Higgs Exotic Decays at future lepton colliders

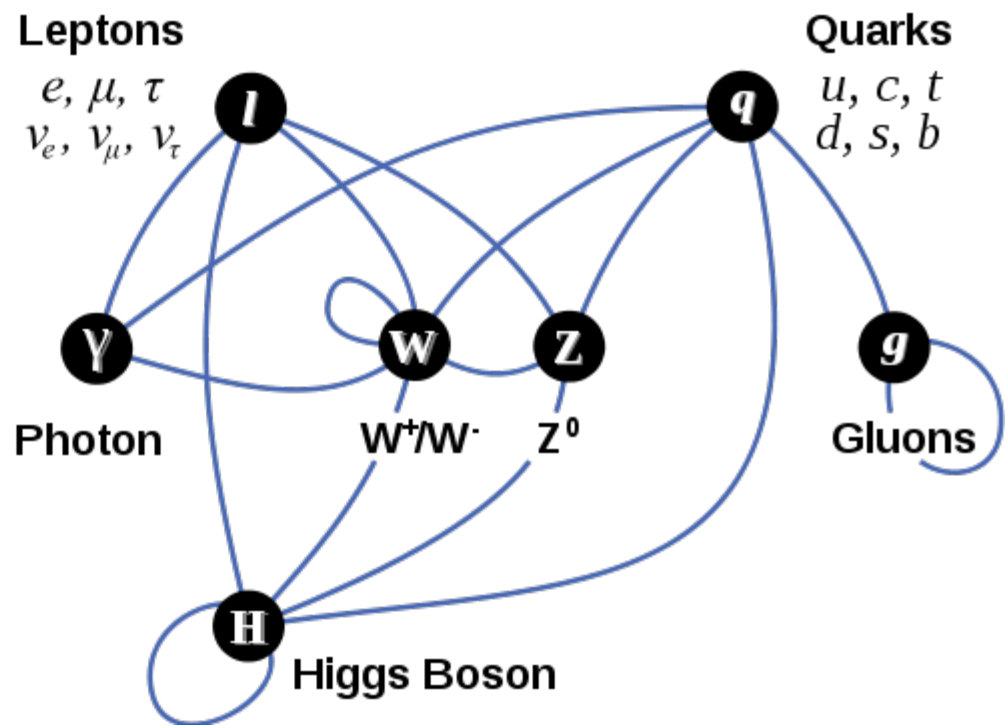
Zhen Liu (FNAL)

Higgs Exotic Decays Meeting @SLAC

Nov. 8th, 2016

New Particle and New Forces

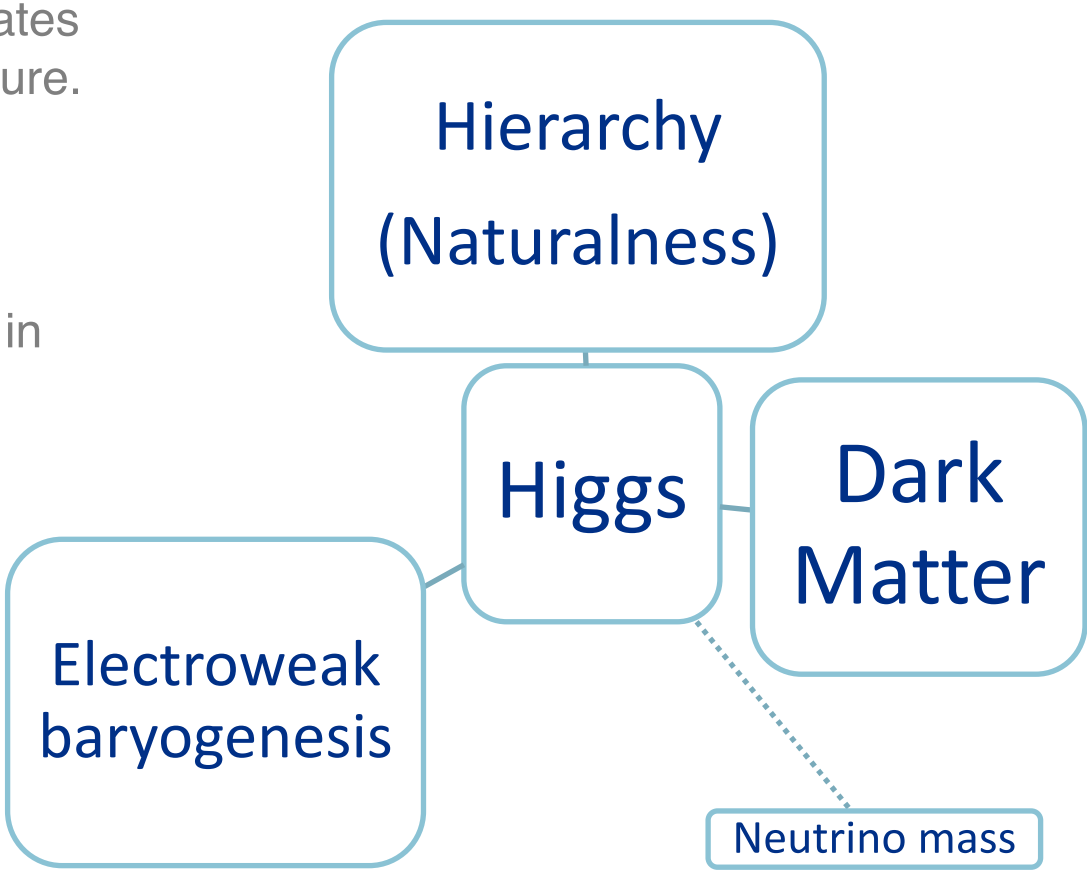
- Gauge coupling
- Yukawa coupling—new forces (9+ Yukawas)
- Self coupling—new force
- Derived couplings
  $H\gamma\gamma, Hgg, HZ\gamma, \ldots$



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 may be revealed in Higgs measurements.



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- New physics can easily couples to Higgs, linking to hierarchy problem, electroweak baryogenesis, naturalness, dark matter, etc.
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While very dramatic

Fig. credit, fivethirtyeight.com

coming close to the final moment, why are we talking about something ~10 years away?

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coming close to the final moment, why are we talking about something ~10 years away?

Aren’t lepton colliders (trivially?) clean and cool, and (simply?) facilitating the measurements the Higgs properties and exotic decays to great precision?

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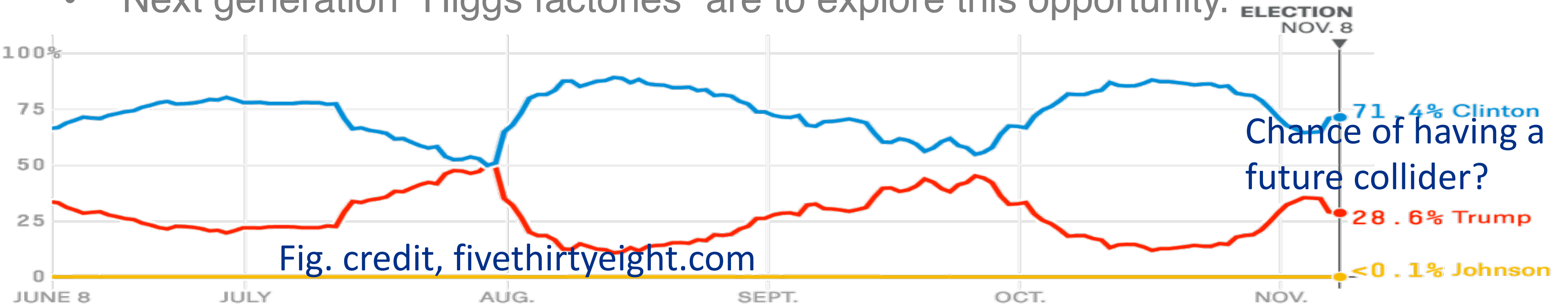

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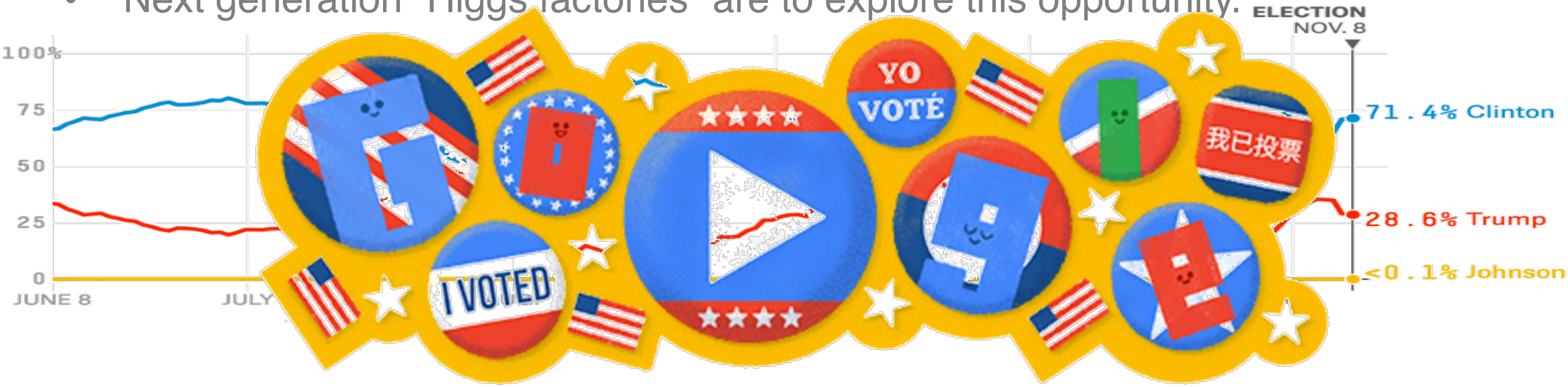


If we do not act, things might well go to a disfavored direction for us.

Proposals and studies are under fast development, under various timelines, CERN (HL-LHC, FCC, CLIC), Japan (ILC), China (CEPC/SPPC)

Phenomenological studies clarifies physics potential, important for the machine design and detector performance goals. The interactions between theory and experiment are crucial for a healthy community for particle physics.

(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

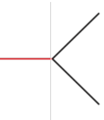
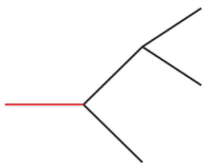
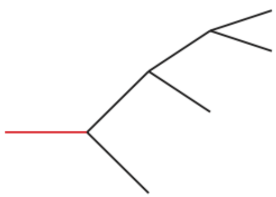
- Higgs can be reconstructed regardless of how the Higgs boson decays (using **recoil mass technic** where the associated Z boson act as a Higgs tagger) , further reduces the background;
- Higgs total production rate can be measured to 0.5% level, bringing little dependence when interpreting the experimental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

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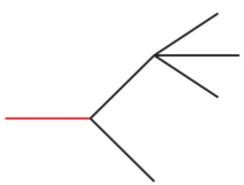
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
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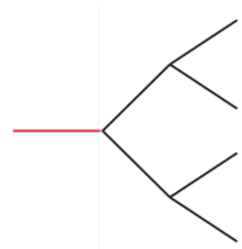
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
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	$h \to (jj)(jj)$
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	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
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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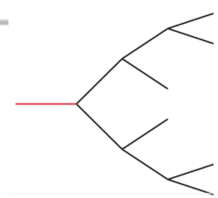
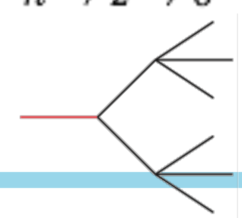
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
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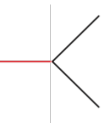
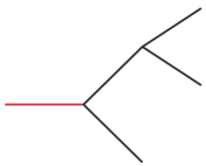
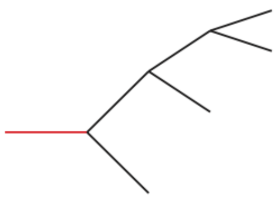
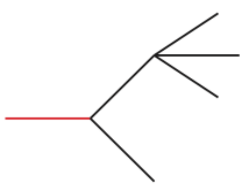
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) +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

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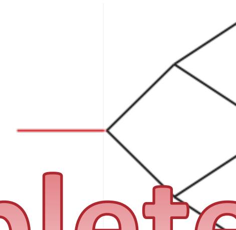
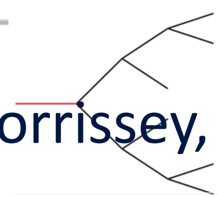
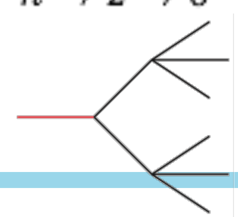
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$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

Incomplete list

many motivations, Felix Yu,

David Morrissey, Gino Isidori

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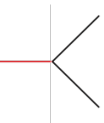

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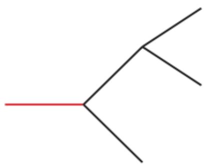
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
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	$h \to (jj) + \not{E}_T$
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	$h \to (\gamma\gamma) +$
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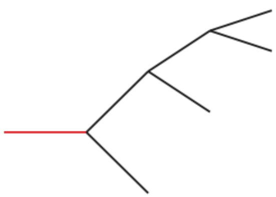
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) +$
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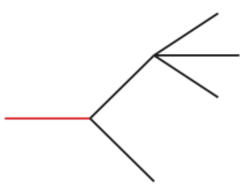
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
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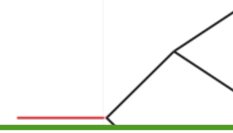
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
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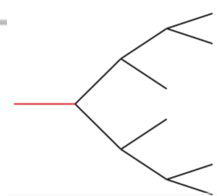
$h \to 2 \to 4 \to 6$ 	$\boxed{h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T}$
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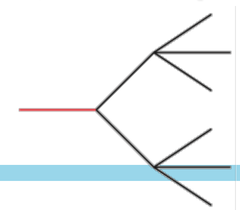
$h \to 2 \to 6$ 	$\boxed{h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T}$
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LHC great sensitivity

Fermilab

Exotic decays of the 125 GeV Higgs boson

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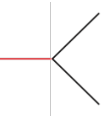

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$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
$h \to 2 \to 3 \to 4$	
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
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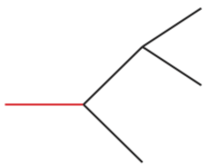

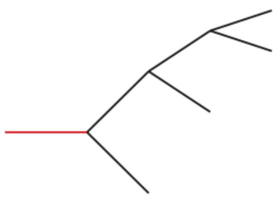

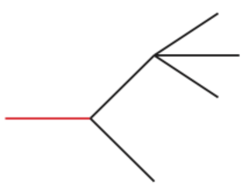

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	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
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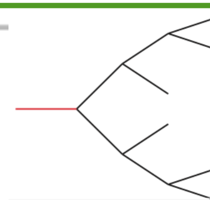
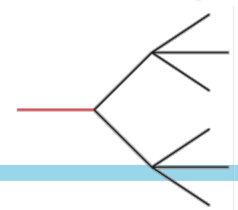
	$h \to \ell^+\ell^- + \not{E}_T + X$





Impressive LHC results presented at this workshop

Mazin Woodrow Khader, James Beacham, Abdollah Mohammadi, Benjamin Eric Kaplan, Alexei Safonov, Nicholas Wardle, Rafael Teixeira De Lima, Allison Mccarn

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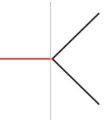
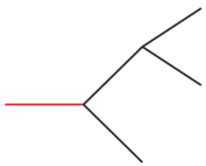
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
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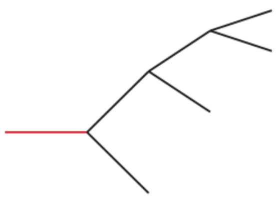
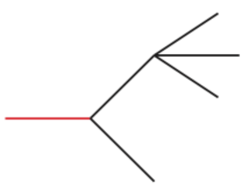
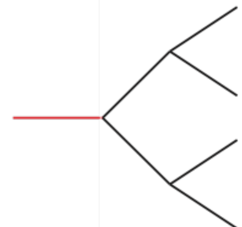
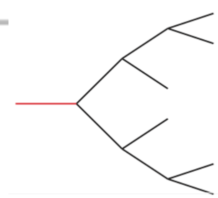
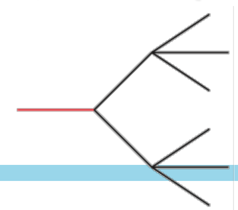
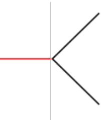
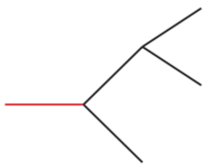
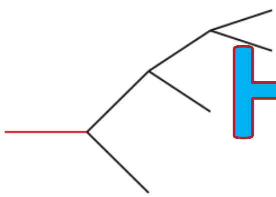
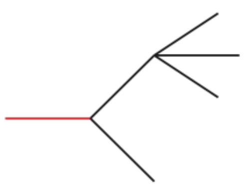
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to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

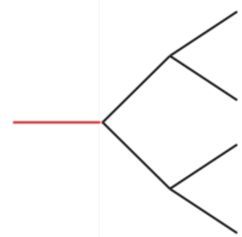
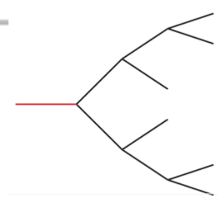
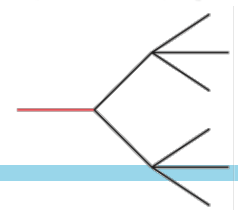
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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

Hard due to MET

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

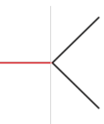
Hard due to MET

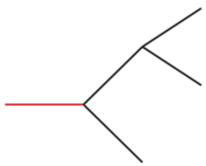
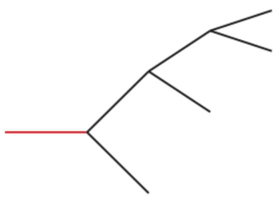
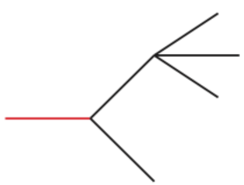
Hard due to Hadronic

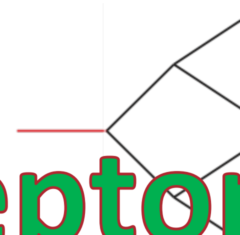
Fermilab

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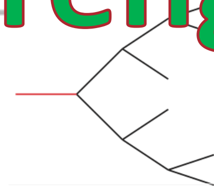
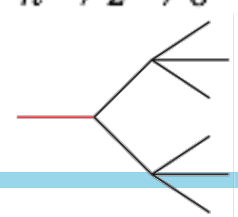
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

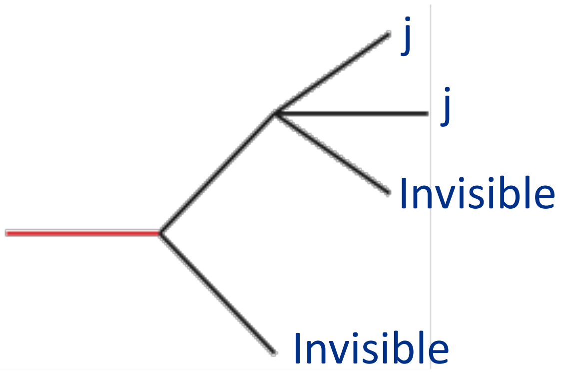
Future lepton Collider's Strength

Exotic Decays—Example I:

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

Very challenging, a nightmare at the LHC

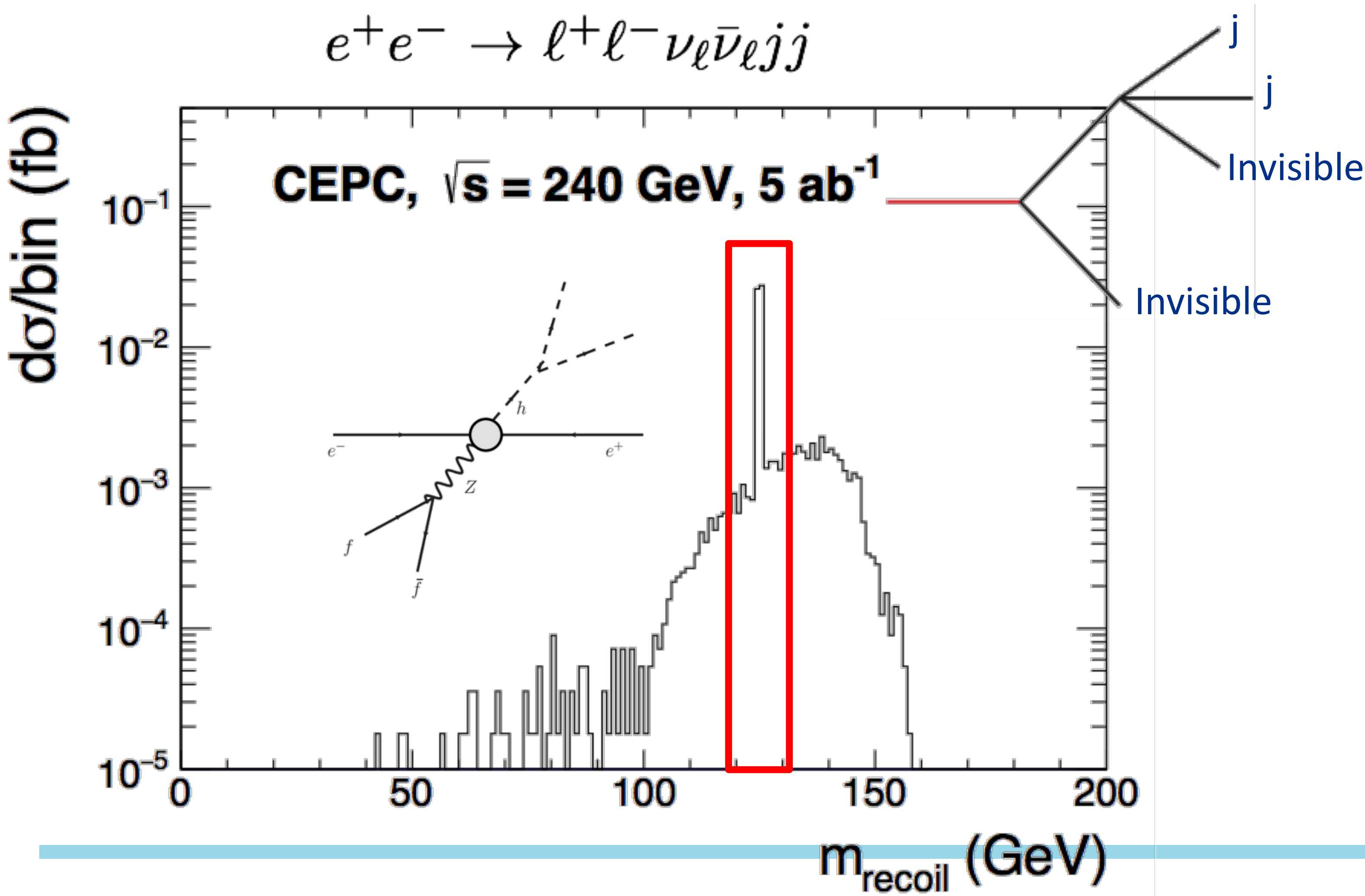
1) MET
2) Only light jets
3) no resonance signature from the dijet system, but rather a wide range of invariant mass bounded by the mass differences.
4) Well-motivated from SUSY, DM, etc



Exotic Decays—Example I:

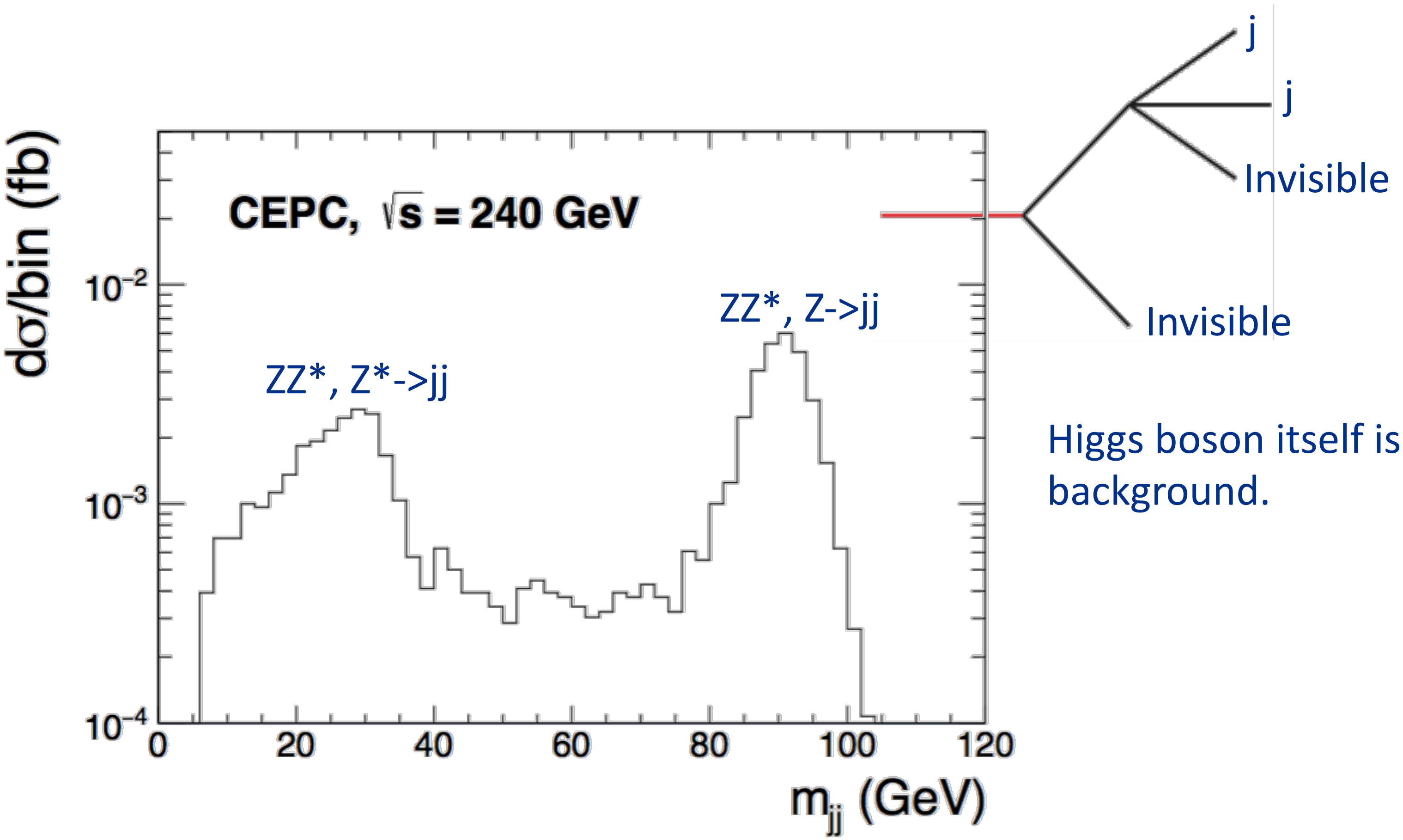
$$H \to x_1, x_2 \to j\,j + MET$$

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



Exotic Decays—Example I:

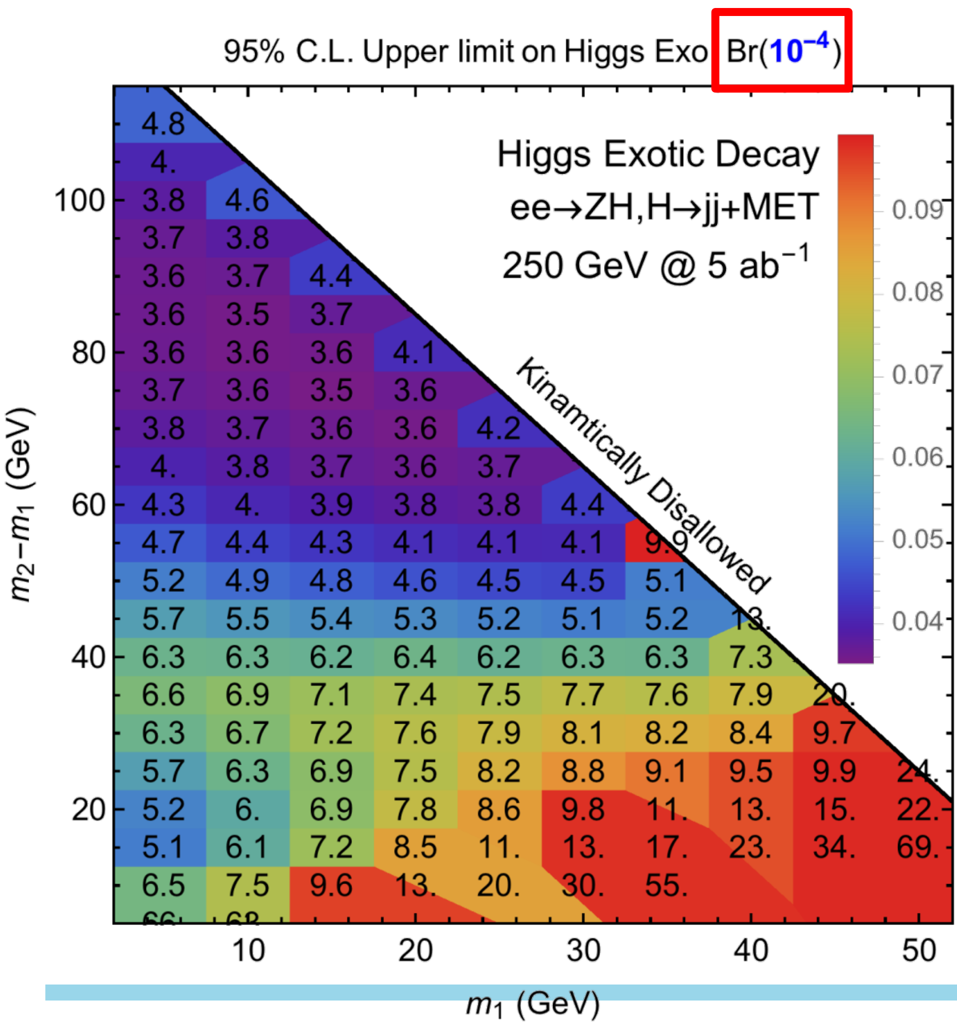
$$H \to x_1, x_2 \to j\, j + MET$$

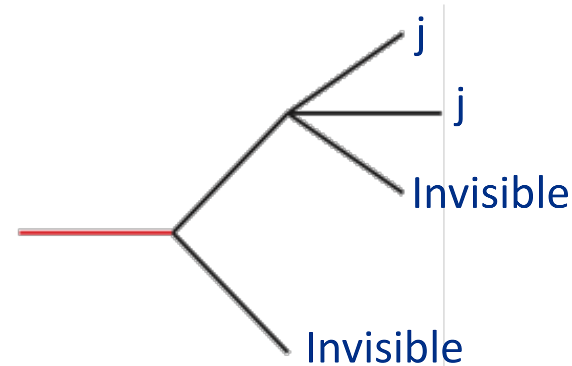


Higgs boson itself is the background.

Exotic Decays—Example I:

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



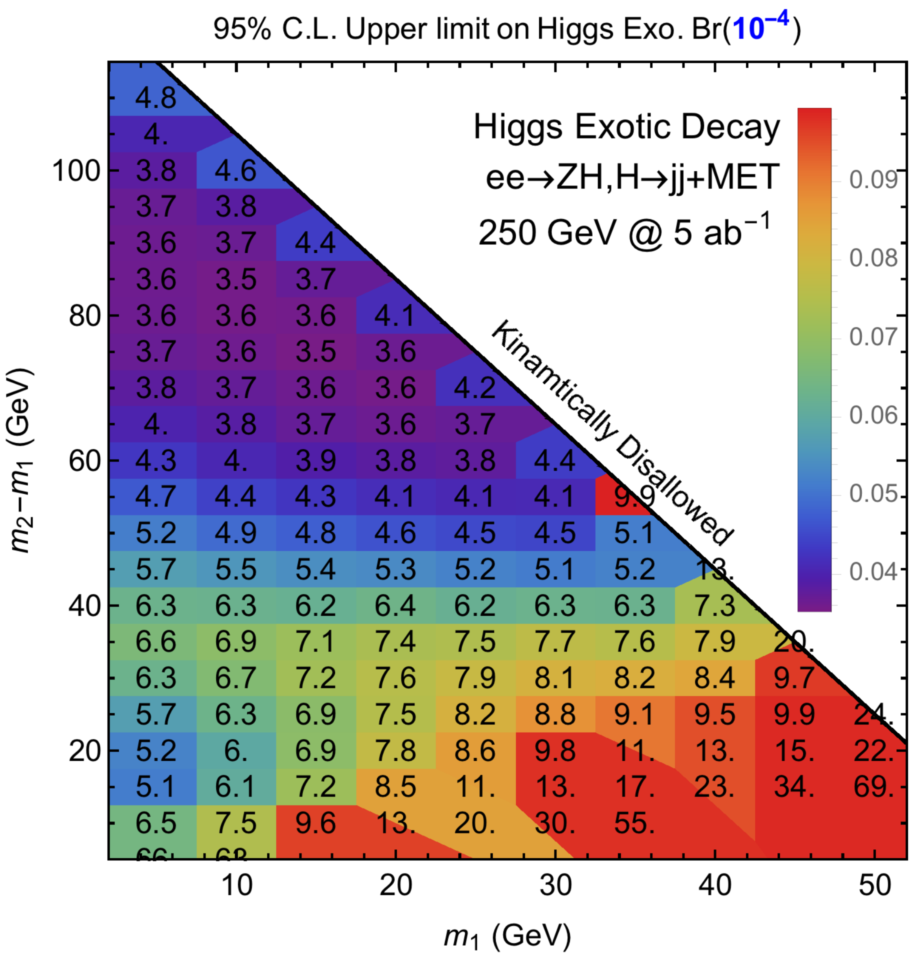


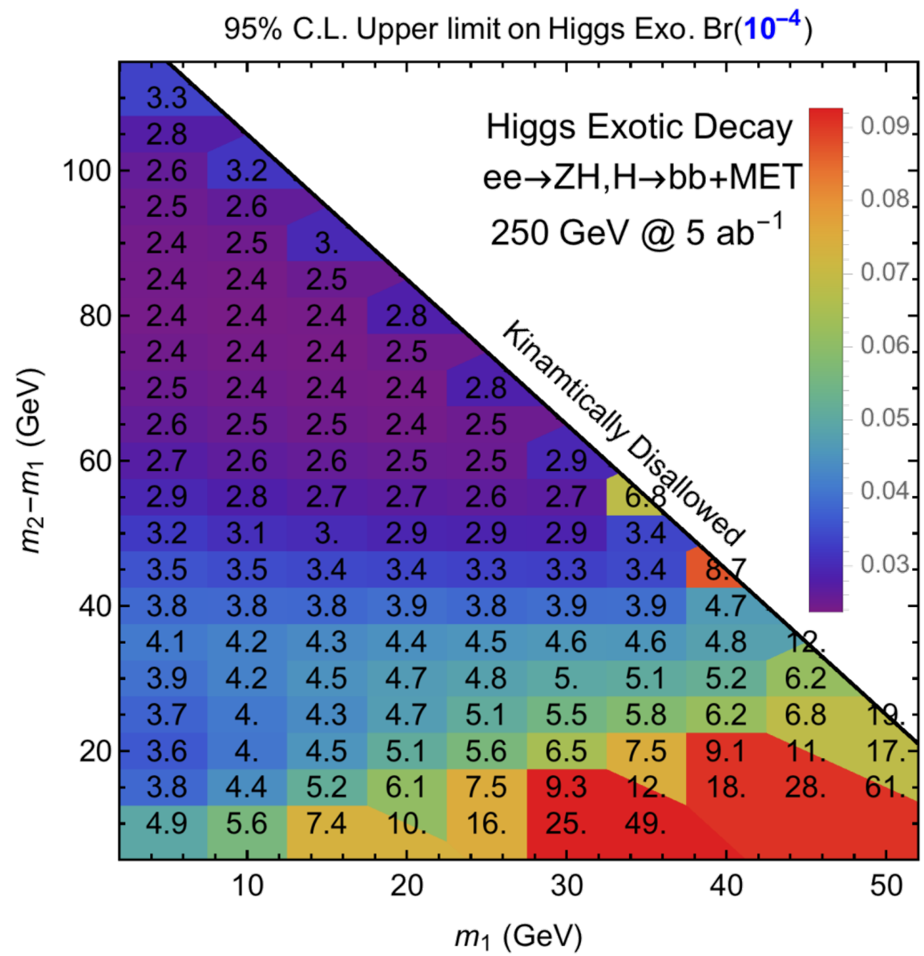
Depending on the masses of the decaying particles, the exclusion reach on Higgs exotic BRs could be as low as 4×10^{-4} and remains at this order for large range, except kinematic edges.

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

Exotic Decays—Example I:

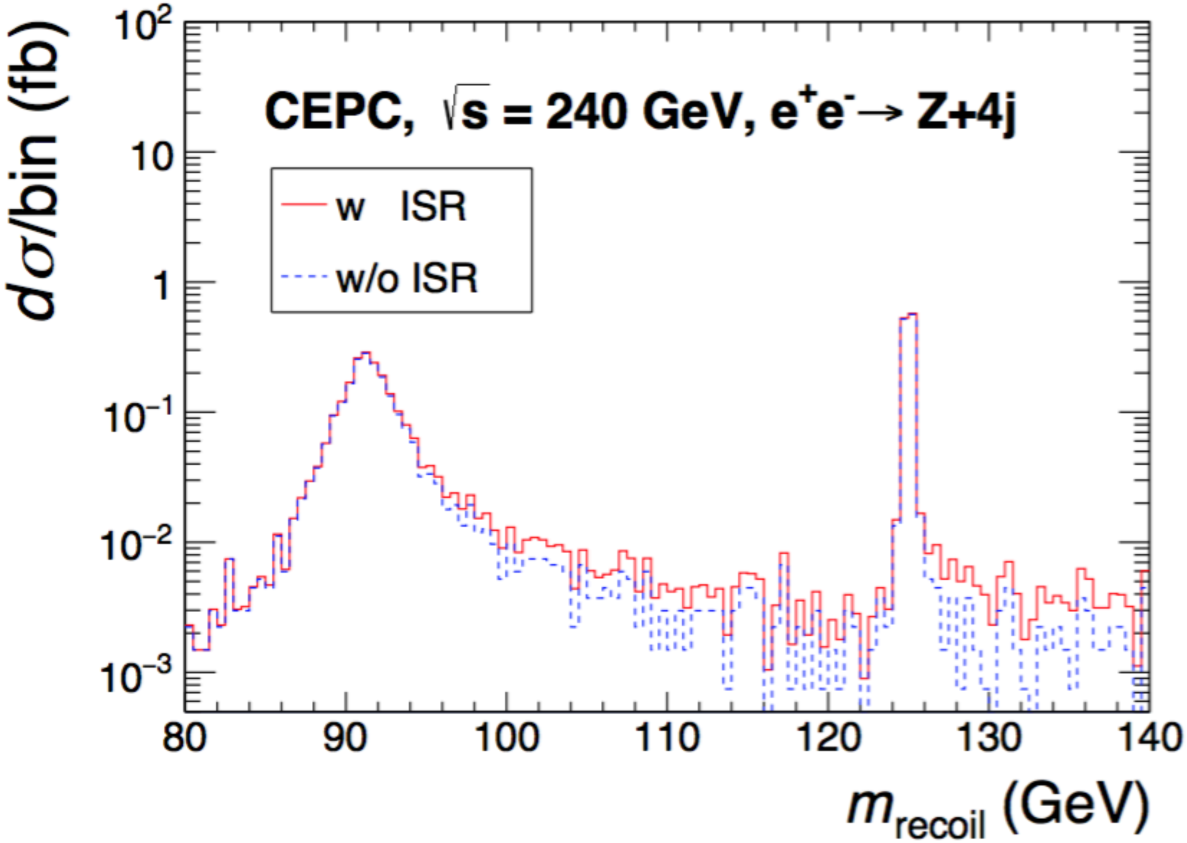
$$H \to x_1, x_2 \to j\,j + MET$$



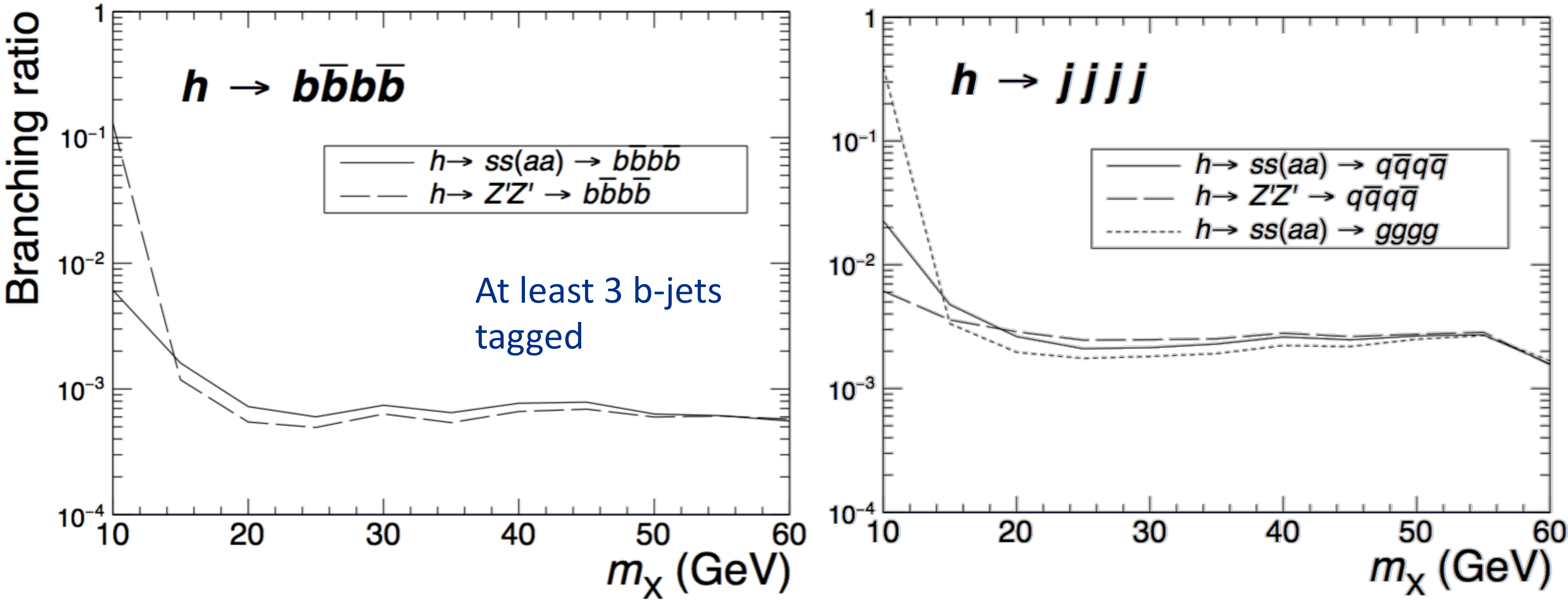


Limits increase by a factor of two or so with heavy flavor tagging.
(in the backup) having resonance dijet increase the limit by factor of a few and more kinematic variations. (see e.g., Felix Yu's talk on this channel at the LHC.)

Exotic Decays—Example II: $H \to aa, VV \to (jj)(jj)$



Exotic Decays—Example II: $H \to aa, VV \to (jj)(jj)$



At least 3 b-jets tagged

O(10^-3) limits on the Higgs Br.!

Outlook

Higgs boson physics is essential for future programs. Now we should study the physics case of future lepton colliders

Instead of showing many results of pheno studies, in this talk I sketch the picture of Higgs exotic decay at future lepton collider and provide a few examples.

Higgs precision (will be covered by several talks at the Higgs couplings conference) and also extensions on using angular observables (e.g., N. Craig, J. Gu, **ZL**, and K. Wang, 15')

More efforts needed

Kinematic corners for exotic decays (detector performance related)

Displaced decays (detector performance related, also needs some organizing principles)

Exclusive flavor changing decays and very rare decays (especially light flavor jets, see many talks in the morning, Yotam Soreq, Emmanuel Stamou, Stefan Alte, Wolfgang Altmannshofer, Hou Keong Lou)

Outlook

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Kinematic corners for exotic decays (detector performance related)

Displaced decays (detector performance related, also needs some organizing principles! Potentially 10^-6 limits on Br.)

Exclusive flavor changing decays and very rare decays (especially light flavor jets, see many talks in the morning, Yotam Soreq, Emmanuel Stamou, Stefan Alte, Wolfgang Altmannshofer, Hou Keong Lou)

For charm-Yukawa, pp could do J\$\psi + \gamma$ while ee could do good charm tagging (talk this morning)

For EBPT, pp and high energy ee could do double Higgs production, ee could do precision measurement of the loop-corrections in ZH production rate and Higgs exotic decays into light scalar pairs

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

Similar to some LEP analysis

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

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

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

- 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: $E_{vis} > 225\mathrm{GeV}.$

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 !

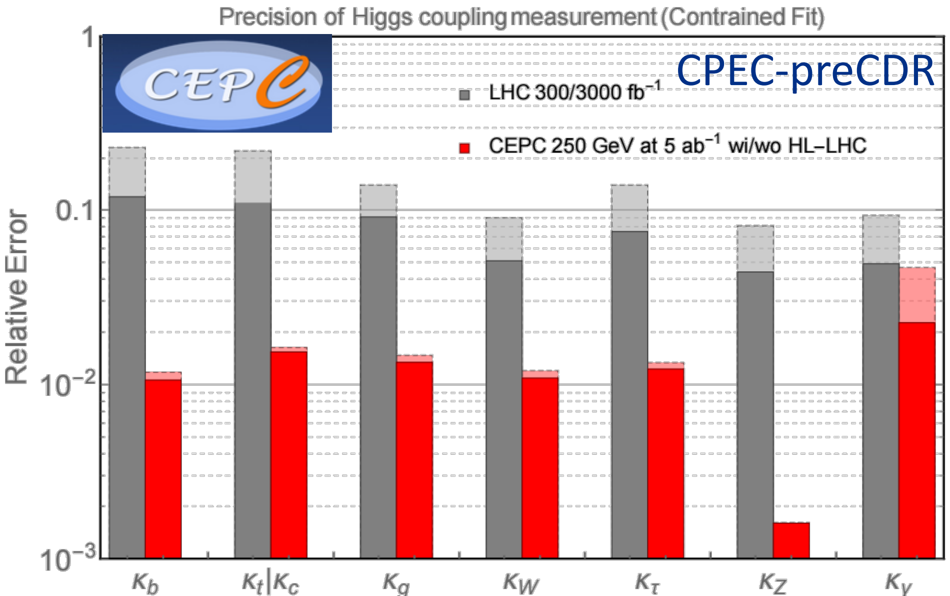
Exotic Production

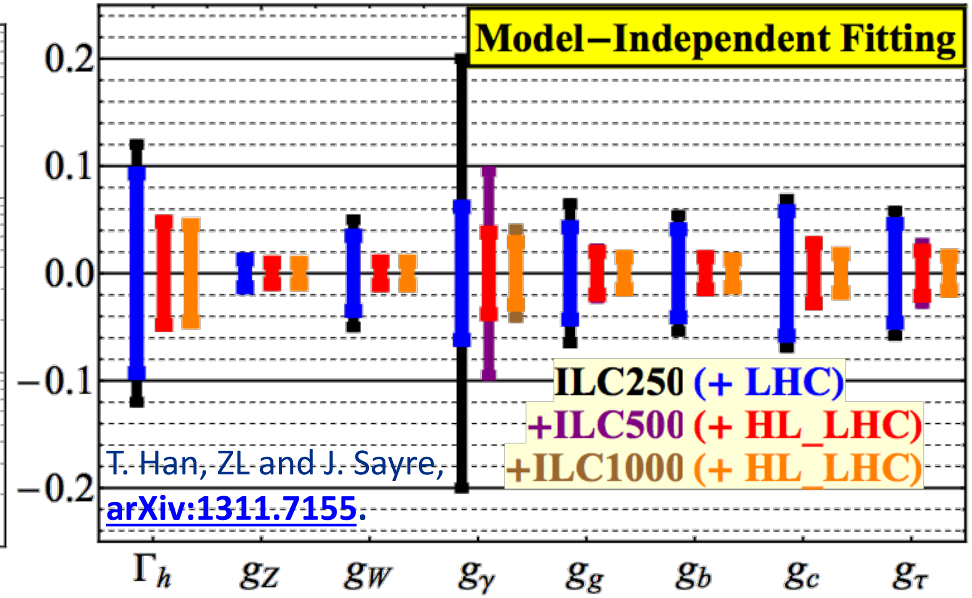
Higgs can act as taggers for new physics through exotic production mechanism, e.g.,

- 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
- …

Precision—couplings

The Higgs physics potential is an essential physics piece for any proposal for future colliders, e.g.





Future e+e- machines
allow “Model-Independent” extraction of the SM Higgs couplings;
improve the precision roughly by one-order of magnitude;

Future pp machines (including HL-LHC)
are good at measuring Higgs (EW) rare decays, H to ZZ →4l, Zγ, $\mu\mu$, $\gamma\gamma$, etc.
improve the lepton colliders precision on these rare modes when combined
can measure the top Yukawa from the tth associated production.

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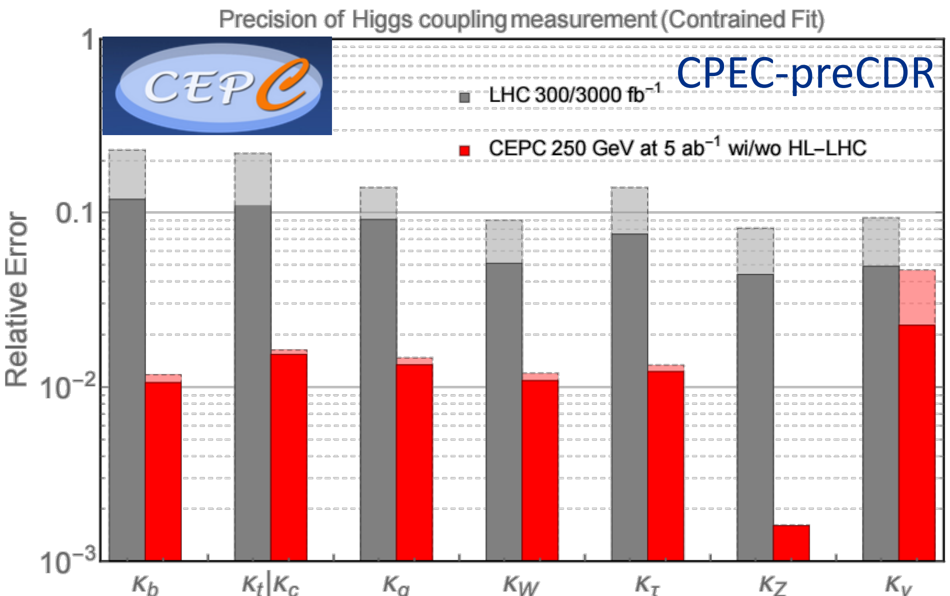

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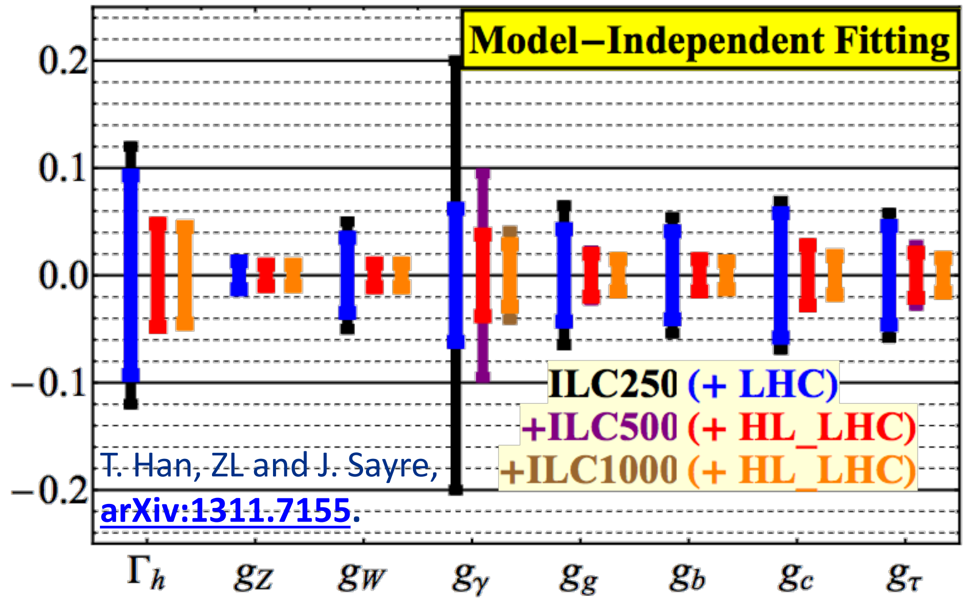

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Fermilab

Emerging colliders

Proposals and studies are under fast development, under various timelines, CERN (HL-LHC, FCC, CLIC), Japan (ILC), China (CEPC/SPPC)

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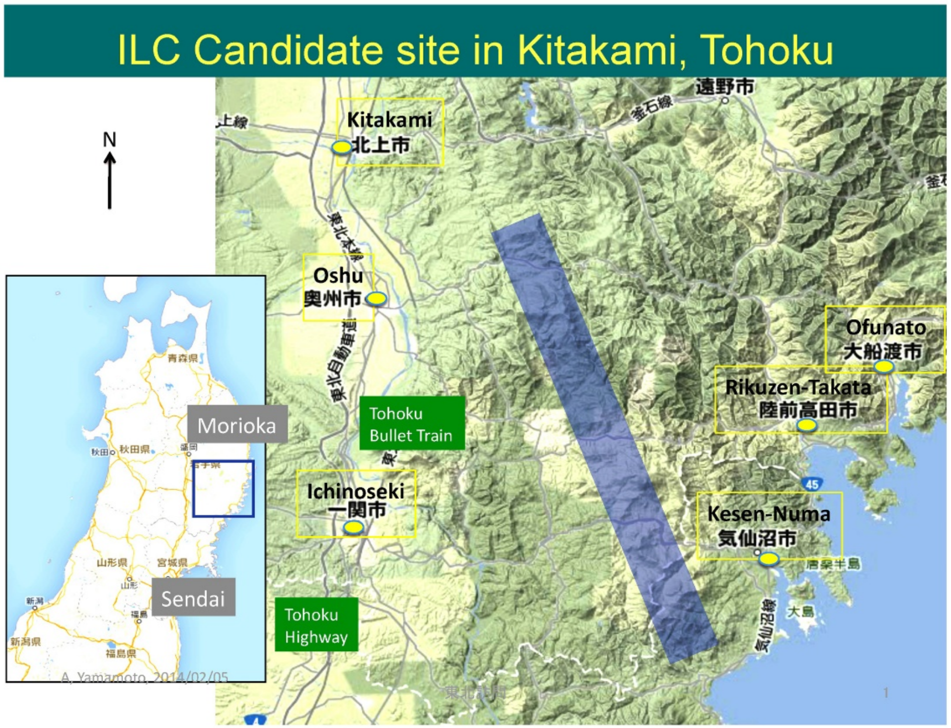
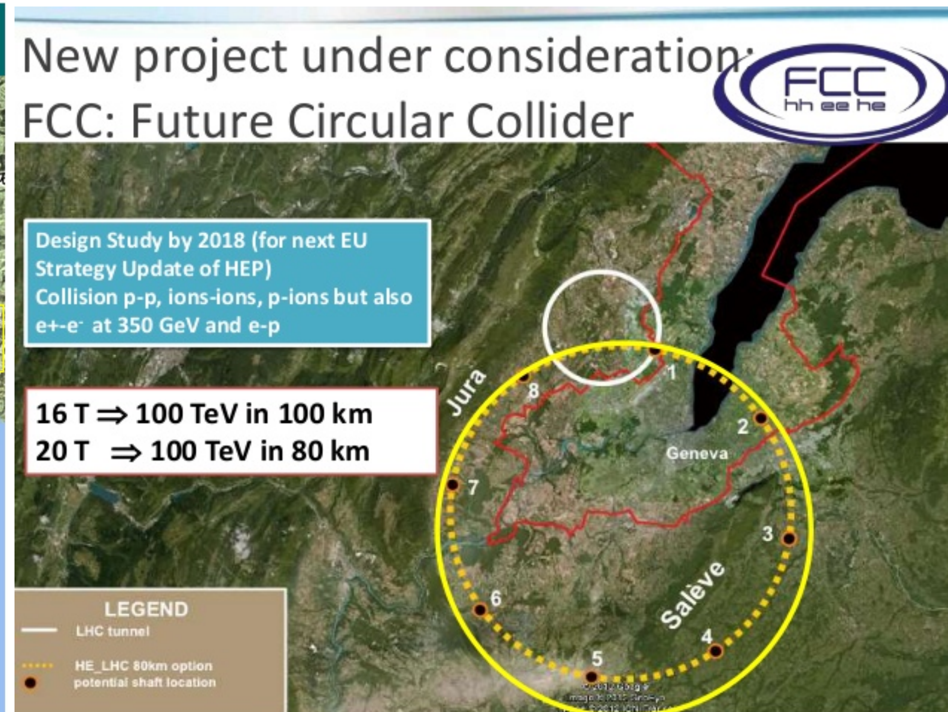




Emerging colliders

Proposals and studies are under fast development, under various timelines, CERN (HL-LHC, FCC, CLIC), Japan (ILC), China (CEPC/SPPC)

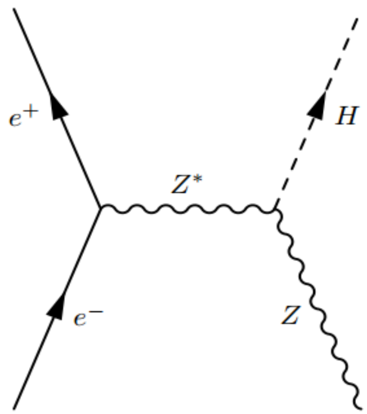
- Higgs physics could directly probe new physics
- New physics can easily couples to Higgs, linking to hierarchy problem, electroweak baryogenesis, naturalness, dark matter, etc.
- Next generation “Higgs factories” are to explore this opportunity.

Too ambitious to cover all the aspects
Instead, I will provide several representative examples for Higgs as a tool for discovery from three different perspectives:

Precision
Exotic Decay
Exotic Production

Precision—beyond

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



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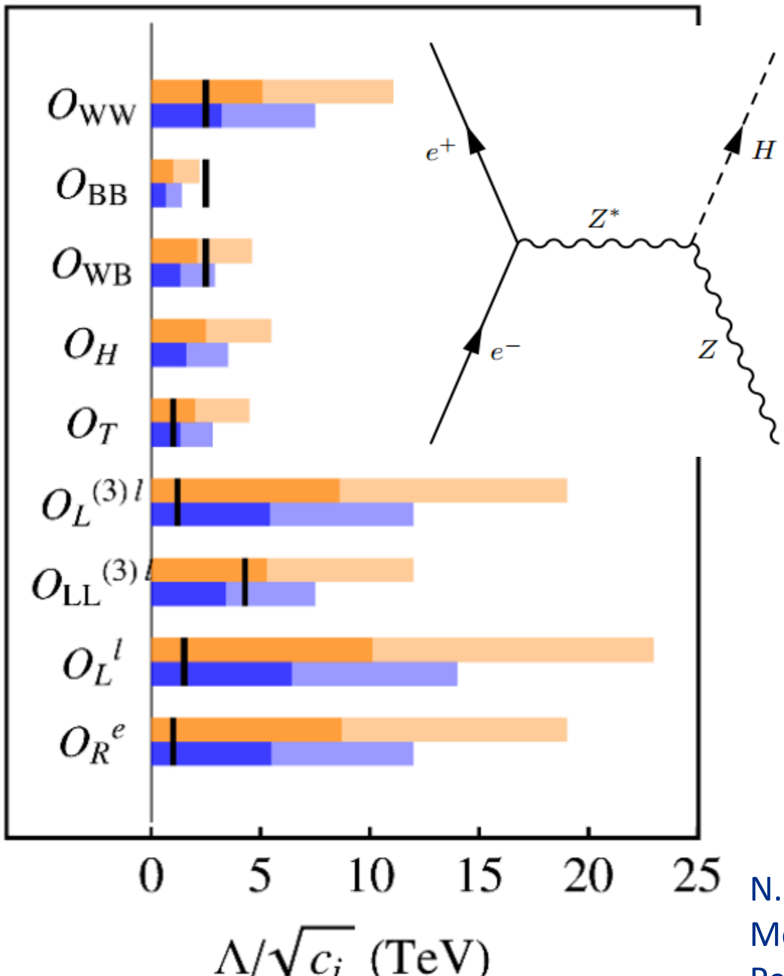

9 operators at dimension-six level contribute to this measurement, beyond our simple parametrization of rescaling HZZ coupling.

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

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

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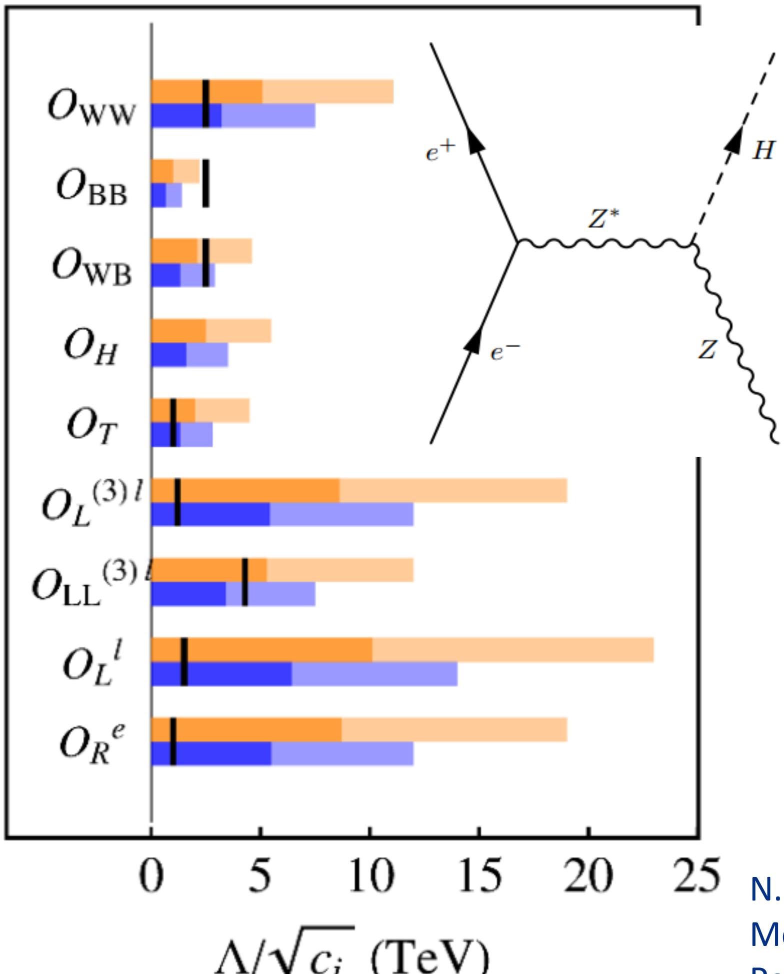

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e+e- machines and pp machines have different solutions

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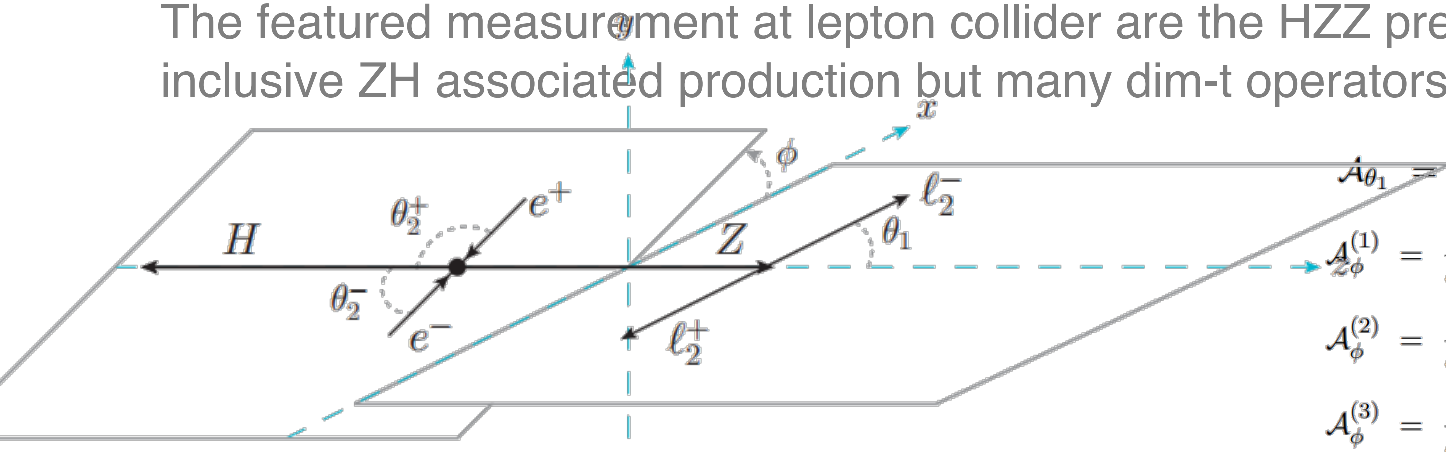
N. Craig, M. Farina, M. McCullough and M. Perelstein arXiv:1411.0676

Precision—beyond (e+e-)

The featured measurement at lepton collider are the HZZ precision from the inclusive ZH associated production but many dim-t operators contribute.



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

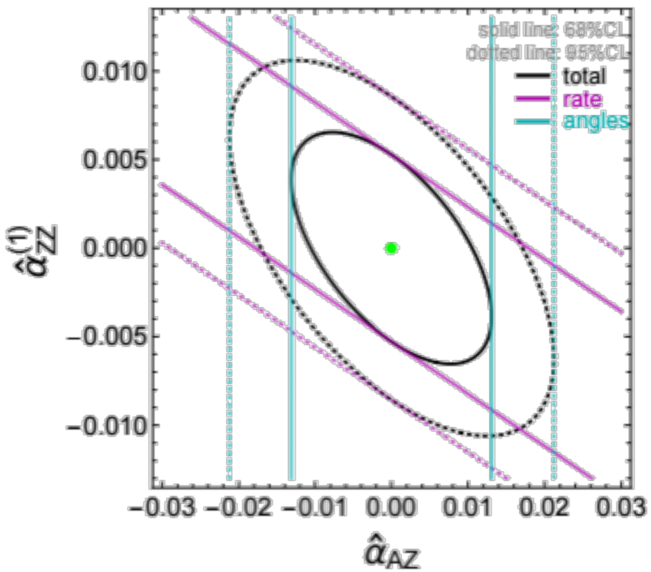
$$\mathcal{A}_{\phi}^{(1)} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\sin\phi)\,\frac{d^2\Gamma}{dq^2 d\phi} =$$

$$\mathcal{A}_{\phi}^{(2)} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\sin(2\phi))\,\frac{d^2\Gamma}{dq^2 d\phi} =$$

$$\mathcal{A}_{\phi}^{(3)} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\cos\phi)\,\frac{d^2\Gamma}{dq^2 d\phi} =$$

$$\mathcal{A}_{\phi}^{(4)} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\cos(2\phi))\,\frac{d^2\Gamma}{dq^2 d\phi} =$$

$$\mathcal{A}_{c\theta_1,c\theta_2} = \frac{1}{d\Gamma/dq^2}\int_{-1}^{1} d\cos\theta_1\ \mathrm{sgn}(\cos\theta$$



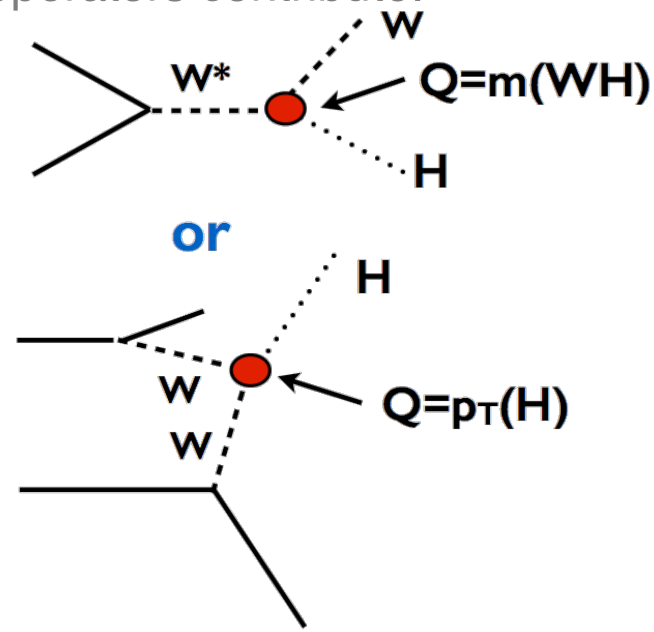
Angular asymmetries for the same process probes the physics of underlying operators with different Lorentz structure.

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

Precision—beyond (pp)

The featured measurement at lepton collider are the HZZ precision from the inclusive ZH associated production but many dim-t operators contribute.

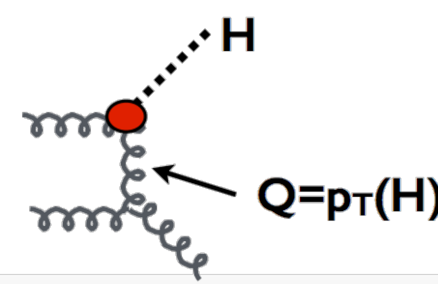
$\delta BR(H \to WW^*)$



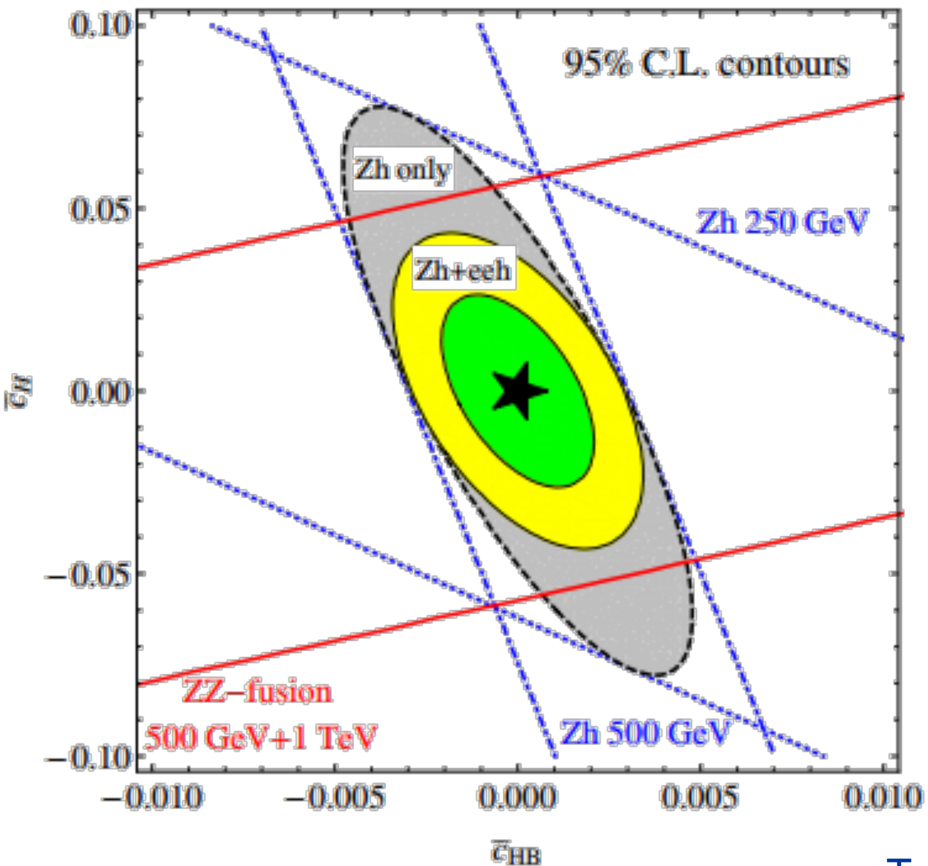
At pp machines, instead, we can go beyond the simple scaling of the couplings via the differential distribution of various Higgs production mechanism.

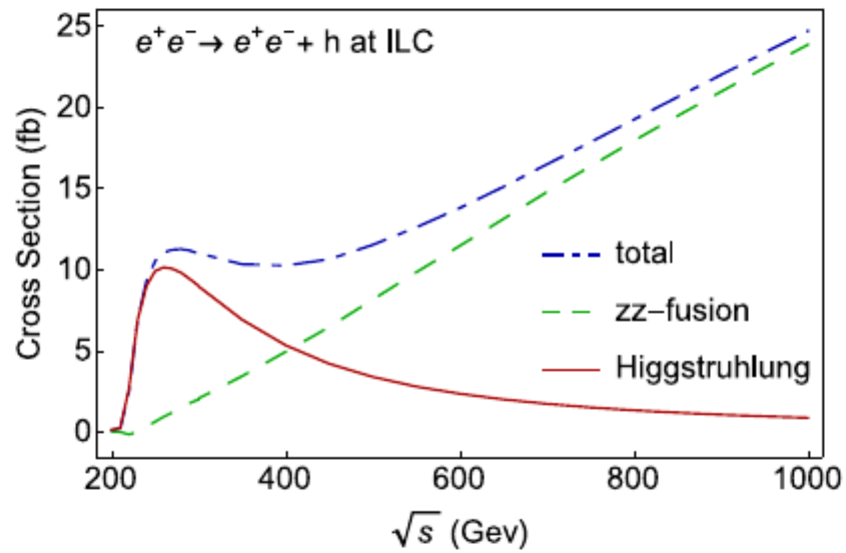
Picture from M. Mangano's 100 TeV talk at ICHEP 2016

$\delta BR(H \to gg)$



Precision—beyond (ee)





To gain more from going to higher energies, we propose to study the ZZ-fusion channel for inclusive measurement. ZZ-fusion break degeneracy and improve sensitivity.

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

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

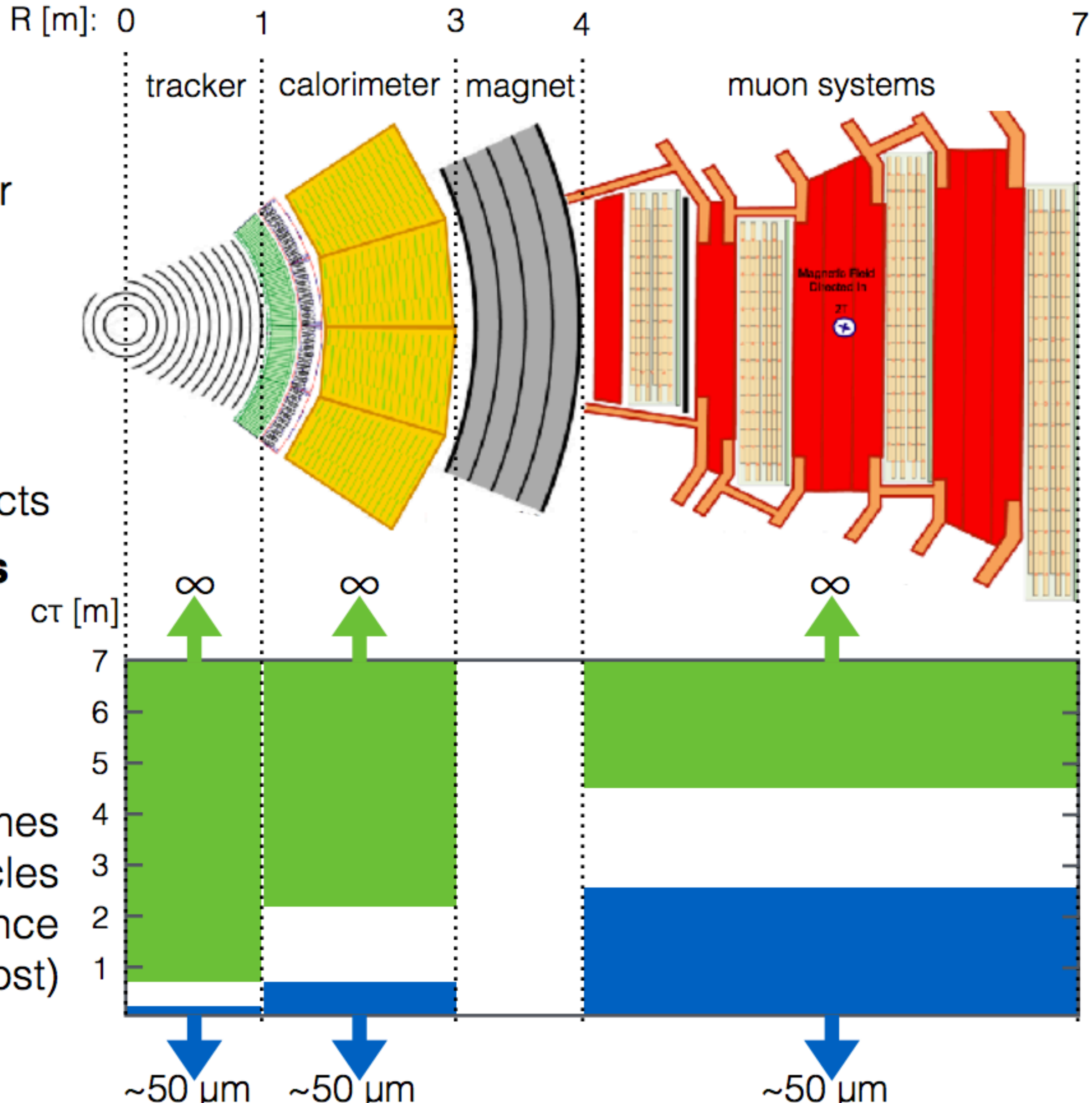
Search strategy driven by targeted lifetime

Direct searches

- observe BSM particle passing through detector
- better for **long lifetimes**
- good for **charged LLPs**

Indirect searches

- detect LLP decay products
- better for **short lifetimes**
- good for **neural LLPs**



Shaded area: range of lifetimes for which half of the particles are within the acceptance (ignoring boost)

We make three assumptions:

- observed 125 GeV state is primarily responsible for EWSB

usually requires “decoupling” limit
h production close to SM
other scenarios possible, but this is generic and minimal

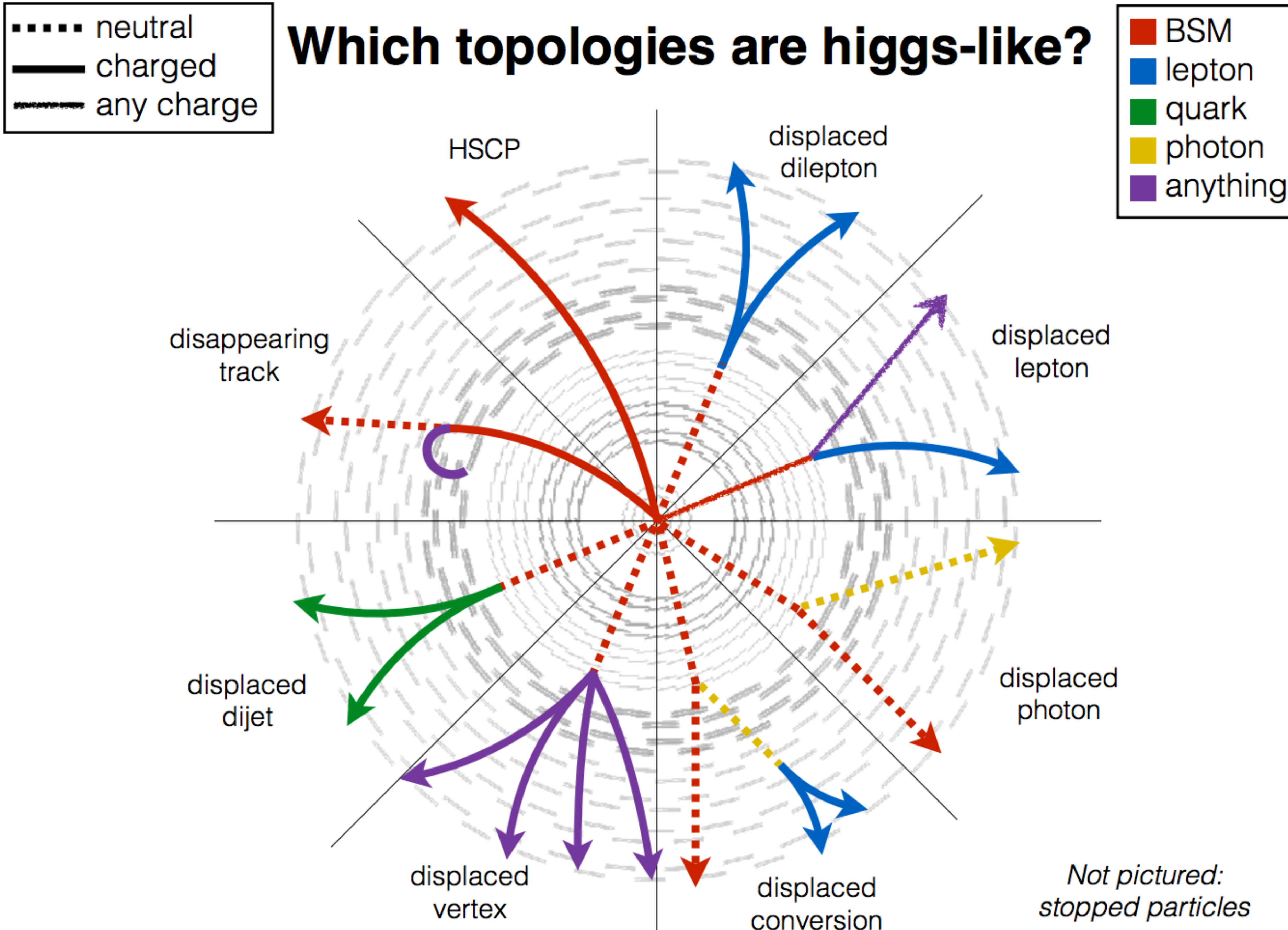
- 125 GeV state decays to new BSM particles

these BSM particles could primarily/only be produced through h decays do not consider rare or nonstandard decays directly to SM particles

- initial decay is 2-body

3-body and higher is possible, but requires new light states w/ substantial coupling to h to overcome phase space suppression

Which topologies are higgs-like?



Not pictured: stopped particles

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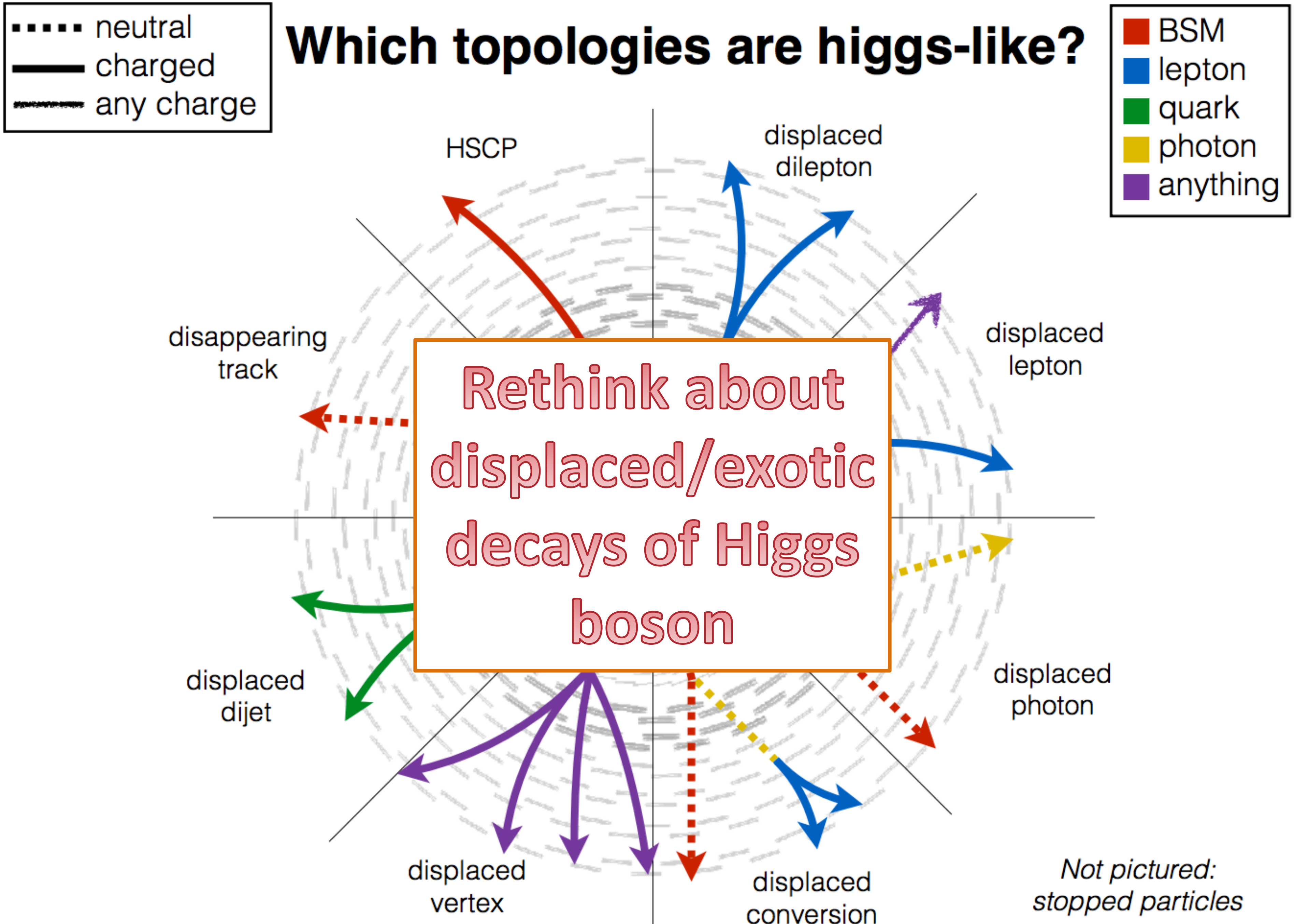

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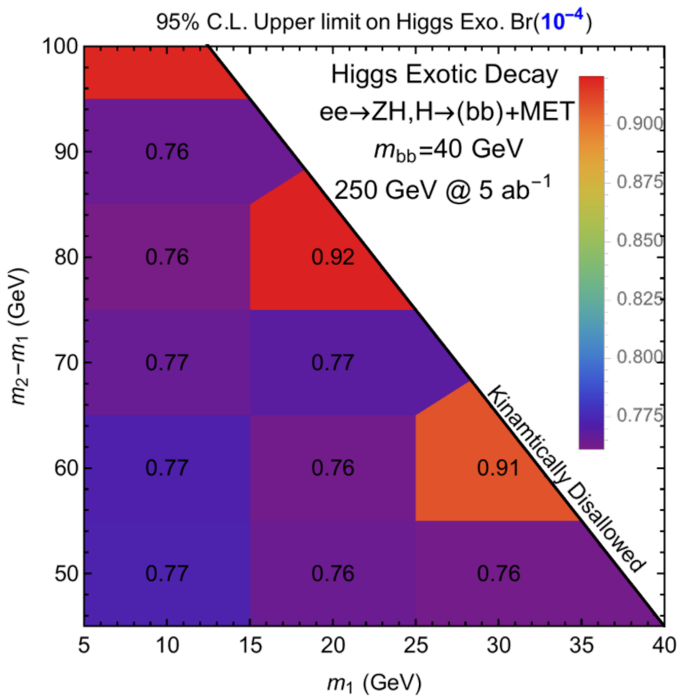
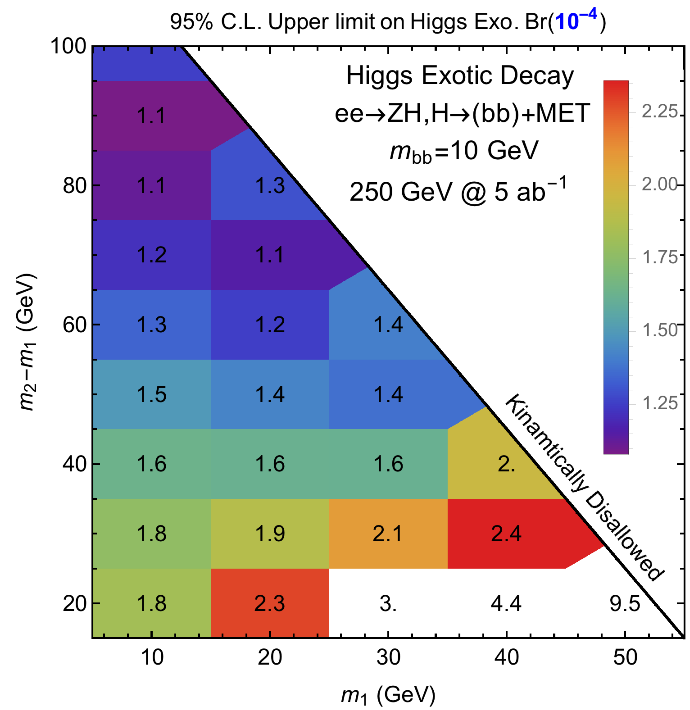
Rethink about displaced/exotic decays of Higgs boson


95% C.L. Upper limit on Higgs Exo. Br(10^{-4})
Higgs Exotic Decay
ee→ZH,H→(bb)+MET
m_{bb}=40 GeV
250 GeV @ 5 ab^{-1}
Kinamtically Disallowed
0.76
0.76
0.92
0.77
0.77
0.77
0.76
0.91
0.77
0.76
0.76
$m_2 - m_1$ (GeV)
m_1 (GeV)


95% C.L. Upper limit on Higgs Exo. Br(10^{-4})
Higgs Exotic Decay
ee→ZH,H→(bb)+MET
m_{bb}=10 GeV
250 GeV @ 5 ab^{-1}
Kinamtically Disallowed
1.1
1.1
1.3
1.2
1.1
1.3
1.2
1.4
1.5
1.4
1.4
1.6
1.6
1.6
2.
1.8
1.9
2.1
2.4
1.8
2.3
3.
4.4
9.5
$m_2 - m_1$ (GeV)
m_1 (GeV)

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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]

- 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

pp machines great at EW final states, as they produce huge amount of Higgs bosons

lepton machines great at (semi-)hadronic final stages, as they benefits from low background

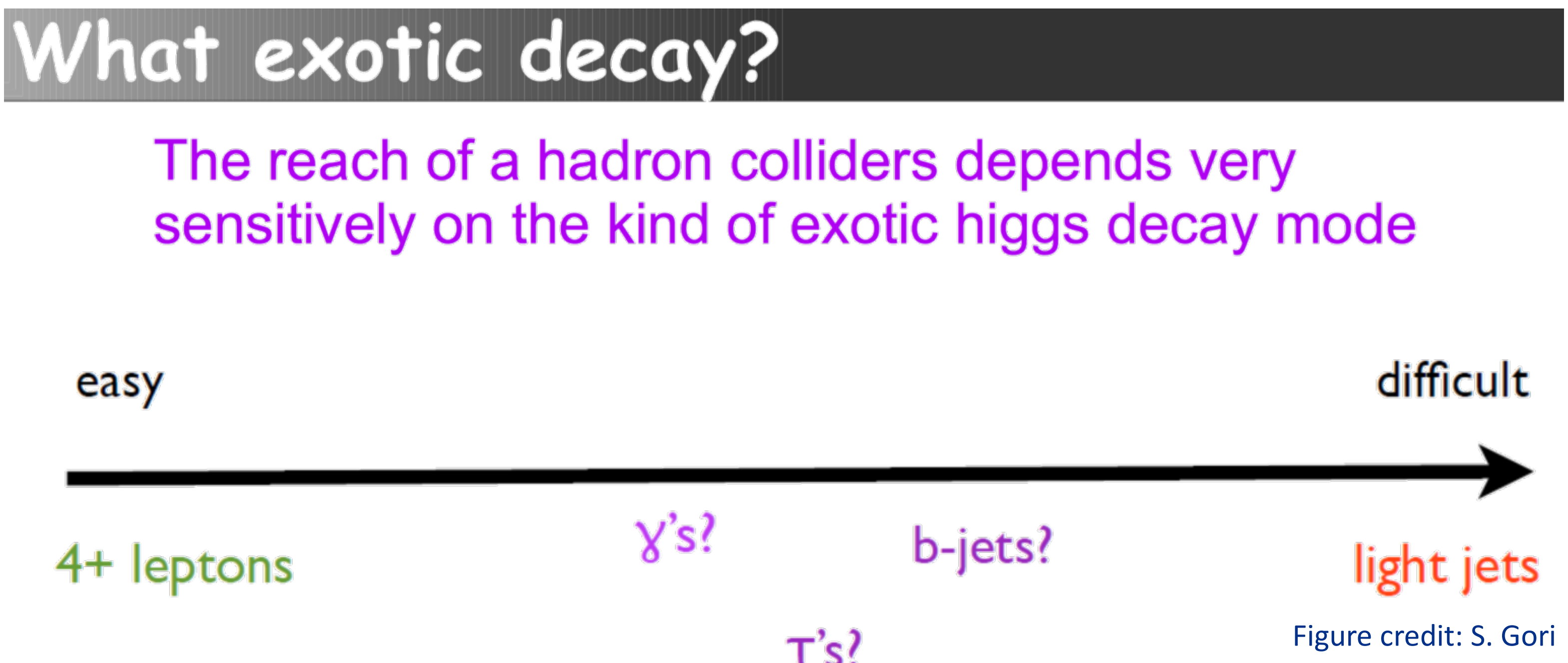

Figure credit: S. Gori

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