Interplay

of the LHC and the LC in Higgs physics

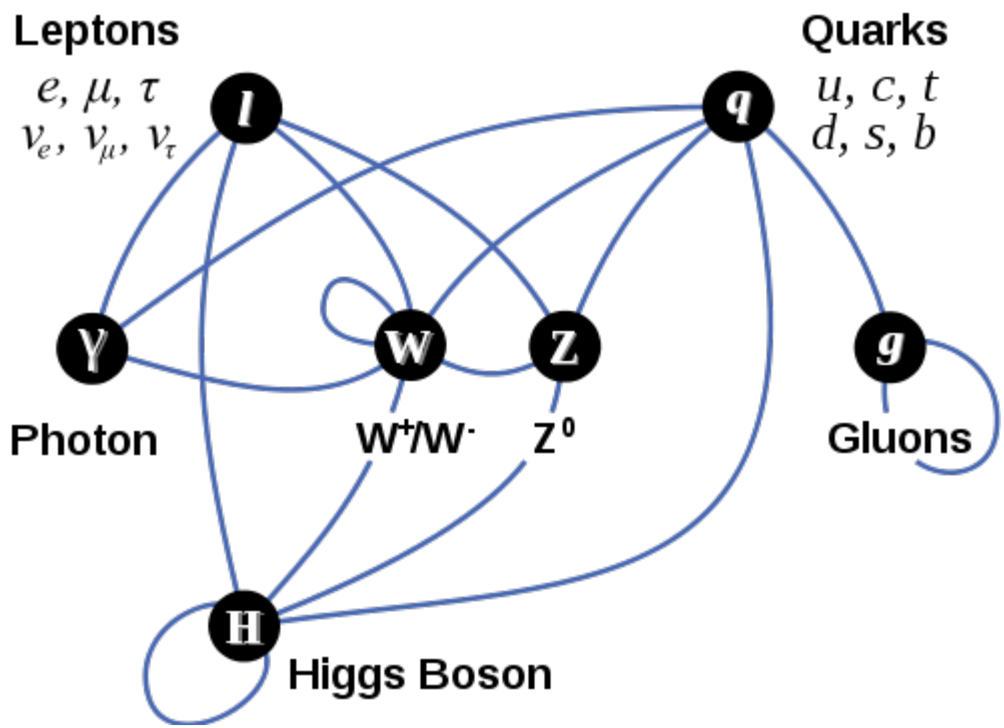
Zhen Liu (Fermilab)

LCWS2016, Morioka, JP

Dec. 8th, 2016

New Particle and New Forces

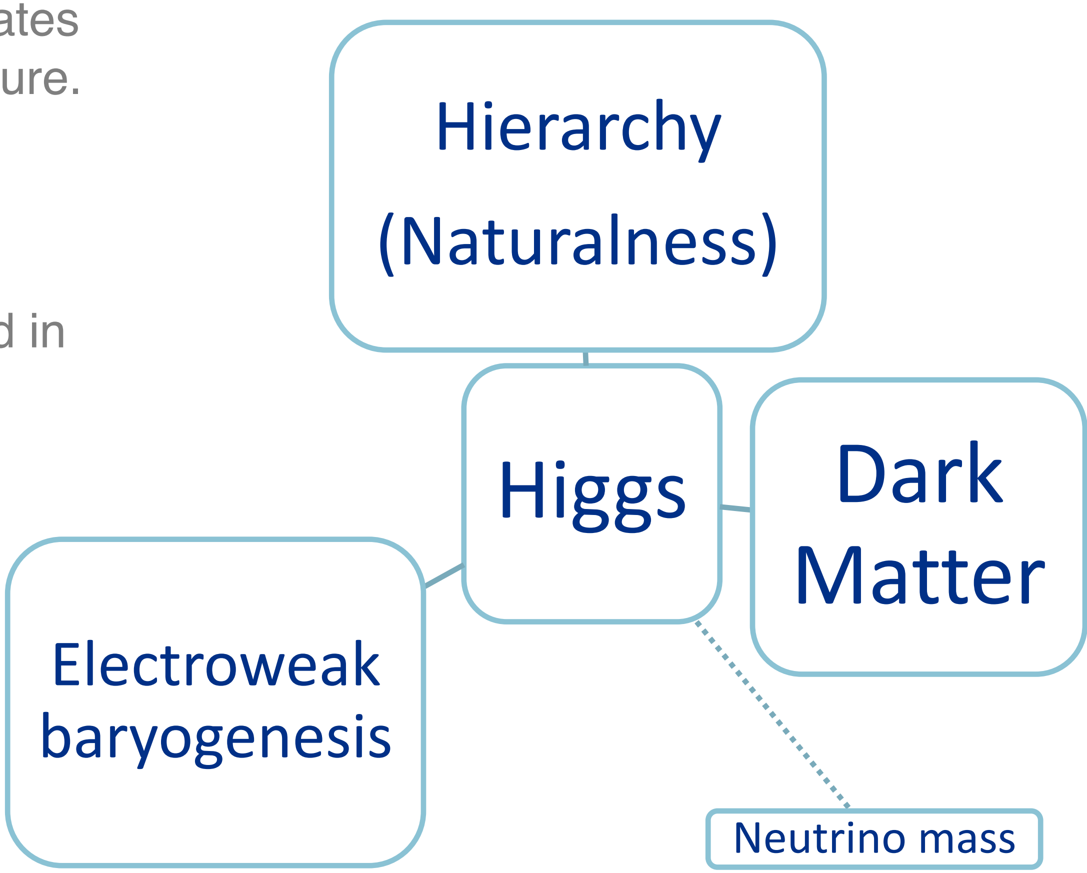
- Gauge coupling
- Yukawa coupling—new forces (9+ Yukawas)
- Self coupling—new force
- Derived couplings
  $H\gamma\gamma, Hgg, HZ\gamma, \ldots$



Key to many Puzzles

Higgs boson discovery substantiates (more) many big questions in nature. It could well be the key to unlock some of nature's secrets.

All connections could be revealed in Higgs measurements.



- Higgs physics could directly probe new physics
- New physics can easily couples to Higgs, linking to hierarchy problem, electroweak baryogenesis, naturalness, dark matter, etc.
- LCs are to explore this opportunity.

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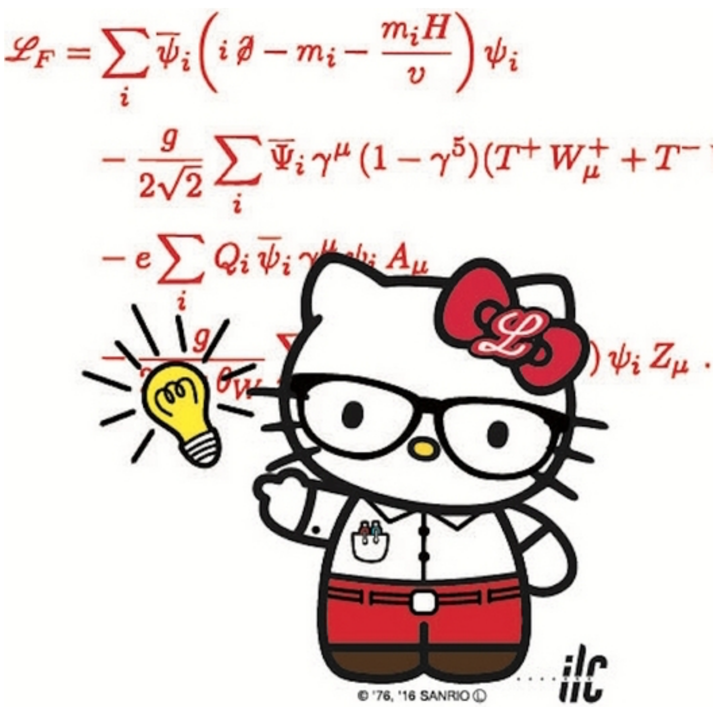

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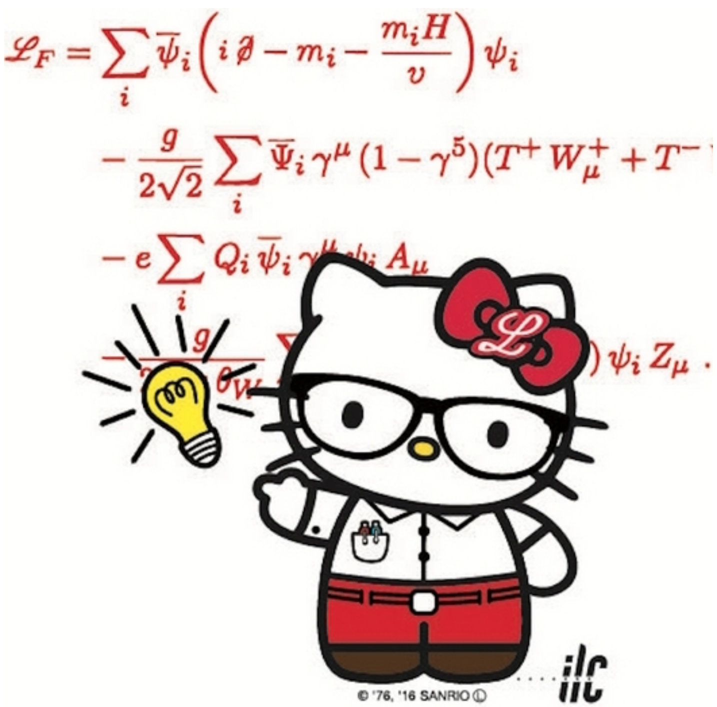
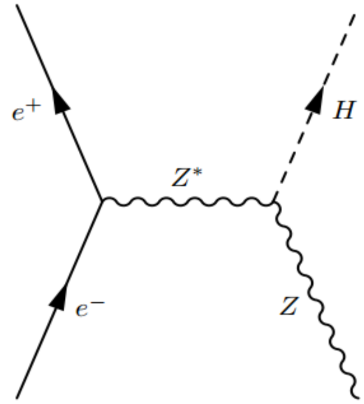
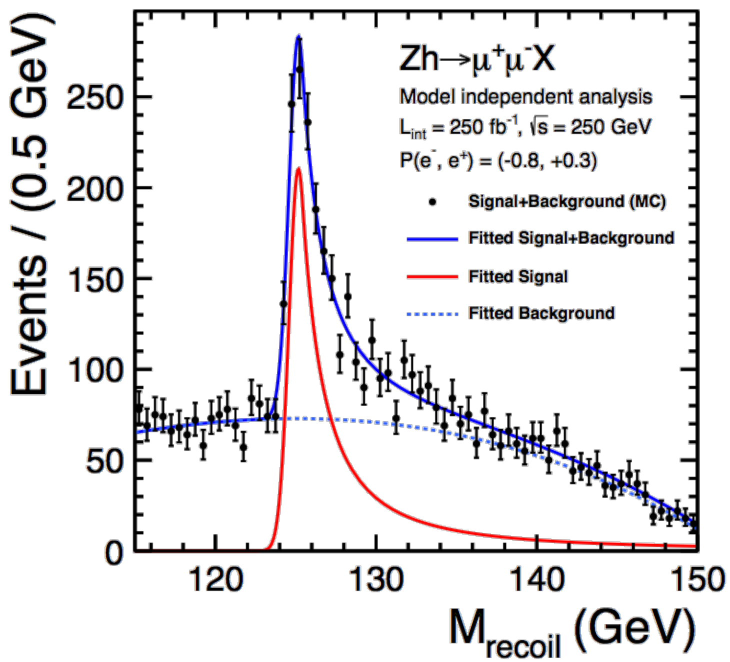


Higgs?

Precision—couplings





Future e+e- machines allow "Model-Independent" (no extra assumptions on the sizes of couplings or BSM decay widths needed in the κ-framework) extraction of the SM Higgs couplings using the recoil-mass technique.

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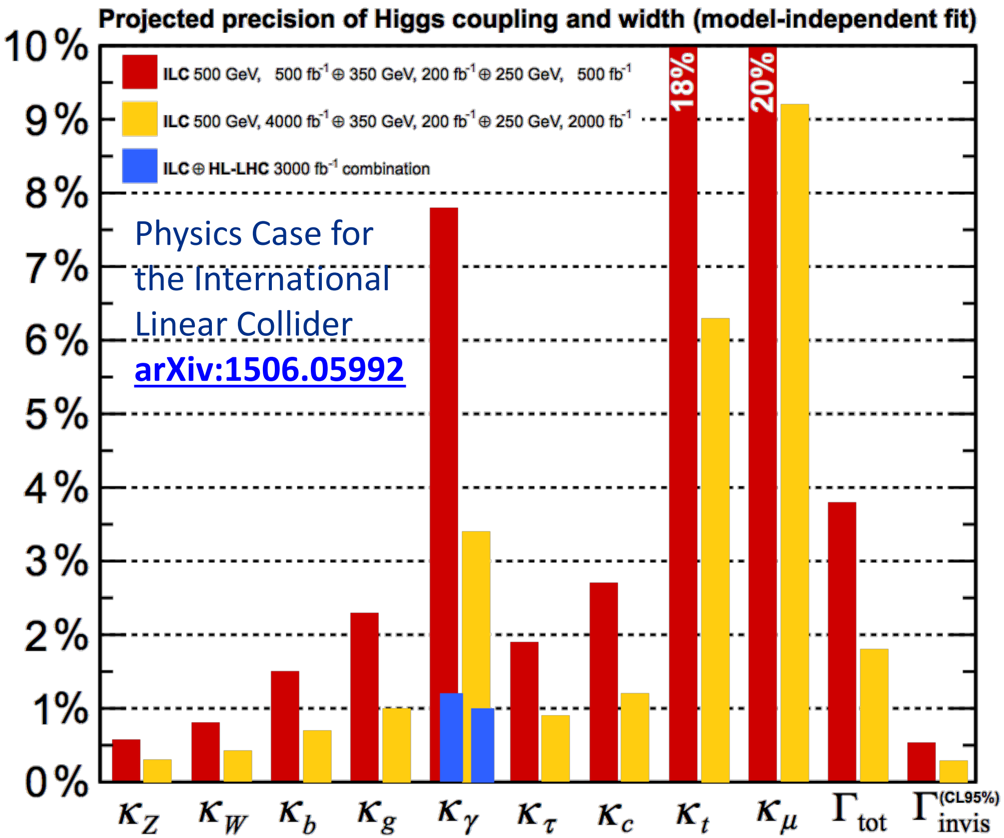
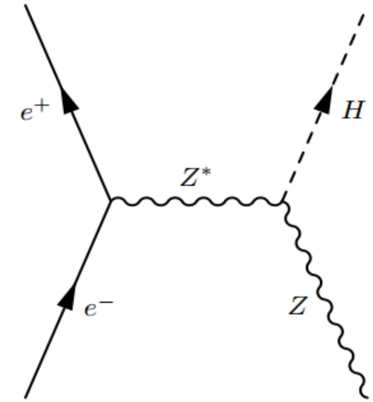
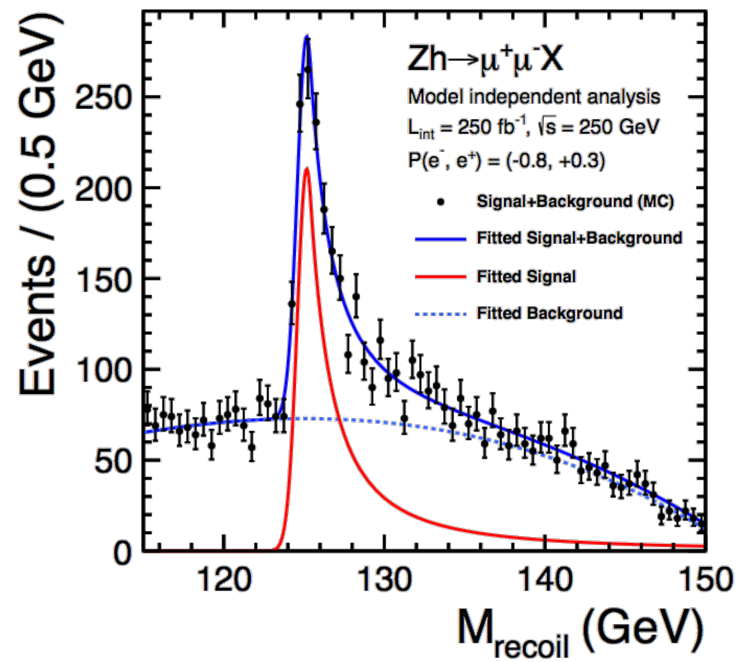


Physics Case for the International Linear Collider
[arXiv:1506.05992]





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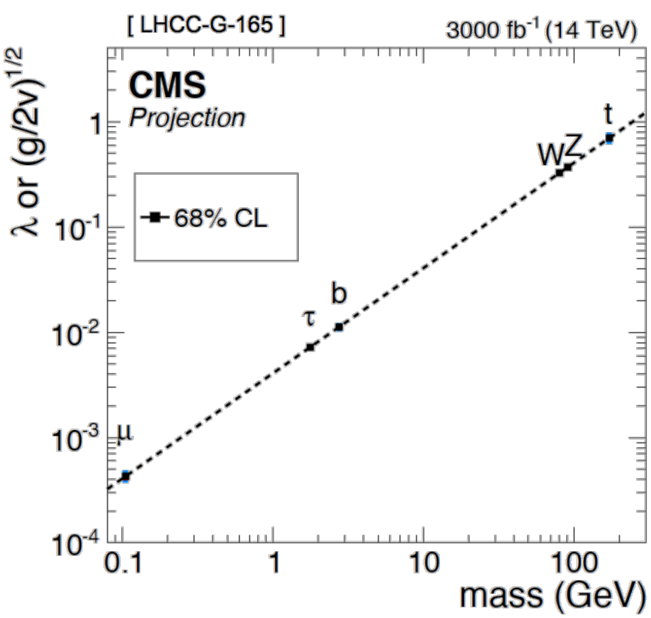

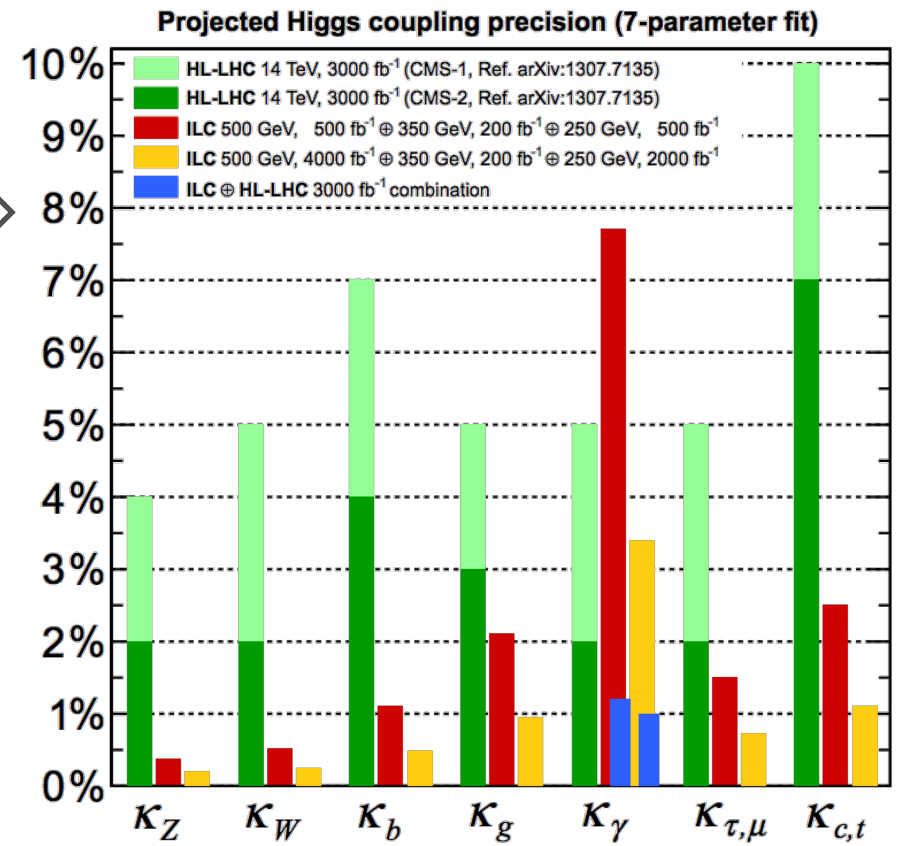

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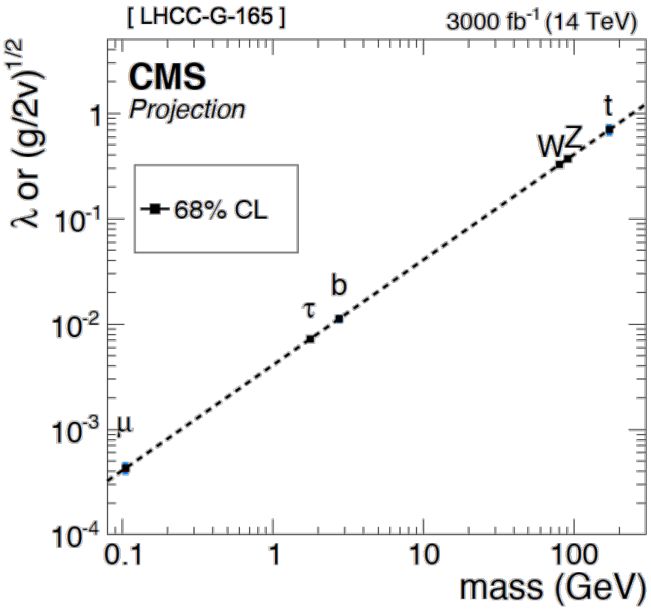
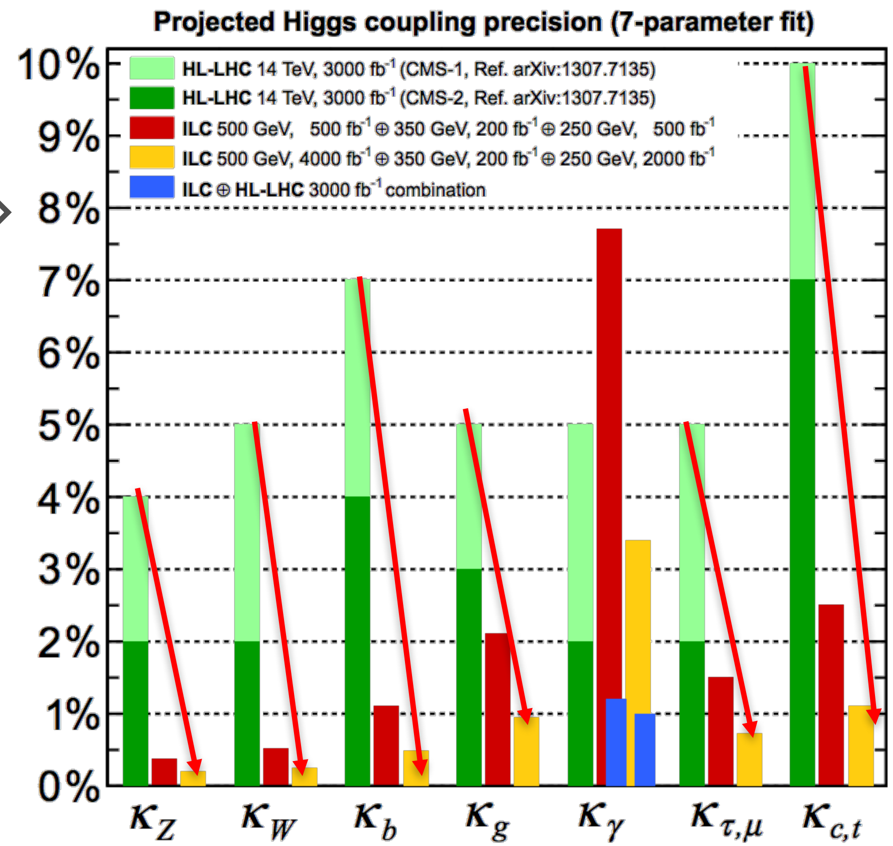
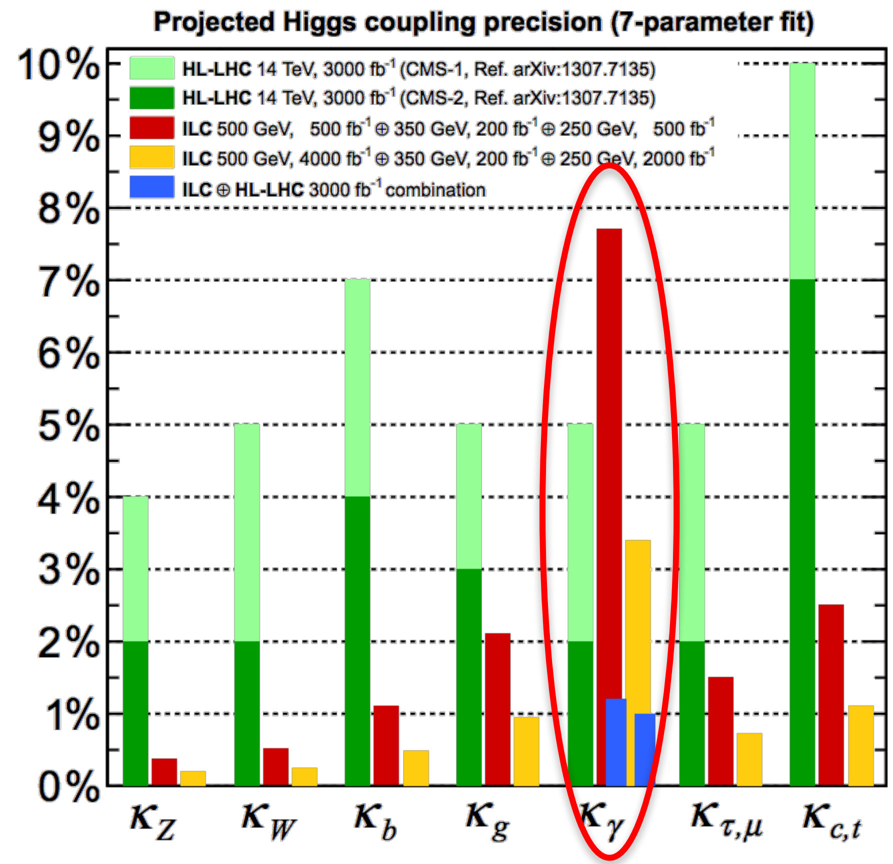




The LC would roughly increase the precision on Higgs couplings by one order of magnitude comparing to HL-LHC.

Precision—couplings (Interplay)

LC features the ``model independent'' determination of Higgs couplings and improves the precision by roughly one order of magnitude.



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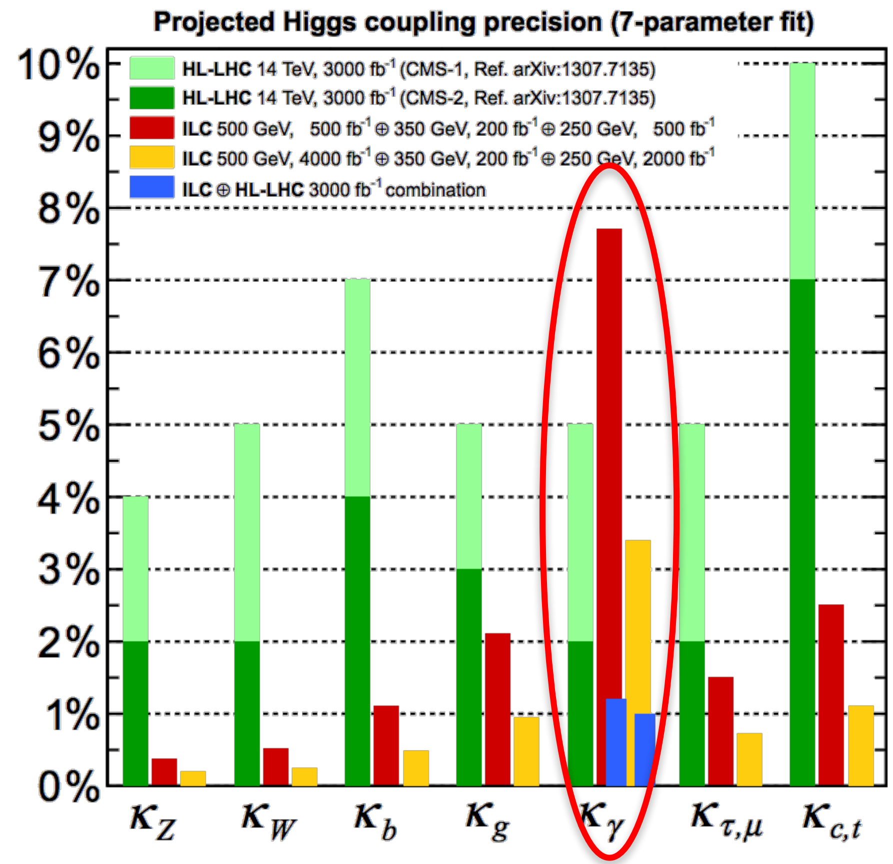

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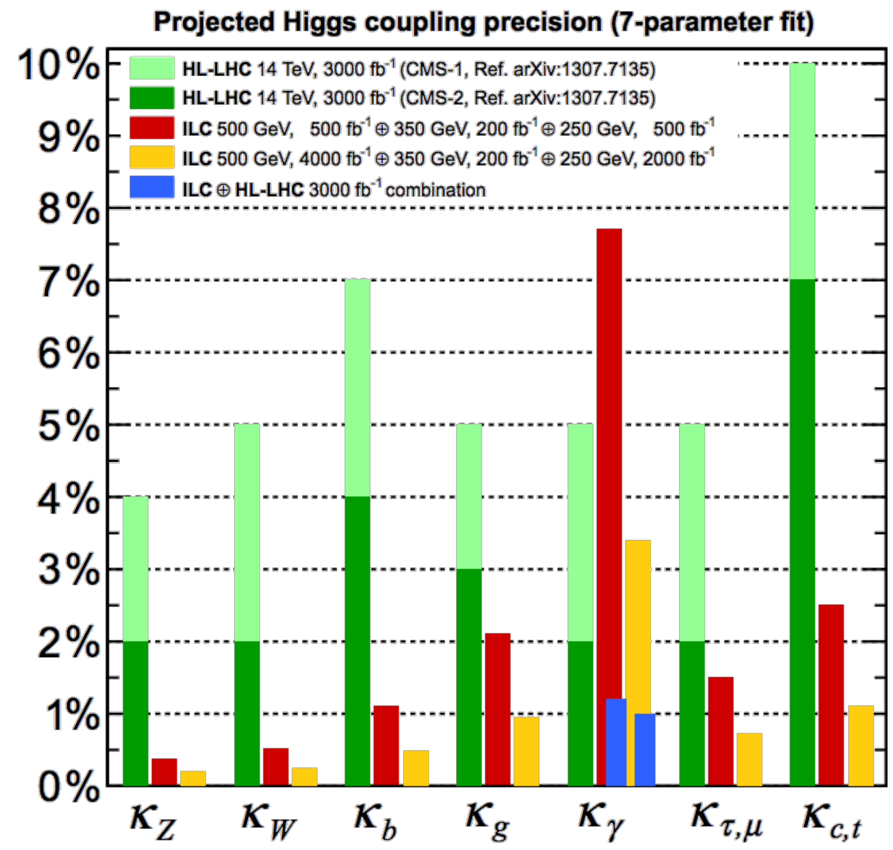
Combining both experimental results improves Higgs precision in a non-trivial way.

Take the $\gamma\gamma$ as an (simplified) example here, the combined precision is much better than directly combining κ_γs.



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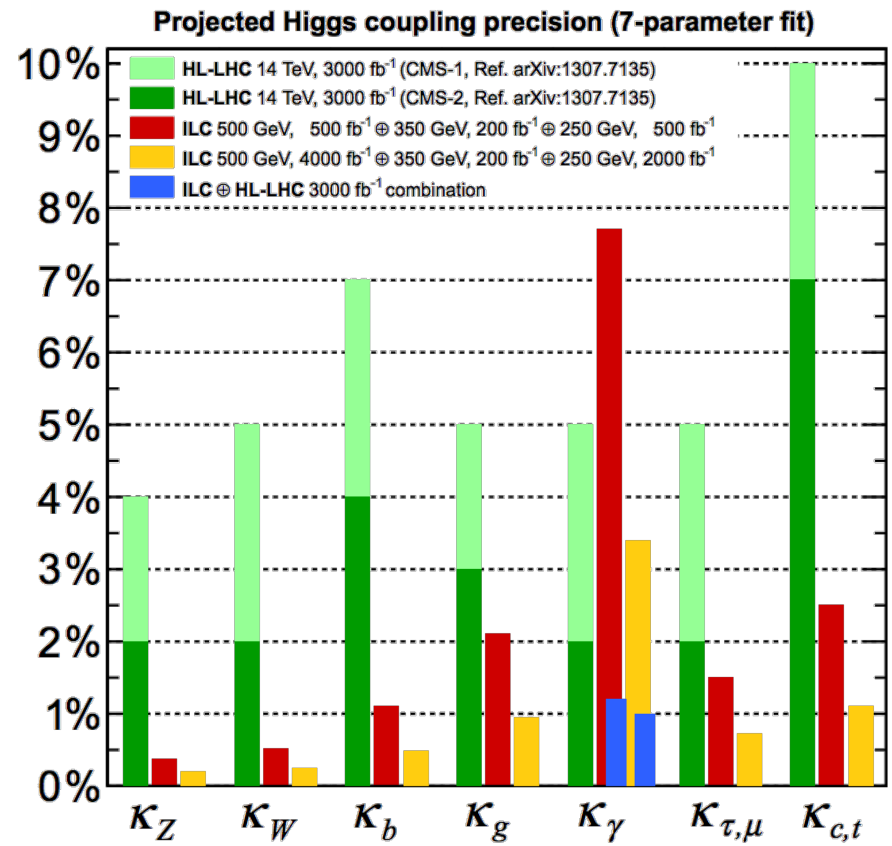
For the top-Yukawa, LC could measure it ``directly'' from ttH (same as LHC) or ``indirectly'' from ggH coupling, combination gains significantly; LHC would further measure the Higgs+jet differential distributes to add more information.



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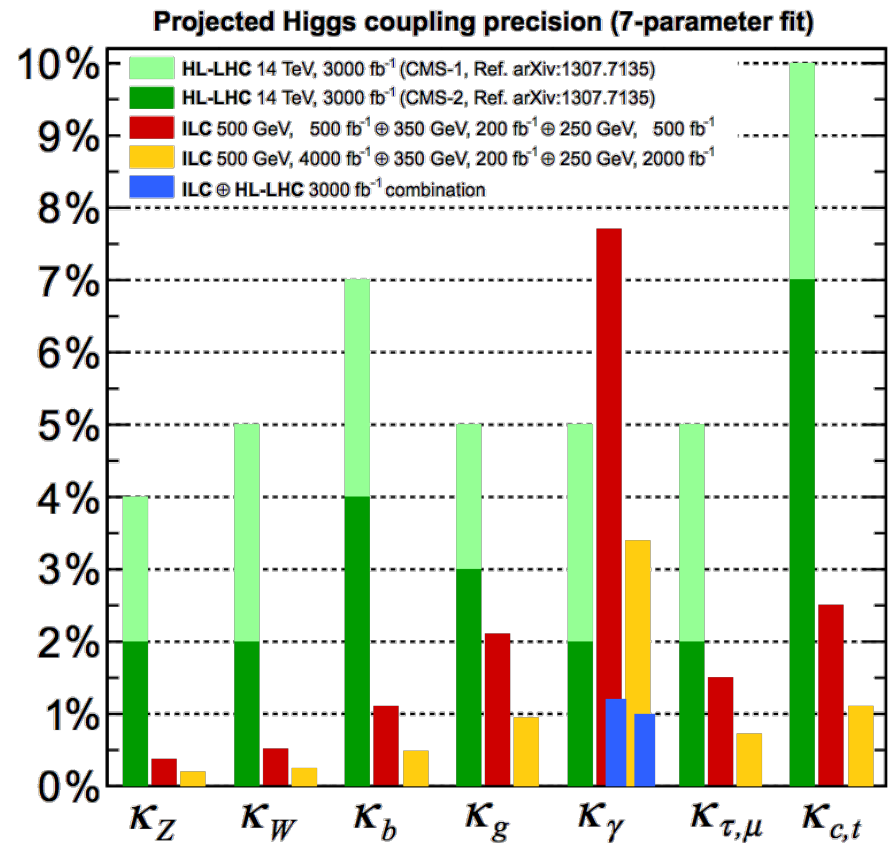

Similar examples include $\mu\mu, gg, cc$ couplings. (See more detailed discussion including more LC-LHC combinations in e.g., T. Han, **ZL** and J. Sayre, arXiv:1311.7155, M. Klute, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, arXiv:1301.1322).

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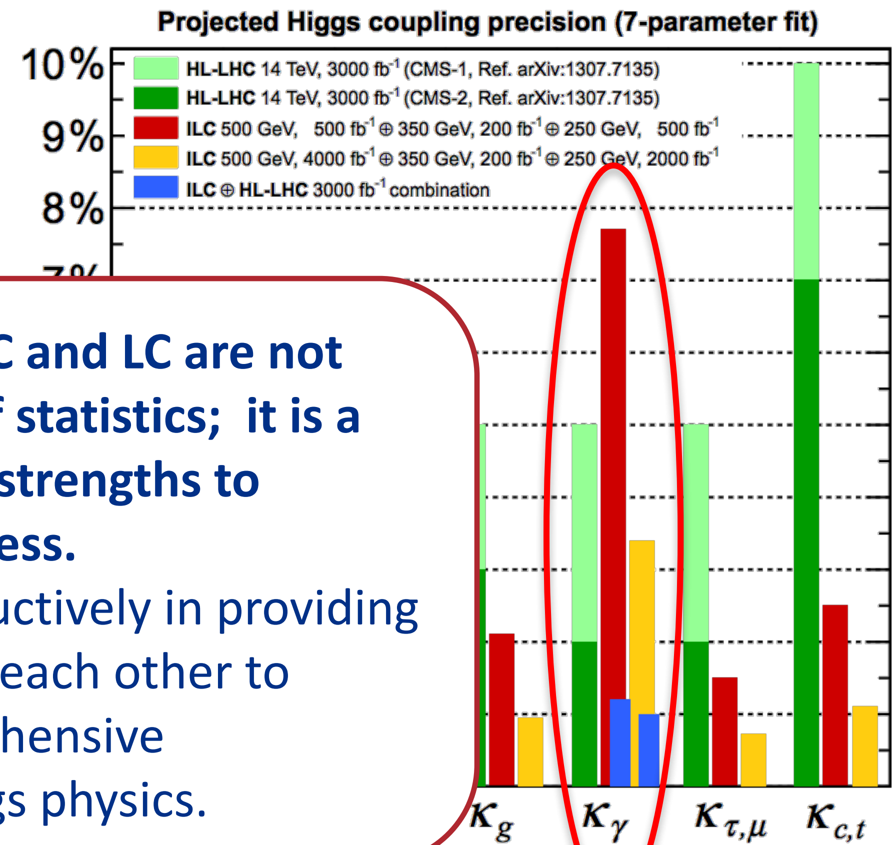
``directly'' from ttH (same as LHC) or ``indirectly'' from ggH coupling, combination gains significantly; LHC would further measure the Higgs+jet differential distributes to add more information.

Higgs precision at LHC and LC are not merely an increase of statistics; it is a combination of their strengths to overcome the weakness.
They interplay constructively in providing useful information to each other to achieve more comprehensive understanding of Higgs physics.



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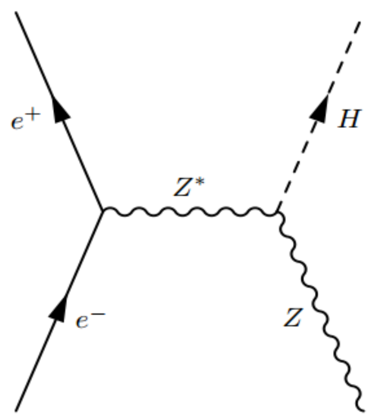
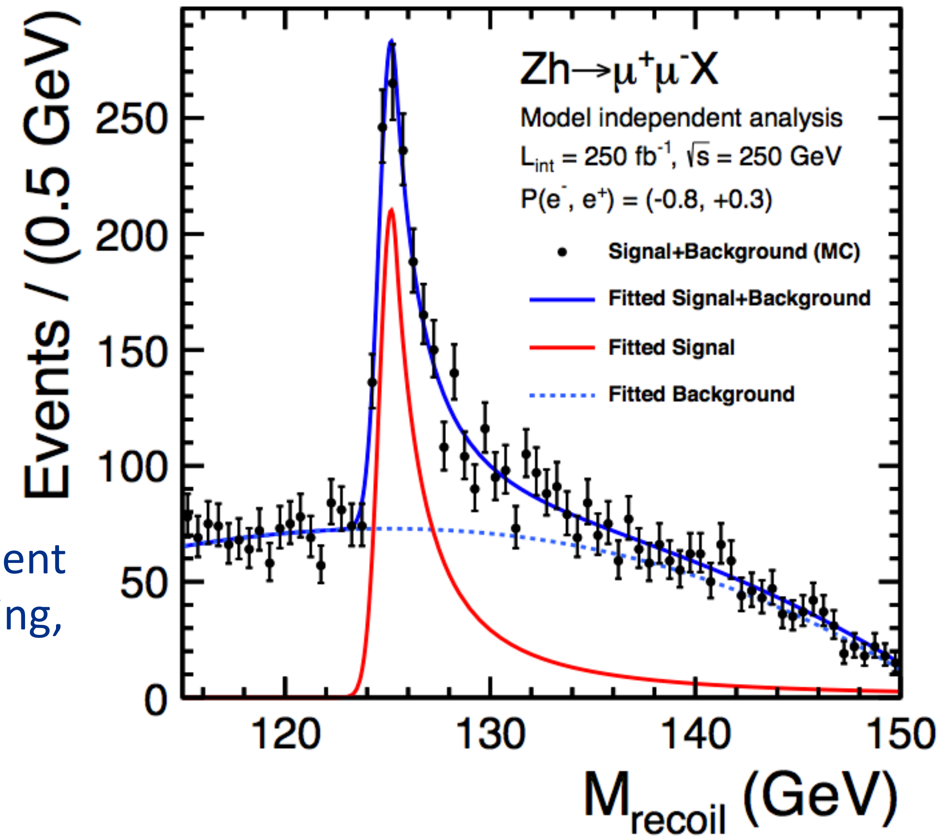
Precision—beyond κ-framework

The feature measurement at lepton collider are the HZZ precision from the inclusive ZH associated production using the ``recoil mass'' technique.





In the κ-framework, this measurement uniquely determines the HZZ coupling, enabling the subsequent ``model independent'' extractions of Higgs couplings and total width.

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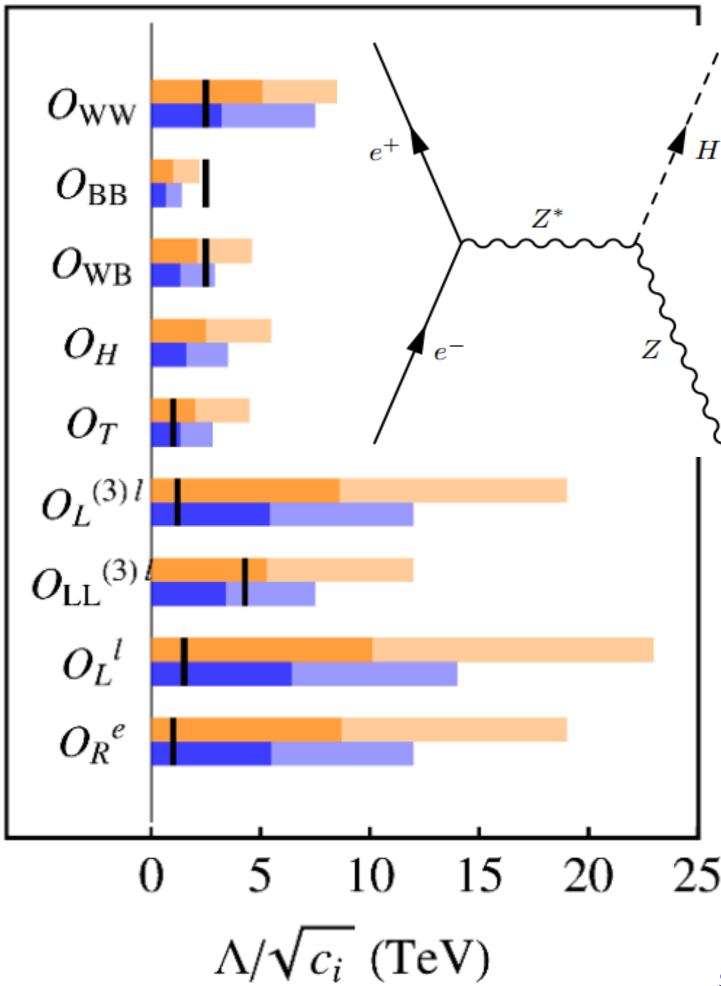

9 operators at dimension-six level contribute to this measurement, beyond our simple parametrization of rescaling HZZ coupling.

N. Craig, M. Farina, M. McCullough and M. Perelstein [arXiv:1411.0676]

$$\mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu}W^{a,\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{WB} = gg' H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu|H|^2\right)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_L^{(3)\ell} = \left(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H\right)\left(\bar{L}_L\gamma^\mu\sigma^a L_L\right)$$
$$\mathcal{O}_{LL}^{(3)\ell} = \left(\bar{L}_L\gamma_\mu\sigma^a L_L\right)\left(\bar{L}_L\gamma^\mu\sigma^a L_L\right)$$
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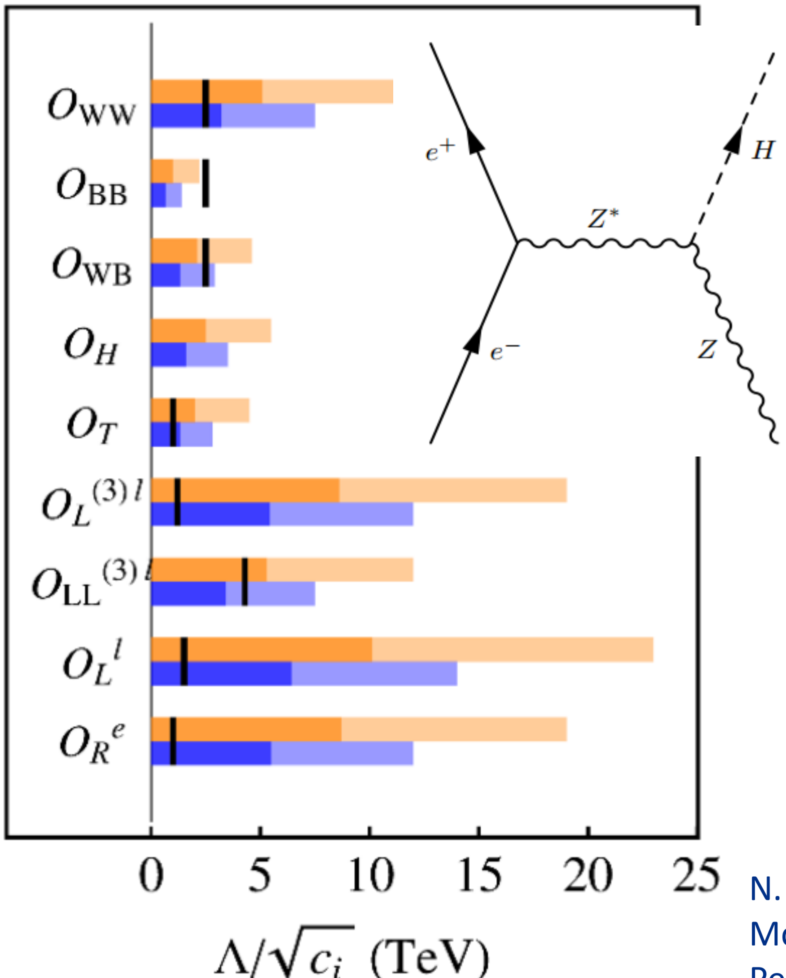

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e+e- machines and pp machines have different solutions

N. Craig, M. Farina, M. McCullough and M. Perelstein arXiv:1411.0676

$$
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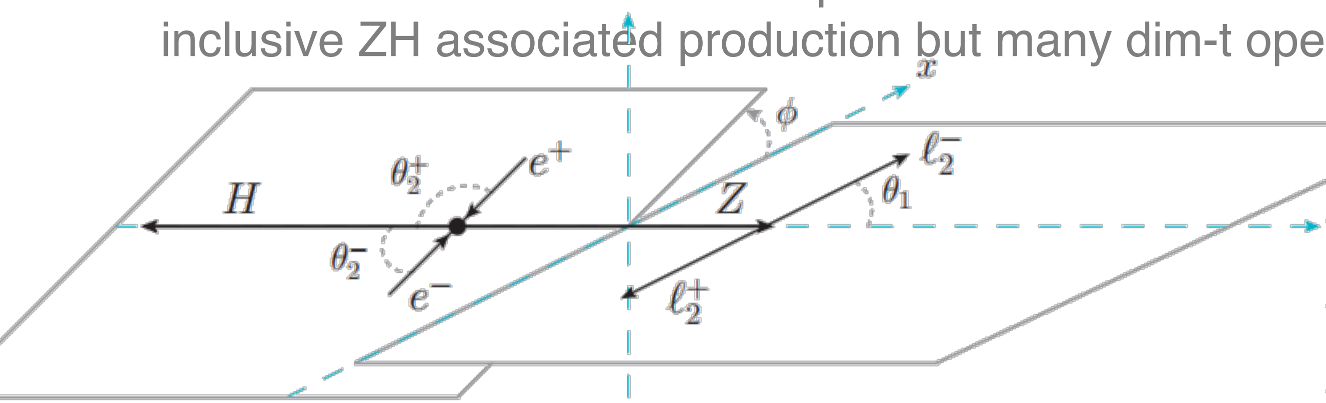

$$\mathcal{A}_{\theta_1} = \frac{1}{d\Gamma/dq^2}\int_{-1}^{1} d\cos\theta_1\ \mathrm{sgn}(\cos(2\theta_1$$

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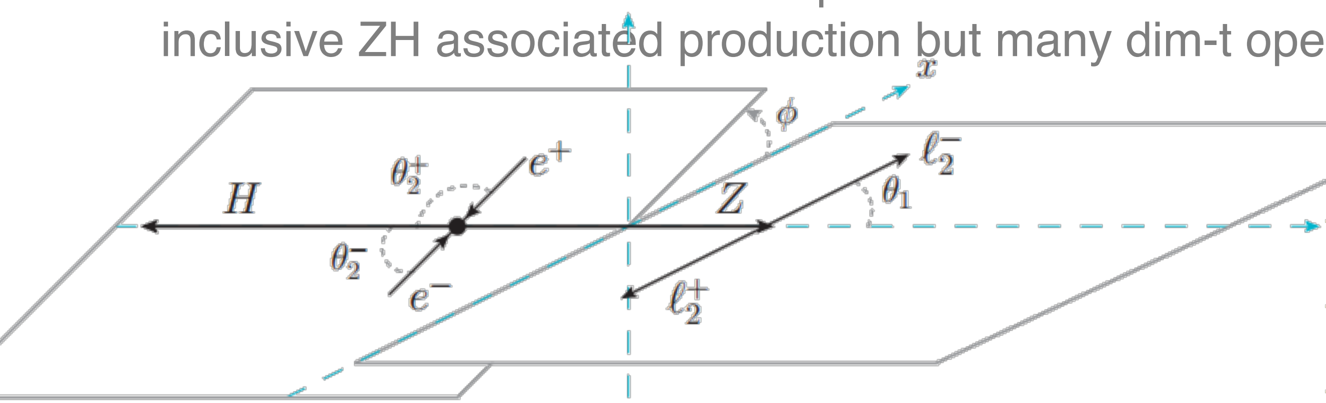

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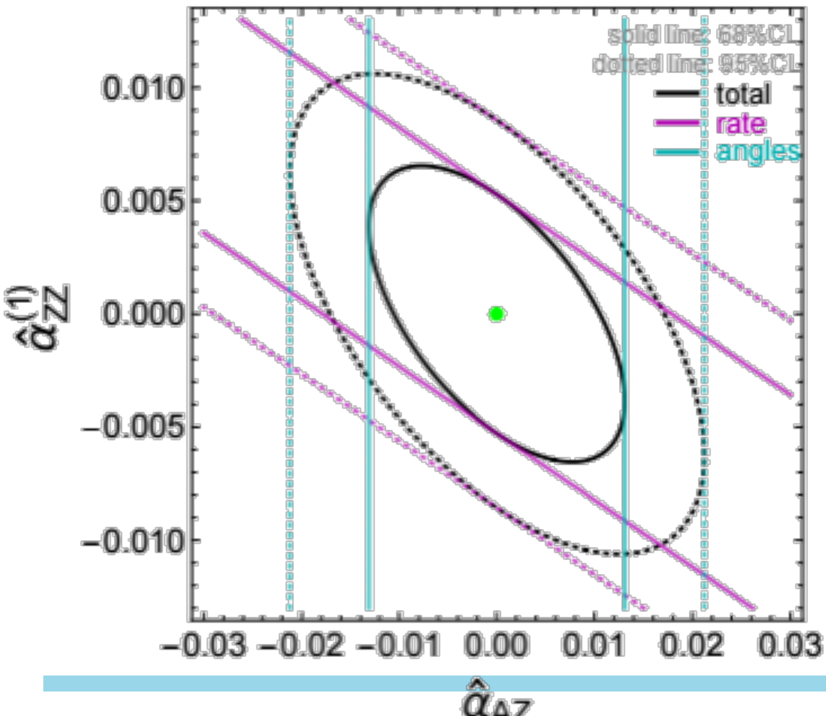

Angular asymmetries for the same process probes the physics of underlying operators with different Lorentz structure.

M. Benekea, D. Boitoa, and Y.-M. Wang, arXiv:1406.1361
N. Craig, J. Gu, ZL. K. Wang arXiv:1512.06877

see also Tomohisa Ogawa's earlier talk and Xin Chen's earlier talk today.

Precision—beyond κ (LHC)

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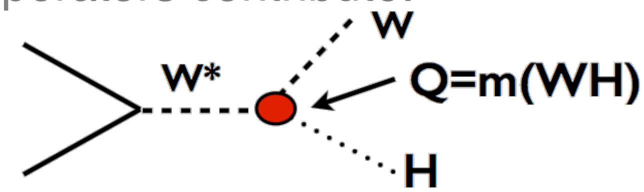
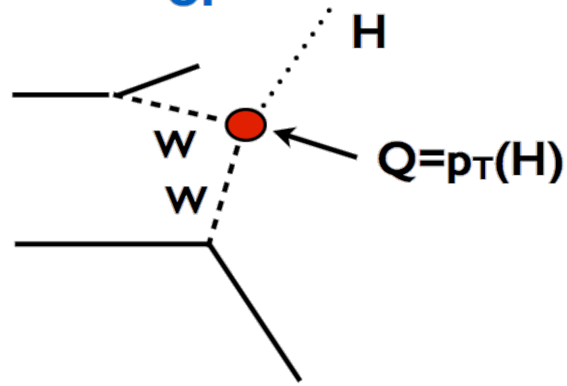


$\delta BR(H \to WW^*)$

or



At pp machines, instead, we can go beyond the simple scaling of the couplings via the differential distribution of various Higgs production mechanism.

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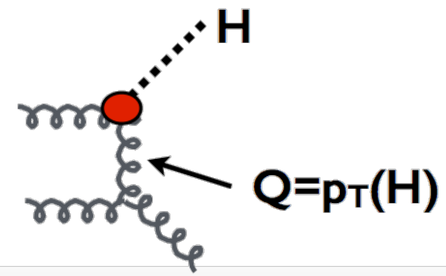

Picture from M. Mangano's talk at ICHEP 2016

Precision—beyond κ (interplay)

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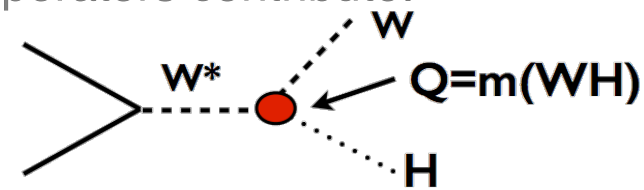

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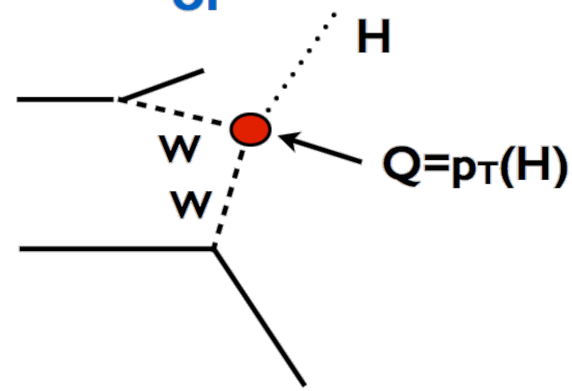

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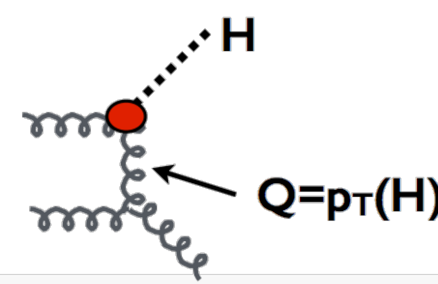
LHC could perform direct searches for heavy d.o.f and provide useful input for physics interpretations. (especially useful if multiple nearby d.o.f involved)

$\delta BR(H \to gg)$ ⟷

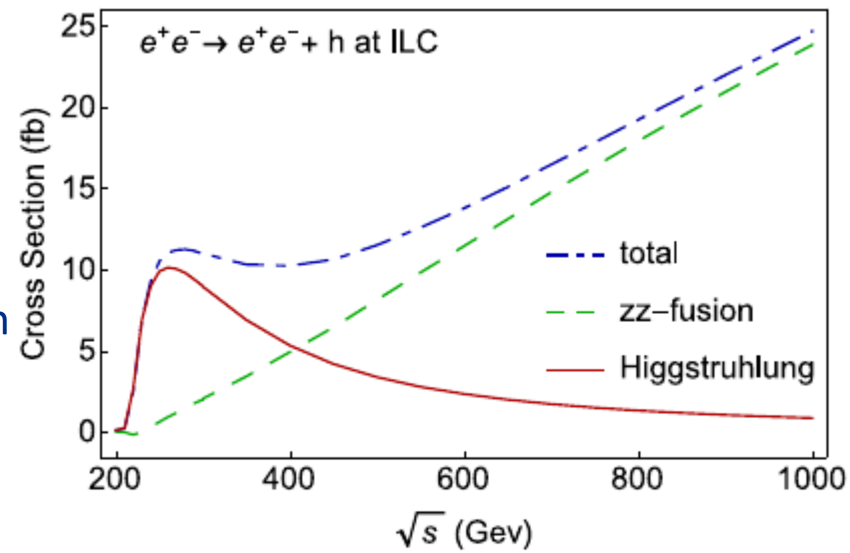


Picture from M. Mangano's talk at ICHEP 2016

Precision—beyond κ (LC)

People usually ignore the ZZ-fusion production rate for ILC, because of its much lower production rate than the WW-fusion channel.

However, as the ``recoil mass'' technique can only be applied to visible spectator particles, 1~TeV ILC does not increase the precision on this crucial channel.



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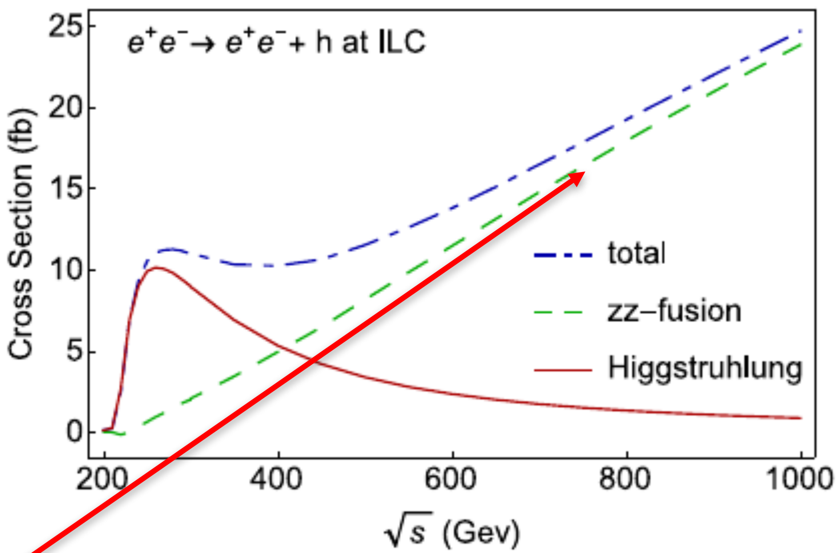

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If we fold in the Z->leptons branching fraction, ZZ-fusion do have advantages at high C.M. energy runs of LC.

Our work show ~20% improvement comparing to the ZH alone analysis in the old ILC running scenario.

T. Han, **ZL**, Z. Qian and J. Sayre, **arXiv:1504.01399**.

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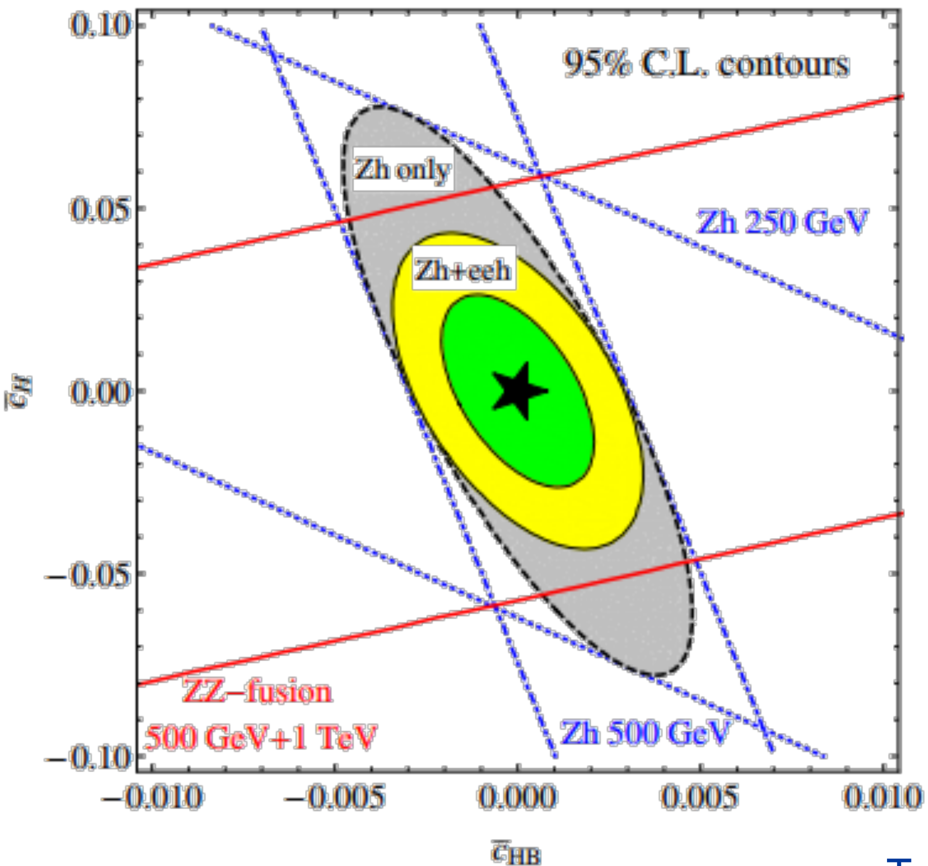

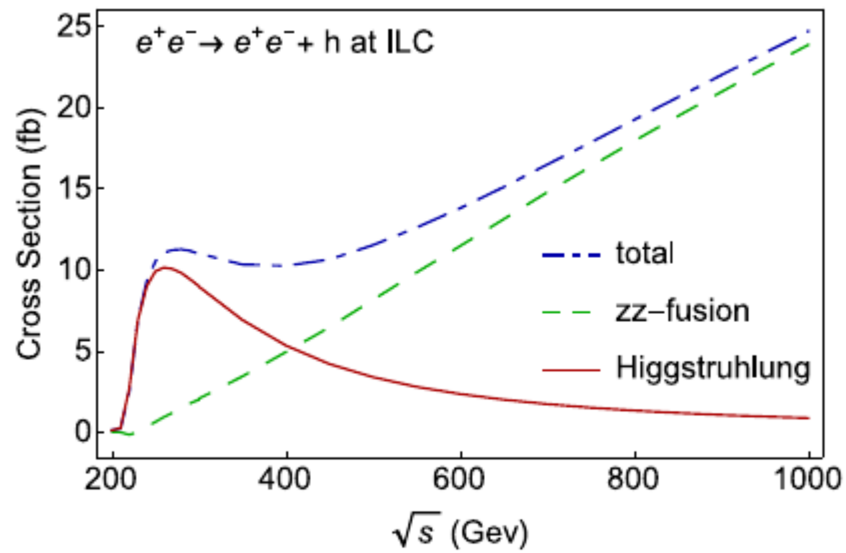

Measuring the rates at different energies with different modes gain significant amount of information of the underlying physics.

T. Han, **ZL**, Z. Qian and J. Sayre, **arXiv:1504.01399**.

Similar to pp-machines, LC with higher energy runs probes the interactions at different energies, and thus can be used to probe different Lorentz structures.

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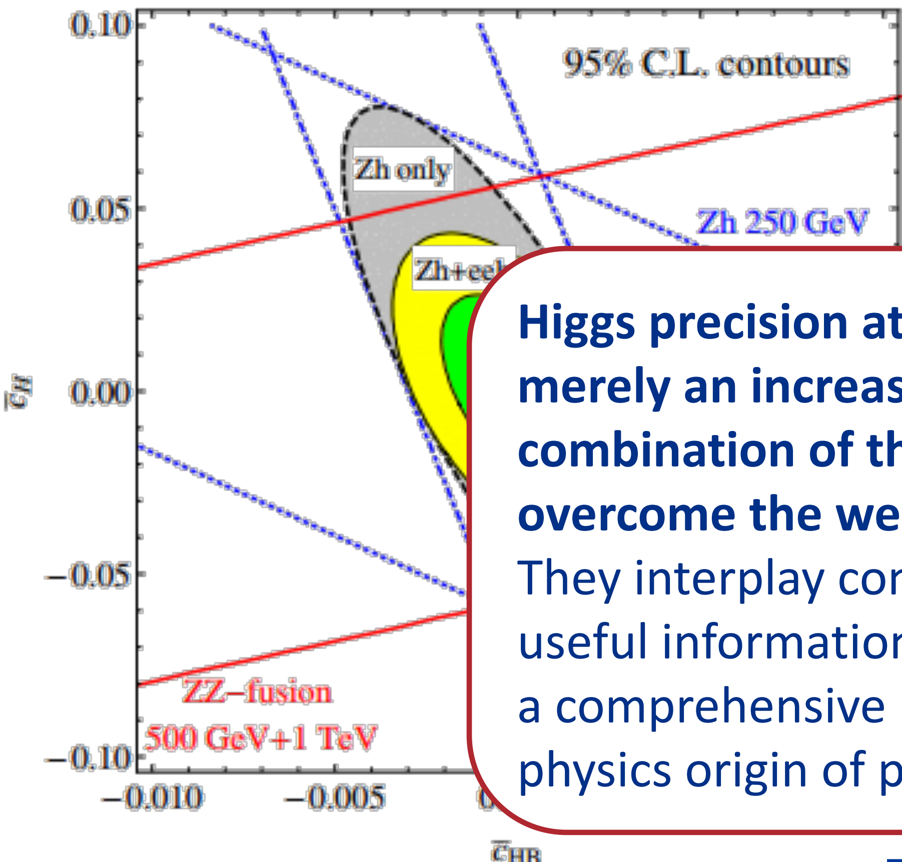

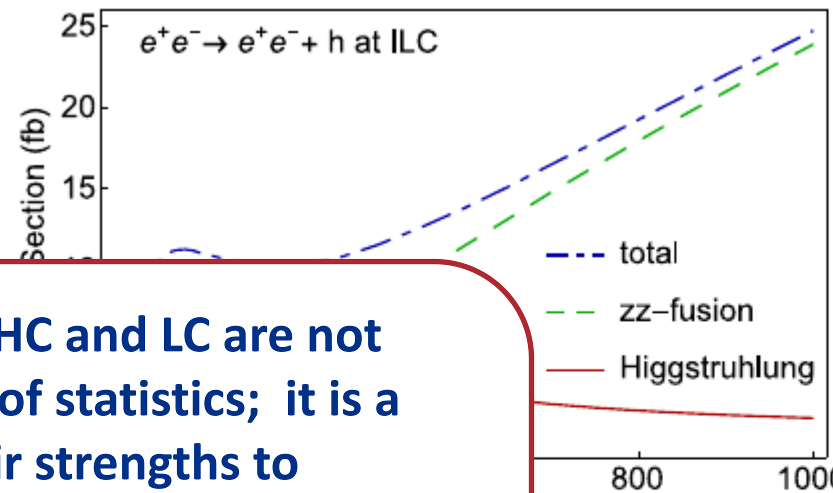

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the underlying

T. Han, **ZL**, Z. Qian and J. Sayre, **arXiv:1504.01399**.

Similar to pp-machines, LC with higher energy runs probes the interactions at different energies, and thus can be used to probe different Lorentz structures.

Exotic Decays

- Higgs boson can easily and well-motivated to be the portal to other BSM sectors. While most searches focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders. (checking all the possibility; theoretical interests.)
- Moreover, the precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. (complementarity)

Exotic Decays

- Higgs boson can easily and well-motivated to be the portal to other BSM sectors. While most search focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders.
- Higgs has tiny width ~4 MeV

$$\frac{\Gamma}{M} = O(10^{-5})$$

- *all* its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.

e.g., dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$

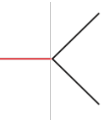
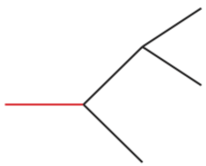
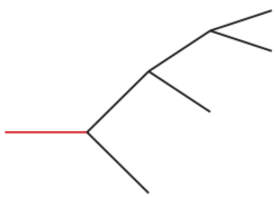
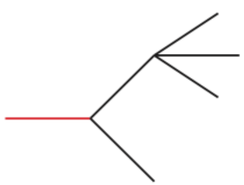
➔

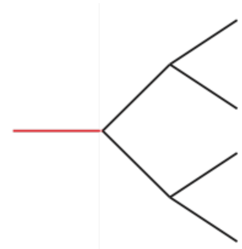
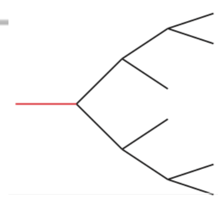
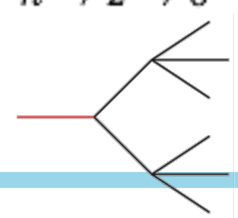
- Any couplings could have sizable width, e.g.,

e.g. L $= \frac{\zeta}{2} s^2 |H|^2$ (common building block 2 in extended Higgs sectors) can give BR(h→ss)~O(10%) for ζ *as small as* 0.01 !

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]

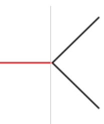
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \slashed{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \slashed{E}_T$
	$h \to (b\bar{b}) + \slashed{E}_T$
	$h \to (jj) + \slashed{E}_T$
	$h \to (\tau^+\tau^-) + \slashed{E}_T$
	$h \to (\gamma\gamma) + \slashed{E}_T$
	$h \to (\ell^+\ell^-) + \slashed{E}_T$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

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

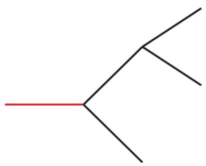
Fermilab

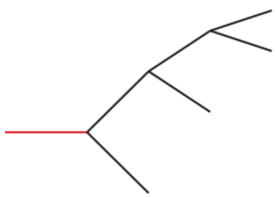
Exotic decays of the 125 GeV Higgs boson

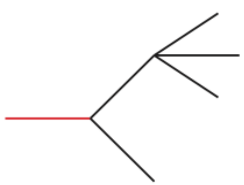
David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]



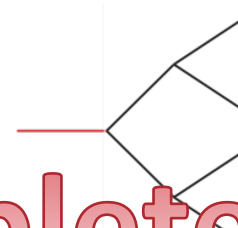
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$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

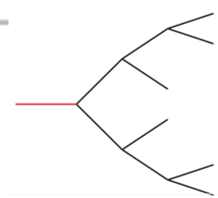


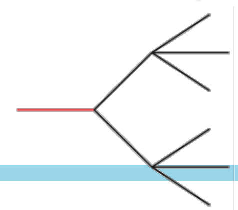




Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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







Incomplete list

Fermilab

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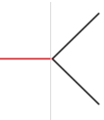
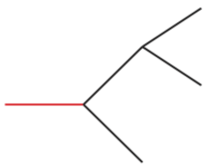
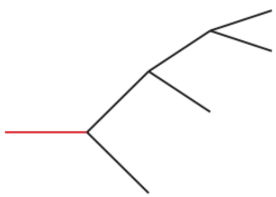
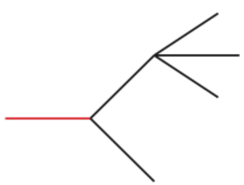
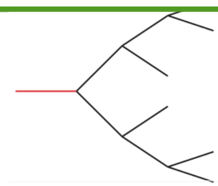
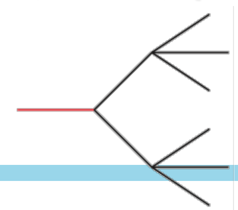
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	h
	$h \to$
	h
	$h \to$
$h \to 2 \to 3 \to 4$ 	h
	h
	$h \to$
	h
	$h \to$
	$h \to$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$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

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

LHC great Sensitivity

$$O(< 10^{-4})$$

Exotic decays of the 125 GeV Higgs boson

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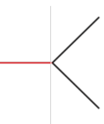
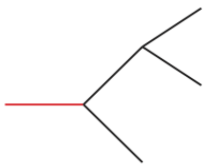
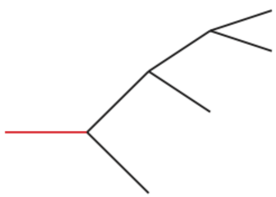
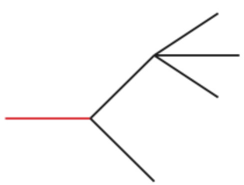


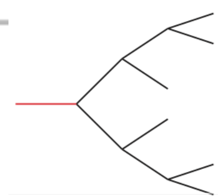
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$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

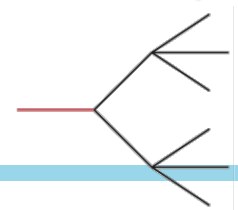






Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (bb)(bb)$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$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





Impressive LHC results presented at this Higgs Exotic Decay meeting @SLAC 2016

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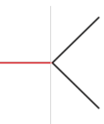
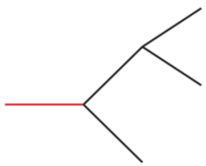
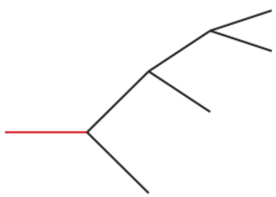
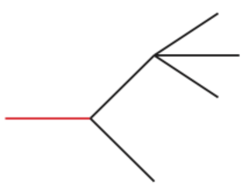
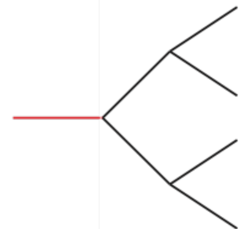
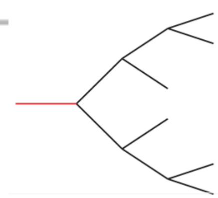
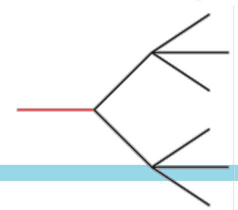


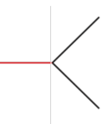
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to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

Hard due to MET

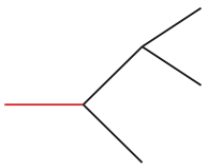
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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

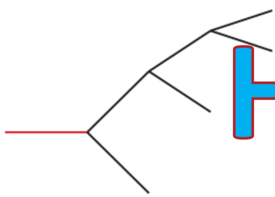
Exotic decays of the 125 GeV Higgs boson

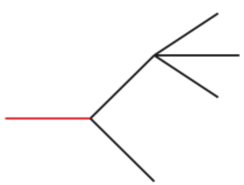
David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]



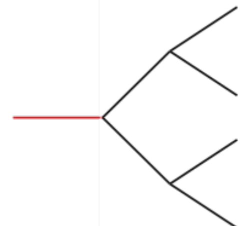
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$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

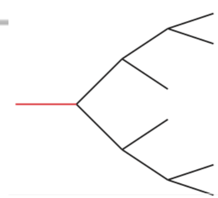


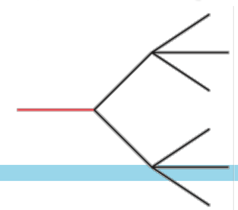




Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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





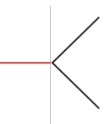
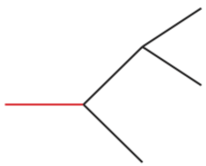
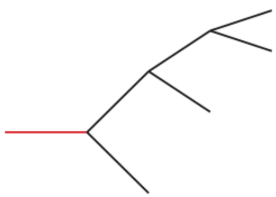
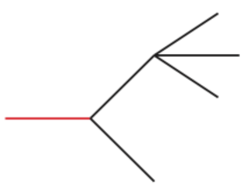


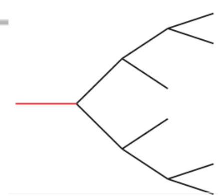
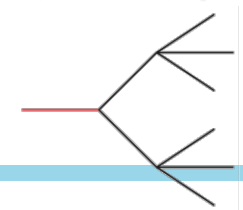
Hard due to MET

Hard due to Hadronic

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]

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

LC's Strength

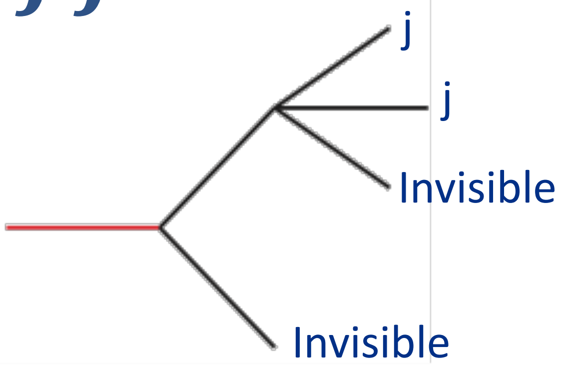
Fermilab

Exotic Decays — (nightmare example for LHC)

$$H \to x_1, x_2 \to j\, j + MET$$

Very challenging, a nightmare at the LHC

1) MET
2) Only light jets
3) no resonance signature from the dijet system, but rather a wide range of invariant mass bounded by the mass differences.
4) Well-motivated from SUSY, DM, etc



Exotic Decays — (nightmare example for LHC)

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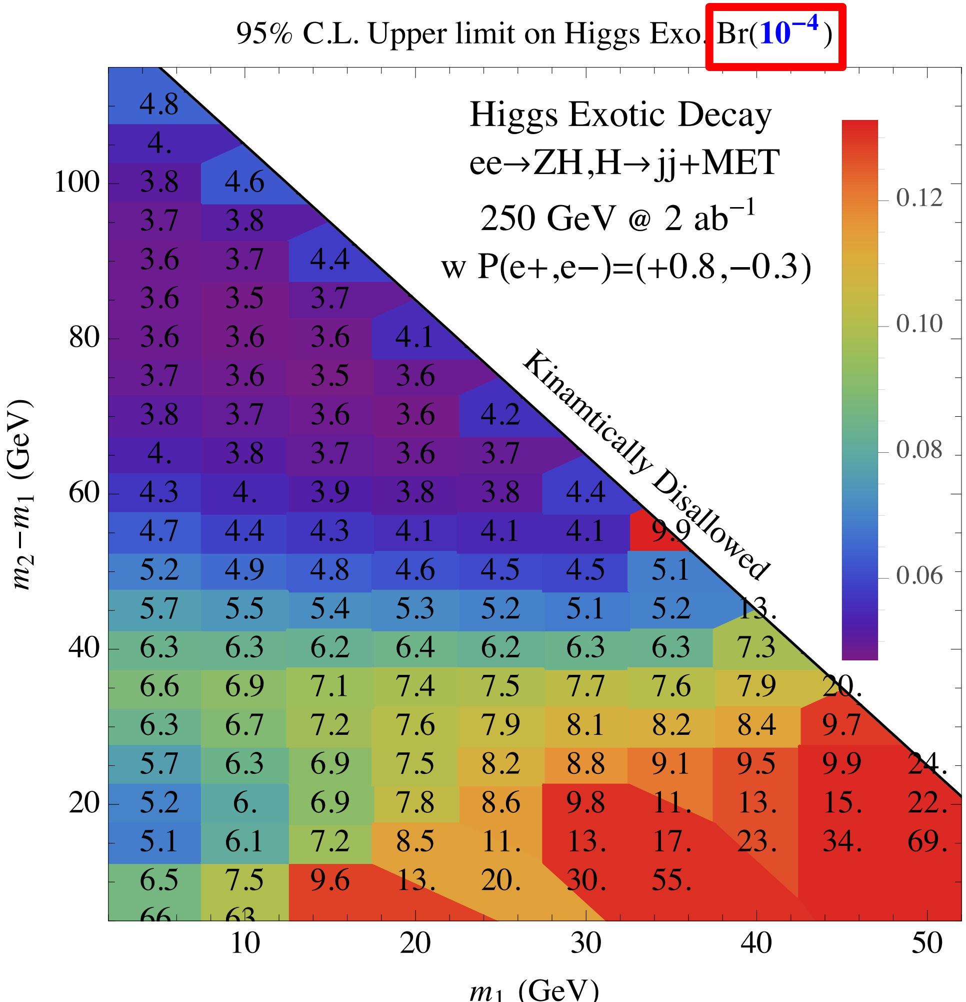

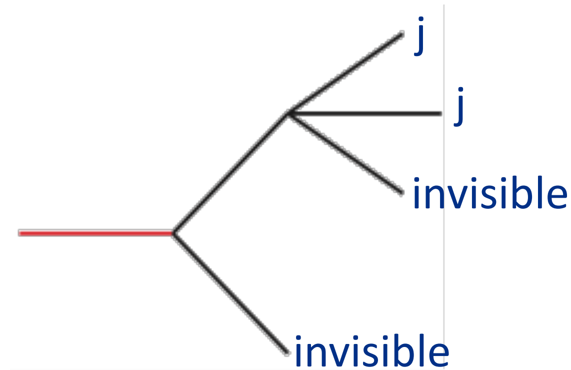

Depending on the masses of the decaying particles, the exclusion reach on Higgs exotic BRs could be as low as 4×10^{-4} and remains at this order for large range, except kinematic edges.

The dijet invariant mass is a distribution since this topology explicitly forbids on-shell case. (SM Higgs decay is the background.)

ZL, L-T. Wang, H. Zhang, to appear

Exotic decays of the 125 GeV Higgs boson

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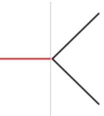
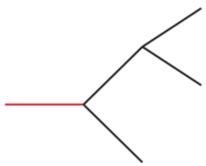
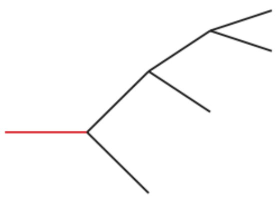
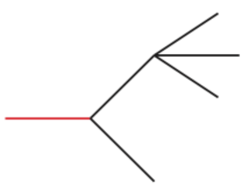
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (bb) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h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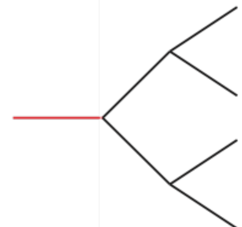
	$h \to \ell^+\ell^- + \not{E}_T$

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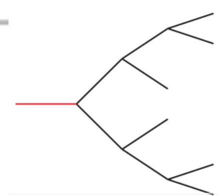
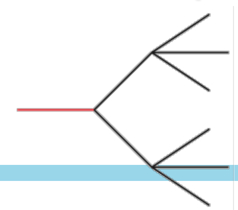
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

Exotic decays of the 125 GeV Higgs boson

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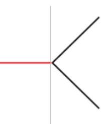
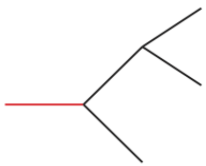
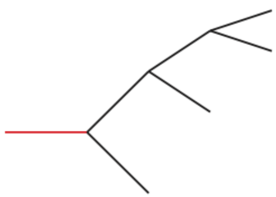
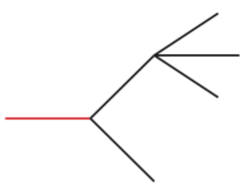
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b b) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	
$h \to 2 \to (1+3)$ 	$h \to \tau^+\tau^- + \not{E}_T$
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	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$\to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
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	$\to (\ell^+\ell^-)(\mu^+\mu^-)$
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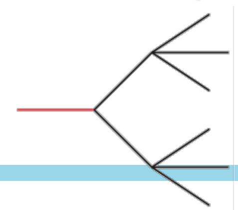
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

Higgs exotic decays at LHC and LC are not merely an increase of statistics; it is a combination of their strengths to overcome the weakness.
They interplay constructively in providing useful information to each other via $O(10^{-3})$ or better sensitivities on exotic Br.

Exotic Production

Higgs can act as taggers for new physics through exotic production mechanism, e.g.,

- Higgs Pair production as a probe for heavy scalar bosons;
- Higgs+ttbar+X production as probe for heavy top partners (stops or T');
- Higgs+W/Z production as a probe for heavy gauge bosons (W', Z');
- Differential distribution of the Higgs+jets/W/Z/VBF as probes for heavy particles in the loop
- Off-shell Higgs effects as indirect probe of Higgs width and interactions
- …

Conclusion

Higgs boson is the key to BSM physics and many puzzles of the SM Higgs boson physics is essential for future programs

While the scope Higgs program is growing rapidly beyond our minimal framework of the precision tests, new ideas are developing around both the LHC and LC programs (see many interesting talks in this workshop).

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The interplay between the LC and LHC Higgs physics should be viewed as **healthy and constructive** (by providing three examples):

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The interplay between the LC and LHC Higgs physics should be viewed as **healthy and constructive** (by providing three examples):

- Higgs couplings precision (the ILC accomplishes ``model-independent" Higgs coupling measurements and improve the precision by one order of magnitude, while combining with the LHC does help for rare decay channels, and also help with top-Yukawa);

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and many more examples (Higgs-CP test, physics interpretations for specific models, trilinear Higgs couplings, Higgs flavor-violating decays, Higgs light fermion Yukawas, etc.)

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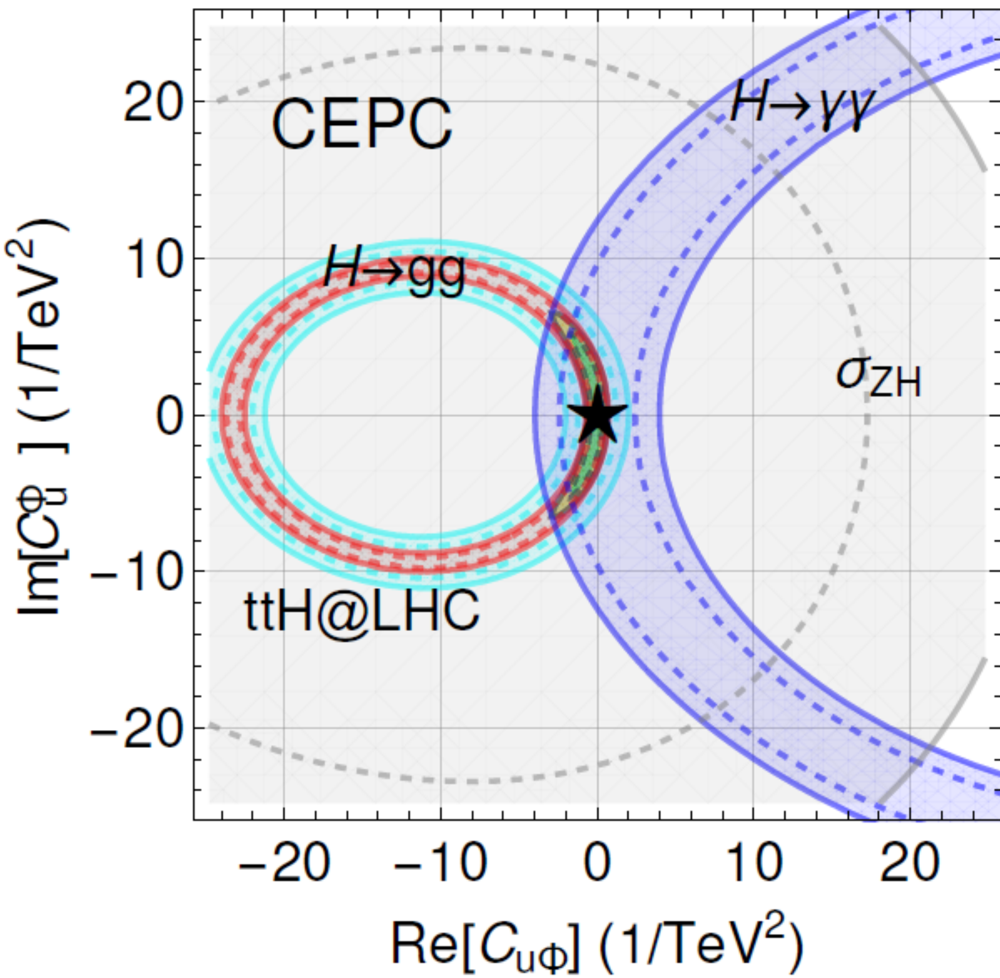
Top quark and Higgs EFT

$$
\begin{aligned}
\mathcal{O}_{u\Phi} &= \frac{1}{\Lambda^2}(\Phi^\dagger\Phi)(\bar{q}_L\tilde{\Phi}t_R),\\
\mathcal{O}_{d\Phi} &= \frac{1}{\Lambda^2}(\Phi^\dagger\Phi)(\bar{q}_L\Phi d_R),\\
\mathcal{O}_{\Phi q} &= \frac{i}{\Lambda^2}(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\bar{q}_L\gamma^\mu q_L),\\
\mathcal{O}^{(3)}_{\Phi q} &= \frac{i}{\Lambda^2}(\Phi^\dagger\tau^I\overleftrightarrow{D}_\mu\Phi)(\bar{q}_L\gamma^\mu\tau^I q_L),\\
\mathcal{O}_{\Phi u} &= \frac{i}{\Lambda^2}(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\bar{u}_R\gamma^\mu u_R),
\end{aligned}
$$

Top-quark and Higgs couplings are the key driver of the hierarchy problem (and subsequent naturalness problem).
Solutions to such problem are likely to induce corrections to these couplings.

Here we choose an complete set of relevant operators, can easily obtain by integrating out heavy particles.

Many challenges, as CEPC/FCC-ee will not operate above ttbar threshold under current plan (due to technical limits such as large synchrotron radiation loss).
Have to go indirect.



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

$$\mathcal{O}_{d\Phi} = \frac{1}{\Lambda^2}(\Phi^\dagger\Phi)(\bar{q}_L\Phi d_R),$$

$$\mathcal{O}_{\Phi q} = \frac{i}{\Lambda^2}(\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\bar{q}_L\gamma^\mu q_L),$$

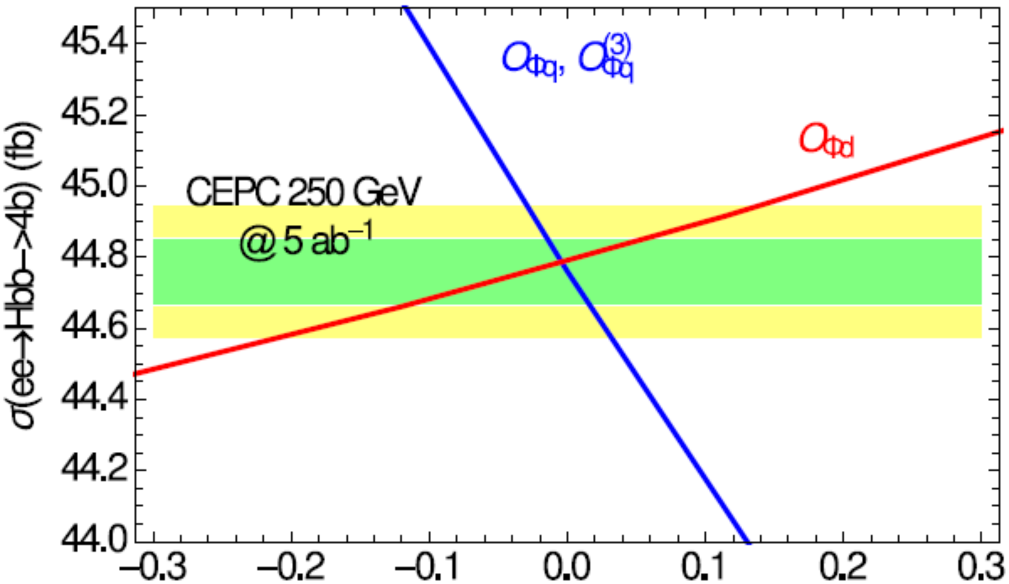
$$\mathcal{O}_{\Phi q}^{(3)} = \frac{i}{\Lambda^2}(\Phi^\dagger\tau^I \overleftrightarrow{D}_\mu\Phi)(\bar{q}_L\gamma^\mu\tau^I q_L),$$

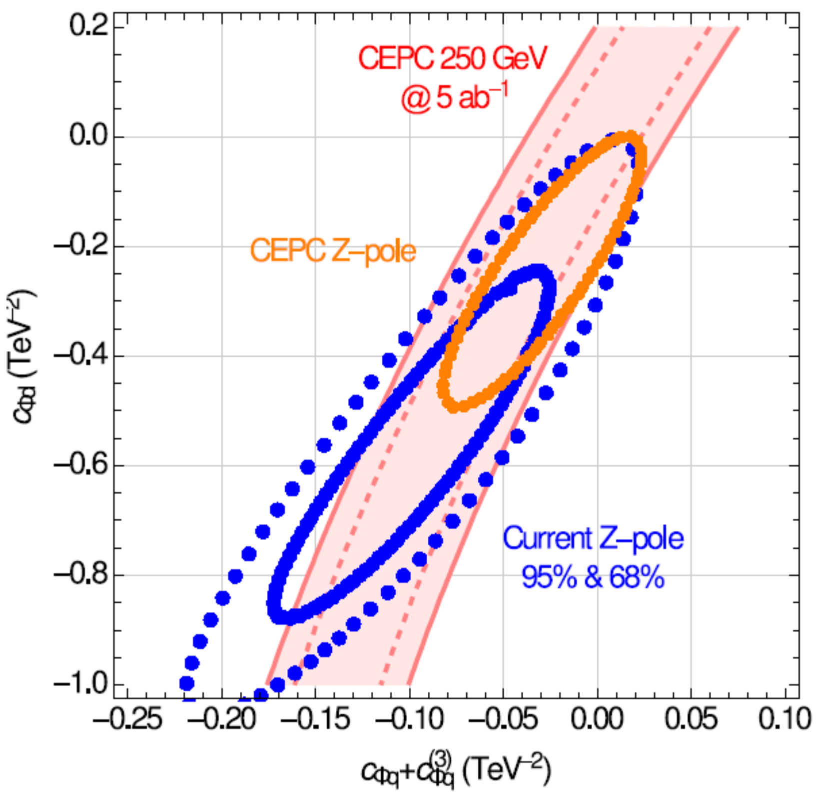
$$\mathcal{O}_{\Phi u} = \frac{i}{\Lambda^2}(\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\bar{u}_R\gamma^\mu u_R),$$

CP-even and CP-odd type of Yukawas, asymmetries too tiny below ttbar threshold.

Sensitivity from loop process.
Glu-glu and diphoton drives the limits, though the precision of corresponding coupling is wrose than κ_Z measurement

Better than HL-LHC tth direct production.





$$
\begin{aligned}
\mathcal{O}_{u\Phi} &= \frac{1}{\Lambda^2}(\Phi^\dagger\Phi)(\bar{q}_L\tilde{\Phi}t_R), \\
\mathcal{O}_{d\Phi} &= \frac{1}{\Lambda^2}(\Phi^\dagger\Phi)(\bar{q}_L\Phi d_R), \\
\mathcal{O}_{\Phi q} &= \frac{i}{\Lambda^2}(\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\bar{q}_L\gamma^\mu q_L), \\
\mathcal{O}_{\Phi q}^{(3)} &= \frac{i}{\Lambda^2}(\Phi^\dagger\tau^I \overleftrightarrow{D}_\mu\Phi)(\bar{q}_L\gamma^\mu\tau^I q_L), \\
\mathcal{O}_{\Phi u} &= \frac{i}{\Lambda^2}(\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\bar{u}_R\gamma^\mu u_R),
\end{aligned}
$$

Operators also modify Zbb and HZbb couplings
ee->H bb could provide constraints on these operators with left-handed doublet.
Comparable precision to current Z-pole precisions.

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Exotic decays of the 125 GeV Higgs boson

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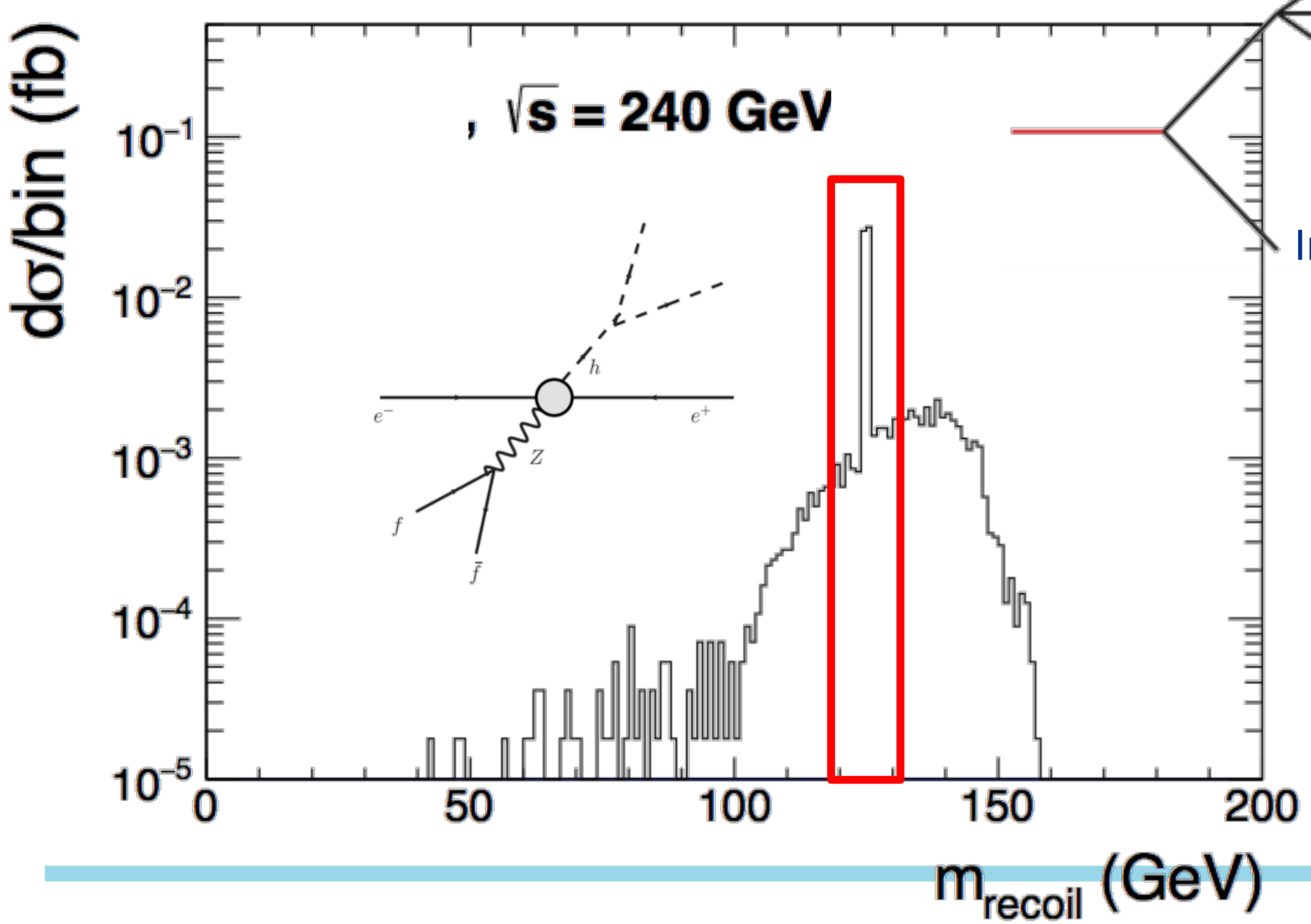
- survey, systematize, prioritize exotic decays
  extensive literature exists, but models need reassessment:
- what BR can be probed? how maximize sensitivity?
  to some extent, develop search strategies, provide viable
- benchmark models/points, inform LHC14 trigger selection
- provide website that will be updated regularly (exotichiggs.physics.sunysb.edu)

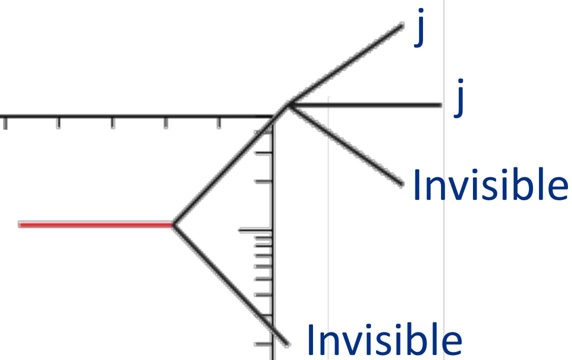
Figure credit: S. Gori

Exotic Decays—Example I:

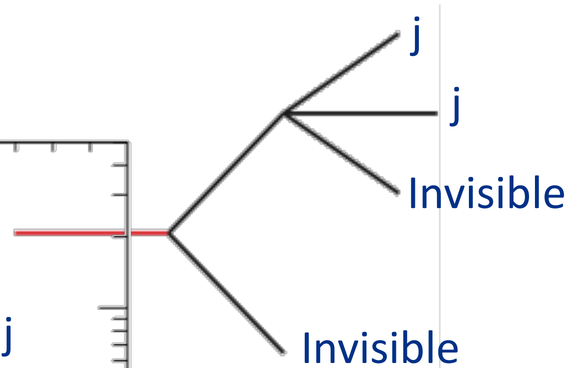
$$H \rightarrow x_1, x_2 \rightarrow j\,j + MET$$

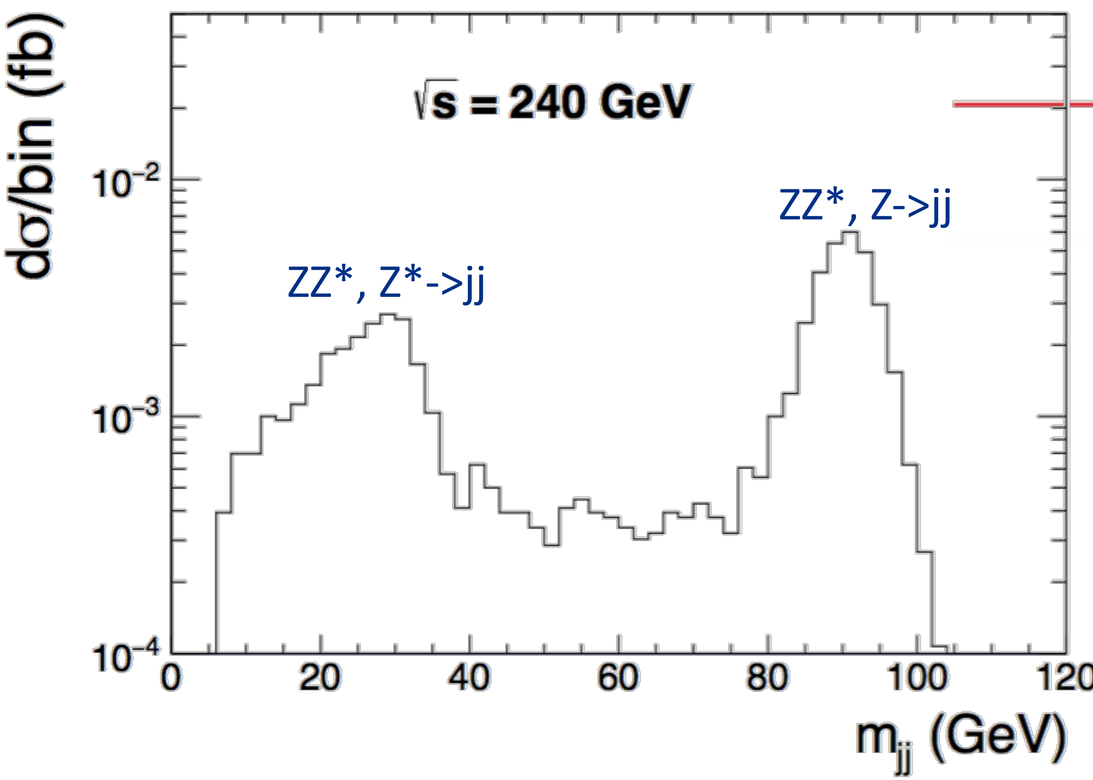
$$e^+e^- \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell jj$$





Exotic Decays—Example I: $H \rightarrow x_1, x_2 \rightarrow j\,j + MET$





Higgs boson itself is the background.

(over simplified) View from a theorist

Lepton collider, clean environment comparing to hadron colliders

By and large that

- Roughly order 1 million Higgs produced (while HL-LHC produces sub billion);
- Records every collision (no trigger issue, keep all events, especially soft ones as well);
- No pile-up, underlying-events, etc.;
- QCD background the same order as QED background;

➔

Implying

- Higgs can be reconstructed regardless of how the Higgs boson decays (using **recoil mass technic** where the associated Z boson act as a Higgs tagger) , further reduced the background;
- Higgs total production rate can be measured to 0.5% level, bringing little dependence when interpreting the experimental result (in contrast to the LHC);
- Great physics potential of probing BSM decays to O($10^{-4}\sim10^{-6}$) universally;
- especially advantageous for hadronic Higgs exotic decays and decays containing missing energy;