# FLAVOR VIOLATING HIGGS DECAYS

Jure Zupan
u. of cincinnati

Harnik, Kopp, JZ, 1209.1397

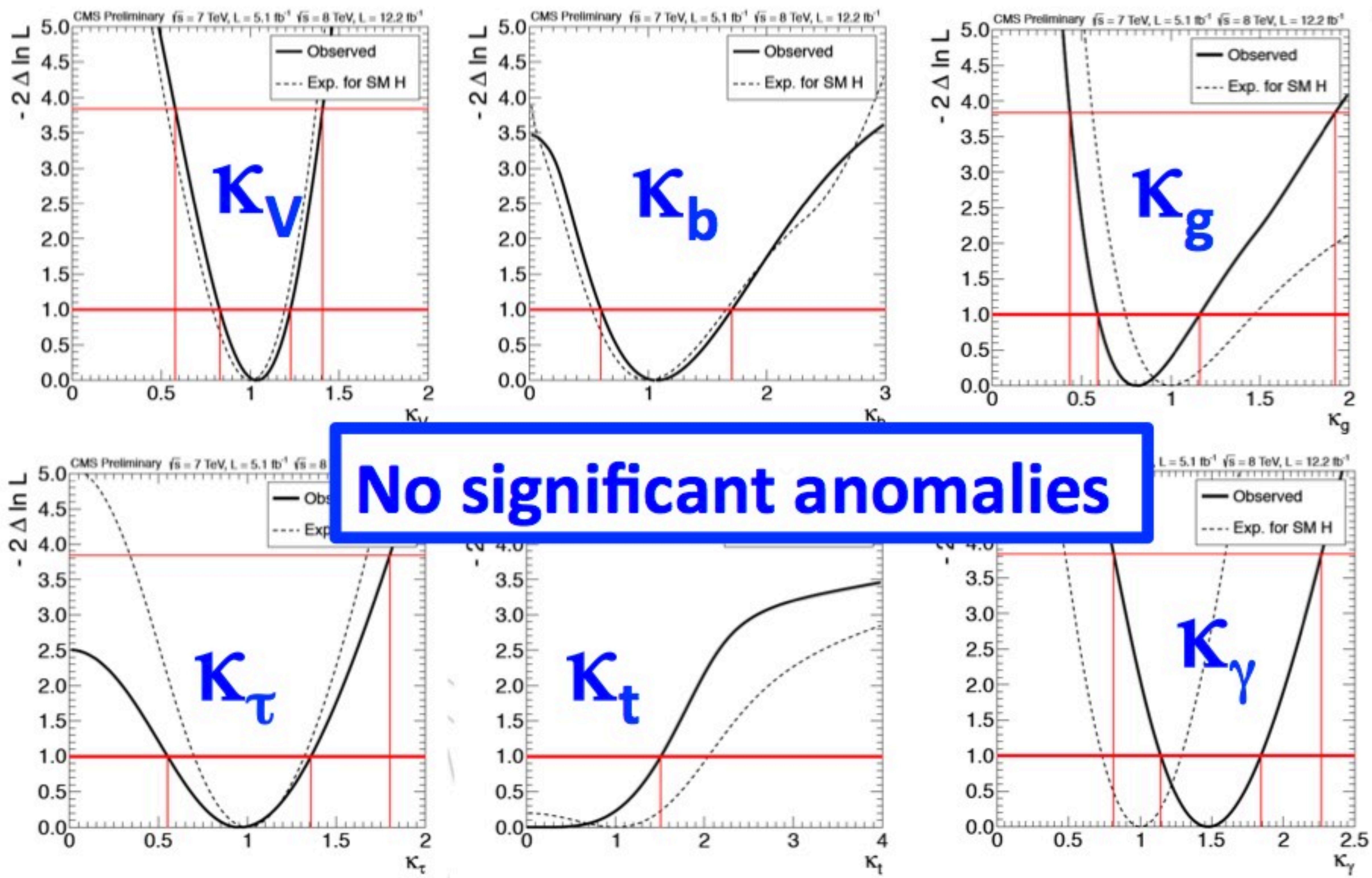
The first three years of the LHC, Mainz, Mar 22 2013

# HIGGS FLAVOR COUPLINGS

- Higgs@125GeV recently discovered
- dual role (in the SM)
  - EWSB
  - fermion masses through Yukawas
- want to ask a general question
  - what do we already know about higgs flavor properties?

# DIRECT CONSTRAINTS

- already some info on 3rd gen. couplings
  - $h\tau\tau$
  - indirectly also *htt* and *hbbar*
- interesting upper bound on $h\mu\mu$
- no direct search for FV
  - how about low eng. constraints?
  - do they make it hopeless/uninteresting?




Mingshui Chen for CMS at Moriond 2013

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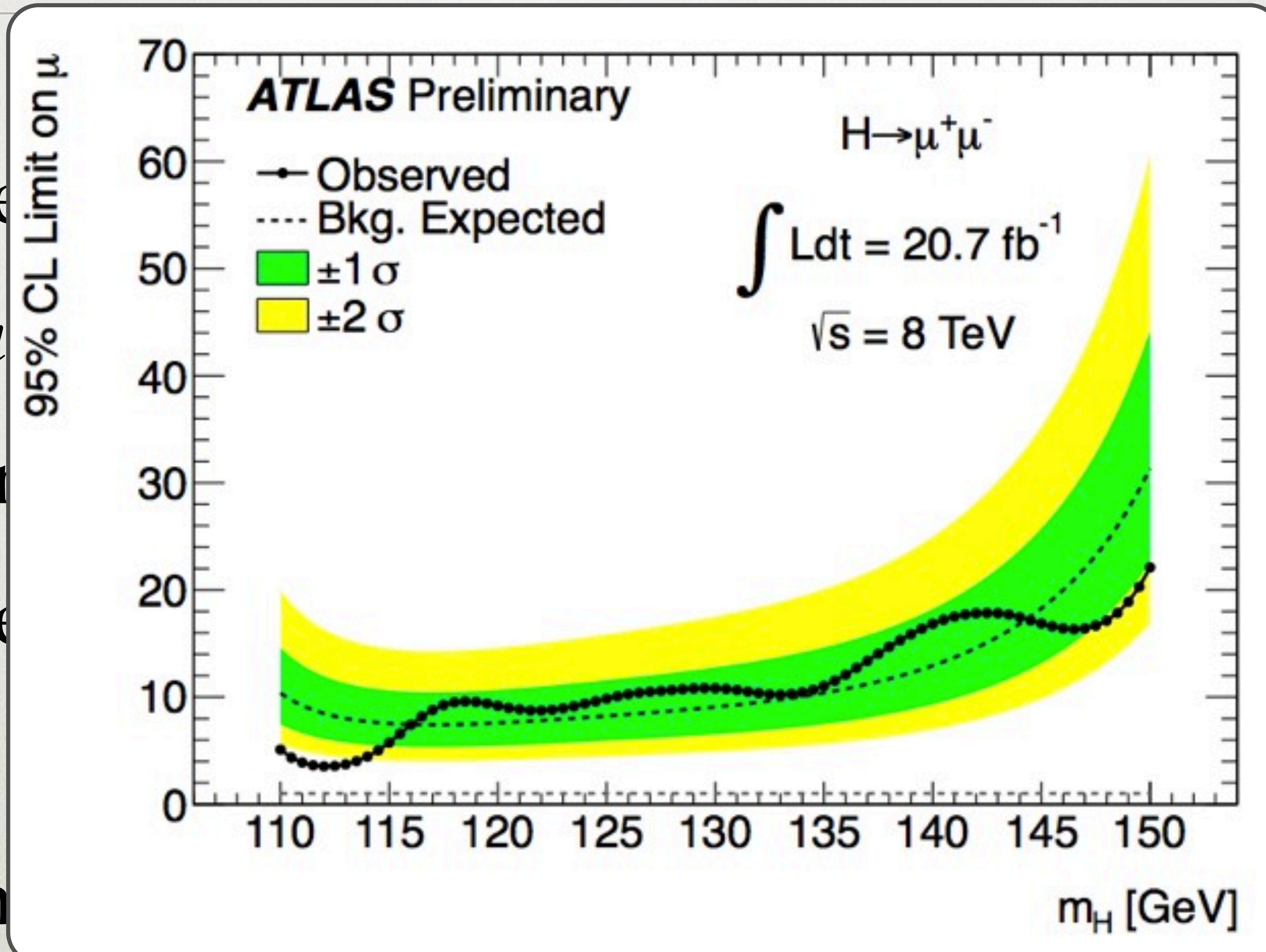


- alre … s
  - *h*
  - i
- inte
- no
  - h
  - do they make it hopeless/uninteresting?

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# HIGGS COUPLINGS

- if NP then Higgs couplings could be modified
- will assume that EFT is valid

Giudice, Lebedev, 0804.1753
Agashe, Contino, 0906.1542
Goudelis, Lebedev, Park, 1111.1715
Arhrib, Cheng, Kong, 1208.4669
McKeen, Pospelov, Ritz, 1208.4597

  - mass gap between SM+Higgs and NP

Casagrande, Goertz, Haisch, Neubert, Pfoh, 0807.4937, ...
Blanke, Buras, Duling, Gori, Weiler, 0809.1073,...
Blankenburg, Ellis, Isidori, 1202.5704
Harnik, Kopp, JZ, 1209.1397
Azatov, Toharia, Liu, 0906.1990

  - higher dim. operators

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

  - *hff* couplings not directly related to mass

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

# FLAVOR VIOLATING HIGGS

- first part of the talk
  - completely agnostic about flavor structure
    - what are the bounds?
- new neutral currents
  - flavor diagonal @LHC
  - flavor violating @Belle2 and LHC
- second part of the talk
  - what can we learn if deviations are found?

# BENCHMARKS

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

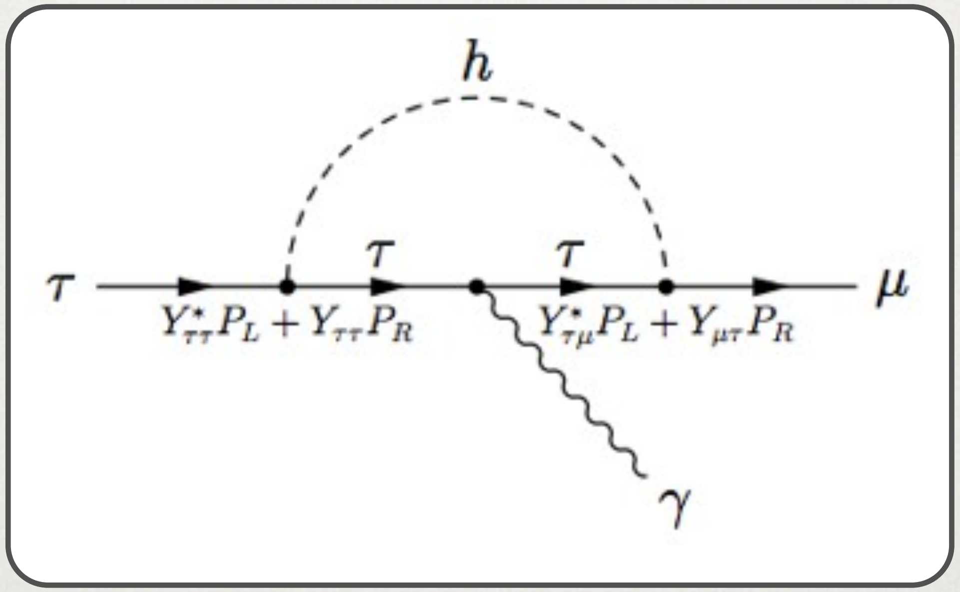
$$|Y_{\tau\mu}Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}$$

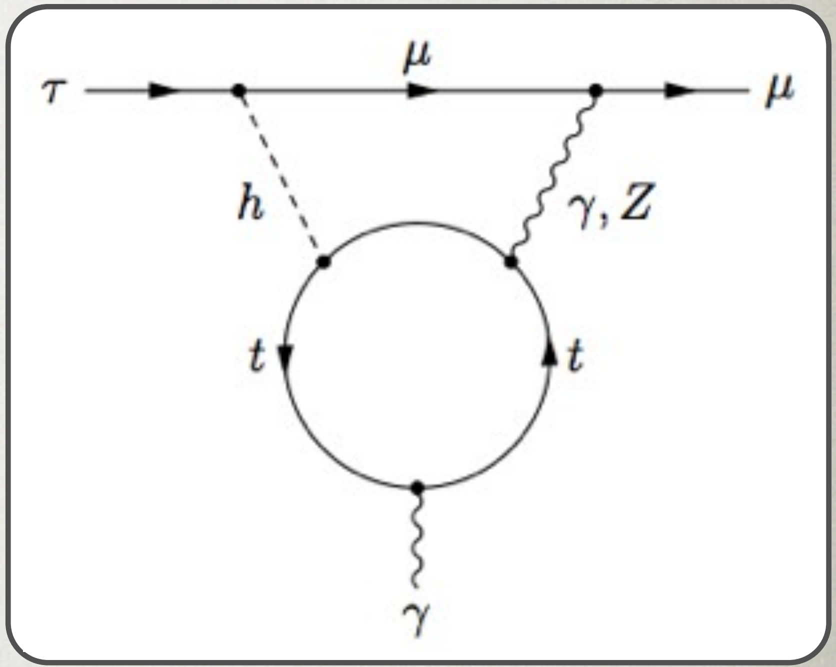
Cheng, Sher, 1987

# $h \to \tau\mu$

Harnik, Kopp, JZ, 1209.1397

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

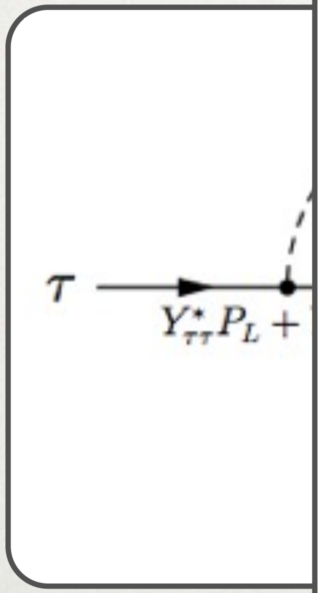


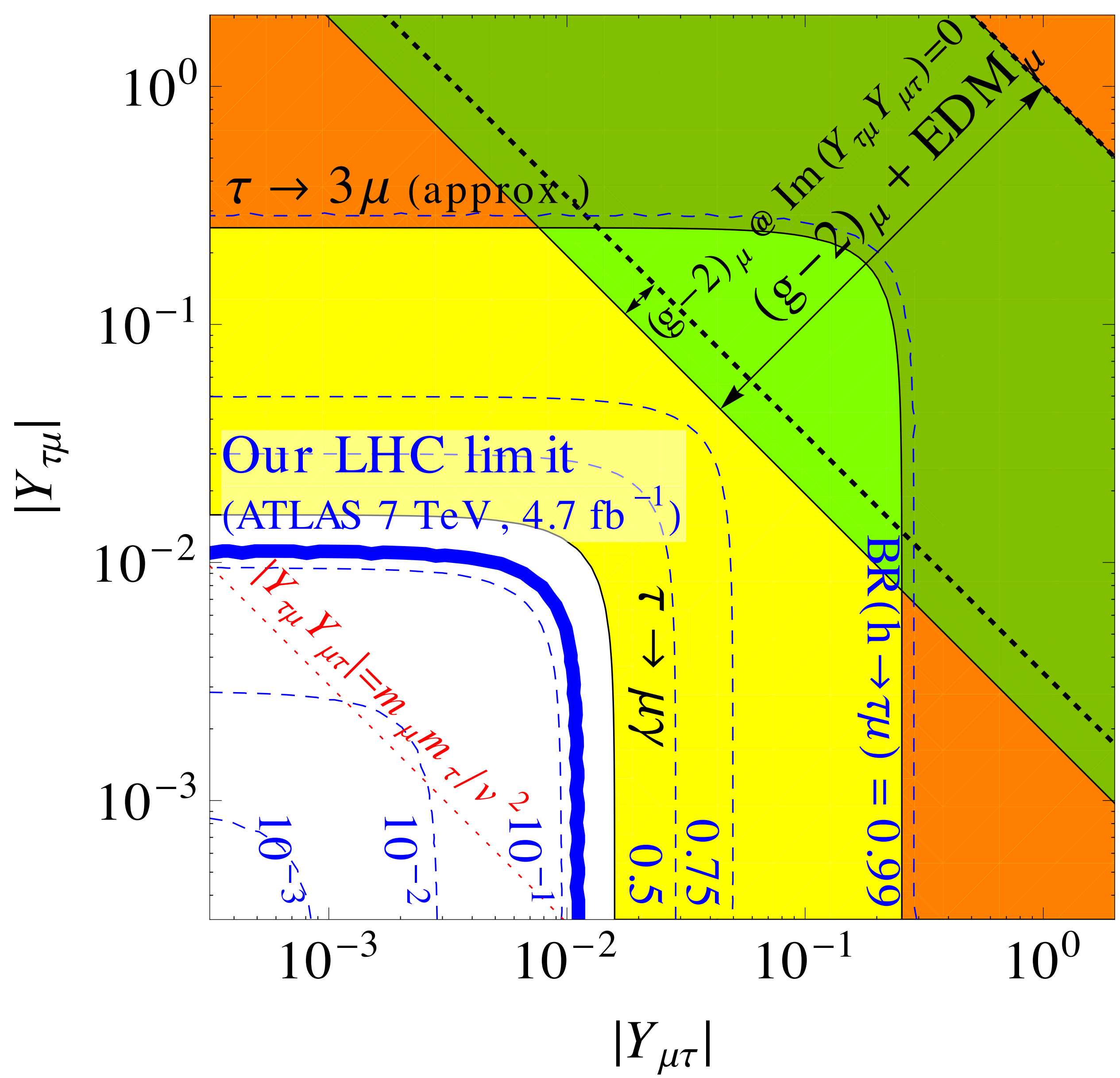



# $h \to \tau\mu$

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

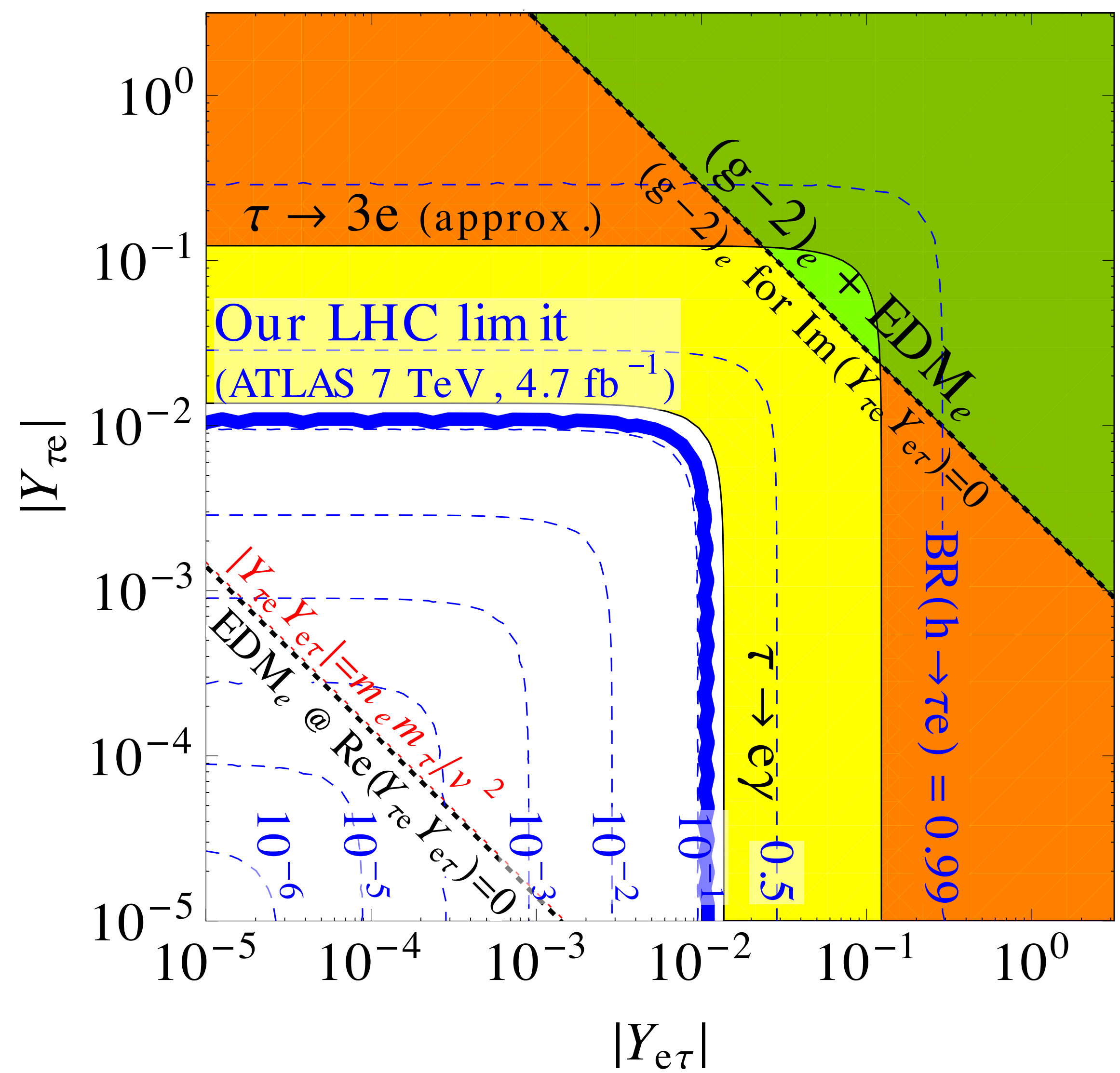



Harnik, Kopp, JZ, 1209.1397

# $h \to \tau e$

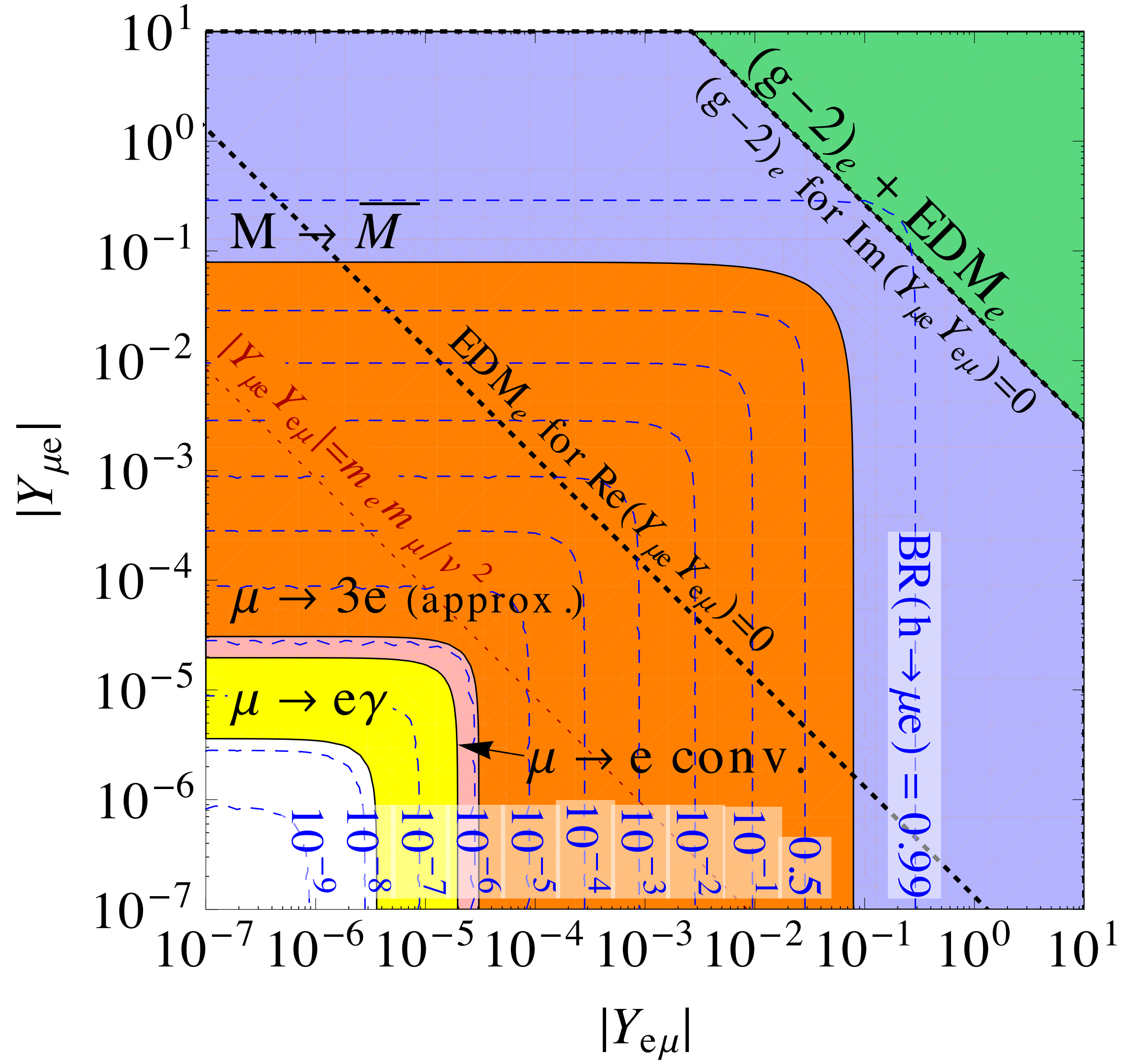
- bounds from
  - $\tau \to e\gamma$
  - $\tau \to 3e$
  - electron *g*-2
  - electr. EDM
- $Br(h \to \tau e) \sim O(10\%)$ allowed




Harnik, Kopp, JZ, 1209.1397

# $h \to \mu e$

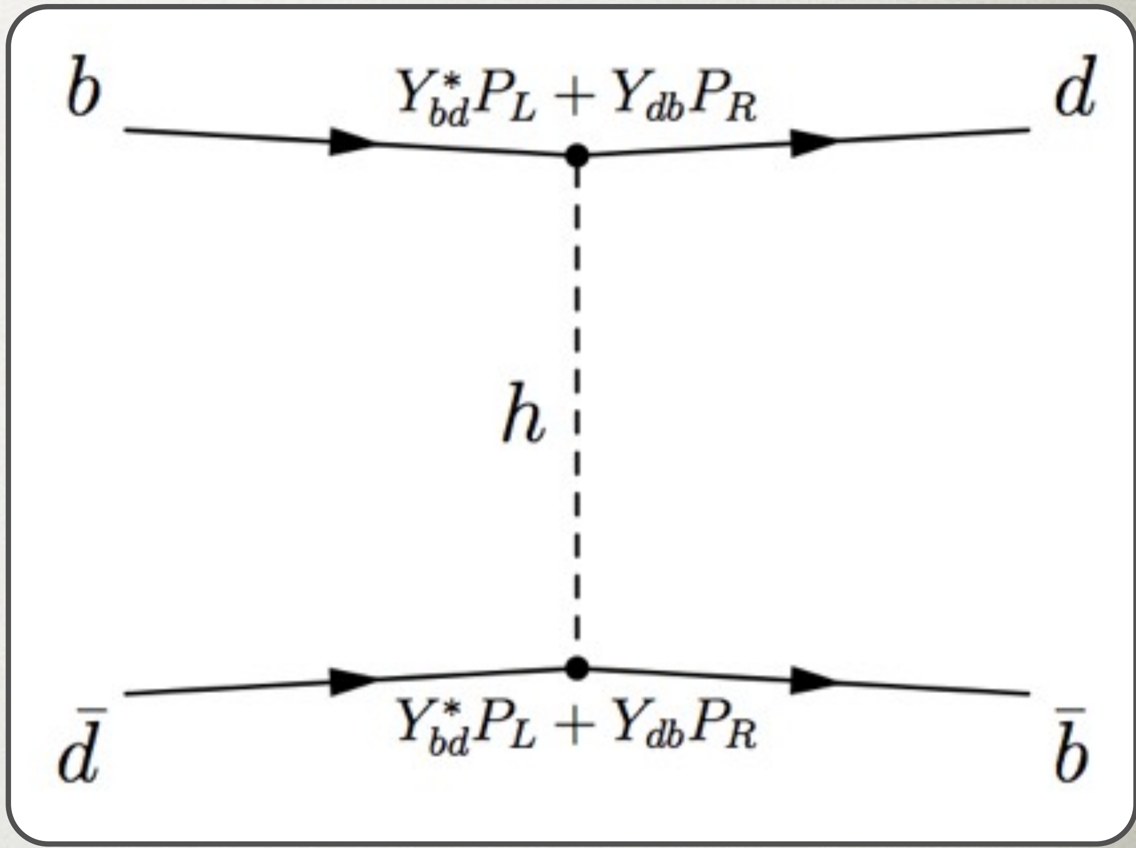
- bounds from
  - $\mu \to e\gamma$
  - $\mu \to 3e$
  - electron g-2
  - electr. EDM
  - $\mu \to e$ conversion
  - M-Mbar osc.
- $Br(h \to \mu e) \lesssim 2\times10^{-8}$ allowed




Harnik, Kopp, JZ, 1209.1397

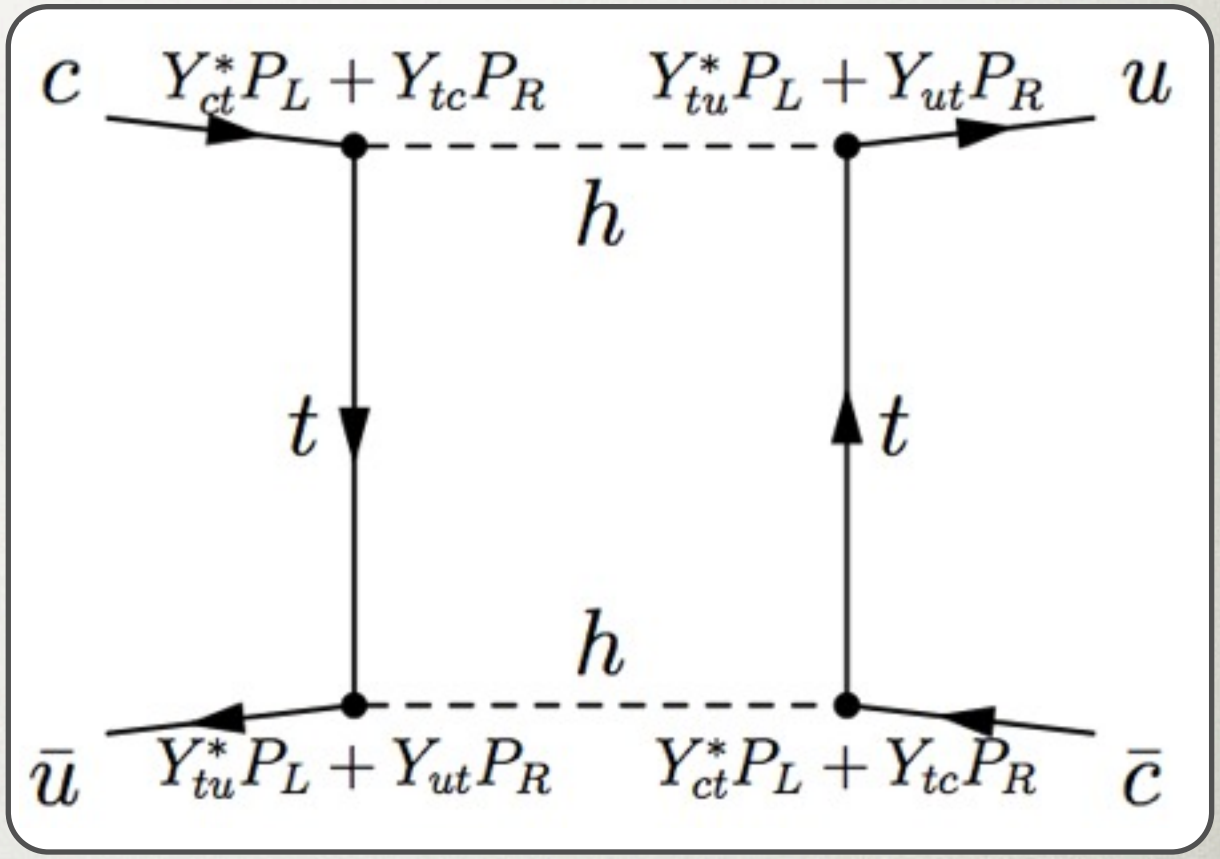
# QUARK COUPLINGS

- 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



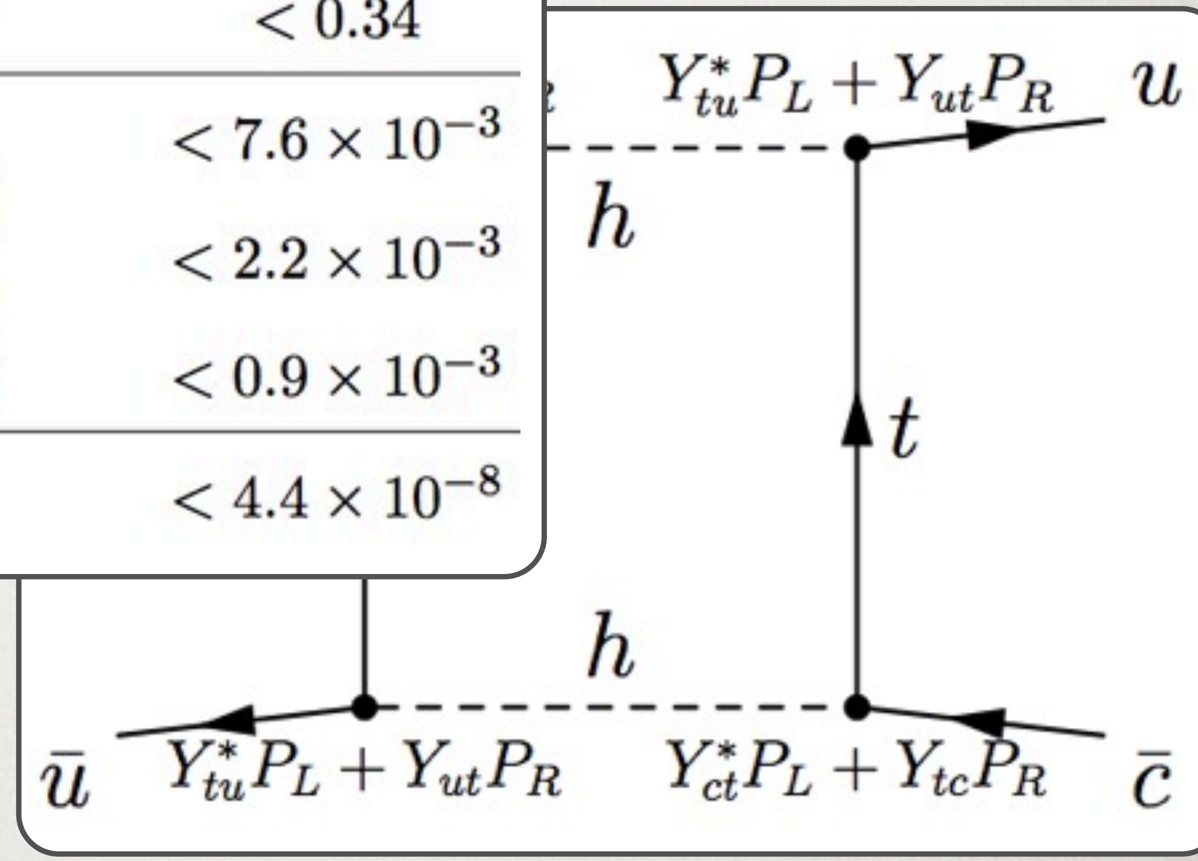
# QUARK COUPLINGS

- $Y_{tc,ct}$ and $Y_{tu,ut}$ less constrained
  - do not reach Cheng Sher ansatz $Y_{tc} \lesssim 0.06$, $Y_{tu} \lesssim 0.003$
  - strongest from *D* osc. and neutron EDM




- constraints on Br
  - $Br(t \to hq) \lesssim 2.7\%$, $Br(h \to t^* q) \lesssim O(10^{-3})$

| | | |
|---|---|---|
| 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] | $\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$ | $< 0.34$ |
| | $\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$ | $< 0.34$ |
| $D^0$ 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] | $\mathrm{Im}(Y_{ut}Y_{tu})$ | $< 4.4 \times 10^{-8}$ |




Cheng Sher ansatz

$Y_{tc} \lesssim 0.06$, $Y_{tu} \lesssim 0.003$

- strongest from *D* osc. and neutron EDM
- constraints on Br
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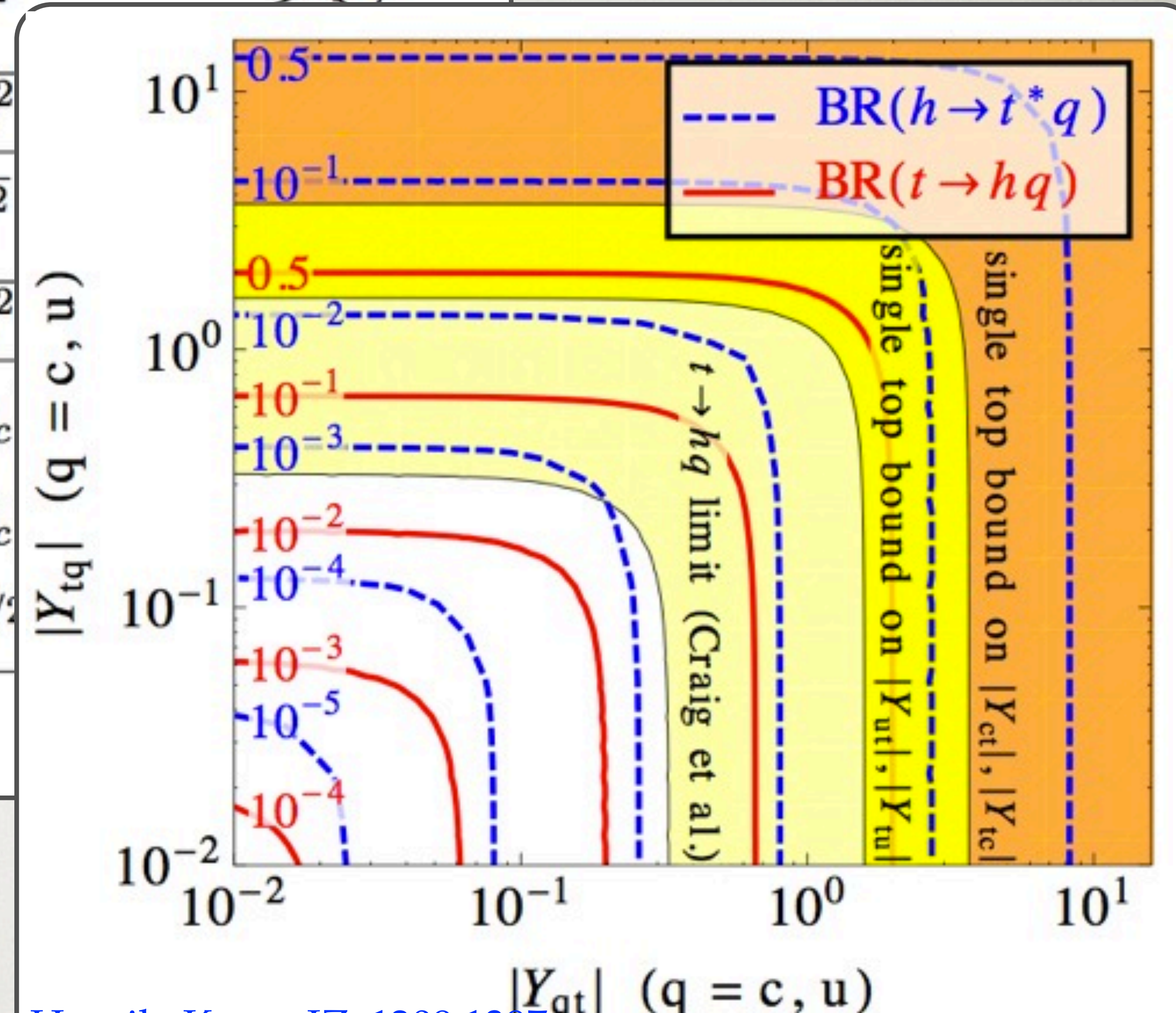



Harnik, Kopp, JZ, 1209.1397

Cheng Sher ansatz

*$Y_{tc} \lesssim 0.06$, $Y_{tu} \lesssim 0.003$*

- strongest from *D* osc. and neutron EDM

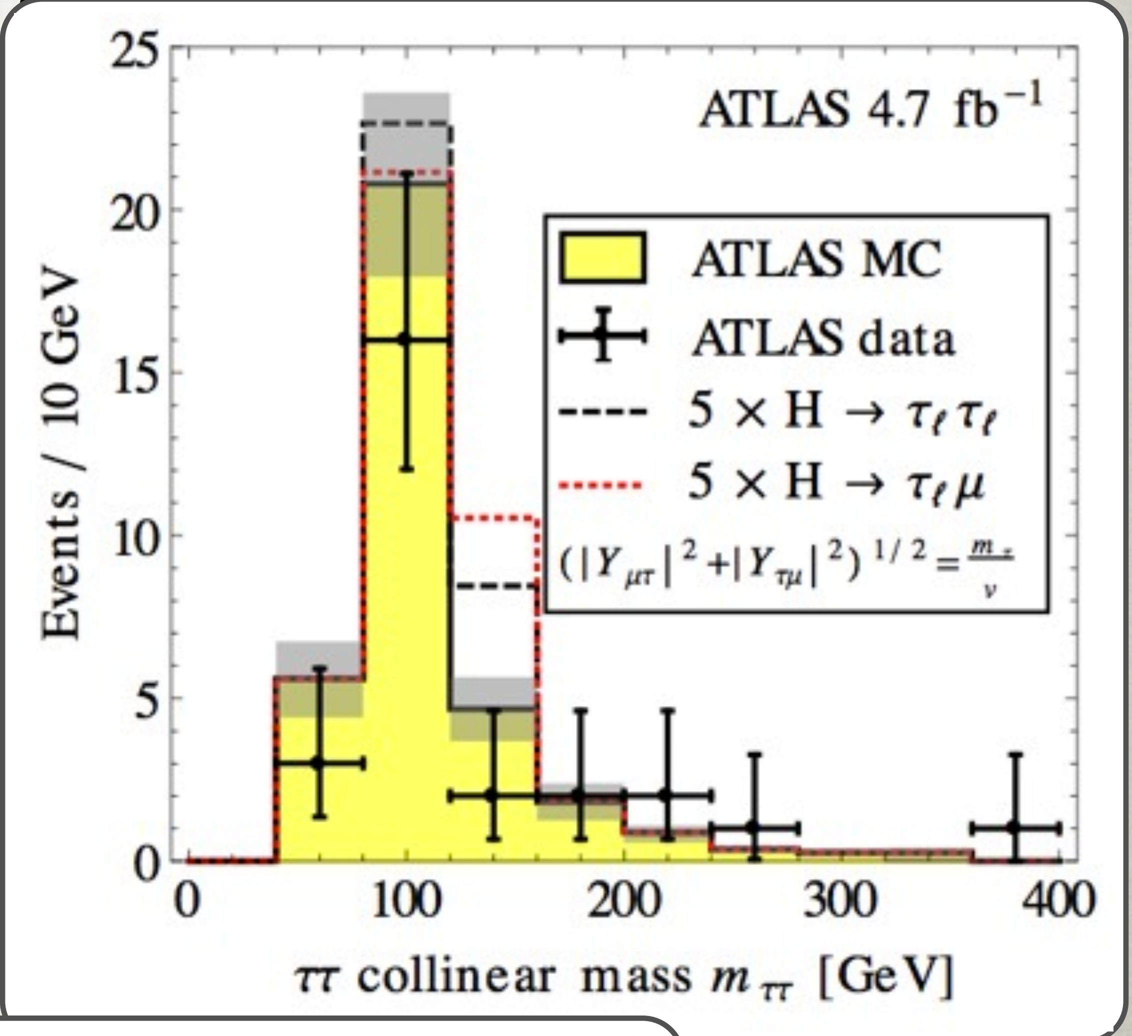
- constraints on Br

- *$Br(t \to hq) \lesssim 2.7\%$, $Br(h \to t^* q) \lesssim O(10^{-3})$*

# SUMMARY OF PRECISION CONSTRAINTS

- FV couplings to higgs
  - involving top or tau relatively poorly constrained
- how well can one do at the LHC?

# $h \to \tau e$ and $h \to \tau\mu$ at LHC



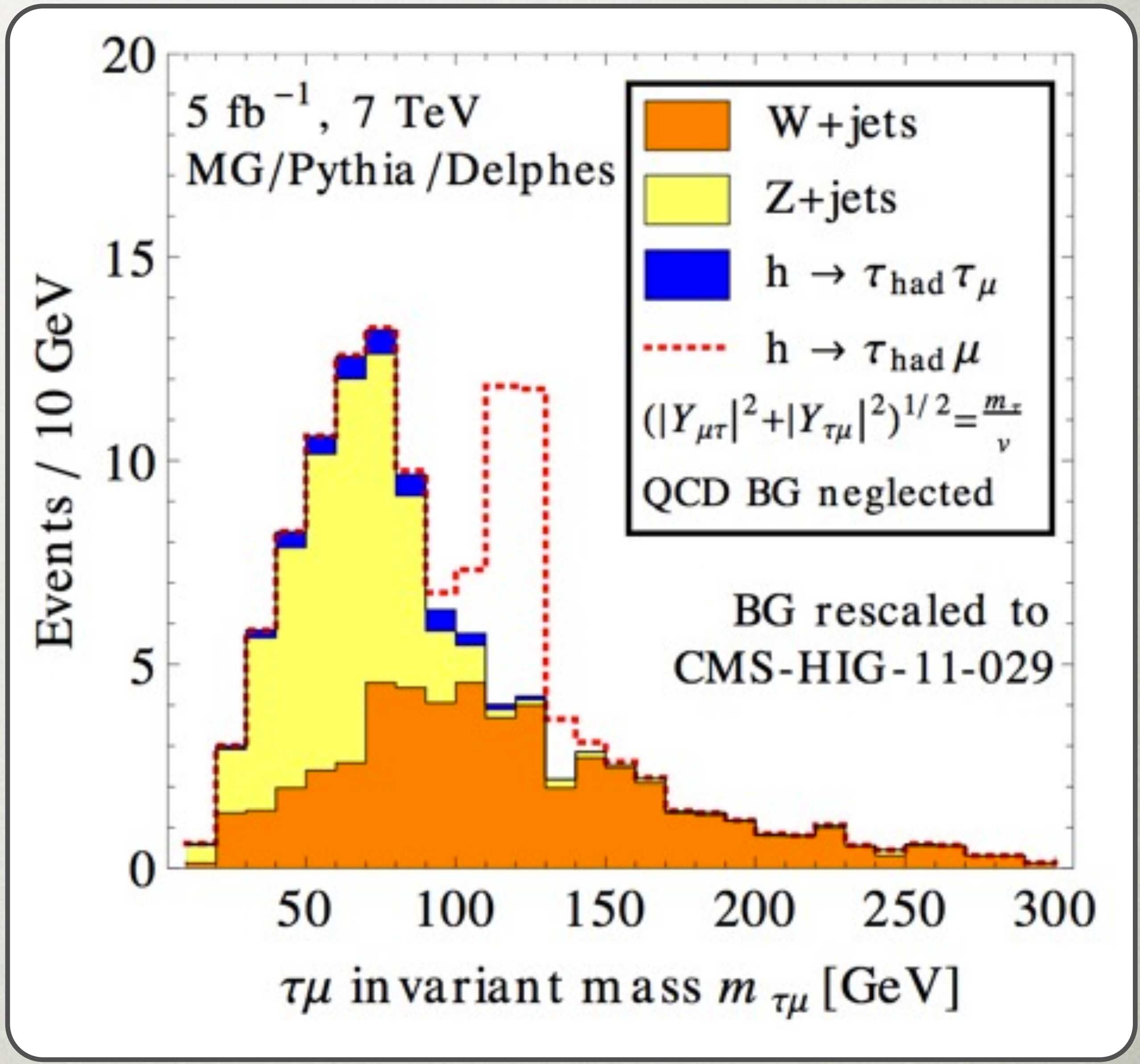

- recast $h \to \tau\tau$ ATLAS search
  - $4.7 fb^{-1}$@7TeV, fully leptonic channel
  - best limits on $Y_{\tau\mu,\tau e}$ are from LHC!

| 95% C.L. limit | $BR(h \to \tau\mu)$ | $\sqrt{Y_{\tau\mu}^2 + Y_{\mu\tau}^2}$ | $BR(h \to \tau e)$ | $\sqrt{Y_{\tau e}^2 + Y_{e\tau}^2}$ |
|---|---|---|---|---|
| expected | 28% | 0.018 | 27% | 0.017 |
| observed | 13% | 0.011 | 13% | 0.011 |

- dedicated searches should do much better

# A DEDICATED ANALYSIS

- the most sensitive searches for $h \to \tau\tau$ are $h \to \tau_{had}\tau_{\mu}$
- closely follow CMS search cuts
  - but omit transverse mass cut $m_T(\mu, p_{miss,T})$
    - since this cuts $W$ background, but also $h \to \tau\mu$




Harnik, Kopp, JZ, 1209.1397

# WHAT IF?

- what if $h \to \mu\mu$ is measured above SM?
- or if $h \to \tau\mu$ is nonzero?
  - what would we learn?

# MODELS OF FLAVOR

- could learn (more) about the origin of flavor structure
- will look at several models, focus on leptons
    - multi Higgs doublet models with natural flavor conservation
      Dery, Efrati, Hochberg, Nir, 1302.3229
    - single Higgs doublet with MFV
    - single Higgs doublet with Froggatt-Nielsen mechanism
    - Higgs dependents Yukawa couplings
      Giudice, Lebedev, 0804.1753
    - Higgs FCNCs in RS models
      Casagrande, Goertz, Haisch, Neubert, Pfoh, 0807.4937, ...
      Blanke, Buras, Duling, Gori, Weiler, 0809.1073,...
      Azatov, Toharia, Liu, 0906.1990
    - composite Higgs and PGB Higgs
      Agashe, Contino, 0906.1542

# MULTI HIGGS AND NATURAL FLAVOR CONSERVATION

- multi Higgs doublets, only one couples to leptons ($\phi_l$)

Dery, Efrati, Hochberg, Nir, 1302.3229

- the discovered BEH boson is an admixture of all neutral components

$$h = \sum_i V_{hi}\phi_i^0,$$

$$Y_{ij} = V_{h\ell}^* \delta_{ij}\sqrt{2}m_i/v_\ell$$

- predicts $Y_{\tau\mu}=Y_{\mu\tau}=0$, $Y_\tau \neq (Y_\tau)_{SM}$, $Y_\mu \neq (Y_\mu)_{SM}$
  - but universal deviation $\Rightarrow Y_\tau/Y_\mu = m_\tau/m_\mu$
  - e.g. type II 2HDM (MSSM)

$$Y_\tau = -(\sin\alpha/\cos\beta)\,Y_\tau^{\rm SM}$$

# SINGLE HIGGS AND MINIMAL FLAVOR VIOLATION

Dery, Efrati, Hochberg, Nir, 1302.3229

- dim-6 ops. related to dim-4 yukawa $\lambda$

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

$$\lambda' = a\lambda + b\lambda\lambda^\dagger\lambda + \mathcal{O}(\lambda^5)$$

- predicts $Y_{\tau\mu}=Y_{\mu\tau}=0$, $Y_\tau \neq (Y_\tau)_{SM}$, $Y_\mu \neq (Y_\mu)_{SM}$

$$Y_{ij} = \frac{\sqrt{2}m_i}{v}\delta_{ij}\left[1 + \frac{av^2}{\Lambda^2} + \frac{2bm_i^2}{\Lambda^2}\right]$$

  - non-universal deviation

$$\frac{Y_\mu}{Y_\tau} = \frac{m_\mu}{m_\tau}\left(1 - \frac{2b(m_\tau^2 - m_\mu^2)}{\Lambda^2}\right)$$

# SINGLE HIGGS AND FROGGATT-NIELSEN

Dery, Efrati, Hochberg, Nir, 1302.3229

- leptonic Yukawas given by $U(1)_H$ charges

$$\lambda_{ij} \propto \epsilon_H^{H(E_j)-H(L_i)}$$

- predicts $Y_{\tau\mu} \neq Y_{\mu\tau} \neq 0$, $Y_\tau \neq (Y_\tau)_{SM}$, $Y_\mu \neq (Y_\mu)_{SM}$
  - e.g.

$$Y_{\mu\tau} = \mathcal{O}\left(\frac{|U_{23}| v m_\tau}{\Lambda^2}\right)$$

  - non-universal deviation

$$\frac{Y_\mu}{Y_\tau} = \frac{m_\mu}{m_\tau}\left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]$$

# HIGGS DEPENDENT YUKAWAS

Dery, Efrati, Hochberg, Nir, 1302.3229
Giudice, Lebedev, 0804.1753

- only top yukawa from dim-4 op.
  - all other assumed to come from irrelevant ops
  - tau from dim-6, mu from dim-8
- predicts $Y_{\tau\mu} \neq Y_{\mu\tau} \neq 0$, $Y_\tau \neq (Y_\tau)_{SM}$, $Y_\mu \neq (Y_\mu)_{SM}$

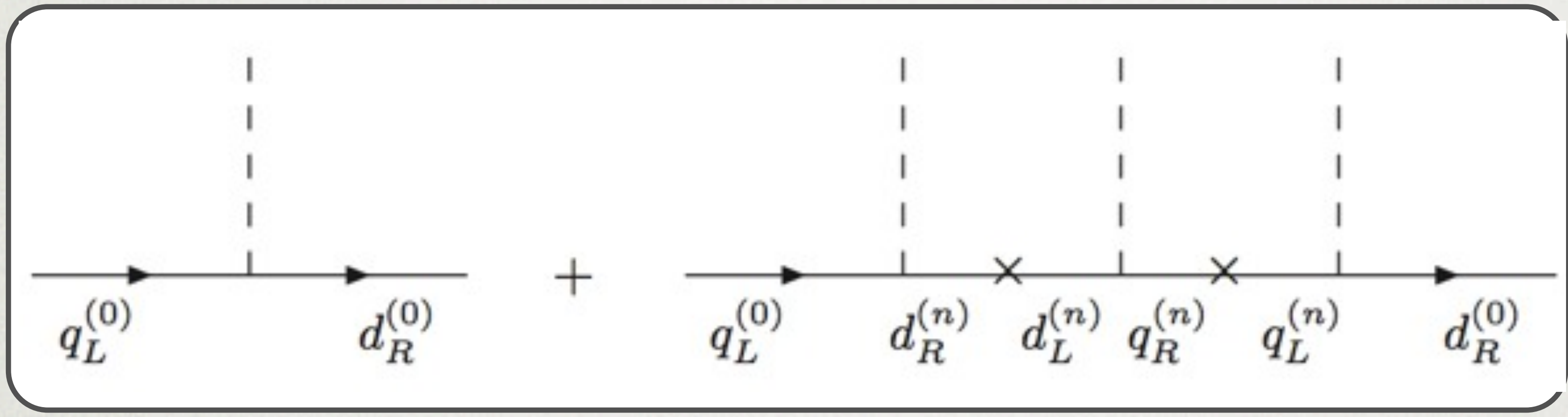
$$Y_{\tau\mu} = \mathcal{O}(Y_\mu)$$

$$Y_\tau \simeq 3\,\frac{\sqrt{2}m_\tau}{v}\,, \quad Y_\mu \simeq 5\,\frac{\sqrt{2}m_\mu}{v}$$

# HIGGS FCNC'S IN RANDALL-SUNDRUM MODELS

- SM yukawas corrected by mixing with KK fermion states

Azatov, Toharia, Liu, 0906.1990
Duling, 0912.4208




- size of off-diagonals depends on neutrino mass model
  - left and right-handed profiles hierarchical

$$Y_{ij} \sim \frac{m_i}{v}\delta_{ij} + \ldots \bar{Y}^2 \left(\frac{v}{m_{KK}}\right)^2 \sqrt{\frac{m_i m_j}{v^2}}$$

  - right-hand. profiles hierarchical, left-hand. similar

$$Y_{ij} \sim \frac{m_i}{v}\delta_{ij} + \ldots \bar{Y}^2 \left(\frac{v}{m_{KK}}\right)^2 \frac{m_j}{v}$$

$$Y_{\mu\tau} \sim 0.5 \left(\frac{\bar{Y}}{3}\right)^2 \left(\frac{3TeV}{m_{KK}}\right)^2 \sqrt{\frac{m_\mu m_\tau}{v^2}}$$

# PSEUDO-GOLDSTONE HIGGS

Agashe, Contino, 0906.1542

- SM fermions and Higgs couple to composite sector

$$\lambda_L \bar{\psi}_L O_R + \lambda_R \bar{\psi}_R O_L + h.c.$$

- if Higgs PGB, this generates

$$y^d_{ij} \sin(h/f) \cos(h/f)\, \bar{q}^i_L \hat{H} d^j_R$$

  - higher dim ops. related to dim-4
  - if just one $O_R$ ,$O_L$ $\Rightarrow$ diagonalize simult.
  - FV only if at least two $O_R$ (or $O_L$) in different reps of global group in comp. sector

# SUMMARY OF MODELS

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

adapted from Dery, Efrati, Hochberg, Nir, 1302.3229

| 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 |

# CONCLUSIONS

- flavor structure of Higgs couplings
  - FV couplings to tau and top poorly constrained
  - interesting info on flavor by measuring diagonal and off-diagonal

# BACKUP SLIDES

# BENCHMARKS

- 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

- different flavor models give

Dery, Efrati, Hochberg, Nir, 1302.3229

| Model | $R_{\tau^+\tau^-}$ | $X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$ | $X_{\mu\tau}$ |
|---|---|---|---|
| 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 | $\mathcal{O}(X_{\mu^+\mu^-})$ |

# HIGGS COUPLINGS

- if NP then Higgs couplings could be modified
- if EFT description valid

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

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- in general thus

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

- new neutral currents
  - flavor diagonal @LHC
  - flavor violating @Belle2 and LHC
- note: both are important for understanding

# PRECISION FLAVOR REACH

Harnik, Kopp, JZ, 1209.1397

- for $Y_{\tau\mu}$, $Y_{\tau e}$ both Belle2 and LHC
- for $Y_{\mu e}$ only precision flavor
- starting to probe Cheng-Sher territory