IFT program: Opportunities at Future High Energy Facilities

Higgs Exotic Decays

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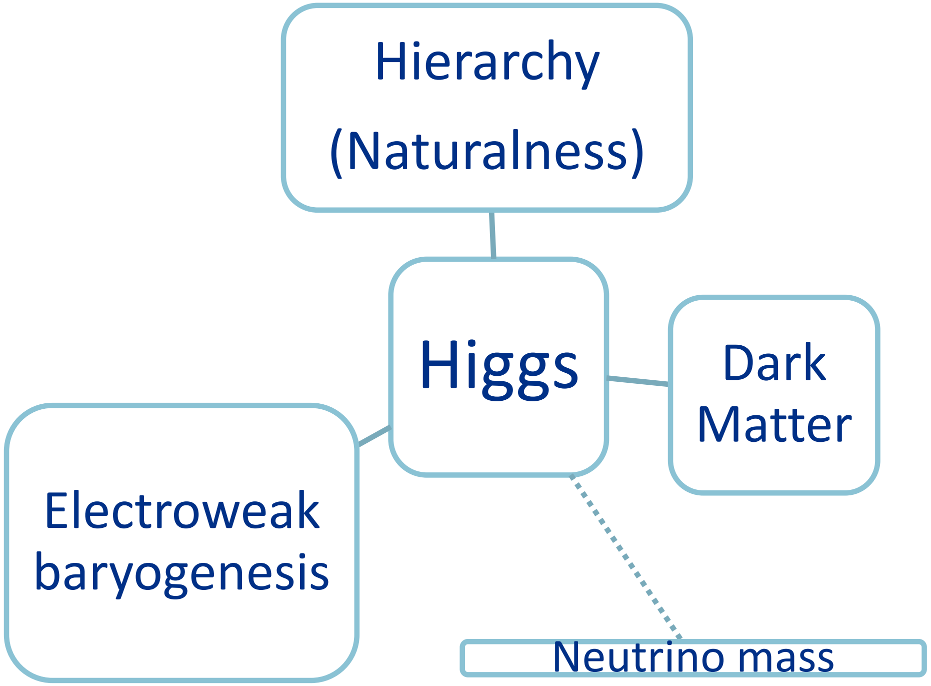
Motivation

Higgs boson discovery substantiates (more) many big questions in nature. It could well be the key to unlock some of nature's secrets.

All connections could be revealed in Higgs measurements.

Higgs is the key to new physics.



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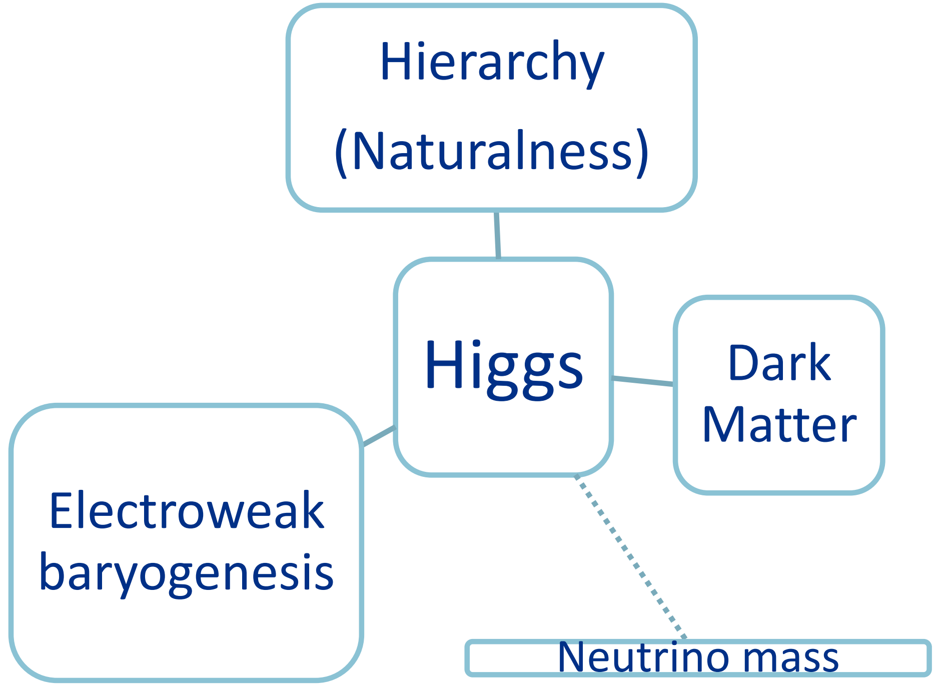
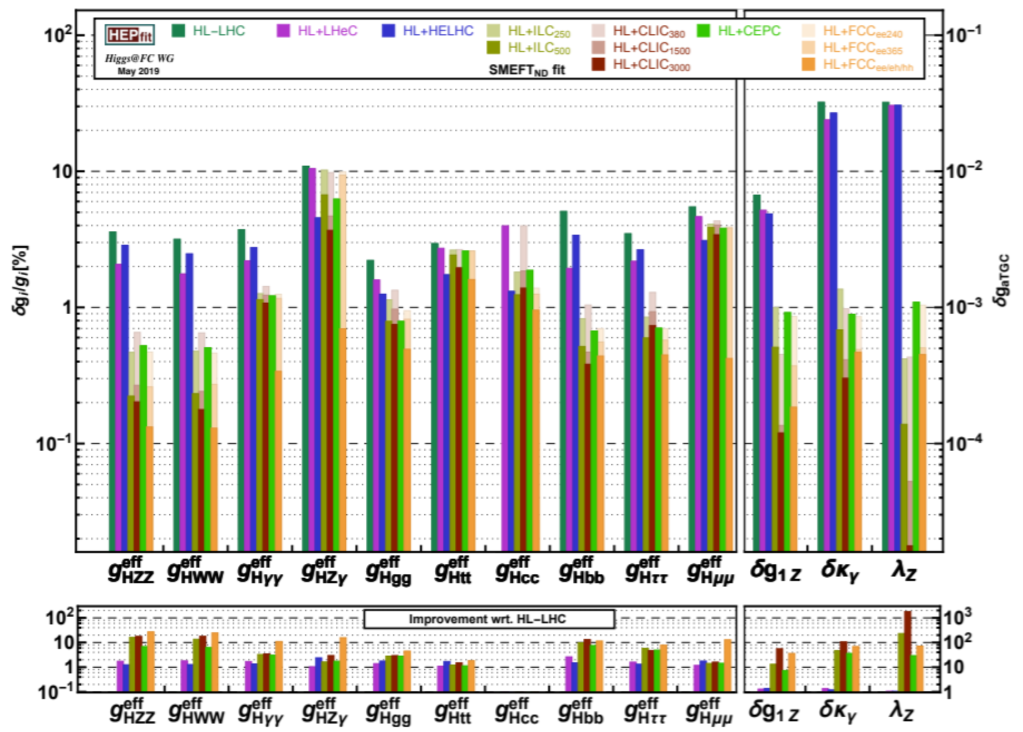


The physics case of building the next generation colliders to further explore fundamental physics, CEPC/SPPC, FCC ILC, CLIC, etc, focusing on the Higgs precision measurements.



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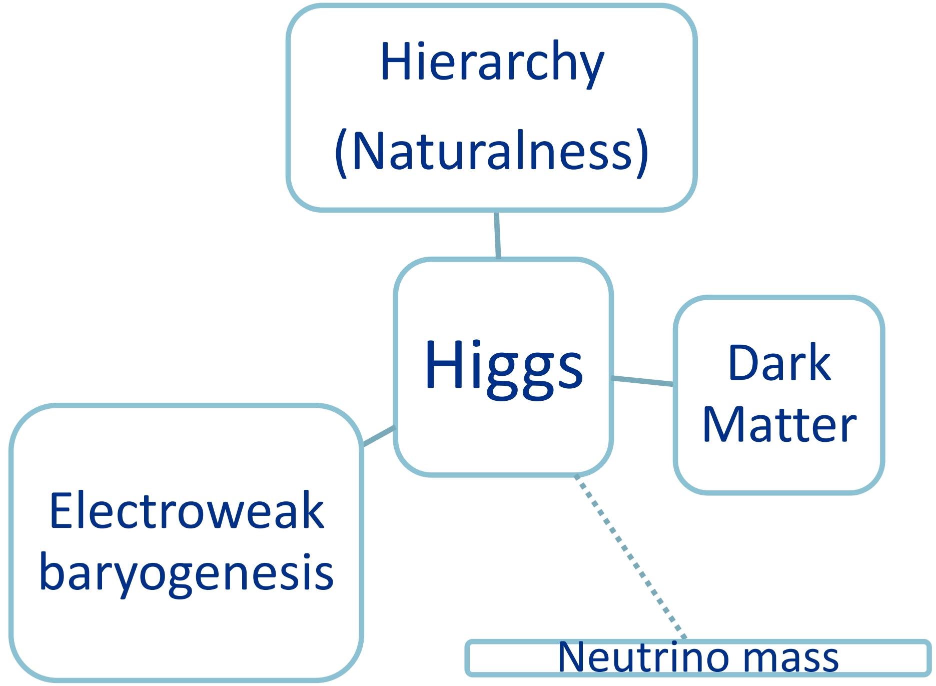
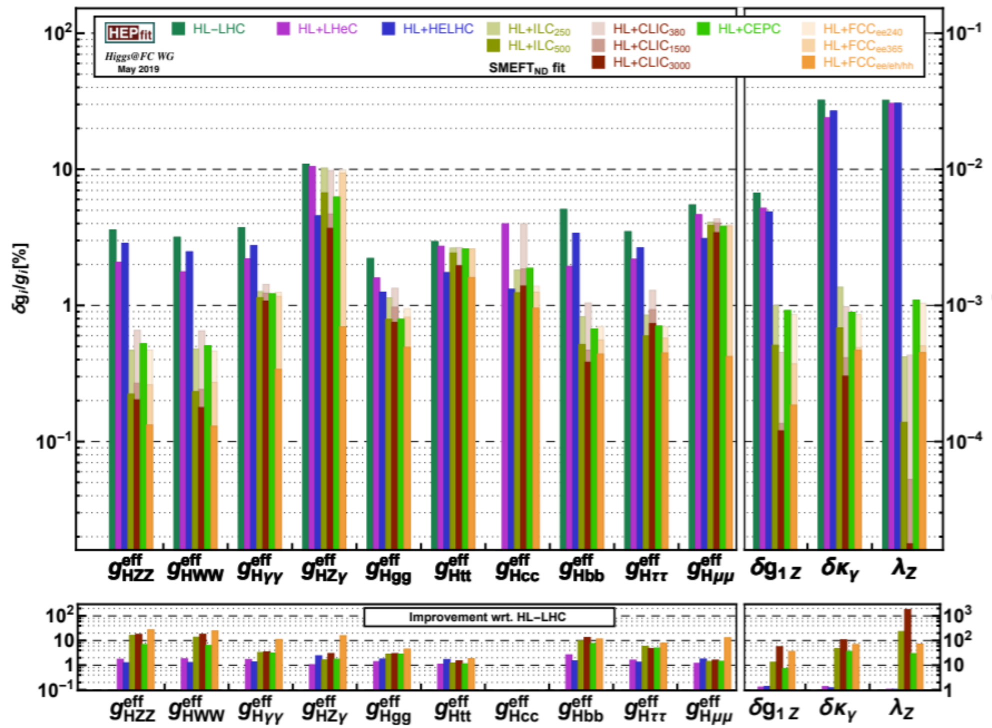


The physics case of building the next generation colliders to further explore fundamental physics, CEPC/SPPC, FCC ILC, CLIC, etc, focusing on the Higgs precision measurements.

Higgs exotic decays is one important missing piece.



Why Exotic Decays?

- Higgs boson can easily and well-motivated to be the portal to other BSM sectors. While most searches focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders.

(checking all the possibility; theoretical interests.)

((H^+H) lowest mass dimensional spinless gauge singlet structure, easily a portal to BSM)

- The precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. **

(complementarity)

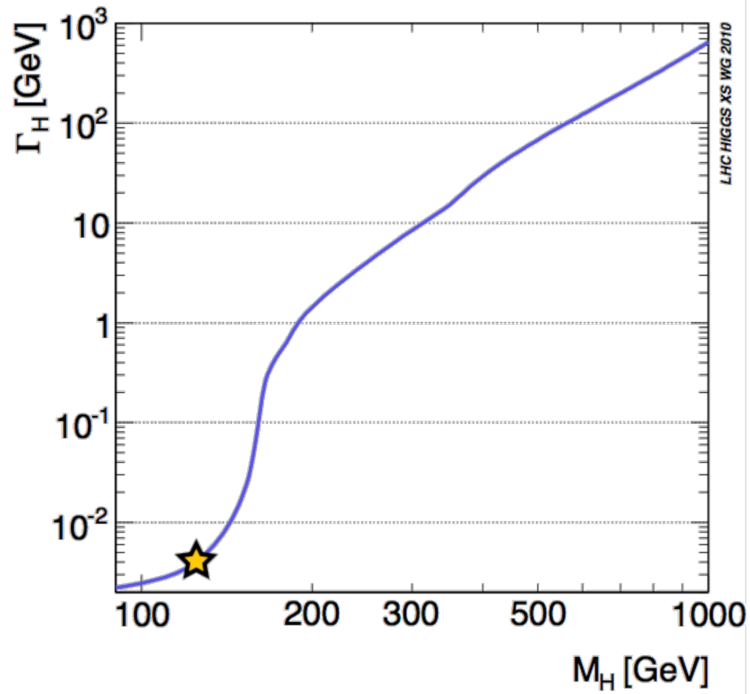
Why Exotic Decays? (continued)

- Higgs has tiny width ~4 MeV

$$\frac{\Gamma}{M} = O(10^{-5})$$

all its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.

Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$



Why Exotic Decays? (continued)

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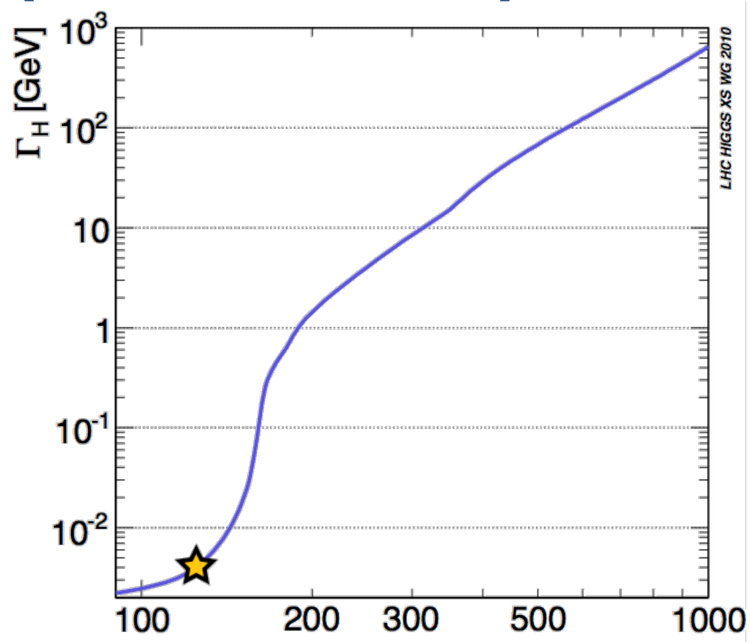
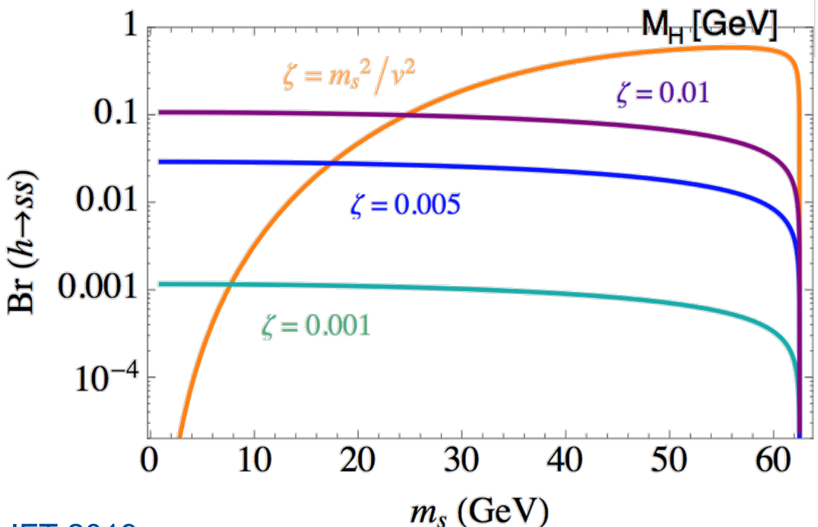


- small couplings to BSM could have sizable branching, e.g.,

$$\mathrm{L} = \frac{\zeta}{2} s^2 |H|^2$$

(common building block in extended Higgs sectors) can give BR(h➞ss)~O(10%) for ζ *as small as* 0.01 !



Organizing the study

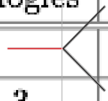
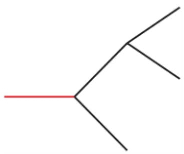
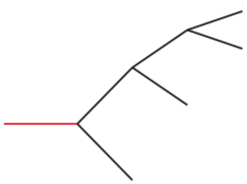
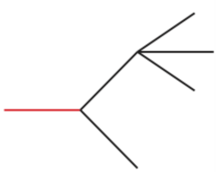
PHYSICAL REVIEW D **90**, 075004 (2014)

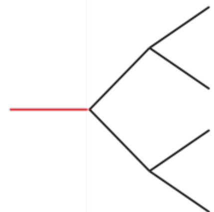
Exotic decays of the 125 GeV Higgs boson

David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

- observed 125 GeV state is primarily responsible for EWSB
  usually requires "decoupling" limit → h production close to SM
  other scenarios possible, but this is generic and minimal
- 125 GeV state decays to new BSM particles
  these BSM particles could primarily/only be produced through h decays do not consider rare or nonstandard decays directly to SM particles (captured in precision program, including angular distributions)
- initial decay is 2-body
  3-body and higher is possible, but requires new light states w/ substantial coupling to h to overcome phase space suppression

Picture of pp vs ee

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
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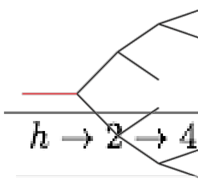
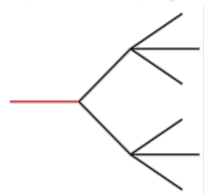
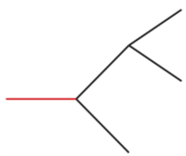
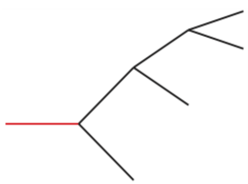
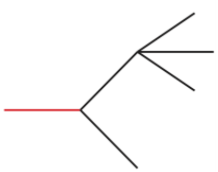
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

LHC's strength

HL-LHC has large number of Higgs produced, having great sensitivity to exotic decays into leptons and photons

Picture of pp vs ee

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

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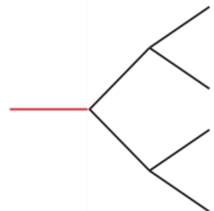
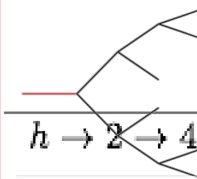
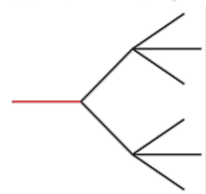
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
 $h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

LHC's strength

Hard at LHC due to missing energy

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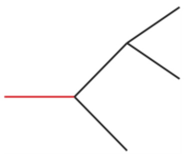
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
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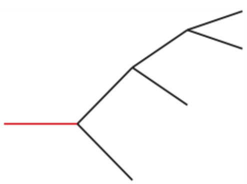
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
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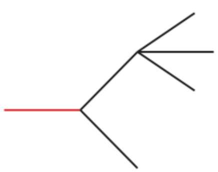
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
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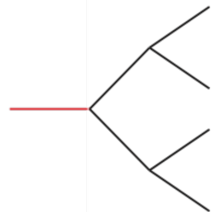
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
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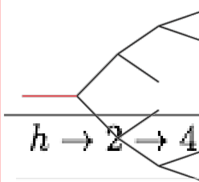
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
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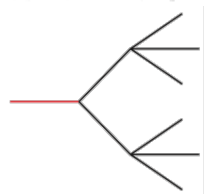
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
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LHC's strength

Hard at LHC due to missing energy

Hard at LHC due to hadronic background

Picture of pp vs ee

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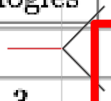
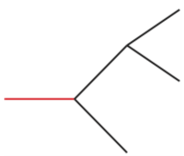
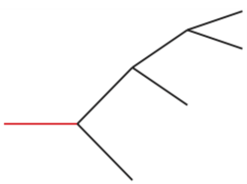
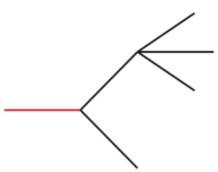
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

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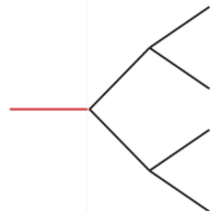
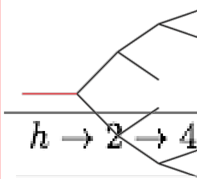
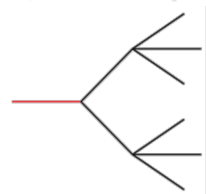
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

LHC's strength

Lepton collider's strength

Lepton collider's strength

Picture of pp vs ee

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not\!\!E_{\rm T}$
$h \to 2 \to 3$	$h \to \gamma + \not\!\!E_{\rm T}$
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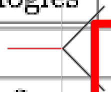
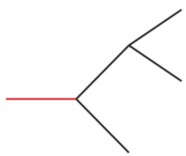
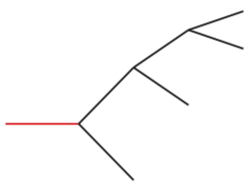
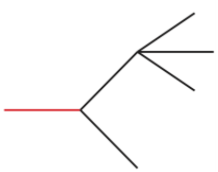
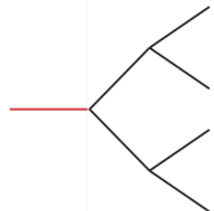
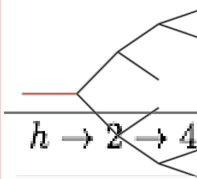
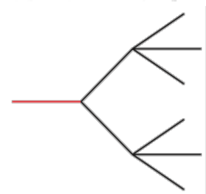
	$h \to (jj) + \not\!\!E_{\rm T}$
	$h \to (\tau^+\tau^-) + \not\!\!E_{\rm T}$
	$h \to (\gamma\gamma) + \not\!\!E_{\rm T}$
	$h \to (\ell^+\ell^-) + \not\!\!E_{\rm T}$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not\!\!E_{\rm T}$
	$h \to (jj) + \not\!\!E_{\rm T}$
	$h \to (\tau^+\tau^-) + \not\!\!E_{\rm T}$
	$h \to (\gamma\gamma) + \not\!\!E_{\rm T}$
	$h \to (\ell^+\ell^-) + \not\!\!E_{\rm T}$
	$h \to (\mu^+\mu^-) + \not\!\!E_{\rm T}$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not\!\!E_{\rm T}$
	$h \to jj + \not\!\!E_{\rm T}$
	$h \to \tau^+\tau^- + \not\!\!E_{\rm T}$
	$h \to \gamma\gamma + \not\!\!E_{\rm T}$
	$h \to \ell^+\ell^- + \not\!\!E_{\rm T}$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not\!\!E_{\rm T}$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not\!\!E_{\rm T}$
	$h \to (\ell^+\ell^-) + \not\!\!E_{\rm T} + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not\!\!E_{\rm T}$
	$h \to \ell^+\ell^- + \not\!\!E_{\rm T} + X$

LHC's strength

Lepton collider's strength

Lepton collider's strength

With this picture in mind, I present two examples of our studies.

H. Zhang, ZL, LT Wang, 1612.09284

Exotic Decays (example 1)

$$H \to aa \to (jj)(jj)$$

h → aa$^{(\prime)}$ → fermions

Well-motivated as in SM+S, 2HDM+S, NMSSM, EWPT, etc.

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV	quarks suppressed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^T $[0.2^L]$	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}	$0.5 - 1$ $[0.2 - 0.8]$	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]

projection/limit based on theory estimate in literature (L), our theory estimate (T), our re-interpretation of an LHC limit (R), or is unknown (U)

Exotic Decays (example 1)

$$H \to aa \to (jj)(jj)$$

h → aa(′) → fermions

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV	quarks suppressed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^T $[0.2^L]$	W	0.8	0.9 [0.2]	0	–
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$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.5-1$ $[0.2-0.8]$	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]

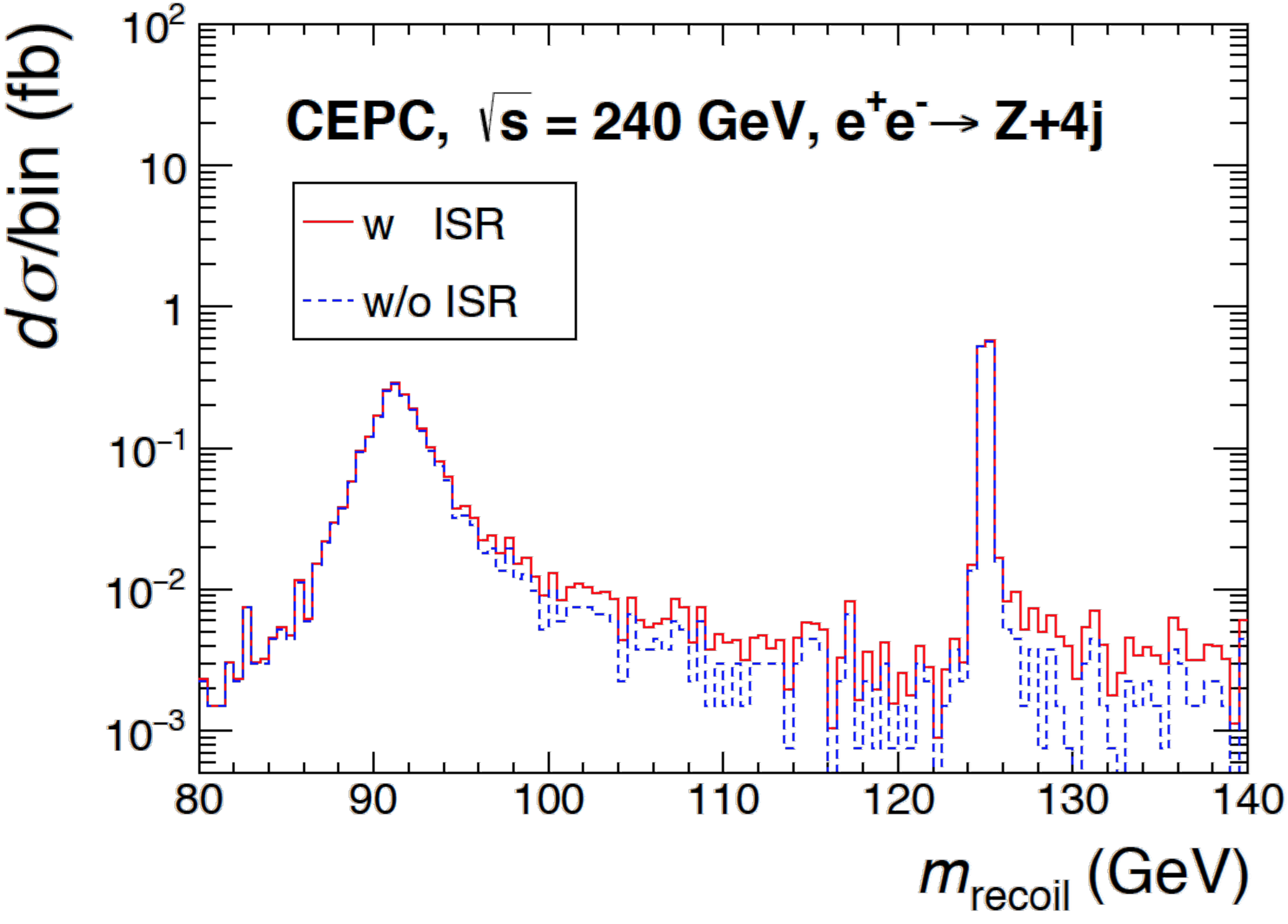
projection/limit based on theory estimate in literature (L), our theory estimate (T), our re-interpretation of an LHC limit (R), or is unknown (U)

Well-motivated as in SM+S, 2HDM+S, NMSSM, EWPT, etc.

LHC projected constraints on the such exotic decay branching fractions of $h \to aa$ around 20%

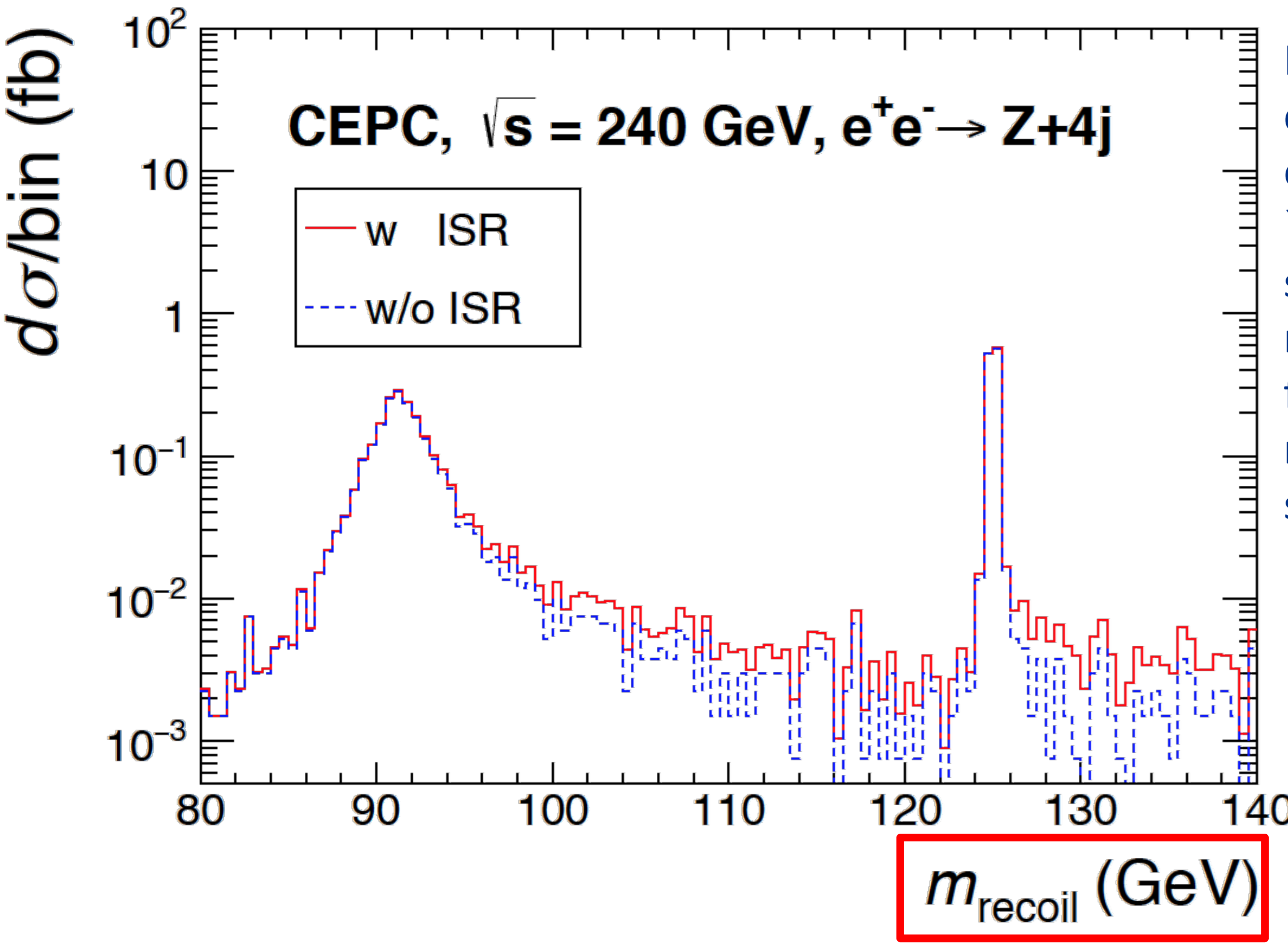
Exotic Decays (example 1)

$H \to aa \to (jj)(jj)$



Exotic Decays (example 1)

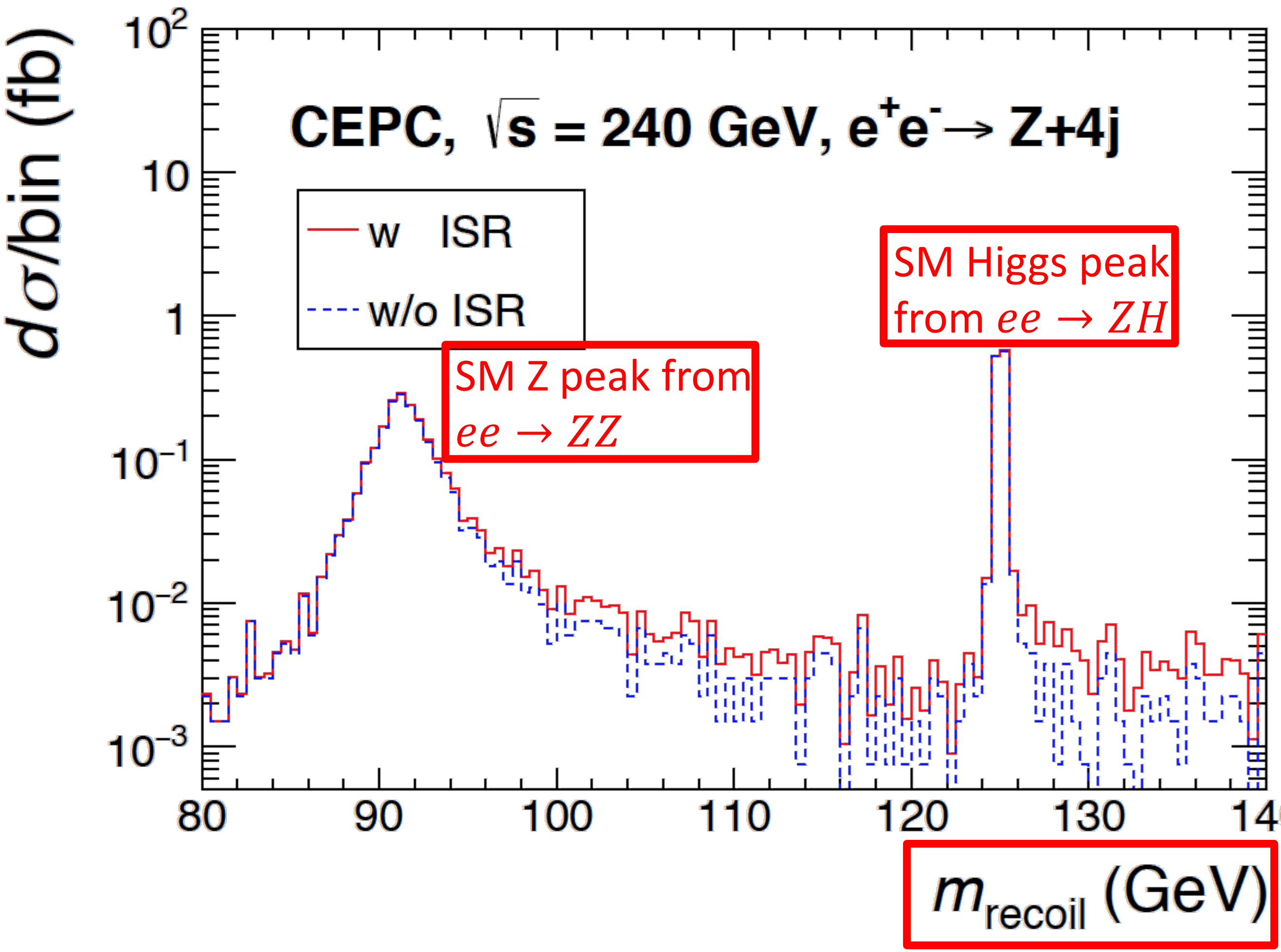
$H \to aa \to (jj)(jj)$



Knowing the exact initial colliding energy ($\hat{s}$) enables us to define ``recoil mass'' by subtracting the four momenta of spectator Z from the initial state four momenta, resulting in a sharp Higgs mass peak.

Exotic Decays (example 1)

$H \to aa \to (jj)(jj)$



Knowing the exact initial colliding energy ($\hat{s}$) enables us to define ``recoil mass'' by subtracting the four momenta of spectator Z from the initial state four momenta, resulting in a sharp Higgs mass peak.

Exotic Decays (example 1)

$$H \to aa \to (jj)(jj)$$

- Preselection cuts: $|\cos\theta_{j,\ell}| < 0.98, E_{j,\ell} > 10\text{GeV},$

Similar to some LEP analysis

$$y_{ij} \equiv \frac{2\min\left(E_i^2, E_j^2\right)(1-\cos\theta_{ij})}{E_{vis}^2} > y_{\text{cut}},$$

a pair of OSSF leptons, $\theta_{\ell\ell} > 80°$

$|m_{\ell\ell} - m_Z| < 10\text{GeV}, |m_{\text{recoil}} - m_h| < 5\text{GeV}.$

- MadGraph5_aMC@NLO.

- The ISR effect of the background is roughly mimicked by generating events with 1 additional photon (with pT>1GeV to avoid the IR divergence).

- Additional cut to suppress the ISR effect: $E_{vis} > 225\text{GeV}.$

Exotic Decays (example 1)

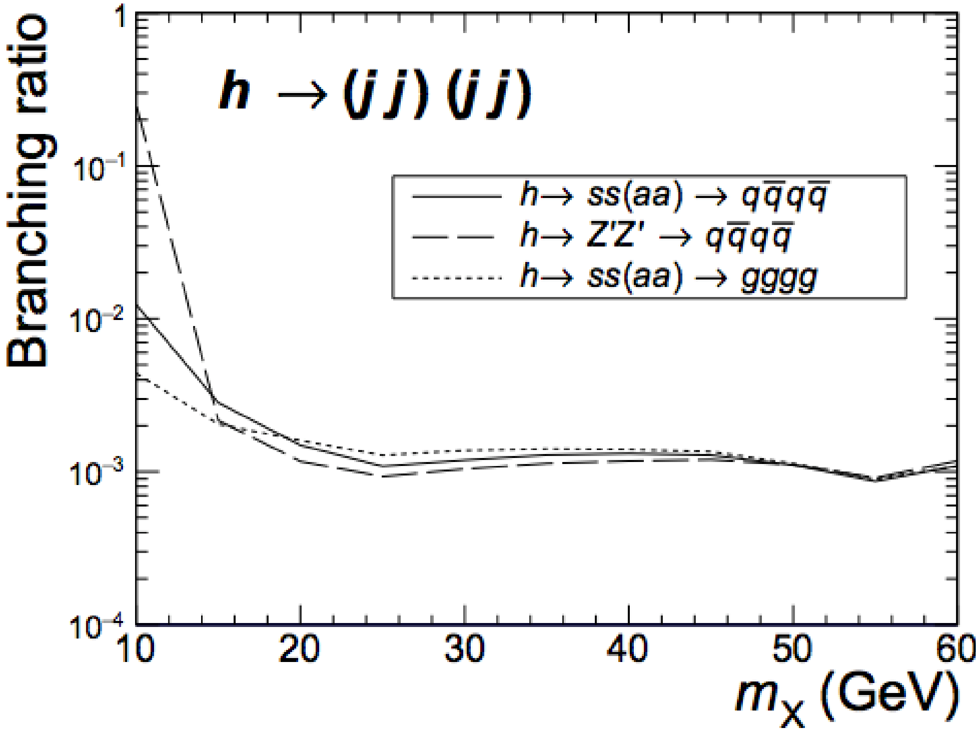
$H \to aa \to (jj)(jj)$

Background mainly from $h \to VV^* \to 4j$ and $h \to jj$ with FSR after pre-selection cuts

$$\delta m \equiv \min_{\sigma \in A_4} \left| m_{j_{\sigma(1)} j_{\sigma(2)}} - m_{j_{\sigma(3)} j_{\sigma(4)}} \right|$$

we choose the correction paring of the four jets into dijet system

then use
δm vs.. $m_{j_1 j_2} + m_{j_3 j_4}$ 2D-likelihood function to selection (define the significance) and derive the limits



Exotic Decays (example 1)

$H \rightarrow aa \rightarrow (jj)(jj)$

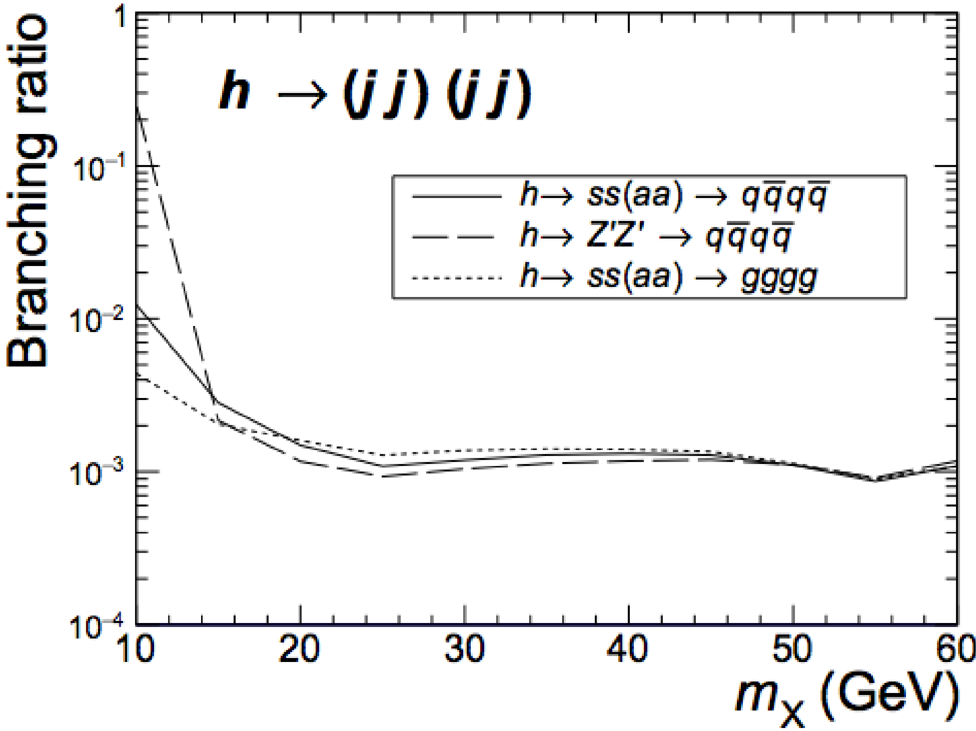
Background mainly from $h \rightarrow VV^* \rightarrow 4j$ after pre-selection cuts

with

$$\delta m \equiv \min_{\sigma \in A_4} \left| m_{j_{\sigma(1)} j_{\sigma(2)}} - m_{j_{\sigma(3)} j_{\sigma(4)}} \right|$$

we choose the correction paring of the four jets into dijet system

then use
δm vs.. $m_{j_1 j_2} + m_{j_3 j_4}$ 2D-likelihood function to selection (define the significance) and derive the limits



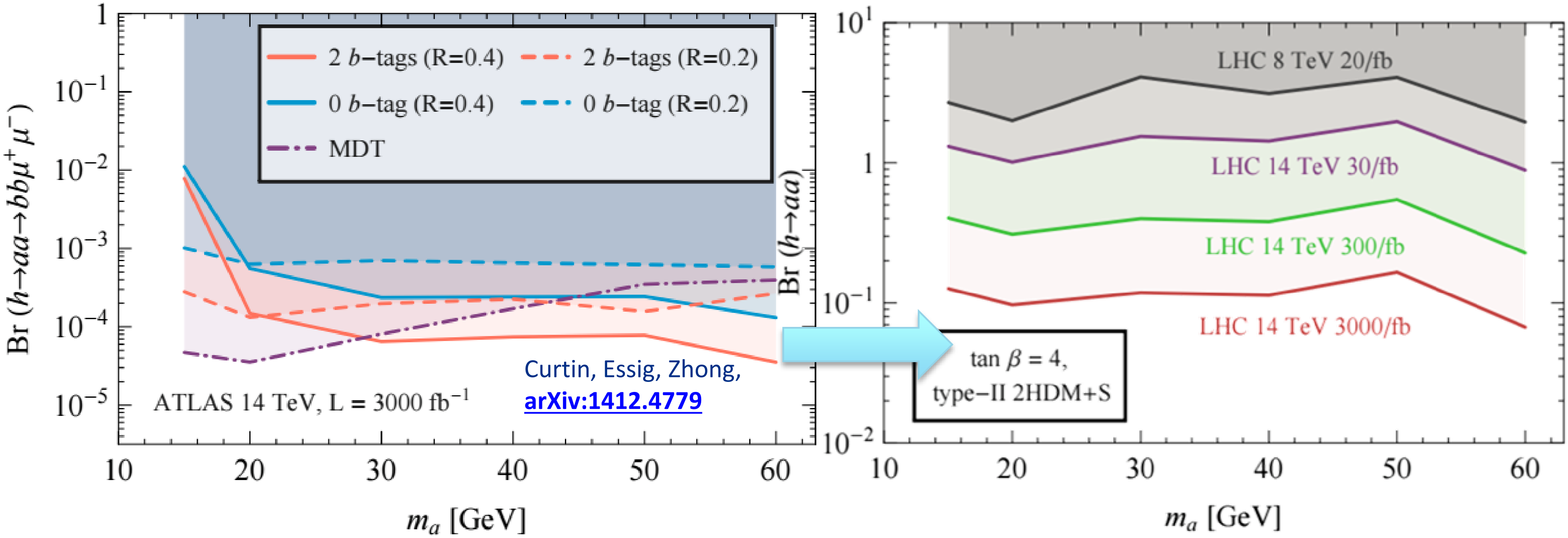
Great sensitivity on exotic branching fraction $O(10^{-3})$

Similar (better) result archived for 4b, 4c, etc.

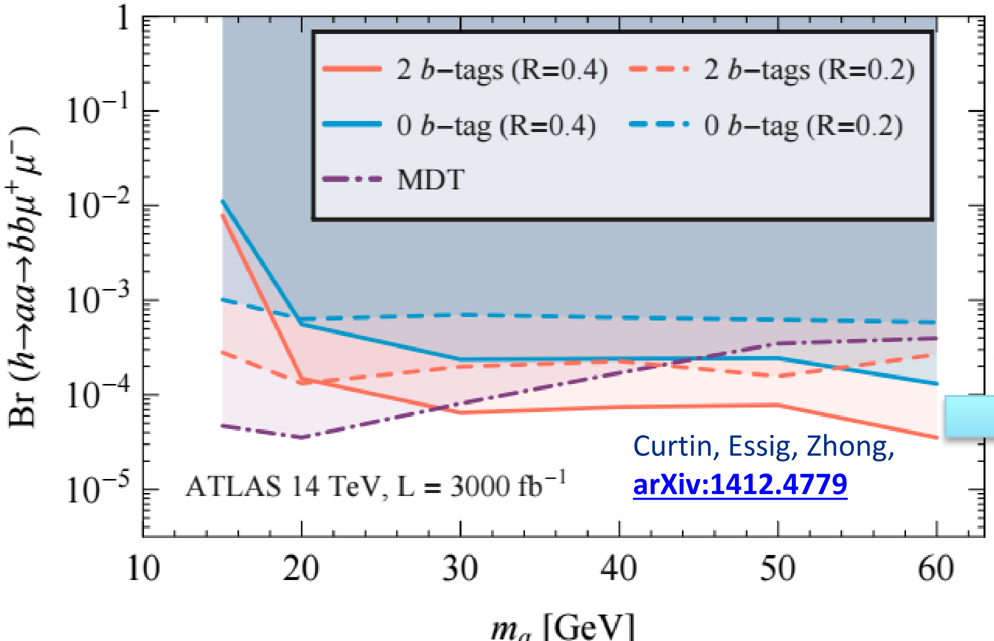
Room for improvement using different strategy treating collimated jets.

Room for improvement including hadronic decaying spectator Z bosons.

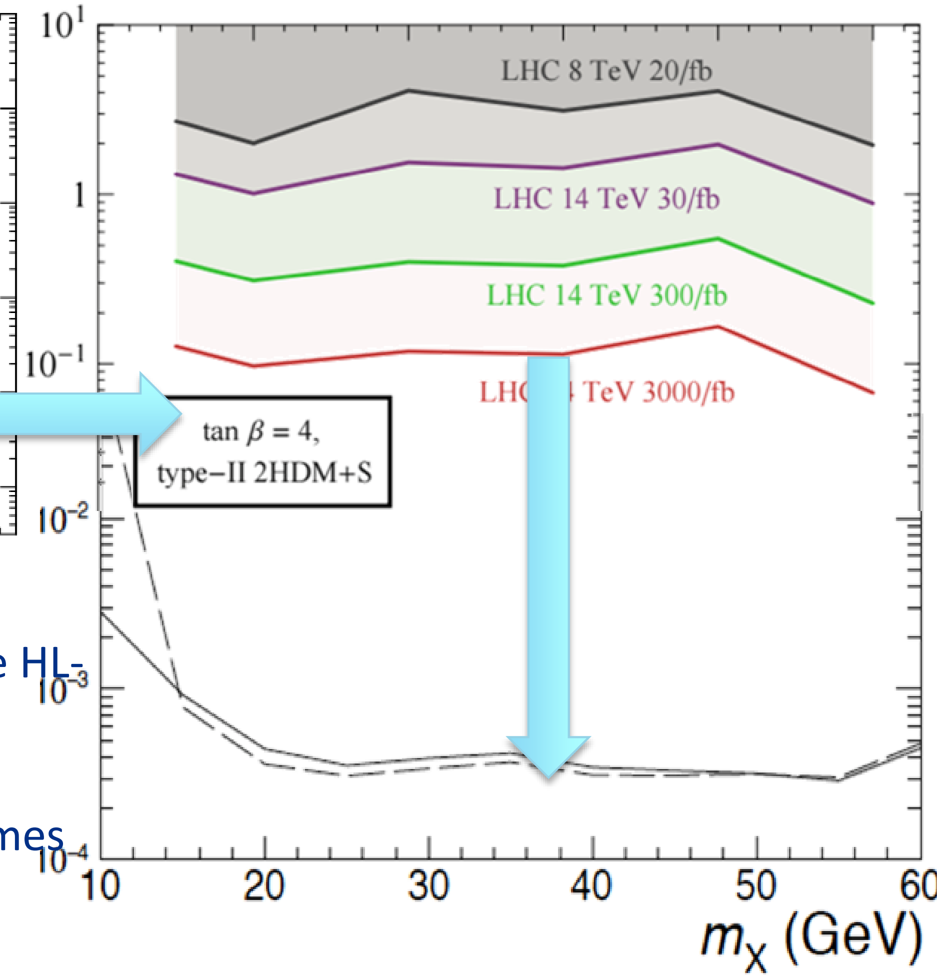
Exotic Decays (example 1)
$H \rightarrow aa$ interpretation



Exotic Decays (example 1)
$H \rightarrow aa$ interpretation



Curtin, Essig, Zhong, arXiv:1412.4779



O(10%) limit on exotic branching fractions at the HL-LHC.

lepton colliders will improve the limits by two orders of magnitude, hitting more relevant regimes for various models' preferred parameter space.

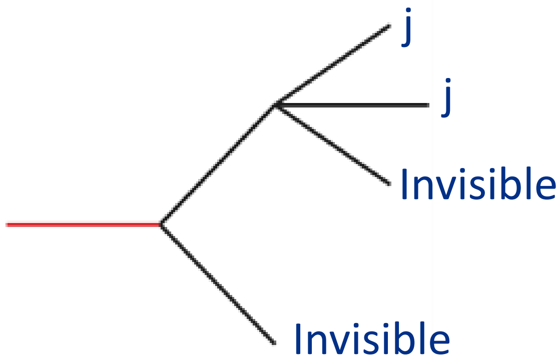
Exotic Decays (example 2)

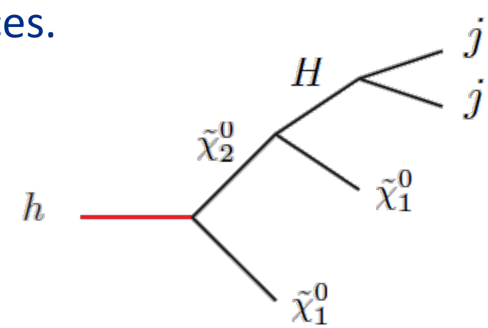
$$H \rightarrow x_1, x_2 \rightarrow j\,j + MET$$

Well-motivated from SUSY with light DM, or general DM models.

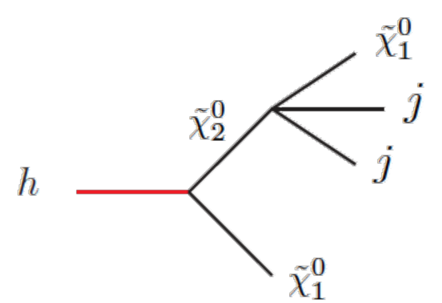
Very challenging, a nightmare at the (HL-) LHC

1) MET
2) Only light jets
3) no resonance signature from the dijet system, but rather a wide range of invariant mass bounded by the mass differences.





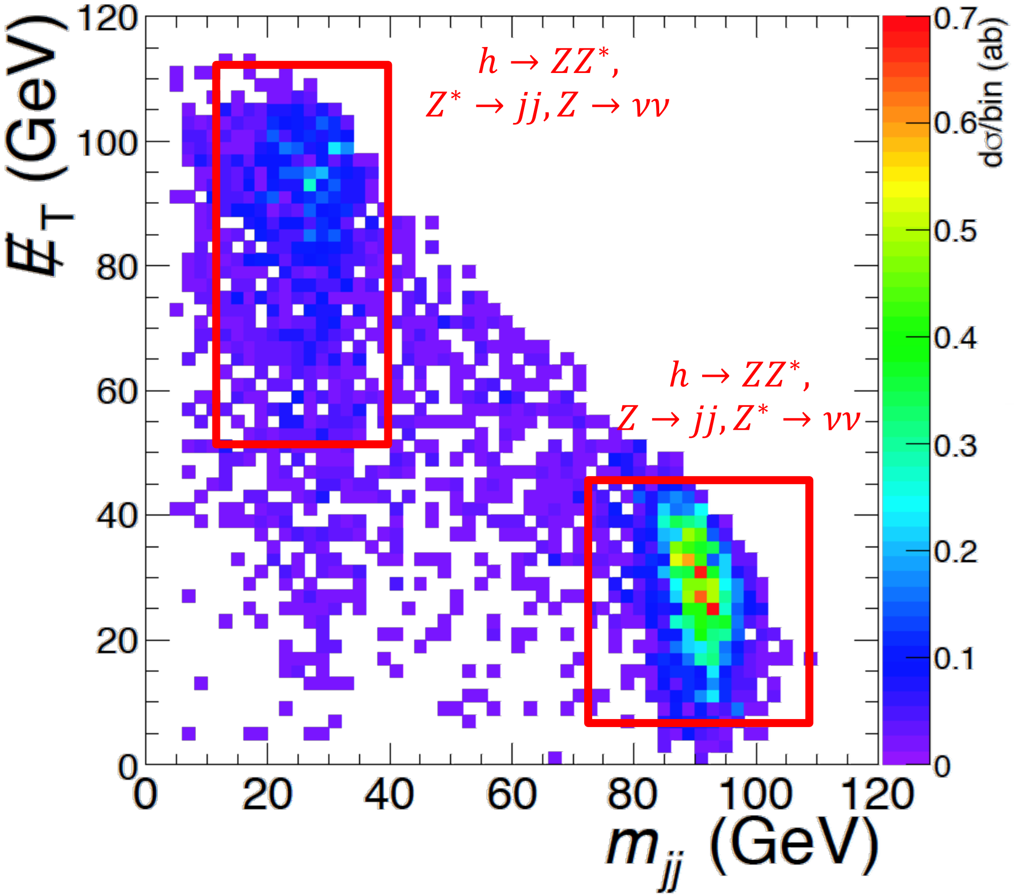
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$

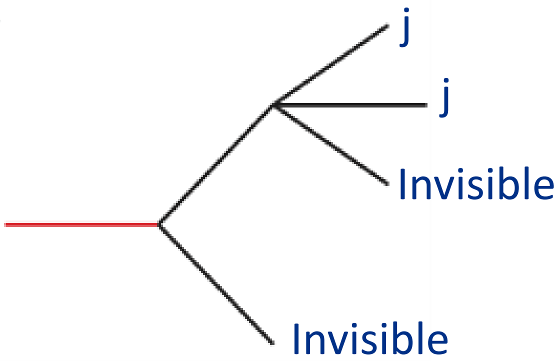


$h \rightarrow 2 \rightarrow (1+3)$

Exotic Decays (example 2)

$$H \rightarrow x_1, x_2 \rightarrow j\, j + MET$$



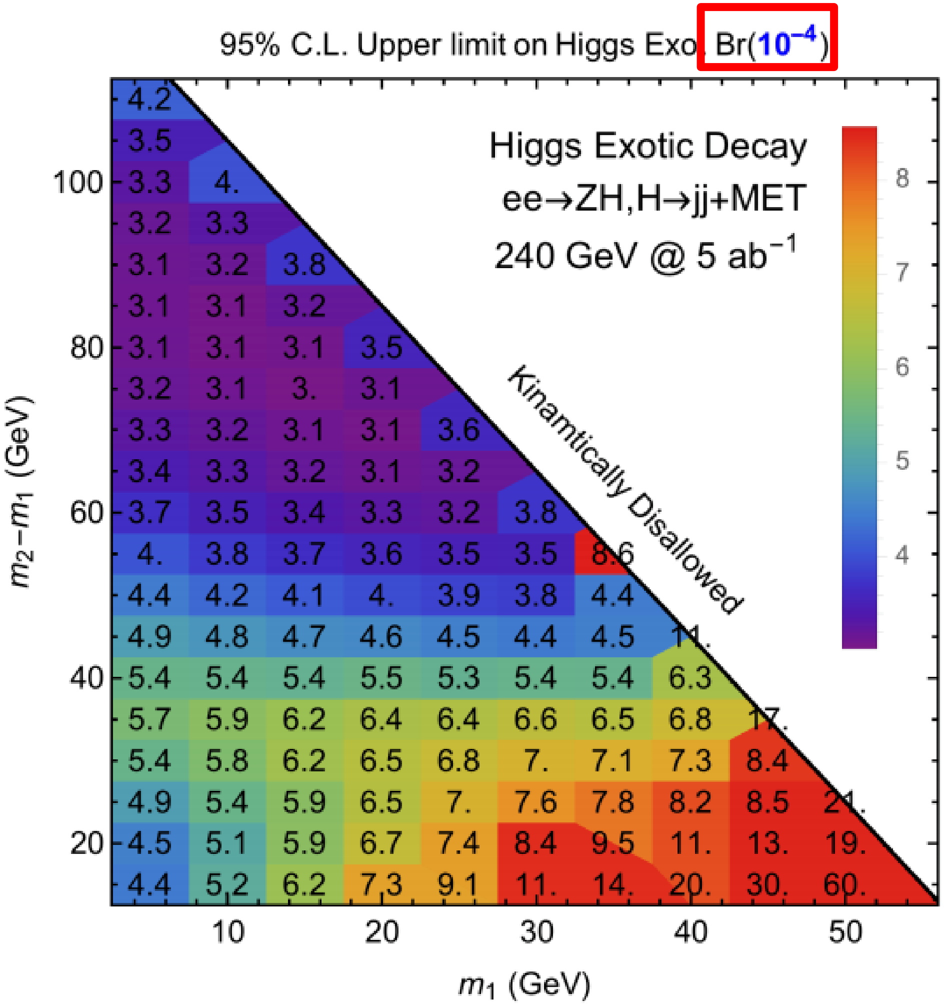


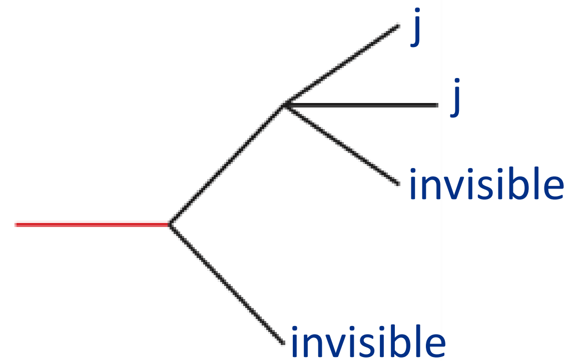
Background dominant by the the SM Higgs decays into four quarks via ZZ* after pre-selection cuts

**another interesting improvement only available at lepton colliders, using ``recoil mass'' again to veto the $Z^{(*)} \rightarrow \nu\nu$ mass peak.

Exotic Decays (example 2)

$$H \rightarrow x_1, x_2 \rightarrow j\, j + MET$$

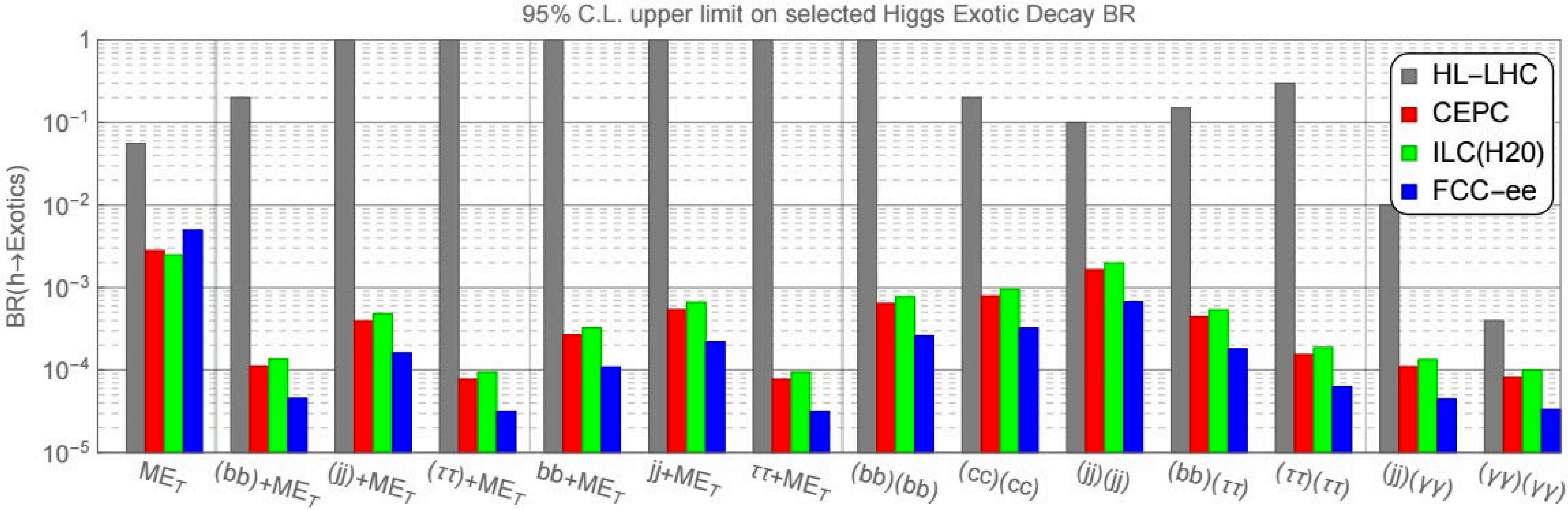




Depending on the masses of the decaying particles, the exclusion reach on Higgs exotic BRs could be as low as 3×10^{-4} and remains this order for large range, except kinematic edges.

Similar (better) result archived for 4b, 4c, etc.
Room for improvement using different strategy treating collimated jets.
Room for improvement including hadronic decaying spectator Z bosons.

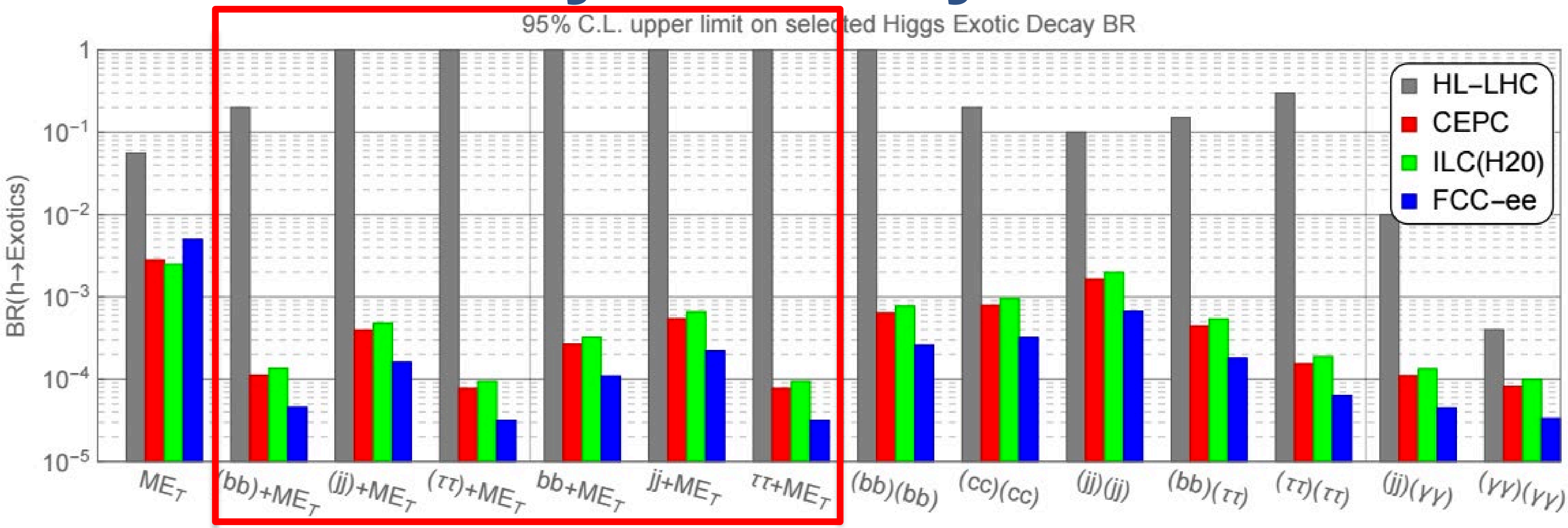
Exotic Decay summary



We visualize the sensitivity on Higgs exotic decay branching factions with some reasonable choice of model parameters.

The HL-LHC are from various studies and projections available in the literature;
The lepton collider sensitivities (except for the first channel, $h \to inv$) are from our study with different $ee \to ZH$ integrated luminosities and beam polarizations for different colliders.

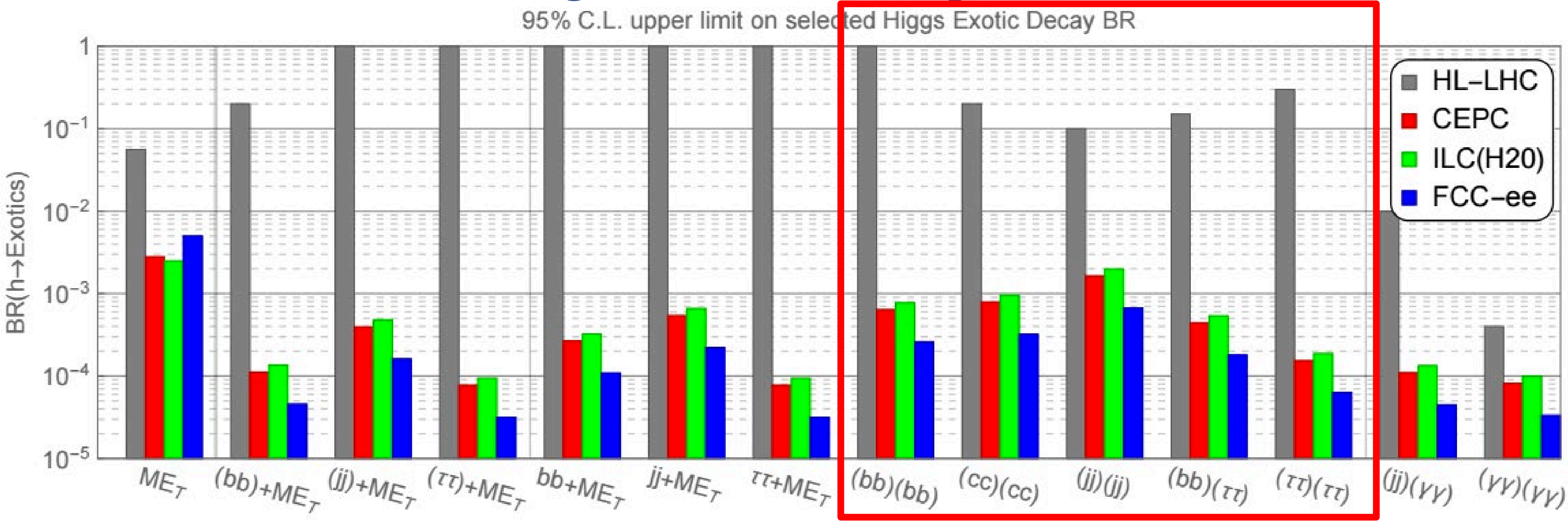
Exotic Decay summary



with missing Energy SUSY motivated, DM motivated channels

3-4 order of magnitude improvement for the constraints on such exotic branching fractions

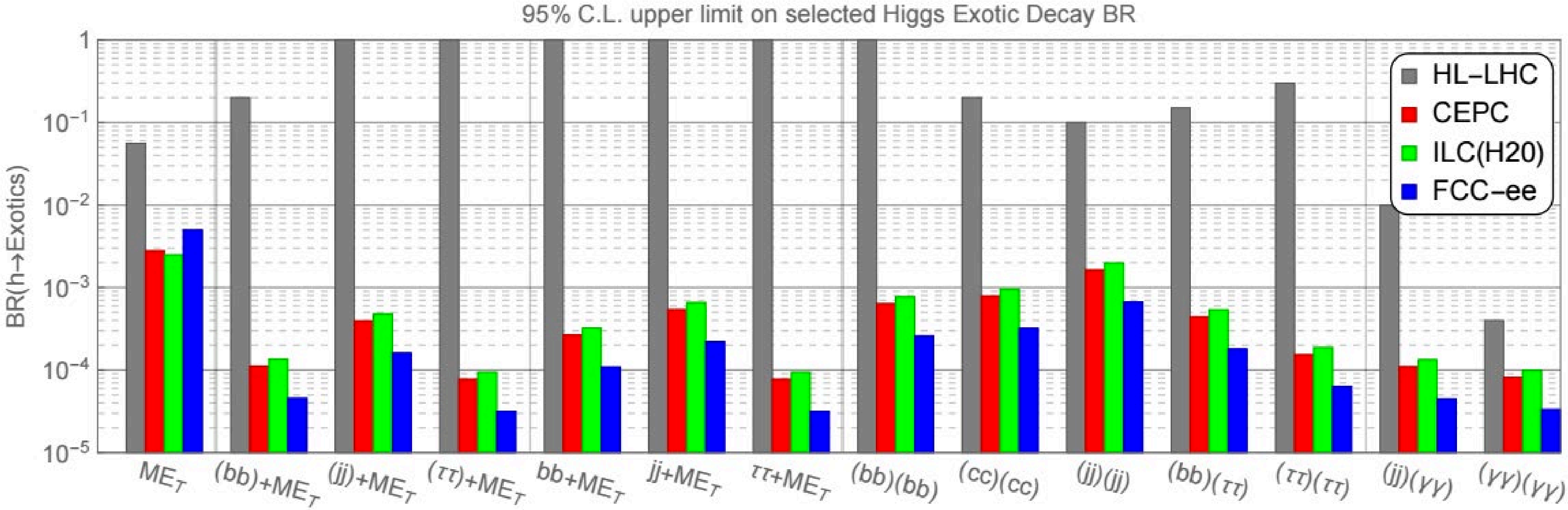
Exotic Decay summary



$h \to 4f$ generic Higgs sector extensions, also Higgs portals

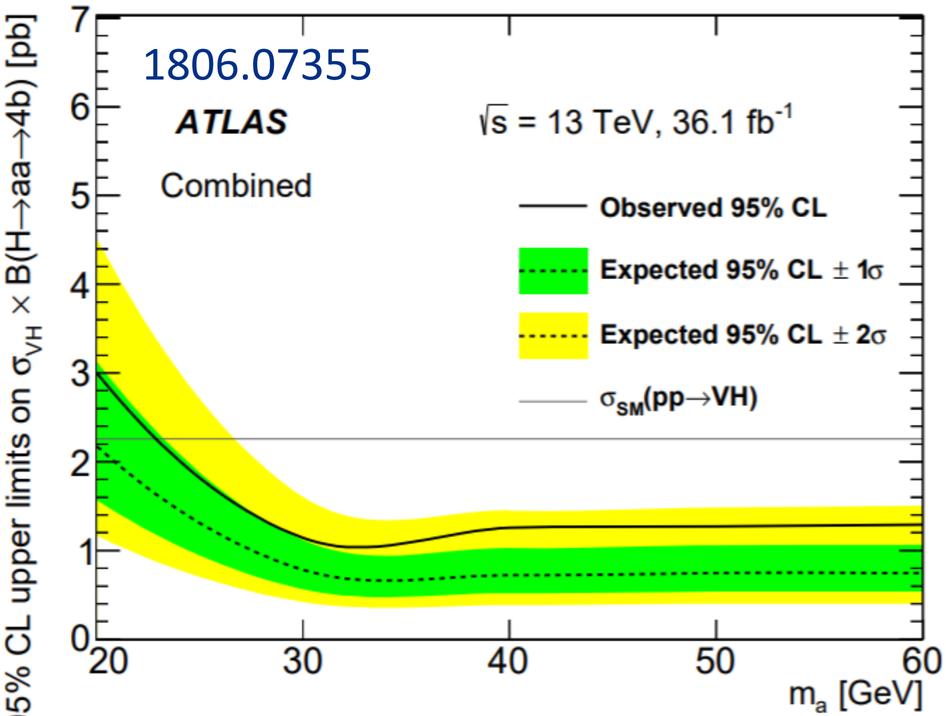
2-3 order of magnitude improvement for the constraints on such exotic branching fractions

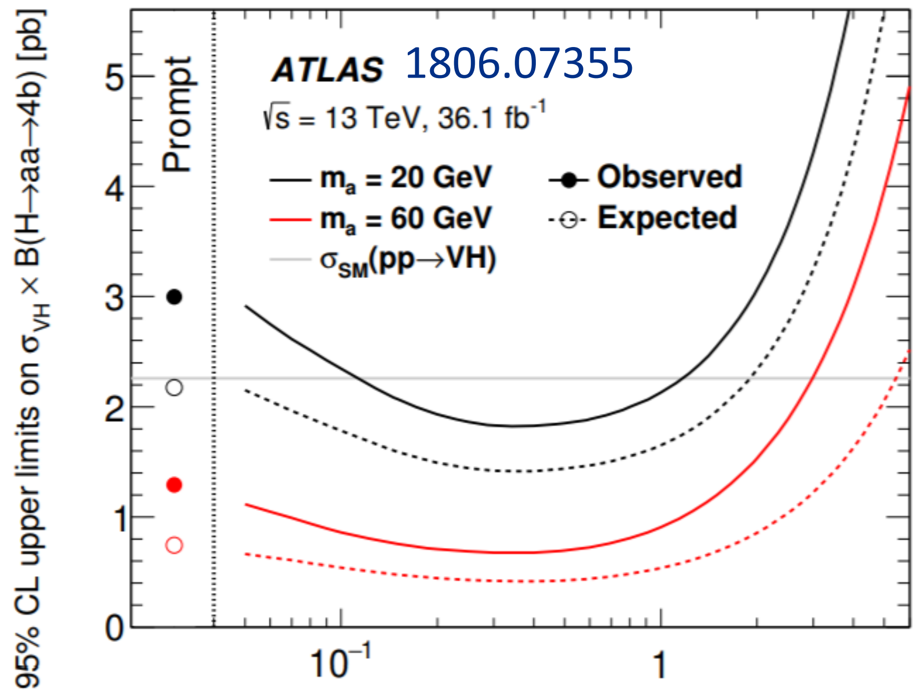
Outlook



Many more works for Higgs exotic decays at both the LHC and future colliders are interesting and are needed.

Prompt→ LLP





Experimental searches use standard particle ID for most searches, where the boundary in displacement the prompt search can be applied to is really hard to guess/estimate.

Higgs exotic decays H->(bb)(bb) made a first step, in a same publication, reinterpreted their own prompt searches for long-lived intermediate particles:

- Prompt limits dies-off above a few mm;
- Long-lived limits is better than prompt limit in a prompt search; (maybe next time when an excess/discovery hard to fit your favorite model in rate, consider LLPs ☺)

Higgs to LLPs

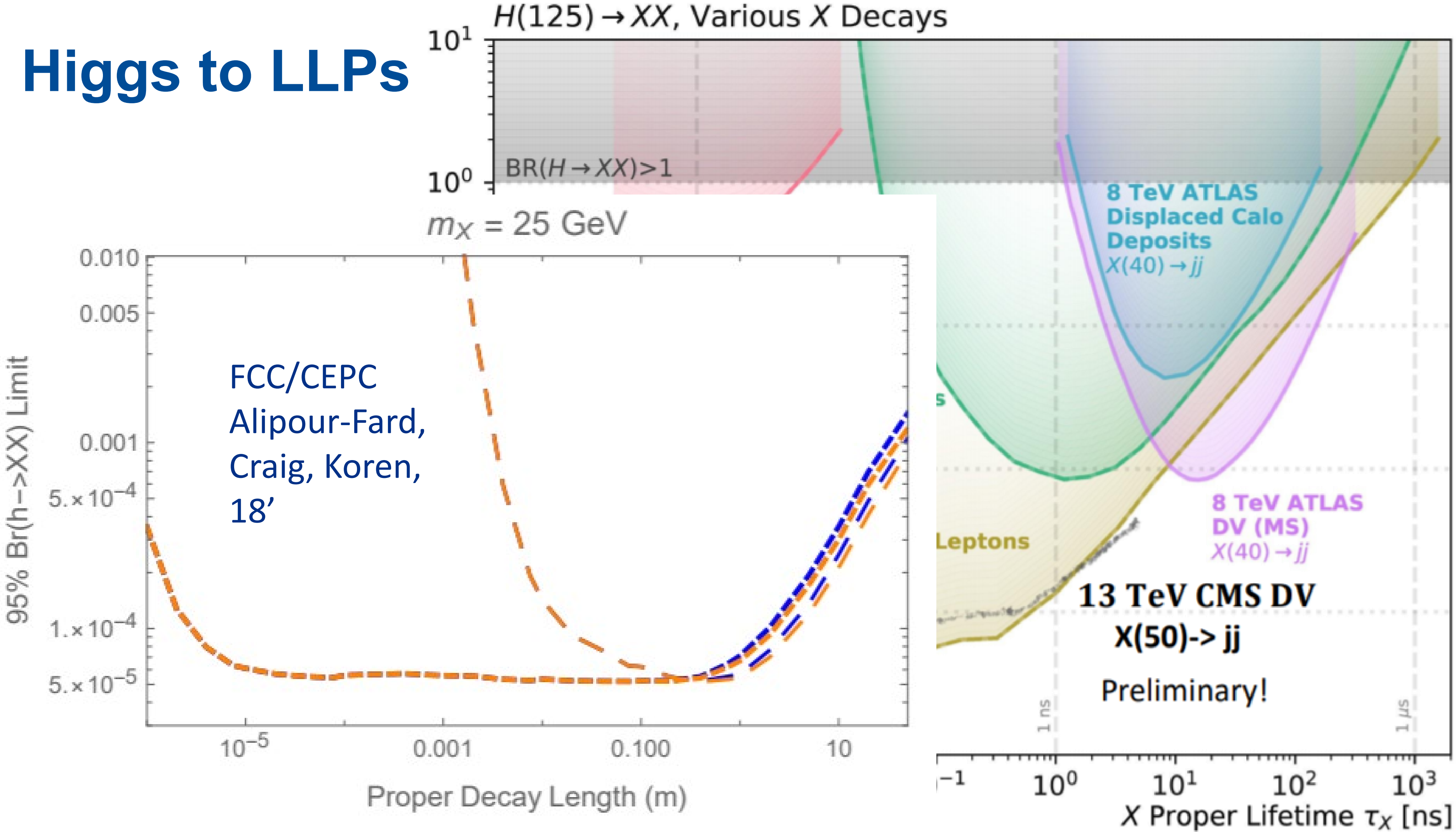


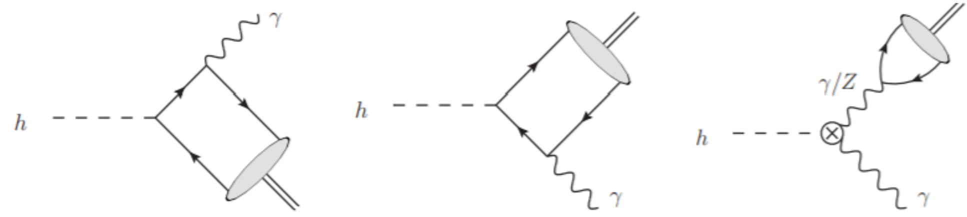
Figure from Lee, Ohm, Soffer, Yu (1810.12602)

New ideas of using timing information at the LHC, J. Liu, ZL, L.T. Wang, 18’

Higgs decay to mesons

Kagan, Perez, Petriello, Soreq, Stoynev, Zupan 14'; Konig, Neubert, 15', +Alte, 16'

Higgs SM rare decays to mesons + photon (or other SM gauge bosons) provides unique window to Higgs to light quark Yukawas



Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^+ W^-$	$4.30 \pm 0.01_f \pm 0.00_{\rm CKM} \pm 0.17_{\Gamma_h}$	130.4 ± 0.2
$h \to \rho^+ W^-$	$10.92 \pm 0.15_f \pm 0.00_{\rm CKM} \pm 0.43_{\Gamma_h}$	207.8 ± 1.4
$h \to K^+ W^-$	$0.33 \pm 0.00_f \pm 0.00_{\rm CKM} \pm 0.01_{\Gamma_h}$	156.2 ± 0.7
$h \to K^{*+} W^-$	$0.56 \pm 0.03_f \pm 0.00_{\rm CKM} \pm 0.02_{\Gamma_h}$	203.2 ± 5.9
$h \to D^+ W^-$	$0.56 \pm 0.03_f \pm 0.04_{\rm CKM} \pm 0.02_{\Gamma_h}$	204.6 ± 5.0
$h \to D^{*+} W^-$	$1.04 \pm 0.12_f \pm 0.07_{\rm CKM} \pm 0.04_{\Gamma_h}$	278 ± 16
$h \to D_s^+ W^-$	$17.12 \pm 0.61_f \pm 0.56_{\rm CKM} \pm 0.67_{\Gamma_h}$	257.5 ± 4.6
$h \to D_s^{*+} W^-$	$25.10 \pm 1.45_f \pm 0.81_{\rm CKM} \pm 0.98_{\Gamma_h}$	311 ± 9
$h \to B^+ W$	[illegible]	[illegible]
$h \to B^{*+} W$	[illegible]	[illegible]
$h \to B_c^+ W$	[illegible]	[illegible]

Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^0 Z$	$2.30 \pm 0.01_f \pm 0.09_{\Gamma_h}$	130.4 ± 0.2
$h \to \eta Z$	$0.83 \pm 0.08_f \pm 0.03_{\Gamma_h}$	$f_\eta^s = -110.7 \pm 5.5$
$h \to \eta' Z$	$1.24 \pm 0.12_f \pm 0.05_{\Gamma_h}$	$f_{\eta'}^s = 135.2 \pm 6.4$
$h \to \rho^0 Z$	$7.19 \pm 0.09_f \pm 0.28_{\Gamma_h}$	216.3 ± 1.3
$h \to \omega Z$	$0.56 \pm 0.01_f \pm 0.02_{\Gamma_h}$	$f_\omega = 194.2 \pm 2.1, \quad f_\omega^s = -13.8 \pm 4.8$
$h \to \phi Z$	$2.42 \pm 0.05_f \pm 0.09_{\Gamma_h}$	$f_\phi = 223.0 \pm 1.4, \quad f_\phi^s = 230.4 \pm 2.6$
$h \to J/\psi Z$	$2.30 \pm 0.06_f \pm 0.09_{\Gamma_h}$	403.3 ± 5.1
[illegible]	[illegible]	684.4 ± 4.6
[illegible]	[illegible]	475.8 ± 4.3
[illegible]	[illegible]	411.3 ± 3.7

Mode	Branching Fraction $[10^{-6}]$		
Method	NRQCD [1486]	LCDA LO [1485]	LCDA NLO [1488]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

Higgs decay to mesons

- Results from 1607.03400, 1507.03031, 1501.03276, 1712.02758, 1507.03031, 1807.00802
- Most results from 8 TeV puts an upper bound of ~1.5x10^{-3}
- 13 TeV 36 fb^{-1} start to lead us to realm of 10^{-4}
- HL/HE-LHC will lead us to the realm of ~10$^{-5\sim6}$ **
- We will be able to measure these these rare decays of the Higgs boson, providing very nontrivial test of the Higgs boson properties, QCD and interference
- Many new modes to measure H->mesons+W, mesons+Z, etc.

New studies on open fermion plus photon search also show compelling reach (in addition to quarks also applies to leptons, T. Han, X. Wang **1704.00790**)

$h \to D_s^{*+} W^-$	$25.10 \pm 1.45_f \pm 0.81_{\rm CKM} \pm 0.98_{\Gamma_h}$	311 ± 9
$h \to B^+ W$		
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684.4 ± 4.6
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$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

Current limits

<8.8x10^{-4}

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<4.8x10^{-4}

<3.5x10^{-4}

<4.9x10^{-4}

<5.9x10^{-4}

<5.7x10^{-4}

**extrapolation on statistical only, FCC-hh will lead us further!

Beyond the Z_2 limit

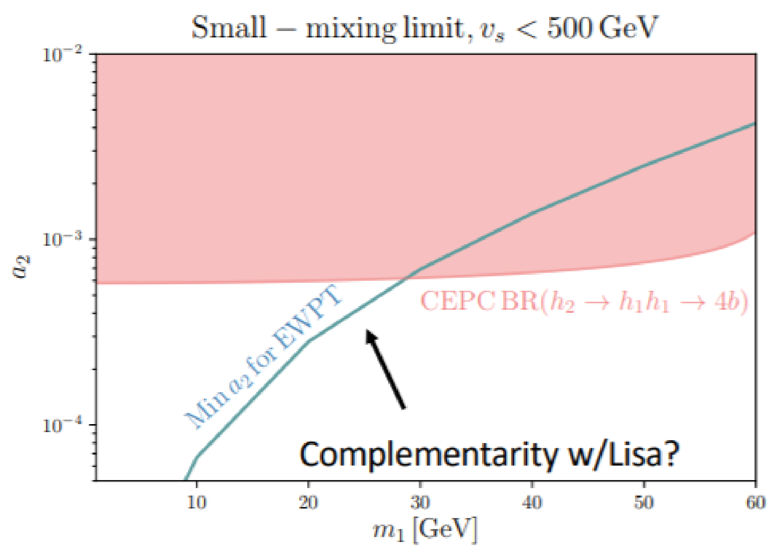
General case more complicated. Simplifies in the small-mixing limit

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} a_1 |H|^2 S + \frac{1}{2} a_2 |H|^2 S^2 + b_1 S + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

Now b_3 can potentially compensate for small a_2. However, imposing requirements from vacuum stability, completion of the PT, etc still place a lower bound on $BR(h_2 \to h_1 h_1)$:

Larger mixing angles require numerical scans; expect similar conclusions

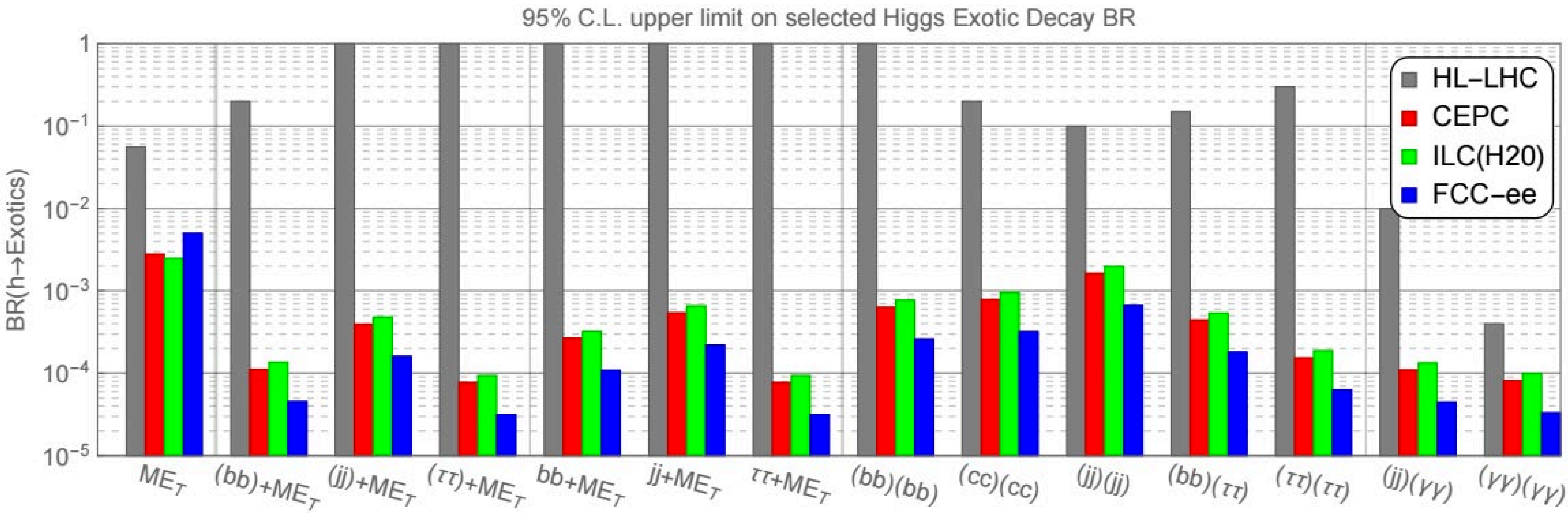
Projected CEPC sensitivity taken from Liu, Wang, Zhang 2016



CEPC should be able to probe light visibly-decaying scalars consistent with a strong EWPT and other pheno requirements down to ~30 GeV.

Work in progress with M. J. Ramsey-Musolf and J. Shelton

Summary



- Higgs Exotic decays is a very important component of Higgs program at future colliders
- Lepton colliders show great advantage for decays that are very challenging at the LHC, such as Higgs decays into jets and Higgs decays with missing energy
- Hadron colliders and lepton colliders are complementary in probing Higgs exotic decays and could together provide a much more coherent picture for discovery
- Many more works for Higgs exotic decays at both the LHC and future colliders are interesting and are needed.

Backup

Exotic Decays (example 1)

$$H \to aa \to (jj)(jj)$$

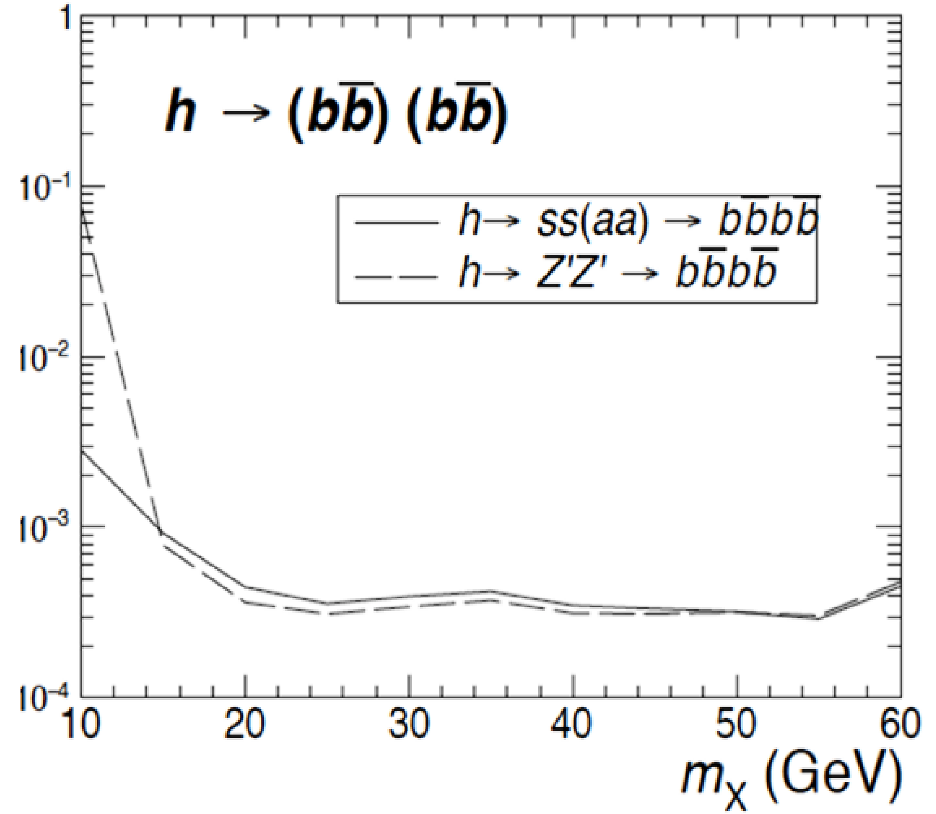
Background mainly from $h \to VV^* \to 4j$ after pre-selection cuts

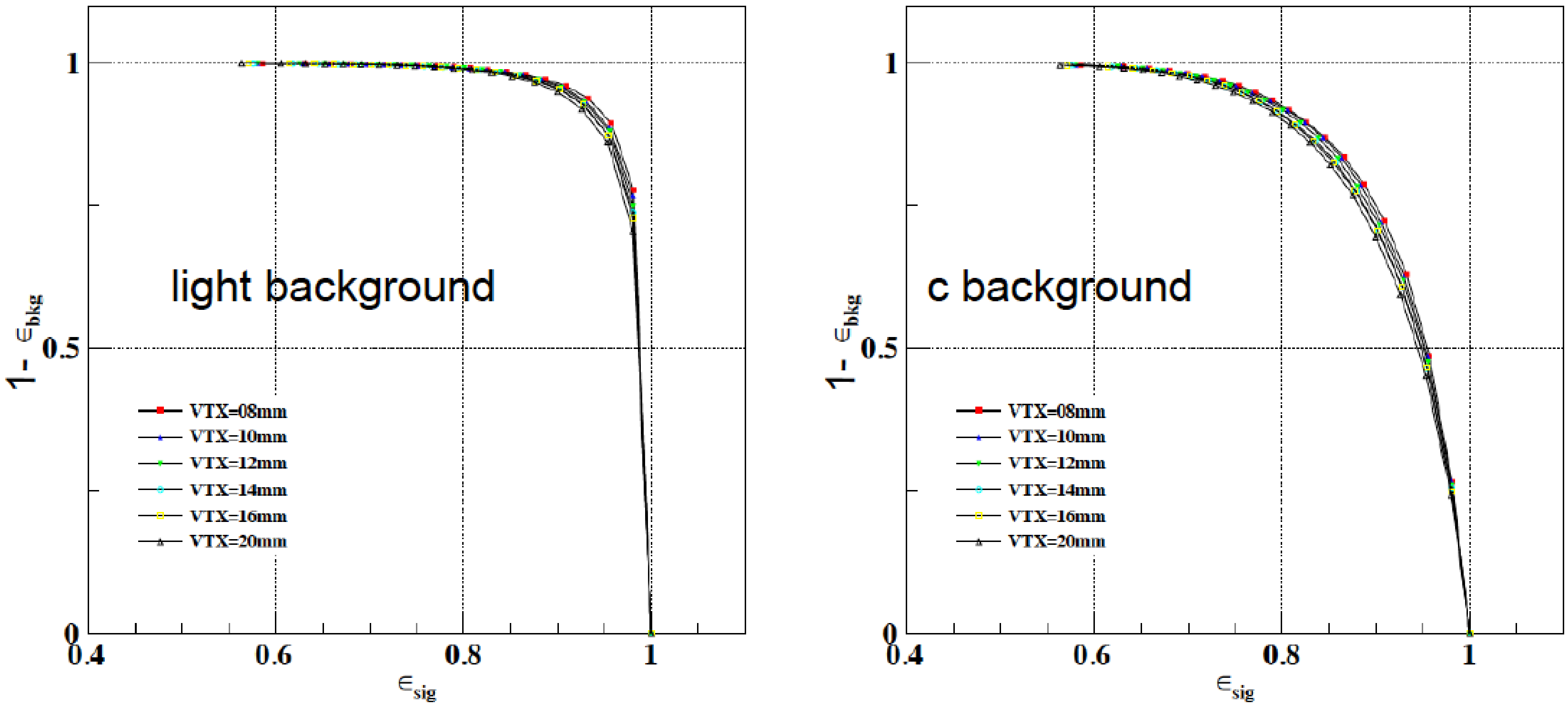
with

$$\delta m \equiv \min_{\sigma \in A_4} \left| m_{j_{\sigma(1)} j_{\sigma(2)}} - m_{j_{\sigma(3)} j_{\sigma(4)}} \right|$$

we choose the correction paring of the four jets into dijet system

then use
δm vs.. $m_{j_1 j_2} + m_{j_3 j_4}$ 2D-likelihood function to selection (define the significance) and derived the limits





Gang Li

- *With 8 – 20 mm VTX Inner radius, very good b-tagging*
  - *At efficiency ~ 80%: almost reject all the light background & only 8-10% c-jets misidentified as b-jets (Purity ~93-96% at Z to qq events).*

Decay Mode	95% C.L. limit on Br				
	LHC	HL-LHC	CEPC	ILC	FCC-ee
$\not{E}_T$	0.23 [37, 38]	0.056 [12–14]	0.0028 [16]	0.0025 [17]	0.005 [18]
$(b\bar{b}) + \not{E}_T$	–	[0.2]	1×10^{-4}	1×10^{-4}	5×10^{-5}
$(jj) + \not{E}_T$	–	–	5×10^{-4}	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-) + \not{E}_T$	–	[1]	8×10^{-4}*	9×10^{-4}	3×10^{-4}
$b\bar{b} + \not{E}_T$	–	–	3×10^{-4}	3×10^{-4}	1×10^{-4}
$jj + \not{E}_T$	–	–	5×10^{-4}	7×10^{-4}	2×10^{-4}
$\tau^+\tau^- + \not{E}_T$	–	–	8×10^{-4}*	9×10^{-4}	3×10^{-4}
$(b\bar{b})(b\bar{b})$	1.7 [48]	(0.2)	4×10^{-4}	8×10^{-4}	3×10^{-4}
$(c\bar{c})(c\bar{c})$	–	(0.2)	8×10^{-4}	1×10^{-3}	3×10^{-4}
$(jj)(jj)$	–	[0.1]	1×10^{-3}	2×10^{-3}	7×10^{-4}
$(b\bar{b})(\tau^+\tau^-)$	[0.1]* [49]	[0.15]	4×10^{-4}*	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)(\tau^+\tau^-)$	[1.2]* [50]	$[0.2 \sim 0.4]$	1×10^{-4}*	1×10^{-4}	5×10^{-5}
$(jj)(\gamma\gamma)$	–	[0.01]	1×10^{-4}	1×10^{-4}	3×10^{-5}
$(\gamma\gamma)(\gamma\gamma)$	$[7\times10^{-3}]$ [51]	4×10^{-4}*	1×10^{-4}	8×10^{-5}	3×10^{-5}