Flavor and CP Violation in Higgs Decays

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University of Mainz / PRISMA Cluster of Excellence

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Partially based on work done in collaboration with
Admir Greljo, Roni Harnik, Jernej Kamenik, Marco Nardecchia and Jure Zupan

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

Flavor Mixing in the Higgs Sector

Motivation

Scenario 1: Several sources of EW symmetry breaking

- If fermion masses have more than one origin, they do not need to be aligned with the Yukawa couplings

  Simplest example: Type III 2-Higgs-Doublet Model

  $$\mathcal{L}_Y \supset -Y^{(1)}_{ij}\bar{L}^i e^j_R H^{(1)} - Y^{(2)}_{ij}\bar{L}^i e^j_R H^{(2)} + h.c.$$

  $$\longrightarrow -m_i \bar{e}^i_L e^i_R - Y^{\text{eff}}_{ij}\bar{e}^i_L e^j_R h + \text{couplings to heavier Higgs bosons} + h.c.$$

  (h = Lightest neutral Higgs boson, $m_h \sim 125$ GeV)

  Assume heavy Higgs bosons are decoupled.

  see for instance Davidson Greiner, arXiv:1001.0434

- Similar couplings for quarks

Motivation (2)

Scenario 2: Extra Higgs couplings

Assume existence of heavy new particles, which induce effective operators of the form

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

$\rightarrow$ after EWSB, new (but misaligned) contributions to mass matrices and Yukawa couplings

Effective Lagrangian is again

$$\mathcal{L}_Y \supset -m_i \bar{e}^i_L e^i_R - Y^{\text{eff}}_{ij} \bar{e}^i_L e^j_R h + h.c.$$

see for instance Giudice Lebedev, arXiv:0804.1753

Effective Yukawa Lagrangfian

Effective Yukawa Lagrangian

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

Previously studied by many authors:

Bjorken Weinberg, PRL **38** (1977) 622
Shanker, Nucl. Phys. B **206** (1982) 253
Babu Nandi, hep-ph/9907213
Han Marfatia, hep-ph/0008141
Kanemura Ota Tsumura, hep-ph/0505191
McWilliams Li, Nucl. Phys. B **179** (1981) 62
Barr Zee, PRL **65** (1990) 21
Diaz-Cruz Toscano, hep-ph/9910233
Arganda Curiel Herrero Temes, hep-ph/0407302
Giudice Lebedev, 0804.1753
Casagrande Goertz Haisch Neubert Pfoh, 0807.4937
Blanke Buras Duling Gori Weiler, 0809.1073
Albrecht Blanke Buras Duling Gemmler, 0903.2415
Aguilar-Saavedra, 0904.2387
Buras Duling Gori, 0905.2318
Agashe Contino, 0906.1542
Azatov Toharia Zhu, 0906.1990
Davidson Greiner, 1001.0434
Goudelis Lebedev Park, 1111.1715
Blankenburg Ellis Isidori, 1202.5704
Wang Huang Li Li Shao Wang, 1208.2902
McKeen Pospelov Ritz, 1208.4597
Arhrib Cheng Kong, 1208.4669
...

Effective Yukawa Lagrangfian

Effective Yukawa Lagrangian

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

More recent studies:

Arhrib Cheng Kong, 1210.8241
Atwood Gupta Soni, 1305.2427
Arroyo Diaz-Cruz Diaz Orduz-Ducuara, 1306.2343
Khatibi Najafabadi, 1402.3073
Gorban Haisch, 1404.4873
Arganda Herrero Marcano Weiland, 1405.4300
...

Dery Efrati Hochberg Nir, 1302.3229
Zhang Maltoni, 1305.7386
Celis Cirigliano Passemar, 1309.3564
Cao Han Wu Yang Zhang, 1404.1241
Crivellin Hoferichter Procura, 1404.7134
Bressler Dery Efrati, 1405.4545

Effective Yukawa Lagrangfian

Effective Yukawa Lagrangian

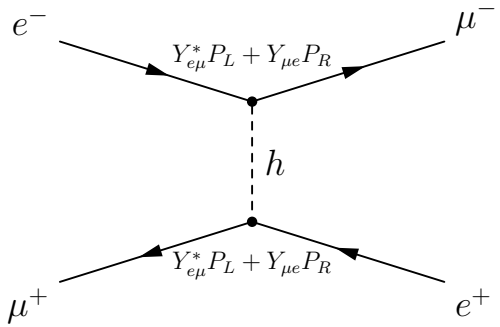
$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}^a (\bar{f}_L^i f_R^j) h^a + h.c. + \cdots$$

In this talk:

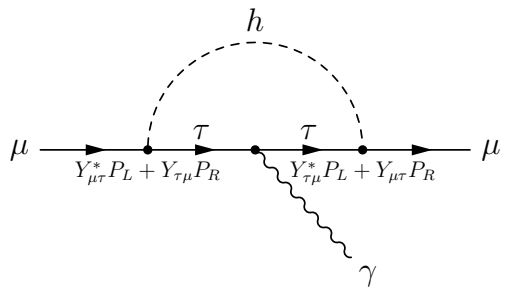
- Low-energy constraints on FV decays
- LHC limits on $h \to \mu\tau$, $h \to e\tau$, $t \to ch$, $t \to uh$
- Strategies for future LHC searches
- Possibility of Flavor + CP violation

FCNC Higgs Couplings to Leptons

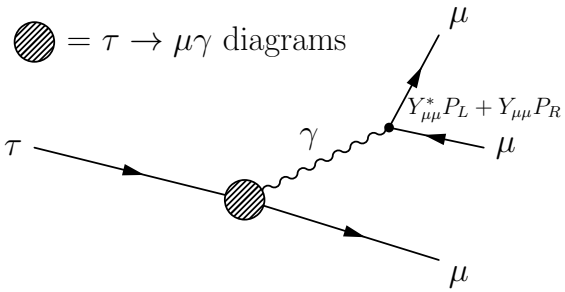
Low-energy constraints on LFV in the Higgs sector



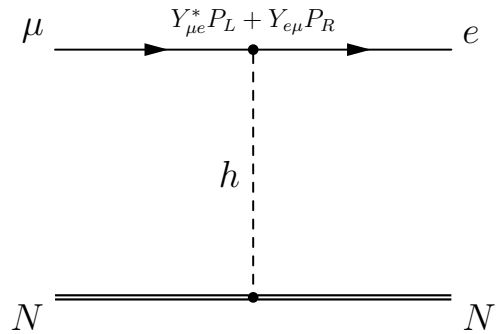
M–$\bar{M}$ oscillations



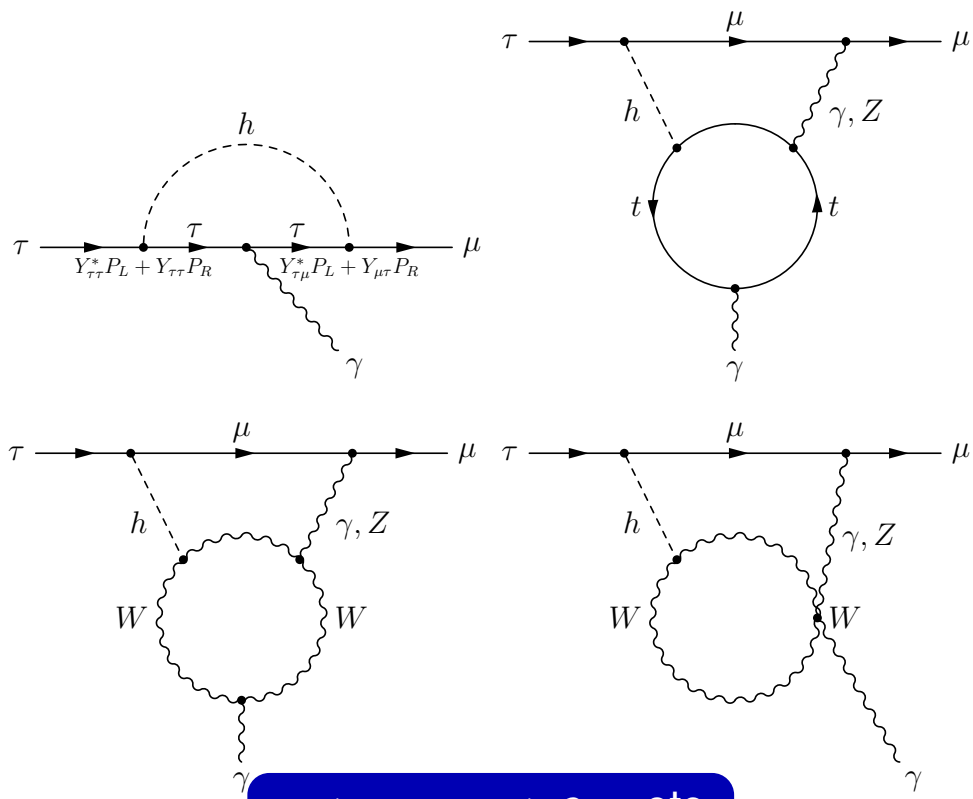
$g-2$, EDMs



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

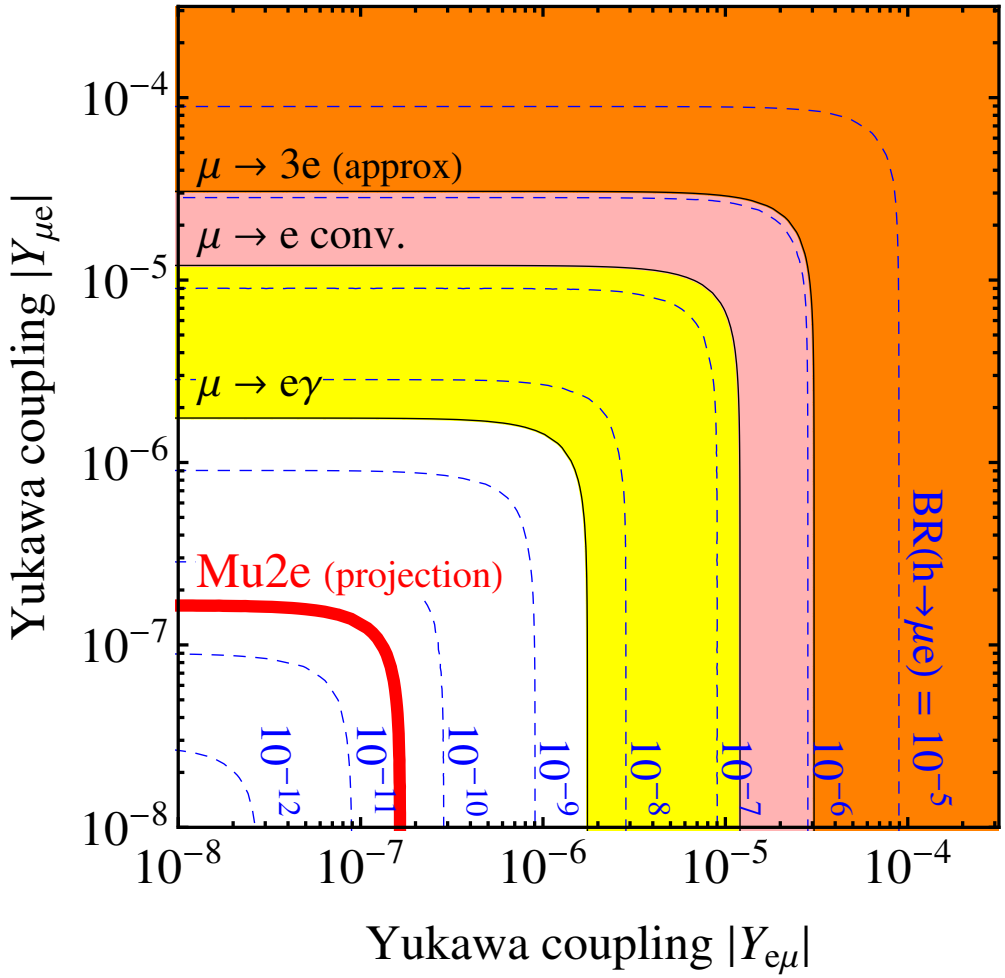


μ–e conversion



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

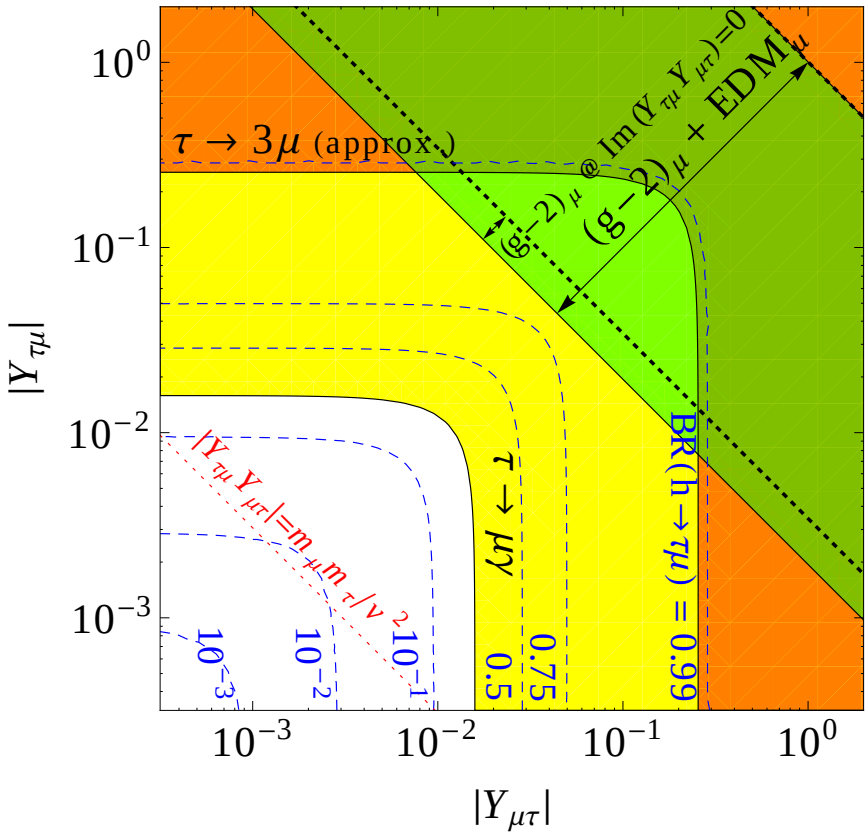
Constraints on $h \to \mu e$

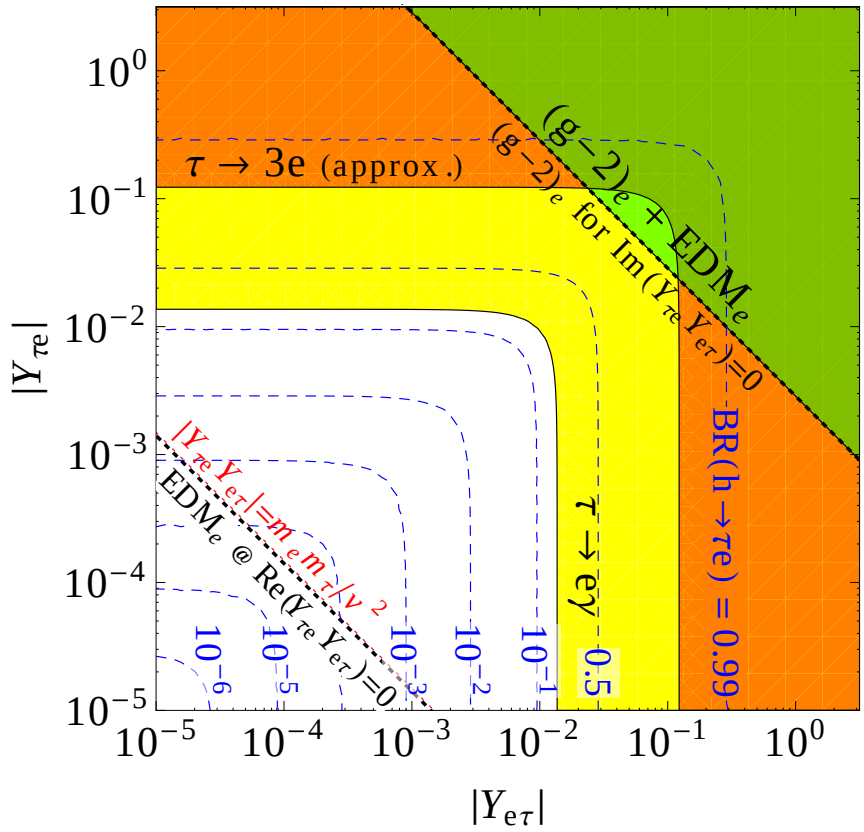


Assumption here:
Diagonal Yukawa couplings unchanged from their SM values.

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 ($BR(h \to \tau\mu, \tau e) \sim 0.01$) perfectly viable.

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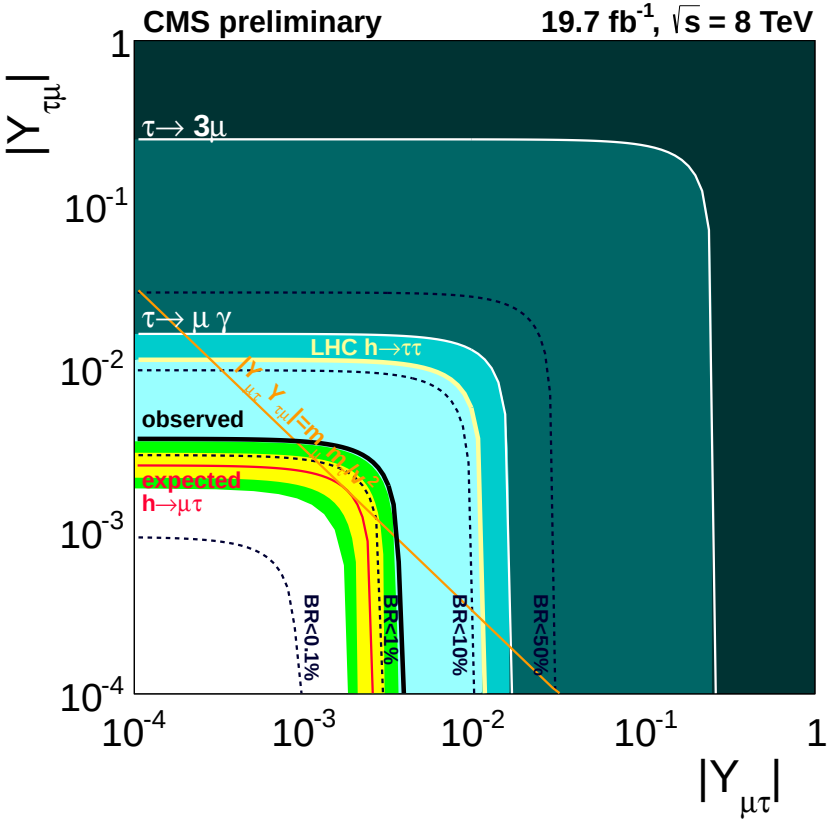
$h \to \tau\mu$ search from CMS

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
- Allows inclusion of gg fusion events

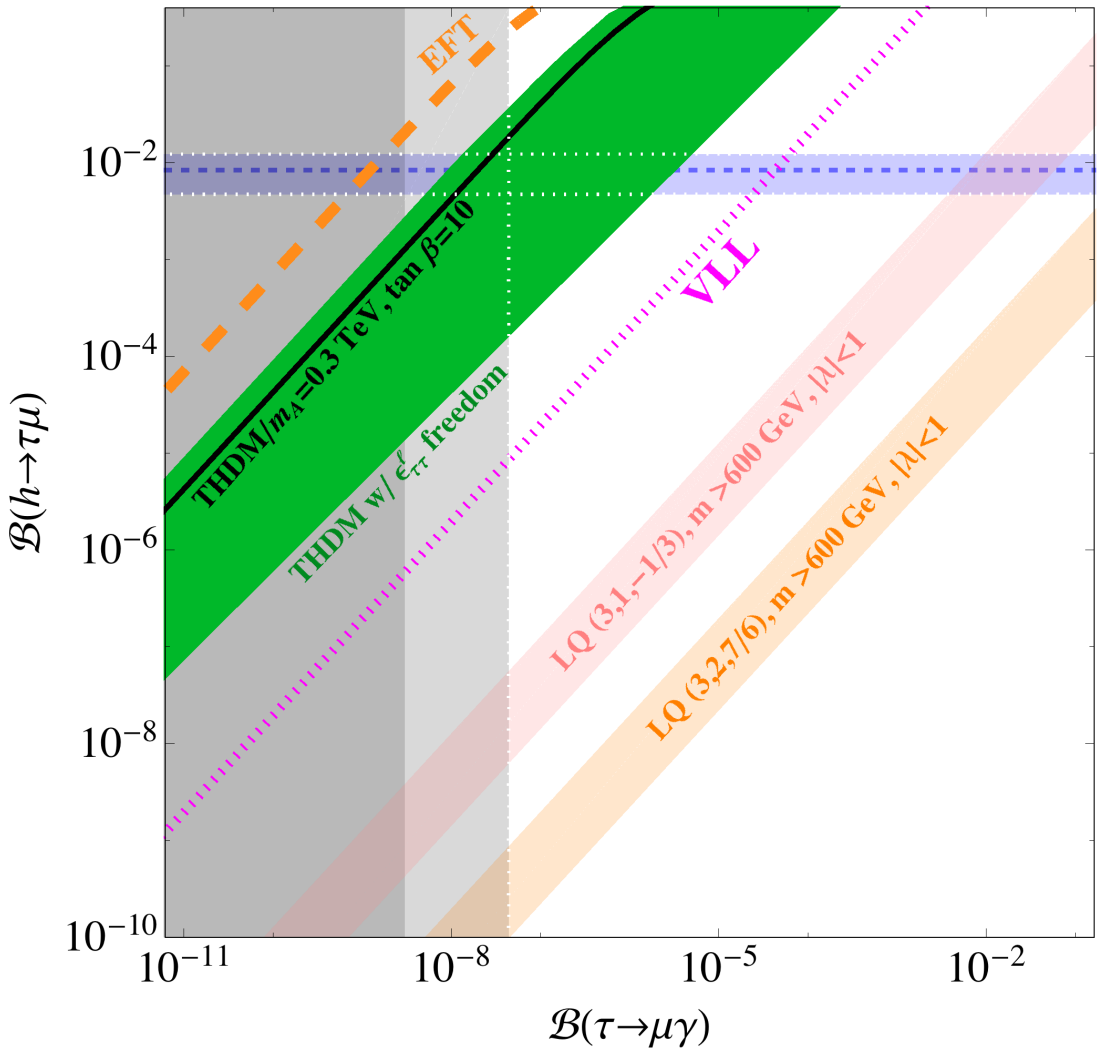
Harnik JK Zupan, arXiv:1209.1397
Davidson Verdier, arXiv:arXiv:1211.1248



CMS-PAS-HIG-14-005

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

- Type III 2HDM seems to work best



Dorsner et al., arXiv:1502.07784
see also Aristizabal-Sierra Vicente, arXiv:1409.7690

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- Example 1: 2HDM with gauged $L_\mu - L_\tau$

  Crivellin D'Ambrosio Heeck, arXiv:1503.00993

  - Simultaneous explanation of $h \to \tau\mu$, $B \to K^* \mu^+ \mu^-$ and $B \to K\mu^+\mu^- / B \to Ke^+e^-$.
  - $L_\mu - L_\tau$ symmetry ensures desired structure of Yukawa couplings
  - Z' boson for the LHCb anomalies
    coupling to quarks via vector-like quarks + $U(1)'$ breaking scalar

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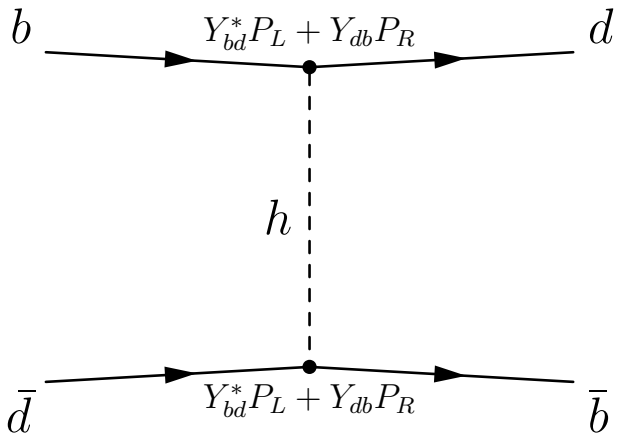
- MFV and Froggatt–Nielsen scenario

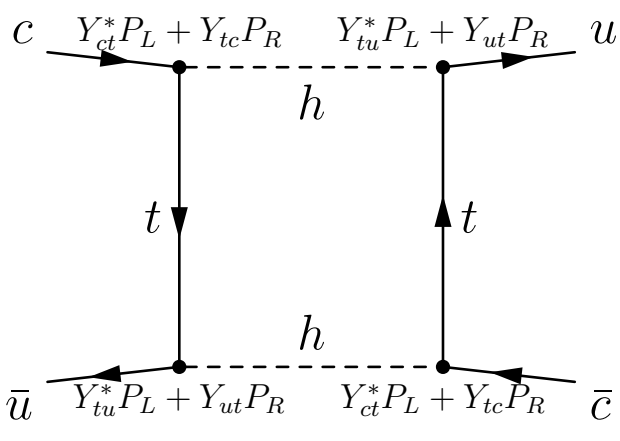
  Dery Efrati Nir Soreq Susič, arXiv:1408.1371

FCNC Couplings to Quarks

Constraints on Higgs couplings to light quarks

- Tight constraints from neutral meson oscillations





Constraints on Higgs 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	$\Re(Y_{ds}^2), \Re(Y_{sd}^2)$	$[-5.9 \dots 5.6] \times 10^{-10}$
	$\Im(Y_{ds}^2), \Im(Y_{sd}^2)$	$[-2.9 \dots 1.6] \times 10^{-12}$
	$\Re(Y_{ds}^* Y_{sd})$	$[-5.6 \dots 5.6] \times 10^{-11}$
	$\Im(Y_{ds}^* Y_{sd})$	$[-1.4 \dots 2.8] \times 10^{-13}$

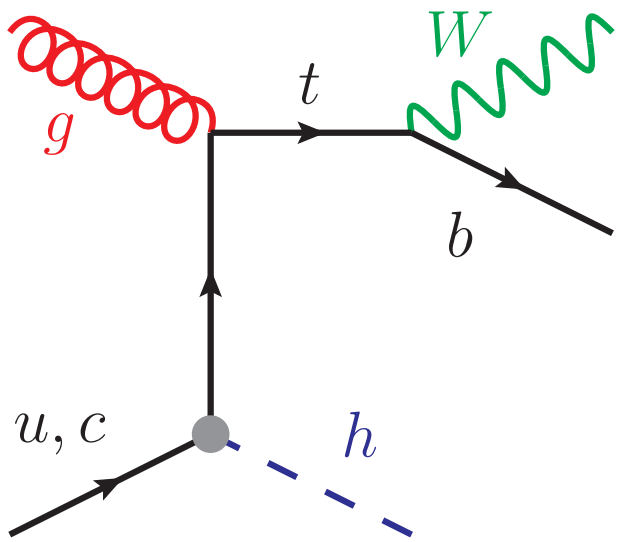
But:

Indirect constraints very weak

for FCNC top couplings

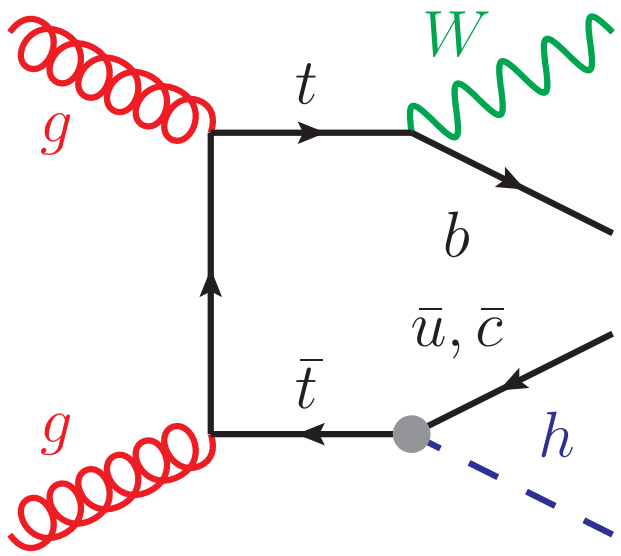
$\Rightarrow$ Discovery potential at the LHC

Multileptons and diphotons from FCNC t–h couplings



single top + Higgs production

- Only relevant for *tuh* couplings (PDF suppression for charm)
- $\ell + 2\gamma$ or up to 5ℓ
- not included in current LHC searches



$t \to hq$ decay

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

LHC limits on $h \to tc$

CMS

- Recasting of multilepton and diphoton channels

$$\mathrm{BR}(t \to cH) < 0.0056 \qquad \leftrightarrow \qquad \sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.14$$

multileptons: CMS arXiv:1404.5801; CMS-SUS-13-002
diphotons: CMS-PAS-HIG-13-034, recasting CMS-PAS-HIG-13-025

ATLAS

- Dedicated $t + (h \to \gamma\gamma)$ analysis

$$\mathrm{BR}(t \to cH) < 0.0079 \qquad \leftrightarrow \qquad \sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.17$$

ATLAS arXiv:1403.6293

Future directions

Some ideas for future improvements

- Include *tuh* couplings $\rightarrow$ leads to factor 1.5 improvement
- Optimize cuts
- Other final states $\rightarrow$ this talk
- η_h as discriminator between *tuh* and *tch* couplings $\rightarrow$ this talk

Greljo Kamenik JK, arXiv: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
    - ⋆ 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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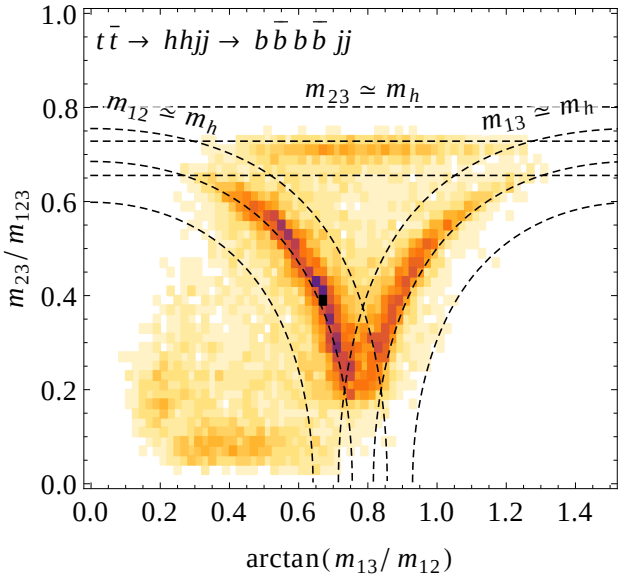
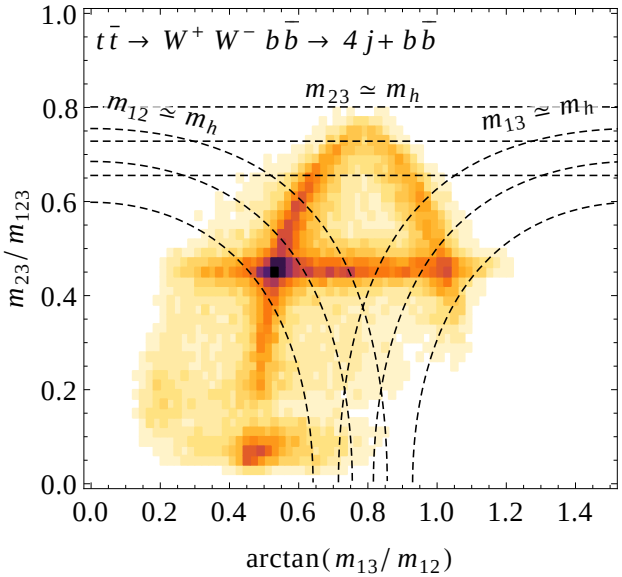
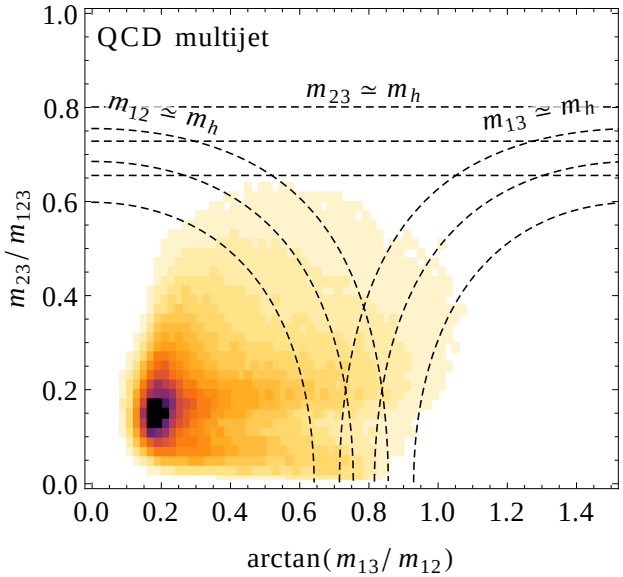
    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
  - Tagging FCNC $t \to hq$ decays: Modified HEPTopTagger
    with adapted kinematic cuts







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

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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

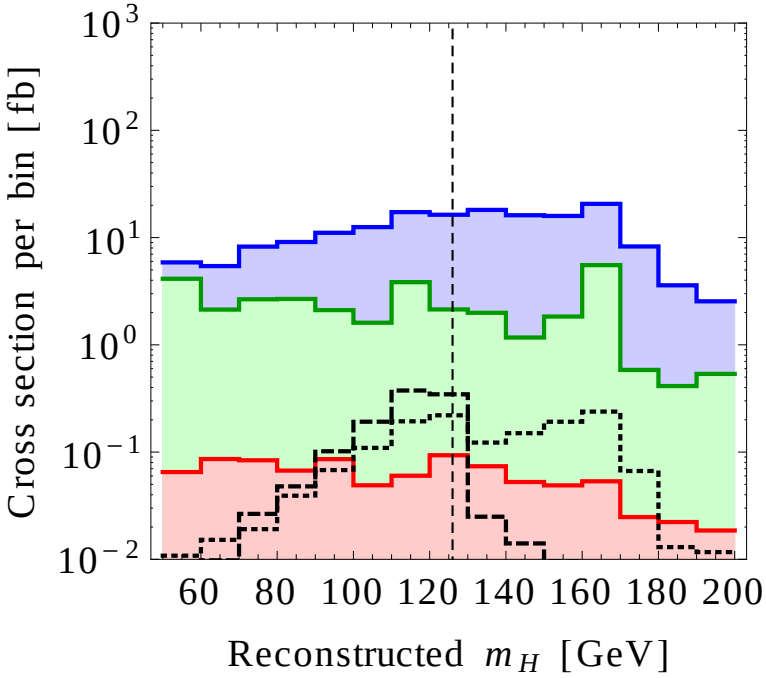
Greljo Kamenik JK, 1404.1278

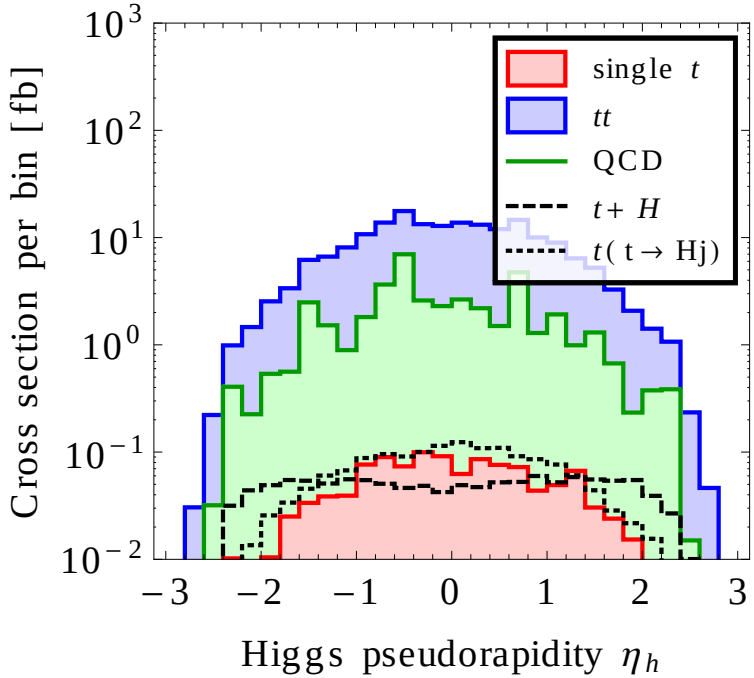
The fully hadronic final state

- 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)

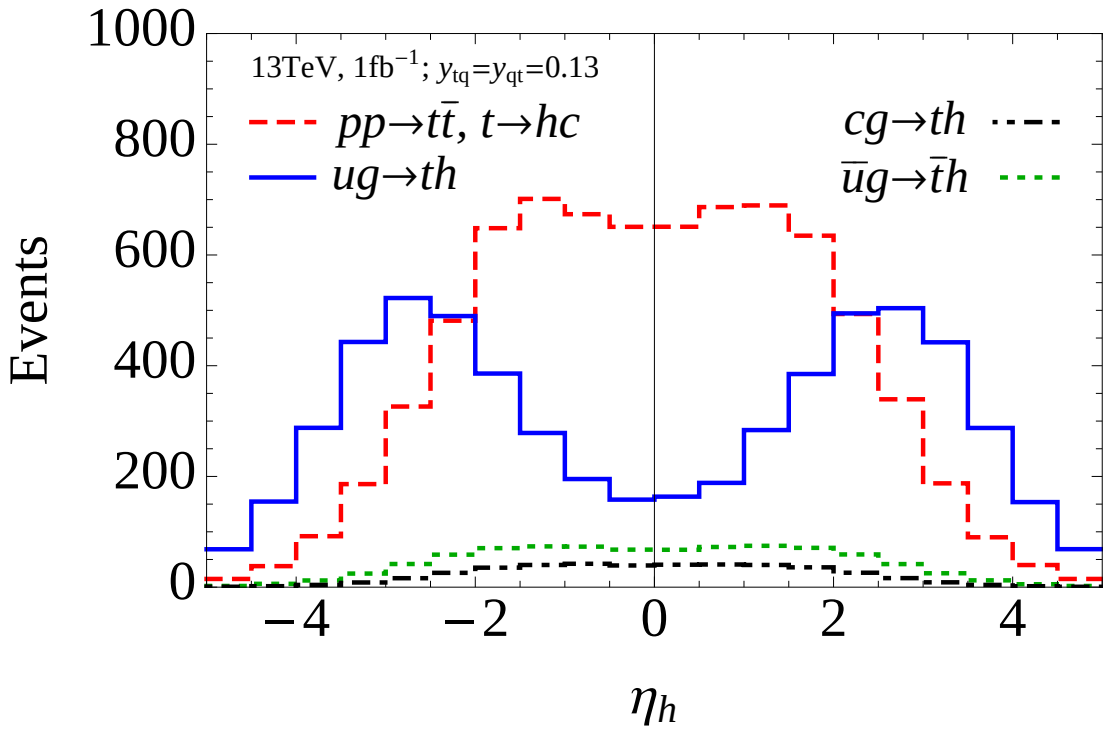




Greljo Kamenik JK, 1404.1278

Discriminating between *tuh* and *tch* couplings

- In $ug \to th$, the t and h are boosted in the direction of the u quark.
  (Valence quarks carry larger fraction of proton momentum.)
- In c.m. frame, h is emitted preferentially in the direction of the up quark
  (angular momentum conservation + chirality flip in *tuh* vertex.)



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

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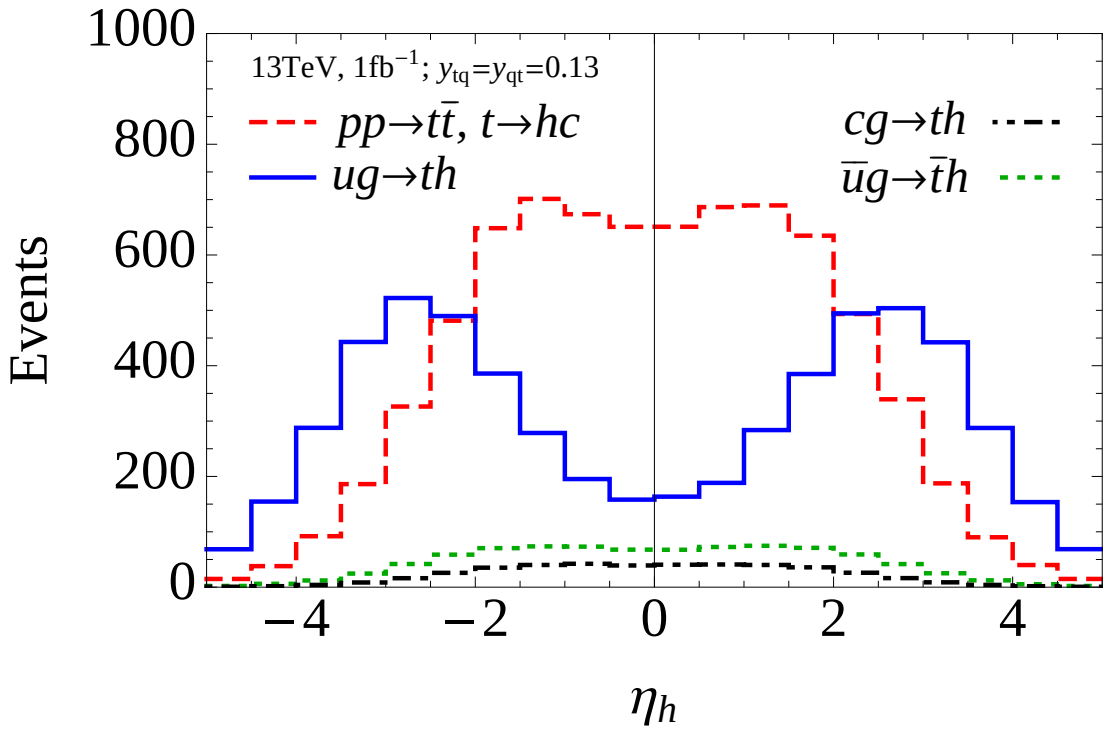
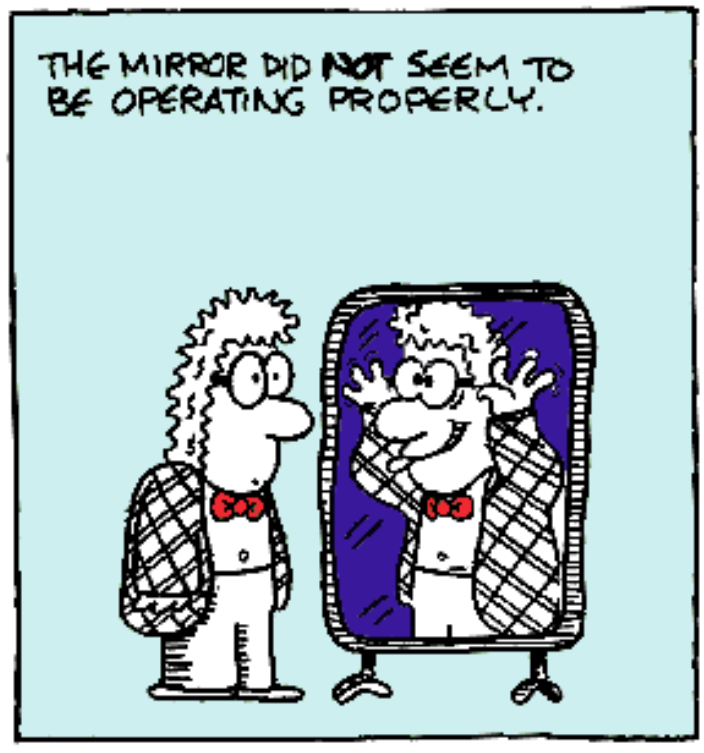


- Final state lepton charges as an additional discriminant.
- Conclusion: For 5σ discovery, 2σ discrimination between *tuh* and *tch*.

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



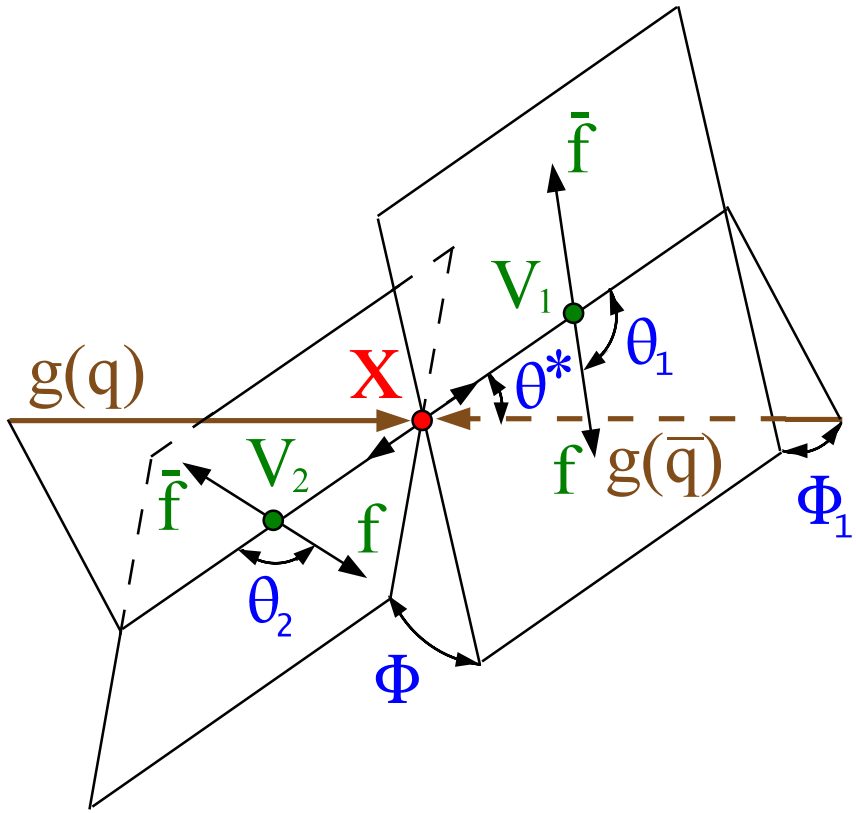
CP Violation in Higgs Decays

CP violation in flavor conserving Higgs decays

- $h \to VV$

$$\mathcal{L} \supset a_1 \frac{m_V^2}{2} H V^\mu V_\mu - \frac{a_3}{2} H V^{\mu\nu} \tilde{V}_{\mu\nu}$$

  - Use angular observables in $h \to ZZ^* \to 4\ell$ and $h \to WW^* \to \ell\nu\ell\nu$.
  - Pure CP-odd Higgs ruled out at 3σ.



CMS, arXiv:1411.3441
ATLS, ATLAS-CONF-2015-008

CP violation in flavor conserving Higgs decays

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- $h \to \tau^+\tau^-$

$$\mathcal{L} \supset -\frac{y_\tau}{\sqrt{2}} h \tau_L^\dagger (\cos\Delta + \sin\Delta\gamma^5)\tau_R + h.c.$$

  - Use kinematics of hadronic τ decay products
  - 5σ sensitivity at 1 ab^{-1}D.

Harnik Martin Okui Primulando Yu, arXiv:1308.1094

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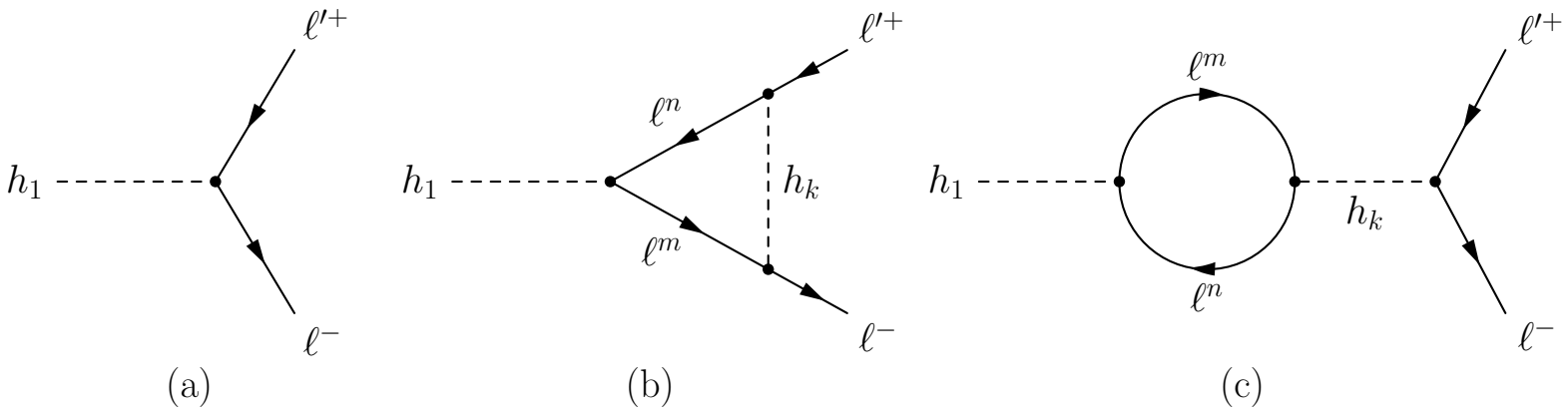
Harnik Martin Okui Primulando Yu, arXiv:1308.1094

- $h \to \gamma\gamma$ with photon conversion to e^+e^-

Bishara Grossman Harnik Robinson Shu Zupan, arXiv:1312.2955

CP violation in FCNC Higgs decays



Basic idea:

- Interference of tree and loop diagrams leads to CP violation
- Weak phase from non-standard Yukawa couplings
- Strong phase from loop function
  (since $m_\ell < m_h/2$)

JK Nardecchia, arXiv:1406.5303

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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Result:

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

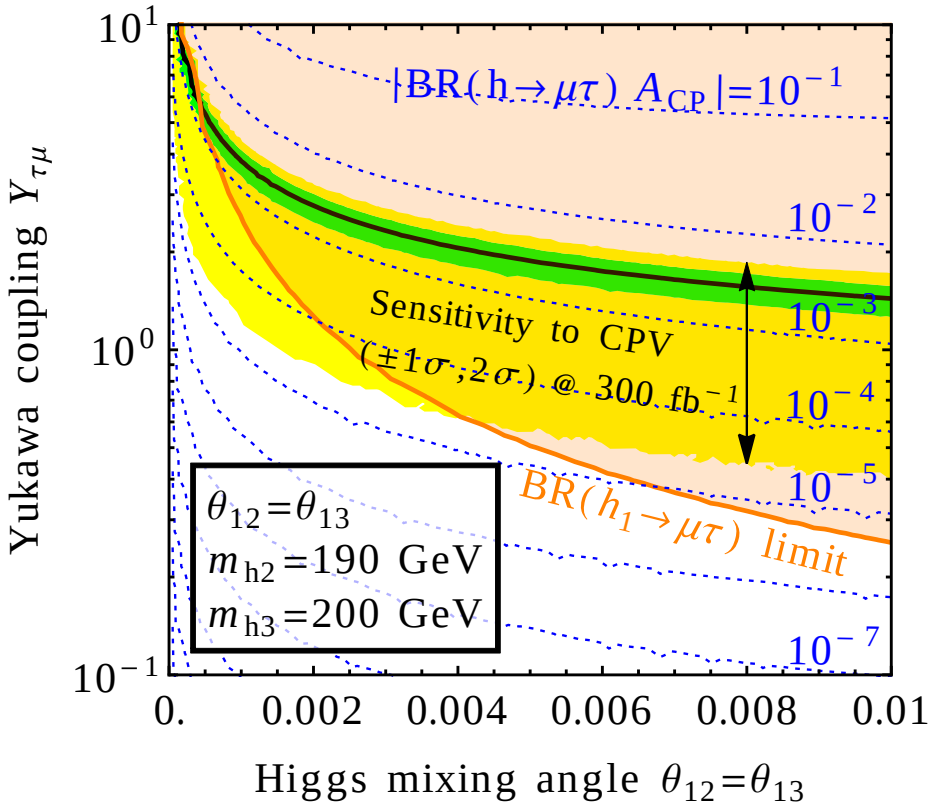
with

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

. . . suppressed only by loop factor

JK Nardecchia, arXiv:1406.5303

Sensitivity to CPV in FCNC Higgs decays @ HL-LHC



- Best discovery potential in small Higgs mixing regime
- CP violation visible only at high-luminosity LHC
- Would require a detection of $h \to \tau\mu$ or $h \to \tau e$ very soon.

JK Nardecchia, arXiv:1406.5303

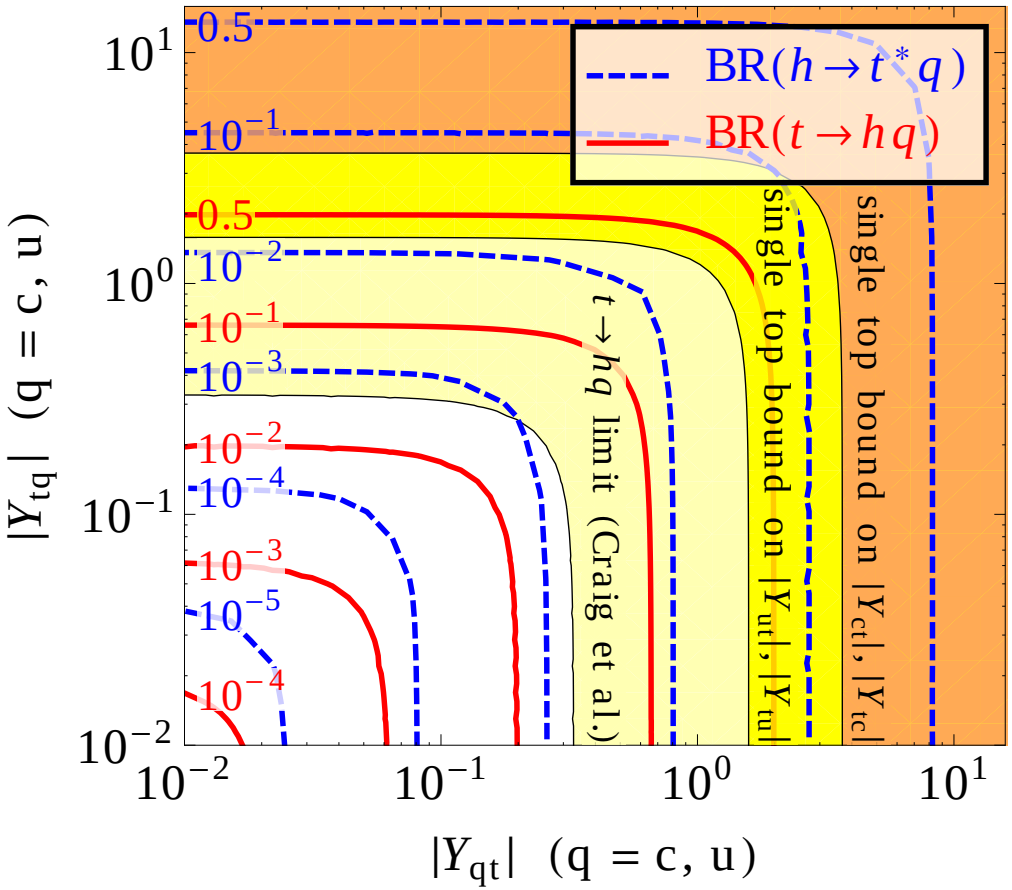
Summary

Summary

- Flavor-violating Higgs couplings arise in
  - Models with several sources of electroweak symmetry breaking
  - Models with heavy fields coupled to the Higgs
- In the lepton sector:
  - In the μ–e sector: strong constraints from LFV searches
  - In the τ–e and τ–μ sectors: strongest constraints from the LHC
  - 2σ excess in CMS
- In the quark sector:
  - Light quarks: strong constraints from meson mixing
  - Top quark: Limits on $t \to ch$ from multileptons, diphotons
  - In the future:
    - Include anomalous single-t production
    - Optimized cuts
    - Other final states
    - Discriminating tuh and tch couplings
- CP violation in Higgs decays
  - Possible effects in $h \to VV$, $h \to \tau^+\tau^-$, $h \to \gamma\gamma$
  - If CMS $h \to \tau\mu$ solidifies
    Possible CPV effects in $h \to \tau\mu$

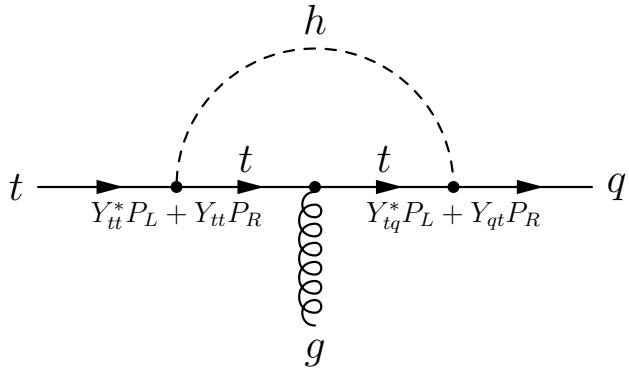
Thank you!

Couplings involving top quarks (anno 2012)



Constraints from

- Single top production



CDF 0812.3400, DØ 1006.3575
ATLAS 1203.0529

- $t \to hq$

Craig et al. 1207.6794
based on CMS multilepton search
1204.5341

Not sensitive

- $t \to Zq$

CMS 1208.0957

Example: Effective Field Theory

$$\mathcal{L}_{\text{EFT}} \supset -m_i \bar{\ell}_L^i \ell_R^i - Y_{ij}^h (\bar{\ell}_L^i \ell_R^j) h + h.c.\,,$$

Result:

$$\begin{aligned} A_{CP}^{\mu\tau} &= \frac{\Gamma(h \to \mu^- \tau^+) - \Gamma(h \to \mu^+ \tau^-)}{\Gamma(h \to \mu^- \tau^+) + \Gamma(h \to \mu^+ \tau^-)} \\ &= \frac{1 - \log 2}{8\pi} \frac{\text{Im}\left[Y_{\tau\tau}^h \left(Y_{e\mu}^h Y_{e\tau}^{h*} Y_{\mu\tau}^{h*} - Y_{\mu e}^h Y_{\tau e}^{h*} Y_{\tau\mu}^{h*} \right) \right]}{\left| Y_{\mu\tau}^h \right|^2 + \left| Y_{\tau\mu}^h \right|^2} \\ &\quad + \frac{1}{8\pi} \frac{m_\tau^2}{m_h^2} \frac{\left| Y_{\mu\tau}^h \right|^2 - \left| Y_{\tau\mu}^h \right|^2}{\left| Y_{\mu\tau}^h \right|^2 + \left| Y_{\tau\mu}^h \right|^2} \text{Im}\left[(Y_{\tau\tau}^h)^2 \right] \,. \end{aligned}$$

... suppressed by m_τ^2/m_h^2 and $Y_{e\mu}^h$, $Y_{\mu e}^h$.