FLAVOUR VIOLATING HIGGS DECAYS

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

HEFT, Chicago, Nov 4 2015

SM HIGGS?

- how closely does the Higgs discovered by ATLAS and CMS resemble the SM Higgs?
  - EWSB: does it couple to *W,Z*?
    - Yes! Higgs mechanism most of EWSB
  - fermion mass generation: does it couple to fermions?
    - 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

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

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

  - decouples mass terms from yukawas

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

  - can lead to flavor violating Higgs decays
  - can lead to CPV Higgs decays
- different models lead to different patterns of flavor diagonal and flavor violating Yukawas

A GENERAL BENCHMARK

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

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

Cheng, Sher, 1987

  - in concrete models it will be typically further suppressed parametrically

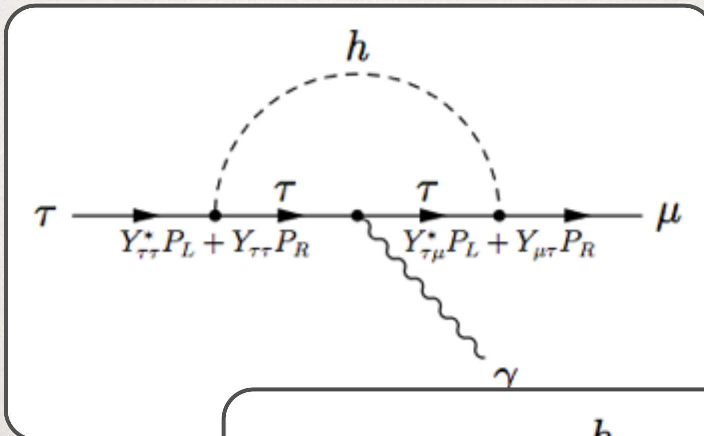
see e.g, Dery, Efrati, Nir, Soreq, Susic, 1408.1371;
Dery, Efrati, Hochberg, Nir, 1302.3229;
Arhrib, Cheng, Kong, 1208.4669

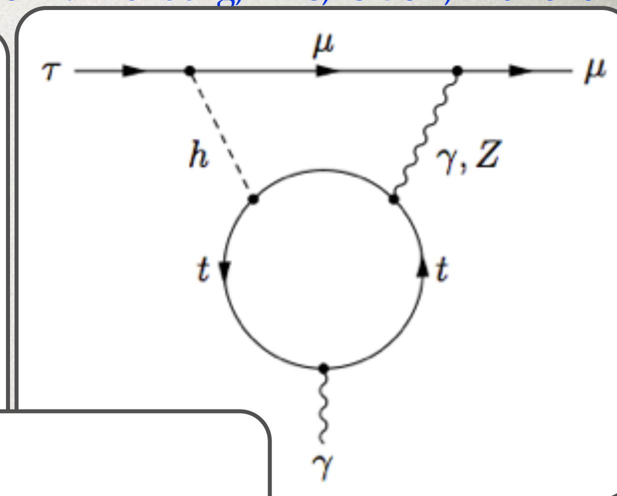
$h \to \tau\mu$

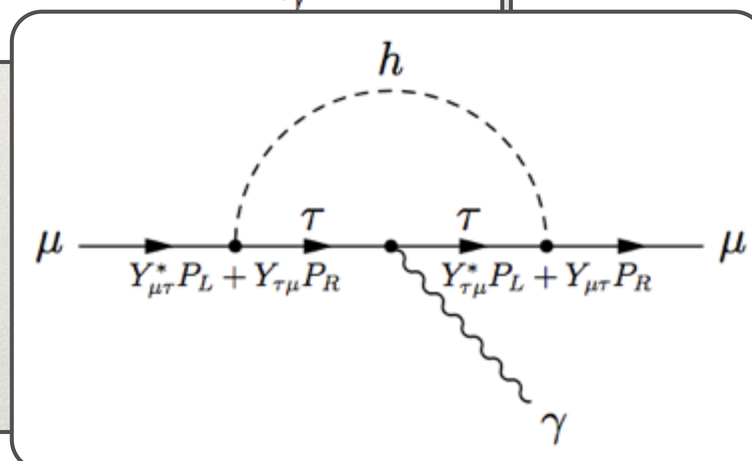
Harnik, Kopp, JZ, 1209.1397

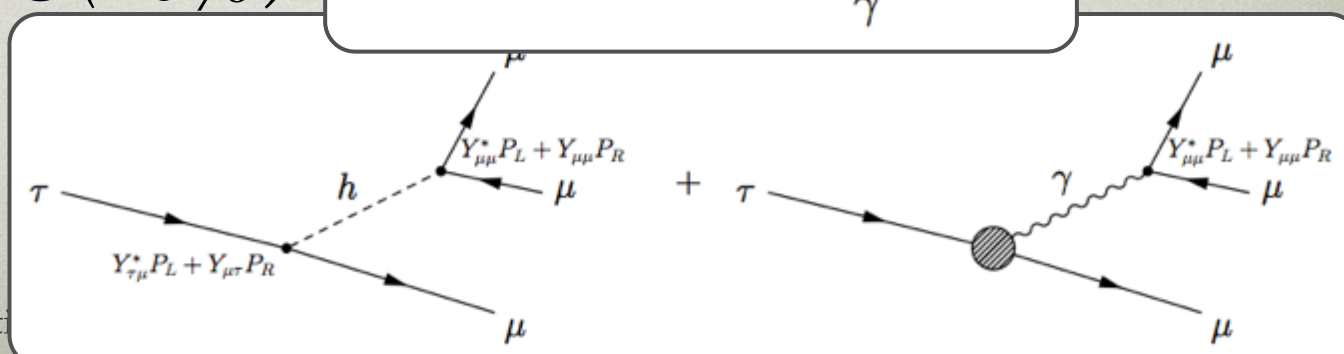
see also Blankenburg, Ellis, Isidori, 1202.5704

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









$h \to \tau\mu$

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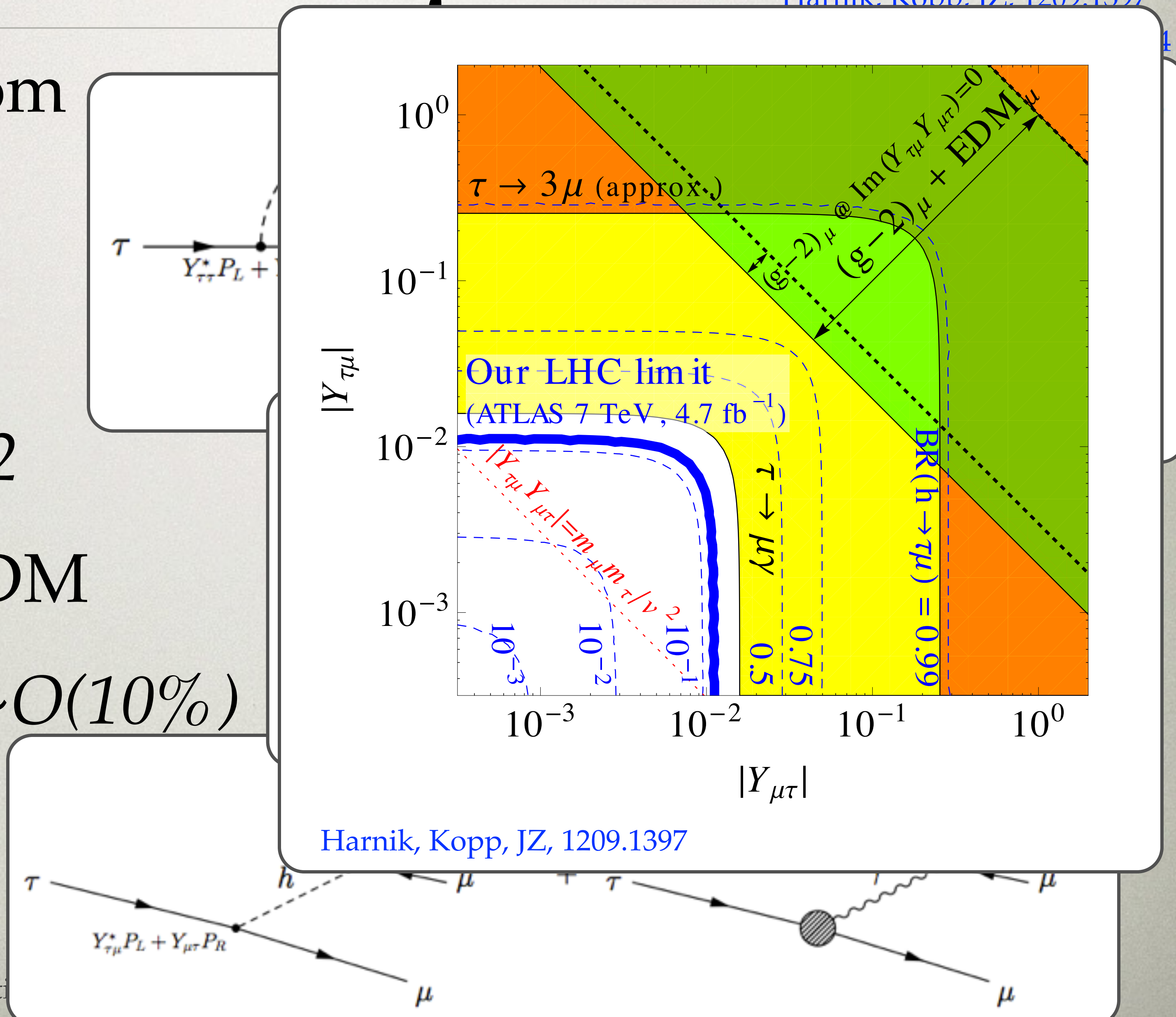
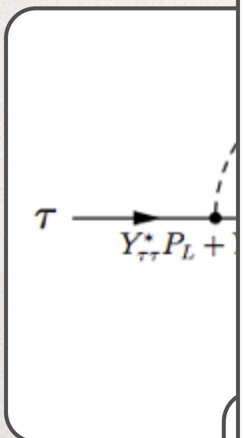
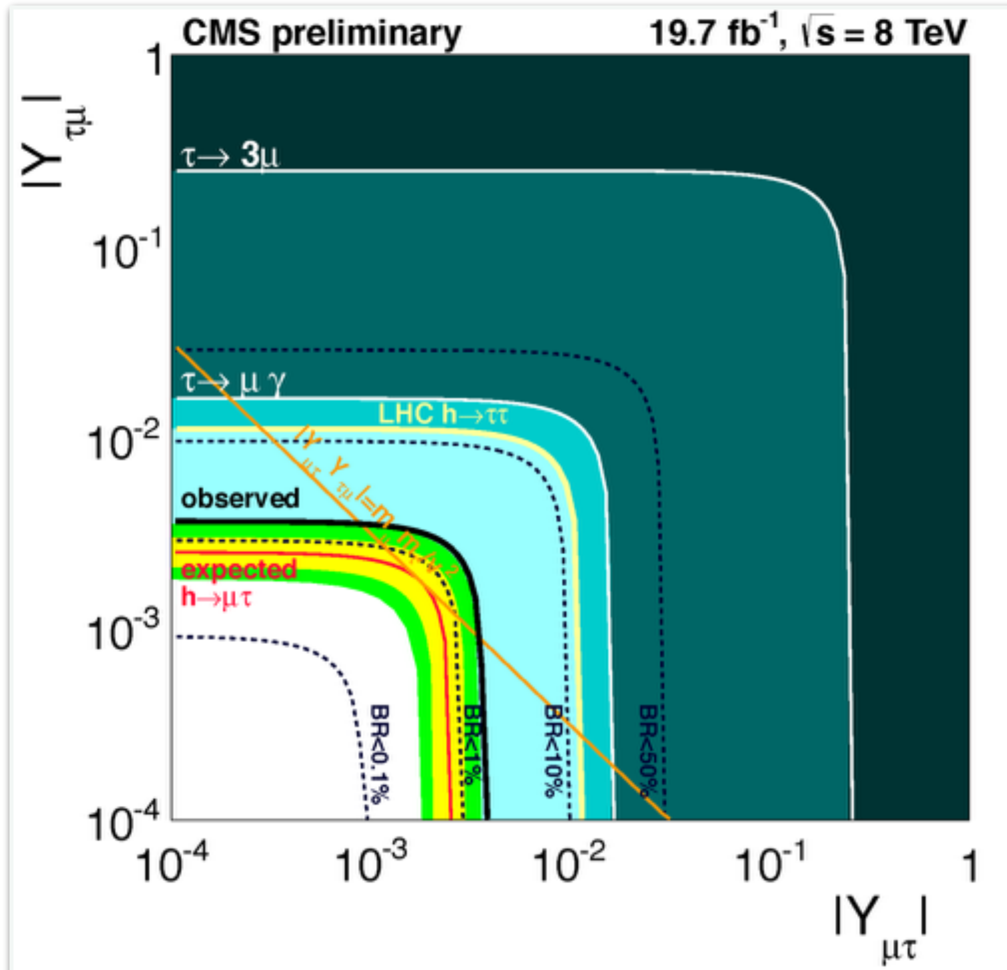


$h \to \tau\mu$

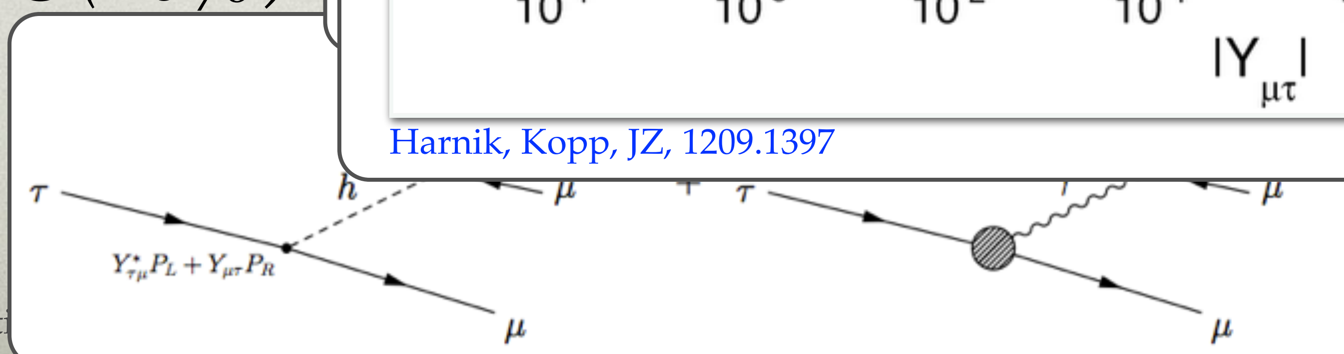
Harnik, Kopp, JZ, 1209.1397

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



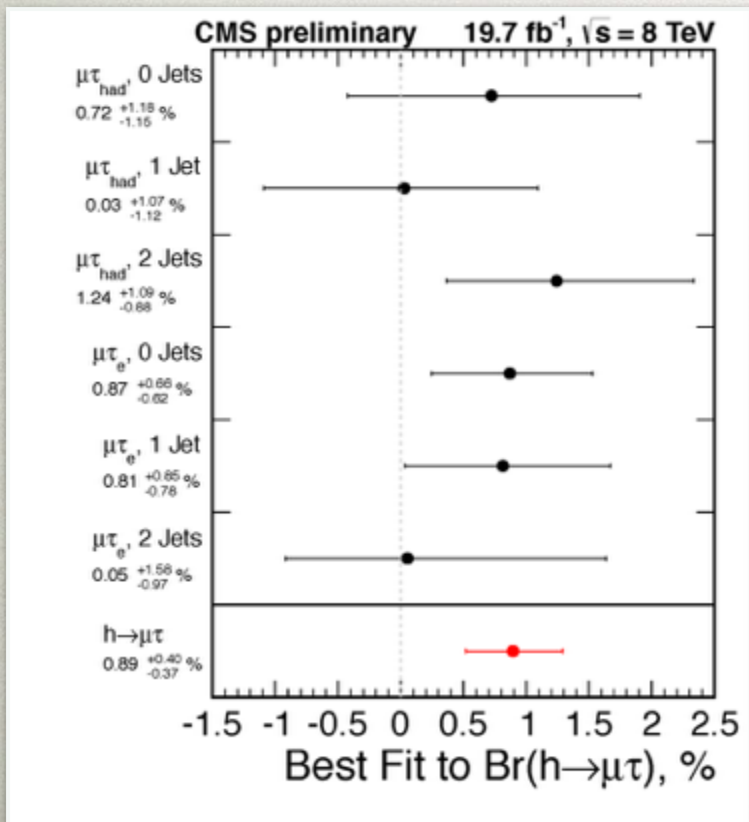


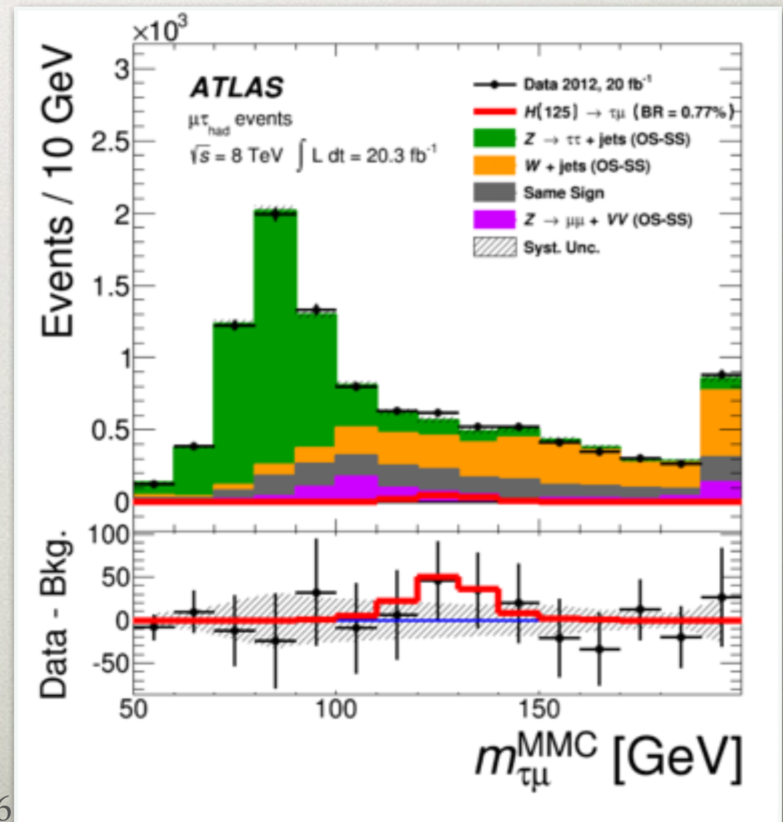
Harnik, Kopp, JZ, 1209.1397



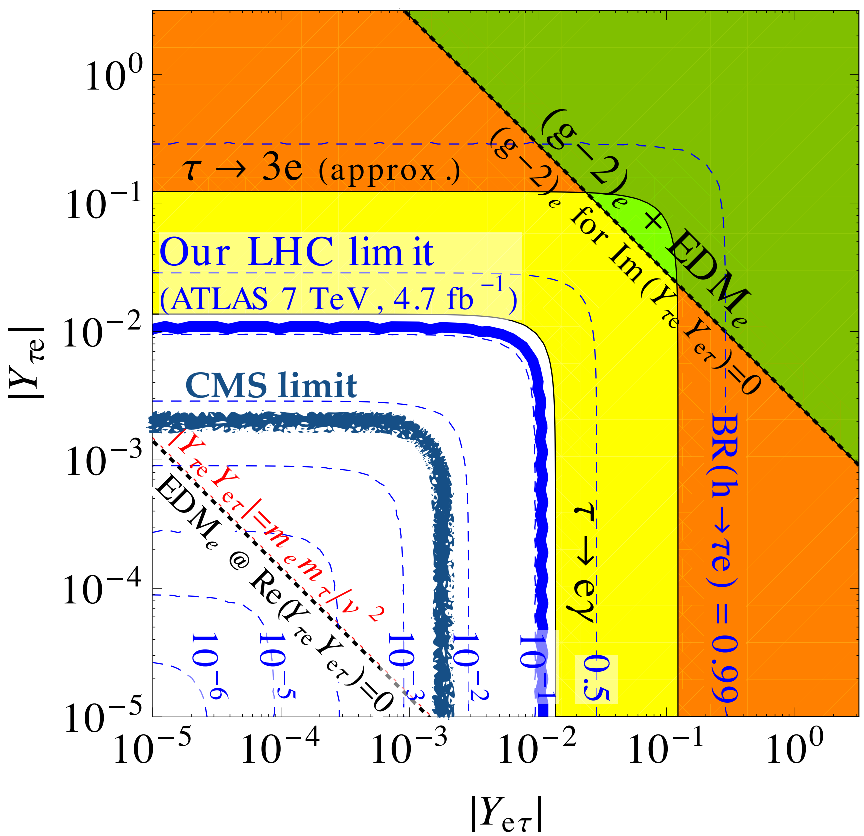
$h \to \tau\mu$ exp. info

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

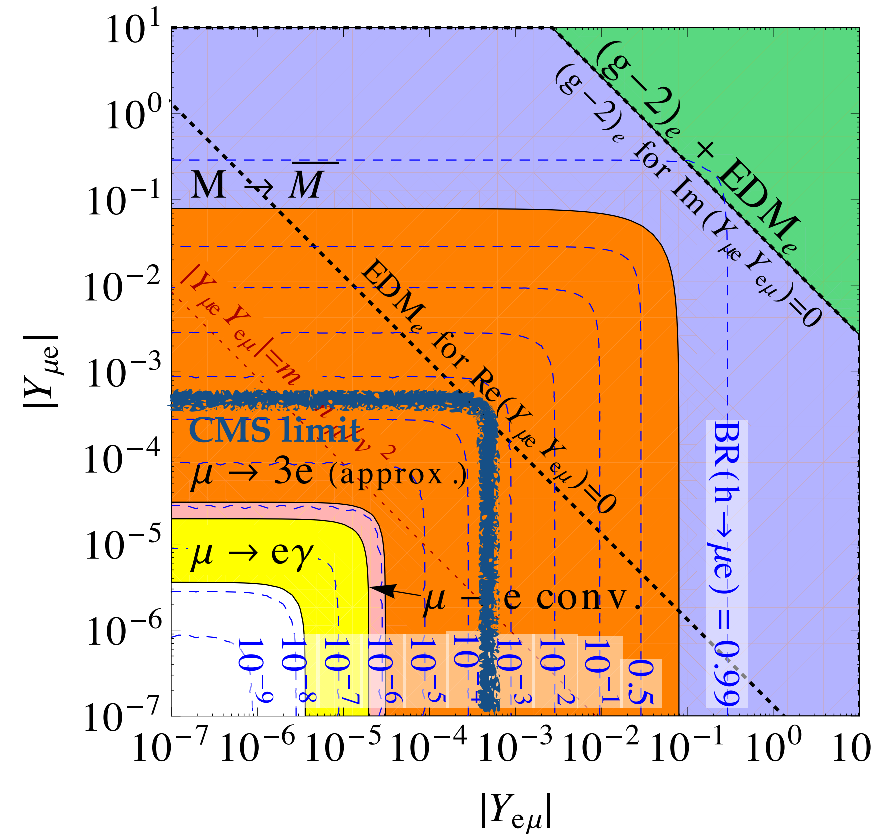




$h \to \tau e$ and $h \to \mu e$



Harnik, Kopp, JZ, 1209.1397



Harnik, Kopp, JZ, 1209.1397

CORRELATED BOUNDS

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

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

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

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

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

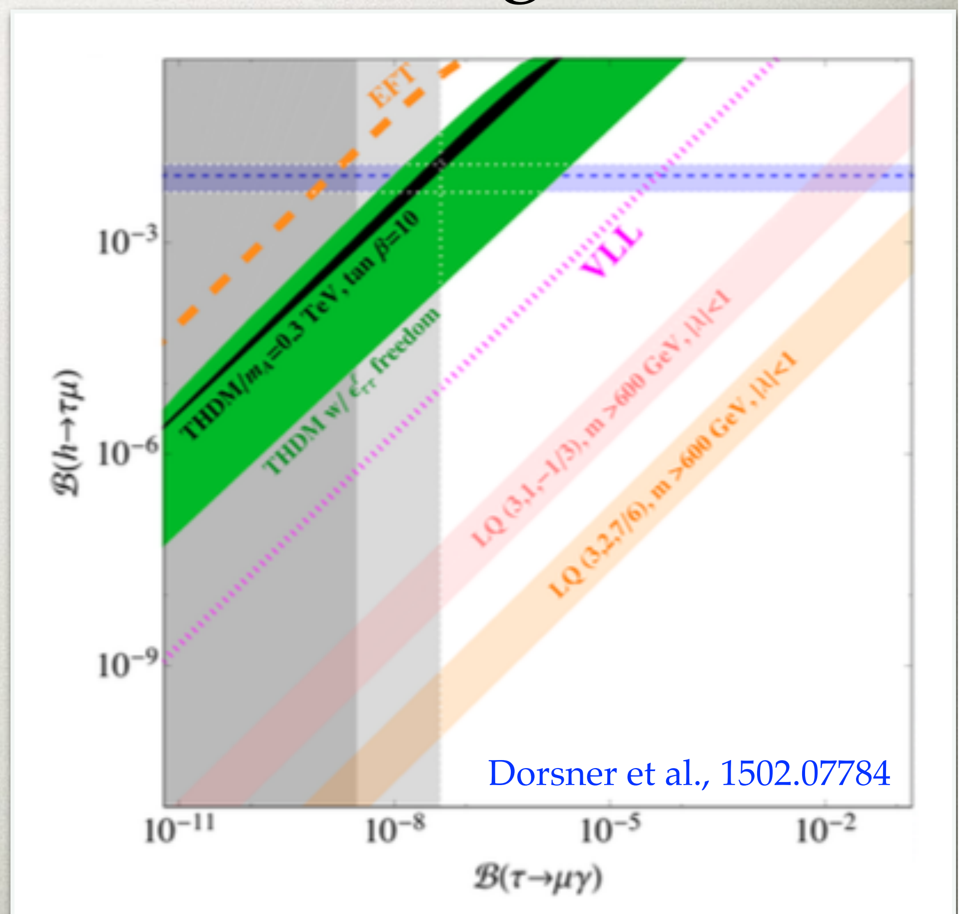
$$\mathcal{B}(h \to \tau\mu) \times \mathcal{B}(h \to \tau e) = 7.95 \times 10^{-10}\left[\frac{\mathcal{B}(\mu \to e\gamma)}{10^{-13}}\right] + 3.15 \times 10^{-4}\left[\frac{\mathcal{B}(\mu \to e)_{\mathrm{Au}}}{10^{-13}}\right]$$

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

LARGE FV HIGGS DECAYS?

- Can one have large flavor violating Higgs decays in reasonable NP models?

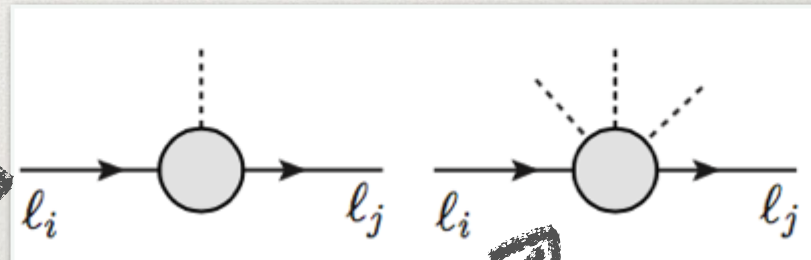
- What is so special about type III 2HDM?



WHAT KIND OF NEW PHYSICS?

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

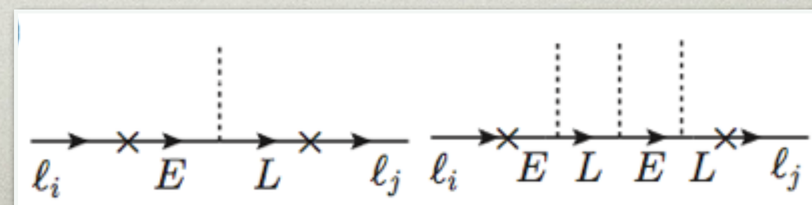
- if Higgs is the only source of EWSB ⇒ the hint for *Br($h \to \tau\mu$)* too large as shown below
  - excluded by $\tau \to \mu\gamma$ (up to cancellations)
- if the lepton mass only from Higgs:



  - if EFT applicable:

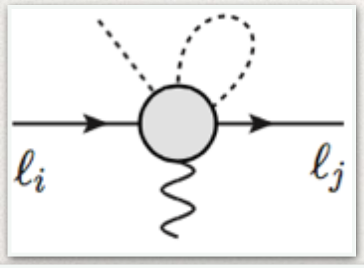
$$-\mathcal{L}_Y = \lambda_{ij}(\bar{\ell}^i_L e^j_R)H + \frac{\lambda'_{ij}}{\Lambda^2}(\bar{\ell}^i_L e^j_R)H(H^\dagger H) + \text{h.c.}, \quad \Longrightarrow \quad Y_{\tau\mu} = \frac{v_W^2}{\sqrt{2}\Lambda^2}\langle \tau_L|\lambda'|\mu_R\rangle,$$

  - realization with vector-like leptons:



DIPOLE OPERATOR

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



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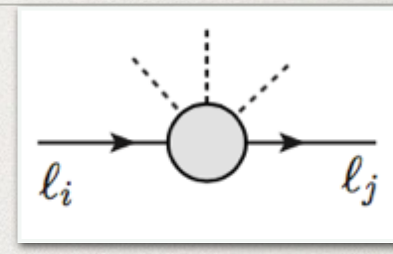

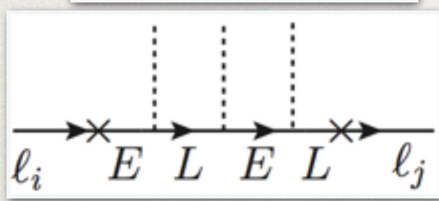

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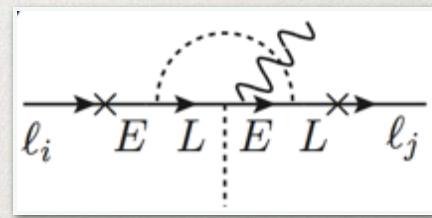


- experimental bound

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

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

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

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

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

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

- in contrast CMS hint $Br(h \to \tau\mu) = (0.89 \pm 0.39)\%$ 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′.

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
- note: in our EFT analysis of low energy constraints the Lagrangian was

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

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

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

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

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

ϕ'

ϕ **and** ϕ'

  - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- 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

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

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

$\tau \to \mu\gamma$ suppression

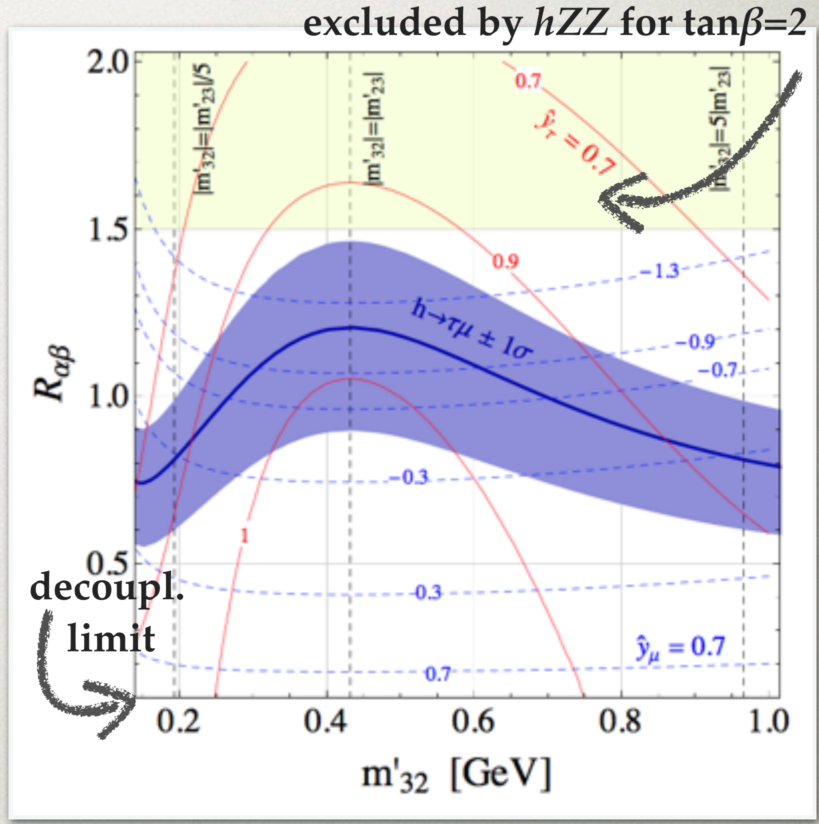
- no longer a direct relation between $h \to \tau\mu$ and $\tau \to \mu\gamma$
- if ΔM_l originates from NP at scale Λ

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

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

VIABLE EW SECTOR

- CMS results requires $R_{\alpha\beta}$~*O(1)*
- this can be obtain, e.g., for m_A~*500GeV*, $\lambda_3 \sim \lambda_4 \sim 2$
- compatible with EWPT



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

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_μ, $m_\tau \Rightarrow$ 1 free param, m_{32}'
  - Higgs couplings fixed by m_{32}', $R_{\alpha\beta}$

DIAGONAL YUKAWAS

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

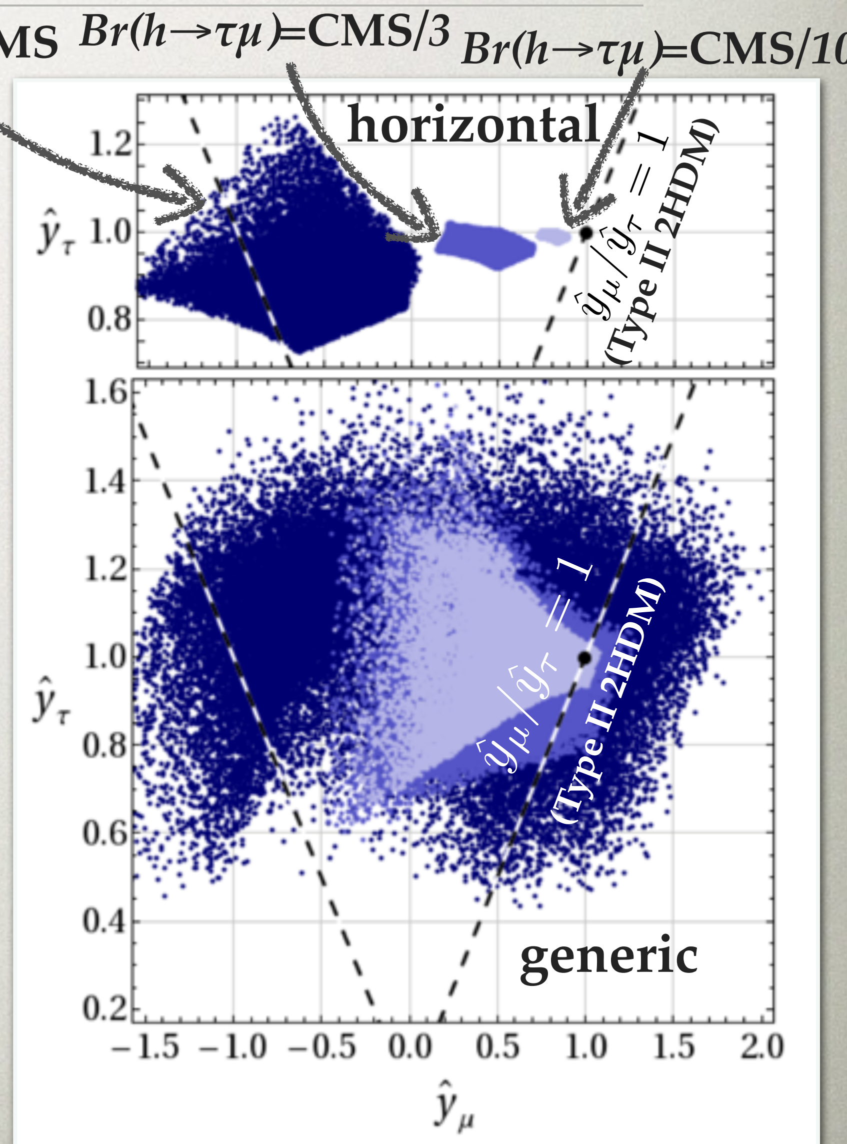
$$1/5 < |m'_{32}/m'_{23}| < 5$$

$$\lambda_{3,4} \le 2,\ m_A \ge 400\,\text{GeV}$$

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

$$|\delta g_{hVV}/g_{hVV}^{\rm SM}| \le 20\%$$

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



QUARK SECTOR

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

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

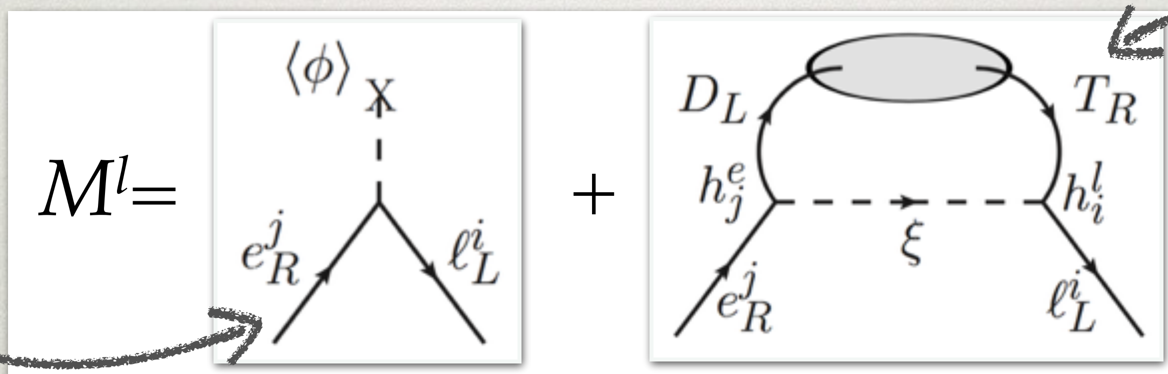
- generation of m_c , m_s and V_{cb} then implies

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

- B_s mixing bound from $(\bar{b}_R s_L)(\bar{b}_L s_R)$ due to Higgs exchange $R_Y^2 \Delta\mathcal{M}_{32}^d \lesssim V_{cb}\, m_b/6$

TECHNICOLOR EXAMPLE

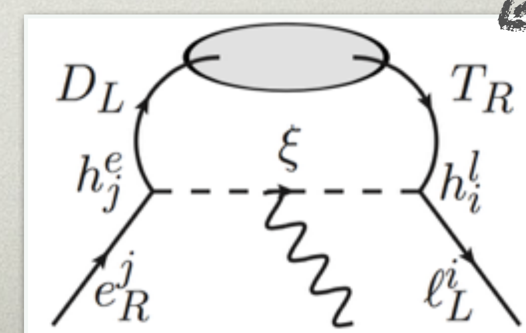
- ΔM_l due to technicolor strong dynamics
  - UV completion is bosonic TC
- Higgs: elementary ϕ + composite heavy scalar σ_{TC}
- ΔM^l from TC condensate, rank 1



$\Delta M^l \propto 1/m_\xi{}^2$

$M^l{}_0$

  - misalignment gives $h \to \tau\mu$
- the $\tau \to \mu\gamma$ is further parametrically suppressed
  - $m_\xi \gtrsim O(10\text{TeV})$

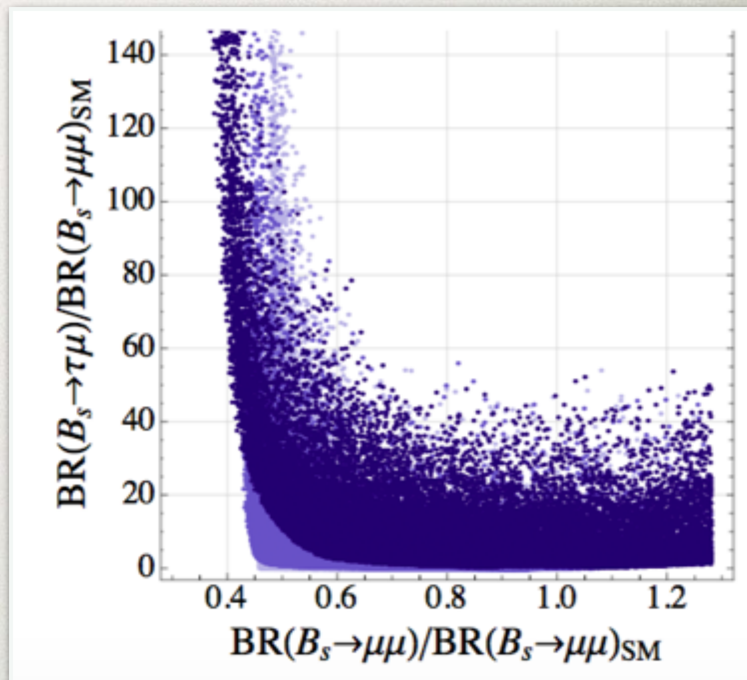


$\Delta M^l \propto 1/m_\xi{}^4$

PHENOMENOLOGICAL IMPLICATIONS

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

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



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

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

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

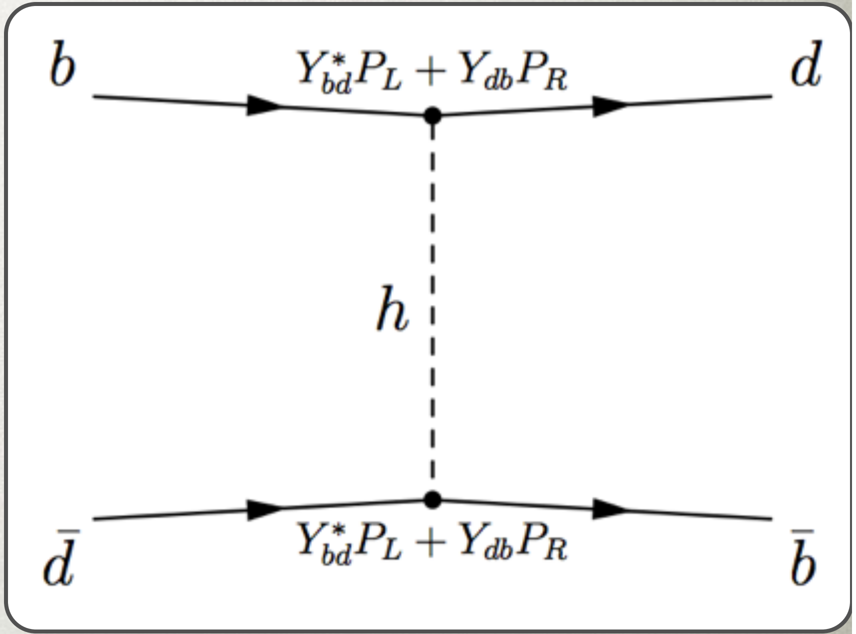
CONCLUSIONS

- CMS $h \to \tau\mu$ 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: $B \to K\tau\mu$, $B \to K^*\tau\mu$, $b \to s\gamma$, $t \to hc$, sum rule,…

BACKUP SLIDES

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

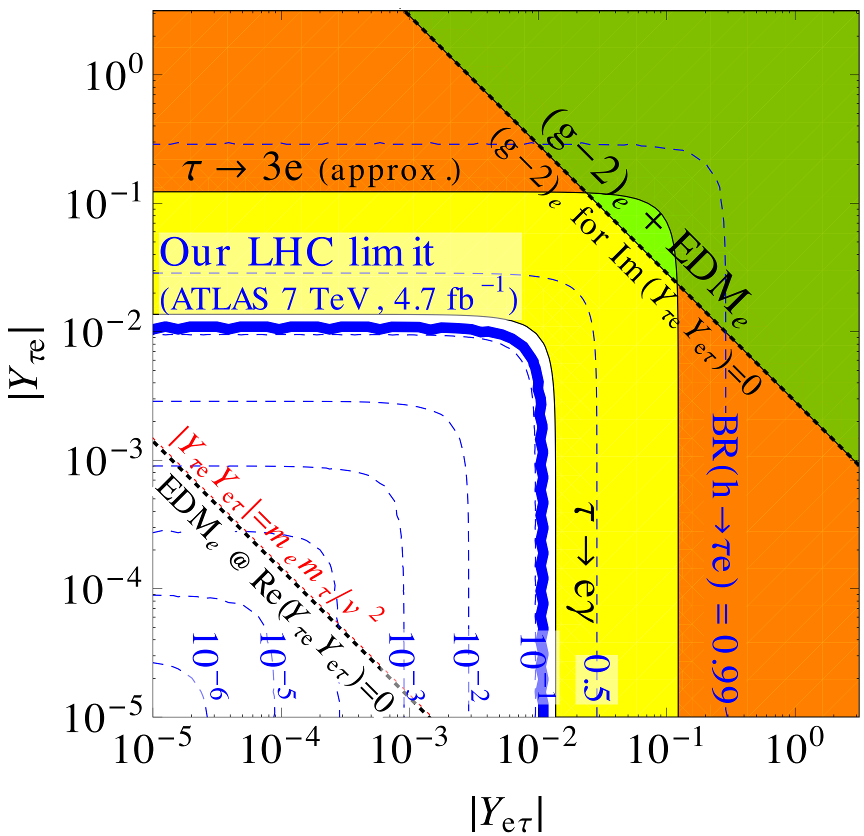
QUARK C

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

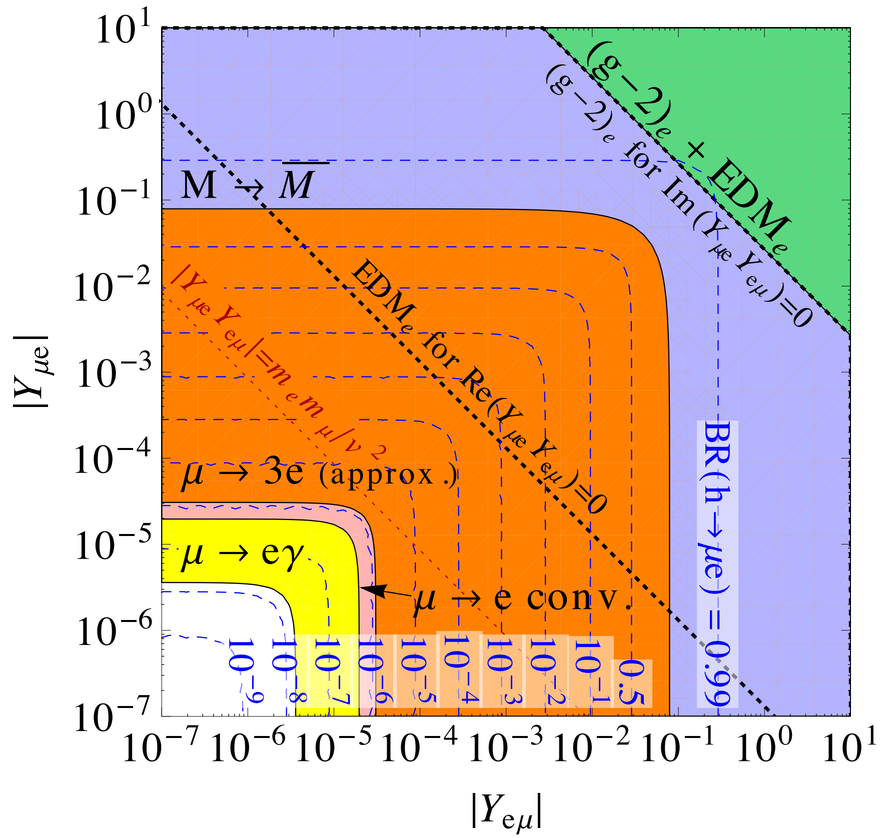
HIG-13-034

- 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
- improvements on these couplings will come from exp&theory improvements in meson mixing

$h\to\tau e$ and $h\to\mu e$



Harnik, Kopp, JZ, 1209.1397

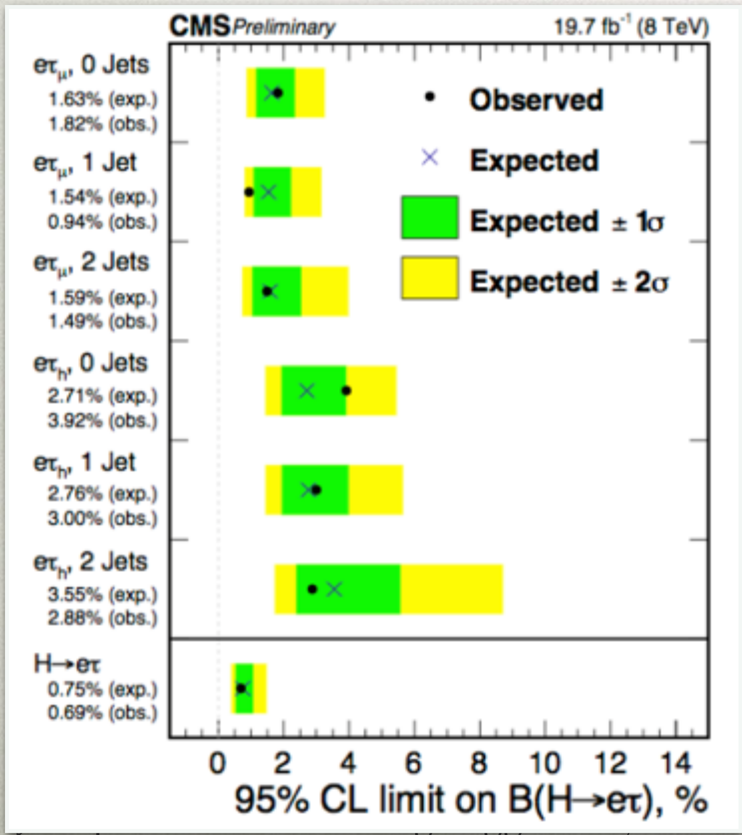


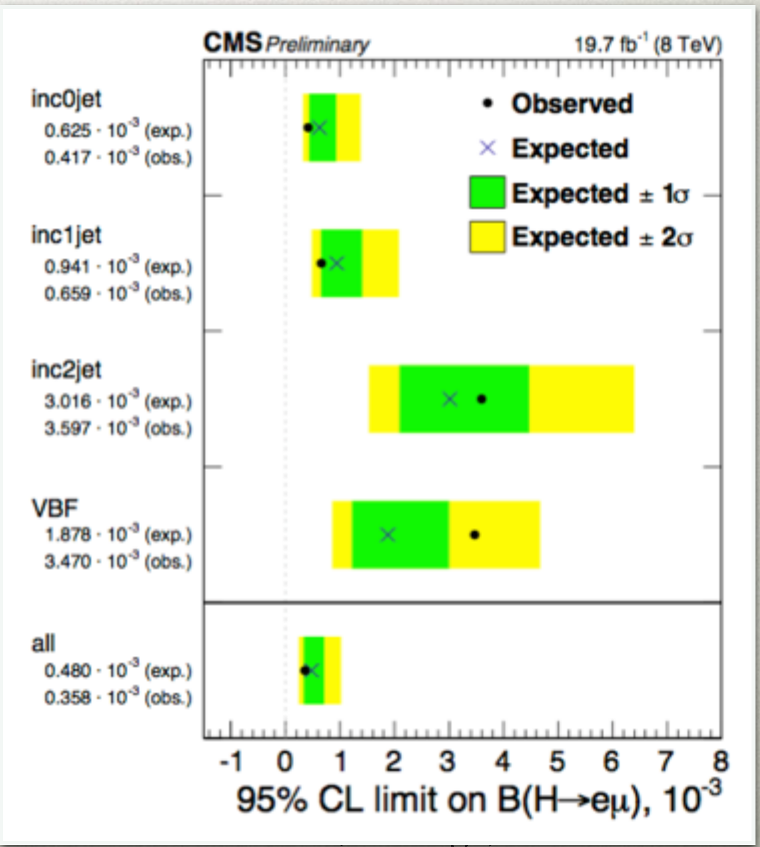
Harnik, Kopp, JZ, 1209.1397

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

- no excess observed (95%CL limits)
  - $Br(H \to e\tau) < 0.69\%$
  - $Br(H \to e\mu) < 3.6 \times 10^{-4}$

CMS-PAS-HIG-14-040

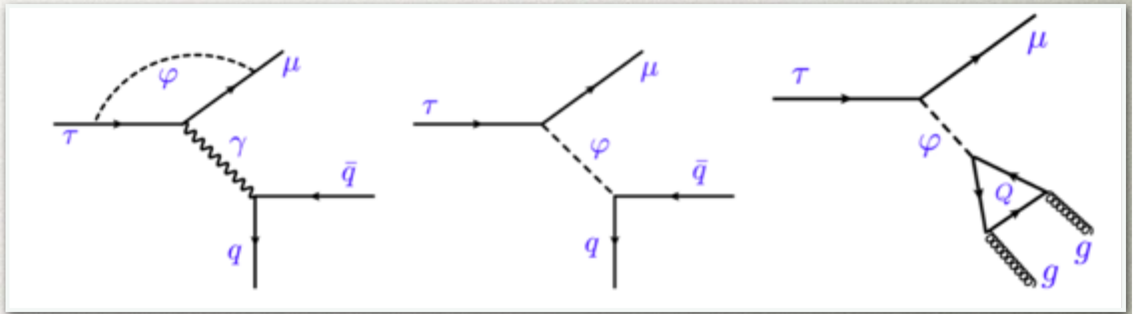




$\tau \to \mu\pi\pi$

- hadronic tau decays $\tau\to\mu\pi+\pi$-,$\tau\to\mu\pi0\pi0$

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

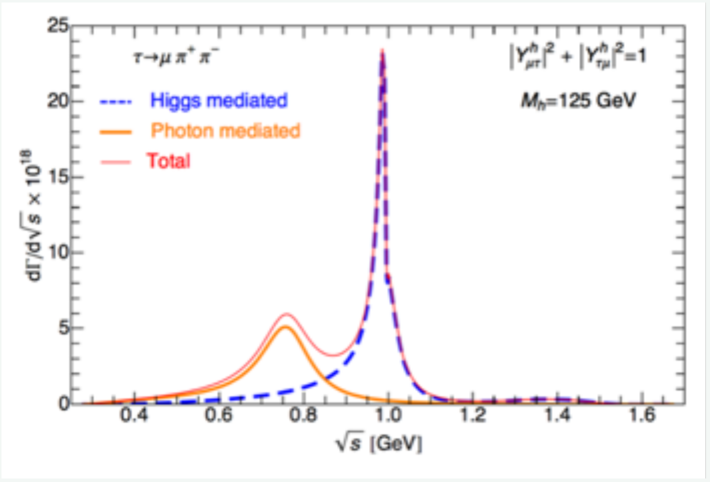


  - sensitive to both $Y_{\tau\mu}, Y_{\mu\tau}$ and light quark yukawas $Y_{u,d,s}$
  - $Y_{u,d,s}$ poorly bounded ~$O(Y_b)$
- for $Y_{u,d,s}$ at their SM values then

$$Br(\tau\to\mu\pi^+\pi^-) < 1.6\times10^{-11}, Br(\tau\to\mu\pi^0\pi^0) < 4.6\times10^{-12}$$
$$Br(\tau\to e\pi^+\pi^-) < 2.3\times10^{-10}, Br(\tau\to e\pi^0\pi^0) < 6.9\times10^{-11}$$

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

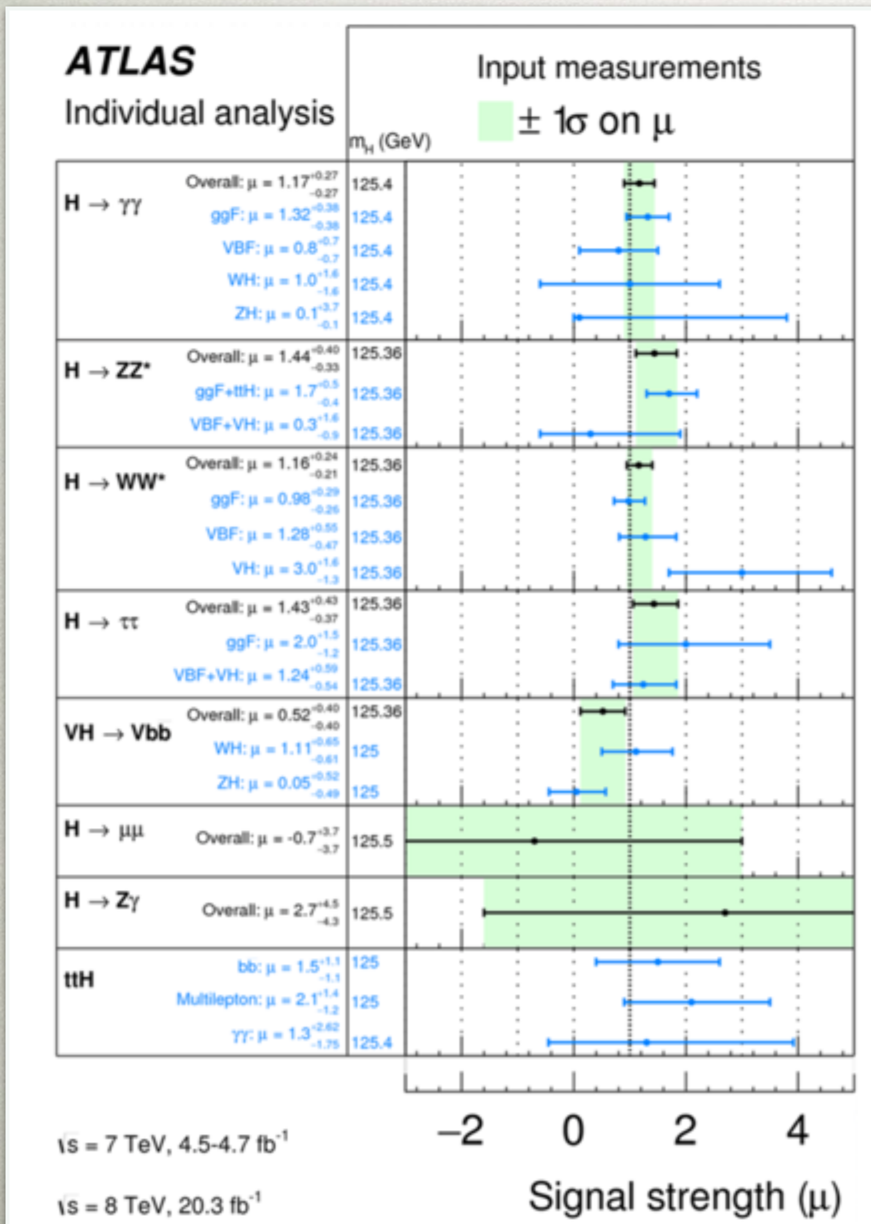
$$Br(\tau\to\mu\pi^+\pi^-) < 3.0\times10^{-8}, Br(\tau\to\mu\pi^0\pi^0) < 1.5\times10^{-8}$$
$$Br(\tau\to e\pi^+\pi^-) < 4.3\times10^{-7}, Br(\tau\to e\pi^0\pi^0) < 2.1\times10^{-7}$$

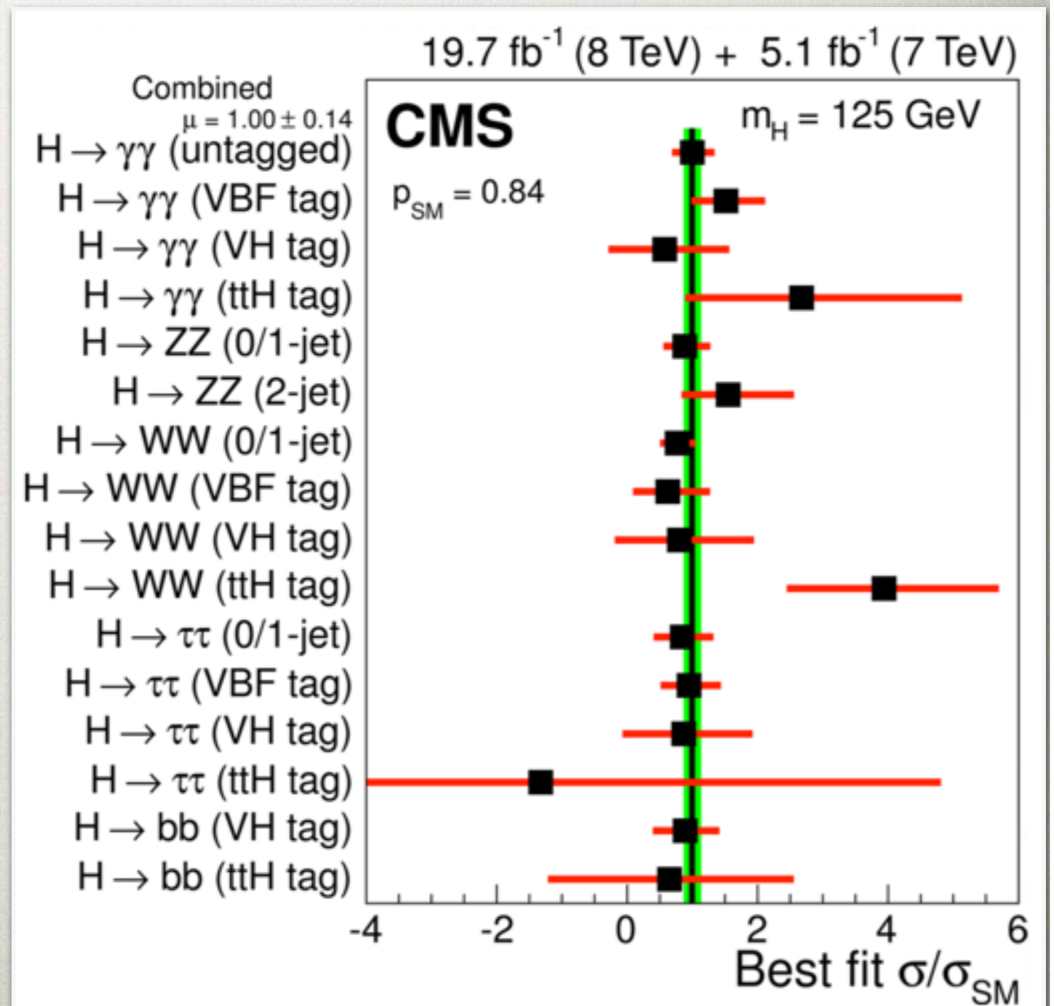


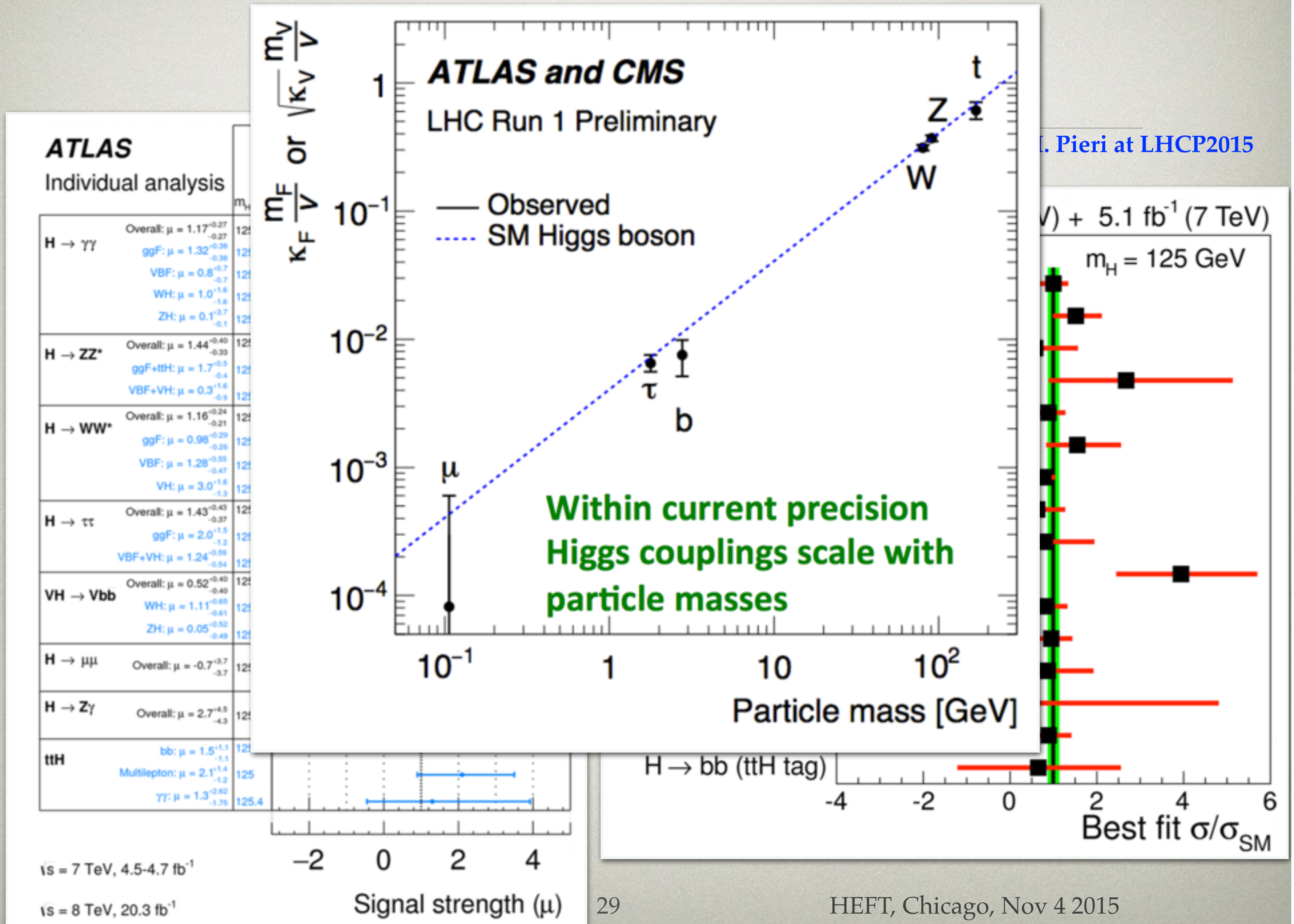
- *Br($\tau\to\mu\pi+\pi$-)* below present exp. limit, if discovered would (among other things) imply upper limit on $Y_{u,d}$
- similarly pseudoscalar Higgses can be bounded from $\tau\to\mu\pi(\eta,\eta')$, $\tau\to e\pi(\eta,\eta')$
  - can saturate present experimental limits

MEASUREMENTS

talk by M. Pieri at LHCP2015






ATLAS and CMS
LHC Run 1 Preliminary
Observed
SM Higgs boson
Within current precision
Higgs couplings scale with
particle masses
Particle mass [GeV]
ATLAS
Individual analysis
Signal strength (μ)
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
. Pieri at LHCP2015
m_H = 125 GeV
H → bb (ttH tag)
Best fit σ/σ_SM

SUMMARY OF MODELS

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

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

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

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

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

- can probe CPV couplings to 3$^{\text{rd}}$ generation, so $f=t,b,\tau$

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

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

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

- the remaining entries

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

- flavor violating Yukawa couplings

$$v_W Y_{\mu\tau} = -R_Y \, (\Delta\mathcal{M}^\ell)_{\mu\tau} \,, \qquad (\Delta\mathcal{M}^\ell)_{\mu\tau} \equiv \langle \mu_L | \Delta\mathcal{M}^\ell | \tau_R \rangle$$

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

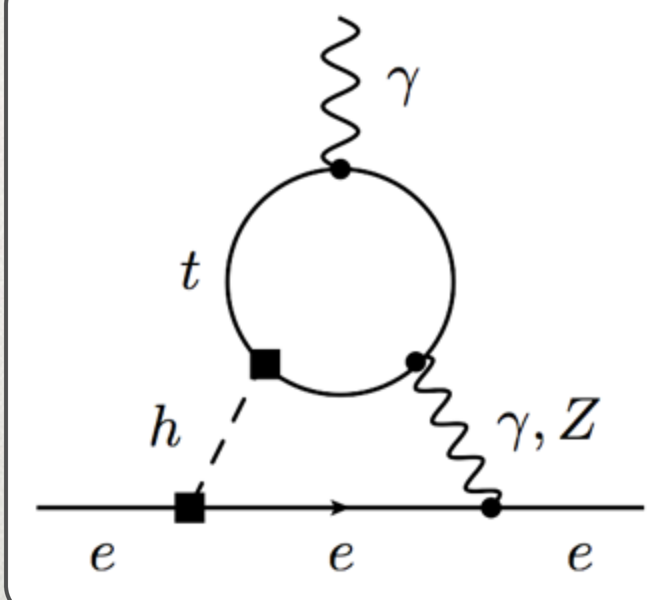
$$(\Delta\mathcal{M}^\ell)_{\mu\tau} \sim (0.45{\pm}0.10)\ \mathrm{GeV}$$

HIGGS-TOP CPV COUPLING

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

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

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



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

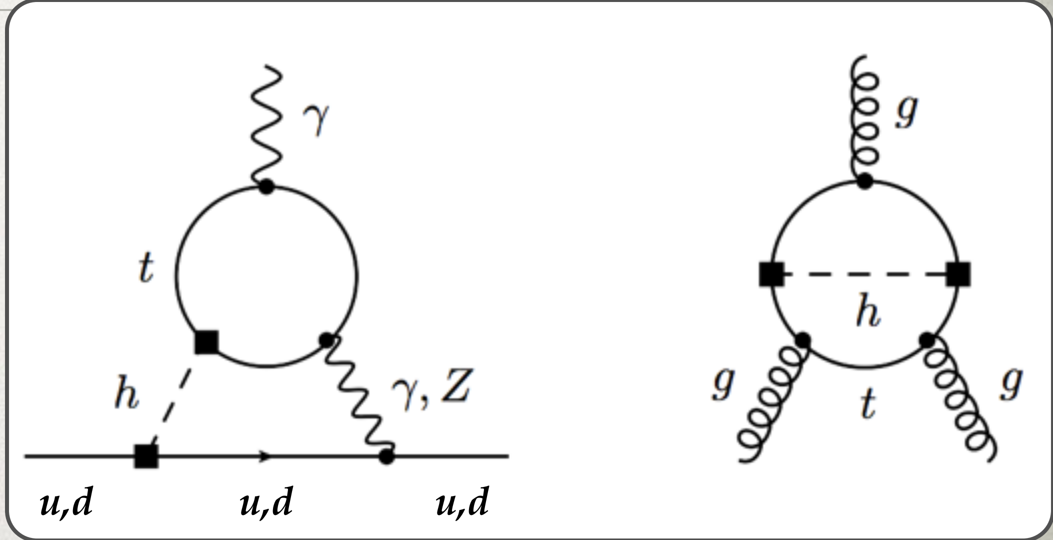
$$|\tilde{\kappa}_t| < 0.01$$

  - 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 ~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 couplngs. of the Higgs to light quarks)



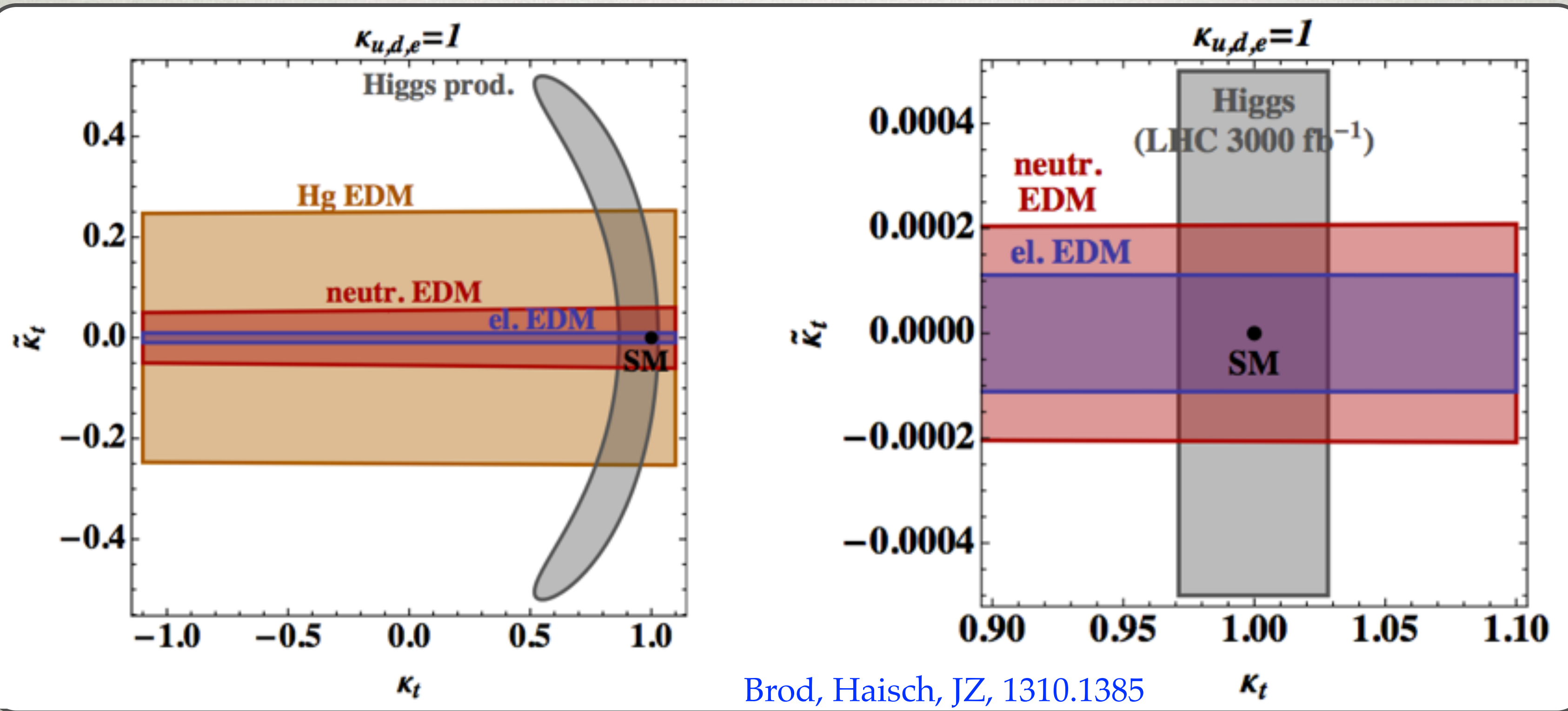
$$\mathcal{L}_{\rm eff} = -d_q\,\frac{i}{2}\,\bar{q}\sigma^{\mu\nu}\gamma_5 q\,F_{\mu\nu} - \tilde{d}_q\,\frac{ig_s}{2}\,\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q\,G^a_{\mu\nu} - w\,\frac{1}{3}f^{abc}\,G^a_{\mu\sigma}G^{b,\sigma}_{\nu}\widetilde{G}^{c,\mu\nu}$$

- 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**

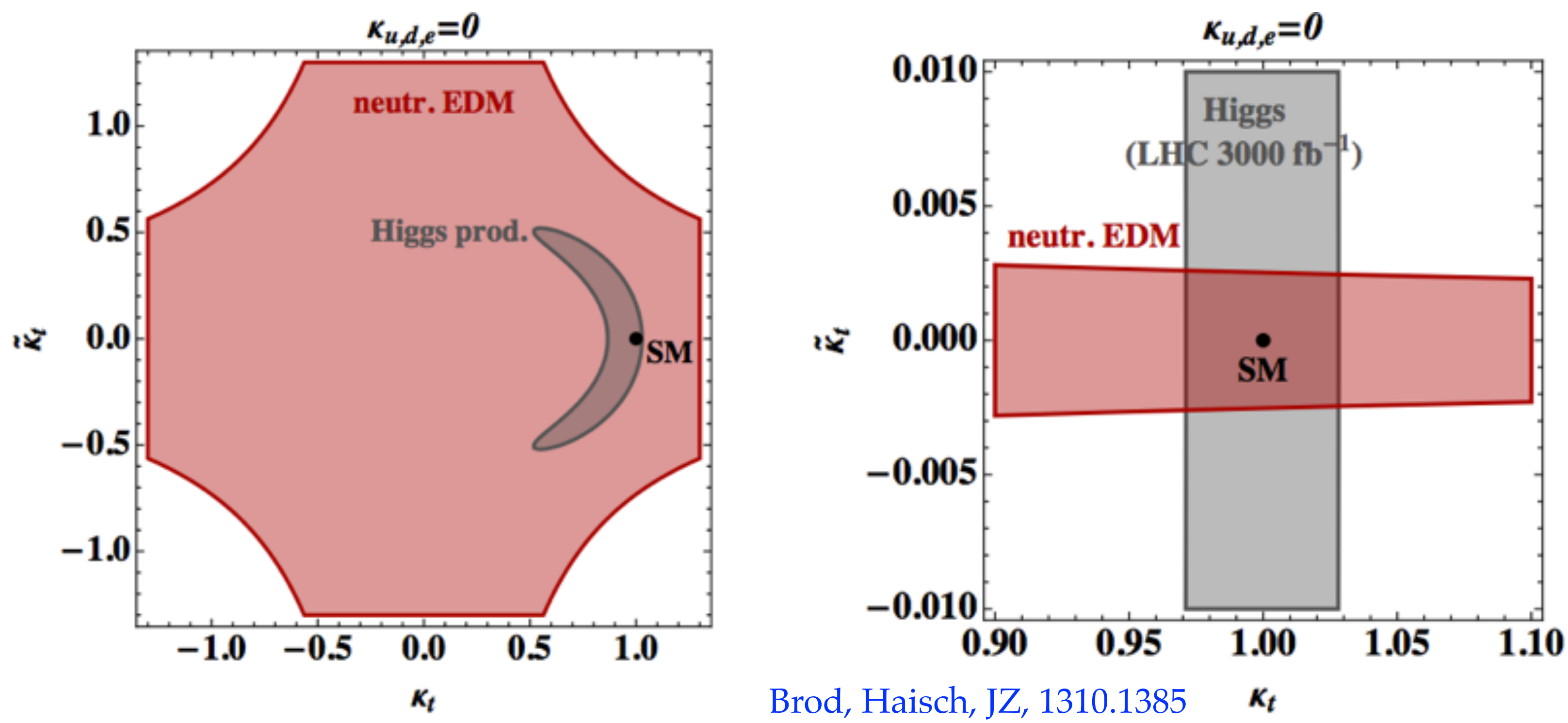


Brod, Haisch, JZ, 1310.1385

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**

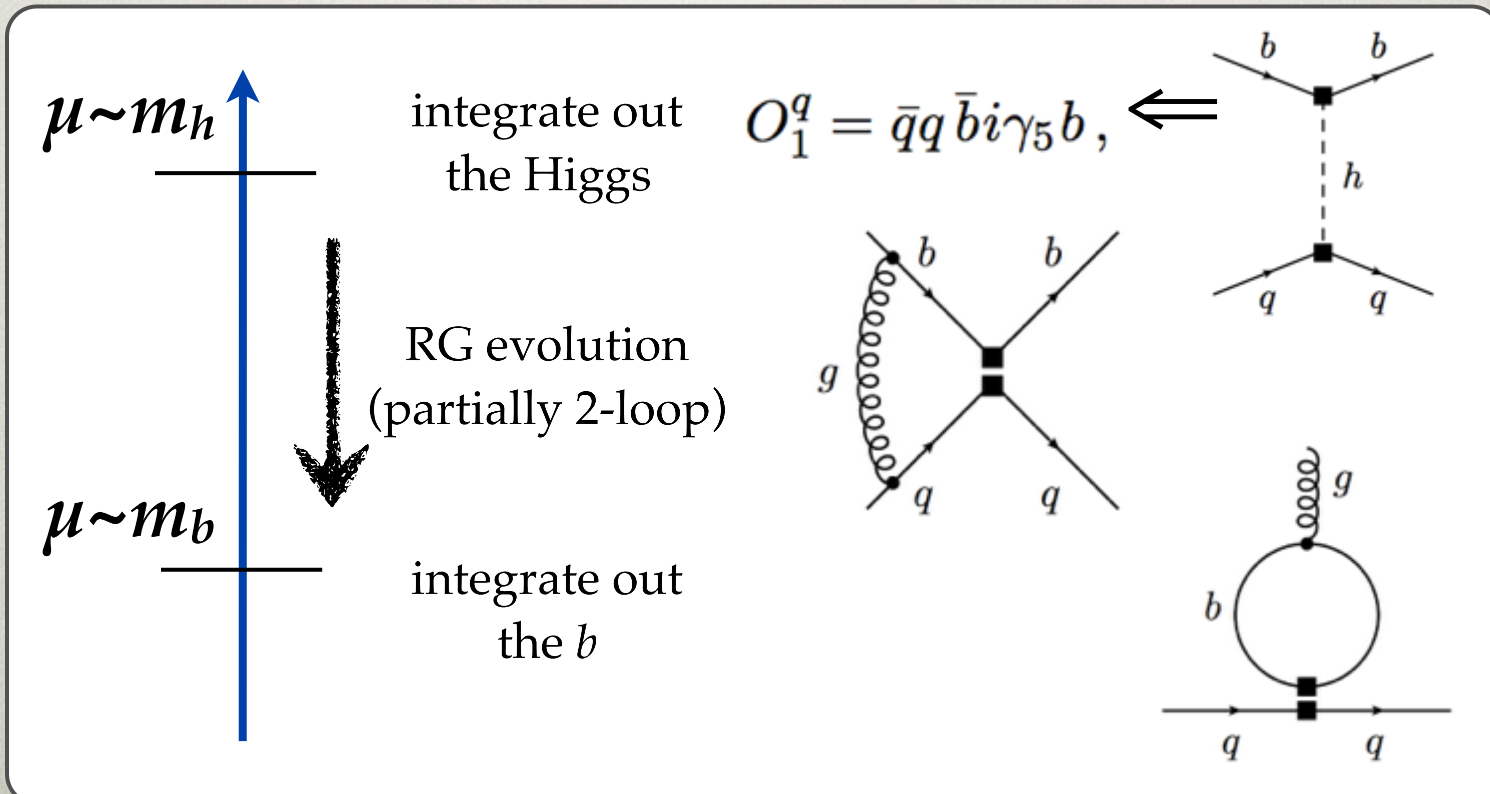


Brod, Haisch, JZ, 1310.1385

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 $x_{b/h}=m_b^2/m_h^2$)



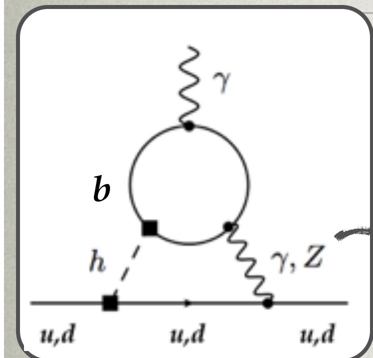
RESUMMATION

Brod, Haisch, JZ, 1310.1385

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

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

$$O_7 = -\frac{1}{3 g_s} f^{abc} G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu} \,,$$

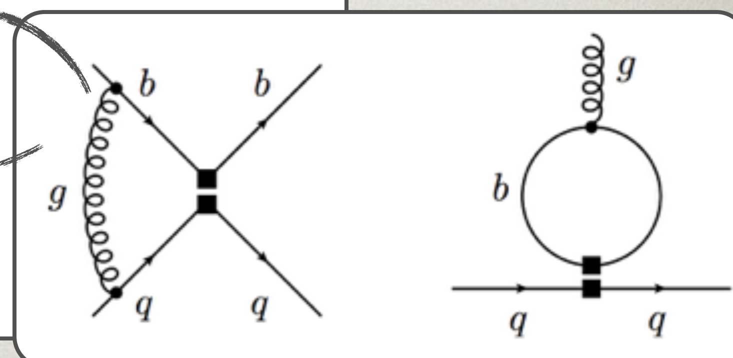


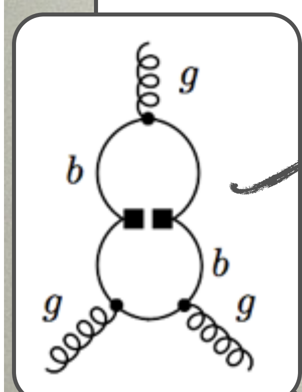
- only one relevant entry of anomalous dimension not known previously, $\gamma_{5,11}^{(1)}$

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

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

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





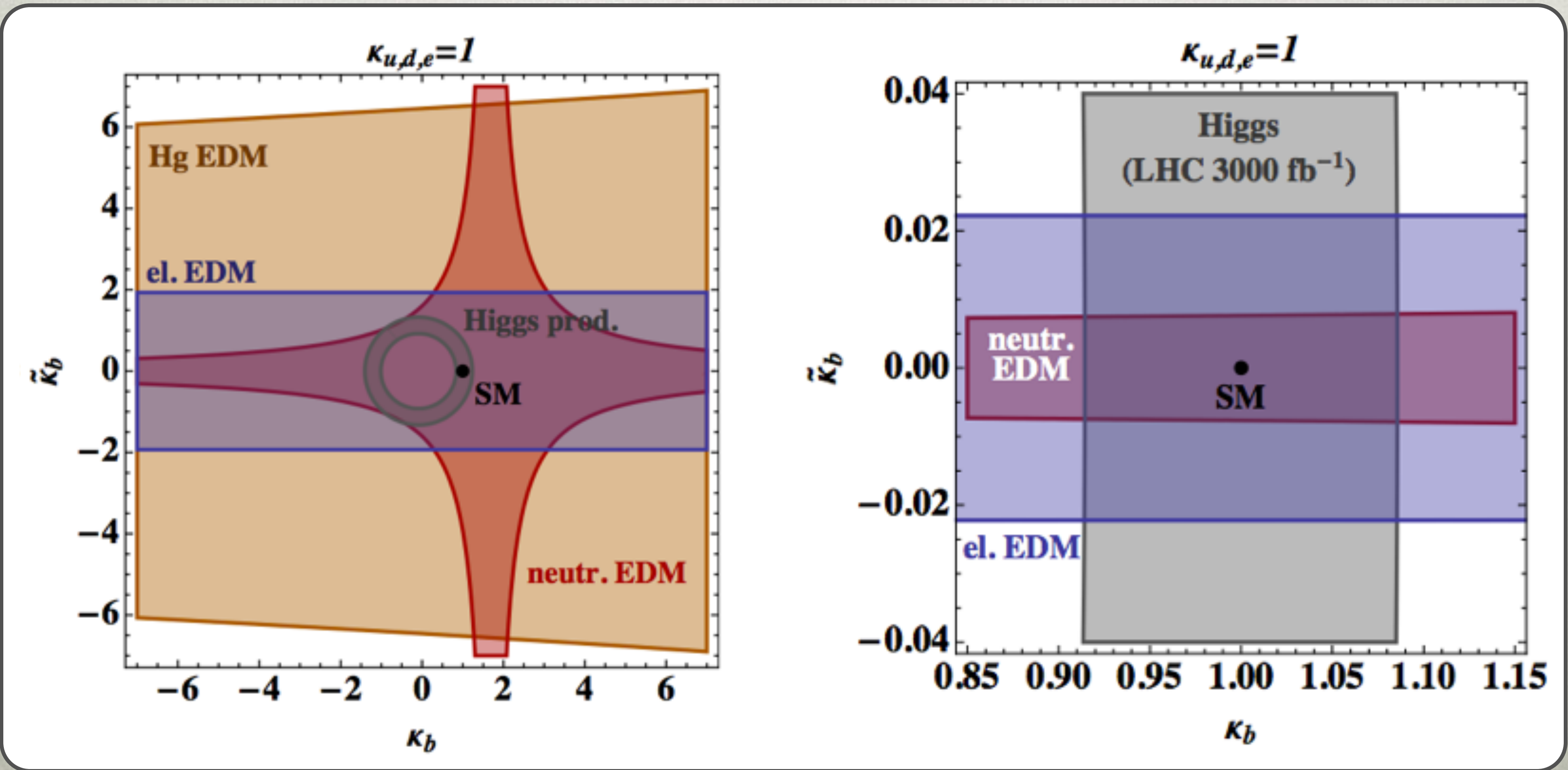
- resummation numerically important
  - without it a factor of ~3 ambiguity in nEDM

CPV coupling to b quark

- the EDM constraints on CPV Higgs coupling to b quark are weaker than the LHC data

Brod, Haisch, JZ, 1310.1385

    - this can change in the future
    - EDMs scale linearly with $\tilde{\kappa}_b$



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Brod, Haisch, JZ, 1310.1385

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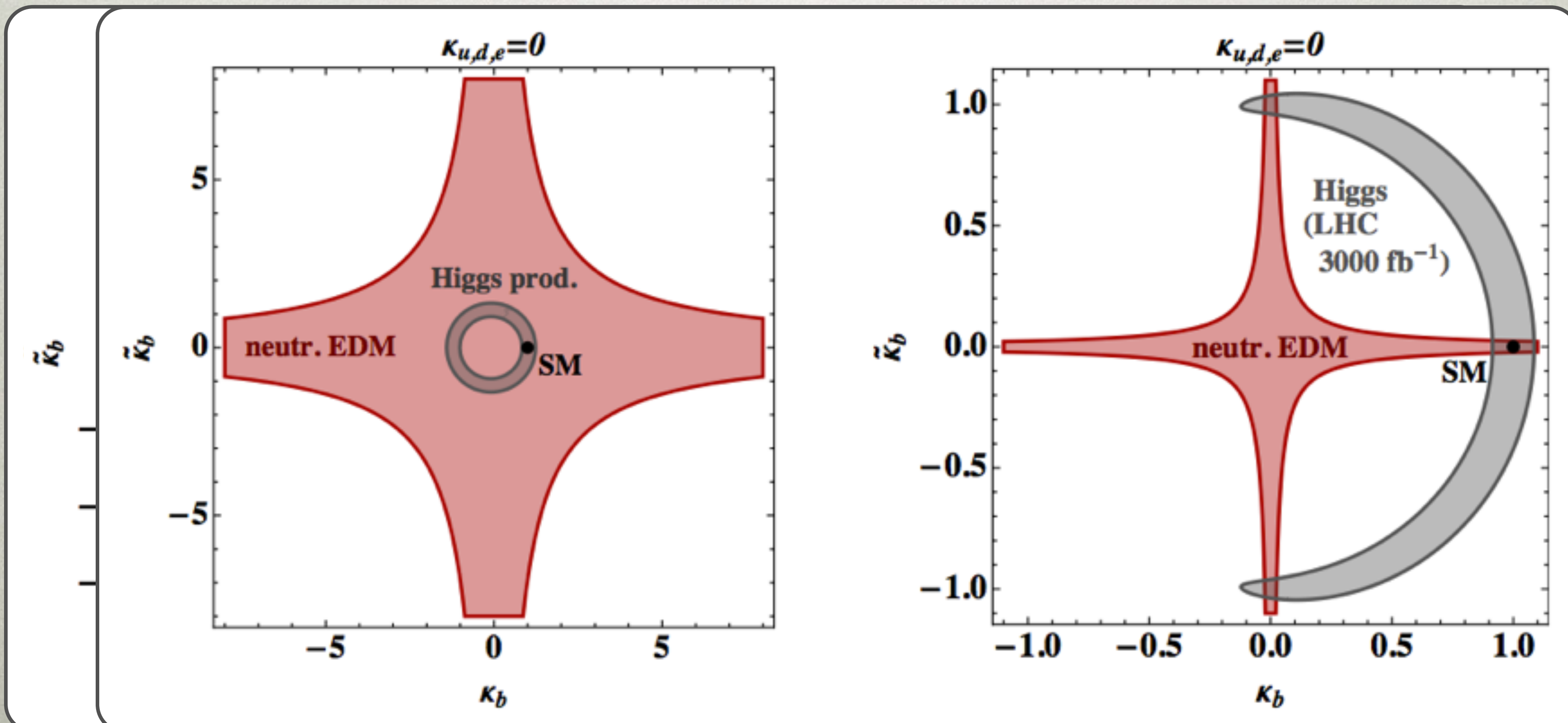

2HDM

- two Higgs doublets Φ and Φ'

$\tan\beta = v/v'$

  - 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

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

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

NOTATION FOR 2HDM

- using Haber, Nir basis

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

$$V = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right)$$

$$+ \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right)\left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right)\left(\Phi_2^\dagger \Phi_1 \right)$$

$$+ \tfrac{1}{2}\lambda_5 \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right] + \tfrac{1}{2} \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right)\left(\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2 \right). \quad (4.1)$$

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

  $SU(2)_{TC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$
  - $SU(2)_L$ 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 Λ_{TC}~$4\pi f_{TC}$, so v_W^2~$f_{TC}^2+v^{2,\prime}$ viable pheno. for f_{TC}≲$80\ GeV$
- 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

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

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

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

BENCHMARK AND SUM RULE

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

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

Br(h→τμ)*=CMS** ***Br(h→τμ)*=CMS - *1σ

  - to all orders in ChPT

$$R_Y > \cos\alpha / \sin\beta \qquad \tan\beta \equiv v/f_{\mathrm{TC}}$$

ϕ - σ_{TC} mixing angle

- a general sum rule

$$\hat{y}_\mu \hat{y}_\tau - \hat{y}_{\tau\mu}\hat{y}_{\mu\tau} = \hat{y}_{t,b}(\hat{y}_\mu + \hat{y}_\tau - \hat{y}_{t,b}) \qquad \hat{y}_{ij} \equiv Y_{ij}/Y_{ii}^{\mathrm{SM}}$$

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