

# BSM DECAYS [OF H(125)]

## THEORY OVERVIEW

Felix Yu  
JGU Mainz



JOHANNES GUTENBERG  
UNIVERSITÄT MAINZ

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# Three top-level statements

1. Higgs mechanism underpins SM

2. Higgs physics touches (most) all of BSM

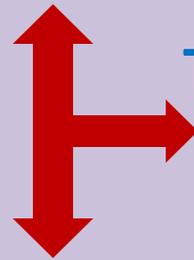


3. (Most all) BSM changes Higgs physics

# Three top-level statements

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This interplay is at the heart of  
BSM Higgs phenomenology

3. (Most all) BSM changes Higgs physics

# Theory overview

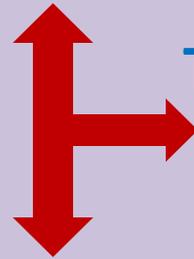
- Rich and diverse program of post-discovery studies of Higgs properties at LHC
  - Mass, spin/parity, couplings, width, exotic production modes, exotic decay modes
- Central question for BSM: what is  $\Lambda_{\text{NP}}$ ?
  - Hierarchy problem, dark matter, baryogenesis, fermion masses and mixings, gauge coupling unification...

# Another top-level statement

0. Existence of BSM physics is not an assumption

1. Higgs mechanism underpins SM

2. Higgs physics touches (most) all of BSM



This interplay is at the heart of  
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3. (Most all) BSM changes Higgs physics

# In a nutshell

*Given that BSM physics is described by a local QFT Lagrangian with new fields and couplings,  
and*

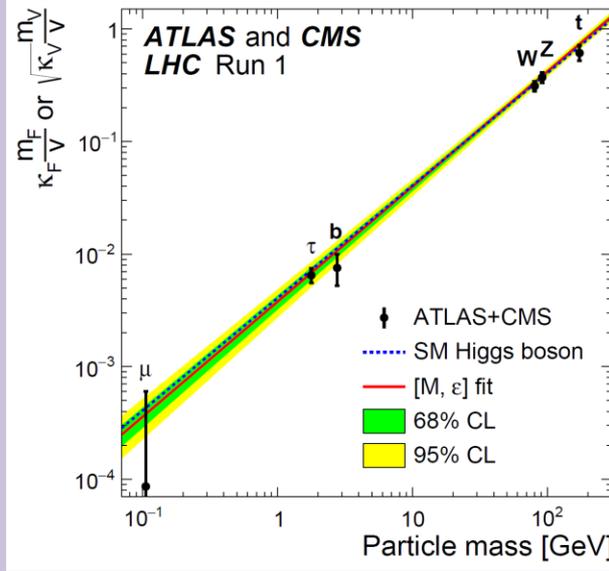
since the Higgs plays such a central, structural role in the SM,  
how do we perform and interpret Higgs  
measurements to explore the vast scope of BSM  
possibilities?

# Janus dichotomy

Vast range of BSM scenarios<sup>1</sup>



## ATLAS and CMS Higgs results



<sup>1</sup>See upcoming talks  
SUSY, 2HDM Type II: **H. Haber**  
Composite Higgs: **A. Falkowski**  
SUSY, DM connections: **T. Tait**  
Strong dynamics: **R. Rattazzi**

ATLAS, CMS JHEP **1608**, 045 (2016)  
[1606.02266]

# Laundry list of Higgs decays

- [Implicit marriage of production modes and decay]
- Yukawa-mediated two-body decays
  - $bb, cc, \tau\tau, \mu\mu, ee$  ( $tt, ss, uu, dd$ )
- Vector coupling-induced decays
  - $4l, l\nu l\nu, l\nu qq$
- Loop-induced decays
  - $gg, \gamma\gamma, Z\gamma$
- Rare decays
  - $J/\psi \gamma, \Upsilon\gamma, \phi\gamma$

Flavor violating Higgs decays: Y. Soreq  
Exotic Higgs decays: S. Gori

# SM and SM-ish Higgs decays

- [Implicit marriage of production modes and decay]

- Yukawa-mediated two-body decays

- $bb, cc, \tau\tau, \mu\mu, ee$  ( $tt, ss, uu, dd$ ) Test Yukawa patterns, CPV phases

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# Motivating patterns of characteristic deviations

- Assume no light degrees of freedom, use effective operators for Higgs characterization
  - HEFT and SMEFT approaches differ in scope, but patterns of deviations require assumptions belying model dependence, symmetry assumptions for NP
    - dim-6: 76 vs. 2499 operators (global B, L conservation, one vs. three fermion generations) Buchmuller, Wyler NPB 268 (1986) 621  
Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]  
Alonso, Jenkins, Manohar, Trott [1312.2014]
    - e.g. SILH basis Giudice, Grojean, Pomarol, Rattazzi [hep-ph/0703164]  
Liu, Pomarol, Rattazzi [1603.03064]
- Adopt concrete, robust models
  - SM+singlet, 2HDM, G-M, MSSM, composite Higgs, ...

# Janus (false) dichotomy

What is  
theoretically  
motivated?



What is  
experimentally  
allowed?

- False dichotomy: Important to answer both!
- Nature's choice of pattern of coupling deviations ultimately revealed by data

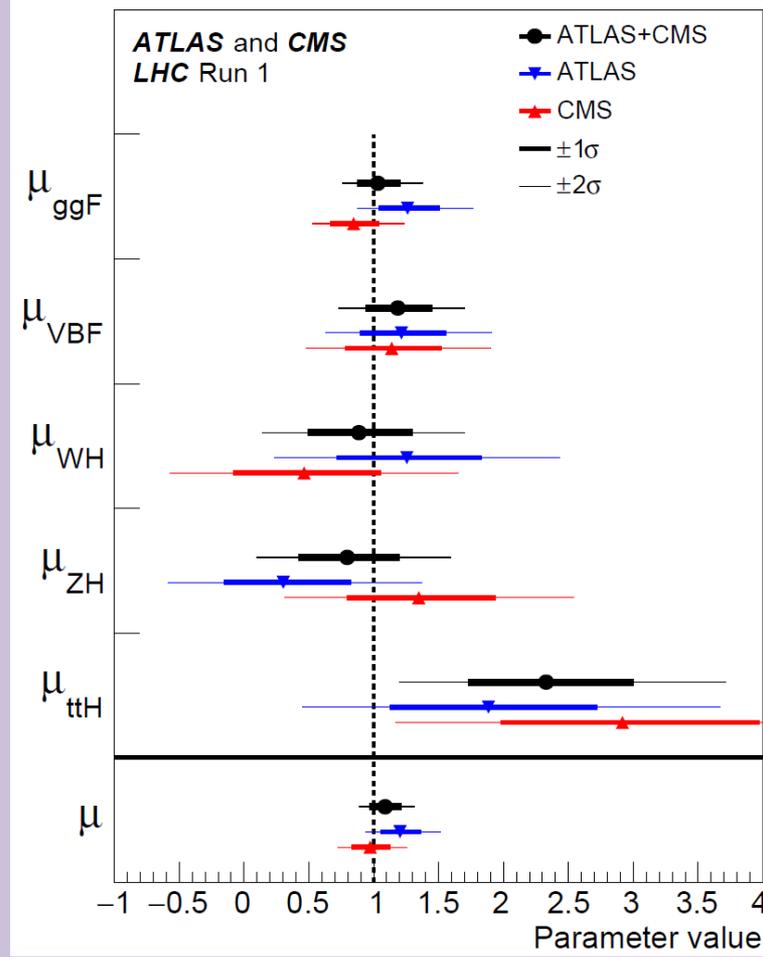
# Simple patterns of characteristic deviations

- SM + real singlet scalar: universal suppression of couplings for h(125) in decays arising from mixing

$$\mathcal{L} = \mathcal{L}_{SM} + (\partial_\mu S)^2 - V(S)$$

$$V(S) = \lambda_1 S + m_S^2 S^2 + \frac{\lambda_3}{3} S^3 + \frac{\lambda_4}{4} S^4 + \frac{\lambda_{HS1}}{2} S H^\dagger H + \frac{\lambda_{HS2}}{2} S^2 H^\dagger H$$

– More effects from S collider phenomenology,  $m_W$ , EWPO



$$\mu = 1.09 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (expt)} \pm 0.03 \text{ (thbgd)}^{+0.07}_{-0.06} \text{ (thsig)}$$

ATLAS, CMS [1606.02266]

See e.g., Brehmer, Freitas, Lopez-Val, Plehn [1510.03443]; Robens, Stefaniak [1601.07880]; Dawson, Lewis [1605.04944] and “It’s not just the Higgs” by S. Dawson

# Simple patterns of characteristic deviations

- SM + new matter content
  - Special case: SM4
    - HLET / non-decoupling<sup>1</sup> in loop-induced hgg and hγγ couplings
  - General case: mixing top quark and top-partners

$$\mu_{gg}|_{\text{SM}+\chi_{L,R}} = \frac{\left| \sum_{f, \text{not } t} \left( \frac{C(r_f)}{v_h} F_F(\tau_f) \right) + \sum_i \frac{C(r_{Fi})}{v_h} \left( \frac{(\hat{V}_h)_{ii}}{m_{Fi}} \right) F_F(\tau_{Fi}) \right|^2}{\left| \sum_f \left( \frac{C(r_f)}{v_h} F_F(\tau_f) \right) \right|^2}$$

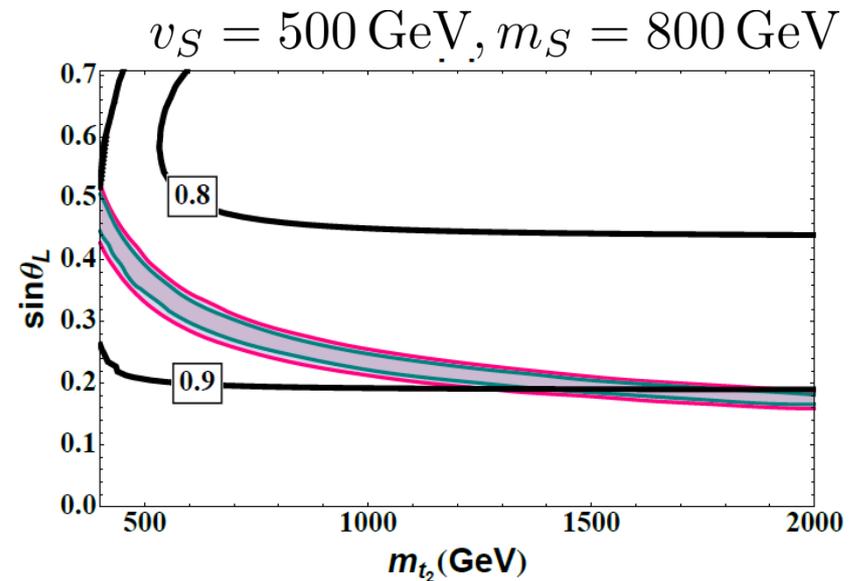
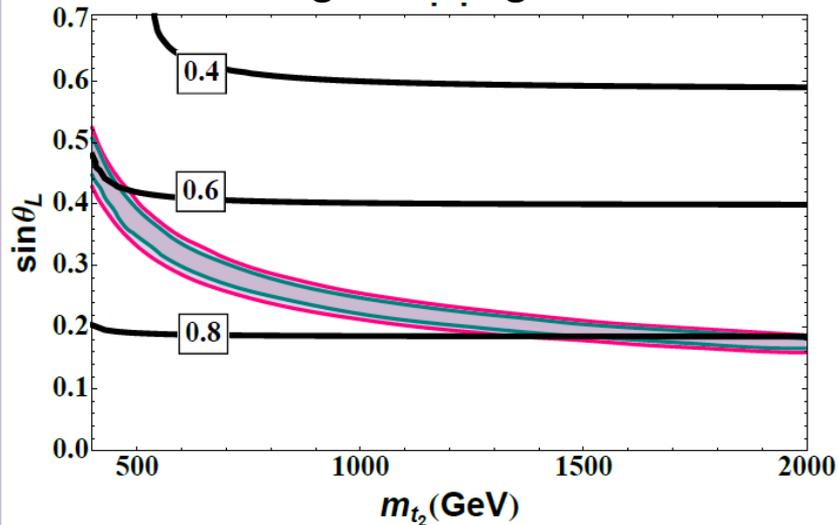
- Again, NP states confront collider constraints, EWPO

Many authors! See e.g., Shifman, Vainshtein, Voloshin, Zakharov, Sov. J. Nucl. Phys. **30**, 711 (1979); Spira, Djouadi, Graudenz, Zerwas (hep-ph/9504378); Pierce, Thaler, Wang [hep-ph/0609049]; Kribs, Plehn, Spannowsky, Tait [0706.3718]; Kumar, Vega-Morales, FY [1205.4244]

# Next-to-simple patterns of characteristic deviations

- Can also combine SM + S + top partners
  - Promote vector-like mass of top partners to vev of S

Gluon fusion signal strength contours



# Structural patterns of characteristic deviations

- 2HDM

- Gauge couplings dictated by mixing angle and ratio of vevs ( $s_{\beta-\alpha}$ ,  $c_{\beta-\alpha}$ ), guaranteed by sum rule
- Yukawa couplings dictated by  $Z_2$  assignment
  - Type 1: SM-like; 2: SUSY; X: lepton-specific; Y: down-specific

	$\Phi_1$	$\Phi_2$	$u_R$	$d_R$	$\ell_R$	$Q_L, L_L$
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+

Again, many authors! See e.g., Dawson, Gunion, Haber, Kane – Higgs Hunter’s Guide  
Kanemura, Tsumura, Yagyu, Yokoya [1406.3294]; Craig, D’Eramo, Draper, Thomas, Zhang [1504.04630]

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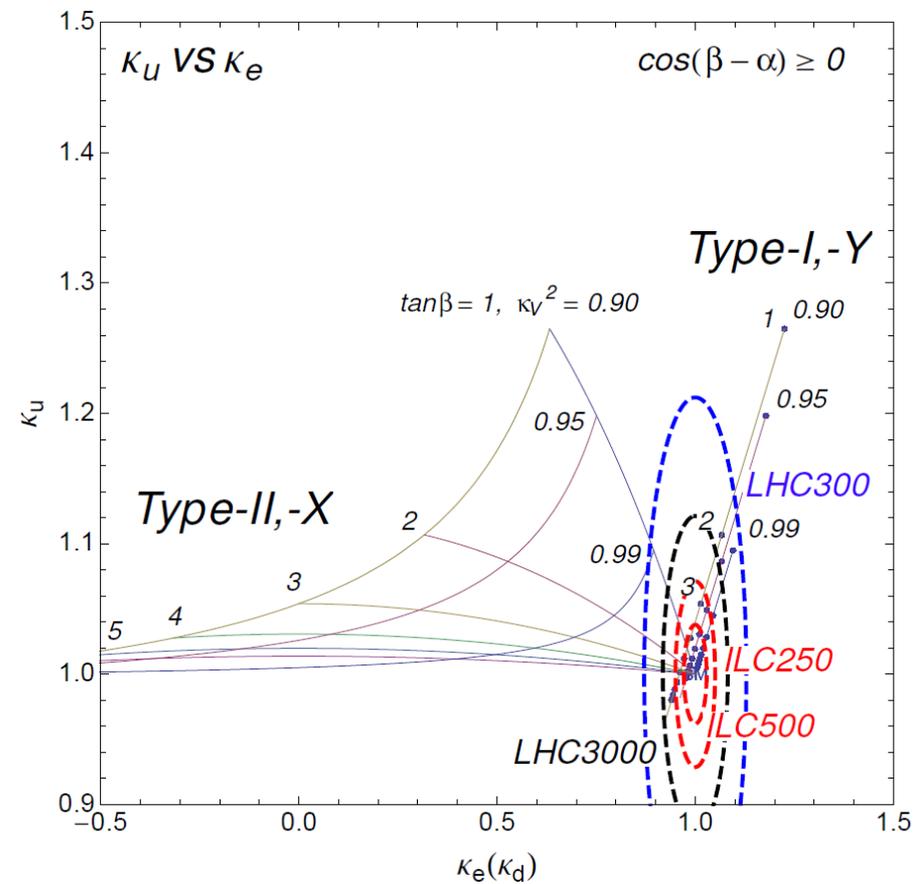
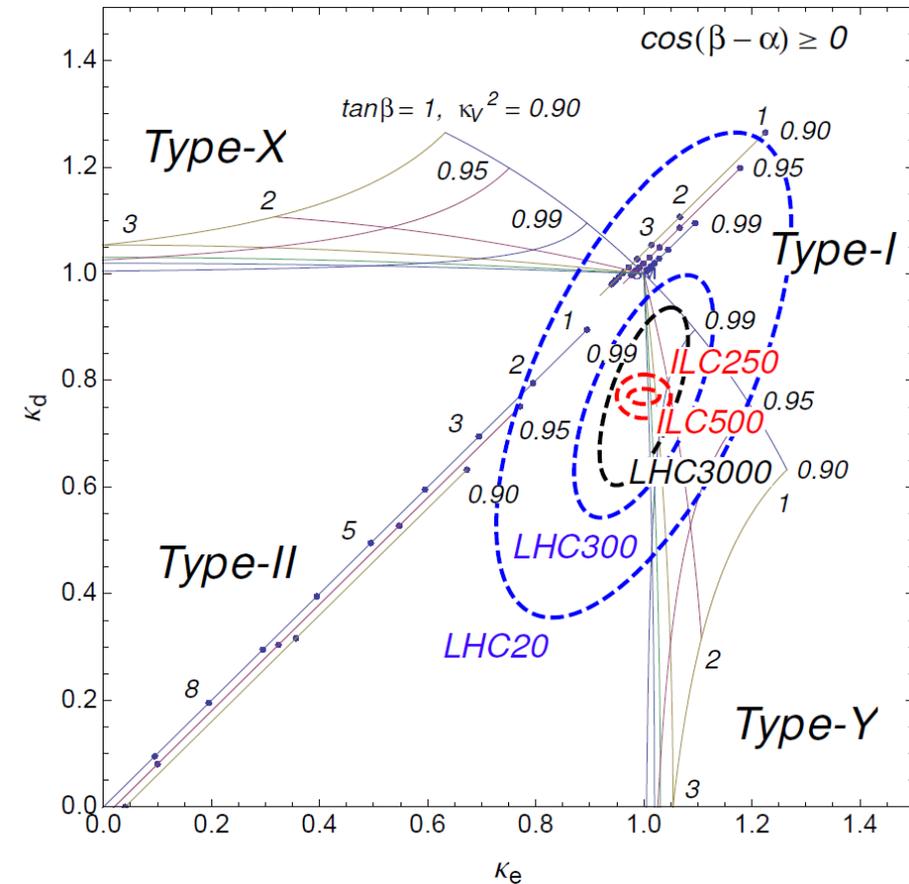
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- Distinct patterns (also drives NP searches and constraints, e.g.  $B_s \rightarrow \mu\mu$ )

	$\xi_h^u$	$\xi_h^d$	$\xi_h^\ell$	$\xi_H^u$	$\xi_H^d$	$\xi_H^\ell$	$\xi_A^u$	$\xi_A^d$	$\xi_A^\ell$
Type-I	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\cot \beta$	$-\cot \beta$	$-\cot \beta$
Type-II	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$-\sin \alpha / \cos \beta$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$	$\cos \alpha / \cos \beta$	$\cot \beta$	$\tan \beta$	$\tan \beta$
Type-X	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$	$\cot \beta$	$-\cot \beta$	$\tan \beta$
Type-Y	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$\cos \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$	$\sin \alpha / \sin \beta$	$\cot \beta$	$\tan \beta$	$-\cot \beta$

# Structural patterns of characteristic deviations

- 2HDM

– Improvements scale readily with precision data



# Motivating ad-hoc deviations

- Use LHC Higgs data to test as much BSM parameter space as possible
  - NP motivation may be remote but nevertheless important to treat all Higgs measurements as a SM consistency test
    - Most straightforward footing for understanding off-shell vs. on-shell Higgs width measurement
      - Kauer, Passarino [1206.4803],  
Caola, Melnikov [1307.4935],  
Campbell, Ellis, Williams [1311.3589, 1312.1628],  
ATLAS [1503.01060], ATLAS-CONF-2016-079,  
CMS [1507.06656], CMS-HIG-16-033

# SM and SM-ish Higgs decays

- [Implicit marriage of production modes and decay]

- Yukawa-mediated two-body decays

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Cannot neglect possible Higgs decays

where SM prediction is  $\approx 0$

CPV, small Yukawa-mediated, flavor violating, or exotic decays

*and*

More luminosity affords us a chance to move beyond testing couplings from Higgs rates to differential shapes

- $J/\psi \gamma, \Upsilon\gamma, \phi\gamma$

Test Yukawa couplings, loop-induced couplings

Flavor violating Higgs decays: Y. Soreq

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# Motivating non-standard Yukawas

- Dimension-6 effective for Yukawas operators

$$\mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y'_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R + y_\ell \bar{L} H \ell_R + y'_\ell \frac{H^\dagger H}{\Lambda^2} \bar{L} H \ell_R \\ + y_d \bar{Q}_L H d_R + y'_d \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{h.c.}$$

– Diagonalize the mass combinations

$$m_f = \frac{y_f v}{\sqrt{2}} + \frac{y'_f v^3}{2\sqrt{2}\Lambda^2}$$

- Resulting Yukawa interactions are not necessarily diagonal, or CP-conserving

$$\frac{y_{f, \text{eff}}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2y'_f v^2}{2\sqrt{2}\Lambda^2}$$

– Depends sensitively on symmetries assumed at dimension-6 level

- Fine-tune mass generation  $\leftrightarrow$  large BSM effects

# CPV in Yukawa couplings

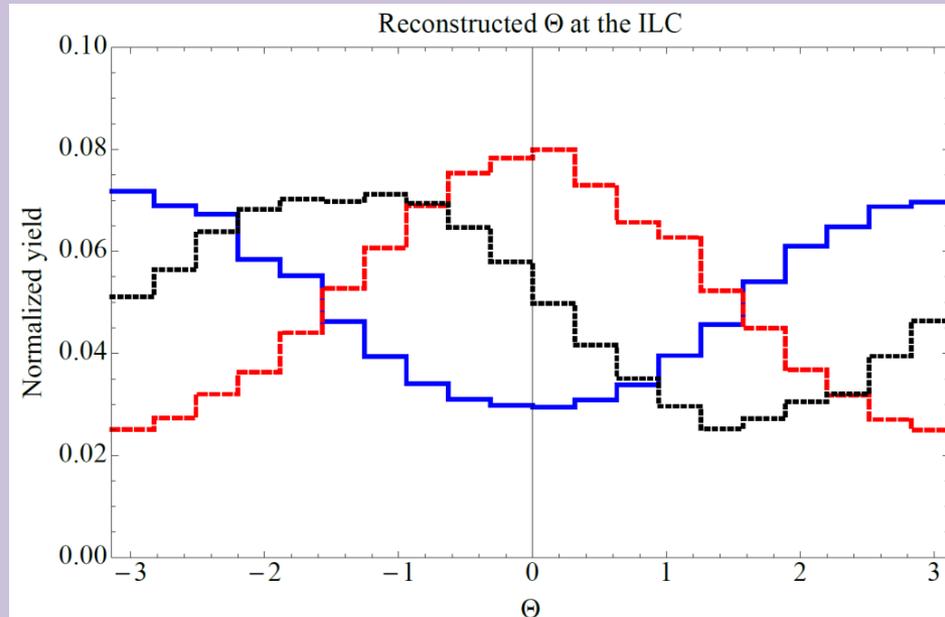
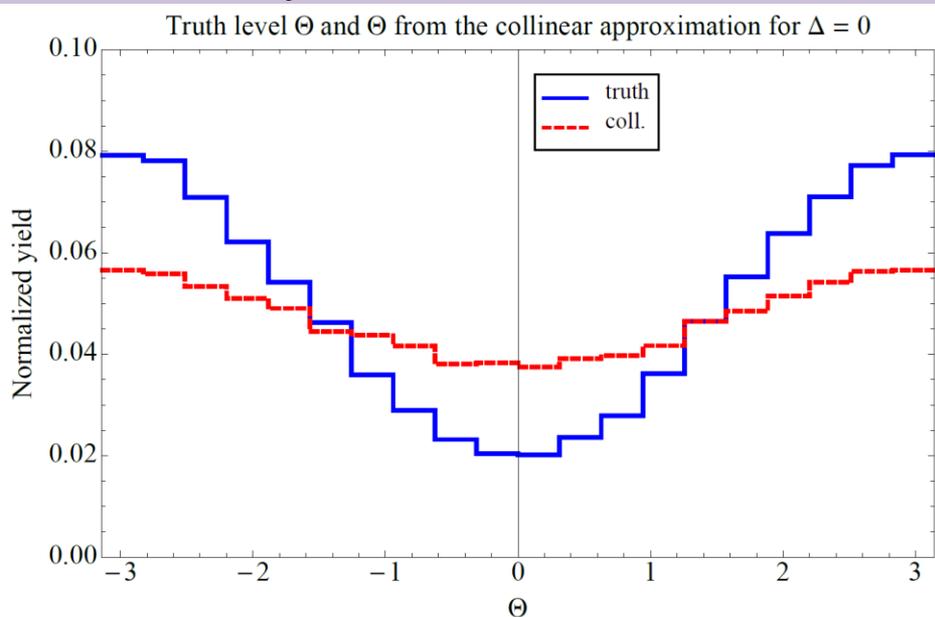
- Top CPV phase naively constrained by electron EDM  
Brod, Haisch, Zupan [1310.1385]
  - Indirect probe, still important to perform direct tests at LHC  
Many people! See Buckley, Goncalves [1507.07926], Mileo, Kies, Szykman, Crane, Gegner [1603.03632]
- Light quark CPV phases confront neutron EDM  
Chien, Cirigliano, Dekens, de Vries, Mereghetti [1510.00725]
- Open room for  $\tau$  Yukawa phase – LHC (and future  $e^+e^-$ ) could provide leading sensitivity  
Harnik, Martin, Okui, Primulando, FY [1308.1094]  
Berge, Bernreuther, Kirchner [1510.03850]

# CPV in the $\tau$ Yukawa coupling

- New CPV phases are primary ingredient of BSM models of baryogenesis
- CPV phases in Higgs Yukawas are a next avenue to explore at LHC and beyond

$$\mathcal{L} = y_f h \bar{f} (\cos \Delta + i \gamma_5 \sin \Delta) f$$

$\Theta$  is an optimal reconstructable angular variable sensitive to CPV in  $h \rightarrow \tau\tau$



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	$h j$	$Z j$
Inclusive $\sigma$	2.0 pb	420 pb
$\text{Br}(\tau^+ \tau^- \text{ decay})$	6.1%	3.4%
$\text{Br}(\tau^- \rightarrow \pi^- \pi^0 \nu)$	26%	26%
Cut efficiency	18%	0.24%
$N_{\text{events}}$	1100	1800

Colliders	LHC	HL-LHC	ILC (1 ab <sup>-1</sup> )	CEPC1	CEPC5	CEPC10
Accuracy(1 $\sigma$ )	25°	8.0°	4.4°	5.5°	2.5°	1.7°

# Survey<sup>1</sup> of proposed collider probes of $\gamma_q$

- Direct decays:  $h \rightarrow bb$  in tandem with  $h \rightarrow cc$ , probes  $\gamma_c$
- Direct production:  $h\bar{c}(c)$ , probes  $\gamma_c$  –
- Total Higgs width lineshape: probes  $\gamma_d, \gamma_u, \gamma_s, \gamma_c$  combination
- Higgs kinematics: probes  $\gamma_d, \gamma_u, \gamma_s, \gamma_c$  combination
- Indirect Higgs width: requires assumptions
- Rare decays, *e.g.*  $h \rightarrow J/\psi \gamma$ : SM expected rates very small
- Searches for fermion partners, heavy Higgses
- Global fit for Higgs couplings: best sensitivity, requires assumptions
- $W^\pm h$  charge asymmetry: probes  $\gamma_d, \gamma_u, \gamma_s, \gamma_c$  combination

<sup>1</sup>Isidori, et. al. [1305.0663]; Kagan, et. al. [1406.1722]; Bodwin, et. al. [1407.6695]; Perez, et. al. [1503.00290, 1505.06689]; König, et. al. [1505.03870]; Zhou [1505.06369]; Brivio, et. al. [1507.02916]; Bishara, et. al. [1606.09253]; Soreq, et. al. [1606.09621]; Bonner, et. al. [1608.04376]; Alte, et. al. [1609.06310]; FY [1609.06592]

# Patterns vs. ad-hoc coupling deviations

- Many more models with predictive patterns
  - Non-decoupling effects easily testable
- Decoupling properties of NP in Higgs physics give sliding scale for sensitivity
- Bottom line: precision measurements are needed
  - Higgs total width from  $e^+e^-$  machine adds significant improvement to global fit Peskin [1312.4974]; Snowmass Higgs WG [1310.8361]
  - Higgs factory also affords synergies with BSM Higgs decays
    - (Answering the inevitable question:)  
Because many NP models exhibit decoupling, every Higgs measurement tests probes new parameter space

# Conclusions

- Many dichotomies confronting BSM Higgs physics
- Concrete NP problems and BSM models to test with Higgs physics
  - EWSB, dark matter, extended Higgs sectors, new scalars, baryogenesis, electroweak phase transition, CP violation, Higgs portal
  - Effects in decays complemented by production
- SM precision and experimental efforts underlie everything
- Patterns of deviations from data will point the path to new physics scales

Double Higgs production: M. Perelstein

SM precision predictions: M. Spira ⊕  
all ATLAS and CMS results

