Rare and Exotic Higgs Decays

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FCC-ee Higgs workshop

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New physics in Higgs decays

- Indirectly:
  - Higher-dimension operators change absolute and differential rates for Higgs decays to SM particles
  - $h \to Z\gamma$, $h \to \mu\tau$, $h \to 4\ell$
  - $h \to M\ell\ell,\ h \to M\gamma$; also decays to light jets
- Directly:
  - Higgs decays produce one or more BSM particles
    - e.g.: $h \to 4b$, $h \to$ lepton jets, $h \to$ *MET*
  - possible correlated signals from other production mechanisms for BSM states: model, machine-dependent

Motivation: why exotic Higgs decays

- Why should new physics be anywhere near the electroweak scale?
  - co-responsible for generating it
  - stabilize it
  - thermal dark matter
  - …why not?

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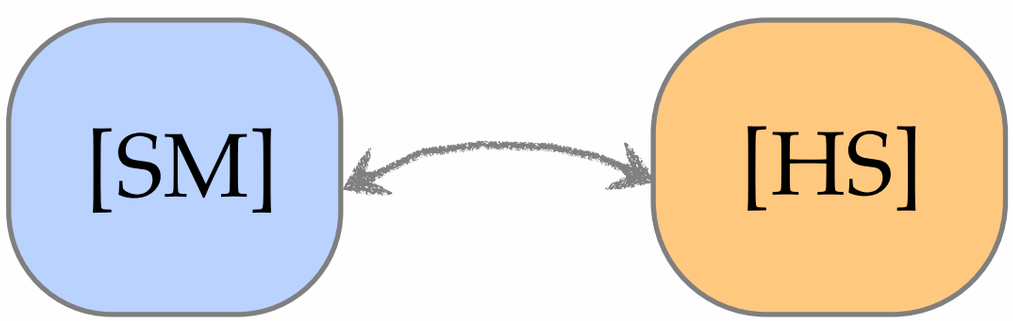
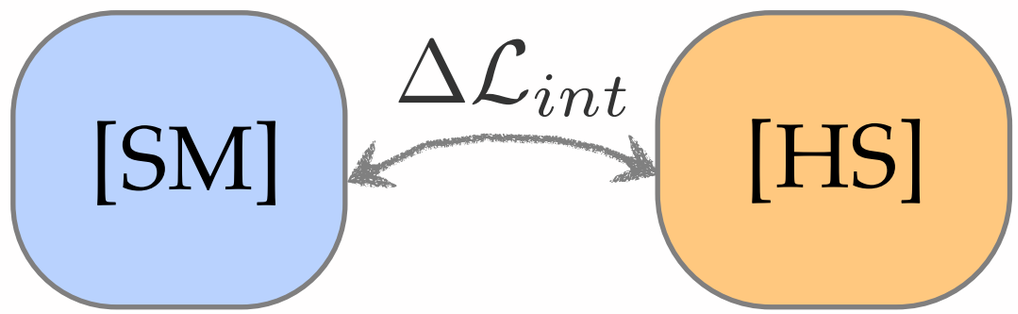
- All of these motivations apply horizontally as well as vertically



Motivation: why exotic Higgs decays

- Hidden sector signatures: driven by size and structure of leading interactions



  - portals: $|H|^2,\ B_{\mu\nu},\ HL_L\ \ldots$

- Energy frontier: unique window on Higgs portal
  - direct on-shell production, small SM width
  - in many cases the leading interaction between SM and new physics

Future Circular Colliders

- lepton machines
  - FCC-ee: 240 GeV, 10 ab^{-1}: 10^6 Higgses
  - smaller data sets limit statistical reach
  - clean: benefits for (e.g.) all-hadronic modes
  - inclusive measurements are possible
- hadron machines
  - HL-LHC: 14 TeV, 3 ab^{-1}: 10^8 Higgses
  - enormous Higgs samples: fantastic statistical reach for clean decay modes
  - high backgrounds, trigger concerns

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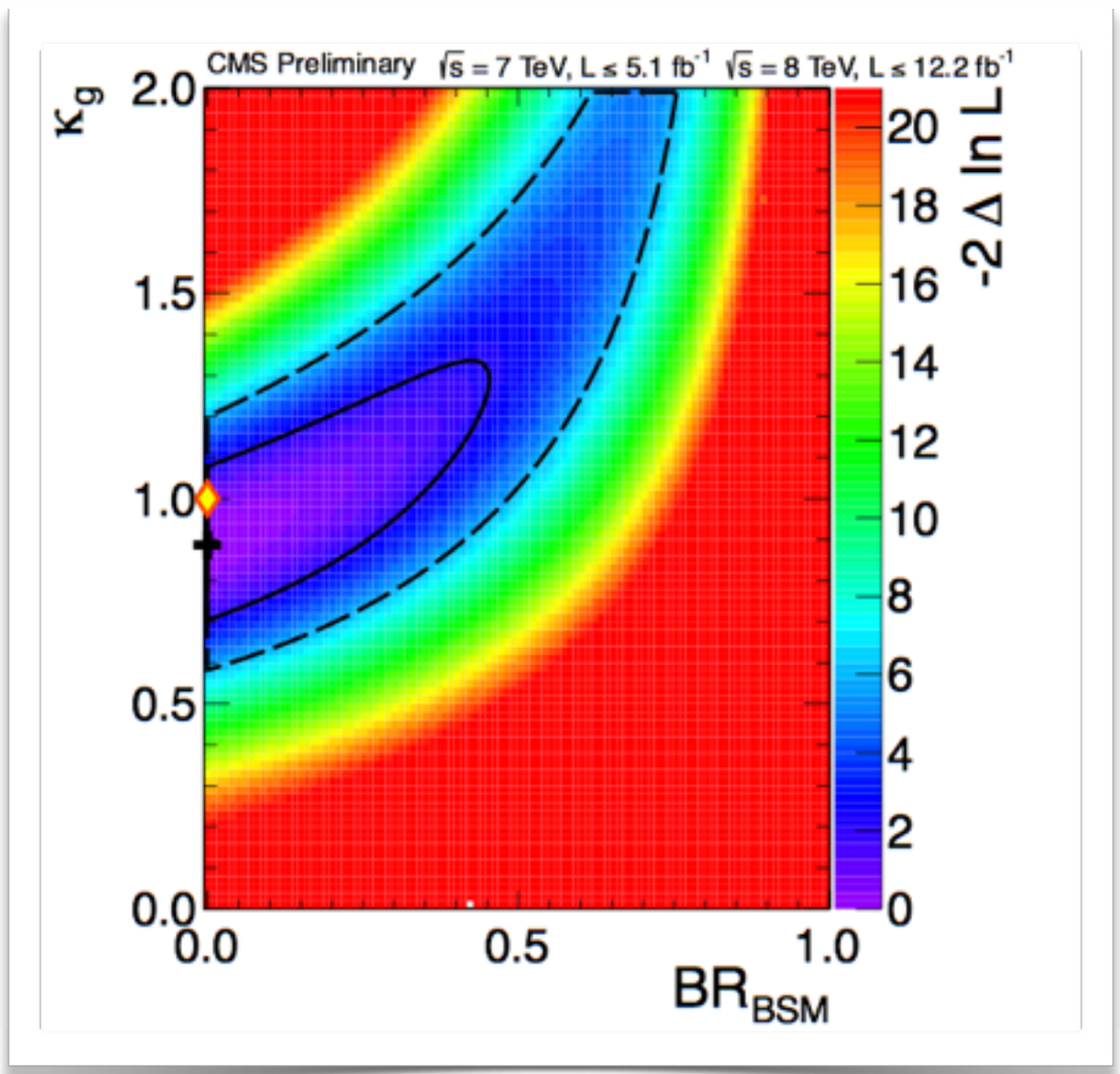
- electron-hadron machines
  - FCC-he: 50 TeV p, 60 GeV e^-, 3 ab^{-1}: 10^6 Higgses

The total Higgs width

- Total Higgs width: needed to understand possible BSM decays in a model-independent way.
  - Tiny! extremely challenging to measure
- at the LHC:
  - interference between Higgs, other SM contributions in diboson spectra
  - from global fit
  - require assumptions about form/nature of BSM physics to interpret as bound on Higgs width

The total Higgs width

- Measuring only exclusive production x decay modes leaves a degeneracy:



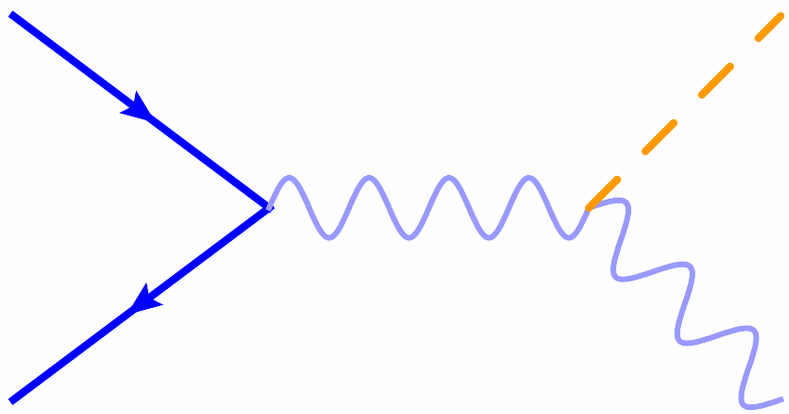
$$\sigma(A \to h \to B)$$

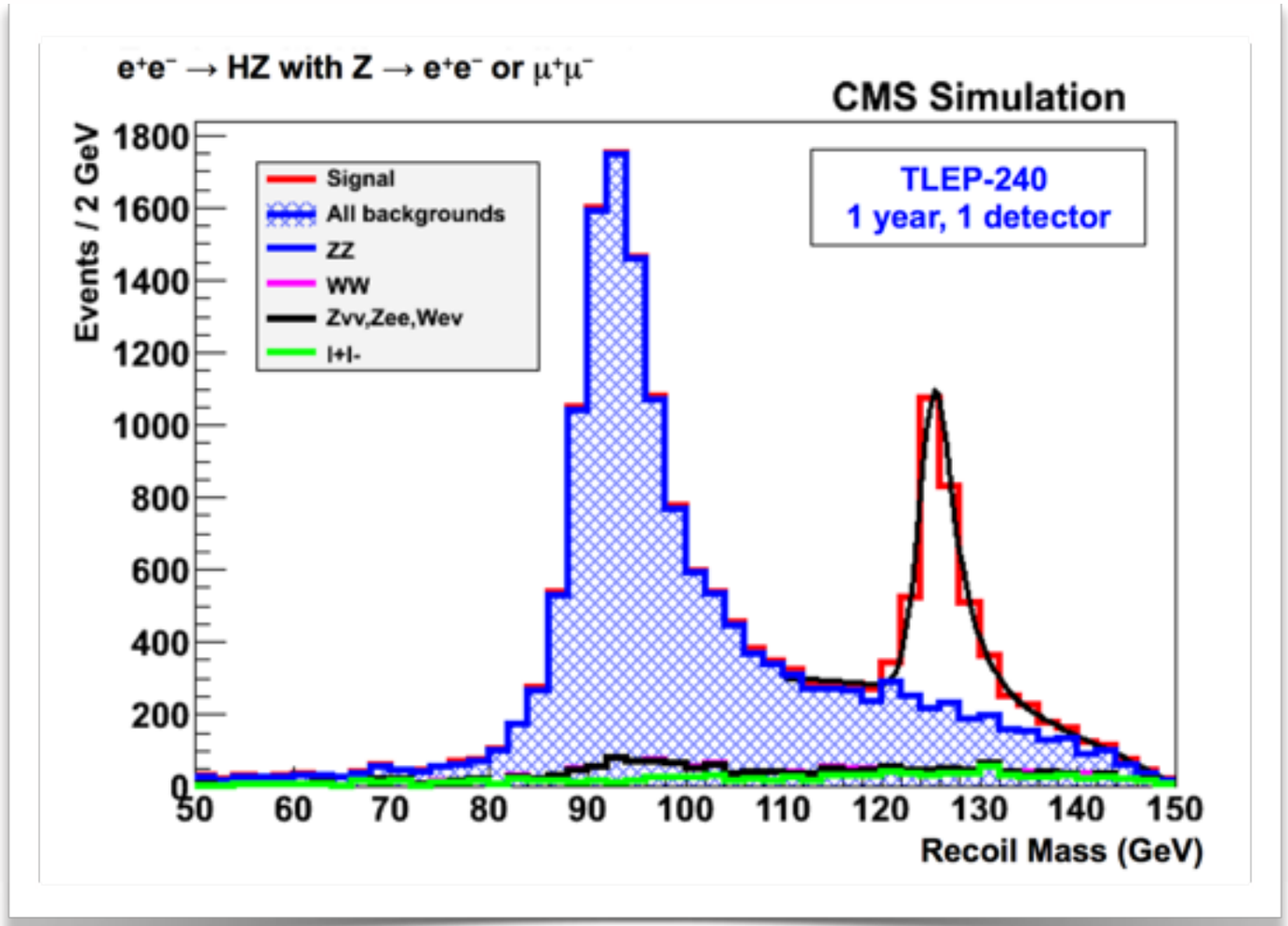
$$\approx \frac{\sigma(A \to h) \times \Gamma(h \to B)}{\Gamma_h}$$

$$\propto \frac{g_{hA}^2 g_{hB}^2}{\Gamma_h}$$

The total Higgs width

- Break the degeneracy with inclusive measurement of *Zh* production:





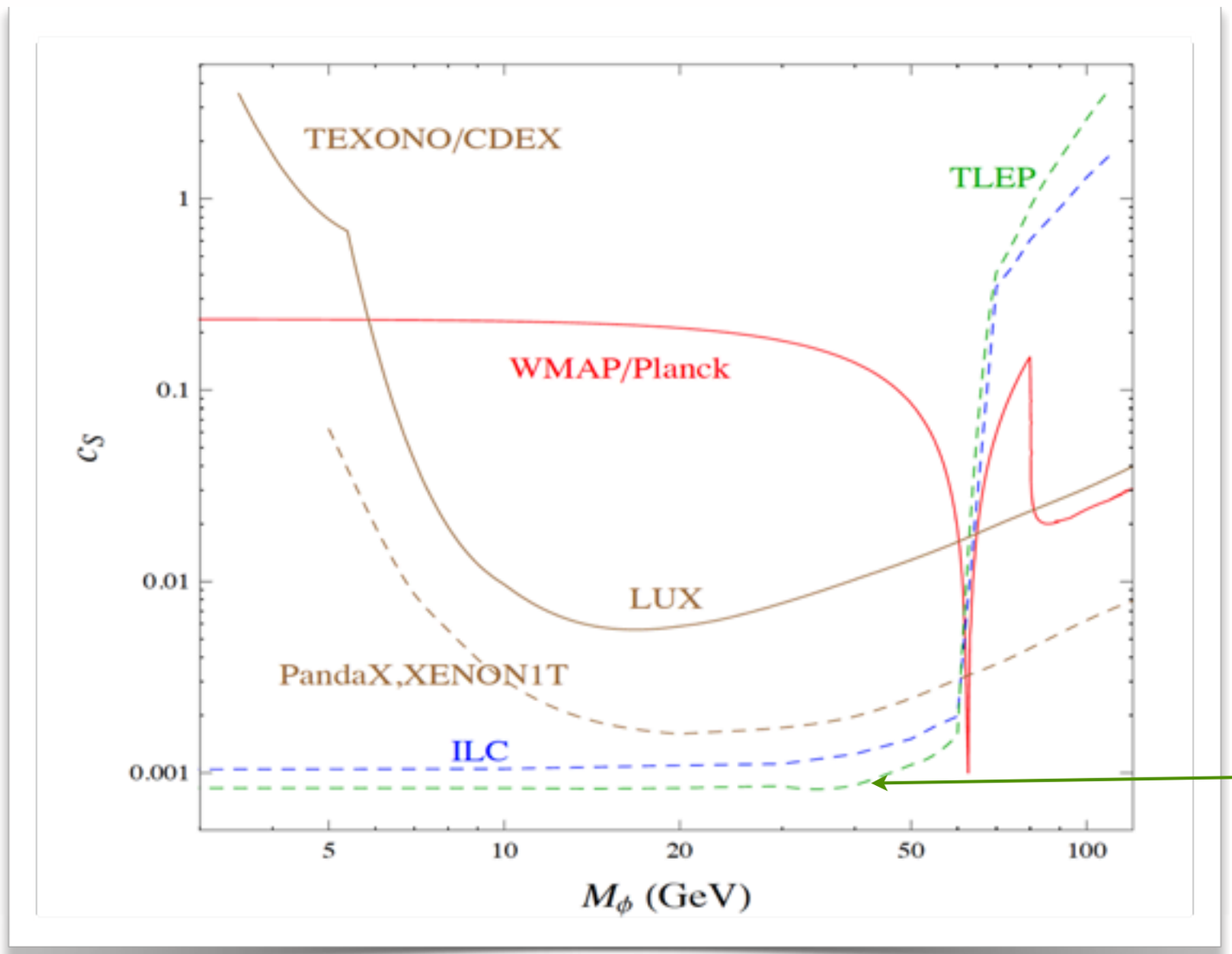
$$\delta\Gamma_h \approx 3.1\%$$

$$(p_{ee} - p_Z)^2 = s + m_Z^2 - 2\sqrt{s}E_Z$$

[TLEP physics case 1308.6176]

Exotic decays: invisibles

- Recoil mass distribution may also be used to search for invisible decays: missing invariant mass



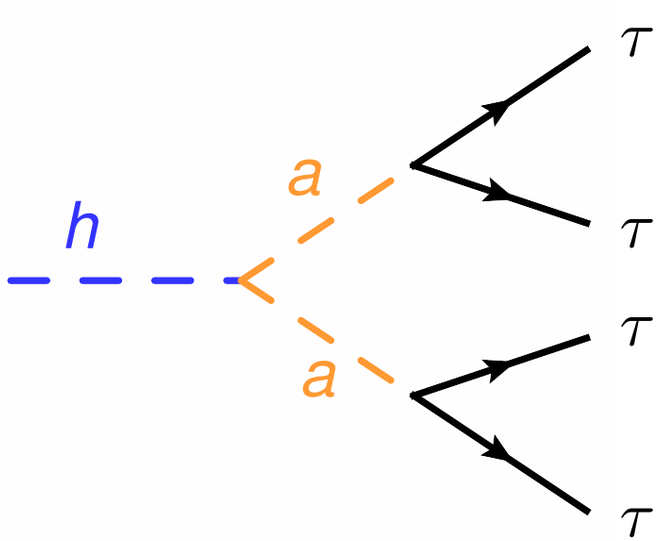
$$\Gamma(h \to \text{inv}) \lesssim 0.1\%$$

FCC-ee, 240 GeV run

[TLEP physics case 1308.6176; Chacko, Cui, Hong '13]

Exotic decays: visible

- One Snowmass study, for ILC: $h \to 4\tau$ [Liu, Potter '13]
  - Interesting decay mode: well-motivated, challenging at LHC thanks to high backgrounds
  - backgrounds at FCC-ee much less prohibitive
  - (this study: geared to specific NMSSM benchmark scenario)



A theorist doing such studies would like to know: where/how to get sufficiently realistic numbers for resolutions, tau (*b*, *c*, ...) IDs, fakes? Can LHC numbers be used as reasonable reference values?

Exotic decays: visible

- Great advantages of lepton colliders:
  - hadronic final states
  - with poor mass resolution (e.g., with *MET*)
  - high multiplicity/low p_T
- Extremely well-motivated decay modes are in this class: Higgs portal couplings to (pseudo-)scalars, $h \to aa,\ ss$
  - Yukawa-weighted - heavy flavor rich
  - gauge-weighted (axion-like) - gluon rich

Exotic decays: visible

- Decays without MET: $h \to aa,\ ss \to 4f$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br}(\text{non-SM})}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br}(\text{non-SM})$ 7+8 [14] TeV	quarks suppressed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br}(\text{non-SM})}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br}(\text{non-SM})$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^R $[0.2^L]$	W	0.8	0.9 [0.2]	0	–
$b\bar{b}\tau\tau$	> 1 $[0.15^L]$	V	0.1	> 1 [1]	0	–
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.7-1$ $[0.2-0.7]$	0	–
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]	1	$0.2-0.4$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]	0.007	$0.04-0.1$ [U]
$\mu\mu\mu\mu$	$1\cdot 10^{-4\ R}$ [U]	G	$1\cdot 10^{-7}$	1000 [U]	$1\cdot 10^{-5}$	10 [U]

Initial prioritization of channels

- Decays without MET: $h \to aa,\ ss \to 4V$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\mathrm{Br}(a \to \gamma\gamma) \approx 0.004$ $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	$\mathrm{Br}(a \to \gamma\gamma) \approx 0.04$ $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$jjjj$	> 1 [0.1*]	W	0.99	> 1 [0.1*]	0.92	> 1 [0.1*]
$\gamma\gamma jj$	0.04 [0.01*]	W	0.008	5 [1*]	0.08	0.5 [0.1*]
$\gamma\gamma\gamma\gamma$	$2 \cdot 10^{-4}$ [$3 \cdot 10^{-5*}$]	G	$1 \cdot 10^{-5}$	20 [1*]	0.001	0.2 [0.03*]

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Lepton collider studies are lacking!

Summary

- A Higgs factory will give an excellent opportunity to search for new physics in Higgs decays
- Many well-motivated BSM theories predict weak-scale particles that couple to the SM dominantly through the Higgs boson
- Major advantages of FCC-ee for exotic Higgs decays:
  - inclusive width measurement
  - direct searches for "messy" decay modes, where hadron machines cannot exploit their statistical advantage
- Exotics: largely unexplored territory!