Flavor and CP Violation in Higgs Decays

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University of Mainz / PRISMA Cluster of Excellence

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

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

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

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
Casagrande Goertz Haisch Neubert Pfoh, 0807.4937
Blanke Buras Duling Gori Weiler, 0809.1073
Aguilar-Saavedra, 0904.2387
Agashe Contino, 0906.1542
Davidson Greiner, 1001.0434
Blankenburg Ellis Isidori, 1202.5704
McKeen Pospelov Ritz, 1208.4597
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
Albrecht Blanke Buras Duling Gemmler, 0903.2415
Buras Duling Gori, 0905.2318
Azatov Toharia Zhu, 0906.1990
Goudelis Lebedev Park, 1111.1715
Wang Huang Li Li Shao Wang, 1208.2902
Arhrib Cheng Kong, 1208.4669

...

Effective Yukawa Lagrangfian

Effective Yukawa Lagrangian

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

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

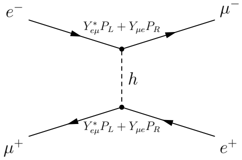
$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}^a (\bar{f}_L^i f_R^j) h^a + h.c. + \cdots$$

New in this talk:

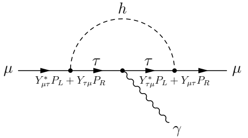
- Up-to-date low-energy constraints on FV decays
- LHC limits on $h \to \mu\tau$, $h \to e\tau$, $t \to ch$, $t \to uh$
- Strategies for future LHC searches
- Possibility of Flavor + CP violation

FCNC Higgs Couplings to Leptons

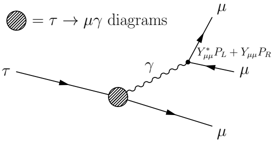
Low-energy constraints on LFV in the Higgs sector



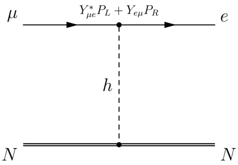
M–$\bar{M}$ oscillations



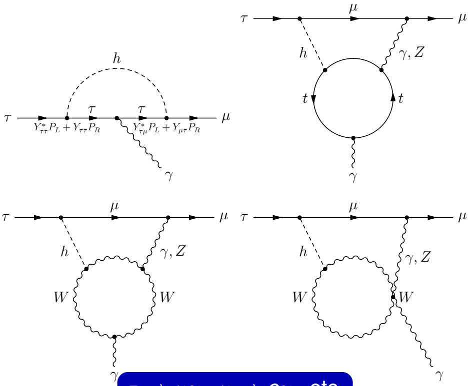
$g-2$, EDMs



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

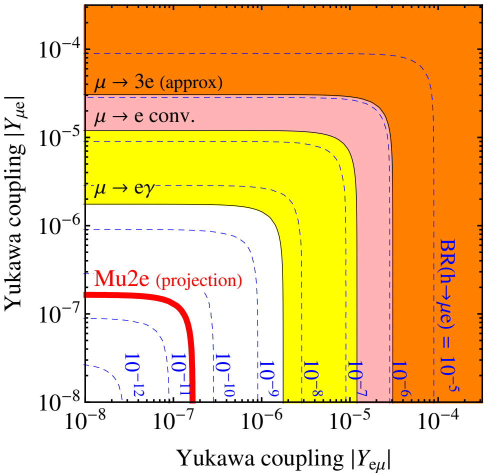


μ–e conversion



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

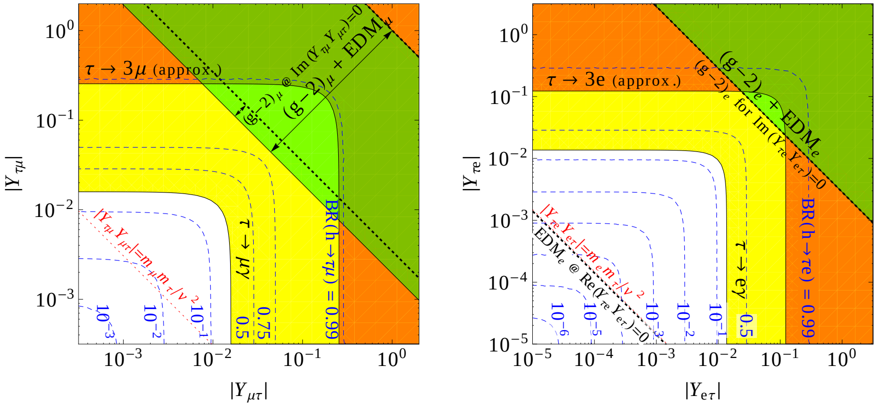
Constraints on $h \to \mu e$



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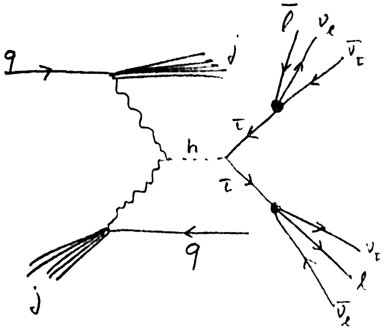
Harnik JK Zupan, arXiv:1209.1397
see also: Blankenburg Ellis Isidori, arXiv:1202.5704
Goudelis Lebedev Park, arXiv:1111.1715
Davidson Greiner, arXiv:1001.0434

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

Basic idea:

- $h \to \tau\ell$ has the same final state as $h \to \tau\tau_\ell$
  (but is enhanced by $1/\mathrm{BR}(\tau \to \ell)$)
- Recast $h \to \tau\tau$ search
  here: ATLAS, arXiv:1206.5971
- Consider only 2-lepton final states
- Use VBF cuts
  (much lower BG than gg fusion)

see however
Davidson Verdier, arXiv:1211.1248



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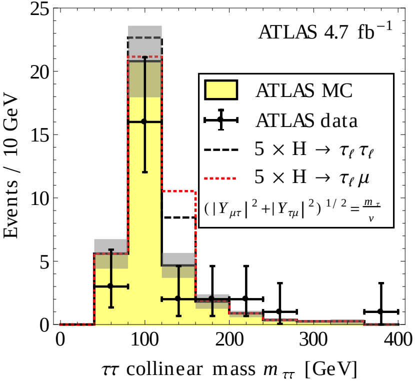
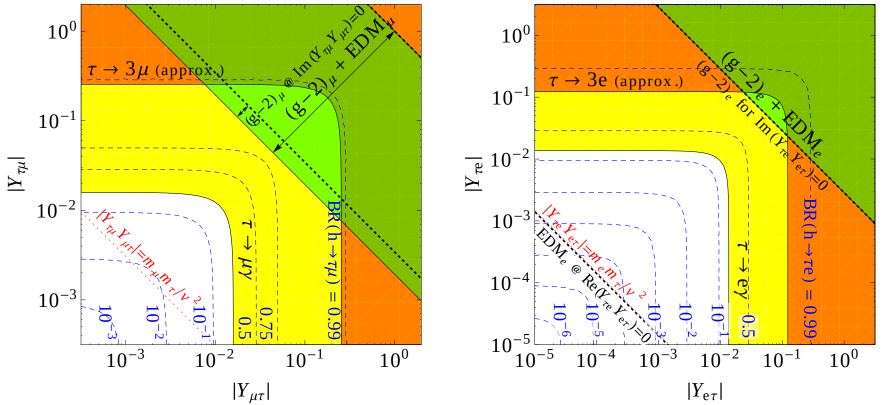
Harnik JK Zupan, arXiv:1209.1397
based on ATLAS, arXiv:1206.5971

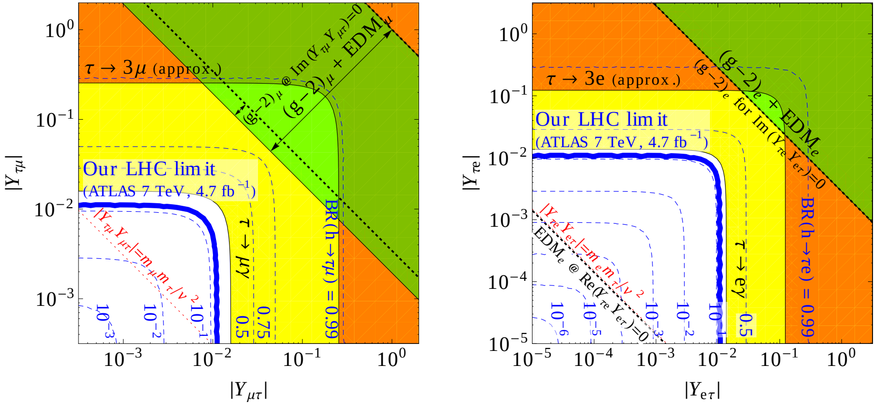


LHC constraints on $h \to \tau\mu$ and $h \to \tau e$



Harnik JK Zupan, arXiv:1209.1397

LHC constraints on $h \to \tau\mu$ and $h \to \tau e$



Harnik JK Zupan, arXiv:1209.1397

Strategy for a dedicated $h \to \tau\mu$ and $h \to \tau e$ search

Possible improvements

- Different invariant mass formula
  - Avoids smearing of signal
  - Shifts $Z \to \tau\tau$ peak to lower invariant mass
- Include hadronic τ's
- Optimized cuts
  - Use higher lepton p_T in $h \to \mu\tau$ compared to $h \to \tau\tau$
  - Use $\Delta\phi$ and M_T cuts
  - Allows inclusion of gg fusion events

Harnik JK Zupan, arXiv:1209.1397
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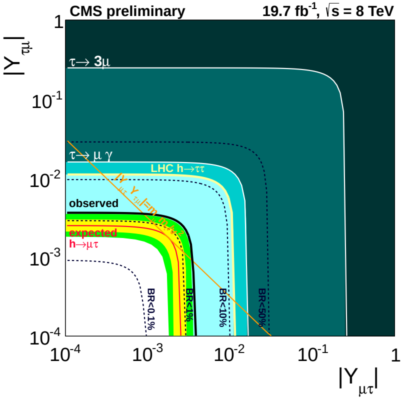
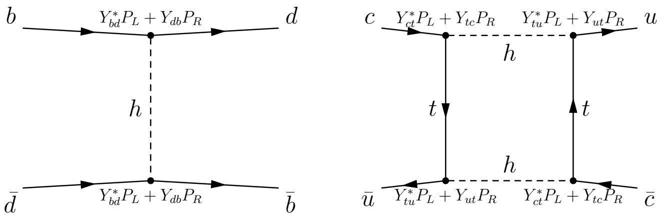


CMS-PAS-HIG-14-005

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

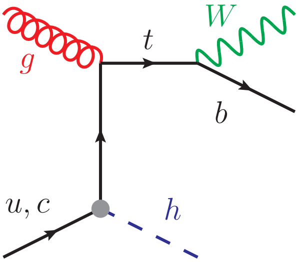
But:

Indirect constraints very weak

for FCNC top couplings

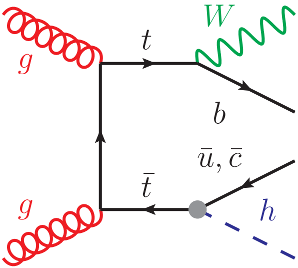
$\Rightarrow$ Discovery potential at the LHC

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 LHC searches



$t \to hq$ decay

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

Combined CMS diphoton + multilepton results

Higgs Decay Mode		observed	expected	1σ range
$\mathrm{H} \to \mathrm{WW}^*$	$(\mathcal{B} = 23.1\,\%)$	1.58 %	1.57 %	(1.02–2.22) %
$\mathrm{H} \to \tau\tau$	$(\mathcal{B} = 6.15\,\%)$	7.01 %	4.99 %	(3.53–7.74) %
$\mathrm{H} \to \mathrm{ZZ}^*$	$(\mathcal{B} = 2.89\,\%)$	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)		1.28 %	1.17 %	(0.85–1.73) %
$\mathrm{H} \to \gamma\gamma$	$(\mathcal{B} = 0.23\,\%)$	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons		0.56 %	0.65 %	(0.46–0.94) %

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

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

see also ATLAS $t + (h \to \gamma\gamma)$ analysis with tailored cuts, slightly worse limit due to unlucky statistical fluctuations

ATLAS arXiv:1403.6293

Future directions

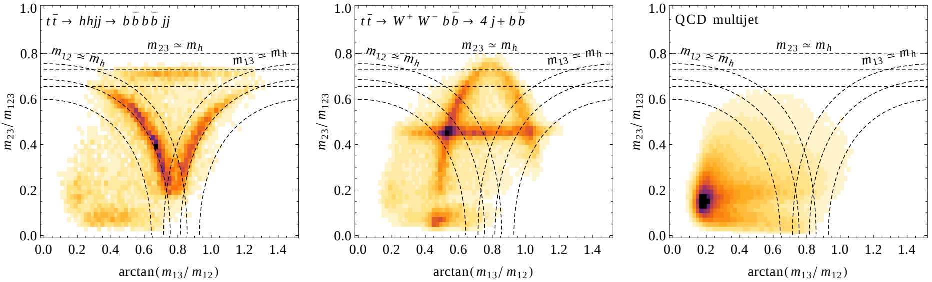
Some ideas for future improvements

- 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

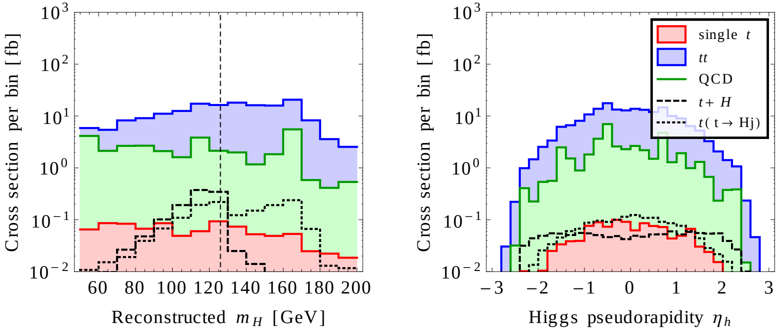
- Analysis 1: $pp \to \bar{t}(t \to hj) \to$ hadrons
  - Tagging SM $t \to Wb$ decays: HEPTopTagger
    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
  - Tagging FCNC $t \to hq$ decays: Modified HEPTopTagger with adapted kinematic cuts
  - Require b tags in likely b subjets



Greljo Kamenik JK, arXiv: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, arXiv:1404.1278

Comparison of current and projected future limits

	$\sqrt{y_{ut}^2 + y_{tu}^2}$	BR($t \to hu$)	$\sqrt{y_{ct}^2 + y_{tc}^2}$	BR($t \to hc$)
New limits from existing data				
Multilepton	< 0.19	< 0.010	< 0.23	< 0.015
Diphoton plus lepton	< 0.12	< 0.0045	< 0.15	< 0.0066
Vector boson plus Higgs	< 0.16	< 0.0070	< 0.21	< 0.012
Projected future limits (13 TeV, 100 fb^{-1})				
Vector boson plus Higgs	< 0.076	< 0.0015	< 0.084	< 0.0019
Multilepton	< 0.087	< 0.0022	< 0.11	< 0.0033
Fully hadronic	< 0.12	< 0.0036	< 0.13	< 0.0048

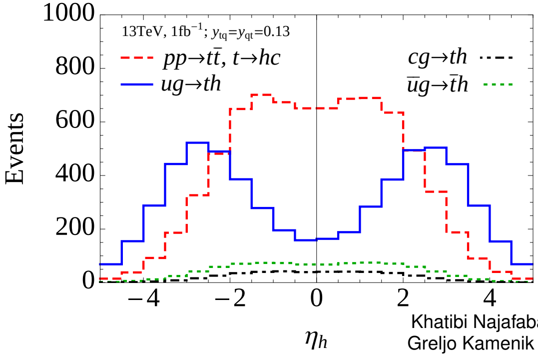
Greljo Kamenik JK, arXiv:1404.1278

Discriminating between *tuh* and *tch* couplings

In $ug \to th$, interaction products tend to be boosted in the direction of the u quark.
(Valence quarks carry larger fraction of proton momentum.)

Moreover: In center of mass frame, Higgs boson is emitted preferentially in the direction of the up quark
(angular momentum conservation + chirality flip in *tuh* Yukawa vertex.)

Result (parton level):



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

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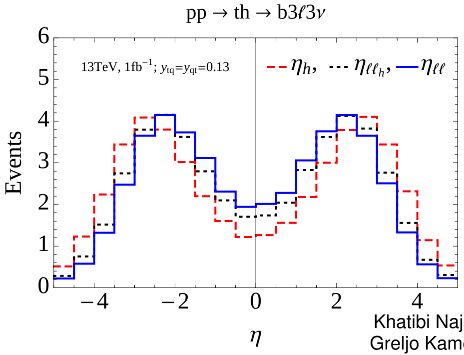
Parton level vs. analysis level:



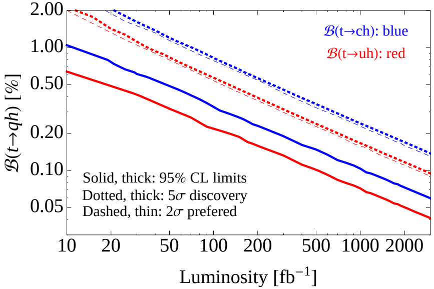
Khatibi Najafabadi, arXiv:1402.3073
Greljo Kamenik JK, arXiv:1404.1278

Discriminating between *tuh* and *tch* couplings (2)

Conclusion: Rapidity $\eta_{\ell\ell}$ of dilepton system from $h \to WW^* \to \ell\ell\nu\nu$ is a good discriminator between *tuh* and *tch* couplings.

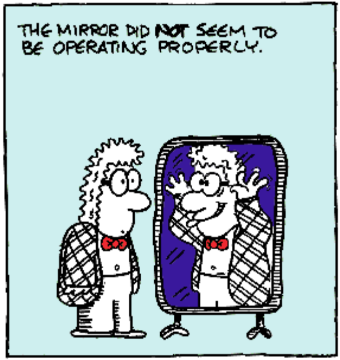
Moreover: Final state lepton charges as an additional discriminant.

Result for multilepton search:



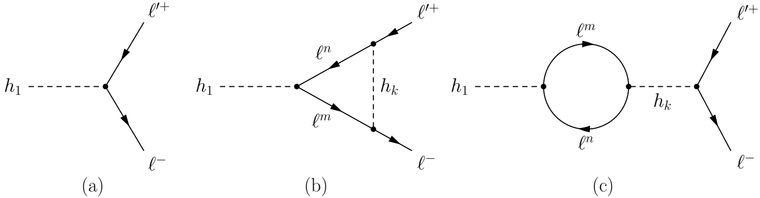
For a 5σ discovery, discrimination between *tuh* and *tch* is possible at 2σ.

Greljo Kamenik JK, arXiv:1404.1278



CP Violation in FCNC Higgs Decays

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

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

In the physical basis:

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

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

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:

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

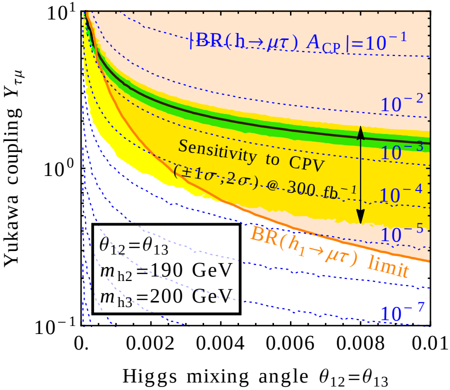
with

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

. . . suppressed only by loop factor

JK Nardecchia, arXiv:1406.5303

Sensitivity to CPV in 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
  - If $h \to \tau\mu$ or $h \to \tau e$ is discovered soon:
    Possibility to look for CP violation in the future.
- In the quark sector:
  - Light quarks: strong constraints from meson mixing
  - Top quark: Limits on $t \to ch$ from multileptons, diphotons
  - Future improvements:
    - ★ Include anomalous single-t production for tuh couplings
    - ★ Optimized cuts
    - ★ Other final states (fully hadronic is feasible with jet substructure techniques)
    - ★ Use Higgs rapidity η_h and lepton charges as a discriminator between tuh and tch couplings

Thank you!

CMS event selection for multilepton analysis

- At least 3 leptons
  (electrons, muons, hadronic tau candidates ("τ_h")
- Standard p_T and η cuts
  - $p_T^{e,\mu} > 10$ GeV, $|\eta^{e,\mu}| < 2.4$
  - $p_T^{\tau_h} > 20$ GeV, $|\eta^{\tau_h}| < 2.3$
  - at least one e or μ must be above 20 GeV
- Isolation criteria
- Lepton tracks required to start close to the primary vertex
- Jets are reconstructed with the anti-k_T algorithm; must have $p_T > 30$ GeV, $|\eta| < 2.5$
- Combined secondary vertex algorithm for b-tagging

CMS arXiv:1404.5801; CMS-SUS-13-002

CMS event classification for multilepton analysis

Events are sorted in non-overlapping categories according to

- Number of leptons (3 or ≥ 4)
- $\not\!\!E_T$
- Number of τ_h candidates
- Number of b-tagged jets
- Number of OSSF ("opposite sign, same flavor") lepton pairs
- OSSF pairs on/off the Z-resonance

→ A very versatile search that is sensitive to many types of new physics

CMS arXiv:1404.5801; CMS-SUS-13-002

Backgrounds for CMS multilepton analysis

- Z + jets
  (two leptons from Z decay, one lepton from misidentified jet or heavy flavor decay)
- SM WZ or ZZ production
- $t\bar{t}$ production
  (two leptons from W decay, one lepton from semileptonic b decay)
- Internal conversion of photons
- Rare processes
  (triple boson production, $t\bar{t} + V$ production)

Relative importance of backgrounds varies significantly between event categories.

So do systematic uncertainties.

CMS arXiv:1404.5801; CMS-SUS-13-002

Results: 3-lepton categories

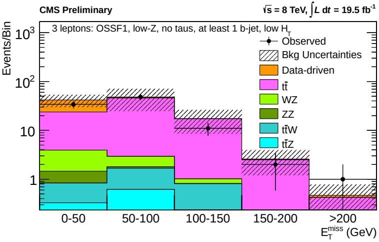
3 leptons $H_T > 200\,\text{GeV}$	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h} = 0, N_b = 0$		$N_{\tau_h} = 1, N_b = 0$		$N_{\tau_h} = 0, N_b \geq 1$		$N_{\tau_h} = 1, N_b \geq 1$	
			Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
OSSF0	—	$(100, \infty)$	5	3.7 ± 1.6	35	33 ± 14	1	5.5 ± 2.2	47	61 ± 30
OSSF0	—	$(50, 100)$	3	3.5 ± 1.4	34	36 ± 16	8	7.7 ± 2.7	82	91 ± 46
OSSF0	—	$(0, 50)$	4	2.1 ± 0.8	25	25 ± 10	1	3.6 ± 1.5	52	59 ± 29
OSSF1	Above-Z	$(100, \infty)$	5	3.6 ± 1.2	2	10.0 ± 4.8	3	4.7 ± 1.6	19	22 ± 11
OSSF1	Below-Z	$(100, \infty)$	7	9.7 ± 3.3	18	14.0 ± 6.4	8	9.1 ± 3.4	21	23 ± 11
OSSF1	On-Z	$(100, \infty)$	39	61 ± 23	17	15.0 ± 4.9	9	14.0 ± 4.4	10	12.0 ± 5.8
OSSF1	Above-Z	$(50, 100)$	4	5.0 ± 1.6	14	11.0 ± 5.2	6	6.8 ± 2.4	32	30 ± 15
OSSF1	Below-Z	$(50, 100)$	10	11.0 ± 3.8	24	19.0 ± 6.4	10	9.9 ± 3.7	25	32 ± 16
OSSF1	On-Z	$(50, 100)$	78	80 ± 32	70	50 ± 11	22	22.0 ± 6.3	36	24.0 ± 9.8
OSSF1	Above-Z	$(0, 50)$	3	7.3 ± 2.0	41	33.0 ± 8.7	4	5.3 ± 1.5	15	23 ± 11
OSSF1	Below-Z	$(0, 50)$	26	25.0 ± 6.8	110	86 ± 23	5	10.0 ± 2.5	24	26 ± 11
OSSF1	On-Z	$(0, 50)$	*135	130 ± 41	542	540 ± 160	31	32.0 ± 6.5	86	75 ± 19
3 leptons $H_T < 200\,\text{GeV}$	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h} = 0, N_b = 0$		$N_{\tau_h} = 1, N_b = 0$		$N_{\tau_h} = 0, N_b \geq 1$		$N_{\tau_h} = 1, N_b \geq 1$	
			Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
OSSF0	—	$(100, \infty)$	7	11.0 ± 4.9	101	111 ± 54	13	10.0 ± 5.3	87	119 ± 61
OSSF0	—	$(50, 100)$	35	38 ± 15	406	402 ± 152	29	26 ± 13	269	298 ± 151
OSSF0	—	$(0, 50)$	53	51 ± 11	910	1035 ± 255	29	23 ± 10	237	240 ± 113
OSSF1	Above-Z	$(100, \infty)$	18	13.0 ± 3.5	25	38 ± 18	10	6.5 ± 2.9	24	35 ± 18
OSSF1	Below-Z	$(100, \infty)$	21	24 ± 9	41	50 ± 25	14	20 ± 10	42	54 ± 28
OSSF1	On-Z	$(100, \infty)$	150	150 ± 26	39	48 ± 13	15	14.0 ± 4.8	19	23 ± 11
OSSF1	Above-Z	$(50, 100)$	50	46.0 ± 9.7	169	140 ± 48	20	18 ± 8	85	93 ± 47
OSSF1	Below-Z	$(50, 100)$	142	130 ± 27	353	360 ± 92	48	48 ± 23	140	133 ± 68
OSSF1	On-Z	$(50, 100)$	*773	780 ± 120	1276	1200 ± 310	56	47 ± 13	81	75 ± 32
OSSF1	Above-Z	$(0, 50)$	178	200 ± 35	1676	1900 ± 540	17	18.0 ± 6.7	115	94 ± 42
OSSF1	Below-Z	$(0, 50)$	510	560 ± 87	9939	9000 ± 2700	34	42 ± 11	226	228 ± 63
OSSF1	On-Z	$(0, 50)$	*3869	4100 ± 670	*50188	50000 ± 15000	*148	156 ± 24	906	925 ± 263

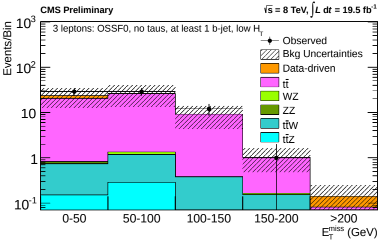
* = channels used for normalization, excluded from new physics searches

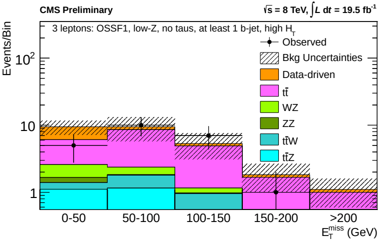
Results: 4-lepton categories

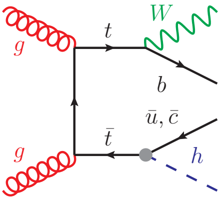
≥4 leptons $H_T > 200$ GeV	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h} = 0, N_b = 0$ Obs.	Exp.	$N_{\tau_h} = 1, N_b = 0$ Obs.	Exp.	$c_{\tau_h} = 0, N_b \geq 1$ Obs.	Exp.	$N_{\tau_h} = 1, N_b \geq 1$ Obs.	Exp.
OSSF0	—	$(100, \infty)$	0	$0.01^{+0.03}_{-0.01}$	0	$0.01^{+0.06}_{-0.01}$	0	$0.02^{+0.04}_{-0.02}$	0	0.11 ± 0.08
OSSF0	—	$(50, 100)$	0	$0.00^{+0.02}_{-0.00}$	0	$0.01^{+0.06}_{-0.01}$	0	$0.00^{+0.03}_{-0.00}$	0	0.12 ± 0.07
OSSF0	—	$(0, 50)$	0	$0.00^{+0.02}_{-0.00}$	0	$0.07^{+0.10}_{-0.07}$	0	$0.00^{+0.02}_{-0.00}$	0	0.02 ± 0.02
OSSF1	Off-Z	$(100, \infty)$	0	$0.01^{+0.02}_{-0.01}$	1	0.25 ± 0.11	0	0.13 ± 0.08	0	0.12 ± 0.12
OSSF1	On-Z	$(100, \infty)$	1	0.10 ± 0.06	0	0.50 ± 0.27	0	0.42 ± 0.22	0	0.42 ± 0.19
OSSF1	Off-Z	$(50, 100)$	0	0.07 ± 0.06	1	0.29 ± 0.13	0	0.04 ± 0.04	0	0.23 ± 0.13
OSSF1	On-Z	$(50, 100)$	0	0.23 ± 0.11	1	0.70 ± 0.31	0	0.23 ± 0.13	1	0.34 ± 0.16
OSSF1	Off-Z	$(0, 50)$	0	$0.02^{+0.03}_{-0.02}$	0	0.27 ± 0.12	0	$0.03^{+0.04}_{-0.03}$	0	0.31 ± 0.15
OSSF1	On-Z	$(0, 50)$	0	0.20 ± 0.08	0	1.3 ± 0.5	0	0.06 ± 0.04	1	0.49 ± 0.19
OSSF2	Off-Z	$(100, \infty)$	0	$0.01^{+0.02}_{-0.01}$	—	—	0	$0.01^{+0.06}_{-0.01}$	—	—
OSSF2	On-Z	$(100, \infty)$	1	$0.15^{+0.16}_{-0.15}$	—	—	0	0.34 ± 0.18	—	—
OSSF2	Off-Z	$(50, 100)$	0	0.03 ± 0.02	—	—	0	0.13 ± 0.09	—	—
OSSF2	On-Z	$(50, 100)$	0	0.80 ± 0.40	—	—	0	0.36 ± 0.19	—	—
OSSF2	Off-Z	$(0, 50)$	1	0.27 ± 0.13	—	—	0	0.08 ± 0.05	—	—
OSSF2	On-Z	$(0, 50)$	5	7.4 ± 3.5	—	—	2	0.80 ± 0.40	—	—
≥4 leptons $H_T < 200$ GeV	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h} = 0, N_b = 0$ Obs.	Exp.	$N_{\tau_h} = 1, N_b = 0$ Obs.	Exp.	$N_{\tau_h} = 0, N_b \geq 1$ Obs.	Exp.	$N_{\tau_h} = 1, N_b \geq 1$ Obs.	Exp.
OSSF0	—	$(100, \infty)$	0	0.11 ± 0.08	0	0.17 ± 0.10	0	$0.03^{+0.04}_{-0.03}$	0	0.04 ± 0.04
OSSF0	—	$(50, 100)$	0	$0.01^{+0.03}_{-0.01}$	2	0.70 ± 0.33	0	$0.00^{+0.02}_{-0.00}$	0	0.28 ± 0.16
OSSF0	—	$(0, 50)$	0	$0.01^{+0.02}_{-0.01}$	1	0.7 ± 0.3	0	$0.00^{+0.02}_{-0.00}$	0	0.13 ± 0.08
OSSF1	Off-Z	$(100, \infty)$	0	0.06 ± 0.04	3	0.60 ± 0.24	0	$0.02^{+0.04}_{-0.02}$	0	0.32 ± 0.20
OSSF1	On-Z	$(100, \infty)$	1	0.50 ± 0.18	2	2.5 ± 0.5	1	0.38 ± 0.20	0	0.21 ± 0.10
OSSF1	Off-Z	$(50, 100)$	0	0.18 ± 0.06	4	2.1 ± 0.5	0	0.16 ± 0.08	1	0.45 ± 0.24
OSSF1	On-Z	$(50, 100)$	2	1.2 ± 0.3	9	9.6 ± 1.6	2	0.42 ± 0.23	0	0.50 ± 0.16
OSSF1	Off-Z	$(0, 50)$	2	0.46 ± 0.18	15	7.5 ± 2.0	0	0.09 ± 0.06	0	0.70 ± 0.31
OSSF1	On-Z	$(0, 50)$	4	3.0 ± 0.8	41	40 ± 10	1	0.31 ± 0.15	2	1.50 ± 0.47
OSSF2	Off-Z	$(100, \infty)$	0	0.04 ± 0.03	—	—	0	0.05 ± 0.04	—	—
OSSF2	On-Z	$(100, \infty)$	0	0.34 ± 0.15	—	—	0	0.46 ± 0.25	—	—
OSSF2	Off-Z	$(50, 100)$	2	0.18 ± 0.13	—	—	0	$0.02^{+0.03}_{-0.02}$	—	—
OSSF2	On-Z	$(50, 100)$	4	3.9 ± 2.5	—	—	0	0.50 ± 0.21	—	—
OSSF2	Off-Z	$(0, 50)$	7	8.9 ± 2.4	—	—	1	0.23 ± 0.09	—	—
OSSF2	On-Z	$(0, 50)$	*156	160 ± 34	—	—	4	2.9 ± 0.8	—	—

The most sensitive channels in the $t \to cH$ search









Relevant are mostly the two lowest $\not{E}_T$ bins.

CMS arXiv:1404.5801; CMS-SUS-13-002

$t \to cH$: CMS Constraints

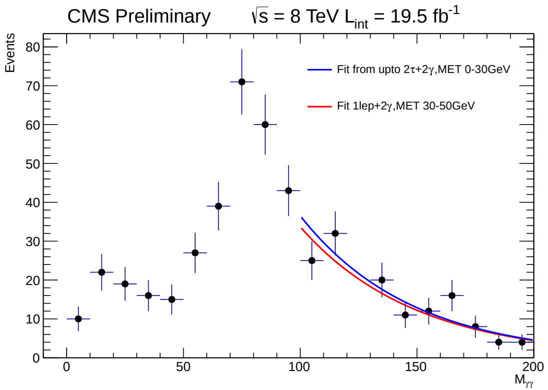
Higgs Decay Mode		obs	exp	1σ range
$h \to WW^*$	(BR = 23.1 %)	1.58 %	1.57 %	(1.02–2.22) %
$h \to \tau\tau$	(BR = 6.15 %)	7.01 %	4.99 %	(3.53–7.74) %
$h \to ZZ^*$	(BR = 2.89 %)	5.31 %	4.11 %	(2.85–6.45) %
combined		1.28 %	1.17 %	(0.85–1.73) %

$$\mathrm{BR}(t \to cH) < 0.013$$

$$\sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.21$$

CMS arXiv:1404.5801; CMS-SUS-13-002

Diphoton + lepton — Backgrounds



Background from sideband fit at $m_{\gamma\gamma} < 120$ GeV and $m_{\gamma\gamma} > 130$ GeV.

CMS-PAS-HIG-13-034, recasting CMS-PAS-HIG-13-025

$t \rightarrow cH$ search in the diphoton + lepton channel

Requirements:

- One isolated lepton ($p_T > 10$ GeV, $|\eta| < 2.4$)
- Two photons ($p_{T1} > 40$ GeV, $p_{T1} > 20$ GeV, $|\eta| < 2.5$)
- $120\ \text{GeV} < m_{\gamma\gamma} < 130\ \text{GeV}$

Events are classified according to

- $\not{E}_T$
- b-tagged jets
- τ_h candidates

CMS-PAS-HIG-13-034, recasting CMS-PAS-HIG-13-025

Diphoton + lepton — Results

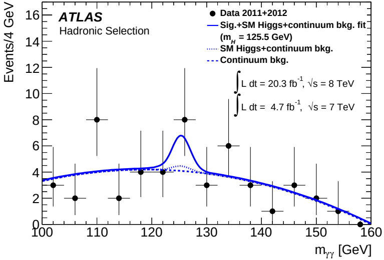
$N_{\tau_{\rm had}}$	$E_{\rm T}^{\rm miss}$ [GeV]	$N_{\rm b\text{-}jets}$	data	background	signal	efficiency [10^{-5}]
0	50–100	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39	3.1 ± 0.4
0	30–50	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30	2.4 ± 0.3
0	0–30	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24	1.9 ± 0.3
0	50–100	0	7	9.5 ± 4.4	2.22 ± 0.31	2.4 ± 0.3
0	> 100	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14	1.0 ± 0.2
0	> 100	0	1	2.2 ± 1.0	0.94 ± 0.17	1.0 ± 0.2
0	30–50	0	29	21 ± 10	1.51 ± 0.22	1.6 ± 0.2
1	30–50	≥ 1	2	2.1 ± 1.2	0.43 ± 0.09	0.5 ± 0.1
1	0–30	≥ 1	6	6.4 ± 3.3	0.48 ± 0.12	0.5 ± 0.1
1	50–100	≥ 1	1	1.5 ± 0.8	0.30 ± 0.08	0.3 ± 0.1

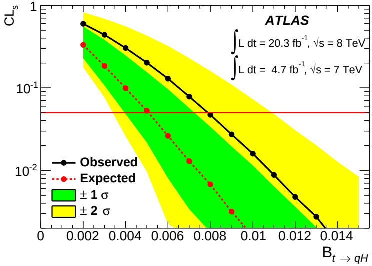
Most sensitive channel has one b-jet, medium $\not{E}_T$, no τ_h.

CMS-PAS-HIG-13-034, recasting CMS-PAS-HIG-13-025

ATLAS $t + (h \to \gamma\gamma)$ analysis

- Includes diphoton + lepton and diphoton + jets final states
- Requires *b*-jets
- Imposes criteria on invariant masses $m_{\gamma\gamma j}$, $m_{\ell\nu j}$, m_{jjj}
- Uses $m_{\gamma\gamma}$ as discrimination variable





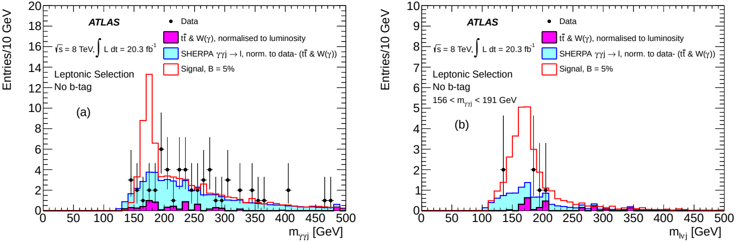
$$\mathrm{BR}(t \to cH) < 0.0079 \quad \leftrightarrow \quad \sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.17$$

(slightly worse than CMS combined limit $\mathrm{BR}(t \to cH) < 0.0056$, $\sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.14$)

ATLAS arXiv:1403.6293

Diphoton analysis from ATLAS

- **Diphoton + lepton analysis**: cuts similar to CMS, but in addition:
  - Require $m_{T,\ell\nu} > 30$ GeV
  - Consider two leading jets (2nd jet replaced by 3rd/4th if 3rd/4th is b-tagged)
  - Require one b-jet
  - Define $m_1 = m_{\gamma\gamma j}$ and $m_2 = m_{\ell\nu j}$ such that either m_1 or m_2 (or both) are close to m_t

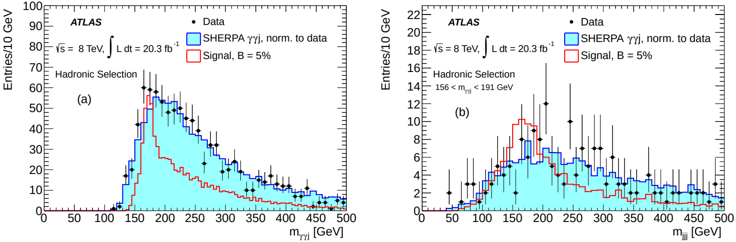


	$t \to cH$	$t\bar{t}$ &$W(\gamma)$	$S_{\gamma\gamma j\to\ell}$	Data
	(%)	Events		
$\gamma\gamma$ selection	34.9	313.7		118500
1 lepton	6.0	21.8	188.2	210
$N_{\text{jets}} \geq 2$, $m_T > 30$ GeV	3.8	3.4	18.8	30
Mass requirements	1.9	1.2	3.5	4
At least 1 b-tag	1.3±0.1	0.9±0.5	0.5±0.2	1

ATLAS arXiv:1403.6293

Diphoton analysis from ATLAS

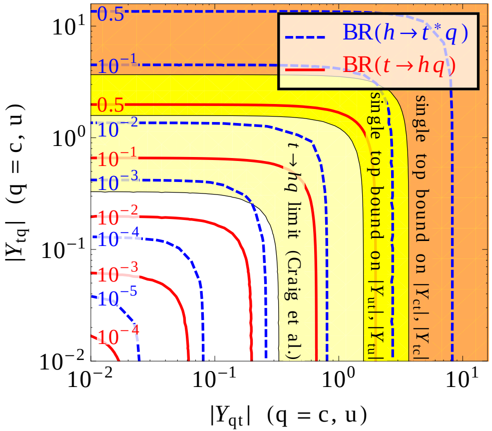
- Diphoton + lepton analysis: cuts similar to CMS, but in addition:
- Diphoton + jets analysis
  - Require two photons as before
  - In addition, four jets, at least one b-jet
  - Define $m_1 = m_{\gamma\gamma j}$ and $m_2 = m_{jjj}$ such that either m_1 or m_2 (or both) are close to m_t



	$t \to cH$ (%)		Data (events)	
	7 TeV	8 TeV	7 TeV	8 TeV
$\gamma\gamma$ selection	34.5	34.2	23683	118500
$N_{jets} \geq 4$	15.2	15.1	227	1349
Mass requirements	5.9	6.1	36	210
At least 1 b-tag	4.2±0.1	4.0±0.1	7	43

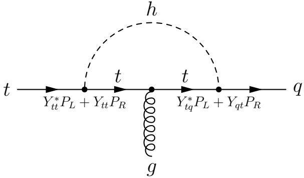
ATLAS arXiv:1403.6293

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

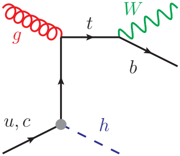
Not sensitive

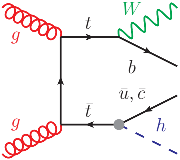
- $t \to Zq$

CMS 1208.0957

Limits on *tuh* couplings

- Recast the CMS multilepton search including also $gq \to th$:

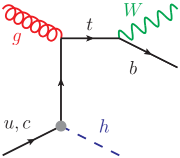


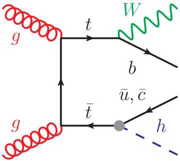


Greljo Kamenik JK, 1404.1278
see also Atwood Gupta Soni, 1305.2427
Khatibi Najafabadi, 1402.3073

Limits on *tuh* couplings

- Recast the CMS multilepton search including also $gq \to th$:





- Result (multileptons)

	OSSF pair	$N_{\text{b-jets}}$	H_T(GeV)	E_T^{miss}(GeV)	$N(t \to hj)$	$N(th)$	N_{obs}	N_{exp}
1.	below Z	≥ 1	≤ 200	$50 - 100$	10.8	6.7	48	48 ± 23
2.	no OSSF	≥ 1	≤ 200	$50 - 100$	4.4	3.0	29	26 ± 13
3.	below Z	≥ 1	≤ 200	≤ 50	6.8	3.8	34	42 ± 11
4.	no OSSF	≥ 1	≤ 200	≤ 50	4.2	2.5	29	23 ± 10
5.	below Z	≥ 1	> 200	$50 - 100$	2.5	0.6	10	9.9 ± 3.7
6.	below Z	≥ 1	> 200	≤ 50	2.0	0.4	5	10 ± 2.5
7.	below Z	0	≤ 200	$50 - 100$	9.2	5.1	142	125 ± 27
8.	no OSSF	0	≤ 200	$50 - 100$	4.0	2.5	35	38 ± 15
9.	above Z	≥ 1	≤ 200	≤ 50	1.9	1.2	17	18 ± 6.7

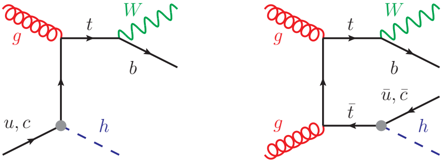
(signal predictions are for $\text{BR}(t \to hu) = 0.01$)

Most sensitive channels have
3 leptons, low H_T, one *b*-jet

Greljo Kamenik JK, 1404.1278
see also Atwood Gupta Soni, 1305.2427
Khatibi Najafabadi, 1402.3073

Limits on *tuh* couplings

- Recast the CMS multilepton search including also $gq \to th$:



- Result (multileptons): Limit on Yukawa couplings $y_{tu}^2 + y_{ut}^2$ is a factor of 1.5 stronger than limit on $y_{tc}^2 + y_{ct}^2$
- Specifically:

$$\mathrm{BR}(t \to hc) < 0.015$$

$$\mathrm{BR}(t \to hu) < 0.010$$

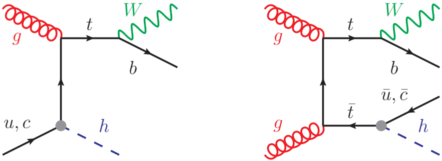
Limit on $\mathrm{BR}(t \to hu)$ is a factor 1.5 better than limit on $\mathrm{BR}(t \to hc)$.

(Our limits are slightly worse than CMS limits because τ_h channels are omitted.)

Greljo Kamenik JK, 1404.1278
see also Atwood Gupta Soni, 1305.2427
Khatibi Najafabadi, 1402.3073

Limits on *tuh* couplings

- Recast the CMS multilepton search including also $gq \to th$:



- Result (multileptons): Limit on Yukawa couplings $y_{tu}^2 + y_{ut}^2$ is a factor of 1.5 stronger than limit on $y_{tc}^2 + y_{ct}^2$
- Result (diphoton+lepton)

	$N_{\text{b-jets}}$	E_T^{miss}(GeV)	$N(t \to hj)$	$N(th)$	N_{obs}	N_{exp}
1.	≥ 1	$50 - 100$	3.2	1.3	1	2.3 ± 1.2
2.	≥ 1	$30 - 50$	2.2	0.92	2	1.1 ± 0.6
3.	≥ 1	≤ 30	1.9	0.83	2	2.1 ± 1.1
4.	0	$50 - 100$	2.4	1.1	7	9.5 ± 4.4
5.	≥ 1	> 100	0.82	0.49	0	0.5 ± 0.4
6.	0	> 100	0.87	0.52	1	2.2 ± 1.0
7.	0	$30 - 50$	1.6	0.64	29	21 ± 10

Greljo Kamenik JK, 1404.1278
see also Atwood Gupta Soni, 1305.2427
Khatibi Najafabadi, 1402.3073

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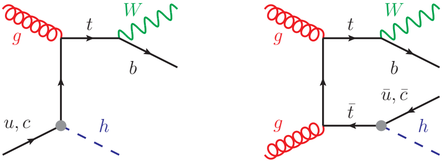

- Result (multileptons): Limit on Yukawa couplings $y_{tu}^2 + y_{ut}^2$ is a factor of 1.5 stronger than limit on $y_{tc}^2 + y_{ct}^2$
- Result (diphoton+lepton): Limit on Yukawa couplings $y_{tu}^2 + y_{ut}^2$ is a factor of 1.5 stronger than limit on $y_{tc}^2 + y_{ct}^2$
- Specifically:

$$\mathrm{BR}(t \to hc) < 0.0066$$
$$\mathrm{BR}(t \to hu) < 0.0045$$

Greljo Kamenik JK, 1404.1278
see also Atwood Gupta Soni, 1305.2427
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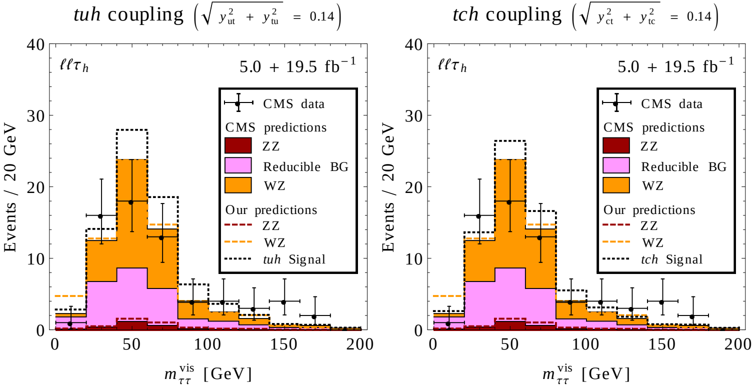
Optimized cuts

Example: recast CMS search for $V + H$ production

CMS-PAS-HIG-12-053
Greljo Kamenik JK, 1404.1278

Cuts:

- Exactly two same-sign light leptons ($\rightarrow$ suppress Z backgrounds)
- One hadronic τ
- Veto ee events ($\rightarrow$ suppress fake leptons)
- Veto b jets ($\rightarrow$ not optimal for *tuh* and *tch* search!)



Optimized cuts

Example: recast CMS search for $V + H$ production

CMS-PAS-HIG-12-053
Greljo Kamenik JK, 1404.1278

Result:

	$\sqrt{y_{ut}^2 + y_{tu}^2}$	$\mathrm{BR}(t \to hu)$	$\sqrt{y_{ct}^2 + y_{tc}^2}$	$\mathrm{BR}(t \to hc)$
Multilepton	< 0.19	< 0.01	< 0.23	< 0.015
Diphoton plus lepton	< 0.12	< 0.0045	< 0.15	< 0.0066
Vector boson plus Higgs	< 0.16	< 0.0070	< 0.21	< 0.012

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, arXiv:1404.1278

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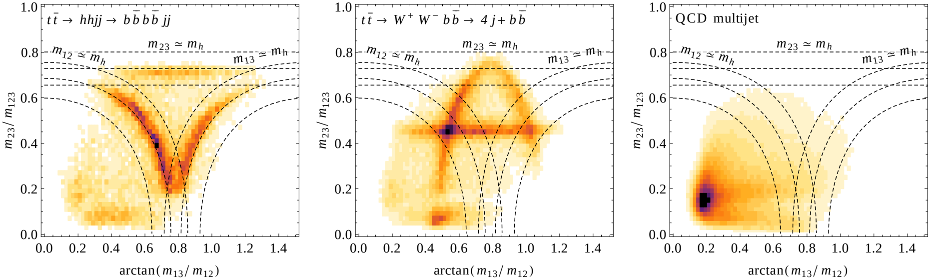
    Plehn Salam Spannowsky Takeuchi Zerwas, arXiv:0910.5472, 1006.2833
  - Tagging FCNC $t \to hq$ decays: Modified HEPTopTagger
    with adapted kinematic cuts



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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

	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

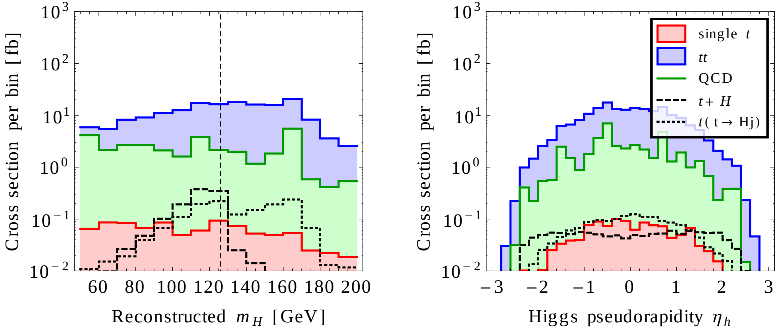
Greljo Kamenik JK, arXiv:1404.1278

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, arXiv:1404.1278

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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, arXiv: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:

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

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

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

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