Flavor and high p_T physics

Jure Zupan
u. of cincinnati & CERN

CKM 2016, Dec 2 2016

NEW PHYSICS FLAVOR PROBLEM

- solutions to the hierarchy problem typically require
  - new states at the TeV scale
  - have *O(1)* couplings to the SM
- often strong FCNC constraints
  - imply nontrivial flavor structure for NP
  - could lead to NP discovery from FCNC probes

FLAVOR AT COLLIDERS

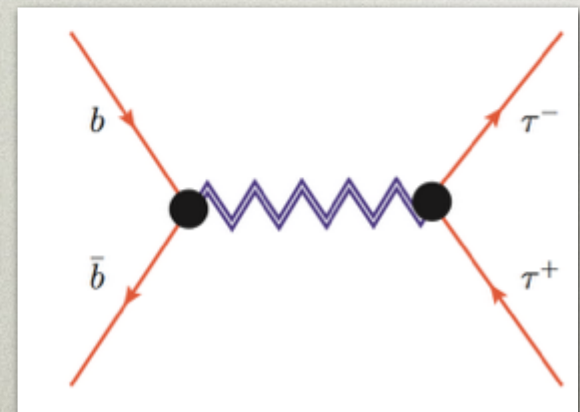
- flavor enters at high p_T in two ways
  - non-MFV flavor structure modifies signatures
    - example: stop searches, $\tilde{t} \to c\chi^0$ instead of $\tilde{t} \to t\chi^0$
    - example: searches for vector-like quarks $B' \to tW$ vs. $B' \to uW$
  - new probe: Higgs and its flavor structure (e.g., $h \to \tau\mu$)
- in addition: high p_T flavor conserving processes constrain possible FCNC searches

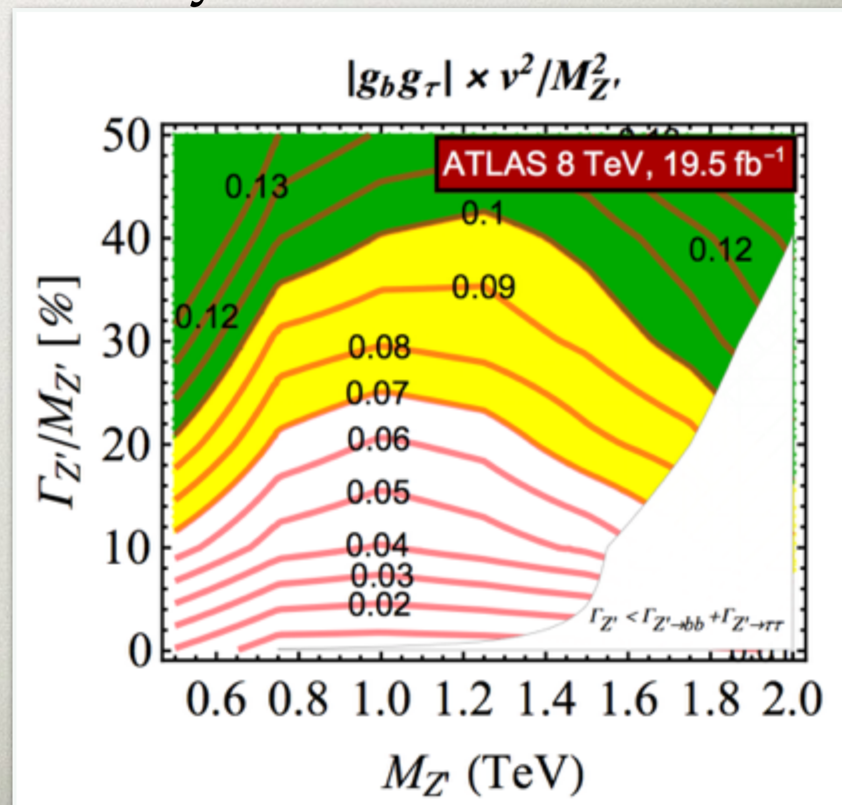
$\tau^+\tau^-$ SEARCHES

Faroughy, Greljo, Kamenik, 1609.07138

- for $b \to c\tau\nu$ anomalies there is a related $b\bar{b} \to \tau^+\tau^-$
- constrained strongly by LHC searches
- example: W' models constrained by $Z' \to \tau^+\tau^-$ searches

$$\mathcal{L}^{\rm eff} \supset c^{ijkl}_{QQLL}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l)$$





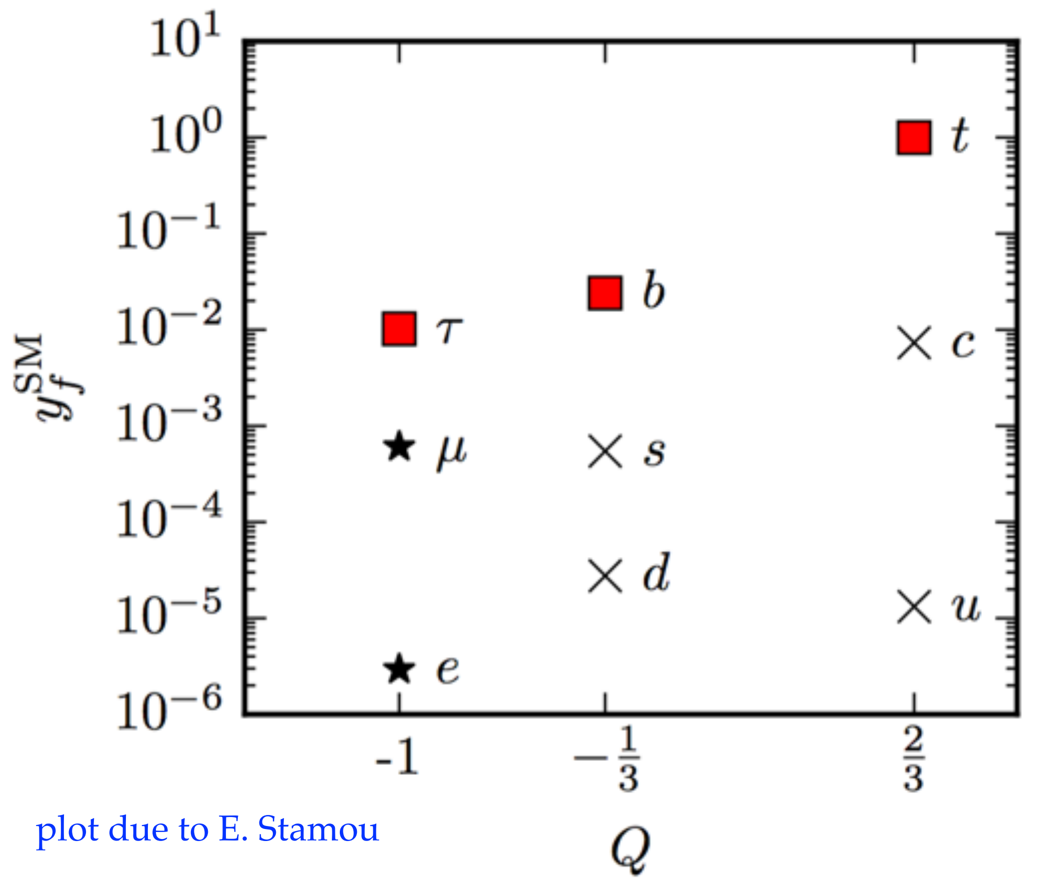
HIGGS AS PROBE OF FLAVOR

YUKAWA COUPLINGS : NONTRIVIAL FLAVOR STRUCTURE

- fermion masses are very hierarchical
- what is the origin of this?
  - the **SM flavor puzzle**
- in the SM

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

- implies Higgs has very hierarchical couplings to fermions
- how well have we tested this?



plot due to E. Stamou

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433

- several questions
  - proportionality

    $$y_{ii} \propto m_i$$

  - factor of proportionality

    $$y_{ii}/m_i = \sqrt{2}/v$$

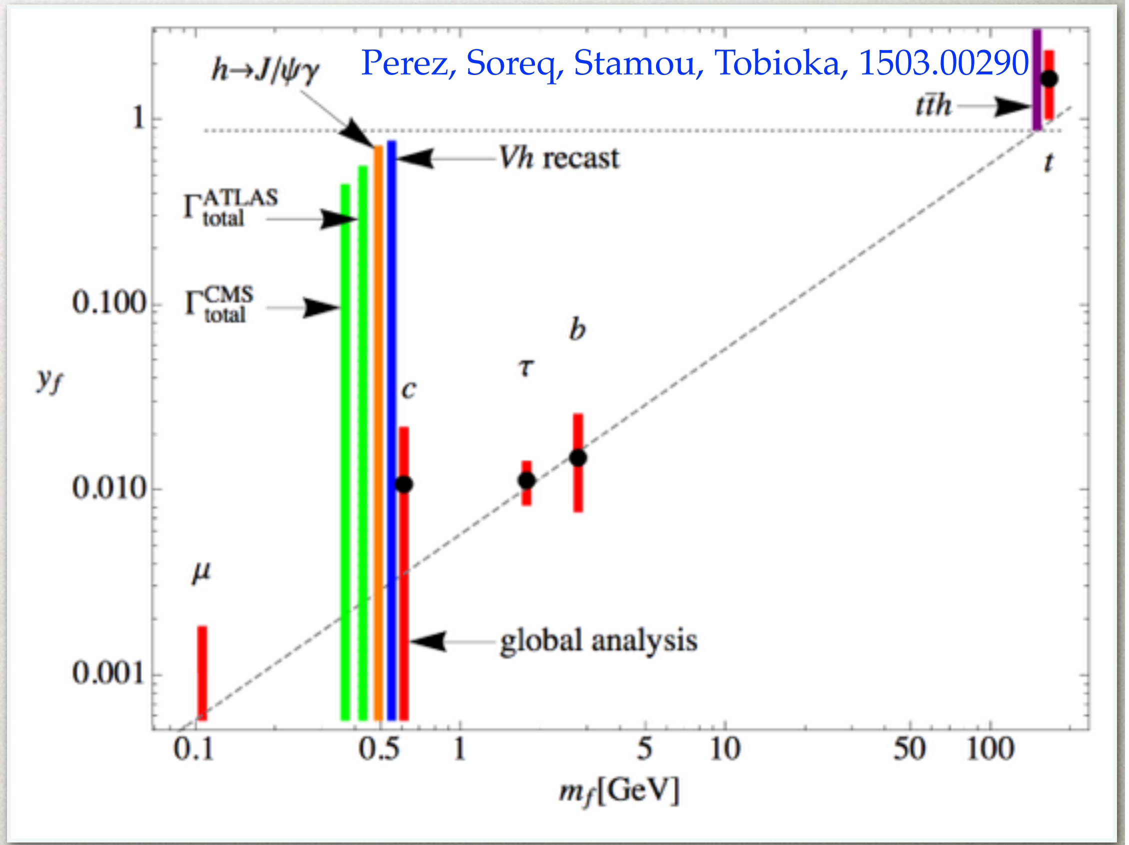
  - diagonality (flavor violation)

    $$y_{ij} = 0, \quad i \neq j$$

  - reality (CP violation)

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

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

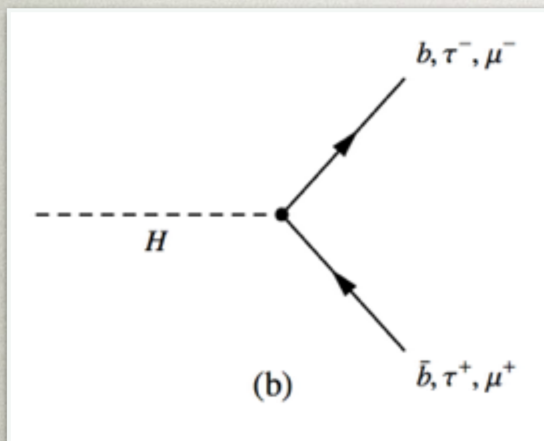


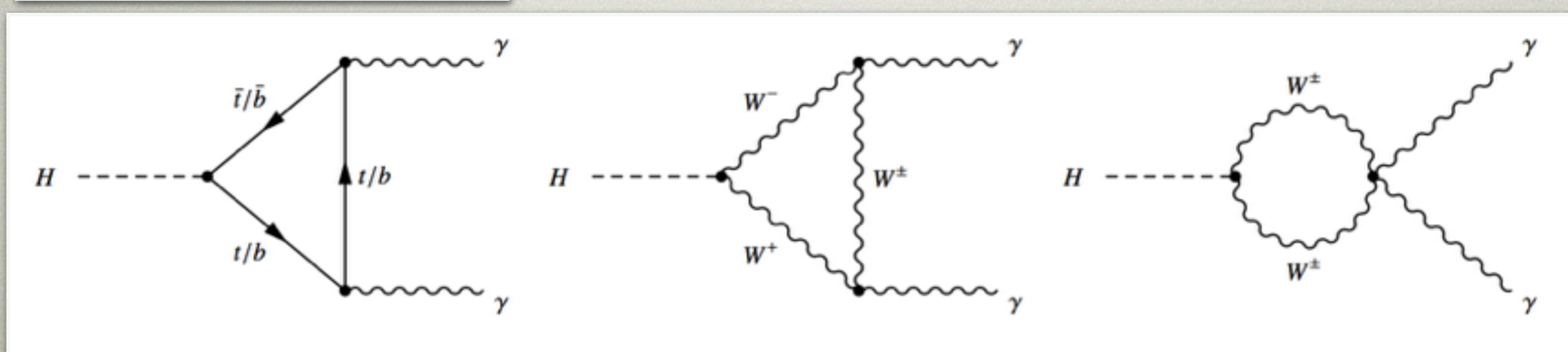
PROPORTIONALITY

- "proportionality" and "factor of proportionality"

$$\boxed{y_{ii} \propto m_i} \qquad \boxed{y_{ii}/m_i = \sqrt{2}/v}$$

- tested for 3rd generation fermions



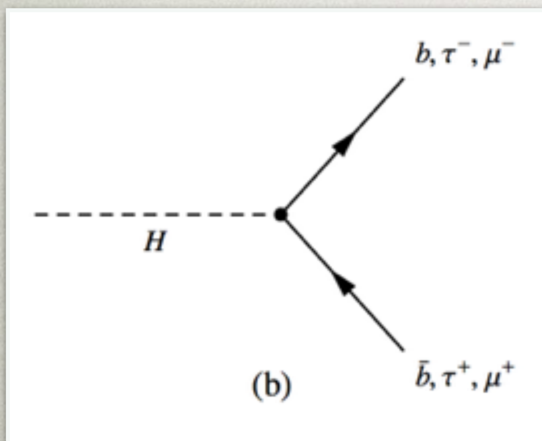


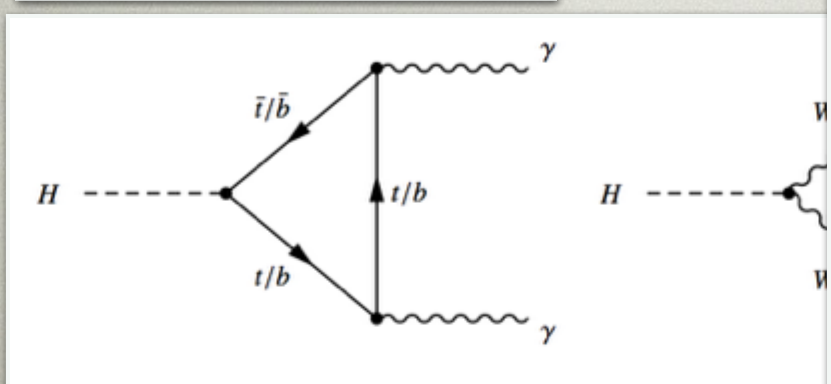
PROPORTIONALITY

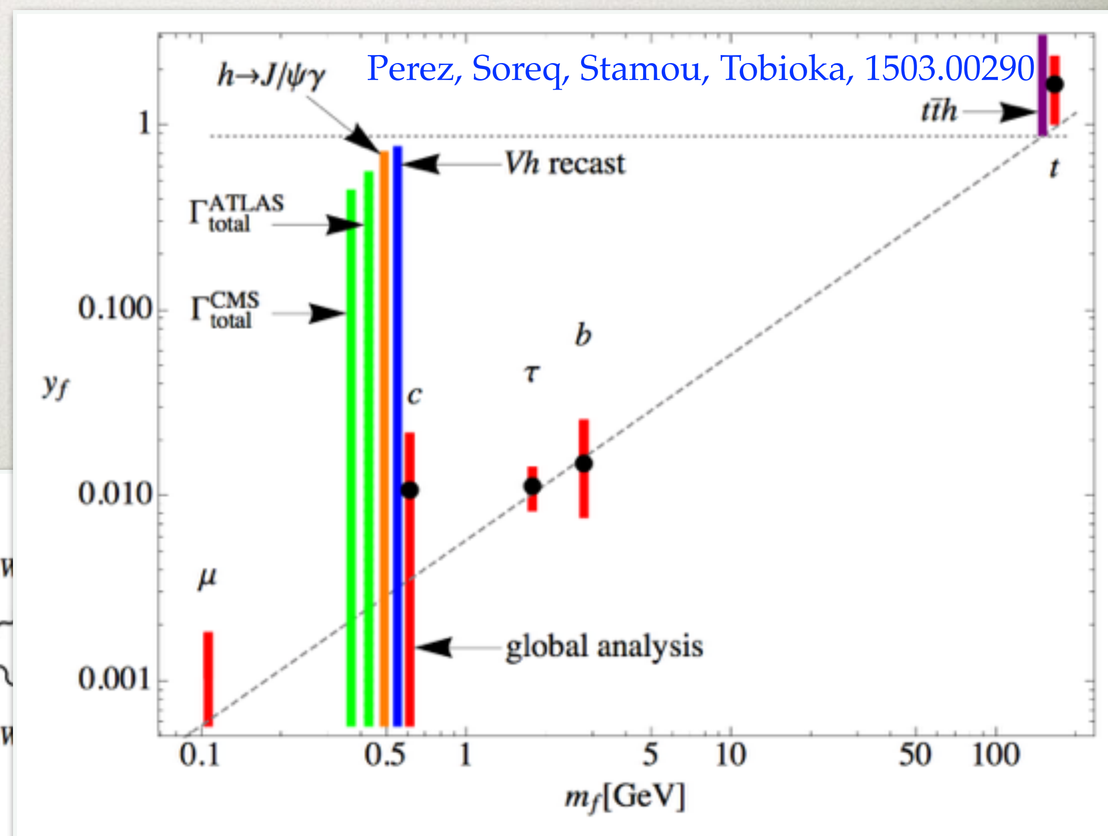
- "proportionality" and "factor of proportionality"

$$\boxed{y_{ii} \propto m_i} \qquad \boxed{y_{ii}/m_i = \sqrt{2}/v}$$

- tested for 3rd generation fermions







HIERARCHICAL COUPLINGS?

Soreq, Zhu, JZ, 1606.09621
Bishara, Haisch, Monni, Re, 1606.09253

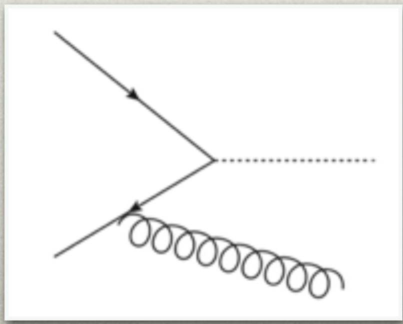
- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - already known for charged leptons and up-quarks

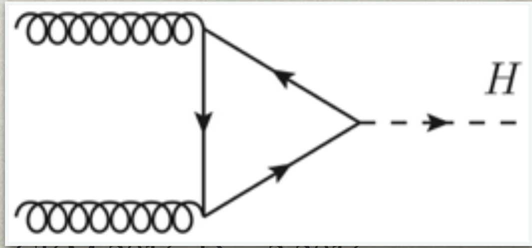
direct measurements

$$\frac{y^{\rm exp}_{e(\mu)}}{y^{\rm exp}_{\tau}} < 0.22(0.28)\,, \qquad \frac{y^{\rm exp}_{u(c)}}{y^{\rm exp}_{t}} < 0.036\,, \qquad \frac{y^{\rm exp}_{d(s)}}{y^{\rm exp}_{b}} < 5.6\,.$$

global fit

  - can we establish this for down quarks?
- seems possible to establish $y_d<y_b$ at high luminosity LHC (~300 fb^{-1})
  - from Higgs + jet p_T distributions



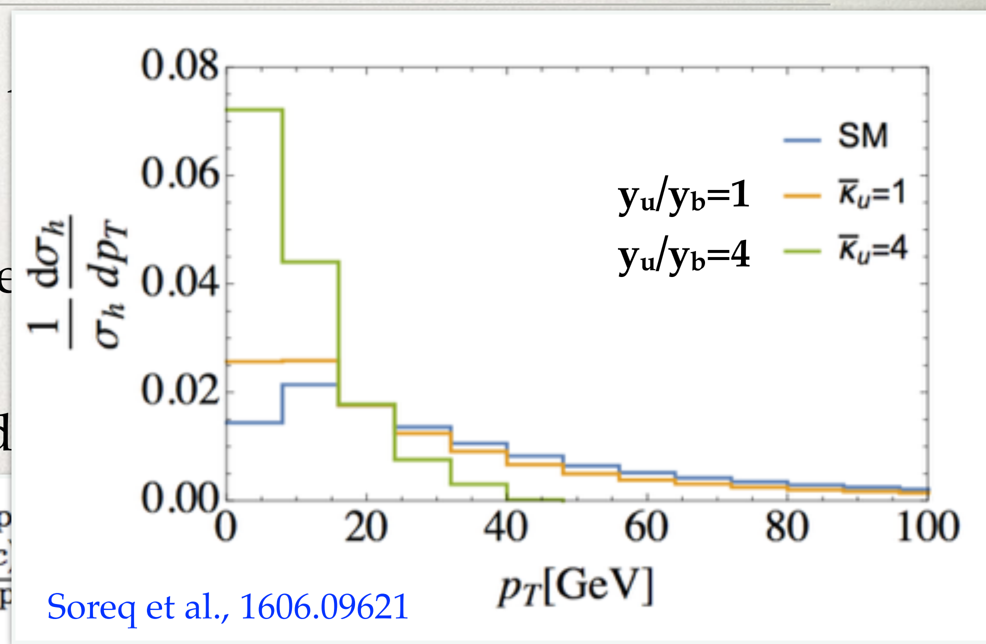


HIERARCHICAL COUPLINGS?

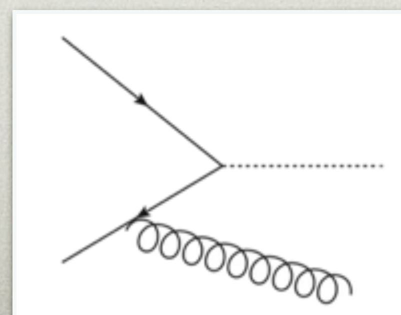
- does Higgs couple to the first t
  - tough: couplings are small
- more modest question: can we
hierarchical?
  - already known for charged

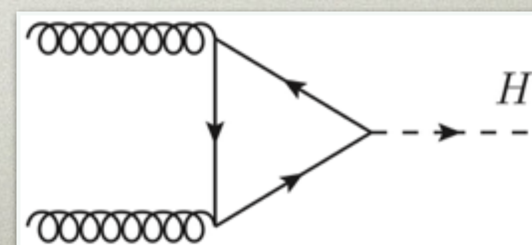
$$\frac{y_{e(\mu)}^{\text{exp}}}{y_\tau^{\text{exp}}} < 0.22(0.28)\,, \qquad \frac{y_{u(c}^{\text{exp}}}{y_t^{\text{exp}}}$$

direct measurements



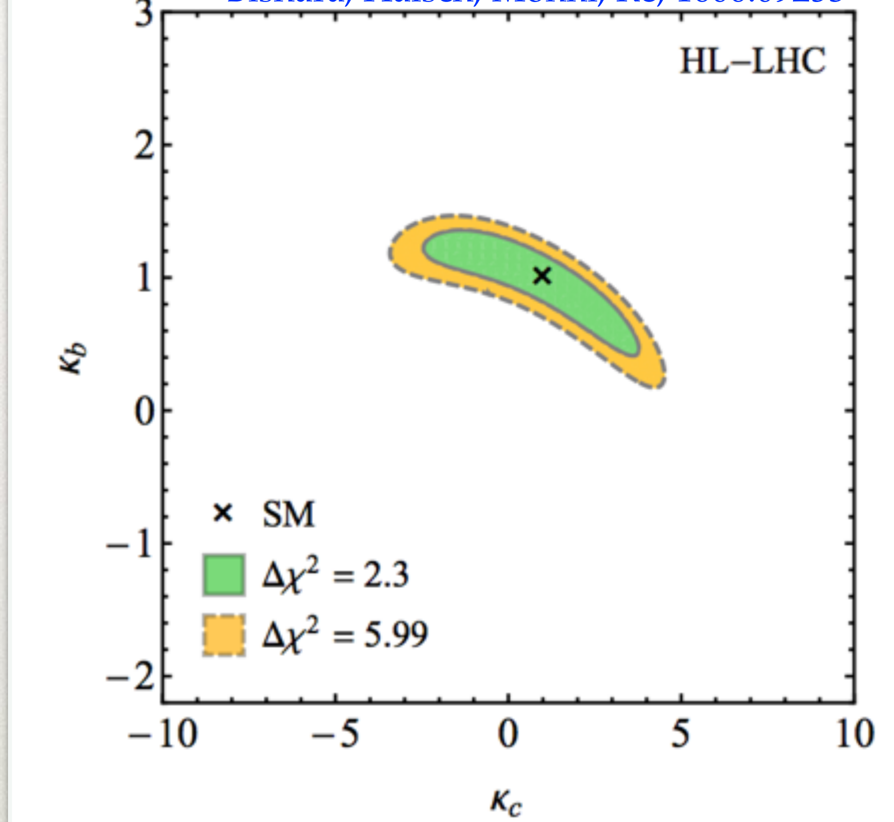
  - can we establish this for down quarks?
- seems possible to establish $y_d < y_b$ at high luminosity LHC (~300 fb^{-1})
  - from Higgs + jet p_T distributions





CHARM YUKAWA

- $3fb^{-1}$ HL-LHC could probe models of *O(1)* enhanced charm Yukawas



- compare with LHCb
  - present LHCb-CONF-2016-006
    (8 TeV, $1.98fb^{-1}$): $\kappa_c<80$
  - future HL-LHCb (13 TeV, $300fb^{-1}$, simple scaling): $\kappa_c \lesssim 4$

using LHCb-CONF-2016-006+C.Parkes's talk

CPV AND FV HIGGS COUPLINGS TO SM FERMIONS

- flavor violating couplings?

$$\boxed{y_{ij} = 0, \quad i \neq j}$$

  - very sensitive indirect probes (from precise bounds on FCNCs, such at $\tau \to \mu\gamma$)
  - from Higgs decays (e.g. $h \to \tau\mu$)

- CP violating couplings?

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

  - severe bounds from precision measurements of CP violating observables (such as electric dipole moments, EDMs)

HOW LARGE?

- a useful rule of thumb for maximal FV
  - do not want fine-tuned cancelations when diagonalizing mass matrix

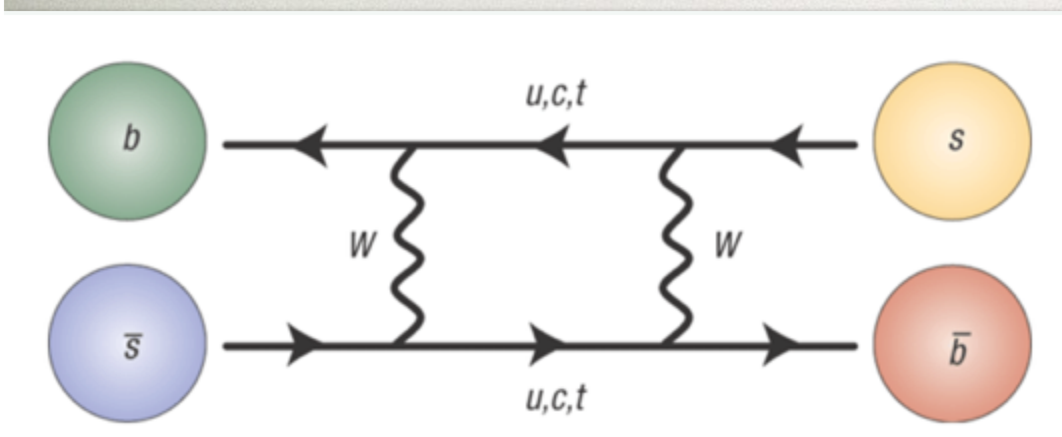
$$y_{\tau\mu}y_{\mu\tau} \lesssim 2\frac{m_\tau m_\mu}{v^2}$$

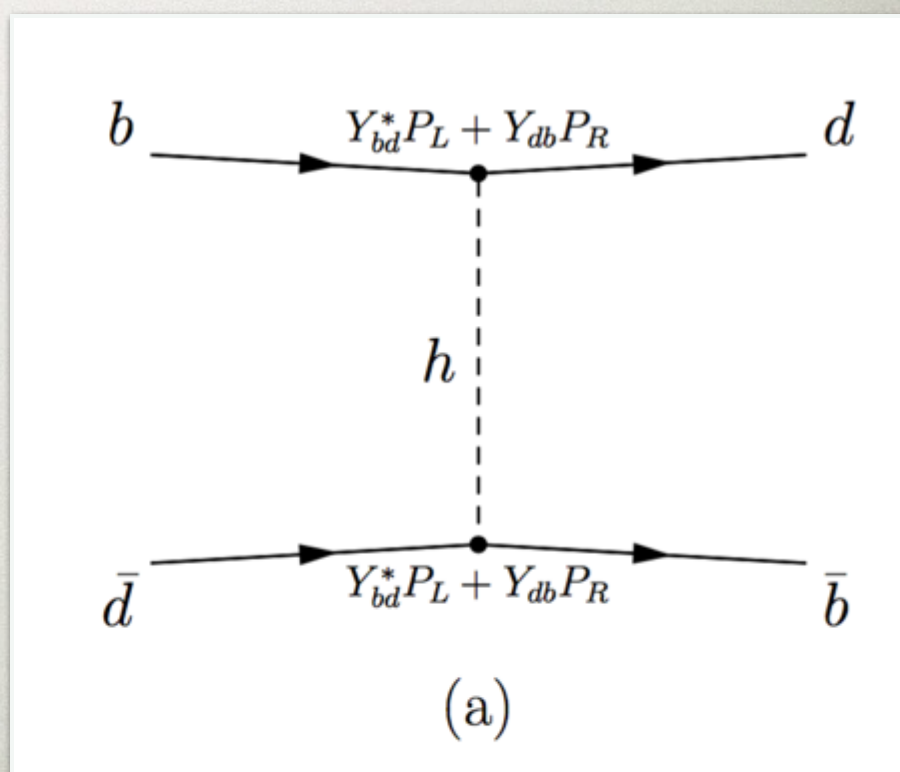
  - also what we would expect for $\Lambda \gtrsim v$
- come from dimension 6 ops. due to NP

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

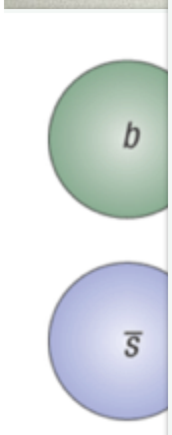
MESON MIXING

- will induce K^0-$\bar{K}^0$, B_d-$\bar{B}_d$, B_s-$\bar{B}_s$, D^0-$\bar{D}^0$ at tree level





Technique	Coupling	Constraint	Norm. Constr.
D^0 oscill. [48]	$\lvert y_{uc}\rvert^2, \lvert y_{cu}\rvert^2$	$< 1.0 \times 10^{-8}$	$< (0.5)^2 y_u^{SM} y_c^{SM}$
	$\lvert y_{uc} y_{cu}\rvert$	$< 1.5 \times 10^{-9}$	$< (0.2)^2 y_u^{SM} y_c^{SM}$
B_d^0 oscill. [48]	$\lvert y_{db}\rvert^2, \lvert y_{bd}\rvert^2$	$< 4.6 \times 10^{-8}$	$< (0.4)^2 y_d^{SM} y_b^{SM}$
	$\lvert y_{db} y_{bd}\rvert$	$< 6.6 \times 10^{-9}$	$< (0.15)^2 y_d^{SM} y_b^{SM}$
B_s^0 oscill. [48]	$\lvert y_{sb}\rvert^2, \lvert y_{bs}\rvert^2$	$< 3.6 \times 10^{-6}$	$< (0.8)^2 y_s^{SM} y_b^{SM}$
	$\lvert y_{sb} y_{bs}\rvert$	$< 5.0 \times 10^{-7}$	$< (0.3)^2 y_s^{SM} y_b^{SM}$
K^0 oscill. [48]	$\mathrm{Re}(y_{ds}^2), \mathrm{Re}(y_{sd}^2)$	$[-1.2 \ldots 1.2] \times 10^{-9}$	$< (0.4)^2 y_d^{SM} y_s^{SM}$
	$\mathrm{Im}(y_{ds}^2), \mathrm{Im}(y_{sd}^2)$	$[-5.8 \ldots 3.2] \times 10^{-12}$	$< (0.03)^2 y_d^{SM} y_s^{SM}$
	$\mathrm{Re}(y_{ds}^* y_{sd})$	$[-1.1 \ldots 1.1] \times 10^{-10}$	$< (0.13)^2 y_d^{SM} y_s^{SM}$
	$\mathrm{Im}(y_{ds}^* y_{sd})$	$[-2.8 \ldots 5.6] \times 10^{-13}$	$< (0.01)^2 y_d^{SM} y_s^{SM}$



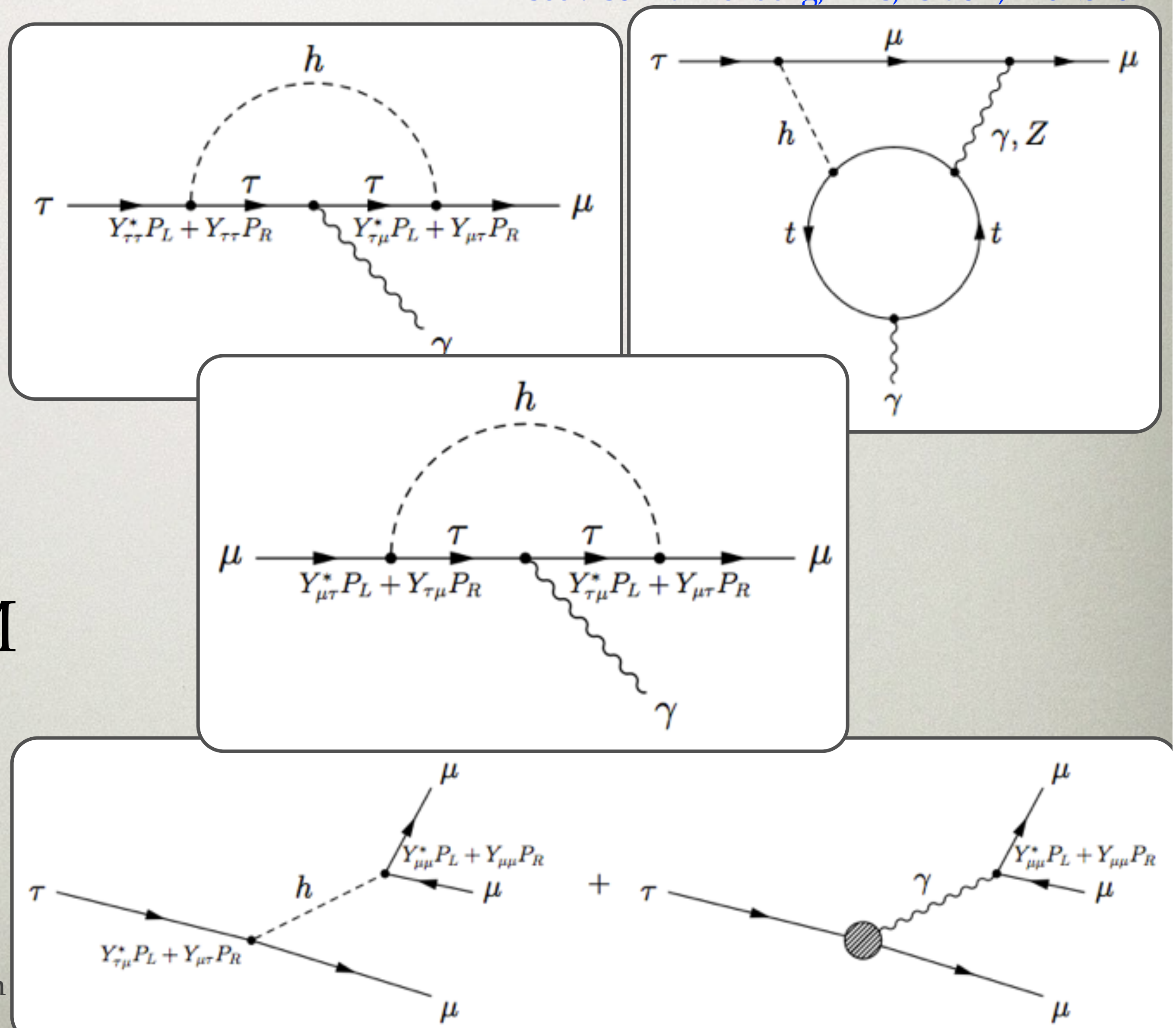
(a)

$h \to \tau\mu$

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

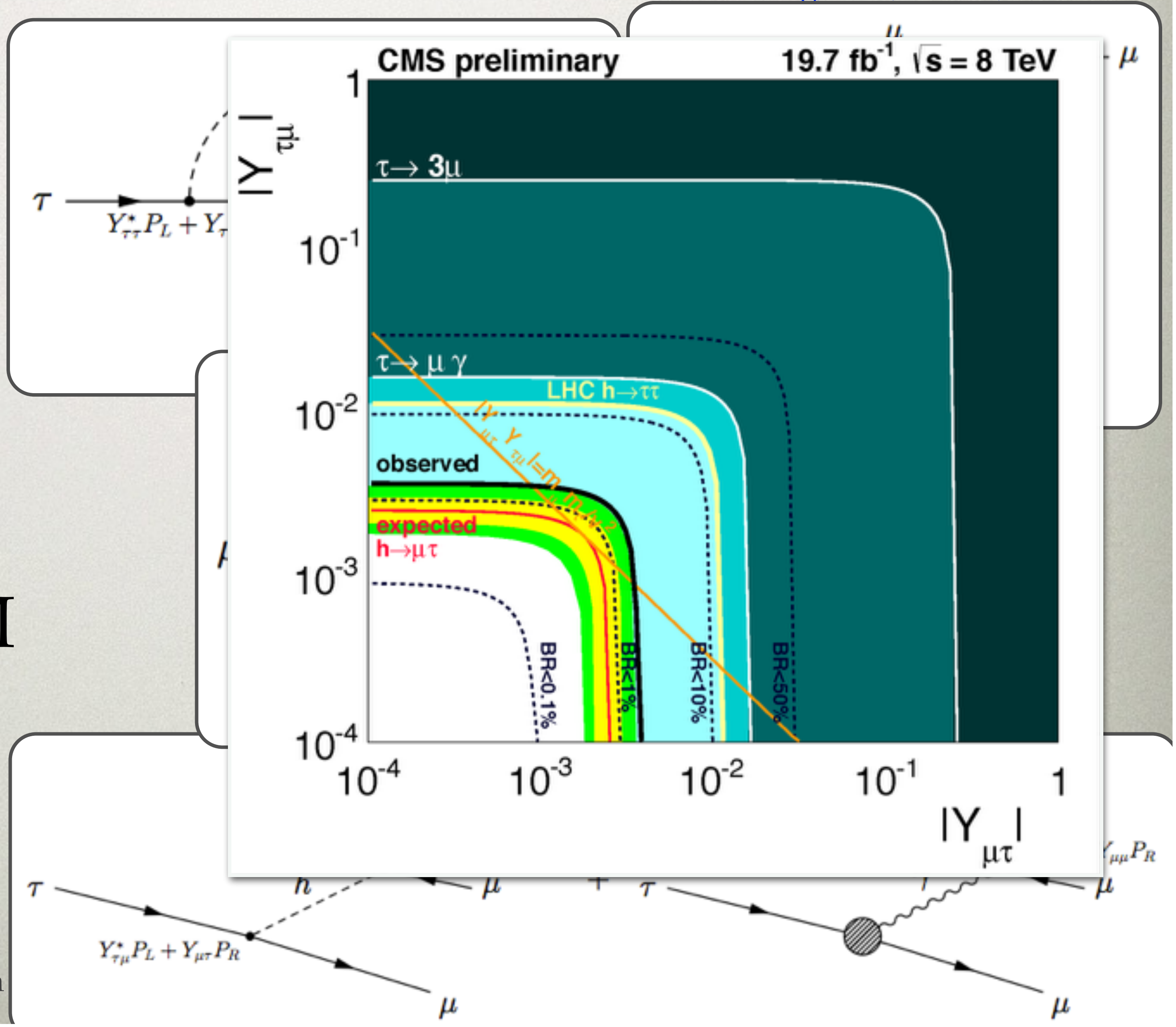


$h \to \tau\mu$

Harnik, Kopp, JZ, 1209.1397

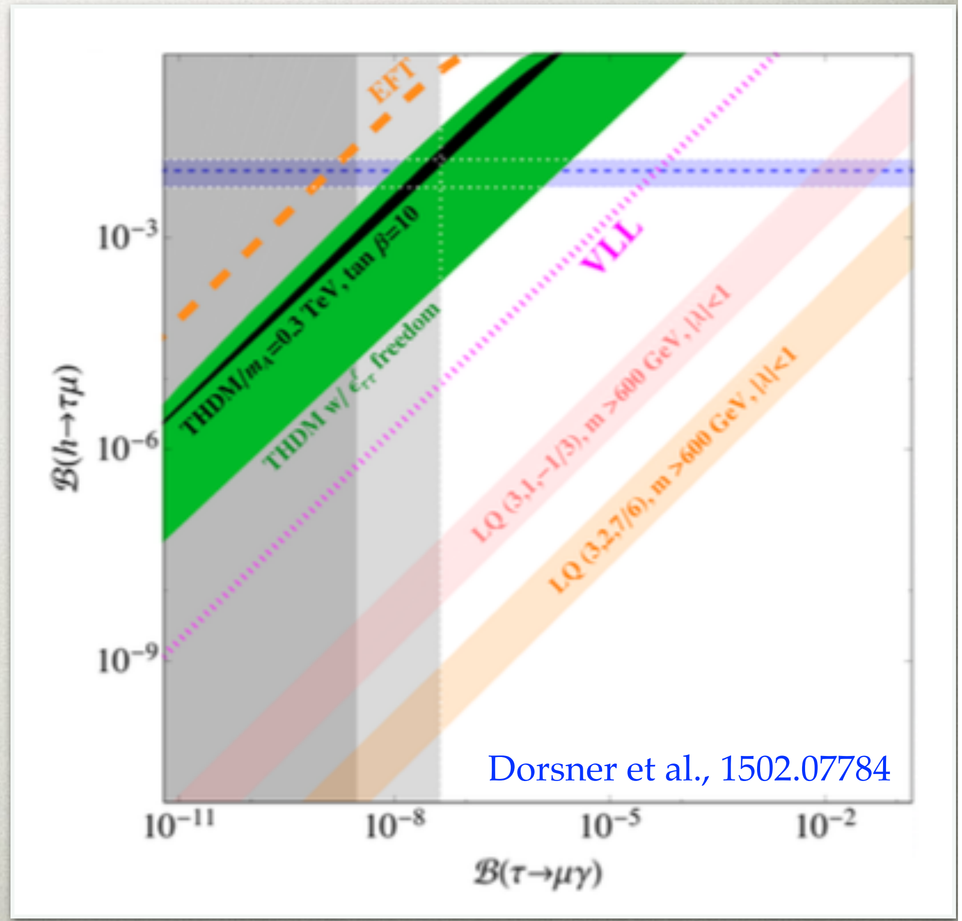
see also Blankenburg, Ellis, Isidori, 1202.5704

- bounds from
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$
  - muon g-2
  - muon EDM



LARGE FV HIGGS DECAYS?

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



VIABLE MODELS: SEQUESTERED MASS GENERATION

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

- a family of viable new physics models
  - lepton mass matrix of the form

$$\mathcal{M}^\ell = \underbrace{\mathcal{M}_0^\ell}_{\text{rank 1 matrix, from } \phi} + \underbrace{\Delta\mathcal{M}^\ell}_{\text{rank 2 or 3 matrix}},$$

  - scalar ϕ the primary component of the Higgs
    - accounts for the bulk of m_τ
  - ΔM_l due to an additional source of EWSB
    - accounts for m_e and m_μ

2HDM

- two Higgs doublets, neutral compts: ϕ, ϕ',vevs v, v'

$$\tan\beta = v/v'$$

  - ϕ couples to 3rd family, ϕ' to all three

$$M^l = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

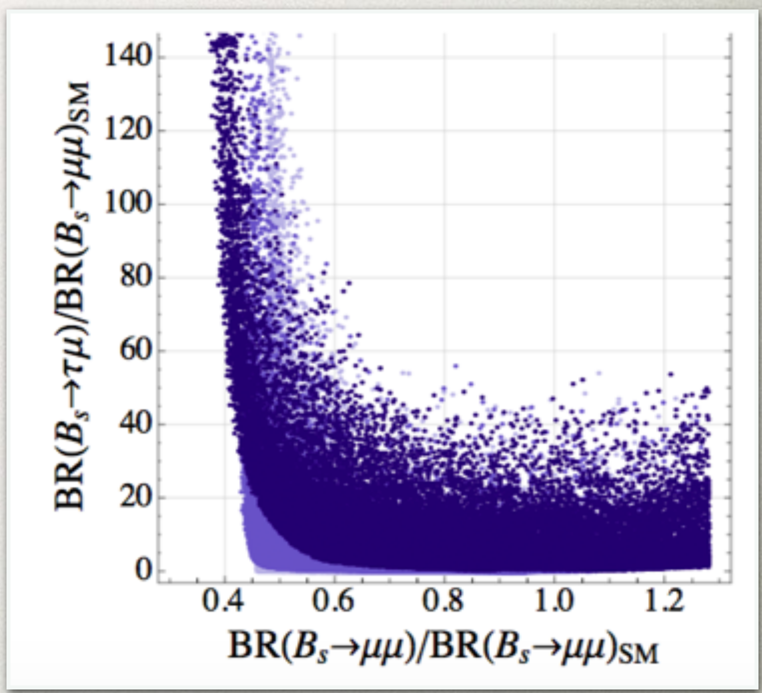
ϕ'

ϕ **and** ϕ'

  - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- can saturate $Br(h \to \tau\mu)$
- $Br(\tau \to \mu\gamma)$ parametrically suppressed (there is an extra y_τ insertion)
- predicts modified phenomenology of heavy Higgses

PHENOMENOLOGICAL IMPLICATIONS

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927



- $B_s \to \mu\mu$ 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 $\mu\mu$ could dominate over $\tau\tau$
  - opposite to Type-II 2HDMs
- $t \to hc$ potentially sizable
- a general sum rule

$$\hat{y}_\mu \hat{y}_\tau - \hat{y}_{\tau\mu}\hat{y}_{\mu\tau} = \hat{y}_{t,b}(\hat{y}_\mu + \hat{y}_\tau - \hat{y}_{t,b})$$

$$\hat{y}_{ij} \equiv Y_{ij}/Y_{ii}^{\rm SM}$$

  - valid to the extent that both ΔM^l and ΔM_0 are rank 1

Altmannshofer, Eby, Gori, Lotito, Martone, Tuckler, 1610.02398

COLLIDER SIGNATURES

- h couplings to 3rd and 2nd generation

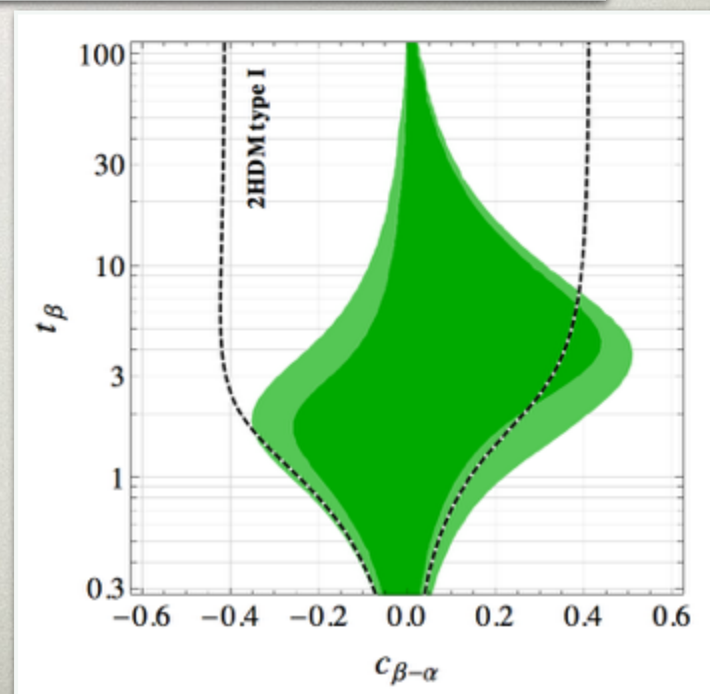
like 2HDM type I

$$\kappa_t \equiv \frac{Y_t}{Y_t^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_c}{m_t}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_b \equiv \frac{Y_b}{Y_b^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_s}{m_b}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_\tau \equiv \frac{Y_\tau}{Y_\tau^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,.$$

differs from natural f.c.

$$\kappa_\mu \equiv \frac{Y_\mu}{Y_\mu^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_c \equiv \frac{Y_c}{Y_c^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_c}{m_t}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_s \equiv \frac{Y_s}{Y_s^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_s}{m_b}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,.$$

- for large tanβ $h\to\mu\mu, cc$ can dominate Γ_h
  - modifies the global fit
- for heavy H the dominant decay can be flavor violating



COLLIDER SIGNATURES

- h couplings to 3rd and 2nd generation

differs from natural f.c.

$$\kappa_t \equiv \frac{Y_t}{Y_t^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_c}{m_t}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha}\,,$$

$$\kappa_b \equiv \frac{Y_b}{Y_b^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_s}{m_b}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha}\,,$$

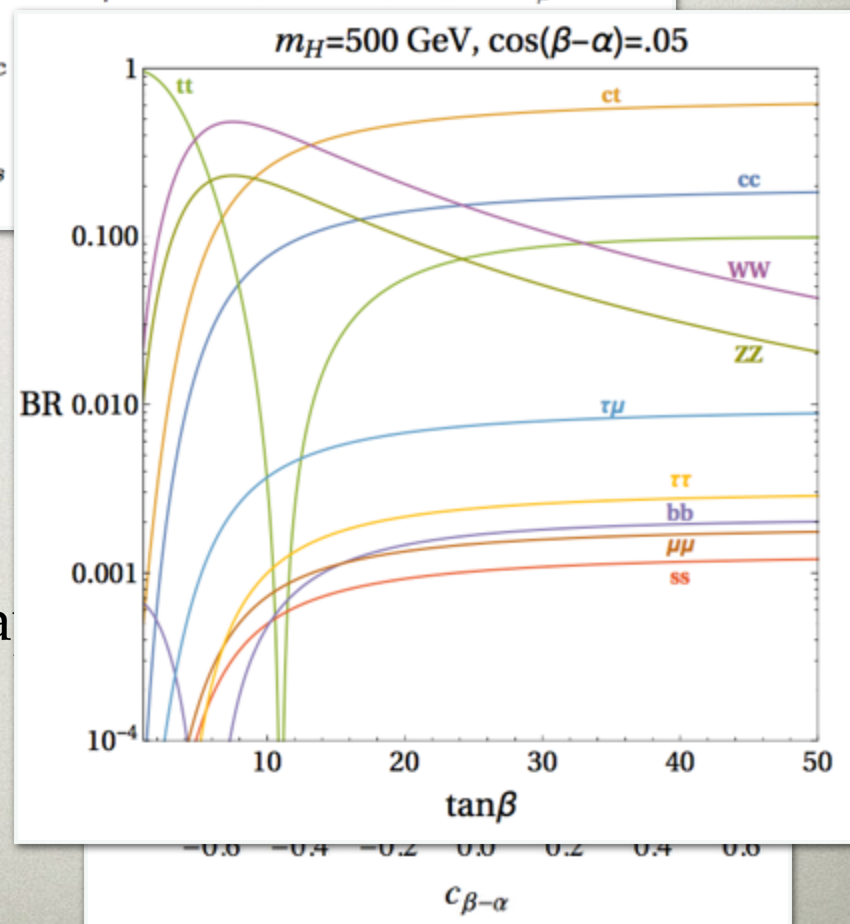
$$\kappa_\tau \equiv \frac{Y_\tau}{Y_\tau^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha}\,.$$

like 2HDM type I

$$\kappa_\mu \equiv \frac{Y_\mu}{Y_\mu^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha}\,,$$

κ_c

κ_s



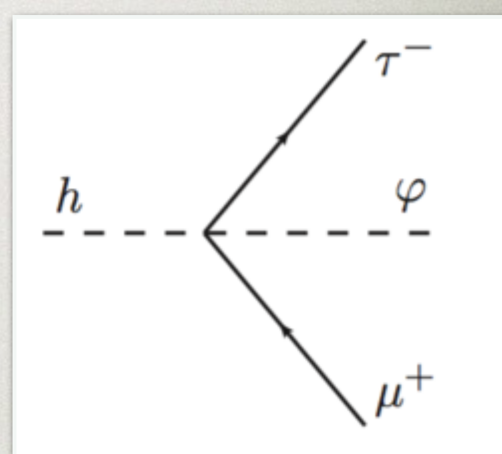
- for large tanβ $h\to\mu\mu, cc$ can dominate Γ_h
  - modifies the global fit
- for heavy H the dominant deca[y] can be flavor violating

FLAVORFUL DARK MATTER

Galon, JZ, to appear

- $h \to \tau\mu$ could be $h \to \tau\mu + MET$,
  no flavor violation if dark sector flavorful

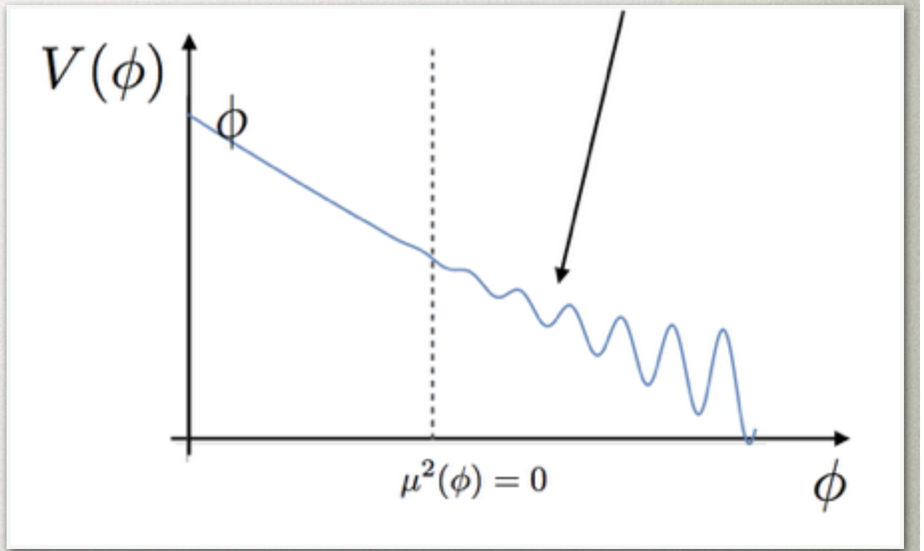
$$\frac{Br(h \to \tau^{\pm}\mu^{\mp}\varphi\ /\varphi^{*})}{Br(h \to \tau^{+}\tau^{-})} \simeq \frac{1}{6}\left(\frac{m_h}{2\pi\Lambda y_\tau}\right)^2 = 0.66 \times \left(\frac{\text{TeV}}{\Lambda}\right)^2\left(\frac{0.01}{y_\tau}\right)^2$$



- φ is the mediator to dark matter
  - dark matter can be a thermal relic
- depending on flavor structure φ could mediate
  - $\text{Br}(\mu \to e\gamma) \sim O(10^{-13})$, $\text{Br}(\mu \to 3e) \sim O(10^{-12})$,
    $\text{Br}(\mu \to 3e + \nu_\mu \bar{\nu}_e) \sim \text{Br}(\tau \to 3\mu, 3e + \nu_\tau \bar{\nu}_\mu) \sim O(10^{-5})$
  - others well below present experimental limits

RELAXION FROM FLAVOR

Flacke, Frugiuele, Fuchs, Gupta, Perez, 1610.02025



- relaxion - a technically natural solution to the hierarchy problem

  Graham, Kaplan, Rajendran, 1504.07551

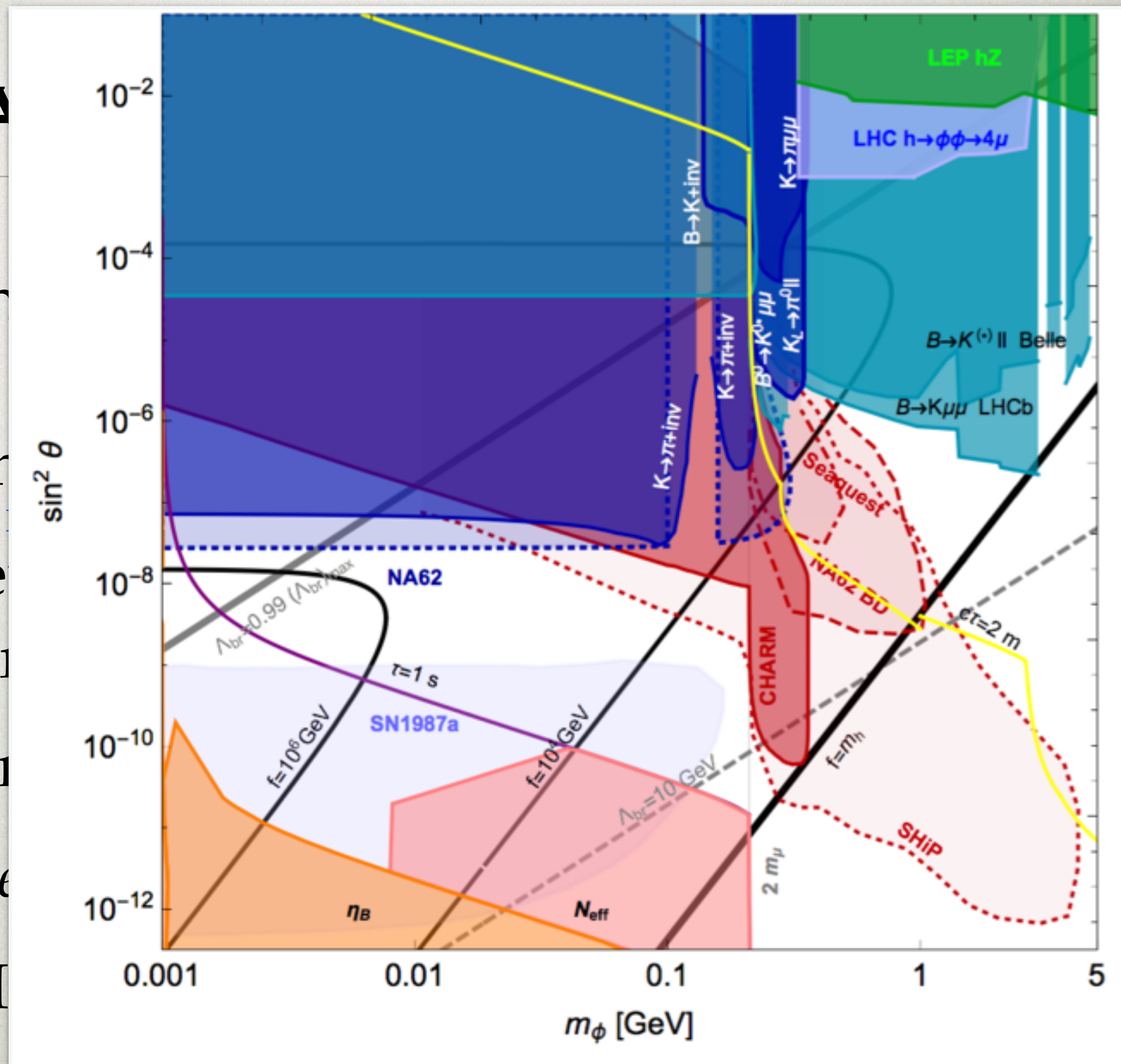
  - no new EW states required in principle

- in general relaxion-higgs mixing
  - $\phi \to ee, \mu\mu, \ldots$ decays controlled by m_ϕ, $\sin\theta$
  - for MeV$\lesssim m_\phi \lesssim$GeV can search for ϕ in rare decays: $K \to \pi^+\phi$, $B \to K^+\phi$

RELA

- relaxion
  natural
  hierarch
  Graham,
  - no ne
    requi
- in gene
  - $\phi \to ee$
  - for M
    decays: $K \to \pi\ \phi$, $B \to K\ \phi$

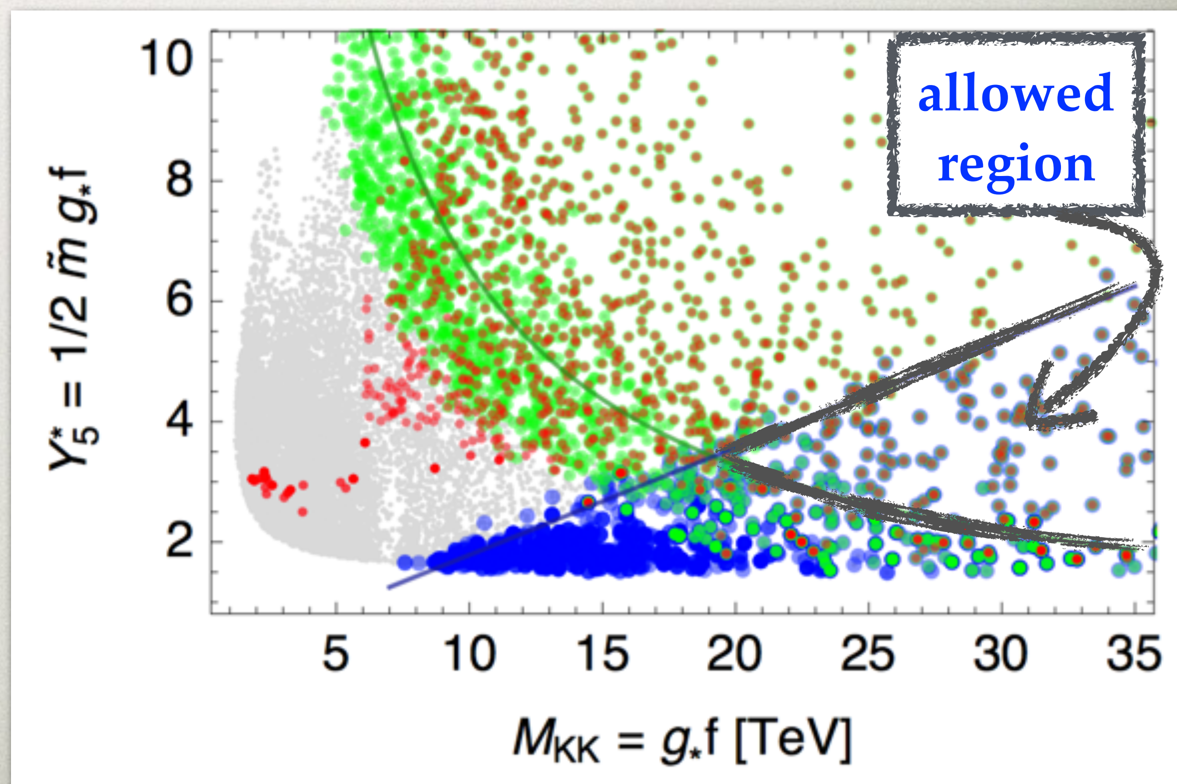
0.02025

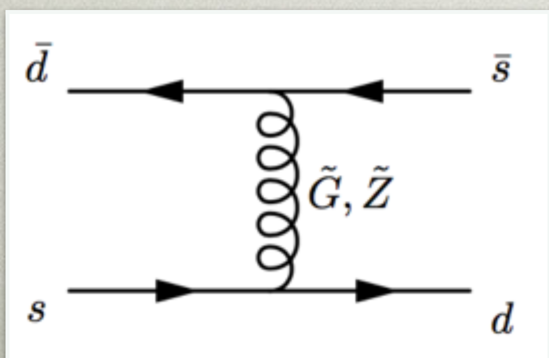


NEUTRAL NATURALNESS

- color neutral states could stabilize the Higgs at 1-loop
  - twin Higgs, folded SUSY
- need to be UV completed at ~10TeV
  - typically requires a bigger structure
  - will lead to FCNCs
  - example:
    composite Twin Higgs

Csaki, Geller, Telem, Weiler, 1512.03427





CONCLUSIONS

- Higgs flavor violation an interesting probe of new physics
- one gets complementary information from high p_T and precision experiments

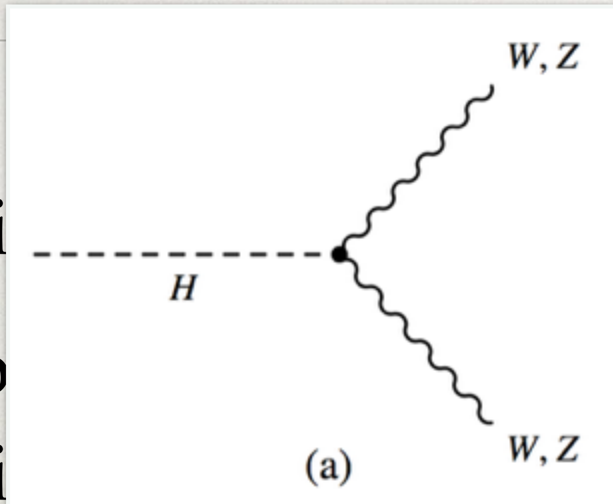
BACKUP SLIDES

SM HIGGS?

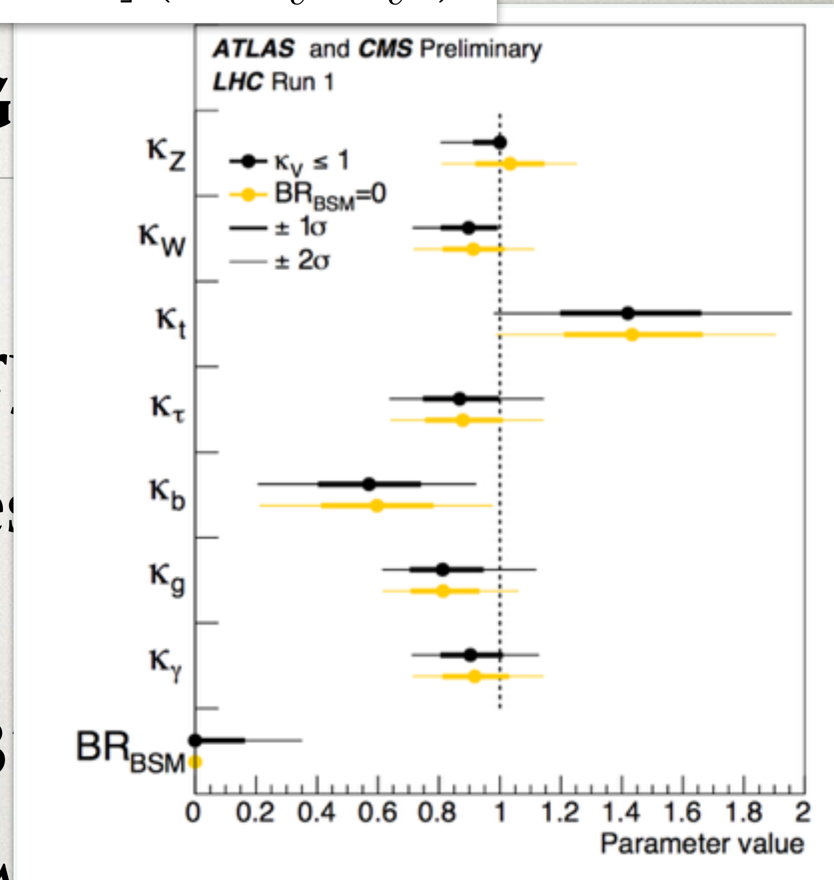
- Higgs boson discovery July 2012
- how closely does it resemble the SM Higgs?
- responsible for EWSB?
    - from couplings to $W,Z \Rightarrow$ yes, most of it
- fermion mass generation
    - does it couple to fermions?

$$\mathcal{L}_\phi \supset \frac{1}{2}\left(\partial_\mu h\right)^2 + \left[\kappa_W m_W^2 W^{\mu +} W_\mu^- + \frac{\kappa_Z}{2} m_Z^2 Z^\mu Z_\mu\right]\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right)$$

SM HIG



(a)



- Hi … er
- ho … re
  Hi
- responsible for EWSB
  - from couplings to $W,Z \Rightarrow$ yes, most of it
- fermion mass generation
  - does it couple to fermions?

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

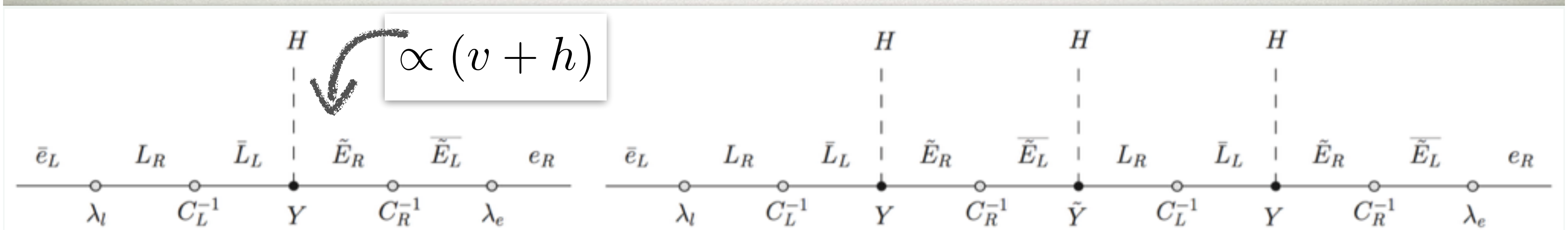
THE EFFECTS OF NEW PHYSICS

- an example: SM + 3 gen. of vectorlike leptons $L_i = (N_i, E_i)$, $\tilde{E}_i$

$$\mathcal{L}_{F,c} = -M\left(\bar{L}C_L L + \bar{E}C_R E\right) - \left(\bar{L}_L Y \tilde{E}_R H + \bar{L}_R \tilde{Y}\tilde{E}_L H + \text{h.c.}\right).$$

$$\mathcal{L}_{\text{mix}} = M\left(\bar{l}_L \lambda_l L_R + \overline{\tilde{E}}_L \lambda_e e_R\right) + \text{h.c.}$$

- imagine that the Higgs only couples to these but not the SM fermions



$$\propto \left(v^3 + 3v^2 h + \cdots\right)$$

- the two contribs. have different flavor structure in general
- the Yukawas misaligned from the masses by $1/M$

$$y_f = \frac{\sqrt{2}}{v} m_f + \frac{v^2}{M^2}\lambda_\ell C_L^{-1} Y C_R^{-1} \tilde{Y} C_L^{-1} Y C_R^{-1} \lambda_e$$

EFFECTIVE FIELD THEORY DESCRIPTION

- this result is general - integrate heavy NP and obtain EFT description

$$\mathcal{L}_{\text{Yuk}} = -\left(Y_f\right)_{ij}\left(\bar{f}^i_L f^j_R\right)\phi + \text{h.c.}$$

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

$$\sqrt{2}m_f = V_L\left(Y_f + \frac{v^2}{2\Lambda^2}\lambda'\right)V_R^\dagger v$$

$$y_f = V_L\left(Y_f + 3\frac{v^2}{2\Lambda^2}\lambda'\right)V_R^\dagger$$

$$\left(y_f\right)_{ij} = \sqrt{2}\frac{m_i}{v}\delta_{ij} + \frac{v^2}{\Lambda^2}\left(V_L\lambda' V_R^\dagger\right)_{ij}$$

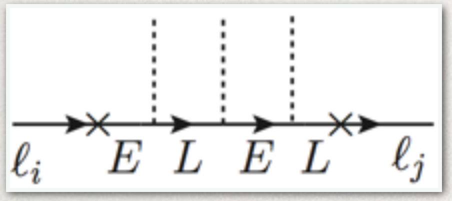
- important: SM Yukawa couplings small for the first two generations
    - Λ can be large but still have an effect for *λ′~ O(1)*
- the effects different in different NP models of flavor
    - can learn about these from measured patterns

DIPOLE TRANSITIONS

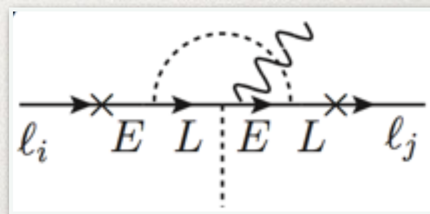
- severe exp. bounds on dipole transitions BaBar, 0908.2381 MEG, 1605.05081

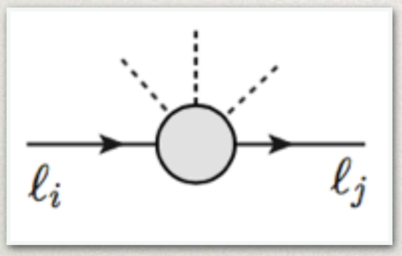
$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$ $\mathrm{Br}(\tau \to e\gamma) < 3.3 \cdot 10^{-8}$ $\mathrm{Br}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$

- same NP diagrams that give $h \to \tau\mu$ generically also give $\tau \to \mu\gamma$ at 1-loop

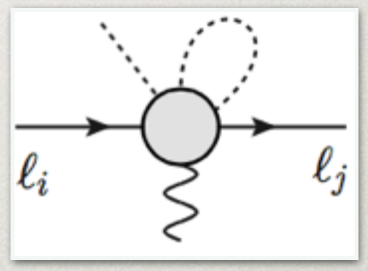


$\Longrightarrow$





$\Longrightarrow$



- NDA estimate for the EM dipole operators

$$y_{\tau\mu} \sim \frac{v^2}{\Lambda^2}\lambda'_{\tau\mu}$$

$$c_{L,R} \sim \frac{v}{m_\tau \Lambda^2}\lambda'_{\tau\mu,\mu\tau} \sim \frac{1}{m_\tau v} y_{\tau\mu,\mu\tau}$$

$$\mathcal{L}_{\text{eff}} = c_{L,R}\, m_\tau \frac{e}{8\pi^2}\left(\bar\mu_{R,L}\sigma^{\mu\nu}\tau_{L,R}\right)F_{\mu\nu}$$

$$y_{\tau\mu} \lesssim 3 \cdot 10^{-5} \qquad y_{\tau e} \lesssim 3 \cdot 10^{-5} \qquad y_{\mu e} \lesssim 4 \cdot 10^{-8}$$

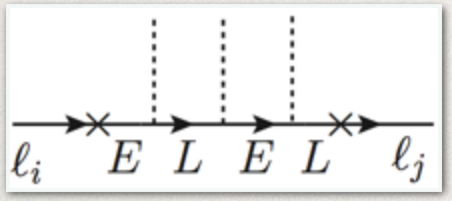
$$\sqrt{y_\mu^{\rm SM} y_\tau^{\rm SM}} = 2.5 \cdot 10^{-3} \qquad \sqrt{y_e^{\rm SM} y_\tau^{\rm SM}} = 1.7 \cdot 10^{-4} \qquad \sqrt{y_e^{\rm SM} y_\mu^{\rm SM}} = 4.2 \cdot 10^{-5}$$

- severe exp. bounds on dipole transitions

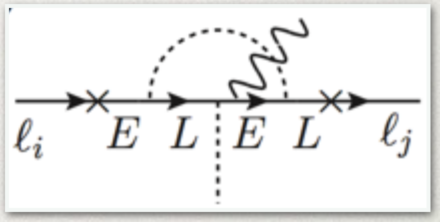
BaBar, 0908.2381 MEG, 1605.05081

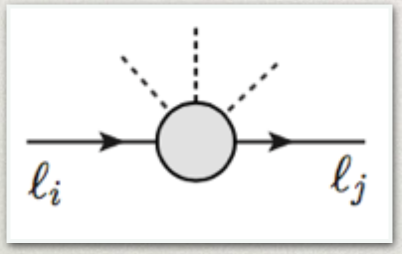
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8} \qquad \mathrm{Br}(\tau \to e\gamma) < 3.3 \cdot 10^{-8} \qquad \mathrm{Br}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$$

- same NP diagrams that give $h \to \tau\mu$ generically also give $\tau \to \mu\gamma$ at 1-loop

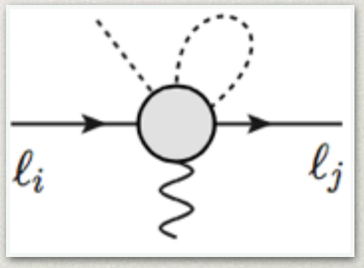


$\Longrightarrow$





$\Longrightarrow$



- NDA estimate for the EM dipole operators

$$y_{\tau\mu} \sim \frac{v^2}{\Lambda^2}\lambda'_{\tau\mu}$$

$$c_{L,R} \sim \frac{v}{m_\tau \Lambda^2}\lambda'_{\tau\mu,\mu\tau} \sim \frac{1}{m_\tau v} y_{\tau\mu,\mu\tau}$$

$$\mathcal{L}_{\rm eff} = c_{L,R}\, m_\tau \frac{e}{8\pi^2}(\bar\mu_{R,L}\sigma^{\mu\nu}\tau_{L,R})F_{\mu\nu}$$

$h \rightarrow \tau\mu$ exp. info

- hint of a signal in $h \rightarrow \tau\mu$ still there? CMS-HIG-14-005
    - CMS: $Br(h \rightarrow \tau\mu) = (0.89 \pm 0.39)\%$
    - ATLAS: $Br(h \rightarrow \mu\tau) = (0.53 \pm 0.51)\%$ ATLAS, 1508.03372; 1604.07730
- first 13 TeV result CMS-PAS-HIG-16-005
    - CMS @ 13 TeV, 2.3 fb^{-1}: no excess, $Br(H \rightarrow \tau\mu) < 1.20\%$ (1.62% expected)

EXCLUDED?

- if Higgs the only* source of ferm. mass ⇒*Br*($\tau \to \mu\gamma$) too large by <u>4 orders</u> of magnitude
  - *and no tunings

for tuned MSSM example see e.g., Aloni, Nir, Stamou, 1511.00979

- alternatively one could do EFT analysis of low energy constraints with the Lagrangian after EWSB

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

  - does not care whether Higgs is part of a doublet
  - or if there are other EWSB sources