Searching exotic decay channels of the SM Higgs boson at CEPC

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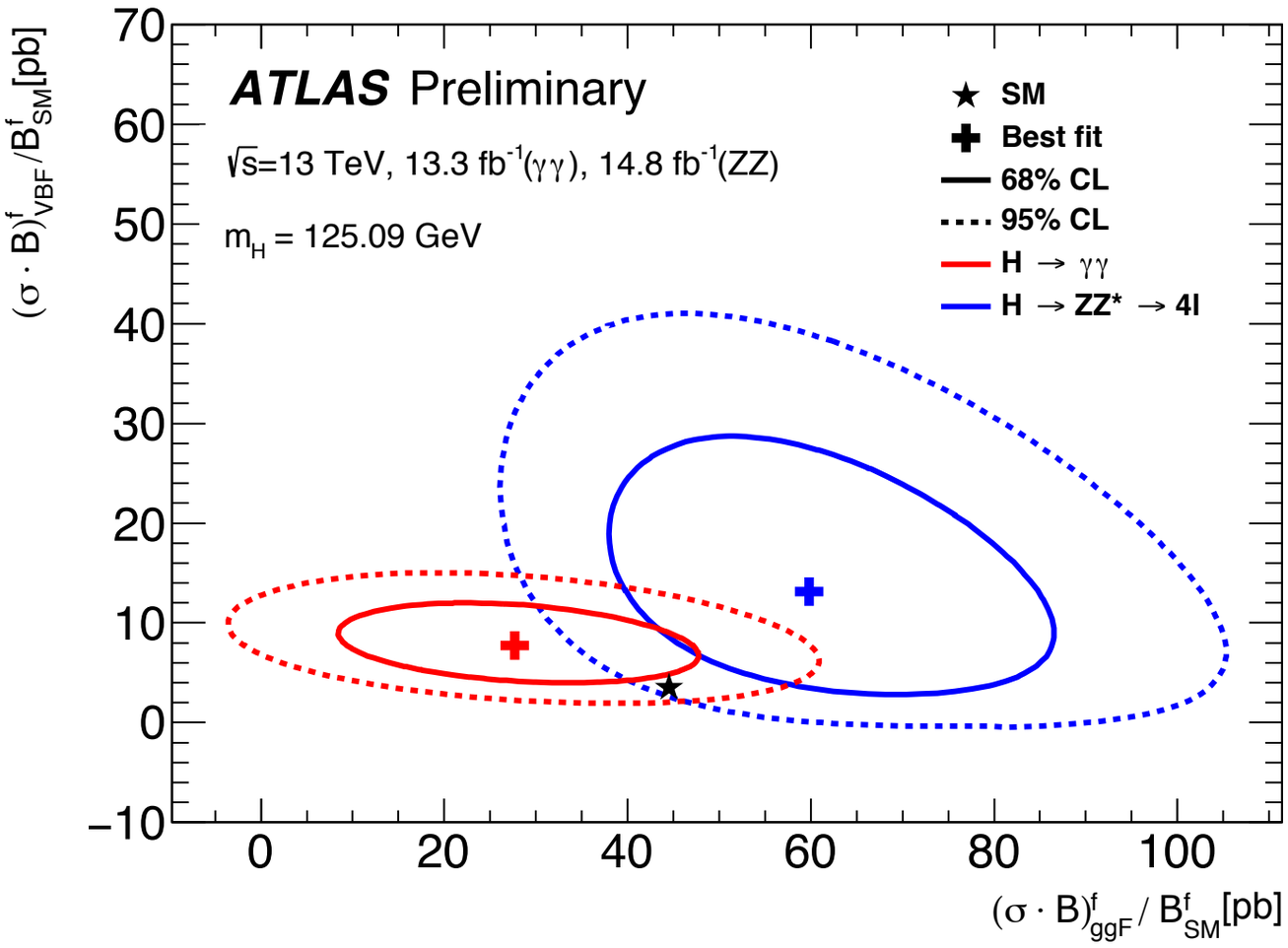
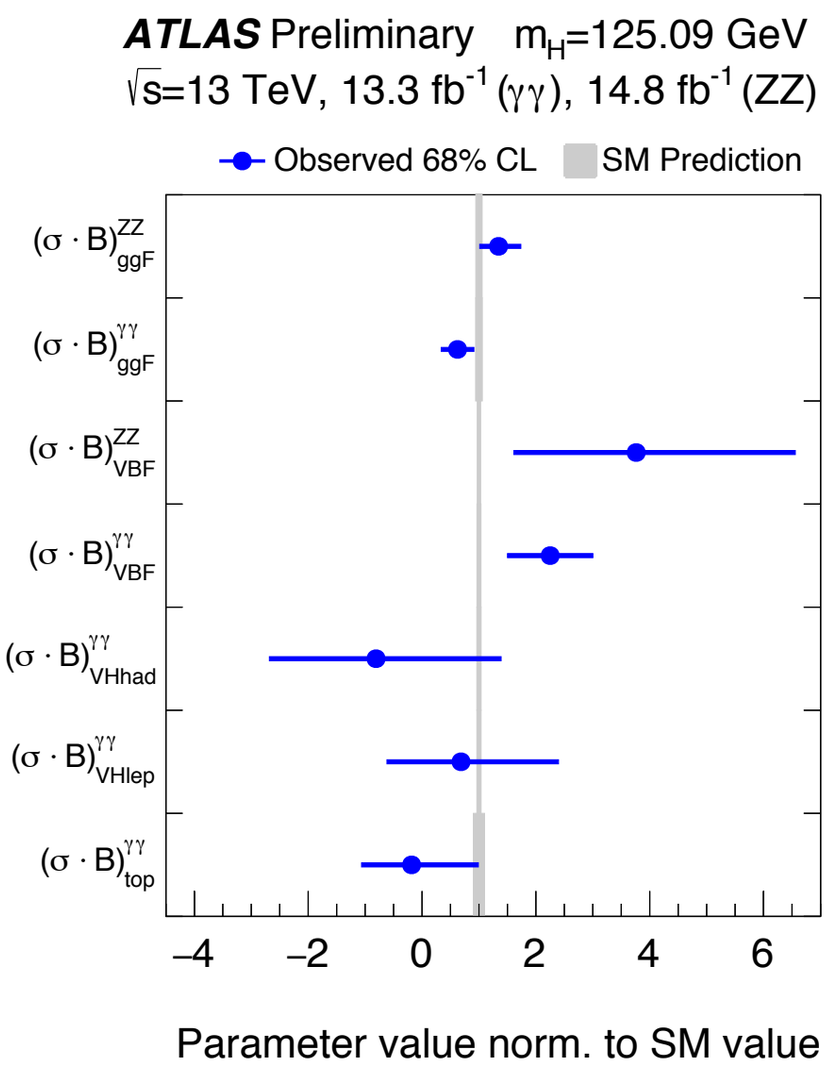
For CEPC Workshop, Dec 13-15, 2016, Beijing

Base on the work in collaboration with Zhen Liu and Lian-Tao Wang.

The SM-like Higgs boson

- The last fundamental particle in the SM.





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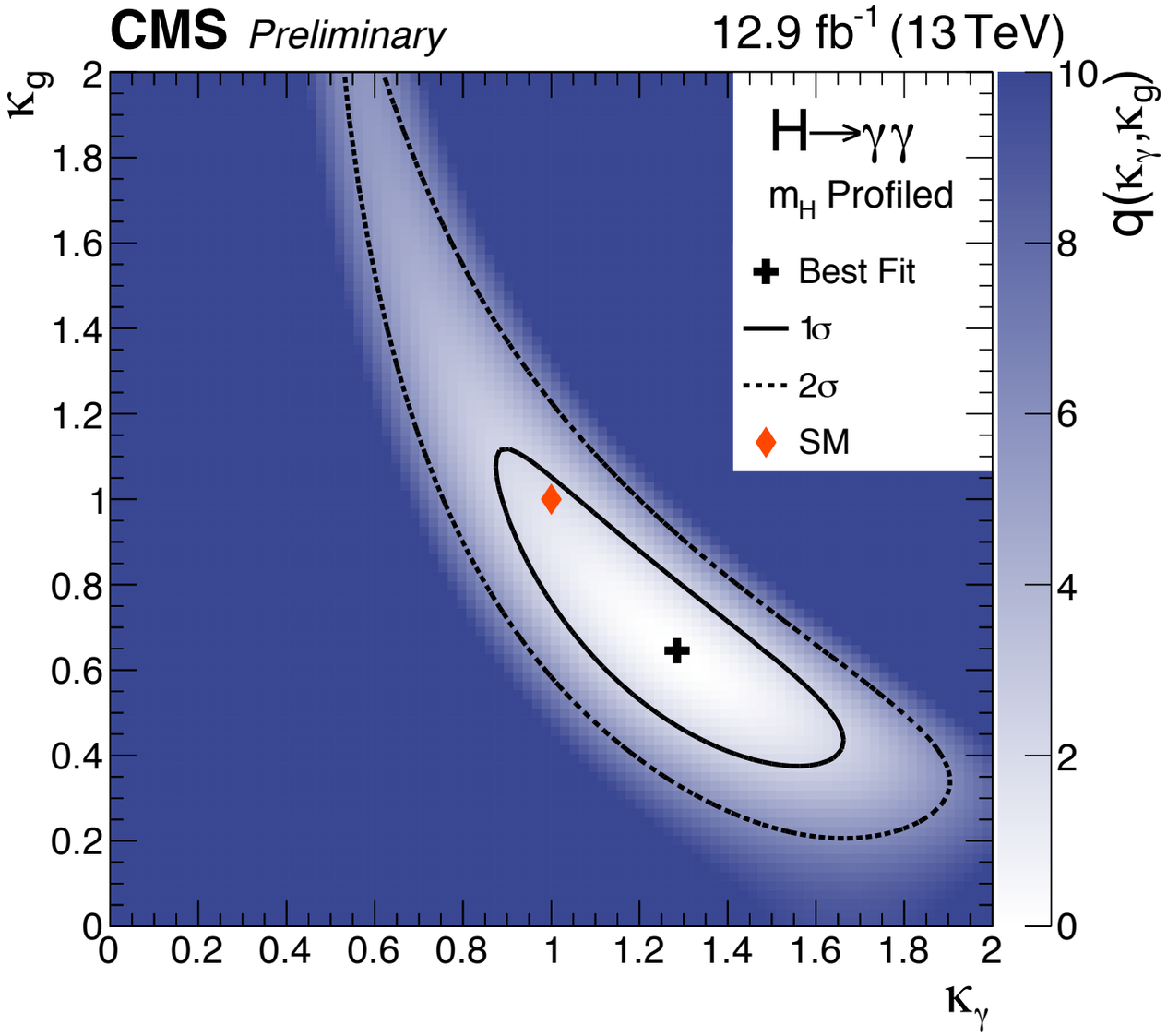
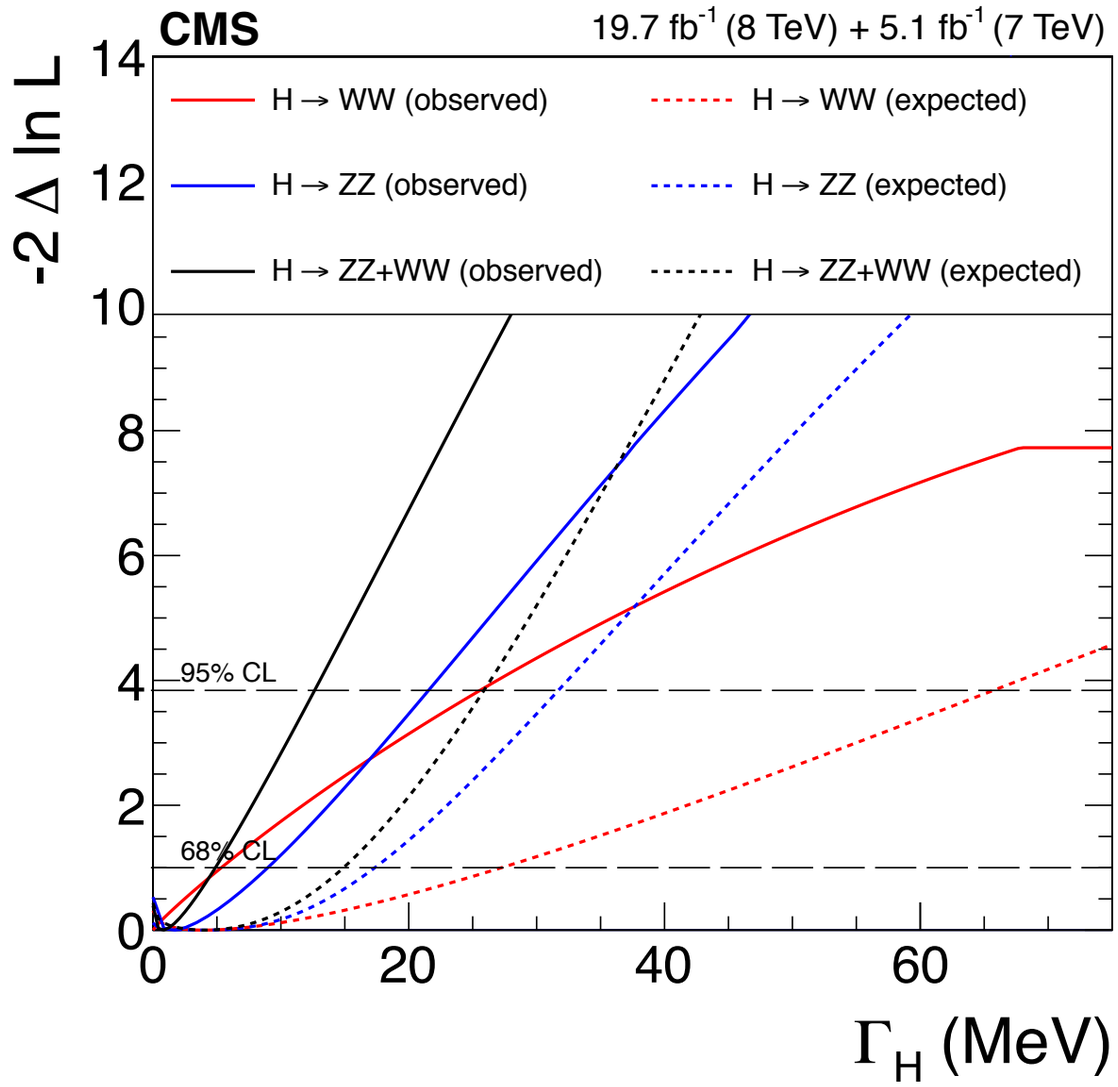




The SM-like Higgs boson

- Question: Can we remove the word “like”?

  1. The new physics comes into the Higgs sector at Λ.

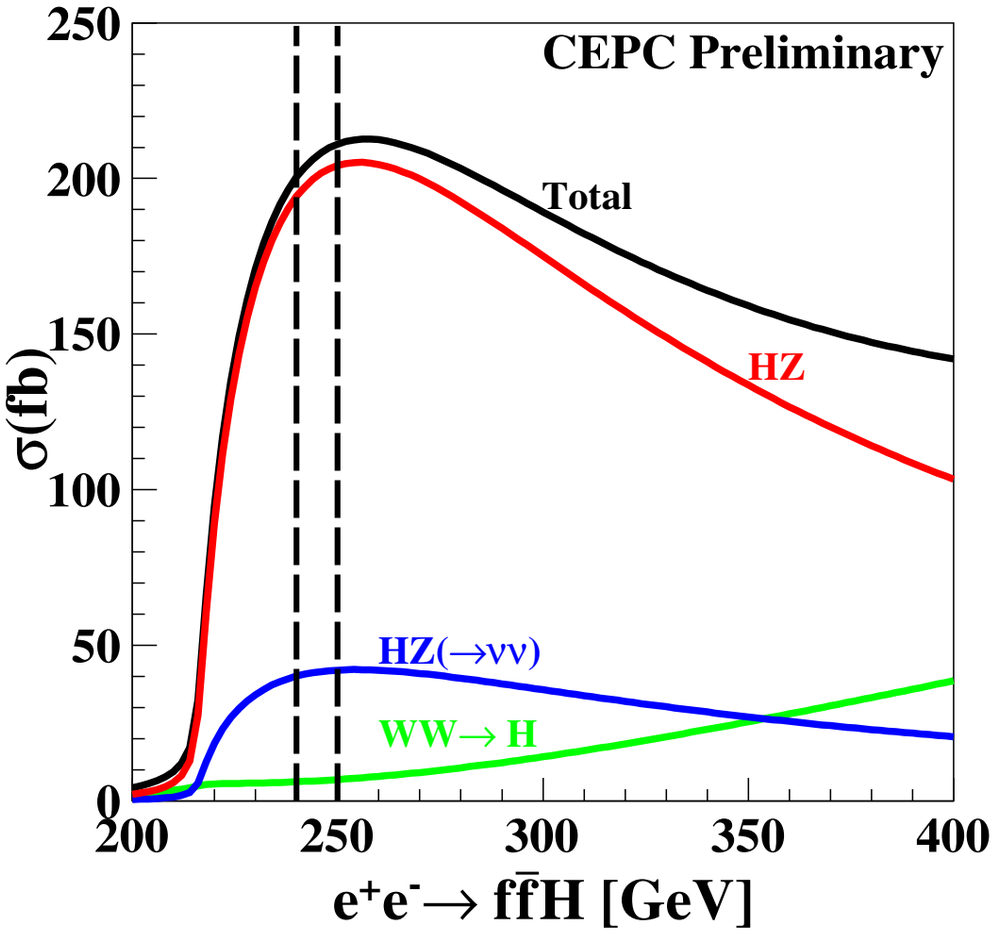
     The “like” could be removed when the scale is much lower than Λ

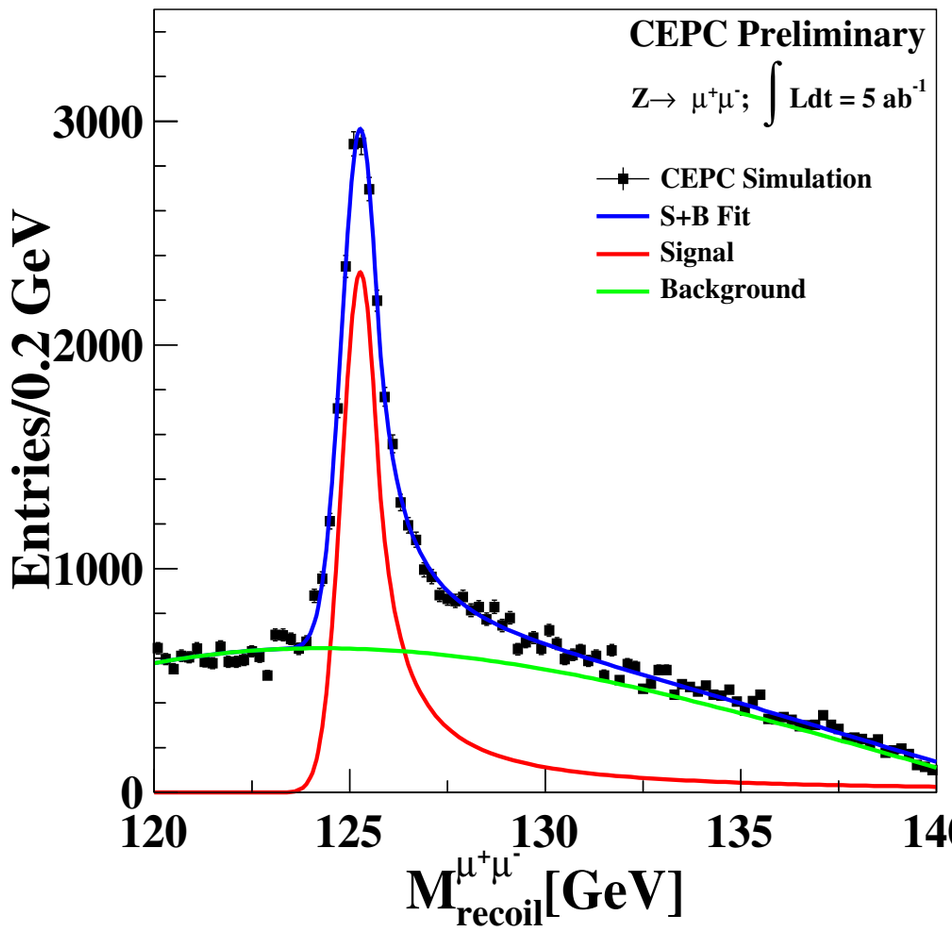
  2. Some light degrees of freedom couple to the Higgs boson.

What can we do at CEPC?

CEPC: a Higgs factory

- More than 1,000,000 ZH signal events in the SM!



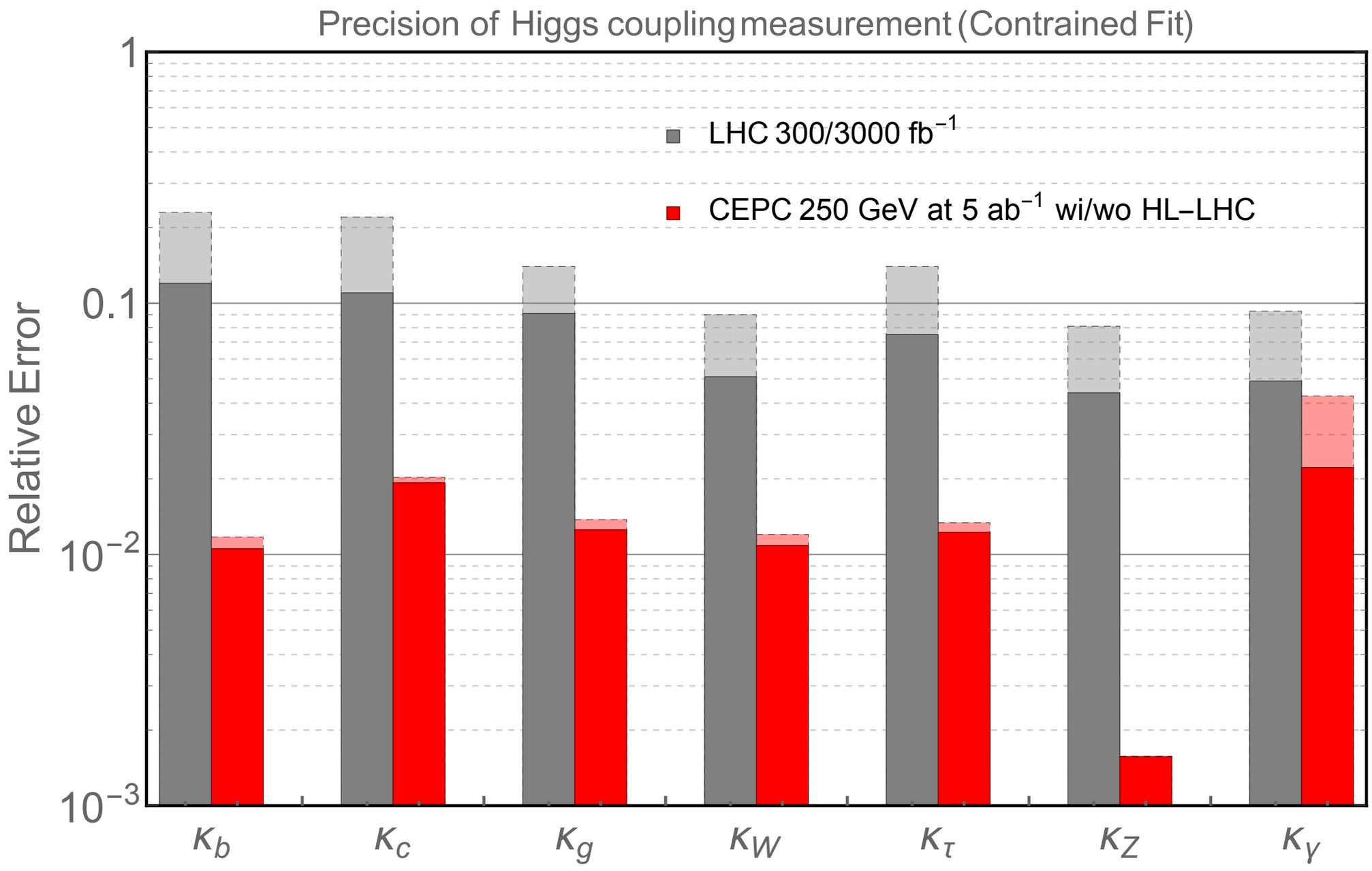


$$m^2_{\text{recoil}} \equiv \left(\sqrt{s} - E_{f\bar{f}}\right)^2 - \overrightarrow{p}^2_{f\bar{f}} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$

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

CEPC: a Higgs factory

- The combination of different Z decay modes gives:



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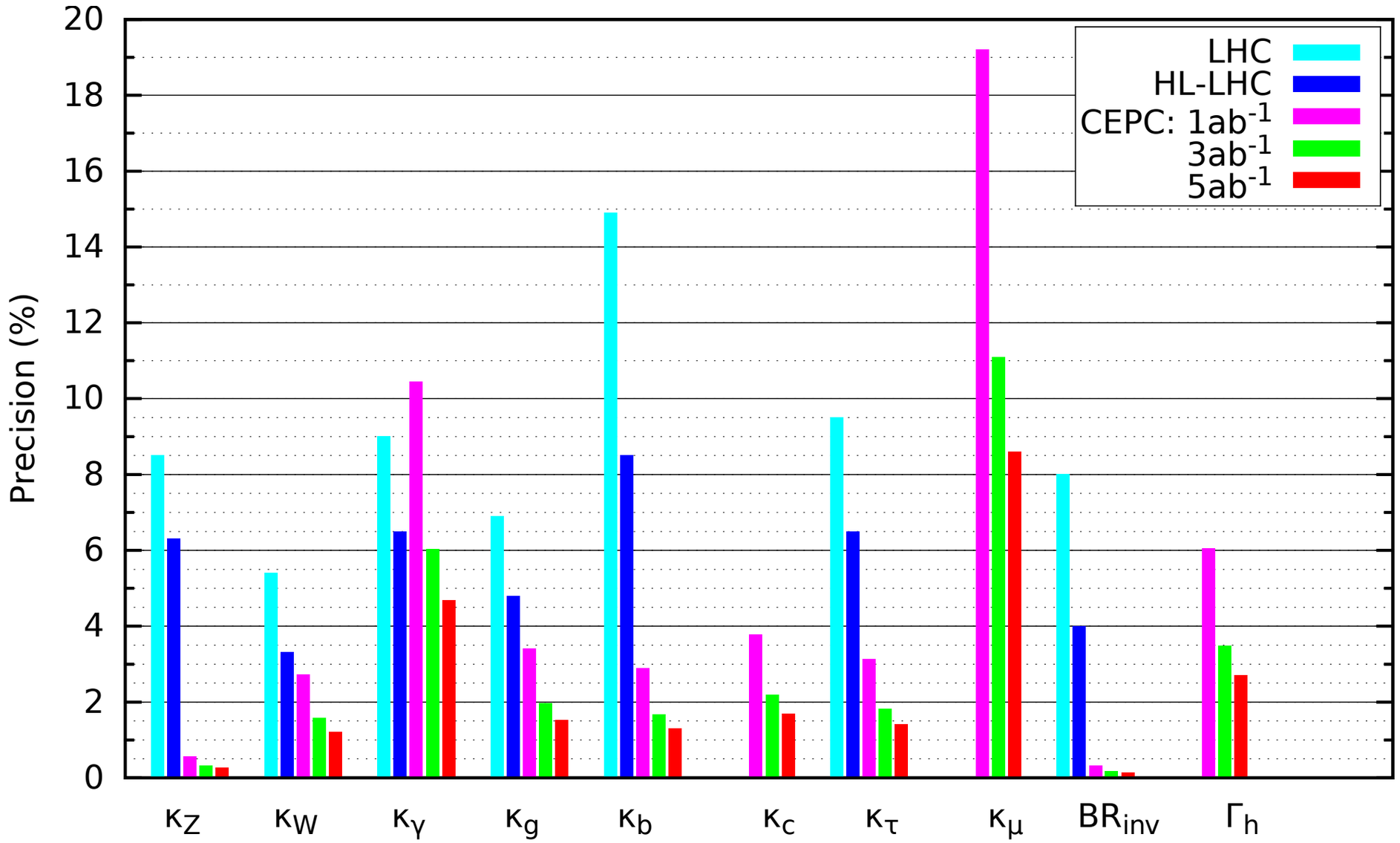
CEPC: a Higgs factory

- The combination of different Z decay modes gives:



What can we do beyond the SM?

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

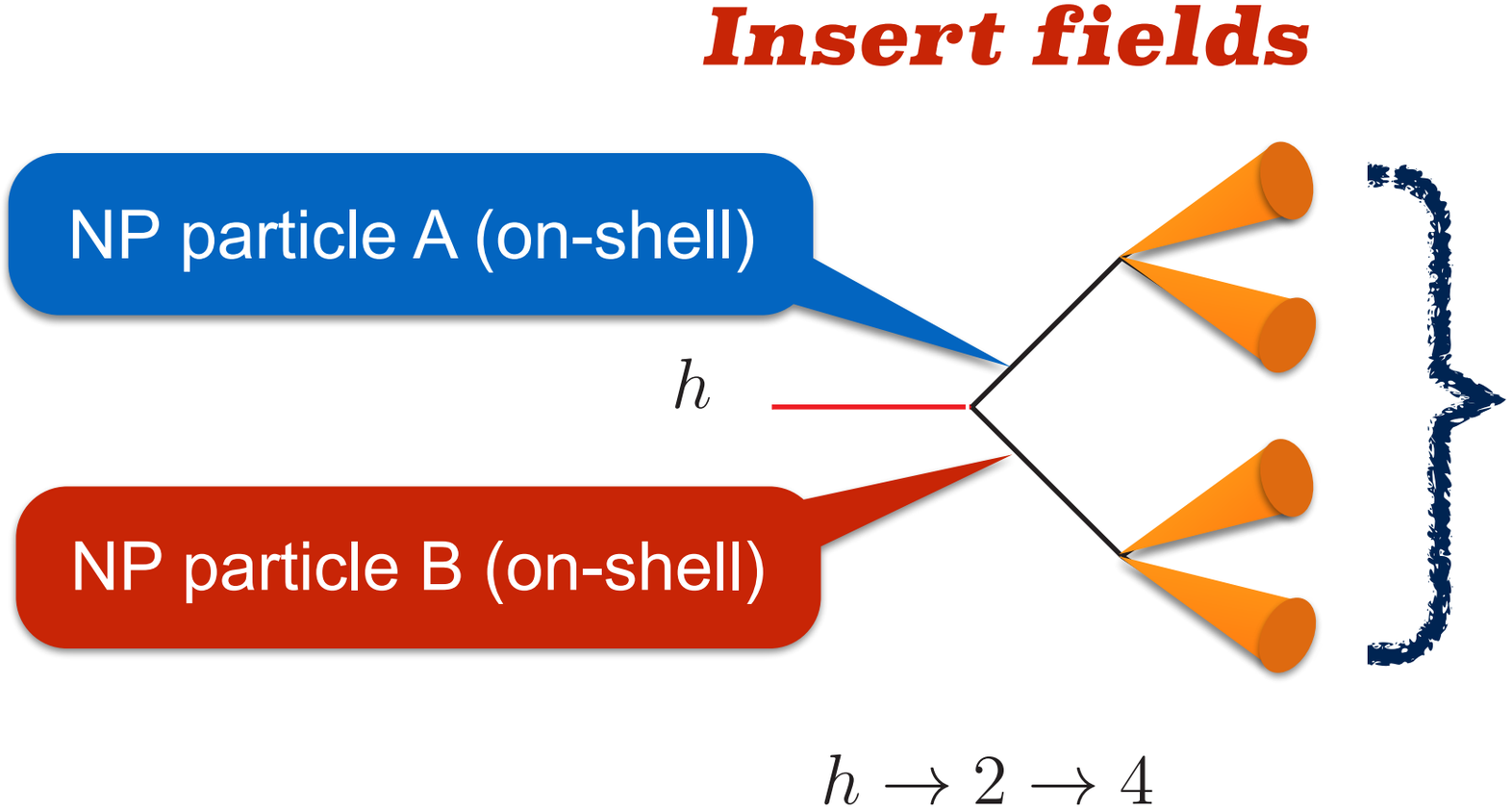
Higgs sector NP at CEPC

- Case 1: usually the LHC and future pp-colliders can do a better job due to the high c.m. energy. CEPC can probably give some constraints or hints with indirect measurements.
- Case 2: exotic Higgs decay signal!

  - SUSY model: MSSM, NMSSM, …
  - Warped Extra Dimension model: light radion;
  - 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

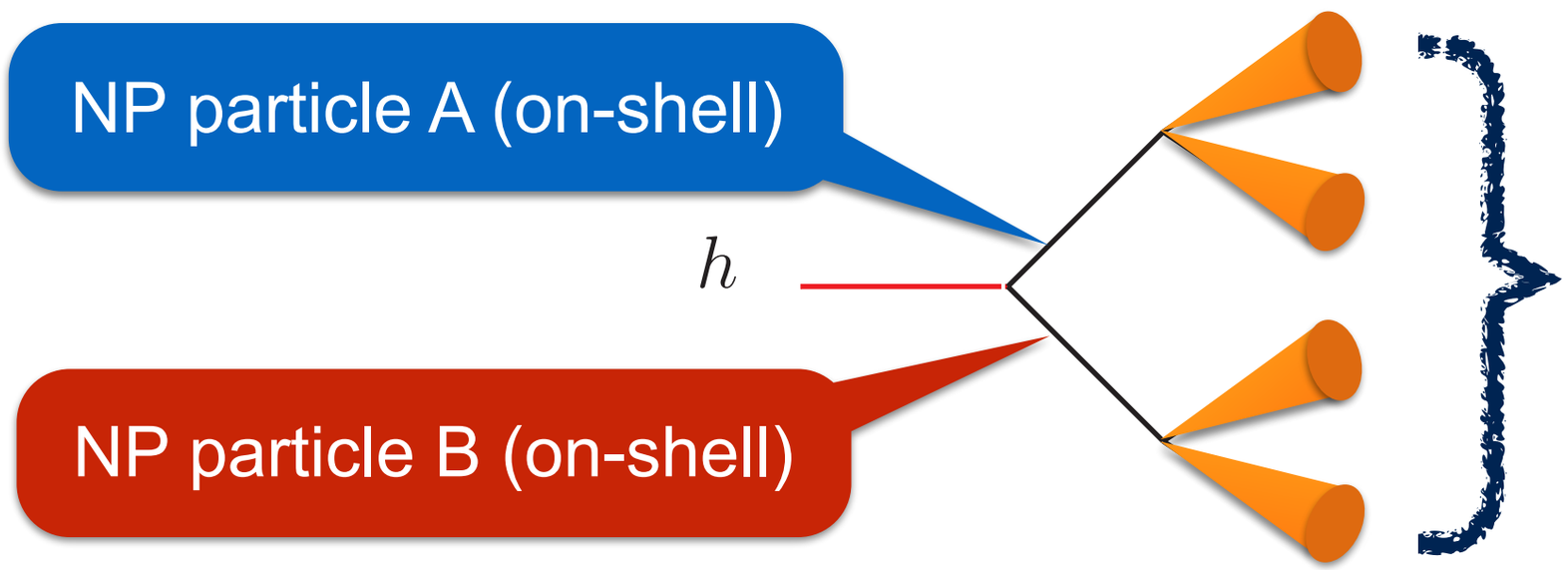
- Phenomenology: investigate the detail of the signals.
- Topology ⇒ Insert fields ⇒ signals at CEPC.
- Example:



Exotic decay of the SM Higgs boson

- Some assumptions:
  - The first decay is two-body decay;
  - In the final state, there are only SM particles or missing energy.

Insert fields



SM particles measured by the detector, dark matter

$$h \to 2 \to 4$$

Exotic decay of the SM Higgs boson

- Some assumptions:
  - The first decay is two-body decay;
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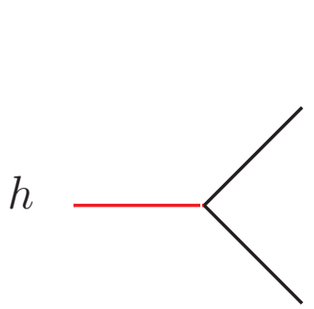
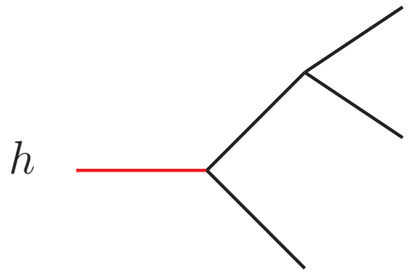
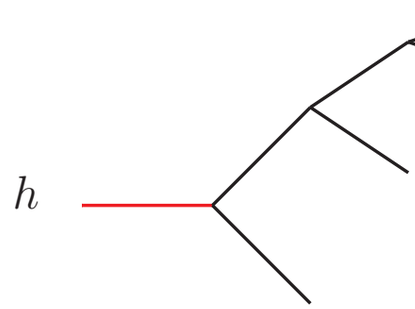


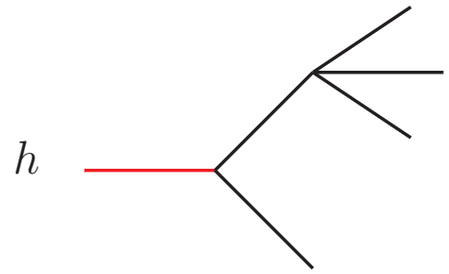
$h \to 2$



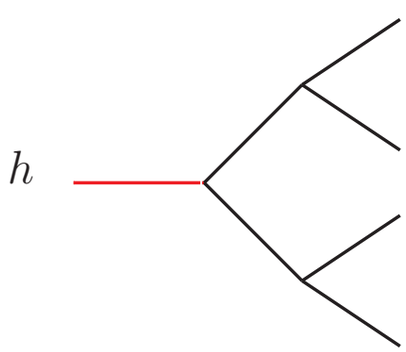
$h \to 2 \to 3$



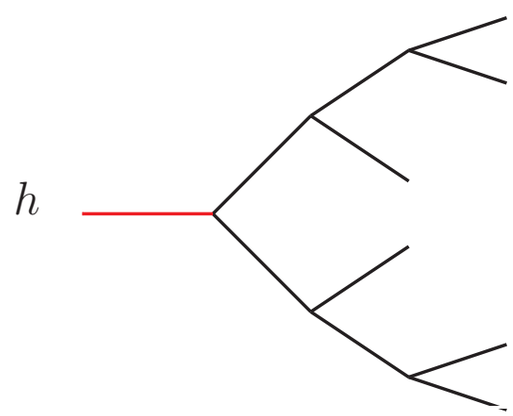
$h \to 2 \to 3 \to 4$



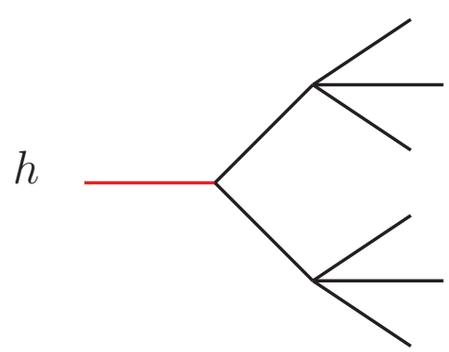
$h \to 2 \to (1+3)$



$h \to 2 \to 4$

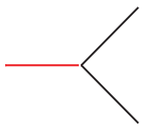


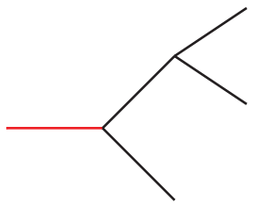
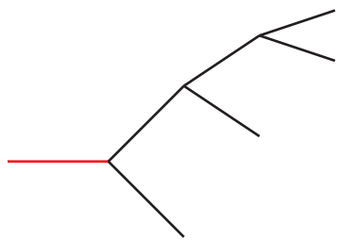
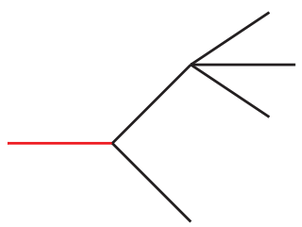
$h \to 2 \to 4 \to 6$

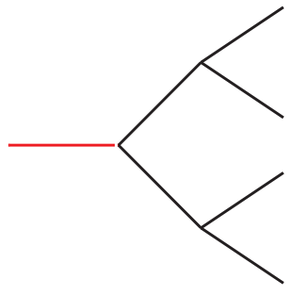
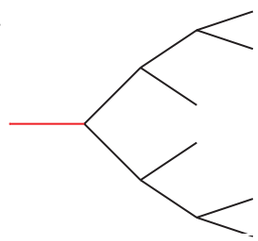
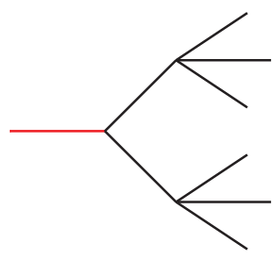


$h \to 2 \to 6$

Exotic decay of the SM Higgs boson



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

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

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

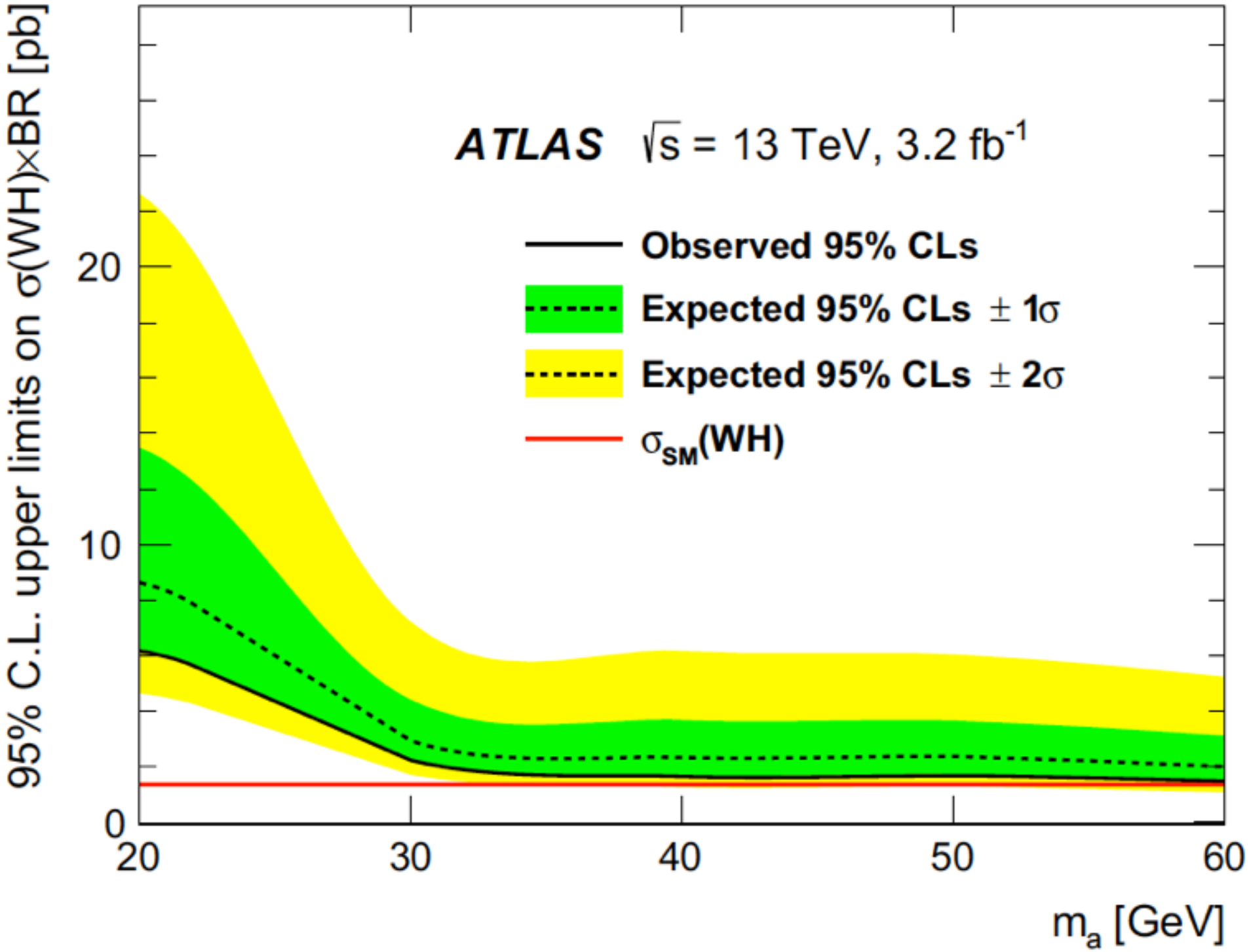
David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

- For some channels the results are bad.

TABLE XIII. As in Table XII, estimates for various processes in $h \to aa$ if a decays only to SM gauge bosons through loops. The central columns show the case where the couplings are generated by initially degenerate $SU(5)$ multiplets; the right columns show the case where the $a \to \gamma\gamma$ rate is enhanced by a factor of 10. *An asterisk denotes that all 14 TeV estimates shown require* 300 fb^{-1} *of data.*

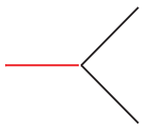
Decay mode $\mathcal{F}_i$	Projected/current 2σ limit on $\text{Br}(\mathcal{F}_i)$ $7+8$ [14] TeV	Production mode	$\text{Br}(a \to \gamma\gamma) \approx 0.004$		$\text{Br}(a \to \gamma\gamma) \approx 0.04$		Comments
			$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ $7+8$ [14] TeV	$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ $7+8$ [14] TeV	
$jjjj$	> 1 [0.1*]	W	0.99	> 1 [0.1*]	0.92	> 1 [0.1*]	Theory study [220,269], Sec. VII

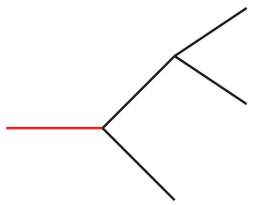
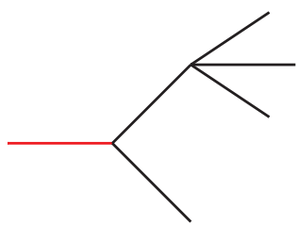
Exotic decay of the SM Higgs boson

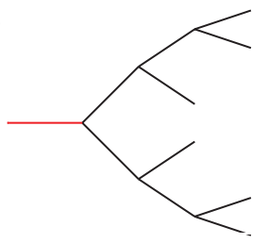


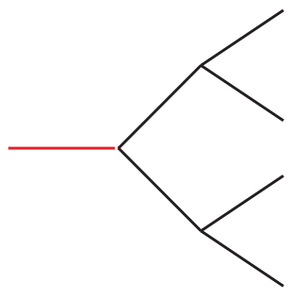
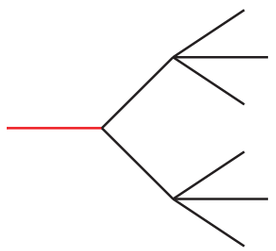
ATLAS Collaboration, EPJC 76, 605 (2016)

Exotic decay of the SM Higgs boson



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



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

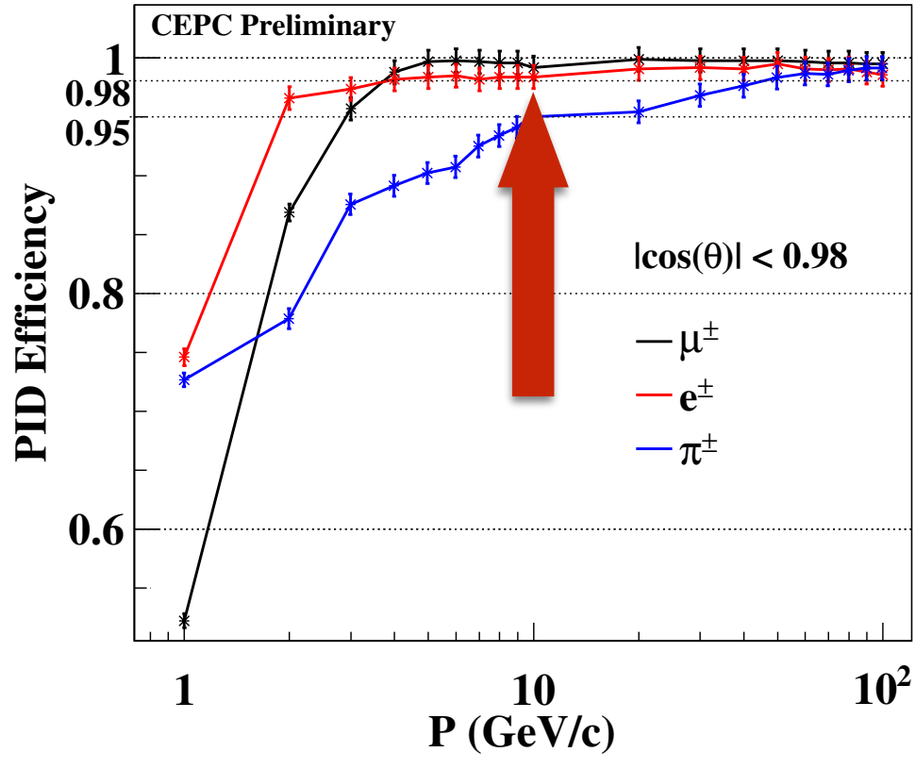
Exotic decay of the SM Higgs boson

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

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

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

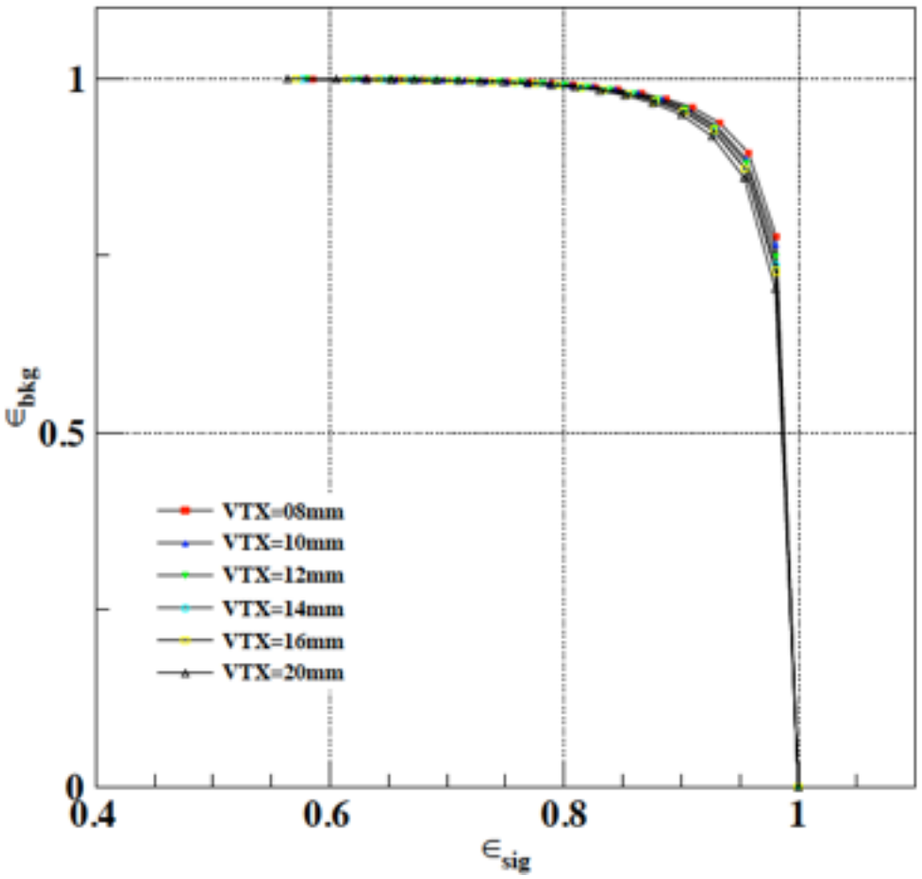
$$\Delta\left(\frac{1}{p_{\mathrm{T},\ell}}\right) = 2\times10^{-5} \oplus \frac{10^{-3}}{p_{\mathrm{T},\ell}\sin\theta_\ell}$$

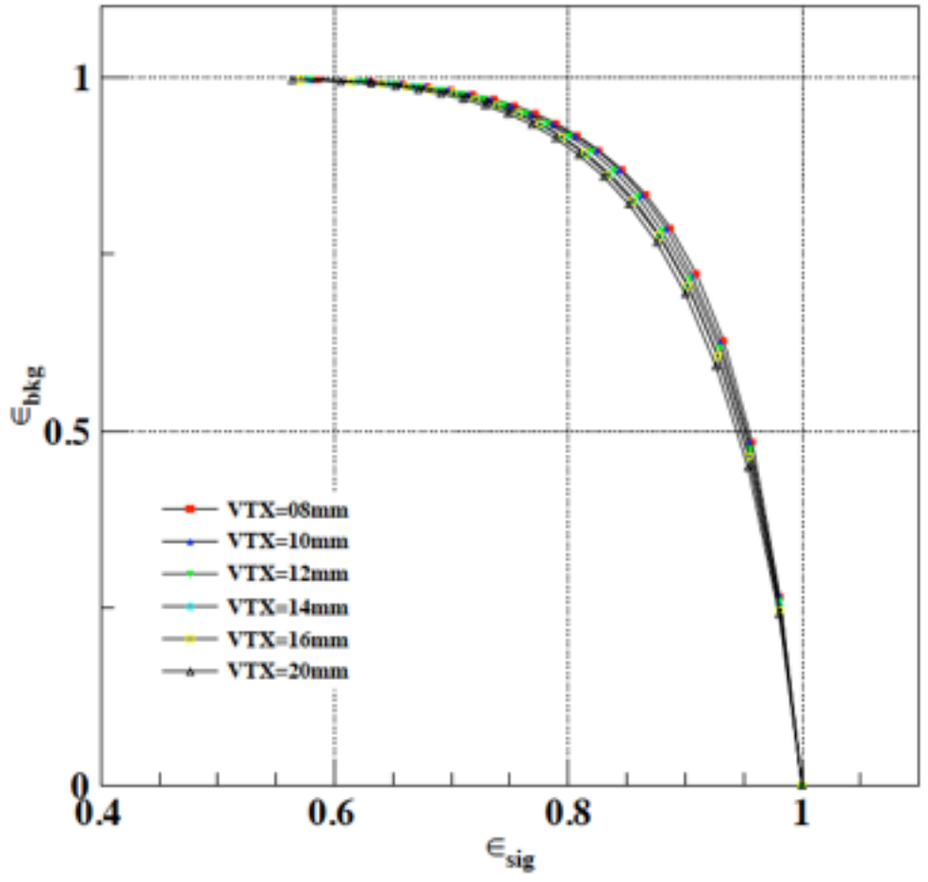


CEPC-SPPC preCDR, Volume I-Physics & Detector, The CEPC-SPPC Study Group

Exotic decay of the SM Higgs boson

- 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

- Phenomenology:

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

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

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

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

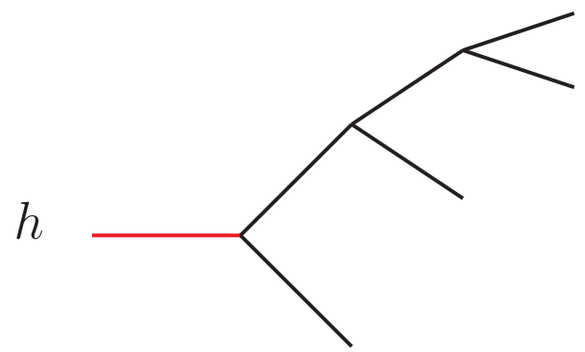
  - MadGraph5_aMC@NLO.

  - 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!)

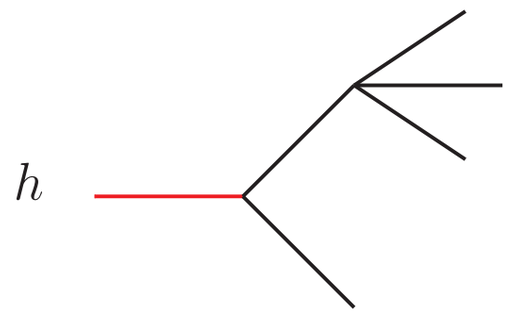
  - Additional cut to suppress the ISR effect: $E_{vis} > 225\mathrm{GeV}.$

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

- The topology

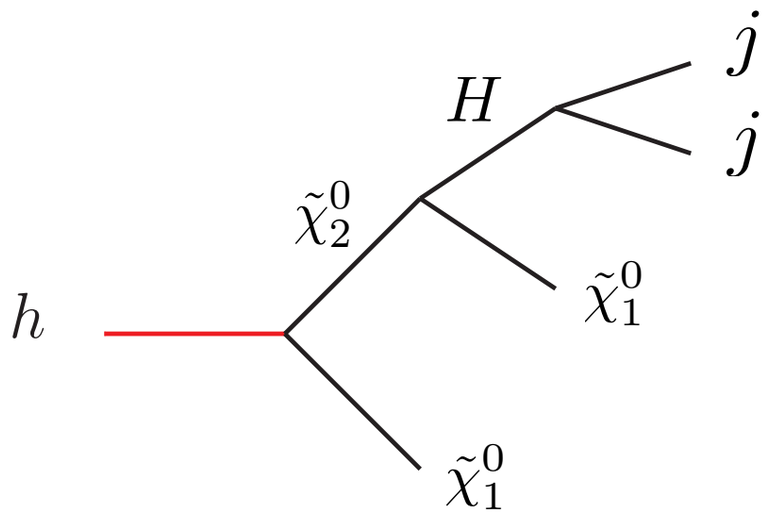


$h \to 2 \to 3 \to 4$

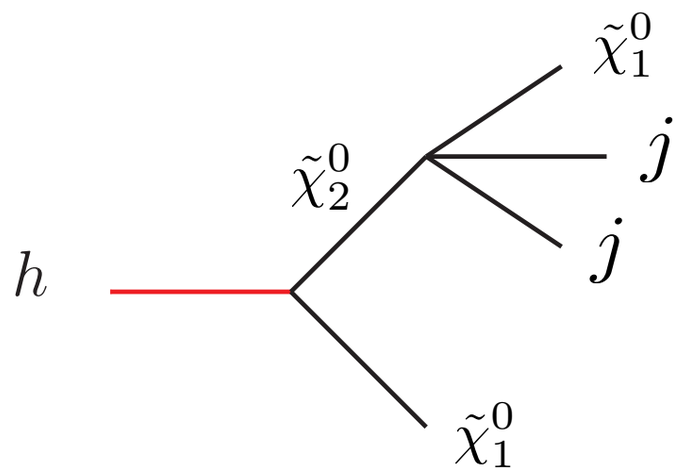


$h \to 2 \to (1+3)$

- Benchmark model: supersymmetry.



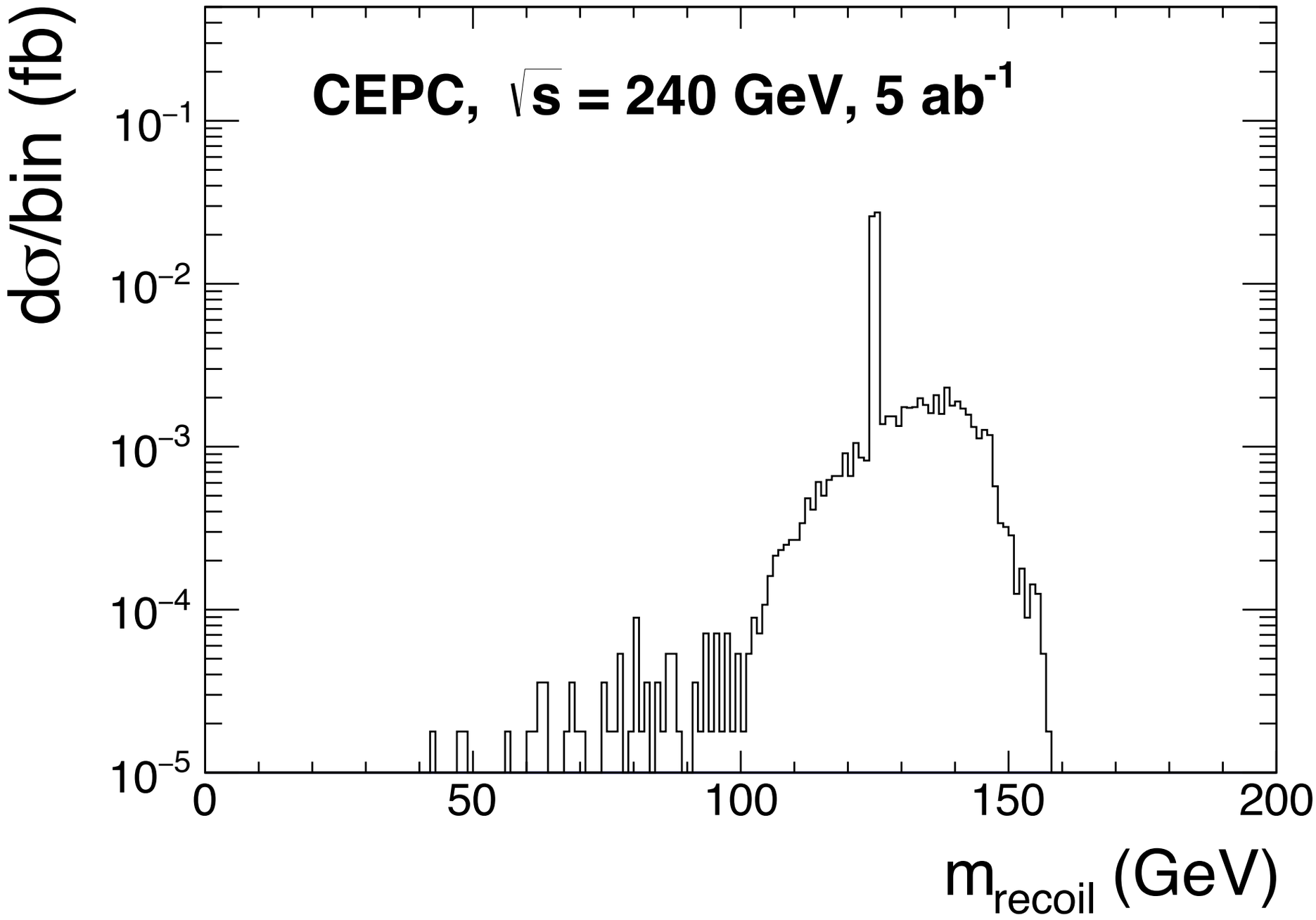
$h \to 2 \to 3 \to 4$



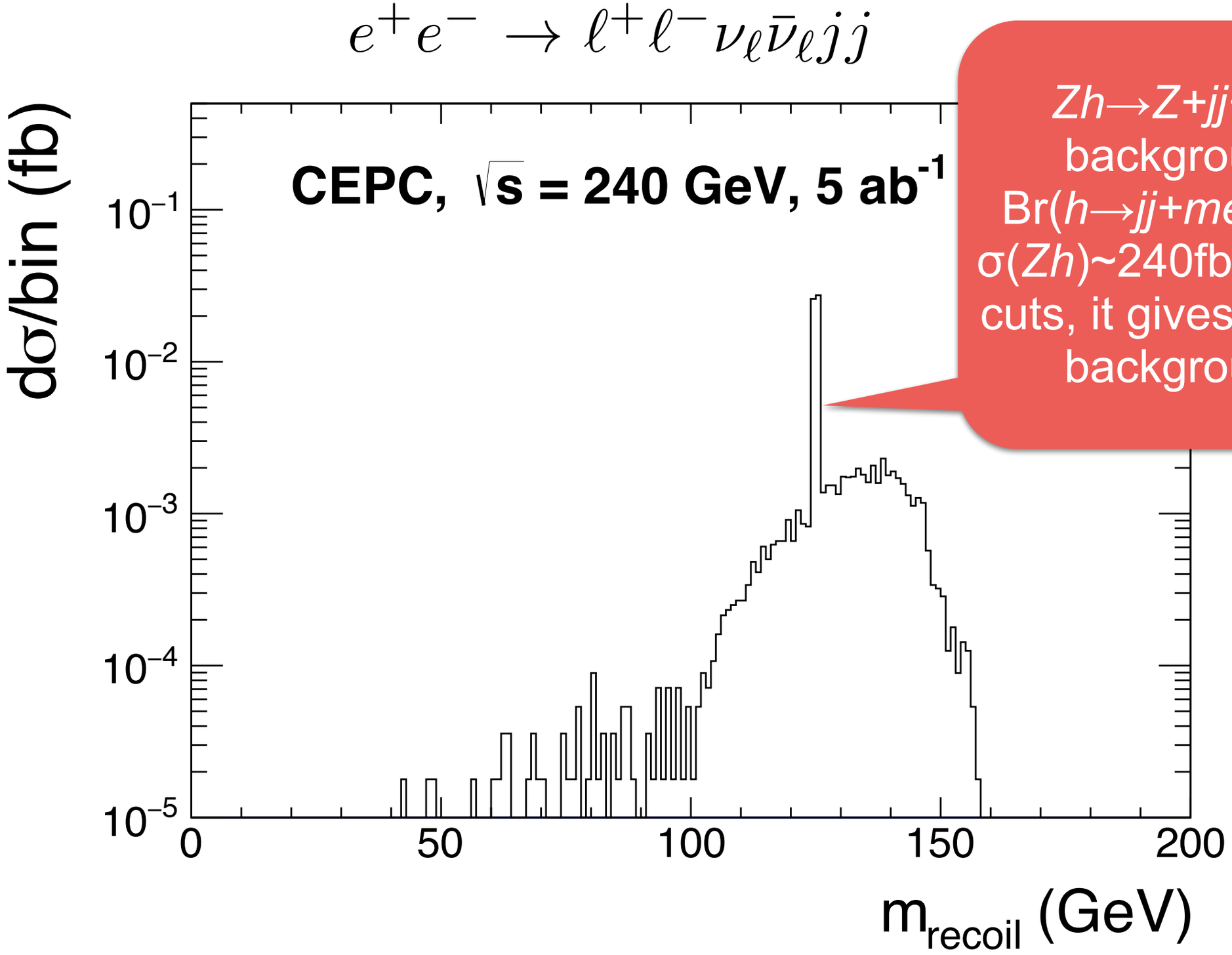
$h \to 2 \to (1+3)$

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

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



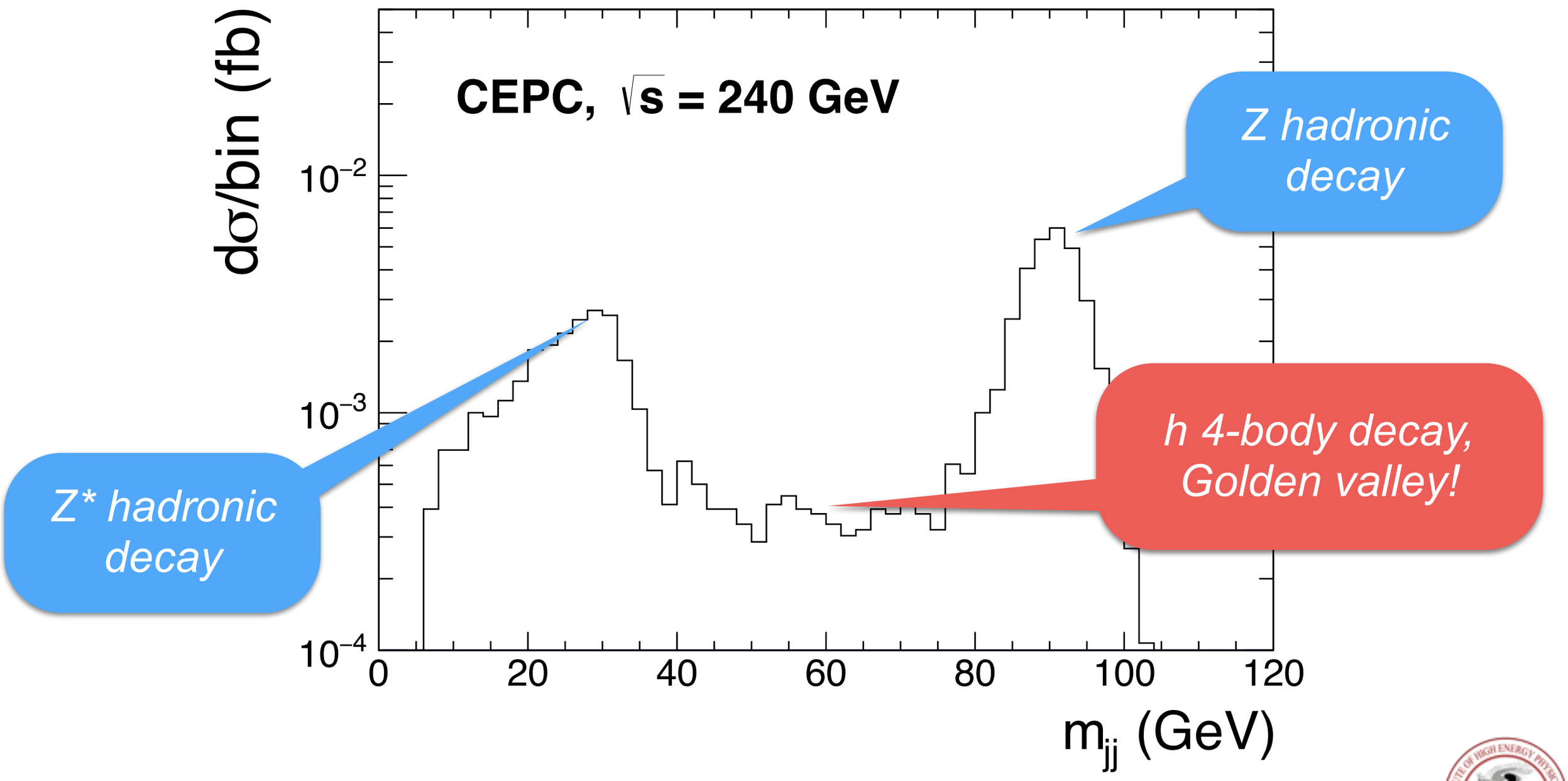
Exotic decay of the SM Higgs boson (*jj*+*met*)



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*)

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



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

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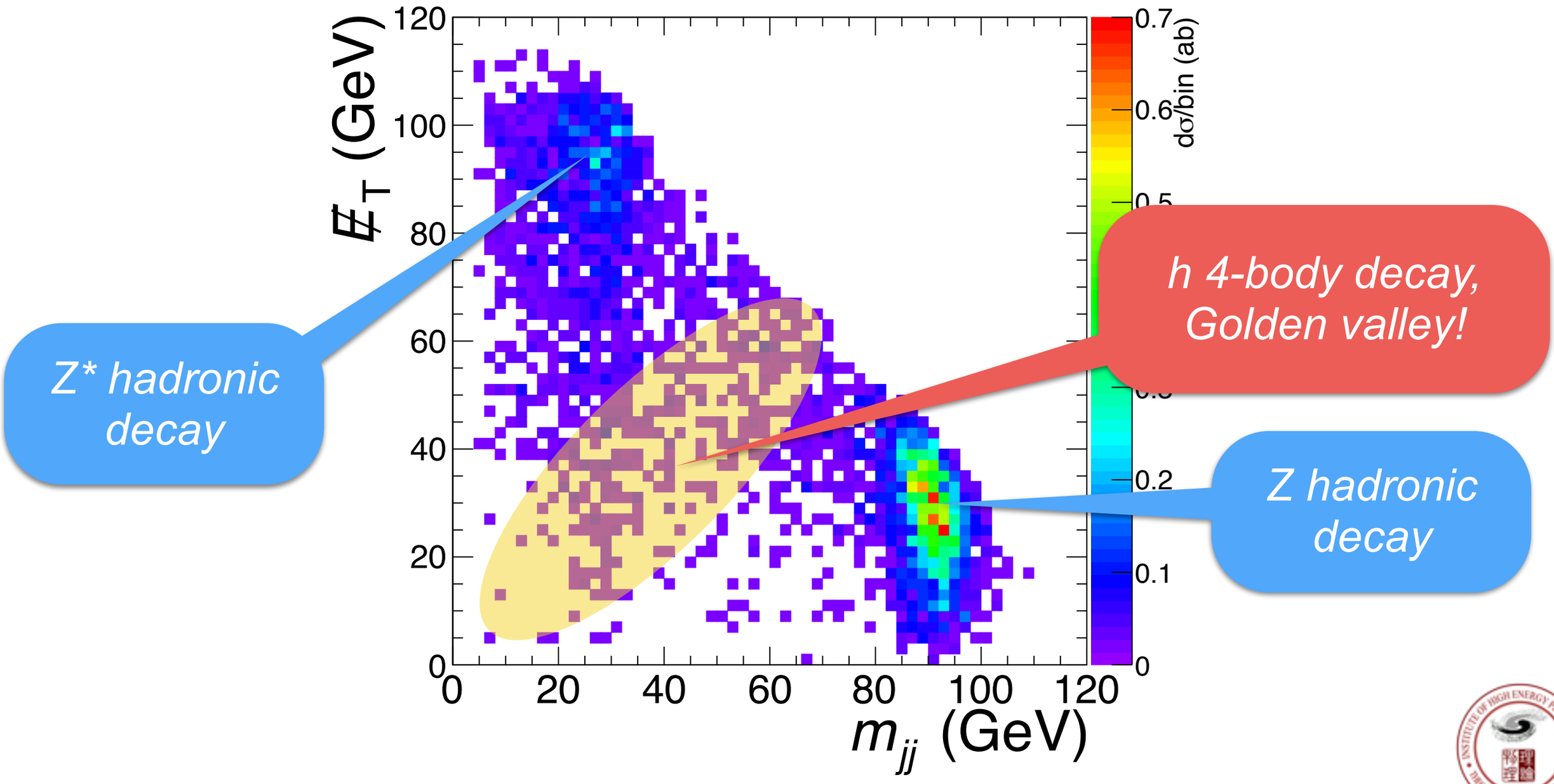
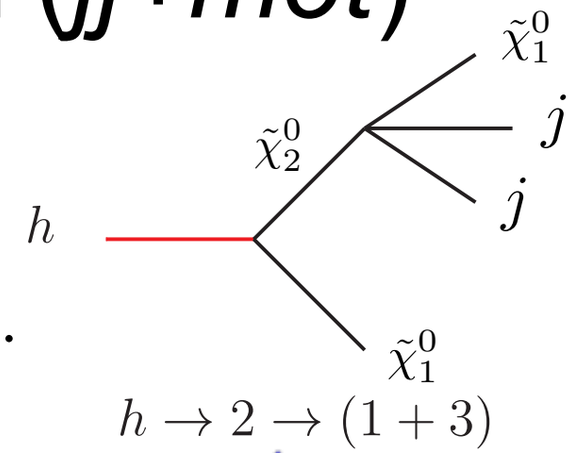


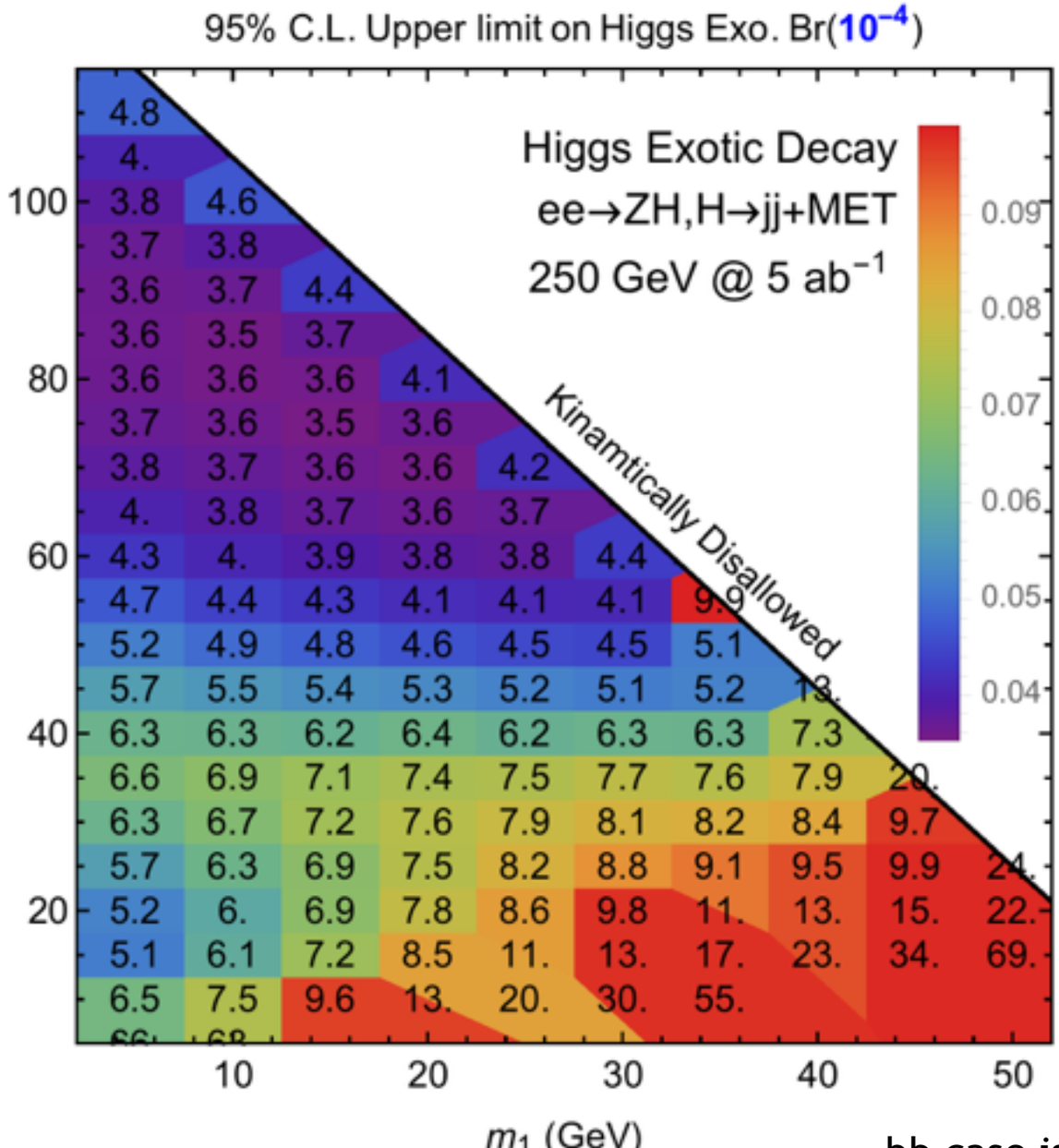
Exotic decay of the SM Higgs boson (*jj+met*)

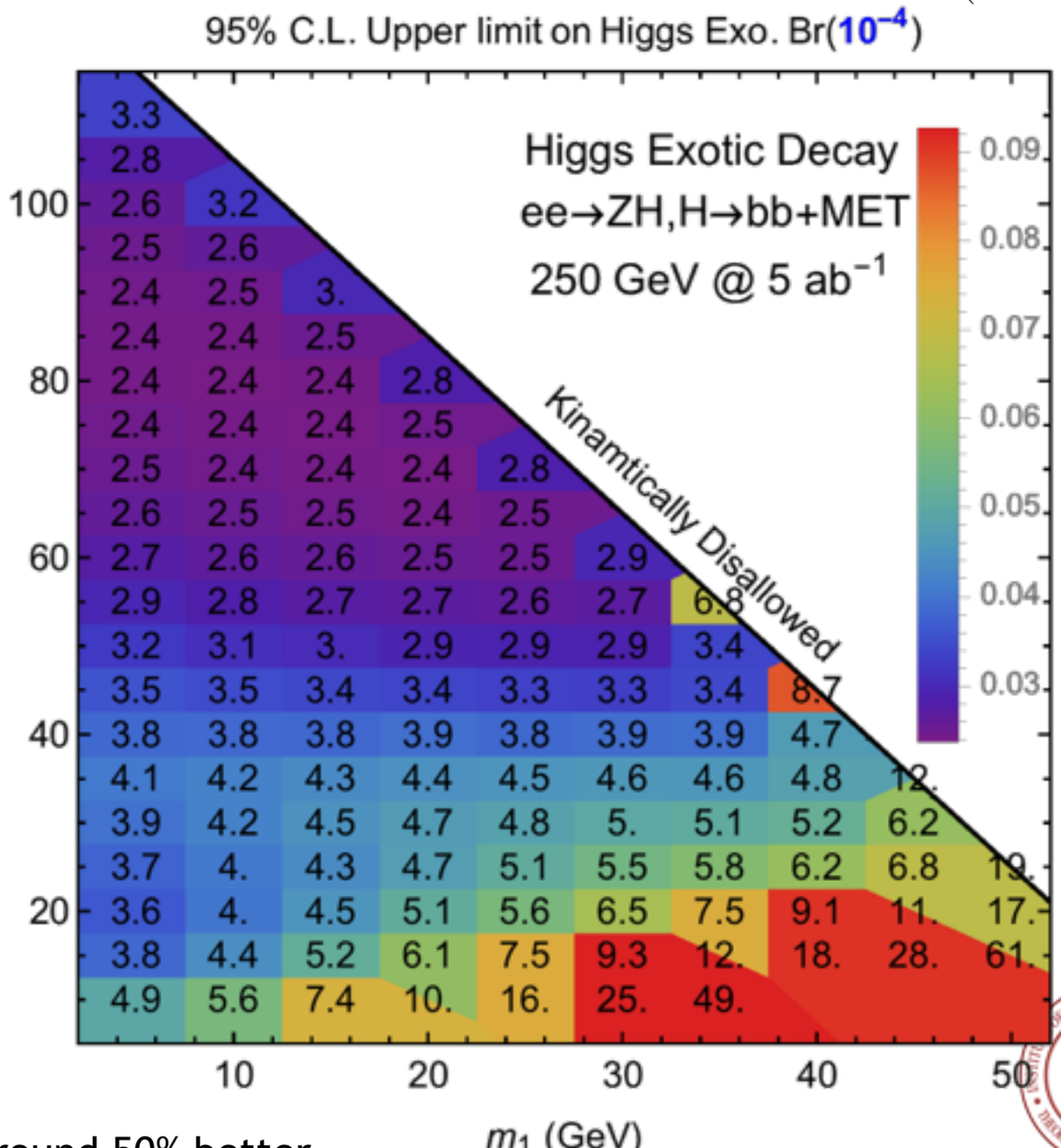
- Nearly 0 bkgd

$$N_{Zh}\mathrm{Br}(Z\to\ell\ell)\mathrm{Br}(h\to X)\sim\mathcal{O}(10),\ \mathrm{Br}(h\to X)\sim 10^{-4}.$$



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





bb case is around 50% better.

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

- Nearly 0 bkgd

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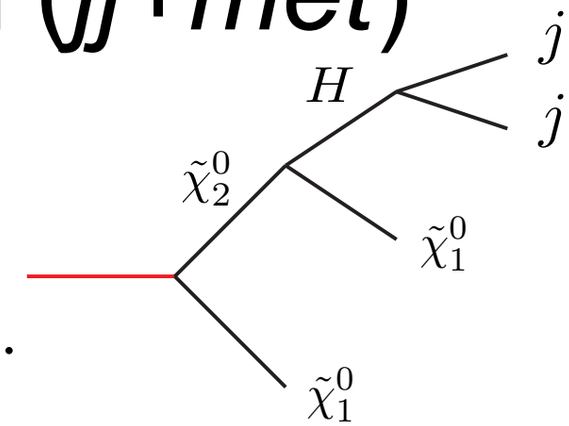
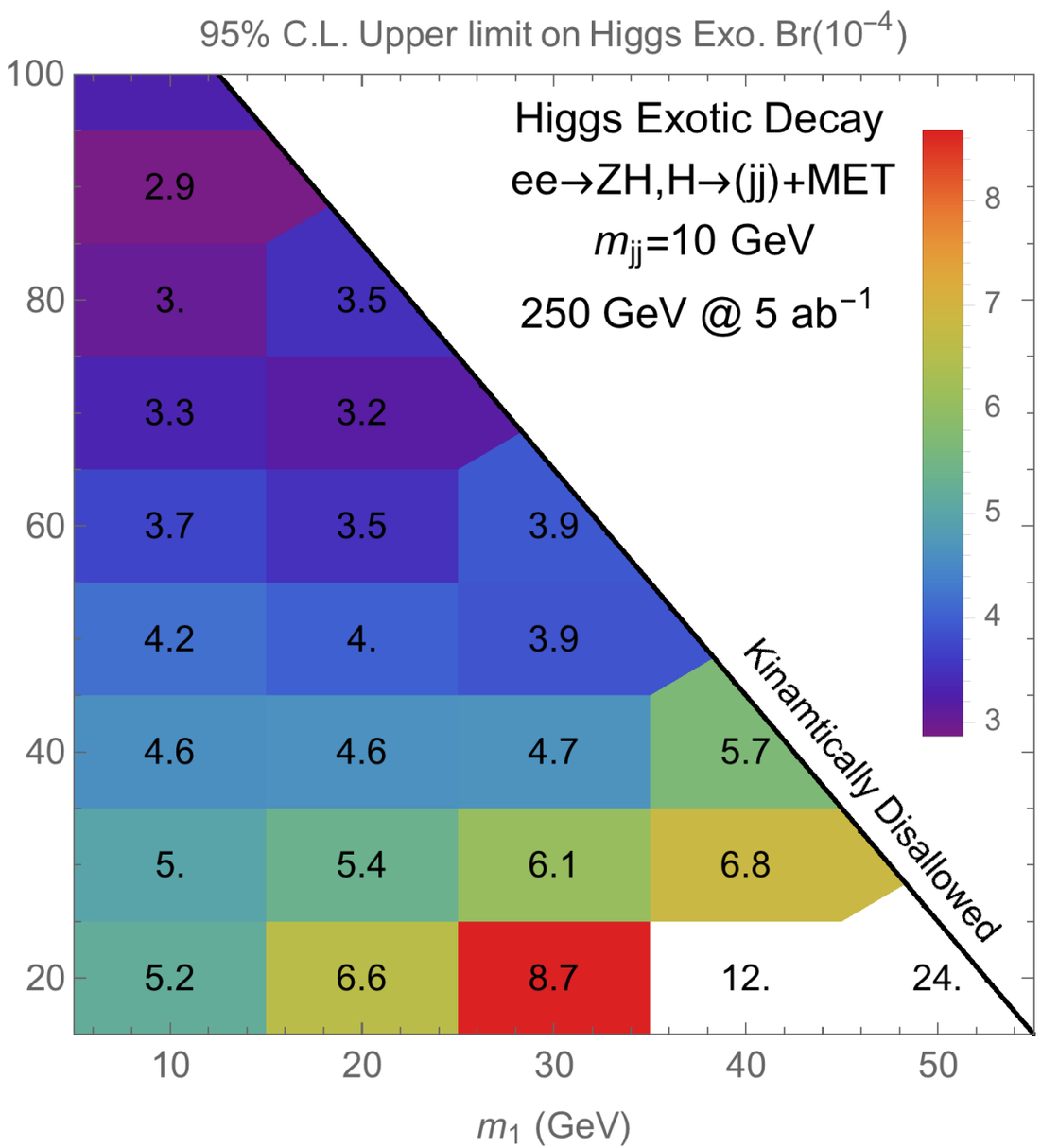
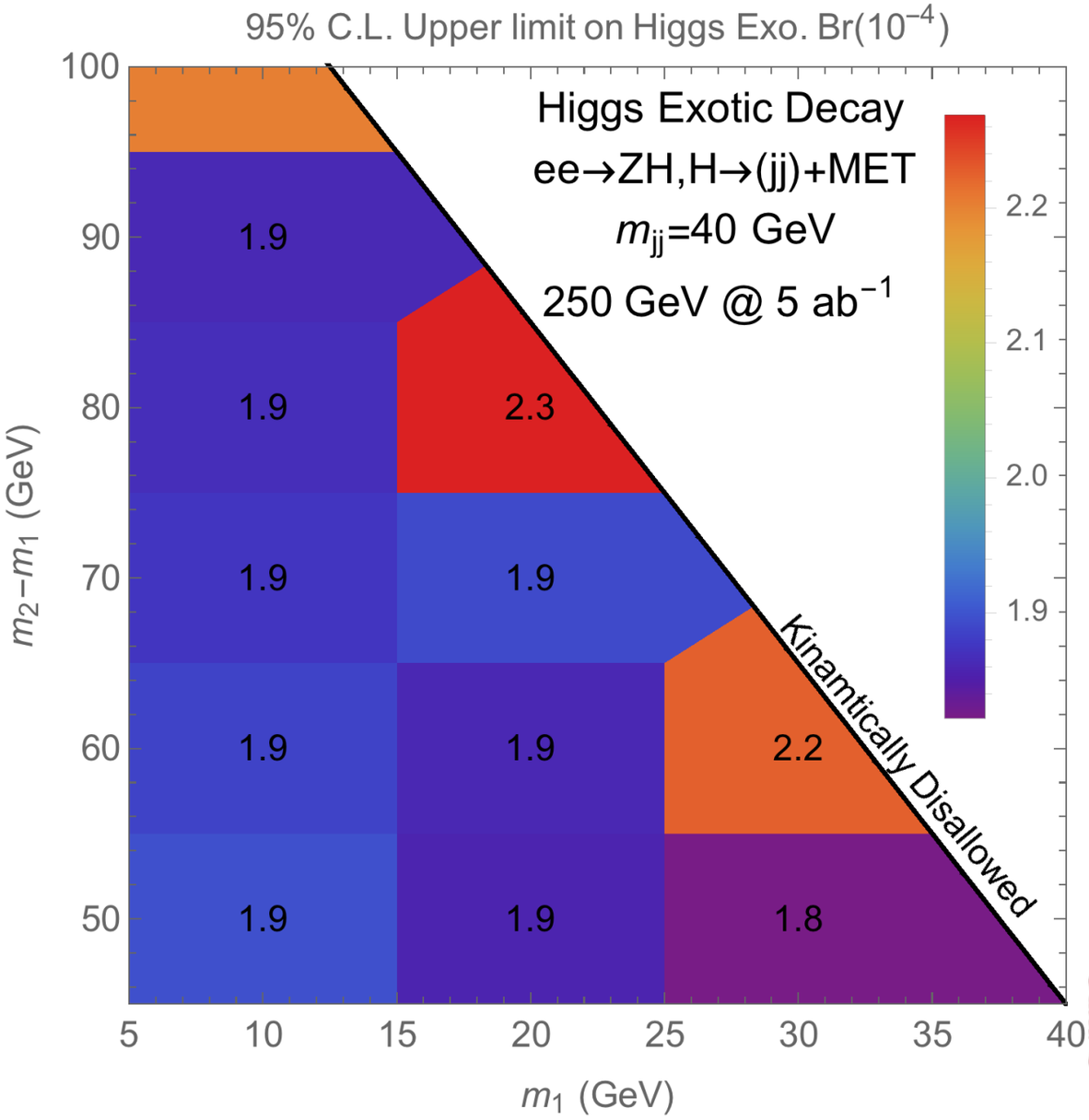


$h \to 2 \to 3 \to 4$





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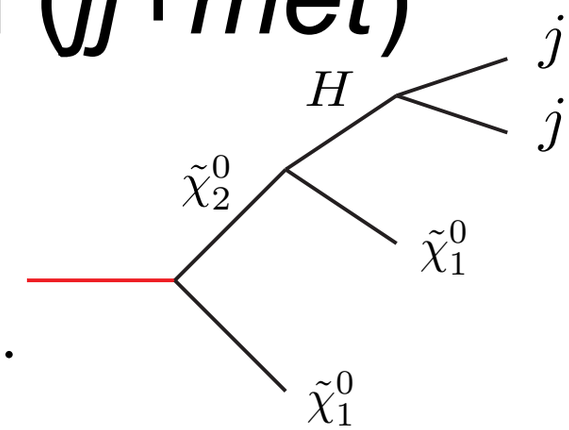
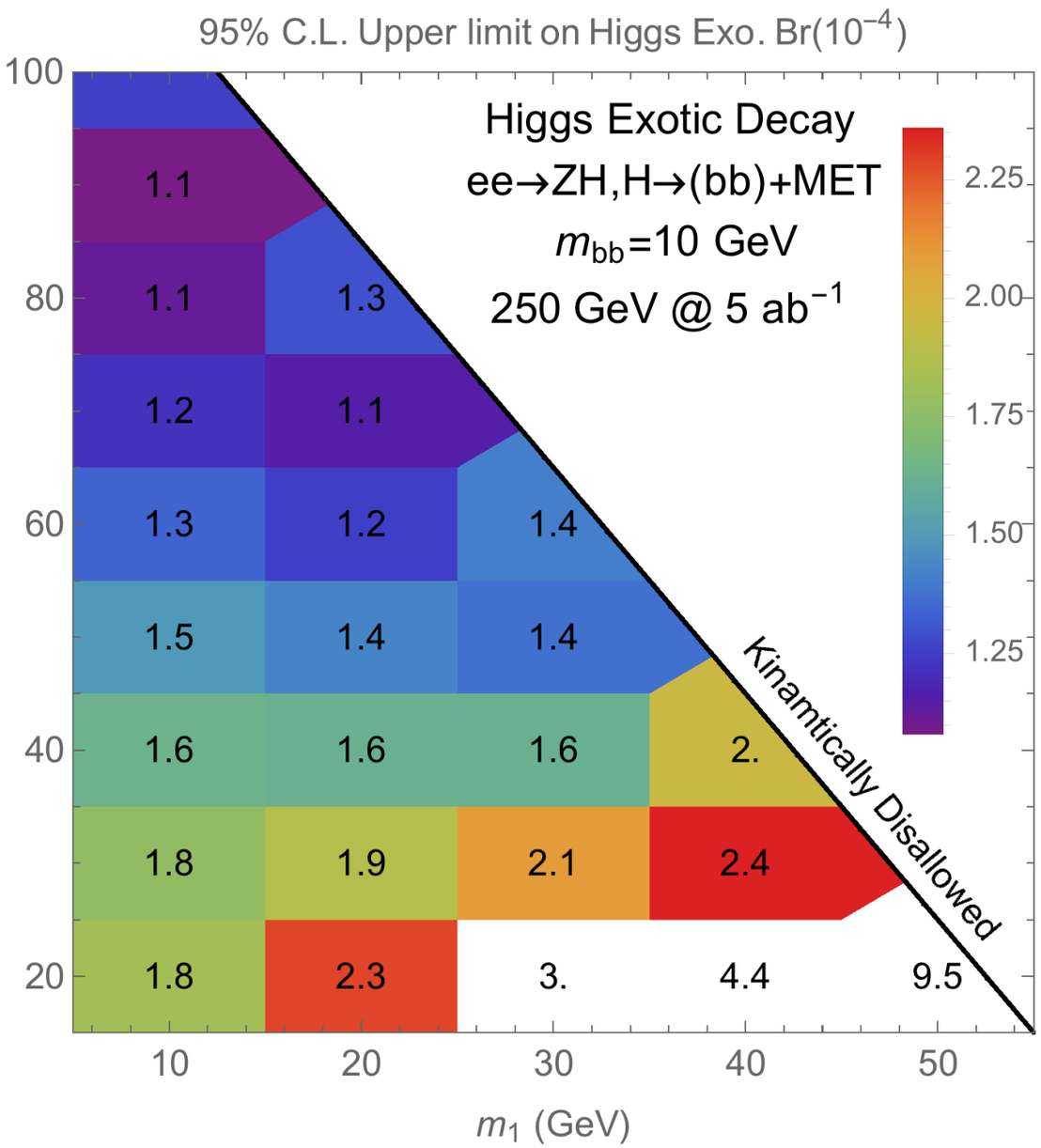
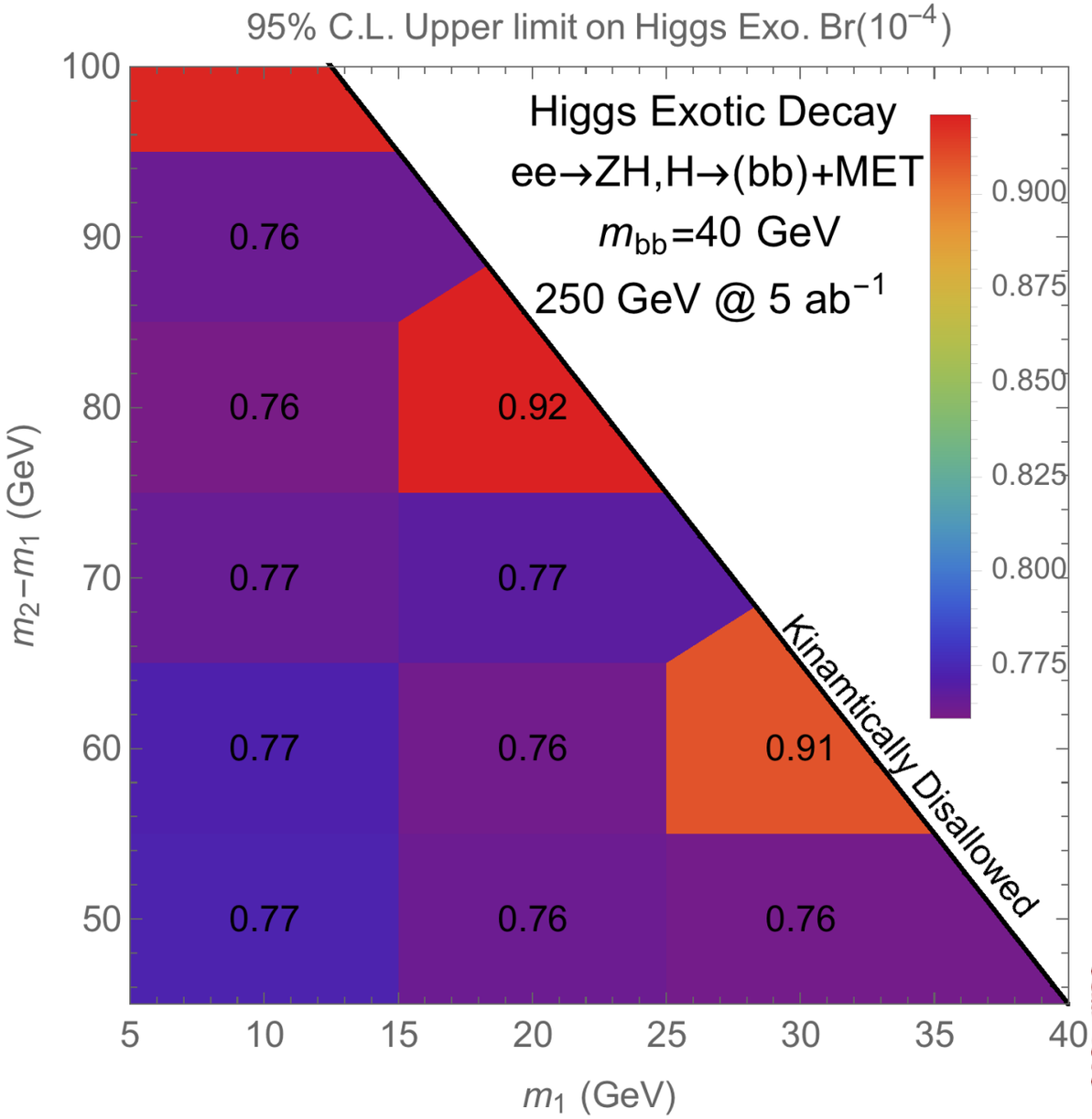


$h \to 2 \to 3 \to 4$





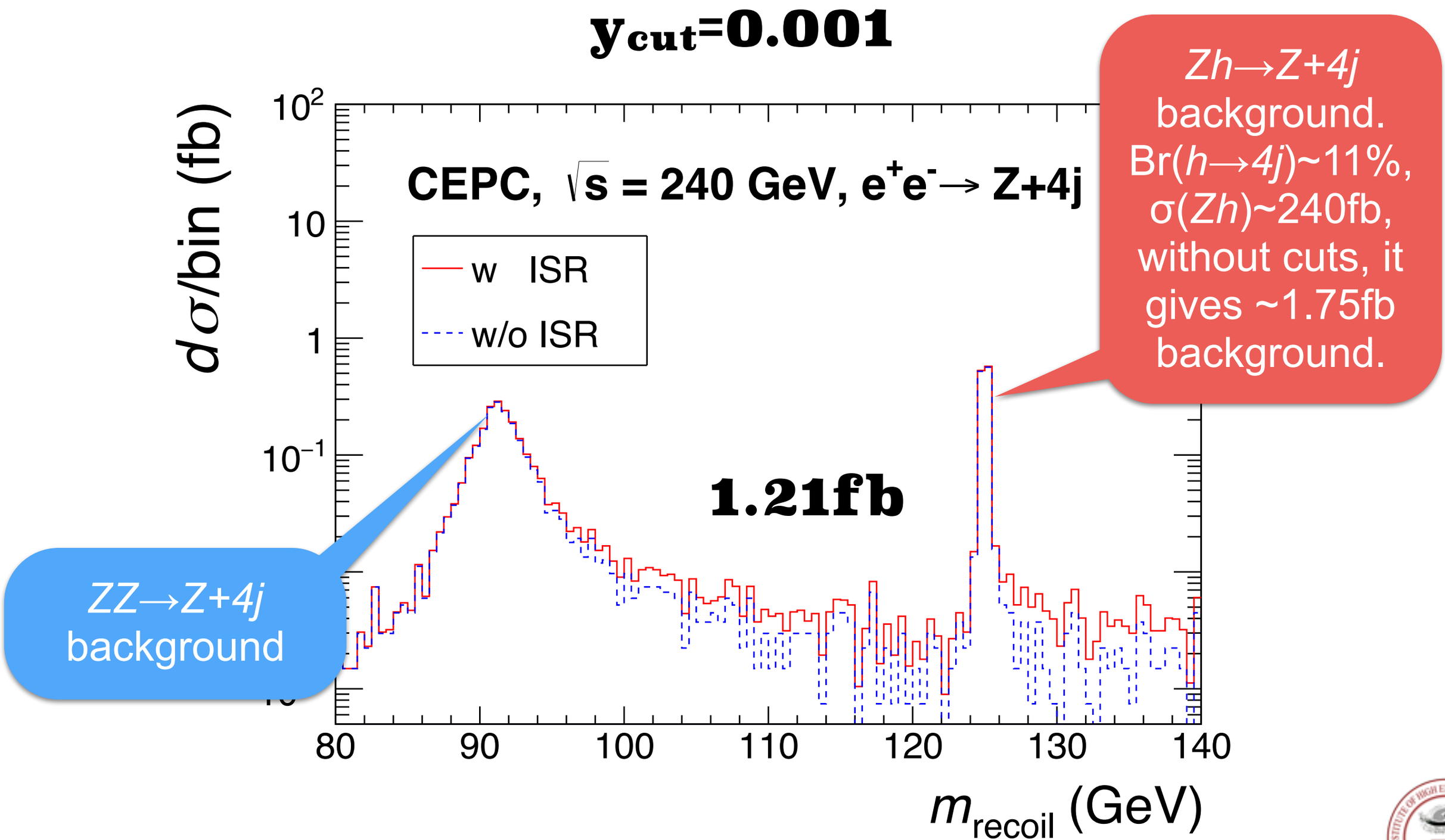
Exotic decay of the SM Higgs boson

- 4-jet channel:
  - $h \to 2 \to 4$
  - Insert light (pseudo)scalar (a, s) or vector boson (Z').
  - $h \to ss(aa) \to (jj)(jj)$, $h \to Z'Z' \to (jj)(jj)$.
  - Effective Lagrangian:

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

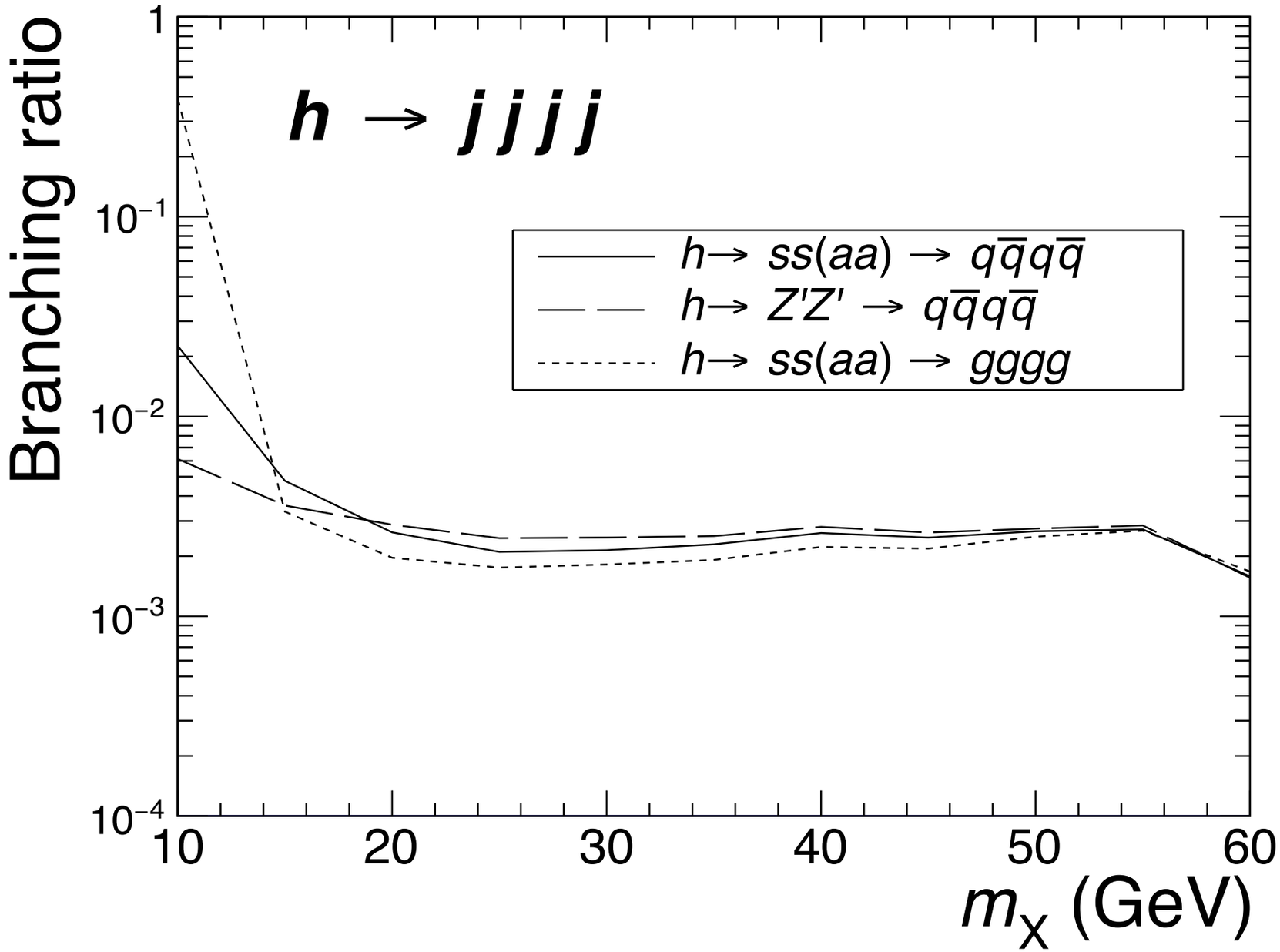
Spin correlations are kept for model distinguishing.

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



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

- Additional cut: $\delta m \equiv \min_{\sigma \in A_4} \left| m_{j_{\sigma(1)} j_{\sigma(2)}} - m_{j_{\sigma(3)} j_{\sigma(4)}} \right| < 5\mathrm{GeV}.$



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

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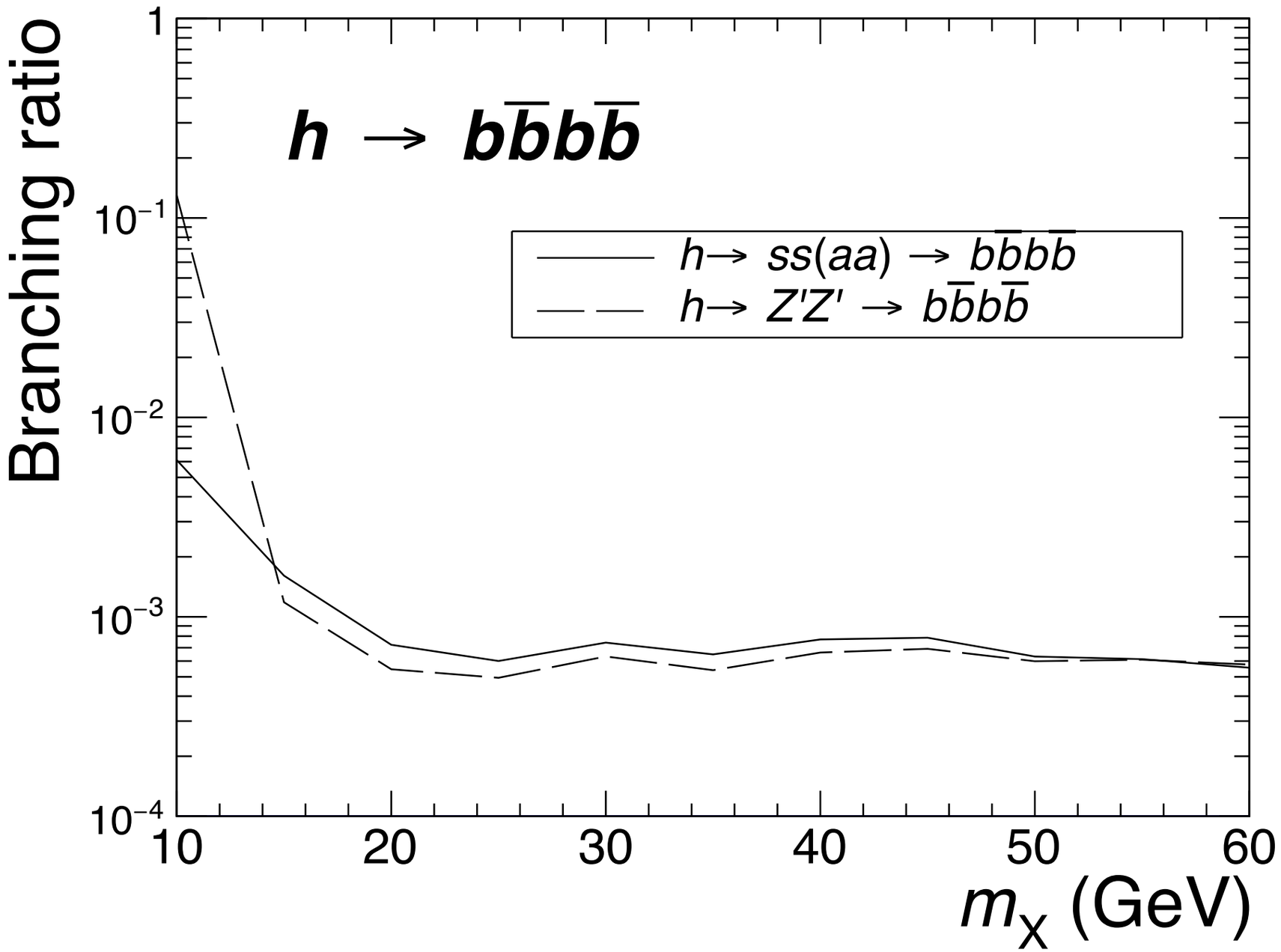

Summary and outlook

- CEPC is a Higgs factory. 1,000,000 Higgs events with $5ab^{-1}$.
- Precisely measurement of the properties of the SM Higgs boson.
- A ideal machine for studying the exotic Higgs decay channels.
- More than an order of magnitude improvement can be achieved without any advanced technology.

Thank you!