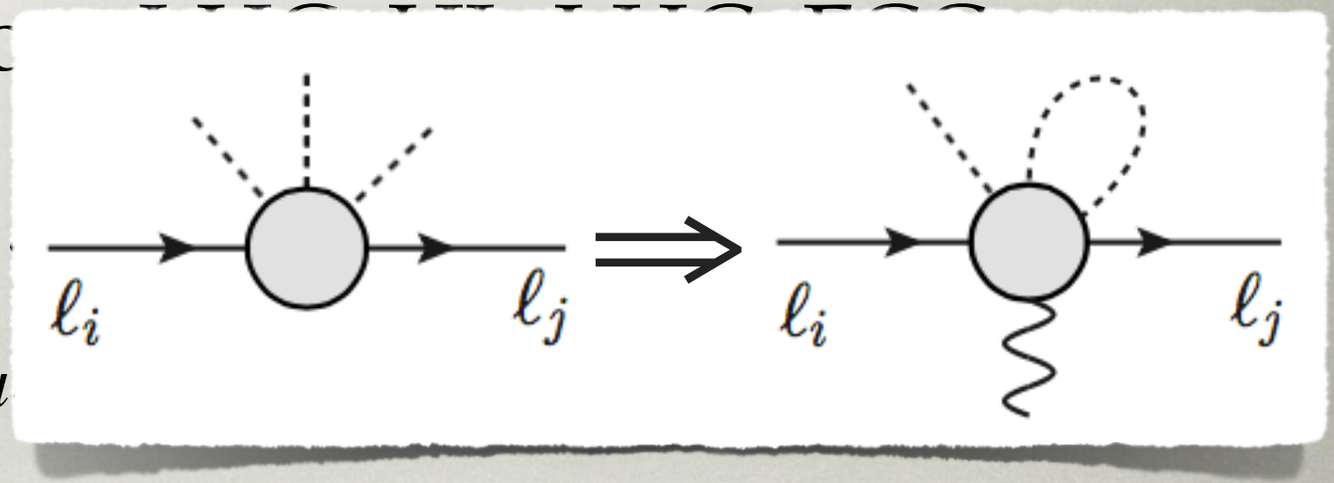

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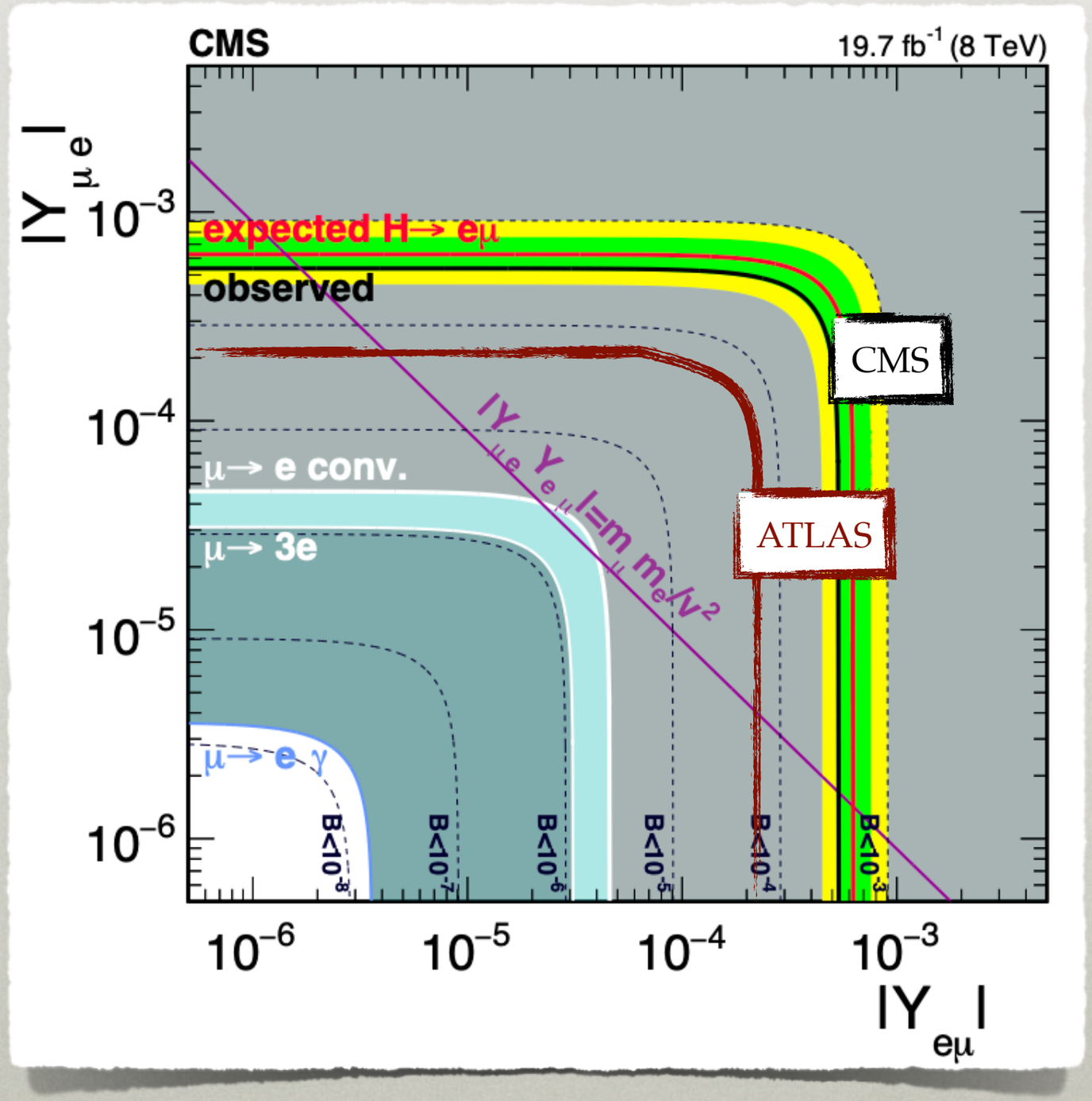
$Y_{\mu e}$ YUKAWA



ATLAS, 1909.10235

CMS, 1607.03561

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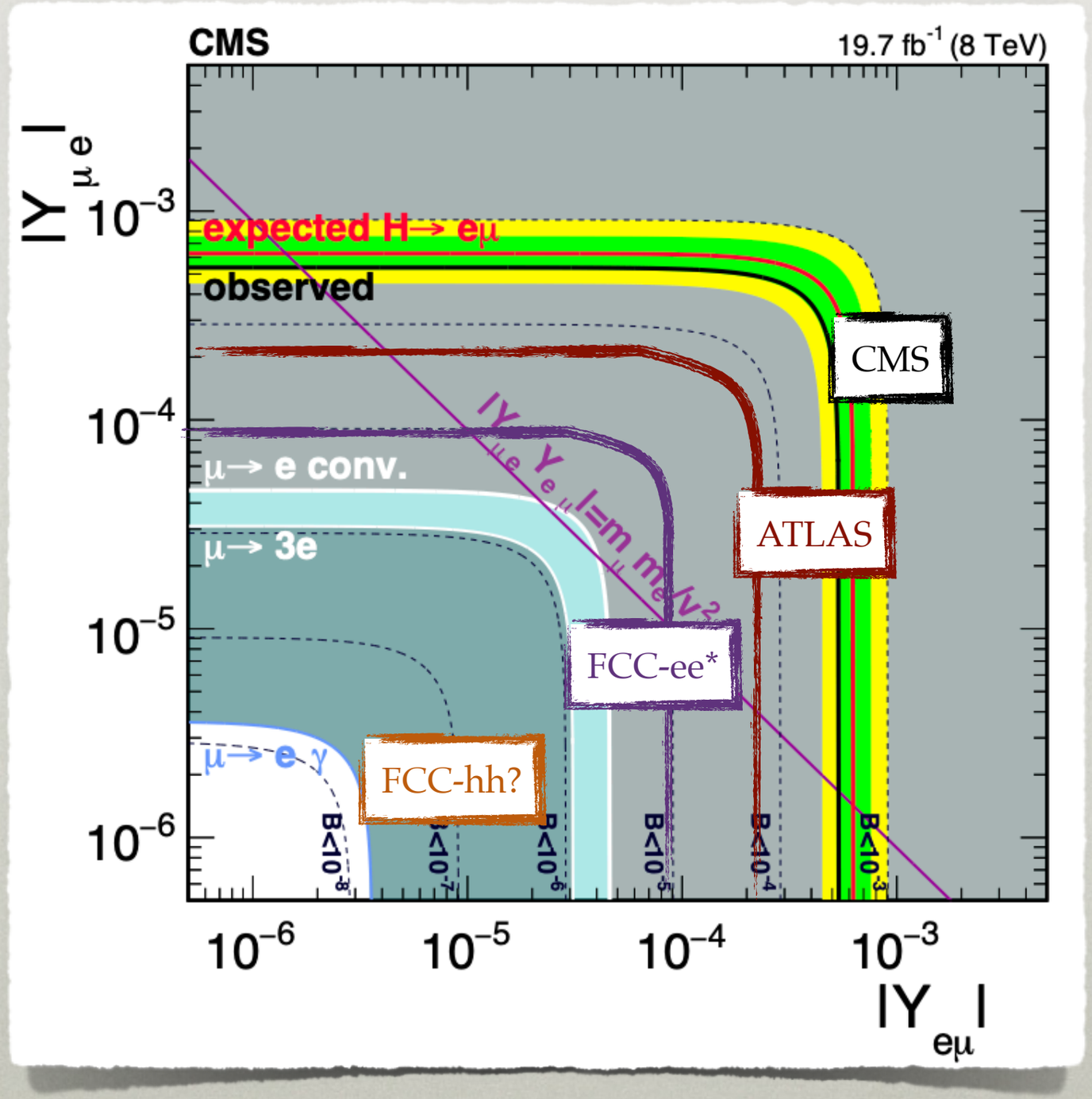

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*from Qin et al, 1711.07243

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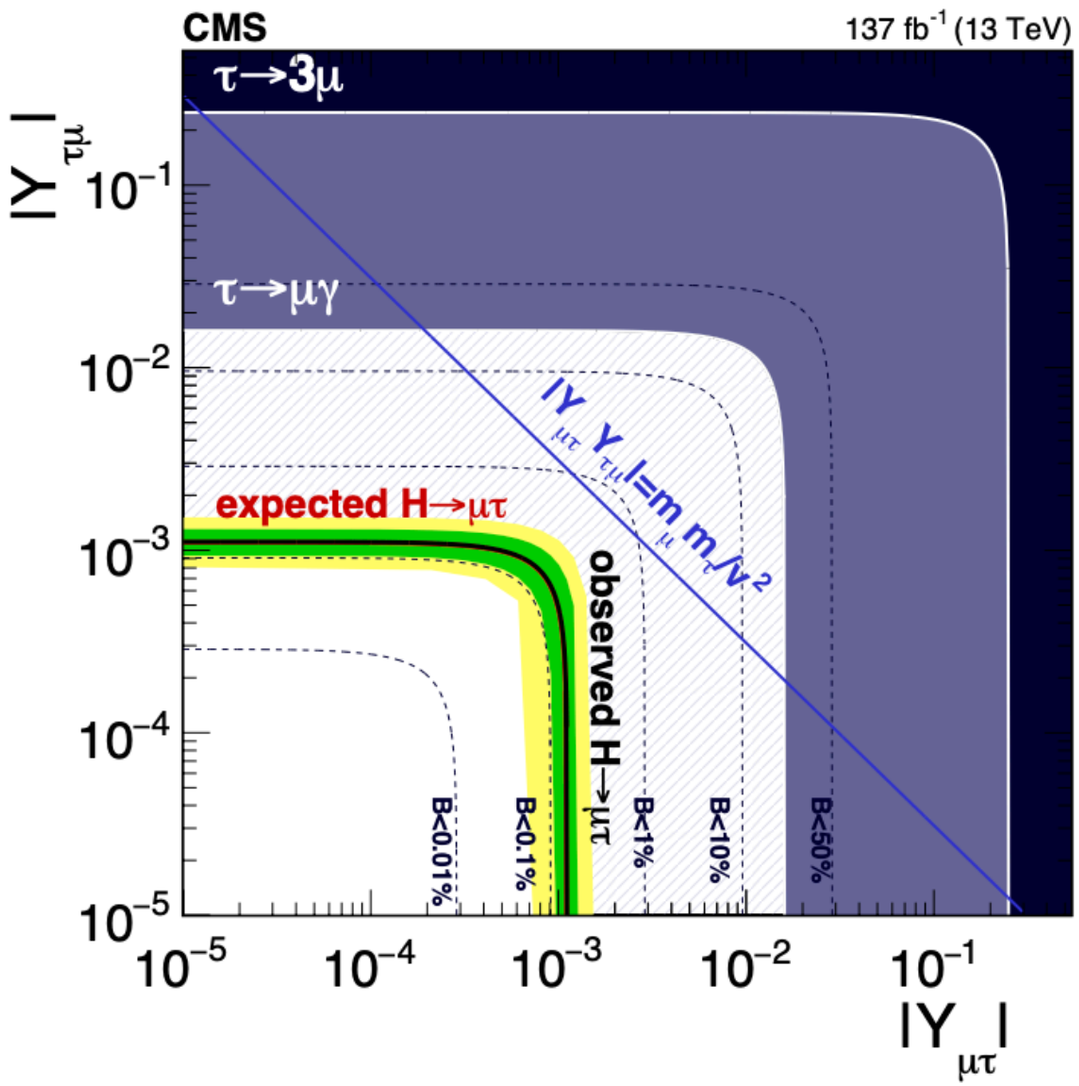
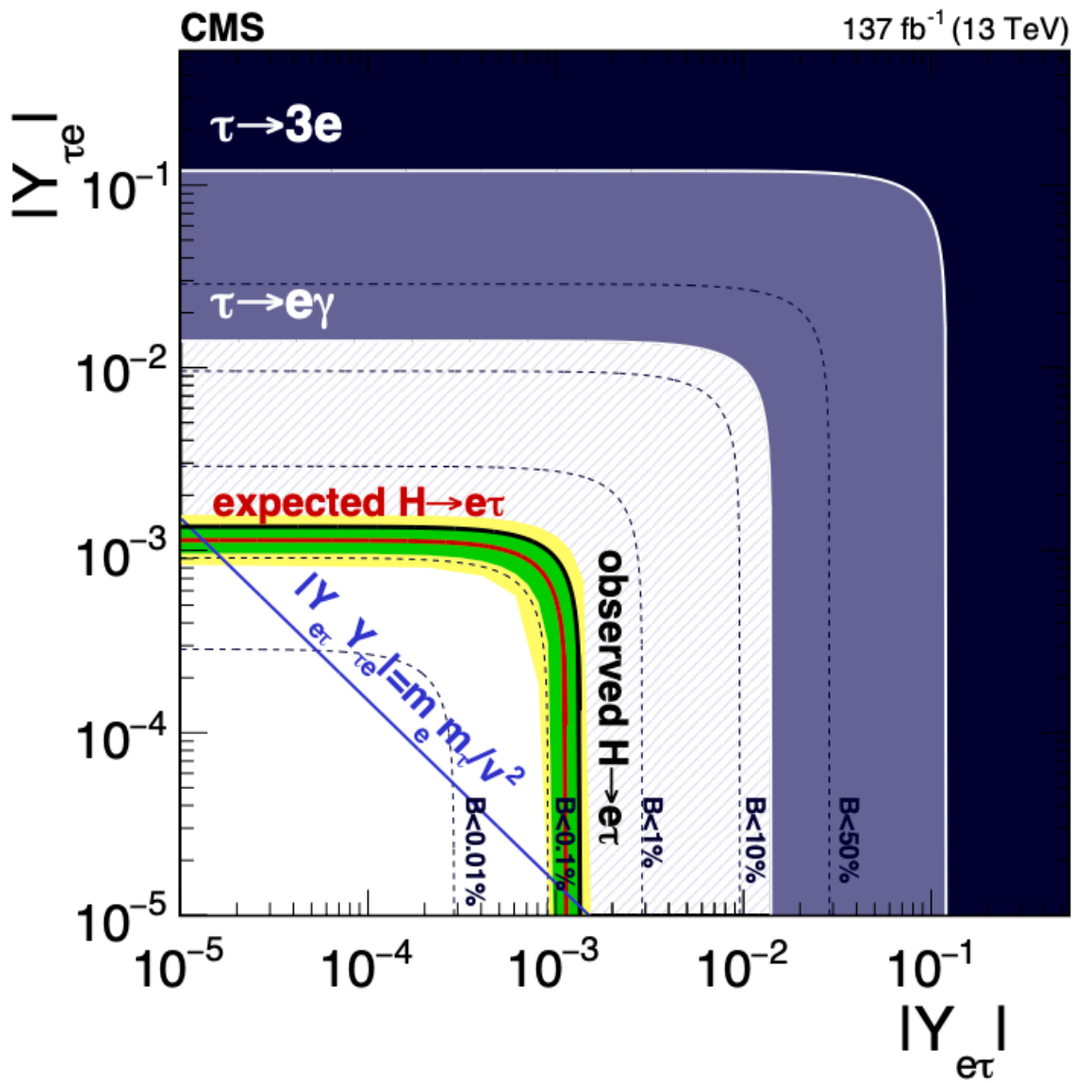
CMS, 2105.03007
ATLAS, 1907.06131

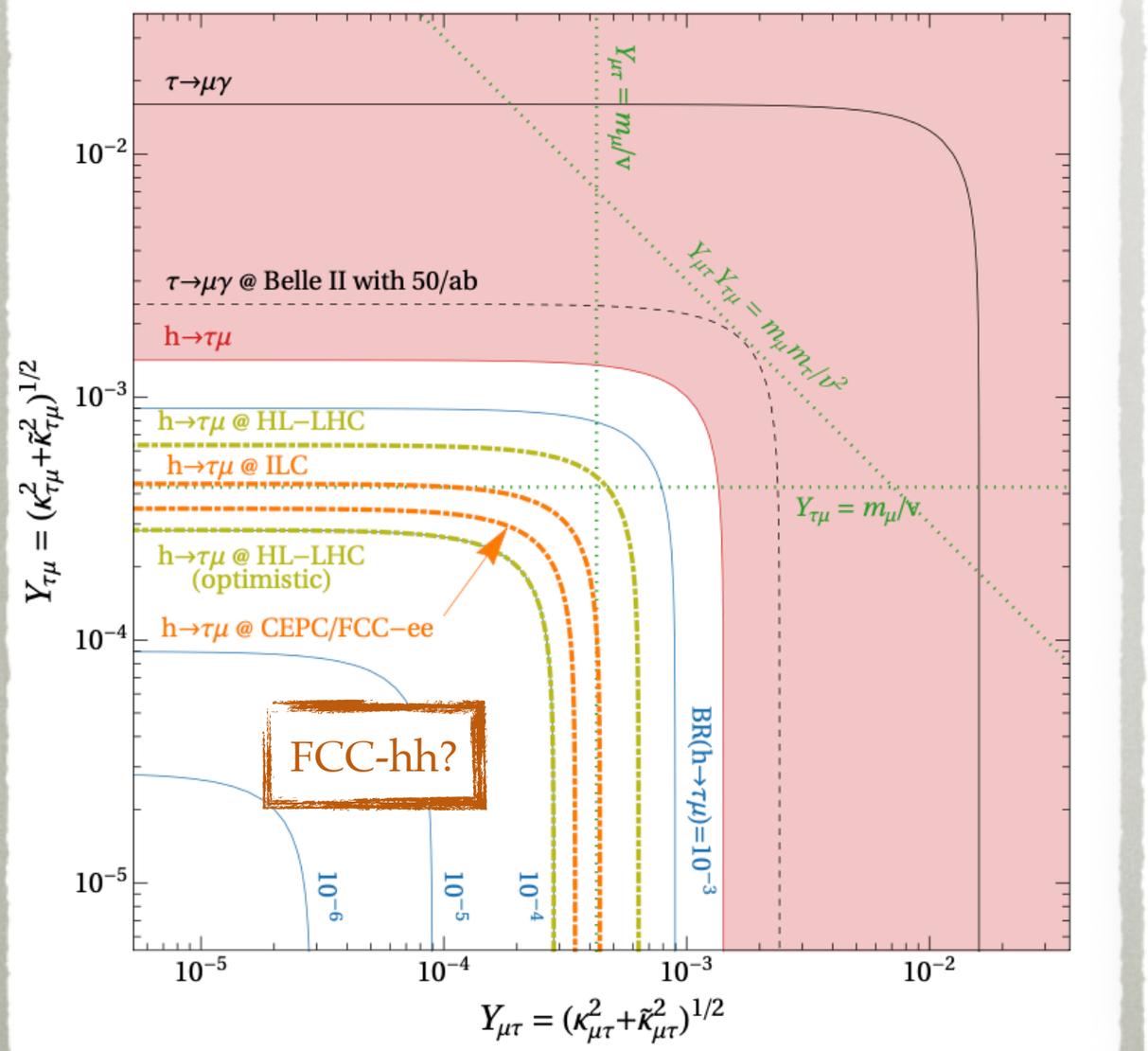




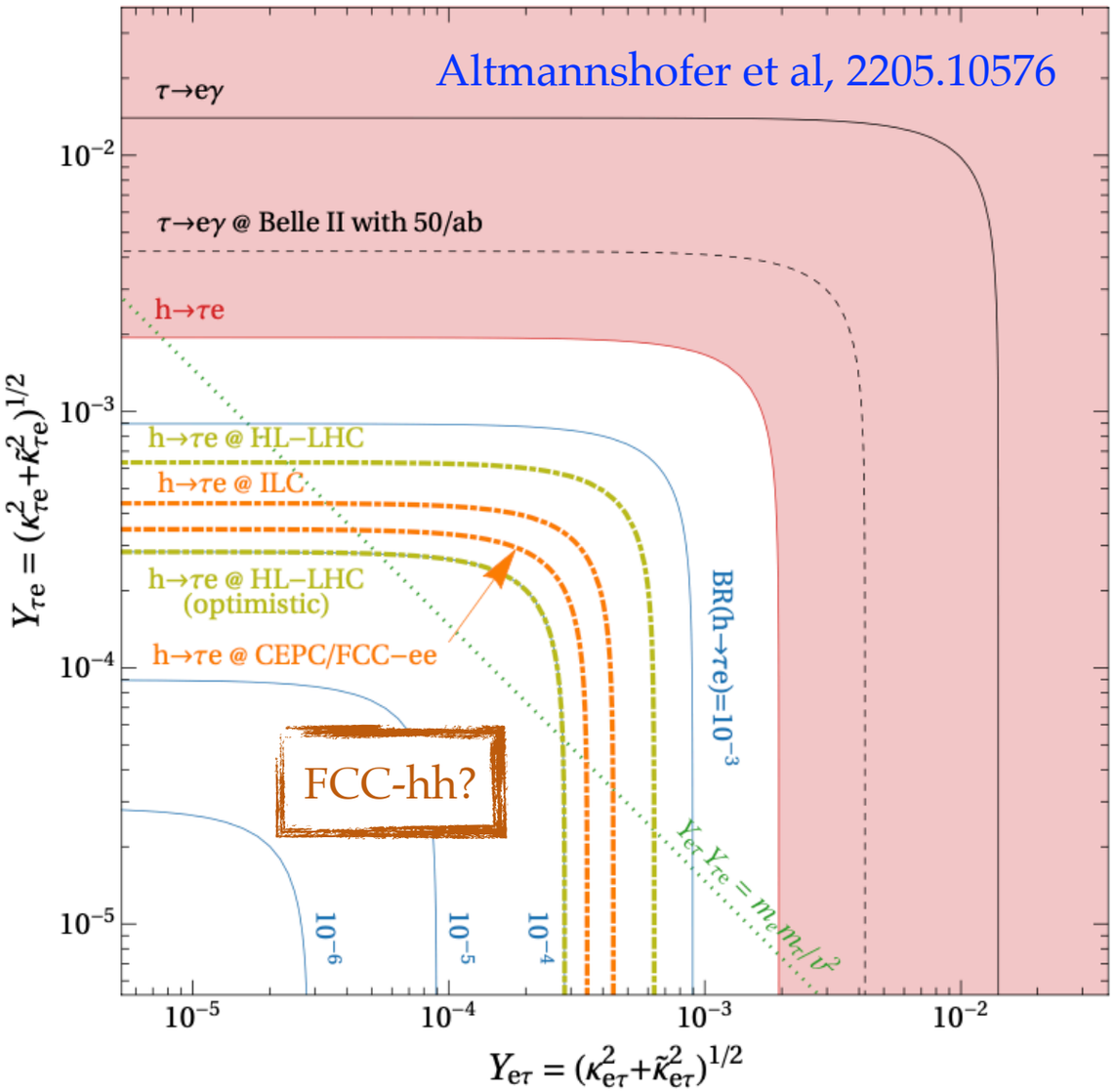
$Y_{\tau\mu}, Y_{\tau e}$ YUKAWAS - FUTURE

see also Qin et al, 1711.07243
Arroyo-Urena et al, 2002.04120

- $\mathrm{Br} \lesssim \mathcal{O}(10^{-4}) \Rightarrow \Lambda \gtrsim 10\,\mathrm{TeV}\ (C_{ij} = 1)$



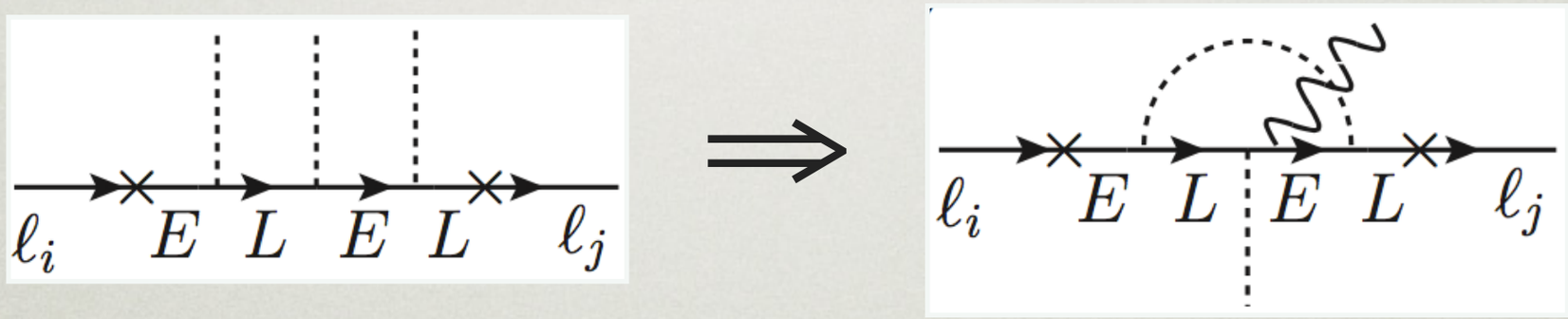
Altmannshofer et al, 2205.10576



WHAT MODELS?

- if SM Higgs the only source of EWSB
  - e.g. NP models with vectorlike leptons or leptoquarks
  - bounds from $\tau \to \mu\gamma, e\gamma$ too stringent Altmannshofer et al, 1507.07927

$\Rightarrow Br(h \to \tau\mu, \tau e)$ below HL-LHC/FCC reach

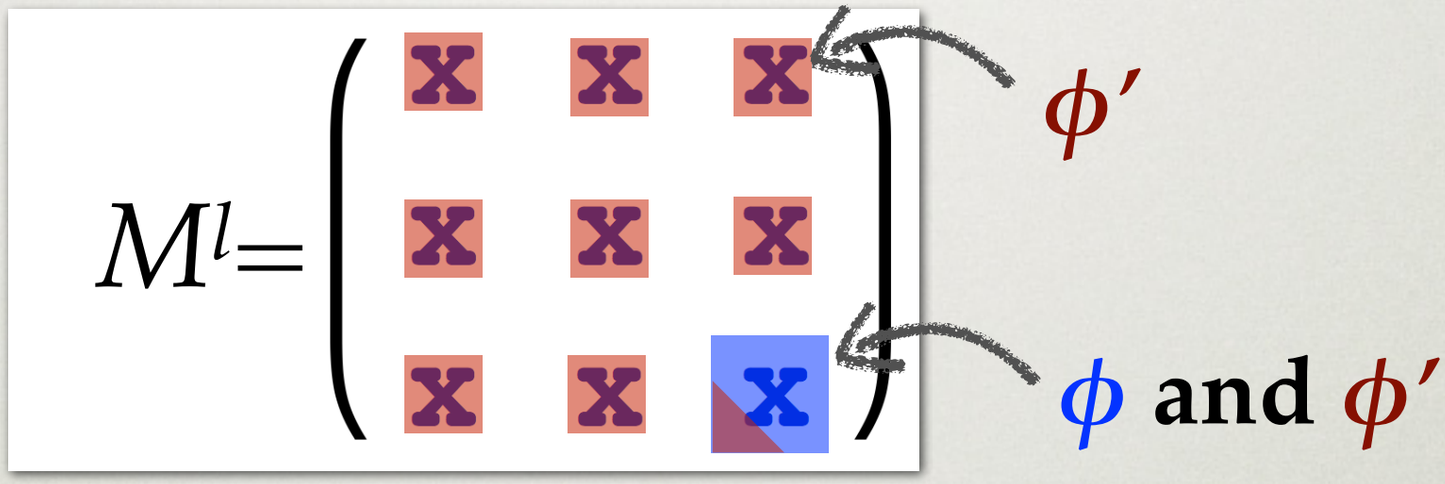


- need new EWSB source
  - models with extended Higgs sectors
  - condensates in strong sector

Altmannshofer et al, 1507.07927

2HDM EXAMPLE

- two Higgs doublets, neutral compts: ϕ, ϕ',vevs v, v'
  - ϕ couples to 3rd family, ϕ' to all three



- consider two flavor structures for ΔM^l
  - *"horizontal"*: only off-diagonal entries nonzero, m_{23}' and m_{32}'
  - *"generic"*: all m_{ij}' nonzero

Altmannshofer et al, 1507.07927

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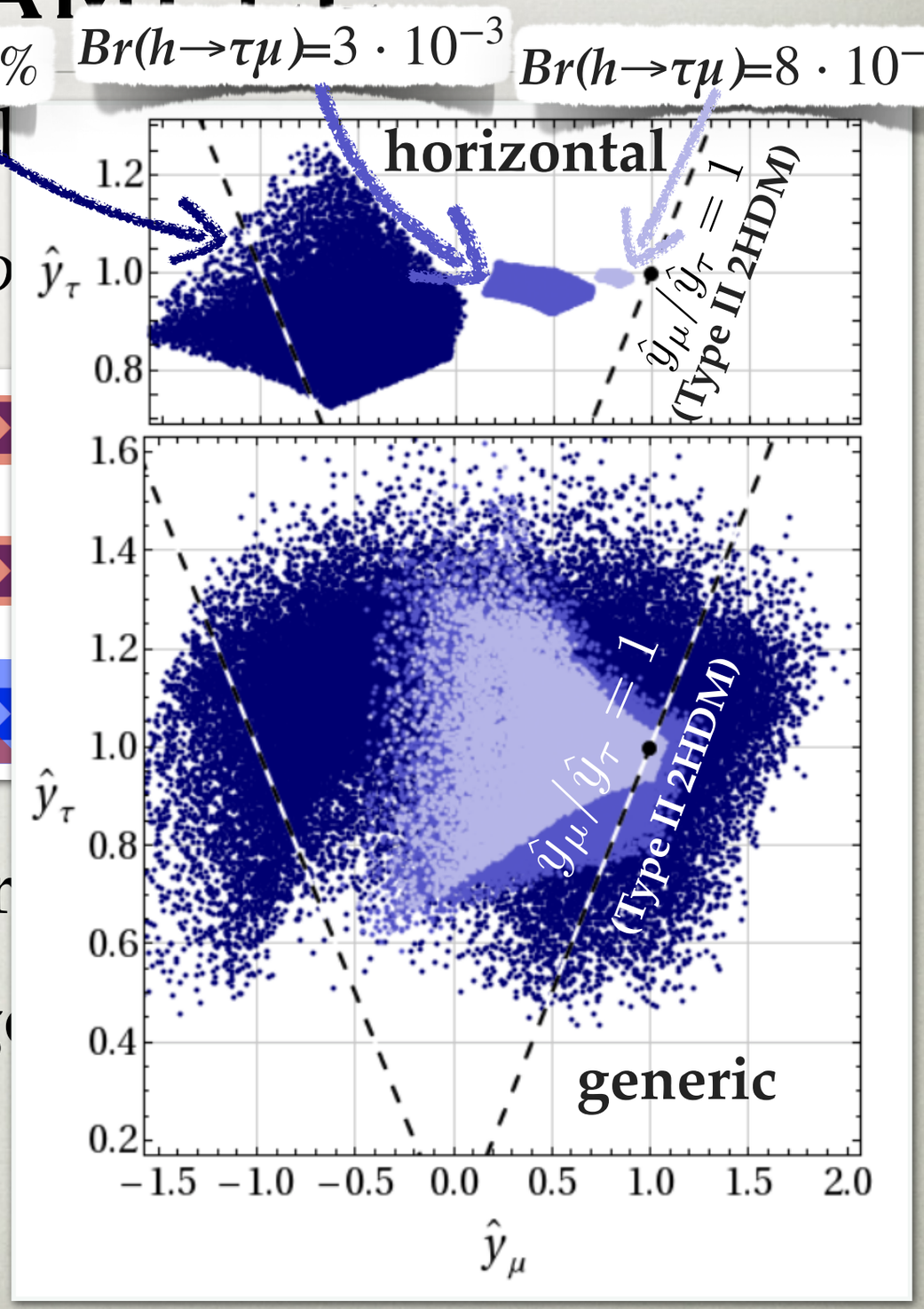

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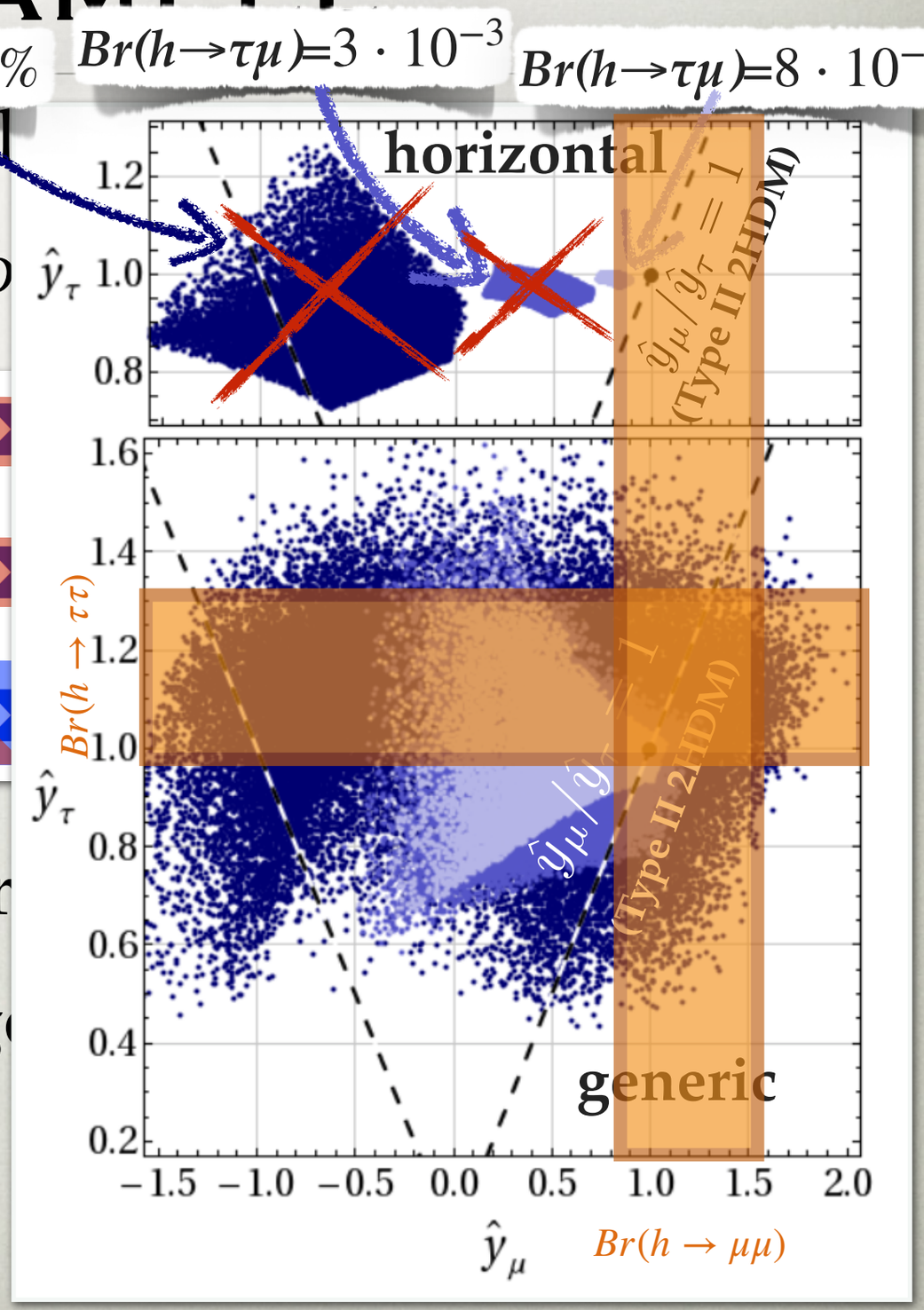
  - *"horizontal"*: only off-diag m_{23}' and m_{32}'
  - *"generic"*: all m_{ij}' nonzero

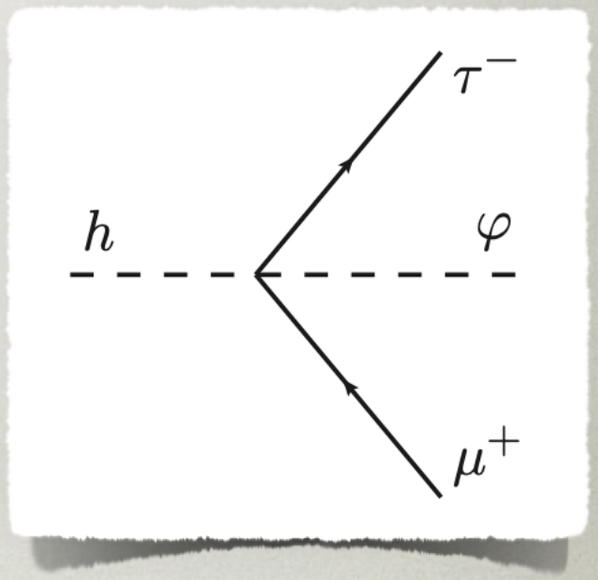


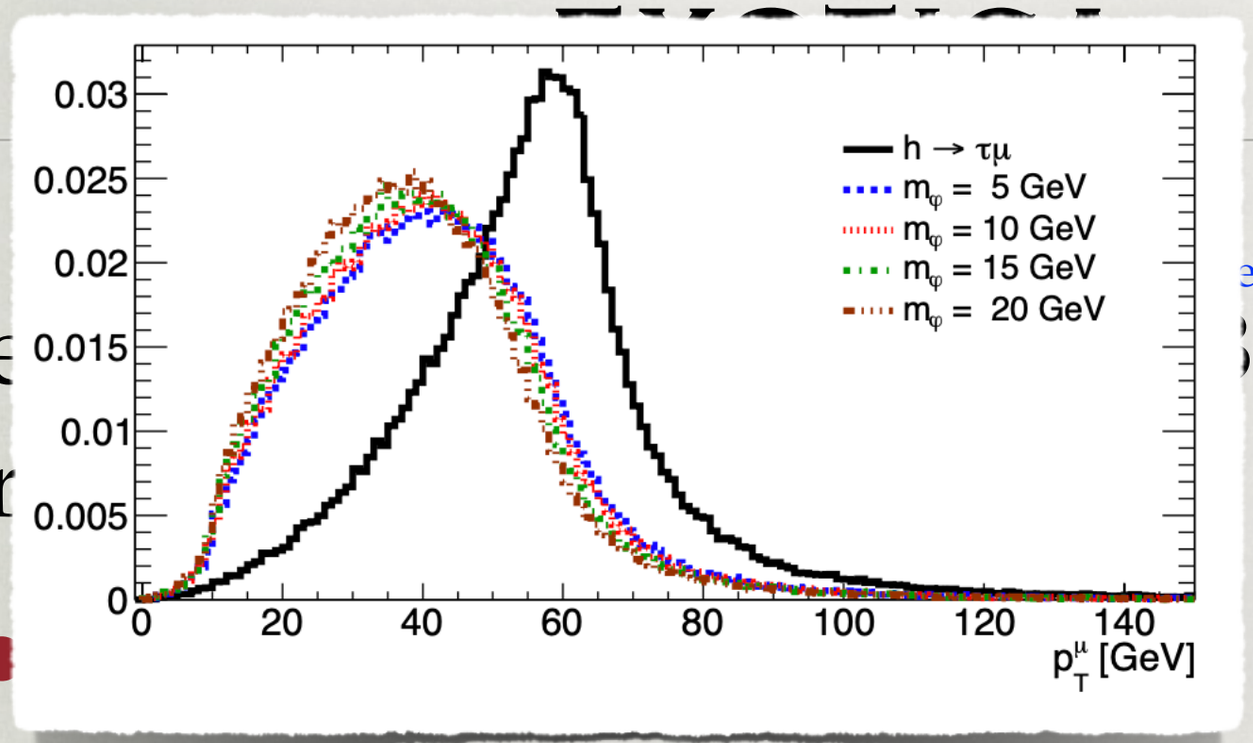
EXOTICA

Galon, JZ, 1701.08767

see also Evans, Tanedo, Zakeri, 1910.07533

- exception to the "new EWSB vev required" rule
  - emission of invisible light NP scalar
  - Br($h \to \tau\mu + \varphi$) enhanced if φ carries flavor charges
  - exp. signatures similar to $h \to \tau\mu$, but slightly shifted distribs.

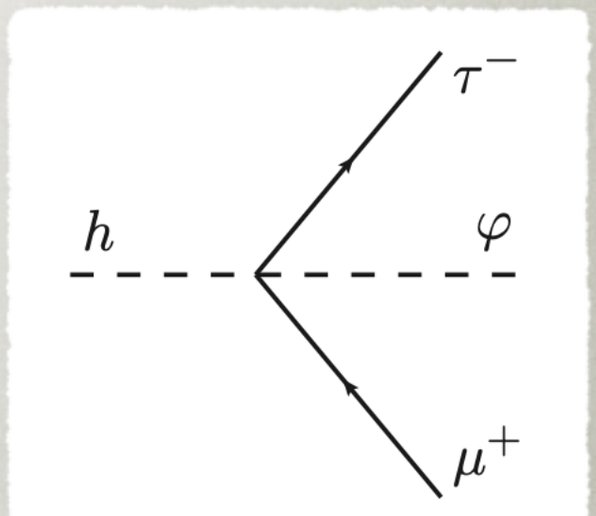




Galon, JZ, 1701.08767

ee also Evans, Tanedo, Zakeri, 1910.07533

- e … vev
  r…
  - …
  light NP scalar



- Br($h \to \tau\mu + \varphi$) enhanced if φ carries flavor charges
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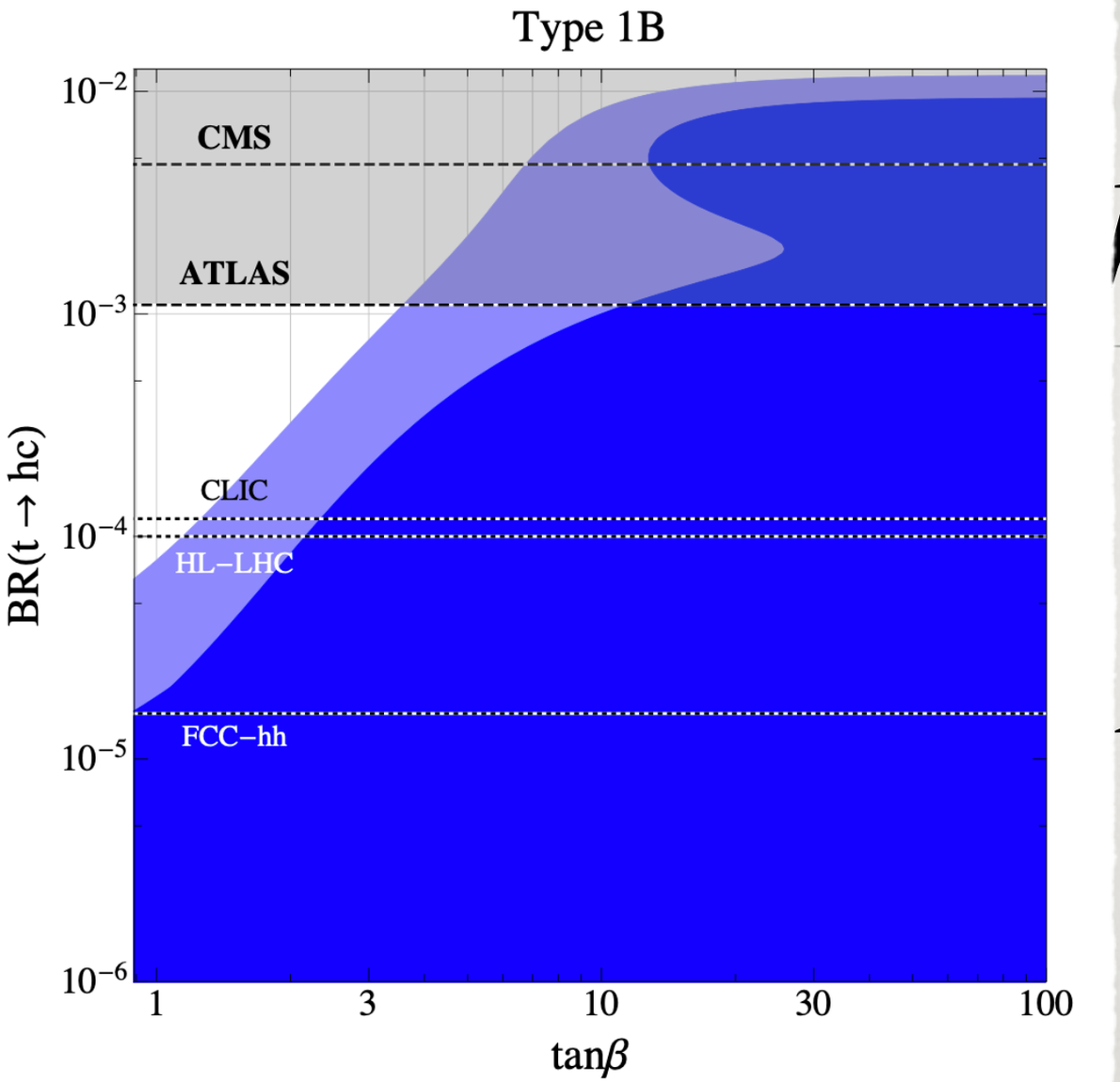
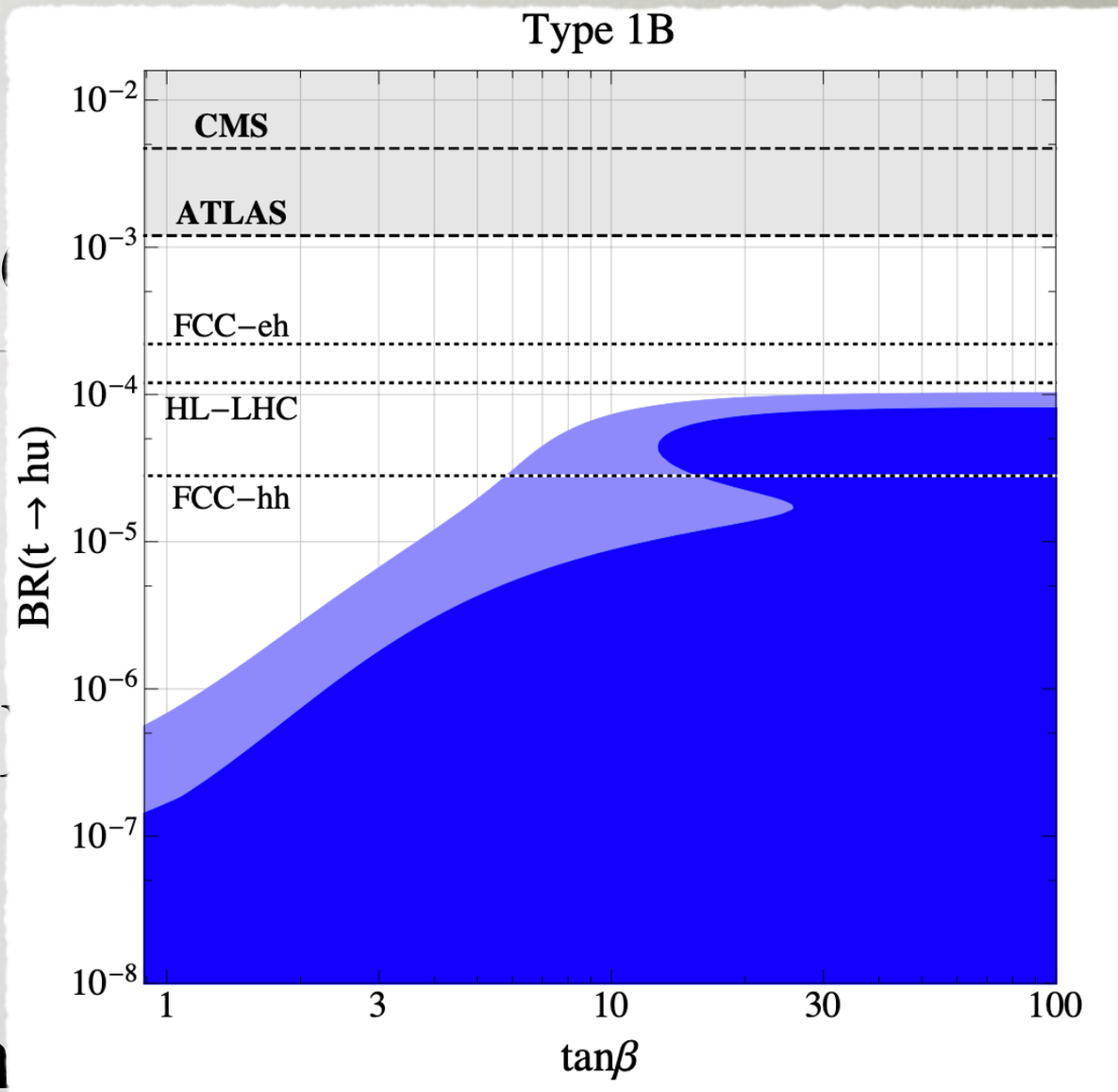
$t \to hc, hu$

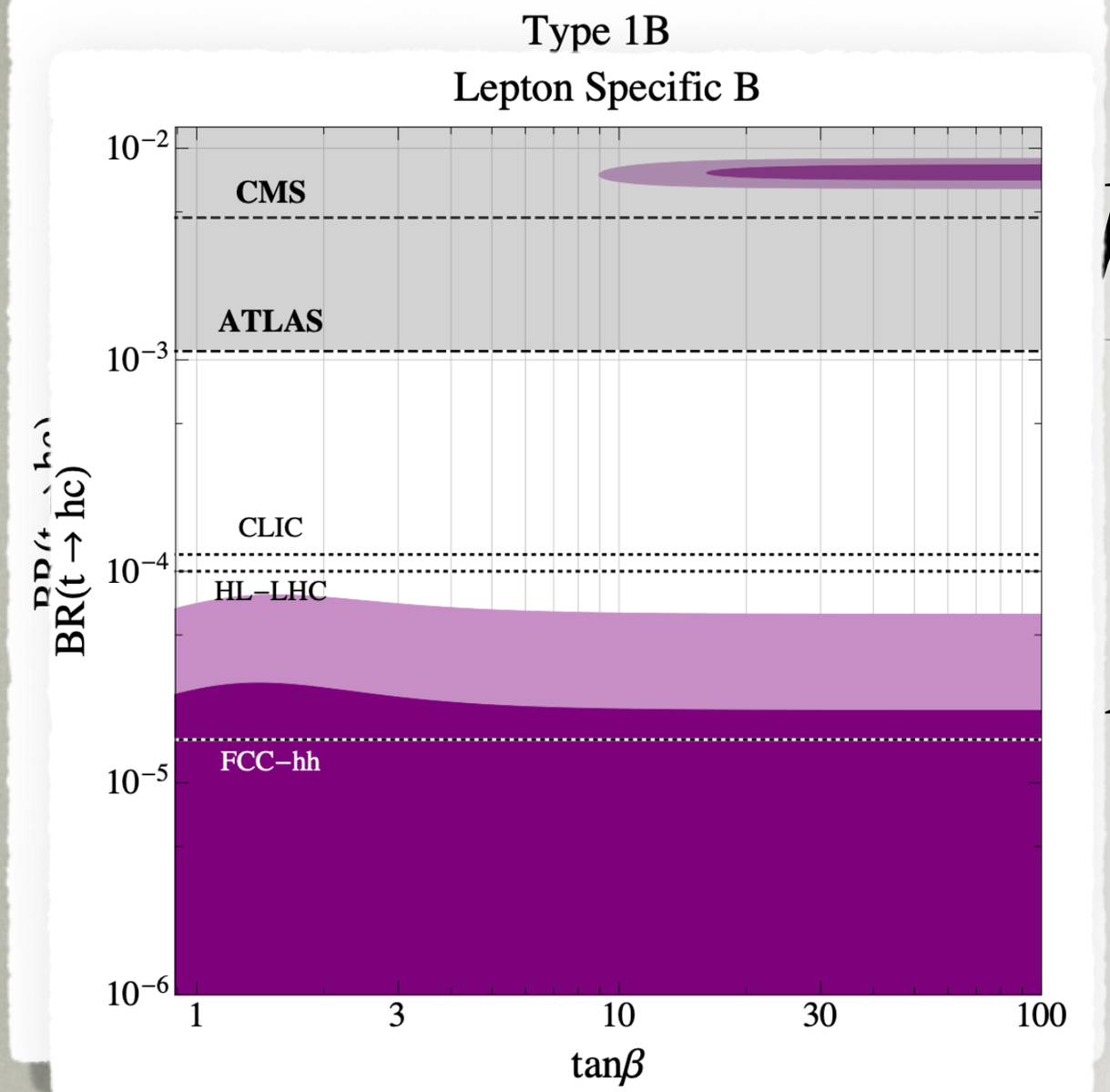
Altmannshofer, Maddock, Tuckler, 1904.10956

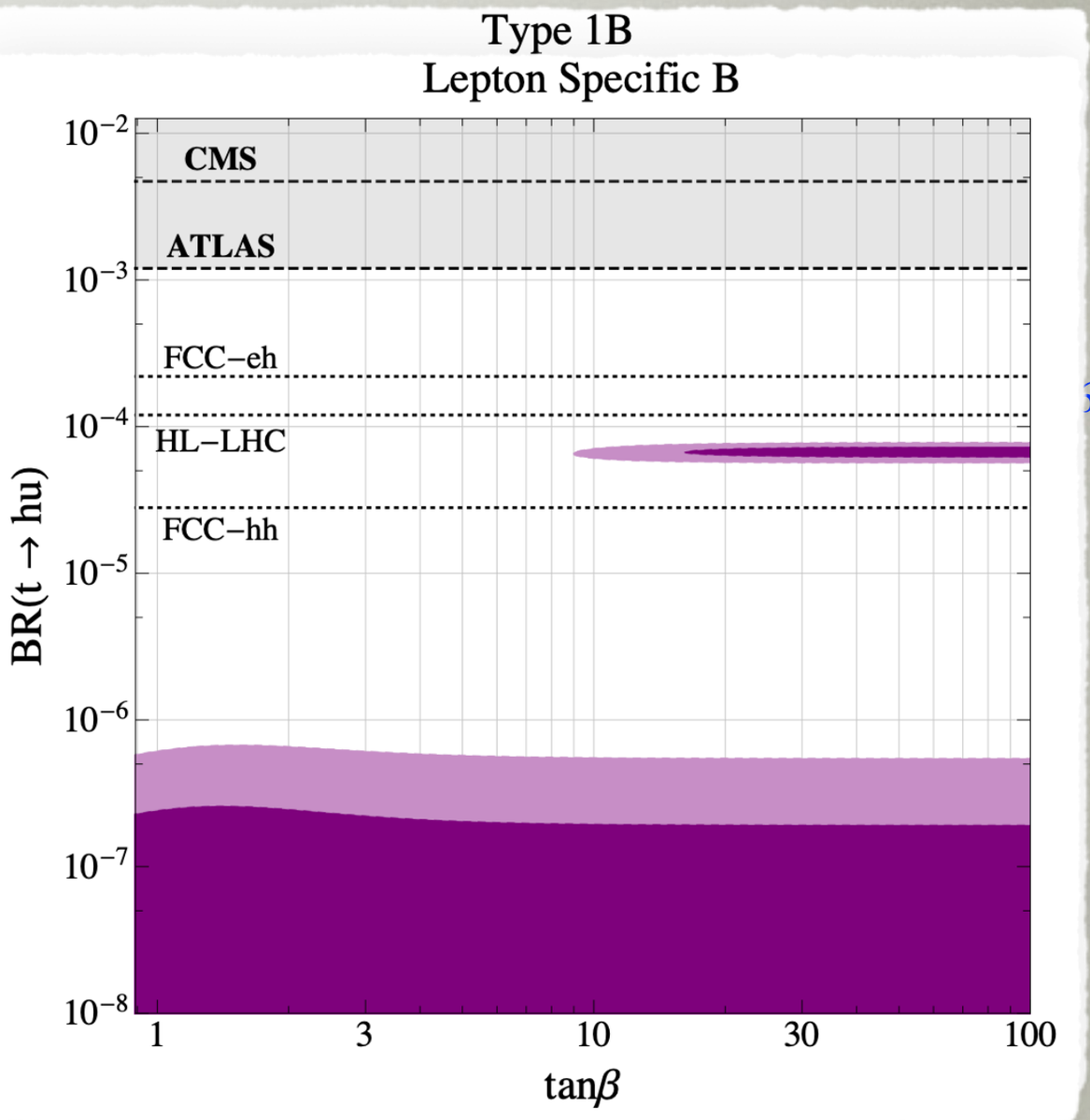
- information about Y_{tc}, Y_{tu} dominated by LHC bounds
- 2HDM in general have Y_{tc}, $Y_{tu} \neq 0$
- depending on assumed flavor structure FCC can make a discovery





- depending on assumed flavor structure FCC can make a discovery





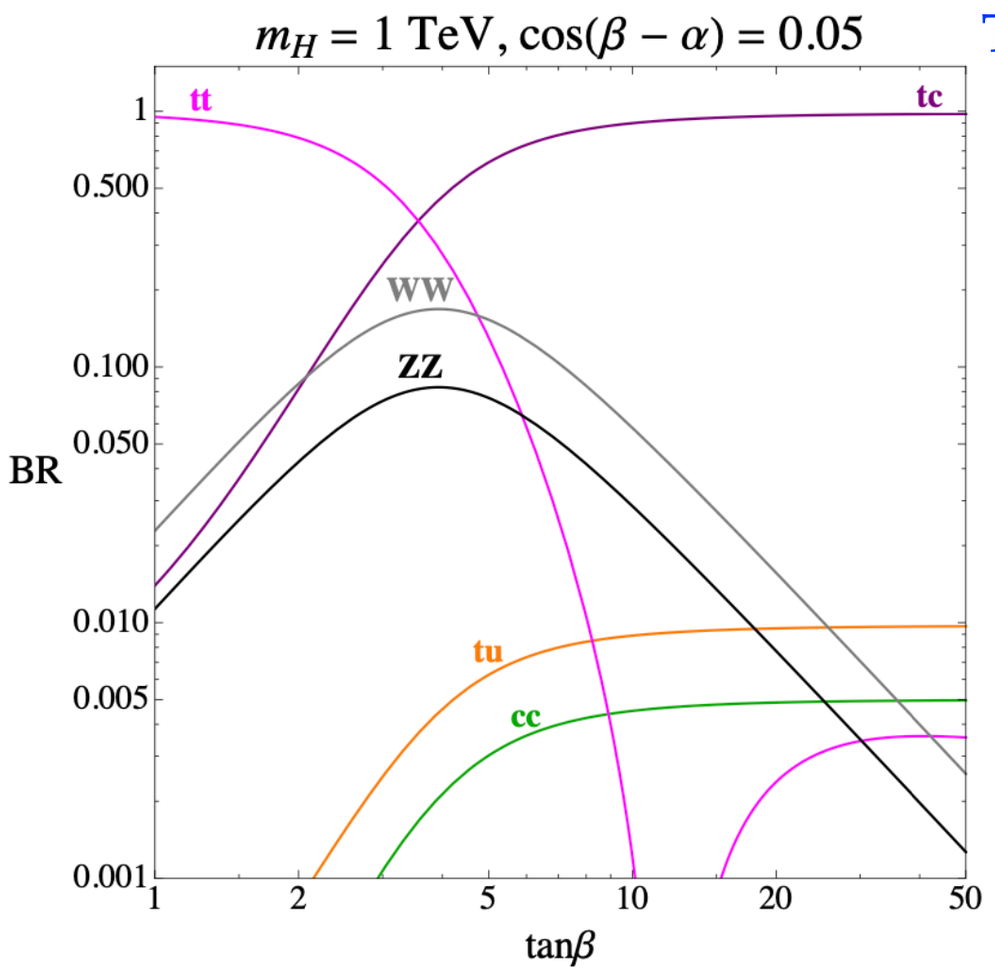
- depending on assumed flavor structure FCC can make a discovery

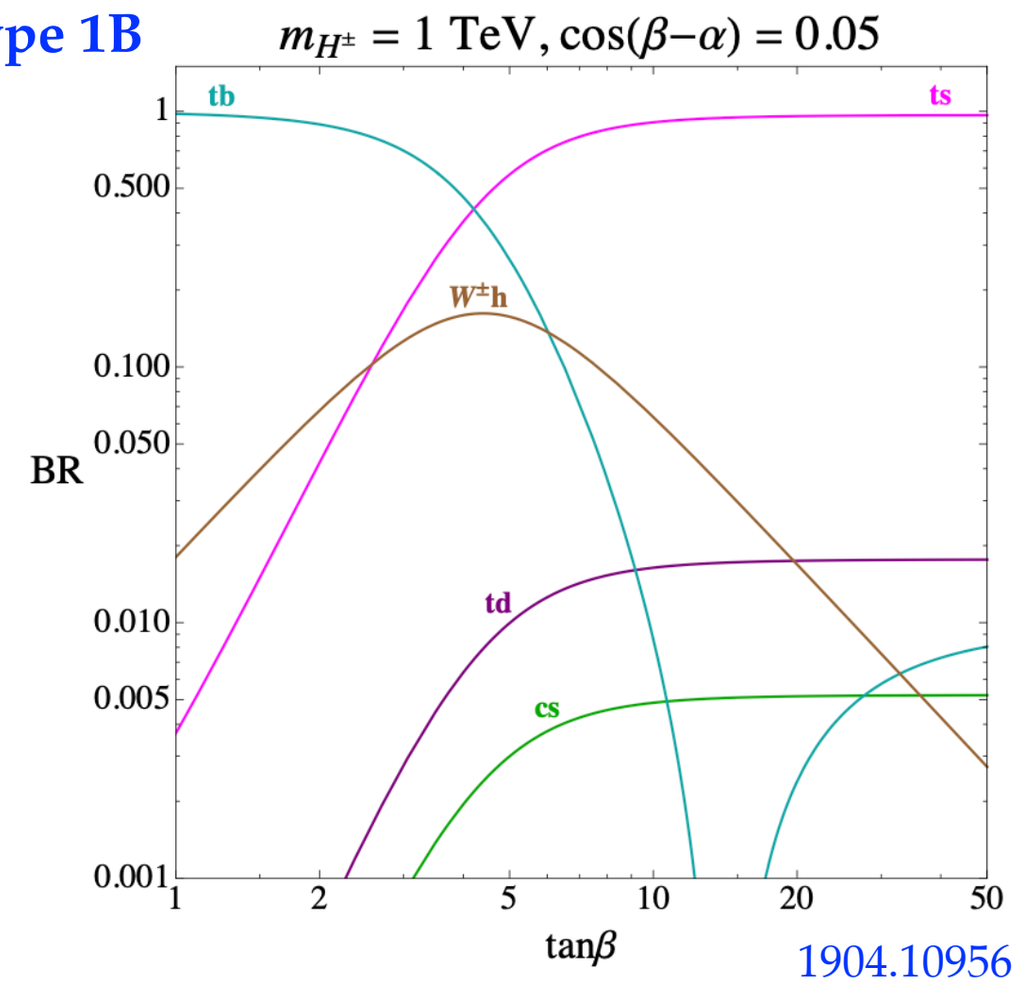
HEAVY HIGGSES

- FV Higgs Yukawas imply that heavy Higgses has FV couplings
  - FV decays can even dominate the branching ratios

Altmannshofer, Maddock, Tuckler, 1904.10956;
see also Altmannshofer, Maddock 2003.01320; Sher, 2207.06771

Type 1B





1904.10956

CONCLUSIONS

- flavor violating Higgs Yukawas accessible at FCC
  - extended Higgs sectors, condensates in strong EW NP sector, or "exotica"
- $h \to \tau\mu, \tau e$ and $t \to hc, hc$ channels wide open

BACKUP SLIDES

SUMMARY OF MODELS

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

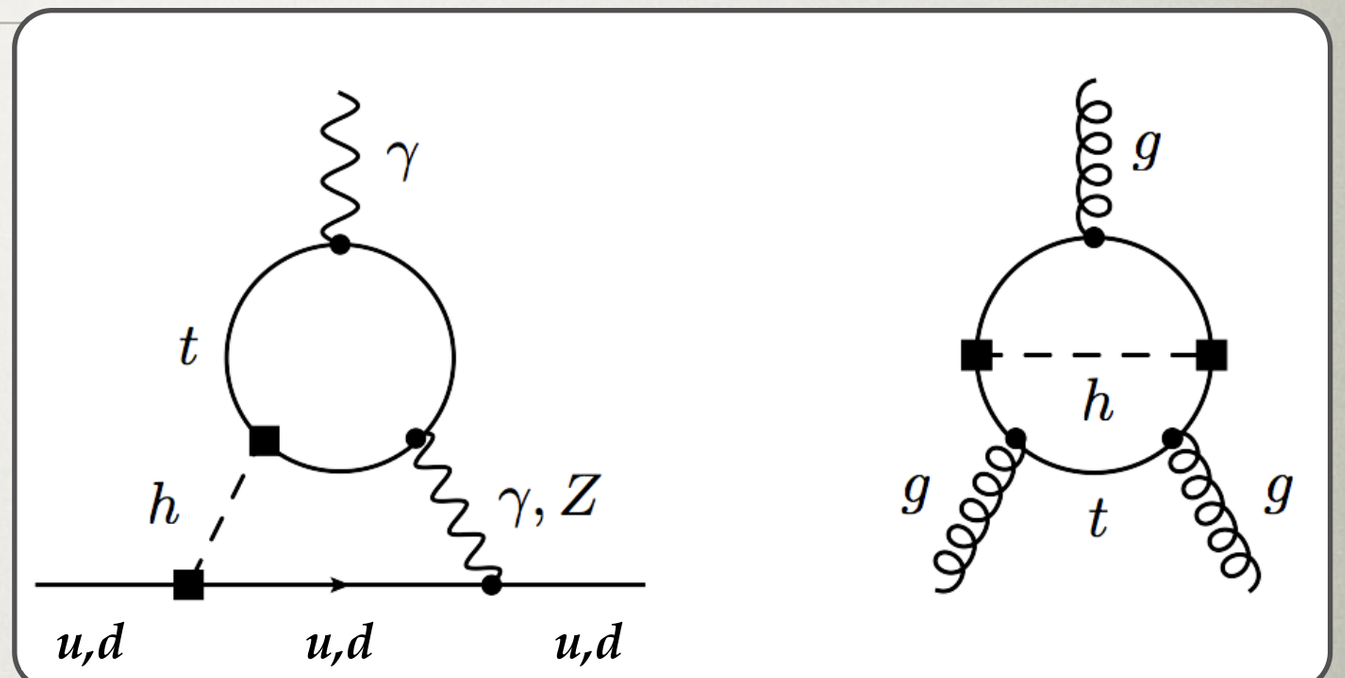
adapted from Dery, Efrati, Hochberg, Nir, 1302.3229 and extended;
see also Bishara, Brod, Uttayarat, JZ, 1504.04022

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)	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)\sqrt{m_\tau/m_\mu}$
RS (ii)	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$
PGB (1 rep.)	$1-v^2/f^2$	1	0

NEUTRON AND MERCURY EDM

Brod, Haisch, JZ, 1310.1385

- neutron and Hg EDM also dominated by Barr-Zee type diagrams (SM-like couplngs. of the Higgs to light quarks)



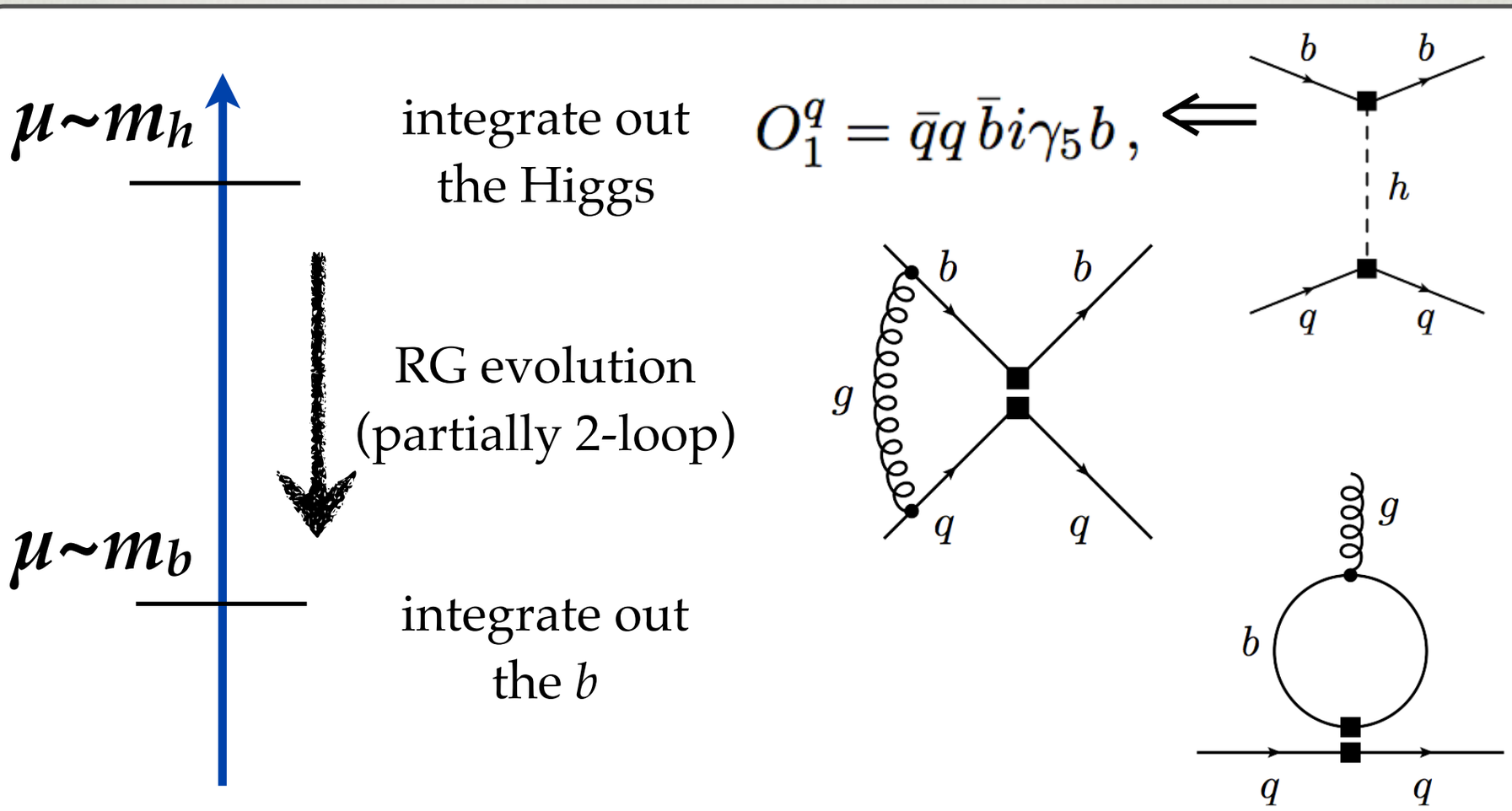
$$\mathcal{L}_{\rm eff} = -d_q \frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \tilde{d}_q \frac{ig_s}{2}\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q\, G^a_{\mu\nu} - w\frac{1}{3}f^{abc}G^a_{\mu\sigma}G^{b,\sigma}_{\nu}\tilde{G}^{c,\mu\nu}$$

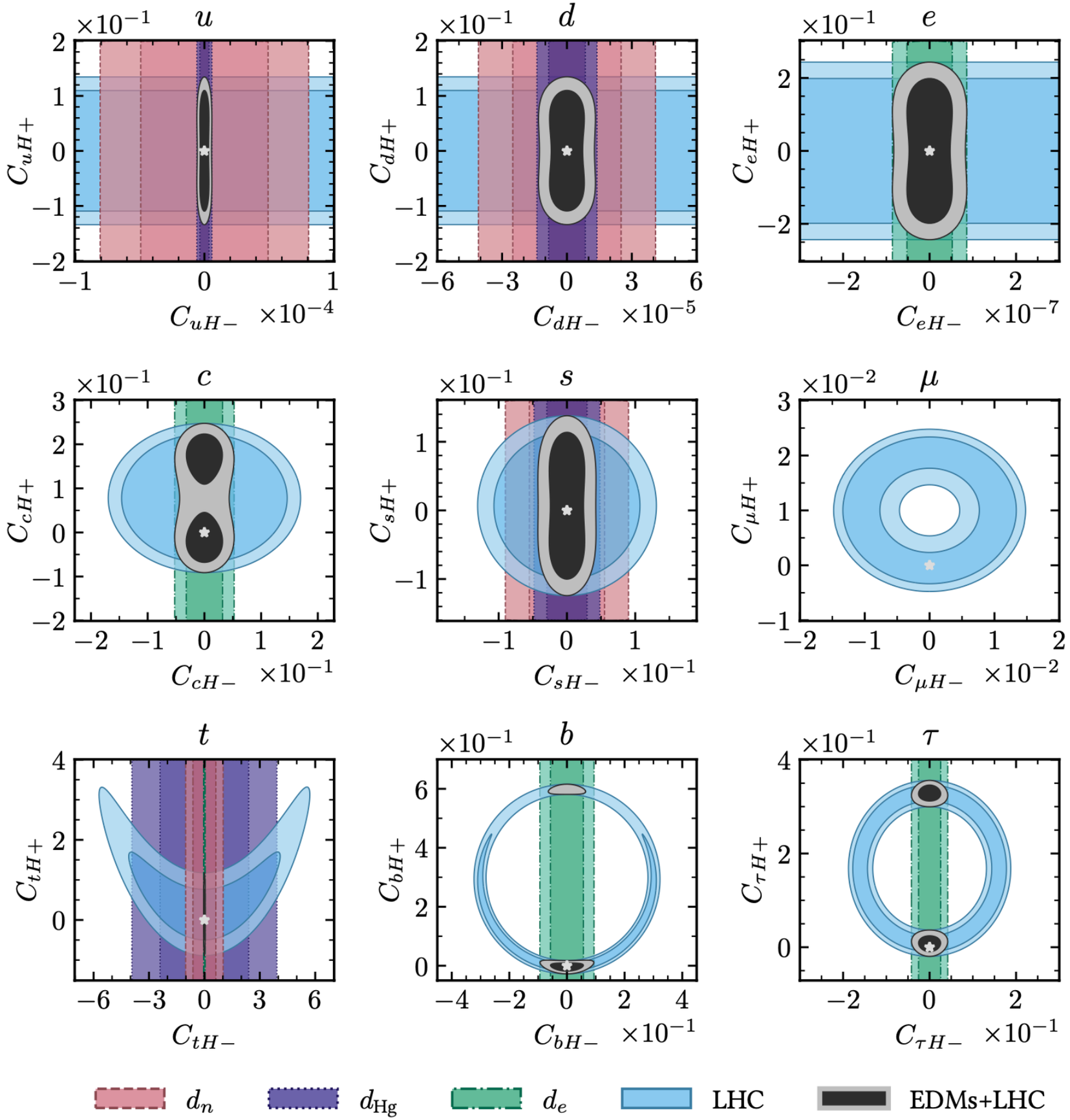
- an important difference: at 2-loop also Weinberg operator is generated
  - is nonzero even, if CPV is only in the Higgs couplings to the 3rd gen. quarks!

CPV COUPLING TO b QUARK

Brod, Haisch, JZ, 1310.1385

- now have an extra scale $m_b \ll m_h$
  - need to re-sum $\alpha_s log(x_{b/h})$ (here $x_{b/h}=m_b^2/m_h^2$)



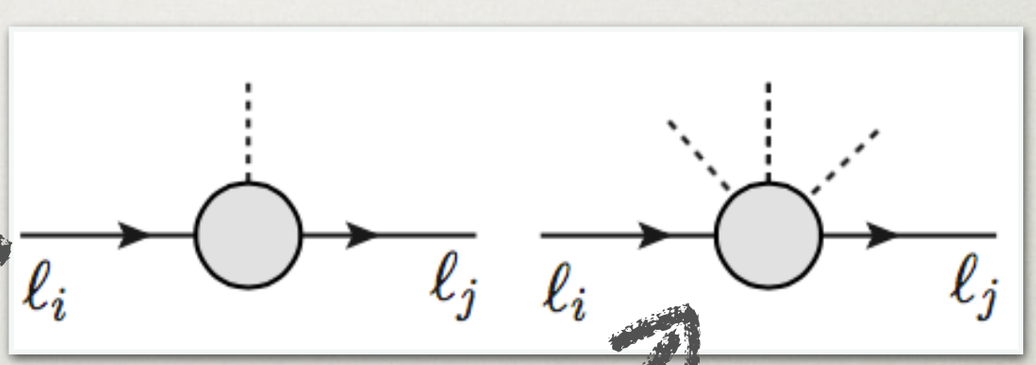

u
d
e
c
s
μ
t
b
τ
C_{uH+}
C_{uH-} $\times 10^{-4}$
C_{dH+}
C_{dH-} $\times 10^{-5}$
C_{eH+}
C_{eH-} $\times 10^{-7}$
C_{cH+}
C_{cH-} $\times 10^{-1}$
C_{sH+}
C_{sH-} $\times 10^{-1}$
$C_{\mu H+}$
$C_{\mu H-}$ $\times 10^{-2}$
C_{tH+}
C_{tH-}
C_{bH+}
C_{bH-} $\times 10^{-1}$
$C_{\tau H+}$
$C_{\tau H-}$ $\times 10^{-1}$
d_n
$d_{\rm Hg}$
d_e
LHC
EDMs+LHC

2203.03736

WHAT KIND OF NEW PHYSICS?

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

- if Higgs is the only source of EWSB ⇒ the hint for $Br(h\to\tau\mu)$ too large as shown below
  - excluded by $\tau\to\mu\gamma$ (up to cancellations)
  - if the lepton mass only from Higgs:

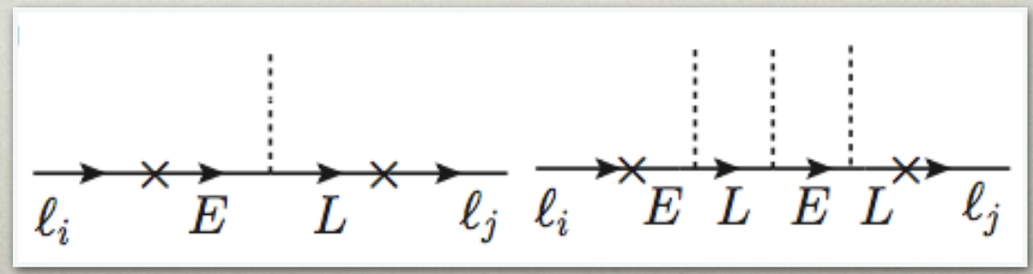


  - if EFT applicable:

$$-\mathcal{L}_Y = \lambda_{ij}(\bar{\ell}_L^i e_R^j)H + \frac{\lambda'_{ij}}{\Lambda^2}(\bar{\ell}_L^i e_R^j)H(H^\dagger H) + \text{h.c.}, \quad \Longrightarrow \quad Y_{\tau\mu} = \frac{v_W^2}{\sqrt{2}\Lambda^2}\langle\tau_L|\lambda'|\mu_R\rangle,$$

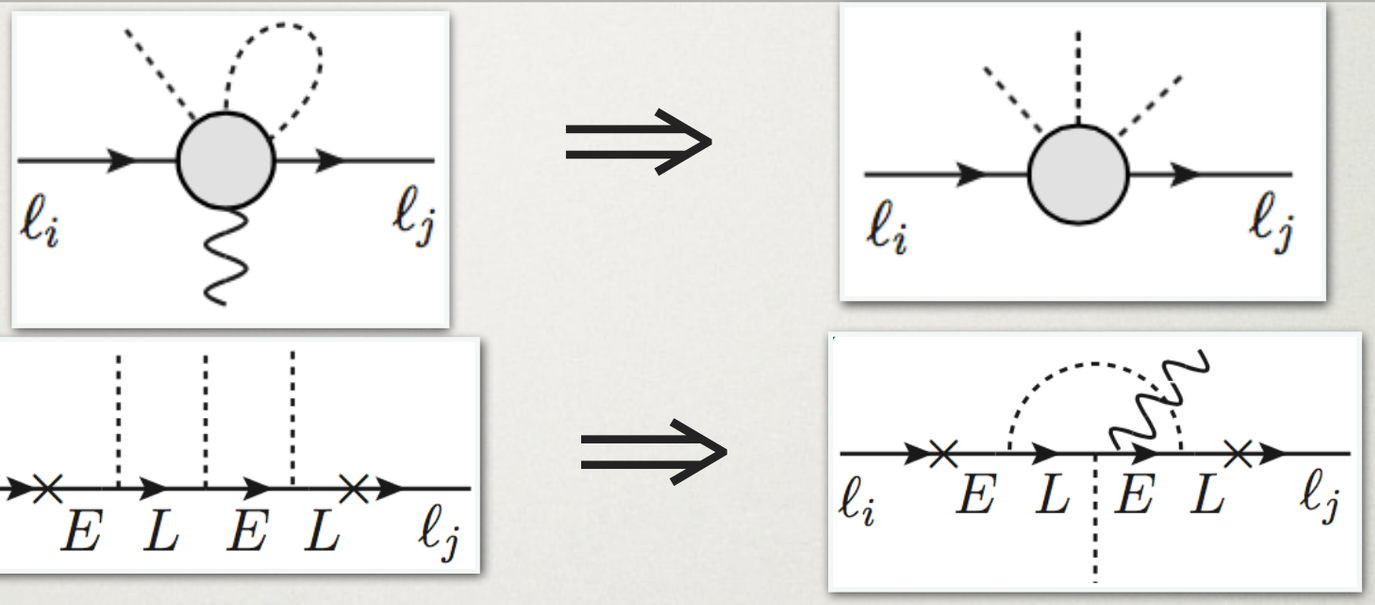
  - realization with vector-like leptons:

see e.g., Falkowski, Straub, Vicente, 1312.5329



DIPOLE OPERATOR

- same diagrams give $\tau \to \mu\gamma$ *



- experimental bound

$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8} \qquad \sqrt{|c_L|^2 + |c_R|^2} < (3.8\ \mathrm{TeV})^{-2}. \qquad \mathcal{L}_{\mathrm{eff}} = c_{L,R}\, m_\tau \frac{e}{8\pi^2} \left(\bar{\mu}_{R,L} \sigma^{\mu\nu} \tau_{L,R}\right) F_{\mu\nu}$$

- NDA estimate for the EM dipole operators (and taking $Y_{\tau\mu} \sim Y_{\mu\tau}$)

$$c_L \sim \frac{v_W}{\sqrt{2} m_\tau \Lambda^2} \langle \tau_L | \lambda' | \mu_R \rangle = \frac{Y_{\tau\mu}}{m_\tau v_W} \qquad \sqrt{|c_L|^2 + |c_R|^2} \sim \left(\frac{Y_{\tau\mu}}{2.2 \cdot 10^{-5}} \right) (3.8\ \mathrm{TeV})^{-2}$$

- compare $Br(h \to \tau\mu) < 0.15\%$ requires

$$\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 1.1 \cdot 10^{-3}$$

* The exception is a tree level exchange of a heavy scalar doublet, H'. But then the tadpole also induces a vev for H'.