



Searching exotic decay channels of the SM Higgs boson at CEPC

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

Why do we need new physics?

- The SM is very VERY successful!

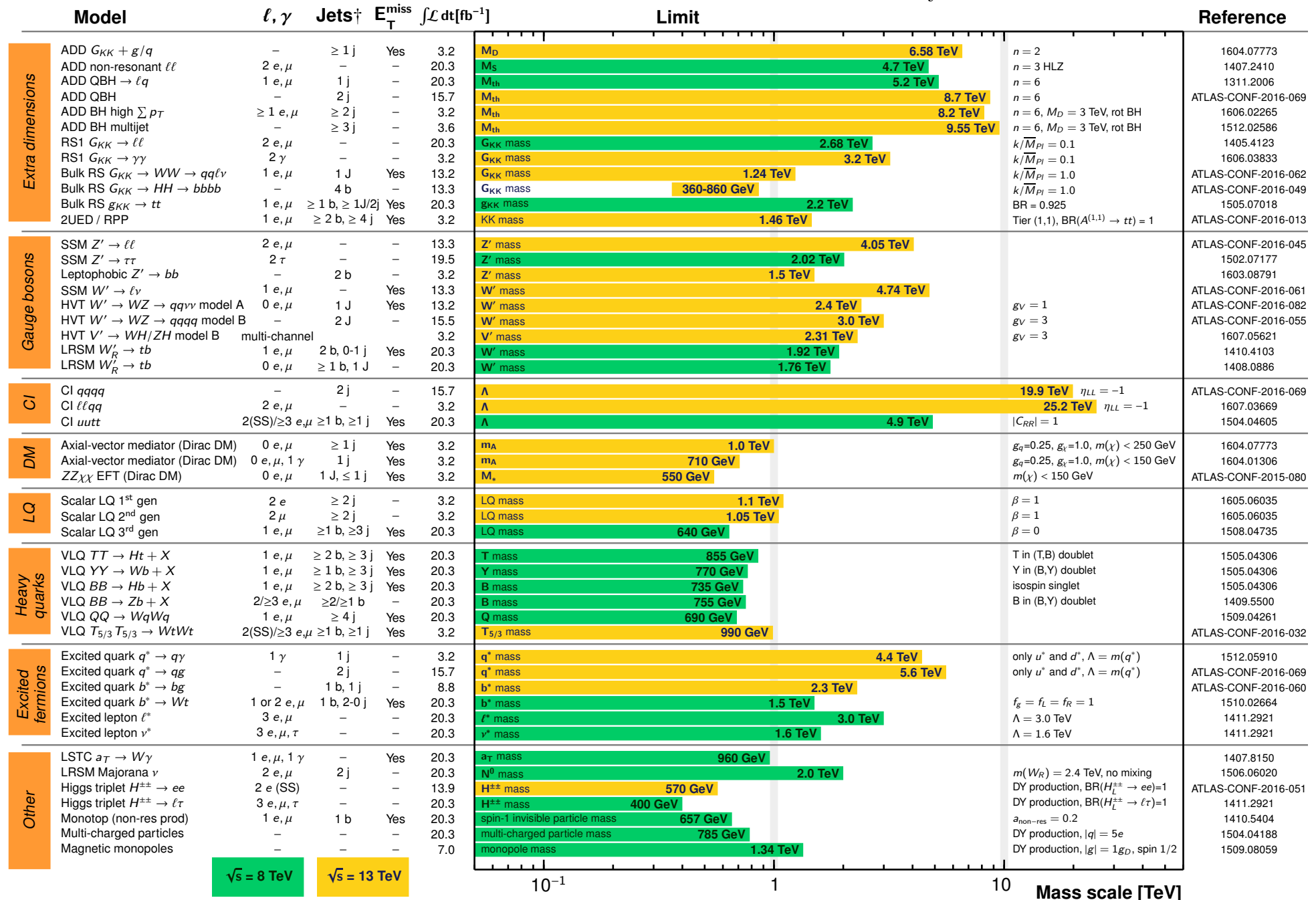
ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$



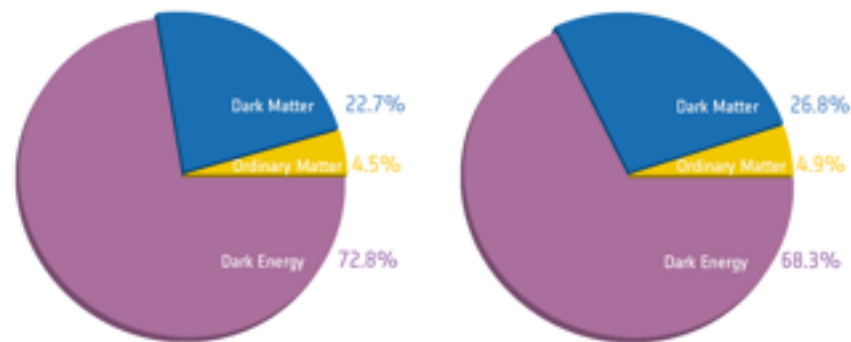
*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).



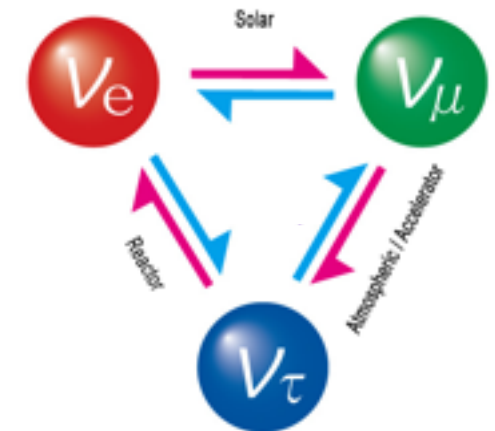
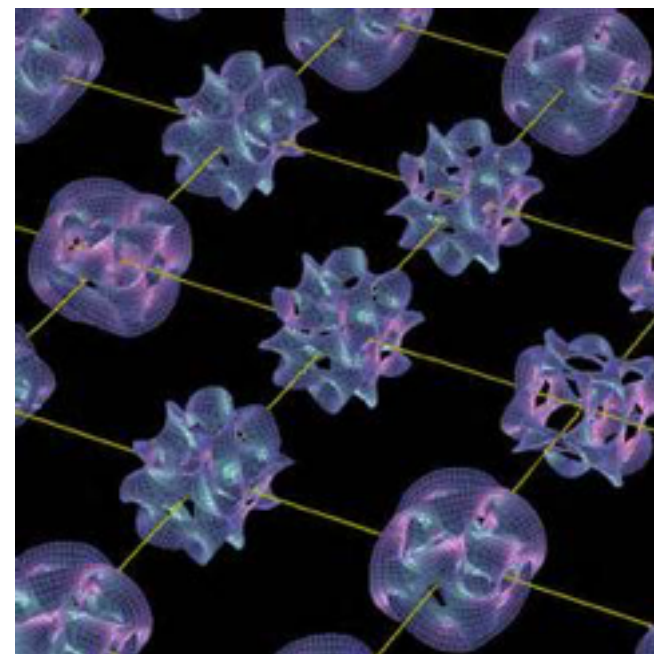
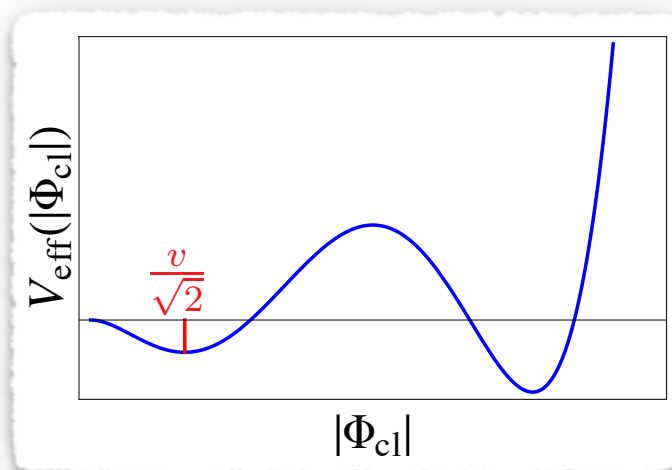
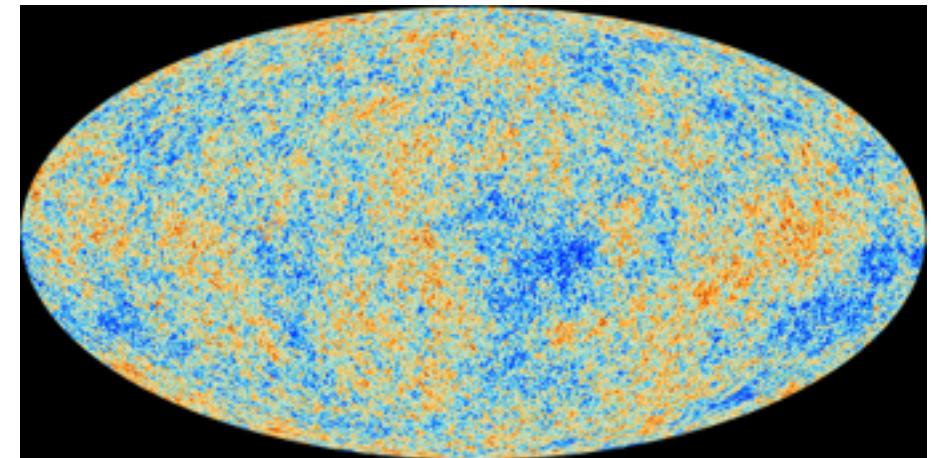
Why do we need new physics?

- The SM is not enough.



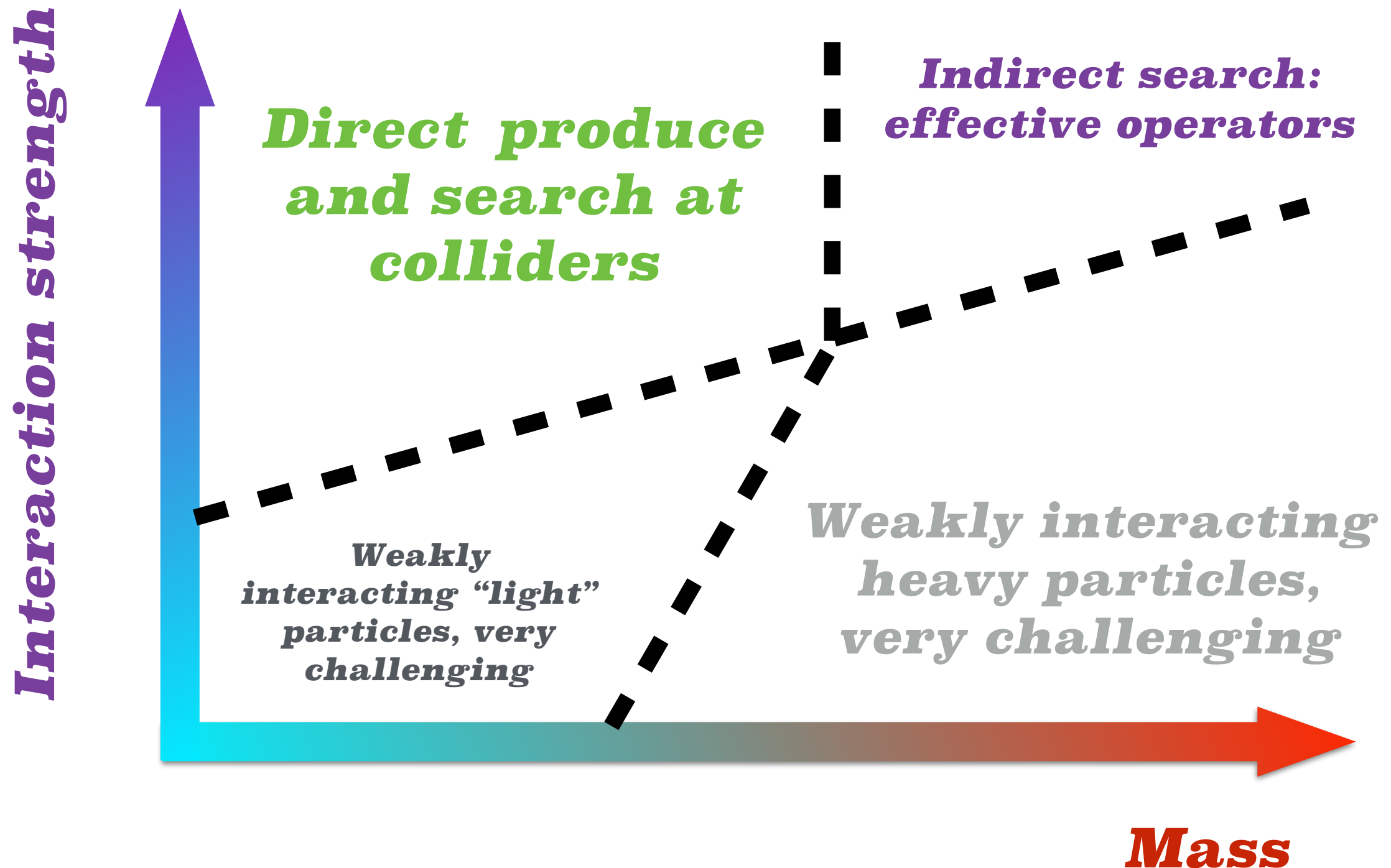
Before Planck

After Planck



Neutrino oscillation between three generations

New physics particles: where are they?

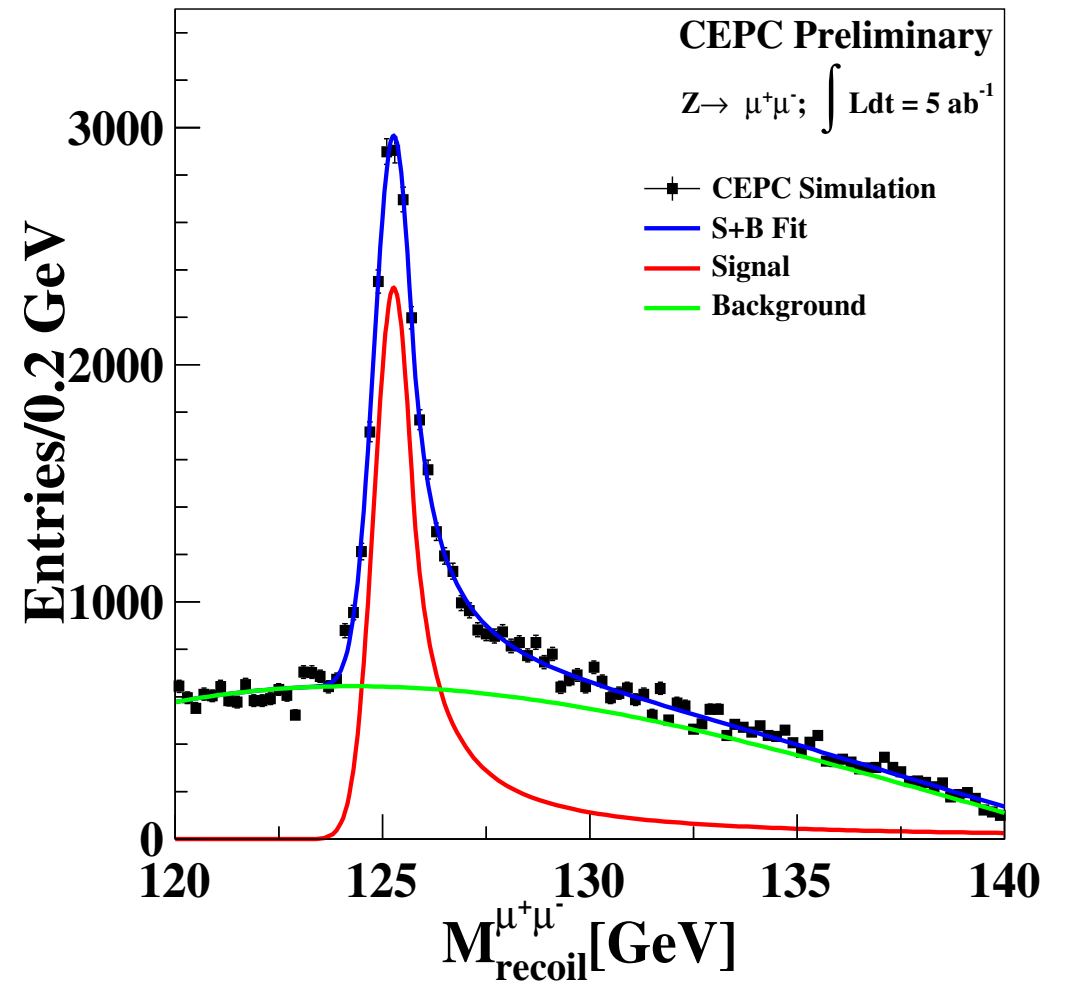
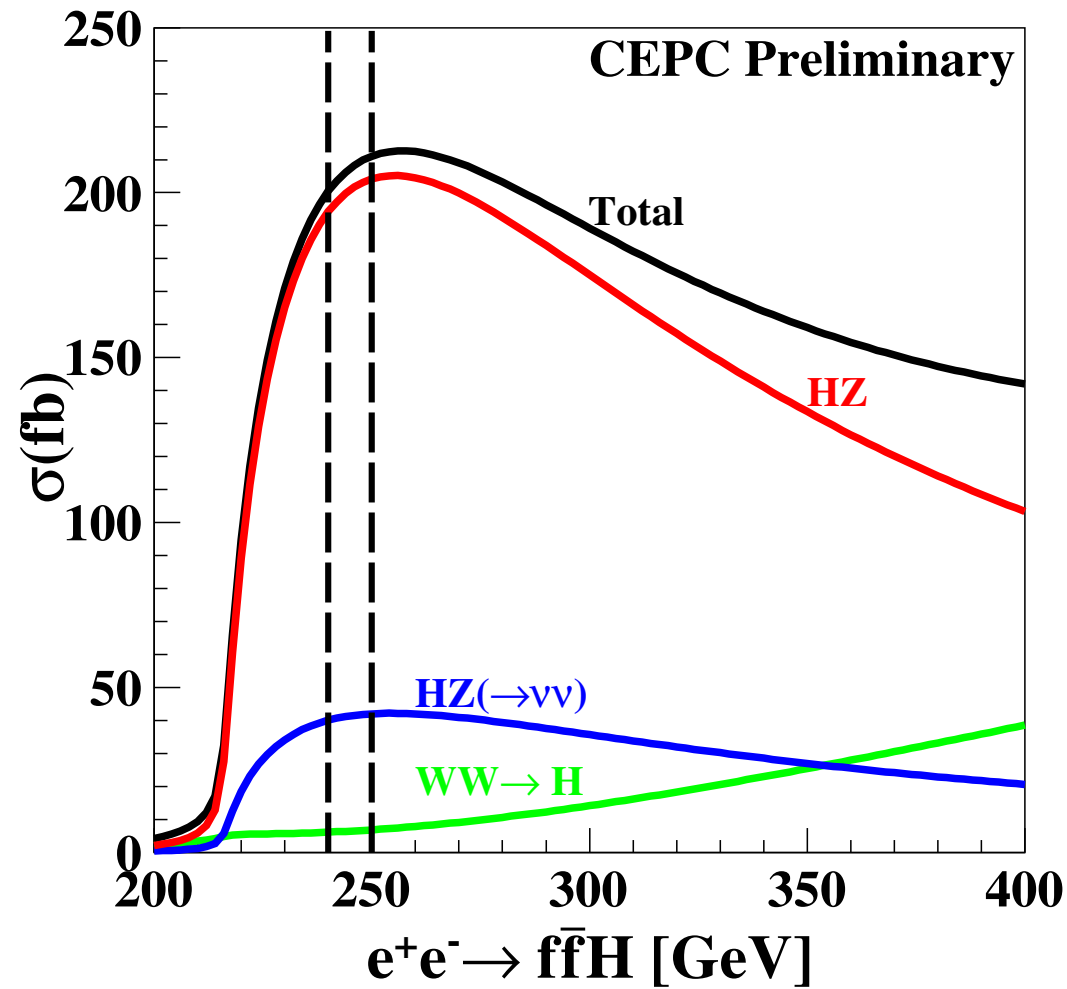


New physics particles: where are they?

- Searching NP particles at colliders.
- Null (or fluctuation) results from the LHC.
- The next generation colliders?
 - VLHC (28-33TeV)
 - Fcc-pp collider (100TeV)
 - SppC (50-80TeV, 100TeV?)
 - ILC (up to TeV)
- How about CEPC? (only 240GeV)

CEPC: a Higgs factory

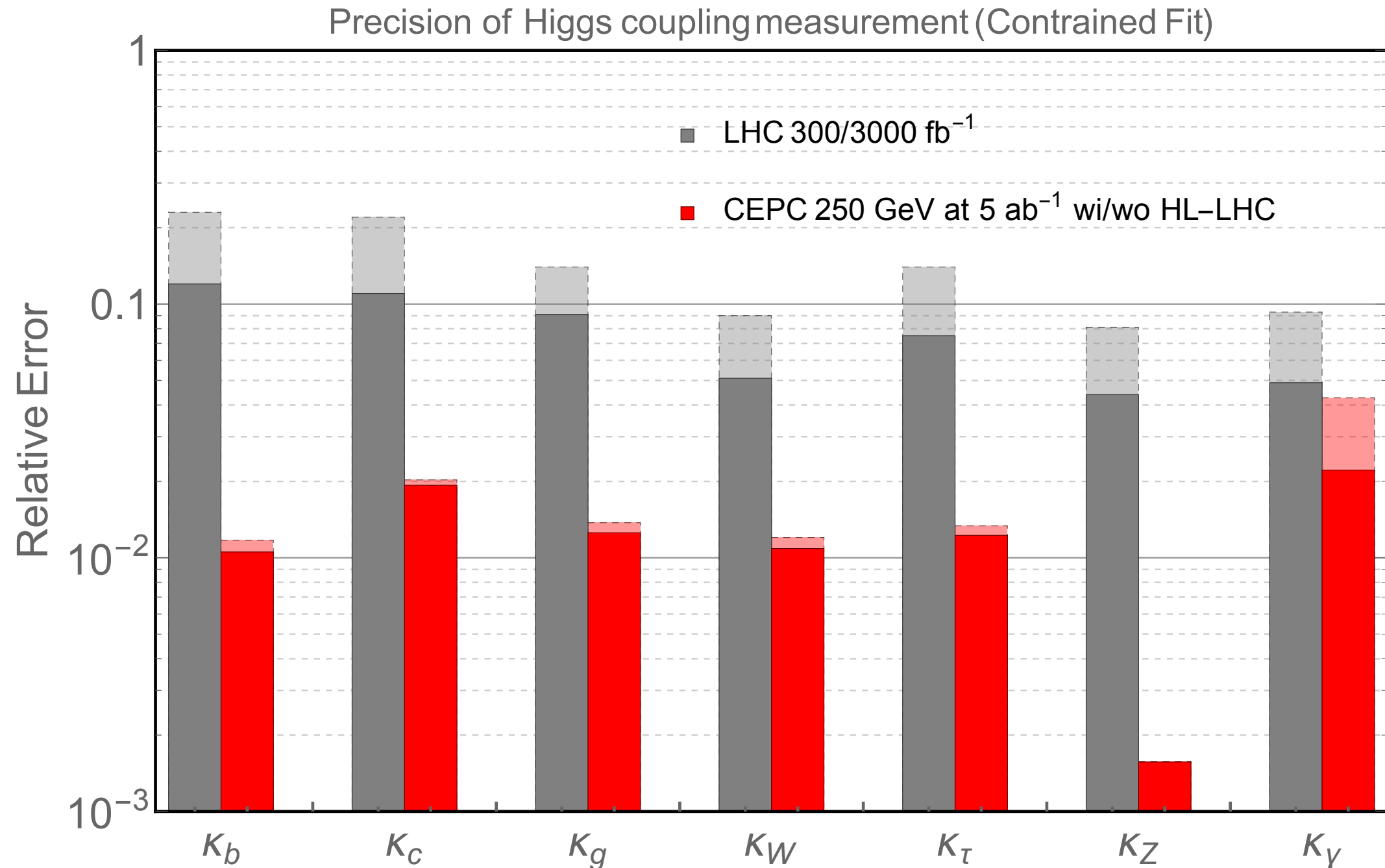
- More than 1,000,000 ZH signal events in the SM!



$$m_{\text{recoil}}^2 \equiv (\sqrt{s} - E_{f\bar{f}})^2 - \vec{p}_{f\bar{f}}^2 = s - 2E_{f\bar{f}}\sqrt{s} + m_{f\bar{f}}^2$$

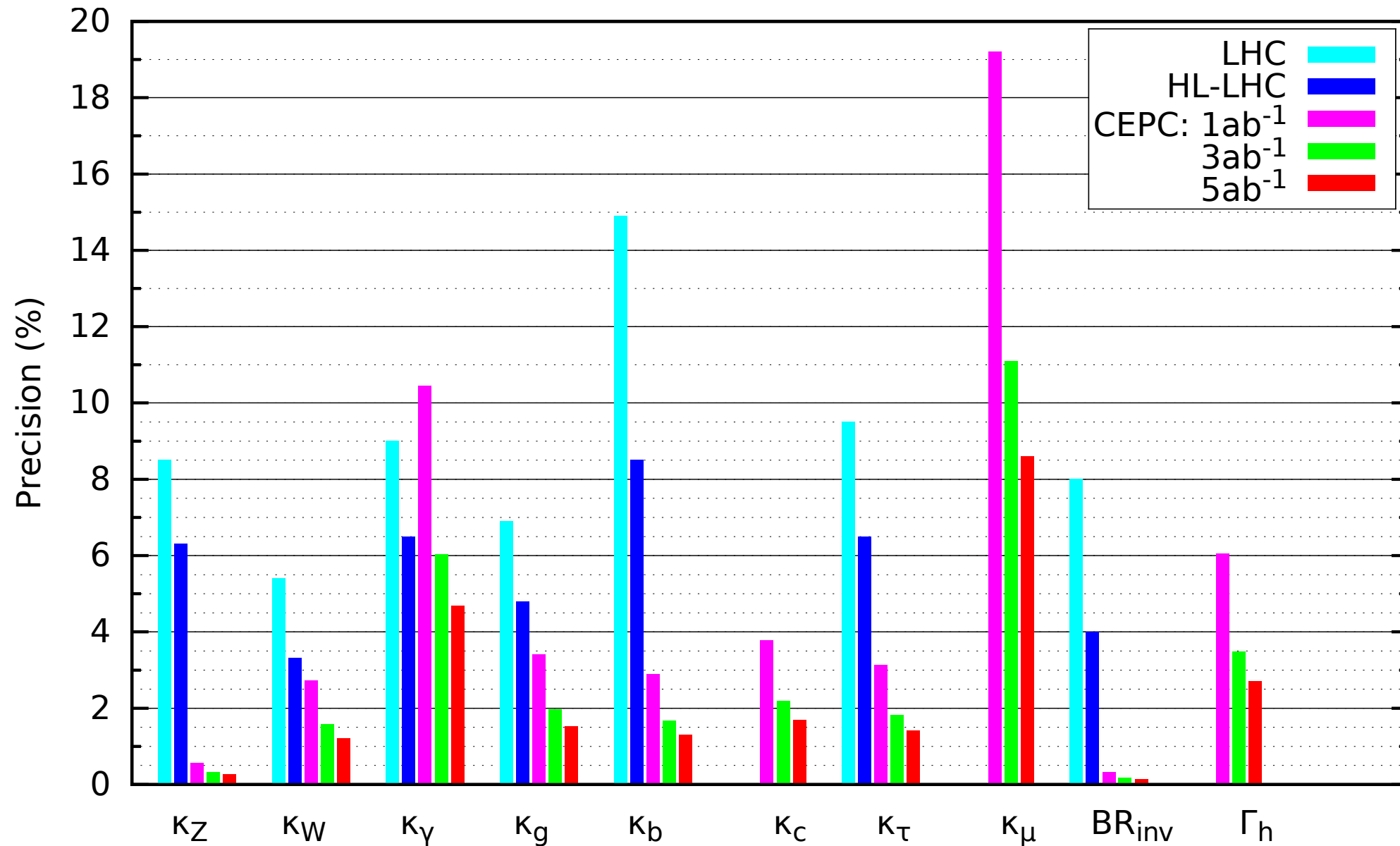
CEPC: a Higgs factory

- The combination of different Z decay modes gives:



CEPC: a Higgs factory

- The combination of different Z decay modes gives:



What can we do beyond the SM?

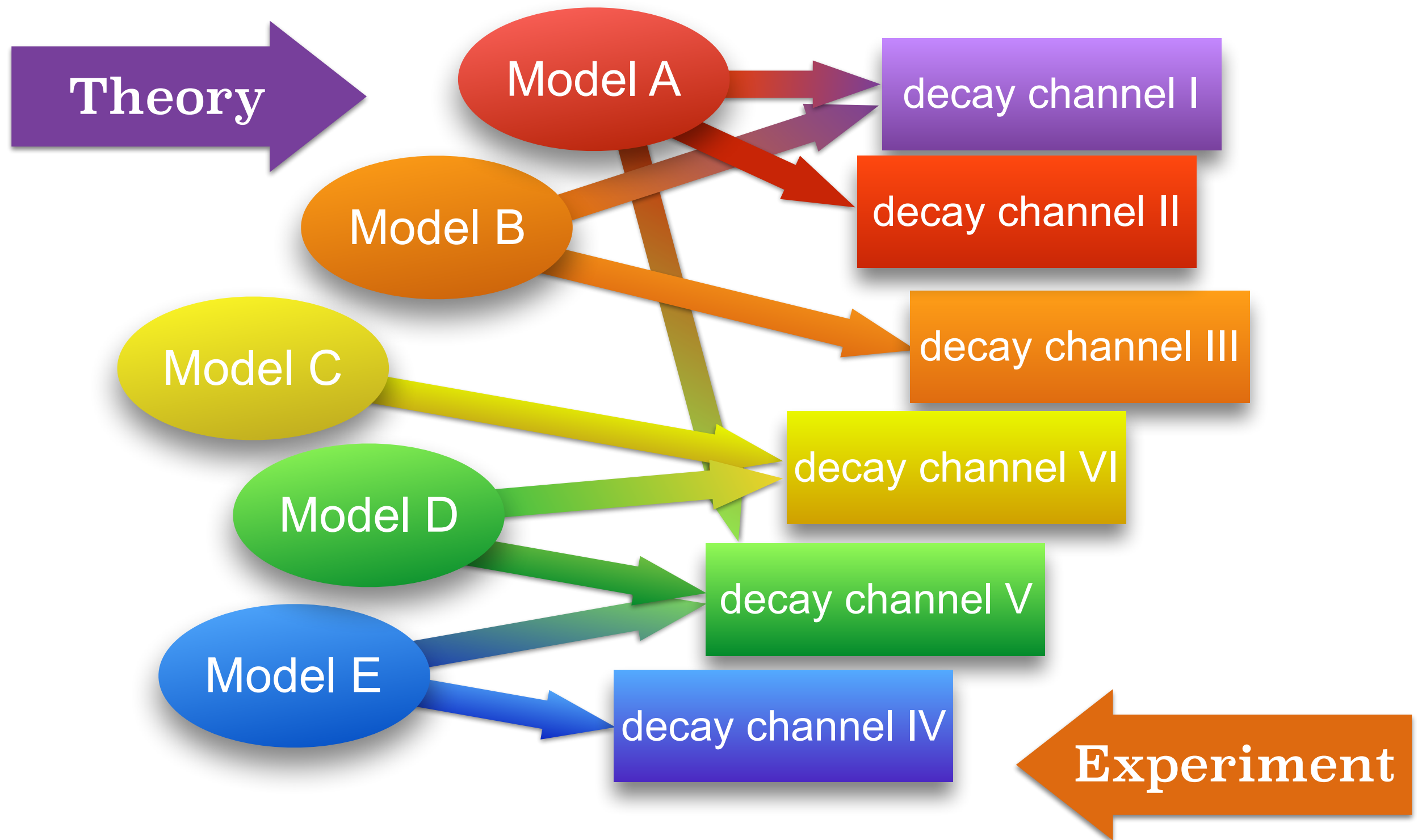


Exotic decay of the SM Higgs boson

- Light exotic particles weakly couple to the SM sector:
 - SUSY model: MSSM, NMSSM, ...
 - Warped Extra Dimension model: light radion;
 - Hidden valley with Higgs boson as the mediator: “Higgs portal”;
 - Dark matter: dark force, ...
 - Baryogenesis: exotic light scalar;
 - Neutrino mass: N -loop radiative seesaw;
 - ...



Exotic decay of the SM Higgs boson

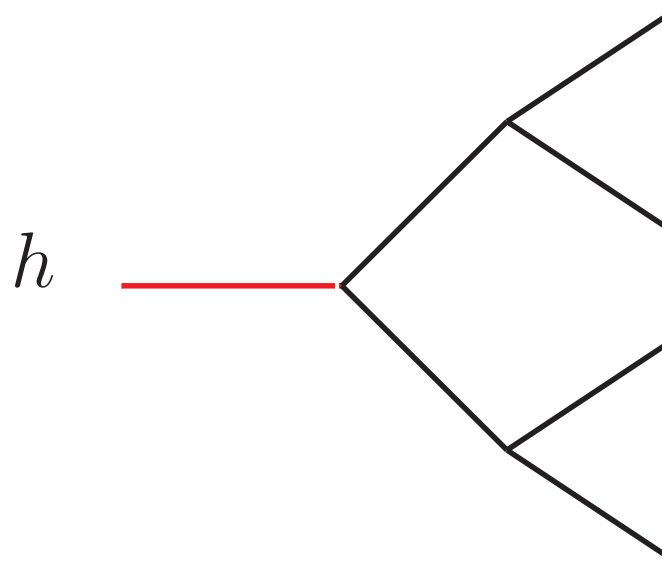


The dictionary links models and signals.

Exotic decay of the SM Higgs boson

- Phenomenology: investigate the detail of the signals.
- Topology $\Rightarrow$ Insert fields $\Rightarrow$ signals at CEPC.
- Example:

Topology

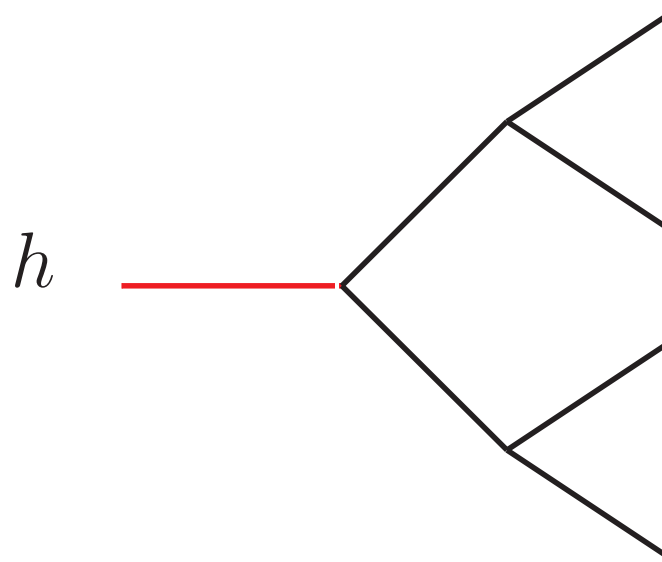


$$h \rightarrow 2 \rightarrow 4$$

Exotic decay of the SM Higgs boson

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- Example:

Insert fields

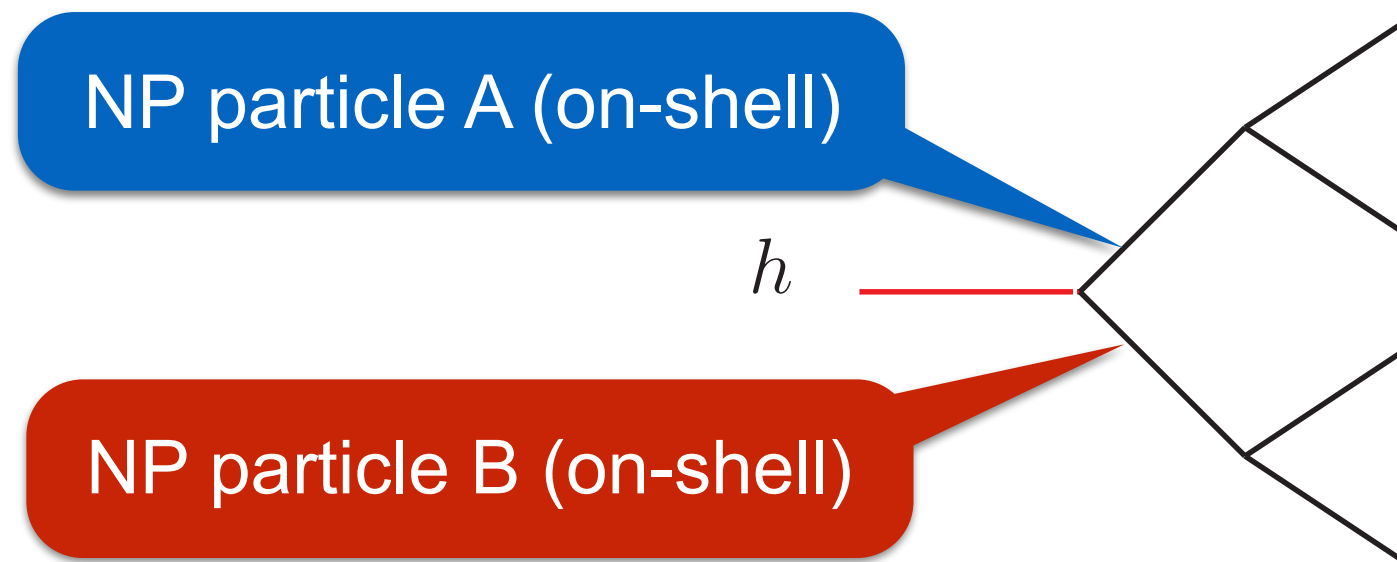


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Exotic decay of the SM Higgs boson

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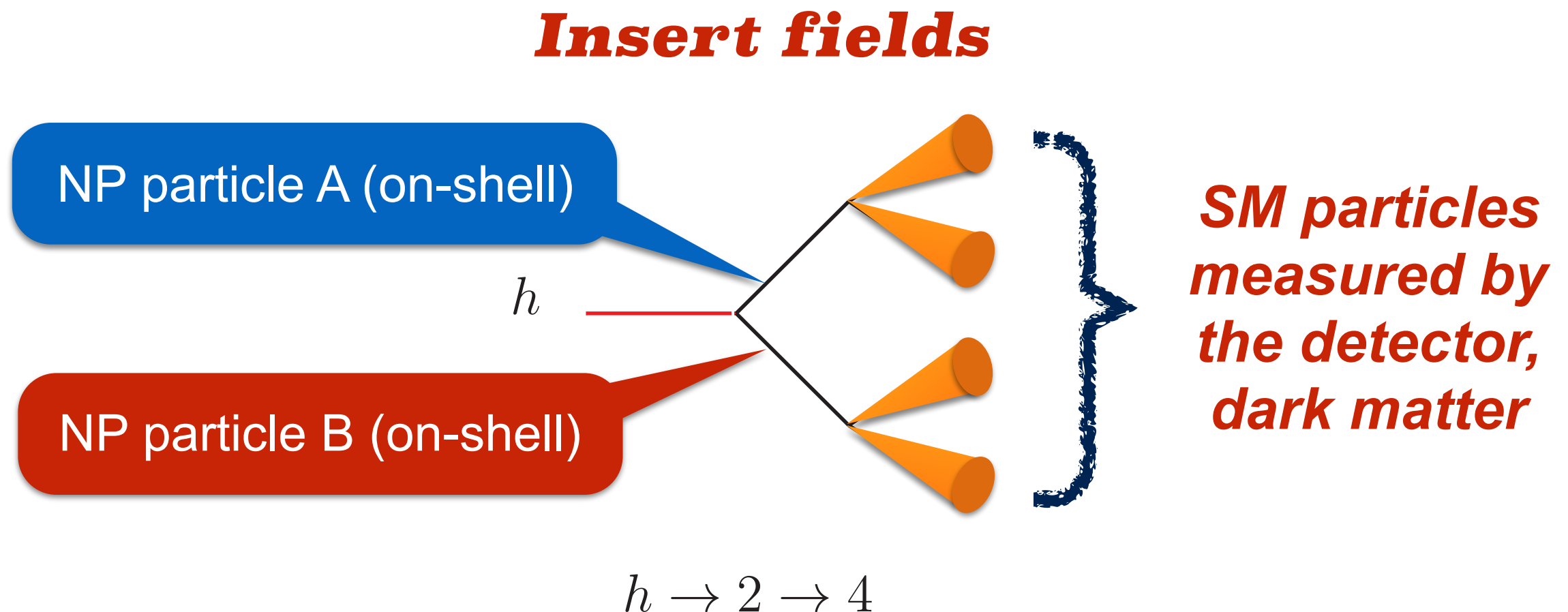
Insert fields



$$h \rightarrow 2 \rightarrow 4$$

Exotic decay of the SM Higgs boson

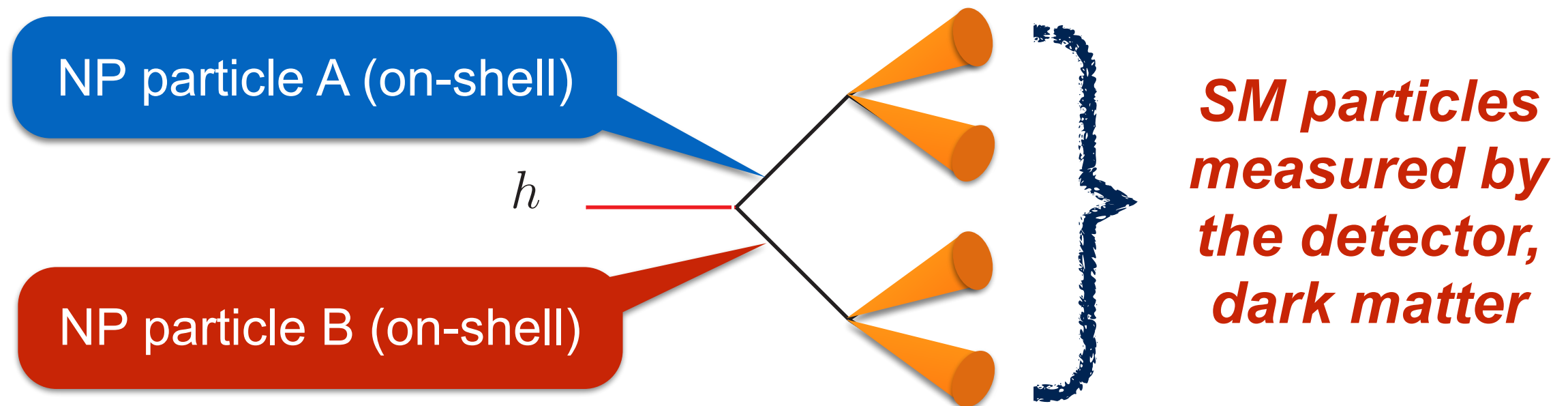
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Exotic decay of the SM Higgs boson

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

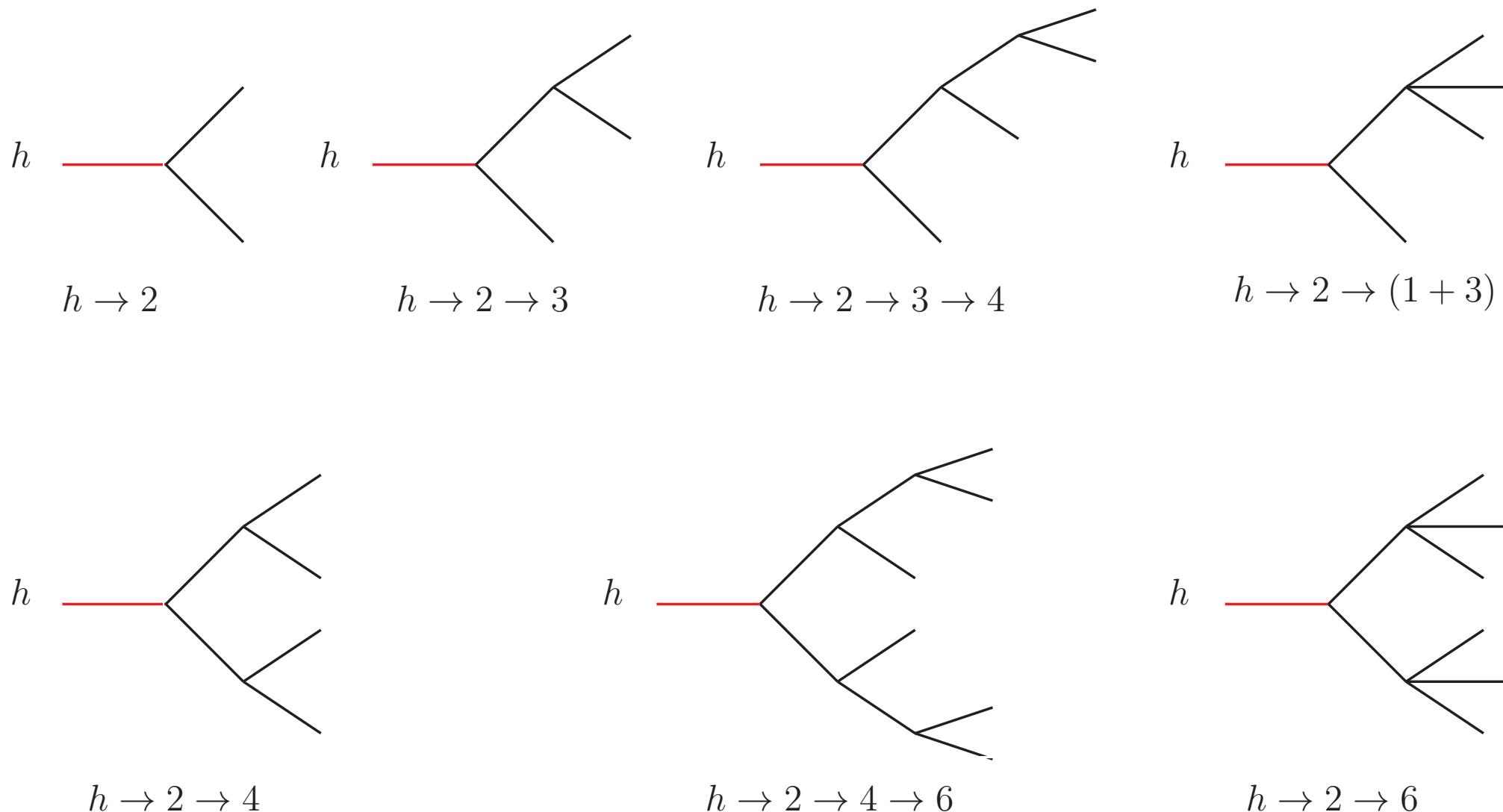
Insert fields



$$h \rightarrow 2 \rightarrow 4$$

Exotic decay of the SM Higgs boson

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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.

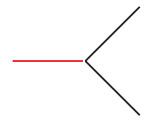
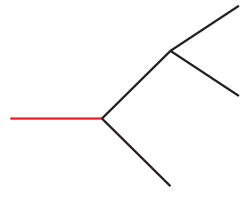
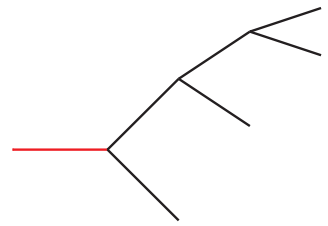
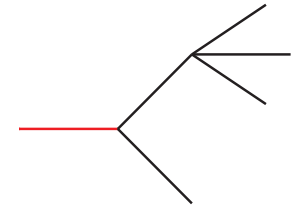
TABLE XIII. As in Table XII, estimates for various processes in $h \rightarrow aa$ if a decays only to SM gauge bosons through loops. The central columns show the case where the couplings are generated by initially degenerate $SU(5)$ multiplets; the right columns show the case where the $a \rightarrow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

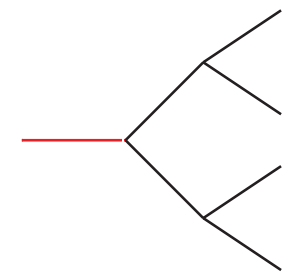
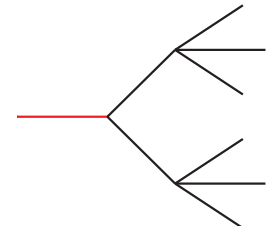
Decay mode $\mathcal{F}_i$	Projected/current 2σ limit on $\text{Br}(\mathcal{F}_i)$ 7 + 8 [14] TeV	Production mode	$\text{Br}(a \rightarrow \gamma\gamma) \approx 0.004$		$\text{Br}(a \rightarrow \gamma\gamma) \approx 0.04$		Comments
			$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$	Limit 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

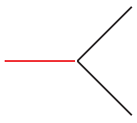
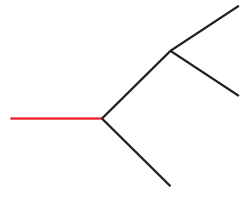
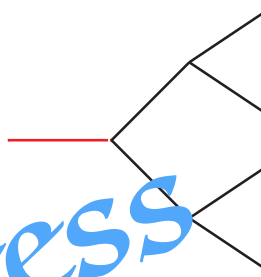
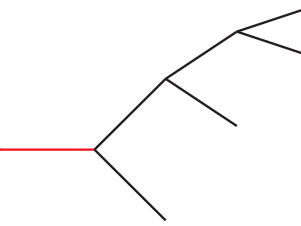
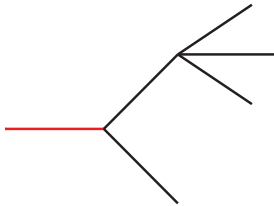
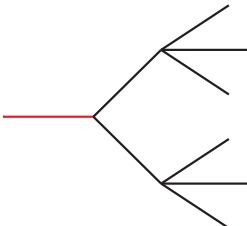
- There should be a list for CEPC.

Decay Topologies	Decay mode $\mathcal{F}_i$
	$h \rightarrow 2$
$h \rightarrow 2 \rightarrow 3$	$h \rightarrow \cancel{E}_T$
	$h \rightarrow \gamma + \cancel{E}_T$ $h \rightarrow (b\bar{b}) + \cancel{E}_T$ $h \rightarrow (jj) + \cancel{E}_T$ $h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$ $h \rightarrow (\gamma\gamma) + \cancel{E}_T$ $h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$	$h \rightarrow (b\bar{b}) + \cancel{E}_T$ $h \rightarrow (jj) + \cancel{E}_T$ $h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$ $h \rightarrow (\gamma\gamma) + \cancel{E}_T$ $h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$ $h \rightarrow (\mu^+\mu^-) + \cancel{E}_T$
	
$h \rightarrow 2 \rightarrow (1 + 3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$ $h \rightarrow jj + \cancel{E}_T$ $h \rightarrow \tau^+\tau^- + \cancel{E}_T$ $h \rightarrow \gamma\gamma + \cancel{E}_T$ $h \rightarrow \ell^+\ell^- + \cancel{E}_T$
	

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \rightarrow 2 \rightarrow 4$	$h \rightarrow (b\bar{b})(b\bar{b})$ $h \rightarrow (b\bar{b})(\tau^+\tau^-)$ $h \rightarrow (b\bar{b})(\mu^+\mu^-)$ $h \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$ $h \rightarrow (\tau^+\tau^-)(\mu^+\mu^-)$ $h \rightarrow (jj)(jj)$ $h \rightarrow (jj)(\gamma\gamma)$ $h \rightarrow (jj)(\mu^+\mu^-)$ $h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$ $h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$ $h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$ $h \rightarrow (\gamma\gamma)(\gamma\gamma)$ $h \rightarrow \gamma\gamma + \cancel{E}_T$
	
$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + \cancel{E}_T$ $h \rightarrow (\ell^+\ell^-) + \cancel{E}_T + X$
$h \rightarrow 2 \rightarrow 6$	$h \rightarrow \ell^+\ell^-\ell^+\ell^- + \cancel{E}_T$ $h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$
	

Exotic decay of the SM Higgs boson

- There should be a list for CEPC.

Decay Topologies	Decay mode $\mathcal{F}_i$	Decay Topologies	Decay mode $\mathcal{F}_i$
	$h \rightarrow 2$	$h \rightarrow 2 \rightarrow 4$	$h \rightarrow (b\bar{b})(b\bar{b})$
	$h \rightarrow 2 \rightarrow 3$		$h \rightarrow (b\bar{b})(\tau^+\tau^-)$
	$h \rightarrow \gamma + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\mu^+\mu^-)$
	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (jj)(jj)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (jj)(\gamma\gamma)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (jj)(\mu^+\mu^-)$
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow \gamma\gamma + \cancel{E}_T$
	$h \rightarrow (\mu^+\mu^-) + \cancel{E}_T$		
$h \rightarrow 2 \rightarrow (1 + 3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + \cancel{E}_T$
	$h \rightarrow jj + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T + X$
	$h \rightarrow \tau^+\tau^- + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 6$	$h \rightarrow \ell^+\ell^-\ell^+\ell^- + \cancel{E}_T$
	$h \rightarrow \gamma\gamma + \cancel{E}_T$		$h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$
	$h \rightarrow \ell^+\ell^- + \cancel{E}_T$		

Exotic decay of the SM Higgs boson

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

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & \sqrt{2}\varepsilon_s v h s s + \sqrt{2}\varepsilon_a v h a a + \varepsilon_1 g'_1 v h Z'_{1\mu} Z'^{\mu}_1 + \varepsilon_2 g'_2 v h Z'_{2\mu} Z'^{\mu}_2 \\ & + y_s s \bar{f} f + i y_a a \bar{f} \gamma_5 f + \frac{\alpha_s c_s}{\Lambda_s} s G_{\mu\nu} G^{\mu\nu} + \frac{\alpha_s c_a}{\Lambda_a} a G_{\mu\nu} \tilde{G}^{\mu\nu} \\ & + g'_1 Z'_{1\mu} \bar{f} \gamma^\mu f + g'_2 Z'_{2\mu} \bar{f} \gamma^\mu P_R f\end{aligned}$$

**Spin correlations are kept
for model distinguishing.**



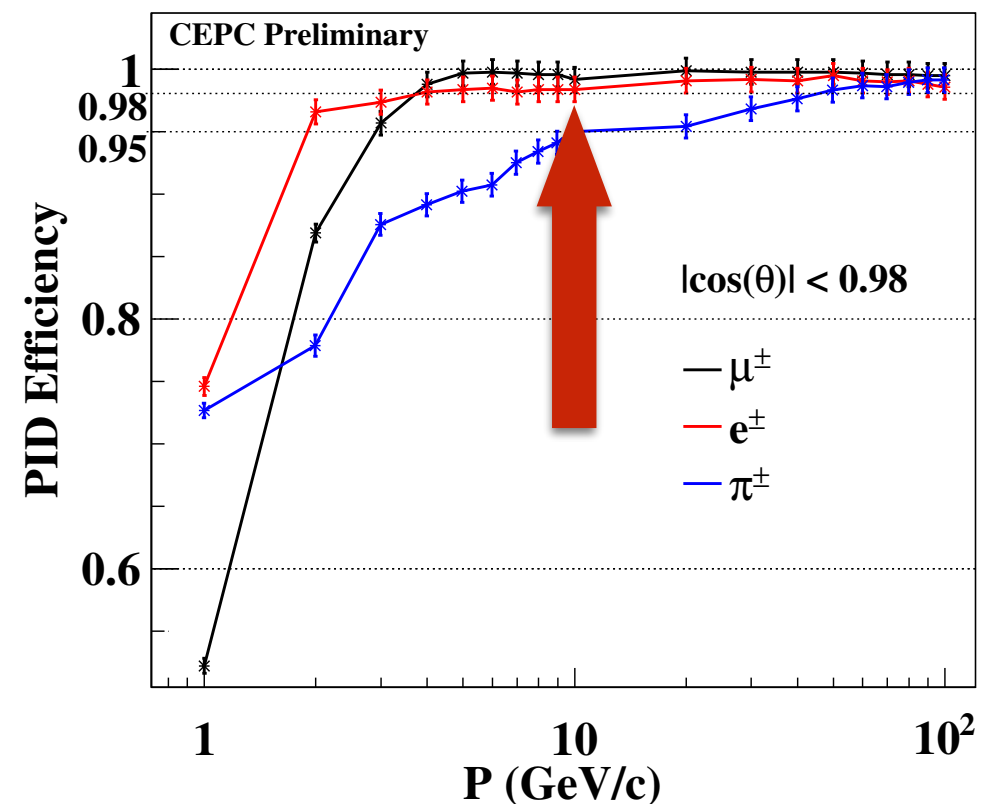
Exotic decay of the SM Higgs boson

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

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

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

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



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.



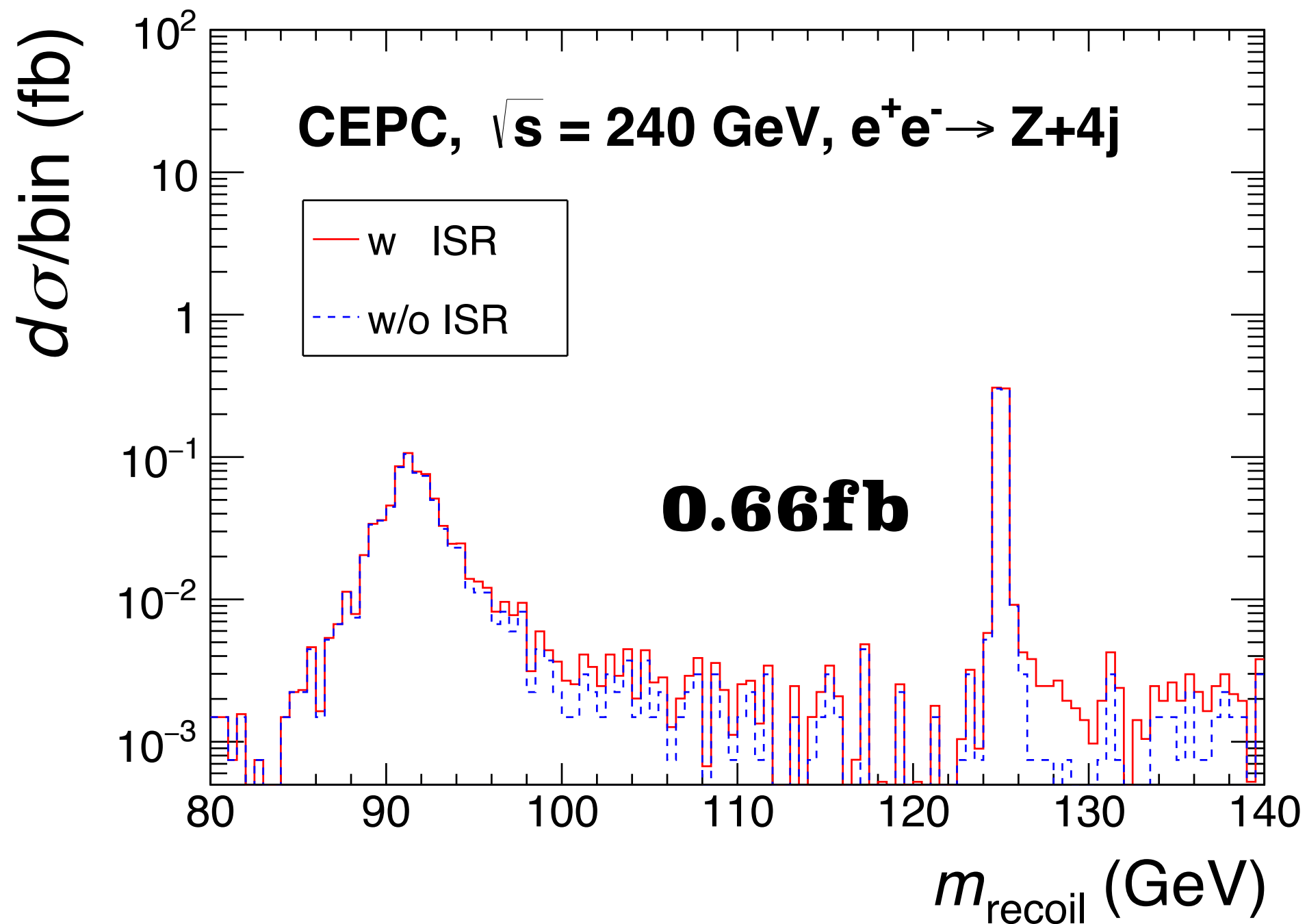
Exotic decay of the SM Higgs boson

- An example:
 - **Preselection cuts:** $|\cos \theta_{j,\ell}| < 0.98, E_{j,\ell} > 10\text{GeV},$
$$y_{ij} \equiv \frac{2\min(E_i^2, E_j^2)(1 - \cos \theta_{ij})}{E_{vis}^2} > y_{\text{cut}},$$
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 $p_T > 1\text{GeV}$ to avoid the IR divergence). (No ISR for signal events!)
 - Additional cut to suppress the ISR effect: $E_{vis} > 225\text{GeV}.$



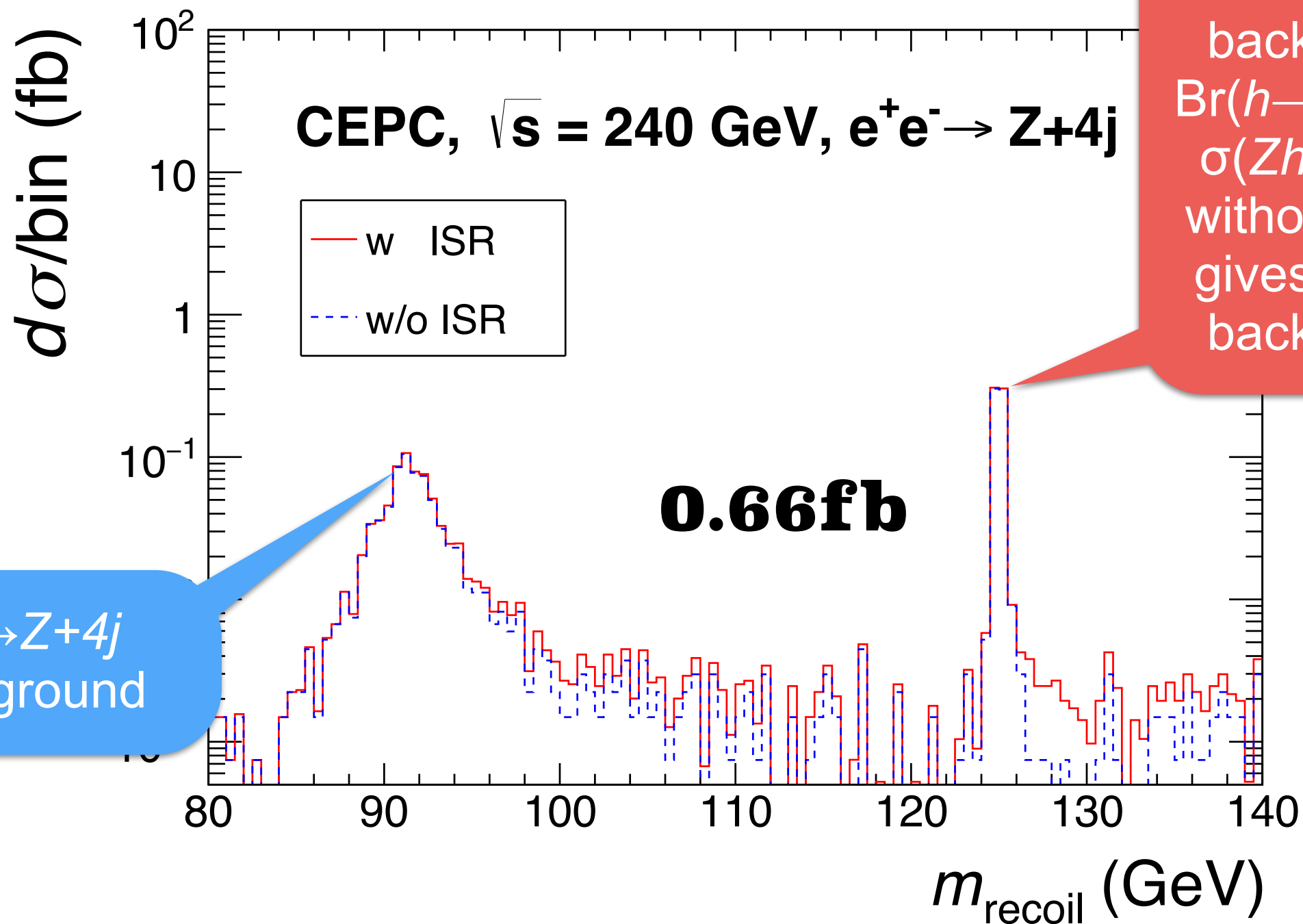
Exotic decay of the SM Higgs boson ($j\bar{j}j\bar{j}$)

$y_{\text{cut}}=0.002$



Exotic decay of the SM Higgs boson ($j\bar{j}j\bar{j}$)

$y_{\text{cut}}=0.002$

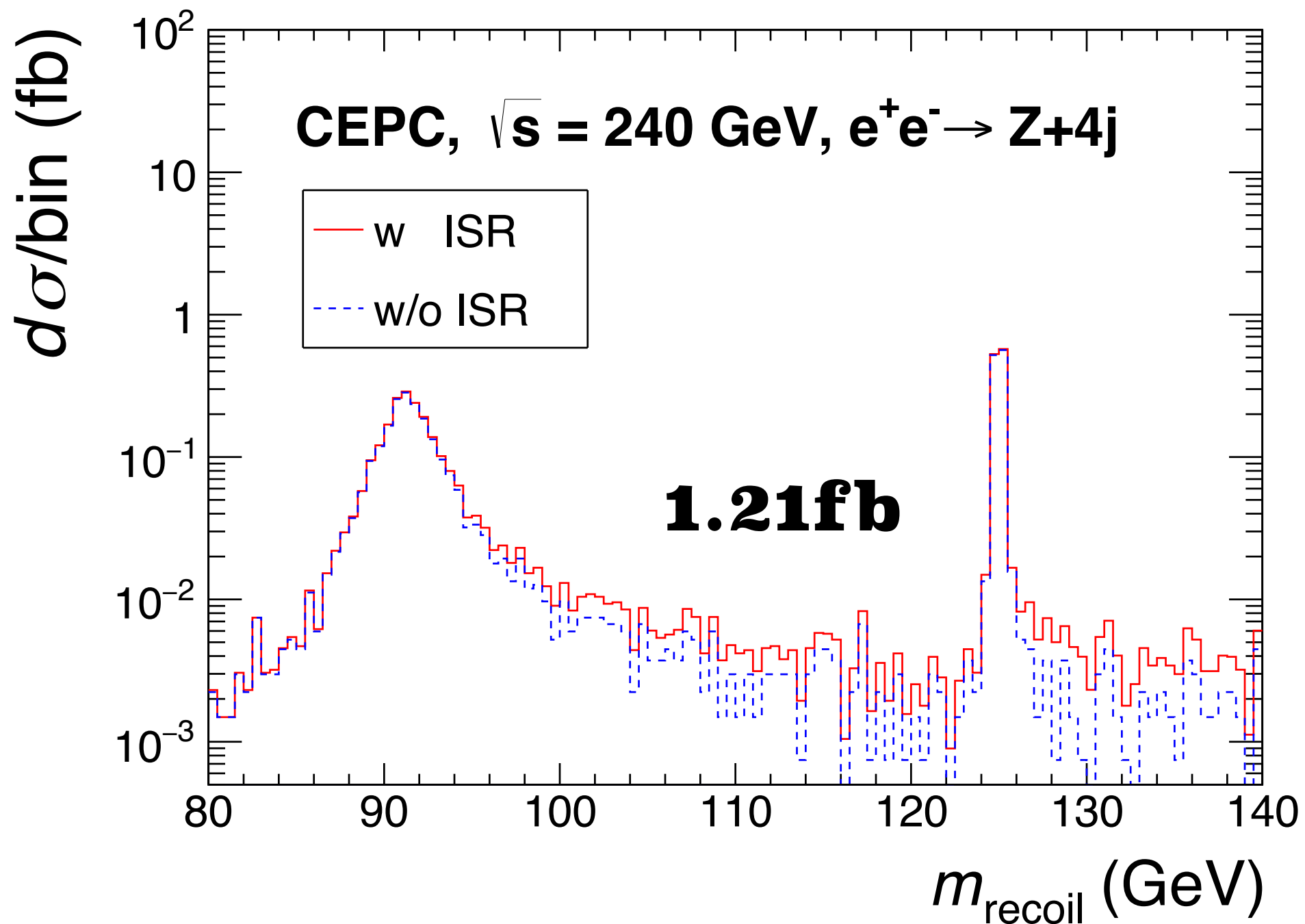


$ZZ \rightarrow Z+4j$
background

$Zh \rightarrow Z+4j$
background.
 $\text{Br}(h \rightarrow 4j) \sim 11\%$,
 $\sigma(Zh) \sim 240\text{fb}$,
without cuts, it
gives $\sim 1.75\text{fb}$
background.

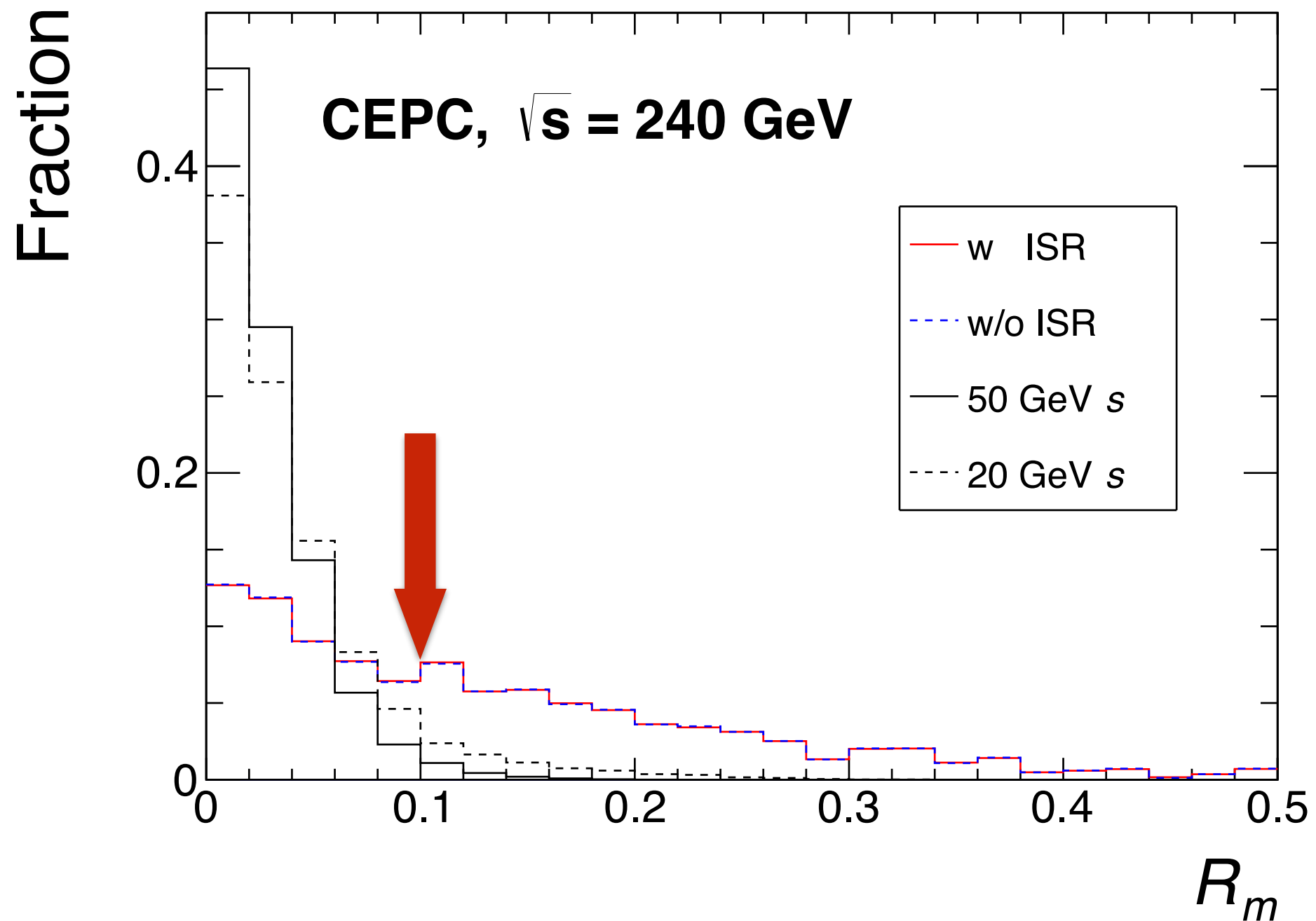
Exotic decay of the SM Higgs boson ($j\bar{j}j\bar{j}$)

$y_{\text{cut}}=0.001$



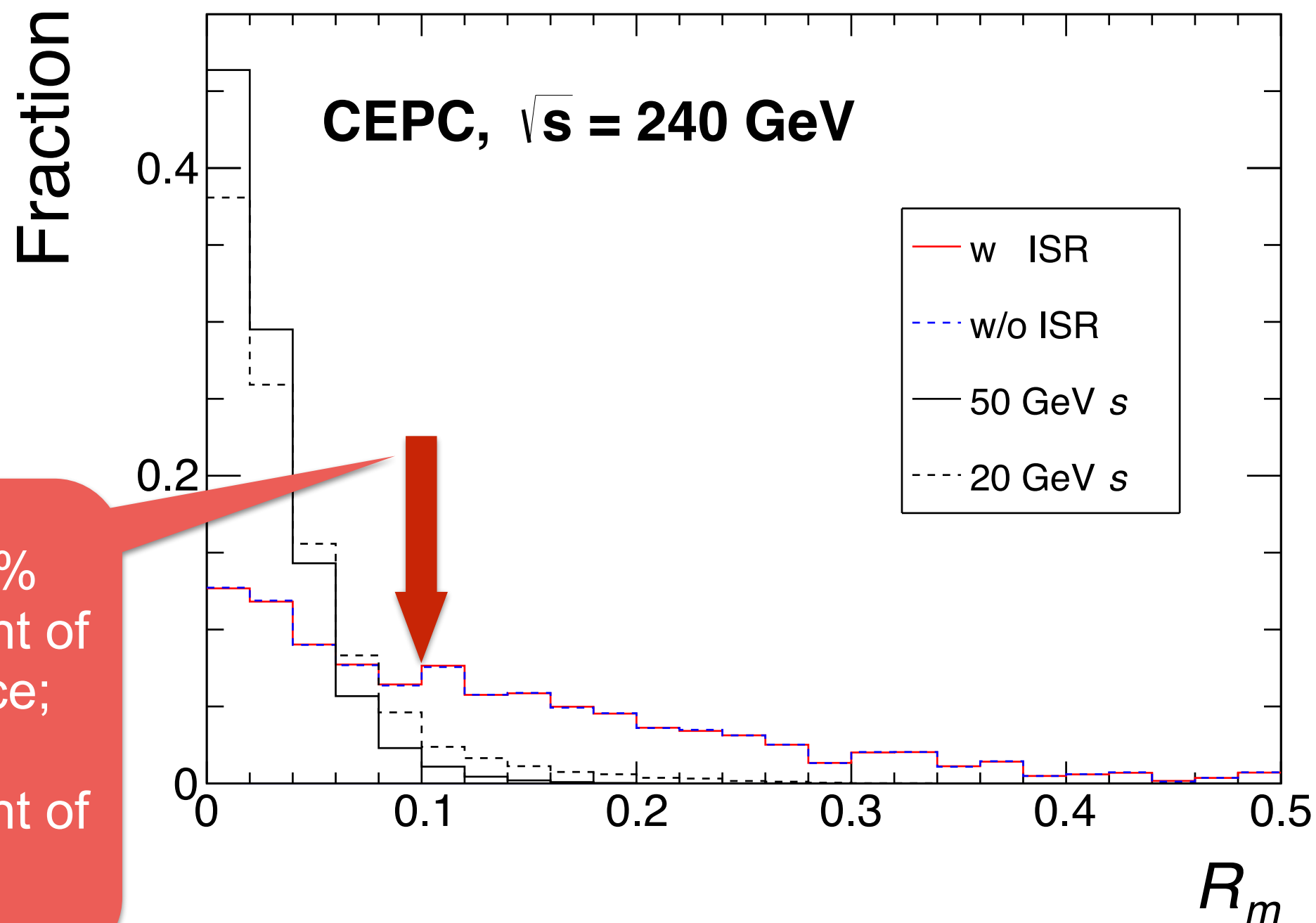
Exotic decay of the SM Higgs boson ($j\bar{j}j\bar{j}$)

- Additional cut: $R_m \equiv \min_{\sigma \in S_4} \left(\frac{|m_{j_{\sigma(1)}j_{\sigma(2)}} - m_{j_{\sigma(3)}j_{\sigma(4)}}|}{m_{j_{\sigma(1)}j_{\sigma(2)}} + m_{j_{\sigma(3)}j_{\sigma(4)}}} \right)$.



Exotic decay of the SM Higgs boson ($j\bar{j}j\bar{j}$)

- Additional cut: $R_m \equiv \min_{\sigma \in S_4} \left(\frac{|m_{j_{\sigma(1)}j_{\sigma(2)}} - m_{j_{\sigma(3)}j_{\sigma(4)}}|}{m_{j_{\sigma(1)}j_{\sigma(2)}} + m_{j_{\sigma(3)}j_{\sigma(4)}}} \right)$.



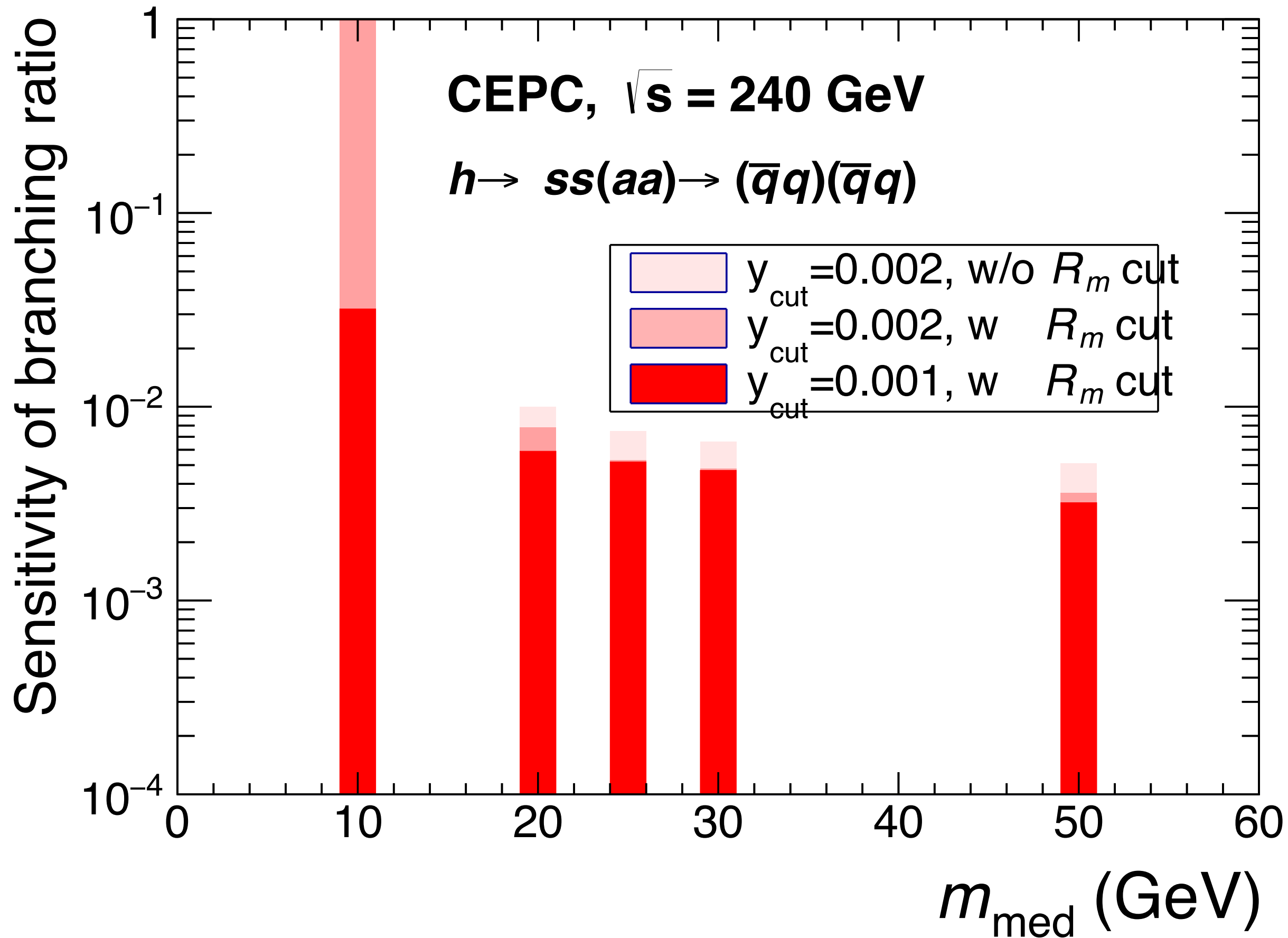
~20%-30%
improvement of
significance;
~100%
improvement of
S/B.

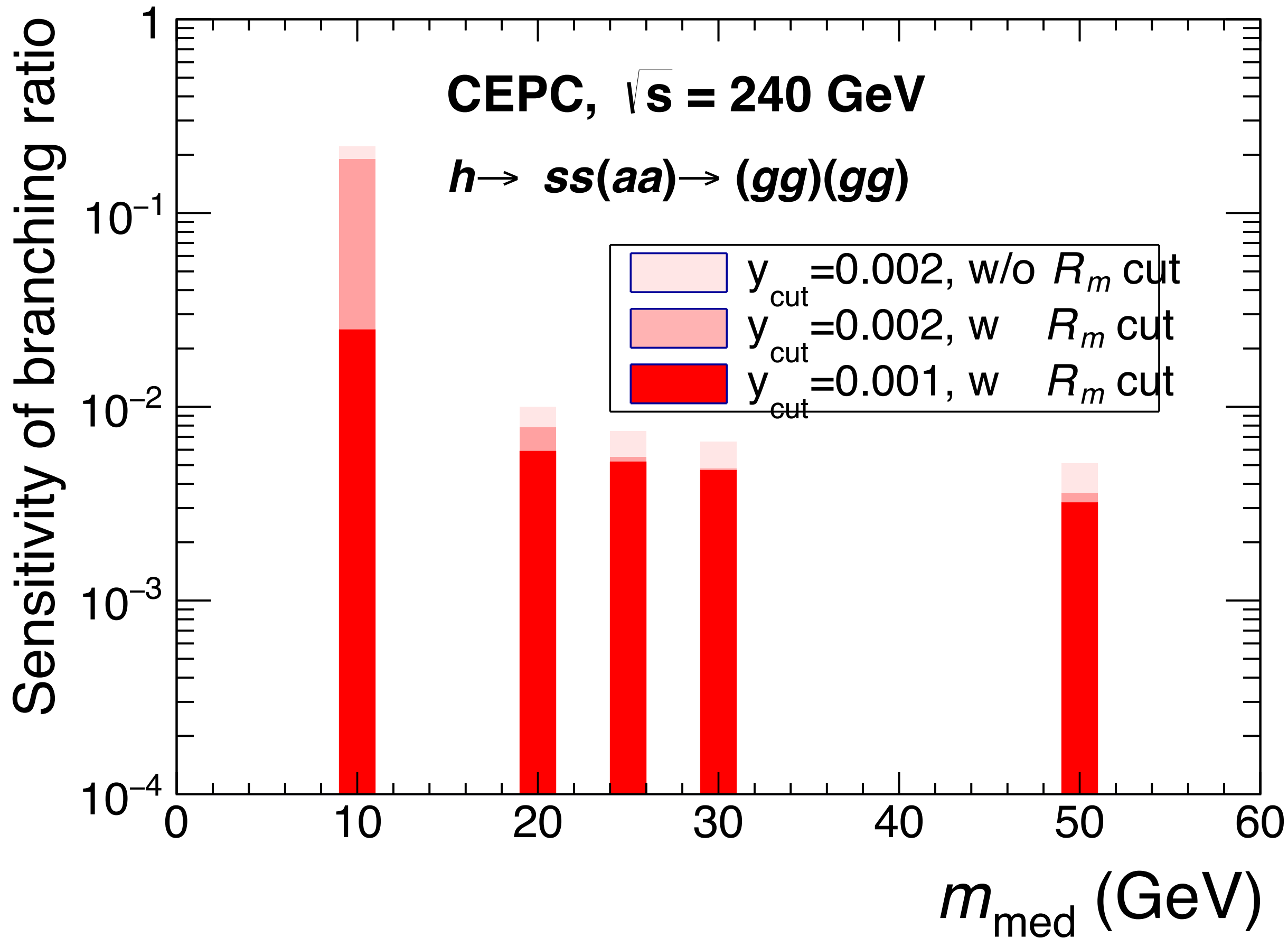
Exotic decay of the SM Higgs boson ($jjjj$)

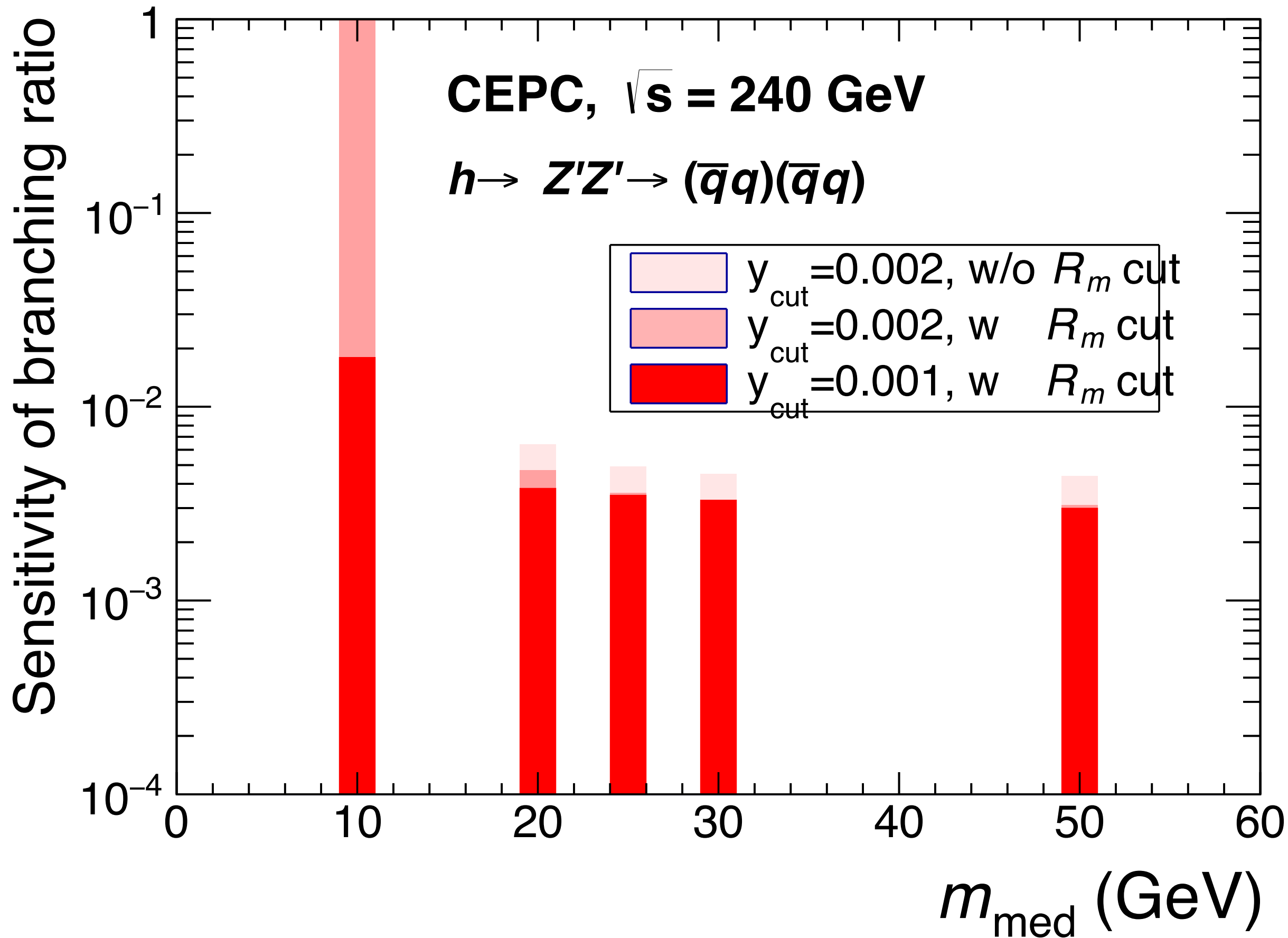
- 3σ sensitivity at $5ab^{-1}$ CEPC.

	m_{med} (GeV)	10	20	25	30	50
$s\bar{f}f, a\bar{f}\gamma_5 f$	$y_{\text{cut}} = 0.002$	$>100\%$	0.78%	0.53%	0.48%	0.36%
	$y_{\text{cut}} = 0.001$	3.2%	0.59%	0.52%	0.47%	0.32%
$sG_{\mu\nu}G^{\mu\nu}, aG_{\mu\nu}\tilde{G}^{\mu\nu}$	$y_{\text{cut}} = 0.002$	19%	0.78%	0.55%	0.48%	0.36%
	$y_{\text{cut}} = 0.001$	2.5%	0.59%	0.52%	0.47%	0.32%
$V_\mu\bar{f}\gamma^\mu f, V_\mu\bar{f}\gamma^\mu P_R f$	$y_{\text{cut}} = 0.002$	$>100\%$	0.47%	0.36%	0.32%	0.31%
	$y_{\text{cut}} = 0.001$	1.8%	0.38%	0.35%	0.33%	0.30%









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

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	m_{med} (GeV)	10	20	25	30	50
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$sG_{\mu\nu}G^{\mu\nu}, aG_{\mu\nu}\tilde{G}^{\mu\nu}$	$y_{\text{cut}} = 0.002$	19%	0.78%	0.55%	0.48%	0.36%
	$y_{\text{cut}} = 0.001$	2.5%	0.59%	0.52%	0.47%	0.32%
$V_\mu\bar{f}\gamma^\mu f, V_\mu\bar{f}\gamma^\mu P_R f$	$y_{\text{cut}} = 0.002$	$>100\%$	0.47%	0.36%	0.32%	0.31%
	$y_{\text{cut}} = 0.001$	1.8%	0.38%	0.35%	0.33%	0.30%

- HL-LHC? Four jets, very difficult!

TABLE XIII. As in Table XII, estimates for various processes in $h \rightarrow aa$ 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 $a \rightarrow \gamma\gamma$ 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	$\text{Br}(a \rightarrow \gamma\gamma) \approx 0.004$		$\text{Br}(a \rightarrow \gamma\gamma) \approx 0.04$		Comments
			Limit on		Limit on		
			$\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$ $7 + 8$ [14] TeV	$\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$ $7 + 8$ [14] TeV	$\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$ $7 + 8$ [14] TeV	$\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$ $7 + 8$ [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 ($jjjj$)

- 3σ sensitivity at $5ab^{-1}$ CEPC.

	m_{med} (GeV)	10	20	25	30	50
$s\bar{f}f, a\bar{f}\gamma_5 f$	$y_{\text{cut}} = 0.002$	$>100\%$	0.78%	0.53%	0.48%	0.36%
	$y_{\text{cut}} = 0.001$	3.2%	0.59%	0.52%	0.47%	0.32%
$sG_{\mu\nu}G^{\mu\nu}, aG_{\mu\nu}\tilde{G}^{\mu\nu}$	$y_{\text{cut}} = 0.002$	19%	0.78%	0.55%	0.48%	0.36%
	$y_{\text{cut}} = 0.001$	2.5%	0.59%	0.52%	0.47%	0.32%
$V_\mu\bar{f}\gamma^\mu f, V_\mu\bar{f}\gamma^\mu P_R f$	$y_{\text{cut}} = 0.002$	$>100\%$	0.47%	0.36%	0.32%	0.31%
	$y_{\text{cut}} = 0.001$	1.8%	0.38%	0.35%	0.33%	0.30%

- HL-LHC? Four jets, very difficult!

TABLE XIV. As in Table XII, estimates for various processes in $h \rightarrow Z_D Z_D$ if $m_{Z_D} > 2m_b$ and couplings are proportional to electric charges. $\ell = e, \mu$ and all numbers represent the *sum* of processes involving e and μ ; j represents all jets except b quarks. An asterisk indicates that 300 fb^{-1} was assumed; otherwise all estimates for 14 TeV assume 100 fb^{-1} .

Decay mode $\mathcal{F}_i$	Projected/current 2σ limit on $\text{Br}(\mathcal{F}_i)$ 7 + 8 [14] TeV	Production mode	$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ 7 + 8 [14] TeV	Comments
$jjjj$	> 1 [0.1*]	W	0.25	> 1 [0.4*]	Theory study [220,269], Sec. VII



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

- 3σ sensitivity at $5ab^{-1}$ CEPC.

	m_{med} (GeV)	10	20	25	30	50
$s\bar{f}f, a\bar{f}\gamma_5f$	$y_{\text{cut}} = 0.002$	$>100\%$	0.78%	0.53%	0.48%	0.36%
	$y_{\text{cut}} = 0.001$	3.2%	0.59%	0.52%	0.47%	0.32%
$sG_{\mu\nu}G^{\mu\nu}, aG_{\mu\nu}\tilde{G}^{\mu\nu}$	$y_{\text{cut}} = 0.002$	19%	0.78%	0.55%	0.48%	0.36%
	$y_{\text{cut}} = 0.001$	2.5%	0.59%	0.52%	0.47%	0.32%
$V_\mu\bar{f}\gamma^\mu f, V_\mu\bar{f}\gamma^\mu P_Rf$	$y_{\text{cut}} = 0.002$	$>100\%$	0.47%	0.36%	0.32%	0.31%
	$y_{\text{cut}} = 0.001$	1.8%	0.38%	0.35%	0.33%	0.30%

- HL-LHC? Four jets, very difficult!

TABLE XIV. As in Table XII, estimates for various processes in $h \rightarrow Z_D Z_D$ if $m_{Z_D} > 2m_b$ and couplings are proportional to electric charges. $\ell = e, \mu$ and all numbers represent the *sum* of processes involving e and μ ; j represents all jets except b quarks. An asterisk indicates that 300 fb^{-1} was assumed; otherwise all estimates for 14 TeV assume 100 fb^{-1} .

Decay mode $\mathcal{F}_i$	Projected/current 2σ limit on $\text{Br}(\mathcal{F}_i)$ 7 + 8 [14] TeV	Production mode $\mathcal{P}_i$ 7 + 8 [14] TeV	Limit on $\text{Br}(\text{non-SM})$ $\sigma_{\text{SM}}/7 + 8 [14] \text{ TeV}$	Comments
<i>jjjj</i>	> 1 [0.1*]	> 1 [0.25]	> 1 [0.4*]	Theory study [220,269], Sec. VII

10% at HL-LHC? Only for very light mediator (jet-substructure)!



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

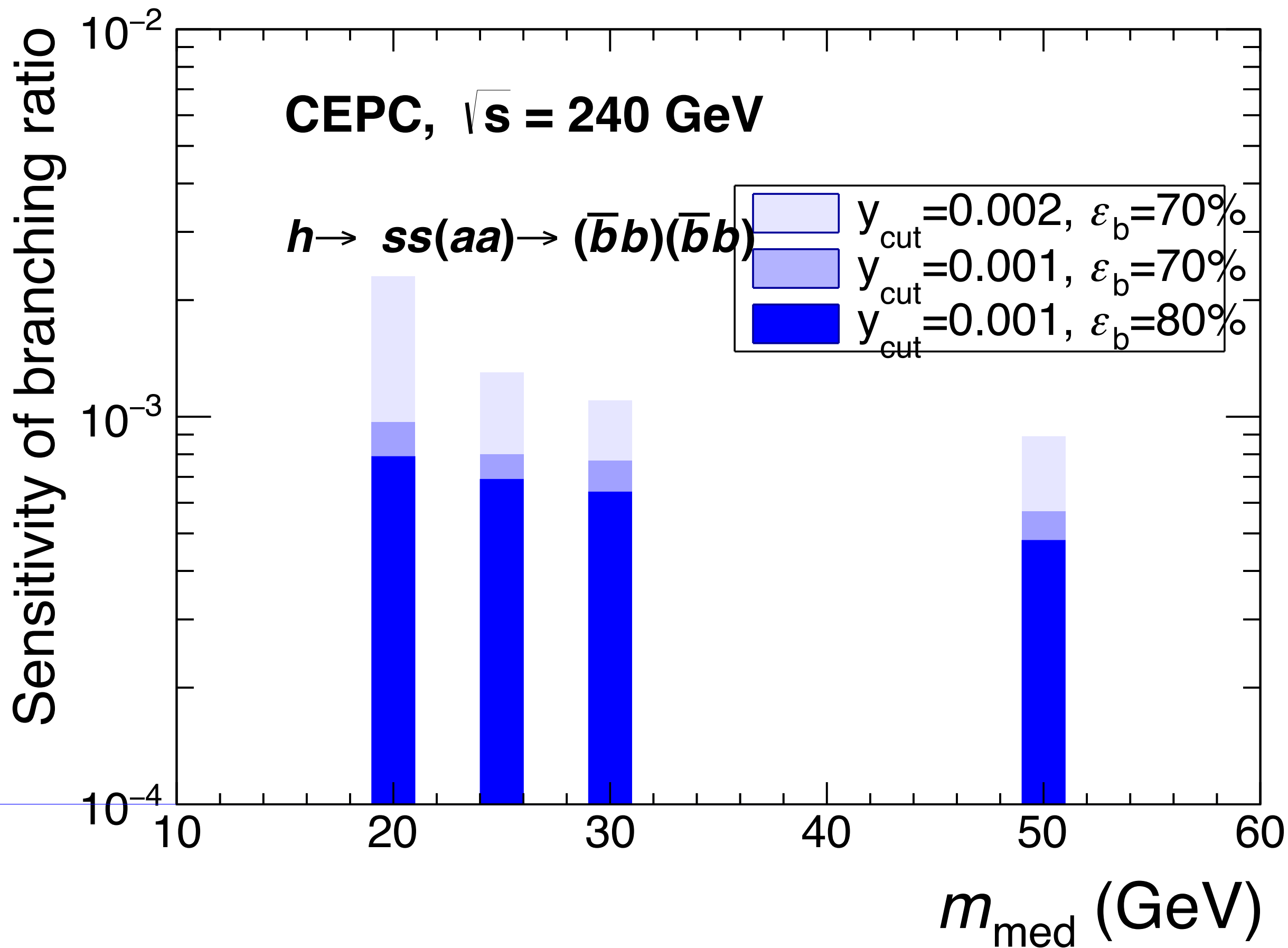
- 3σ sensitivity of $h \rightarrow ss(aa) \rightarrow (bb)(bb)$, $h \rightarrow Z'Z' \rightarrow (bb)(bb)$.

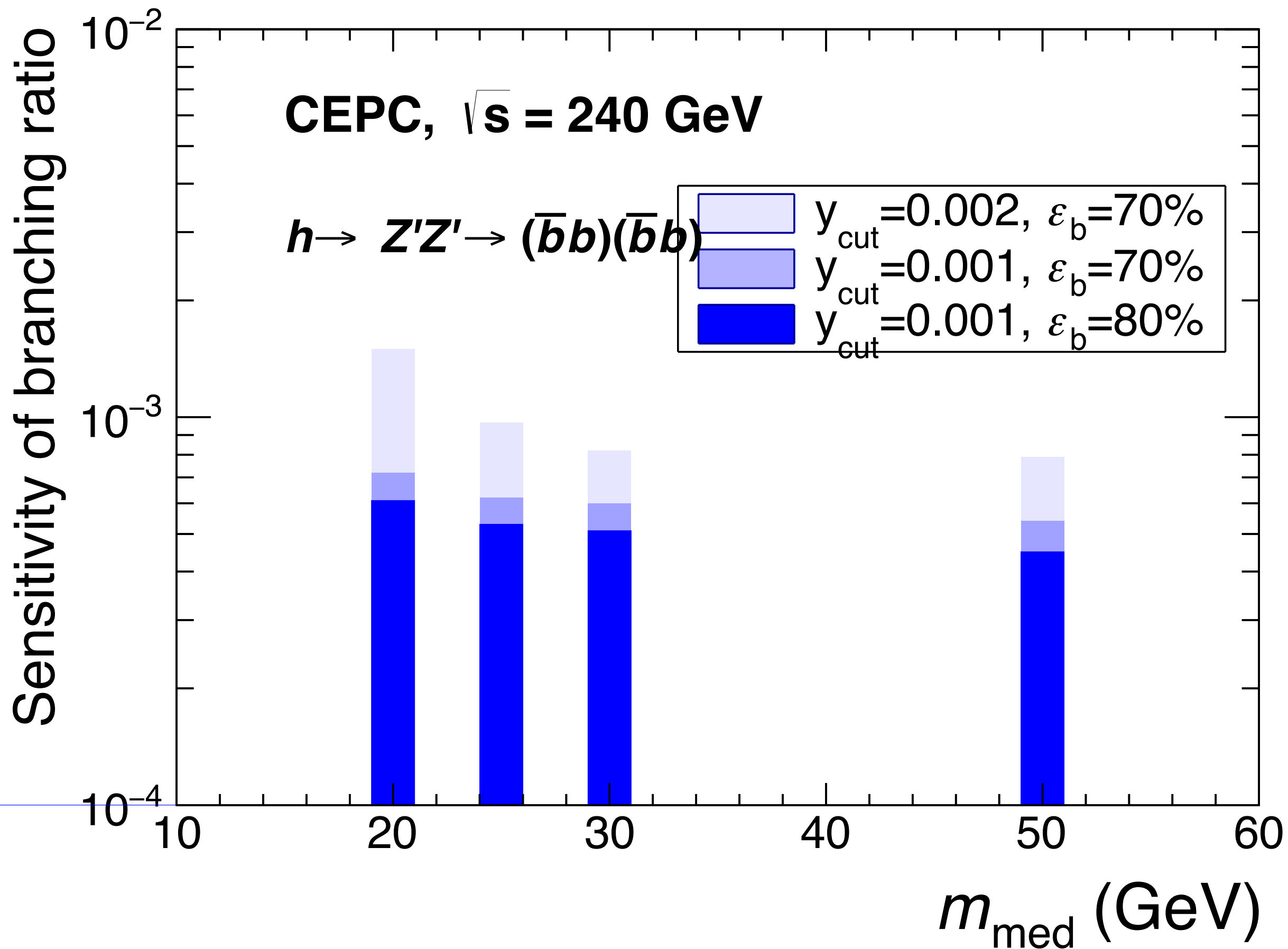
	mass of the mediator (GeV)	20	25	30	50
$s\bar{f}f, a\bar{f}\gamma_5 f$	$y_{\text{cut}} = 0.002, \epsilon_b = 70\%$	0.23%	0.13%	0.11%	0.089%
	$y_{\text{cut}} = 0.002, \epsilon_b = 80\%$	0.13%	0.072%	0.061%	0.049%
	$y_{\text{cut}} = 0.001, \epsilon_b = 70\%$	0.097%	0.080%	0.077%	0.057%
	$y_{\text{cut}} = 0.001, \epsilon_b = 80\%$	0.079%	0.069%	0.064%	0.048%
$V_\mu \bar{f}\gamma^\mu f, V_\mu \bar{f}\gamma^\mu P_R f$	$y_{\text{cut}} = 0.002, \epsilon_b = 70\%$	0.15%	0.097%	0.082%	0.079%
	$y_{\text{cut}} = 0.002, \epsilon_b = 80\%$	0.084%	0.052%	0.046%	0.043%
	$y_{\text{cut}} = 0.001, \epsilon_b = 70\%$	0.072%	0.062%	0.060%	0.054%
	$y_{\text{cut}} = 0.001, \epsilon_b = 80\%$	0.061%	0.053%	0.051%	0.045%

- HL-LHC? Four b -jets, also difficult!

Decay mode $\mathcal{F}_i$	Projected/ current 2σ limit on $\text{Br}(\mathcal{F}_i)$ 7 + 8 [14] TeV	Production mode	Quarks allowed		Qua $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$
			Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br}(\text{non-SM})$ 7 + 8 [14] TeV		
			$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br}(\text{non-SM})}$		
$b\bar{b}b\bar{b}$	0.7 [0.2]	W	0.8	0.9 [0.2]	0

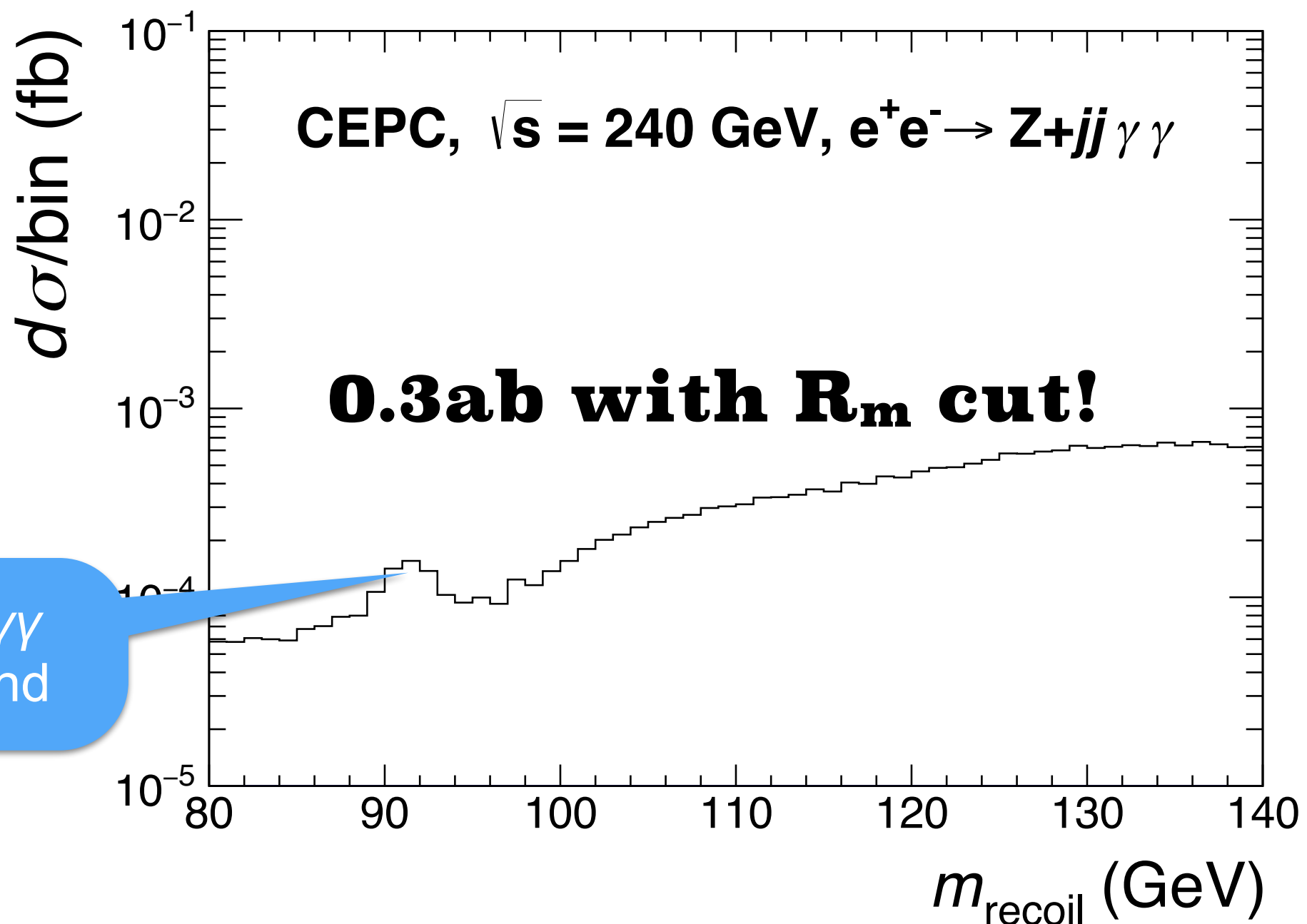






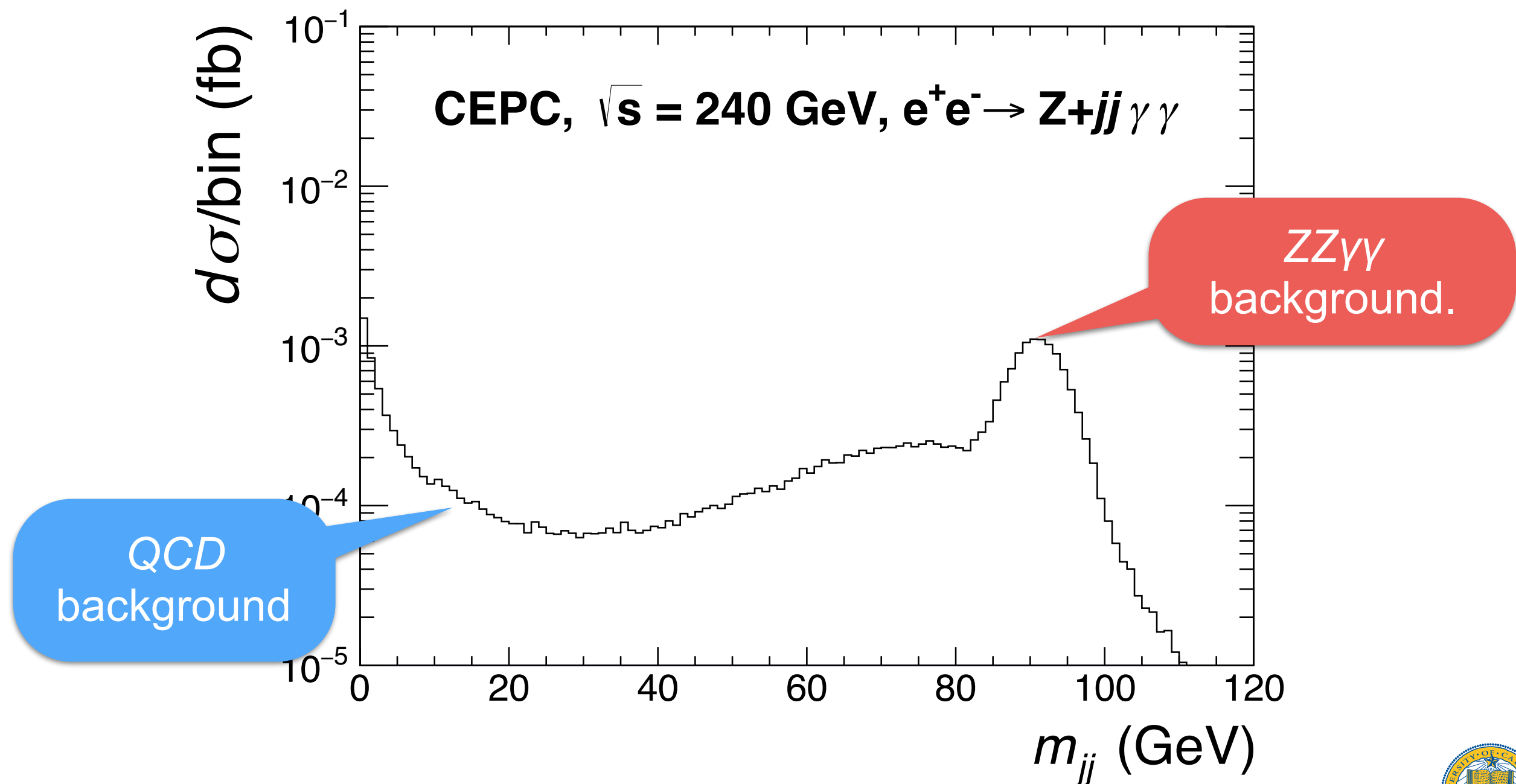
Exotic decay of the SM Higgs boson ($jj\gamma\gamma$)

$y_{\text{cut}}=0.001$



Exotic decay of the SM Higgs boson ($jj\gamma\gamma$)

$y_{\text{cut}}=0.001$



Exotic decay of the SM Higgs boson ($jj\gamma\gamma$)

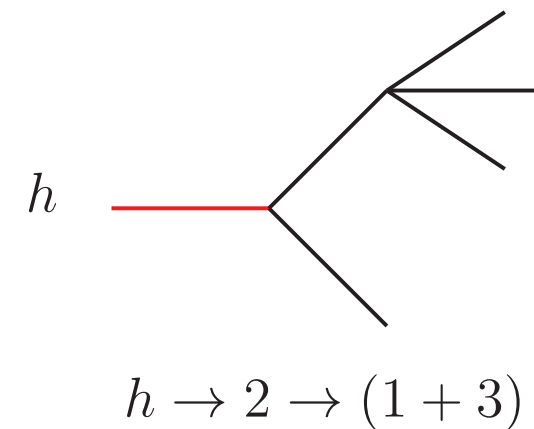
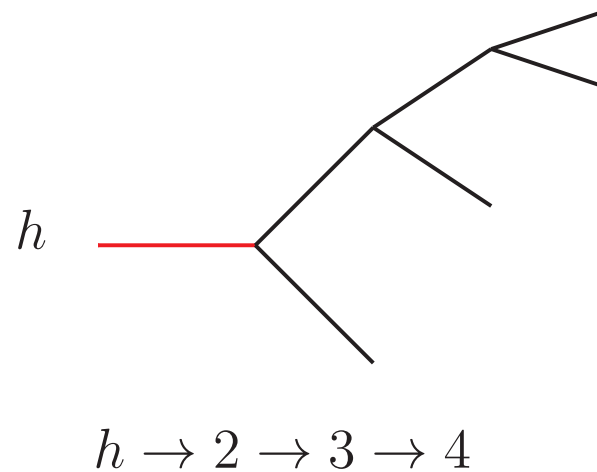
- 3σ sensitivity at 5ab^{-1} CEPC.

m_{med} (GeV)	10	20	25	30	50
$y_{\text{cut}} = 0.002$	0.3%	0.01%	0.009%	0.007%	0.006%
$y_{\text{cut}} = 0.001$	0.04%	0.01%	0.01%	0.009%	0.006%

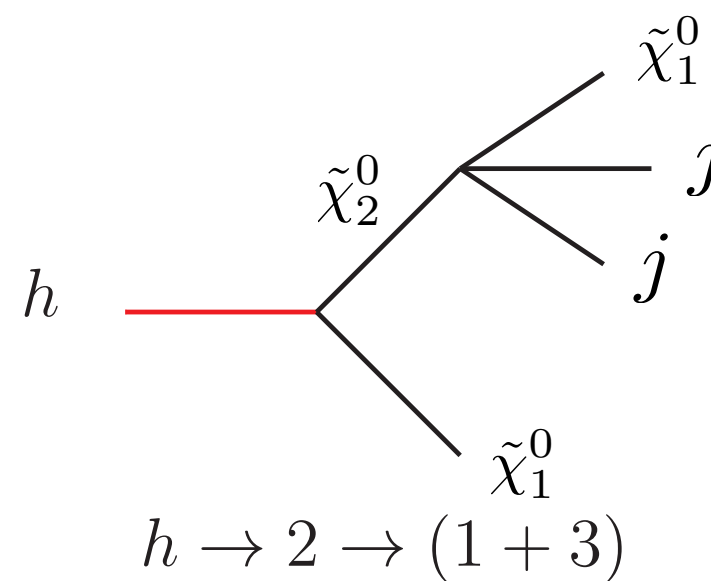
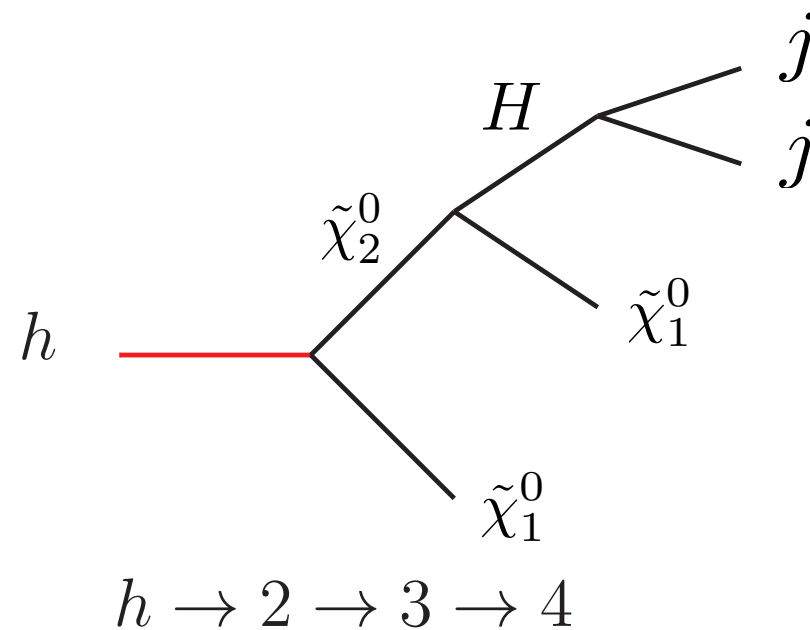


Exotic decay of the SM Higgs boson ($jj+met$)

- Another topology

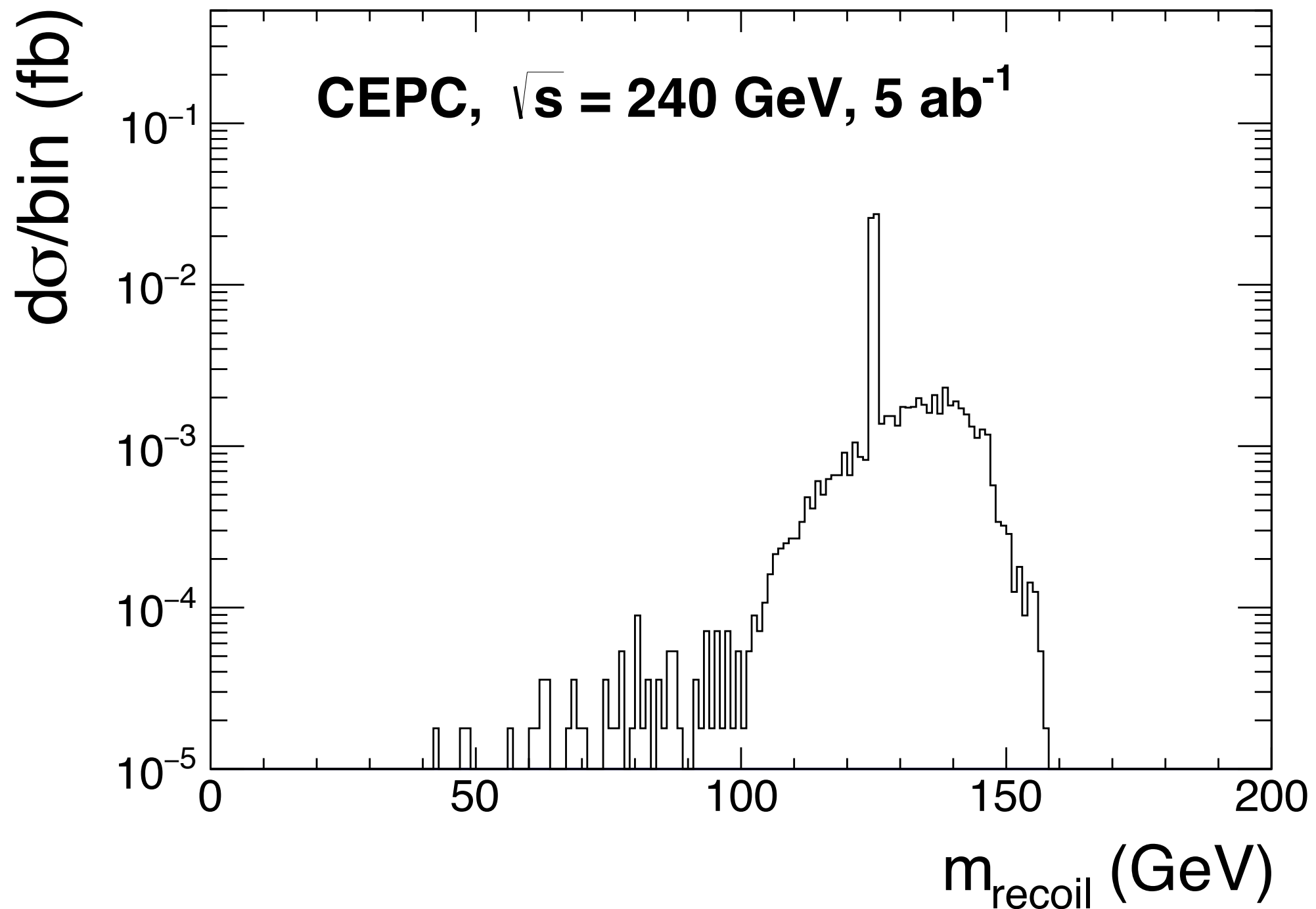


- Benchmark model: supersymmetry.



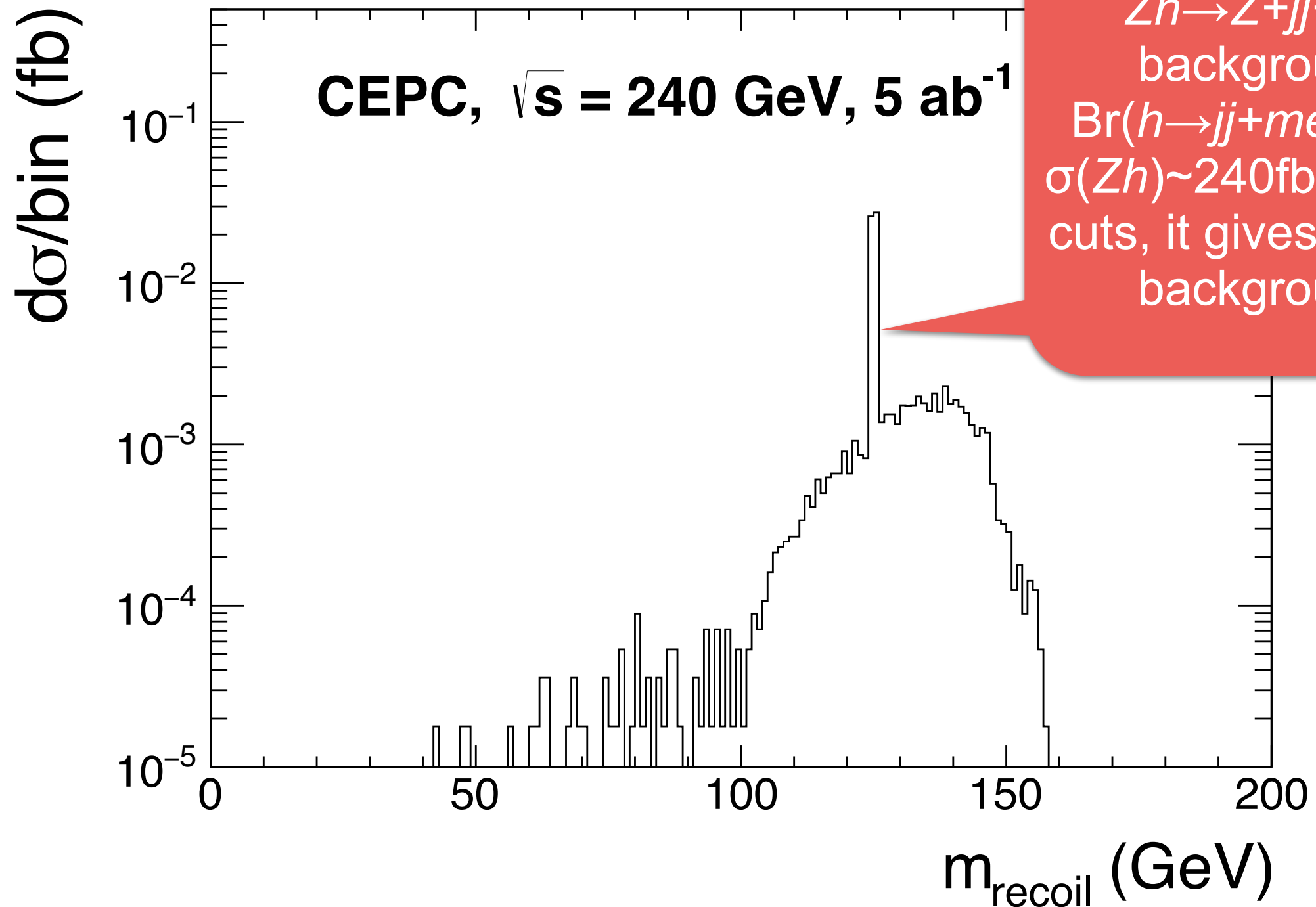
Exotic decay of the SM Higgs boson ($jj+met$)

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



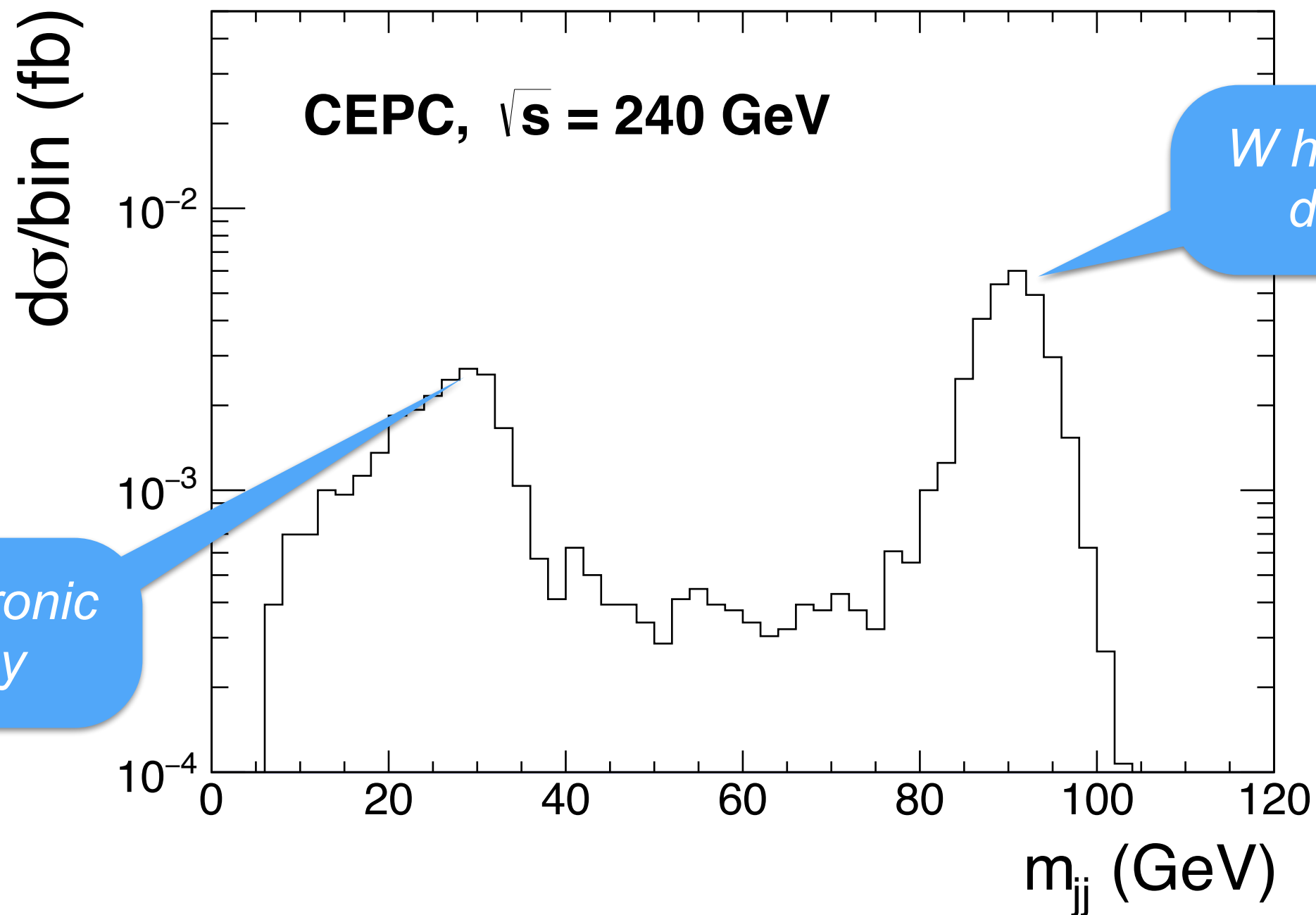
Exotic decay of the SM Higgs boson ($jj+met$)

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



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

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

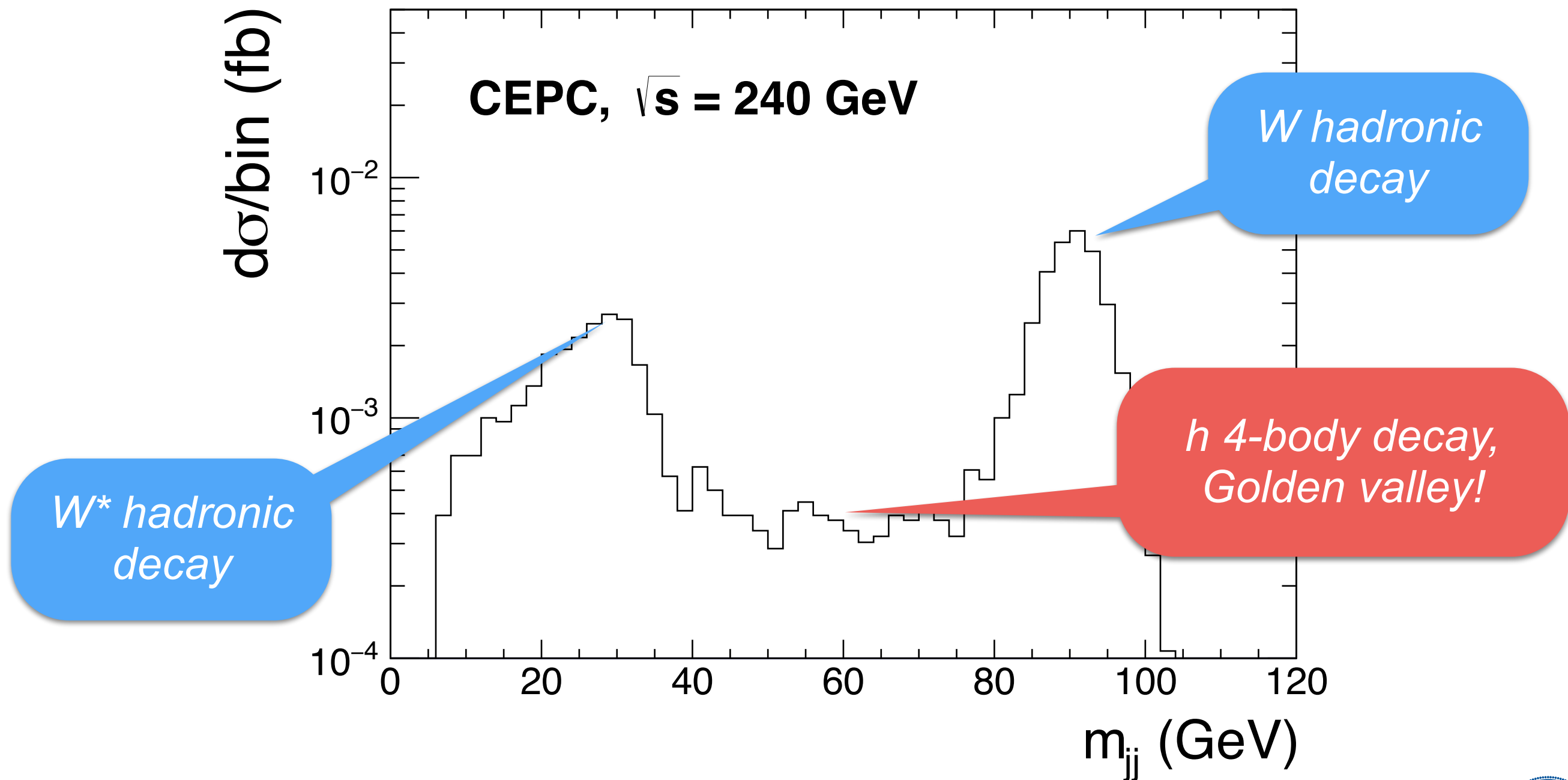


W hadronic
decay*

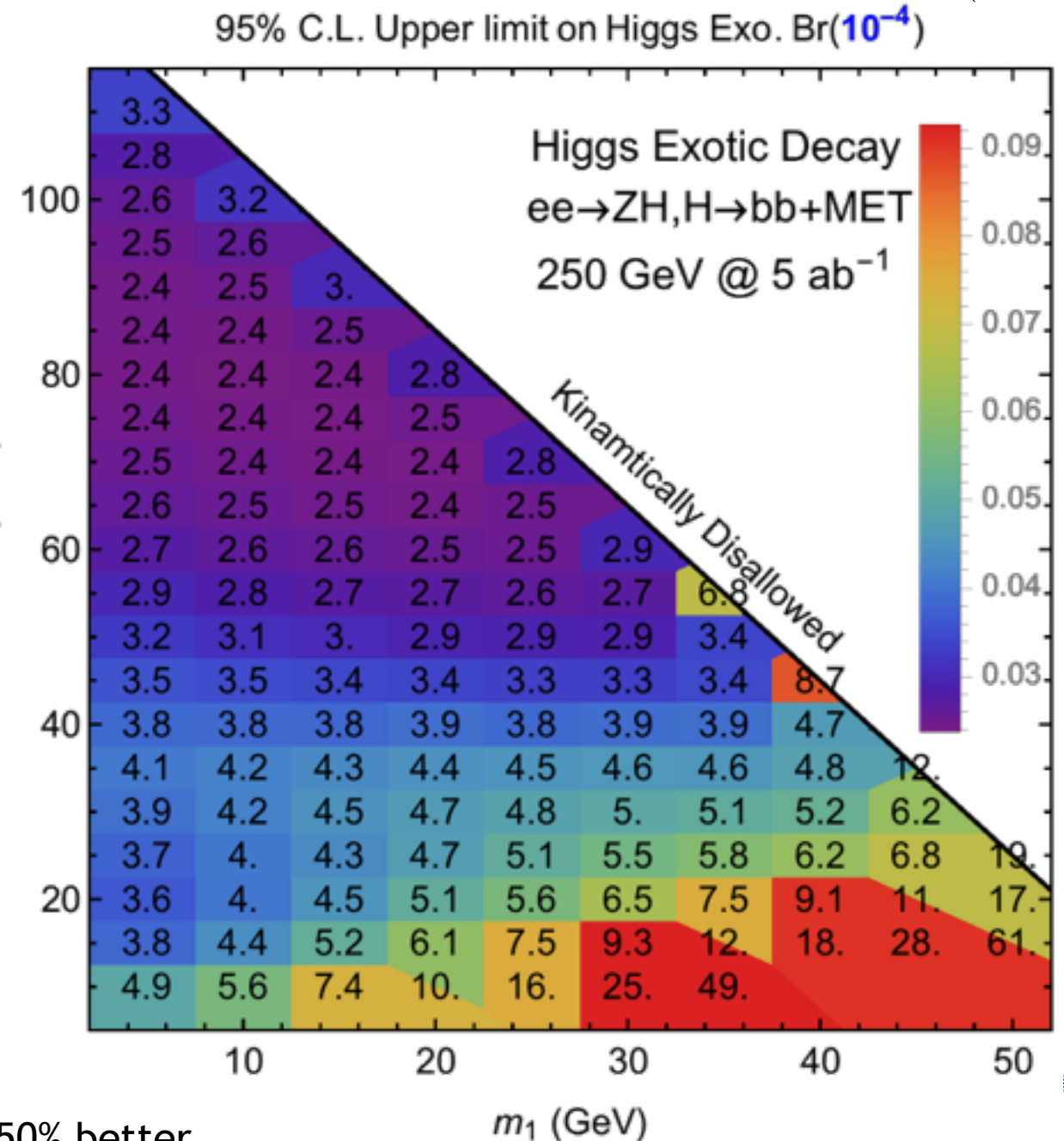
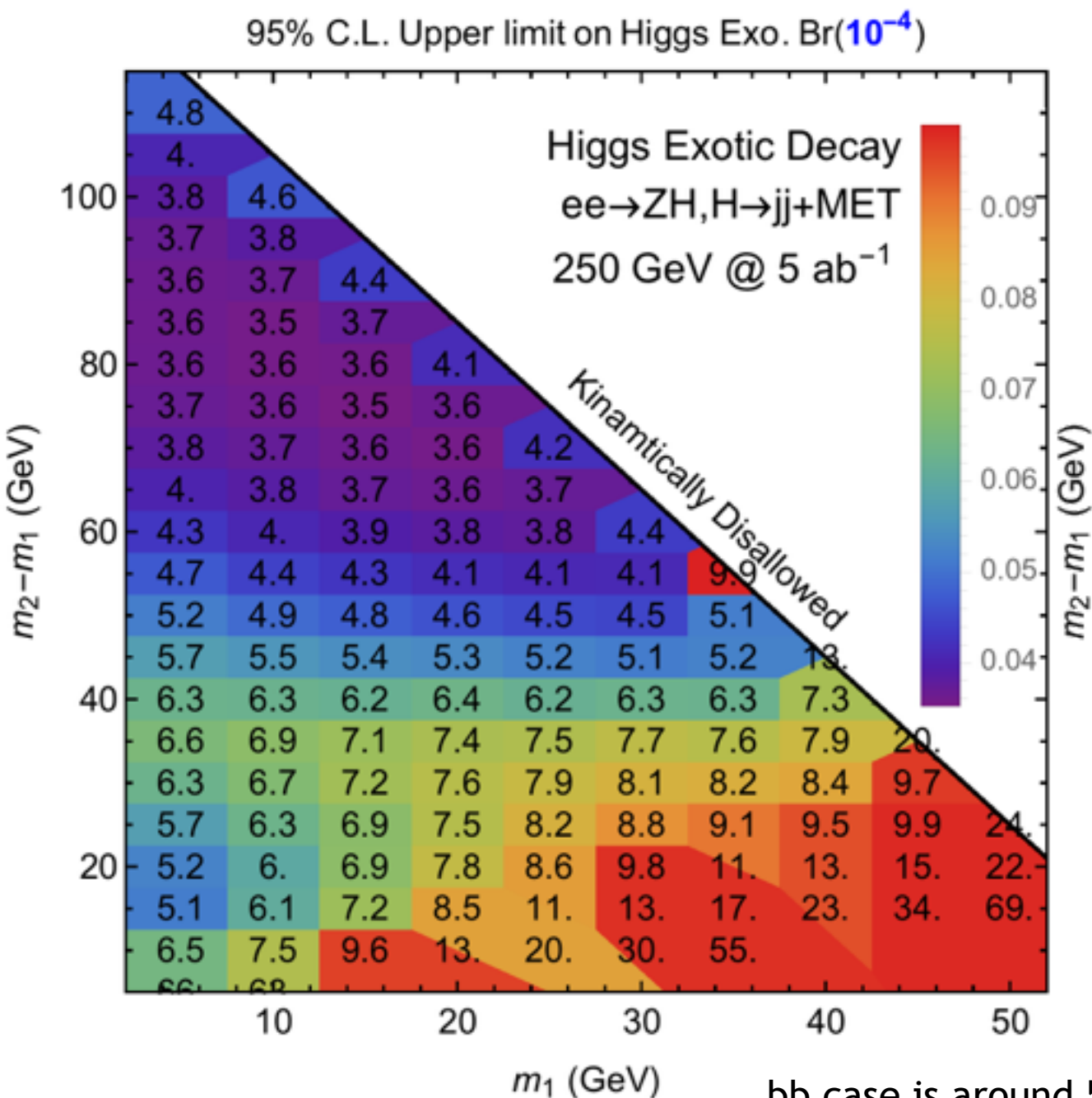
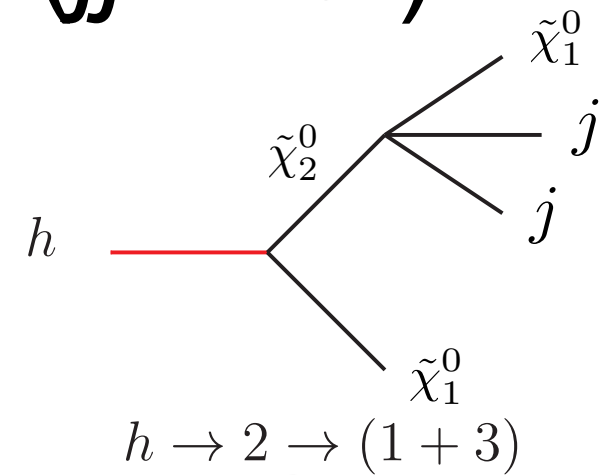
*W hadronic
decay*

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

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



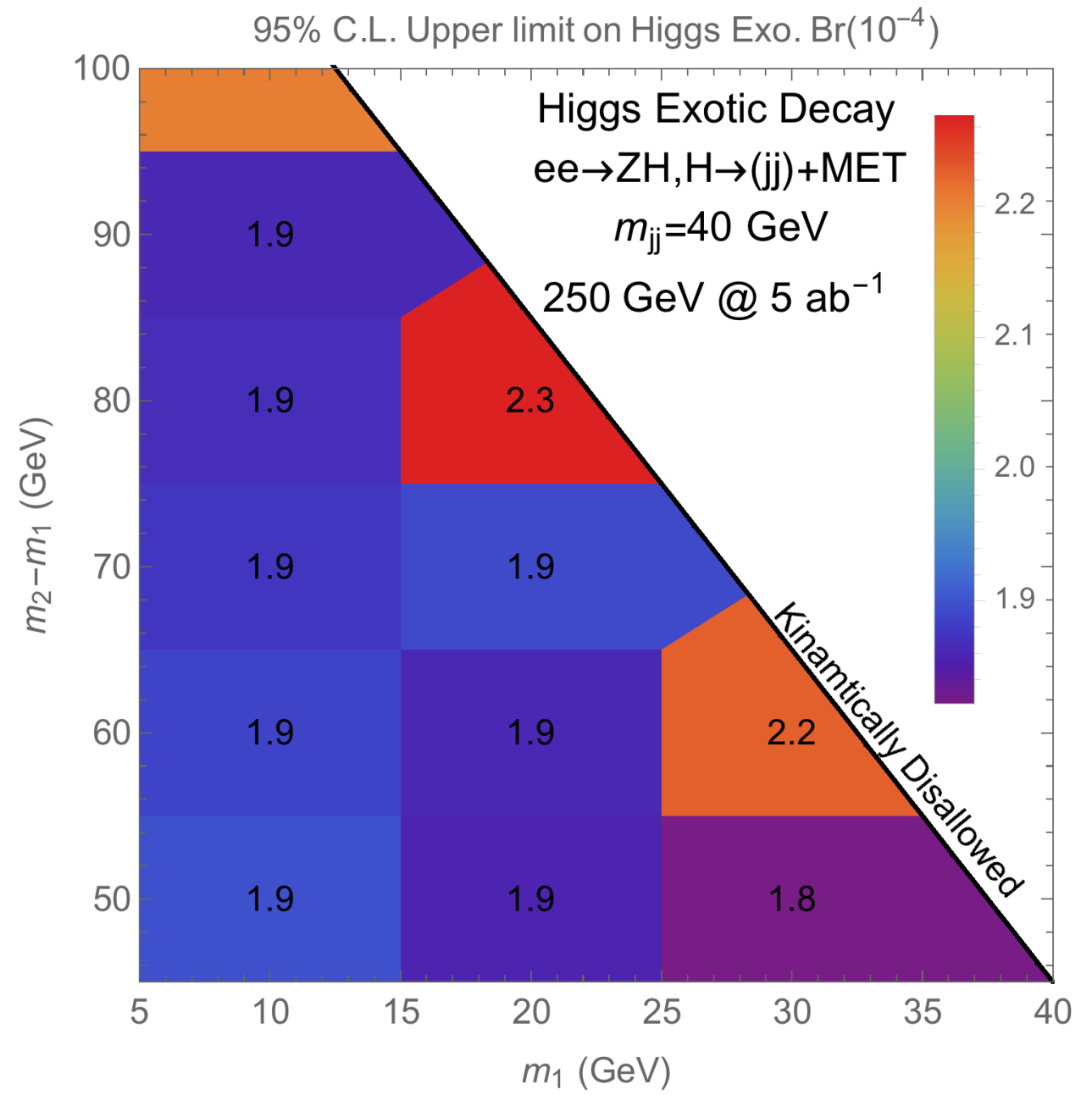
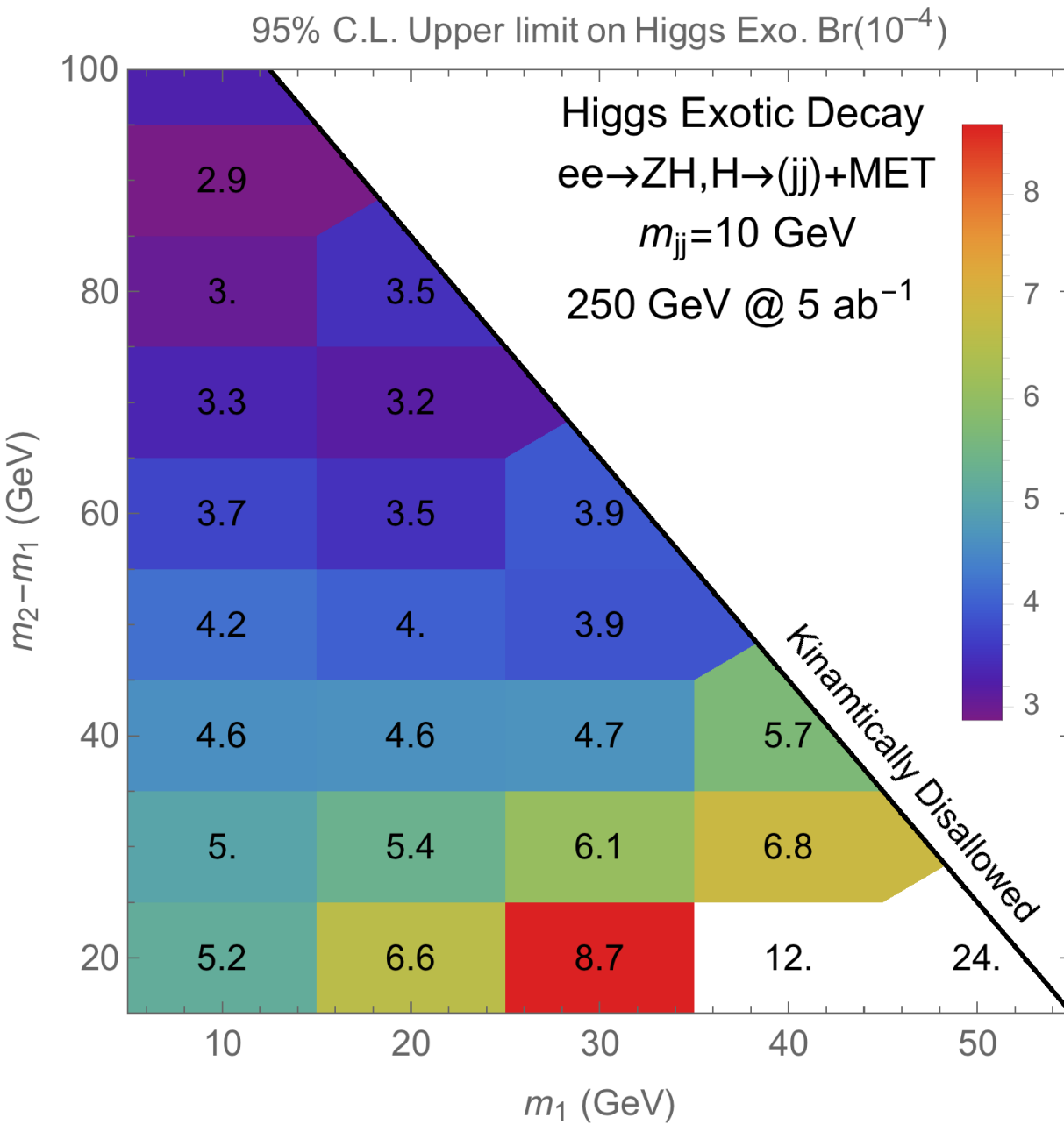
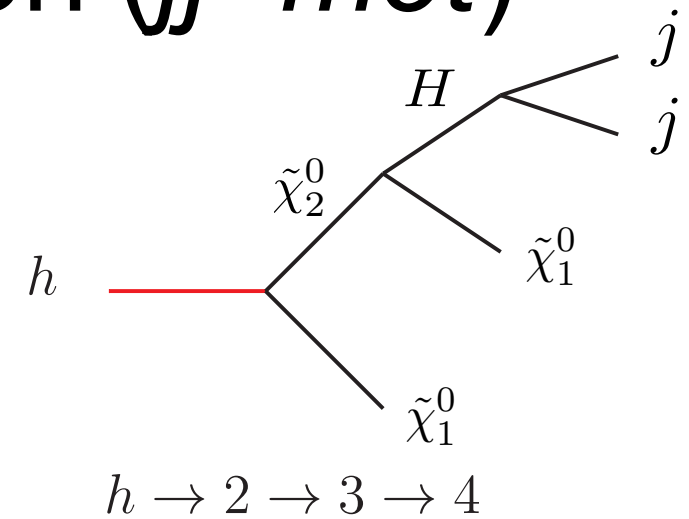
Exotic decay of the SM Higgs boson ($jj+met$)



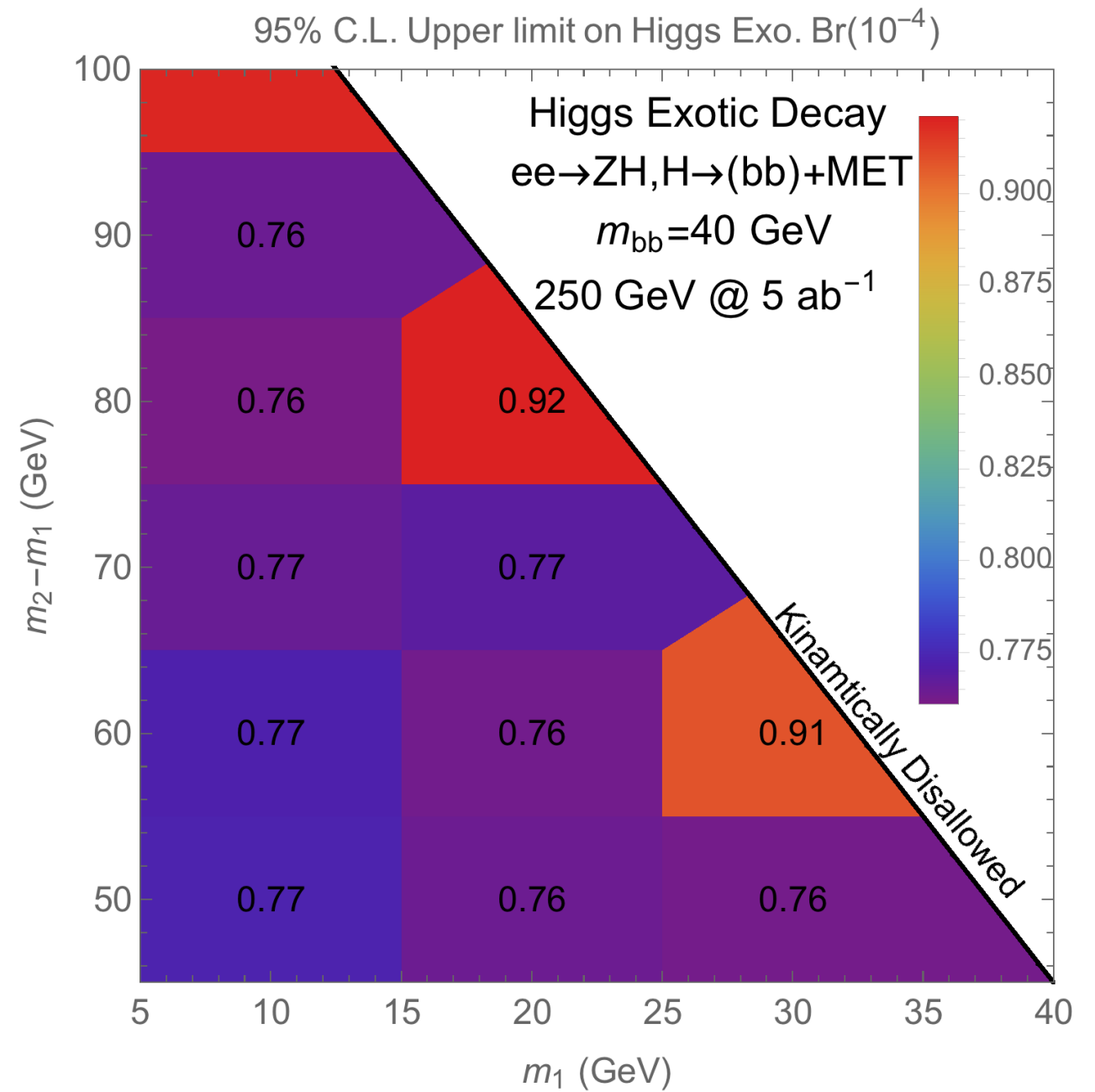
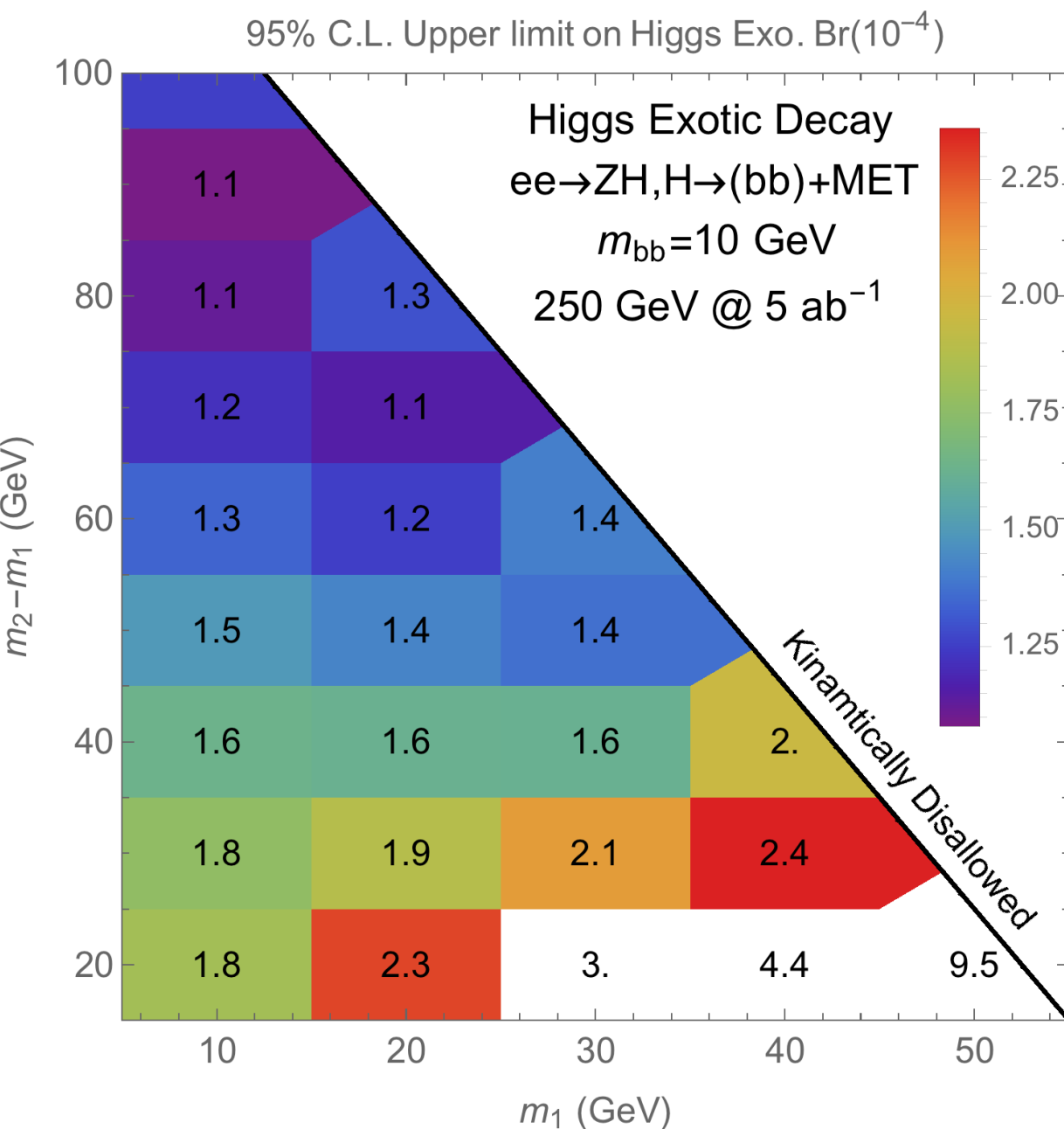
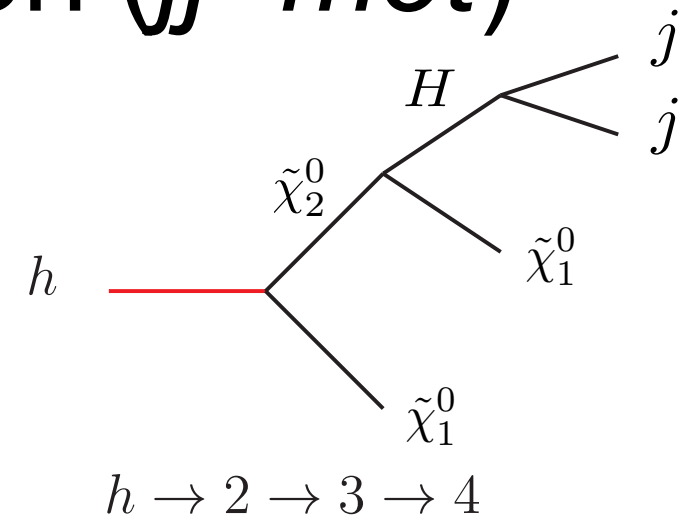
bb case is around 50% better.



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



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



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.
- More channels are in progress.

Thank you!

