Exotic Higgs Decays at Higgs Factories

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HKIAS HEP Program

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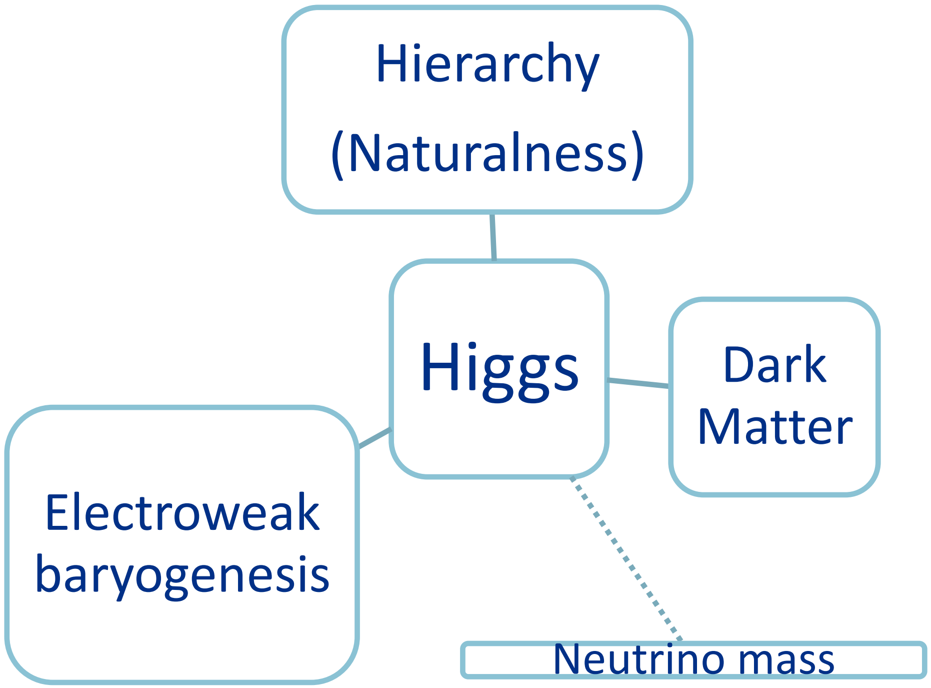
based on work with L-T. Wang, H. Zhang, arXiv:1612.09284

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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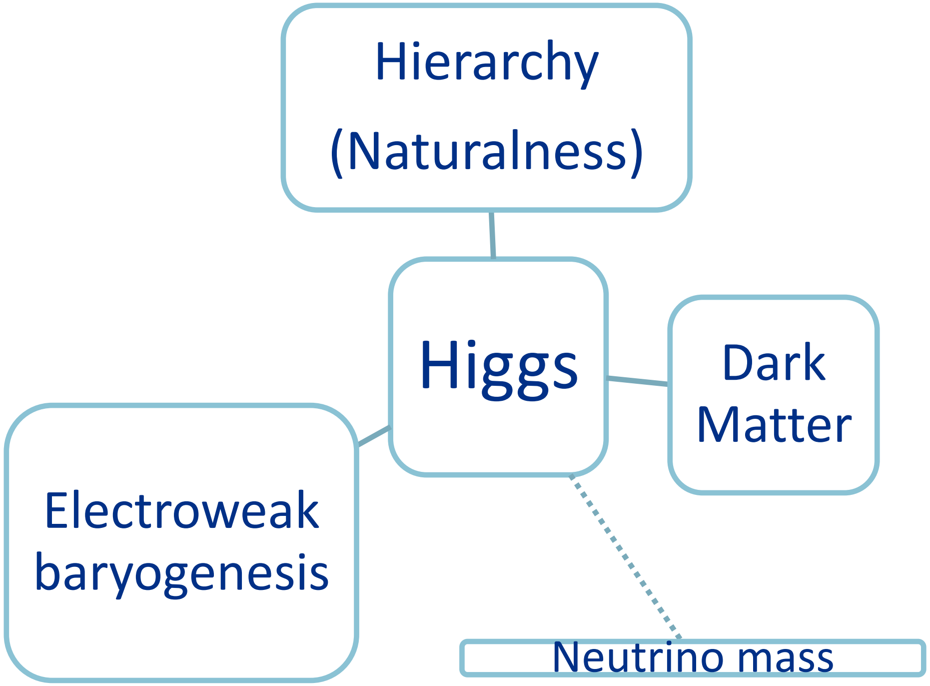

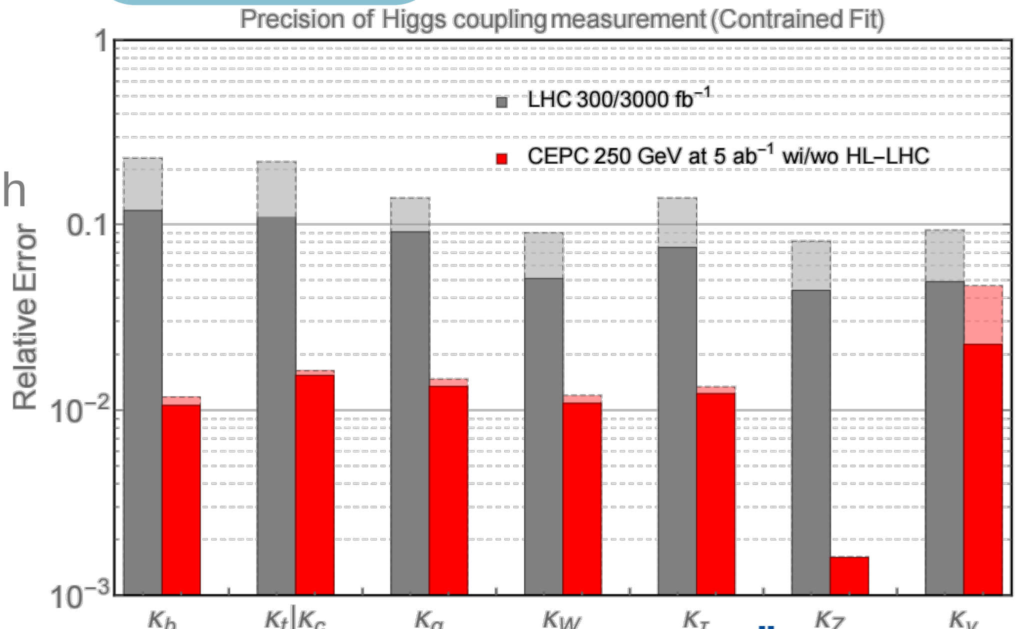

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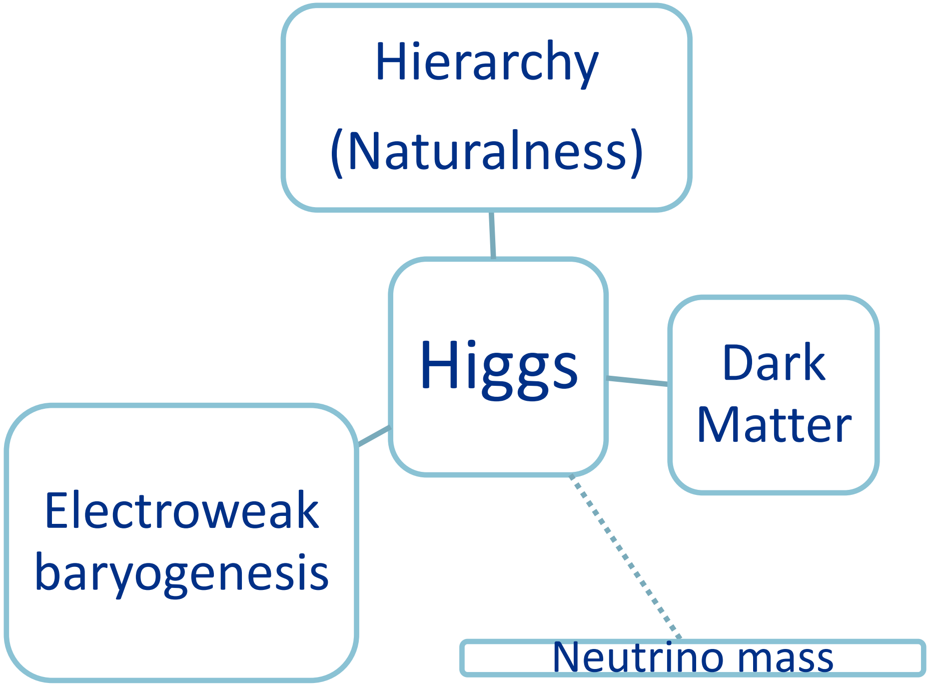

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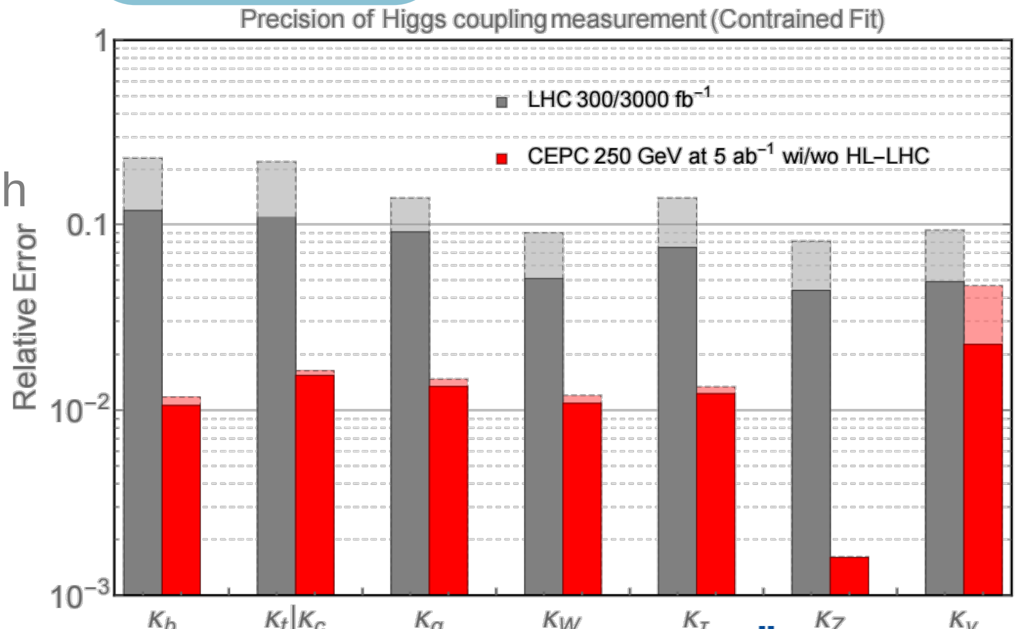


We think the Higgs exotic decays is one important missing piece.

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)

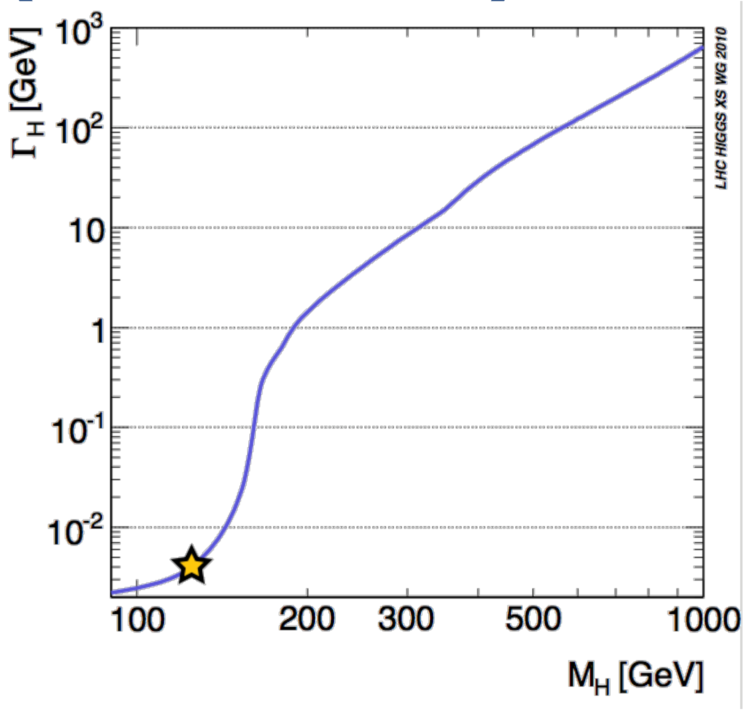
Why Exotic Decays? (continued)

- 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 $y_b = 0.017$



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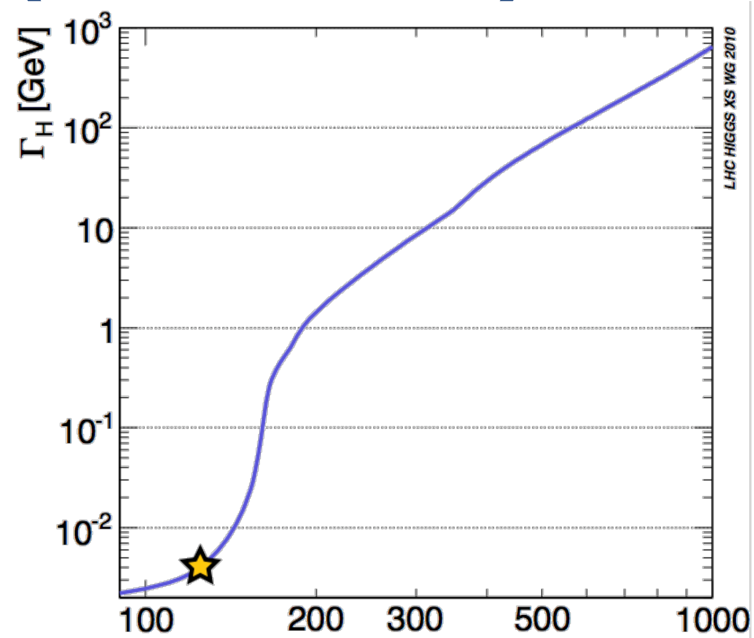
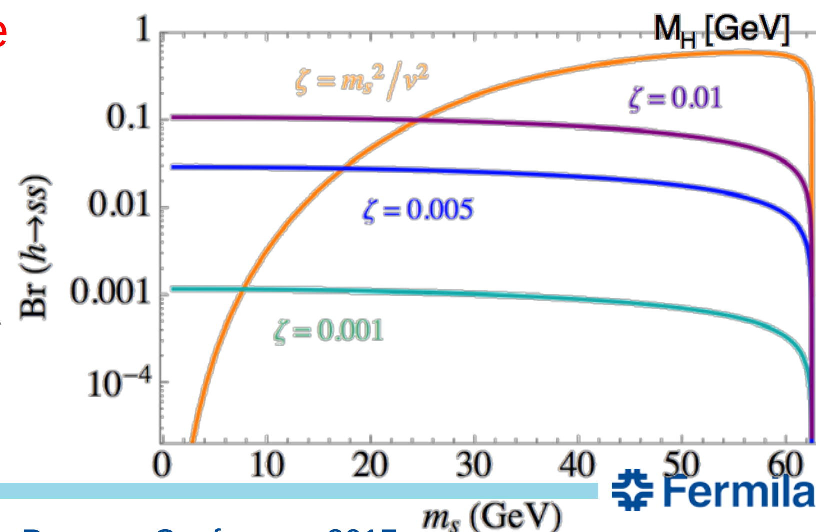


- small couplings to BSM could have sizable branching, e.g.,

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

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



Organizing the study

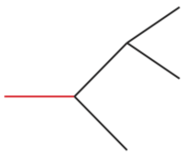
PHYSICAL REVIEW D **90**, 075004 (2014)

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 $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_{\mathrm{T}}$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_{\mathrm{T}}$
	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
	$h \to (jj) + \not{E}_{\mathrm{T}}$
	$h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$
	$h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$
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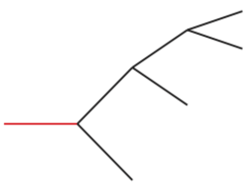
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
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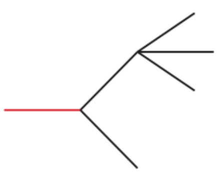
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_{\mathrm{T}}$
	$h \to jj + \not{E}_{\mathrm{T}}$
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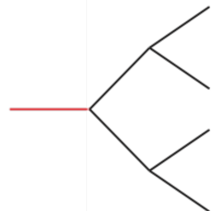
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
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	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
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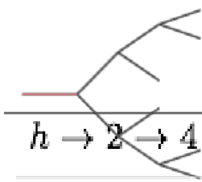
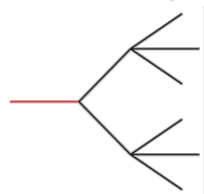
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_{\mathrm{T}}$
	$h \to (\ell^+\ell^-) + \not{E}_{\mathrm{T}} + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\mathrm{T}}$
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LHC's strength

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

Picture of pp vs.. ee

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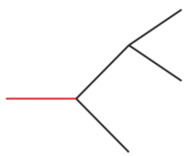
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
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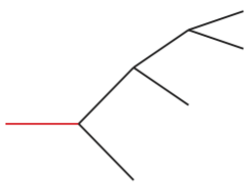
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
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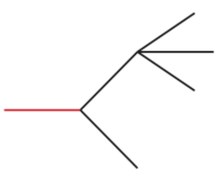
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
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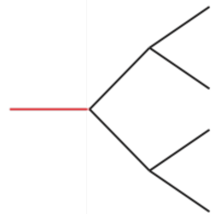
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
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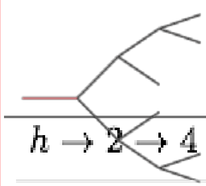	$h \to \gamma\gamma + \not{E}_T$
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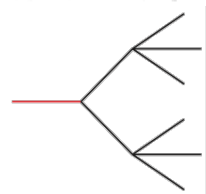
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
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Hard at LHC due to missing energy

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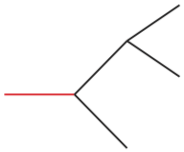
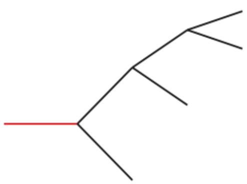
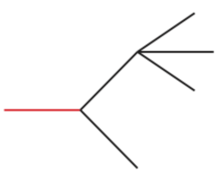
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-)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

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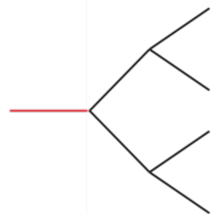
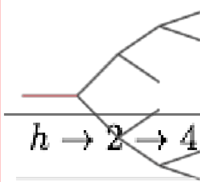
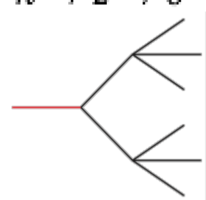
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$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

LHC's strength

Hard at LHC due to missing energy

Hard at LHC due to hadronic background

Picture of pp vs.. ee

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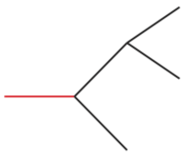
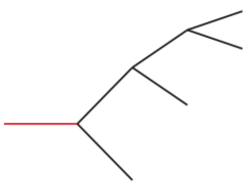
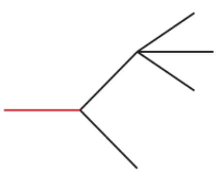
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-)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

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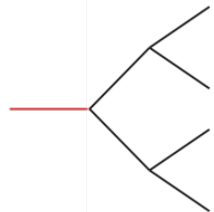
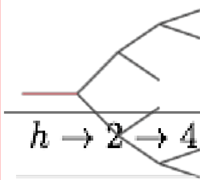
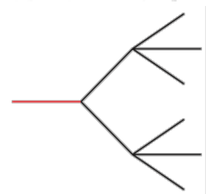
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$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

LHC's strength
Lepton collider's strength
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Picture of pp vs.. ee

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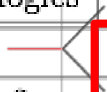
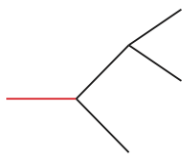
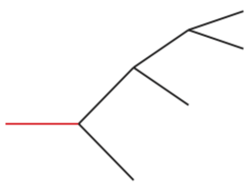
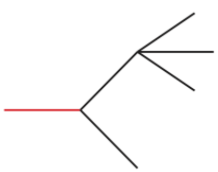
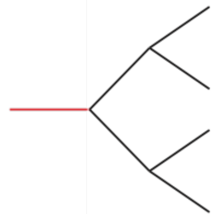
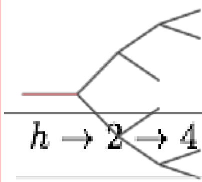
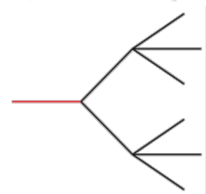
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) +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

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

LHC's strength
Lepton collider's strength
Lepton collider's strength

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

Exotic Decays (example 1)

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

h → aa(′) → fermions

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

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on Br($\mathcal{F}_i$) 7+8 [14] TeV	Production Mode	quarks allowed		quarks suppressed	
			$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV	$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	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	–
$b\bar{b}\tau\tau$	> 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 $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	quarks suppressed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{Br(non\text{-}SM)}$ 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	–
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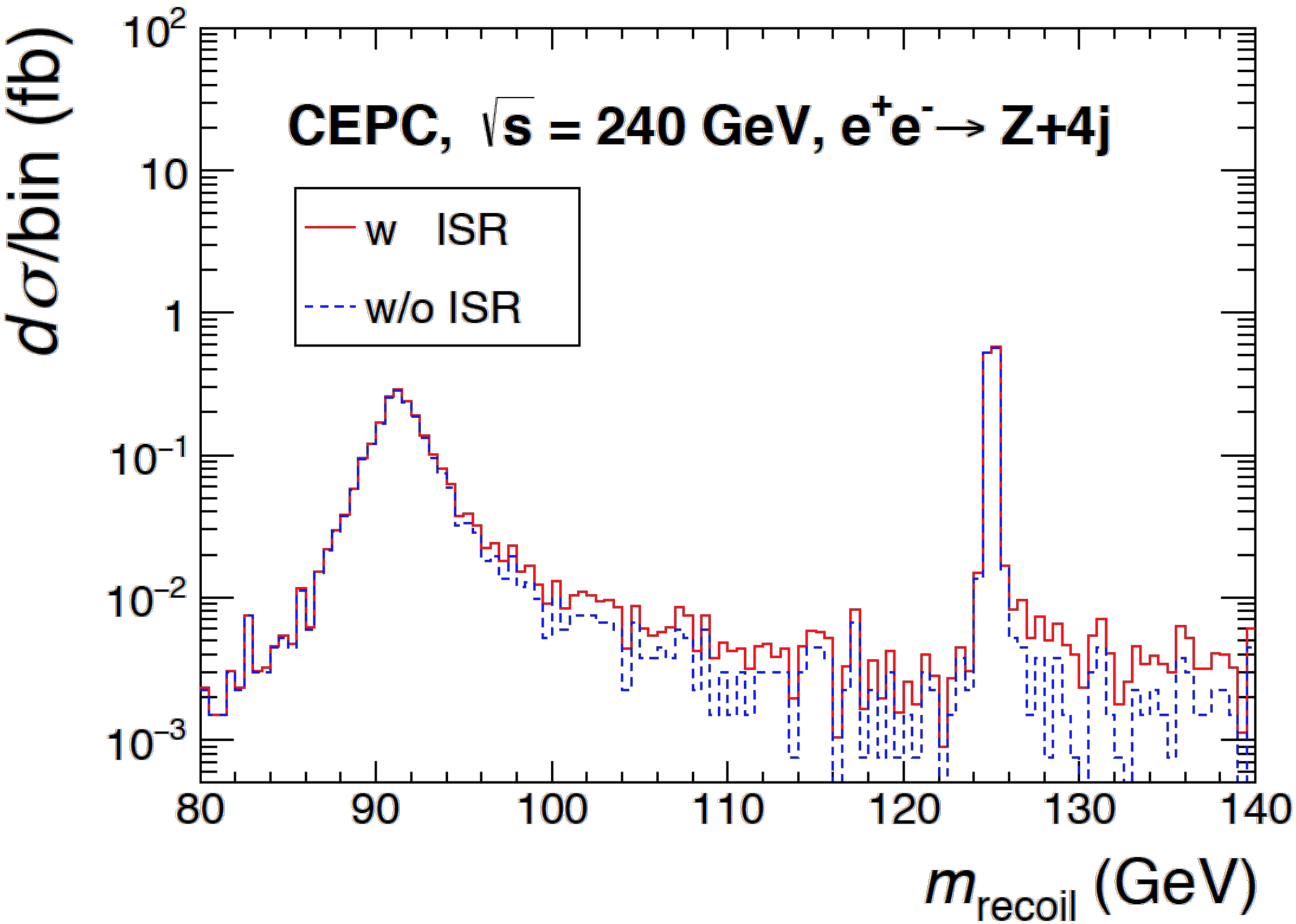
projection/limit based on theory estimate in literature (L), our theory estimate (T), our re-interpretation of an LHC limit (R), or is unknown (U)

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%

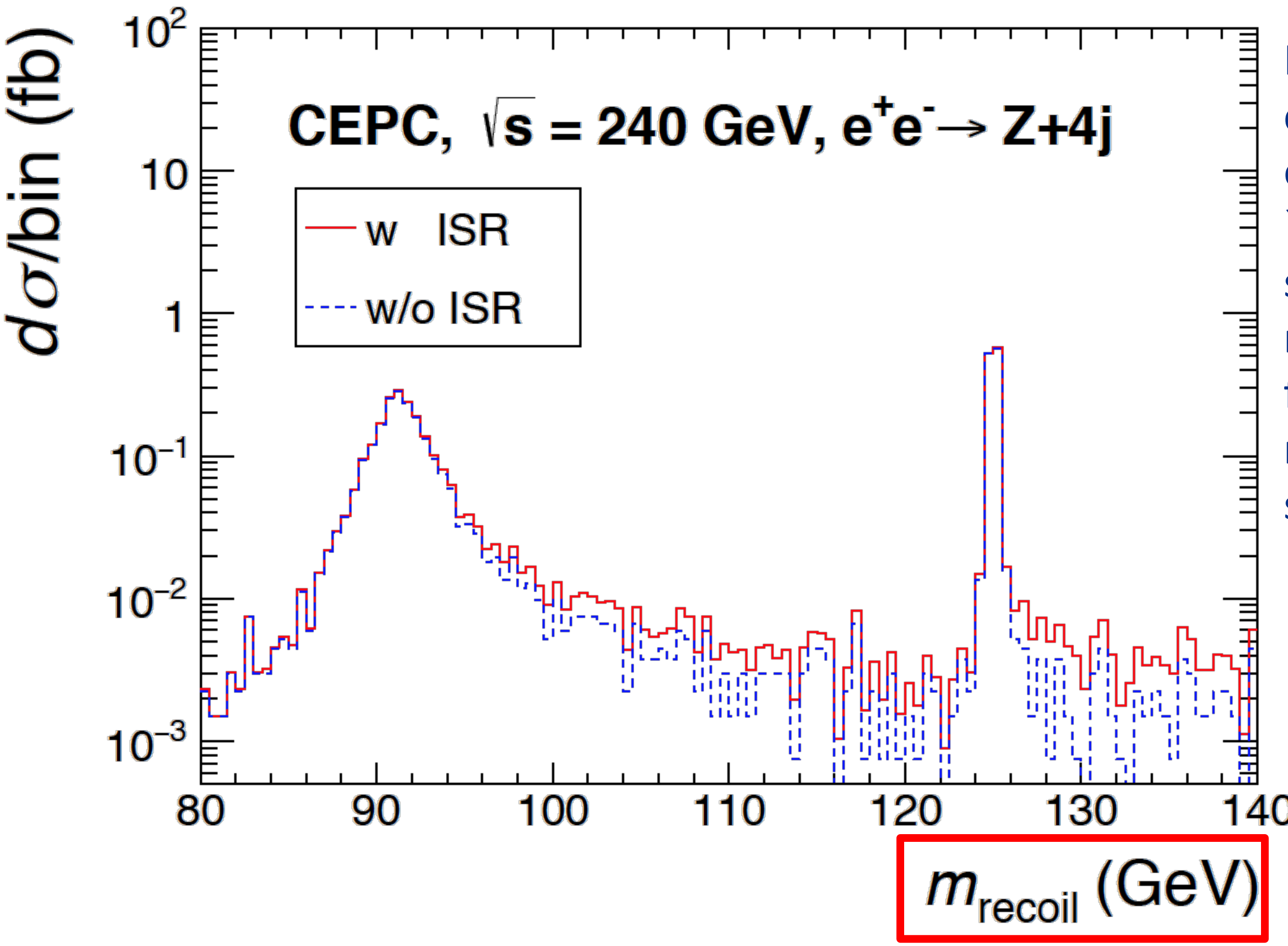
Exotic Decays (example 1)

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



Exotic Decays (example 1)

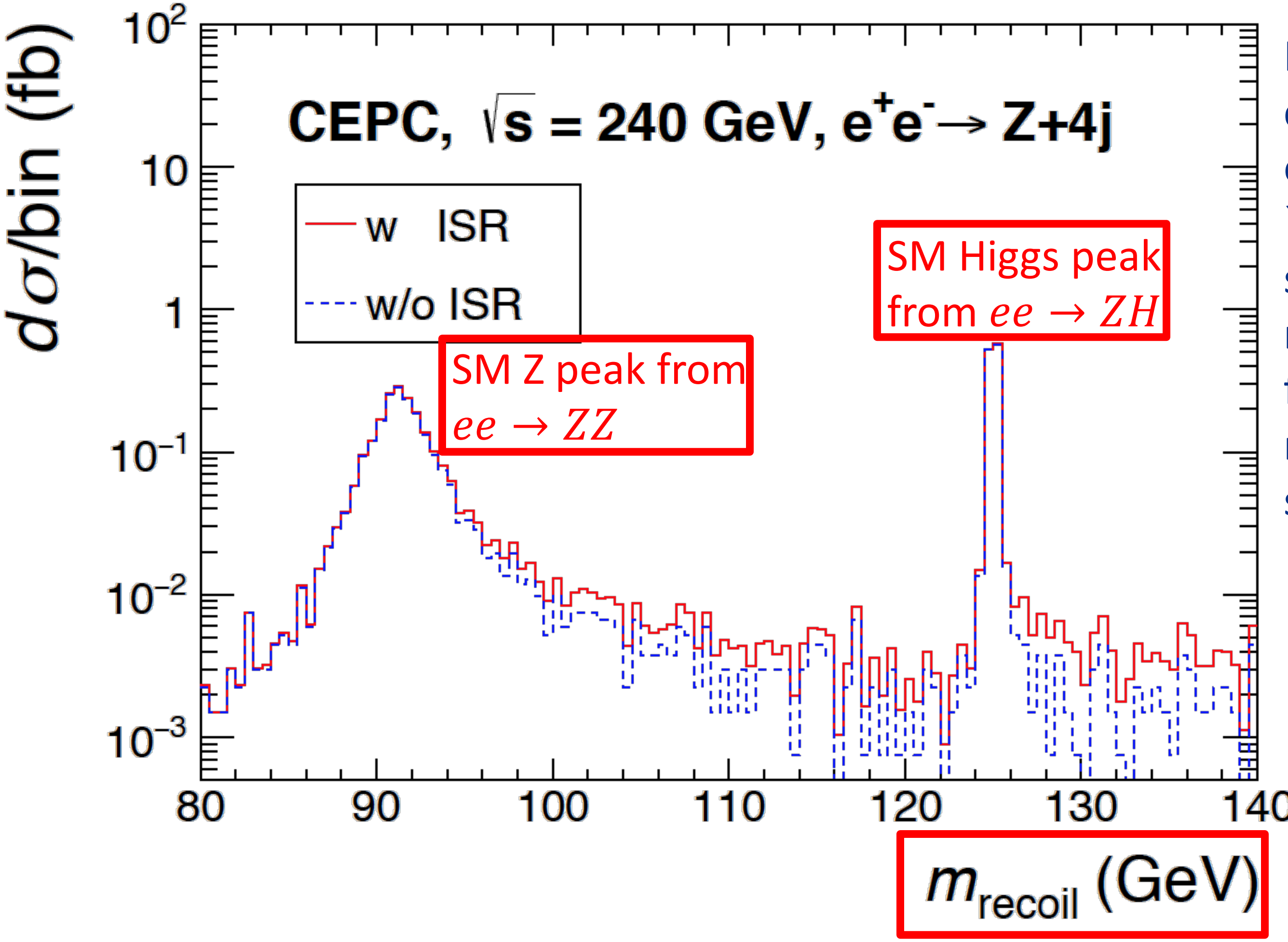
$$H \to aa \to (jj)(jj)$$



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)

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



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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, $\theta_{\ell\ell} > 80^\circ$

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

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

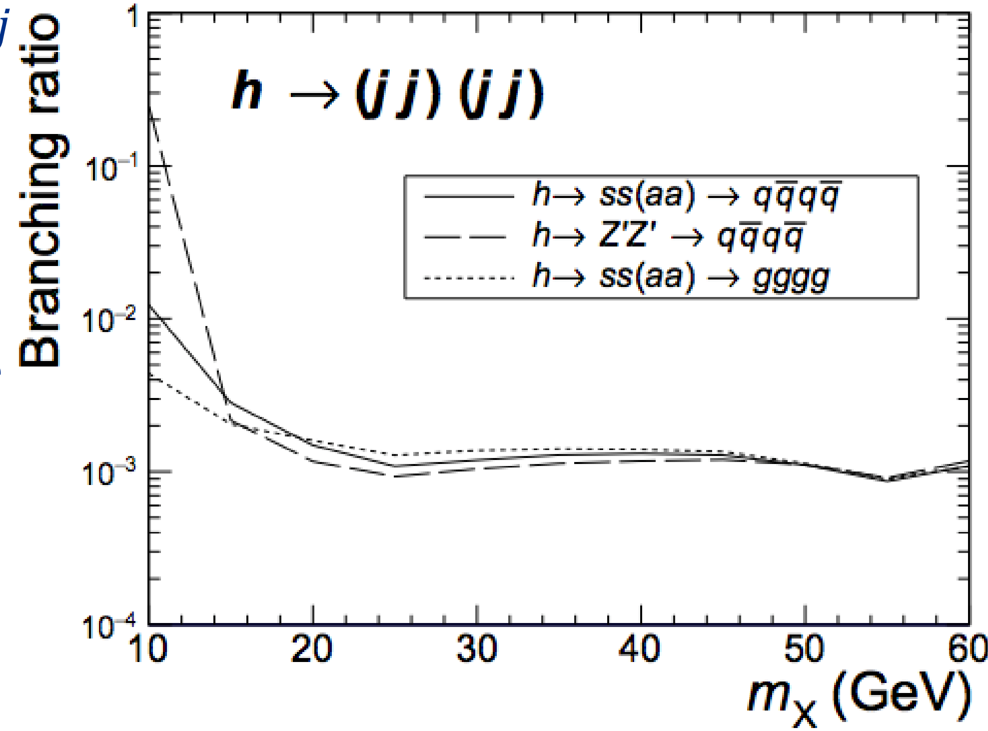
with

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

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



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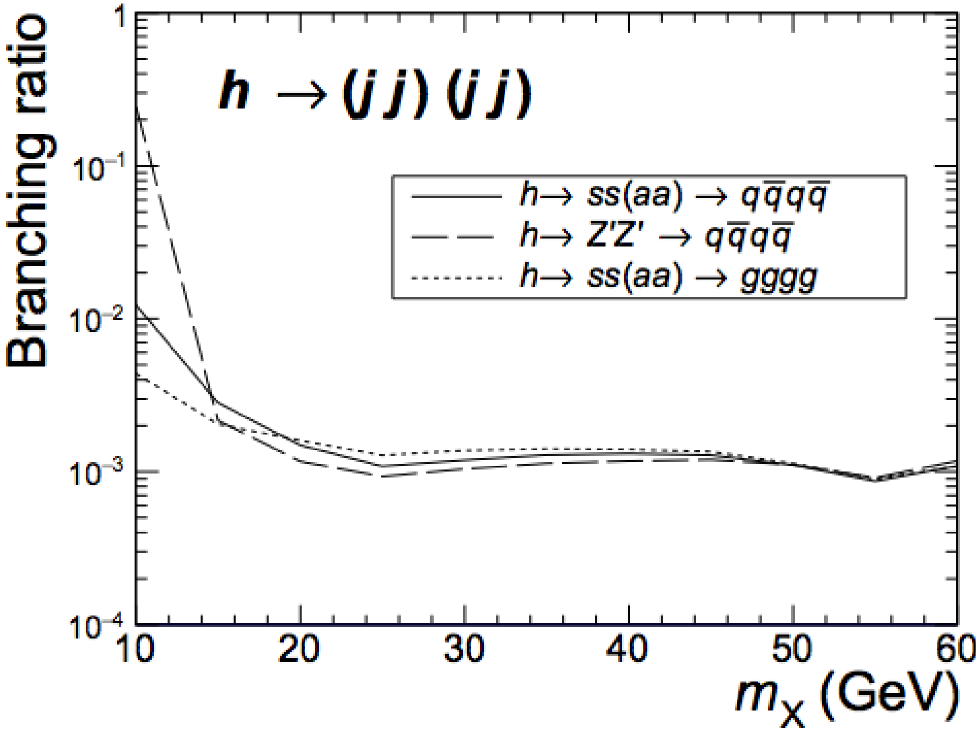


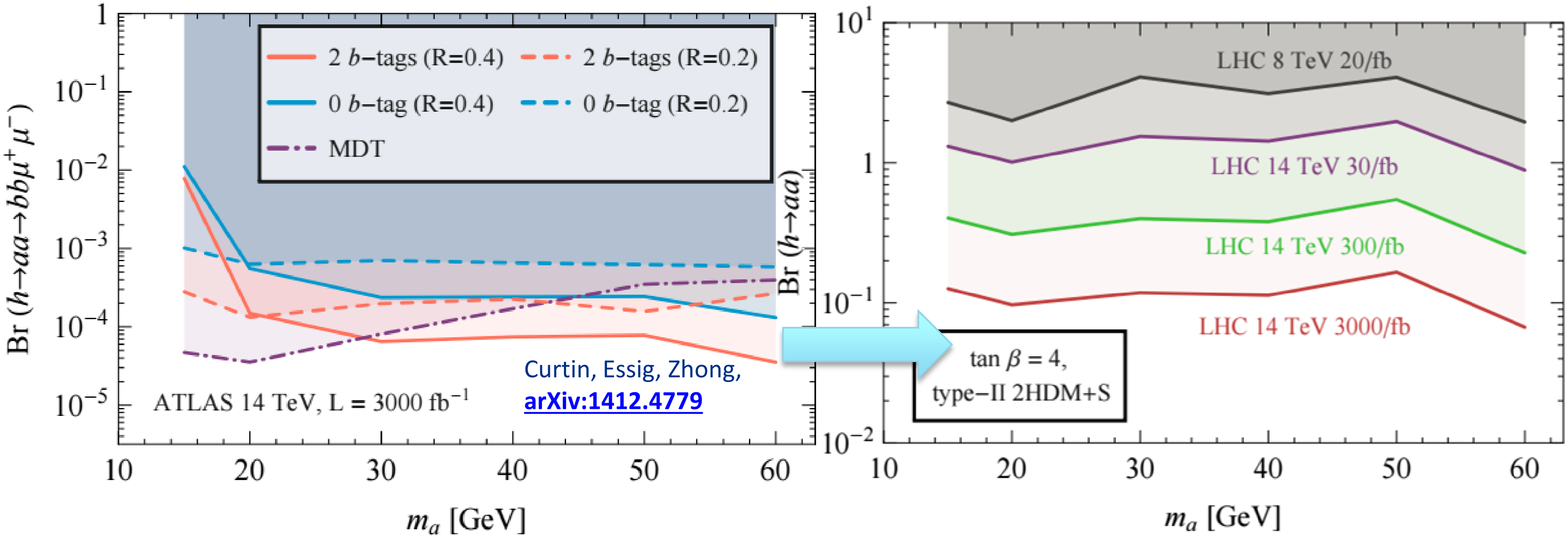
Great sensitivity on exotic branching fraction $O(10^{-3})$

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

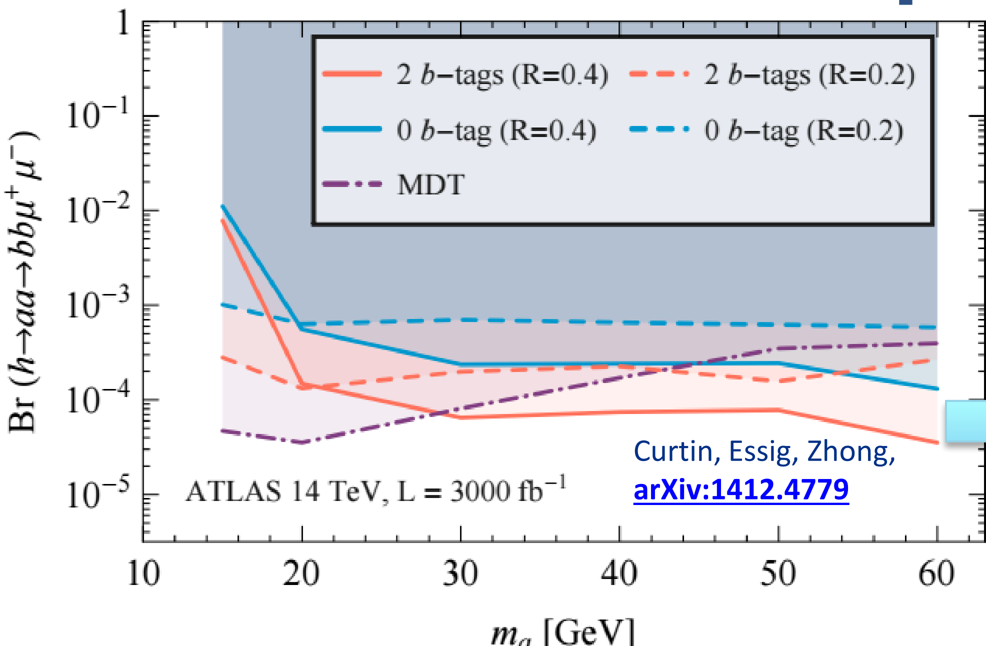
Room for improvement using different strategy treating collimated jets.

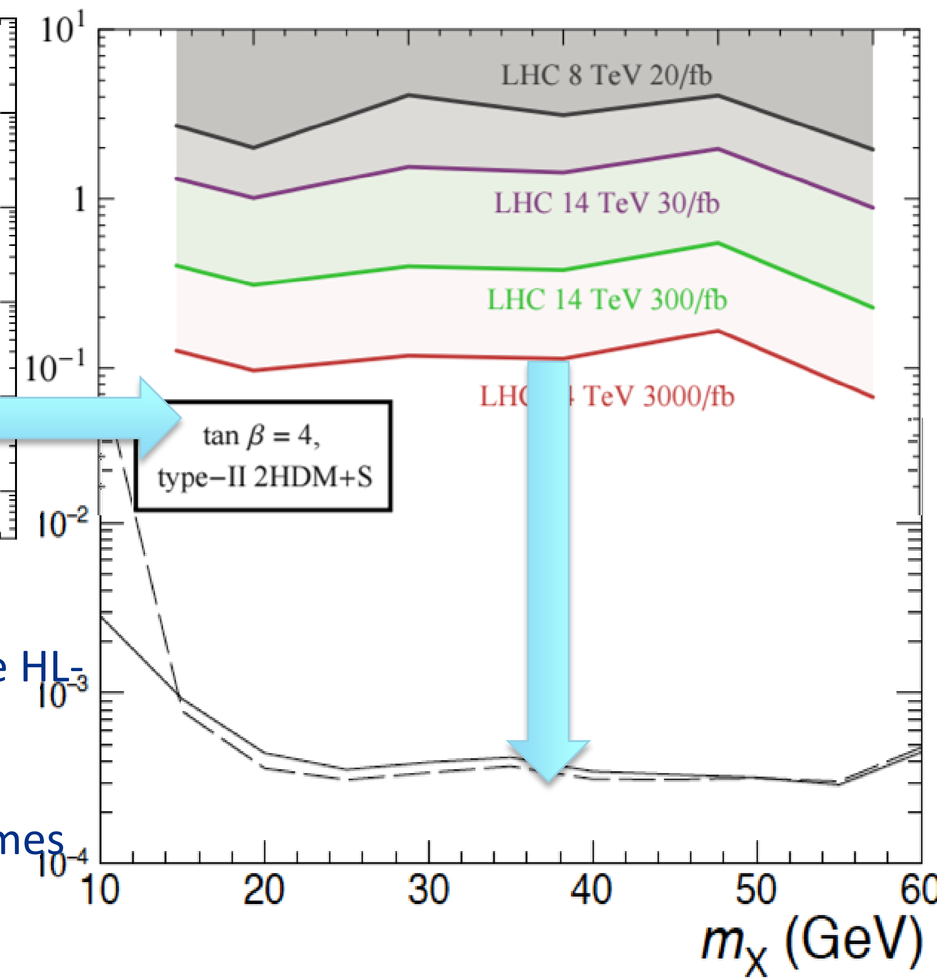
Room for improvement including hadronic decaying spectator Z bosons.

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



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





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.

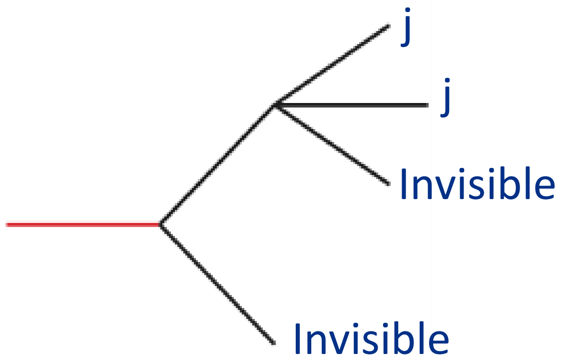
Exotic Decays (example 2)

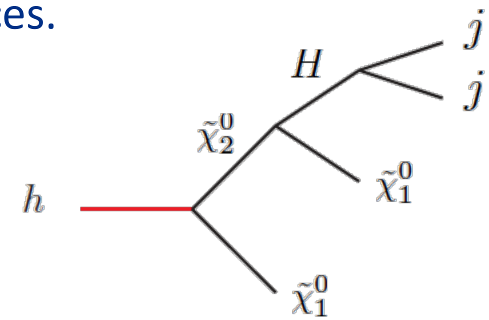
$$H \rightarrow x_1, x_2 \rightarrow j\,j + MET$$

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

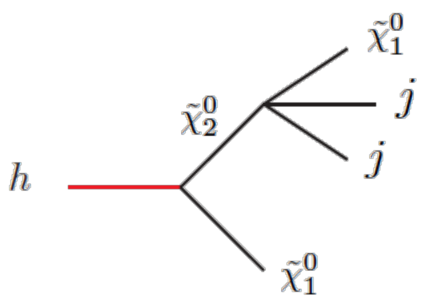
Very challenging, a nightmare at the (HL-) LHC

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.





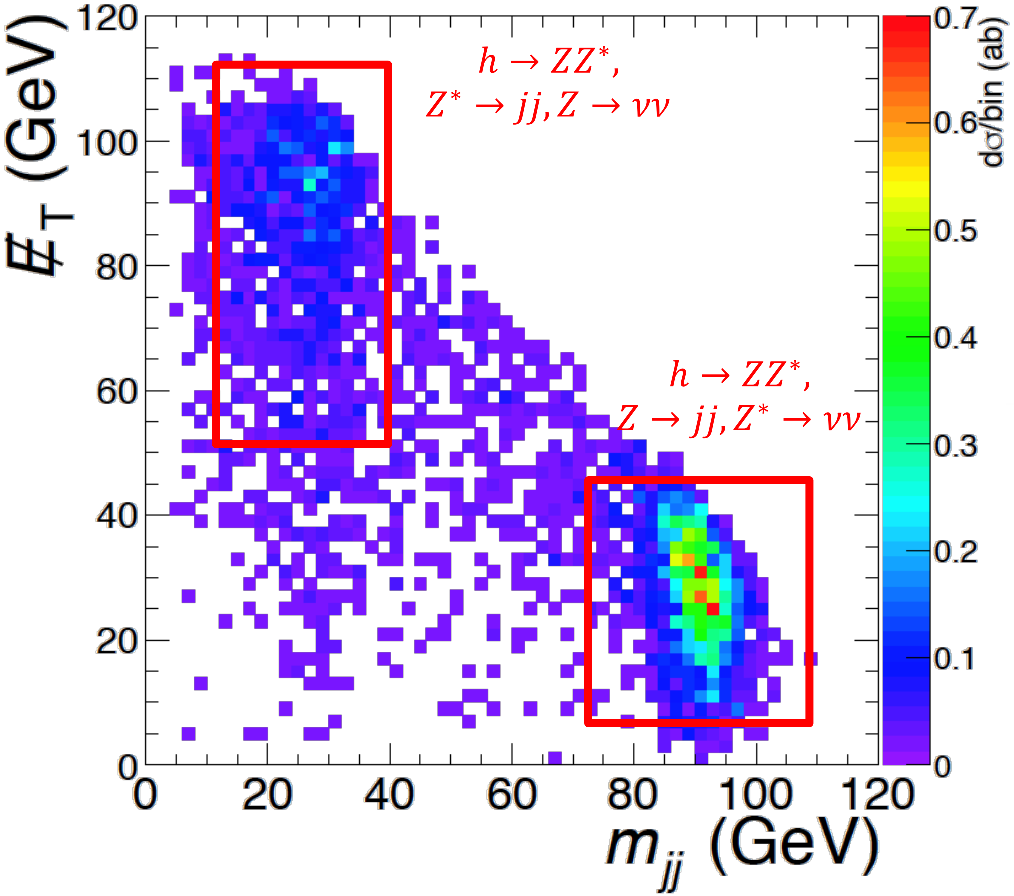
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$

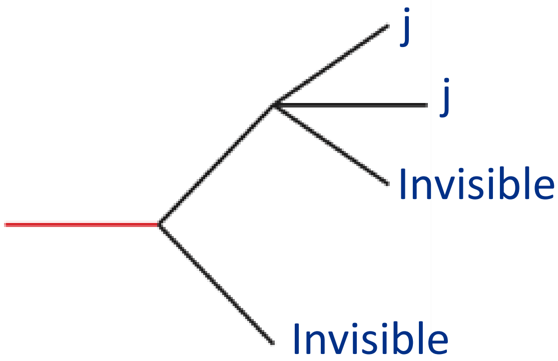


$h \rightarrow 2 \rightarrow (1+3)$

Exotic Decays (example 2)

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



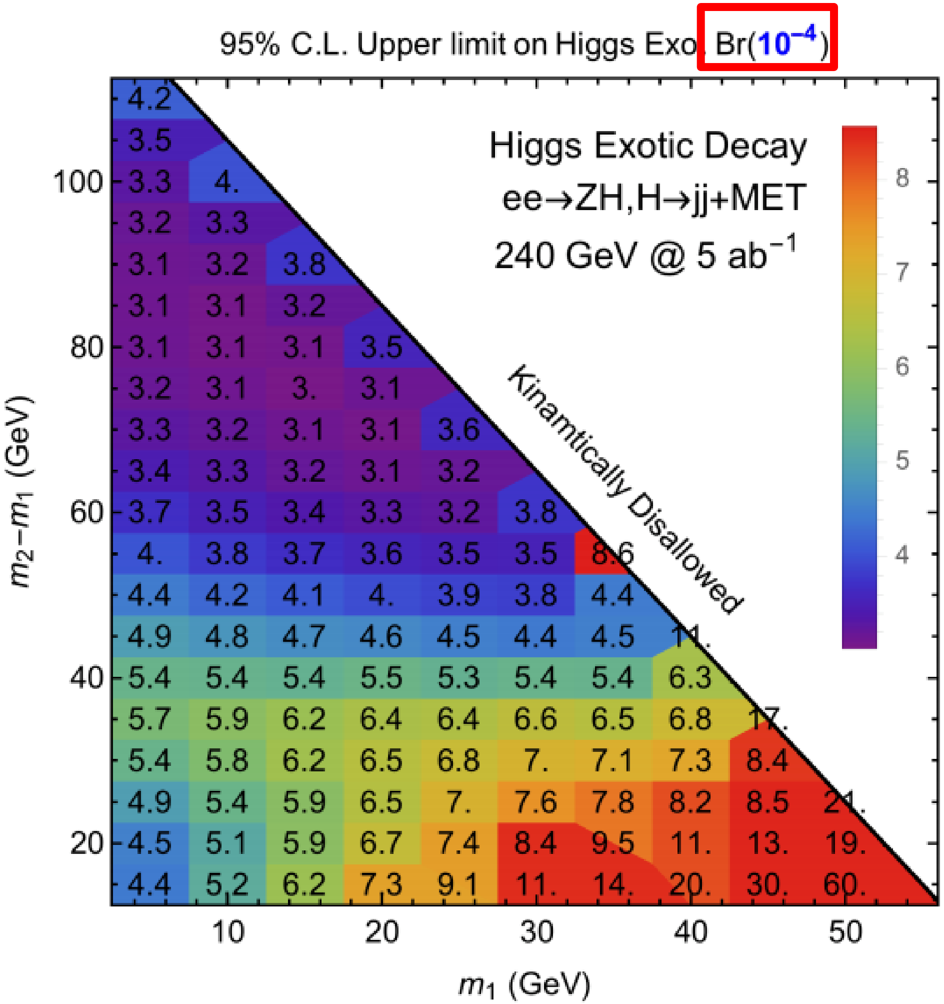


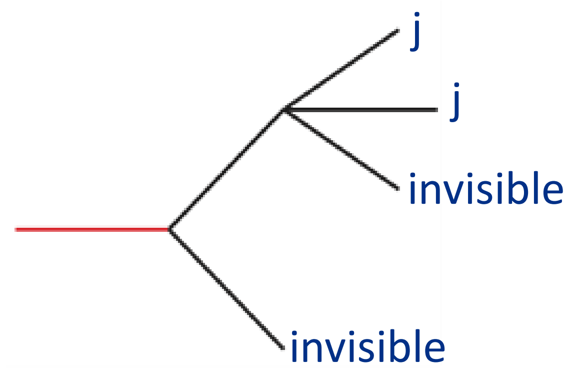
Background dominant by the the SM Higgs decays into four quarks via ZZ* after pre-selection cuts

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

Exotic Decays (example 2)

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

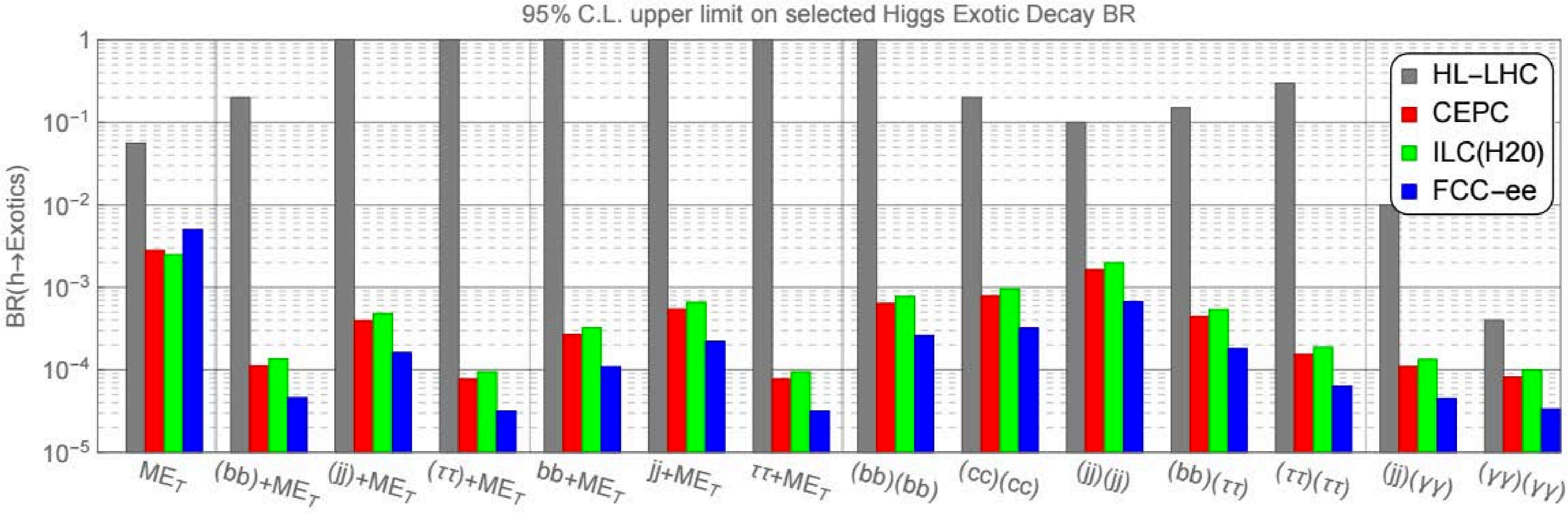




Depending on the masses of the decaying particles, the exclusion reach on Higgs exotic BRs could be as low as 3×10^{-4} and remains this order for large range, except kinematic edges.

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.

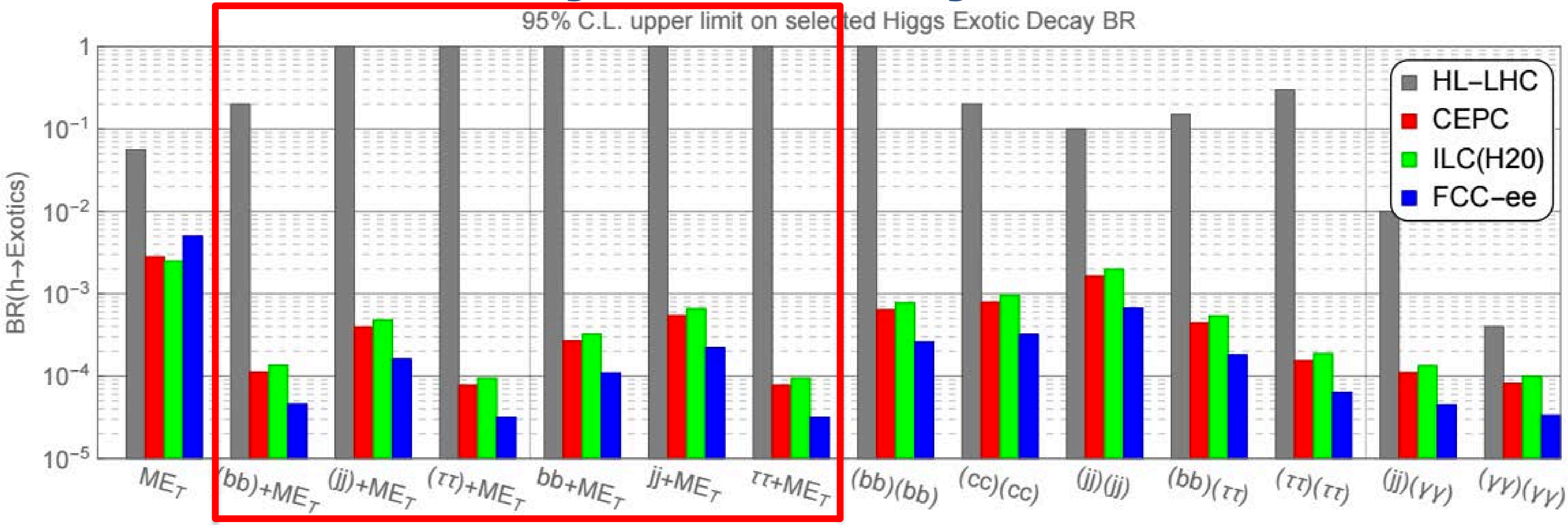
Exotic Decay summary



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.

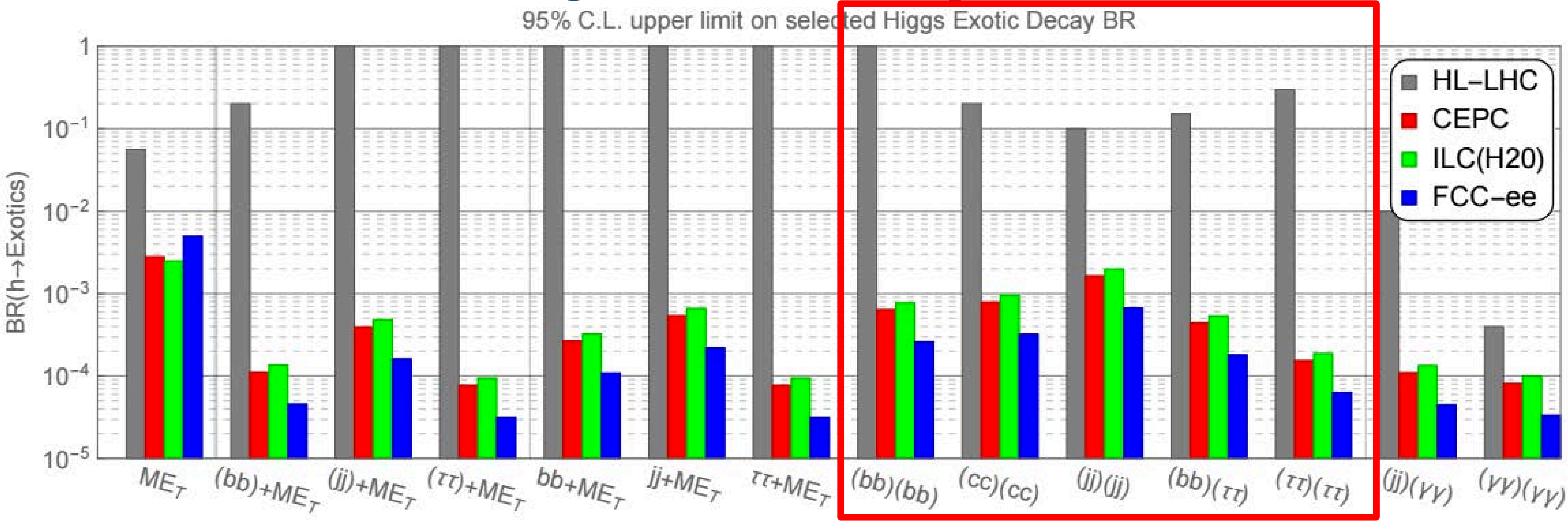
Exotic Decay summary



with missing Energy SUSY motivated, DM motivated channels

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

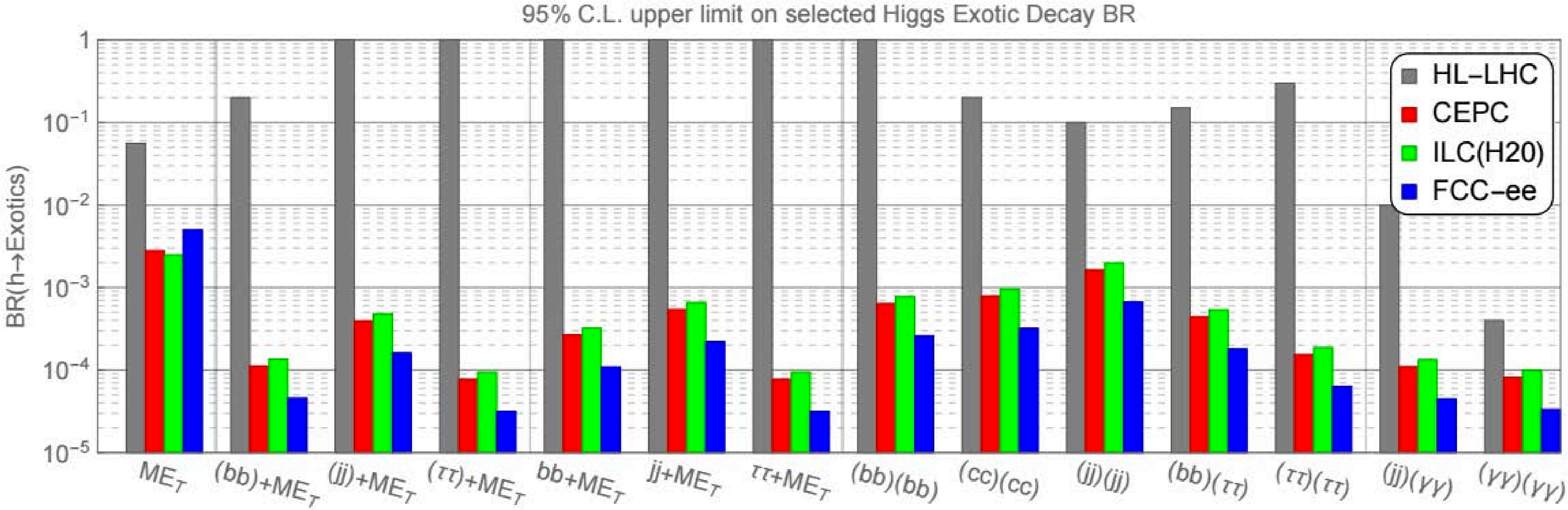
Exotic Decay summary



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

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

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.

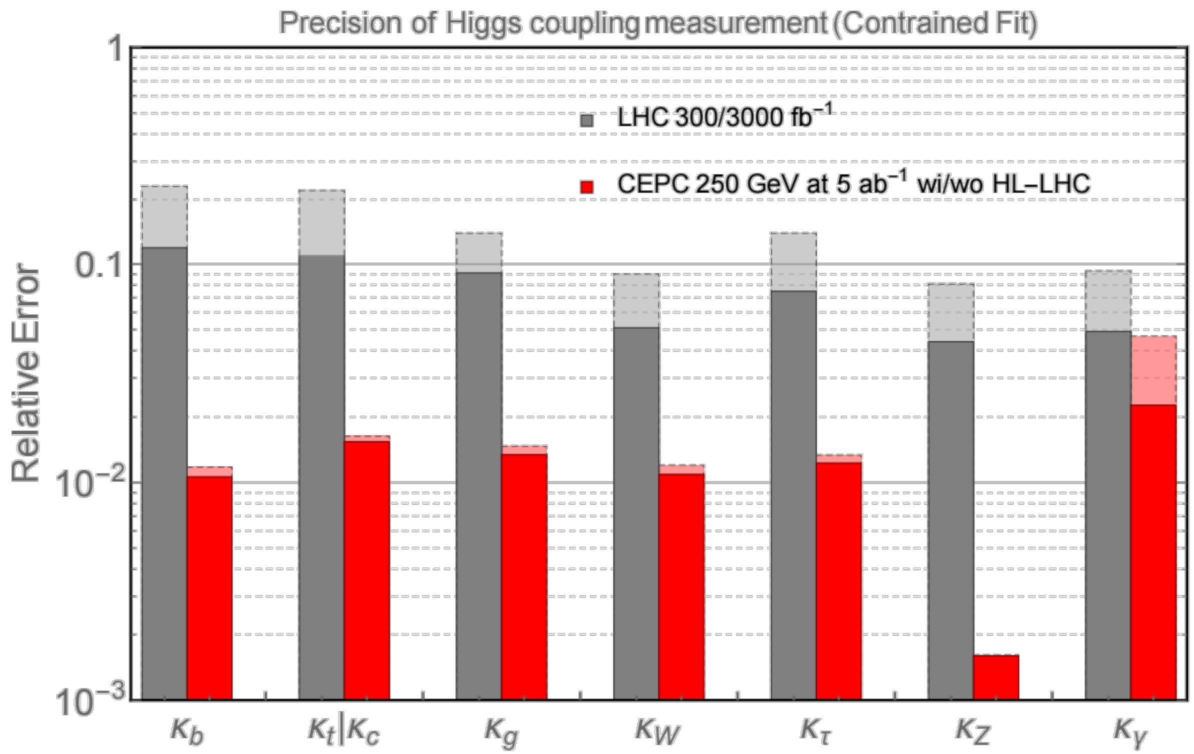
Backup

Precision—couplings

LC features the ``model independent'' determination of Higgs couplings and improves the precision by roughly one order of magnitude.

(HL-)LHC has advantages over measuring Higgs (EW) rare decays, H to ZZ →4l, Zγ, $\mu\mu$, $\gamma\gamma$, etc.

Combining both experimental results improves Higgs precision in a non-trivial way.



Similar examples include $\mu\mu, gg, cc$ couplings.

(See more detailed discussion including more LC-LHC combinations in e.g., T. Han, **ZL** and J. Sayre, **arXiv:1311.7155**, M. Klute, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, **arXiv:1301.1322**).

Exotic Decays (example 1)

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

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

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

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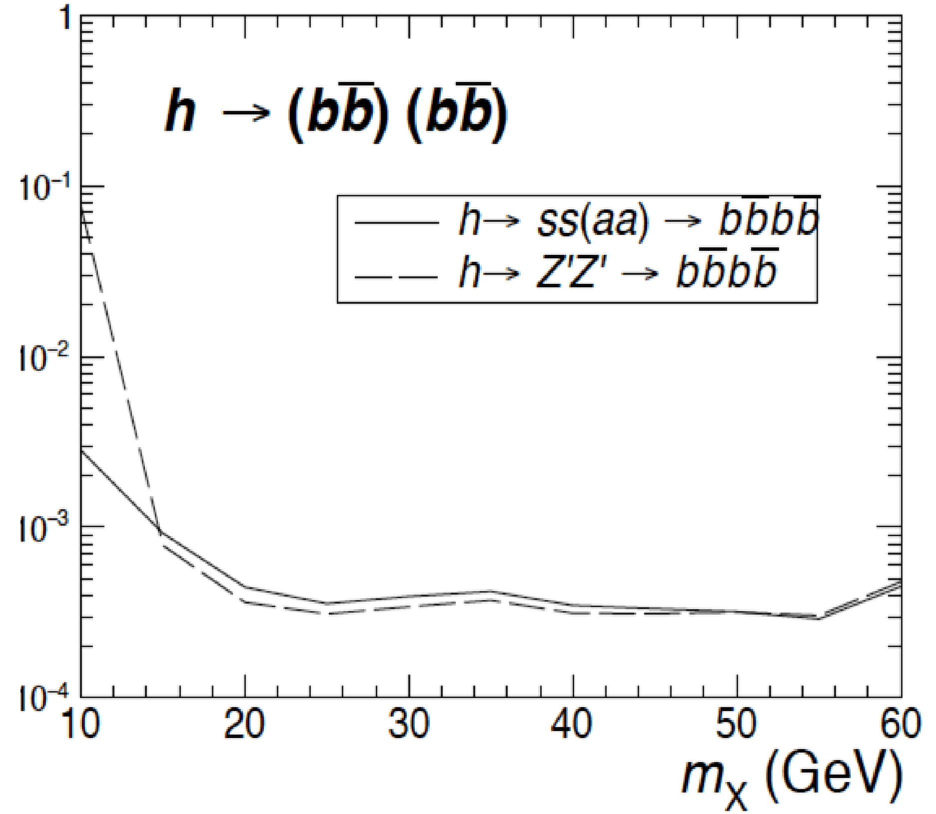
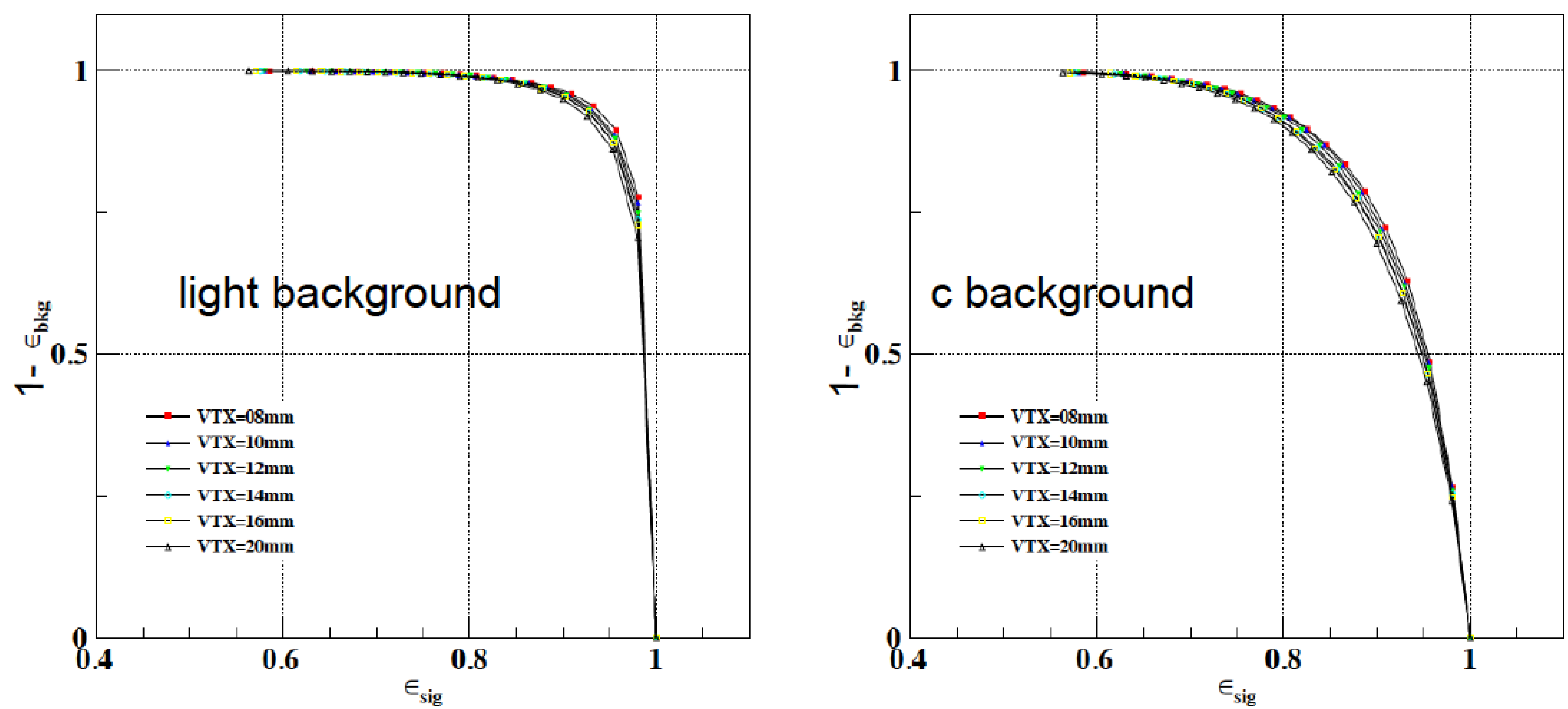




Gang Li

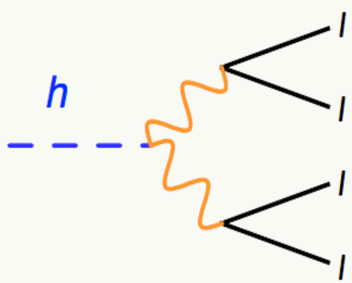
- *With 8 – 20 mm VTX Inner radius, very good b-tagging*
  - *At efficiency ~ 80%: almost reject all the light background & only 8-10% c-jets misidentified as b-jets (Purity ~93-96% at Z to qq events).*

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]	$8\times10^{-4}*$	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}
$\tau^+\tau^-+\not{E}_T$	–	–	$8\times10^{-4}*$	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]	$4\times10^{-4}*$	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)(\tau^+\tau^-)$	[1.2]* [50]	$[0.2\sim0.4]$	$1\times10^{-4}*$	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]	$4\times10^{-4}*$	1×10^{-4}	8×10^{-5}	3×10^{-5}

Picture of pp vs.. ee

- Prospects depend in detail on the particles in the final state, and range from spectacular to very hard

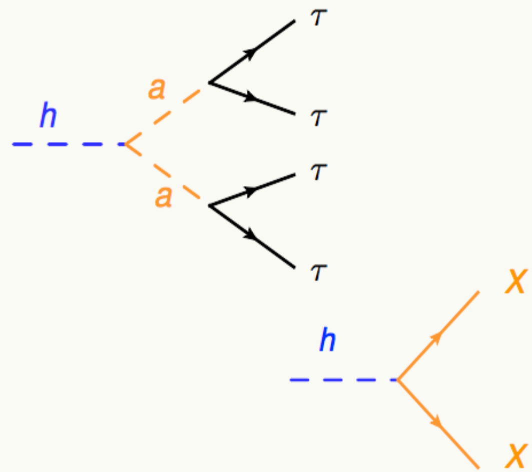
Slide from J. Shelton



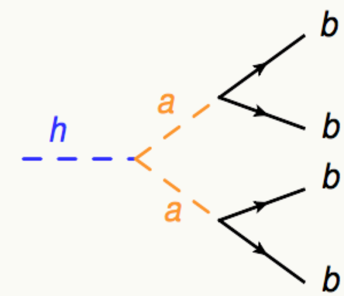
Easy: multiple resonant light leptons

$\mathrm{Br} \lesssim 4 \times 10^{-4}$

Moderate: multiple electroweak objects, poor mass resolution



$\mathrm{Br} \lesssim 0.1 - 0.6$



Hard: all-hadronic

$\mathrm{Br} \lesssim 0.9$