

HIGGS AND FLAVOUR

JURE ZUPAN
U. OF CINCINNATI

based on Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

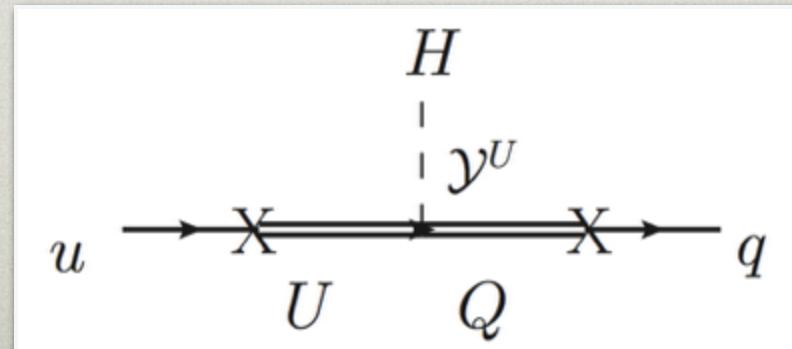
Higgs and beyond, Pittsburgh, Dec 4 2015

HIGGS AND FLAVOR

- connection between Higgs and flavor:
 - in SM Higgs Yukawas the origin of flavor
 - test this through Higgs production and decays
 - solutions to hierarchy problem generically suffer from FCNCs
 - indirect test of weak scale new physics

INDIRECT PROBES

- active experimental program
 - Belle, BaBar, LHCb, Belle2, MEG, Mu2e, Mu3e, ...
- very stringent constraints
 - also have seen significant improvements in the past years
- example: composite Higgs with partial compositeness



CONSTRAINTS

- FCNC constraints due to composite resonances (parametric estimates)
 - from K mixing ($\text{Im } C_4^K$)

UTFit 1411.7233

$$M_* \gtrsim \frac{g_*}{Y_*} 60 \text{ TeV}$$

~ 30 TeV in 2007

UTFit 0707.0636

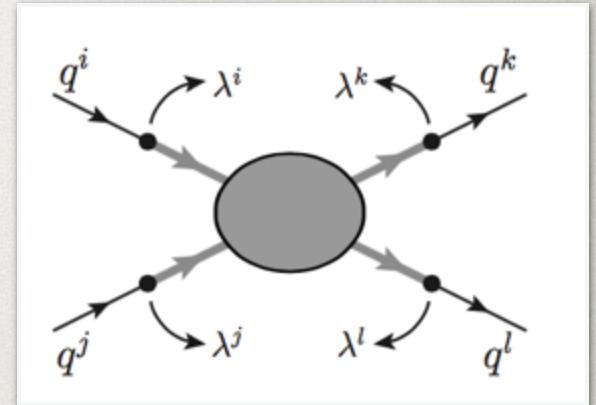
- from D mixing ($\text{Im } C_4^D$)

UTFit 1411.7233

$$M_* \gtrsim \frac{g_*}{Y_*} 9 \text{ TeV},$$

~ 1.5 TeV in 2007

UTFit 0707.0636



HIGGS FLAVOR VIOLATION

- bottom line: FCNCs a challenge for any solution to the hierarchy problem
 - NP flavor problem
 - requires nontrivial flavor structure in the UV (MFV, etc.)
- the topic of this talk
 - given these constraints is it possible to have large flavor violation in Higgs coupling?
 - what would these teach us?
 - will show: FV can probe fermion mass generation

CPV AND FV HIGGS COUPLINGS TO SM FERMIONS

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

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

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

- decouples mass terms from yukawas

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

- 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

HOW LARGE?

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

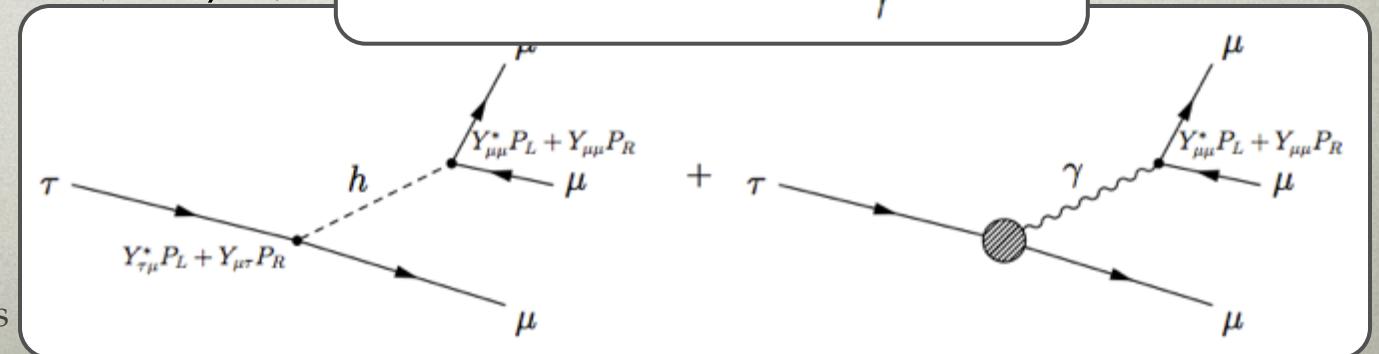
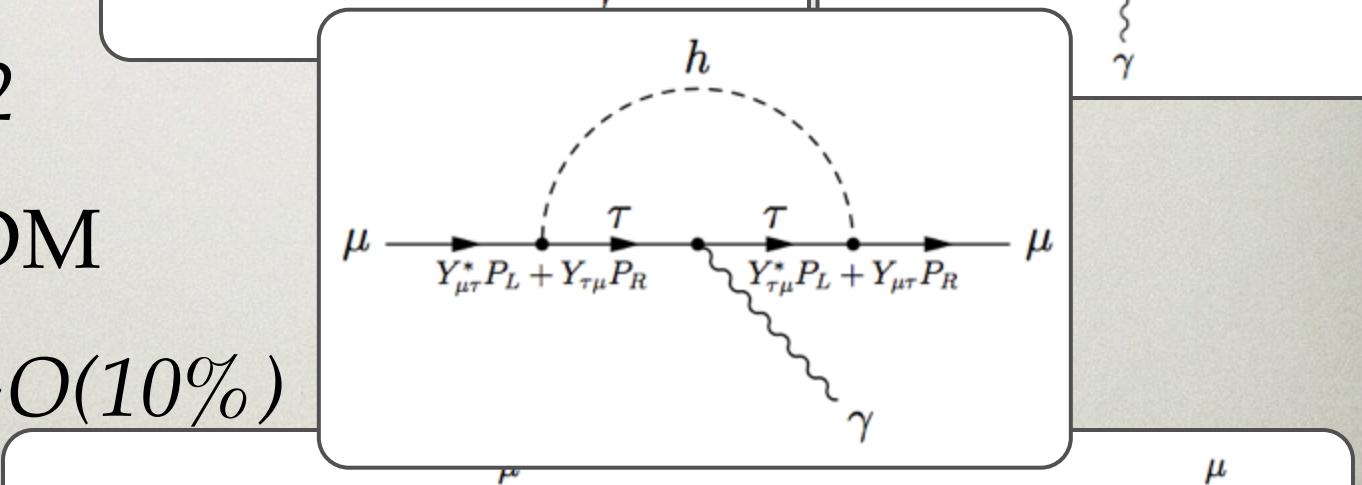
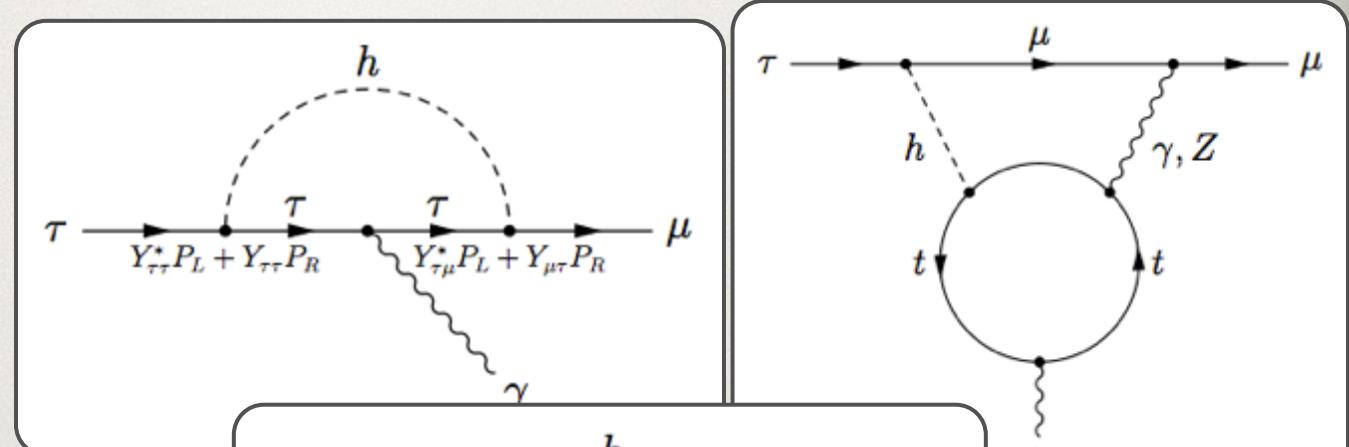
$h \rightarrow \tau\mu$

Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- bounds from

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

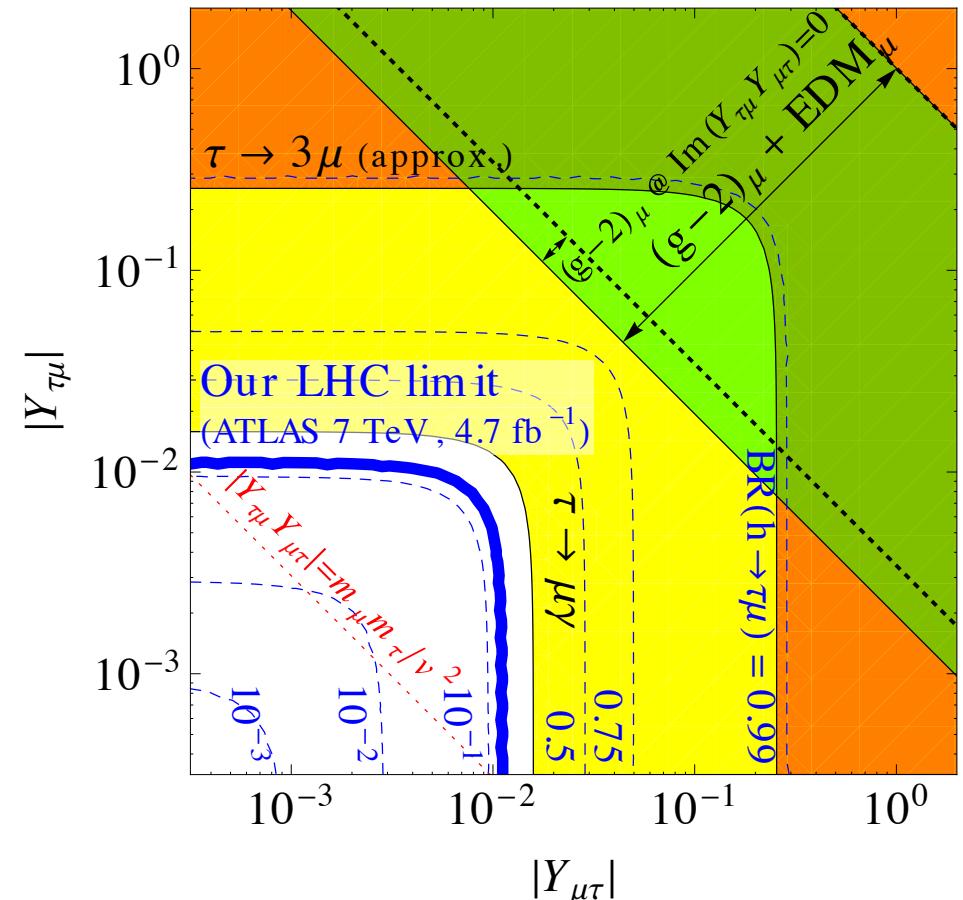
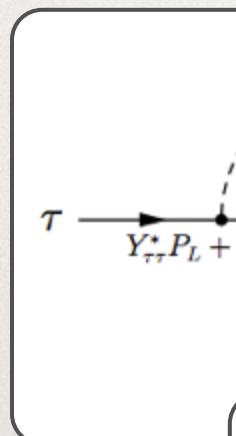


$h \rightarrow \tau\mu$

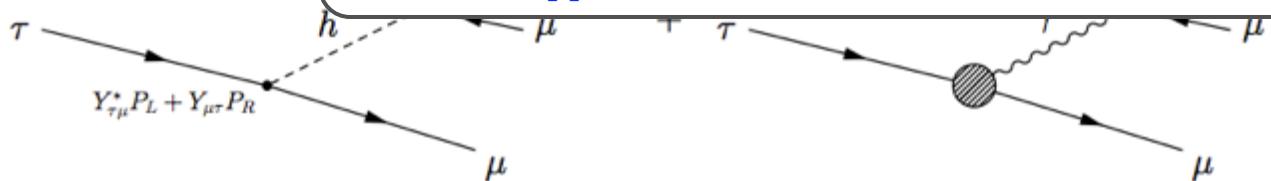
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Harnik, Kopp, JZ, 1209.1397

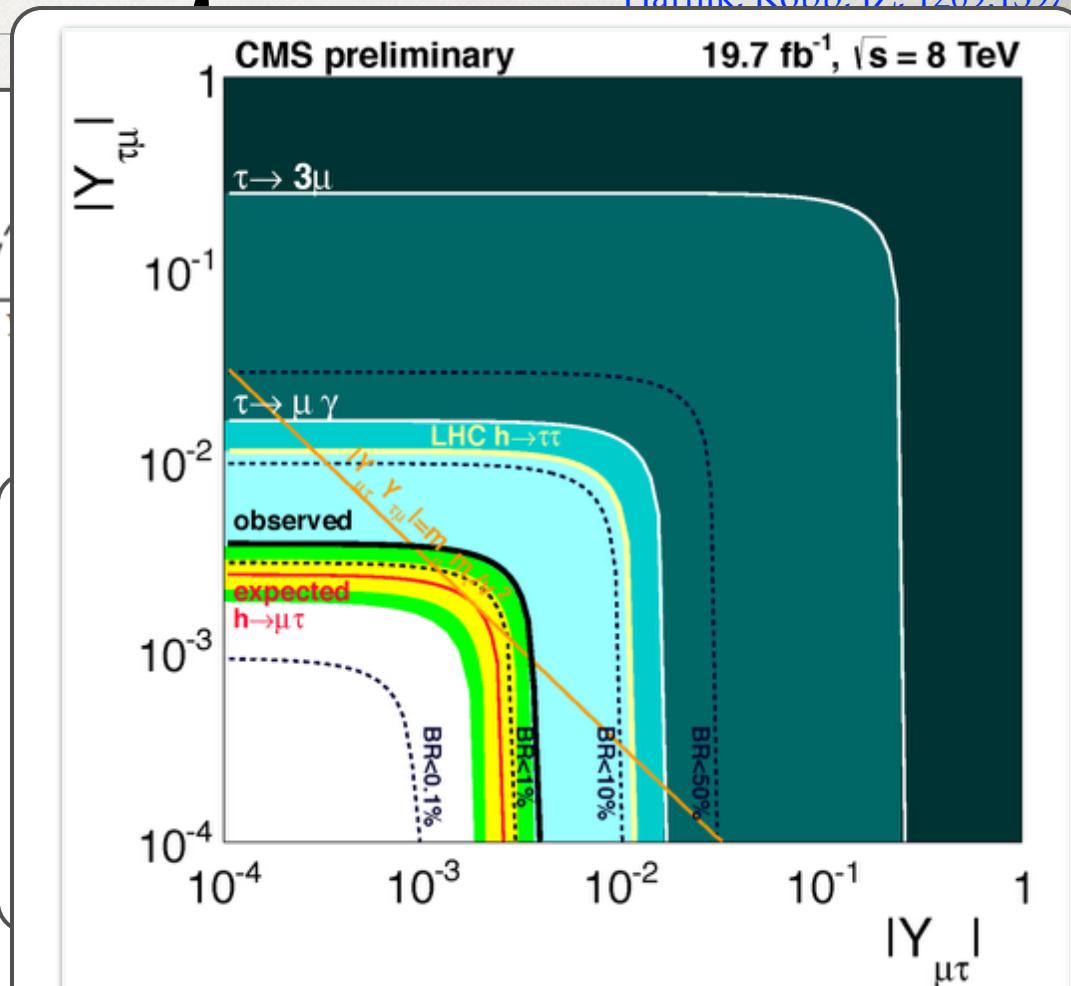
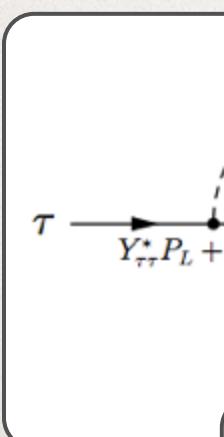


$h \rightarrow \tau \mu$

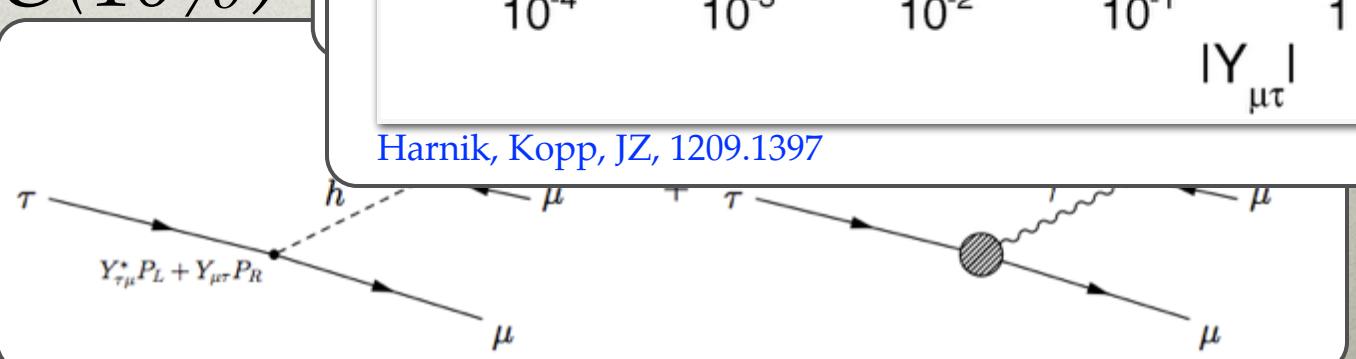
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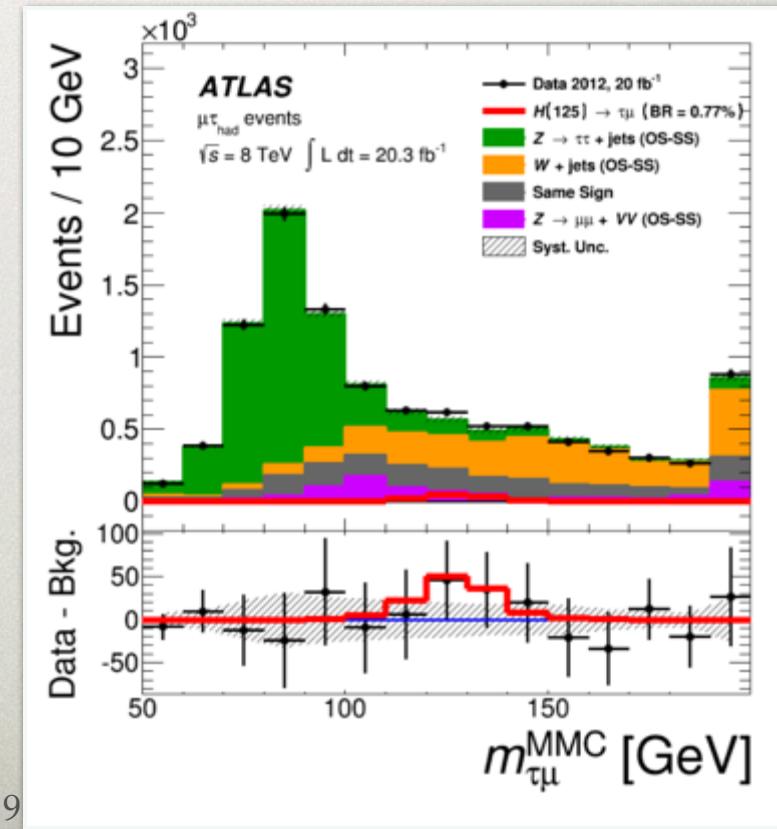
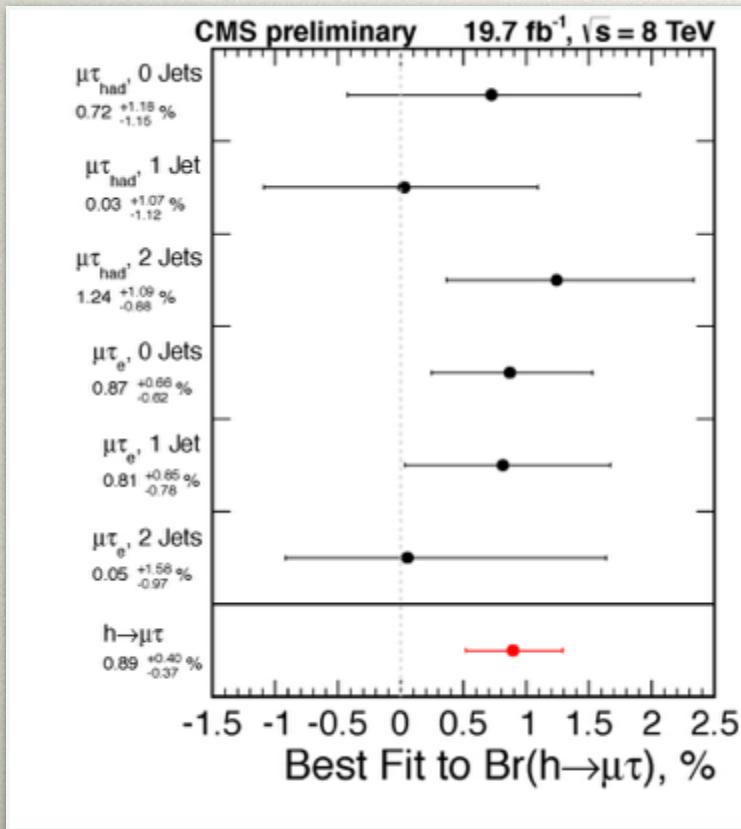
Harnik, Kopp, JZ, 1209.1397



J. Zupan Higgs

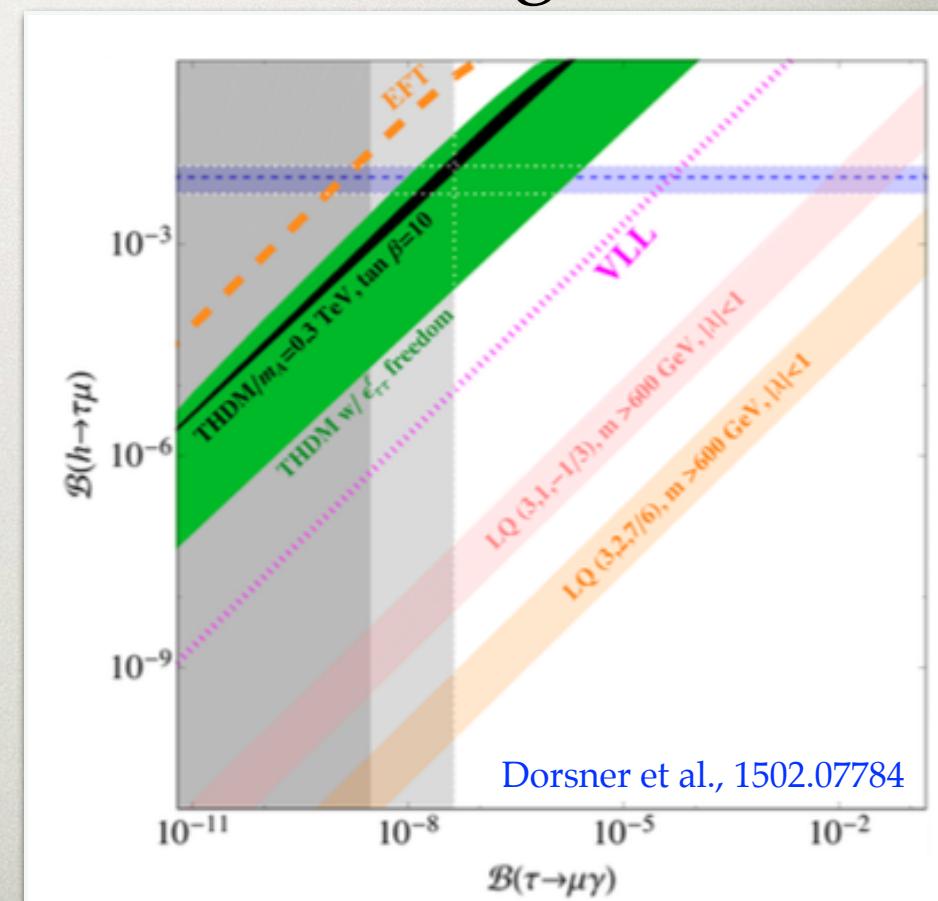
$h \rightarrow \tau\mu$ exp. info

- hint of a signal in $h \rightarrow \tau\mu$? see talk by Aliaksandr Pranko
- CMS: $Br(h \rightarrow \tau\mu) = (0.89 \pm 0.39)\%$ CMS-HIG-14-005
- ATLAS: $Br(H \rightarrow \mu\tau) = (0.77 \pm 0.62)\%$ ATLAS, 1508.03372



LARGE FV HIGGS DECAYS?

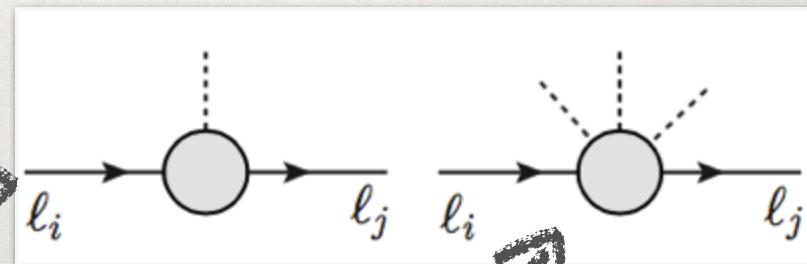
- Can one have large flavor violating Higgs decays in reasonable NP models?
- What is so special about type III 2HDM?



WHAT KIND OF NEW PHYSICS?

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

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

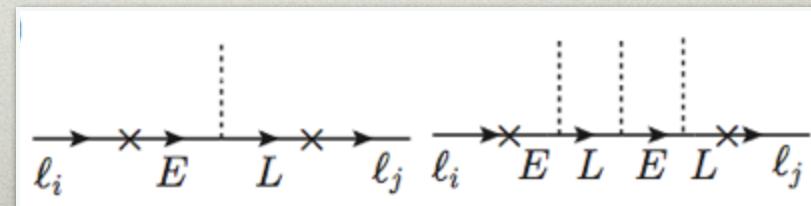


- if EFT applicable:

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

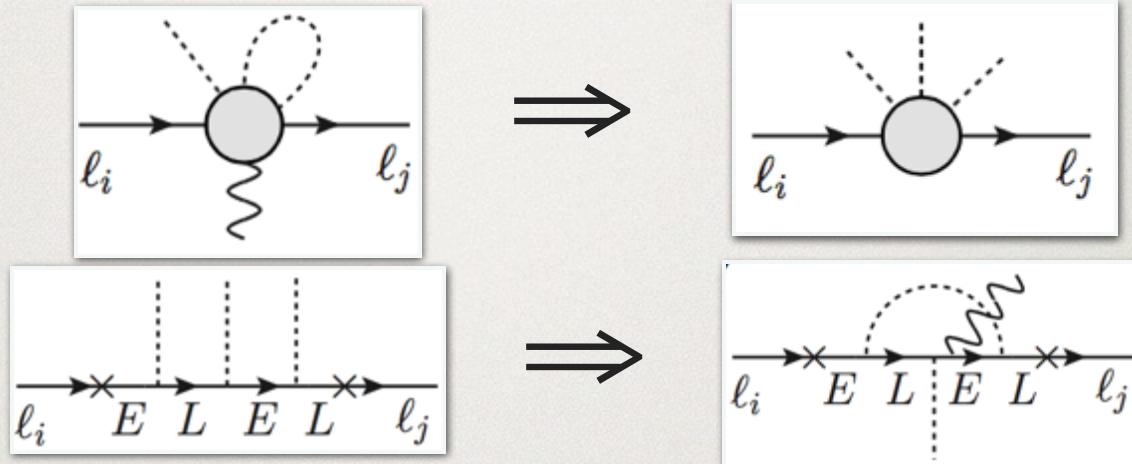
- realization with vector-like leptons:

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



DIPOLE OPERATOR

- same diagrams give $\tau \rightarrow \mu\gamma^*$



- experimental bound

$$\text{Br}(\tau \rightarrow \mu\gamma) < 4.4 \cdot 10^{-8}$$

$$\sqrt{|c_L|^2 + |c_R|^2} < (3.8 \text{ TeV})^{-2}.$$

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

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

$$c_L \sim \frac{v_W}{\sqrt{2}m_\tau \Lambda^2} \langle \tau_L | \lambda' | \mu_R \rangle = \frac{Y_{\tau\mu}}{m_\tau v_W}$$

$$\sqrt{|c_L|^2 + |c_R|^2} \sim \left(\frac{Y_{\tau\mu}}{2.2 \cdot 10^{-5}} \right) (3.8 \text{ TeV})^{-2}$$

- in contrast CMS hint $\text{Br}(h \rightarrow \tau\mu) = (0.89 \pm 0.39)\%$ requires

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

* The exception is a tree level exchange of a heavy scalar doublet, H' . But then the tadpole also induces a vev for H' .
 J. Zupan Higgs and flavor 12 Higgs and beyond, Pitt, Dec 4 2015

EXCLUDED

- if Higgs the only* source of ferm. mass $\Rightarrow \text{Br}(\tau \rightarrow \mu\gamma)$ too large by 4 orders of magnitude
 - *and no tunings for tuned MSSM example see e.g., Aloni, Nir, Stamou, 1511.00979
- note: in our EFT analysis of low energy constraints the Lagrangian was

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

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

VIABLE MODELS: 3RD GENERATION SPECIAL

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

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

↑ ↗
rank 1 matrix, from ϕ 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

MODELS

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

- will show two concrete realizations
 - two Higgs doublet model
 - technicolor model

2HDM

- two Higgs doublets, neutral compts: ϕ, ϕ' , vevs v, v'
 - ϕ couples to 3rd family, ϕ' to all three $\tan \beta = v/v'$

$$M^l = \begin{pmatrix} \textcolor{violet}{x} & \textcolor{violet}{x} & \textcolor{violet}{x} \\ \textcolor{brown}{x} & \textcolor{brown}{x} & \textcolor{brown}{x} \\ \textcolor{brown}{x} & \textcolor{violet}{x} & \textcolor{blue}{x} \end{pmatrix}$$

- a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- off diagonal Higgs Yukawas

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

$$R_Y = R_{\alpha\beta} \equiv 2 \cos(\alpha - \beta) / \sin 2\beta$$

- flavor diagonal Yukawas

$$\hat{y}_a \equiv Y_{aa} / Y_{aa}^{\text{SM}}$$

$$\hat{y}_a = \cos \alpha / \sin \beta - R_Y (\Delta\mathcal{M}^\ell)_{aa} / m_a, \quad a = \mu, \tau,$$

$\tau \rightarrow \mu \gamma$ suppression

- no longer a direct relation between $h \rightarrow \tau \mu$ and $\tau \rightarrow \mu \gamma$
- if ΔM_l originates from NP at scale Λ

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

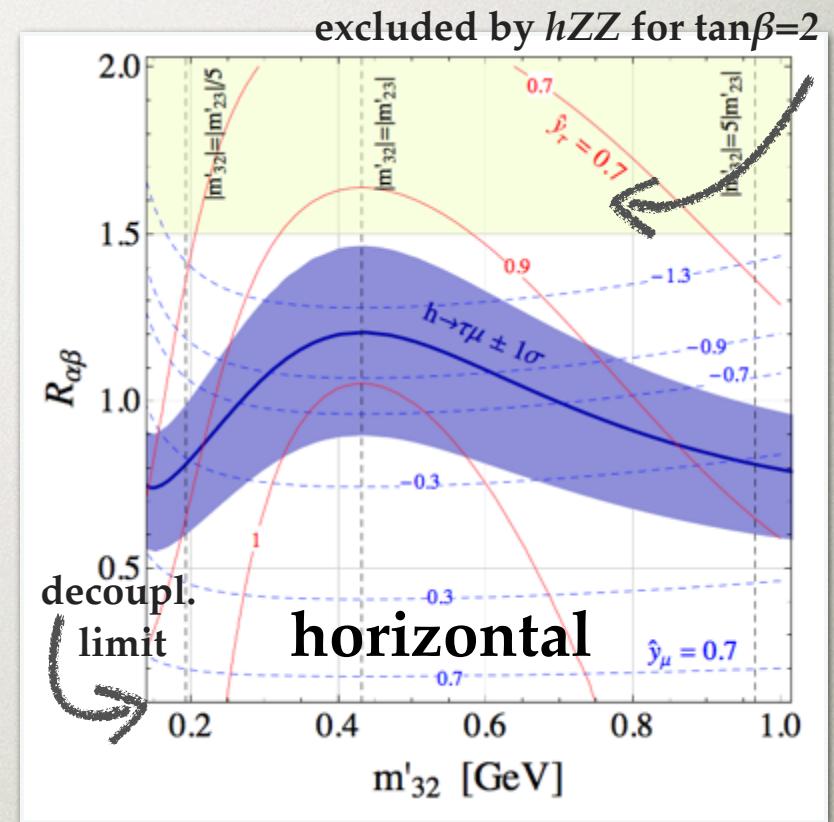
- compared to before - an extra v_W^2/Λ^2 suppression
- consistency with $\tau \rightarrow \mu \gamma$ for $\Lambda \geq O(10) \text{ TeV}$

TWO FLAVOR CASES

- consider two flavor structures for ΔM^l
 - “horizontal”: only off-diagonal entries nonzero, m_{23}' and m_{32}'
 - “generic”: all m_{ij}' nonzero
- in horizontal case: M^l has 3 params, m_{33}, m_{23}', m_{32}'
 - 2 fixed by $m_\mu, m_\tau \Rightarrow$ 1 free param, m_{32}'
 - Higgs couplings fixed by $m_{32}', R_{\alpha\beta}$

VIABLE EW SECTOR

- CMS results requires $R_{\alpha\beta} \sim O(1)$
- this can be obtain, e.g., for $m_A \sim 500 \text{ GeV}$, $\lambda_3 \sim \lambda_4 \sim 2$
- compatible with EWPT
- no Landau poles below $O(30) \text{ TeV}$
- if allow for PQ breaking, $\lambda_7 \neq 0$, no poles till M_{GUT}



DIAGONAL YUKAWAS

- scanning over mass matrix entries and imposing
 - that m_μ, m_τ are eigenvalues
 - the heavy Higgs xsec bounds

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

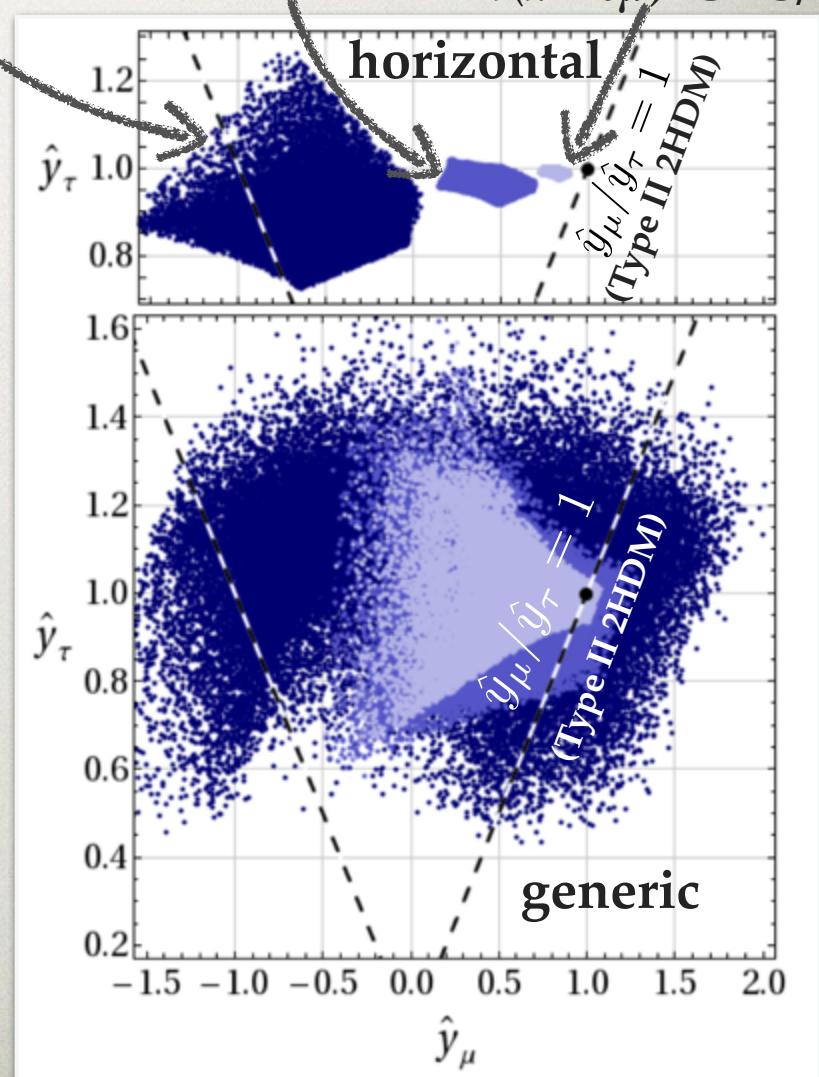
$$\lambda_{3,4} \leq 2, m_A \geq 400 \text{ GeV}$$

$$|(\Delta\mathcal{M}^\ell)_{ij}| < 5m_\mu$$

$$|\delta g_{hVV}/g_{hVV}^{\text{SM}}| \leq 20\%$$

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

$\text{Br}(h \rightarrow \tau\mu) = \text{CMS}$ $\text{Br}(h \rightarrow \tau\mu) = \text{CMS}/3$ $\text{Br}(h \rightarrow \tau\mu) = \text{CMS}/10$



QUARK SECTOR

- consider a case where the same sources of EWSB also give quark masses \Rightarrow the same R_Y
- similarly to before assume

$$(\mathcal{M}_0^{u,d})_{33} \sim m_{t,b}$$

$$(\mathcal{M}_0^{u,d})_{33} \sim m_{t,b}$$

- generation of m_c , m_s and V_{cb} then implies

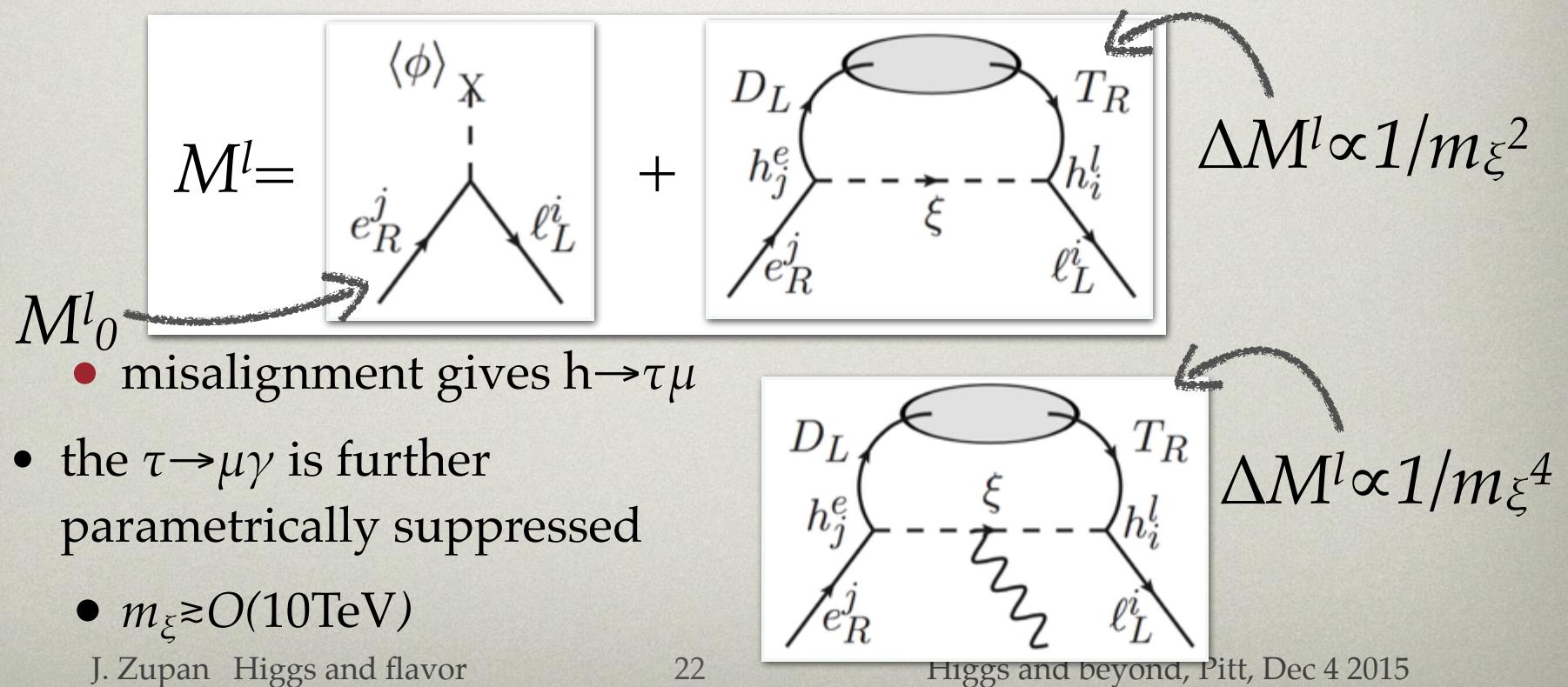
$$(\Delta\mathcal{M}^{u,d})_{22} \approx m_{c,s}, \quad (\Delta\mathcal{M}^d)_{23} \approx V_{cb} m_b,$$

- B_s mixing bound from $(\bar{b}_{RS_L})(\bar{b}_{LS_R})$ due to Higgs exchange

$$R_Y^2 \Delta\mathcal{M}_{32}^d \lesssim V_{cb} m_b / 6$$

TECHNICOLOR EXAMPLE

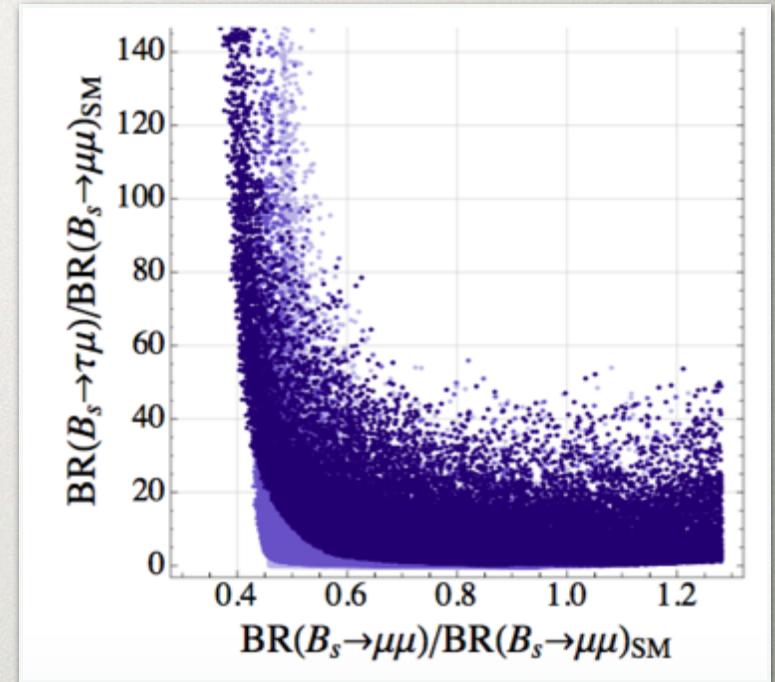
- ΔM_l due to technicolor strong dynamics
 - UV completion is bosonic TC
- Higgs: elementary ϕ + composite heavy scalar σ_{TC}
- ΔM^l from TC condensate, rank 1



PHENOMENOLOGICAL IMPLICATIONS

- $B_s \rightarrow \mu\mu$ can be modified by $O(1)$
- sizable $B_s \rightarrow \tau\mu$, $B \rightarrow K\tau\mu$, $B \rightarrow K^*\tau\mu$
- anomalies could be seen in B_s mixing, $\tau \rightarrow \mu\gamma$, $b \rightarrow s\gamma$
- leptonic heavy Higgs (H) decays to $\mu\mu$ dominate over $\tau\tau$
 - opposite to Type-II 2HDMs
- $t \rightarrow hc$ potentially sizable
- a general sum rule

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



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

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

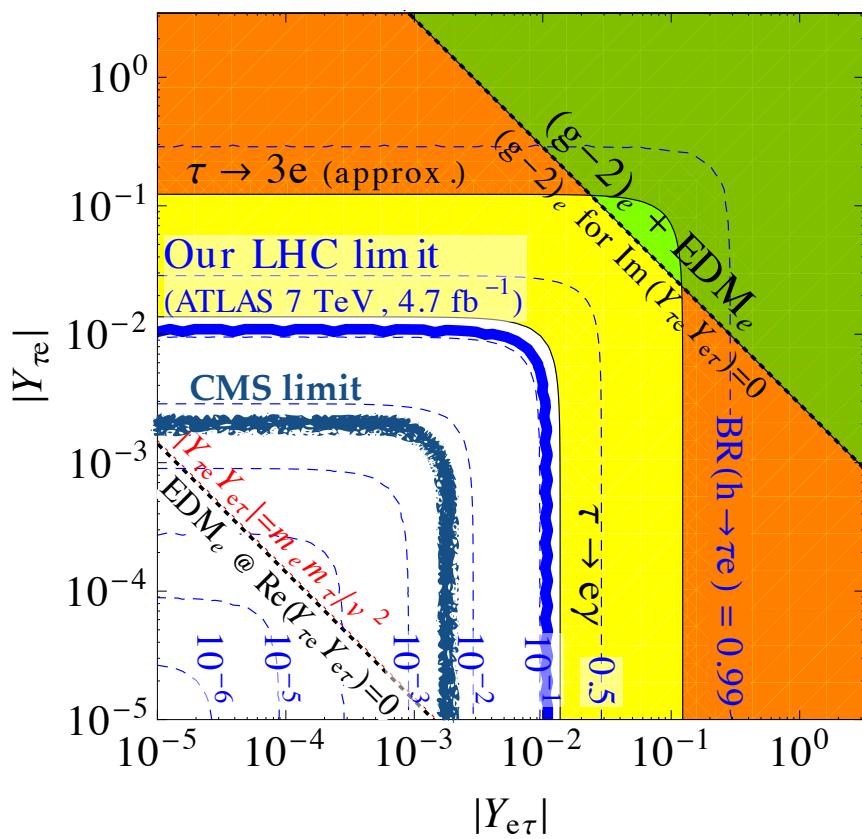
- valid to the extent that both ΔM^l and ΔM_0 are rank 1
- is explicitly true in our TC example

CONCLUSIONS

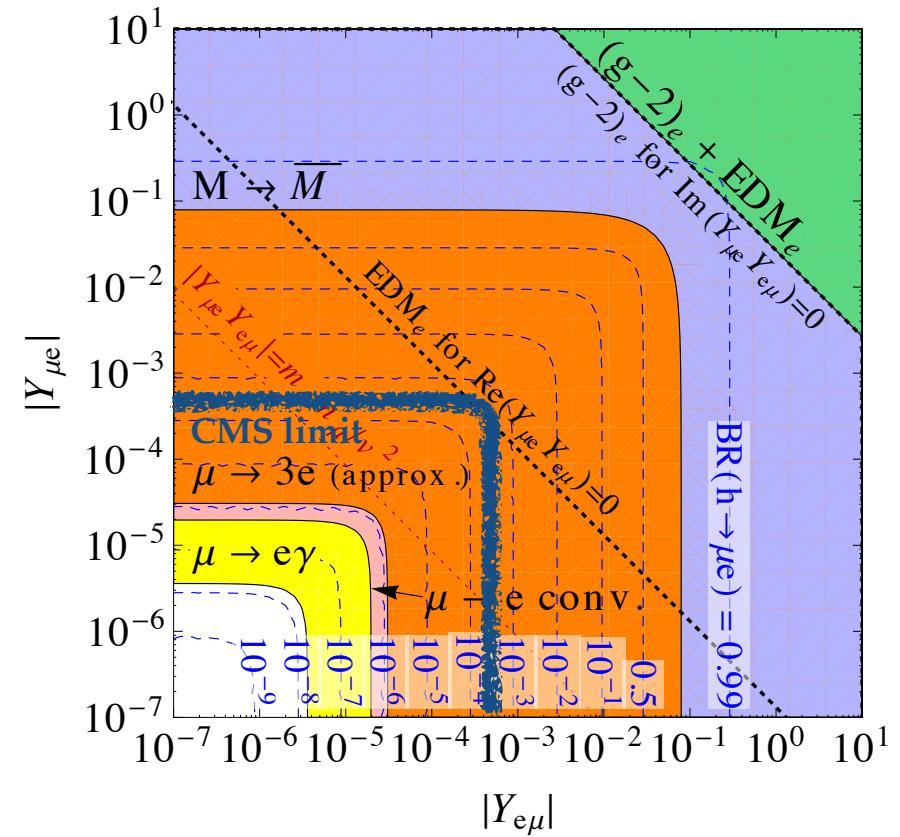
- CMS $h \rightarrow \tau\mu$ excess can be explained
 - if 3rd gen. mass mostly from Higgs vev
 - 1st and 2nd gen. mass from other source (examples 2HDM and TC)
- a number of probes: $B \rightarrow K\tau\mu$, $B \rightarrow K^*\tau\mu$, $b \rightarrow s\gamma$, $t \rightarrow hc$, sum rule,...

BACKUP SLIDES

$h \rightarrow \tau e$ and $h \rightarrow \mu e$



Harnik, Kopp, JZ, 1209.1397



Harnik, Kopp, JZ, 1209.1397

A GENERAL BENCHMARK

- what is a reasonable aim for precision on Y_{ij} ?
 - if off-diagonals are large \Rightarrow spectrum in general not hierarchical
 - no tuning, if

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

Cheng, Sher, 1987

- in concrete models it will be typically further suppressed parametrically

see e.g, Dery, Efrati, Nir, Soreq, Susic, 1408.1371;
Dery, Efrati, Hochberg, Nir, 1302.3229;
Arhrib, Cheng, Kong, 1208.4669

CORRELATED BOUNDS

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

$$\mathcal{B}(\mu \rightarrow e\gamma) \simeq \mathcal{B}_0^{\mu \rightarrow e\gamma} (|y_{\mu\tau} y_{\tau e}|^2 + |y_{\tau\mu} y_{e\tau}|^2) , \quad \mathcal{B}_0^{\mu \rightarrow e\gamma} = 185 .$$

$$\mathcal{B}(\mu \rightarrow e)_{\text{Au}} = \mathcal{B}_0^{\mu e} (|y_{e\tau} y_{\mu\tau}|^2 + |y_{\tau e} y_{\tau\mu}|^2) , \quad \mathcal{B}_0^{\mu e} = 4.67 \times 10^{-4} ,$$

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

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

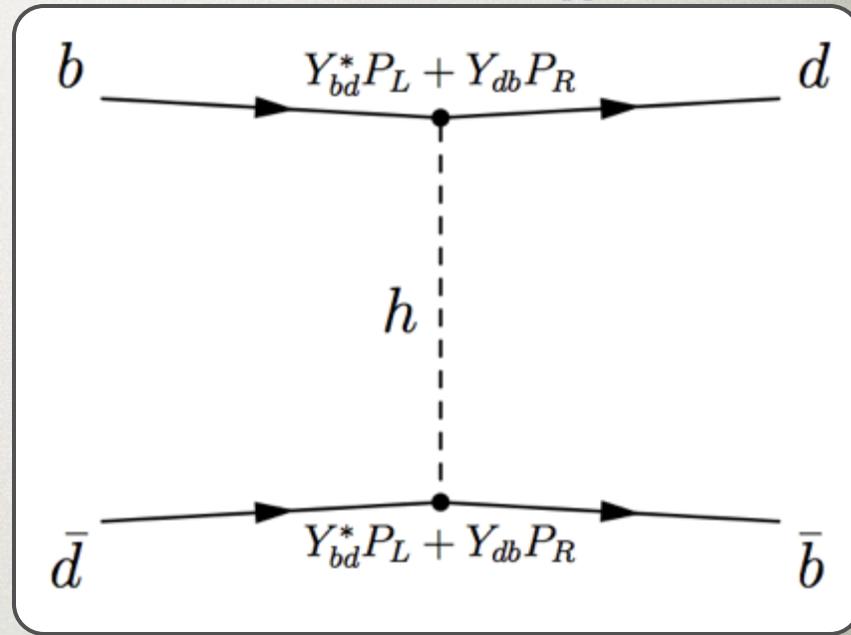
$$\mathcal{B}(h \rightarrow \tau\mu) \times \mathcal{B}(h \rightarrow \tau e) = 7.95 \times 10^{-10} \left[\frac{\mathcal{B}(\mu \rightarrow e\gamma)}{10^{-13}} \right] + 3.15 \times 10^{-4} \left[\frac{\mathcal{B}(\mu \rightarrow e)_{\text{Au}}}{10^{-13}} \right]$$

- \Rightarrow if $Br(h \rightarrow \tau\mu)$ is at the CMS central value, then $Br(h \rightarrow \tau e)$ need to be small

QUARK COUPLINGS

Harnik, Kopp, JZ, 1209.1397

- constraints from
 - D, B, B_s, K oscillations
 - bounds on $Y_{uc}, Y_{uc}, Y_{db}, Y_{bd}, Y_{sb}, Y_{bs}, Y_{sd}, Y_{ds}$
 - strong constraints
 - $O(0.1)$ - $O(0.01)$ of Cheng-Sher ansatz
- improvements on these couplings will come from exp&theory improvements in meson mixing



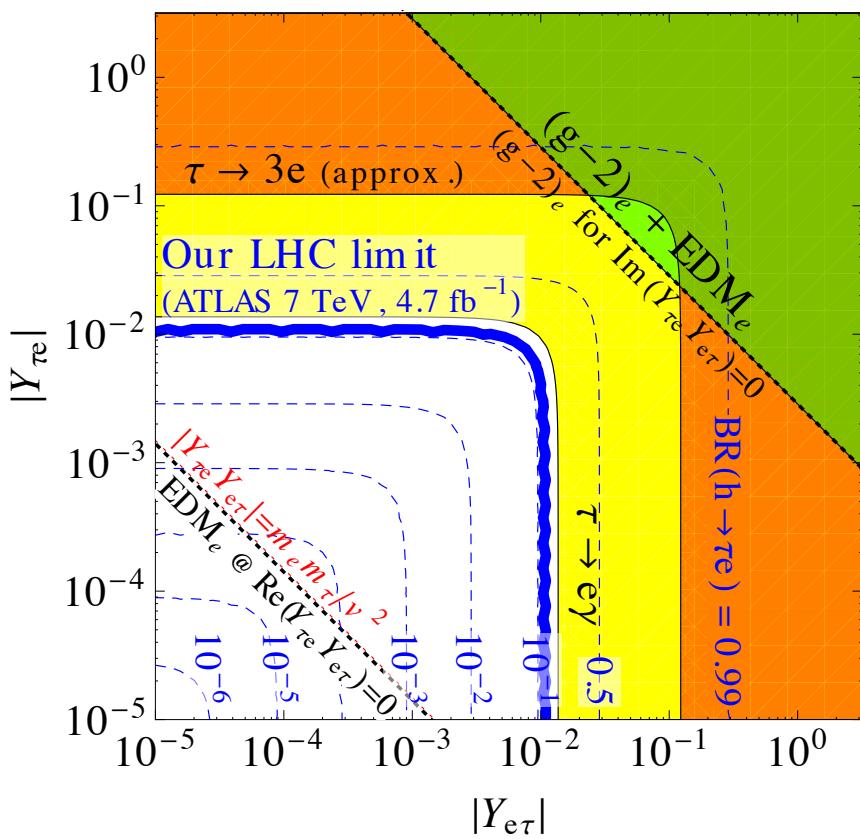
QUARK C

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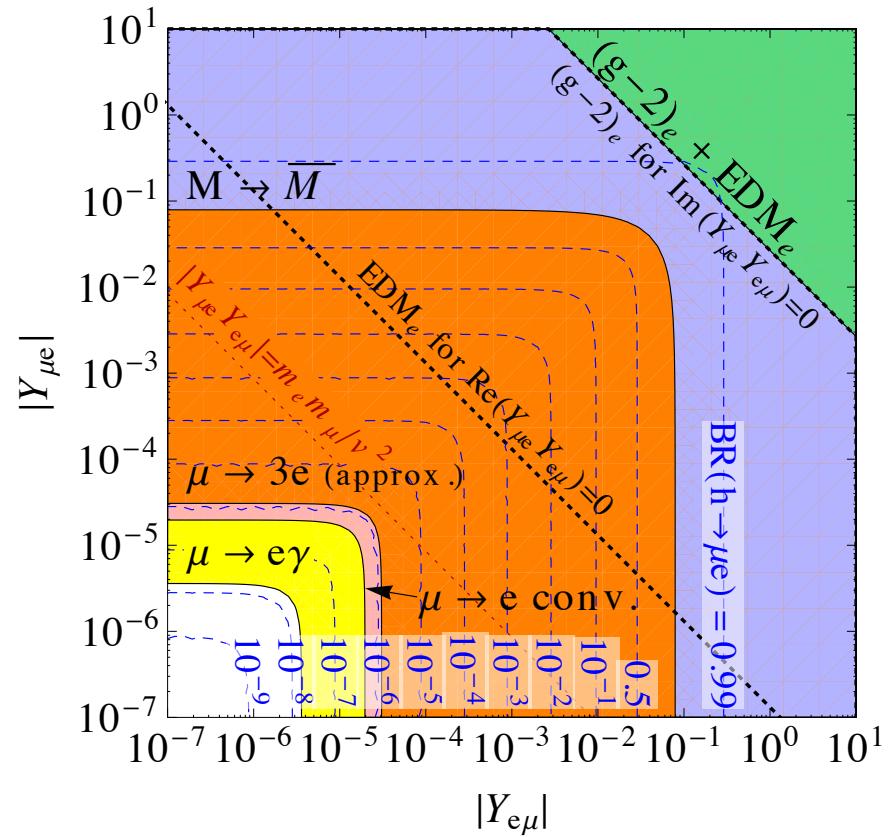
Technique	Coupling	Constraint
D^0 oscillations [48]	$ Y_{uc} ^2, Y_{cu} ^2$	$< 5.0 \times 10^{-9}$
	$ Y_{uc}Y_{cu} $	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$ Y_{db} ^2, Y_{bd} ^2$	$< 2.3 \times 10^{-8}$
	$ Y_{db}Y_{bd} $	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$ Y_{sb} ^2, Y_{bs} ^2$	$< 1.8 \times 10^{-6}$
	$ Y_{sb}Y_{bs} $	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\text{Re}(Y_{ds}^2), \text{Re}(Y_{sd}^2)$	$[-5.9 \dots 5.6] \times 10^{-10}$
	$\text{Im}(Y_{ds}^2), \text{Im}(Y_{sd}^2)$	$[-2.9 \dots 1.6] \times 10^{-12}$
	$\text{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \dots 5.6] \times 10^{-11}$
	$\text{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \dots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{ Y_{tc}^2 + Y_{ct} ^2}$	< 3.7
	$\sqrt{ Y_{tu}^2 + Y_{ut} ^2}$	< 1.6
$t \rightarrow h j$ [50]	$\sqrt{ Y_{tc}^2 + Y_{ct} ^2}$	< 0.10
	$\sqrt{ Y_{tu}^2 + Y_{ut} ^2}$	< 0.10
D^0 oscillations [48]	$ Y_{ut}Y_{ct} , Y_{tu}Y_{tc} $	$< 7.6 \times 10^{-3}$
	$ Y_{tu}Y_{ct} , Y_{ut}Y_{tc} $	$< 2.2 \times 10^{-3}$
	$ Y_{ut}Y_{tu}Y_{ct}Y_{tc} ^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\text{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

HIG-13-034

$h \rightarrow \tau e$ and $h \rightarrow \mu e$



Harnik, Kopp, JZ, 1209.1397



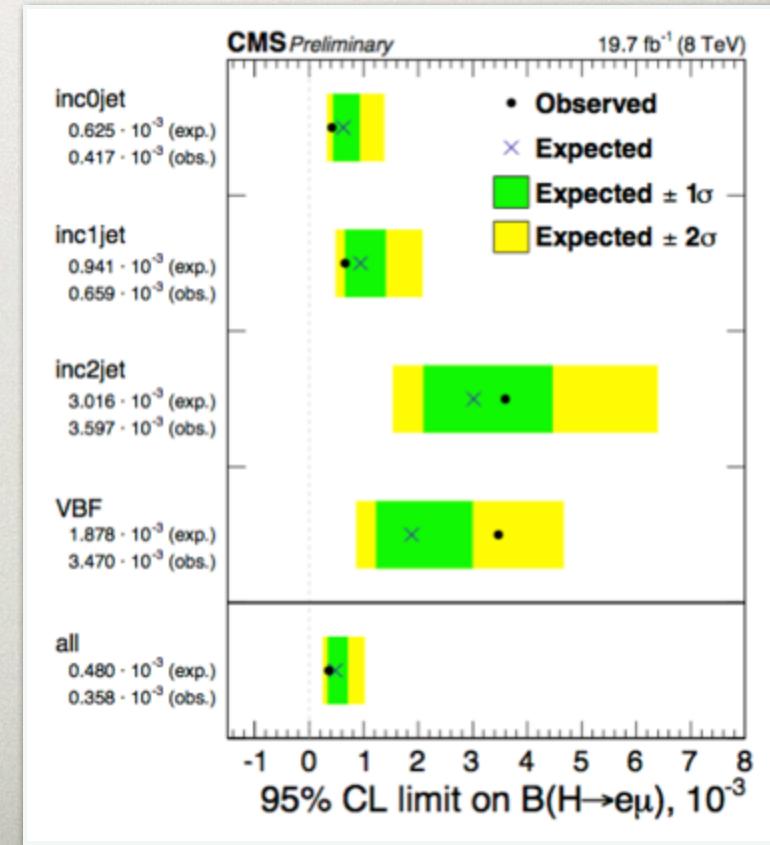
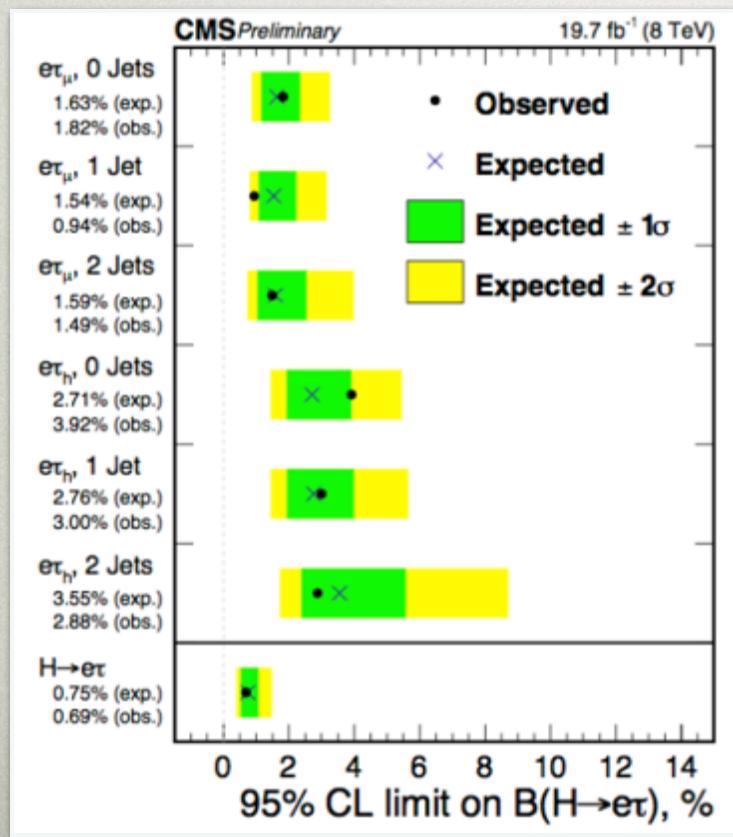
Harnik, Kopp, JZ, 1209.1397

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

- no excess observed (95%CL limits)

CMS-PAS-HIG-14-040

- $Br(H \rightarrow e\tau) < 0.69\%$
- $Br(H \rightarrow e\mu) < 3.6 \times 10^{-4}$

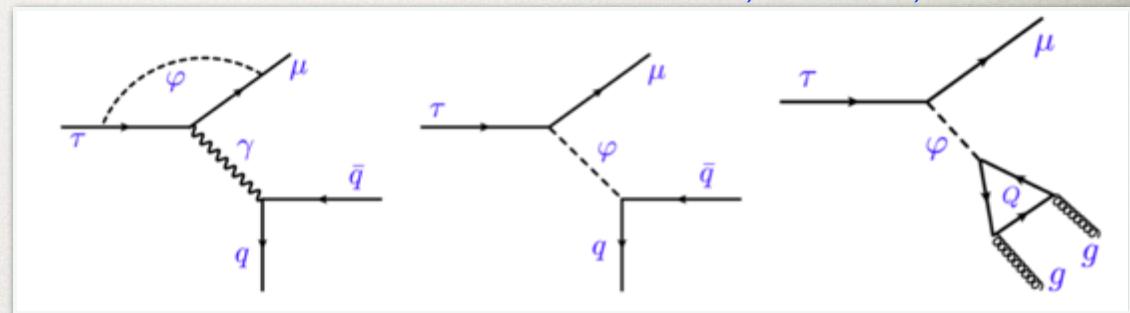


$\tau \rightarrow \mu \pi \pi$

- hadronic tau decays $\tau \rightarrow \mu \pi^+ \pi^-$, $\tau \rightarrow \mu \pi^0 \pi^0$

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

- sensitive to both $Y_{\tau \mu' \mu \tau}$ 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



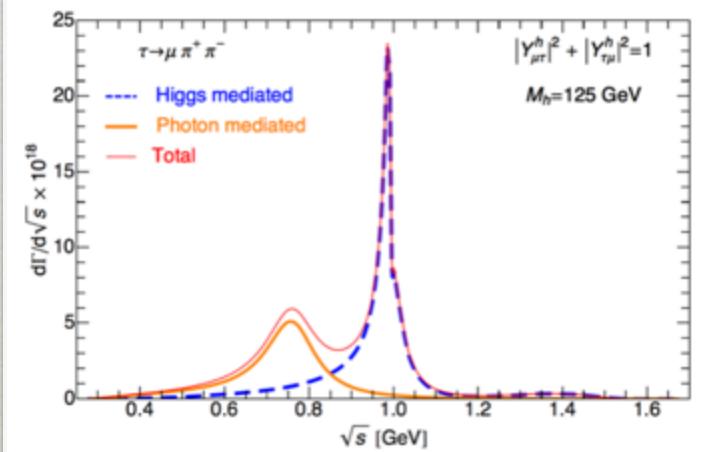
$$Br(\tau \rightarrow \mu \pi^+ \pi^-) < 1.6 \times 10^{-11}, Br(\tau \rightarrow \mu \pi^0 \pi^0) < 4.6 \times 10^{-12}$$

$$Br(\tau \rightarrow e \pi^+ \pi^-) < 2.3 \times 10^{-10}, Br(\tau \rightarrow e \pi^0 \pi^0) < 6.9 \times 10^{-11}$$

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

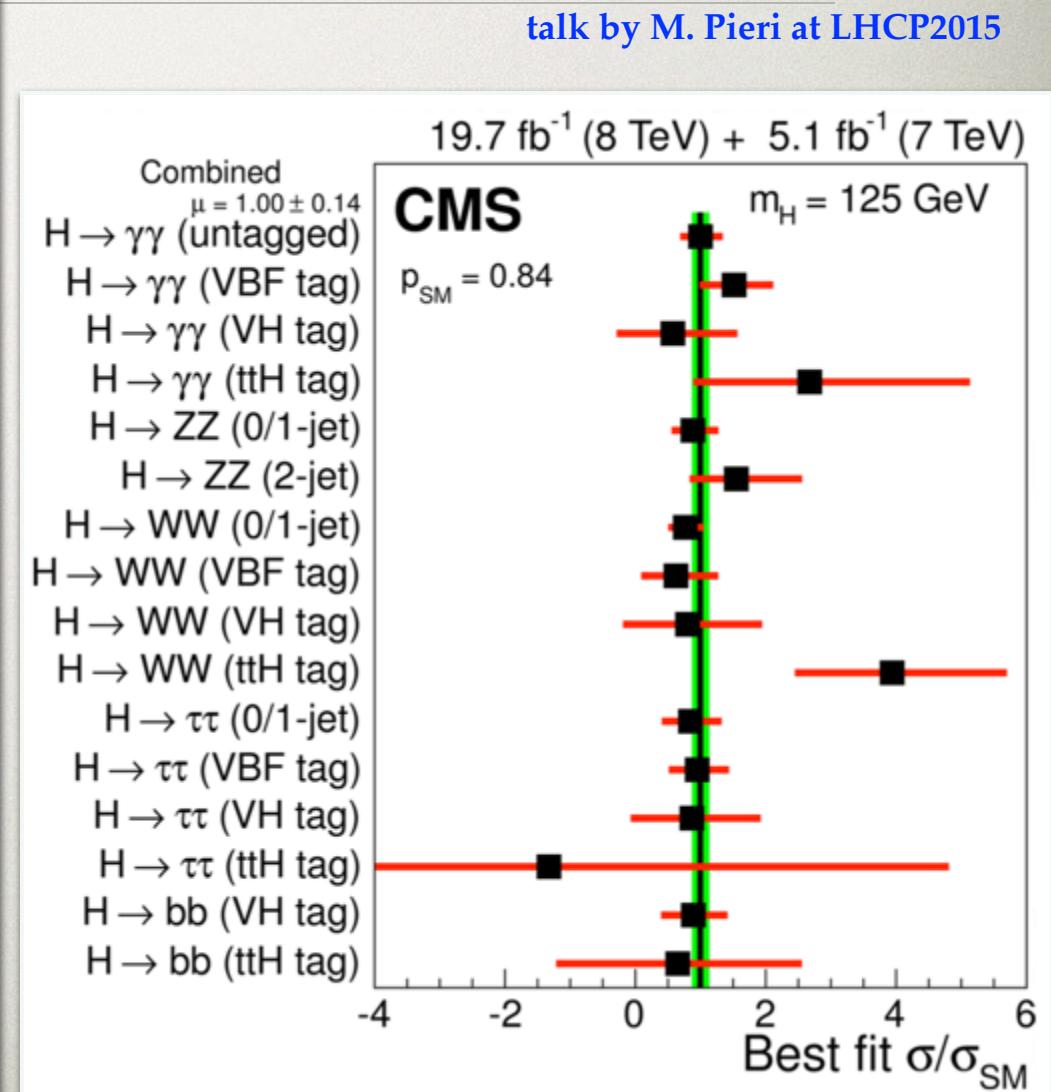
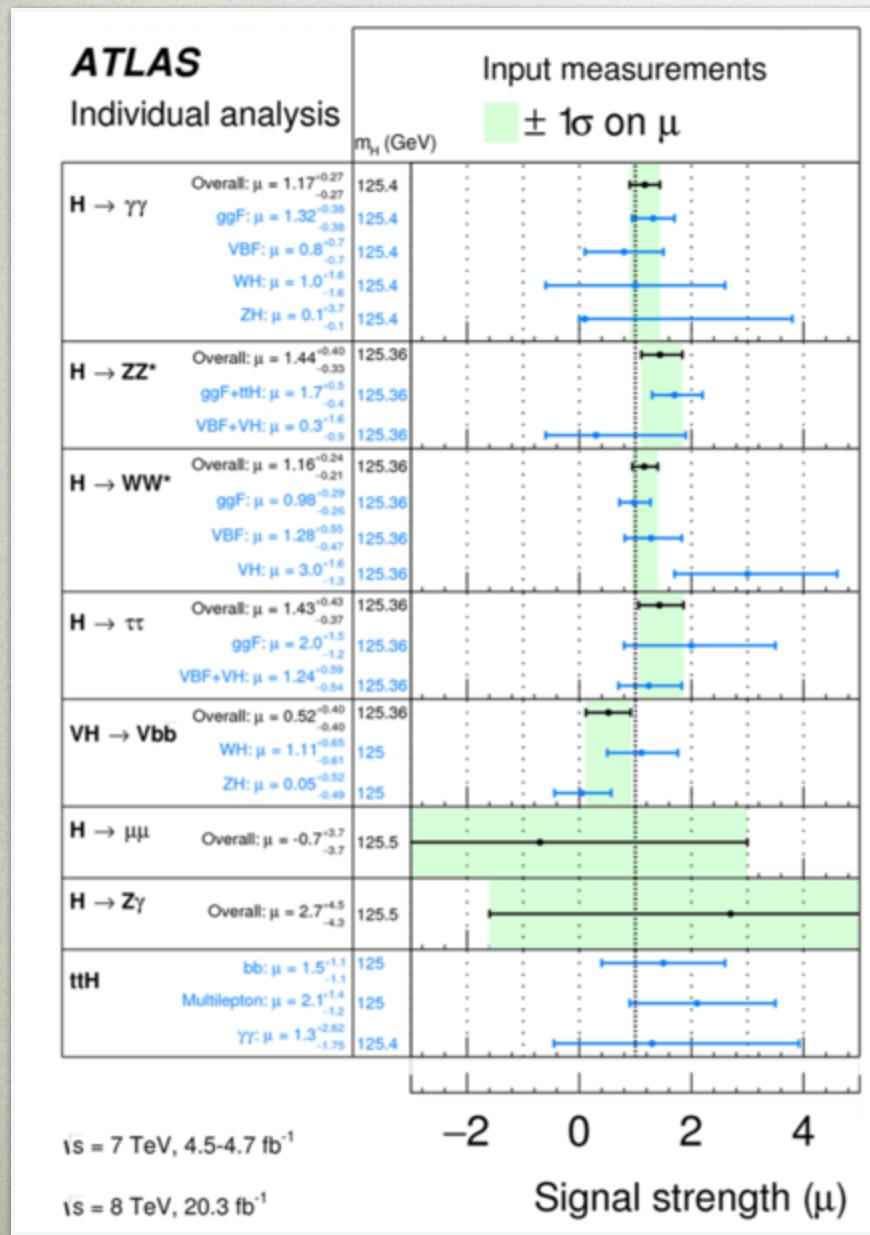
$$Br(\tau \rightarrow \mu \pi^+ \pi^-) < 3.0 \times 10^{-8}, Br(\tau \rightarrow \mu \pi^0 \pi^0) < 1.5 \times 10^{-8}$$

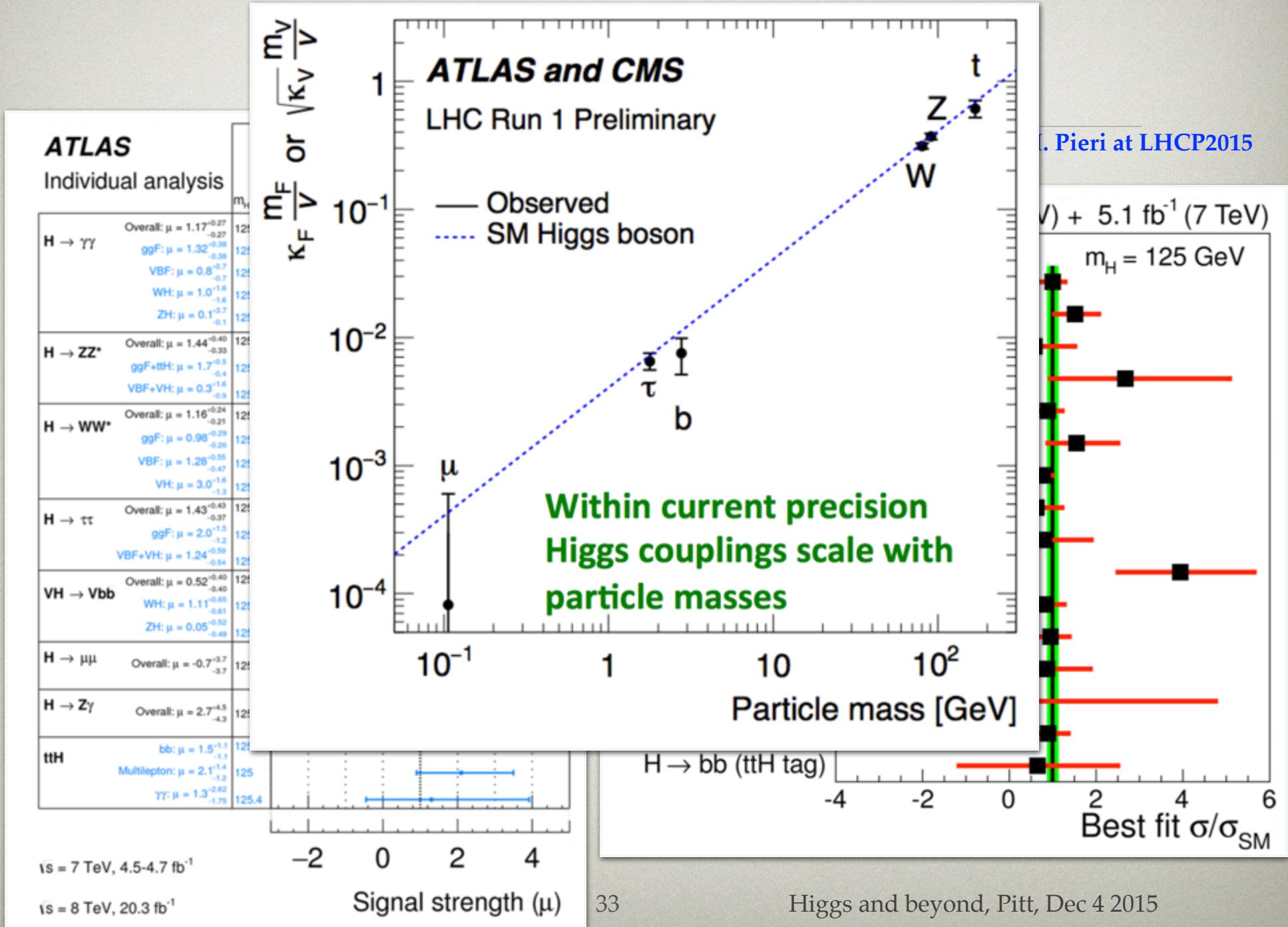
$$Br(\tau \rightarrow e \pi^+ \pi^-) < 4.3 \times 10^{-7}, Br(\tau \rightarrow e \pi^0 \pi^0) < 2.1 \times 10^{-7}$$



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

MEASUREMENTS





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	$1 + \mathcal{O}(v^2/\Lambda^2)$	$1 + \mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(U_{23} ^2 v^4/\Lambda^4)$
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

CPV HIGGS COUPLINGS

- couplings of Higgs to other SM fields can be CPV
- CPV for Higgs couplings to gauge bosons from on shell production

F. Bishara, Y. Grossman, R. Harnik, D. Robinson, J. Shu, JZ, 1312.2955

- e.g., $h \rightarrow \gamma\gamma$ potentially from Bethe-Heitler photon conversion, or from $h \rightarrow \gamma\gamma \rightarrow 4l$ (this also CPV in $h \rightarrow ZZ$)
Chen, Roni Harnik, Vega-Morales, 1404.1336; Falkowski, Vega-Morales, 1405.1095
- CPV in $h \rightarrow gg$ from $h+2j$ production
Anderson et al., 1309.4819
Delaunay, Perez, de Sandes, Skiba, 1308.4930
- CPV in $h \rightarrow WW$ from hW associated production
- focus on CP violating Higgs couplings to fermions Brod, Haisch, JZ, 1310.1385
 - the notation
- can probe CPV couplings to 3rd generation, so $f=t,b,\tau$

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

2ND AND 3RD GENS. ONLY

- focus on the 2nd and 3rd generations

2x2 matrix

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

rank 2 matrix

- choose flavor basis so the only nonzero entry of M_0^ℓ is

$$(\mathcal{M}_0^\ell)_{33} \sim m_\tau$$

$$(\mathcal{M}_0^{u,d})_{i,j} \sim m_{c,s}$$

- the remaining entries

$$(\Delta\mathcal{M}^\ell)_{ij} = \mathcal{O}(m_\mu), \quad i, j = 2, 3.$$

- flavor violating Yukawa couplings

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

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

- R_Y only depends on the details of the EWSB
- for $R_Y \sim 1$ and $Y_{\mu\tau} \sim Y_{\tau\mu}$ the CMS hint

$$(\Delta\mathcal{M}^\ell)_{\mu\tau} \sim (0.45 \pm 0.10) \text{ GeV}$$

HIGGS-TOP CPV COUPLING

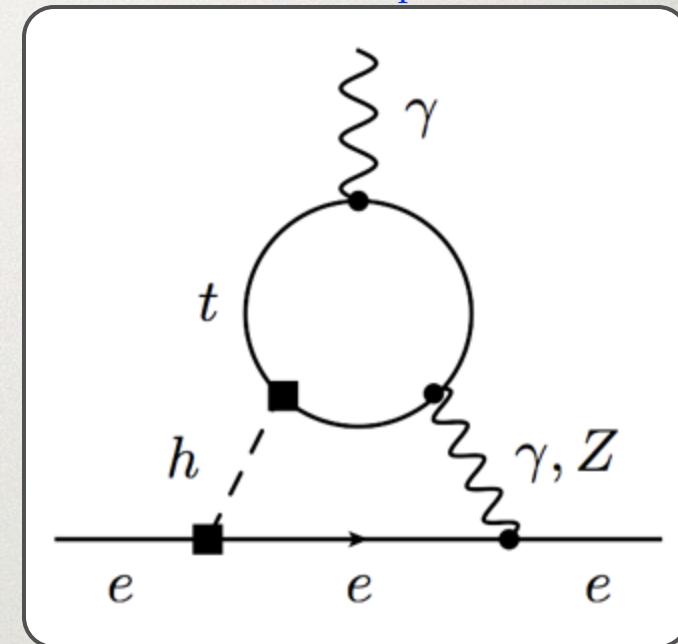
- electron EDM: dominant contribution from 2-loop Barr-Zee type diagram

$$\mathcal{L}_{\text{eff}} = -d_e \frac{i}{2} \bar{e} \sigma^{\mu\nu} \gamma_5 e F_{\mu\nu}$$

- depends on electron yukawa
 - setting $y_e=1$ is then quite constraining

$$|\tilde{\kappa}_t| < 0.01$$

Brod, Haisch, JZ, 1310.1385,
updated to ACME 1310.7534

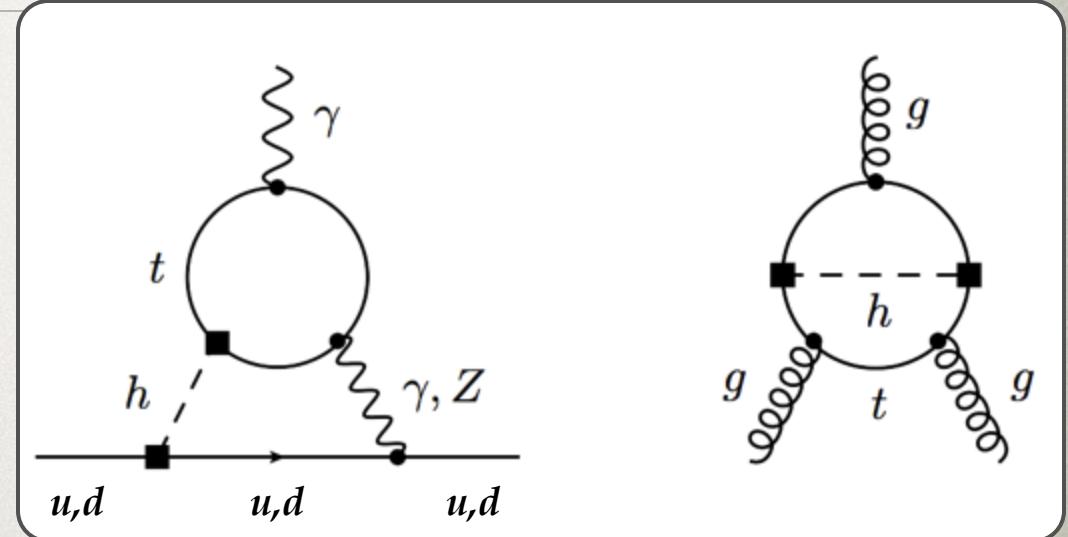


- the constraint vanishes, if the Higgs does not couple to electrons
- if it only couples to the 3rd gen. still a constraint from neutron EDM
 - relevant in the future (at a permit level), now $\sim O(1)$ allowed

NEUTRON AND MERCURY EDM

Brod, Haisch, JZ, 1310.1385

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



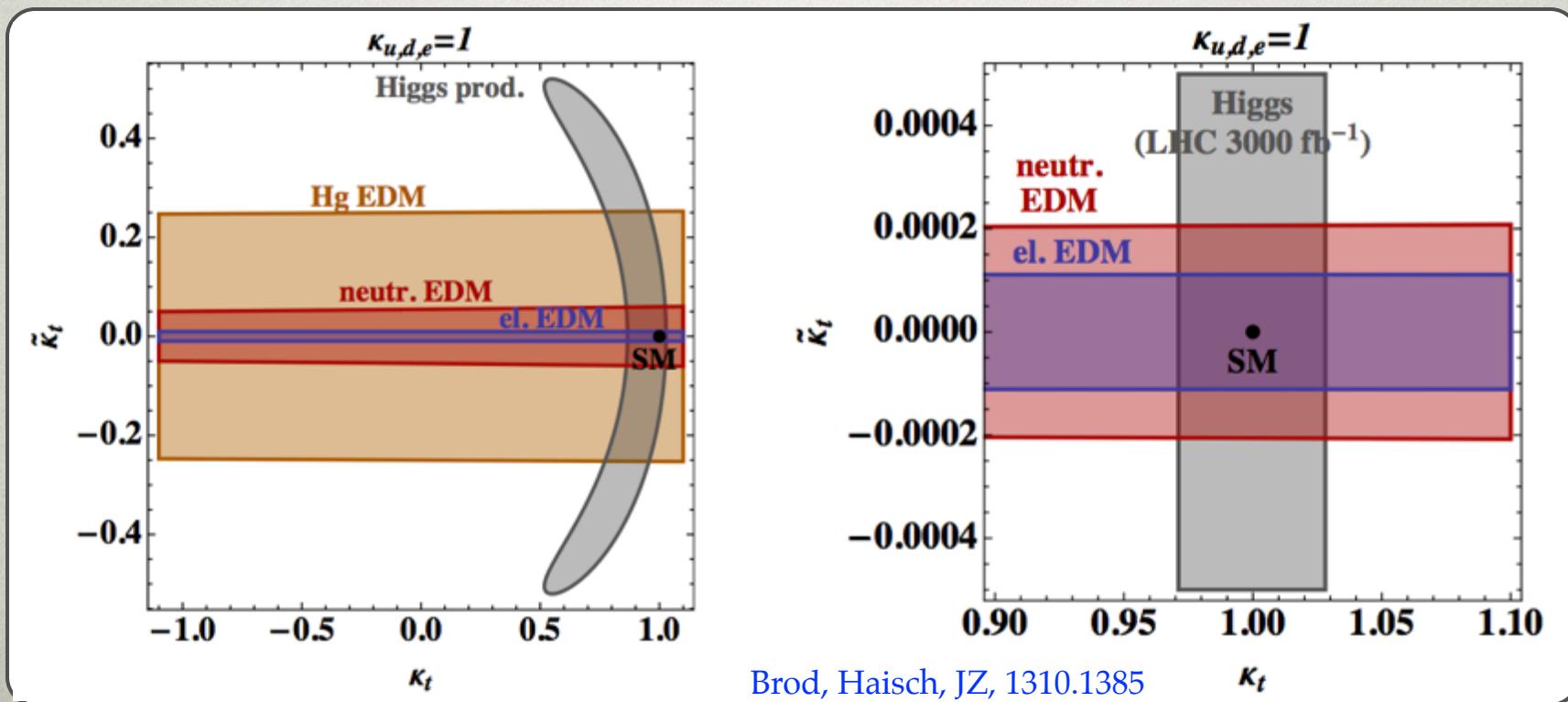
$$\mathcal{L}_{\text{eff}} = -d_q \frac{i}{2} \bar{q} \sigma^{\mu\nu} \gamma_5 q F_{\mu\nu} - \tilde{d}_q \frac{ig_s}{2} \bar{q} \sigma^{\mu\nu} T^a \gamma_5 q G_{\mu\nu}^a - w \frac{1}{3} f^{abc} G_{\mu\sigma}^a G_{\nu}^{b,\sigma} \tilde{G}^{c,\mu\nu}$$

- 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 TOP

Brod, Haisch, JZ, 1310.1385

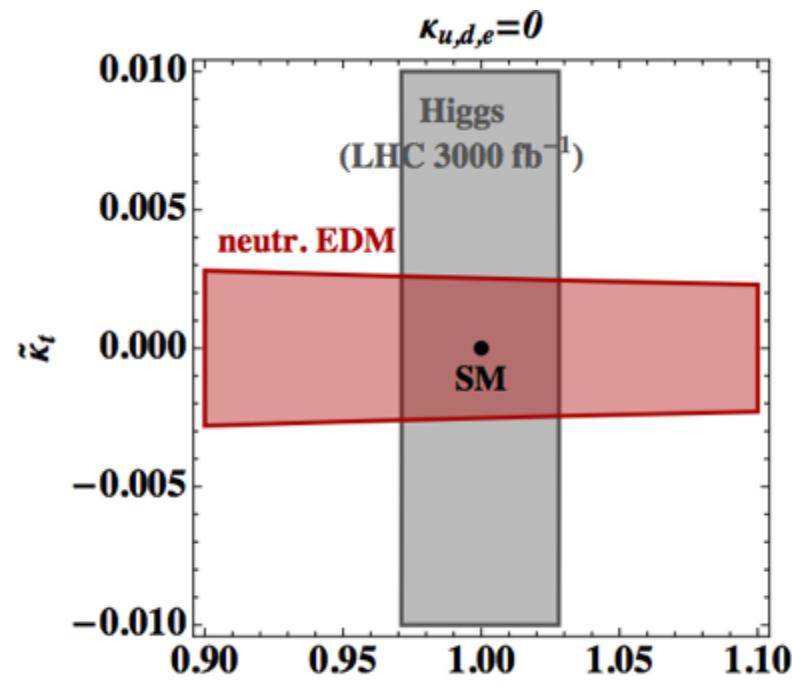
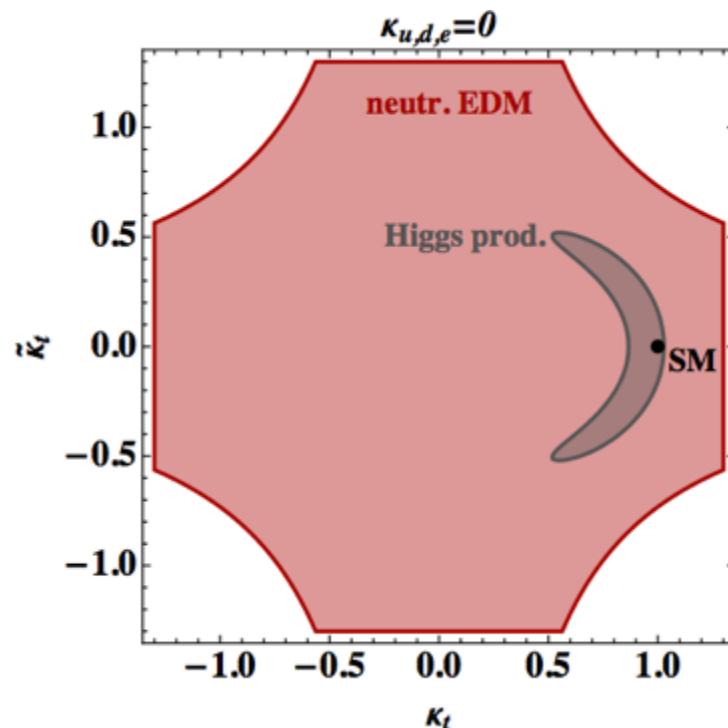
- comparing with the LHC reach
 - assuming that no CPV measurements at the LHC
- for 1st gen. Yukawas equal to the SM



CPV COUPLING TO TOP

Brod, Haisch, JZ, 1310.1385

- comparing with the LHC reach
 - assuming that no CPV measurements at the LHC
- 1st gen. Yukawas set to zero

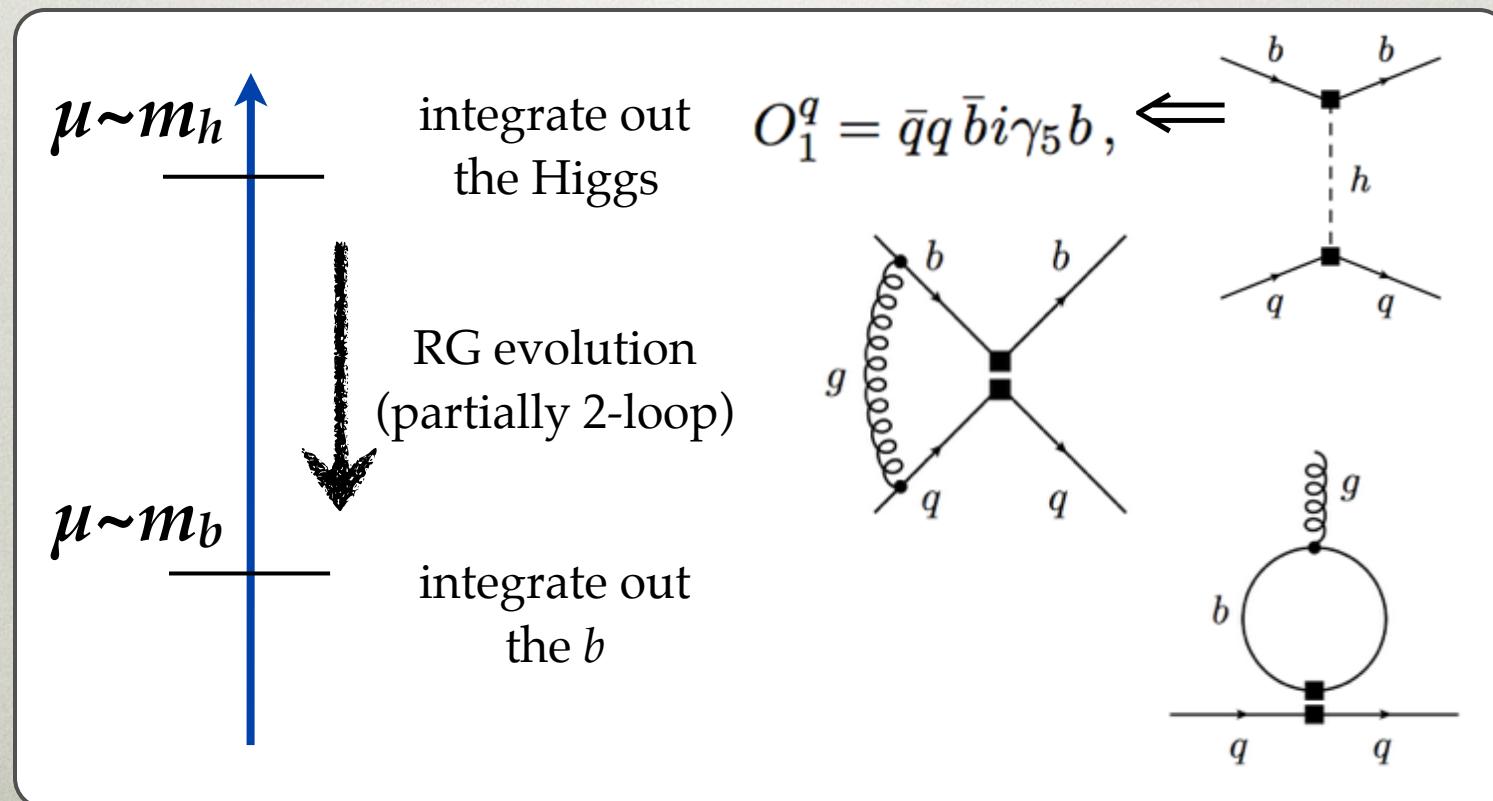


Brod, Haisch, JZ, 1310.1385

CPV COUPLING TO b QUARK

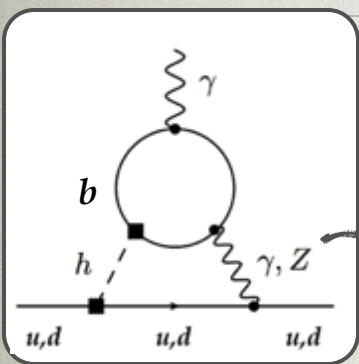
Brod, Haisch, JZ, 1310.1385

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



RESUMMATION

Brod, Haisch, JZ, 1310.1385



- only one relevant entry of anomalous dimension not known previously, $\gamma_{5,11}^{(1)}$

$$O_5^q = -\frac{i}{2} e Q_b \frac{m_b}{g_s^2} \bar{q} \sigma^{\mu\nu} \gamma_5 q F_{\mu\nu},$$

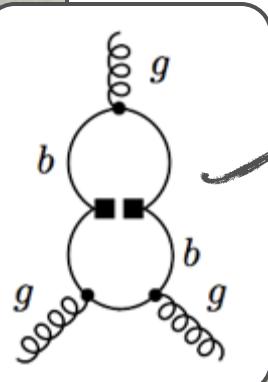
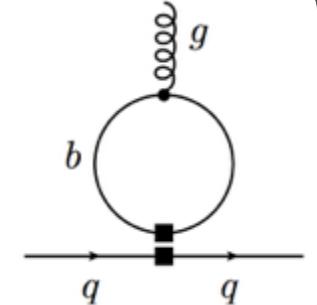
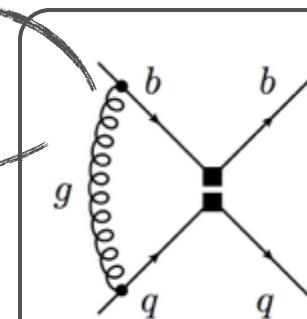
$$O_6^q = -\frac{i}{2} \frac{m_b}{g_s} \bar{q} \sigma^{\mu\nu} T^a \gamma_5 q G_{\mu\nu}^a,$$

$$O_7 = -\frac{1}{3g_s} f^{abc} G_{\mu\sigma}^a G_{\nu}^{b,\sigma} \tilde{G}^{c,\mu\nu},$$

$$C_5^q(\mu_b) \simeq -4 \frac{\alpha \alpha_s}{(4\pi)^2} Q_q \ln^2 x_{b/h} + \left(\frac{\alpha_s}{4\pi}\right)^3 \frac{\gamma_{14}^{(0)} \gamma_{48}^{(0)} \gamma_{87}^{(0)}}{48} \ln^3 x_{b/h} + \mathcal{O}(\alpha_s^4)$$

$$C_6^q(\mu_b) \simeq \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{14}^{(0)} \gamma_{48}^{(0)}}{8} \ln^2 x_{b/h} + \mathcal{O}(\alpha_s^3)$$

$$C_7(\mu_b) \simeq \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{5,11}^{(1)}}{2} \ln x_{b/h} + \mathcal{O}(\alpha_s^3)$$

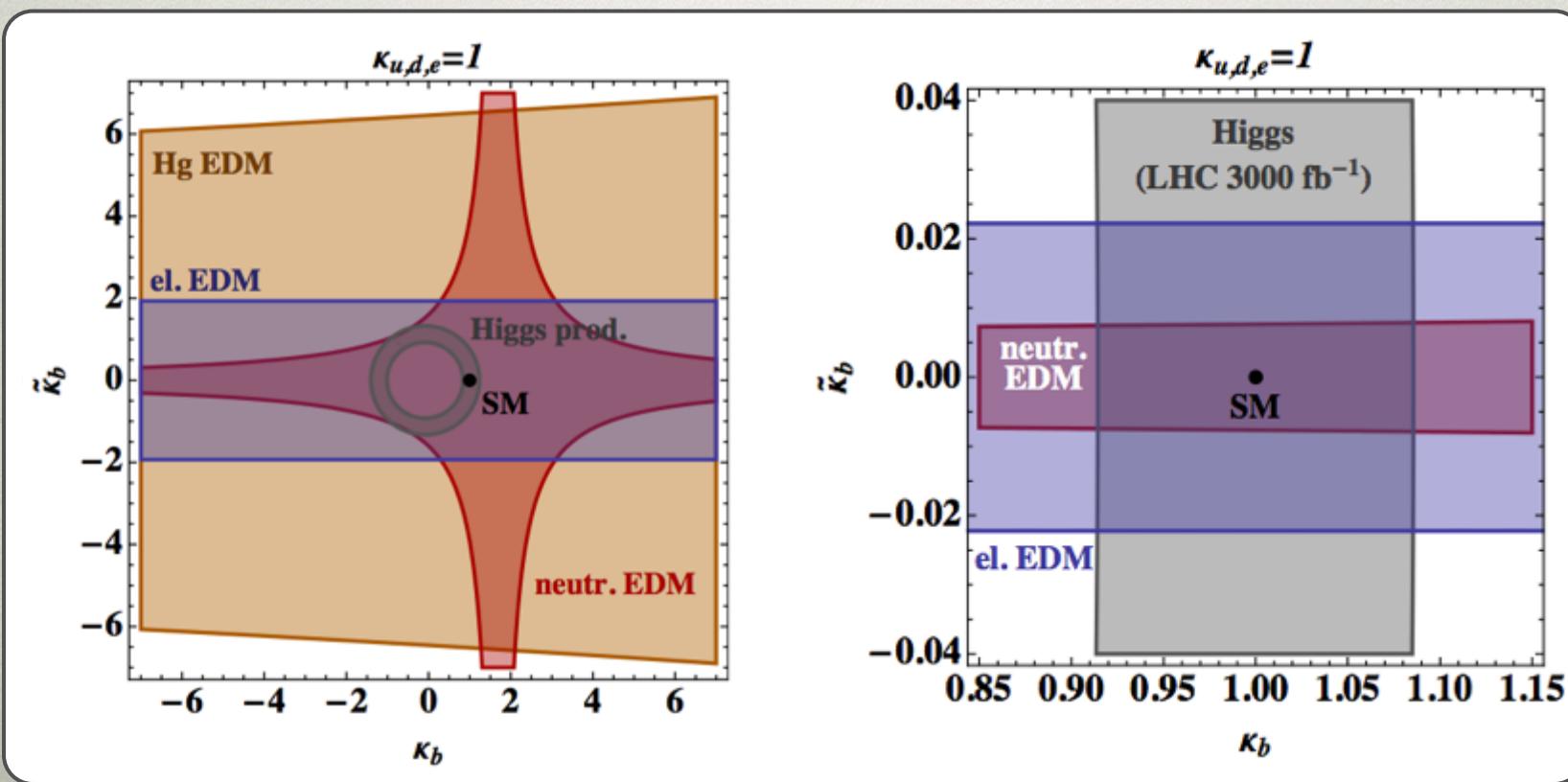


- resummation numerically important
- without it a factor of ~3 ambiguity in nEDM

CPV COUPLING TO b QUARK

- the EDM constraints on CPV Higgs coupling to b quark are weaker than the LHC data
 - this can change in the future
 - EDMs scale linearly with $\tilde{\kappa}_b$

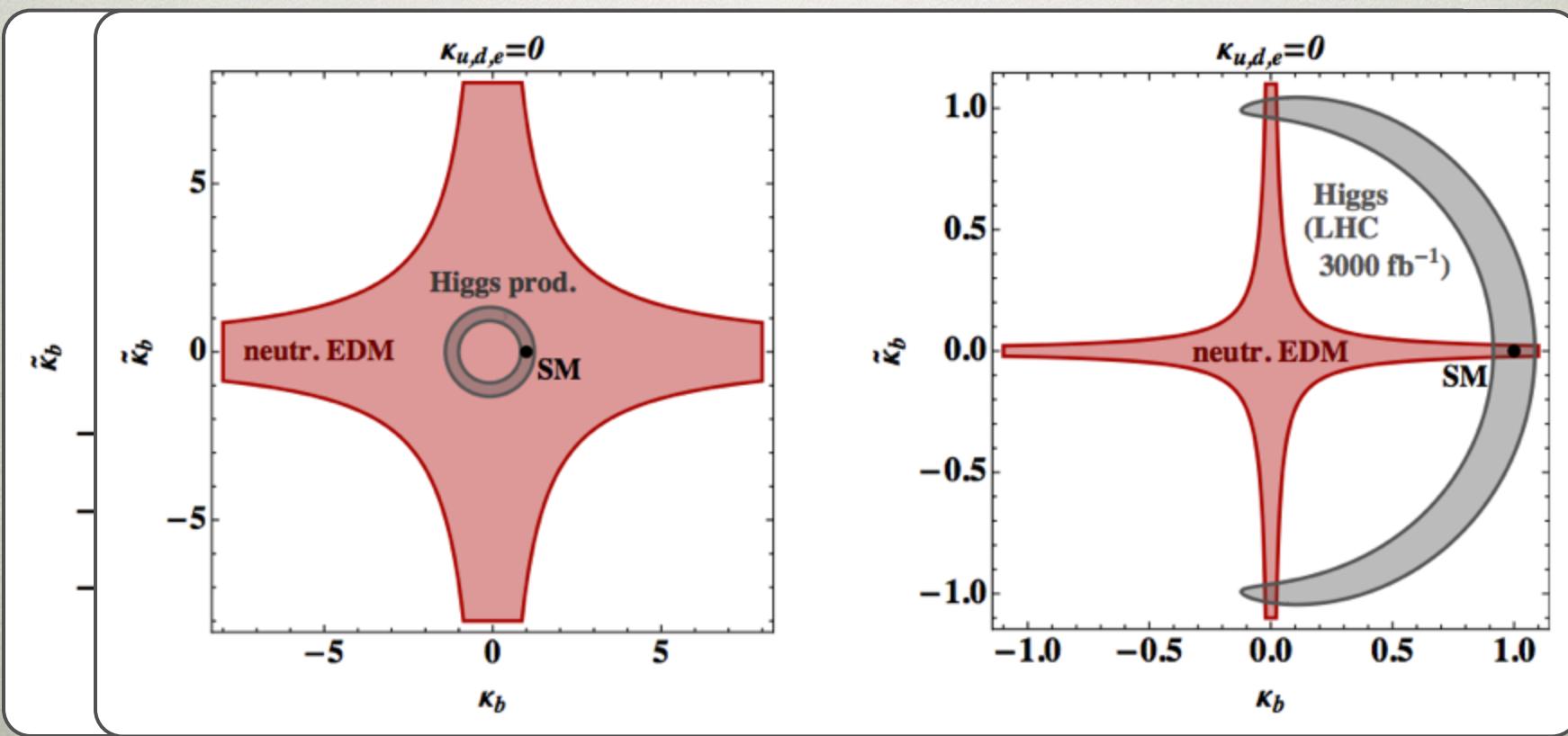
Brod, Haisch, JZ, 1310.1385



CPV COUPLING TO b QUARK

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Brod, Haisch, JZ, 1310.1385



2HDM

- two Higgs doublets Φ and Φ'
 - neutral components: ϕ and ϕ' , vevs v, v'
 - ϕ couples to 3rd family $\phi \bar{\ell}_L^3 e_R^3$
 - ϕ' couples to all three families
 - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- off diagonal Higgs Yukawas

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

$$R_Y = R_{\alpha\beta} \equiv 2\cos(\alpha - \beta)/\sin 2\beta$$

- flavor diagonal Yukawas

$$\hat{y}_a \equiv Y_{aa}/Y_{aa}^{\text{SM}}$$

$$\hat{y}_a = \cos \alpha / \sin \beta - R_Y (\Delta\mathcal{M}^\ell)_{aa} / m_a, \quad a = \mu, \tau,$$

NOTATION FOR 2HDM

- using Haber, Nir basis

Haber, Nir, Nucl.Phys. B335 (1990) 363

$$\begin{aligned} V = & m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \tfrac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] + \tfrac{1}{2} (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) (\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2). \quad (4.1) \end{aligned}$$

TECHNICOLOR EXAMPLE

- ΔM_l due to technicolor strong dynamics
 - UV completion is bosonic TC
- Higgs admixture of elementary ϕ and a composite heavy scalar, σ_{TC}
- confining TC gauge group is $SU(2)_{TC}$
- technifermions are
 - $SU(2)_L$ doublet T_R (2,1,2,0)
 - $SU(2)_L$ singlets D_L (2,1,1,1) and U_L (2,1,1, 2)
- techniscalar $SU(2)_L$ singlet ξ (2,1,1,1)
- elem. scalar Φ couples to $\bar{e}_{3L}e_{3R}$, the other couplings are

$$\lambda_D \bar{D}_L \tilde{\Phi} T_R + \lambda_U \bar{U}_L \Phi T_R + h_i^\ell \xi \bar{\ell}_L^i T_R + h_i^{e\dagger} \xi^* \bar{D}_L e_R^i,$$

MUON MASS FROM TC CONDENSATE

- TC confines at $\Lambda_{TC} \sim 4\pi f_{TC}$, so $v_W^2 \sim f_{TC}^2 + v^2$, viable pheno. for $f_{TC} \lesssim 80 \text{ GeV}$
- two roles of TC condensates $\langle \bar{D}D \rangle, \langle \bar{U}U \rangle$
 - induces the Higgs vev (the bulk of EWSB) through tadpole

$$\lambda_D \bar{D}_L \tilde{\Phi} T_R + \lambda_U \bar{U}_L \Phi T_R$$

- contribute to the lepton mass matrix ΔM^l

$$h_i^\ell \xi \bar{\ell}_L^i T_R + h_i^{e\dagger} \xi^* \bar{D}_L e_R^i \xrightarrow[\text{integrating out } \xi]{} \frac{h_i^\ell h_j^{e\dagger}}{m_\xi^2} \bar{\ell}_L^i T_R \bar{D}_L e_R^j + \text{h.c.}$$

- TC condensates give rank 1 contrib. to ΔM^l

$$(\Delta \mathcal{M}^\ell)_{ij} = \eta \kappa \frac{4\pi f_{TC}^3}{2m_\xi^2} h_i^\ell h_j^{e\dagger}$$

- the $\tau \rightarrow \mu \gamma$ is further parametrically suppressed

$$\frac{h_i^\ell h_j^{e\dagger}}{m_\xi^4} T_R \bar{D}_L \bar{\ell}_L^i \sigma_{\mu\nu} e_R^j F^{\mu\nu} \xrightarrow{} \frac{c_L}{8\pi^2} = Q_\xi \frac{(\Delta \mathcal{M}^\ell)_{\tau\mu}}{2m_\xi^2 m_\tau}$$

BENCHMARK AND SUM RULE

- straightforward to obtain a viable benchmark with $O(1)$ couplings
 - the bound on $\tau \rightarrow \mu\gamma$ requires

$$\sqrt{R_Y} m_\xi \gtrsim 10 \text{ (8.7) TeV}$$

$Br(h \rightarrow \tau\mu) = \text{CMS}$ \uparrow $Br(h \rightarrow \tau\mu) = \text{CMS} - 1\sigma$

- to all orders in ChPT

$$R_Y > \cos \alpha / \sin \beta$$

$\phi - \sigma_{TC}$ mixing angle

$\tan \beta \equiv v/f_{TC}$

- a general sum rule

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

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

- valid to the extent that both ΔM^l and ΔM_0 are rank 1
- is explicitly true in our TC example