Uncovering mass generation through Higgs flavor violation

$$h \to \tau\mu, B_s \to \tau\mu, \ldots$$

Alex Kagan

University of Cincinnati

based on Wolfgang Altmannshofer, Stefania Gori, AK, Luca Silvestrini, Jure Zupan

1507.07927

Plan

- Introduction
  - $h \to \tau\mu$ motivates an additional source of electroweak symmetry breaking
- The lepton and quark "1-3" mass matrix paradigm with two sources of EWSB
  also see Perez et al. 1503.00290; Ghosh, Gupta, Perez 1508.01501

$$\mathcal{M}^{\ell,q} = \mathcal{M}_0 \text{ (rank 1)} + \Delta\mathcal{M} \text{ (rank 2 or 3)}$$

- Examples
  - a second fundamental Higgs doublet
  - a second composite Higgs
- pheno implications

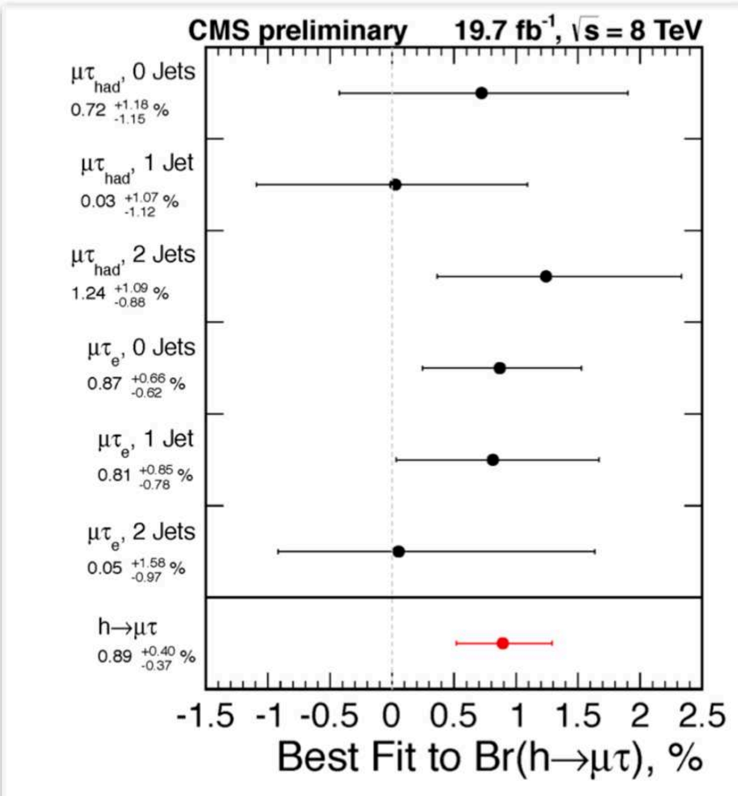
Introduction

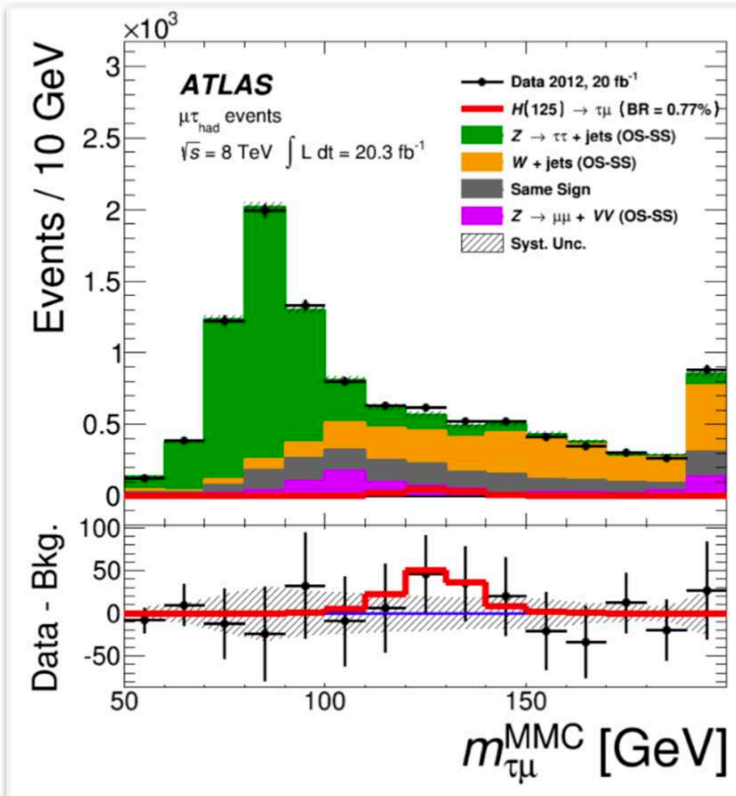
- The CMS “anomaly” (2.4 σ) CMS-HIG-14-005 : assuming SM Higgs production

$$Br(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\ \%$$

- ATLAS (hadronic τ decay) 1508.03372 :

$$Br(h \to \tau\mu) = (0.77 \pm 0.62)\ \%$$





Yukawa couplings

Defining the Yukawa couplings

$$Y_{\tau\mu} h\, \bar{\tau}_L \mu_R + Y_{\mu\tau} h\, \bar{\mu}_L \tau_R$$

and assuming $\Gamma_h = \Gamma_h^{\rm SM} + \Gamma(h \to \tau\mu)$

$$\Rightarrow \sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} \approx (2.6 \pm 0.6) \cdot 10^{-3}$$

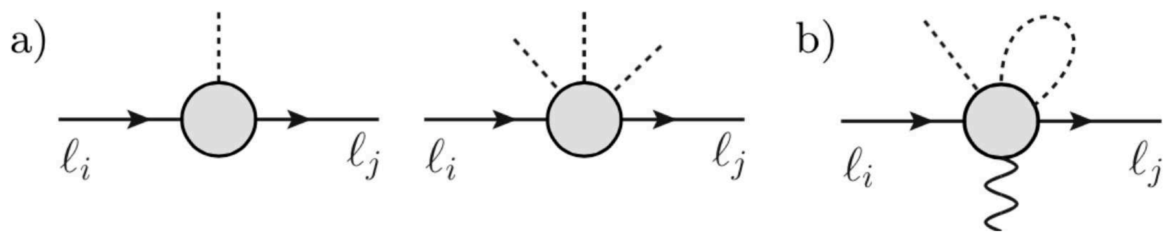
All fermion masses from a single Higgs?

- EFT approach: integrating out the new physics at scale Λ

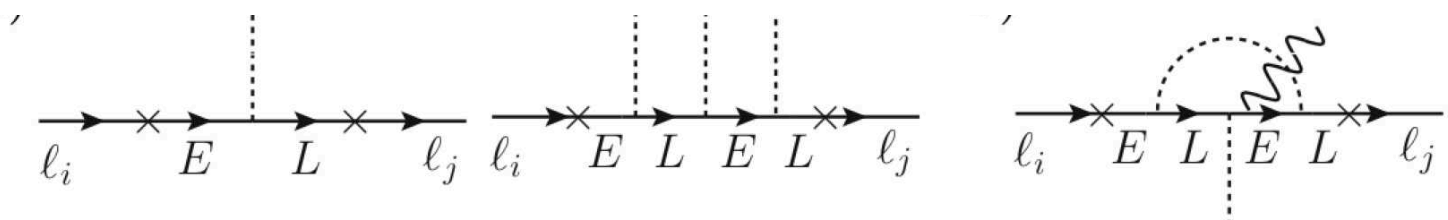
$$-\mathcal{L}_{\rm Yuk.} = \lambda_{ij}(\bar{\ell}^i_L \ell^j_R)H \;+\; \frac{\lambda'_{ij}}{\Lambda^2}(\bar{\ell}^i_L \ell^j_R)H(H^\dagger H) + ... \Rightarrow \; Y_{\tau\mu} = \frac{v^2}{\sqrt{2}\Lambda^2}\langle \tau_L|\lambda'|\mu_R\rangle$$

- the "blobs" must contain charged fields $\Rightarrow$ EM dipole operators

$$L_{\rm eff} = c_{L,R}\, m_\tau \frac{e}{8\pi^2}\left(\bar{\mu}\sigma^{\mu\nu}\tau_{L,R}\right)F_{\mu\nu}, \quad c_{L,R} \sim \frac{Y_{\tau\mu,\,\mu\tau}}{m_\tau v}$$



contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)



Realization of EFT with exchange of vectorlike leptons

- experimental bound on $\tau \to \mu\gamma$

$$Br(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \text{ (90\% CL)} \Rightarrow \sqrt{|c_L|^2 + c_R|^2} < \frac{1}{(3.8\text{TeV})^2}$$

$$\Rightarrow \quad Y_{\tau\mu,\mu\tau} \lesssim 3 \cdot 10^{-5}$$

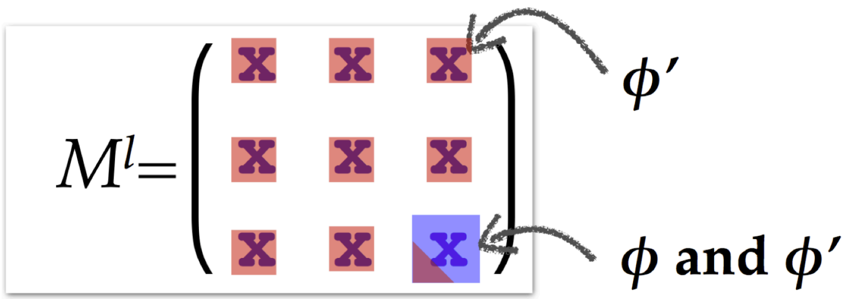
- $\tau \to \mu\gamma$ generically excludes the CMS central value $Y_{\tau\mu} \sim 3 \times 10^{-3}$ by O(100)
  - $O(100)$ reduction in $Br(h \to \tau\mu)$ still exceeds $Y_{\tau\mu}$ bound by $O(10)$
- CMS central value $\Rightarrow$ $\tau \to \mu\gamma$ diagrams must be canceled at the $\%$ level

Additional source of EWSB, or 3rd generation is special

$$\mathcal{M}^\ell = \mathcal{M}_0^\ell + \Delta\mathcal{M}^\ell$$

- M_0 due to scalar ϕ: primary Higgs component, accounts for bulk of m_τ
- $\Delta\mathcal{M}^\ell$ (rank-2 or 3) due to additional source of EWSB: accounts for m_e, m_μ, small contribution to m_τ $\Rightarrow$ subleading Higgs component, ϕ'

$$h = \cos\alpha\,\phi - \sin\alpha\,\phi'$$



- Choose flavor basis in which
  - one non-zero entry for $\mathcal{M}_0^\ell$: $(\mathcal{M}_0^\ell)_{33} \sim m_\tau$
  - generically for 2nd, 3rd generations: $(\Delta\mathcal{M}^\ell)_{ij} = \mathcal{O}(m_\mu),\ \ i,j = 2,3$
  - adding 1st generation: $(\Delta\mathcal{M}^\ell)_{i1,\,1i} = \mathcal{O}(m_e),\ \ i = 1,2,3$

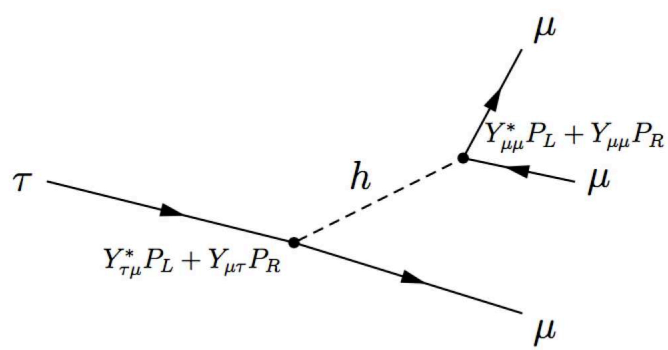
Flavor violating Yukawa couplings

$$Y_{\mu\tau} = -R_Y \frac{(\Delta\mathcal{M}^\ell)_{\mu\tau}}{v_W},$$

$$\text{where } (\Delta\mathcal{M}^\ell)_{\mu\tau} \equiv \langle \mu_L | \Delta\mathcal{M}^\ell | \tau_R \rangle$$

- R_Y only depends on details of EWSB sector: e.g., in 2HDMs: α, $\langle\phi'\rangle/\langle\phi\rangle$
- for $R_Y \sim 1$ and $Y_{\mu\tau} \sim Y_{\tau\mu}$, the CMS hint $\Rightarrow$ $(\Delta\mathcal{M}^\ell)_{\mu\tau} \sim (0.45 \pm 0.10)$ GeV, consistent with $(\Delta\mathcal{M}^\ell) = \mathcal{O}(m_\mu)$

- $\tau \to \mu\mu\mu$ well below the bound
- $\mu \to eee$ well below the bound, for $(\Delta\mathcal{M}^\ell)_{i1,\,1i} = \mathcal{O}(m_e)$

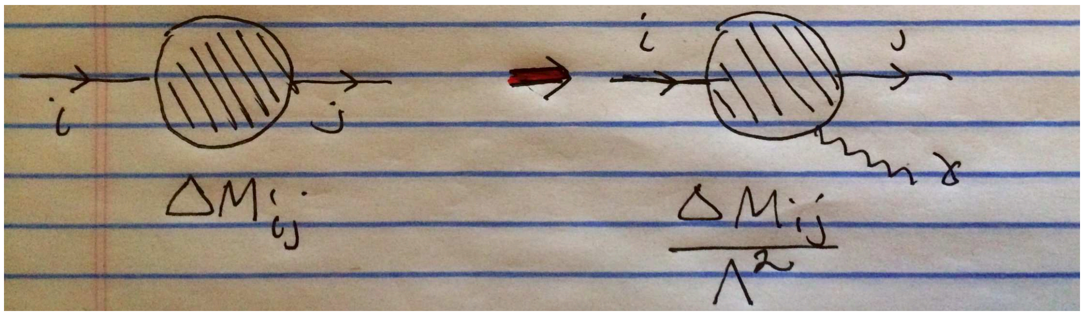


$\tau \to \mu\gamma$ suppression and the scale of New Physics

- If $\Delta\mathcal{M}^\ell$ originates from NP at scale Λ, the dipole operator coefficients due to NP in the loops scale as

$$c_{L,R} \sim Y_{\tau\mu,\mu\tau} \frac{8\pi^2}{m_\tau v_W} \frac{v_W^2}{\Lambda^2}$$

  - extra v_W^2/Λ^2 suppression compared to one source of EWSB
  - consistency of CMS "hint" with $\mathrm{Br}(\tau \to \mu\gamma)$ achieved for $\Lambda \geq O(10)$ TeV



- consistency of CMS "hint" with $\mathrm{Br}(\mu \to e\gamma)$ from the "NP blobs", for $(\Delta\mathcal{M}^\ell)_{i1,\,1i} = \mathcal{O}(m_e)$, would require $\Lambda \geq O(\mathrm{few}) \times 10$ TeV

Extending to the quark sector

- minimal choice: new source of EWSB same for quarks and leptons $\Rightarrow$ same R_Y

$$\mathcal{M}^q = \mathcal{M}_0^q + \Delta\mathcal{M}^q$$

  - generically

$$(\Delta\mathcal{M}^{u,d})_{ij} = \mathcal{O}(m_{c,s}), \quad i,j = 2,3$$

  - generation of m_c, m_s, V_{cb} requires

$$(\Delta\mathcal{M}^{u,d})_{22} \approx m_{c,s}, \quad (\Delta\mathcal{M}^{d})_{23} \approx V_{cb}\, m_b$$

- bound on $B_s - \bar{B}_s$ mixing operator $(\bar{b}_R s_L)(\bar{b}_L s_R)$ from Higgs exchange

$$\Rightarrow \quad \Delta\mathcal{M}_{32}^d \lesssim \frac{V_{cb}\, m_b}{6}$$

- scaling for $b \to s\gamma$ is analogous to $\tau \to \mu\gamma$. Bound on NP scale Λ^q,

$$Br(b \to s\gamma) \;\Rightarrow\; \Lambda^q \gtrsim 5 \;\; TeV$$

- combining $h \to \tau\mu$ and V_{cb} $\Rightarrow$ potentially observable $B_s \to \tau\mu$, $B \to K^{(*)}\tau\mu$ via exchange of Higgs,..... - come back to this

- For $(\Delta\mathcal{M}^{u,d})_{1i,i1} = \mathcal{O}(m_{u,d})$, θ_c and V_{ub} generated in the down sector, via $\Delta M^d_{12} \approx \theta_c m_s$,...

  - $\Rightarrow$ bound on ϵ_K operator $(\bar{s}_R d_L)(\bar{s}_L d_R)$, from Higgs exchange

$$(\Delta\mathcal{M}^d)_{31} \lesssim \frac{(\Delta\mathcal{M}^d)_{13}}{10}, \quad (\Delta\mathcal{M}^d)_{32} \lesssim \frac{(\Delta\mathcal{M}^d)_{23}}{10}$$

- entertaining possibility of larger entries in $(\Delta\mathcal{M}^u)$, could generate large contributions to θ_c, V_{cb}, V_{ub} in the up sector, accompanied by large flavor violation in the up sector from Higgs exchange, eg.

  - CPV in $D-\bar{D}$ mixing near current bound

  - potentially observable $t \to ch$ decay!

    - for example,

$$\Delta M_{23,32} \approx V_{cb} m_t \Rightarrow \mathrm{Br}(t \to ch) \approx 5 \times 10^{-4}$$

compare with current ATLAS sensitivity: $\mathrm{Br}(t \to ch) = 0.22 \pm 0.14\%$

Example 1: 2HDMs

- Consider two Higgs doublets Φ and Φ'
- neutral components ϕ and ϕ' with vev's v and v': $\tan\beta = v/v'$
- Higgs mass eigenstates

$$h = \cos\alpha\,\sqrt{2}\,\mathrm{Re}\phi - \sin\alpha\,\sqrt{2}\,\mathrm{Re}\phi', \quad H = \sin\alpha\,\sqrt{2}\,\mathrm{Re}\phi + \cos\alpha\,\sqrt{2}\,\mathrm{Re}\phi'$$

- Higgs off-diagonal couplings:

$$y^h_{\mu\tau} = -\frac{\langle\mu_L|\delta M|\tau_R\rangle}{v_W} R_Y\,, \qquad R_Y = 2\,\frac{\cos(\alpha-\beta)}{\sin 2\beta}$$

- Higgs diagonal couplings:

$$\hat{y}_a \equiv Y_{aa}/Y^{\mathrm{SM}}_{aa}\,:\ \ \hat{y}_a = \cos\alpha/\sin\beta - R_Y(\Delta\mathcal{M}^\ell)_{aa}/m_a,\ \ a = \mu, \tau, \ldots.$$

- $\tau \to \mu\gamma$ constraint:
  - if ϕ' couplings are tree-level, then $\tau \to \mu\gamma$ is suppressed - no new physics “blob” with a large “internal” chirality flip

Two flavor examples for the leptons

- considered two illustrative flavor structures for $\Delta\mathcal{M}^\ell$
  - "horizontal": only off-diagonal entries $m'_{23},\ m'_{32} \neq 0$
  - "generic": all $(\Delta\mathcal{M}^\ell)_{ij} \neq 0$, with $|(\Delta\mathcal{M}^\ell)|_{ij} < 5 m_\mu$
- in both cases, CMS result requires $R_Y = O(1)$
  - obtained for reasonable (perturbative) values of scalar quartic couplings

Diagonal Yukawas

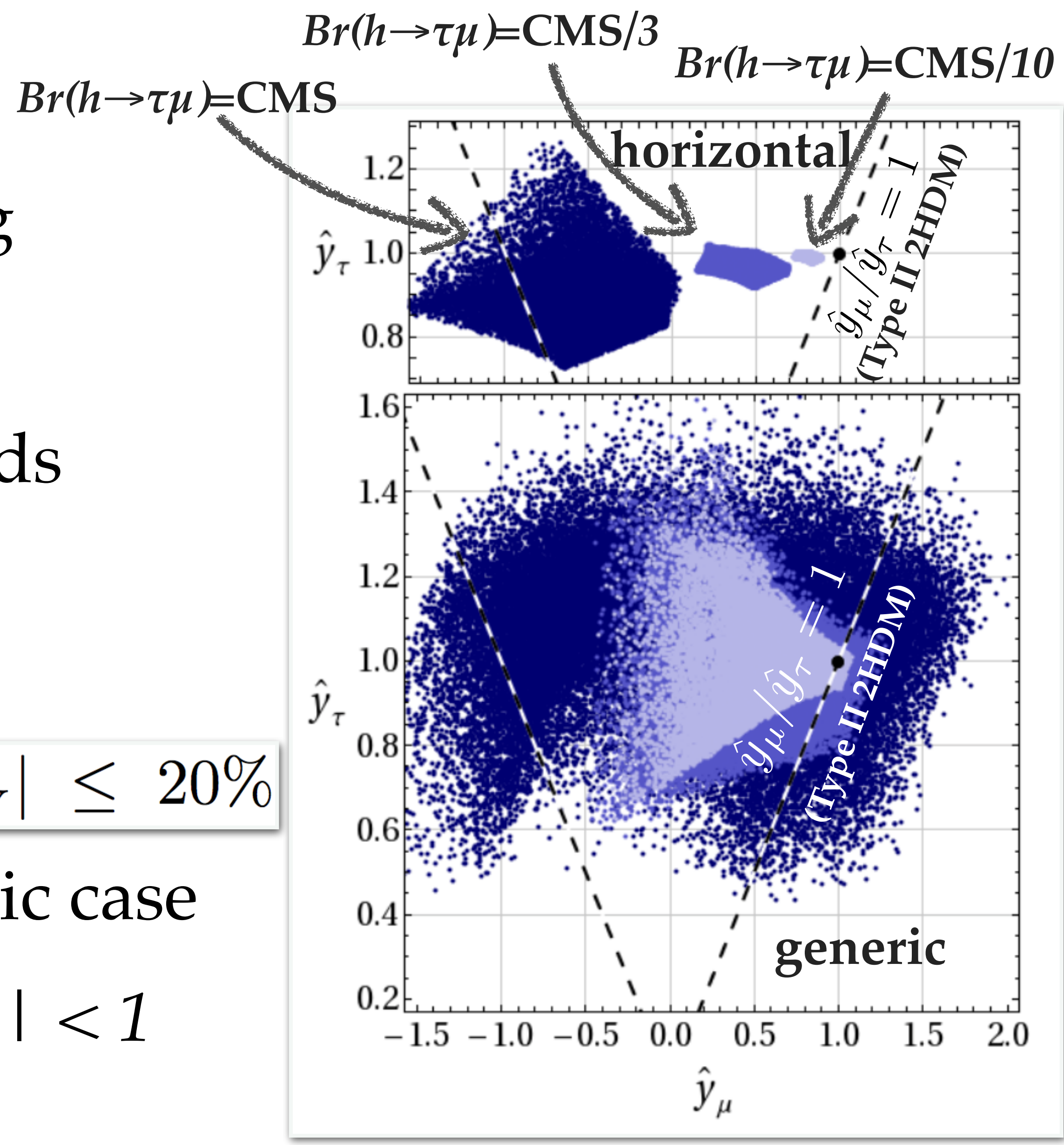
- scanning over mass matrix entries and imposing
  - m_μ, m_τ
  - heavy Higgs xsec bounds

$$1/5 < |m'_{32}/m'_{23}| < 5$$

$$\lambda_{3,4} \leq 2,\ m_A \geq 400\,\mathrm{GeV}$$

$$|(\Delta\mathcal{M}^\ell)_{ij}| < 5m_\mu \qquad |\delta g_{hVV}/g_{hVV}^{\mathrm{SM}}| \leq 20\%$$

- deviations larger in generic case
- ratios $|\hat{y}_\mu| < 1$ and $|\hat{y}_\mu/\hat{y}_\tau| < 1$ favored



Quarks in 2HDM

- the scatter plots are for scenario with V_{cb} generated in down sector, i.e.

$$(\Delta\mathcal{M}^{u,d})_{ij} = \mathcal{O}(m_{c,s}), \quad i,j = 2,3$$

  - new contributions to $B_s \to \mu\mu$: A-exchange is the largest - $\tan\beta$ enhanced
  - $Br(B_s \to \mu\mu)$ constraint imposed in the scatter plots
  - $\approx 80\%$ of the points do not require tuned cancelations of m_μ and $B_s \to \mu\mu$

- diagonal quark couplings
  - $\hat{y}_c, \hat{y}_s$ typically $O(1)$ suppressed - could even vanish in tuned regions of parameter space also see G. Perez et al. '2015
  - $\hat{y}_t, \hat{y}_b$ receive $\leq 20\%$ corrections

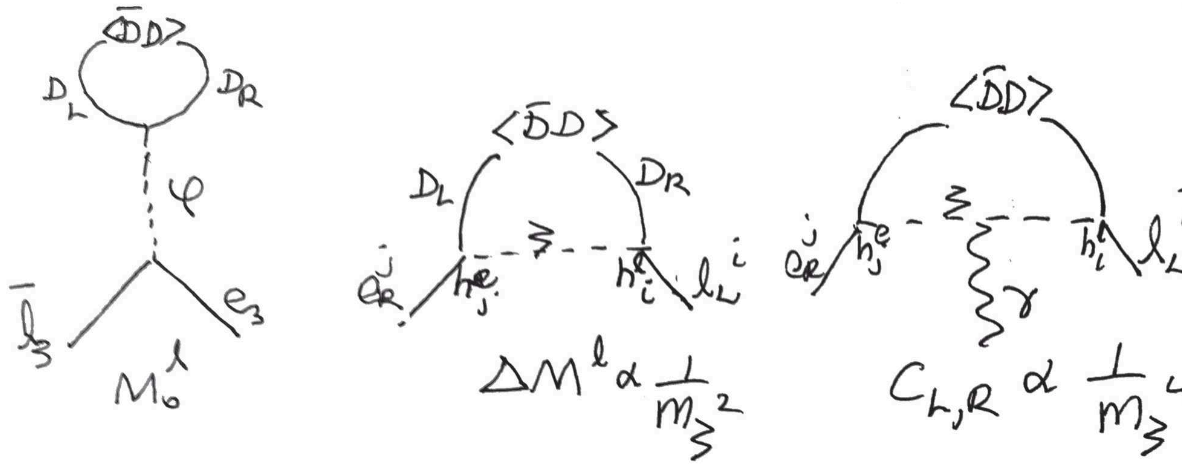
Example 2: Technicolor with scalars

- $\Delta\mathcal{M}^\ell$ is due to technicolor (TC) strong dynamics

- Higgs is a mixture of elementary ϕ and composite heavy scalar $\sigma_{\rm TC}$, with $R_Y \gtrsim 1$

- as in 2HDM, in addition to heavy Higgs $H \sim \sigma_{\rm TC}$, have psedoscalar, A, and charged Higgs which are partially composite.

- TC condensates $\langle \bar{D} D\rangle$, $\langle \bar{U} U\rangle$ induce Higgs VEV $\langle \phi \rangle$ through a "tadpole", and induce a rank-1 $\Delta\mathcal{M}^{\ell,q}$ via exchange of a heavy technicolored scalar



- $\tau \to \mu\gamma$ bound requires $m_\xi \gtrsim 10$ TeV, as in earlier naive dimensional analysis

- straightforward to obtain viable benchmarks for 2nd+3rd generation leptons, quarks with $O(1)$ technical Yukawa couplings, $h_i^e, h_i^\ell = O(1)$,... which respect $\tau \to \mu\gamma$, $b \to s\gamma$ bounds and reproduce the CMS central value

- large deviations from SM in flavor diagonal Higgs couplings, e.g. for leptons

$$|\hat{y}_\mu| \approx 0.2 - 0.9, \quad \hat{y}_\tau \approx 0.9 - 1.6, \quad |\hat{y}_\mu / \hat{y}_\tau| \approx (0.2 - 0.6)$$

  - in quark sector, have $O(1)$ suppression of charm, strange Yukawas

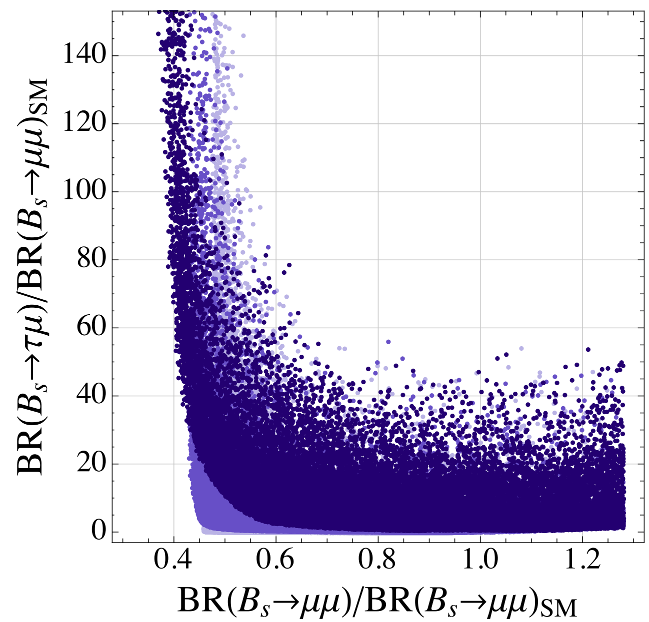
$$\cos\alpha / \sin\beta \approx 1 \;\Rightarrow\; \hat{y}_{c,s} \approx 1 - R_Y\,, \quad \hat{y}_{t,b} \approx 1$$

Phenomenological Implications: $b \to s\tau\bar{\mu}$

- accounting for CMS $h \to \tau\mu$ and V_{cb} within our framework can lead to sizable flavor violating $B_s \to \tau\mu$ and related $B \to K^{(*)}\tau\mu$ decay rates
  - via tree-level exchanges of A, H which are $\propto (\tan\beta)^4$, and h
  - in $B_s \to \mu\mu$, A exchange dominates but $\propto (\tan\beta)^2$

$\Rightarrow$ sizable $R_{\tau\mu} \equiv \mathrm{Br}(B_s \to \tau\mu)/\mathrm{Br}(B_s \to \mu\mu)_{\mathrm{SM}}$ is possible,
without tuned cancelations in $\mathrm{Br}(B_s \to \mu\mu)$

- e.g., in the generic 2HDM case, at $\tan\beta \lesssim 10$, $\mathrm{Br}(B_s \to \tau\mu,\ K^{(*)}\tau\mu) = O(10^{-7})$ is possible, accompanied by $\sim 50\%$ suppression Br$(B_s \to \mu\mu)$



Other phenomenological implications

- Sum rule for Higgs Yukawa couplings: if m_μ is due to rank-1 $\Delta\mathcal{M}^\ell$, as in the BTC case, and in certain radiative approaches to the fermion mass hierarchy ($\hat{y}_{ij} \equiv Y_{ij}/Y_{ii}^{\rm SM}$)

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

  holds up to $\mathcal{O}(m_c/m_t, m_s/m_b, m_e/m_\mu)$

  - allows precision test of rank-1 hypothesis in the "1-3" paradigm

- anomalies could be seen in B_s mixing, and in $\tau \to \mu\gamma$, $\mu \to e\gamma$, $b \to s\gamma$

- scaling analogous to $\tau \to \mu\gamma$ for $s \to dg$ dipole operators could play a role in ϵ'/ϵ, accounting for a potential anomaly

- if CKM mixing receives large contributions from the up sector, large CPV in $D - \bar{D}$ mixing and observable $t \to ch$ are possible

- leptonic heavy Higgs (H) decays to $\mu\mu$ dominate over $\tau\tau$, opposite to Type-II 2HDMs

Conclusion

- The CMS $h \to \tau\mu$ hint can be understood in models in which a second source of EWSB accounts for the masses of the 1st and 2nd generations and CKM mixing
  - the appearance of this anomaly before other anomalies in 3-2 flavor transitions would follow if the NP scale $\Lambda \gtrsim 10$ TeV (no such constraint in tree-level 2HDM)
- a rich phenomenology is possible at both low and high p_T
- next step: construction of explicit flavor models realizing the paradigm, e.g. via abelian $U(1)$, non-abelian $U(2)$ horizontal symmetries, radiatively induced Yukawas for the new source of EWSB,...

Back-up slides

- Higgs mass eigenstates

$$h = \cos\alpha\,\sqrt{2}\,\mathrm{Re}\phi - \sin\alpha\,\sqrt{2}\,\mathrm{Re}\phi', \quad H = \sin\alpha\,\sqrt{2}\,\mathrm{Re}\phi + \cos\alpha\,\sqrt{2}\,\mathrm{Re}\phi'$$

- Higgs off-diagonal couplings:

$$y^h_{\mu\tau} = -\frac{\langle \mu_L|\delta M|\tau_R\rangle}{v_W} R_{\alpha\beta}, \qquad R_{\alpha\beta} = 2\,\frac{\cos(\alpha-\beta)}{\sin 2\beta}$$

  - to leading order in v_W^2/m_A^2, and showing the relevant terms,

$$R_{\alpha\beta} = \frac{v_W^2}{m_A^2}\,(\lambda_3 + \lambda_4 + \lambda_7 \tan\beta + ...)$$

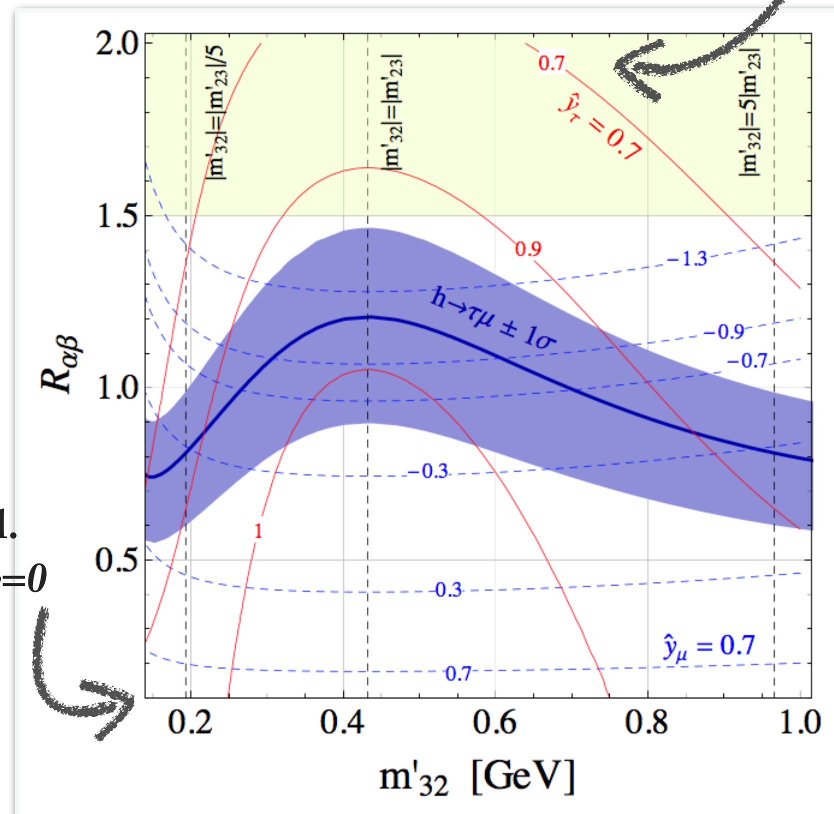
$$V_{\mathrm{quartic}} = \lambda_3(\phi^\dagger\phi)(\phi'^\dagger\phi') + \lambda_4(\phi^\dagger\phi')(\phi'^\dagger\phi) + \lambda_7|\phi|^2(\phi\phi') + ...$$

Viable EW Sector

"Generic" case:

- CMS result requires $R_{\alpha\beta}$~$O(1)$
- can be obtained, e.g., for m_A~$500GeV$, λ_3~λ_4~2
- compatible with EWPT

excluded by *hZZ* for tanβ=2



decoupl. limit $R_{\alpha\beta}$=0

- no Landau poles below $O(30)$ TeV
- if allow for PQ breaking, $\lambda_7 \neq 0$, no poles till M_{GUT}