# Flavor Violation in the Scalar Sector

Joachim Kopp

Higgs Tasting Workshop, May 18, 2016

Partially based on work done in collaboration with
Malte Buschmann, Admir Greljo, Roni Harnik, Jernej Kamenik,
Jia Liu, Marco Nardecchia, Jure Zupan, Xiao-Ping Wang

PRiSMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U


# Flavor Mixing in the Scalar Sector

# Motivation

## In the SM

$$\mathcal{L} \supset -y_{ij} \bar{L}^i e_R^j H \quad \to \quad -\frac{y_{ij} v}{\sqrt{2}} \bar{e}_L^i e_R^j - \frac{y_{ij}}{\sqrt{2}} \bar{e}_L^i e_R^j h$$

Masses and Yukawa couplings have same flavor structure.

## Beyond the SM

$$\mathcal{L} \supset -m_{ij} \bar{e}_L^i e_R^j - \frac{y_{ij}}{\sqrt{2}} \bar{e}_L^i e_R^j h$$

Mass and Yukawa matrices can be misaligned in flavor space.

# Consequences

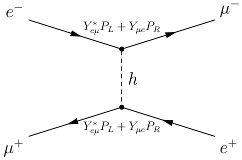
- Flavor physics bonanza
- $h \to \ell\ell'$
- $t \to hq$
- $ug \to th$
- Model building playground

# Consequences

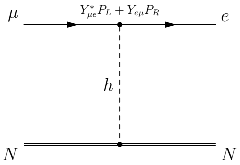
- Flavor physics bonanza
- $h \to \ell\ell'$ $\quad$ ($\to$ CMS excess in $h \to \mu\tau$)
- $t \to hq$
- $ug \to th$
- Model building playground


# FCNC Yukawa Couplings to Leptons

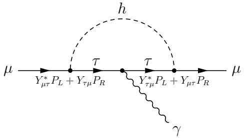
# Low-energy constraints on LFV in the scalar sector



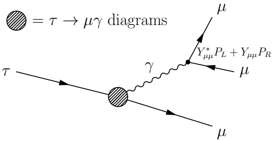

**$M$–$\bar{M}$ oscillations**



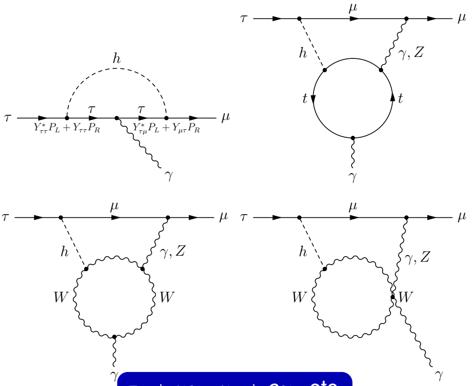

**$\mu$–$e$ conversion**




**$g-2$, EDMs**

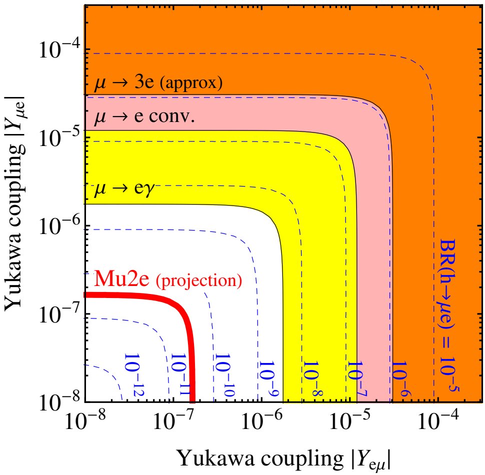



**$\tau \to 3\mu$, $\mu \to 3e$, etc.**




**$\tau \to \mu\gamma$, $\mu \to e\gamma$, etc.**

# Constraints on $h \to \mu e$

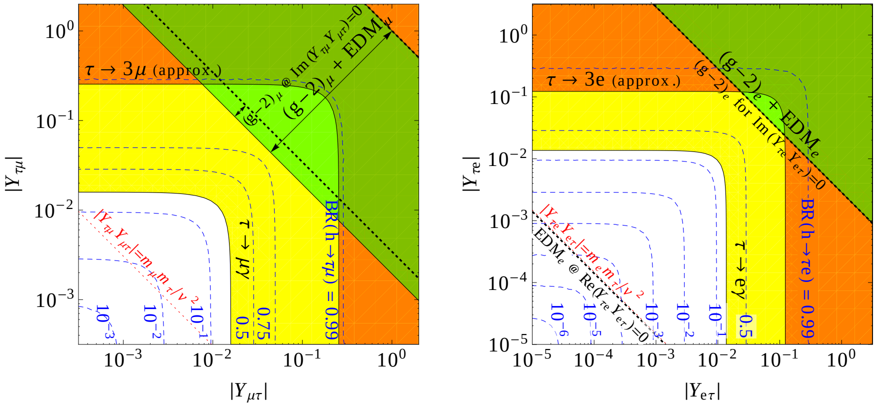



Assumption here:

Diagonal Yukawa couplings unchanged from their SM values.

Harnik JK Zupan, arXiv:1209.1397
see also Blankenburg Ellis Isidori, arXiv:1202.5704
Goudelis Lebedev Park, arXiv:1111.1715

# Constraints on $h \to \tau\mu$ and $h \to \tau e$




Substantial flavor violation ($BR(h \to \tau\mu, \tau e) \sim 0.1$) possible.

**Assumption here:**
Diagonal Yukawa couplings unchanged from their SM values.

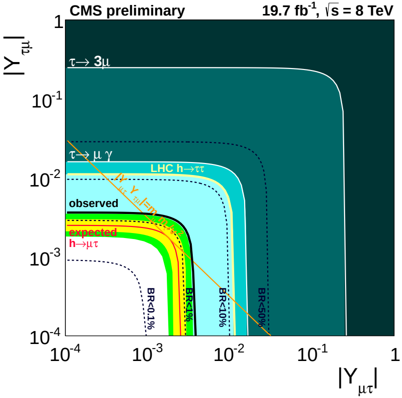
Harnik JK Zupan, arXiv:1209.1397
see also: Blankenburg Ellis Isidori, arXiv:1202.5704
Goudelis Lebedev Park, arXiv:1111.1715
Davidson Greiner, arXiv:1001.0434

# $h \to \tau\mu$ searches from CMS and ATLAS

## Main features

- Compute $\mu\tau$ invariant mass in collinear approximation
- Muon $p_T$ much higher than in $h \to \tau\tau_\mu$
- Use $\Delta\phi$ and $M_T$ cuts
- Sensitive to $gg \to h$

Harnik JK Zupan, arXiv:1209.1397
Davidson Verdier, :arXiv:1211.1248



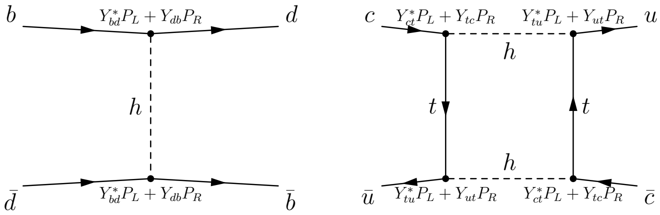

CMS-PAS-HIG-14-005

- ATLAS results compatible with CMS, but also with zero (arXiv:1508.03372)
- Note: if $h \to \tau\mu$ is large, $h \to \tau e$ must be small (otherwise conflict with $\mu \to e\gamma$)


# FCNC Couplings to Quarks

# Constraints on FCNC couplings to light quarks

- Tight constraints from neutral meson oscillations



# Constraints on FCNC couplings to light quarks

- Tight constraints from neutral meson oscillations
- Work in Effective Field Theory:

$$H_{\text{eff}} = C_2^{db} (\bar{b}_R d_L)^2 + \tilde{C}_2^{db} (\bar{b}_L d_R)^2 + C_4^{db} (\bar{b}_L d_R)(\bar{b}_R d_L) + \dots$$

- Wilson coefficients constrained by UTfit (Bona et al.), arXiv:0707.0636

see also Blankenburg Ellis Isidori, arXiv:1202.5704

| Technique | Coupling | Constraint |
|---|---|---|
| $D^0$ oscillations | $\lvert Y_{uc}\rvert^2, \lvert Y_{cu}\rvert^2$<br>$\lvert Y_{uc} Y_{cu}\rvert$ | $< 5.0 \times 10^{-9}$<br>$< 7.5 \times 10^{-10}$ |
| $B_d^0$ oscillations | $\lvert Y_{db}\rvert^2, \lvert Y_{bd}\rvert^2$<br>$\lvert Y_{db} Y_{bd}\rvert$ | $< 2.3 \times 10^{-8}$<br>$< 3.3 \times 10^{-9}$ |
| $B_s^0$ oscillations | $\lvert Y_{sb}\rvert^2, \lvert Y_{bs}\rvert^2$<br>$\lvert Y_{sb} Y_{bs}\rvert$ | $< 1.8 \times 10^{-6}$<br>$< 2.5 \times 10^{-7}$ |
| $K^0$ oscillations | $\Re(Y_{ds}^2), \Re(Y_{sd}^2)$<br>$\Im(Y_{ds}^2), \Im(Y_{sd}^2)$<br>$\Re(Y_{ds}^* Y_{sd})$<br>$\Im(Y_{ds}^* Y_{sd})$ | $[-5.9 \dots 5.6] \times 10^{-10}$<br>$[-2.9 \dots 1.6] \times 10^{-12}$<br>$[-5.6 \dots 5.6] \times 10^{-11}$<br>$[-1.4 \dots 2.8] \times 10^{-13}$ |

# Constraints on FCNC couplings to light quarks

- Tight constraints from neutral meson oscillations
- Work in Effective Field Theory:

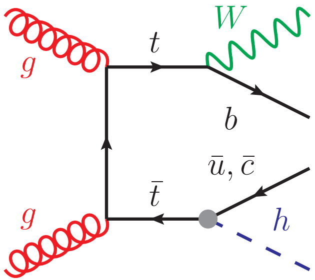
$$H_{\text{eff}} = C_2^{db}(\bar{b}_R d_L)^2 + \tilde{C}_2^{db}(\bar{b}_L d_R)^2 + C_4^{db}(\bar{b}_L d_R)(\bar{b}_R d_L) + \dots$$

- Wilson coefficients constrained by UTfit (Bona et al.), arXiv:0707.0636

  see also Blankenburg Ellis Isidori, arXiv:1202.5704
- But: Indirect constraints very weak for FCNC top couplings

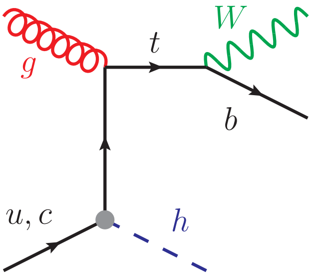
  $\Rightarrow$ Discovery potential at the LHC

# FCNC *t–h* couplings




$t \to hq$ decay

- Relevant for *tuh* and *tch* couplings (no PDF suppression)
- $\ell + 2\gamma$ or up to $5\ell$




single top + *h* production

- Only relevant for *tuh* couplings (PDF suppression for charm)
- $\ell + 2\gamma$ or up to $5\ell$

Greljo Kamenik JK, arXiv:1404.1278

# LHC limits on $t \to hq$

Dedicated searches by both ATLAS and CMS.

## ATLAS

$$\text{BR}(t \to cH) < 0.0046 \qquad \leftrightarrow \qquad \sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.13$$

arXiv:1509.06047
see also arXiv:1403.6293

## CMS

$$\text{BR}(t \to cH) < 0.0047 \qquad \leftrightarrow \qquad \sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.13$$

CMS-PAS-TOP-14-019
see also CMS-PAS-TOP-14-020

# Future directions

- Include $ug \to th$: leads to 50% improvement

Greljo Kamenik JK, arXiv:1404.1278

# Future directions

- Include $ug \to th$: leads to 50% improvement
- Other final states
  - For instance: $t \to hq \to$ hadrons and $gu \to th \to$ hadrons

# The fully hadronic final state

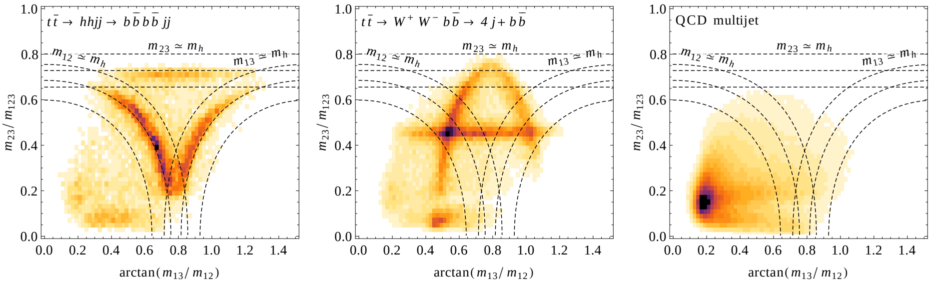
- Analysis 1: $pp \to \bar{t}(t \to hj) \to$ hadrons
  - Tagging SM $t \to Wb$ decays: HEPTopTagger

    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
    - ⋆ Cluster "fat jets" ($R = 1.5$)
    - ⋆ Uncluster to find three subjets most likely to originate from top decay based on their invariant mass $m_{123}$
    - ⋆ Along the way, use filtering to remove pile-up and underlying event contamination
    - ⋆ Impose cuts on invariant masses of subjet pairs to require one pair to be $\sim m_W$

Greljo Kamenik JK, 1404.1278

# The fully hadronic final state

- Analysis 1: $pp \to \bar{t}(t \to hj) \to$ hadrons
  - Tagging SM $t \to Wb$ decays: HEPTopTagger
    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
  - Tagging FCNC $t \to hq$ decays: Modified HEPTopTagger
    with adapted kinematic cuts




Greljo Kamenik JK, 1404.1278

# The fully hadronic final state

- Analysis 1: $pp \to \bar{t}(t \to hj) \to$ hadrons
  - Tagging SM $t \to Wb$ decays: HEPTopTagger

    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
  - Tagging FCNC $t \to hq$ decays: Modified HEPTopTagger with adapted kinematic cuts
  - Require $b$ tags in likely $b$ subjets
  - Dominant backgrounds:
    - $t\bar{t}$
    - single top
    - QCD

| | Background | | | $\sqrt{y_{ut}^2 + y_{tu}^2} = 0.1$ | | $\sqrt{y_{ct}^2 + y_{tc}^2} = 0.1$ | |
|---|---|---|---|---|---|---|---|
| | $t\bar{t}$ | single-$t$ | QCD | $t \to hu$ | $t + h$ | $t \to hc$ | $t + h$ |
| **Analysis 1: *th* tag + top tag** | | | | | | | |
| loose *th* tags | 3 510 | 5.5 | 125 | 70 | 4.0 | 69 | 0.57 |
| tight *th* tags | 324 | 0.52 | 85 | 28 | 1.1 | 26 | 0.15 |

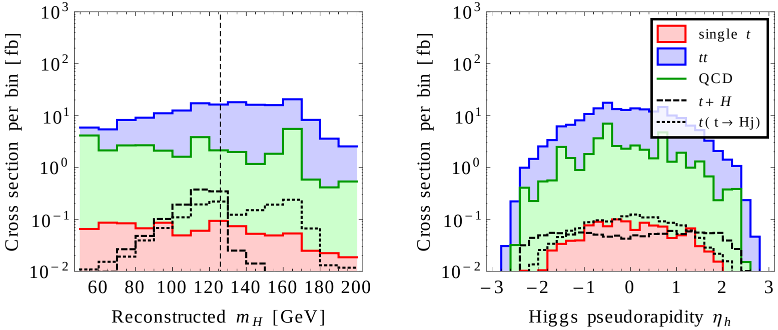
Greljo Kamenik JK, 1404.1278

# The fully hadronic final state

- Analysis 1: $pp \to \bar{t}(t \to hj) \to \text{hadrons}$
- Analysis 2: $pp \to th \to \text{hadrons}$ (single top + Higgs productions)
  - Tagging SM $t \to Wb$ decays: HEPTopTagger

    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
  - Higgs tagging: Mass drop tagger

    Butterworth Davison Rubin Salam 0802.2470; Cacciari Salam Soyez 1111.6097
  - Require $b$ tags in likely $b$ subjets
  - Cuts on $m_H$ (reconstructed Higgs mass) and $|\eta_h|$ (reconstructed Higgs rapidity)




Greljo Kamenik JK, 1404.1278

# The fully hadronic final state

- Analysis 1: $pp \to \bar{t}(t \to hj) \to$ hadrons
- Analysis 2: $pp \to th \to$ hadrons (single top + Higgs productions)
  - Tagging SM $t \to Wb$ decays: HEPTopTagger
    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
  - Higgs tagging: Mass drop tagger
    Butterworth Davison Rubin Salam 0802.2470; Cacciari Salam Soyez 1111.6097
  - Require $b$ tags in likely $b$ subjets
  - Cuts on $m_H$ (reconstructed Higgs mass) and $|\eta_h|$ (reconstructed Higgs rapidity)

| | Background | | | $\sqrt{y_{ut}^2 + y_{tu}^2} = 0.1$ | | $\sqrt{y_{ct}^2 + y_{tc}^2} = 0.1$ | |
|---|---|---|---|---|---|---|---|
| | $t\bar{t}$ | single-$t$ | QCD | $t \to hu$ | $t + h$ | $t \to hc$ | $t + h$ |
| **Analysis 1: *th* tag + top tag** | | | | | | | |
| loose *th* tags | 3 510 | 5.5 | 125 | 70 | 4.0 | 69 | 0.57 |
| tight *th* tags | 324 | 0.52 | 85 | 28 | 1.1 | 26 | 0.15 |
| **Analysis 2: Higgs tag + top tag** | | | | | | | |
| preselection | 14 800 | 113 | 4 125 | 152 | 120 | 209 | 14.0 |
| final cuts | 450 | 2.3 | 71 | 6.9 | 32.6 | 8.4 | 1.1 |

Greljo Kamenik JK, 1404.1278

# Future directions

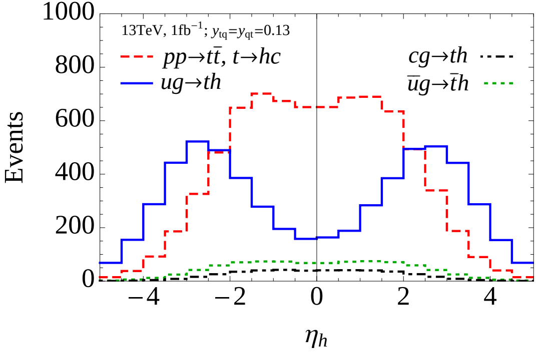
- Include *ug* $\to$ *th*: leads to 50% improvement

  Greljo Kamenik JK, arXiv:1404.1278
- Other final states
  - For instance: $t \to hq \to$ hadrons and $gu \to th \to$ hadrons
  - weaker limits than multi-$\ell$ and $\ell\gamma\gamma$, but potentially of the same order
- Distinguish *tuh* and *tch* couplings

# Distinguishing *tuh* and *tch* couplings

- Determine if $ug \to th$ contributes to the signal
- Observables:
  - $\eta$ distribution of $h$,
  - lepton charges

In $ug \to th$, $h$ is emitted preferentially in the direction of the $u$ quark.




- Final state lepton charges as an additional discriminant
- Result: For $5\sigma$ discovery, $2\sigma$ discrimination between *tuh* and *tch*.

Khatibi Najafabadi, arXiv:1402.3073, Greljo Kamenik JK, arXiv:1404.1278


# Models with FCNC in the Scalar Sector

# Interpreting the excess: models for $h \to \tau\mu$

- Two Higgs Doublet Models (e.g. Crivellin D'Ambrosio Heeck, arXiv:1503.00993)

# Interpreting the excess: models for $h \to \tau\mu$

- Two Higgs Doublet Models (e.g. Crivellin D'Ambrosio Heeck, arXiv:1503.00993)
- MFV and Froggatt–Nielsen models (Dery Efrati Nir Soreq Susič, arXiv:1408.1371)
  - Large BR($h \to \tau\mu$) possible in MFV with accidentally suppressed $Y_{e\mu}$
  - Large BR($h \to \tau\mu$) possible in SUSY FN scenarios with specifcally chosen FN charges

# Interpreting the excess: models for $h \to \tau\mu$

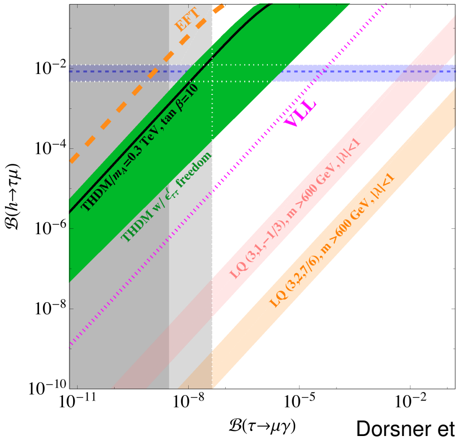
- Two Higgs Doublet Models (e.g. Crivellin D'Ambrosio Heeck, arXiv:1503.00993)
- MFV and Froggatt–Nielsen models (Dery Efrati Nir Soreq Susič, arXiv:1408.1371)
- Inverse Seesaw Models (Arganda Herrero Miarcano Weiland, arXiv:1508.04623)

# Interpreting the excess: models for $h \to \tau\mu$

- Two Higgs Doublet Models (e.g. Crivellin D'Ambrosio Heeck, arXiv:1503.00993)
- MFV and Froggatt–Nielsen models (Dery Efrati Nir Soreq Susič, arXiv:1408.1371)
- Inverse Seesaw Models (Arganda Herrero Miarcano Weiland, arXiv:1508.04623)
- Leptoquarks (Cheung Keung Tseng, arXiv:1508.01897)
  - Tuning required to avoid $\tau \to \mu\gamma$

# Interpreting the excess: models for $h \to \tau\mu$

- Two Higgs Doublet Models (e.g. Crivellin D'Ambrosio Heeck, arXiv:1503.00993)
- MFV and Froggatt–Nielsen models (Dery Efrati Nir Soreq Susič, arXiv:1408.1371)
- Inverse Seesaw Models (Arganda Herrero Miarcano Weiland, arXiv:1508.04623)
- Leptoquarks (Cheung Keung Tseng, arXiv:1508.01897)
- Strongest signals in Type III 2HDM




Dorsner et al., arXiv:1502.07784

# Beyond the CMS excess: FCNC Higgs couplings in other models

- MSSM (Aloni Nir Stamou, arXiv:1511.00979)
  - Even with fine-tuning, BR($h \to \tau\mu$) is beyond LHC reach

# Beyond the CMS excess: FCNC Higgs couplings in other models

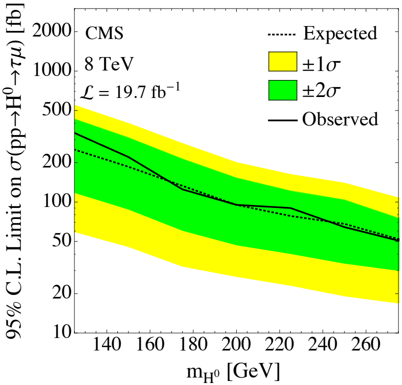
- MSSM (Aloni Nir Stamou, arXiv:1511.00979)
  - Even with fine-tuning, BR($h \to \tau\mu$) is beyond LHC reach
- Composite Higgs Models (Azatov Panico Perez Soreq, arXiv:1408.4525)
  - $t \to ch$ unobservable, but $t \to cZ$ within LHC reach

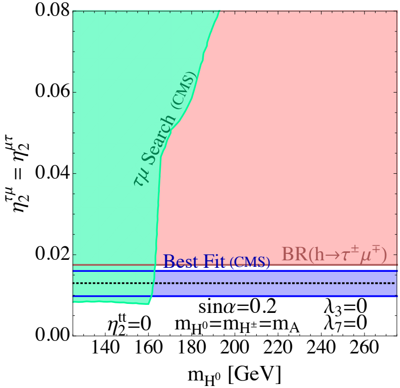
# Constraining FCNC in 2HDMs

- Basic idea: small FCNC for $h$ related to large FCNC for $H^0$

# Constraining FCNC in 2HDMs

- Basic idea: small FCNC for $h$ related to large FCNC for $H^0$
- $H^0 \to \tau\mu$
  - Theorist-level recasting of CMS $h \to \tau\mu$ search



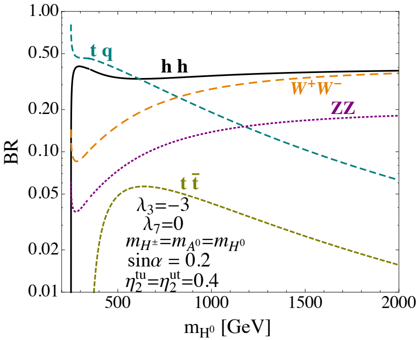

Buschmann JK Liu Wang, arXiv:1601.02616

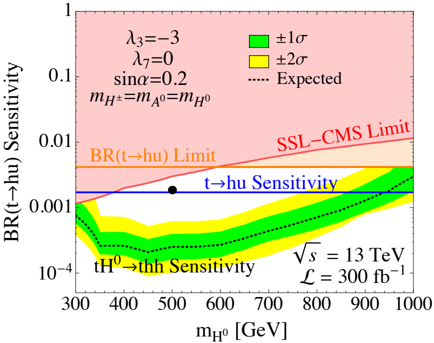
# Constraining FCNC in 2HDMs

- Basic idea: small FCNC for $h$ related to large FCNC for $H^0$
- $H^0 \to \tau\mu$

# Constraining FCNC in 2HDMs

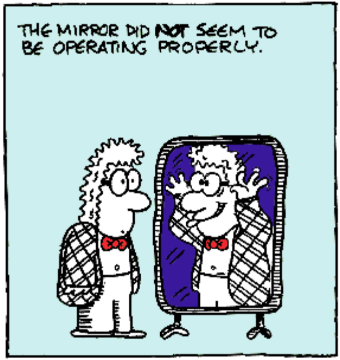
- Basic idea: small FCNC for $h$ related to large FCNC for $H^0$
- $H^0 \to \tau\mu$
- FCNC top couplings in $pp \to tH^0 \to thh$



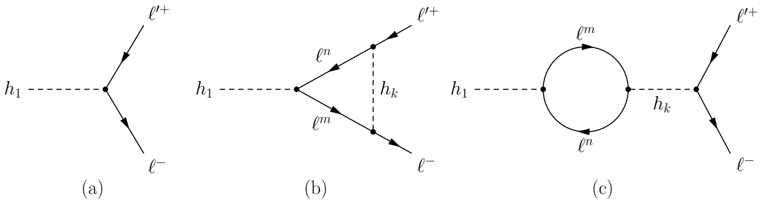

- Enhanced heavy scalar ($H^0$) production
- Promising decay: $H^0 \to hh$

Buschmann JK Liu Wang, arXiv:1601.02616




# CP Violation in the Scalar Sector

# CP violation in the Scalar Sector




## Basic idea:

- Interference of tree and loop diagrams leads to CP violation
- Observable: asymmetry between $h \to \tau^+\mu^-$ and $h \to \tau^-\mu^+$

JK Nardecchia, arXiv:1406.5303

# Example: Effective Field Theory

$$\mathcal{L}_{\text{EFT}} \supset -m_i \bar{\ell}^i_L \ell^i_R - Y^h_{ij} (\bar{\ell}^i_L \ell^j_R) h + h.c.\,,$$

Result:

$$A^{\mu\tau}_{CP} = \frac{\Gamma(h \to \mu^- \tau^+) - \Gamma(h \to \mu^+ \tau^-)}{\Gamma(h \to \mu^- \tau^+) + \Gamma(h \to \mu^+ \tau^-)}$$

$$= \frac{1 - \log 2}{8\pi} \frac{\text{Im}\left[ Y^h_{\tau\tau} \left( Y^h_{e\mu} Y^{h*}_{e\tau} Y^{h*}_{\mu\tau} - Y^h_{\mu e} Y^{h*}_{\tau e} Y^{h*}_{\tau\mu} \right) \right]}{\left| Y^h_{\mu\tau} \right|^2 + \left| Y^h_{\tau\mu} \right|^2}$$

$$+ \frac{1}{8\pi} \frac{m_\tau^2}{m_h^2} \frac{\left| Y^h_{\mu\tau} \right|^2 - \left| Y^h_{\tau\mu} \right|^2}{\left| Y^h_{\mu\tau} \right|^2 + \left| Y^h_{\tau\mu} \right|^2} \text{Im}\left[ (Y^h_{\tau\tau})^2 \right]\,.$$

... suppressed by $m_\tau^2 / m_h^2$ and $Y^h_{e\mu}$, $Y^h_{\mu e}$.

# Example: A Two Higgs-Doublet Model

$$\mathcal{L} \supset -\frac{\sqrt{2}m_i}{v}\delta_{ij}\,\bar{L}_L^i \ell_R^j \Phi_1 - \sqrt{2}\,Y_{ij}\,\bar{L}_L^i \ell_R^j \Phi_2 + h.c.\,,$$

In the physical basis:

$$\mathcal{L} = -m_i \bar{\ell}_L^i \ell_R^i - \sum_{r=1,2,3} Y_{ij}^{h_r}\,\bar{\ell}_L^i \ell_R^j\, h_r + h.c. \qquad (r = 1, 2, 3)$$

with

$$Y_{ij}^{h_r} = \frac{m_i \delta_{ij}}{v} O_{1r} + Y_{ij} O_{2r} + i\,Y_{ij} O_{3r}\,,$$

$O = SO(3)$ (real $3 \times 3$) rotation matrix

JK Nardecchia, arXiv:1406.5303

# Example: A Two Higgs-Doublet Model

$$\mathcal{L} \supset -\frac{\sqrt{2}m_i}{v}\delta_{ij}\,\bar{L}_L^i \ell_R^j \Phi_1 - \sqrt{2}Y_{ij}\,\bar{L}_L^i \ell_R^j \Phi_2 + h.c.\,,$$

Result:

$$A_{CP}^{\mu\tau} = \sum_{\alpha=2,3} \frac{1}{4\pi} \frac{|Y_{\tau\mu}|^2 - |Y_{\mu\tau}|^2}{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} \left( |Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2 + |Y_{\tau\tau}|^2 \right) \times R_\alpha \times \left[ g\left(\frac{m_h^2}{m_{h_\alpha}^2}\right) + \frac{m_h^2}{m_h^2 - m_{h_\alpha}^2} \right]$$

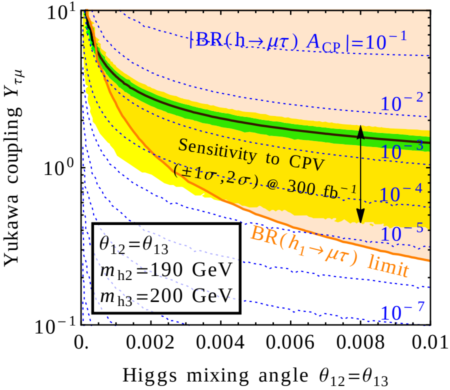
with

$$R_\alpha = \frac{(O_{3\alpha}O_{21} - O_{2\alpha}O_{31})(O_{2\alpha}O_{21} + O_{3\alpha}O_{31})}{O_{21}^2 + O_{31}^2}$$

. . . suppressed only by loop factor

JK Nardecchia, arXiv:1406.5303

# Sensitivity to CPV in the Scalar Sector for 2HDMs




- Best discovery potential in small mixing regime
- Would require a detection of $h \to \tau\mu$ or $h \to \tau e$ very soon.

JK Nardecchia, arXiv:1406.5303

# Summary

# Summary

- Large FCNC allowed in the $\tau$ and top sectors
- Leptonic FCNC
  - Small excess in CMS
- Quark FCNC: *tuh* and *tch*
  - Include $pp \to th$
  - New final states (e.g. fully hadronic)?
  - Discrimination between *tuh* and *tch*
- Models for FCNC in the scalar sector
  - 2HDM offers largest signals
  - Interesting constraints from $H^0 \to \tau\mu$ and $H^0 \to hh$
- CP violation in the scalar sector
  - Asymmetry between $h \to \tau^+\mu^-$ and $h \to \tau^-\mu^+$ may be observable if CMS excess is confirmed

# Thank you!

Malte Buschmann

Admir Greljo

Jia Liu

Marco Nardecchia

Xiao-Ping Wang