Searching exotic decay channels of the SM Higgs boson at CEPC

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Base on Chinese Phys C 41 (2016) 063102 in collaboration with Zhen Liu and Lian-Tao Wang.

New Physics beyond the SM

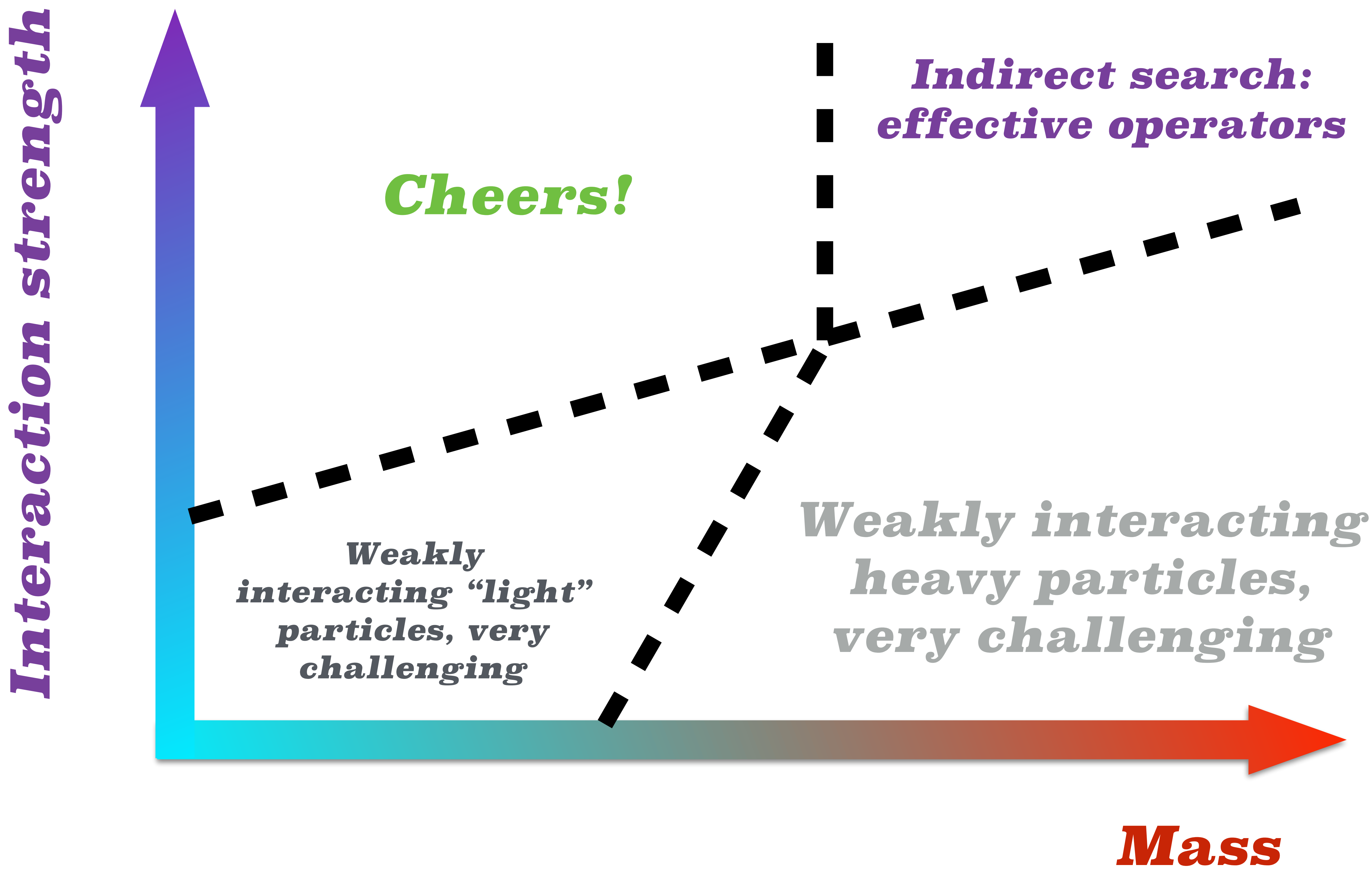
- The particle physics SM is one of the most successful model in the last century.

- It is an effective field theory up to electroweak symmetry breaking scale for particles interact with our sector strongly enough.

- In principle, NP must be introduced at some scale due to lots of theoretical and phenomenological reasons.

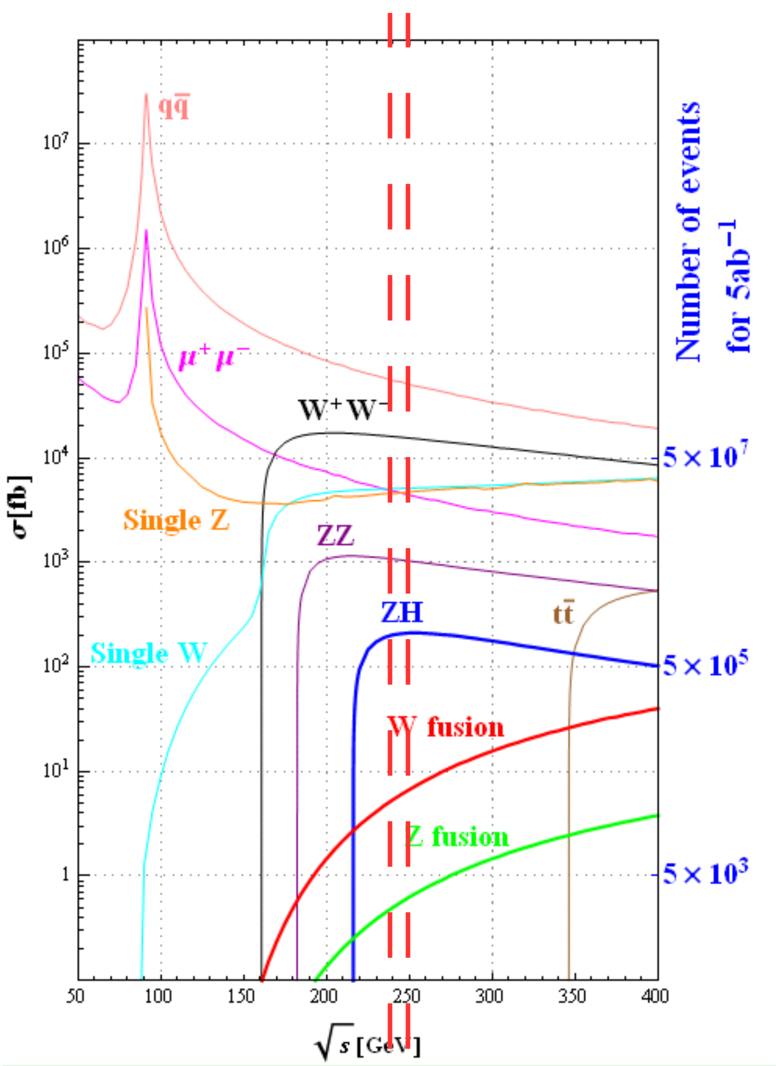
- Although there are some comments according to the “naturalness” defined by the preference of Homo Sapiens, in practice, nobody really knows when it will appear. TeV? 10 TeV? 100TeV? (tree level, 1-loop level, 2-loop level, …) Seesaw? GUT or Planck scale?

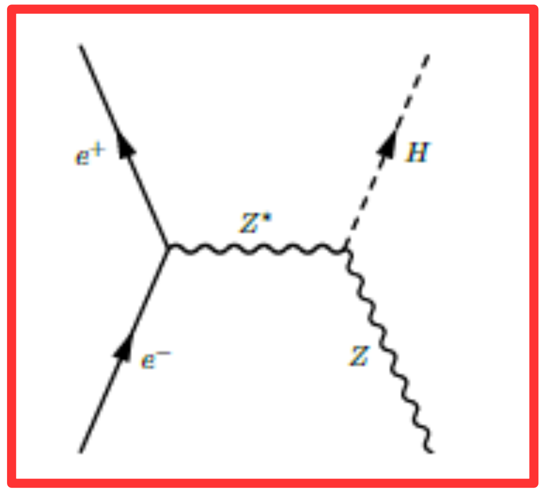
New physics “particles”: where are they?

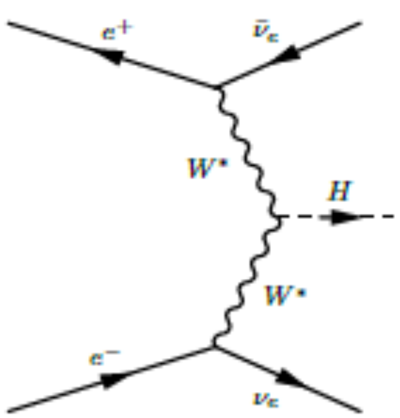


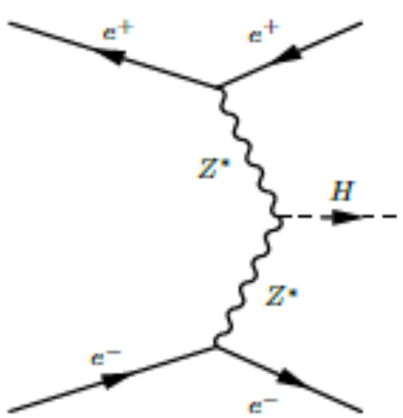
What can we do with CEPC?

- As a Higgs factory, CEPC will generate ~ 1,000,000 SM Higgs bosons.







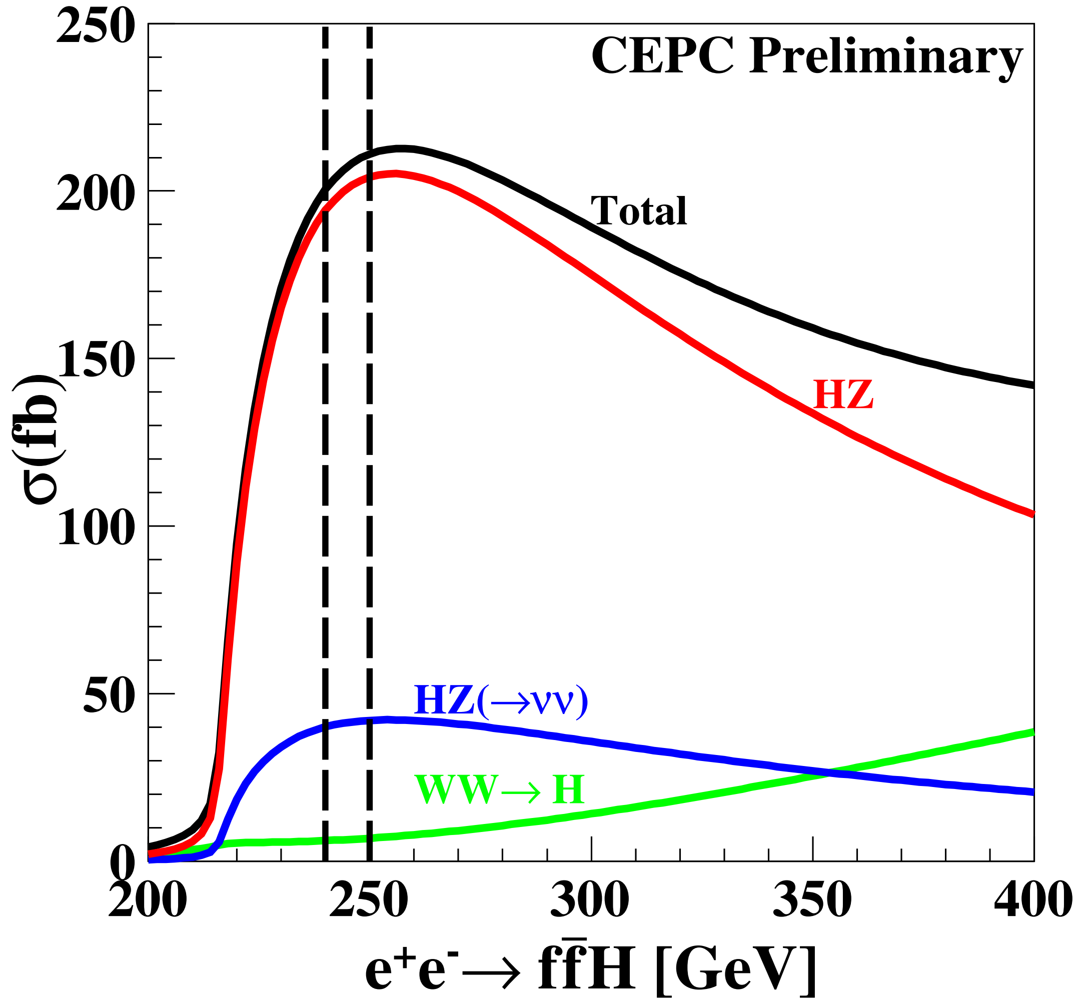


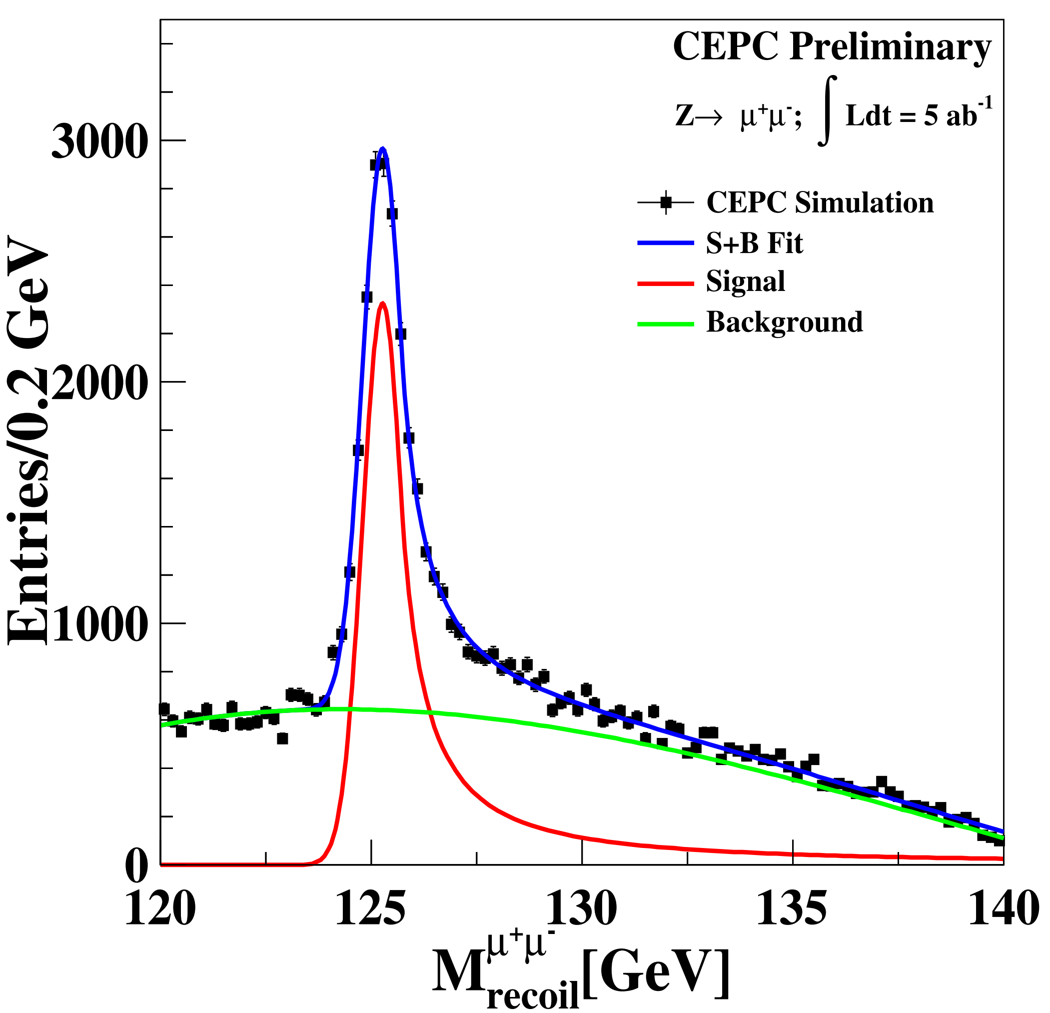
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

From Manqi Ruan

What can we do with CEPC?

- As a Higgs factory, CEPC will generate ~ 1,000,000 SM Higgs bosons.
- One of the most important scientific motivation of CEPC is understanding the properties of the SM Higgs and the nature of the SM EWSB.





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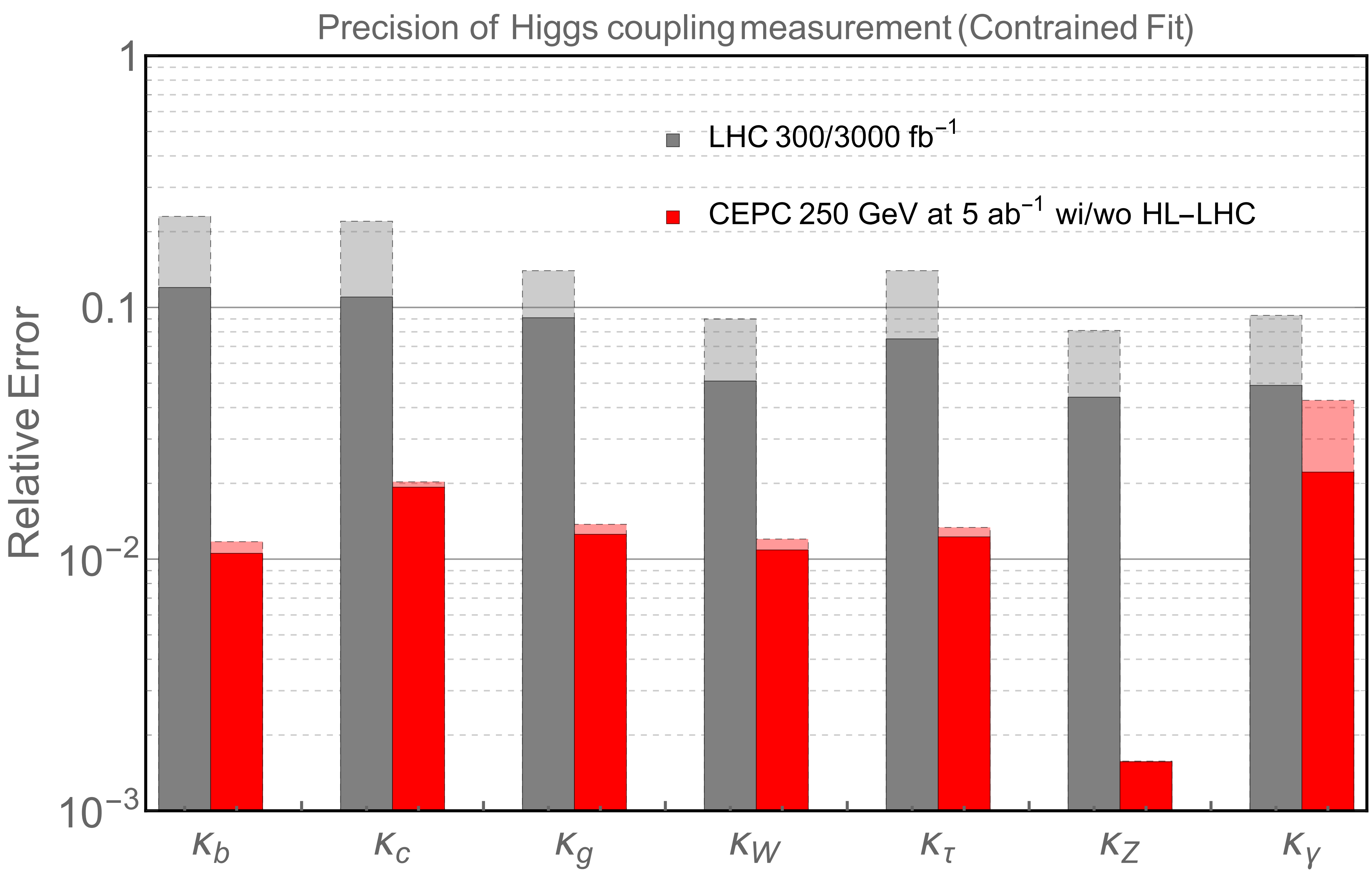
What can we do with CEPC?

- The combination of different Z decay modes gives:



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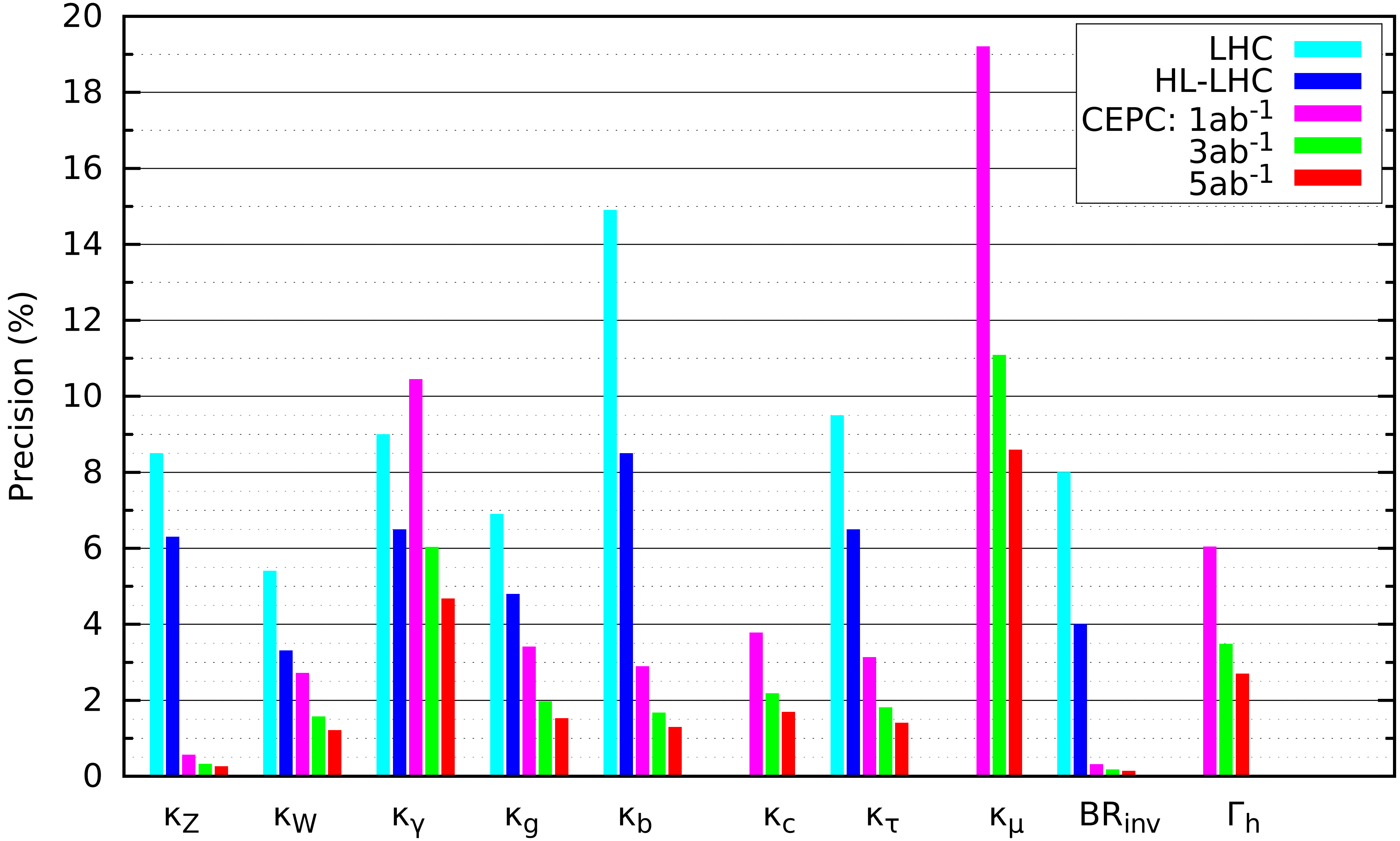

What can we do beyond the SM?

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What can we do with CEPC?

- As a Higgs factory, CEPC will generate ~ 1,000,000 SM Higgs bosons.

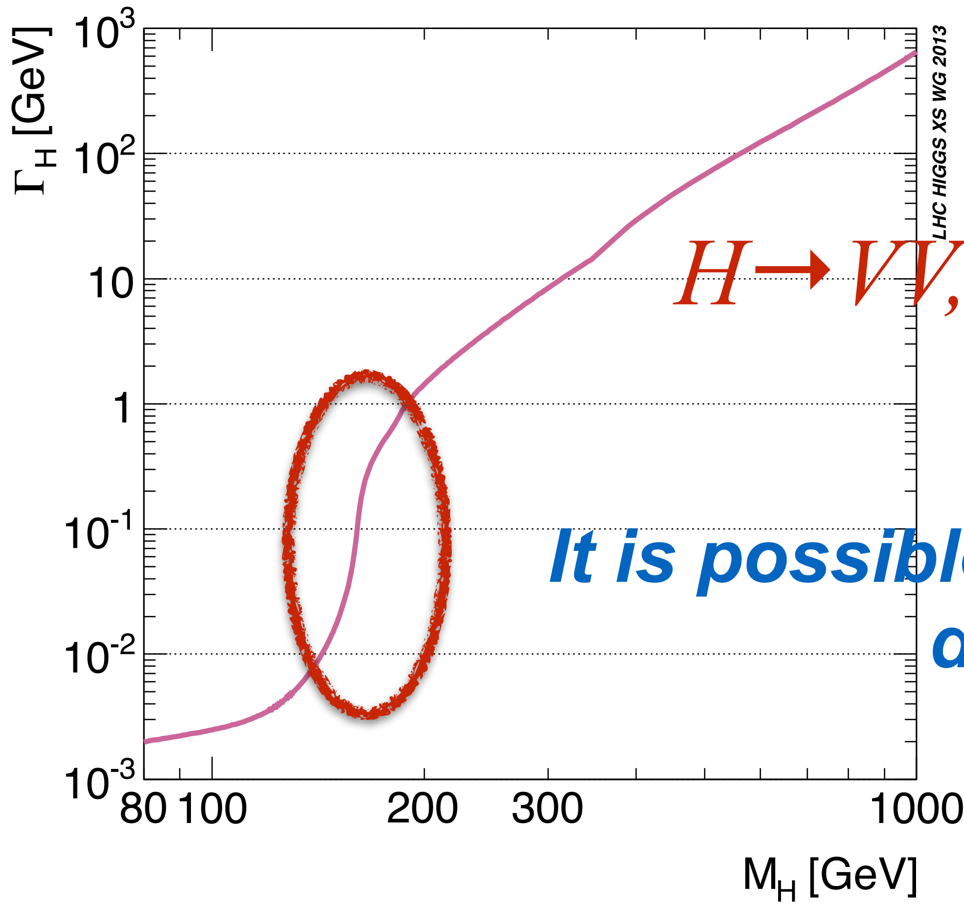
$\sqrt{s}$	schemes	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)
240	$\alpha(0)$	223.14 ± 0.47	229.78 ± 0.77	$232.21^{+0.75+0.10}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.03 ± 0.60	$228.36^{+0.82}_{-0.81}$	$231.28^{+0.80+0.12}_{-0.79-0.25}$
	G_μ	239.64 ± 0.06	$232.46^{+0.07}_{-0.07}$	$233.29^{+0.07+0.03}_{-0.06-0.07}$
250	$\alpha(0)$	223.12 ± 0.47	229.20 ± 0.77	$231.63^{+0.75+0.12}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.01 ± 0.60	$227.67^{+0.82}_{-0.81}$	$230.58^{+0.80+0.14}_{-0.79-0.25}$
	G_μ	239.62 ± 0.06	231.82 ± 0.07	$232.65^{+0.07+0.04}_{-0.07-0.07}$

~ 1% theoretical error at NNLO (EW+QCD) level

TABLE II from Q.-F S, F Feng, Y Jia, W.-L Sang, Phys. Rev. D96 (2017) 051301, see also
Y Gong, Z Li, X Xu, L.L Yang, X Zhao, Phys. Rev. D95(2017) 093003

What can we do with CEPC?

- Higgs boson is sensitive to the NP.
- It decays VERY VERY slow!



It is possible to measure the NP effect in the Higgs decay process even it is tiny.

	Z	W	t	H
Width (GeV)	2.4952	2.085	1.41	0.00407
M/Γ	36.545	38.55	123	3.07×10^4

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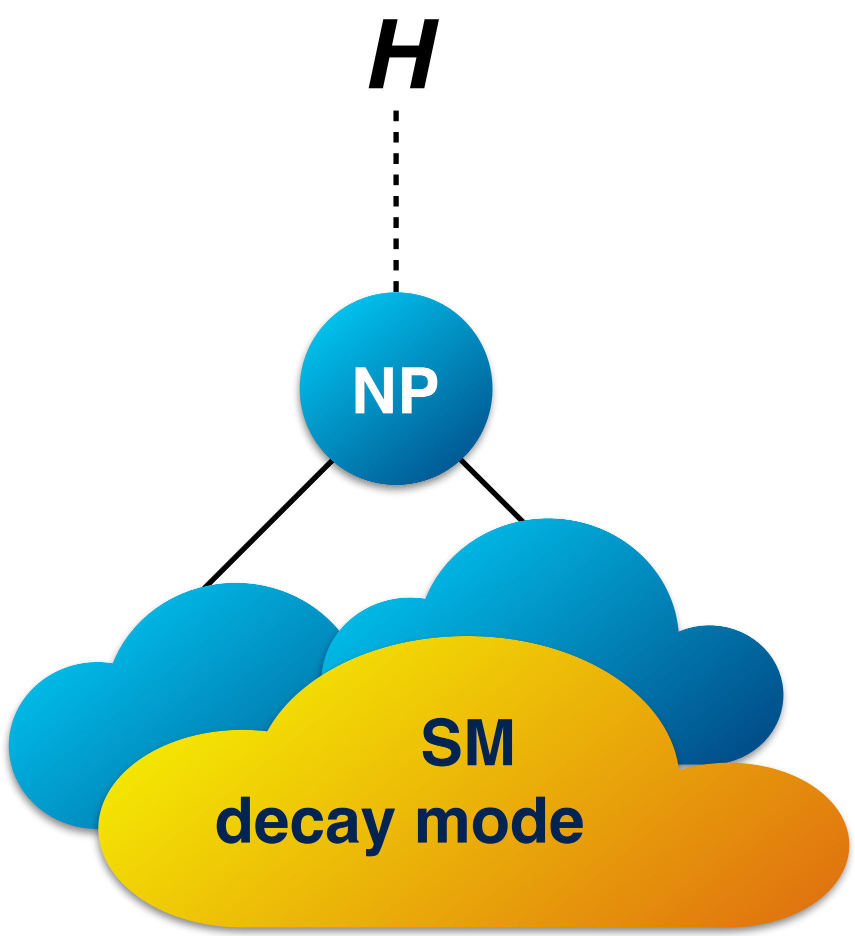
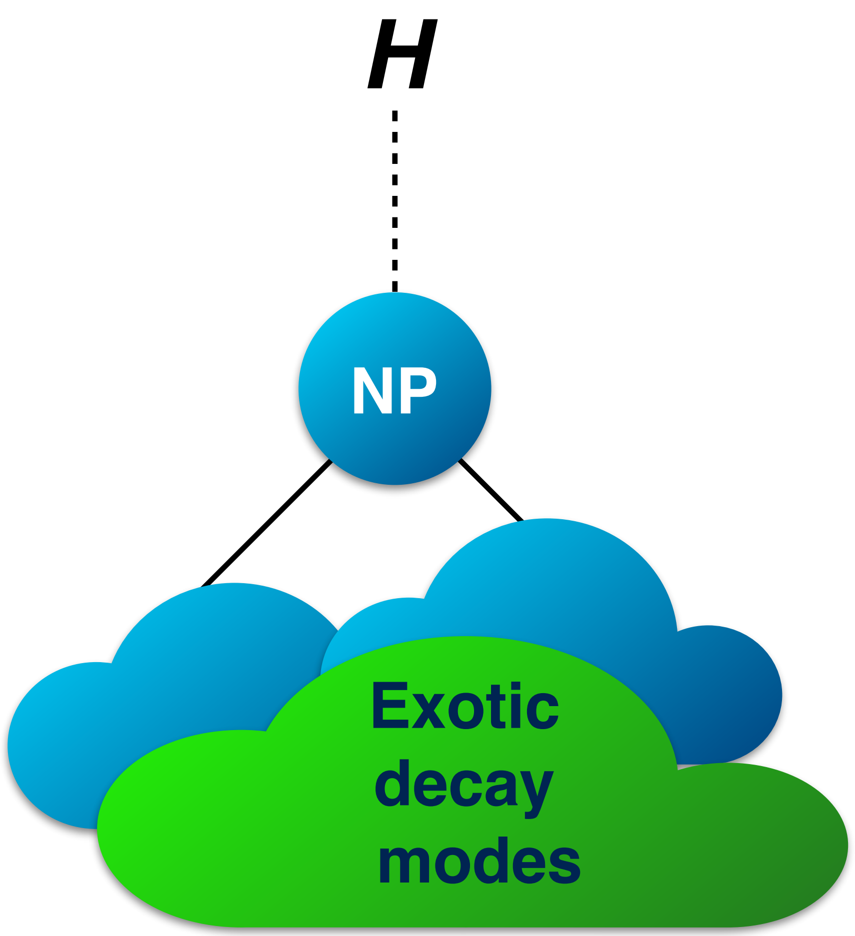
Exotic decay of the SM Higgs boson

- NP at high energy scale can modified the branching ratios of the Higgs decay modes. If the effect is significant, ~percent level, we may discover it indirectly.

- On the other hand, there are chances that the Higgs boson decays into exotic light particles in the NP!



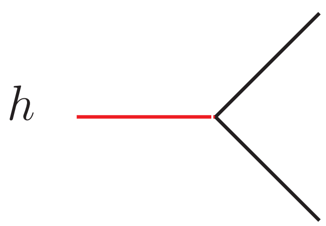


Exotic decay of the SM Higgs boson

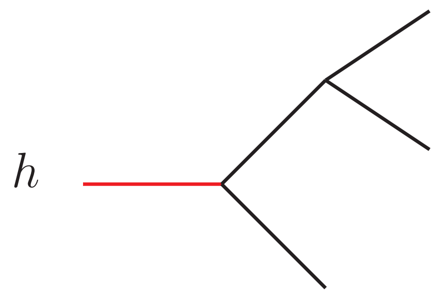
- Light exotic particles weakly couple to the SM sector:
  - SUSY model: MSSM, NMSSM, … light neutralinos, gravitino;
  - Hidden valley with Higgs boson as the mediator: “Higgs portal”;
  - Dark matter: dark force, …
  - Bayrogenesis: exotic light scalar;
  - Neutrino mass: *N*-loop radiative seasaw;
  - …

Exotic decay of the SM Higgs boson

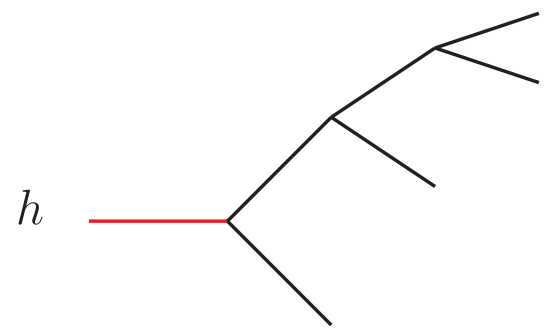
- Some technical assumptions:
  - The first decay is two-body decay;
  - In the final state, there are only SM particles or missing energy. (For exotic decay modes with displaced vertices, please see Nathaniel's talk.)



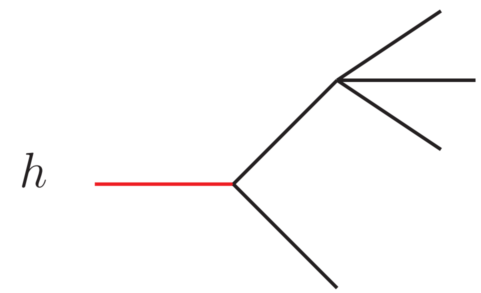
$h \to 2$



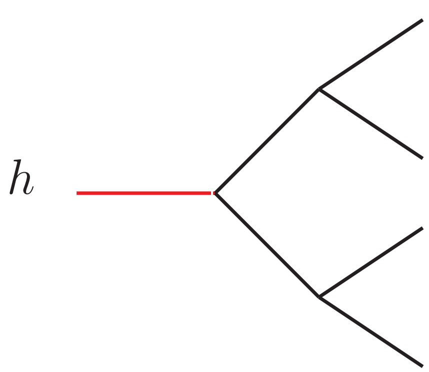
$h \to 2 \to 3$



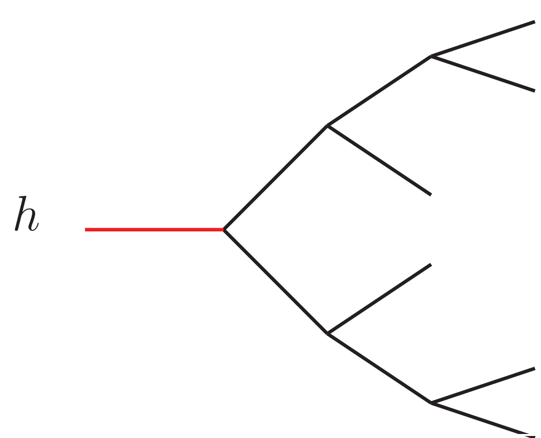
$h \to 2 \to 3 \to 4$



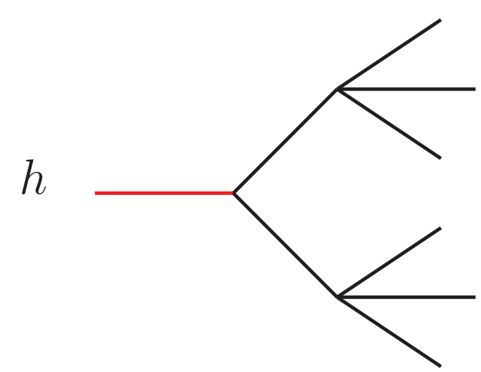
$h \to 2 \to (1+3)$



$h \to 2 \to 4$



$h \to 2 \to 4 \to 6$



$h \to 2 \to 6$

Exotic decay of the SM Higgs boson

- What can we do with HL-LHC?

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]

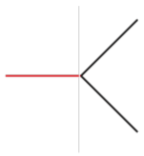
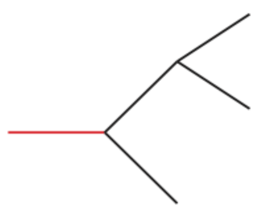
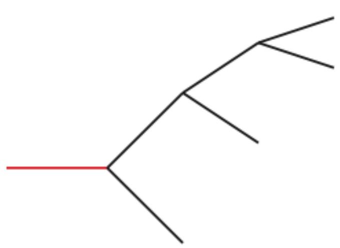
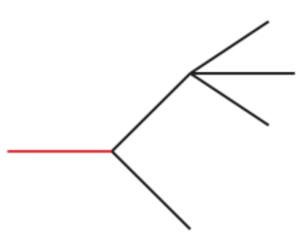
- Assume we have 1,000,000 ZH events, with zero background, we still need the branching ratio to be ~ 5×10^{-5} to reach a 95% C.L.

- If the LHC can give a competitive result, we need to work hard to combine the data from other Z decay model and Higgs production channels.

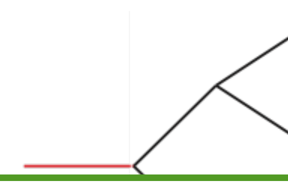
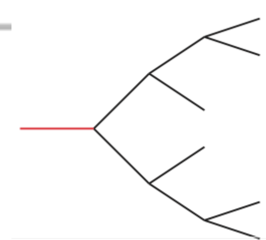
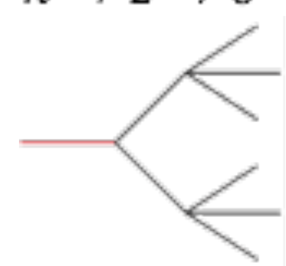
- If the LHC gives a much better result than this. CEPC can hardly give better result.

Exotic decay of the SM Higgs boson

- What can we do with HL-LHC?

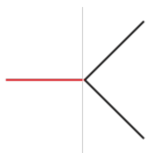
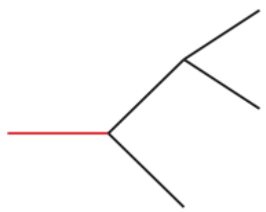
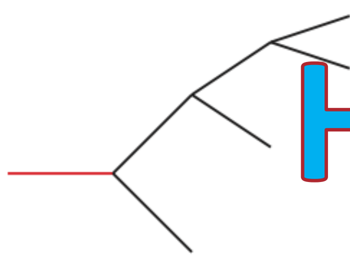
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) +$ [hidden]
	$h \to (\ell^+\ell^-)$ [hidden]
$h \to 2 \to 3 \to 4$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

LHC great sensitivity

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

Exotic decay of the SM Higgs boson

- What can we do with HL-LHC?

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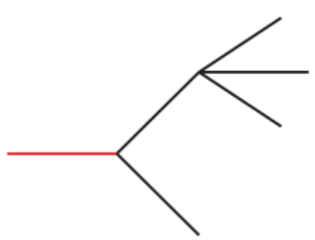
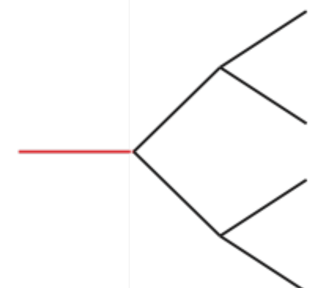
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

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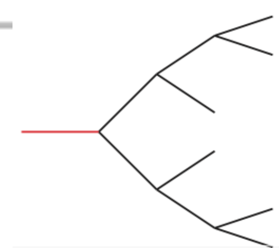
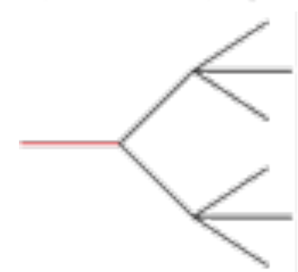
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

Hard due to MET

Hard due to Hadronic

Exotic decay of the SM Higgs boson

- Our simulation, what we do and what we do not do.

✓ Parton level event generation, with Higgs and Z boson decay;

✓ Gaussian smearing effect, b-tagging and veto;

✓ Parton level background event generation;

✓ Optimize cuts for each specific channel.

x Full ISR and initial state effects 🙁;

x Parton showering, hadronization, jet clustering 🙁;

x Jet substructure analysis 🙂;

x BDT or MVA technology 🙂;

x Hadronic Z decay mode 🙂.

Exotic decay of the SM Higgs boson

- An example:
  - *h*→2→4
  - Insert light (pseudo)scalar (*a*, *s*) or vector boson (*Z'*).
  - *h*→*ss*(*aa*)→(*jj*)(*jj*), *h*→*Z'Z'*→(*jj*)(*jj*).
  - Effective Lagrangian:

$$\begin{aligned}\mathcal{L}_{\rm eff} =& \sqrt{2}\varepsilon_s v h s s + \sqrt{2}\varepsilon_a v h a a + \varepsilon_1 g_1' v h Z'_{1\mu} Z_1'^{\mu} + \varepsilon_2 g_2' v h Z'_{2\mu} Z_2'^{\mu} \\ & + y_s s \bar{f} f + i y_a a \bar{f}\gamma_5 f + \frac{\alpha_s c_s}{\Lambda_s} s G_{\mu\nu} G^{\mu\nu} + \frac{\alpha_s c_a}{\Lambda_a} a G_{\mu\nu}\tilde{G}^{\mu\nu} \\ & + g_1' Z'_{1\mu} \bar{f}\gamma^\mu f + g_2' Z'_{2\mu}\bar{f}\gamma^\mu P_R f\end{aligned}$$

Spin correlations are kept in our simulation.

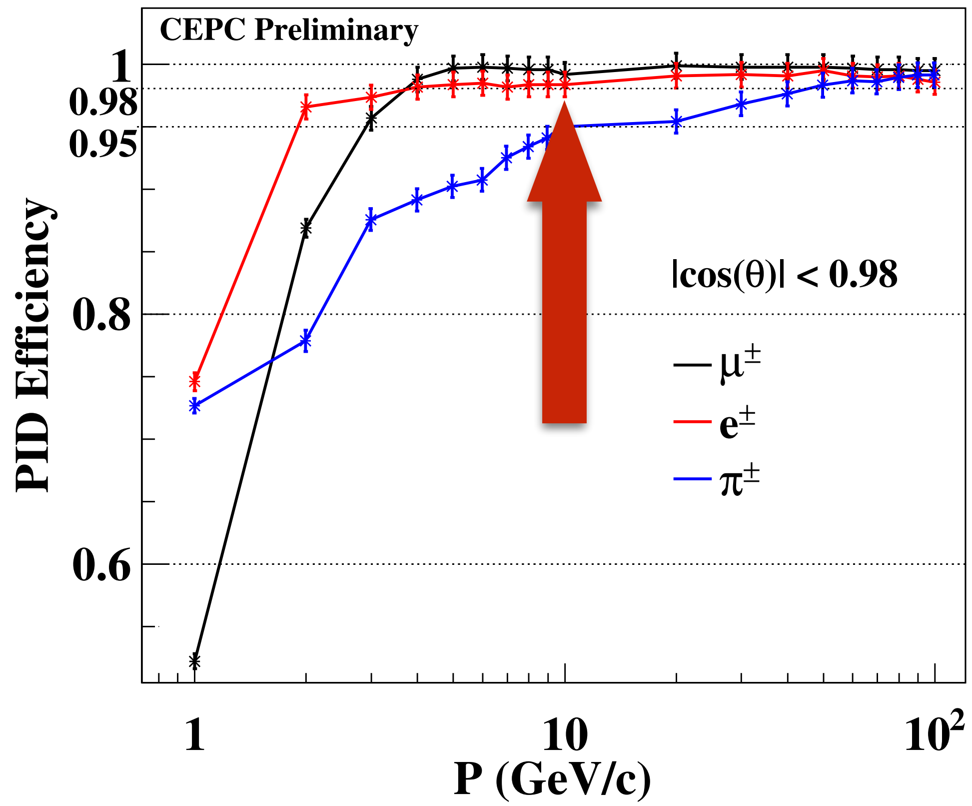
Exotic decay of the SM Higgs boson

- An example:
  - Parton level simulation.
  - Detector effects (energy resolution, PID efficiency):

$$\frac{\delta E_j}{E_j} = \frac{0.3}{\sqrt{E_j/\mathrm{GeV}}} \oplus 0.02$$

$$\frac{\delta E_\gamma}{E_\gamma} = \frac{0.16}{\sqrt{E_\gamma/\mathrm{GeV}}} \oplus 0.01$$

$$\Delta\left(\frac{1}{p_{\mathrm{T},\ell}}\right) = 2\times 10^{-5} \oplus \frac{10^{-3}}{p_{\mathrm{T},\ell}\sin\theta_\ell}$$



CEPC-SPPC preCDR, Volume I-Physics & Detector, The CEPC-SPPC Study Group

Exotic decay of the SM Higgs boson

- An example:
  - Parton level simulation.
  - Main SM backgrounds: $e^+e^-\rightarrow Zjjjj+X$.
  - Systematic error of the simulation due to the ISR effect. (We thank M.-Q Ruan for helpful discussion.)
  - A parton level simulation which could give a reasonable estimation of the significance with clearly error estimation is acceptable in current study.

Exotic decay of the SM Higgs boson

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

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

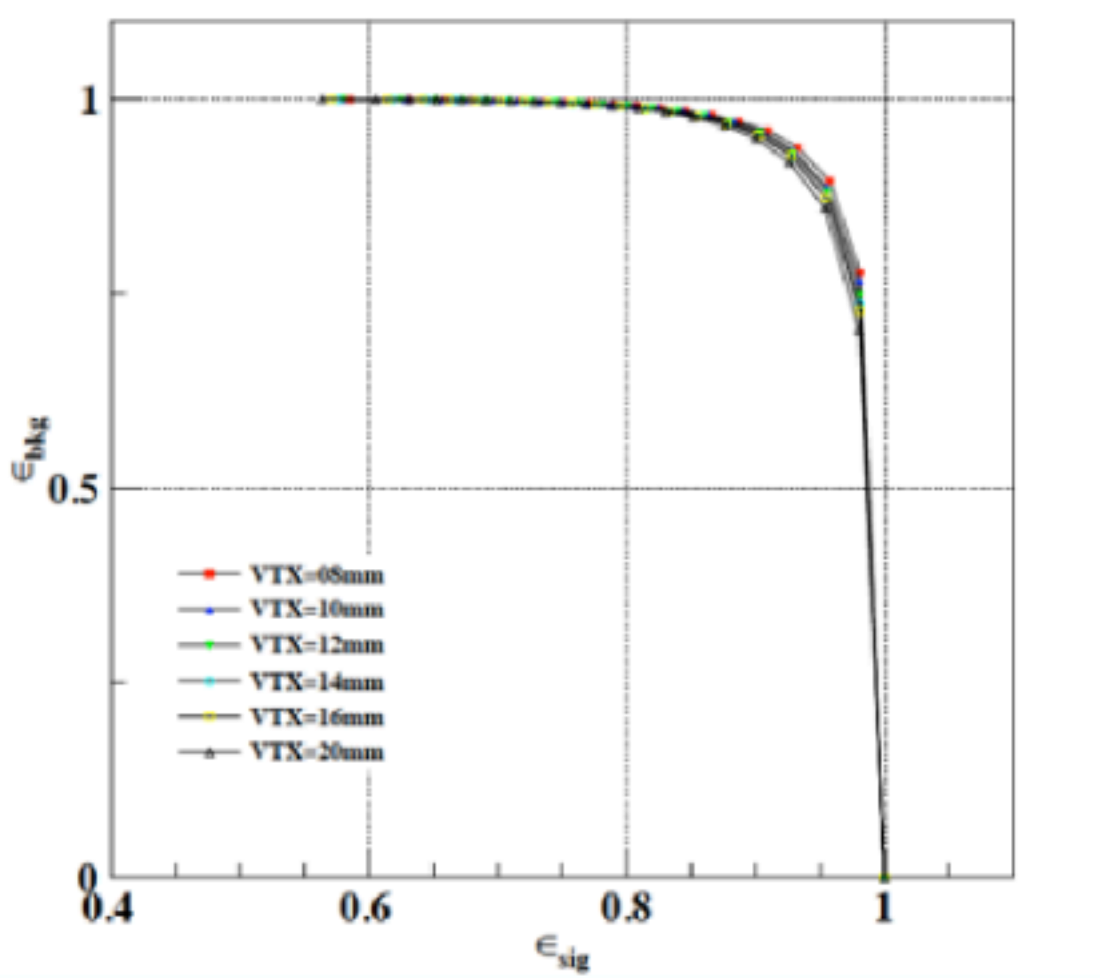
a pair of OSSF leptons, $\theta_{\ell\ell} > 80^\circ$

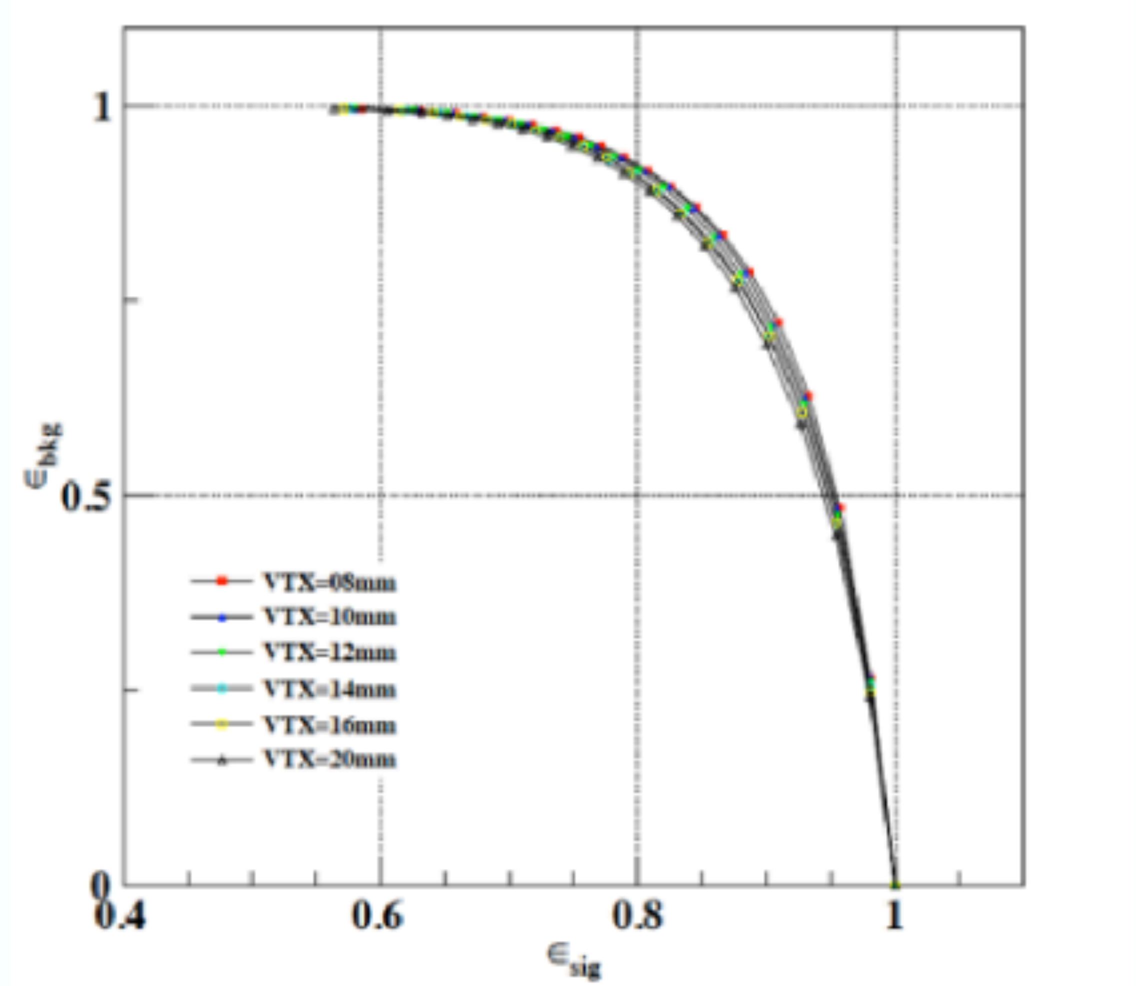
$$|m_{\ell\ell} - m_Z| < 10\text{GeV}, |m_{\text{recoil}} - m_h| < 5\text{GeV}.$$

  - 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). (No ISR for signal events!)
  - Additional cut to suppress the ISR effect: $E_{vis} > 225\text{GeV}.$

Exotic decay of the SM Higgs boson

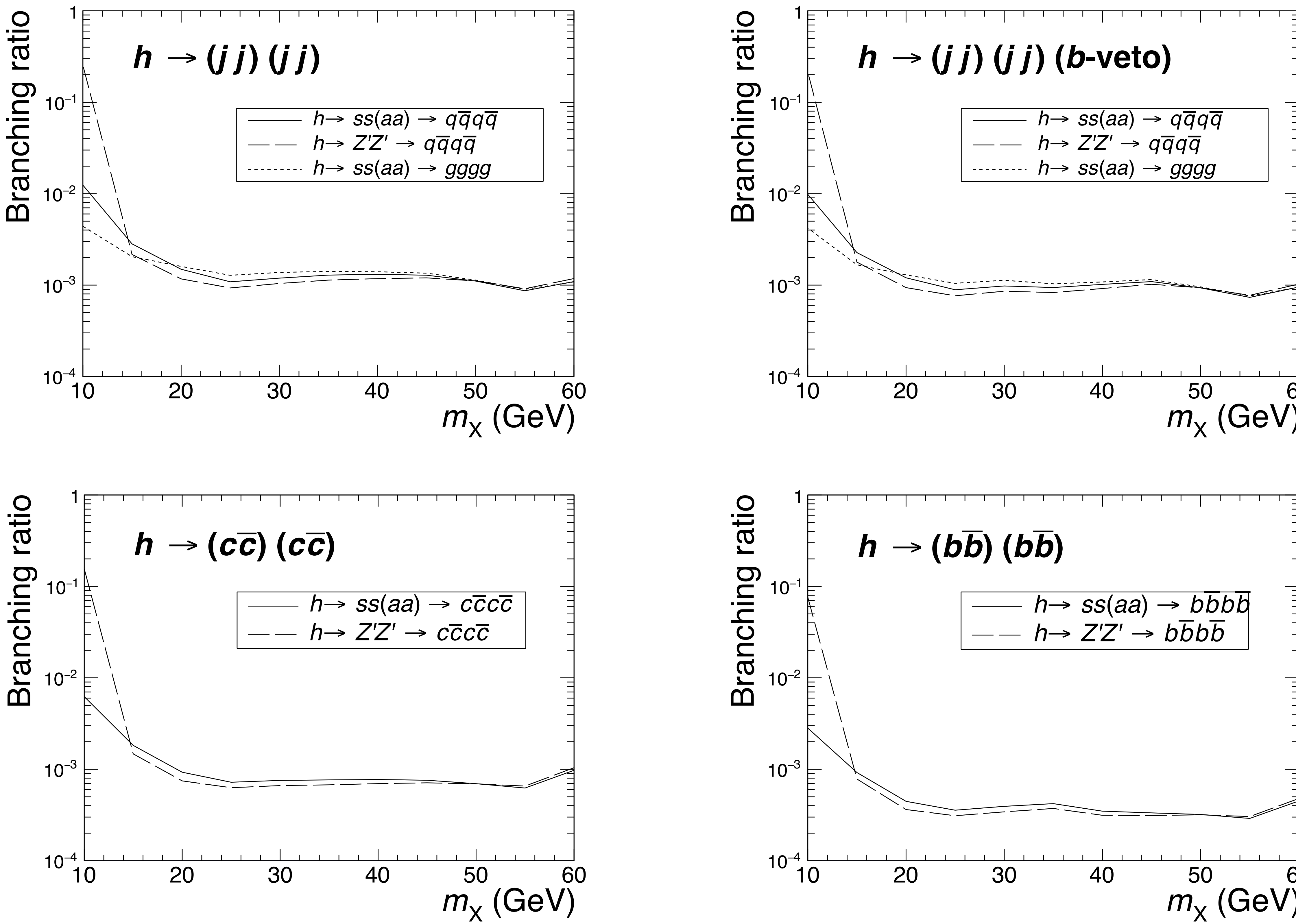
- Phenomenology:
  - Parton level simulation.
  - Detector effects (energy resolution, PID efficiency).
  - b-tagging efficiency:



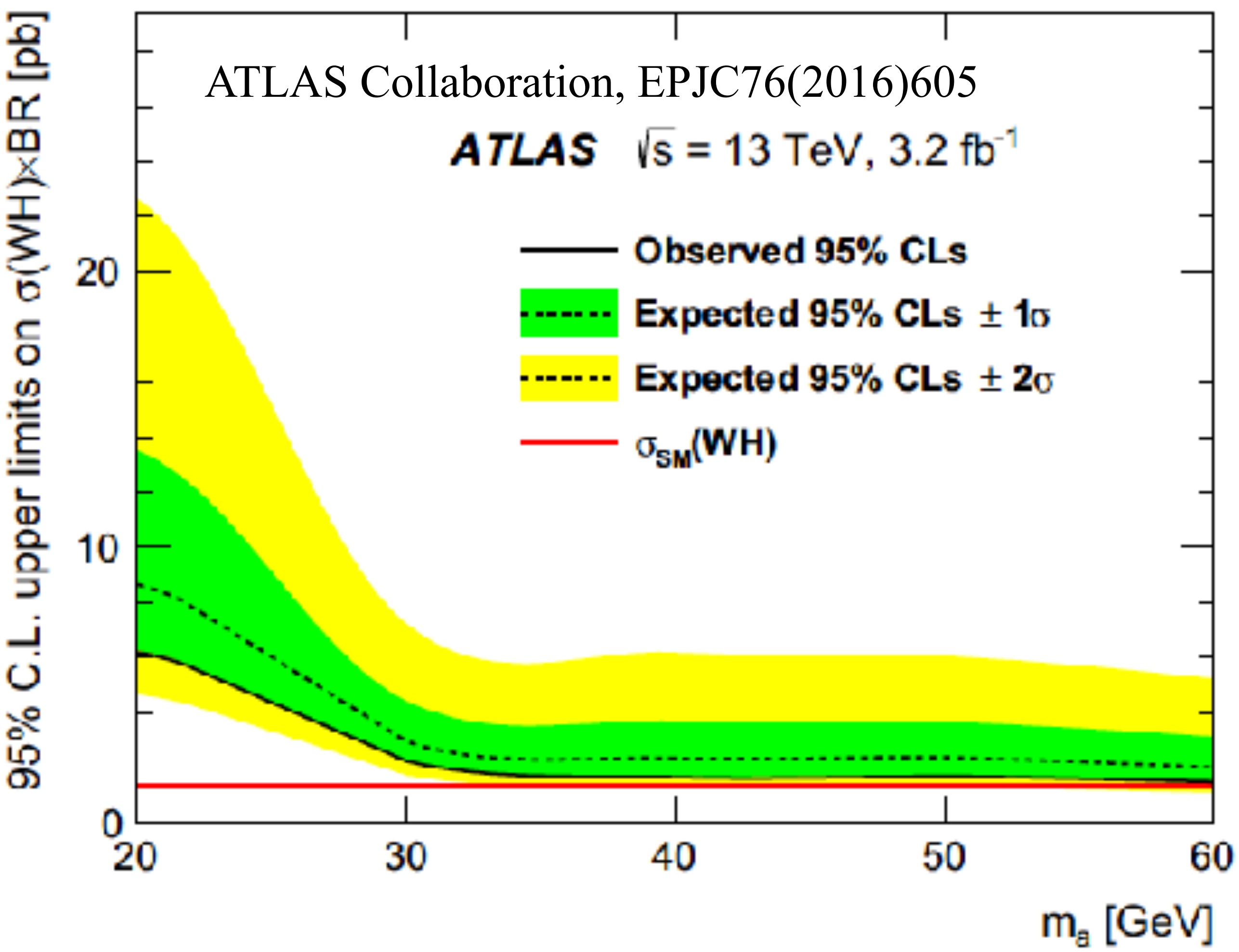


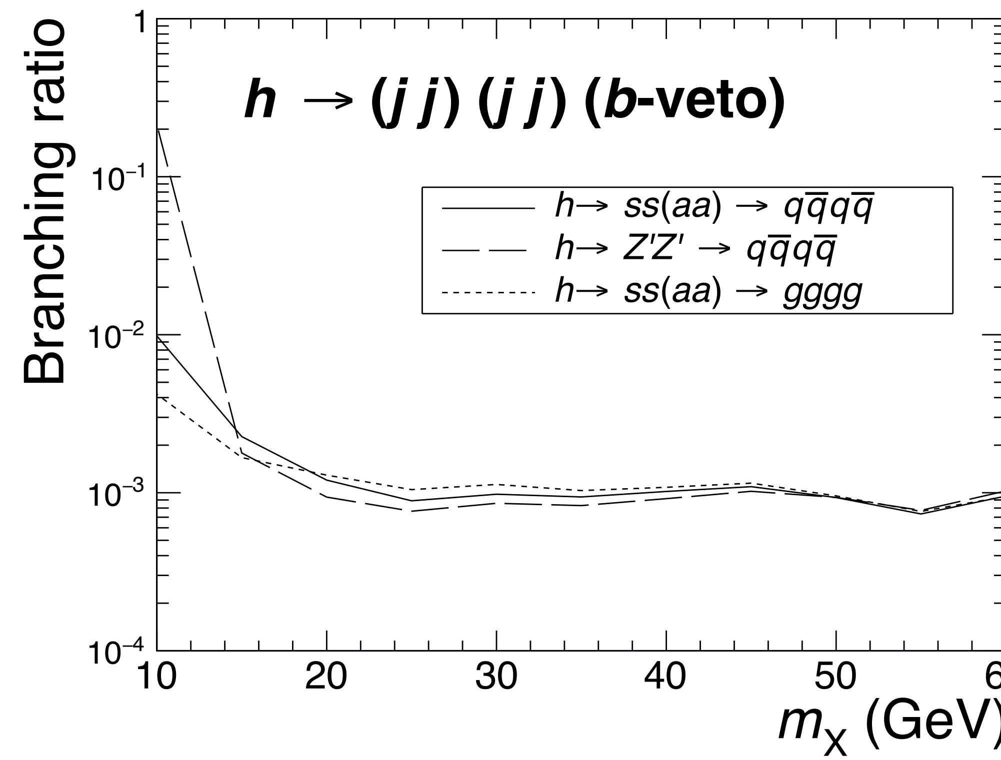
From Manqi's slide: Higgs analysis and Detector Optimization at CEPC, 2016/02/09

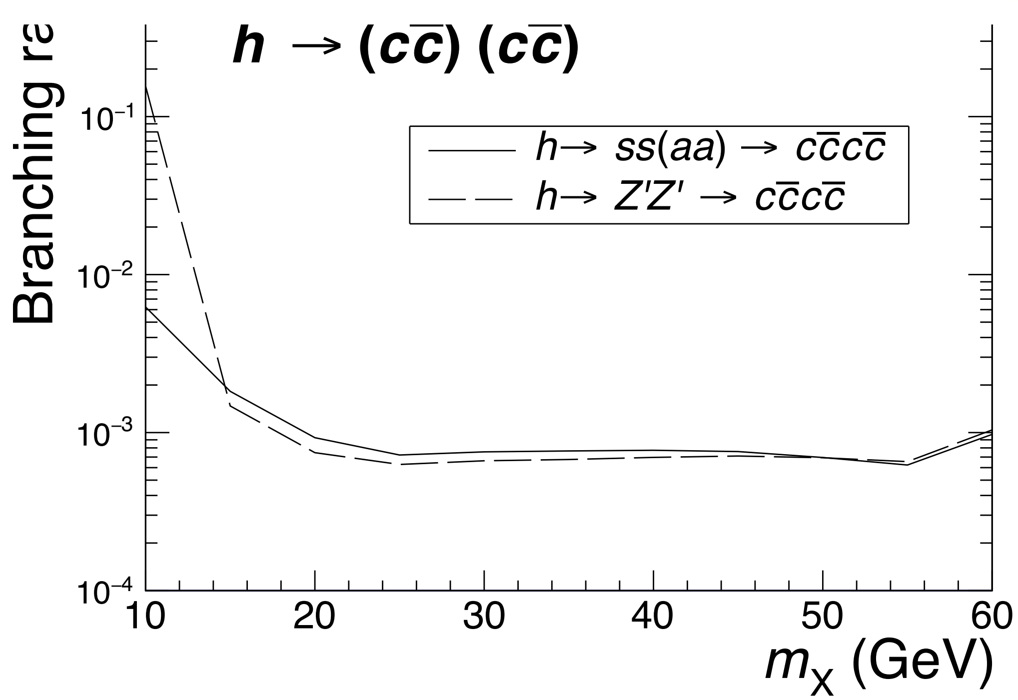
Exotic decay of the SM Higgs boson (*jjjj*)

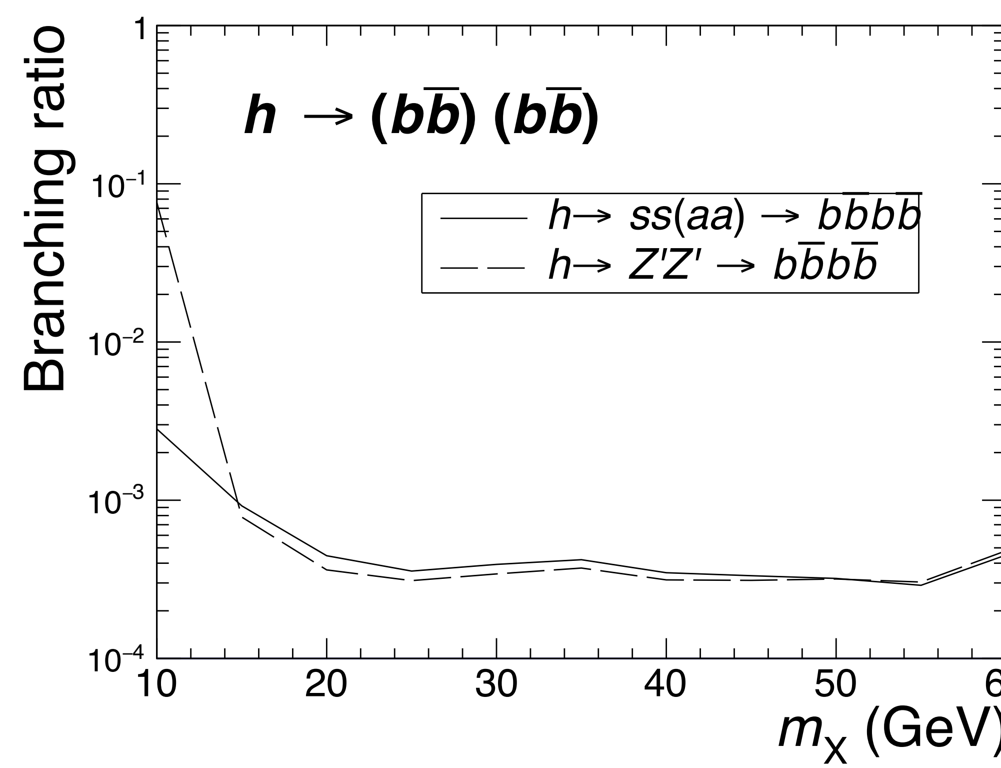


Exotic decay of the SM Higgs boson (*jjjj*)



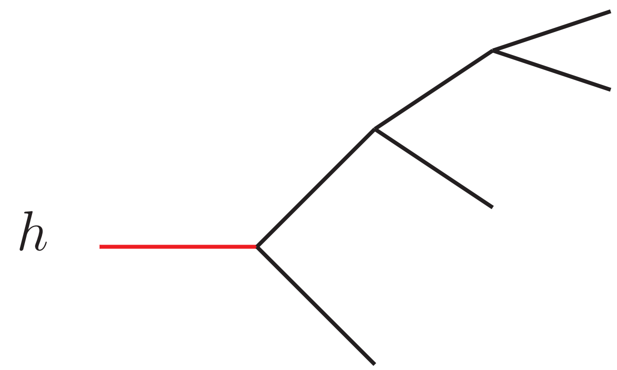




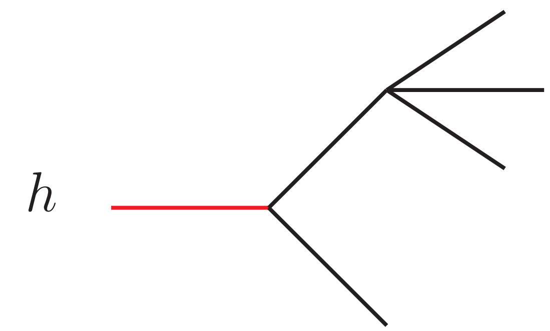


Exotic decay of the SM Higgs boson (*jj*+*met*)

- Another topology

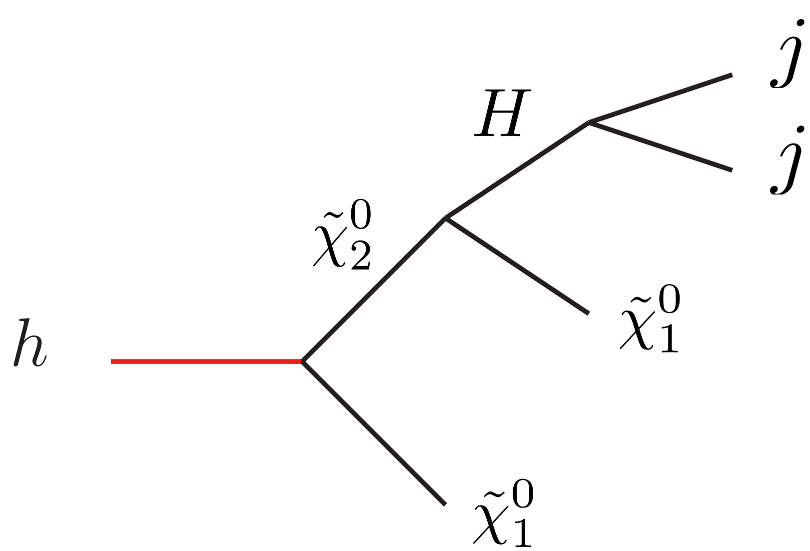


$h \to 2 \to 3 \to 4$

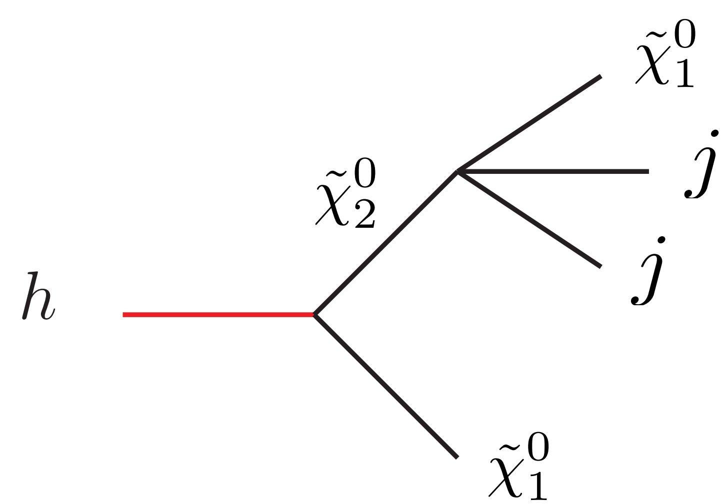


$h \to 2 \to (1+3)$

- Benchmark model: supersymmetry.

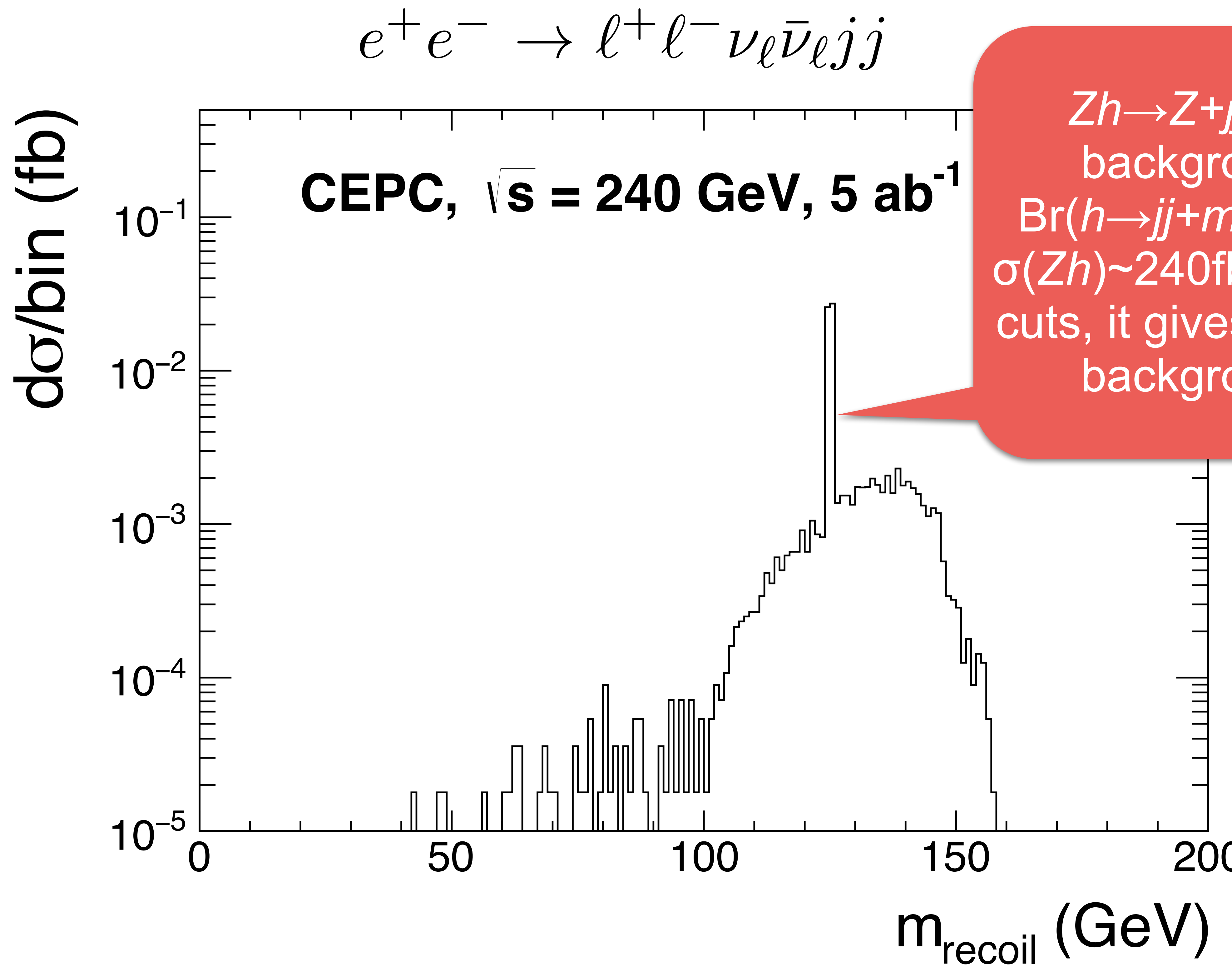


$h \to 2 \to 3 \to 4$



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

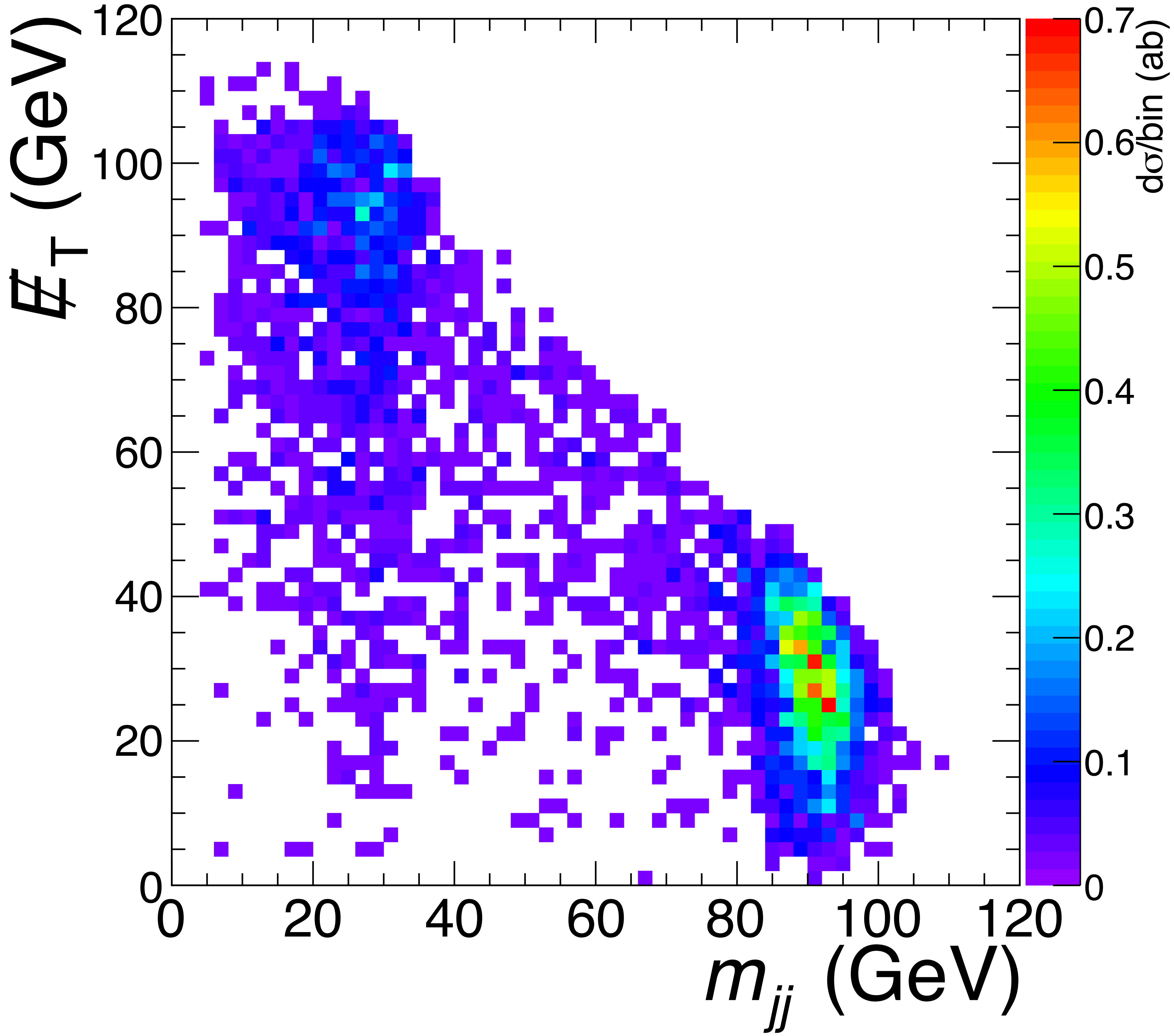
Exotic decay of the SM Higgs boson (*jj+met*)



Zh→Z+jj+met background. Br(*h→jj+met*)~1%, σ(*Zh*)~240fb, without cuts, it gives ~0.17fb background.

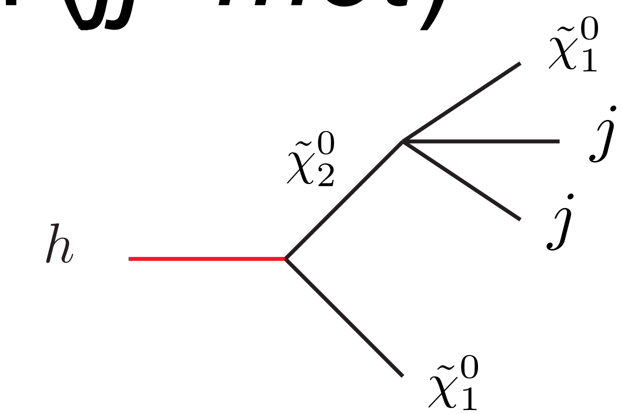
Exotic decay of the SM Higgs boson (*jj*+*met*)

$$e^+e^- \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell jj$$

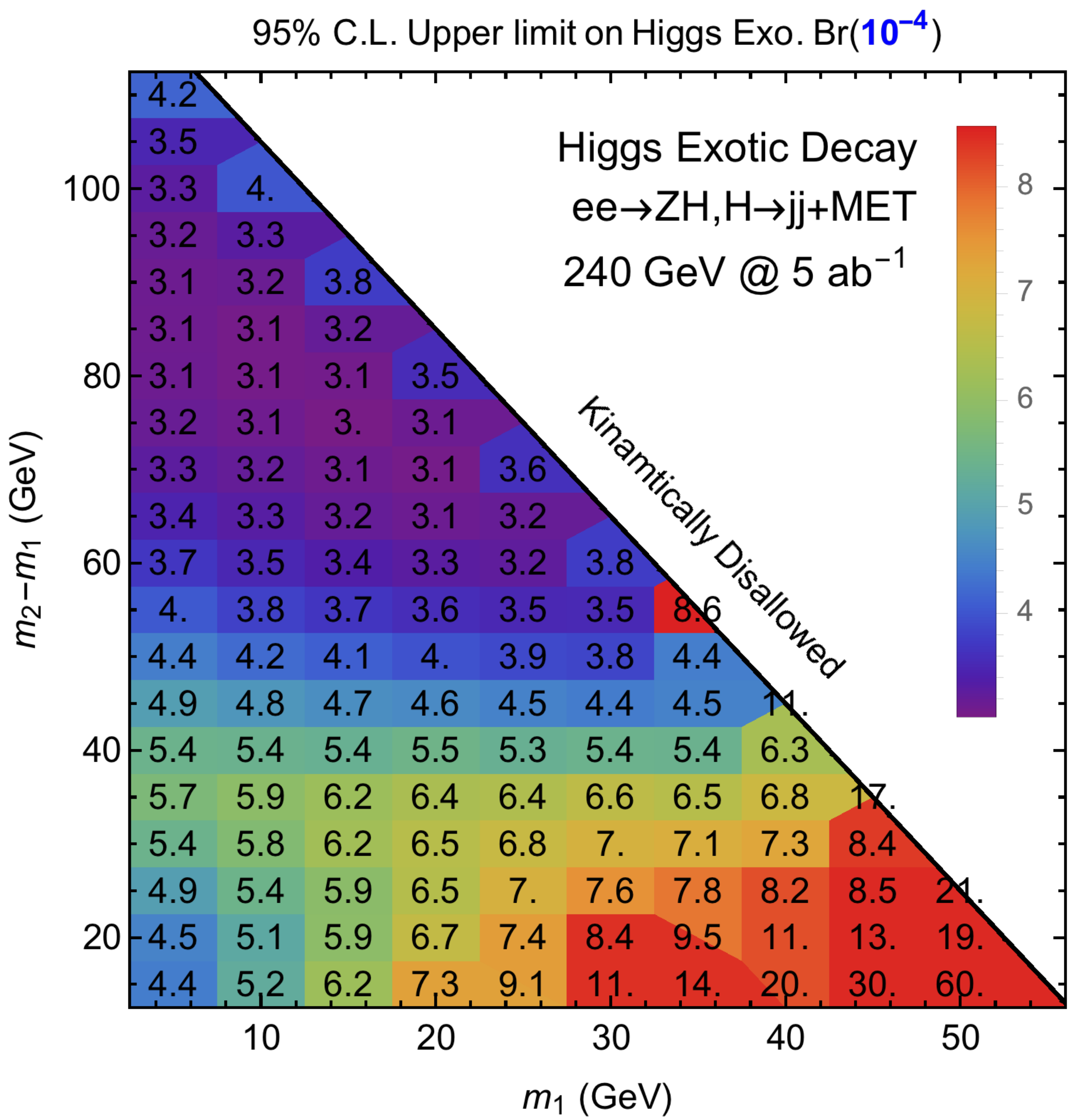


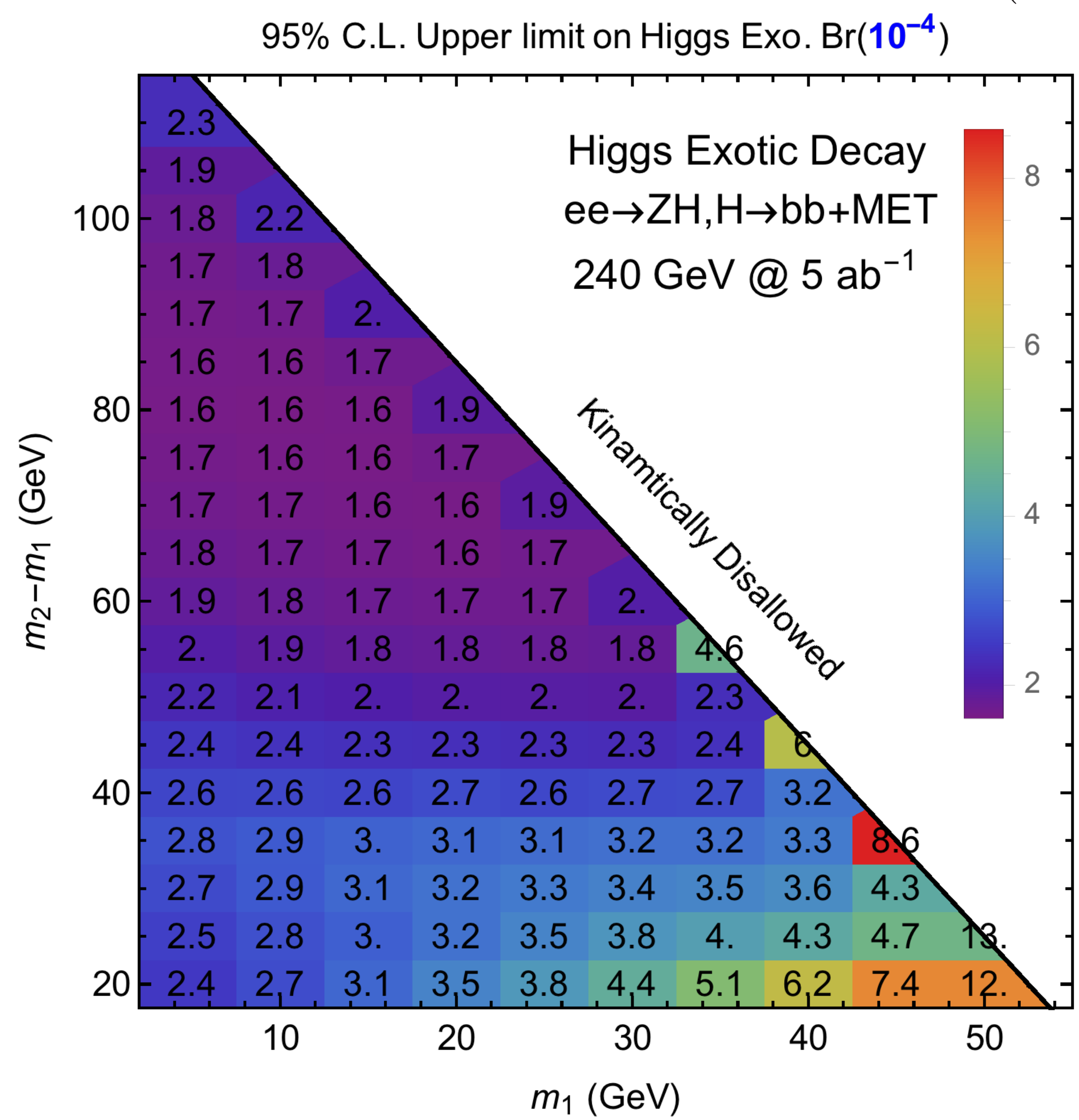
Exotic decay of the SM Higgs boson (*jj+met*)

- Off-shell χ_2 decay.
- Large m_2: $m_{jj} \sim 2m_2/3$.

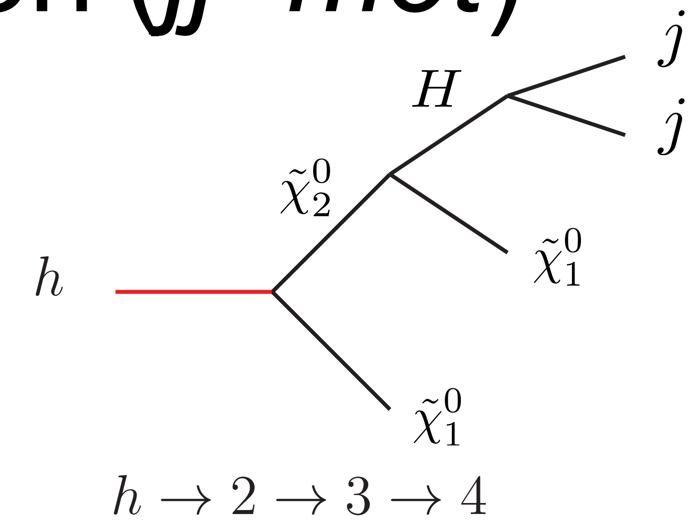


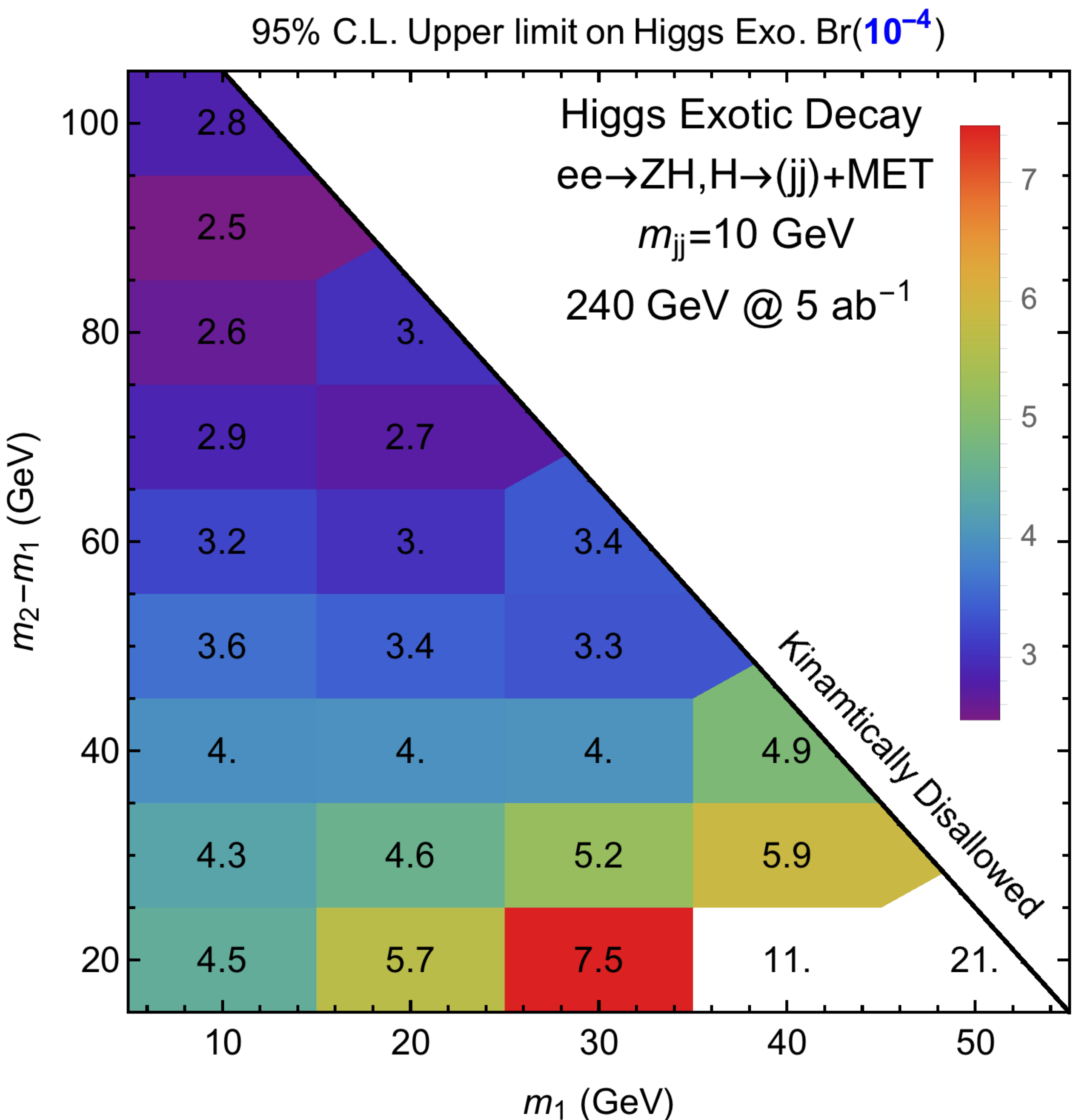
$h \to 2 \to (1+3)$

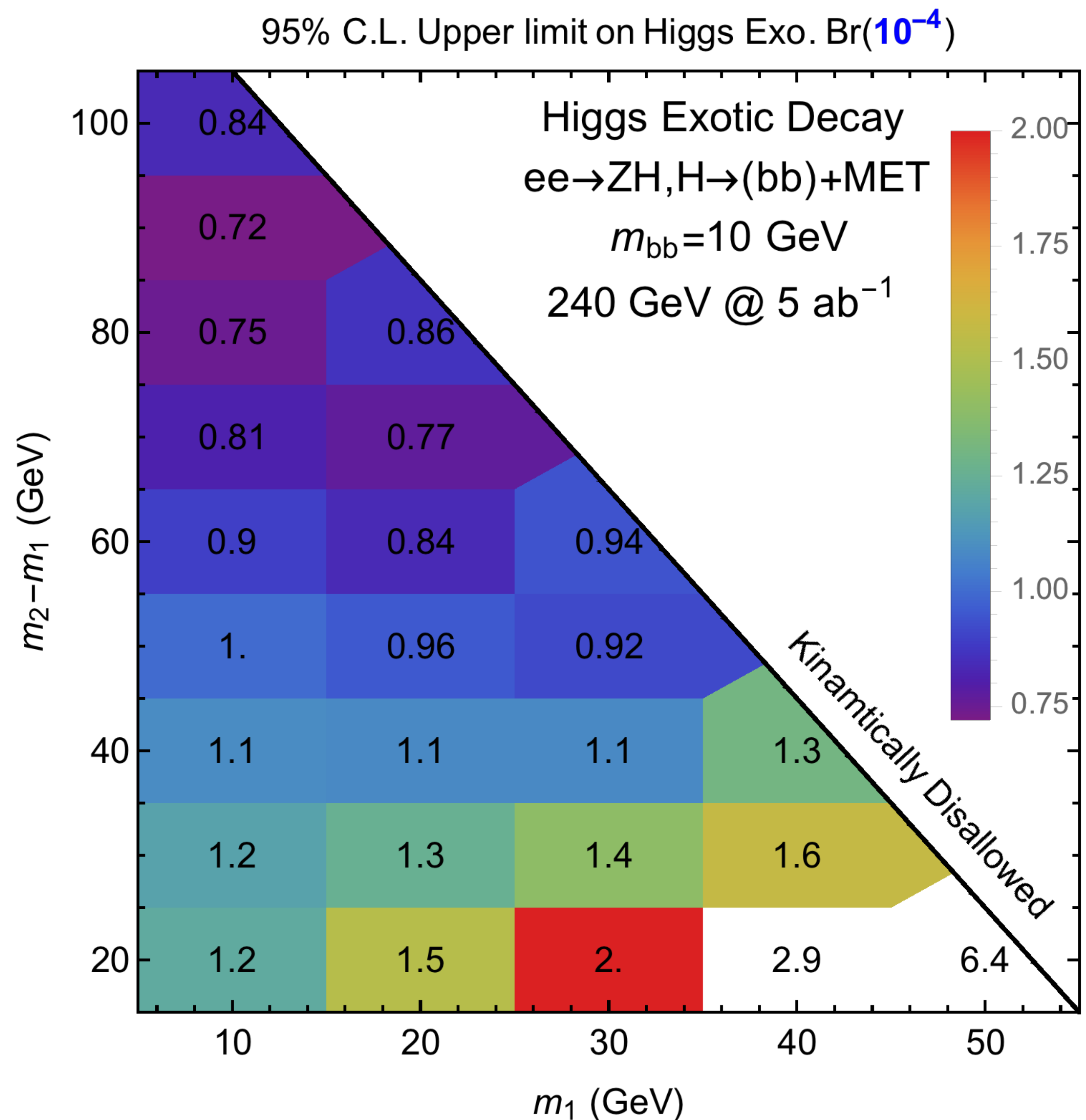




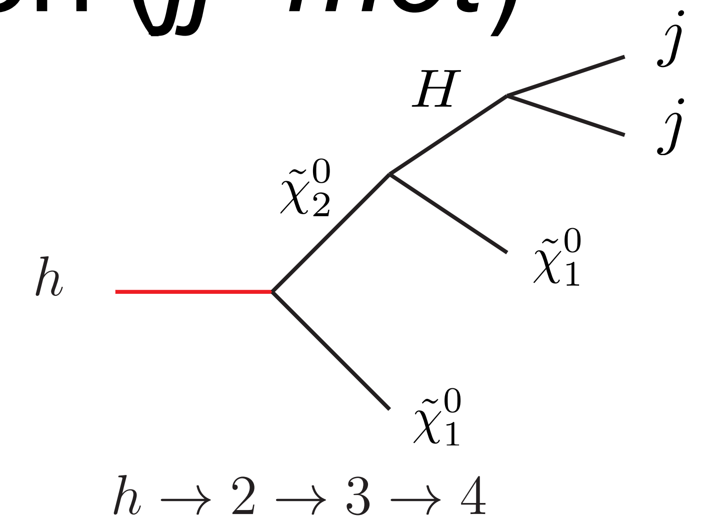
Exotic decay of the SM Higgs boson (*jj*+*met*)

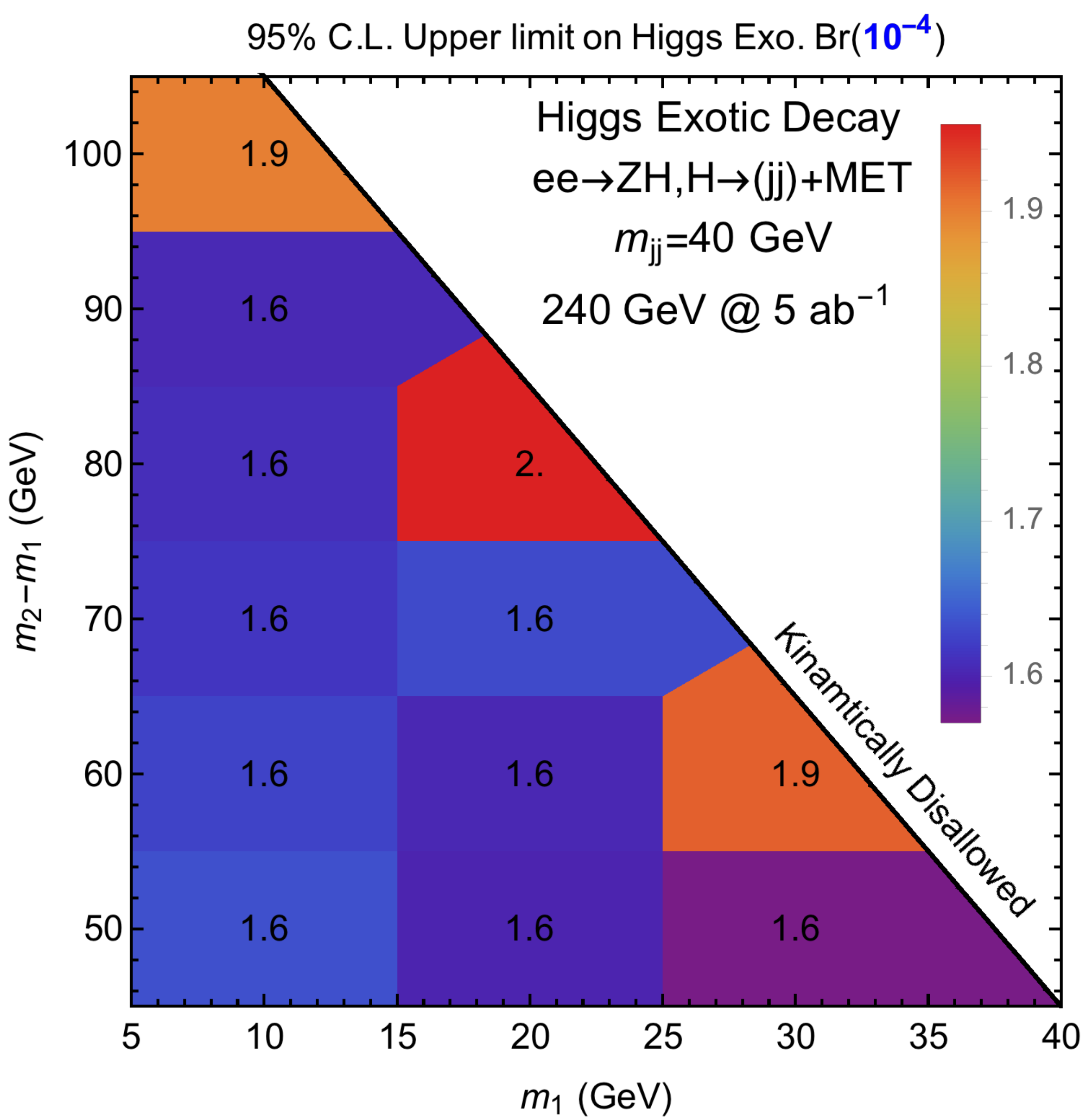


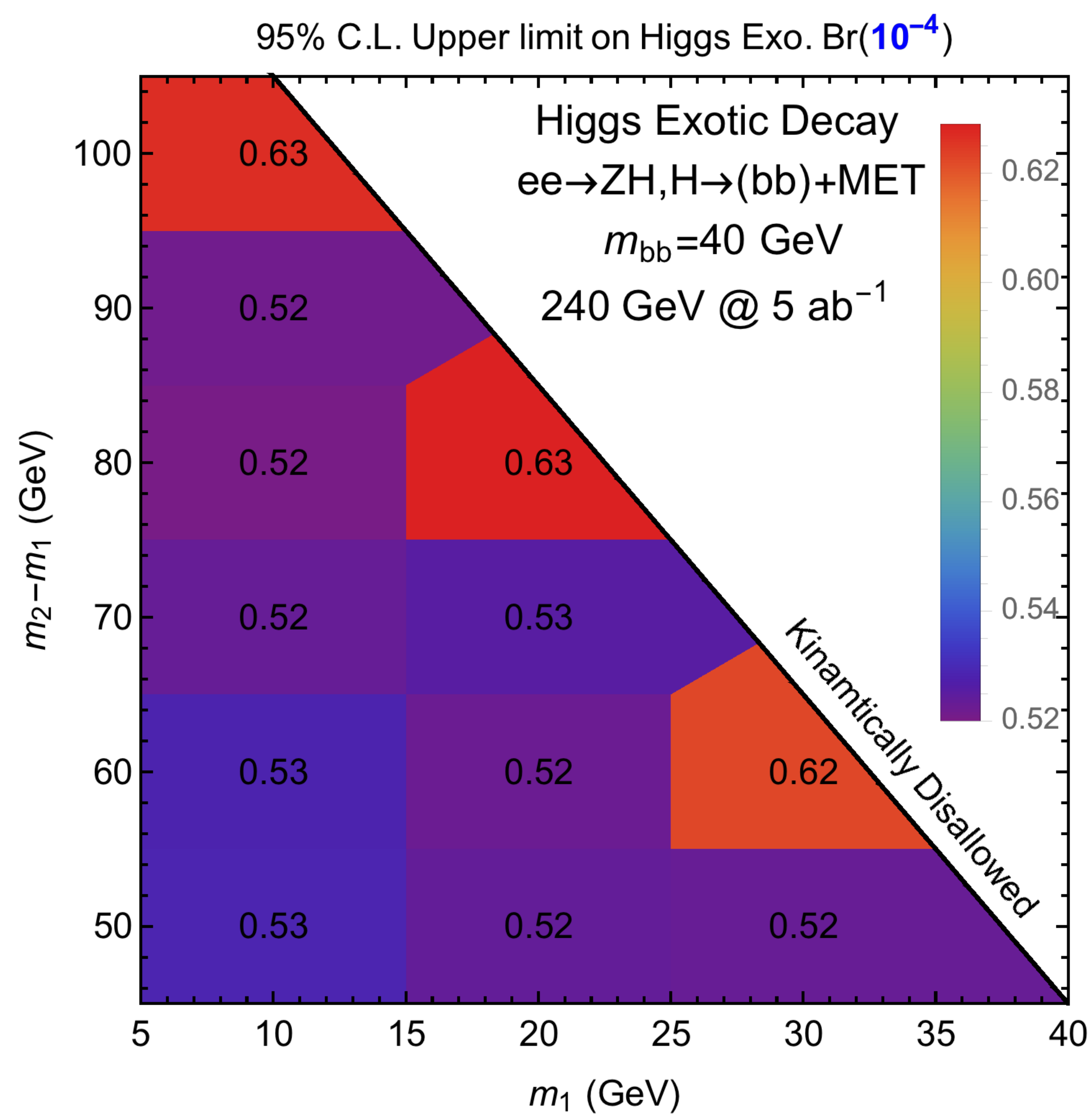




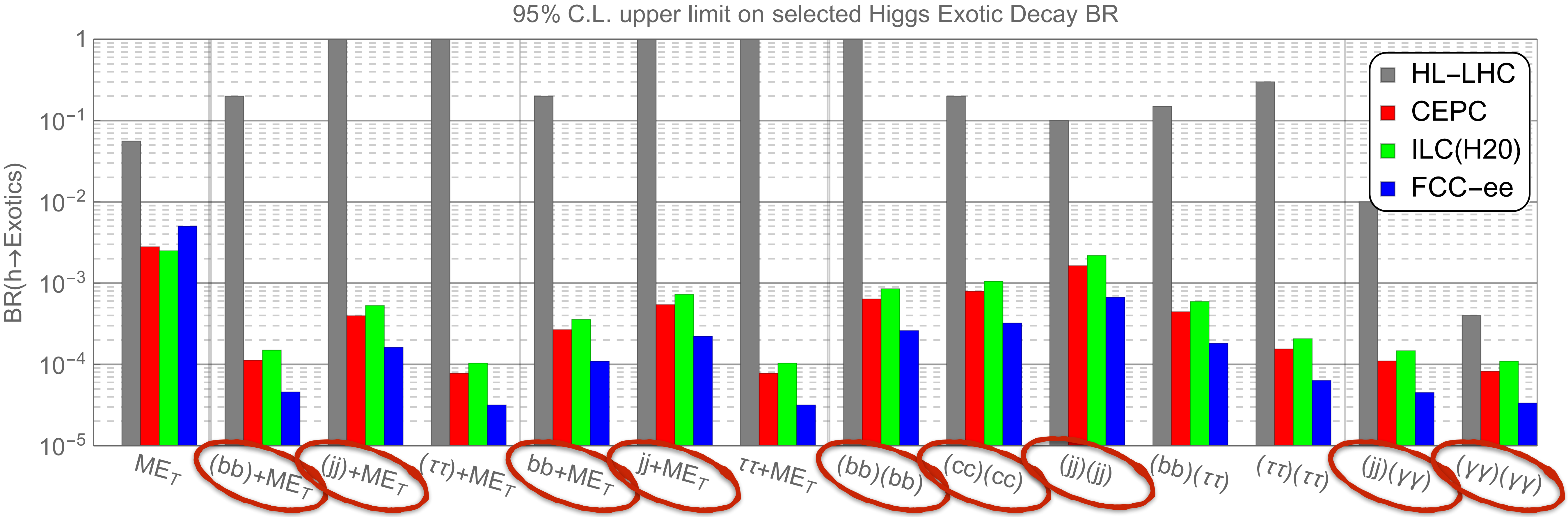
Exotic decay of the SM Higgs boson (*jj*+*met*)





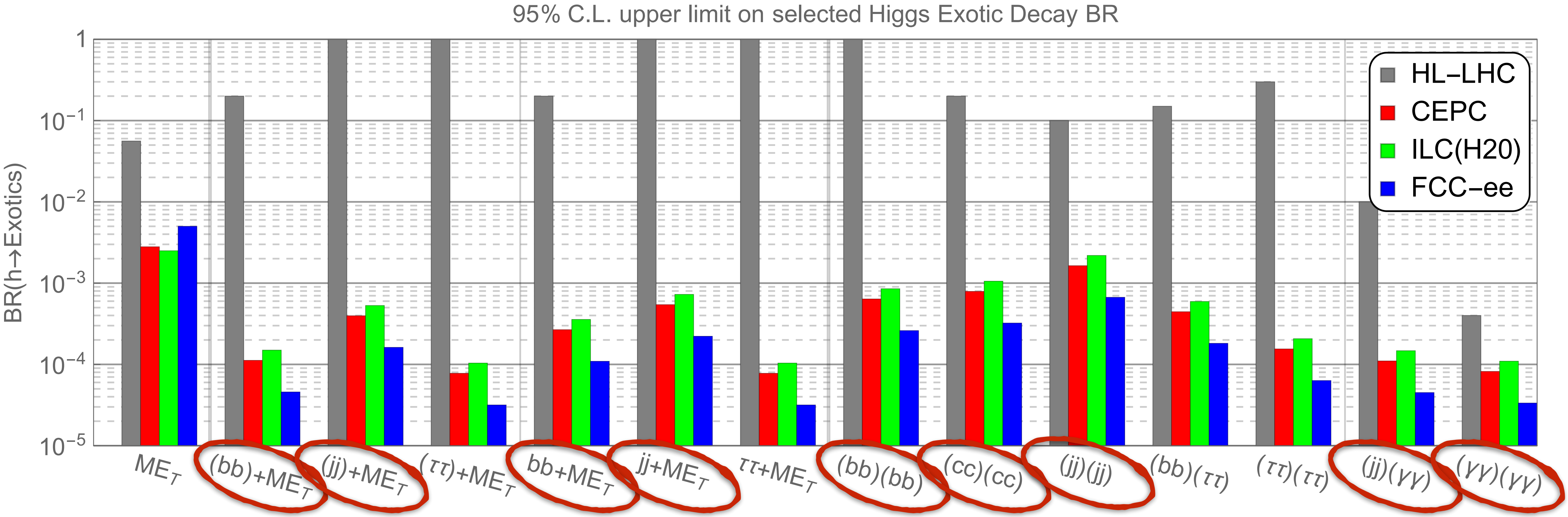


Summary and outlook



- The sensitivity to the invisible Higgs decay has been well studied and the results are from literatures.
- The tau channels are extrapolated from our simulation with 40% tau tagging rate and more backgrounds considered.
- The ILC(H20, polarized) and FCC-ee results are rescaled with luminosity.

Summary and outlook



- The accuracy of the measurement of the total width of the Higgs boson is expected to be ~ 2.7%. Thus this offers a much worse sensitivity to most of the exotic decay channels.

- The initial state effect, parton showering and hadronization effect, full detector simulation, hadronic Z decay mode, and jet substructure analysis are neglected in this work. However, they should be considered in a more complete version of the investigation of these NP signals.


Thank you!

Backup

Exotic decay of the SM Higgs boson (*jjjj*)