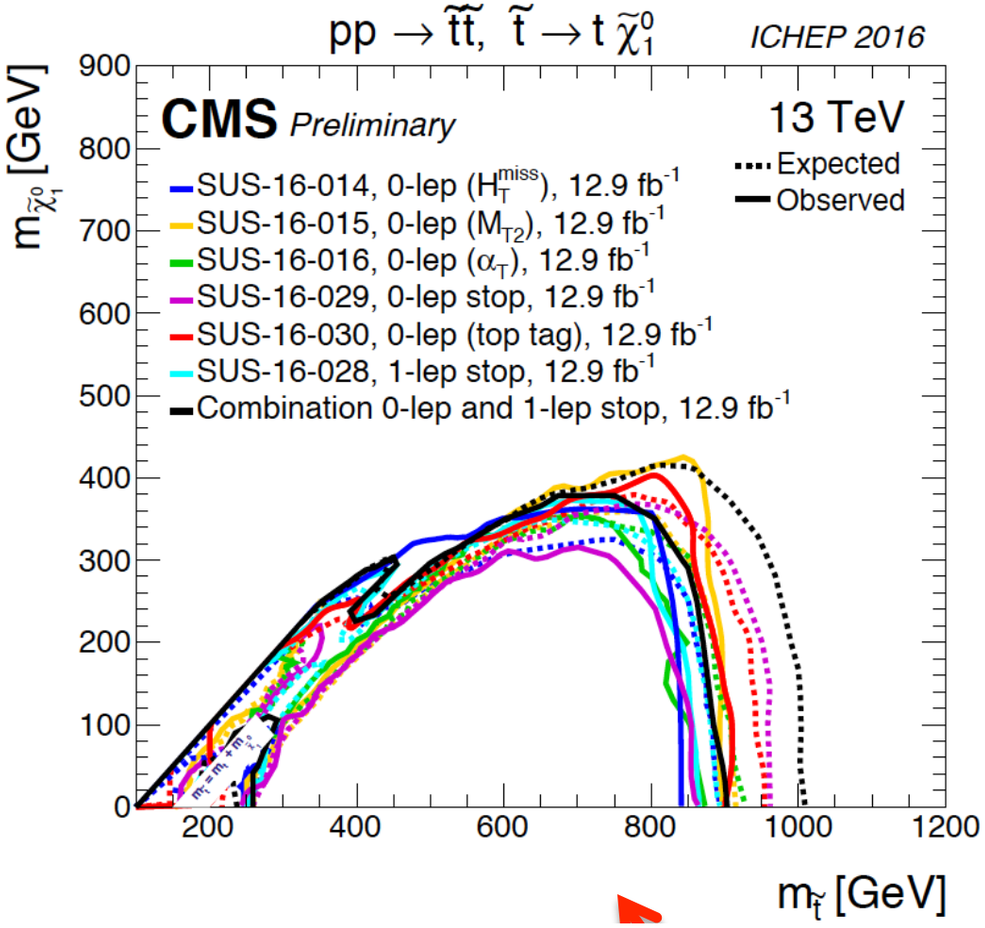
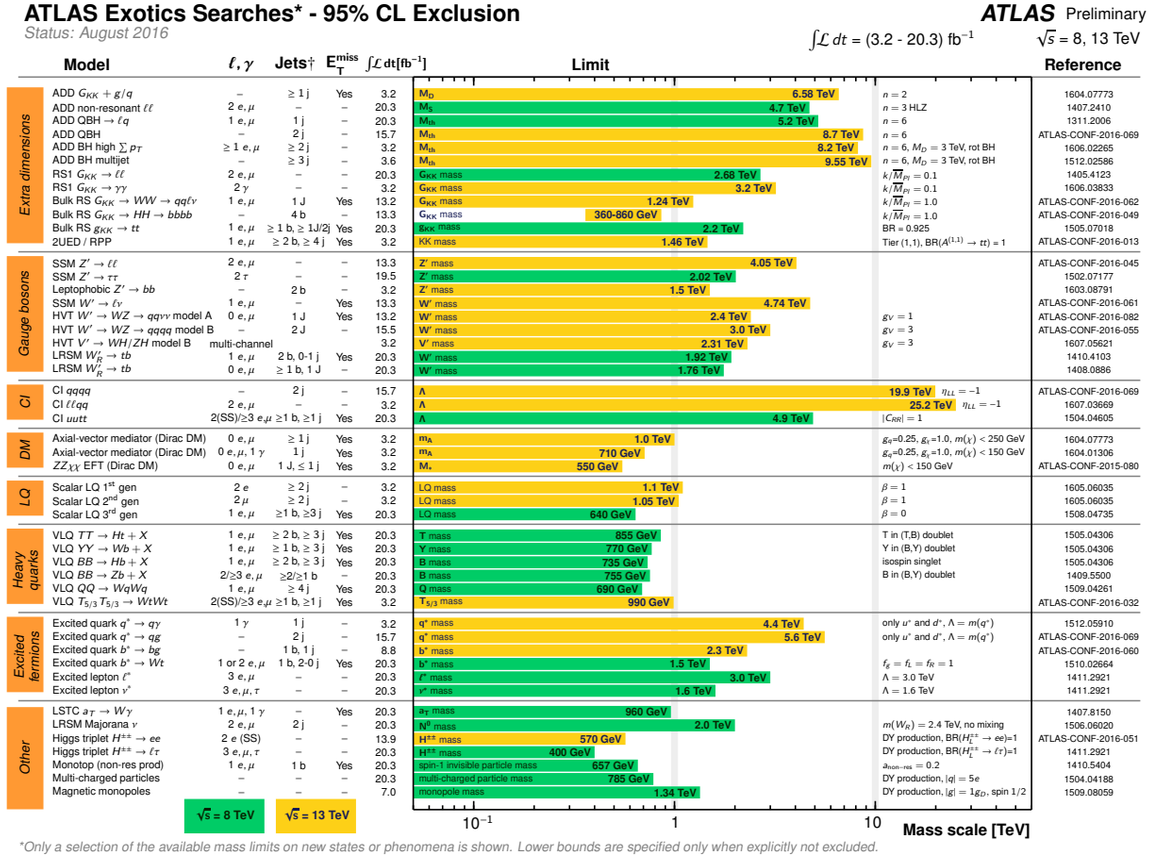
Precision Higgs Measurements at Higgs factories

LianTao Wang
University of Chicago

ICTP. Sept. 8, 2016
A first glance beyond the energy frontier

Present





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

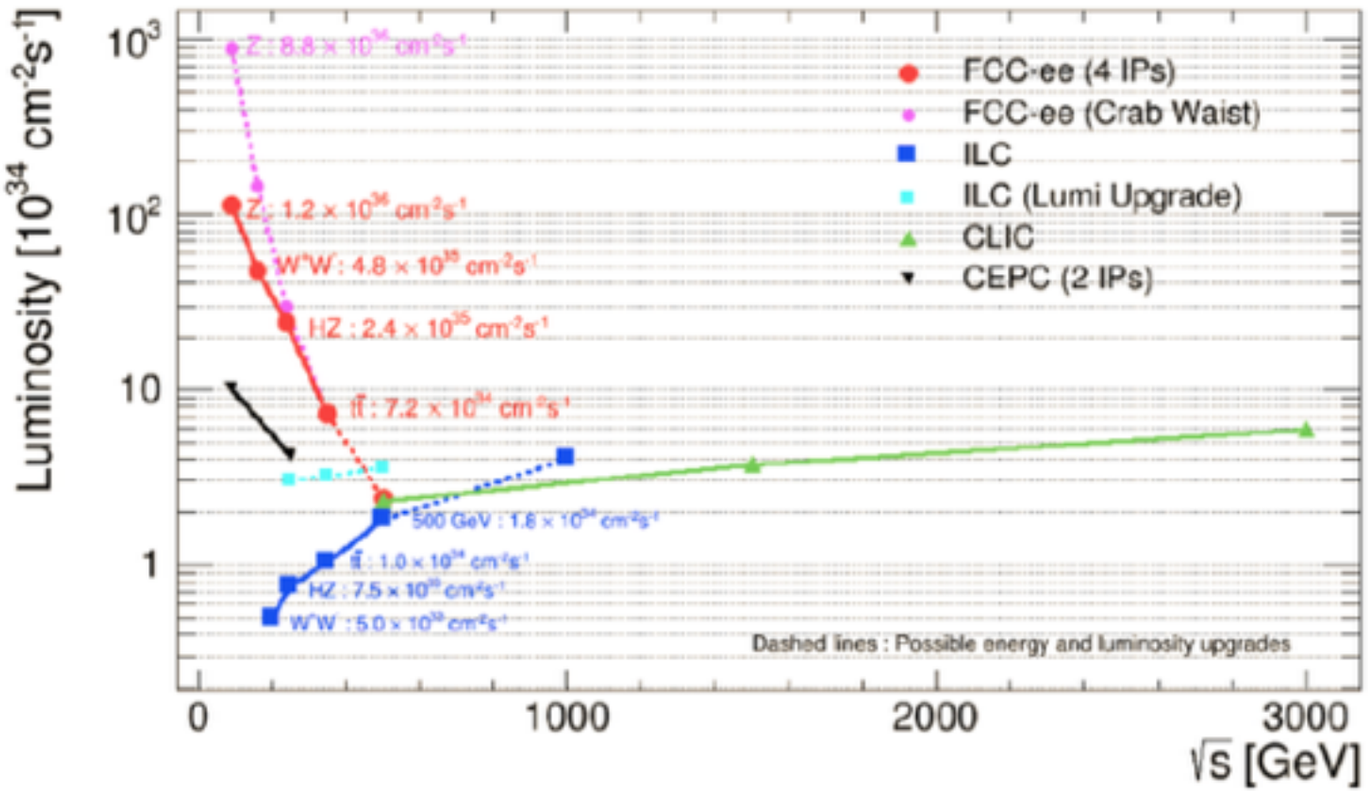
- No "early" discovery.
- Next?

This talk

- Focus on longer term future.
- Higgs measurements at Higgs factories and what we can learn from it.
  - Assuming no LHC discovery.
- General picture. (brief)
- A couple of new studies.

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.



Probing NP with precision measurements

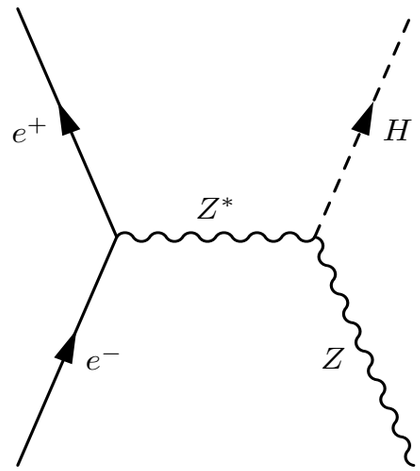
- CEPC: clean environment, good for precision.
- We are going after deviations of the form

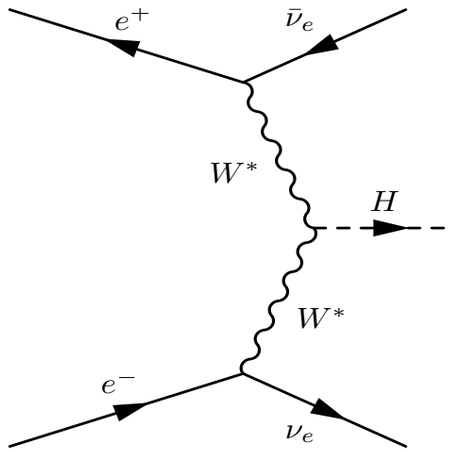
$$\delta \simeq c\frac{v^2}{M_{\rm NP}^2}$$

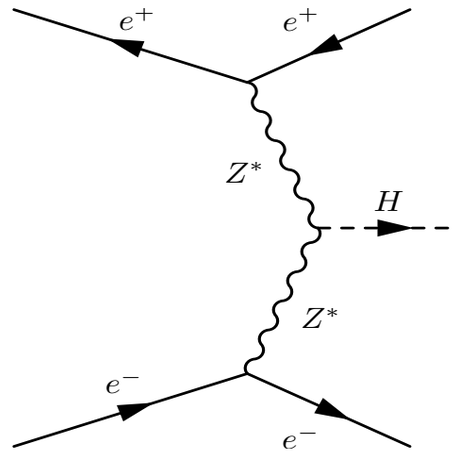
M_{NP} : mass of new physics
c: $O(1)$ coefficient

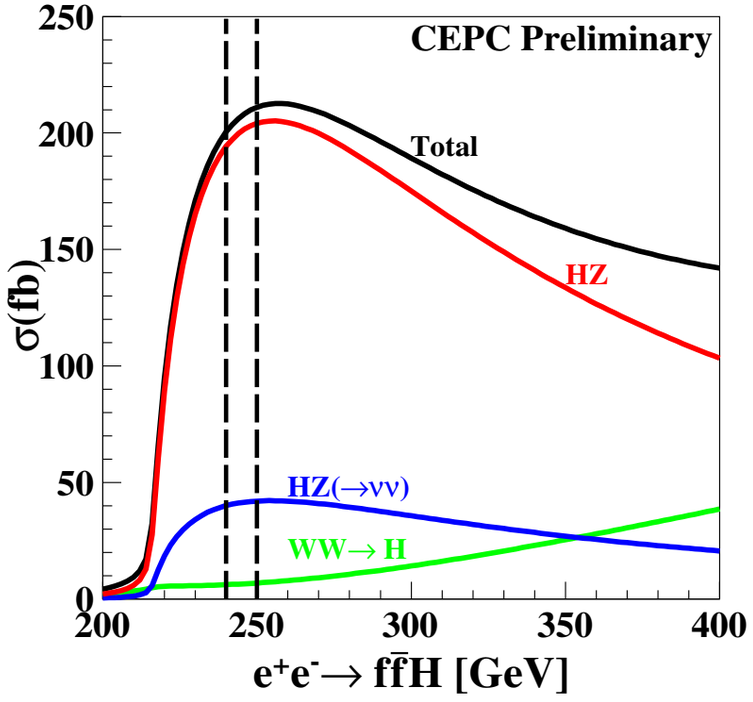
- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

Higgs factory processes



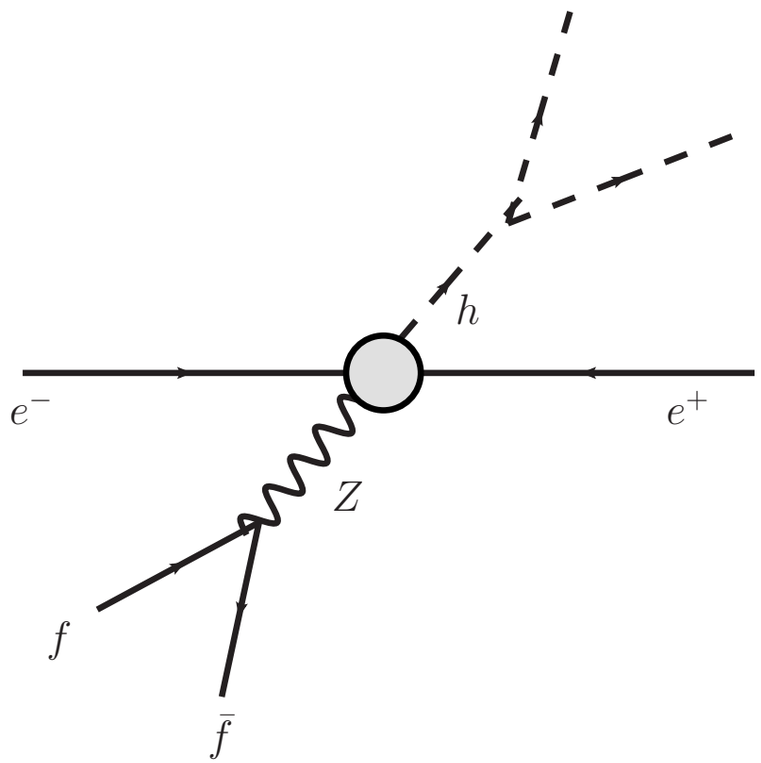


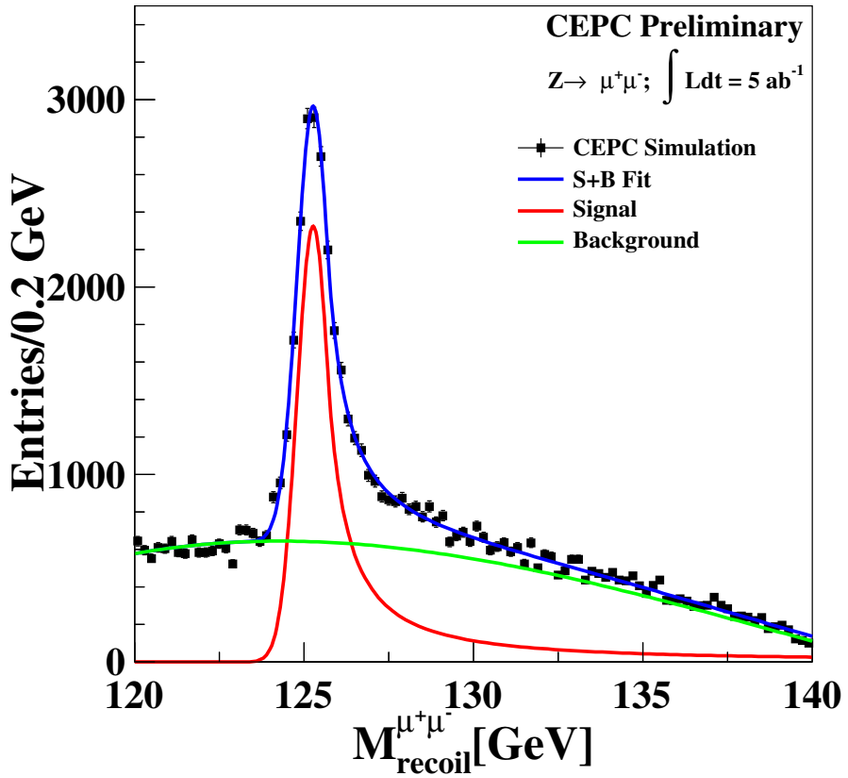




Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6

Zh cross section





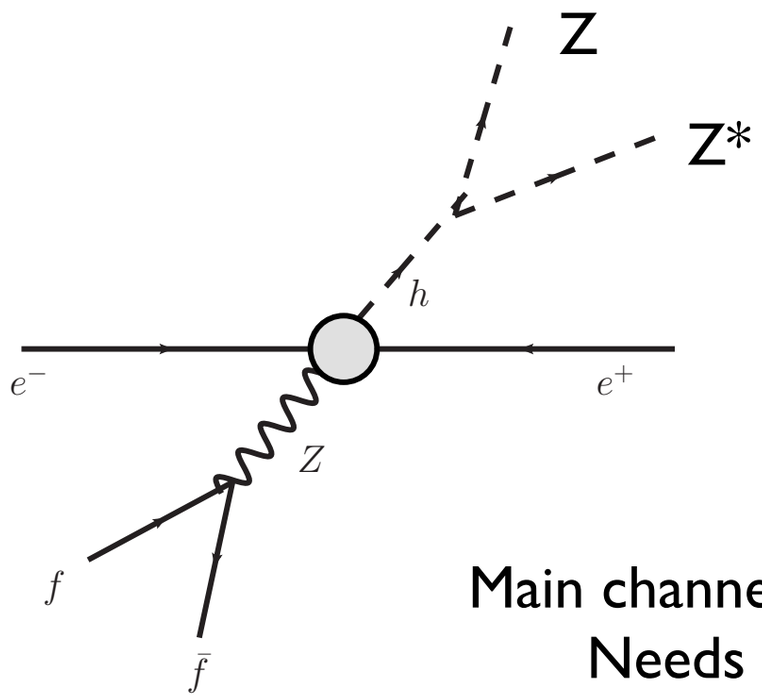
$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

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

⇒ inclusive measurement of Zh cross section

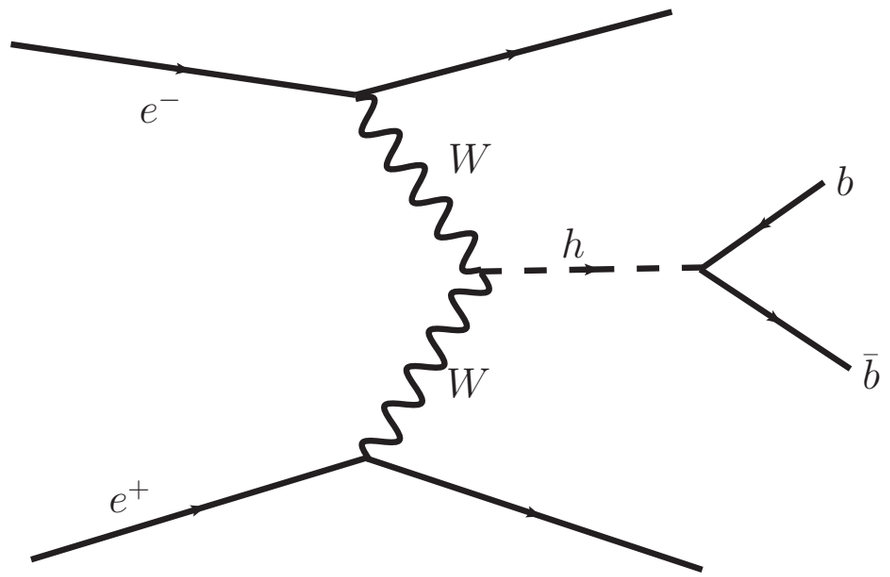
Higgs width.

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

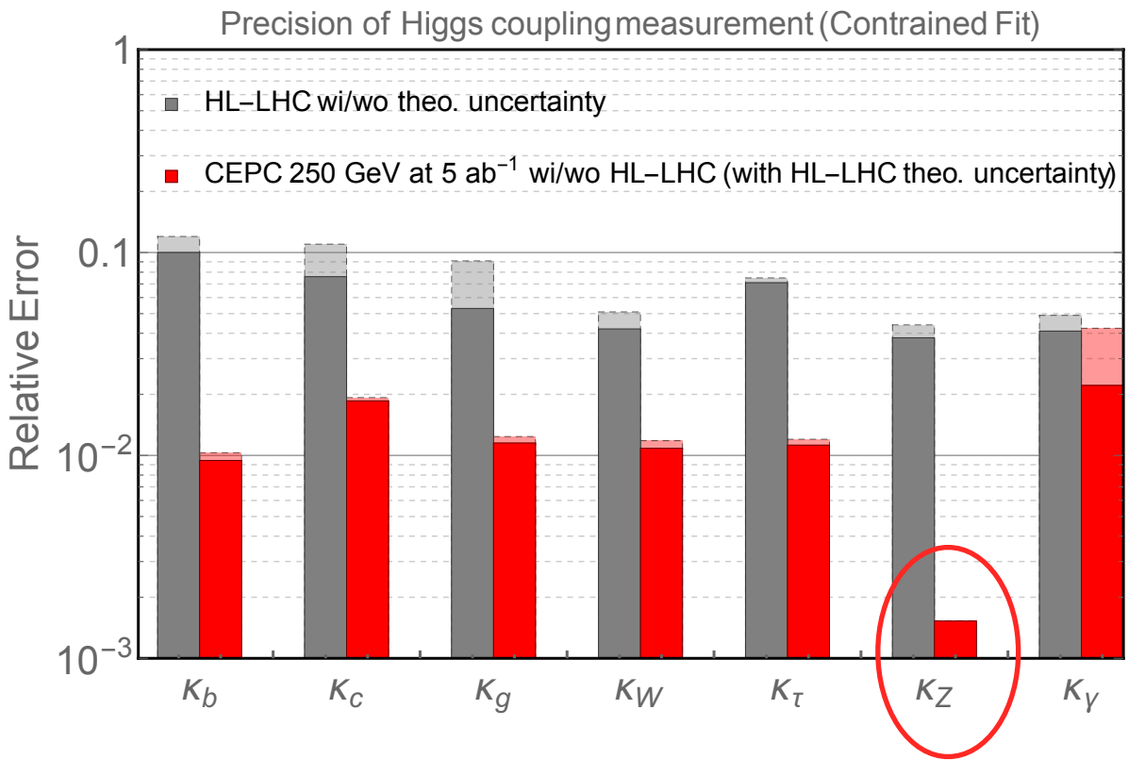


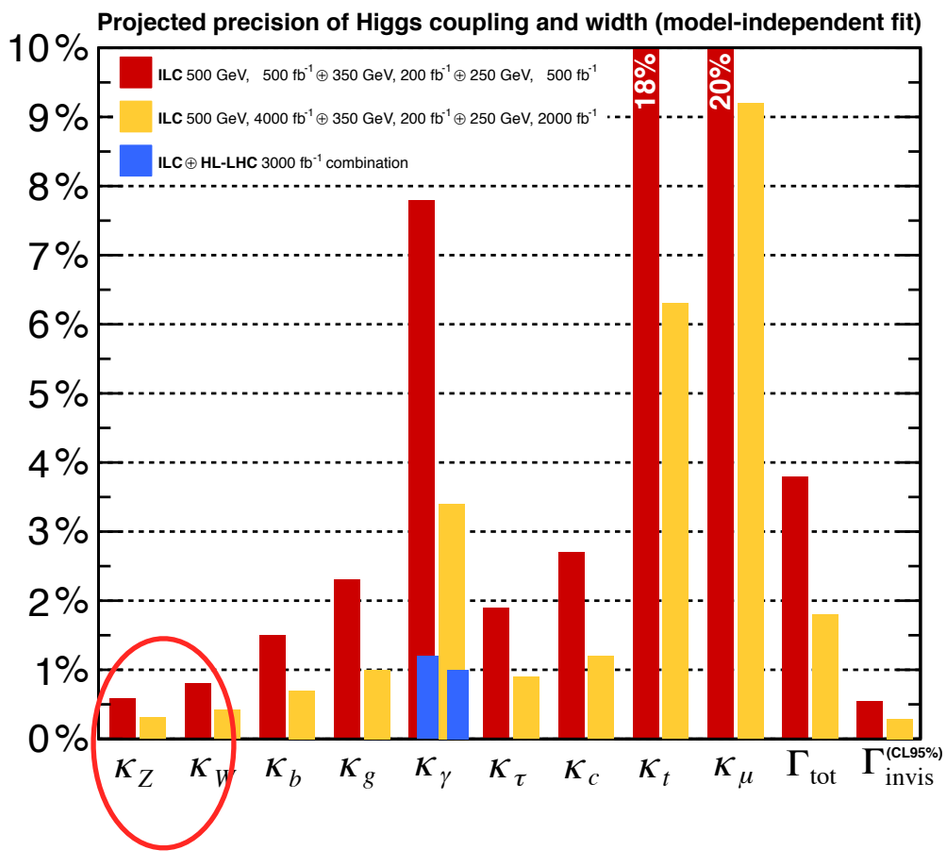
$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

Needs to go beyond 250.

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%

Higgs factories

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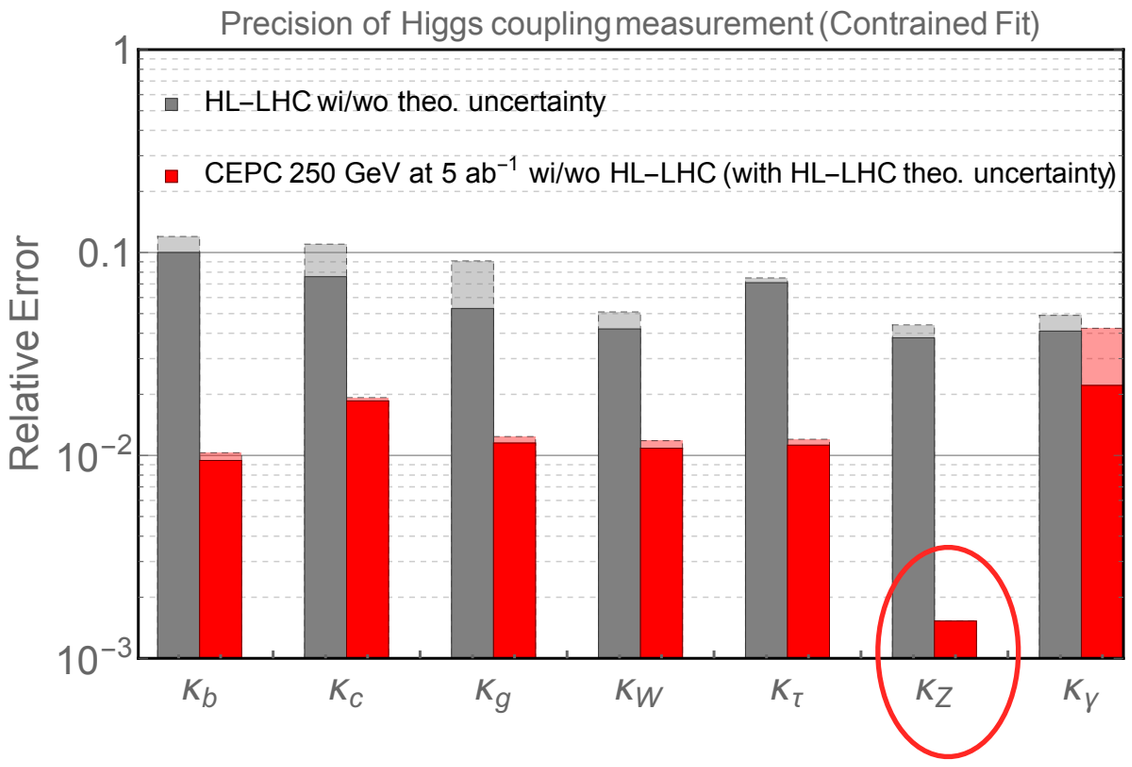

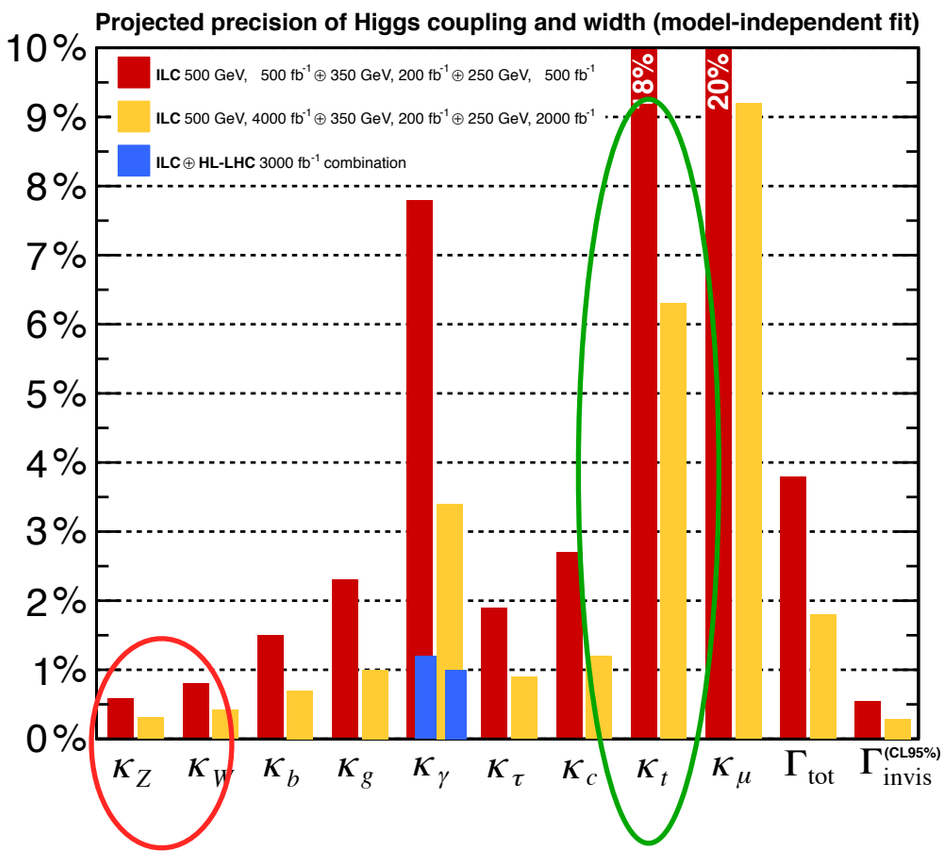

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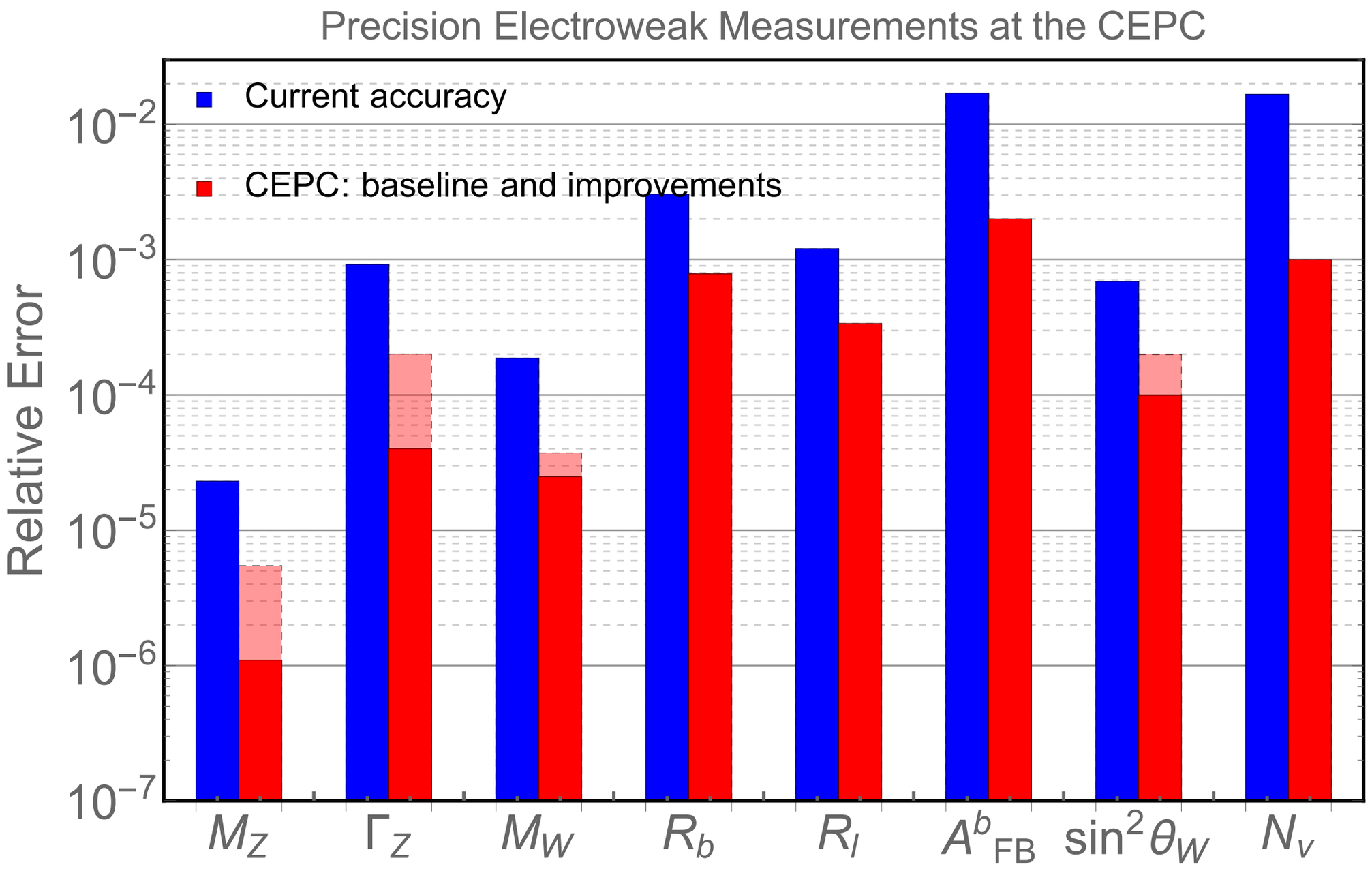
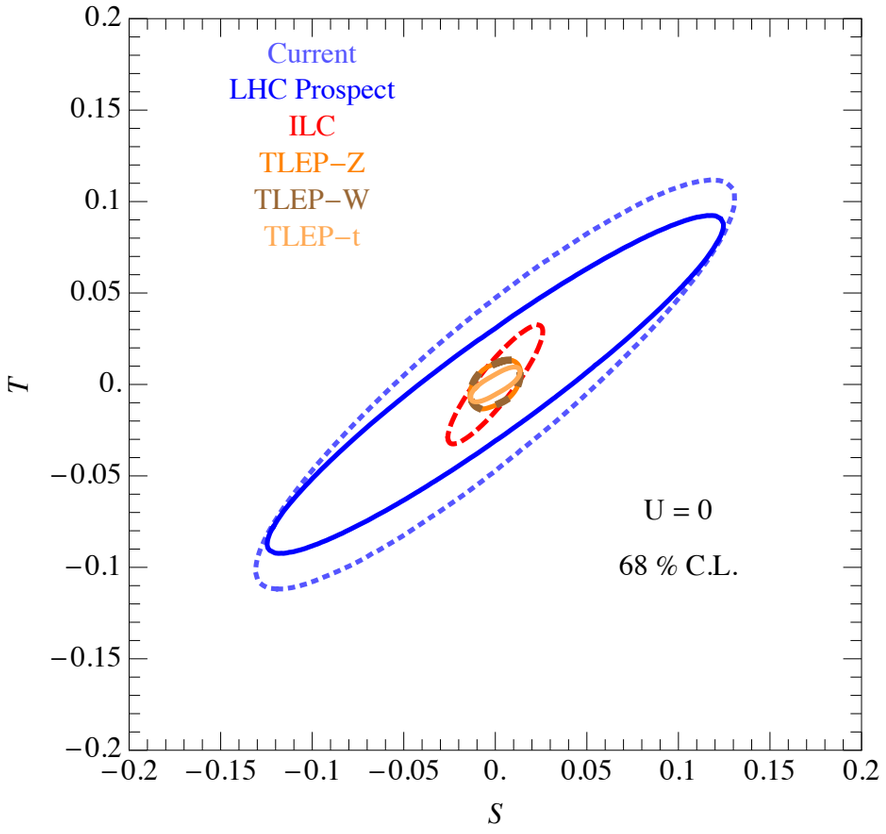
Big advance in electroweak precision

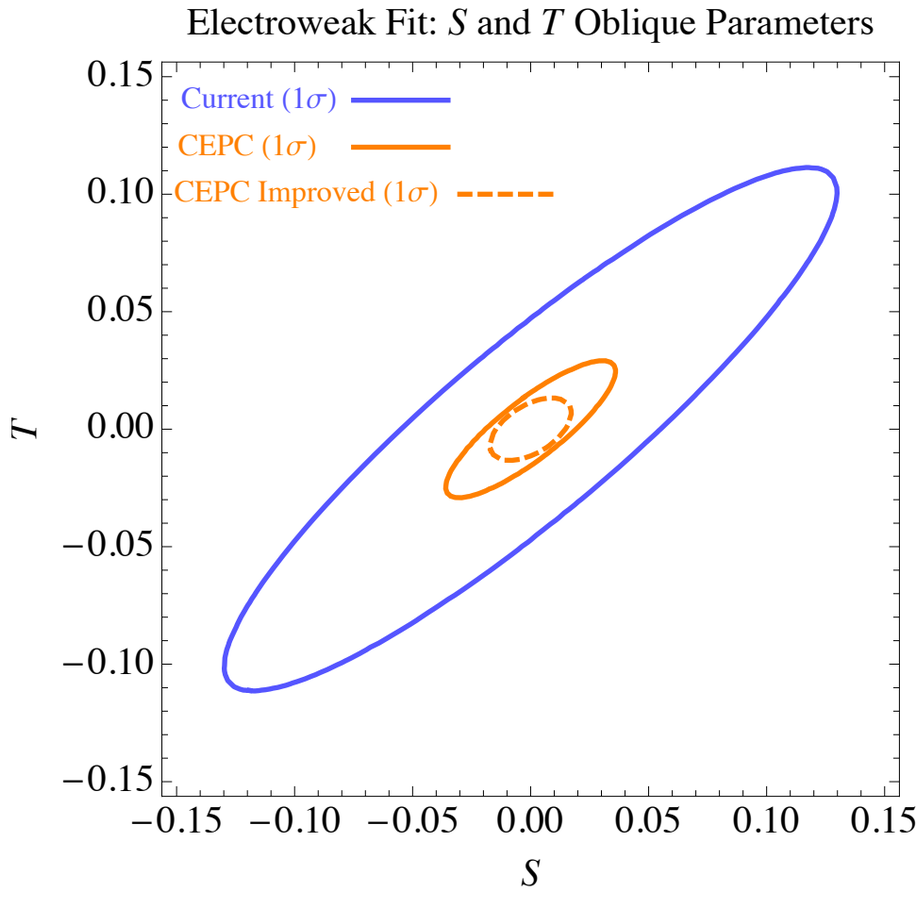


Large improvements across the board

Electroweak precision at CEPC

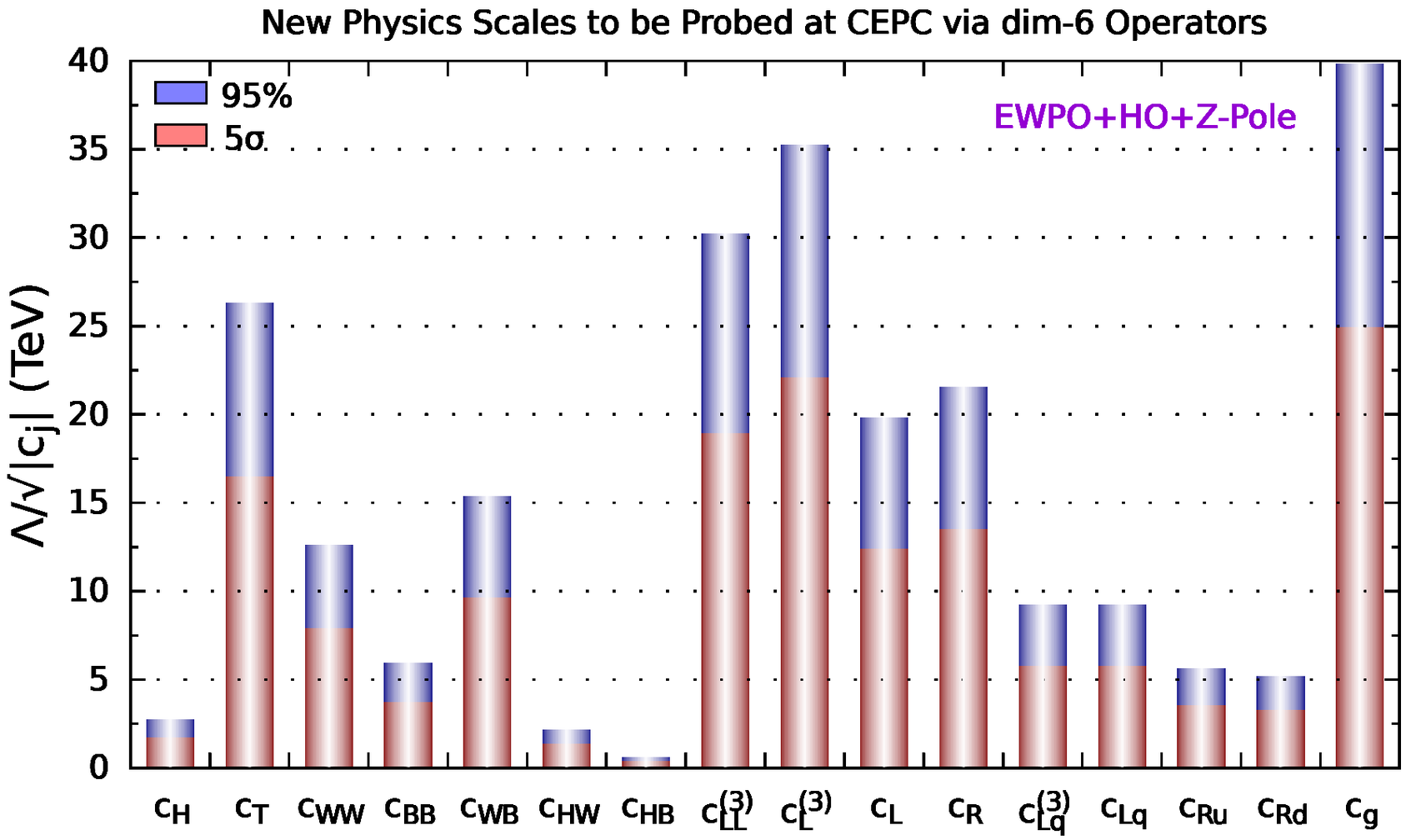
- A big step beyond the current precision.





J. Fan, M. Reece, LT Wang, 1411.1054

Scale of new physics.

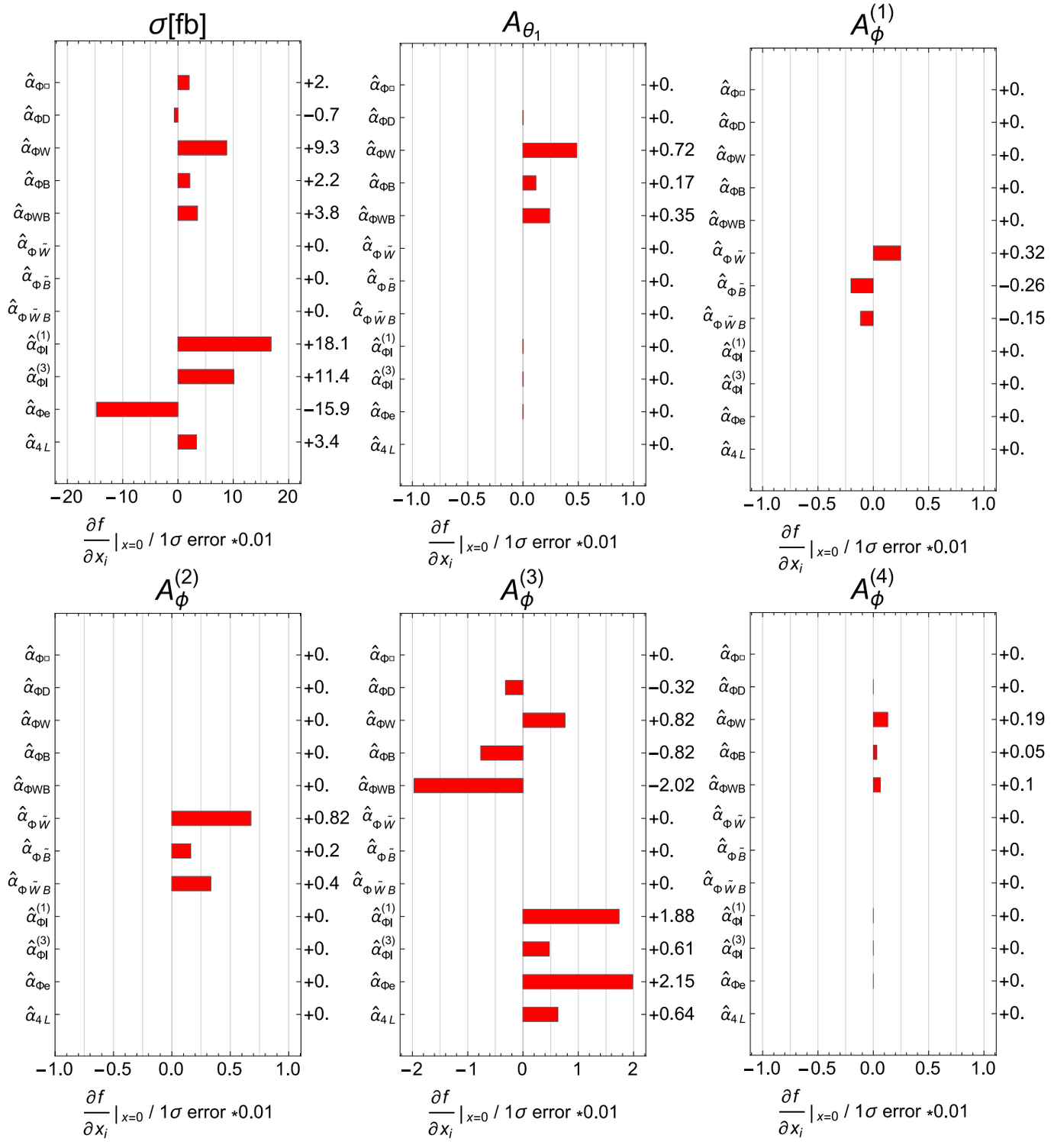


S. Ge, H. He, R. Xiao, 1603.03385

In the regime of multiple TeVs!

More details, more understanding.

NC, Jiayin Gu, Zhen Liu, Kechen Wang, *In Progress*



CEPC sensitive not only to coupling shifts, but different tensor structures.

- Truncate flat directions in the HEFT.
- Improve BSM reach by using added information.
- Distinguish between different BSM models with similar total cross section shifts.

N. Craig, J. Gu, Z. Liu, K. Wang

Case study 1:

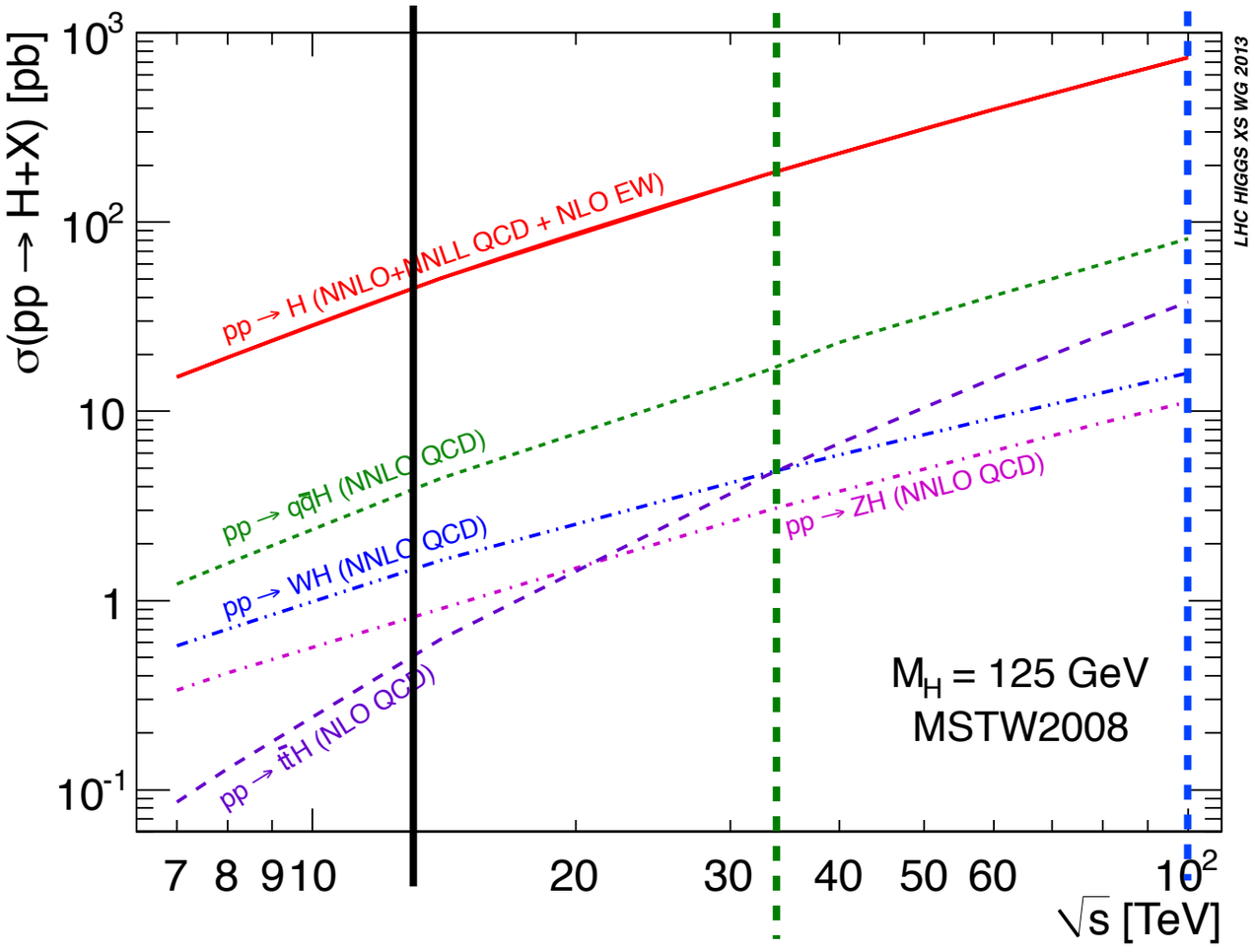
Higgs rare decay

Work in progress with Zhen Liu and Hao Zhang

Some slides from Hao Zhang

vs 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 Higgs factories

Hadron collider good for rare but clean signal

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]
	$h \to (b\bar{b}) + \not{E}_T$	
	$h \to (jj) + \not{E}_T$	
	$h \to (\tau^+\tau^-) + \not{E}_T$	
	$h \to (\gamma\gamma) + \not{E}_T$	
	$h \to (\ell^+\ell^-) + \not{E}_T$	
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$	$0.2[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (jj) + \not{E}_T$	
	$h \to (\tau^+\tau^-) + \not{E}_T$	$1[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (\gamma\gamma) + \not{E}_T$	
	$h \to (\ell^+\ell^-) + \not{E}_T$	
	$h \to (\mu^+\mu^-) + \not{E}_T$	$0.07[7 + 8\text{TeV}]$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$	
	$h \to jj + \not{E}_T$	
	$h \to \tau^+\tau^- + \not{E}_T$	
	$h \to \gamma\gamma + \not{E}_T$	
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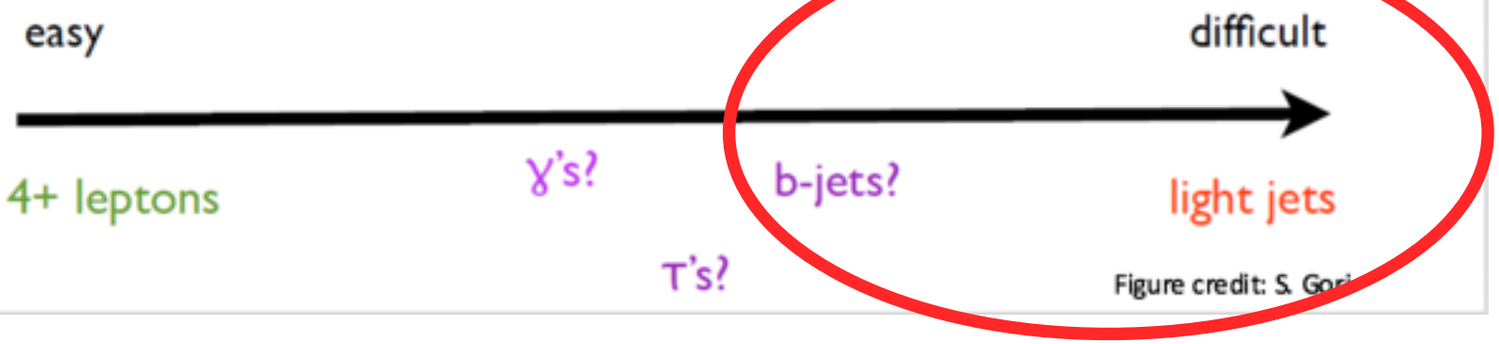
Decay Topologies	Decay mode $\mathcal{F}_i$	2σ LHC sensitivity to Br
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$	$0.2[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (b\bar{b})(\tau^+\tau^-)$	$0.15[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (b\bar{b})(\mu^+\mu^-)$	$(0.6-2) \times 10^{-4}[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$	$0.2 - 0.4[7 + 8\text{TeV}]$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$	$(3-7) \times 10^{-4}[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (jj)(jj)$	$0.1[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (jj)(\gamma\gamma)$	$0.01[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (jj)(\mu^+\mu^-)$	$(5-20) \times 10^{-5}[14\text{TeV}, 100\text{fb}^{-1}]$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$	$4 \times 10^{-5}[7 + 8\text{TeV}]$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$	$4 \times 10^{-5}[7 + 8\text{TeV}]$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$	$10^{-4}[7 + 8\text{TeV}]$
	$h \to (\gamma\gamma)(\gamma\gamma)$	$3 \times 10^{-5}[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to \gamma\gamma + \not{E}_T$	
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$	
	$h \to (\ell^+\ell^-) + \not{E}_T + X$	
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$	
	$h \to \ell^+\ell^- + \not{E}_T + X$	

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?

Our starting point.

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

Decay Topologies	Decay mode $\mathcal{F}_i$	2σ LHC sensitivity to Br
$h \to 2$	$h \to \not{E}_{\rm T}$	$0.25[14\text{TeV}, 300\text{fb}^{-1}]$
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	$h \to (b\bar{b}) + \not{E}_{\rm T}$	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 $h \to ZZ^*, WW^*$
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$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_{\rm T}$	$0.2[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (jj) + \not{E}_{\rm T}$	Bkg same as above block
	$h \to (\tau^+\tau^-) + \not{E}_{\rm T}$	$1[14\text{TeV}, 300\text{fb}^{-1}]$
	$h \to (\gamma\gamma) + \not{E}_{\rm T}$	
	$h \to (\ell^+\ell^-) + \not{E}_{\rm T}$	
	$h \to (\mu^+\mu^-) + \not{E}_{\rm T}$	$0.07[7 + 8\text{TeV}]$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_{\rm T}$	– last step off-shell
	$h \to jj + \not{E}_{\rm T}$	Bkg same as above
	$h \to \tau^+\tau^- + \not{E}_{\rm T}$	–
	$h \to \gamma\gamma + \not{E}_{\rm T}$	–
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$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$	$0.2[14\text{TeV}, 100\text{fb}^{-1}]$
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	$h \to (\ell^+\ell^-) + \not{E}_{\rm T} + X$	inclusive measurement
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\rm T}$	
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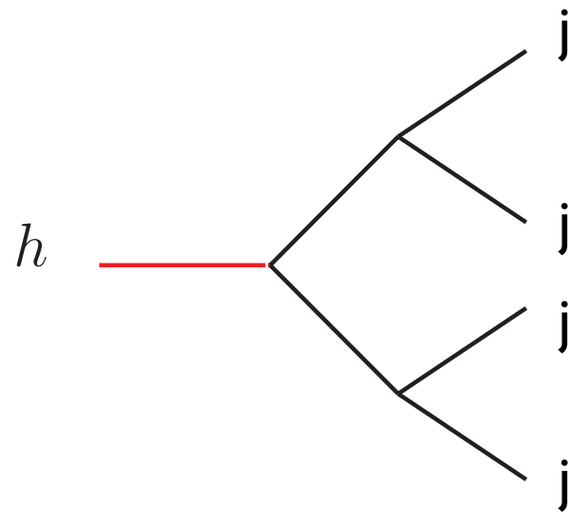
LHC can do well

For example



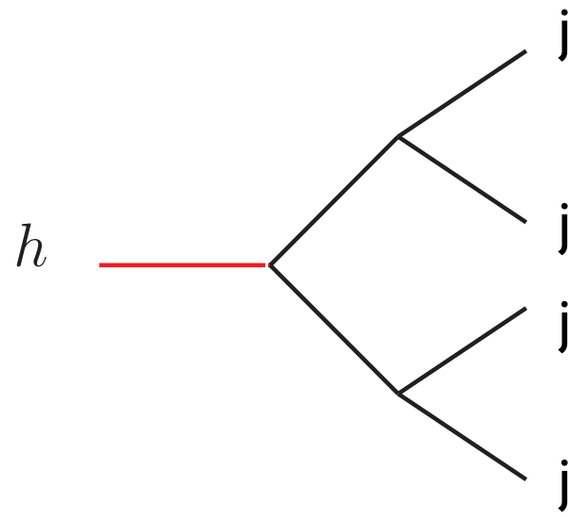
$h \to 2 \to 4$

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
			$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7 + 8 [14] TeV	$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7 + 8 [14] TeV	
jjjj	> 1 [0.1*]	*W*	0.99	> 1 [0.1*]	0.92	> 1 [0.1*]	Theory study [220,269], Sec. VII

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

For example



$h \to 2 \to 4$

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.*

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
			$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ $7+8$ [14] TeV	$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ $7+8$ [14] TeV	
jjjj	> 1 [0.1*]	*W*	0.99	> 1 [0.1*]	0.92	> 1 [0.1*]	Theory study [220,269], Sec. VII

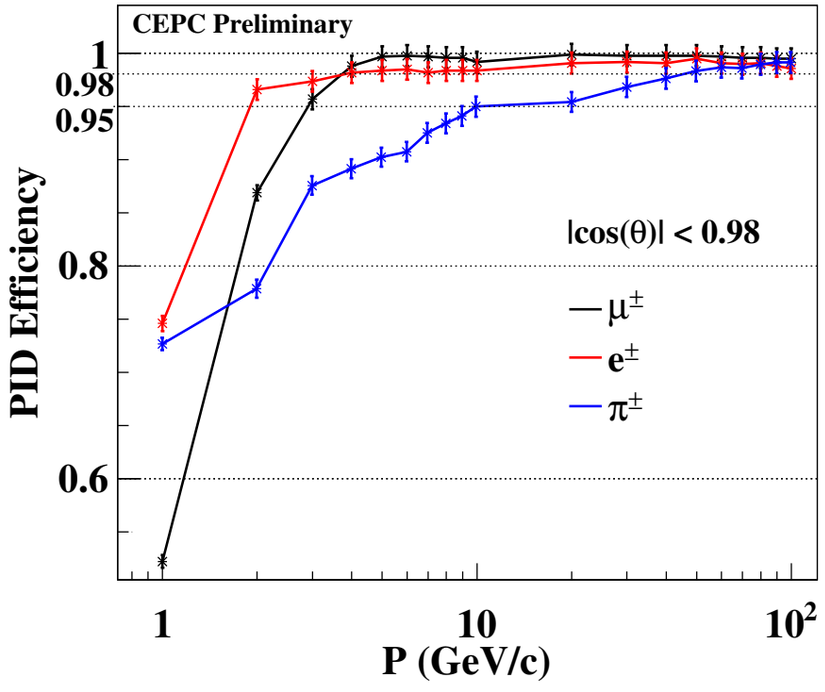
Note: boosted analysis, $m_a < 10$ GeV.
Weaker limit other wise.

- 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

Cuts and simulation.

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

  Similar to some LEP analysis

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

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

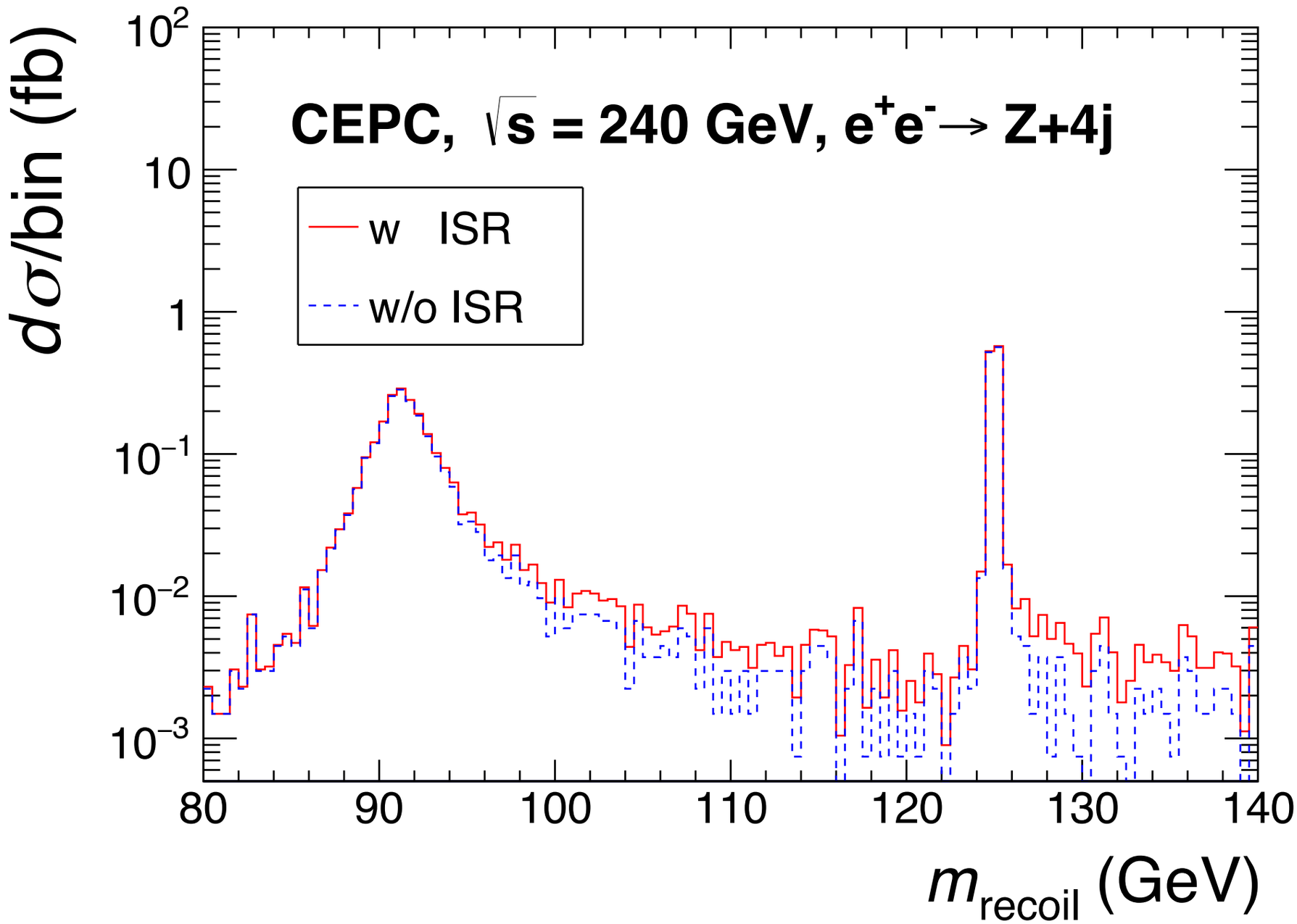
  $|m_{\ell\ell} - m_Z| < 10\mathrm{GeV}, |m_{\mathrm{recoil}} - m_h| < 5\mathrm{GeV}.$

- MadGraph5_aMC@NLO.

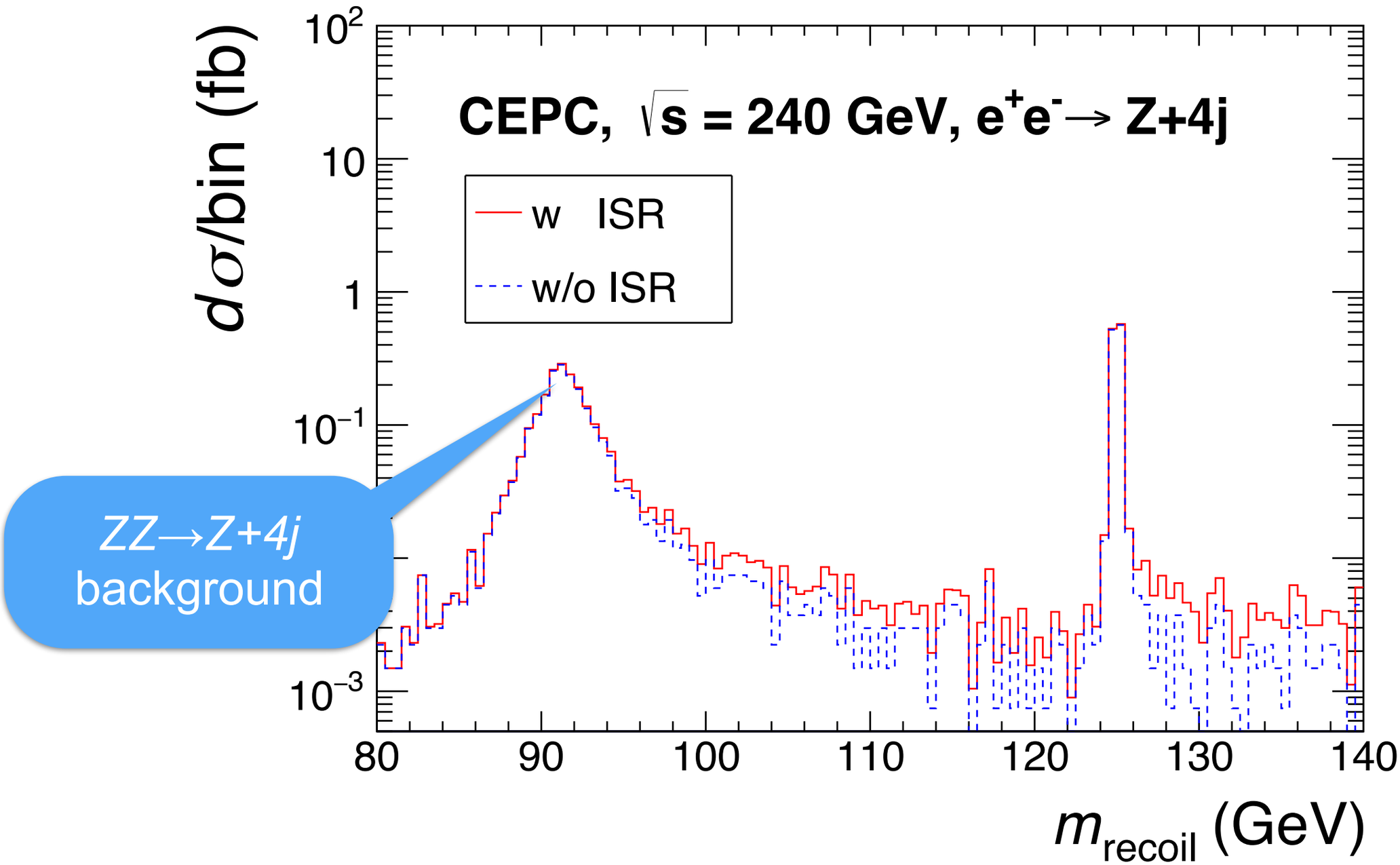
- The ISR effect of the background is roughly mimicked by generating events with 1 additional photon (with pT>1GeV to avoid the IR divergence).

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

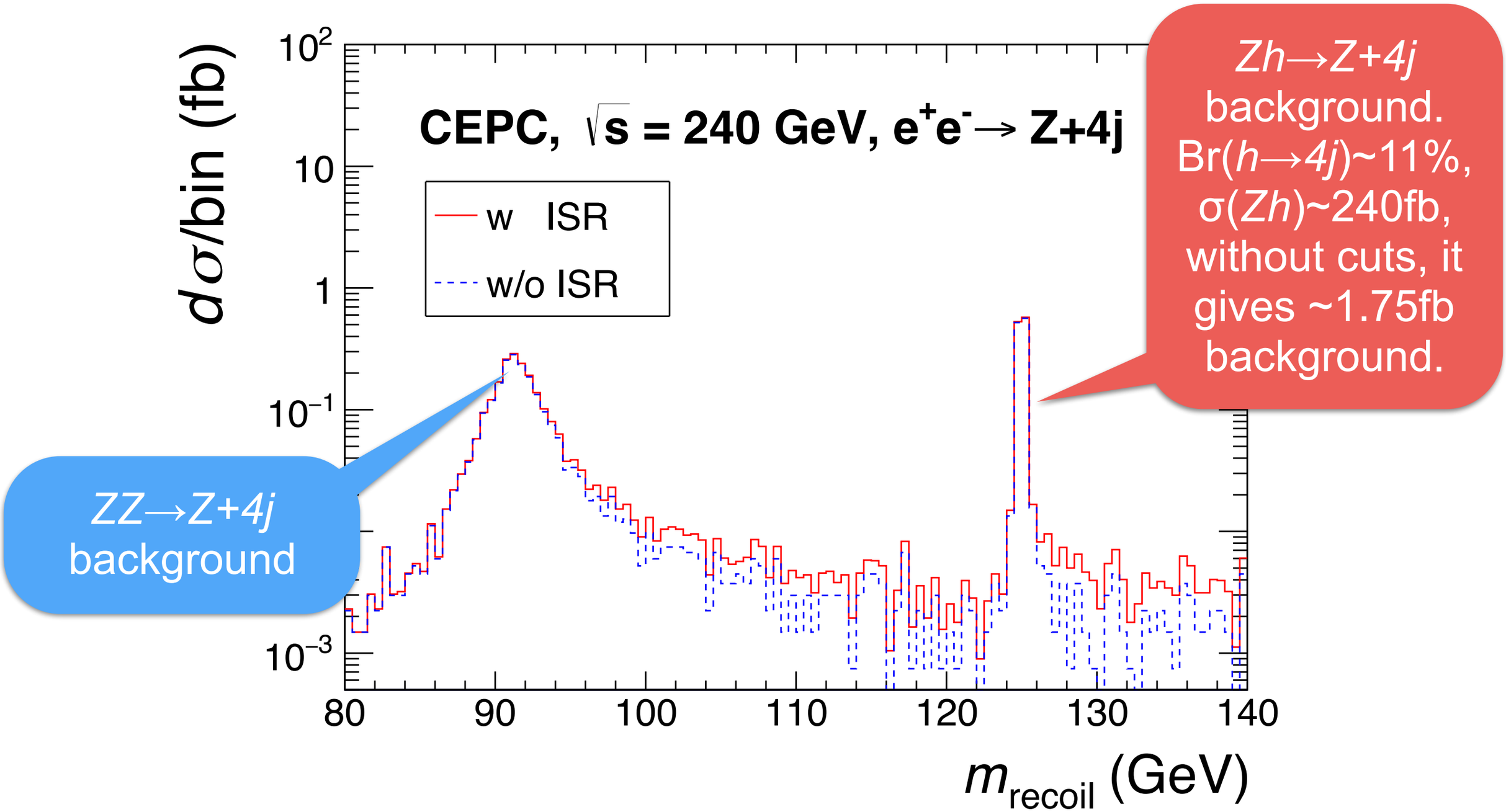
SM background



SM background

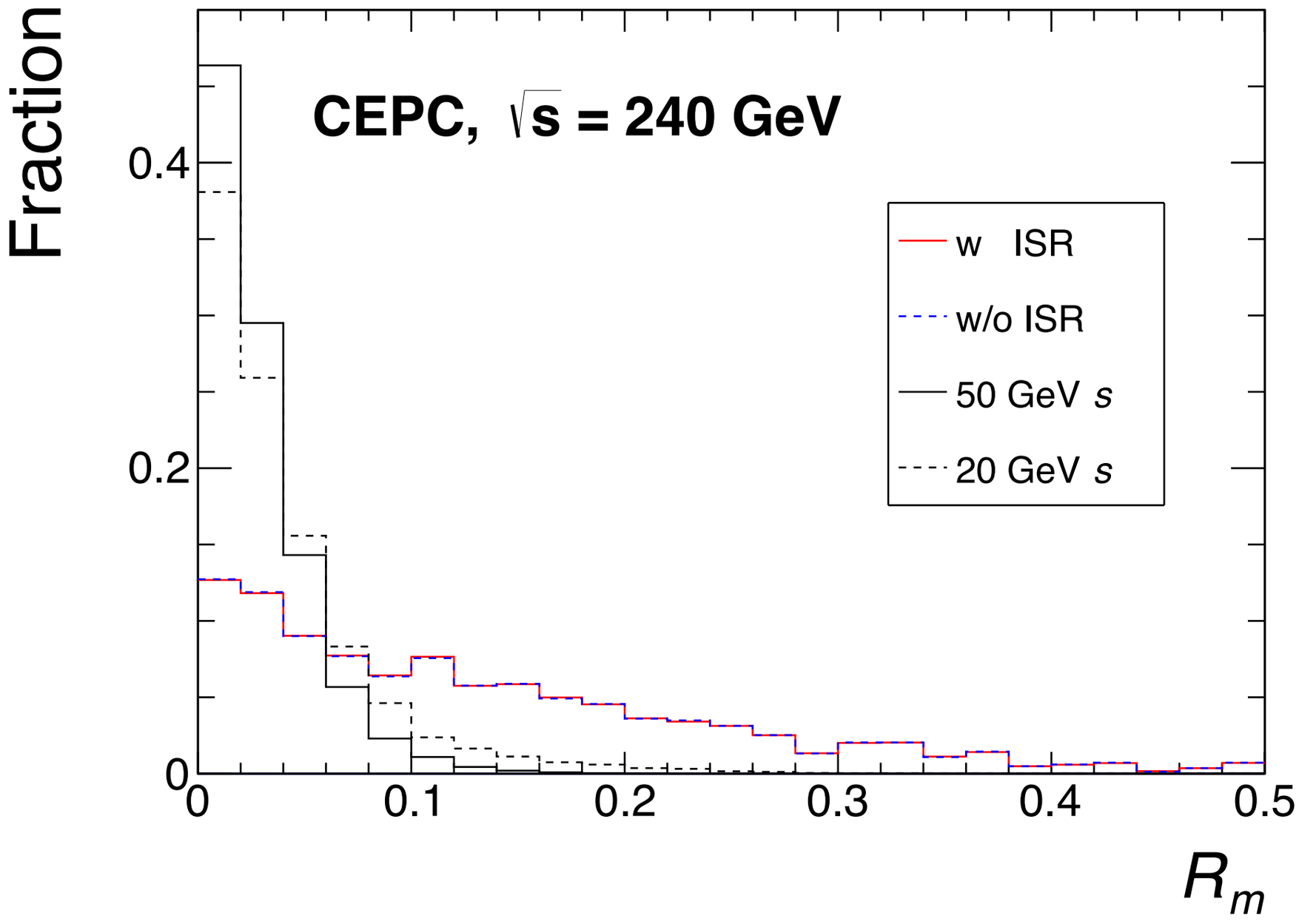


SM background



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

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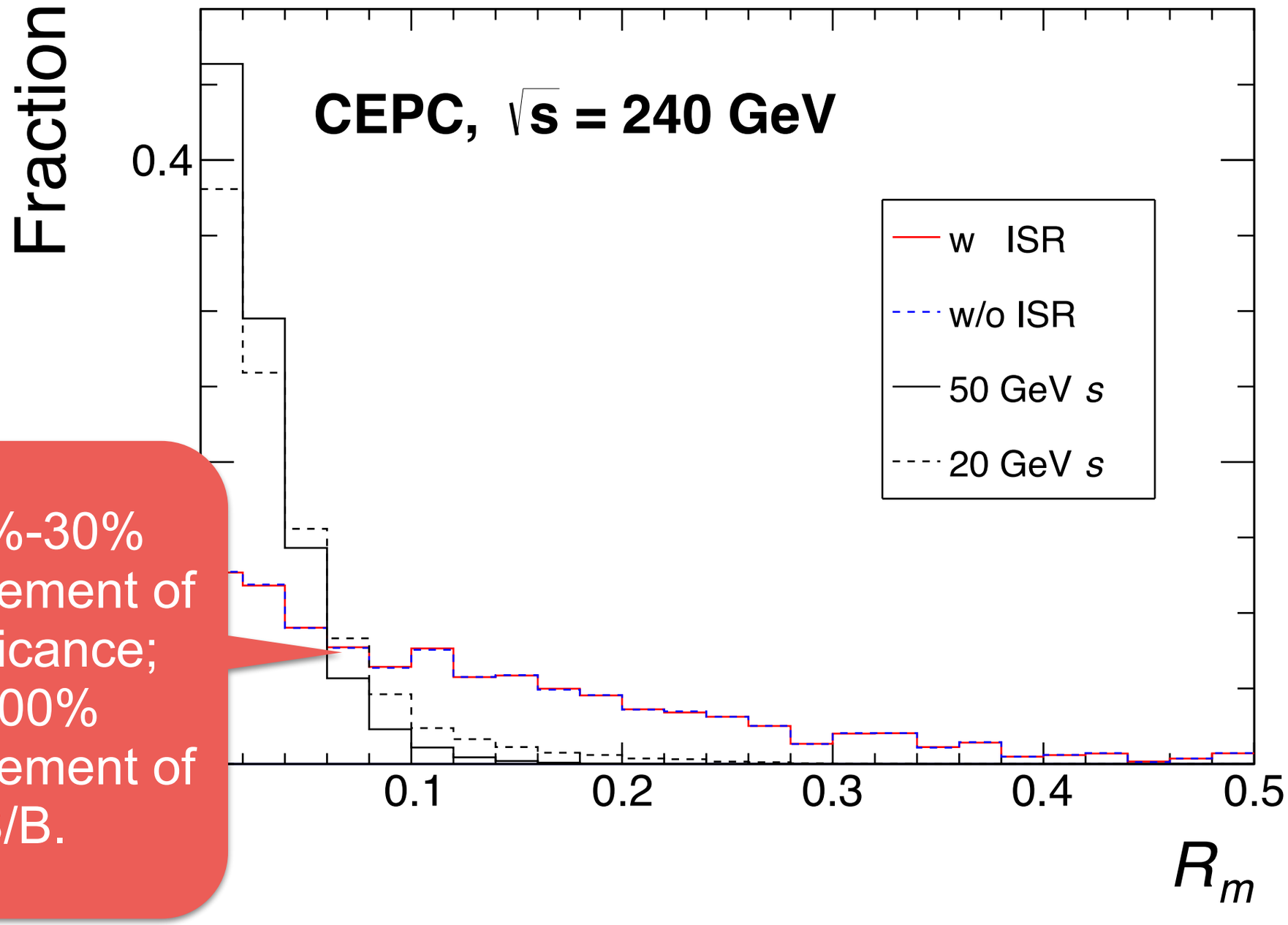
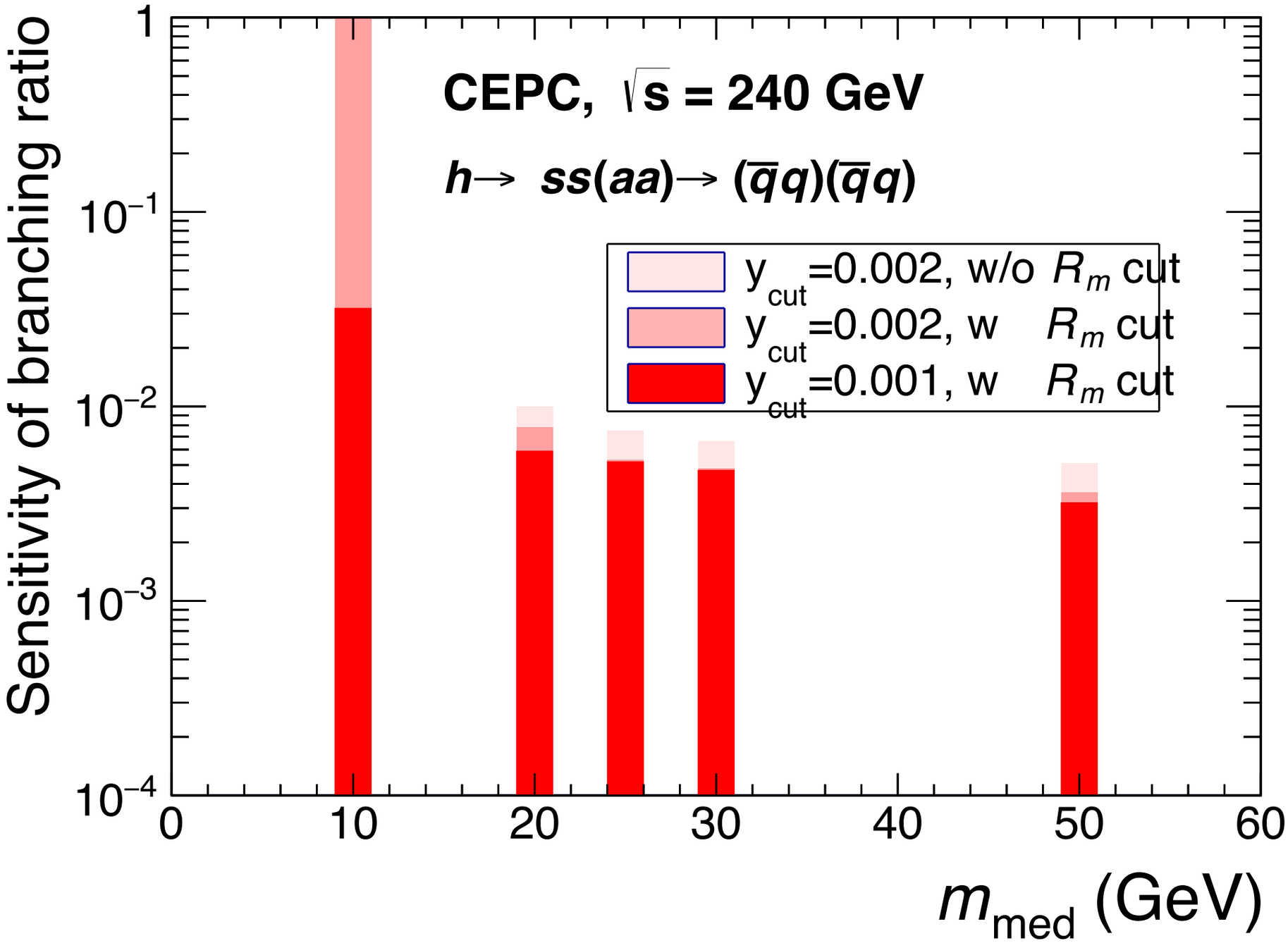


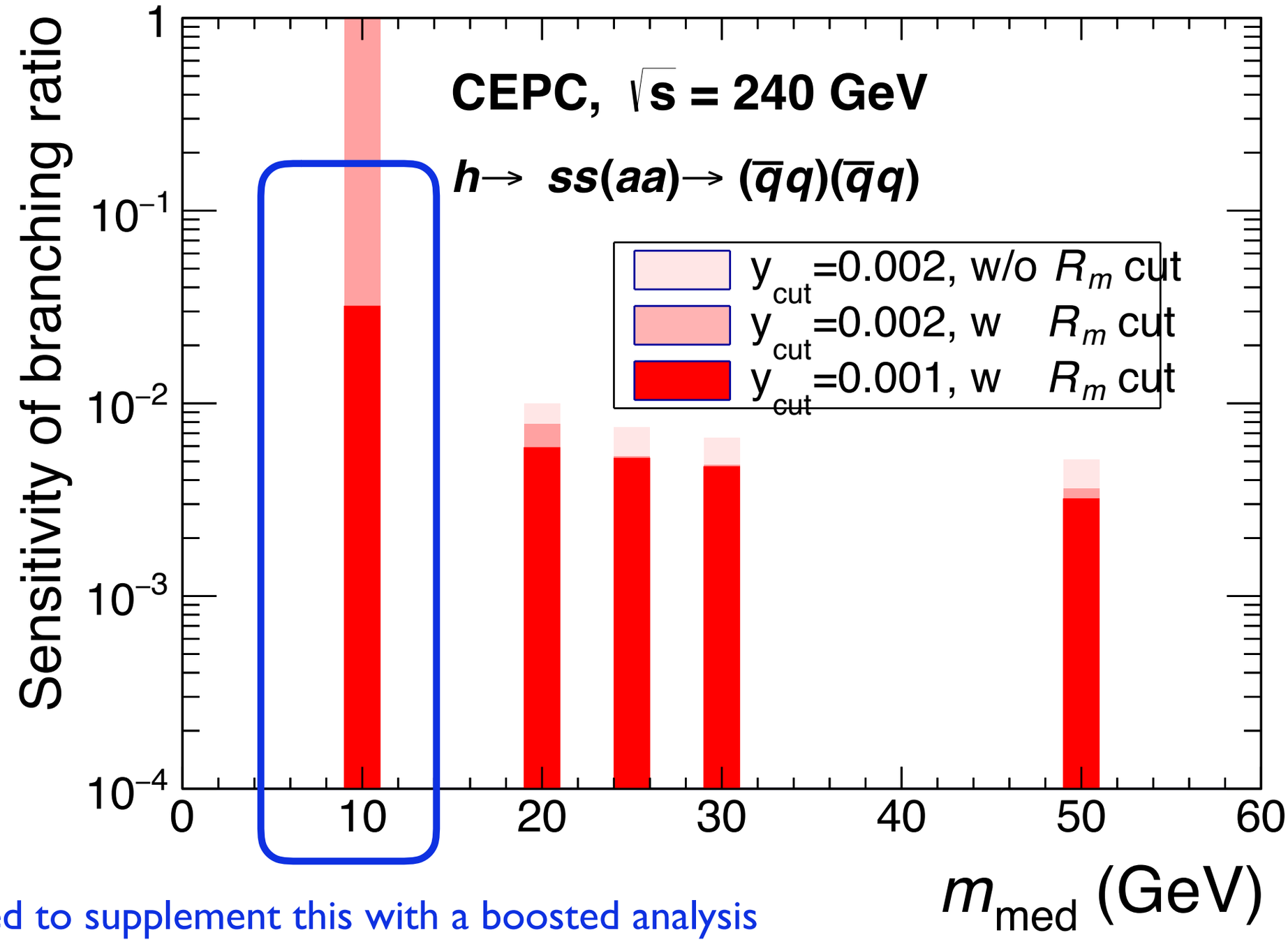
~20%-30% improvement of significance; ~100% improvement of S/B.



Precision at level < 1%.

In comparison, O(1) for LHC

Can be improved further with reconstructing a resonance.

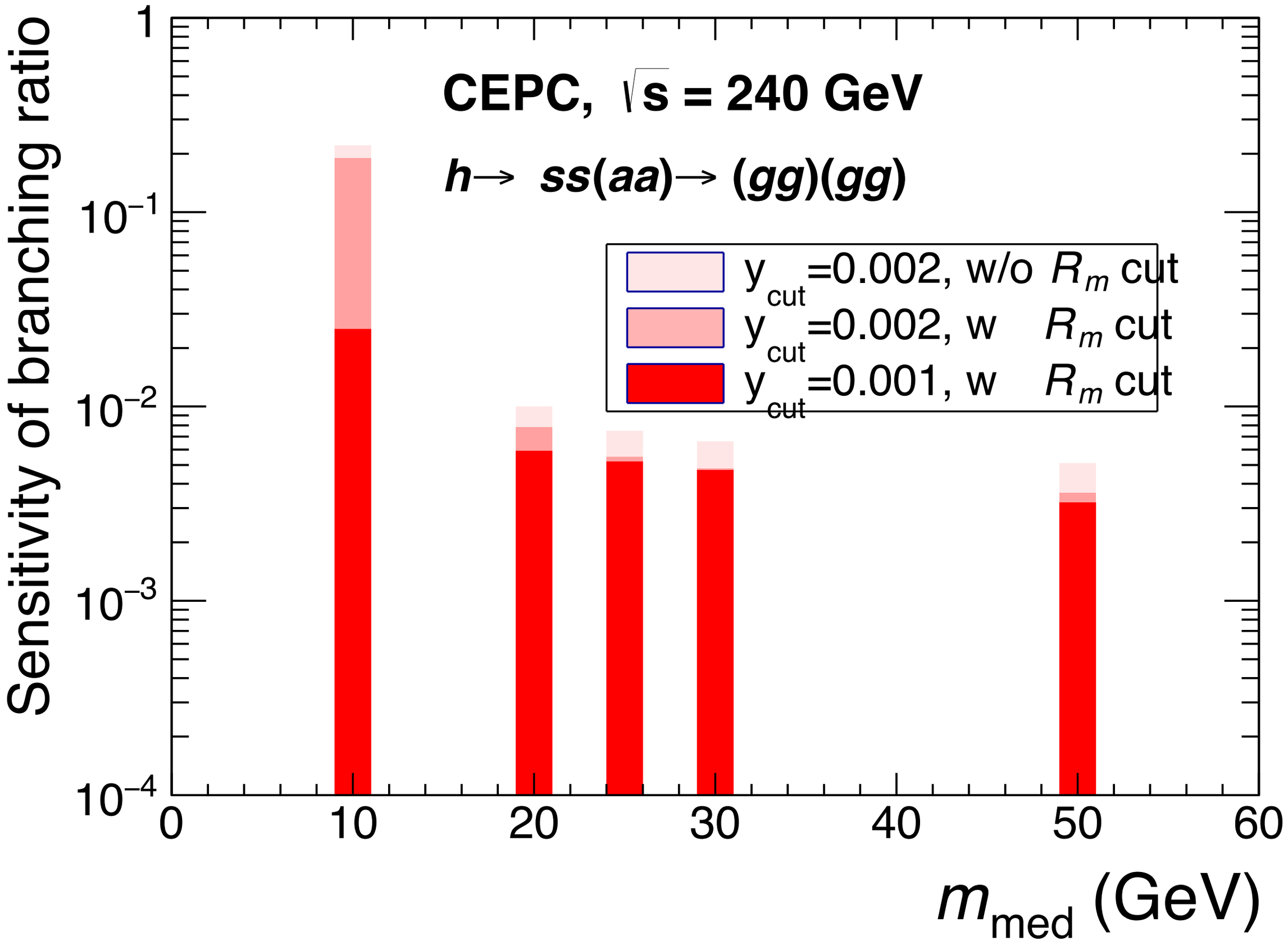


need to supplement this with a boosted analysis
similar improvement expected.

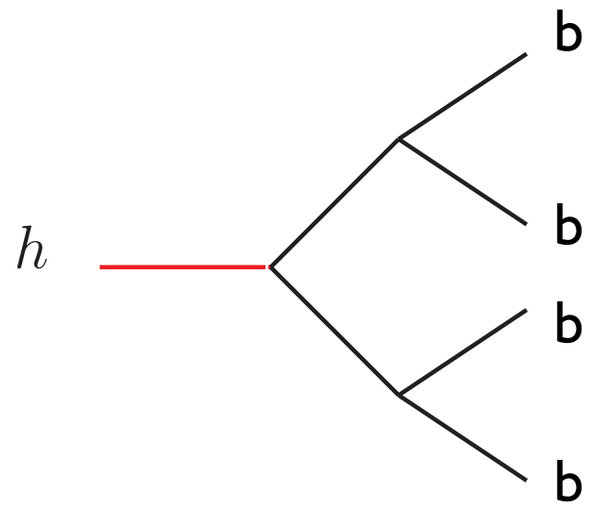
Precision at level < 1%.

In comparison, O(1) for LHC

Can be improved further with reconstructing a resonance.


CEPC, √s = 240 GeV
h→ ss(aa)→ (gg)(gg)
y_cut=0.002, w/o R_m cut
y_cut=0.002, w R_m cut
y_cut=0.001, w R_m cut
Sensitivity of branching ratio
1
10^−1
10^−2
10^−3
10^−4
0
10
20
30
40
50
60
m_med (GeV)

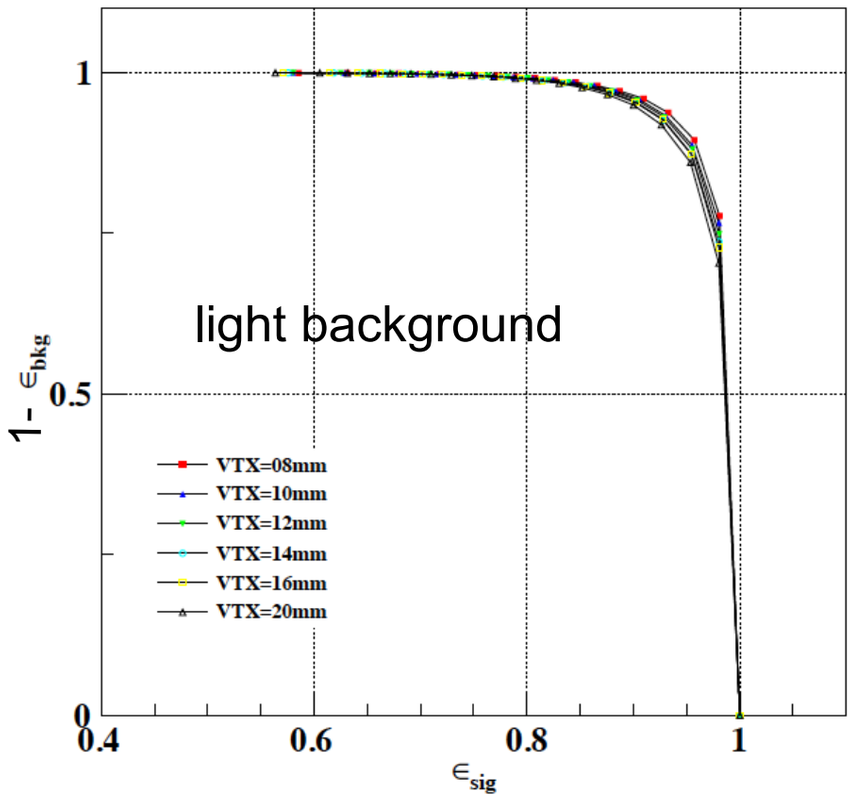
4 bottom final state

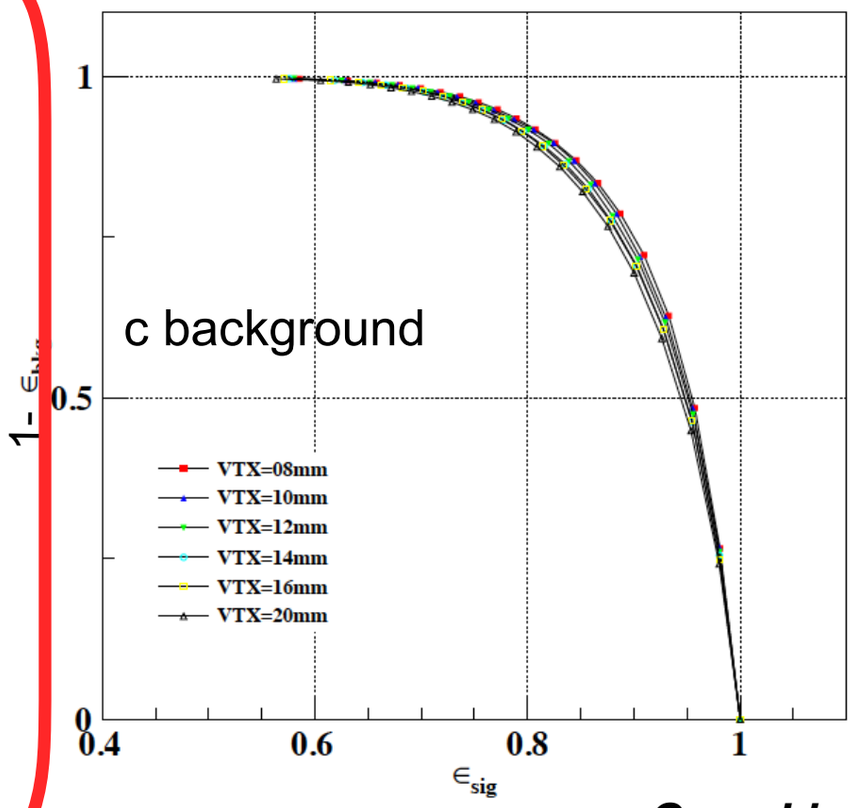


$h \to 2 \to 4$

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

Good b-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).*

CEPC, $\sqrt{s}$ = 240 GeV

$h \to ss(aa) \to (\bar{b}b)(\bar{b}b)$

y_{cut}=0.002, ε_b=70%

y_{cut}=0.001, ε_b=70%

y_{cut}=0.001, ε_b=80%

Sensitivity of branching ratio

10^{-2}

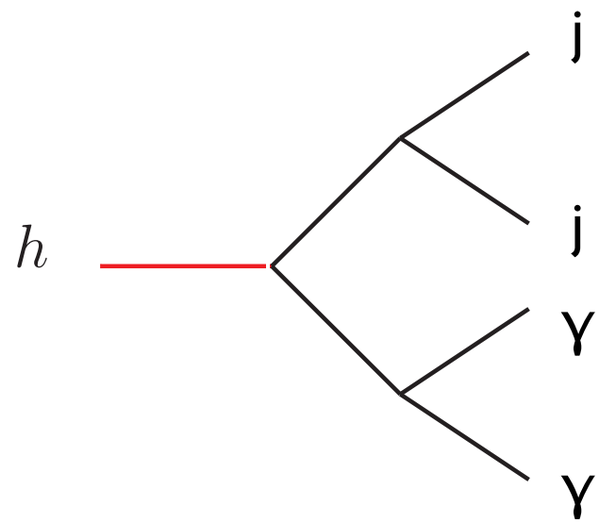
10^{-3}

10^{-4}

10 20 30 40 50 60

m_{med} (GeV)

For example



$h \to 2 \to 4$

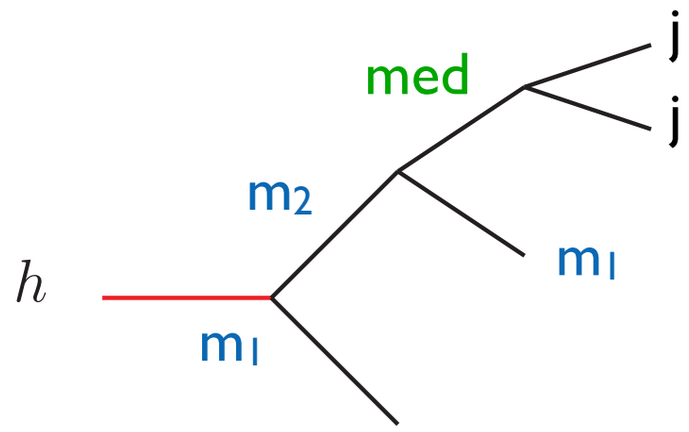
Main background: ZZ → Z jj γγ

$m_{\rm med}$ (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%

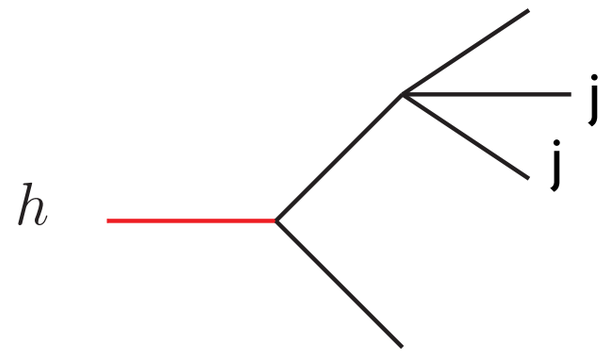
LHC: about 1%

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

- Another topology

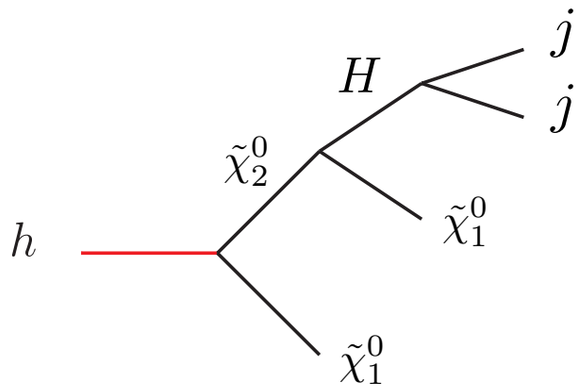


$h \to 2 \to 3 \to 4$

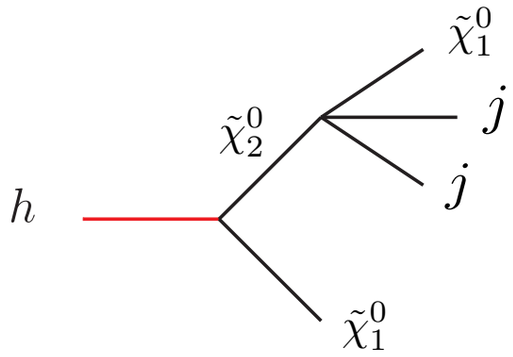


$h \to 2 \to (1+3)$

For example:



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

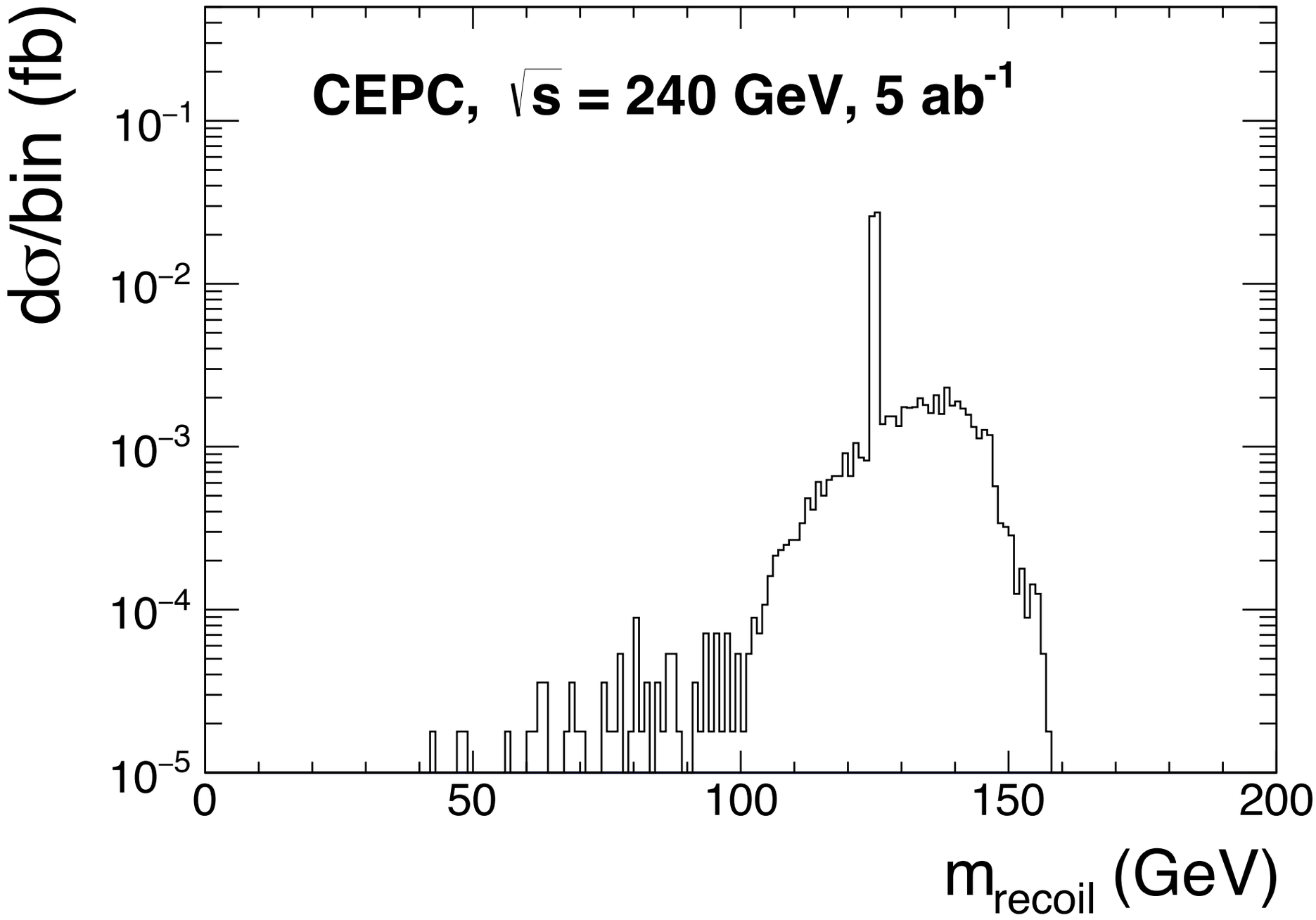


$h \to 2 \to (1+3)$

LHC: 10(s)%

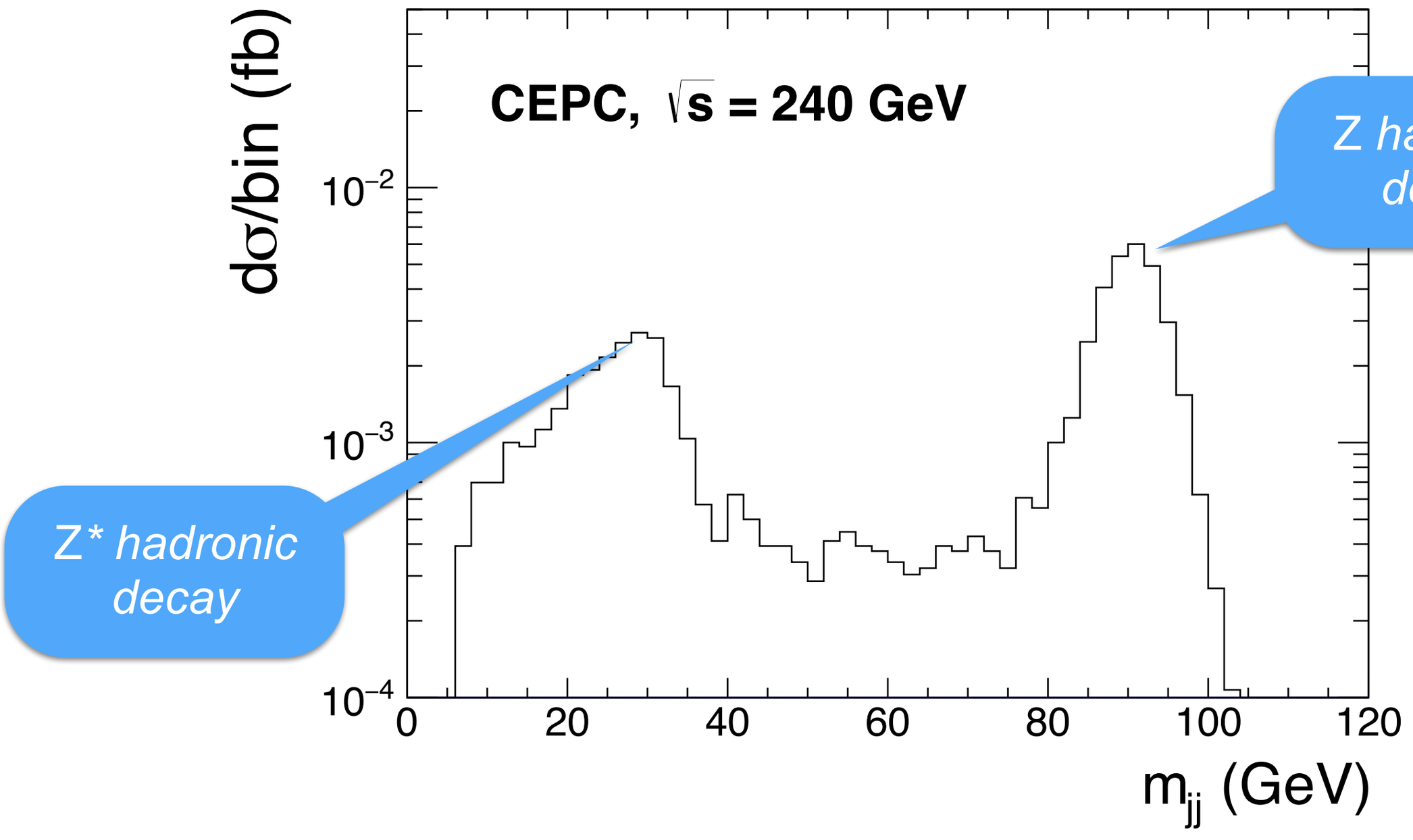
Background. $e^+e^- \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell jj$

ee → Zh, followed by h → Z* Z



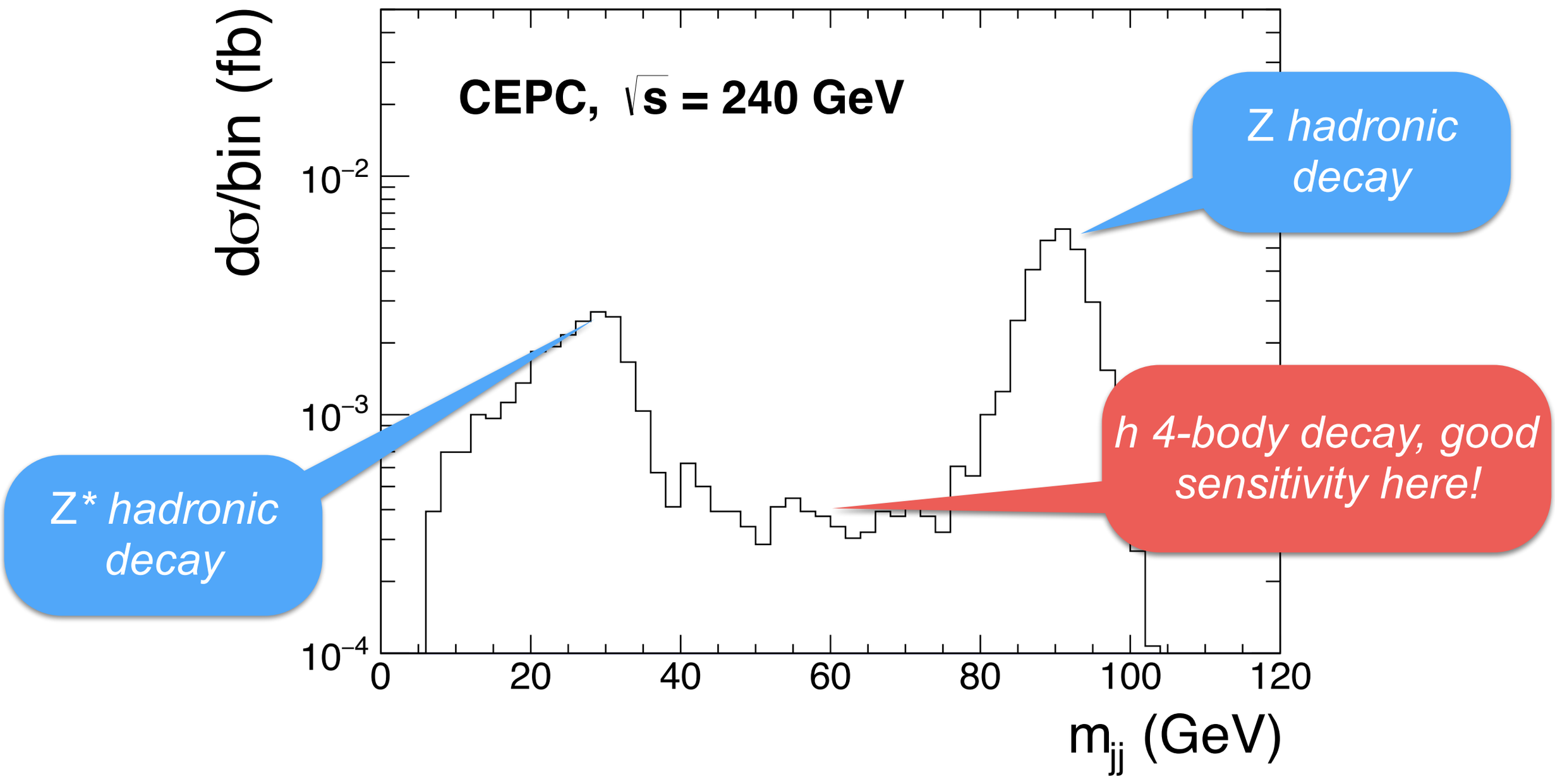
Exotic decay of the SM Higgs boson (jj+met)

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

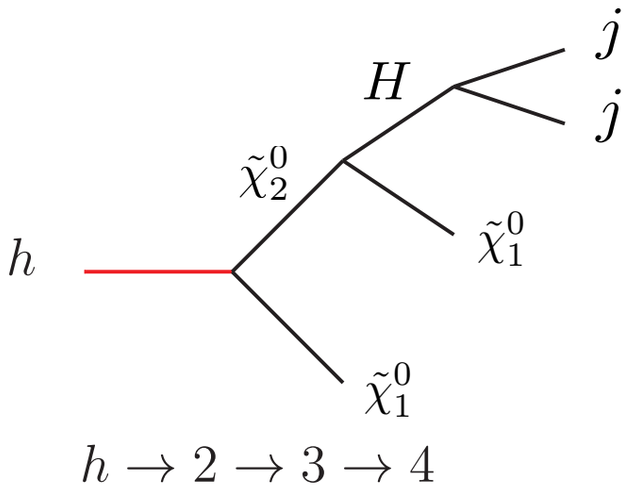


Exotic decay of the SM Higgs boson (jj+met)

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

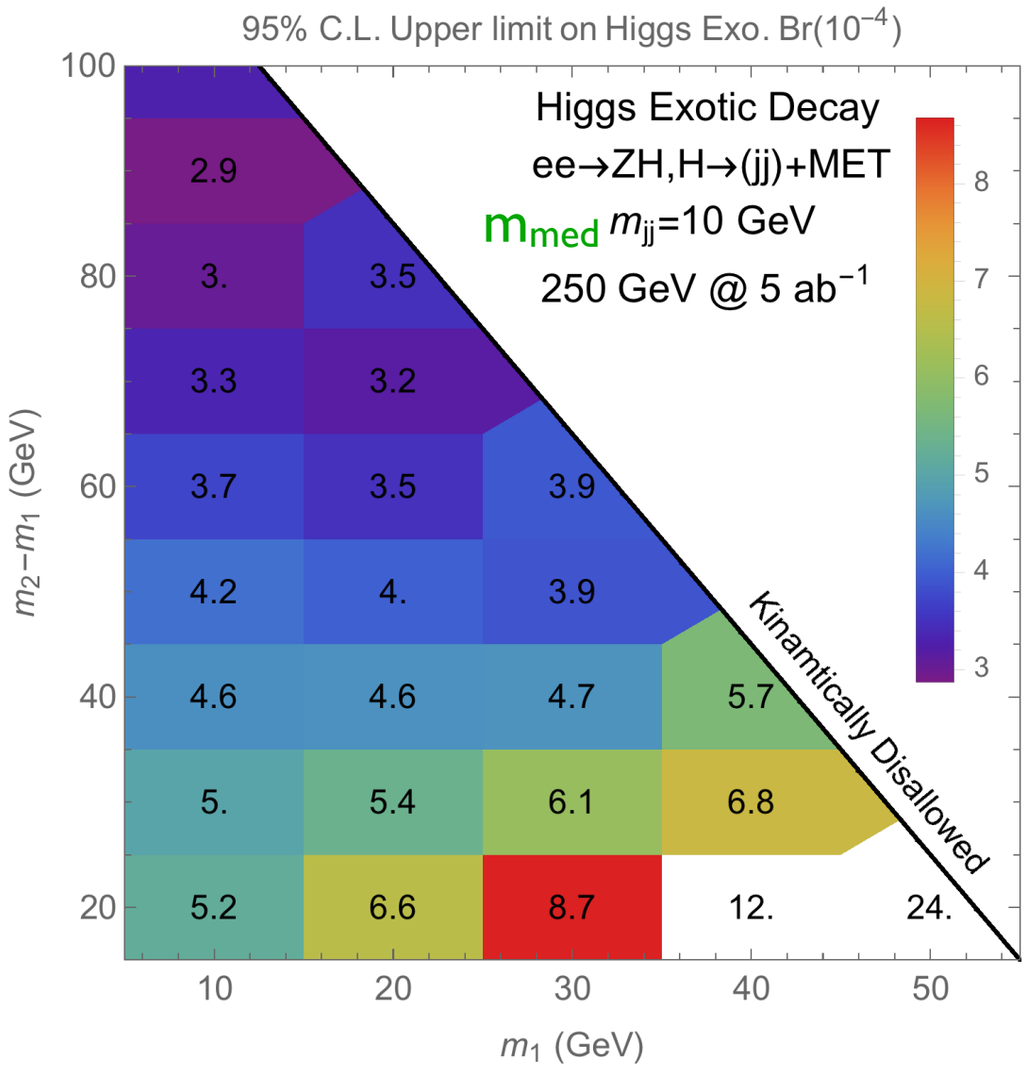


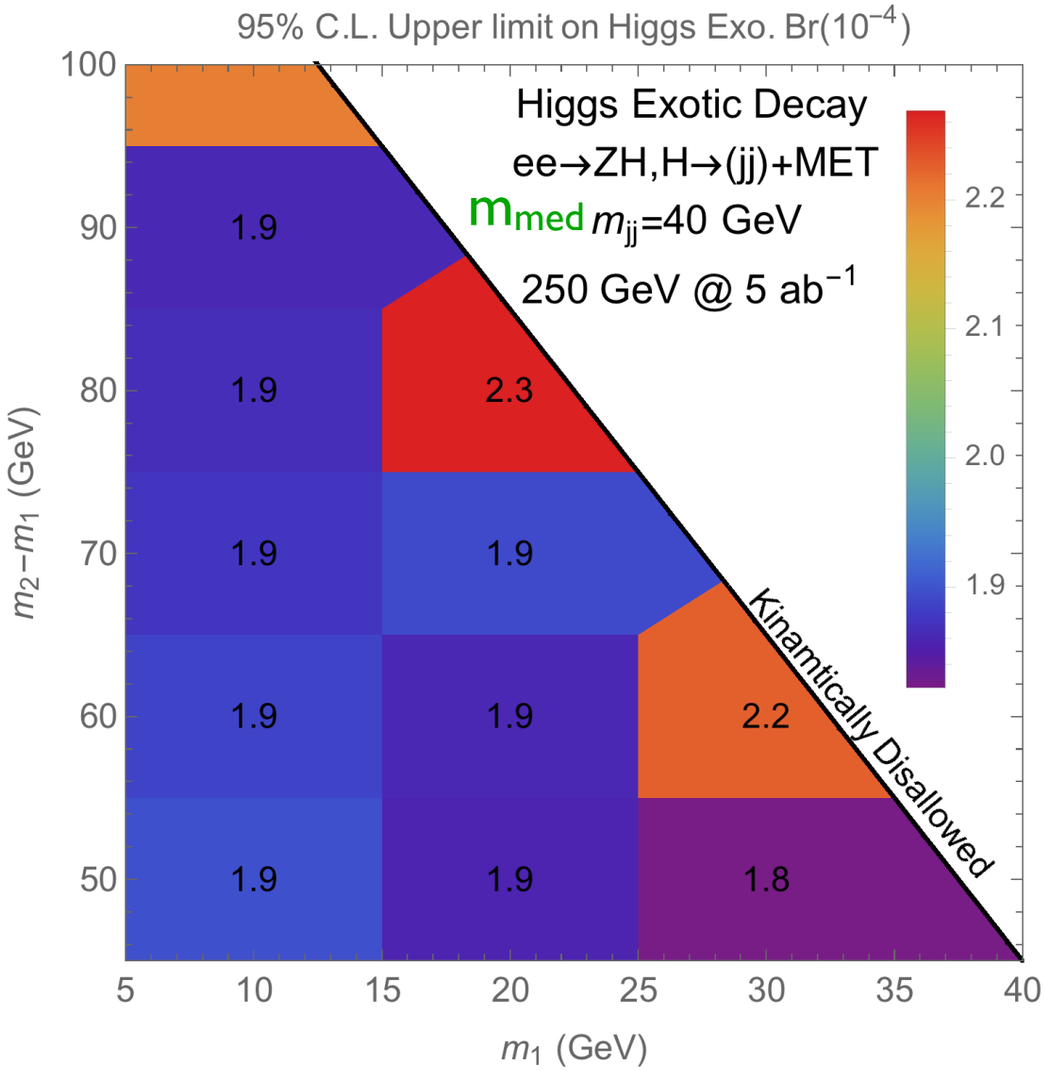
Exotic decay of the SM Higgs boson (jj+met)



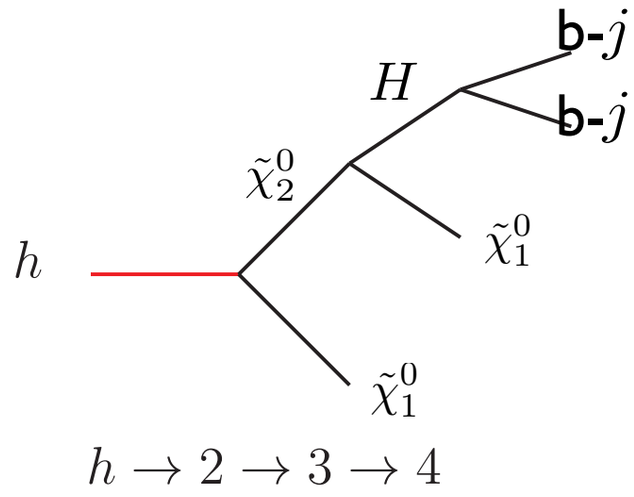
$h \to 2 \to 3 \to 4$

10^{-4} level at Higgs factories



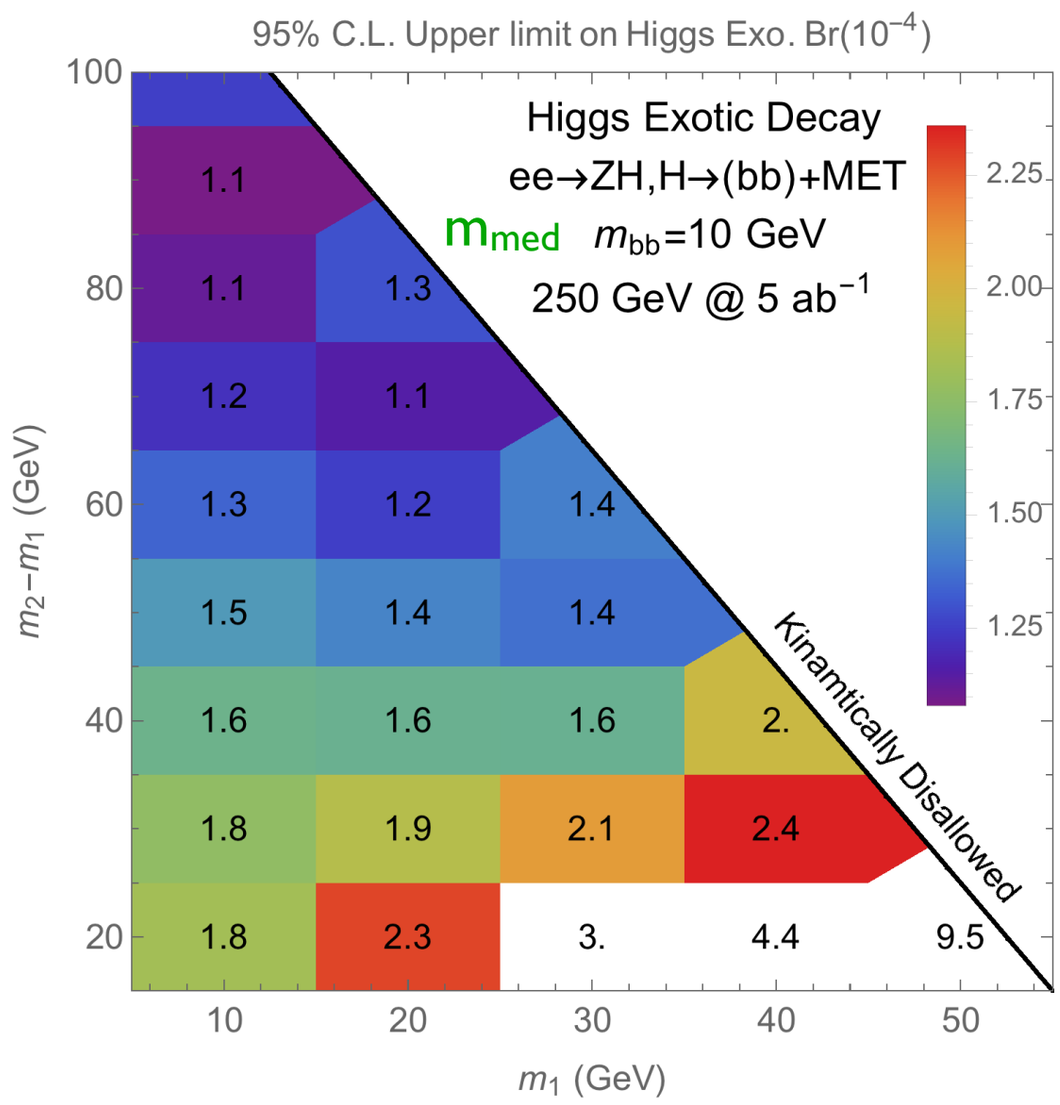


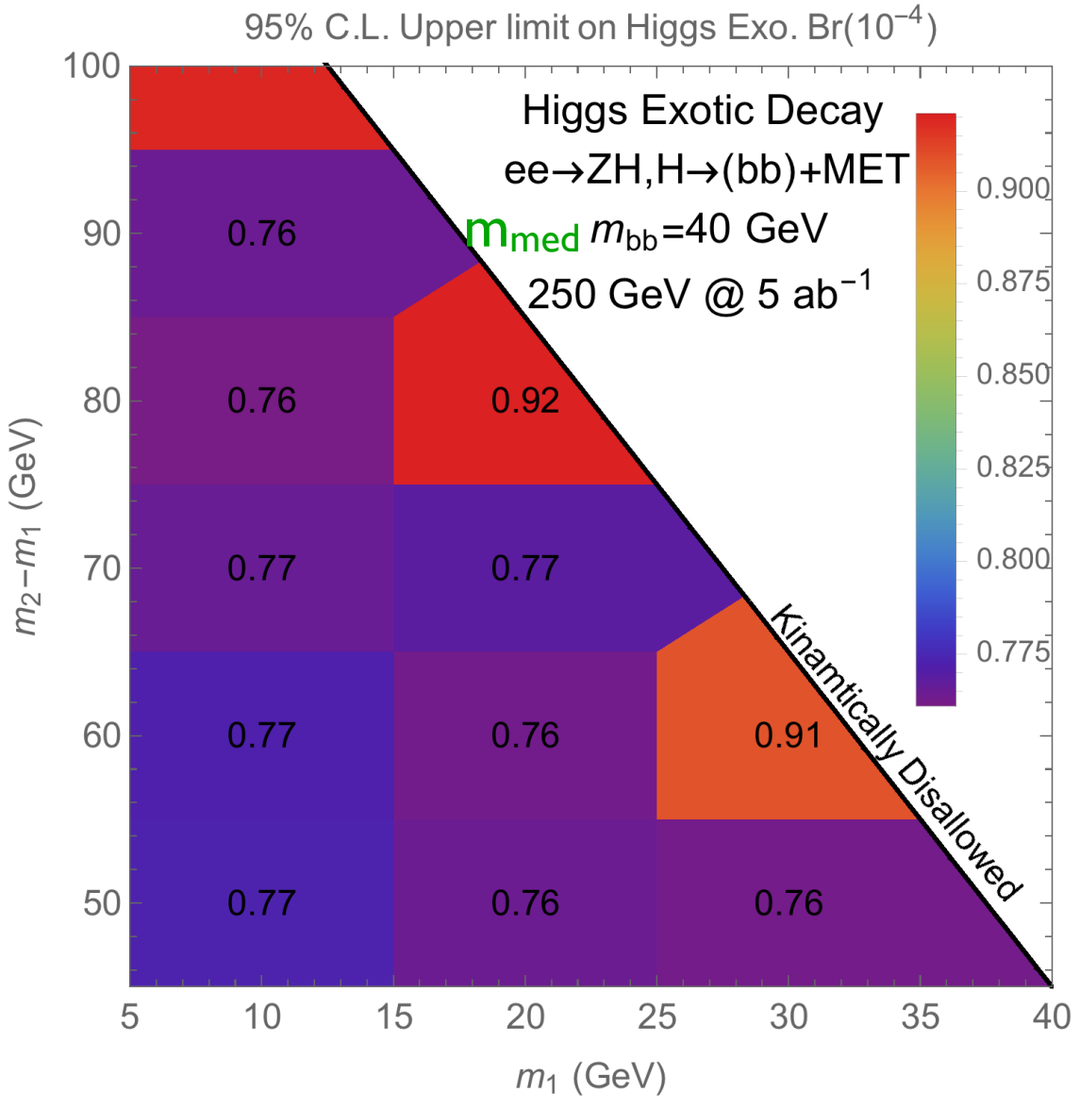
Exotic decay of the SM Higgs boson (jj+met)



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

10^{-4} level at Higgs factories



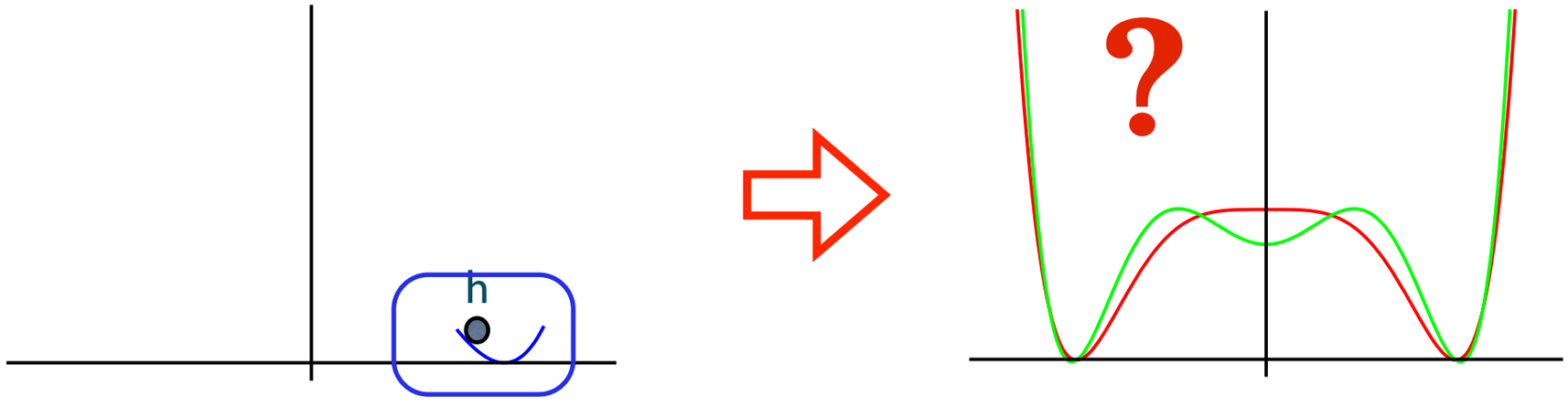


What can we learn from precision Higgs measurement.

Case studies

- EWSB phase transition in early universe.
- Top related couplings.

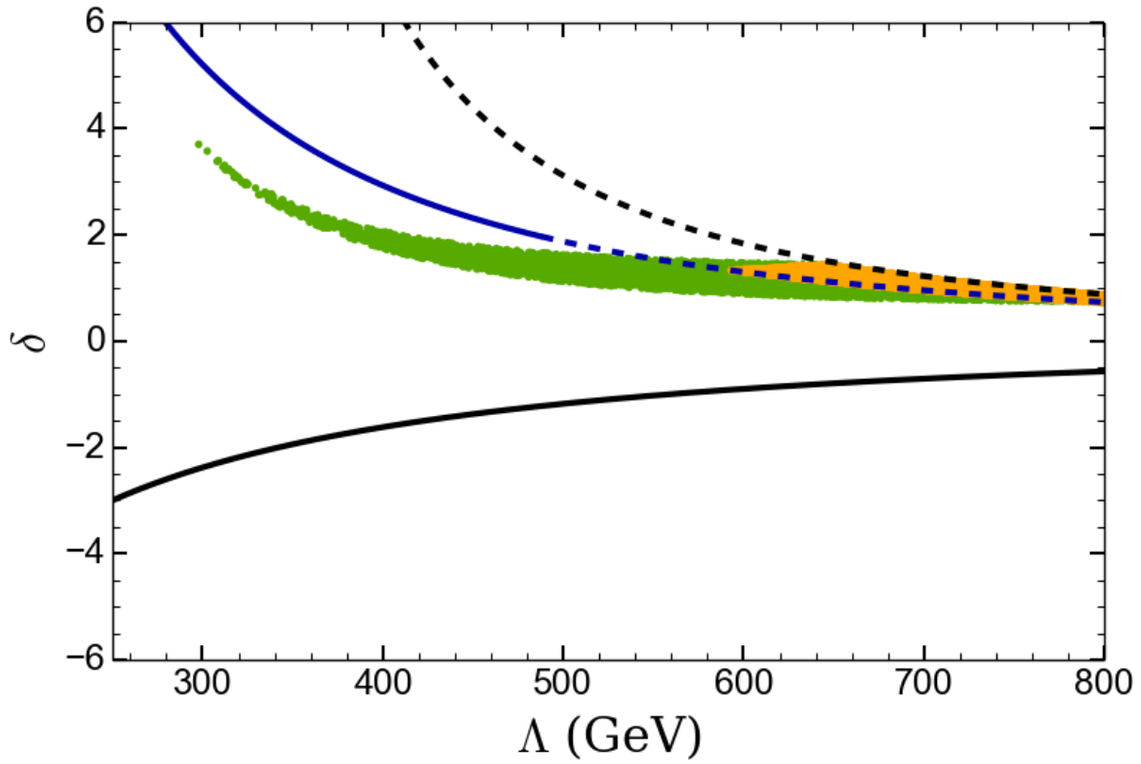
Nature of EW phase transition



What we know from
LHC and upgrades won't go much further

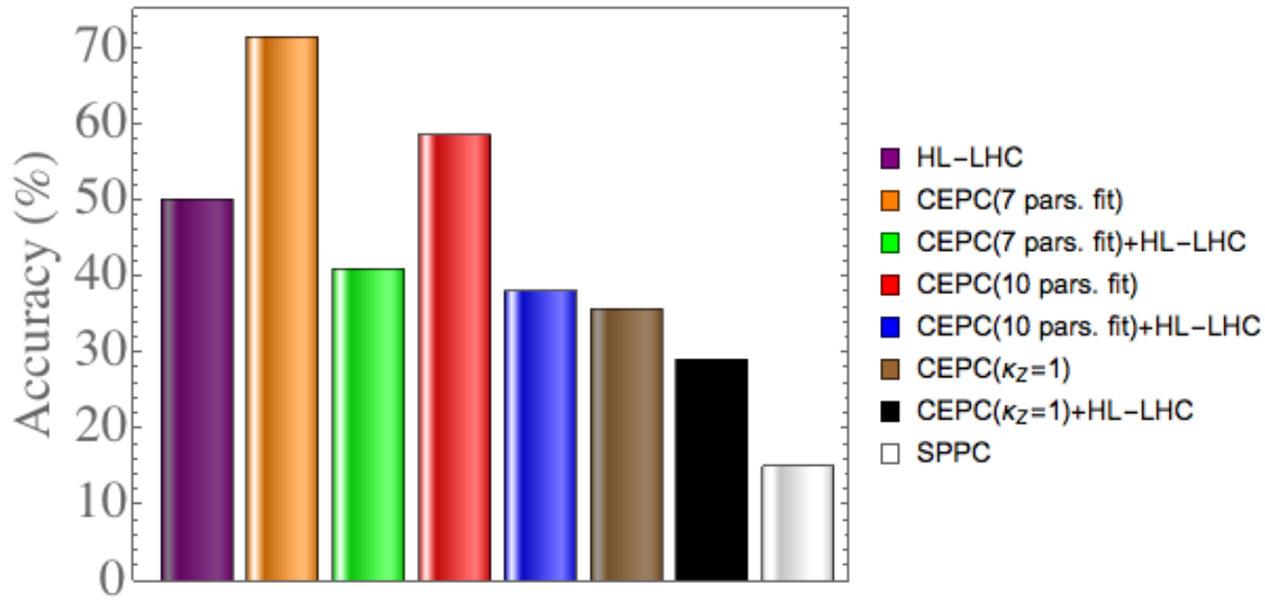
Order 1 deviation in triple Higgs coupling.

1st order phase transition



Huang, Joglekar, Li, Wagner, 1512.00068

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \dots$$



Triple Higgs coupling at 100 TeV pp collider

30 ab^{-1}

$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh + \text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh + \text{jet} \end{cases}$$

Barr, Dolan, Englert, de Lima, Spannowsky

ILC 500: 27%

ILC ultimate, 1 TeV 5 ab-1: 10%

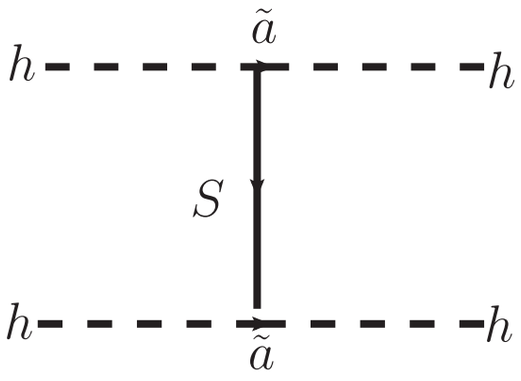
Generically, there is more

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \dots$$

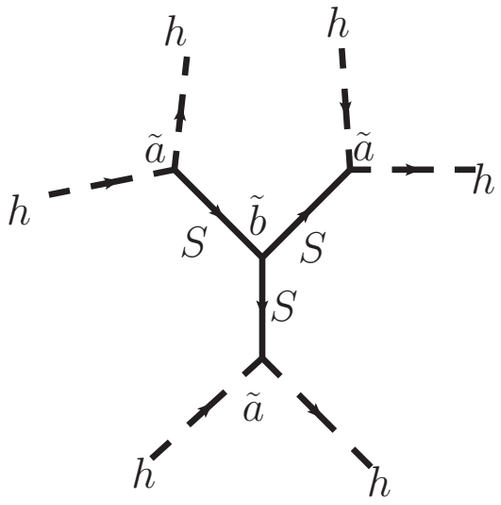
- 1st order EW phase transition means there is new physics close to the weak scale.
- Can be difficult to discover at the LHC.
  - Can only couple weakly to the Higgs.
- Will leave more signature in Higgs coupling.

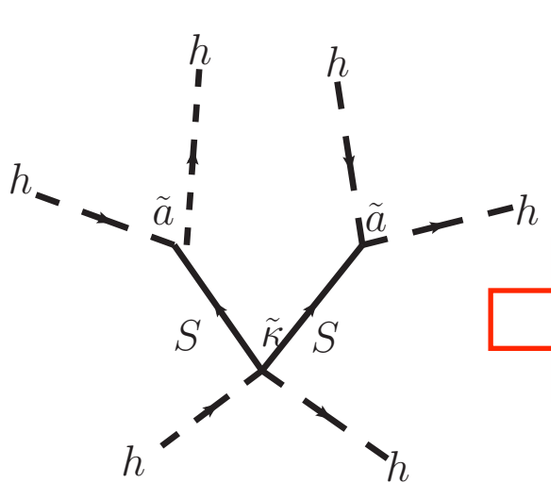
For example

$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$

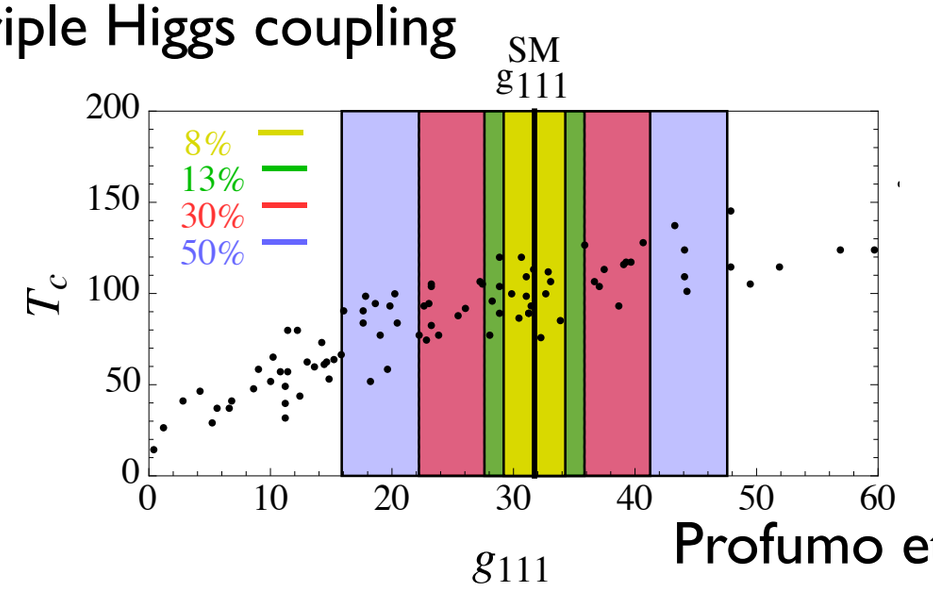


shift in h-Z coupling



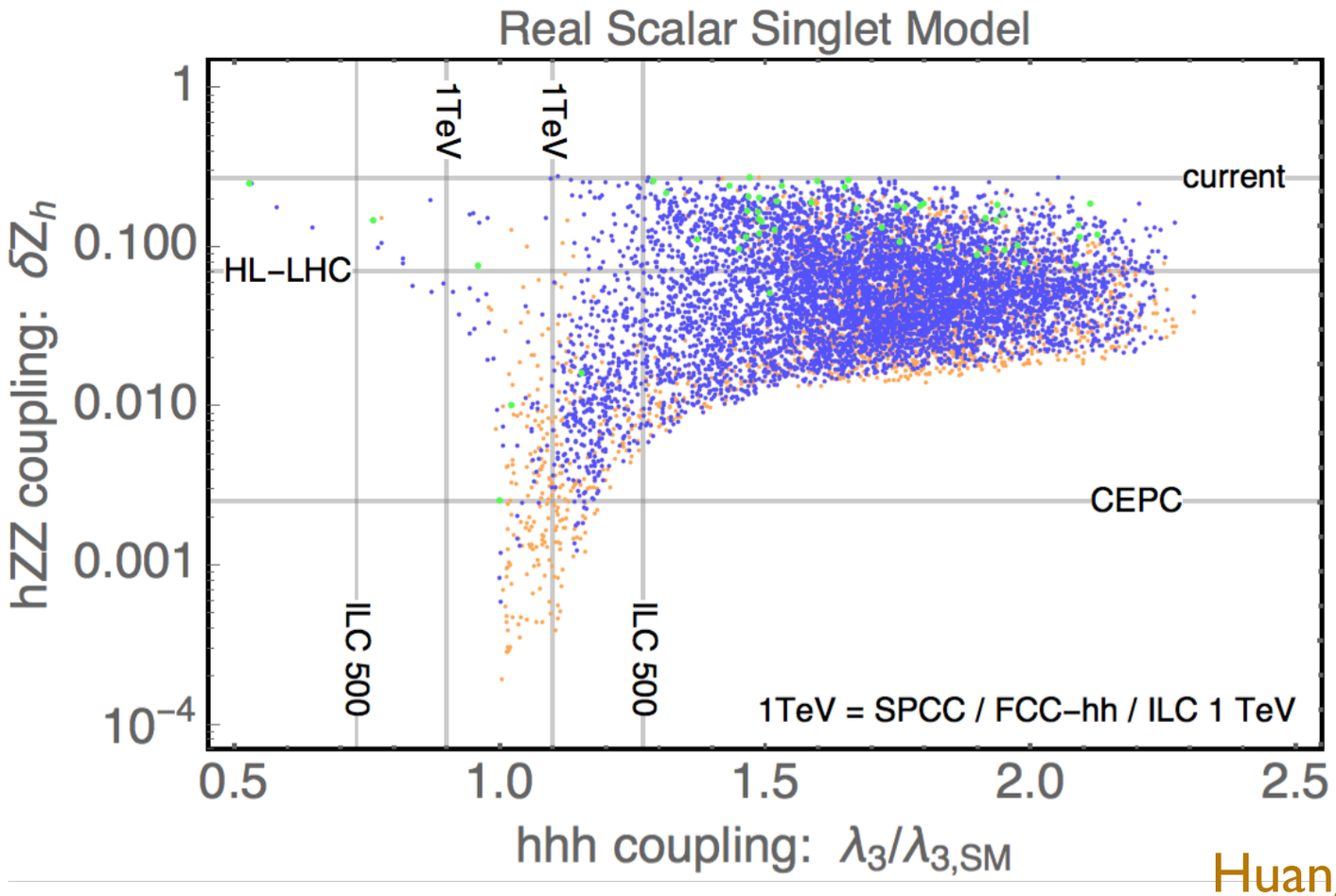


triple Higgs coupling



Profumo et al

Probing EWSB at higgs factories



Huang, Long, LTW, 1608.06619

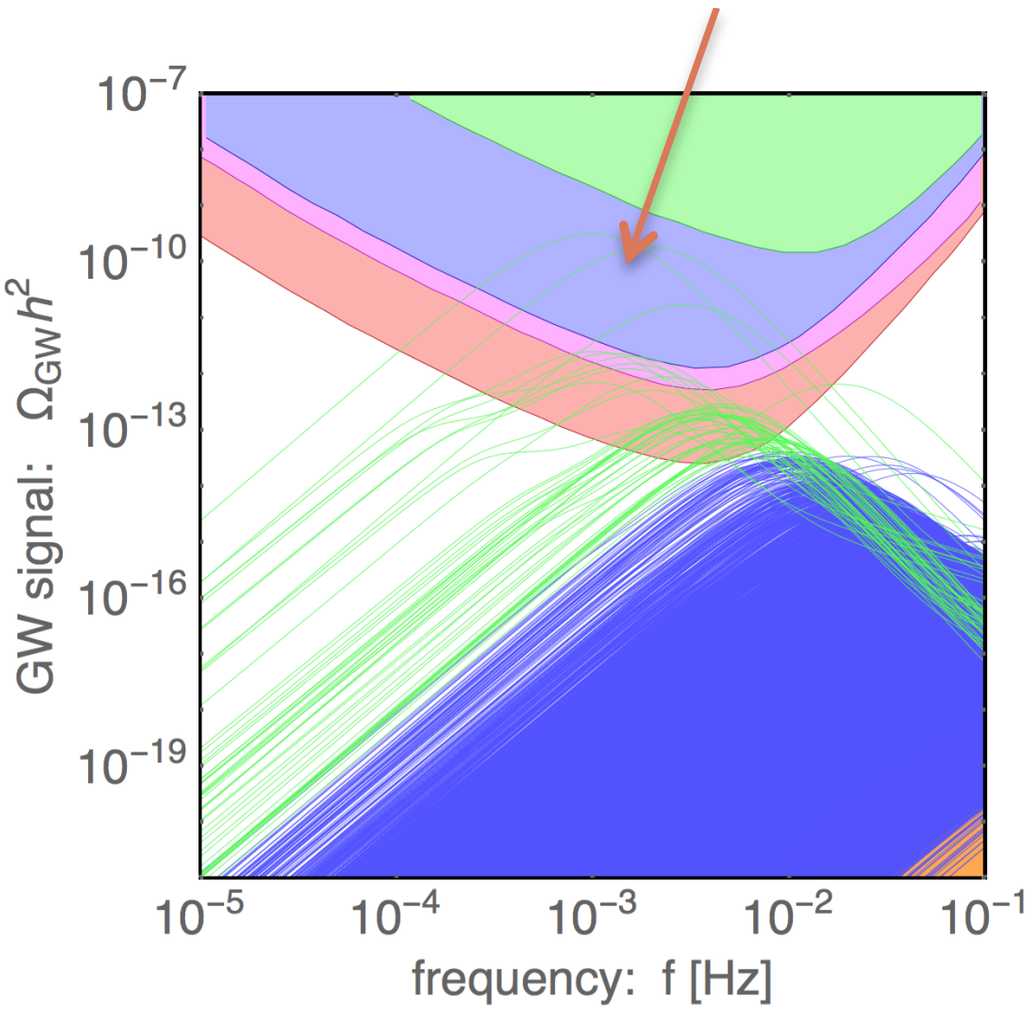
Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Good coverage in model space

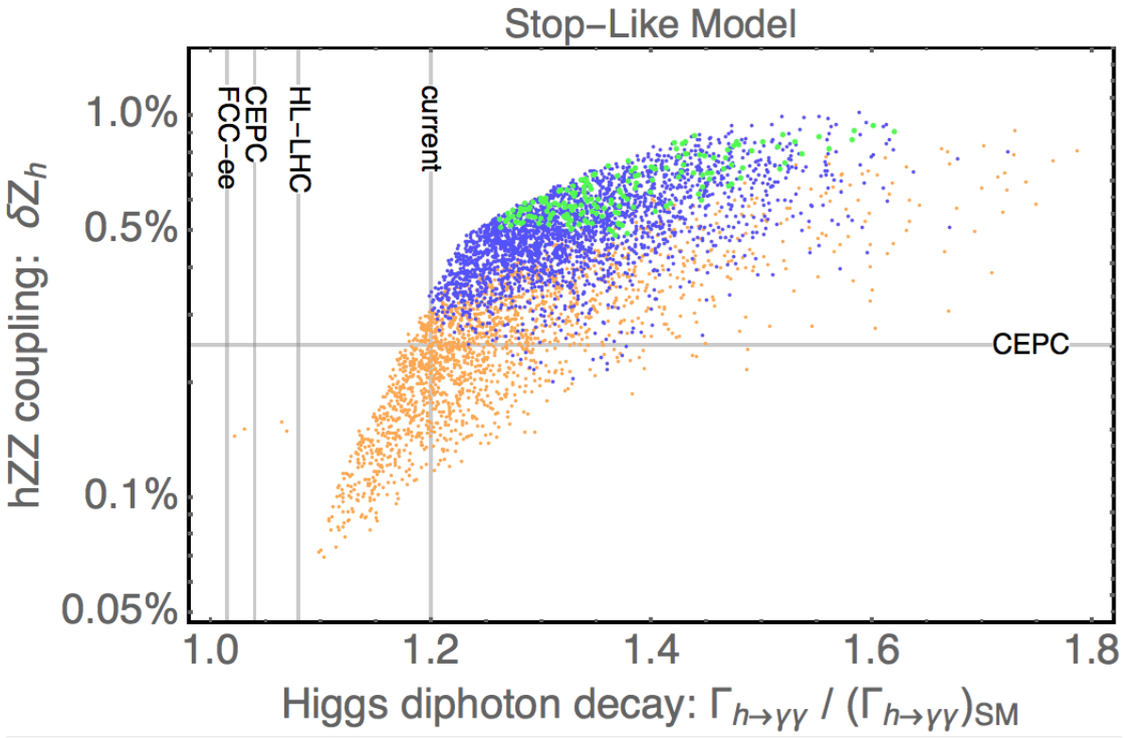
Combining with eLISA?

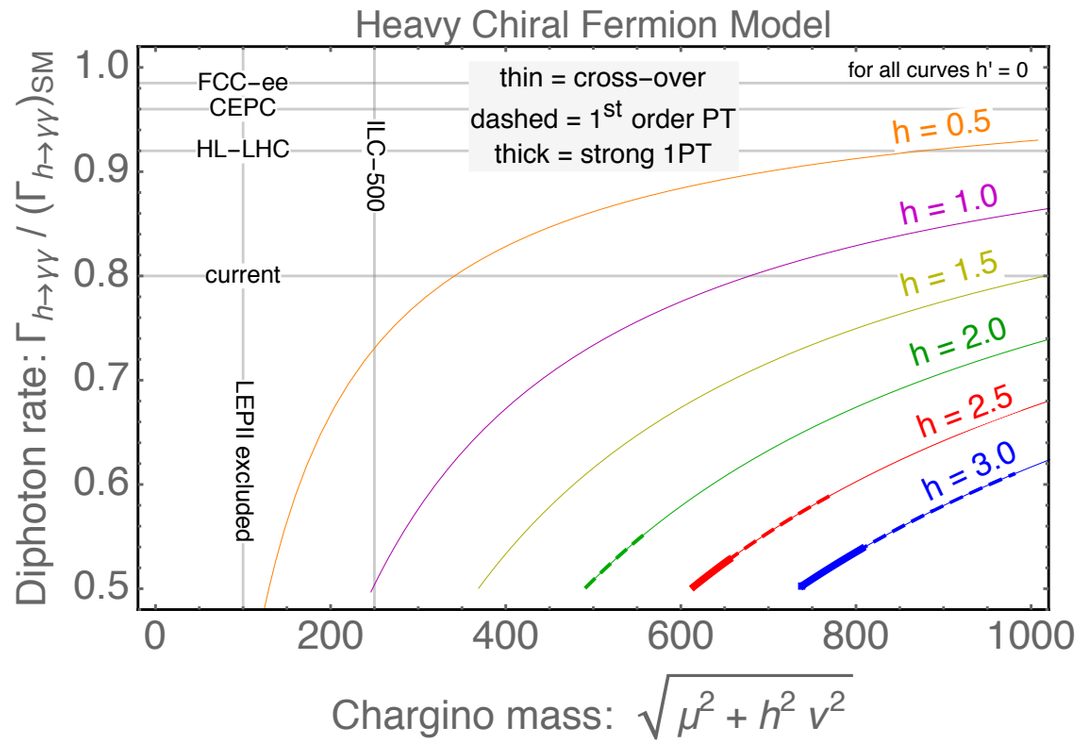
- Pushing our understanding of early universe. significant back.

- Implications for baryogengesis, etc.

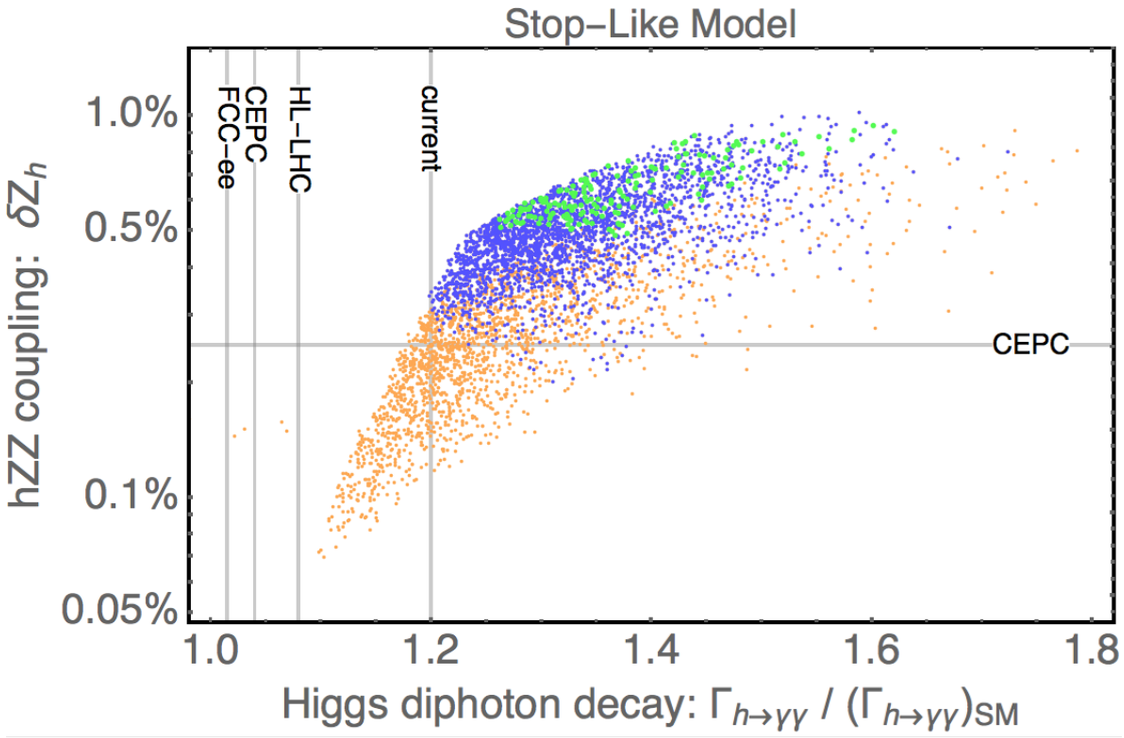


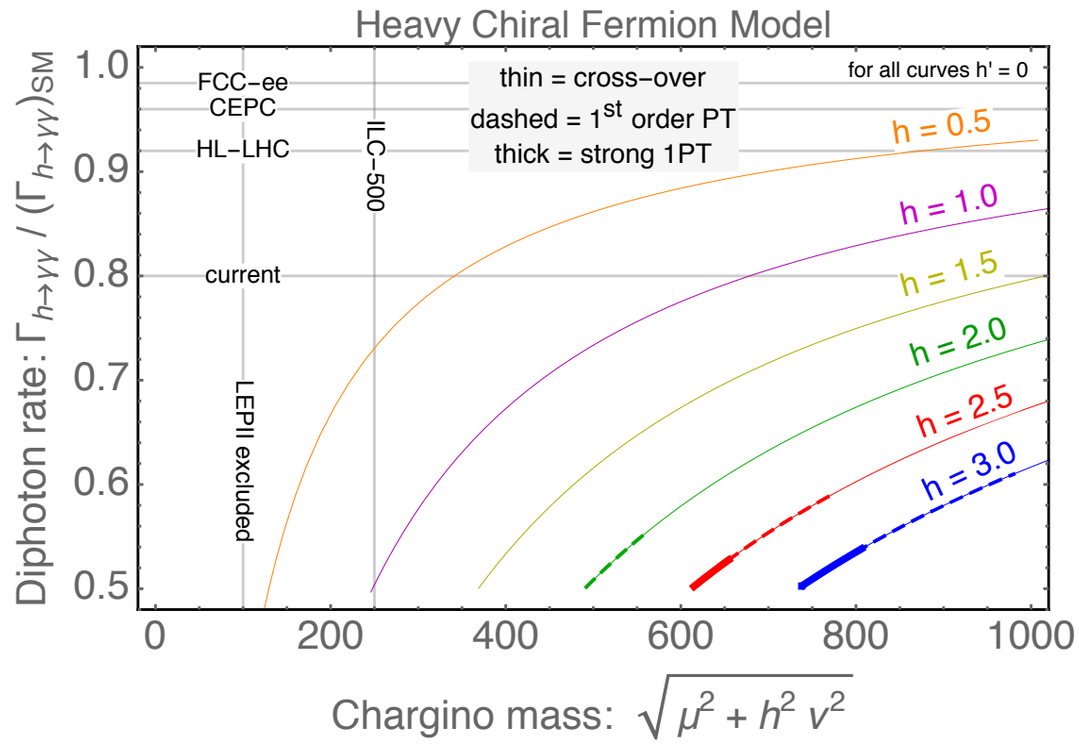
More elaborated model
⇒ more signal





More elaborated model
⇒ more signal





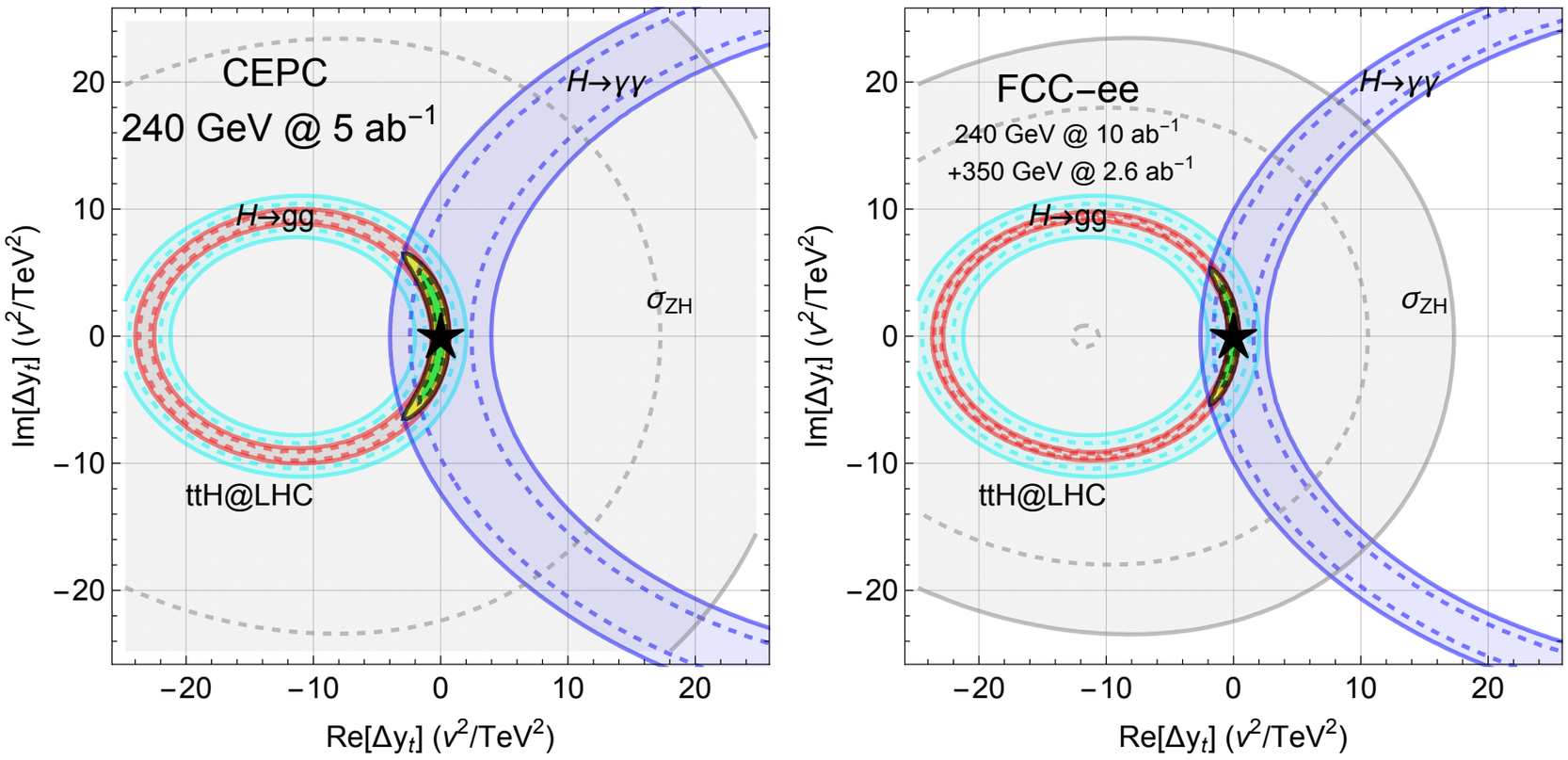
If electroweak phase transition is of first order,
Higgs factory has a great chance to see indications.

Higgs-top coupling.

- Dim-6 operators parameterization.

$$\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R),$$
$$\mathcal{O}_{bH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R),$$
$$\mathcal{O}_{DHq} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L),$$
$$\mathcal{O}^{(3)}_{DHq} = \frac{i}{\Lambda^2}(H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu \tau^I q_L),$$
$$\mathcal{O}_{DHt} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R),$$
$$\mathcal{O}_{DHb} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),$$

$$\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R)$$



Coefficient can be complex in general.
Affect h→ gg, although determining CP can be difficult.
h→γγ with a different sign
Sub-leading contribution to hZZ as well.

$$\mathcal{O}_{bH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R)$$ well constrained by h→bb

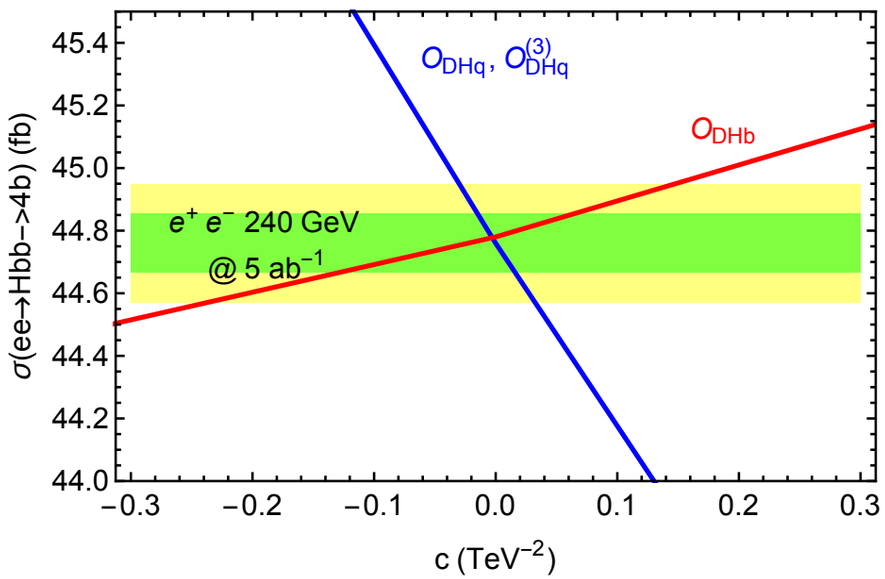
$$\mathcal{O}_{DHq} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L),$$
$$\mathcal{O}^{(3)}_{DHq} = \frac{i}{\Lambda^2}(H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu \tau^I q_L),$$
$$\mathcal{O}_{DHt} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R),$$
$$\mathcal{O}_{DHb} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),$$

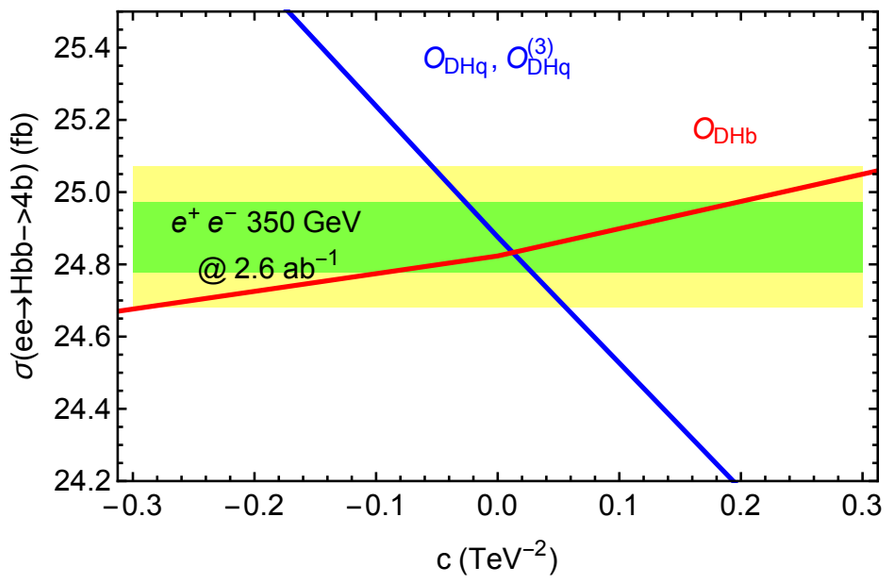
Do not modify Higgs coupling to tops.

Generate h-Z-bb …

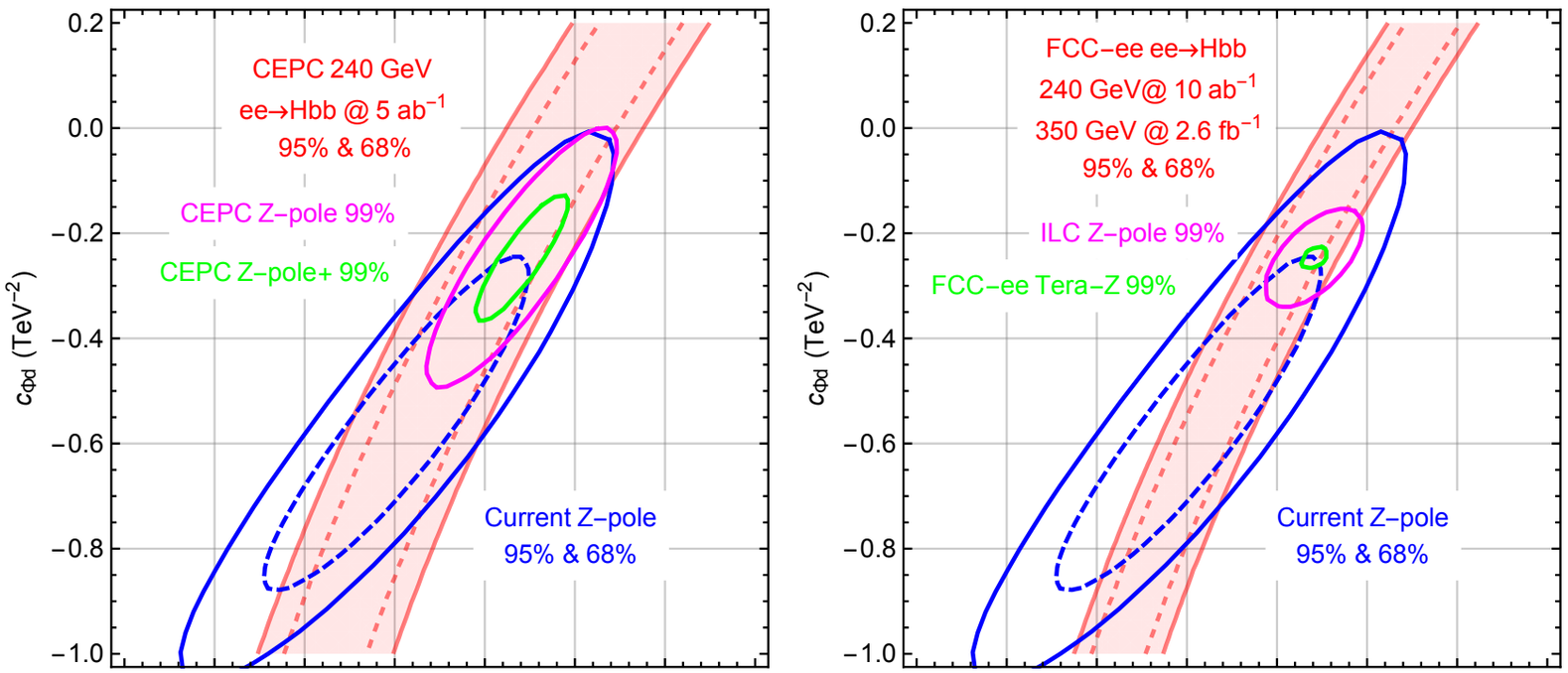
Modify Z-bb and Z-tt couplings

3-body process, ee→hbb





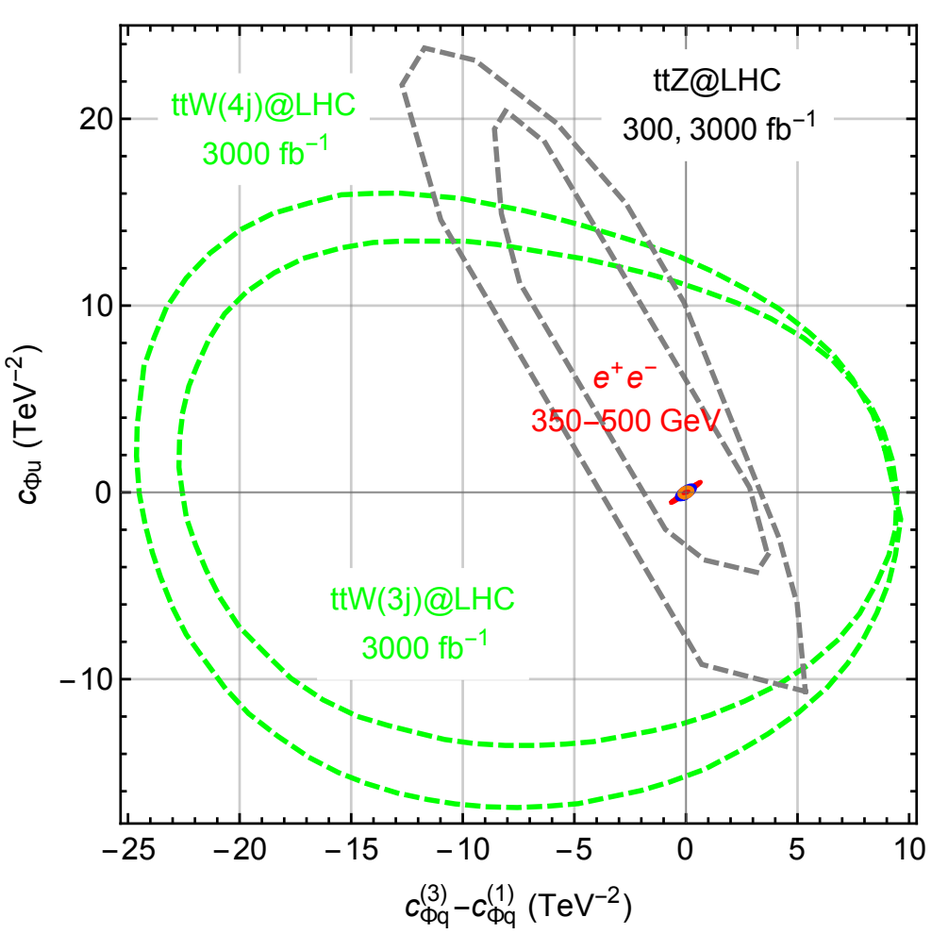
Z-pole

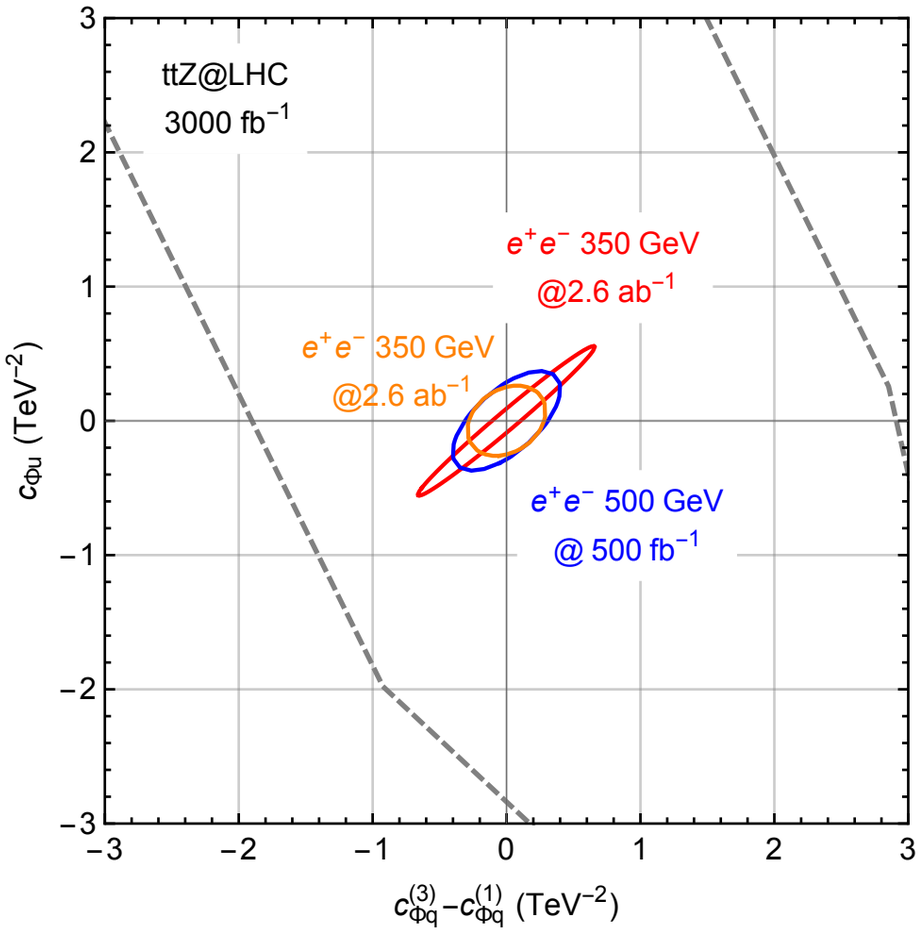


$$\Delta_{Zb\bar{b}} = -\left(C_{DHq} + C^{(3)}_{DHq}\right)\frac{v^2}{\Lambda^2}\frac{\sqrt{g_1^2+g_2^2}}{2}\; Z_\mu \bar{b}_L \gamma^\mu b_L - C_{DHb}\;\frac{v^2}{\Lambda^2}\frac{\sqrt{g_1^2+g_2^2}}{2}\; Z_\mu \bar{b}_R \gamma^\mu b_R$$

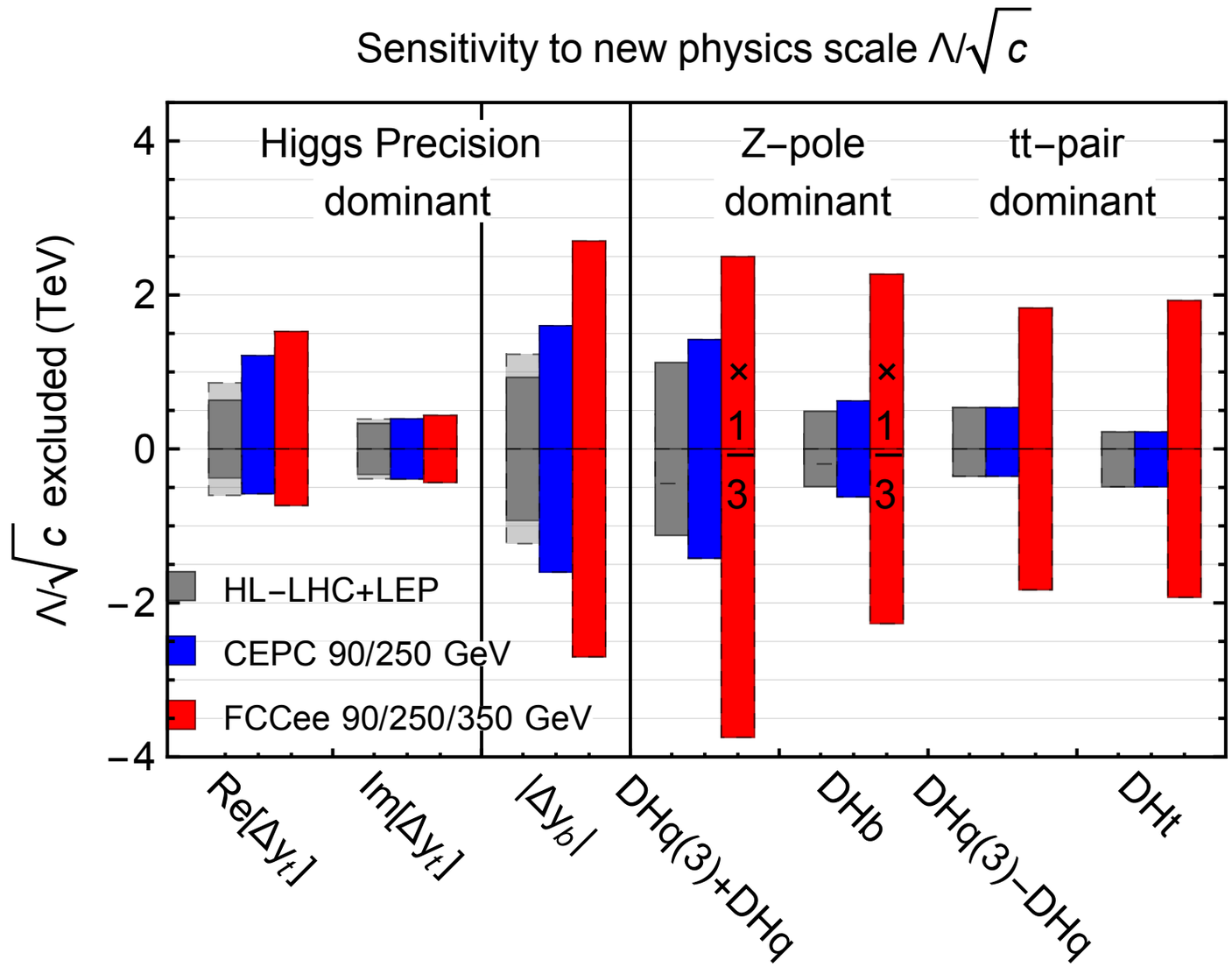
$$\Delta_{Zt\bar{t}} = \left(C^{(3)}_{DHq} - C_{DHq}\right)\;\frac{v^2}{\Lambda^2}\frac{\sqrt{g_1^2+g_2^2}}{2}\; Z_\mu \bar{t}_L \gamma^\mu t_L - C_{DHt}\;\frac{v^2}{\Lambda^2}\frac{\sqrt{g_1^2+g_2^2}}{2}\; Z_\mu \bar{t}_R \gamma^\mu t_R$$

At ttbar threshold





Sensitivity to new physics scales

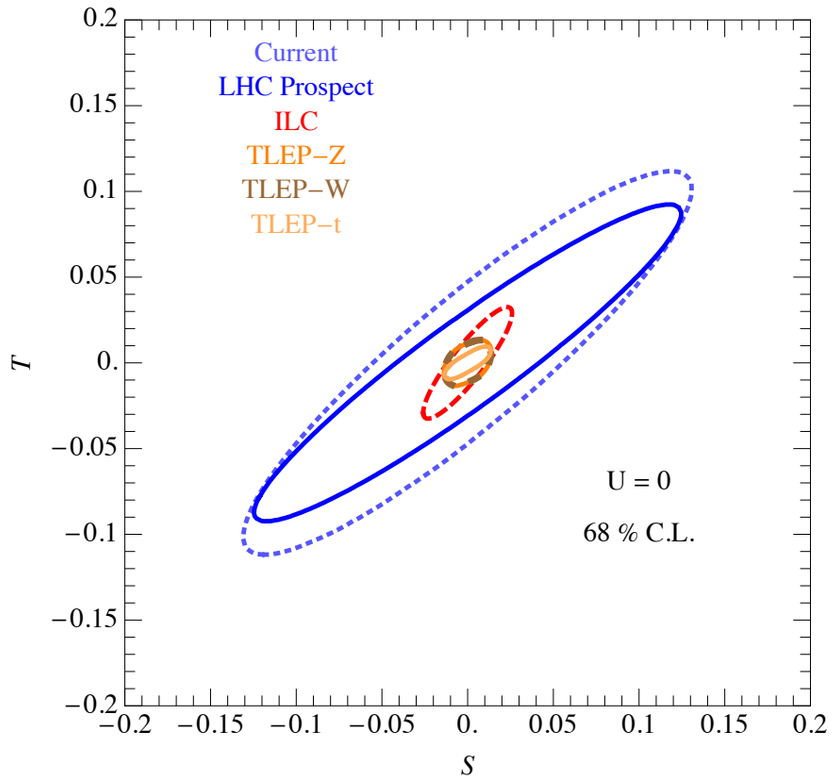


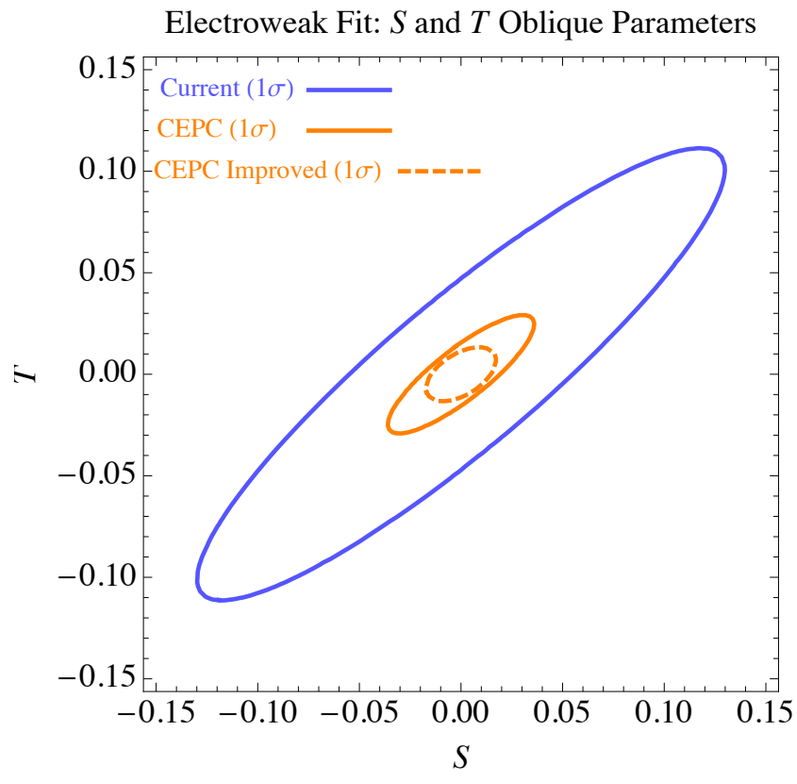
Open questions

In general

- Cover more detailed aspects of Higgs factory phenomenology.
  - More channels, better simulations...
- What are the other "killer-apps"?

On the Z-pole





- "Bread and butter" precision measurement
  - Gain a factor of 10 with about Giga Z.
  - Very valuable information, complimentary to Higgs measurements

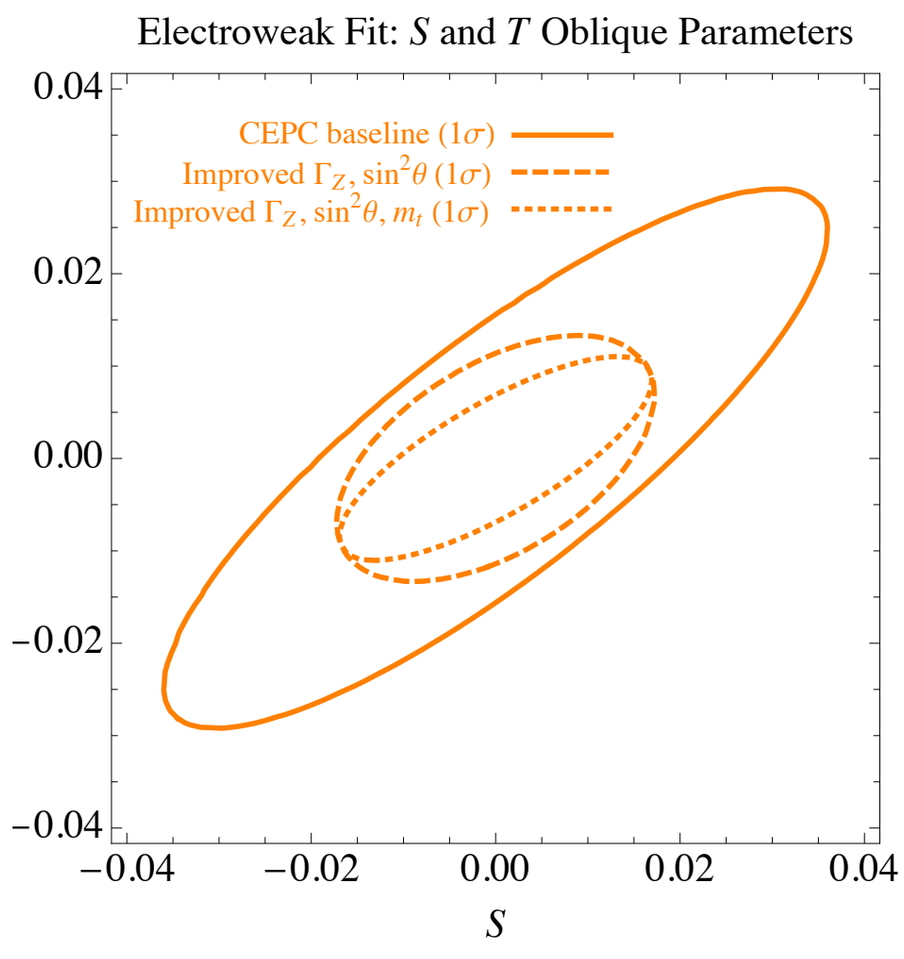
Z-factory

- Tera-Z or more?
  - Can do a lot more with precision measurements.
  - Many interesting topics.
  - Exotic Z-decay, sterile neutrino, dark sector…
  - tau, B, QCD…

More work needed to make concrete physics cases.

CEPC: ttbar threshold?

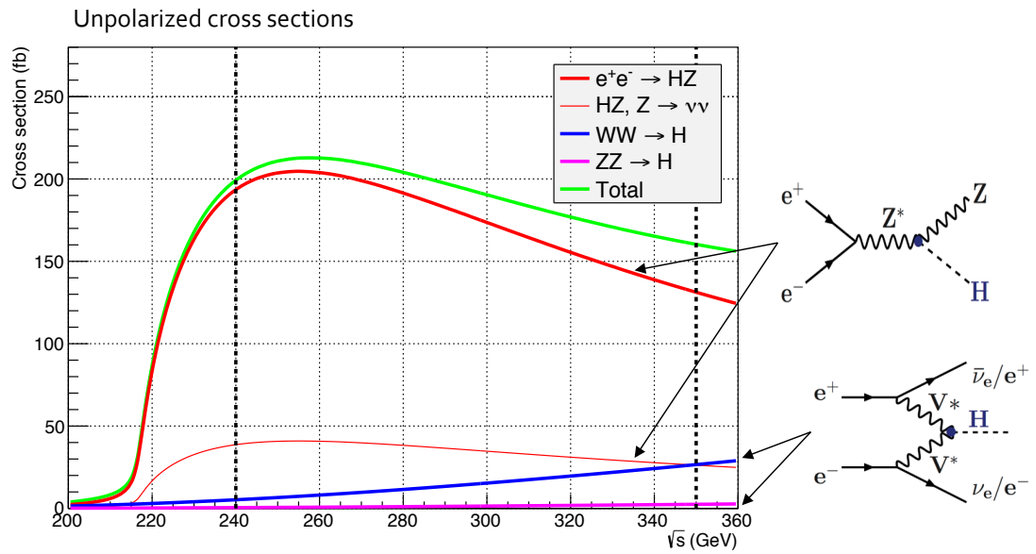
- Seems not as crucial for precision electroweak.
- A small improvement for the fit to S and T.
- Is this optimistic or pessimistic on the systematics?



CEPC: higher energy, ttbar

- However, going up from 250 to 350 can improve other measurements.

For example:

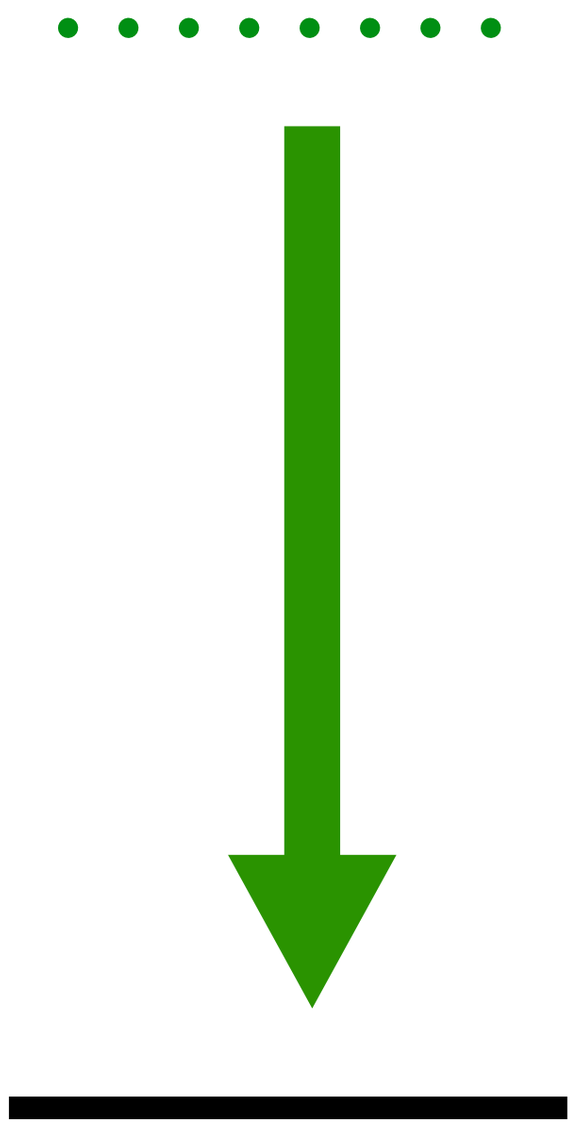


- Scan, energy dependence brings in more discovery and distinguishing power.

- Many more studies needed.

More "service" work needed.

Explaining EWSB: naturalness



Λ: a cut-off.
The energy scale of new physics responsible for EWSB

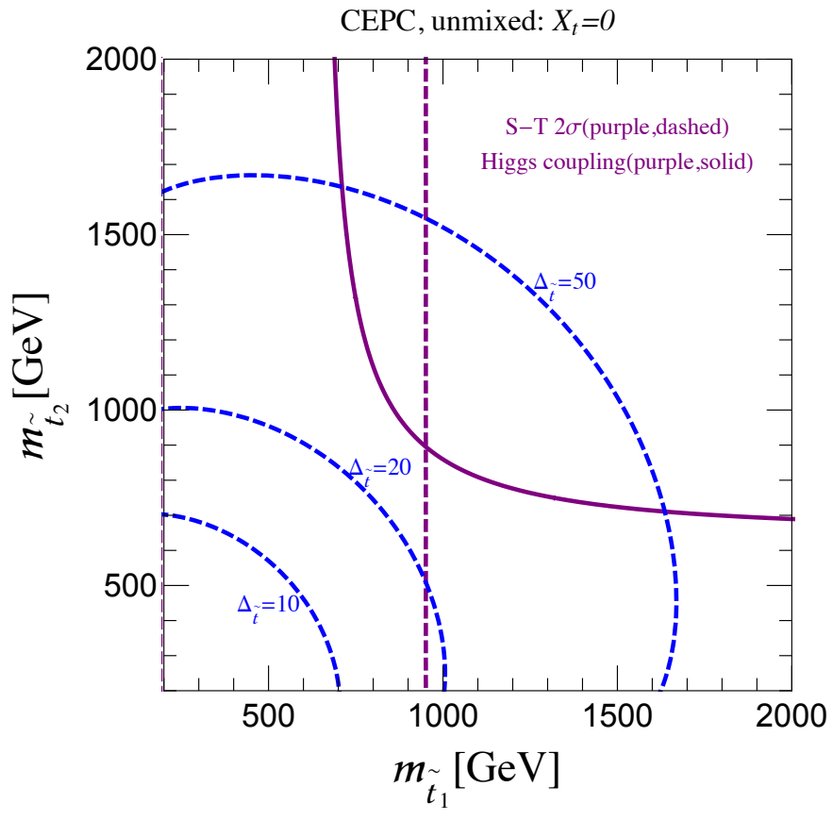
What is Λ? Can it be very high, such as $M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness, fine-tuning

- LHC searches model dependent, many blind spots.
- Precision measurement at CEPC provides a powerful and complementary probe.



J. Fan, M. Reece, LT Wang, 1412.3107

- Testing fine-tuning down to percent level.

Composite Higgs at lepton collider

Higgs is not (quite) elementary, will have deviations in Higgs couplings.

$$\delta W_h \sim \delta Z_h \sim \frac{v^2}{f^2}$$

Composite resonances couples to W and Z. Will give rise to deviation in EW precision observables.

$$S \simeq \frac{N}{4\pi}\frac{v^2}{f^2}$$

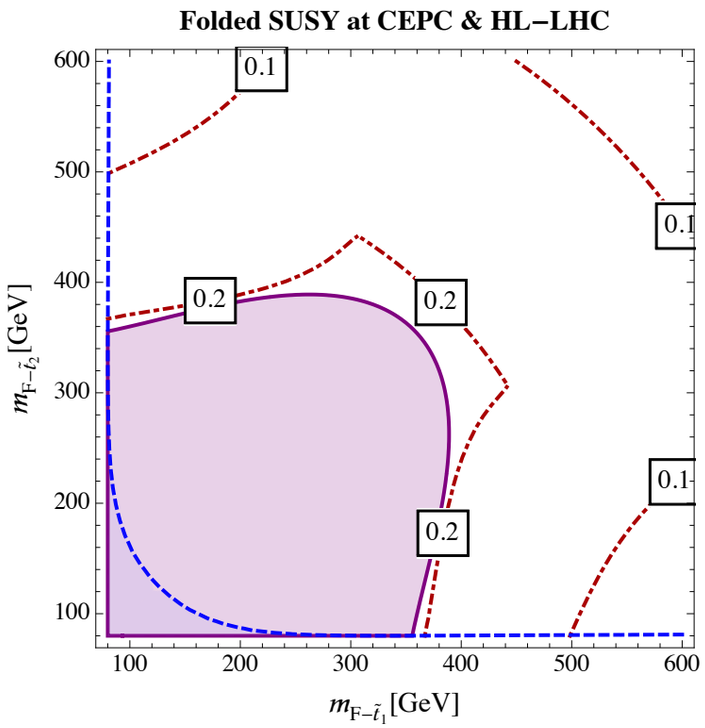
Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

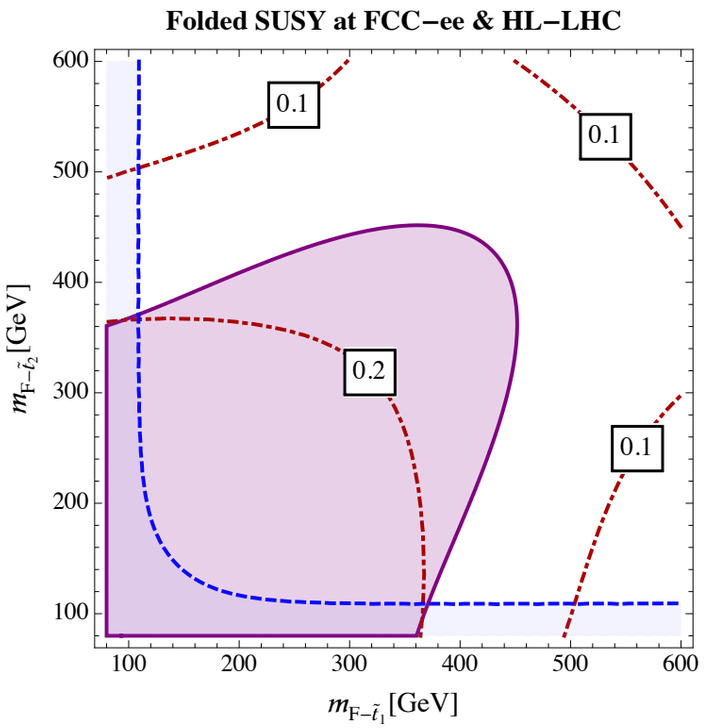
Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

Lesson: when both type of corrections generated at the same order, Higgs coupling measurement is typically stronger.

Folded SUSY

- Top partner has SM electroweak couplings only.
- No hgg. Only $h\gamma\gamma$. Weaker.





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80+ km vs 50 km

SPPC Parameter Choice and Optimize

Table 1: SPPC Parameter List. Version 201607

	SPPC(Pre-CDR)	SPPC-59.2Km	SPPC-100Km	SPPC-100Km	SPPC-80Km
Main parameters and geometrical aspects					
Beam energy[E_0]/TeV	35.6	35.0	50.0	65.0	50.0
Circumference[C_0]/km	54.7	59.2	100.0	100.0	80.0
Dipole field[B]/T	20	19.70	15.52	19.83	19.74
Dipole curvature radius[ρ]/m	5928	5921.5	10924.4	10924.4	8441.6
Bunch filling factor[f_2]	0.8	0.8	0.8	0.8	0.8
Arc filling factor[f_1]	0.79	0.78	0.78	0.78	0.78
Total dipole length [L_{Dipole}]/m	37246	37206	68640	68640	53040
Arc length[L_{ARC}]/m	47146	47700	88000	88000	68000
Straight section length[L_{ss}]/m	7554	11500	12000	12000	12000
Physics performance and beam parameters					

- completely discover and study the new physics showing up in precision measurements of CEPC.
- Other benefits, easier to go to higher energy, tt threshold?

Electroweak precision tests: roughly estimated targets

- δm_W < 5 MeV
- $\delta \sin^2\theta_{eff}$ < 2×10^{-5} (and/or Γ_Z about 100 keV)
- δm_Z < 500 keV
- δm_t < 100 MeV
- Theoretical/experimental improvement of $\Delta \alpha_{had}$

Much more work needed to produce more accurate and realistic numbers.

Current Status of CEPC

- **Pre-CDR completed**
  - **No show-stoppers**
  - **Technical challenges identified → R&D issues**
  - **Preliminary cost estimate**
- **R&D issues identified and funding request underway**
  - **Seed money from IHEP available: 12 M RMB/3 years**
  - **MOST: ~ 80 M RMB / 5yr, 36M RMB has been proved in June 2016**
  - **Onters topical issue funds from NSFC, CAS and the Science and Technoogy Bureau of Beijing Municipal: ~9M RMB**
  - **Working towards CDR, Accelerator by 2016 and Detector by 2017**
  - **A working machine on paper solving the problems left by Pre-CDR**
- **Site selections**
- **Internationalization & organization**

J. Gao

R&D Funding

- **IHEP seed money**

  12 M RMB/3 years (2015-2017)

- **Chinese Ministry of Sci. & Technology**

  ~ 90 M / 6 years (2016-2021)

  1st grant of ~36M RMB approved

- **China National Commission on Dev. & Reform**

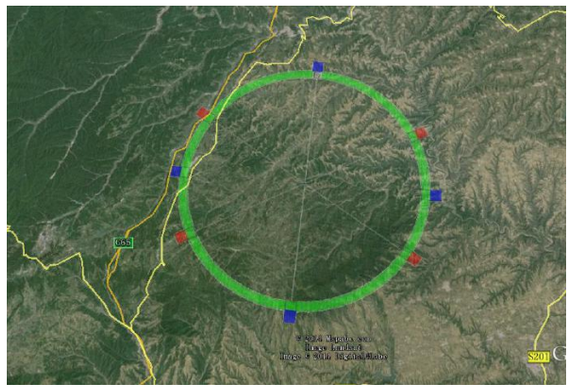
  No funding in 13th 5-year plan

we are seeking funding from other sources

X. Lou

Site selections (some main places)

1)



2)

3)

1) Qinhuangdao

2) Shanxi Province

3) Near Shenzhen and Hongkong

J. Gao

My personal sense

- R&D is moving forward.
- Biggest challenge
  - Time is tight. CDR in a year. "shovel ready" in 5-ish years?
  - Domestic man-power and expertise growing (not enough yet).
  - Need a lot of international collaboration.

Inputs for the further study

Baseline option

	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [17]	$\pm 1.0 \times 10^{-4}$ [18]
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [19]	$\pm 4.7 \times 10^{-5}$ [20]
m_Z [GeV]	91.1875 ± 0.0021 [21]	$\pm\mathbf{0.0005}$
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [22] $\pm 0.5_{\rm th}$ [20]	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$ [20]
m_h [GeV]	125.14 ± 0.24 [20]	$< \pm 0.1$ [20]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [17] $\pm 0.004_{\rm th}$ [23]	$(\pm\mathbf{3}_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [23]
$\sin^2\theta^\ell_{\rm eff}$	$(23153 \pm 16) \times 10^{-5}$ [21]	$(\pm\mathbf{4.6}_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [24]
Γ_Z [GeV]	2.4952 ± 0.0023 [21]	$(\pm\mathbf{5}_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [25]
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.21629 ± 0.00066 [21]	$\pm\mathbf{1.7} \times 10^{-4}$
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.767 ± 0.025 [21]	$\pm\mathbf{0.007}$

With possible improvements.

CEPC	$\sin^2\theta^\ell_{\rm eff}$	Γ_Z [GeV]	m_t [GeV]
Improved Error	$(\pm 2.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$

x4 statistics off Z-pole

energy calibration

ILC?

CEPC-SppC

Phase 1: e^+e^- **Higgs (Z) factory** **two detectors, 1M ZH events in ~10yrs**

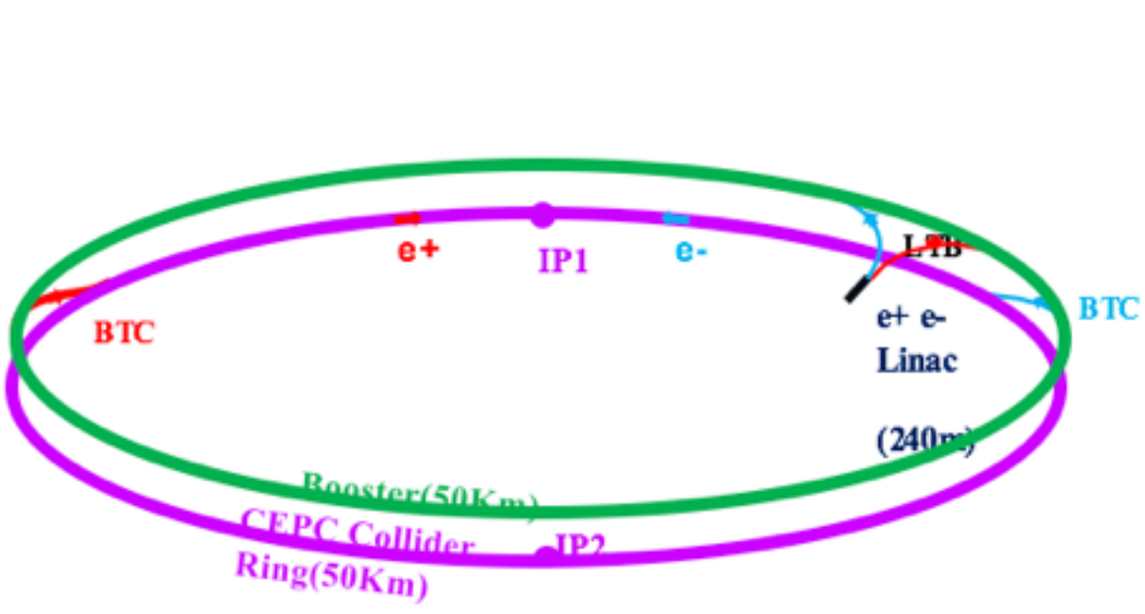
Circular Electron Positron Collider (CEPC)

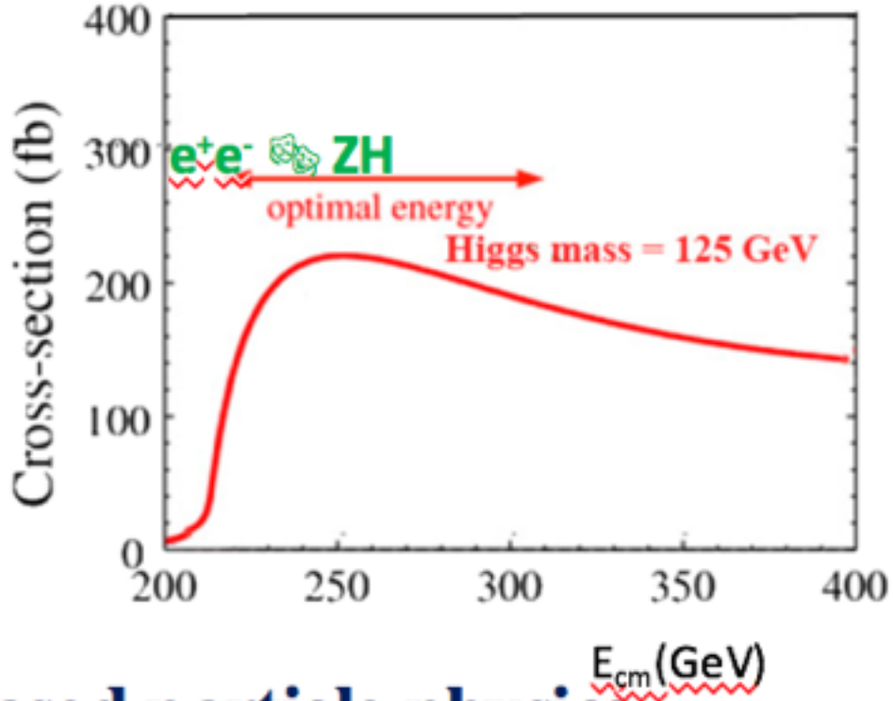
E_{cm} =240GeV, luminosity ~2×10^{34} $cm^{-2}s^{-1}$, can also run at the Z-pole

Precision measurement of the Higgs boson (and the Z boson)

Phase 2: **a discovery machine**; pp collision with E_{cm} ~50-100 TeV; ep, HI options

Super proton-proton Collider (SppC)



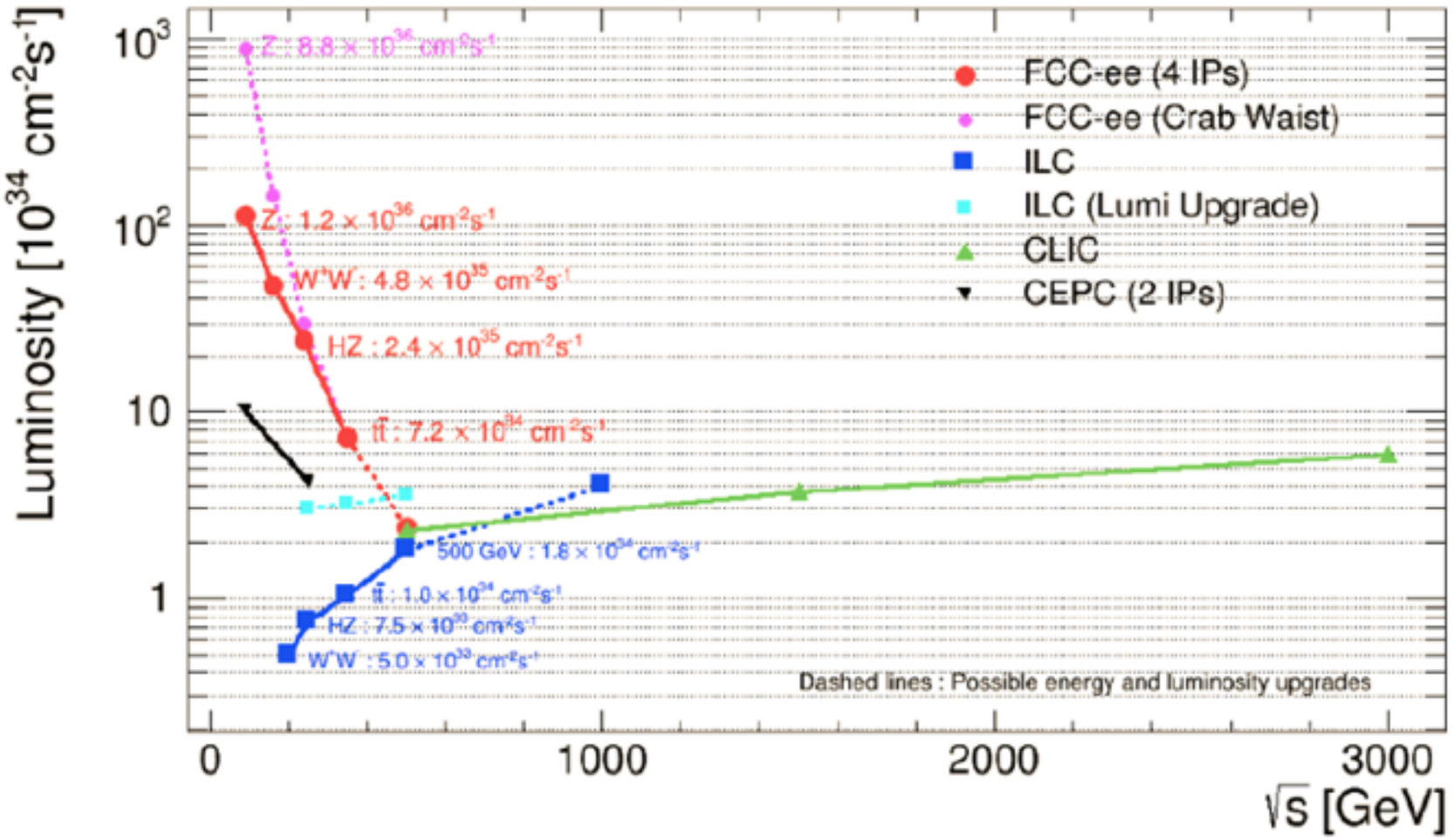


favored post BEPCII accelerator based particle physics program in China

X. Lou

CEPC design goal

- Limit SR power to 50 MW per beam
- CEPC: single ring, head-on collision, up to 250 GeV
- FCC-ee: double ring, large crossing angle, up to 350 GeV

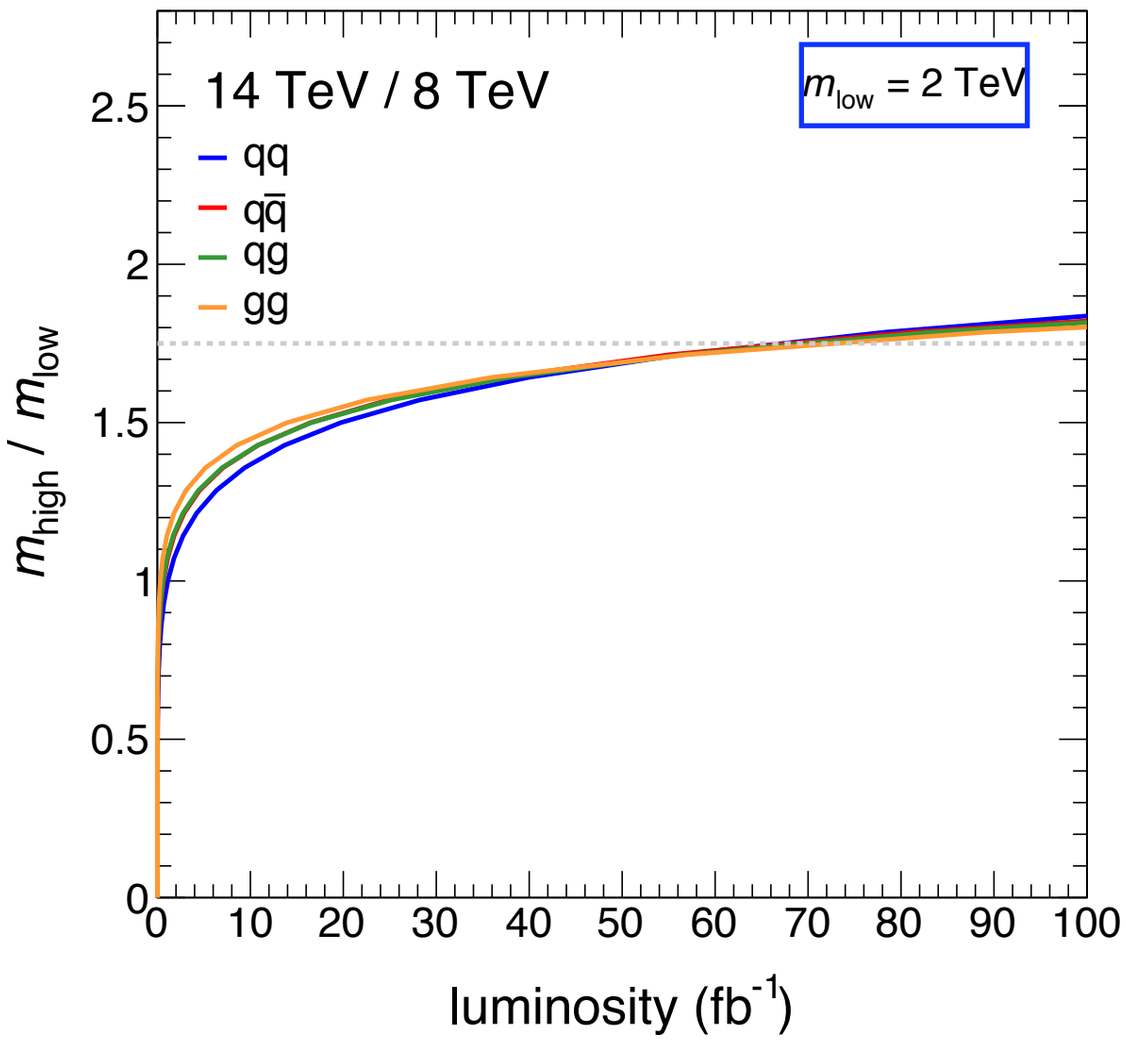


CEPC:
10^6 Higgs
10^{10} Z
FCC-ee:
10^7 Higgs
$10^{12\text{-}13}$ Z

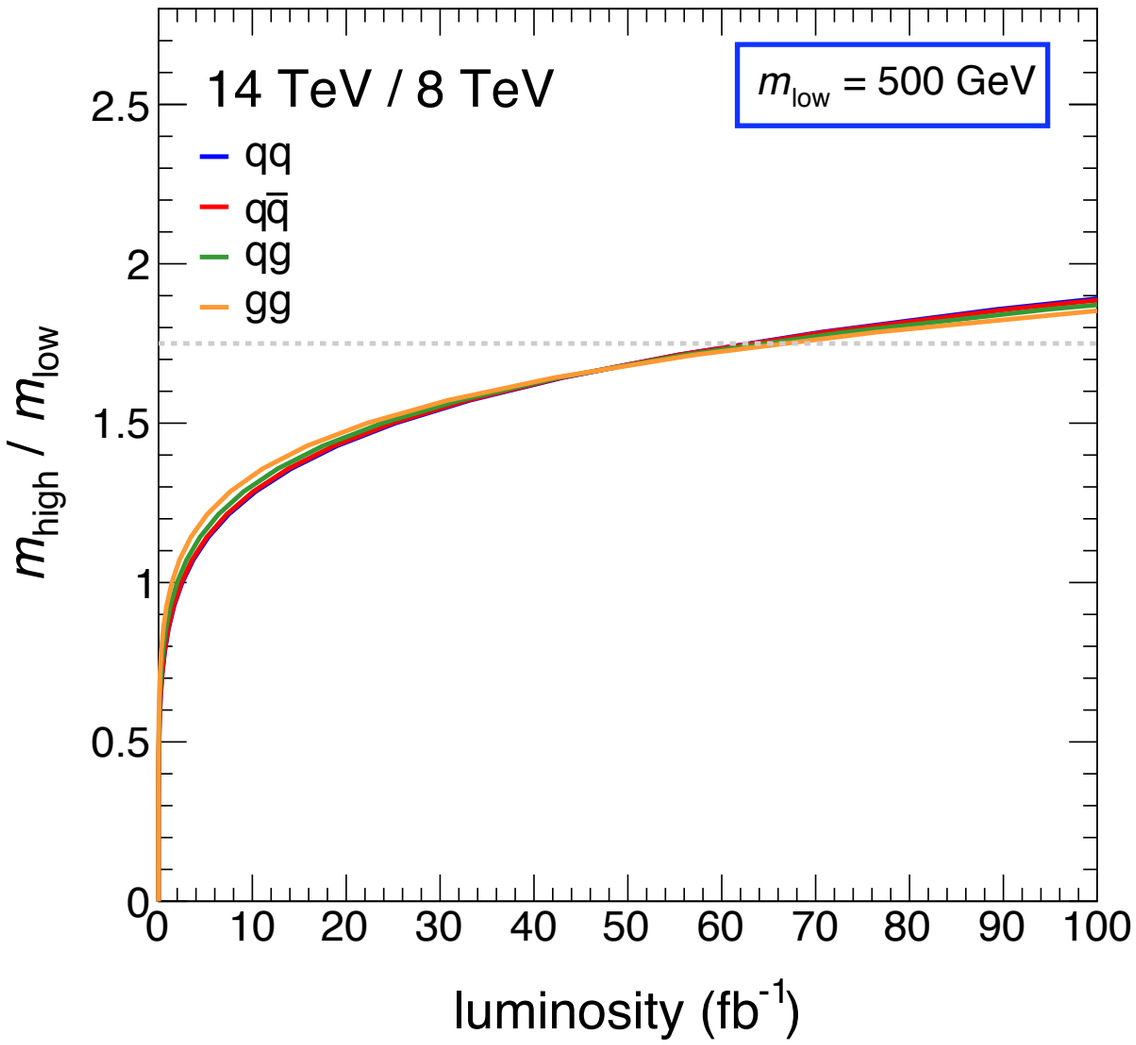
X. Lou

As data accumulates

Run I limit 2 TeV, e.g. pair of 1 TeV gluino.



500 GeV, e.g. pair of 250 GeV electroweak-ino

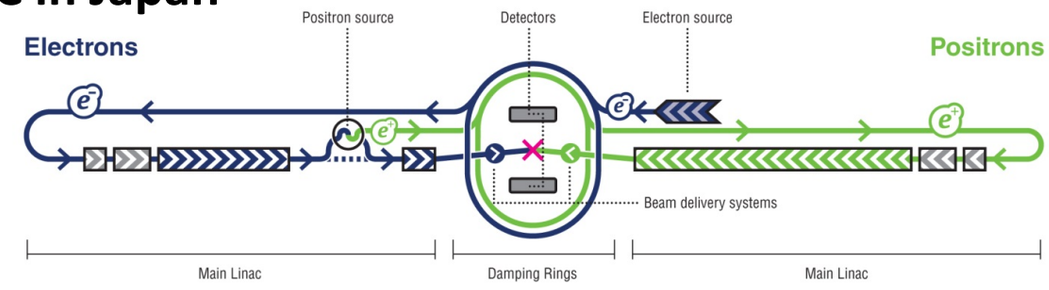


Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

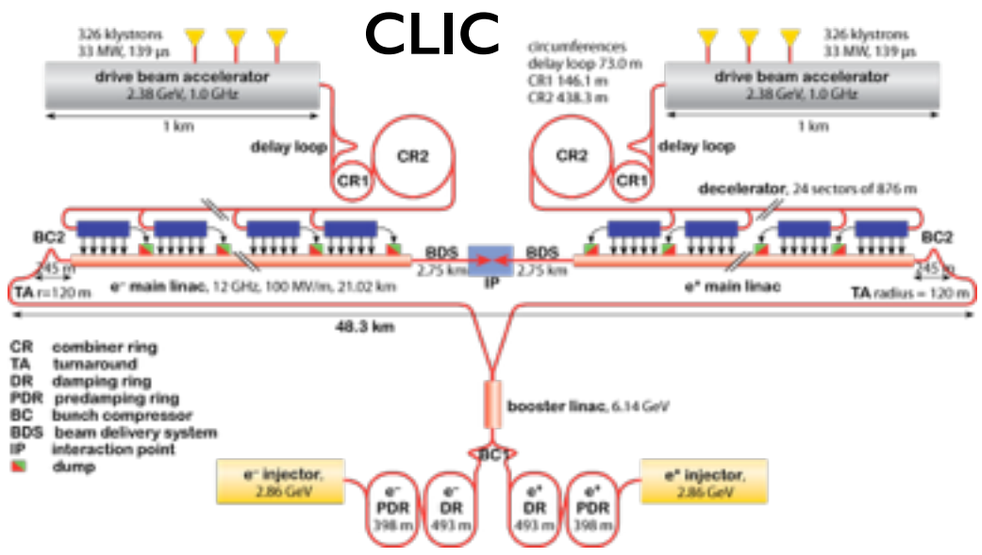
Reaching the "slow" phase after Moriond 2017

Beyond the LHC, future facilities

ILC in Japan



CLIC

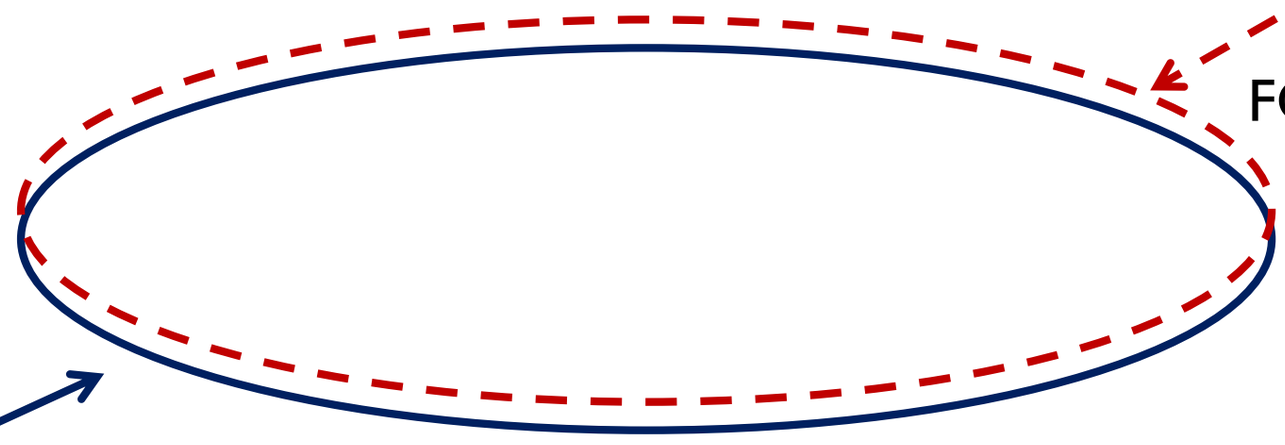


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

FCC-hh (CERN), SppC(China)



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

FCC-ee (CERN), CEPC(China)

My talk have more content on CEPC