Higgs Exotic Decay at e^+e^- Higgs factories

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Based on collaborations with Zhen Liu and Hao Zhang

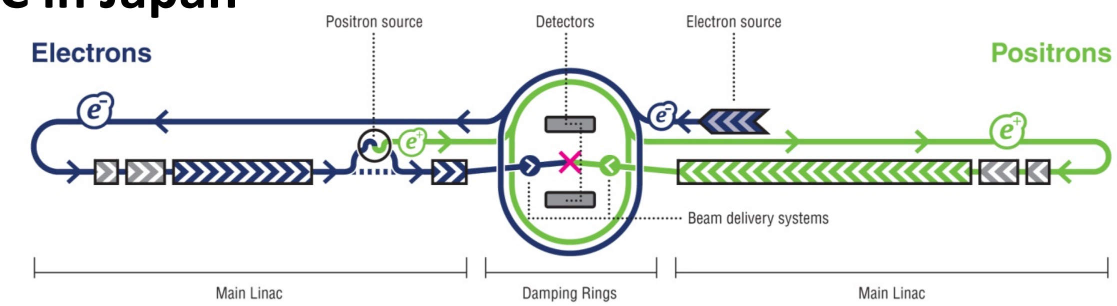
CERN. FCC week. Jan. 18, 2017

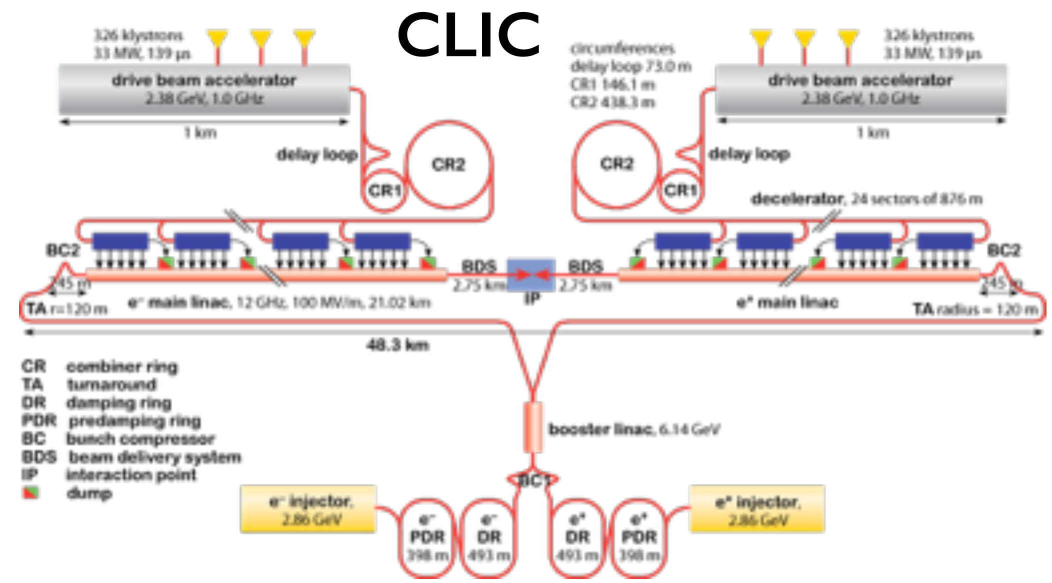
Why Higgs exotic decay?

- It can teach us a lot.
  - Dark sector related to weak scale?
- It can be there.
  - Higgs is a new particle. Couples to almost all known particles. Could couple to unknown particles too.
- It can be significant.
  - From $HH^{\dagger}$ one can build most relevant couplings to the unknown.
  - Higgs SM width is tiny. Exotic decay can have sizable BR.

Higgs factories

ILC in Japan



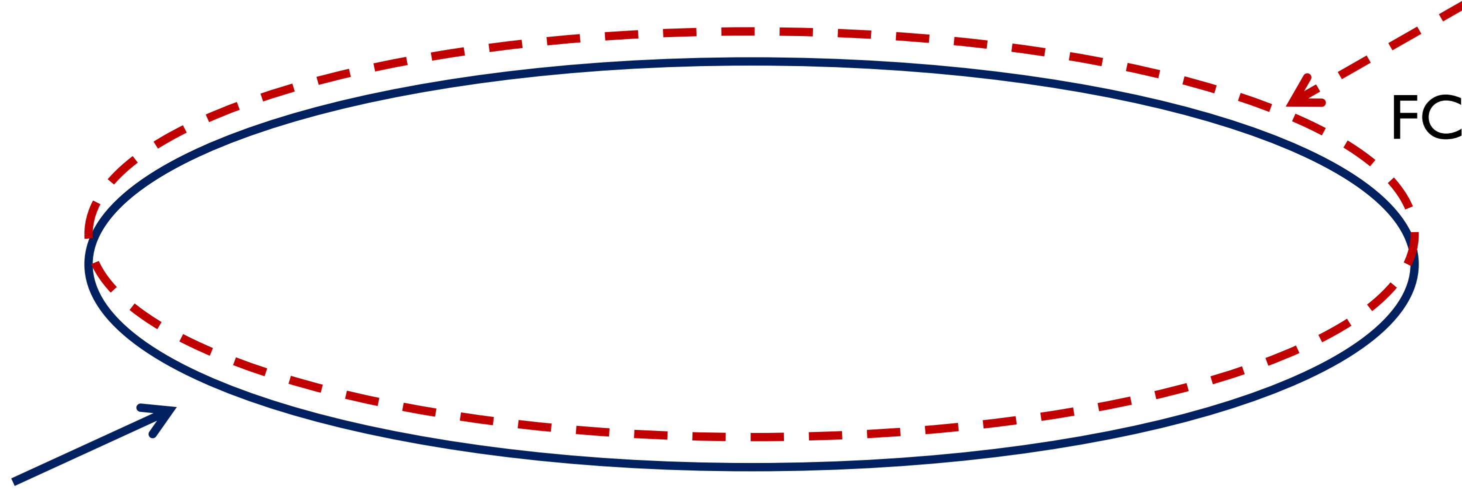


Circular. “Scale up” LEP+LHC

~100 TeV

pp collider

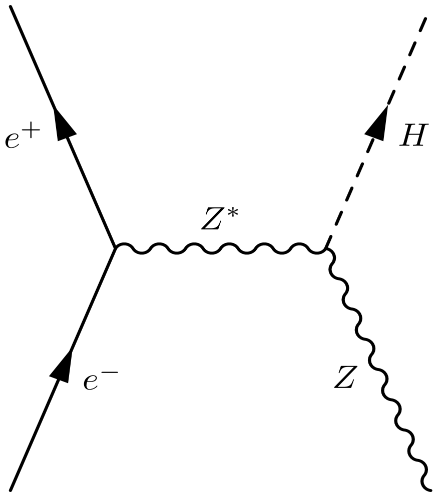
FCC-hh (CERN), SppC(China)

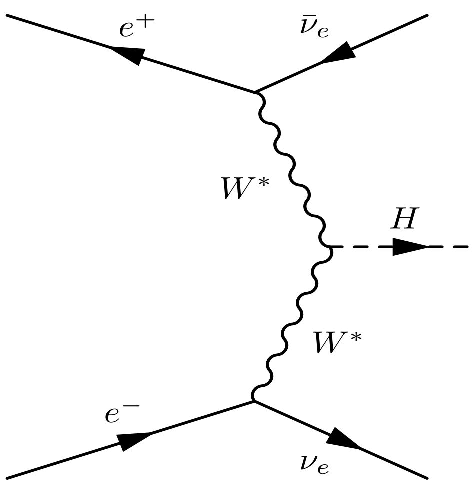


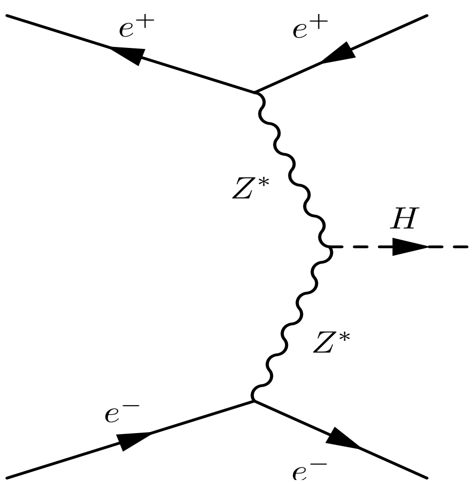
250 GeV **e^-e^+ Higgs Factory**

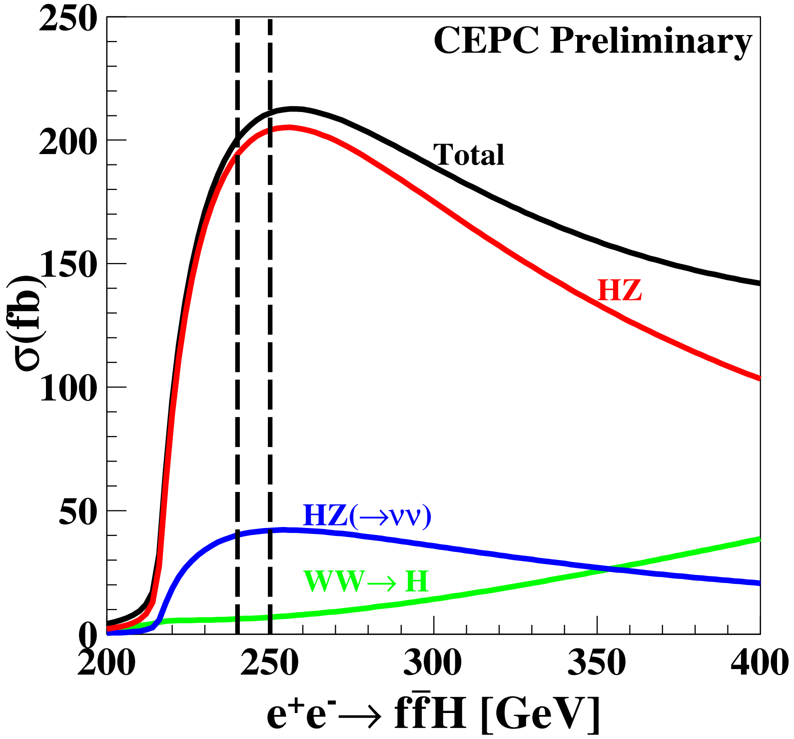
FCC-ee (CERN), CEPC(China)

Higgs factory processes



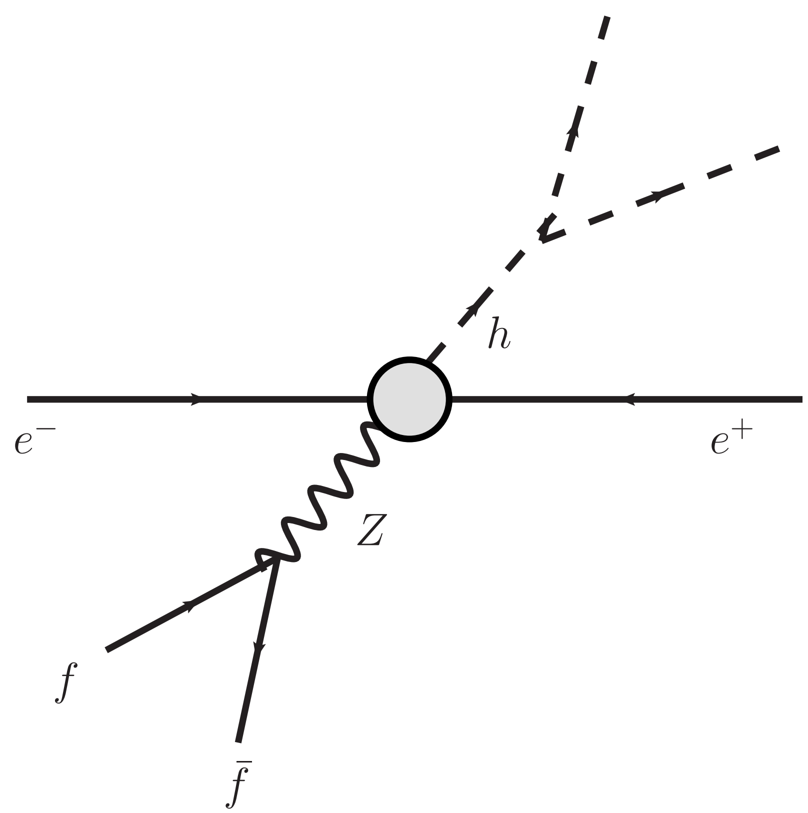


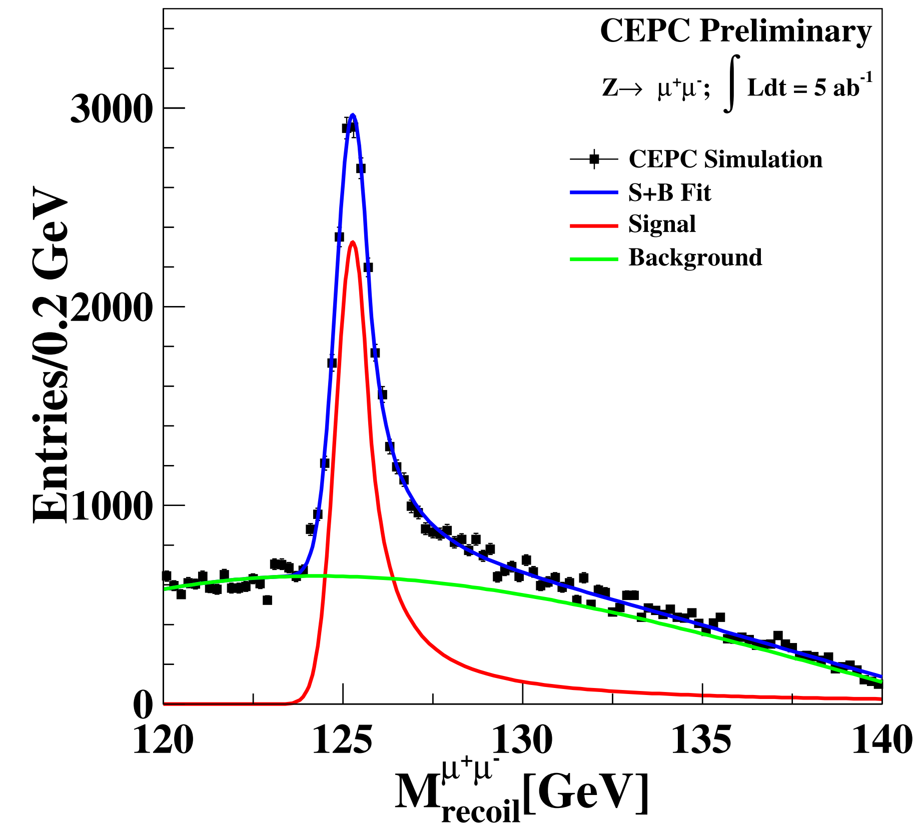




Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6

Zh cross section





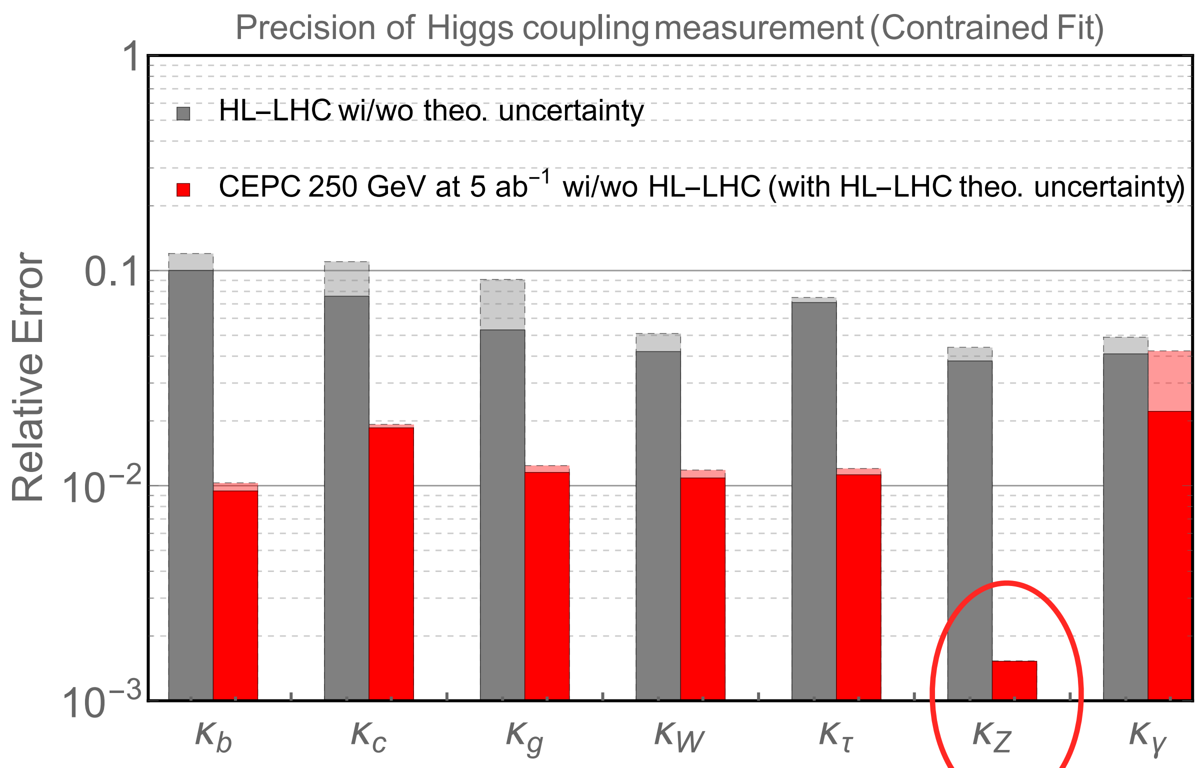
$$M^2_{\rm recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

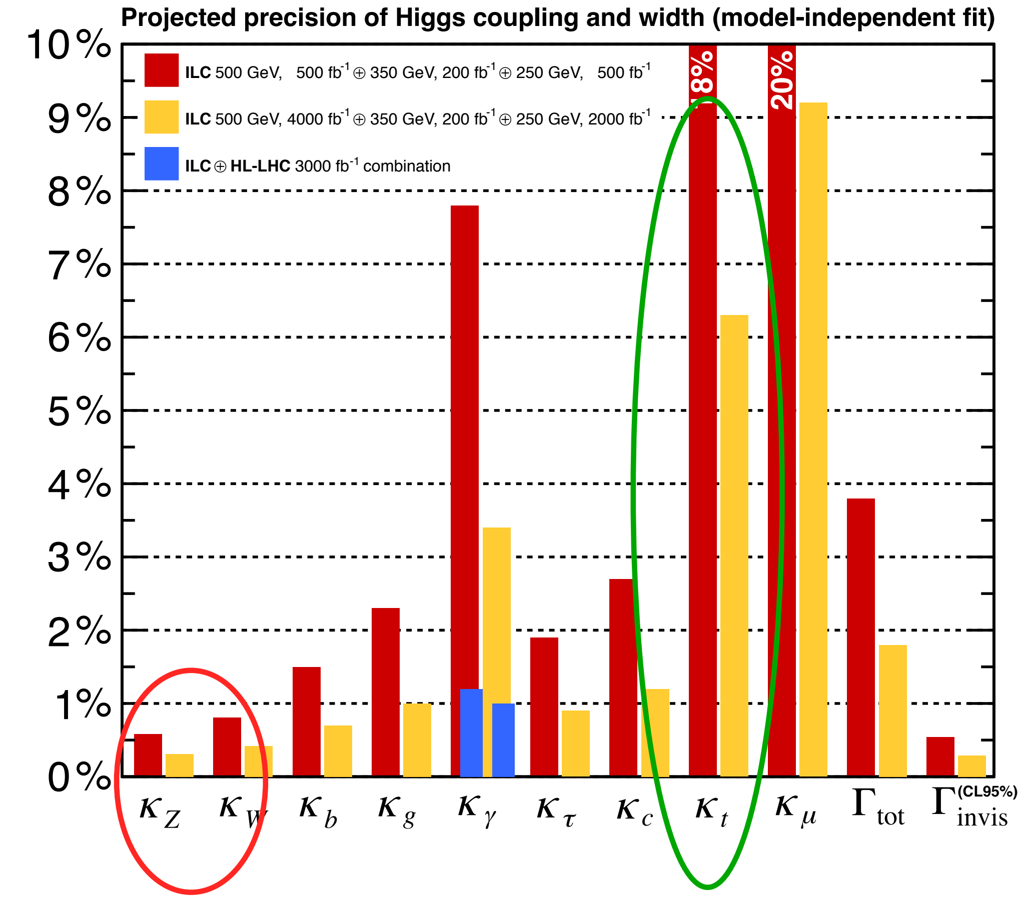
Can use recoil mass to identify Zh process, independent of Higgs decay

⇒ inclusive measurement of Zh cross section

Higgs factories

$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$



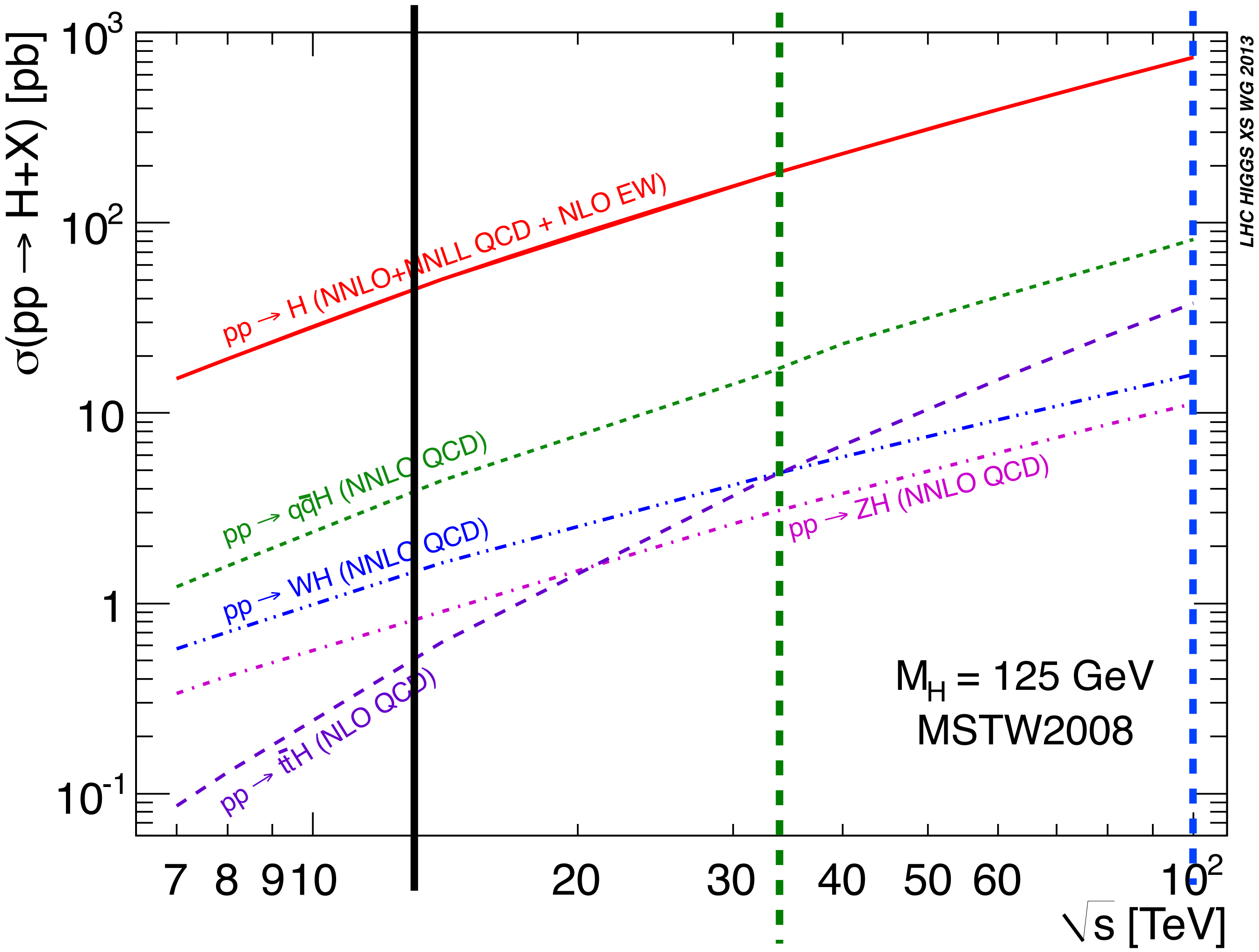


Highlights:

HZ coupling to sub-percent level.
Many couplings to percent level.
Model independent measurement of total width.
Sensitive to the triple Higgs coupling: 20-30%

Hadron collider

- The "ultimate" Higgs factories



# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

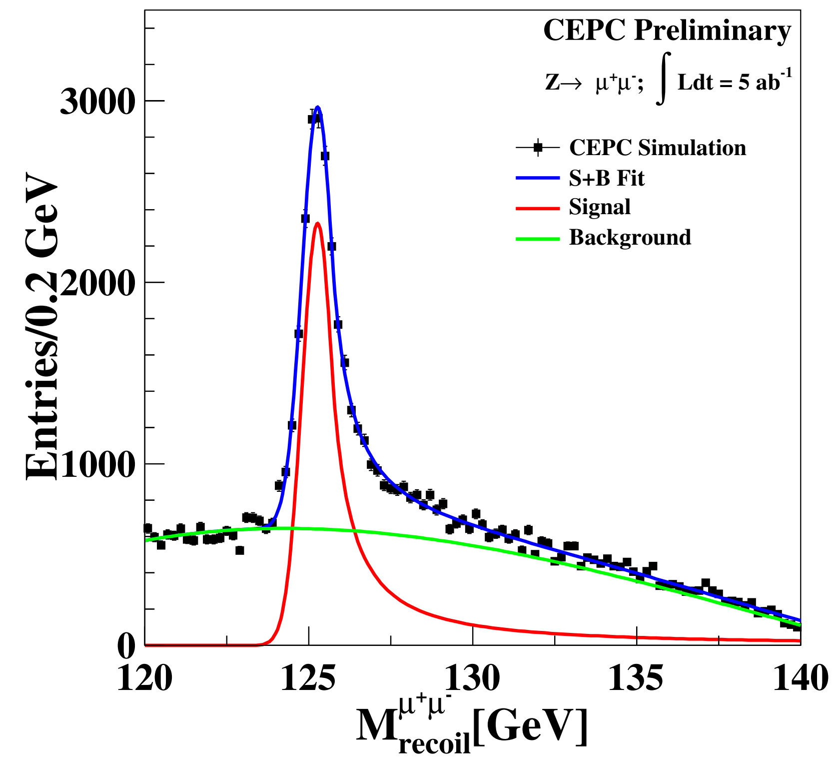
33 TeV > 500 million

14 TeV > 150 million

In comparison, O(million) Higgs at ee Higgs factories

Hadron collider good for rare but clean signal

At ee Higgs factories



- Clean environment. Manageable background.
- Missing mass a powerful tool to tag the Higgs.
  - Very useful in searching for exotic decays.
- Despite of limited statistics, complementary to the LHC.
- Rest of this talk: simple examples as demo

Our starting point.

Zhen Liu, LTW, Hao Zhang, 1612:09284

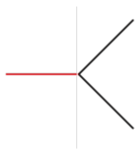
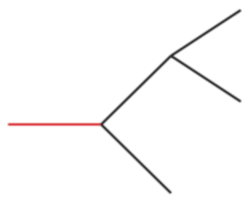
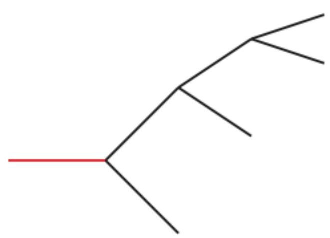
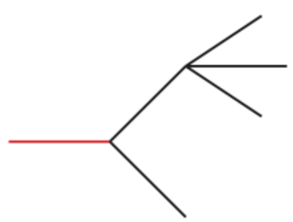
PHYSICAL REVIEW D **90,** 075004 (2014)

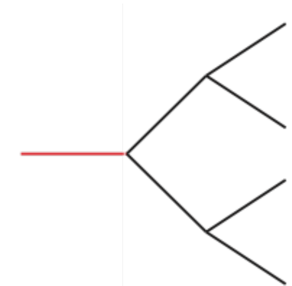
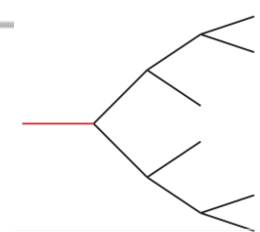
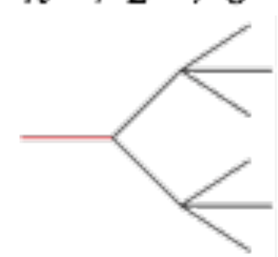
Exotic decays of the 125 GeV Higgs boson

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]

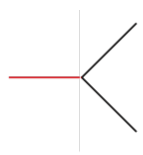
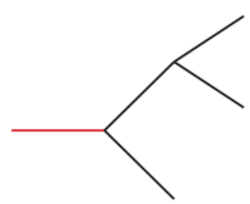
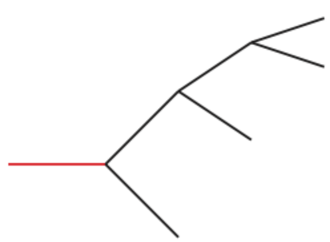
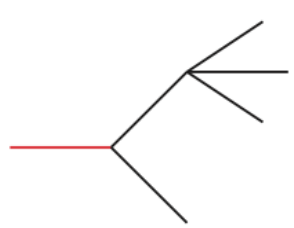
With list of channels
and
preliminary projections

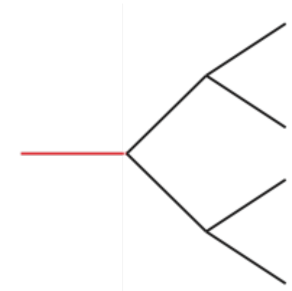
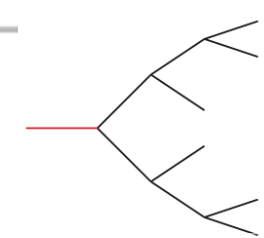
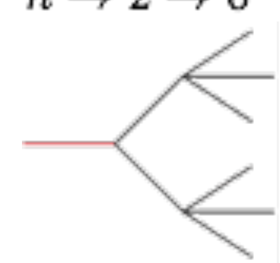
Some possible channels

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

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

Some possible channels

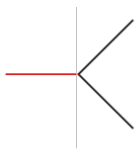
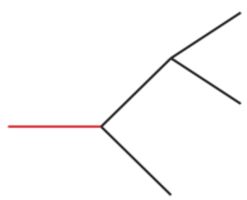
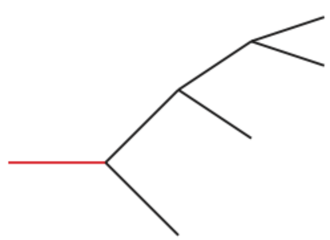
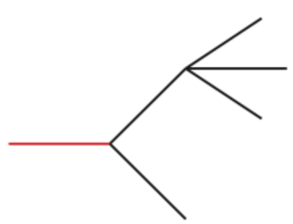
Decay Topologies	Decay mode $\mathcal{F}_i$
 $h \to 2$	$h \to \not{E}_{\mathrm{T}}$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_{\mathrm{T}}$
	$h \to (b\bar{b}) + \not{E}_{\mathrm{T}}$
	$h \to (jj) + \not{E}_{\mathrm{T}}$
	$h \to (\tau^+\tau^-) + \not{E}_{\mathrm{T}}$
	$h \to (\gamma\gamma) + \not{E}_{\mathrm{T}}$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

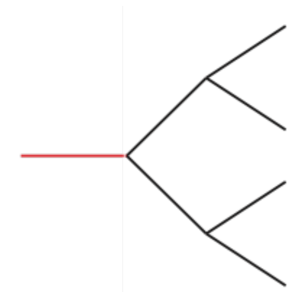
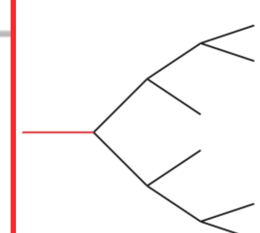
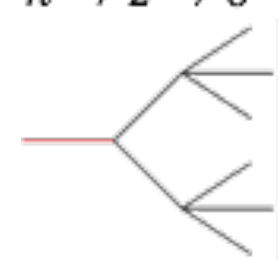
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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

adapted from slides of Zhen Liu

Good sensitivity from the LHC

Some possible channels

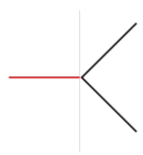
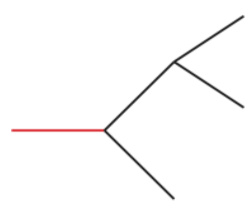
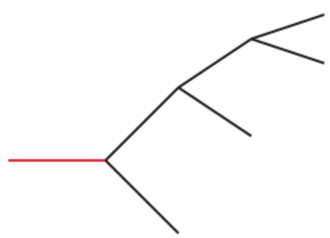
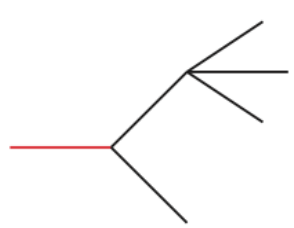
Decay Topologies	Decay mode $\mathcal{F}_i$
 $h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to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

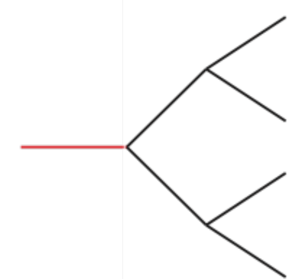
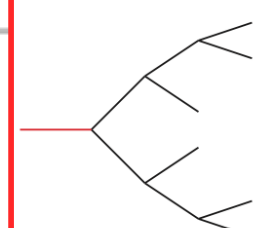
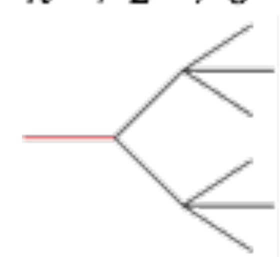
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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

With MET, less lepton

Great sensitivity from the LHC

Some possible channels

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

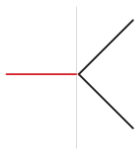
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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

More hadronic

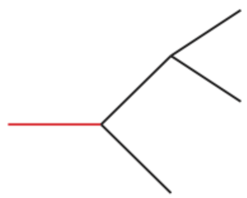
With MET, less lepton

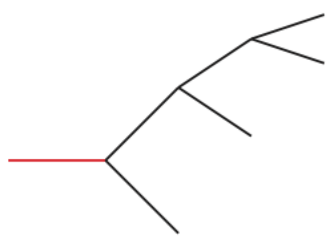
Great sensitivity from the LHC

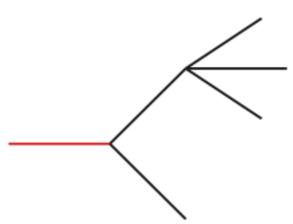
Some possible channels



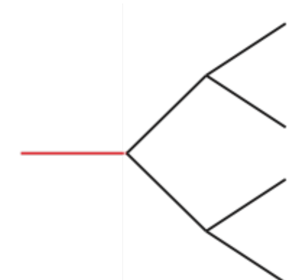
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$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

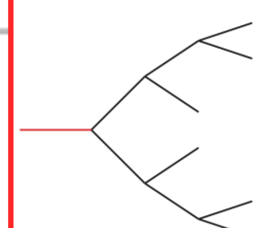


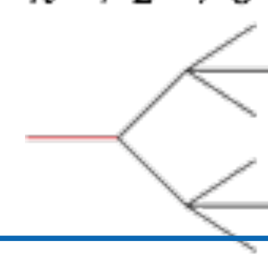




Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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







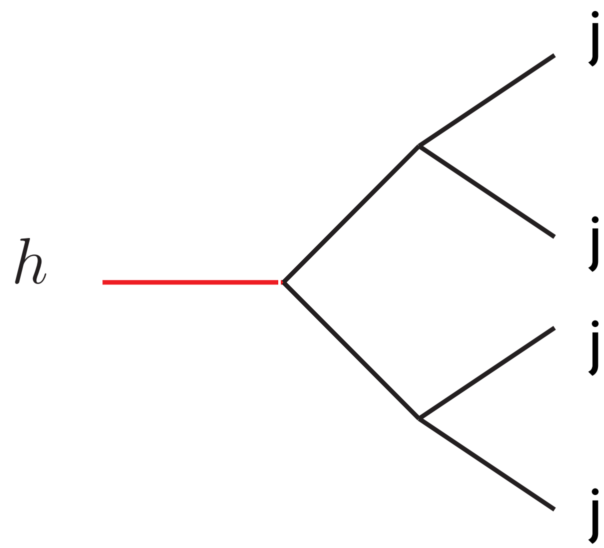
Strong areas of Higgs factories

More hadronic

With MET, less lepton

Great sensitivity from the LHC

Example 1 (hadronic)



$h \to 2 \to 4$

Signal at Higgs factories

ee → Zh → Z jjjj

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.*

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

Note: boosted analysis, assuming m_a < 10 GeV.
Weaker limit other wise.

Cuts and simulation.

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

  Similar to some LEP analysis

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

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

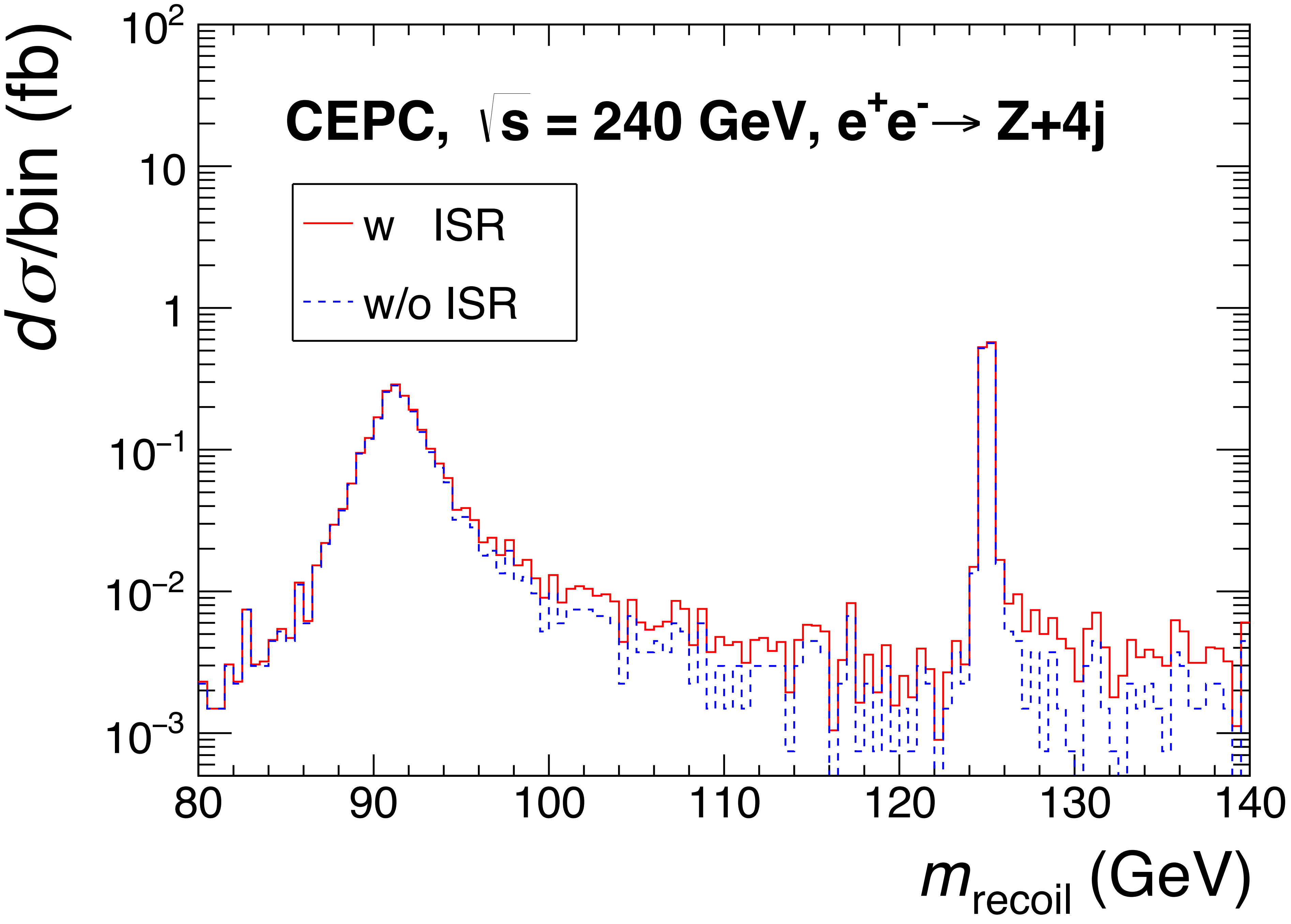
  $|m_{\ell\ell} - m_Z| < 10\text{GeV}, |m_{\text{recoil}} - m_h| < 5\text{GeV}.$

- MadGraph5_aMC@NLO.

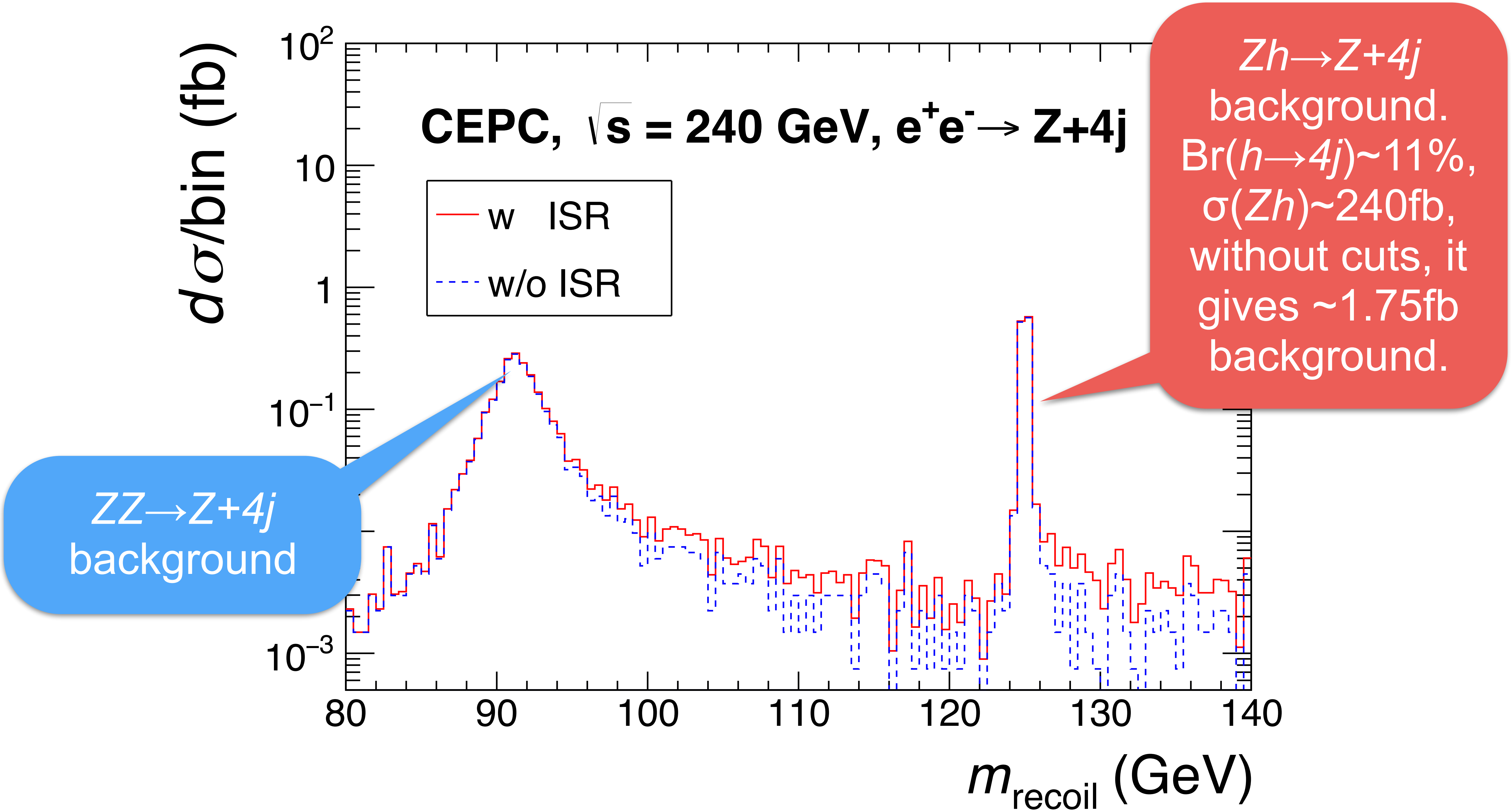
- The ISR effect of the background is roughly mimicked by generating events with 1 additional photon (with pT>1GeV to avoid the IR divergence).

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

SM background

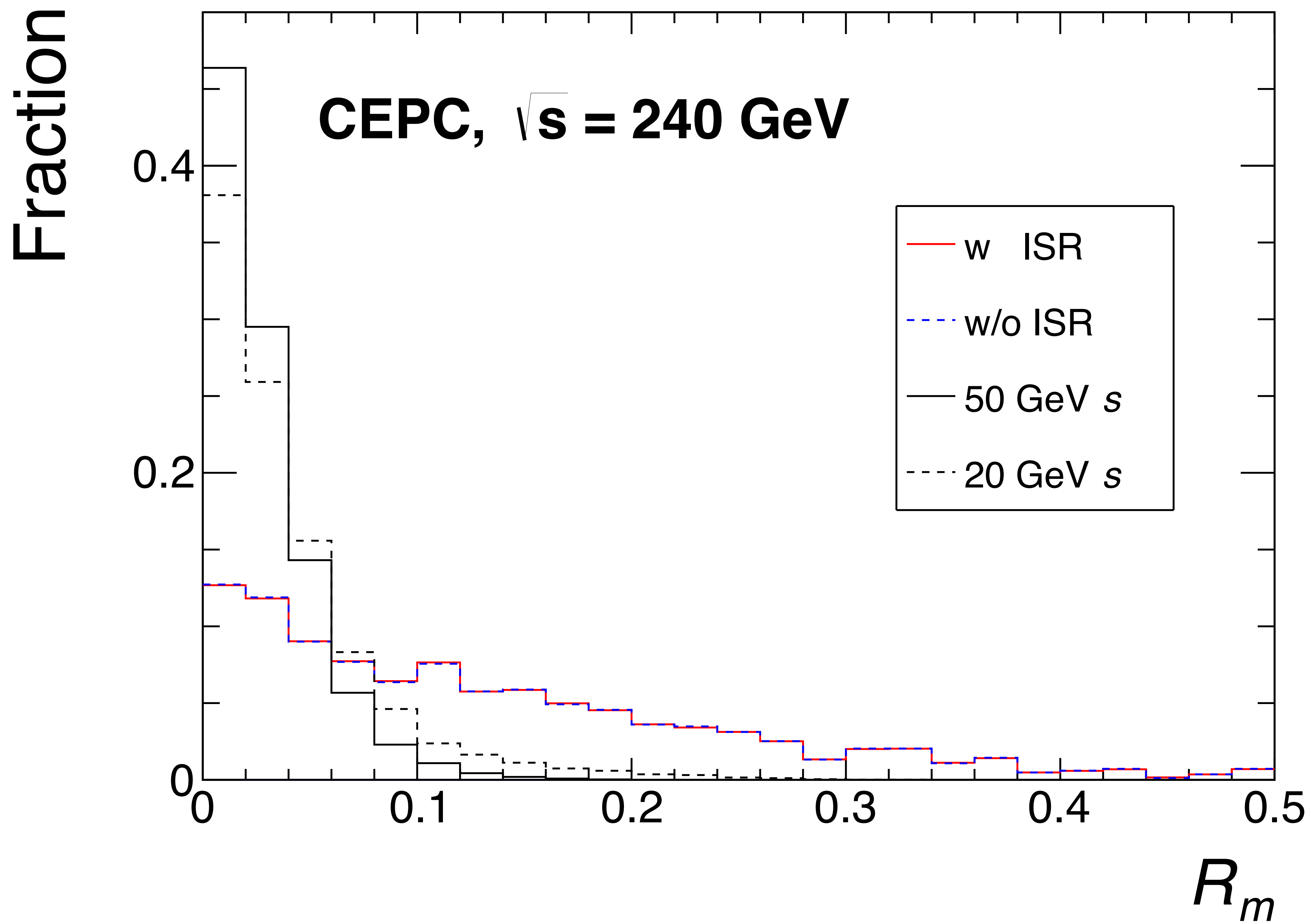


SM background



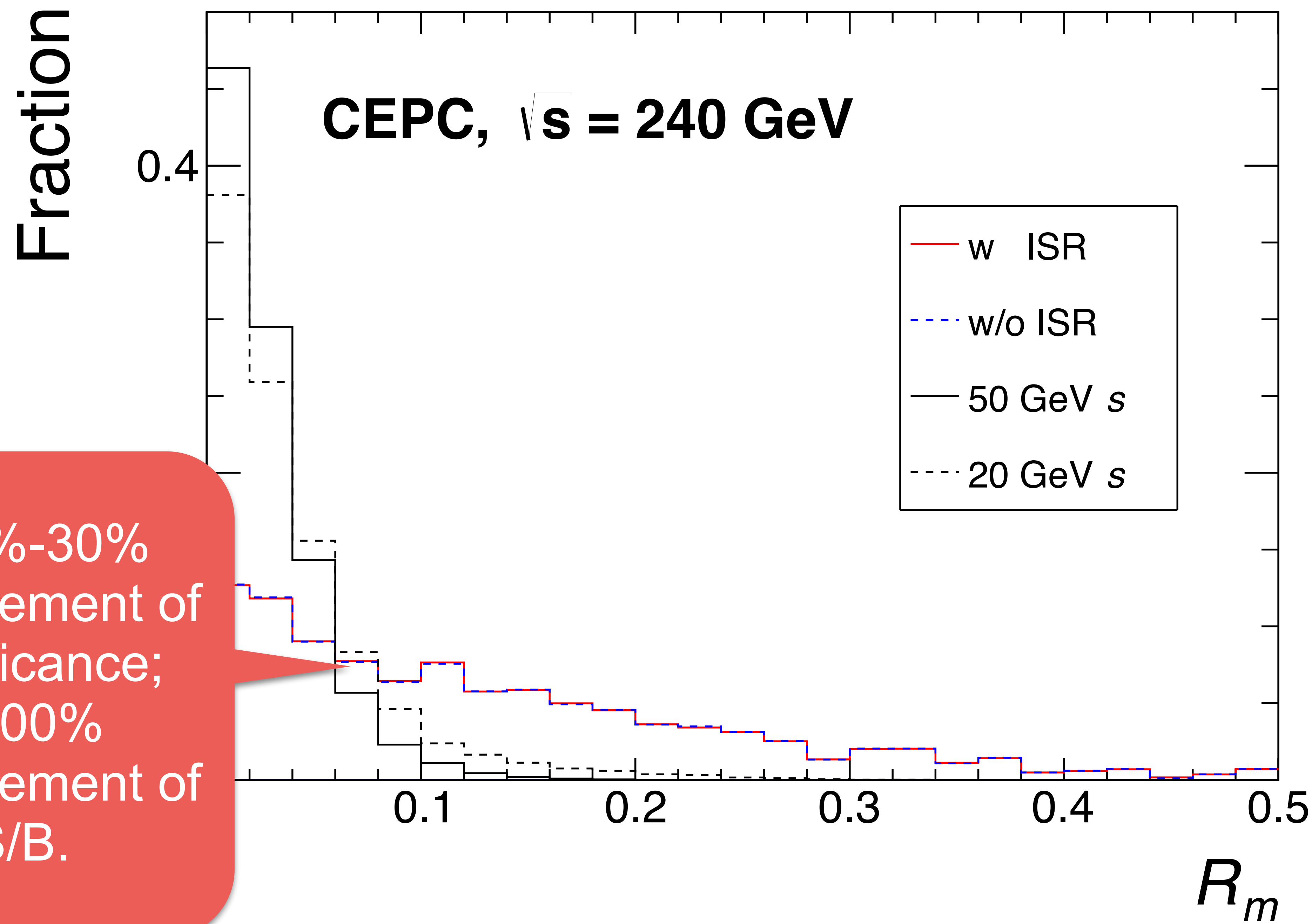
Additional simple cut

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

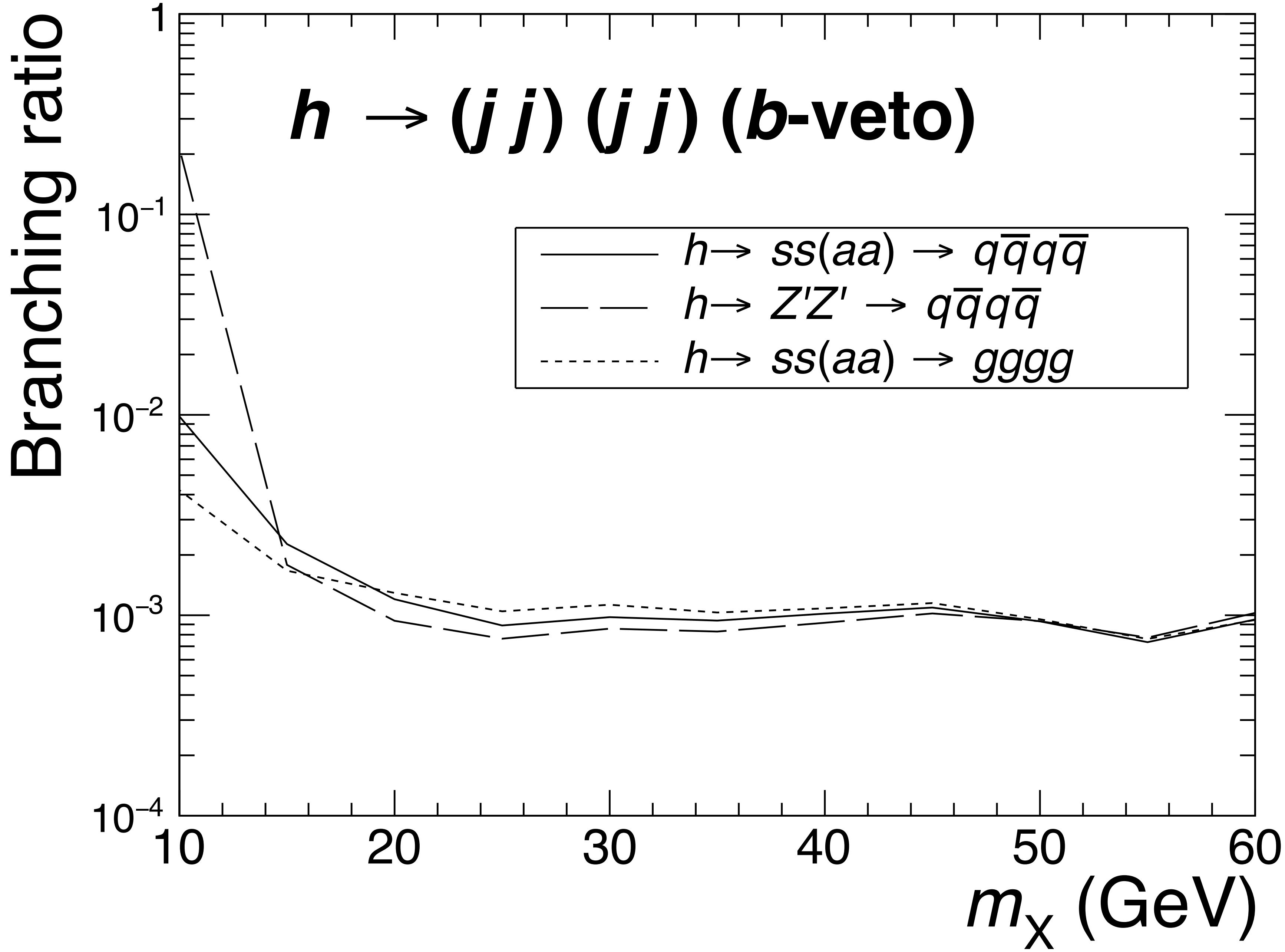


Additional simple cut

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



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

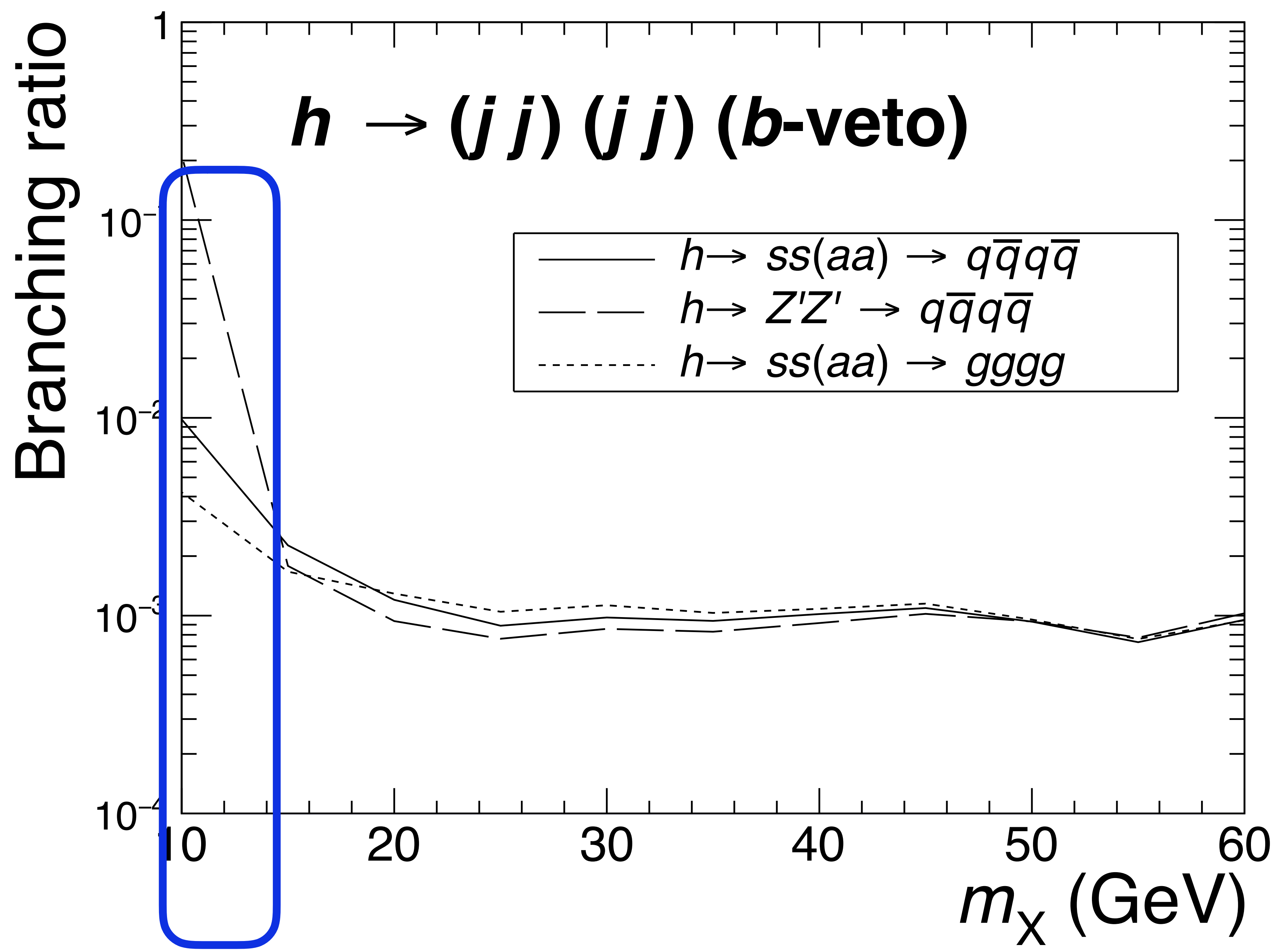


X=s, a, Z'…

Precision at level about 0.1%.

In comparison, O(1) for LHC

Can be improved further with reconstructing a resonance.

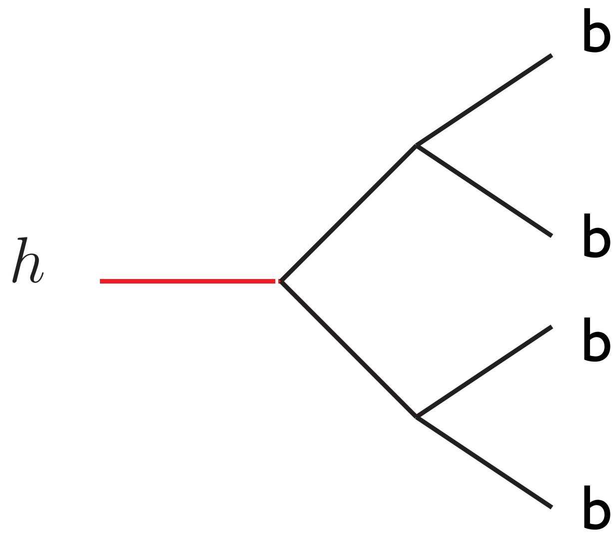


X=s, a, Z'…

need to supplement this with a boosted analysis
similar improvement expected.

Precision at level about 0.1%.
In comparison, O(1) for LHC
Can be improved further with reconstructing a resonance.

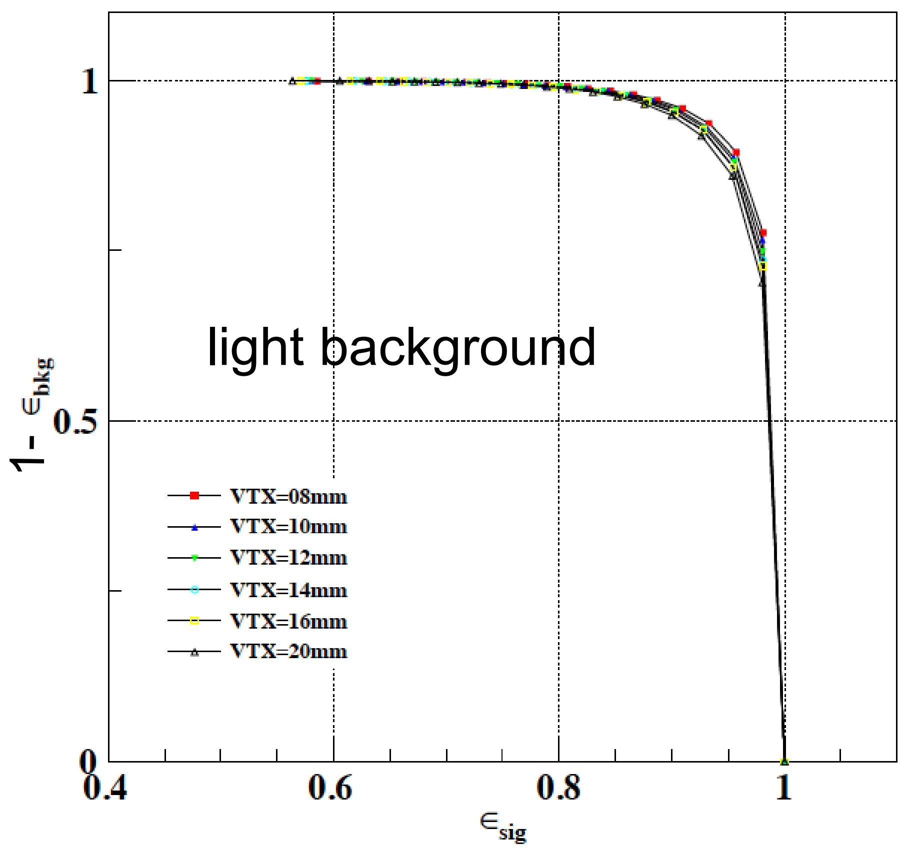
4 bottom final state

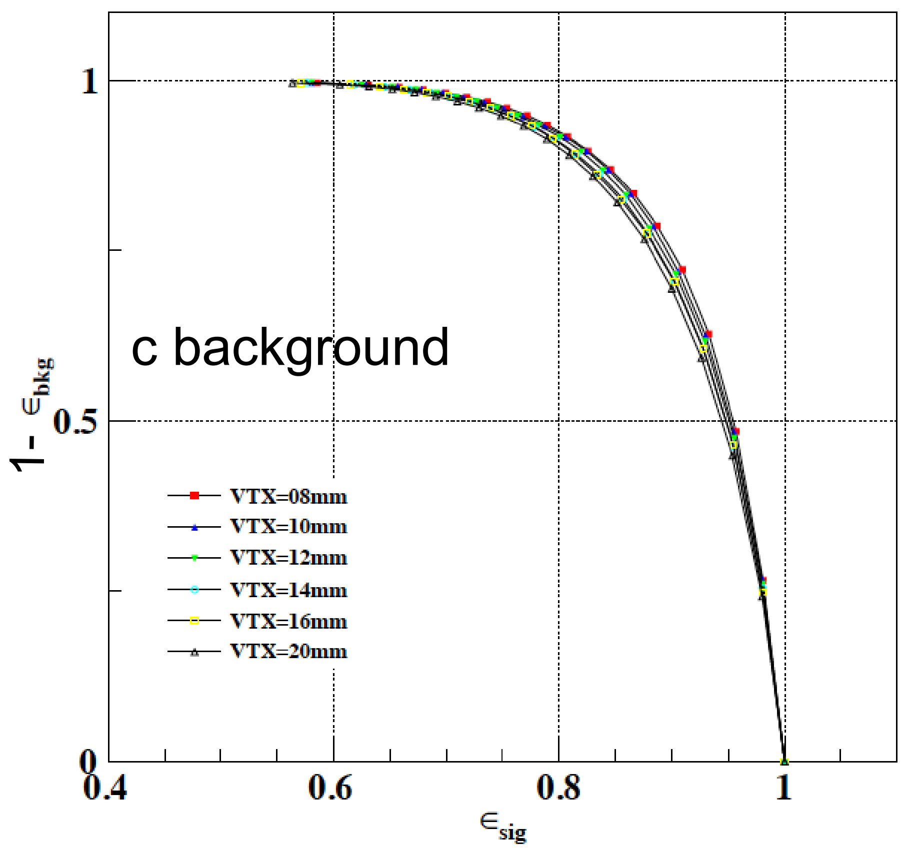


$$h \to 2 \to 4$$

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

Good b(c)-tagging performance.

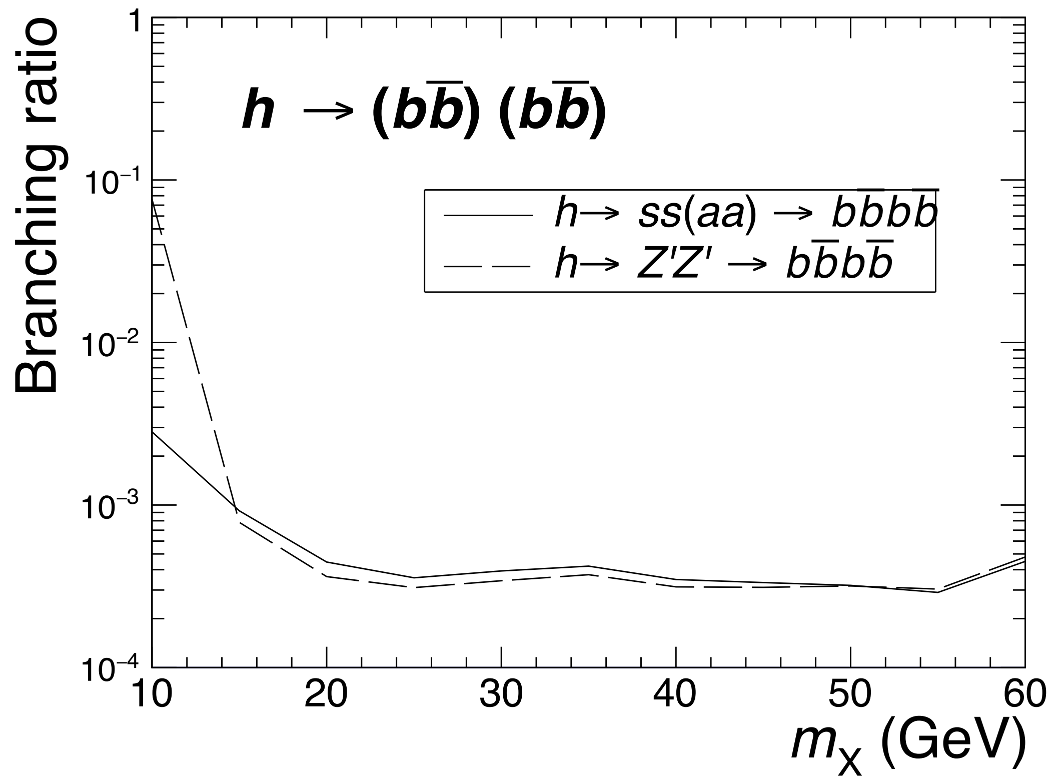


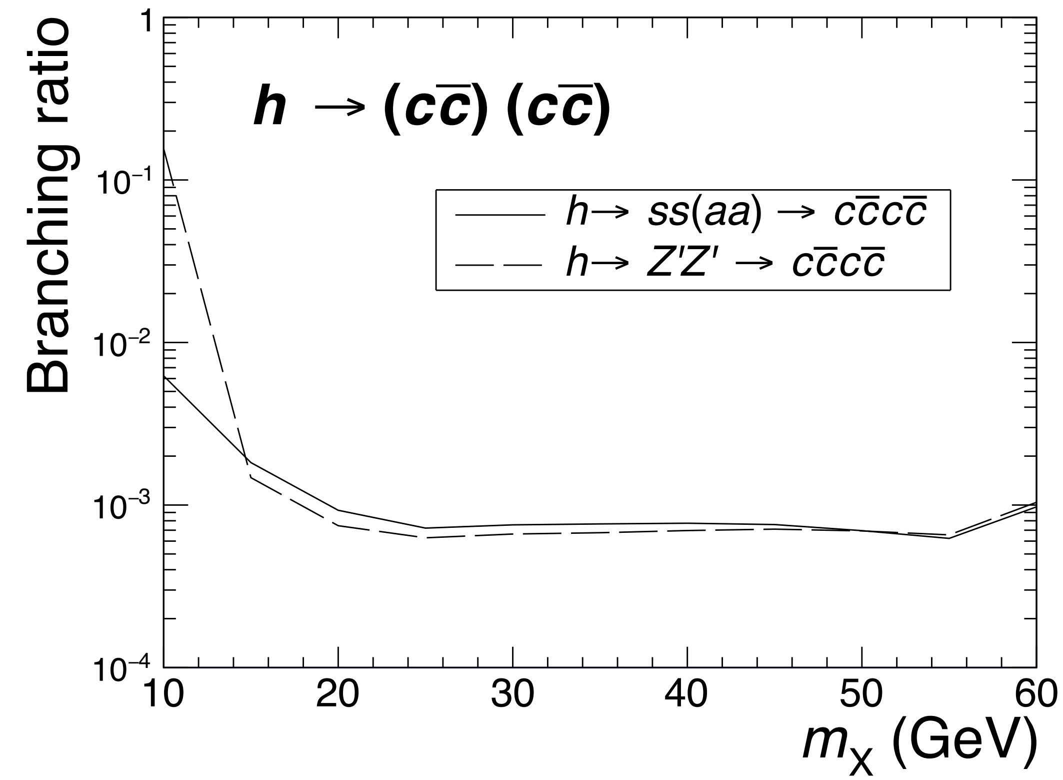


Gang Li

- *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).*

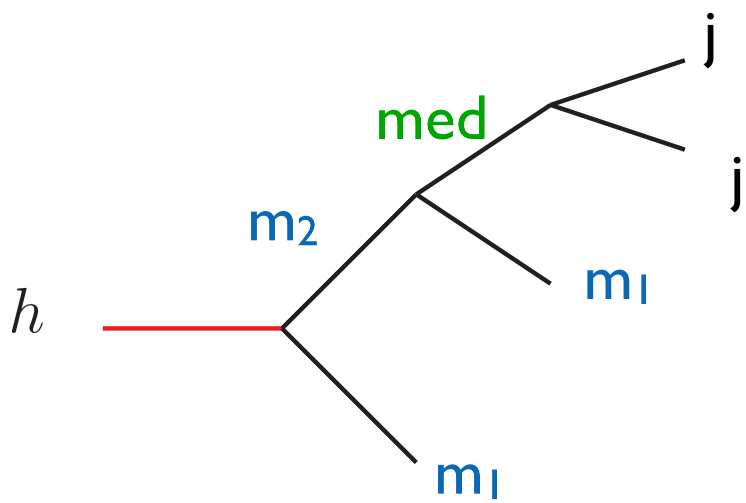
4 bottom (charm) final state



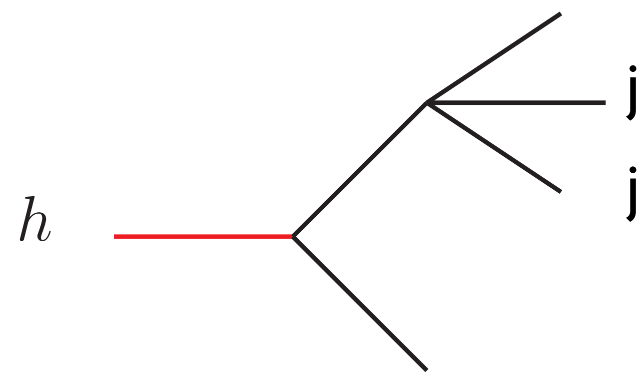


Decay mode $\mathcal{F}_i$	Projected/ current 2σ limit on $\mathrm{Br}(\mathcal{F}_i)$ $7+8$ [14] TeV	Production mode	Quarks allowed		Qua
			$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ $7+8$ [14] TeV	$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$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

Example 2 (with MET):
Exotic decay of the SM Higgs boson (jj+met)

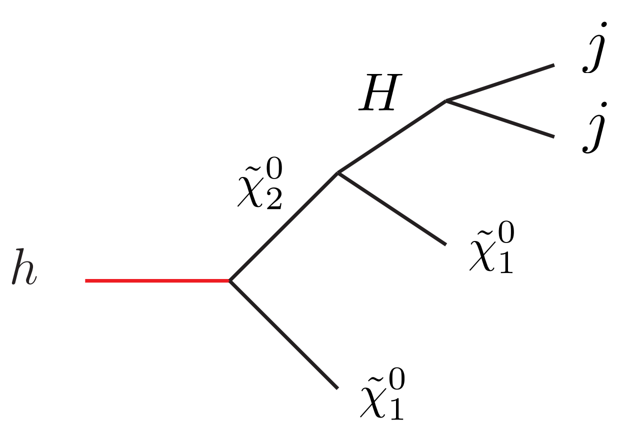


$h \to 2 \to 3 \to 4$

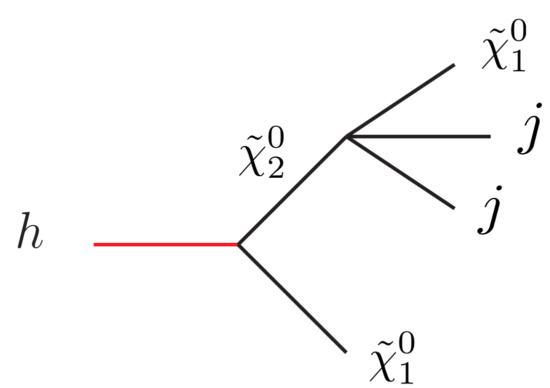


$h \to 2 \to (1 + 3)$

For example:



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

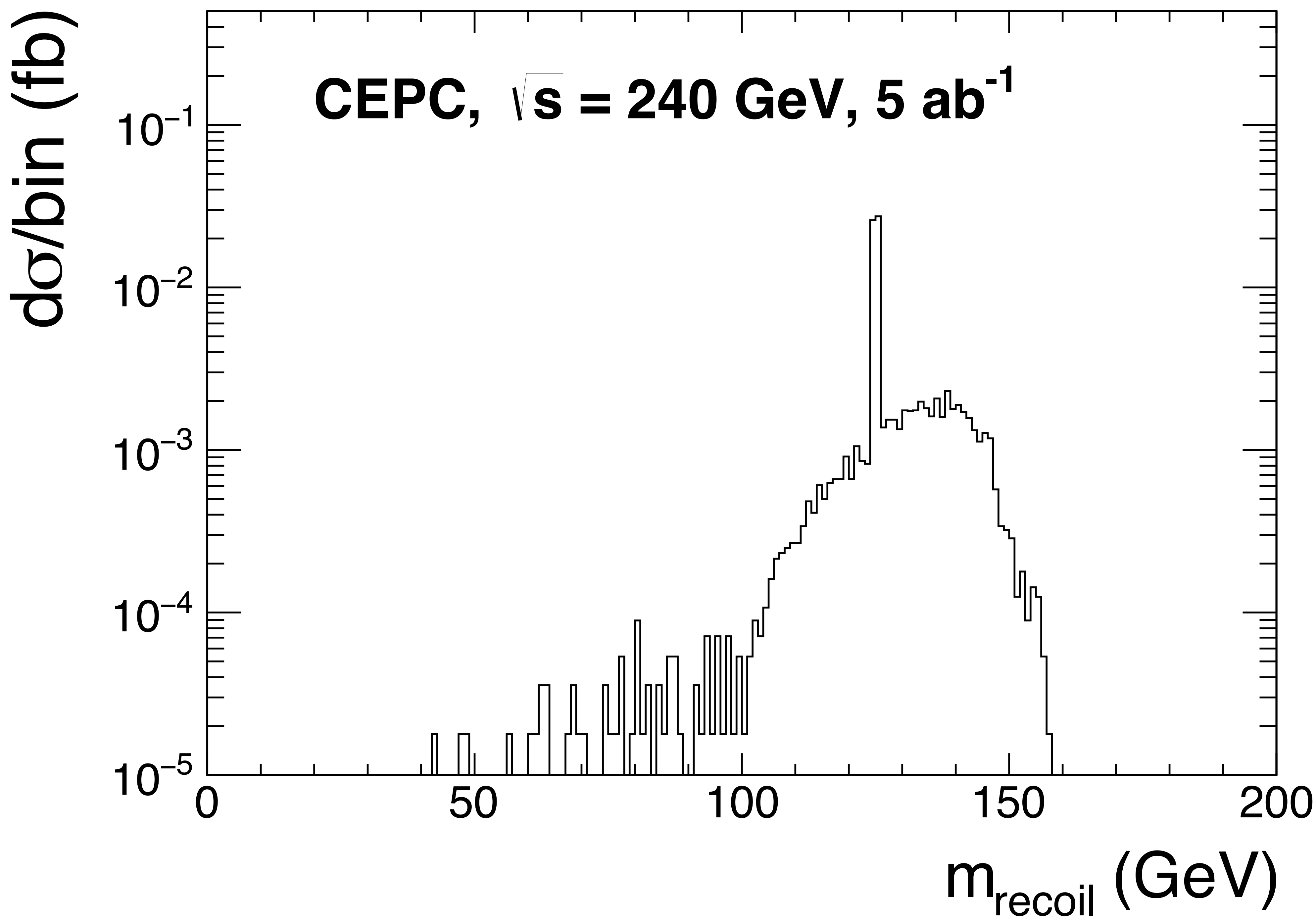


$h \to 2 \to (1 + 3)$

LHC: 10(s)%

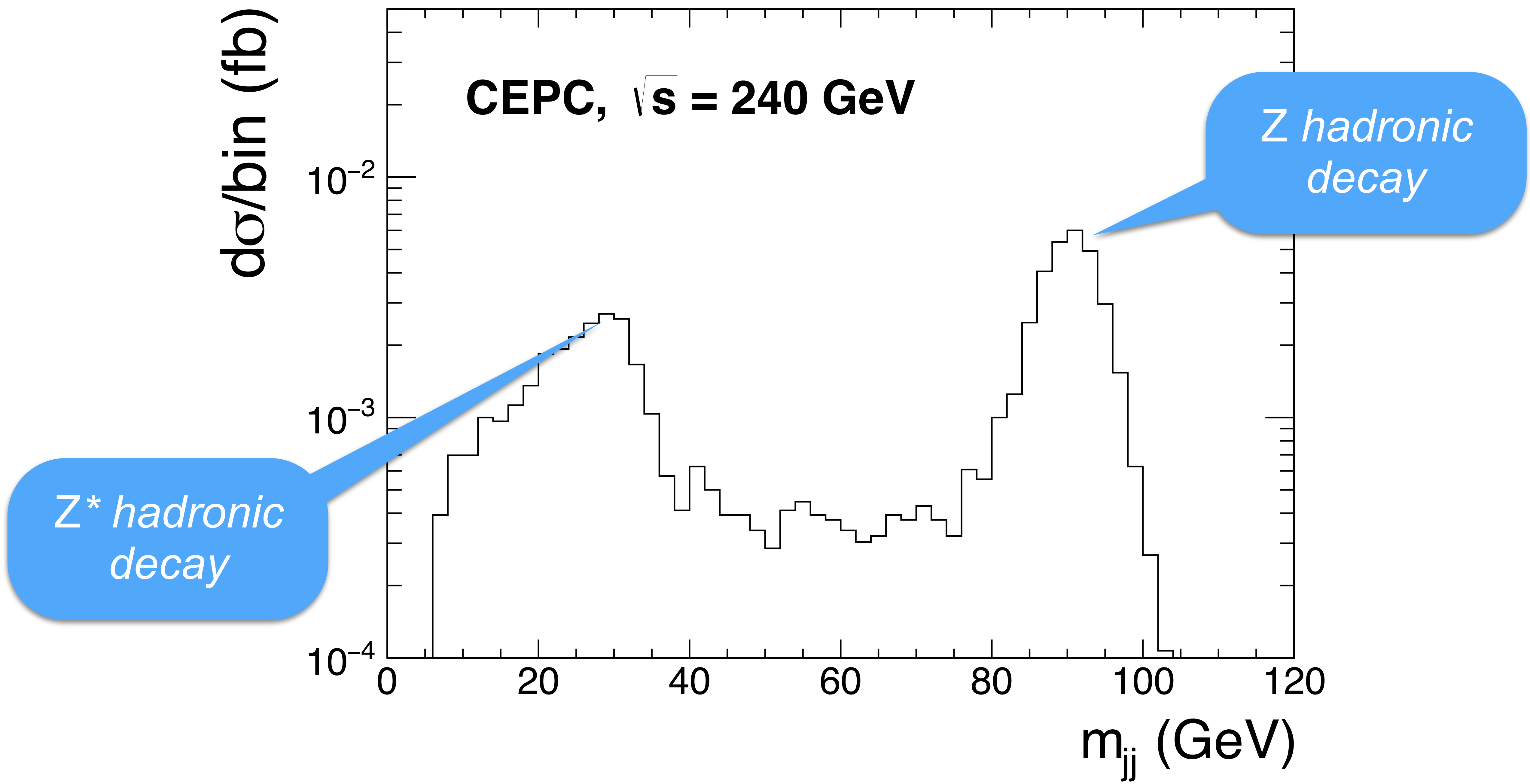
Background. $e^+e^- \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell jj$

ee → Zh, followed by h→ Z^* Z



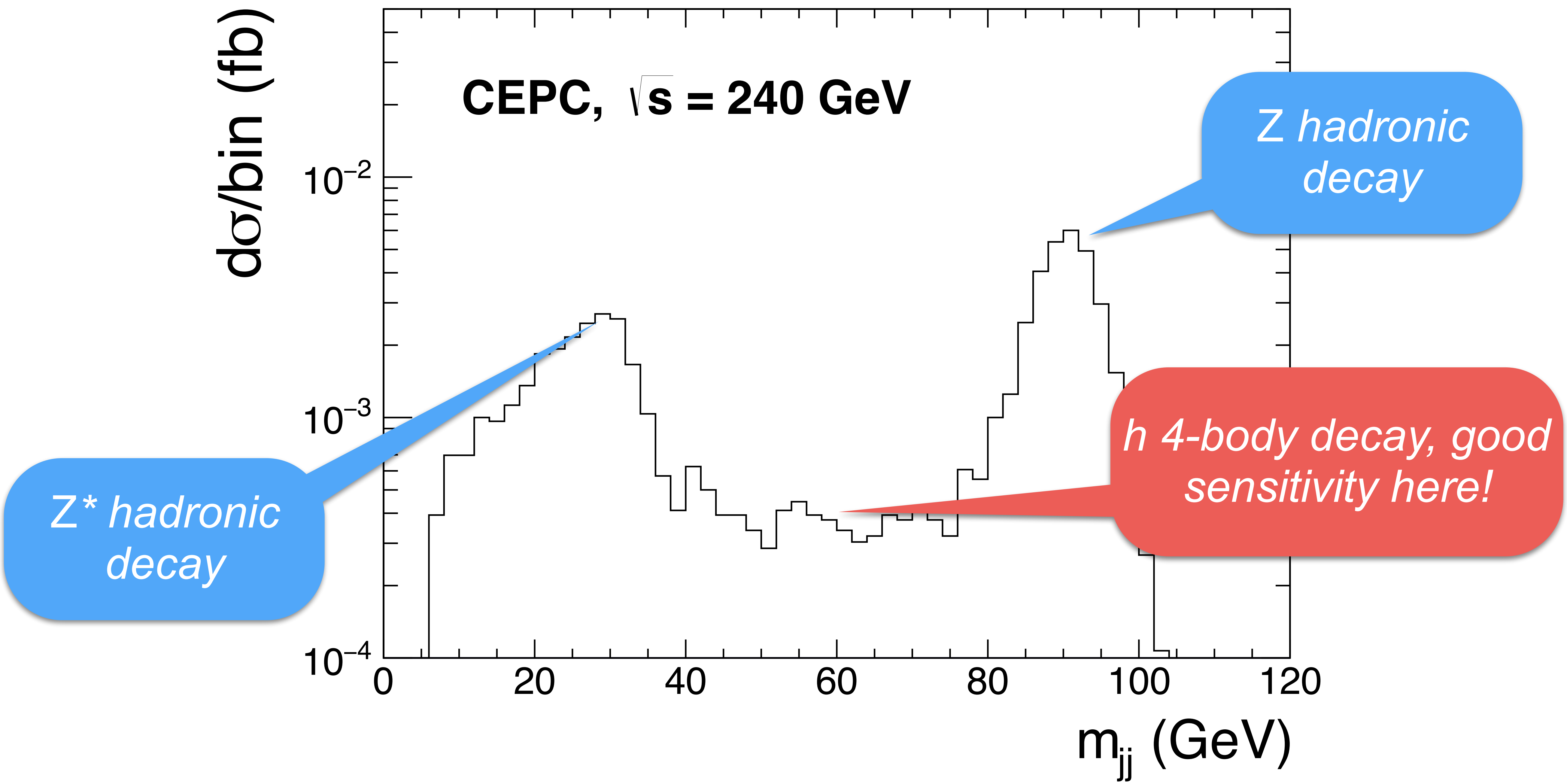
Exotic decay of the SM Higgs boson (jj+met)

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

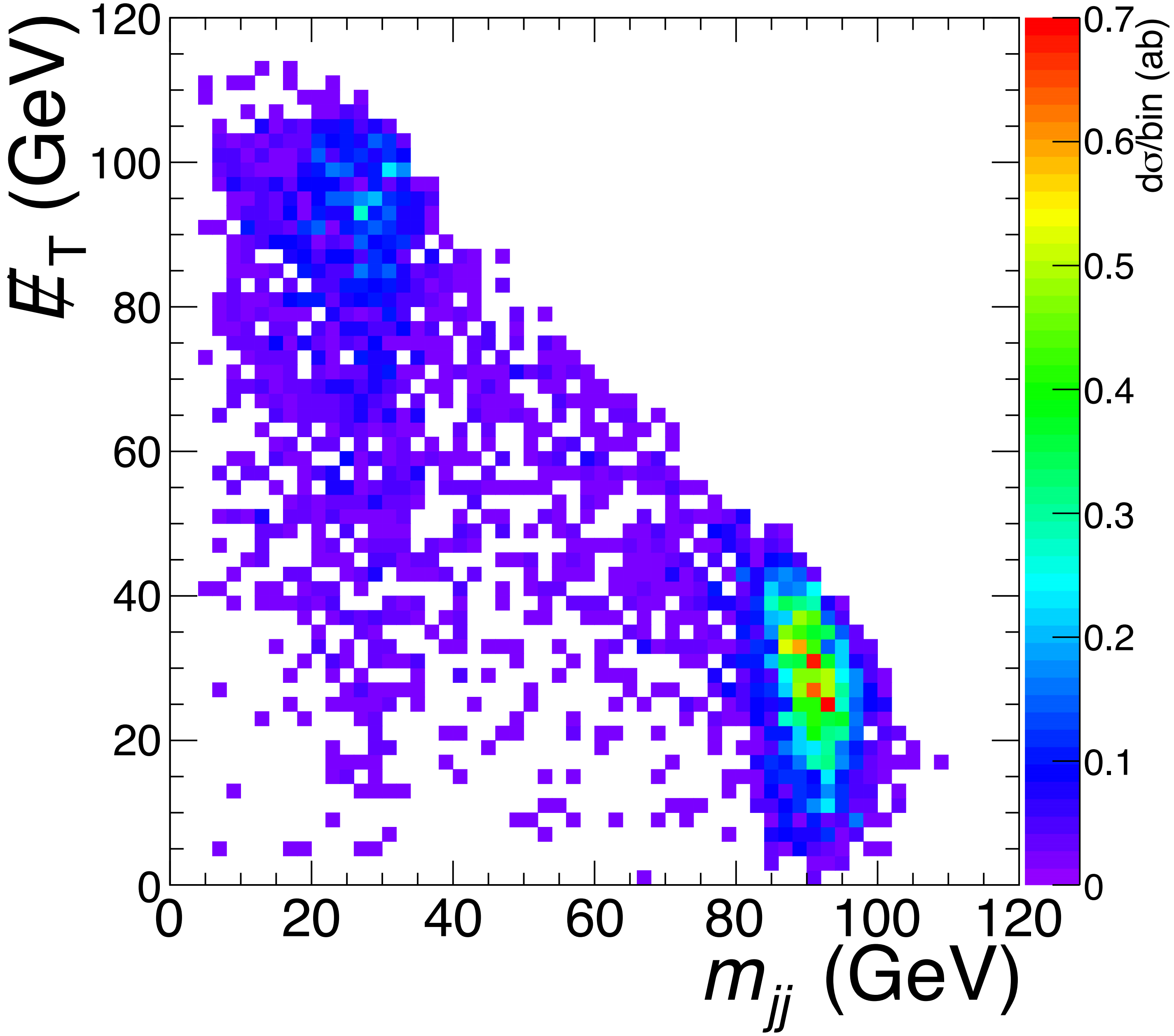


Exotic decay of the SM Higgs boson (jj+met)

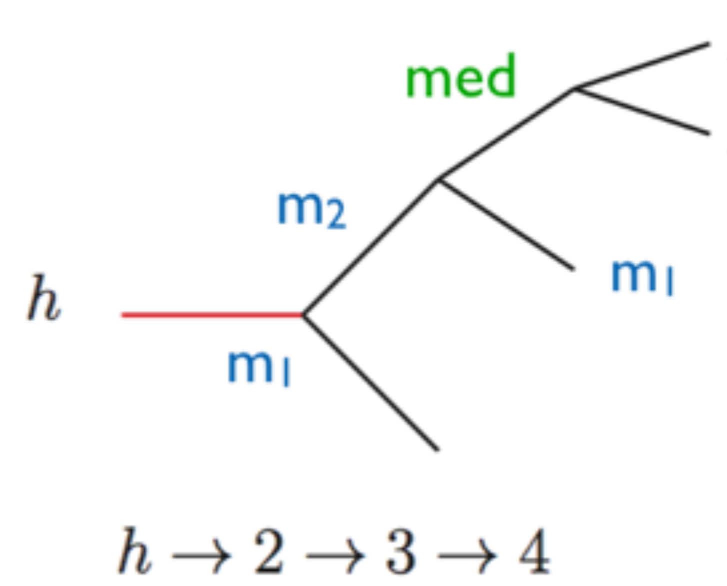
$$e^+e^- \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell jj$$



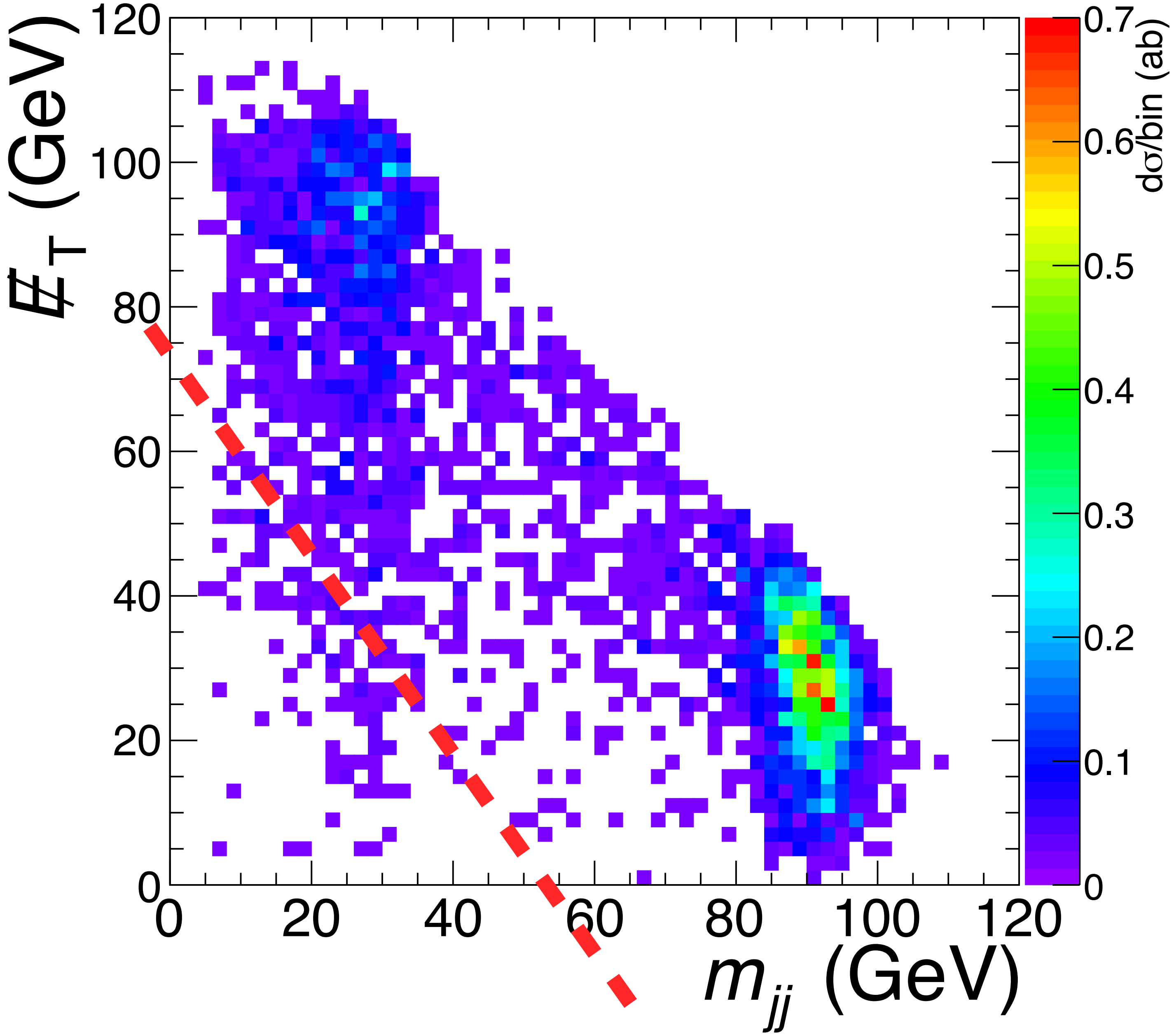
Better sensitivity with mediator mass falls in this valley

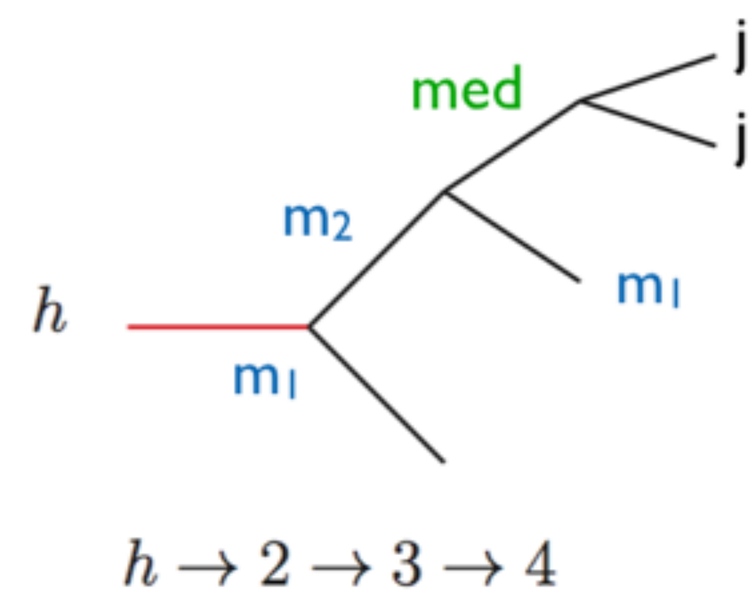


$\not{E}_T$ (GeV)
m_{jj} (GeV)
dσ/bin (ab)



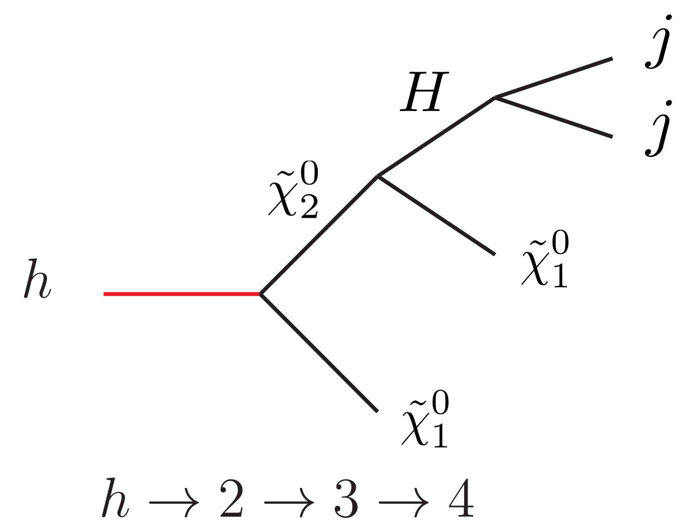
h
m₁
m₂
med
m₁
j
j
$h \to 2 \to 3 \to 4$



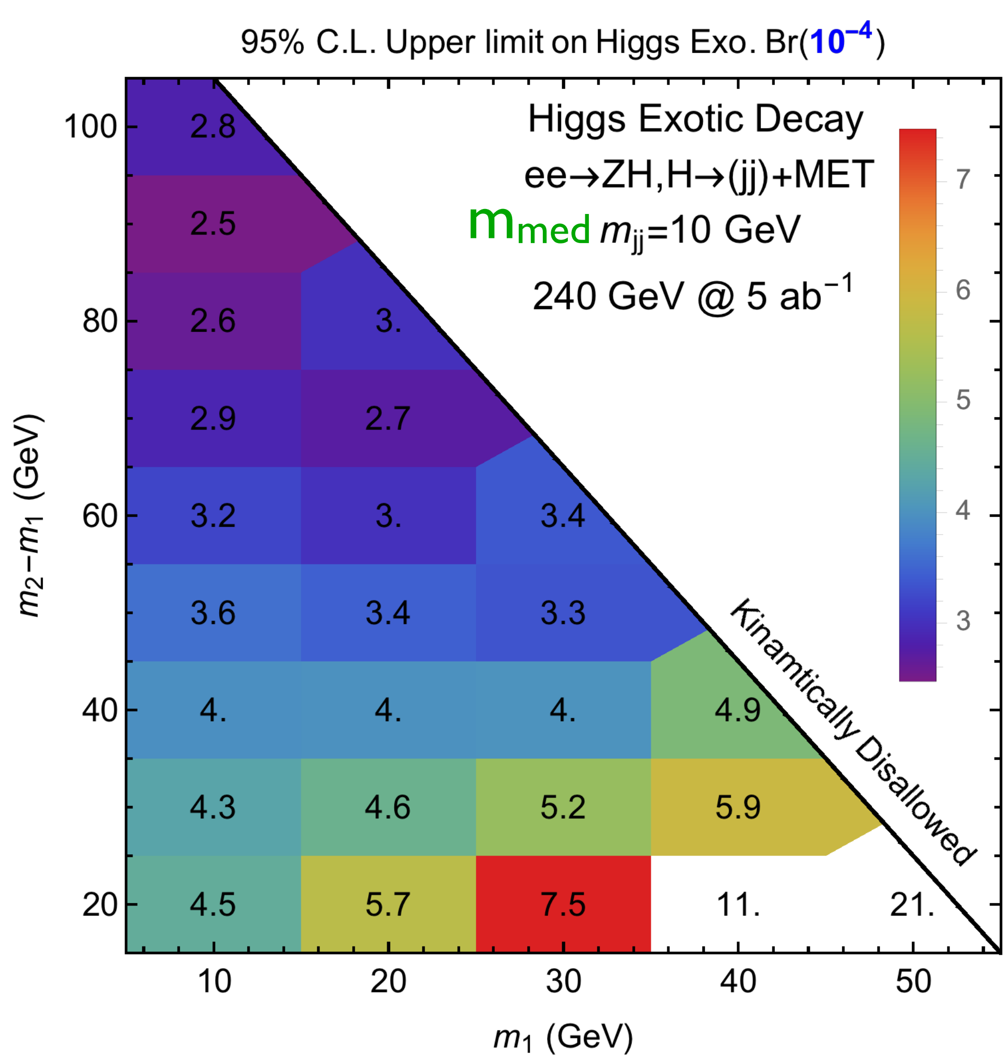


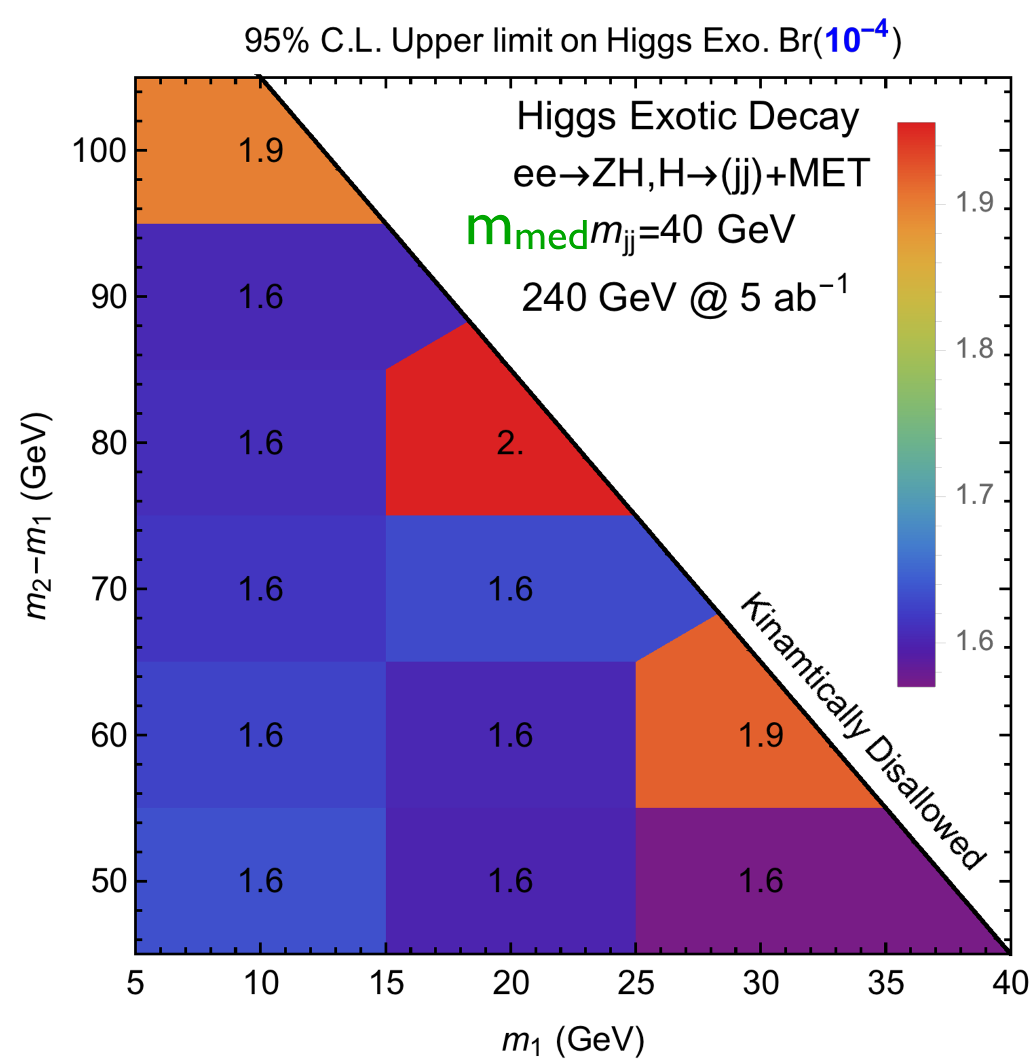
For signal: larger m_2 - m_1 , smaller MET, lower SM background, better sensitivity

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

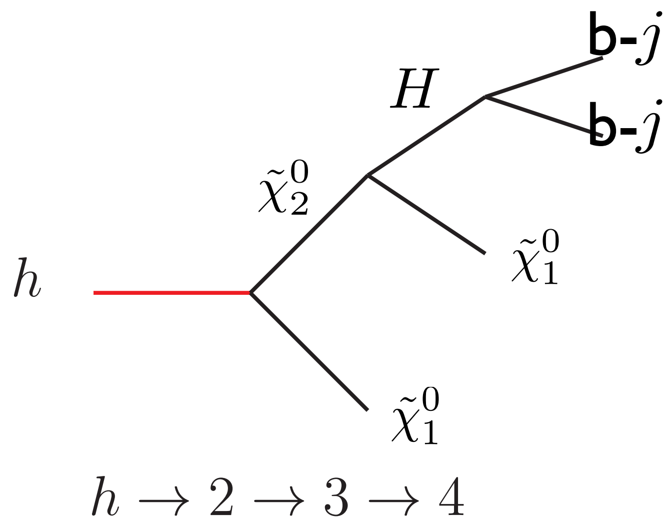


10^{-4} level at Higgs factories

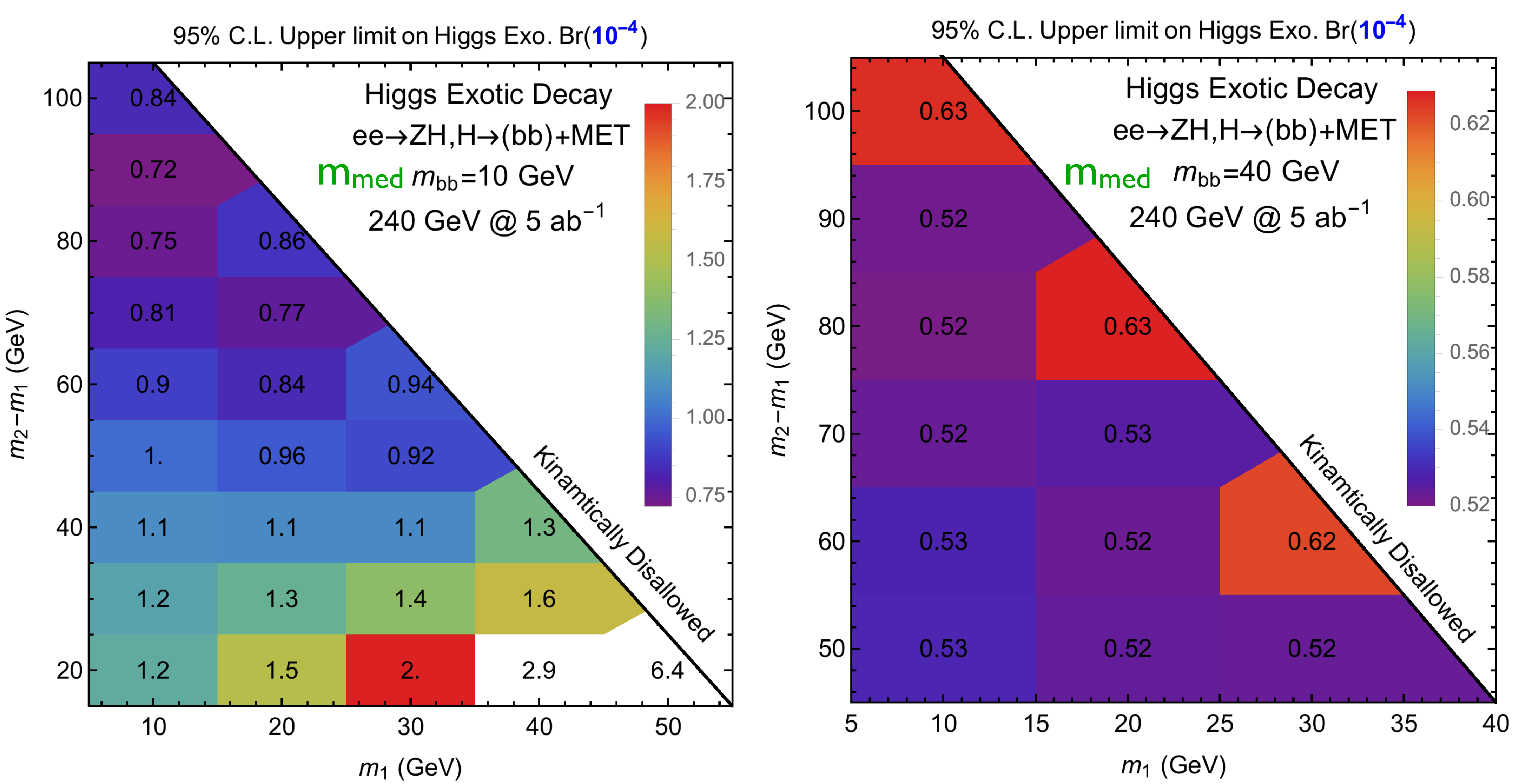




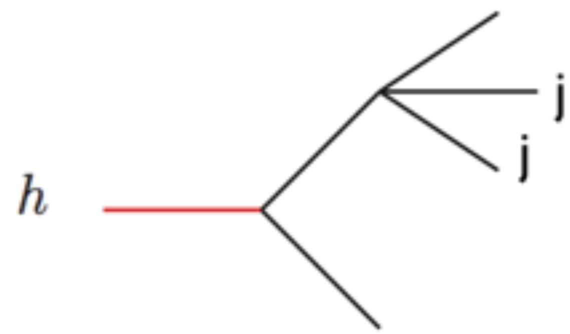
Exotic decay of the SM Higgs boson (jj+met)



10^{-4} level at Higgs factories

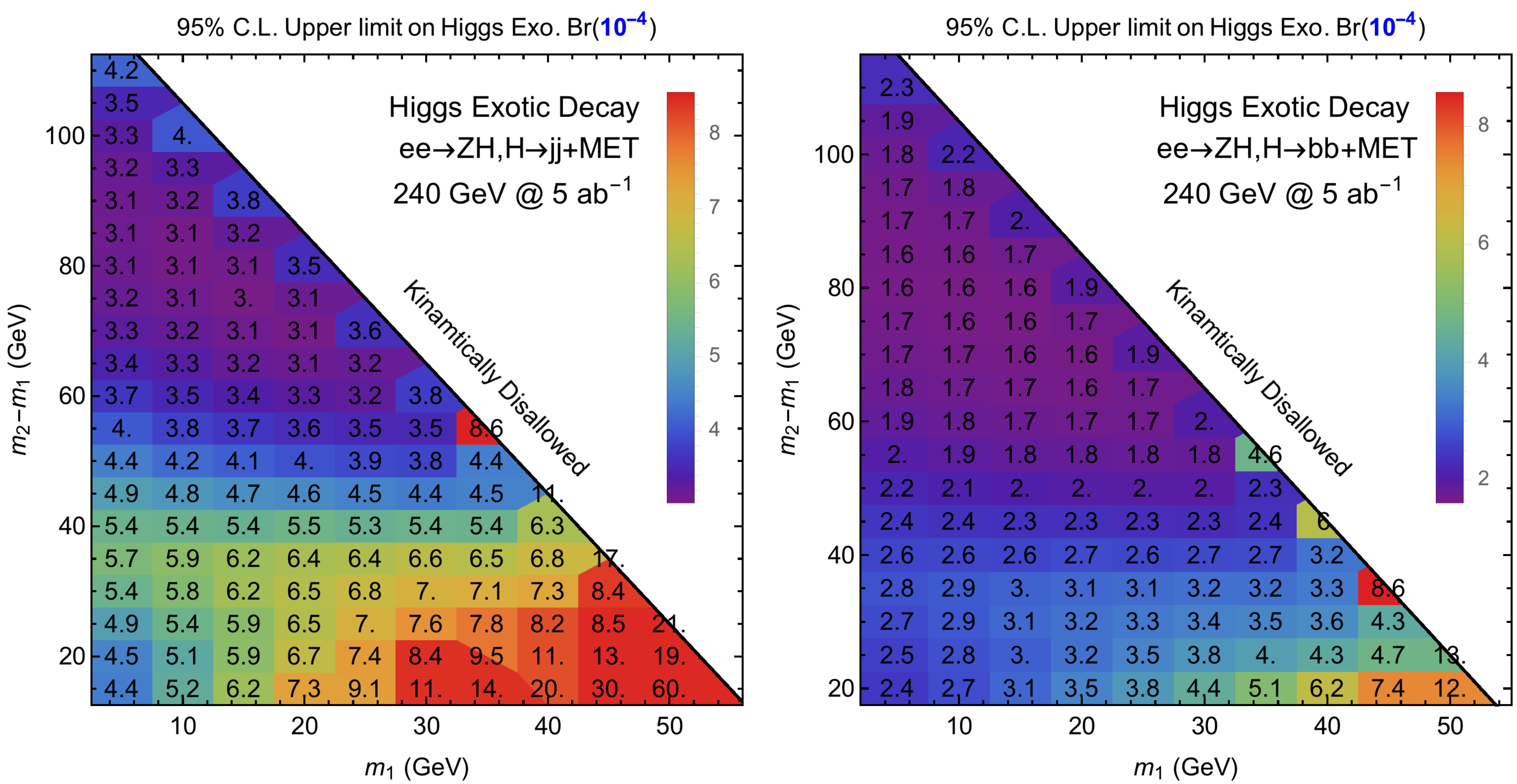


Exotic decay of the SM Higgs boson (jj+met) without di-jet resonance

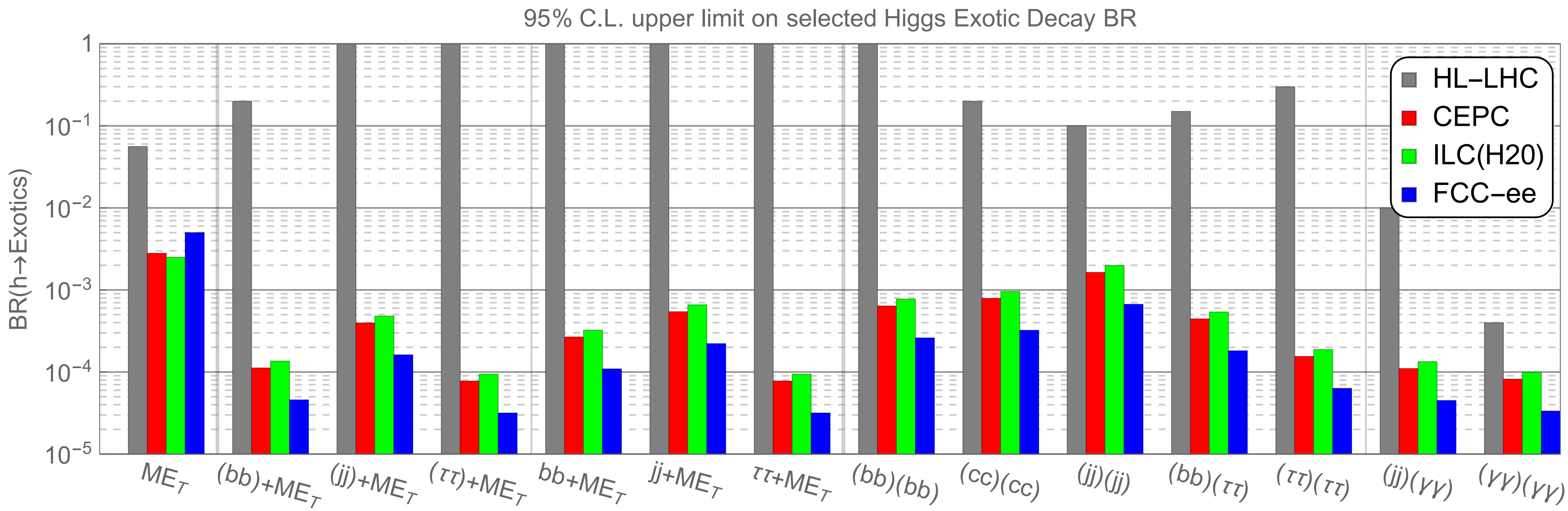


$$h \to 2 \to (1+3)$$

10^{-4} level at Higgs factories



Summary

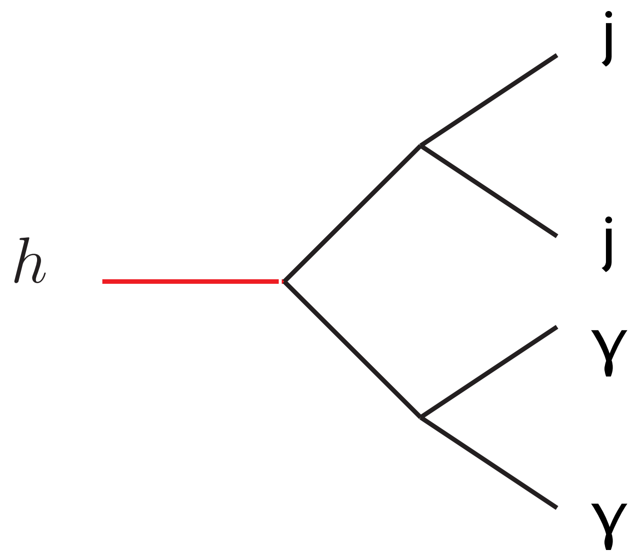


- Higgs factories can push these BR to 10^{-4}. Impressive reach and complementarity with HL-LHC

Next steps

- Used simplified models as a way of demonstrating the physics potential of the Higgs factories.
  - What can we learn with these precisions?
- More channels, with better theory motivation?
- Exotic decay at the HL-LHC deserves more studies too!

For example



$h \to 2 \to 4$

Main background: ZZ →Z jj γγ

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

LHC: about 1%

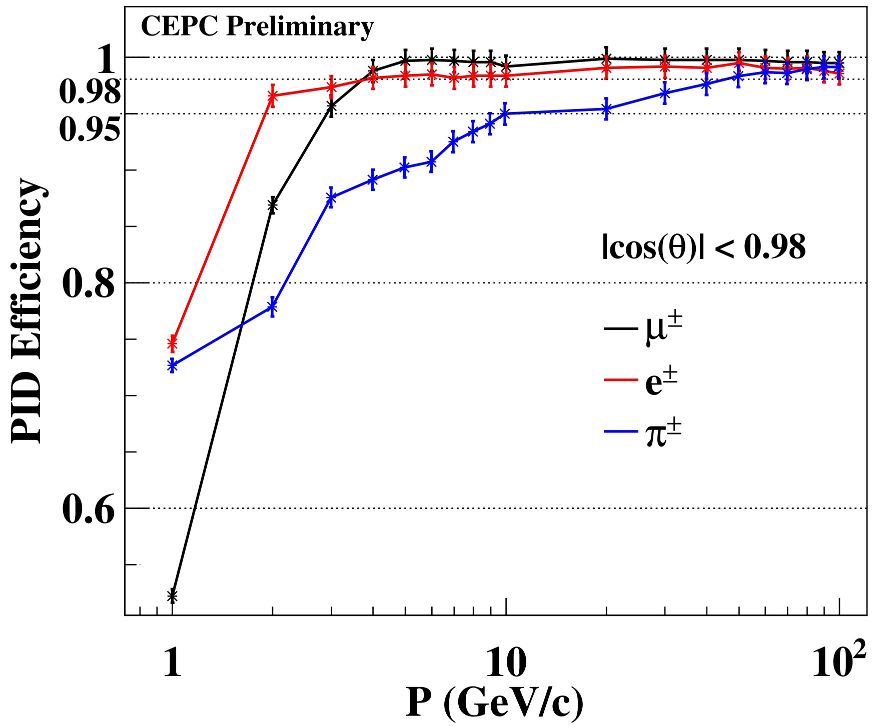
Decay Mode	95% C.L. limit on Br				
	LHC	HL-LHC	CEPC	ILC	FCC-ee
$\not{E}_T$	0.23 [37, 38]	0.056 [12–14]	0.0028 [16]	0.0025 [17]	0.005 [18]
$(b\bar{b}) + \not{E}_T$	–	[0.2]	1×10^{-4}	1×10^{-4}	5×10^{-5}
$(jj) + \not{E}_T$	–	–	5×10^{-4}	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-) + \not{E}_T$	–	[1]	$8\times10^{-4}*$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

- Parton level simulation.
- Main SM backgrounds: $e^+e^- \to Zjjjj+X$.
- Important to take into account the simulation due to the ISR effect.

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

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

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



From CEPC pre-CDR

Probing NP with precision measurements

- CEPC: clean environment, good for precision.

- We are going after deviations of the form

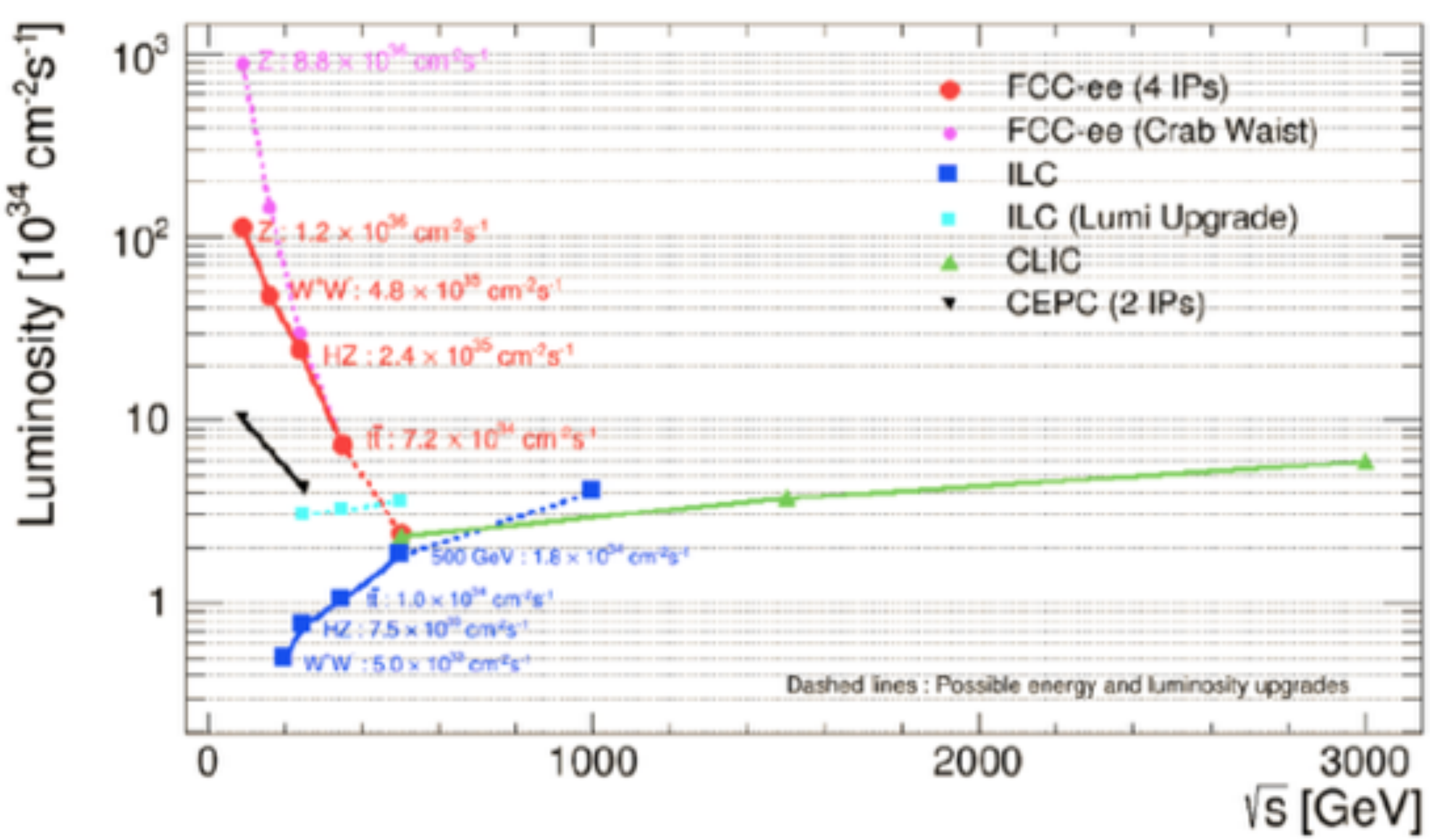
$$\delta \simeq c\frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: $O(1)$ coefficient

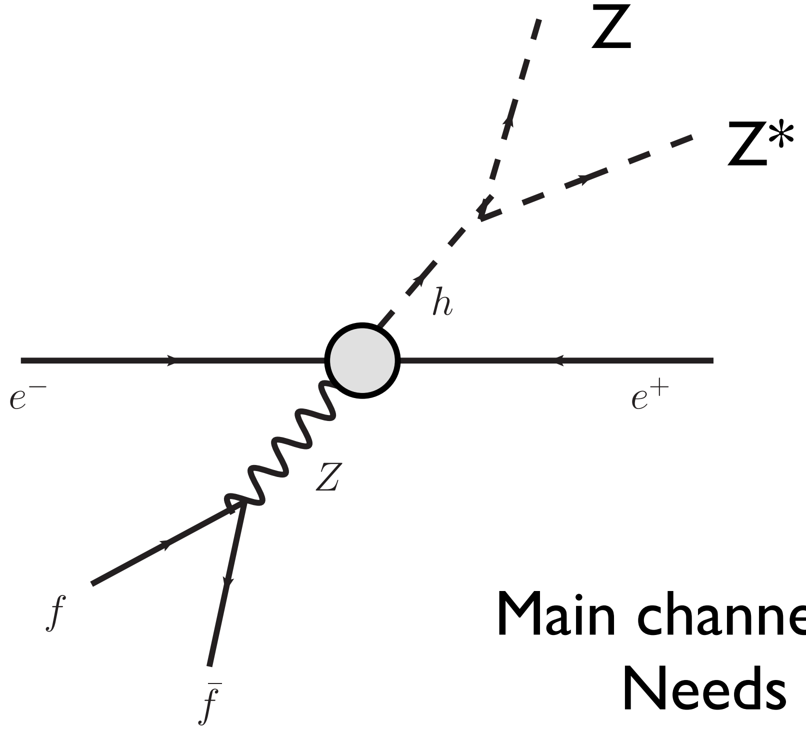
- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

Higgs factories

- FCC-ee, CEPC, ILC, CLIC.
- Physics case relatively independent of the outcome of the LHC.
  - Reach further than the LHC.
  - Address questions that LHC can't answer.

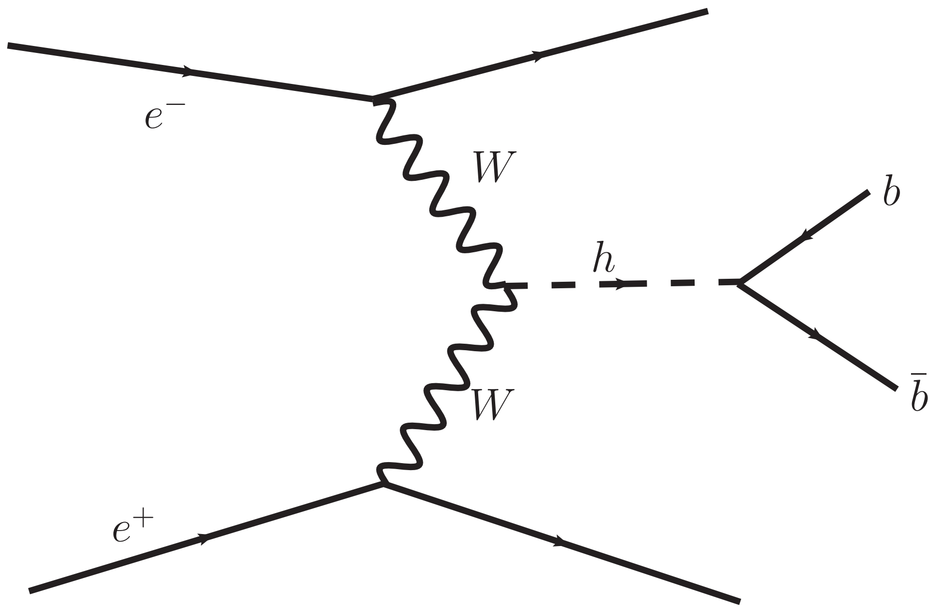


Higgs width. Unique capability of lepton colliders.



$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

Main channel at 250 GeV.
Needs statistics



$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

Needs to go beyond 250.

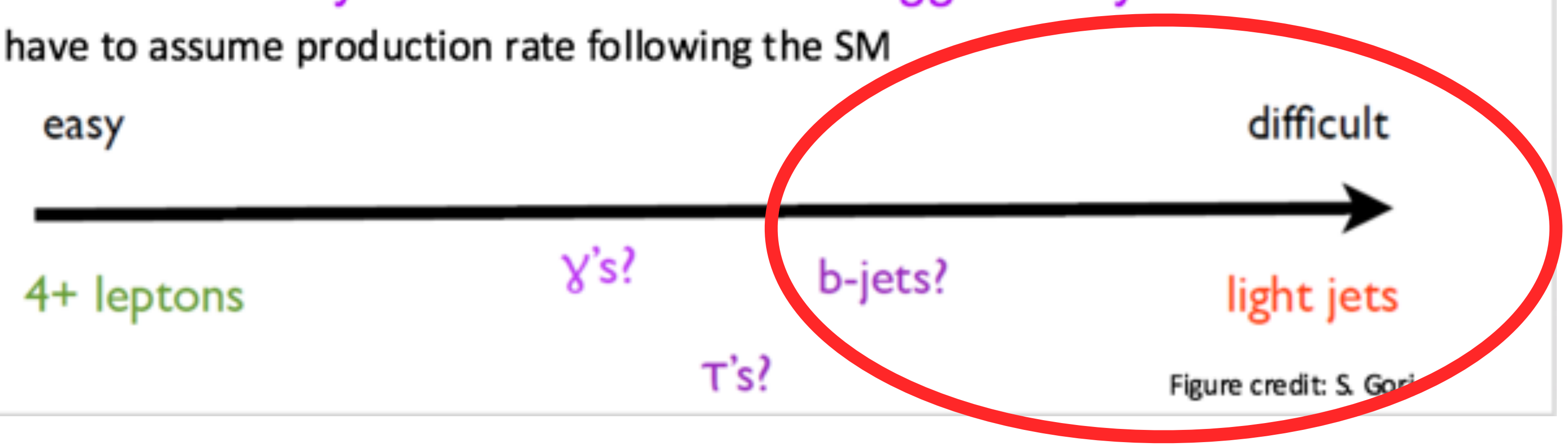
Decay Topologies	Decay mode $\mathcal{F}_i$	2σ LHC sensitivity to Br
$h \to 2$	$h \to \not{E}_T$	$0.25[14\text{TeV}, 300\text{fb}^{-1}]$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$	$0.57,\ 0.32,\ 0.13$ [4]
	$h \to (b\bar{b}) + \not{E}_T$	
	$h \to (jj) + \not{E}_T$	
	$h \to (\tau^+\tau^-) + \not{E}_T$	
	$h \to (\gamma\gamma) + \not{E}_T$	
	$h \to (\ell^+\ell^-) + \not{E}_T$	
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$	$0.2[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (jj) + \not{E}_T$	
	$h \to (\tau^+\tau^-) + \not{E}_T$	$1[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (\gamma\gamma) + \not{E}_T$	
	$h \to (\ell^+\ell^-) + \not{E}_T$	
	$h \to (\mu^+\mu^-) + \not{E}_T$	$0.07[7 + 8\text{TeV}]$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$	
	$h \to jj + \not{E}_T$	
	$h \to \tau^+\tau^- + \not{E}_T$	
	$h \to \gamma\gamma + \not{E}_T$	
	$h \to \ell^+\ell^- + \not{E}_T$	

Decay Topologies	Decay mode $\mathcal{F}_i$	2σ LHC sensitivity to Br
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$	$0.2[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (b\bar{b})(\tau^+\tau^-)$	$0.15[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (b\bar{b})(\mu^+\mu^-)$	$(0.6-2) \times 10^{-4}[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$	$0.2-0.4[7+8\text{TeV}]$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$	$(3-7) \times 10^{-4}[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (jj)(jj)$	$0.1[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (jj)(\gamma\gamma)$	$0.01[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (jj)(\mu^+\mu^-)$	$(5-20) \times 10^{-5}[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$	$4 \times 10^{-5}[7+8\text{TeV}]$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$	$4 \times 10^{-5}[7+8\text{TeV}]$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$	$10^{-4}[7+8\text{TeV}]$
	$h \to (\gamma\gamma)(\gamma\gamma)$	$3 \times 10^{-5}[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to \gamma\gamma + \not{E}_T$	
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$	
	$h \to (\ell^+\ell^-) + \not{E}_T + X$	
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$	
	$h \to \ell^+\ell^- + \not{E}_T + X$	

What exotic decay?

The reach of a hadron colliders depends very sensitively on the kind of exotic higgs decay mode

LHC limits, have to assume production rate following the SM



strength of Higgs factory

- Compelling physics case for exotic decay?

Decay Topologies	Decay mode $\mathcal{F}_i$	2σ LHC sensitivity to Br
$h \to 2$	$h \to \not{E}_{\rm T}$	$0.25[14{\rm TeV}, 300{\rm fb}^{-1}]$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_{\rm T}$	0.57, 0.32, 0.13 [4]
	$h \to (b\bar{b}) + \not{E}_{\rm T}$	Underlying model $h \to 2s$ or ss'
	$h \to (jj) + \not{E}_{\rm T}$	Background mainly are
	$h \to (\tau^+\tau^-) + \not{E}_{\rm T}$	1) $ZZ + (n\gamma)$ $Z\gamma + X$
	$h \to (\gamma\gamma) + \not{E}_{\rm T}$	2) Zh $h \to ZZ^*, WW^*$
	$h \to (\ell^+\ell^-) + \not{E}_{\rm T}$	
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_{\rm T}$	$0.2[14{\rm TeV}, 300{\rm fb}^{-1}]$
	$h \to (jj) + \not{E}_{\rm T}$	Bkg same as above block
	$h \to (\tau^+\tau^-) + \not{E}_{\rm T}$	$1[14{\rm TeV}, 300{\rm fb}^{-1}]$
	$h \to (\gamma\gamma) + \not{E}_{\rm T}$	
	$h \to (\ell^+\ell^-) + \not{E}_{\rm T}$	
	$h \to (\mu^+\mu^-) + \not{E}_{\rm T}$	$0.07[7+8{\rm TeV}]$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_{\rm T}$	$-$ last step off-shell
	$h \to jj + \not{E}_{\rm T}$	Bkg same as above
	$h \to \tau^+\tau^- + \not{E}_{\rm T}$	$-$
	$h \to \gamma\gamma + \not{E}_{\rm T}$	$-$
	$h \to \ell^+\ell^- + \not{E}_{\rm T}$	
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$	$0.2[14{\rm TeV}, 100{\rm fb}^{-1}]$
	$h \to (b\bar{b})(\tau^+\tau^-)$	$0.15[14{\rm TeV}, 300{\rm fb}^{-1}]$
	$h \to (b\bar{b})(\mu^+\mu^-)$	$(0.6-2)\times 10^{-4}[14{\rm TeV}, 100{\rm fb}^{-1}]$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$	$0.2-0.4[7+8{\rm TeV}]$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$	$(3-7)\times 10^{-4}[14{\rm TeV}, 100{\rm fb}^{-1}]$
	$h \to (jj)(jj)$	$0.1[14{\rm TeV}, 300{\rm fb}^{-1}]$
	$h \to (jj)(\gamma\gamma)$	$0.01[14{\rm TeV}, 300{\rm fb}^{-1}]$
	$h \to (jj)(\mu^+\mu^-)$	$(5-20)\times 10^{-5}[14{\rm TeV}, 100{\rm fb}^{-1}]$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$	$4\times 10^{-5}[7+8{\rm TeV}]$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$	$4\times 10^{-5}[7+8{\rm TeV}]$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$	$10^{-4}[7+8{\rm TeV}]$
	$h \to (\gamma\gamma)(\gamma\gamma)$	$3\times 10^{-5}[14{\rm TeV}, 300{\rm fb}^{-1}]$
	$h \to \gamma\gamma + \not{E}_{\rm T}$	
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_{\rm T}$	
	$h \to (\ell^+\ell^-) + \not{E}_{\rm T} + X$	inclusive measurement
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\rm T}$	
	$h \to \ell^+\ell^- + \not{E}_{\rm T} + X$	same as above