Flavor Violation in the Scalar Sector

Joachim Kopp

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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

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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

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- $h \to \ell\ell'$ $(\to$ CMS excess in $h \to \mu\tau)$
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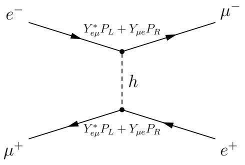
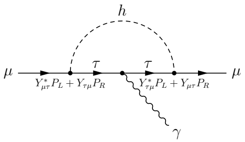
FCNC Yukawa Couplings to Leptons

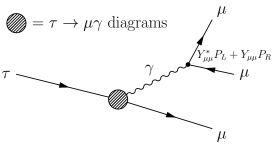
Low-energy constraints on LFV in the scalar sector



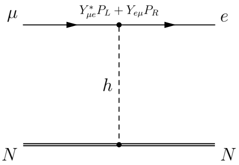
M–$\bar{M}$ oscillations



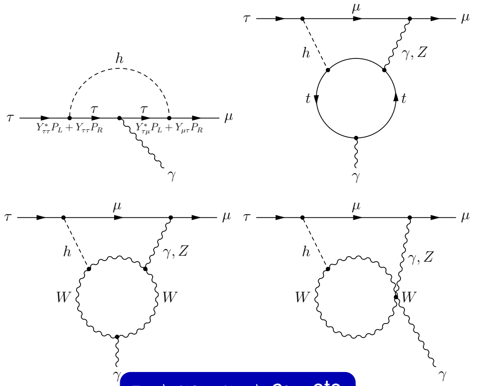
$g-2$, EDMs



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

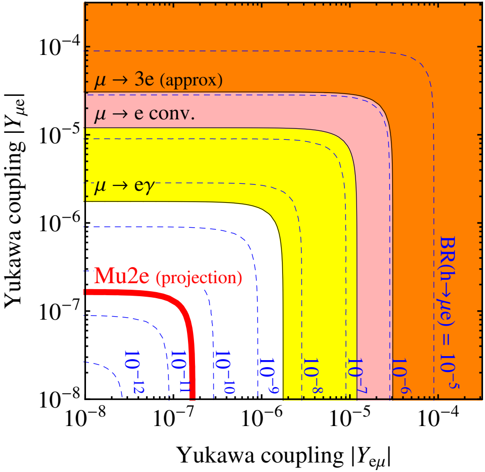


μ–e conversion



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

Constraints on $h \to \mu e$



Assumption here:

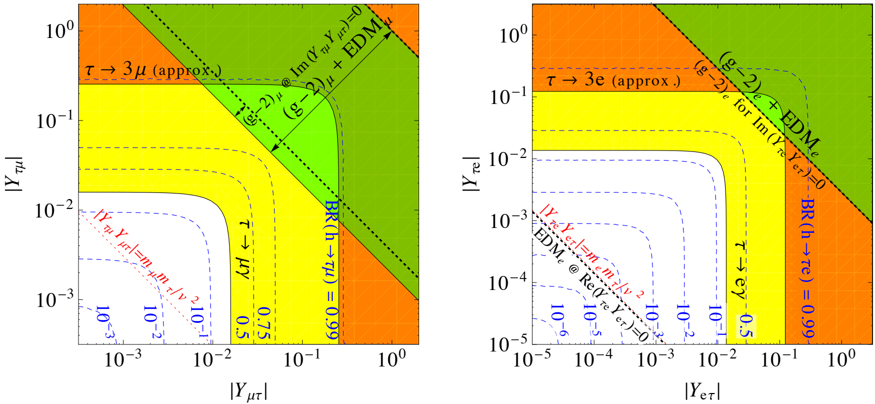
Diagonal Yukawa couplings unchanged from their SM values.

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.

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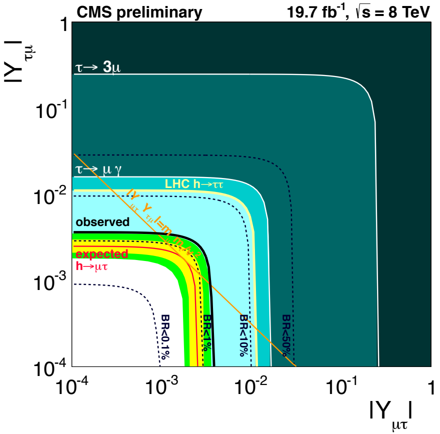
Harnik JK Zupan, arXiv:1209.1397
see also: Blankenburg Ellis Isidori, arXiv:1202.5704
Goudelis Lebedev Park, arXiv:1111.1715
Davidson Greiner, arXiv:1001.0434

$h \to \tau\mu$ search from CMS and ATLAS



CMS-PAS-HIG-14-005

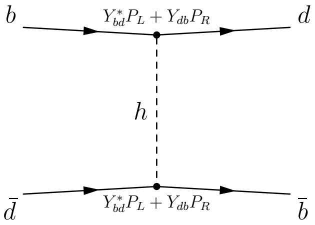
Davidson Verdier, arXiv:1211.1248, Harnik JK Zupan, arXiv:1209.1397

- 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

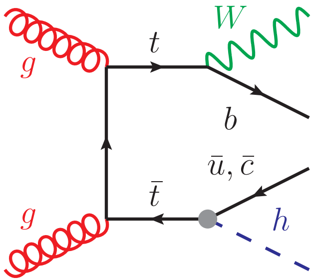
Constraints on FCNC couplings to light quarks

- Tight constraints from neutral meson oscillations

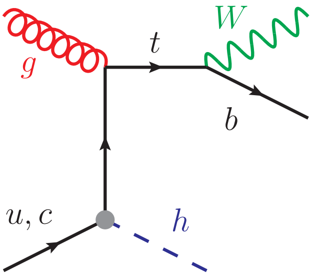


- But: Indirect constraints very weak for FCNC top couplings
  $\Rightarrow$ Discovery potential at the LHC

FCNC *t–h* couplings



$t \to hq$ decay



single top + *h* production

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

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

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

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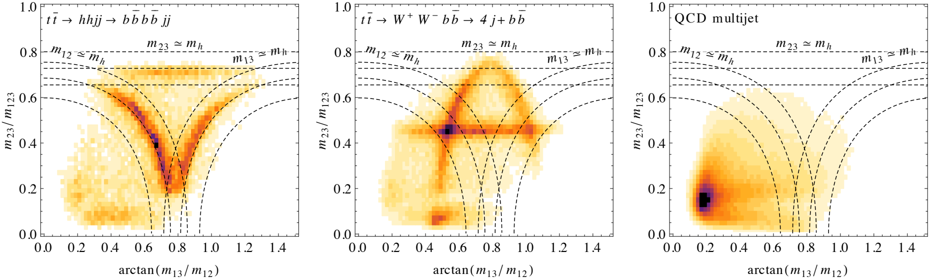
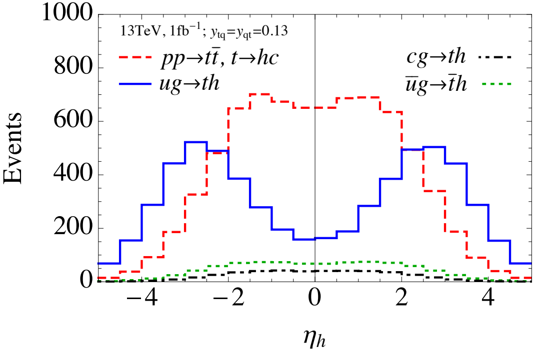
- Include $ug \to th$: leads to 50% improvement
- Other final states
  - For instance: $t \to hq \to$ jets
    $\to$ Modified HEPTopTagger achieves $S/B \sim 1\%$



Greljo Kamenik JK, arXiv:1404.1278
Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833

Future directions

- Include $ug \to th$: leads to 50% improvement
- Other final states
- Distinguish tuh and tch couplings
  - Determine if $ug \to th$ contributes to the signal
  - Observables:
    - ★ η distribution of h,
    - ★ lepton charges



  - Result: For 5σ discovery, 2σ 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)

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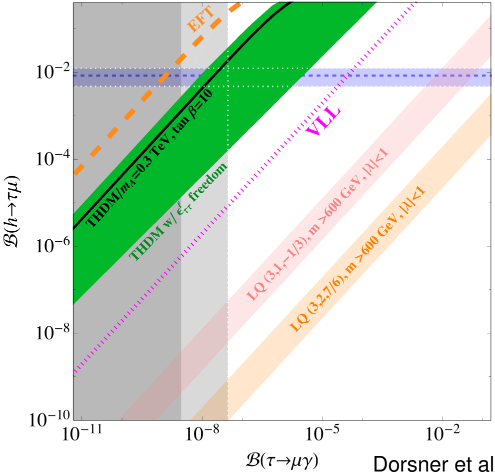
- Strongest signals in Type III 2HDM



Dorsner et al., arXiv:1502.07784

Constraining FCNC in 2HDMs

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

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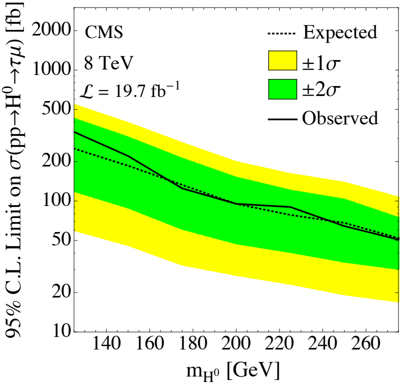
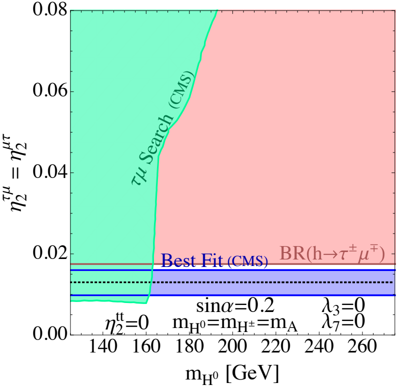
- Basic idea: small FCNC for *h* related to large FCNC for H^0
- $H^0 \to \tau\mu$
  - Theorist-level recasting of CMS $h \to \tau\mu$ search





Buschmann JK Liu Wang, arXiv:1601.02616

Constraining FCNC in 2HDMs

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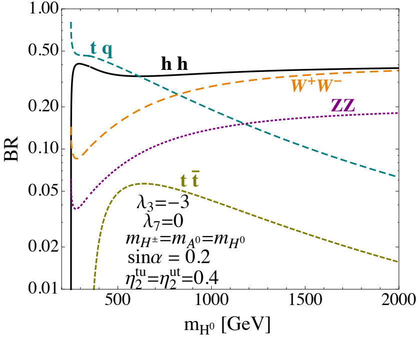
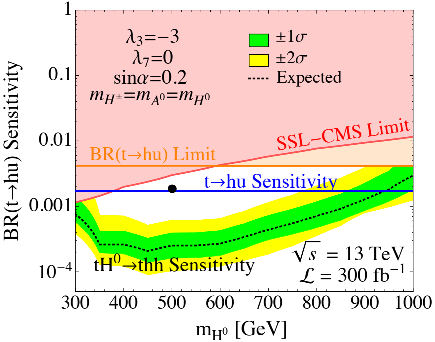
Constraining FCNC in 2HDMs

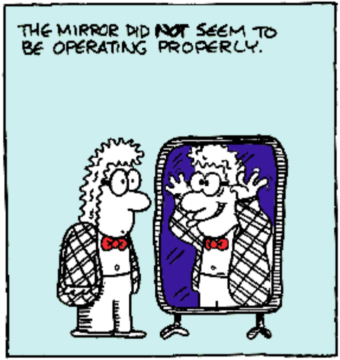
- Basic idea: small FCNC for h related to large FCNC for H^0
- $H^0 \to \tau\mu$
- FCNC top couplings in $pp \to tH^0 \to thh$





- 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

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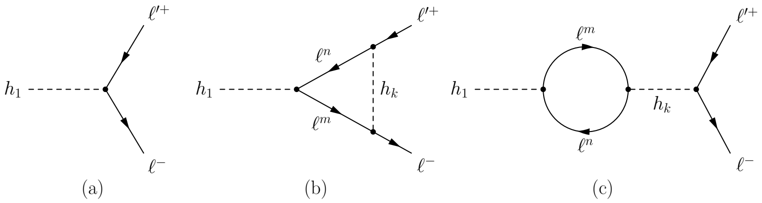
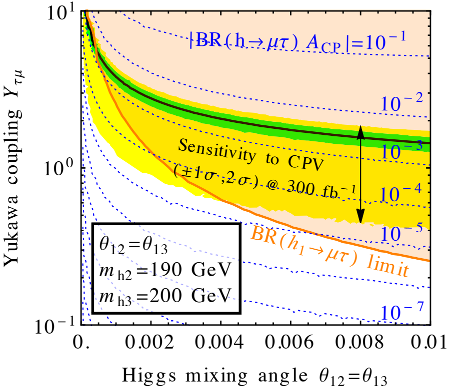


Basic idea:

- 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

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 τ 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

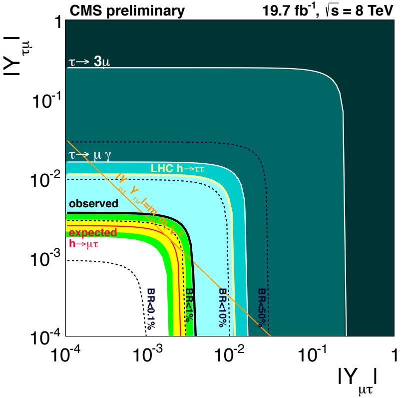
Bonus Slides

$h \to \tau\mu$ search from CMS

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 $gg \to h$

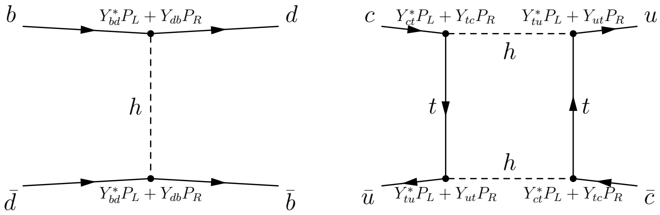
Harnik JK Zupan, arXiv:1209.1397
Davidson Verdier, :arXiv:1211.1248



CMS-PAS-HIG-14-005

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

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

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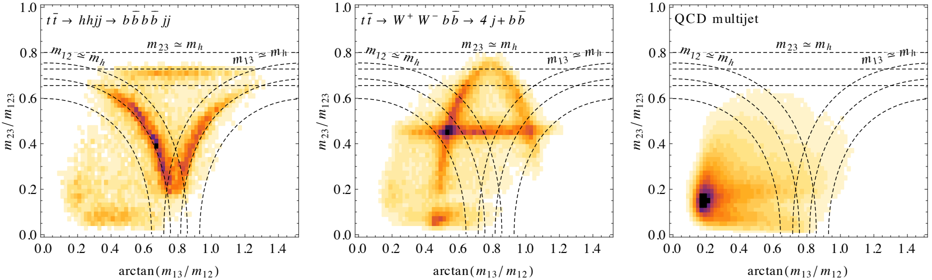
  - Tagging FCNC $t \to hq$ decays: Modified HEPTopTagger with adapted kinematic cuts



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  - 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

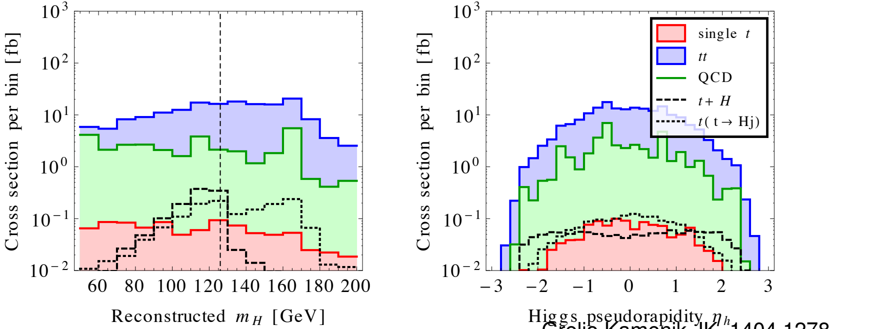
Greljo Kamenik JK, 1404.1278

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)



Greljo Kamenik JK, 1404.1278

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:

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

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

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

... suppressed by m^2_τ / m^2_h and $Y^h_{e\mu}$, $Y^h_{\mu e}$.

Example: A Two Higgs-Doublet Model

$$\mathcal{L} \supset -\frac{\sqrt{2}m_i}{v}\delta_{ij}\,\bar{L}^i_L \ell^j_R \Phi_1 - \sqrt{2}Y_{ij}\,\bar{L}^i_L \ell^j_R \Phi_2 + h.c.\,,$$

In the physical basis:

$$\mathcal{L} = -m_i \bar{\ell}^i_L \ell^i_R - \sum_{r=1,2,3} Y^{h_r}_{ij}\,\bar{\ell}^i_L \ell^j_R\, h_r + h.c. \qquad (r = 1, 2, 3)$$

with

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

$O = SO(3)$ (real 3×3) rotation matrix

JK Nardecchia, arXiv:1406.5303

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

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