Exotic Higgs Decays at HE/HL-LHC

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HE/HL-LHC workshop @FNAL

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Outline

- (mini-)Motivation
- Overall picture
- A few notable benchmarks
  - Prompt decays
  - Long-lived decays
- Complementarity (a case study)

Why 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.

(theoretical interests)

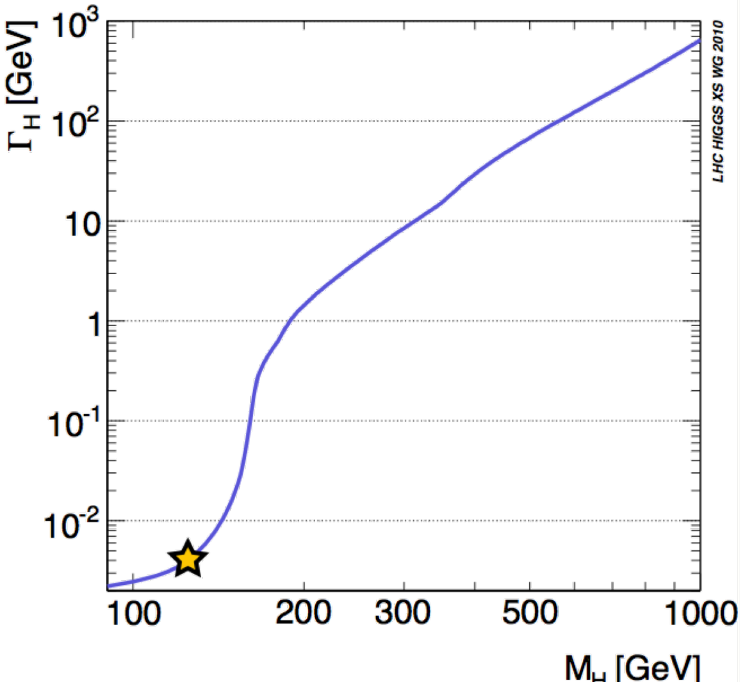
- The precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. **

(complementarity)

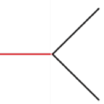
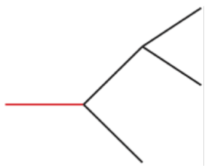
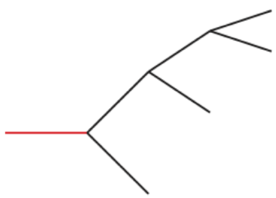
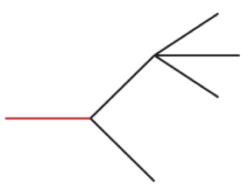
- Higgs has tiny width ~4 MeV

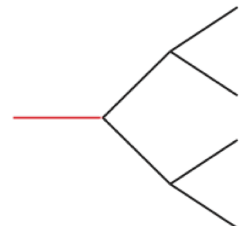
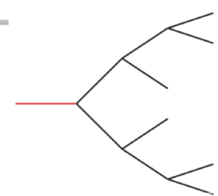
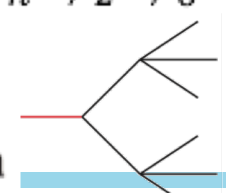
$$\frac{\Gamma}{M} = O(10^{-5})$$

all its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.
Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$



Organizing the study: A List

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

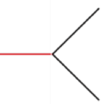
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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

Exotic decays of the 125 GeV Higgs boson

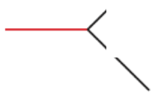
David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

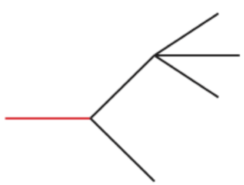
Coverage & Potential

- ~0.2 Billion Higgs produced at HL-LHC;
- ~2 Billion Higgs produced at HE-LHC;
- 3 orders of magnitude more than future Higgs factories;
- Unique Higgs properties can be learned and great discovery potential for certain channels;



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



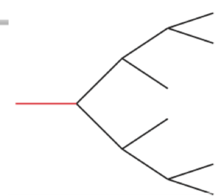


HL-LHC great Sensitivity

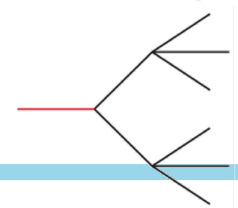
$O(< 10^{-5})$

HE-LHC great Sensitivity

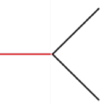
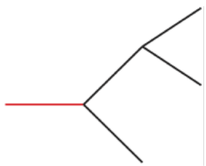
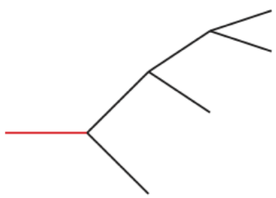
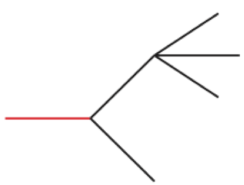
$O(< 10^{-6})$

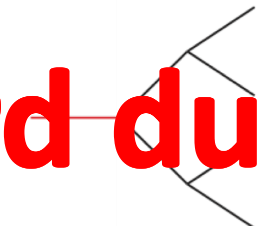
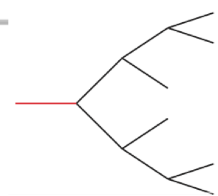
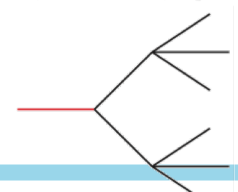


	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) +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



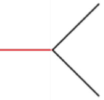
Coverage & Potential

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

Coverage & Potential



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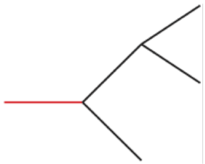
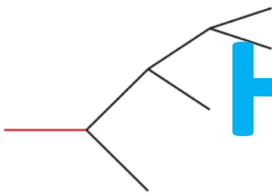
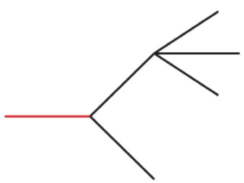
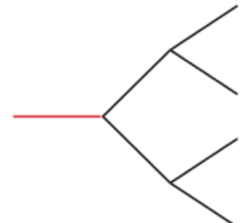
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma)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

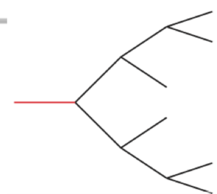


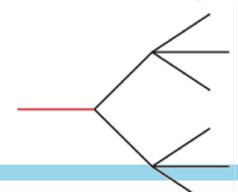




Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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

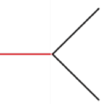
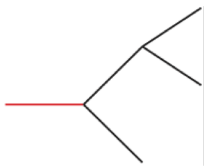
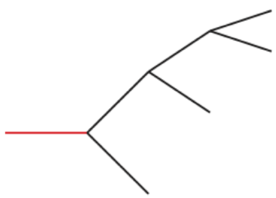






Hard due to Hadronic

Coverage & Potential

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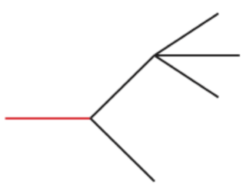
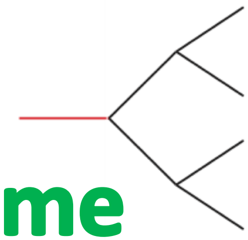
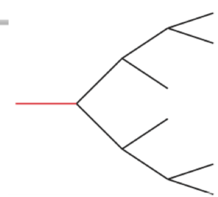
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

Some Challenges taken already

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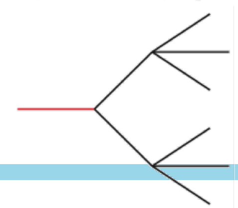
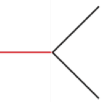
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

Coverage & Potential



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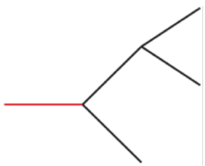
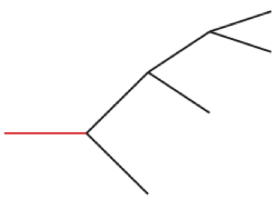
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
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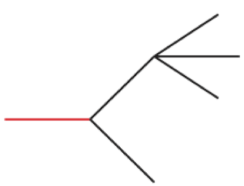
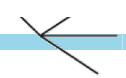
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

Still a lot of uncharted territory for new searches!

Can be conquered using HL-LHC and HE-LHC with advanced <u>analysis tools</u> and <u>new detectors</u>.

For existing searches, there are new possibilities such as unequal masses, etc.

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



From Exotic Higgs group report
talk by Cécile Caillol, Mar. 2018

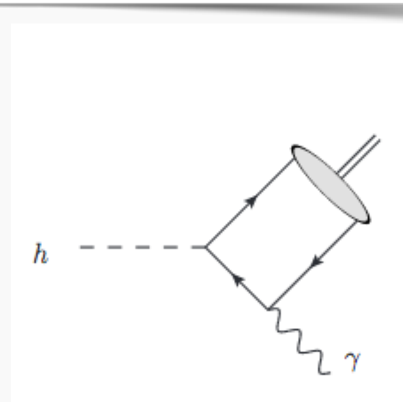
Higgs to mesons

- Rare decays of the Higgs boson to a meson and a photon give a direct window to the Yukawa couplings.

Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^+ W^-$	$4.30 \pm 0.01_f \pm 0.00_{\rm CKM} \pm 0.17_{\Gamma_h}$	130.4 ± 0.2
$h \to \rho^+ W^-$	$10.92 \pm 0.15_f \pm 0.00_{\rm CKM} \pm 0.43_{\Gamma_h}$	207.8 ± 1.4
$h \to K^+ W^-$	$0.33 \pm 0.00_f \pm 0.00_{\rm CKM} \pm 0.01_{\Gamma_h}$	156.2 ± 0.7
$h \to K^{*+} W^-$	$0.56 \pm 0.03_f \pm 0.00_{\rm CKM} \pm 0.02_{\Gamma_h}$	203.2 ± 5.9
$h \to D^+ W^-$	$0.56 \pm 0.03_f \pm 0.04_{\rm CKM} \pm 0.02_{\Gamma_h}$	204.6 ± 5.0
$h \to D^{*+} W^-$	$1.04 \pm 0.12_f \pm 0.07_{\rm CKM} \pm 0.04_{\Gamma_h}$	278 ± 16
$h \to D_s^+ W^-$	$17.12 \pm 0.61_f \pm 0.56_{\rm CKM} \pm 0.67_{\Gamma_h}$	257.5 ± 4.6
$h \to D_s^{*+} W^-$	$25.10 \pm 1.45_f \pm 0.81_{\rm CKM} \pm 0.98_{\Gamma_h}$	311 ± 9
$h \to B^+ W$		
$h \to B^{*+} W$		
$h \to B_c^+ W$		

Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^0 Z$	$2.30 \pm 0.01_f \pm 0.09_{\Gamma_h}$	130.4 ± 0.2
$h \to \eta Z$	$0.83 \pm 0.08_f \pm 0.03_{\Gamma_h}$	$f_\eta^s = -110.7 \pm 5.5$
$h \to \eta' Z$	$1.24 \pm 0.12_f \pm 0.05_{\Gamma_h}$	$f_{\eta'}^s = 135.2 \pm 6.4$
$h \to \rho^0 Z$	$7.19 \pm 0.09_f \pm 0.28_{\Gamma_h}$	216.3 ± 1.3
$h \to \omega Z$	$0.56 \pm 0.01_f \pm 0.02_{\Gamma_h}$	$f_\omega = 194.2 \pm 2.1, \quad f_\omega^s = -13.8 \pm 4.8$
$h \to \phi Z$	$2.42 \pm 0.05_f \pm 0.09_{\Gamma_h}$	$f_\phi = 223.0 \pm 1.4, \quad f_\phi^s = 230.4 \pm 2.6$
$h \to J/\psi\, Z$	$2.30 \pm 0.06_f \pm 0.09_{\Gamma_h}$	403.3 ± 5.1
		684.4 ± 4.6
		475.8 ± 4.3
		411.3 ± 3.7

Mode / Method	NRQCD [1486]	LCDA LO [1485]	LCDA NLO [1488]
	Branching Fraction $[10^{-6}]$		
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$



Higgs to mesons

- Results from 1607.03400, 1507.03031, 1501.03276, 1712.02758, 1507.03031
- Most results from 8 TeV puts an upper bound of ~1.5×10^{-3}
- 13 TeV 36 fb^{-1} start to lead us to realm of 10^{-4}
- HL-LHC will lead us to the realm of ~10^{-5} **
- HE-LHC will lead us to the realm of **~10^{-6}** **
- We will be able to measure these these rare decays of the Higgs boson, providing very nontrivial test of the Higgs boson properties, QCD and interference
- Many new modes to measure H->mesons+W, mesons+Z, etc. (Study and recommendation ongoing)

$h \to D_s^{+} W$	$25.10 \pm 1.45_f \pm 0.81_{\rm CKM} \pm 0.98_{\Gamma_h}$	311 ± 9
$h \to B^+ W$		684.4 ± 4.6
$h \to B^{*+} W$		475.8 ± 4.3
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$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

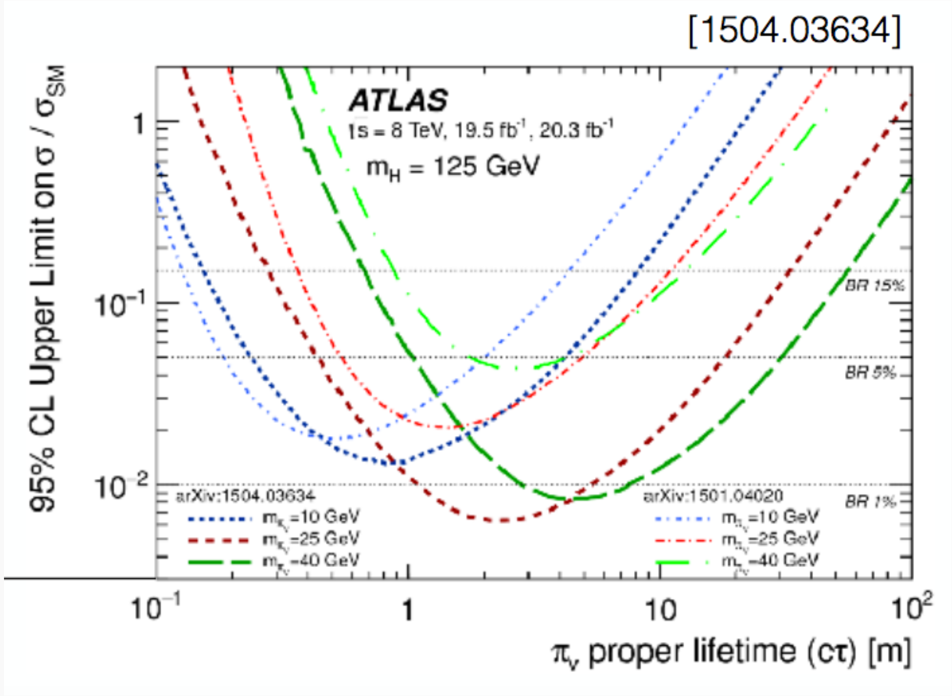
Current limits
<8.8×10^{-4}
<?
<4.8×10^{-4}
<1.5×10^{-3}
<1.3×10^{-3}
<1.9×10^{-3}
<1.3×10^{-3}

**extrapolation on statistical

Higgs to long-lived at ATLAS

- Many public results from Run 1 and 2 involving LLPs coming from the Higgs boson, specially exotic signatures looking for:
  - Displaced jets (arXiV:1504.03634, 1501.04020)
  - Displaced lepton-jets (ATLAS-CONF-2016-043)

- New ideas and possible analysis re-interpretations currently being considered.



Complementarity (a case study)*

Trilogy of Z-pole, Higgs, and high energy

Taking the operators for example:

- Putting both Higgs on VEV, they modify the Zqq gauge vertex
- Putting on Higgs on VEV, they modify the ZqqH vertex
- Similar modifications to the Wud and WudH vertex for the triplet operator
- Also allowed for flavor structure

$$\mathcal{O}_{Hq}^{(1)} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L\gamma^\mu q_L),$$
$$\mathcal{O}_{Hq}^{(3)} = \frac{i}{\Lambda^2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{q}_L\gamma^\mu \sigma^a q_L),$$
$$\mathcal{O}_{Hu} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R),$$
$$\mathcal{O}_{Hd} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R),$$

→

$$Z_\mu \bar{u}_R\gamma^\mu u_R : \ -g_Z\frac{v^2}{2\Lambda^2}C_{Hu}^{(1)}$$
$$Z_\mu \bar{u}_L\gamma^\mu u_L : \ -g_Z\frac{v^2}{2\Lambda^2}(C_{Hq}^{(1)} - C_{Hq}^{(3)})$$
$$Z_\mu \bar{d}_R\gamma^\mu d_R : \ -g_Z\frac{v^2}{2\Lambda^2}C_{Hd}^{(1)}$$
$$Z_\mu \bar{d}_L\gamma^\mu d_L : \ -g_Z\frac{v^2}{2\Lambda^2}(C_{Hq}^{(1)} + C_{Hq}^{(3)})$$
$$W_\mu^+ \bar{u}_L\gamma^\mu d_L : \ g_2\frac{v^2}{\sqrt{2}\Lambda^2}C_{Hq}^{(3)},$$

*preliminary results

Z-pole

- We measured the Z total width to sub per mille precision.
- However, our knowledge of the Zqq vertex are only at a few percent level

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$e^+ e^-$		(3.363 ±0.004) %	
Γ_2	$\mu^+ \mu^-$		(3.366 ±0.007) %	
Γ_3	$\tau^+ \tau^-$		(3.370 ±0.008) %	
Γ_4	$\ell^+ \ell^-$	[a]	(3.3658±0.0023) %	
Γ_5	$\ell^+ \ell^- \ell^+ \ell^-$	[b]	(3.5 ±0.4) $\times 10^{-6}$	S=1.7
Γ_6	invisible		(20.00 ±0.06) %	
Γ_7	hadrons		(69.91 ±0.06) %	
Γ_8	$(u\overline{u}+c\overline{c})/2$		(11.6 ±0.6) %	
Γ_9	$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ±0.4) %	
Γ_{10}	$c\overline{c}$		(12.03 ±0.21) %	
Γ_{11}	$b\overline{b}$		(15.12 ±0.05) %	
Γ_{12}	$b\overline{b}b\overline{b}$		(3.6 ±1.3) $\times 10^{-4}$	
Γ_{13}	ggg		< 1.1 %	CL=95%
Γ_{14}	$\pi^0\gamma$		< 2.01 $\times 10^{-5}$	CL=95%
Γ_{15}	$\eta\gamma$		< 5.1 $\times 10^{-5}$	CL=95%
Γ_{16}	$\omega\gamma$		< 6.5 $\times 10^{-4}$	CL=95%
Γ_{17}	$\eta'(958)\gamma$		< 4.2 $\times 10^{-5}$	CL=95%
Γ_{18}	$\phi\gamma$		< 8.3 $\times 10^{-6}$	CL=95%
Γ_{19}	$\gamma\gamma$		< 1.46 $\times 10^{-5}$	CL=95%

PDG

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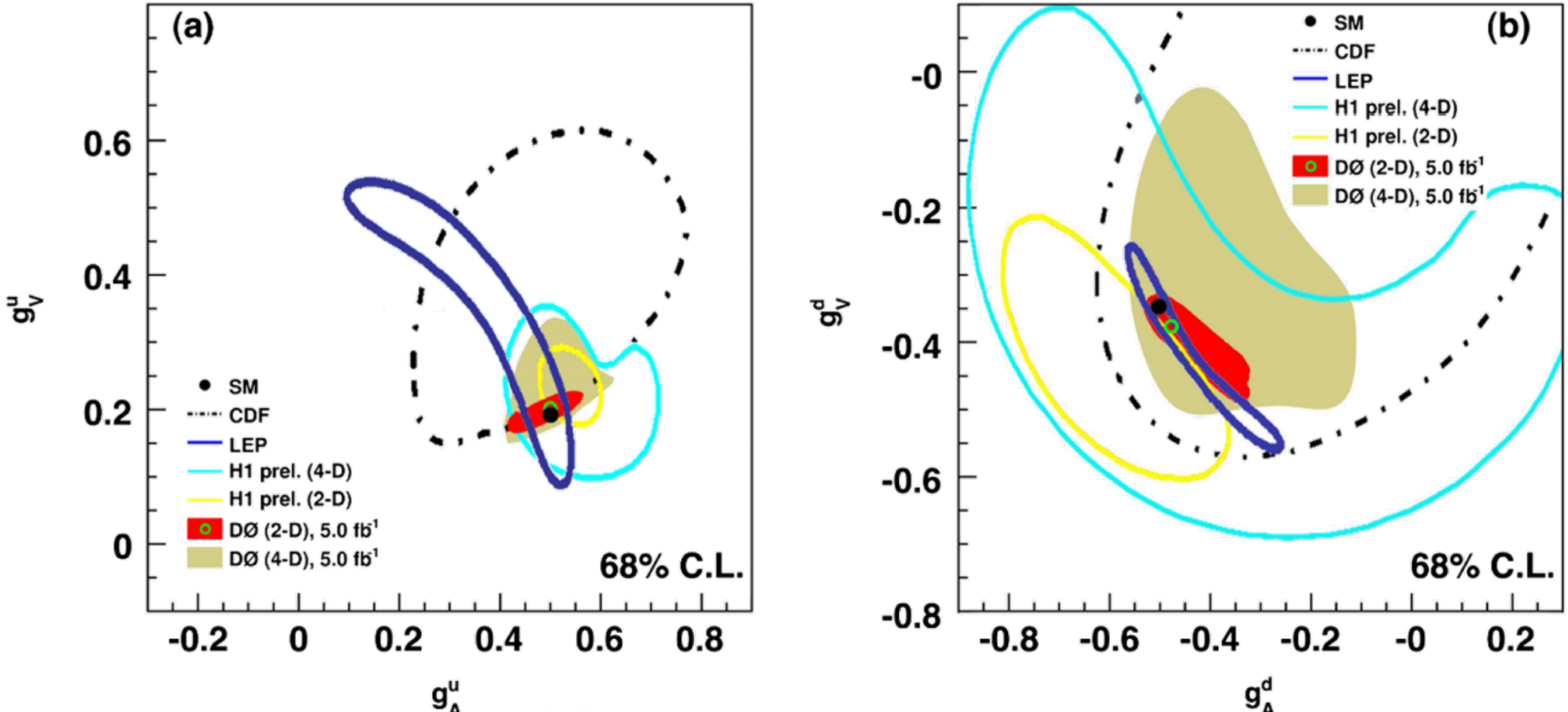
Z-pole



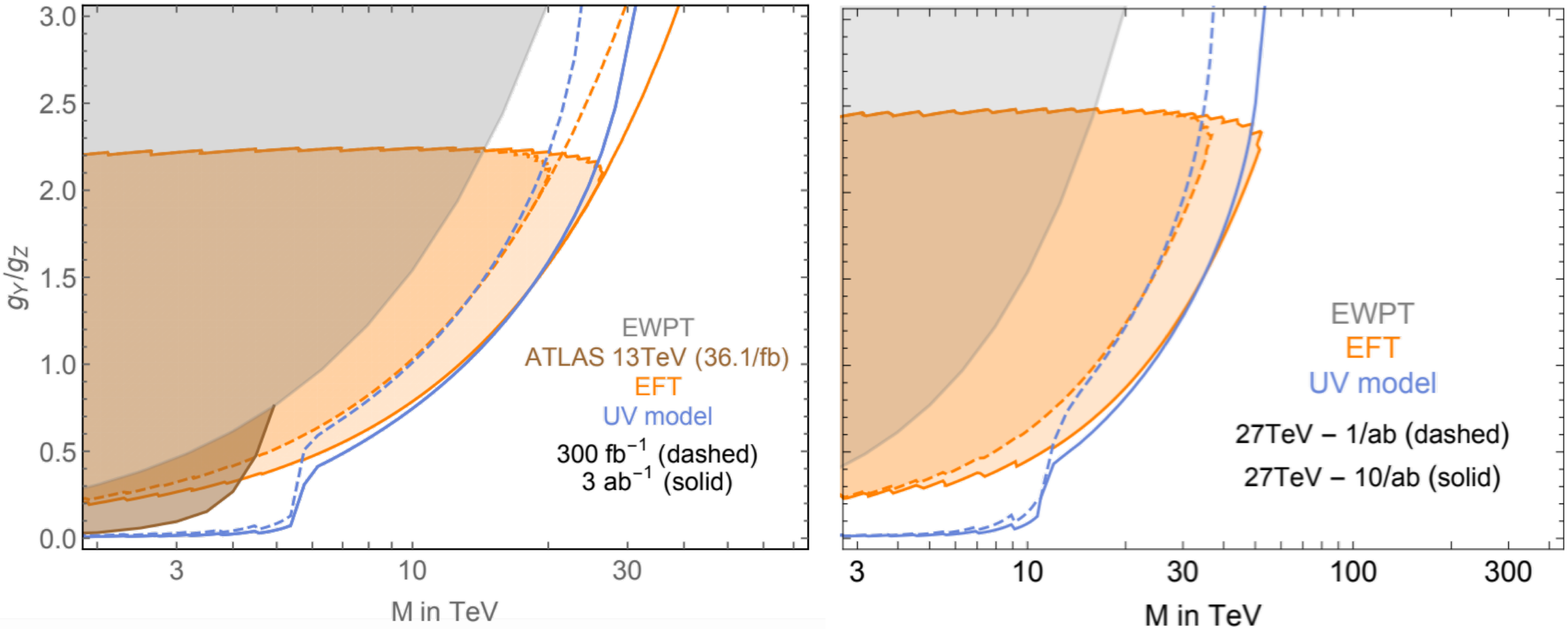
Measurement of $\sin^2\theta^{\ell}_{\rm eff}$ and Z-light quark couplings using the forward-backward charge asymmetry in $p\bar{p} \to Z/\gamma^* \to e^+e^-$ events with $\mathcal{L} = 5.0\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 1.96$ TeV

D0, **Phys.Rev. D84 (2011) 012007**

If we further ask the question of the chiral couplings, D0 from the forward-backward asymmetry analysis provides complementary/better constraints.

HE DY process

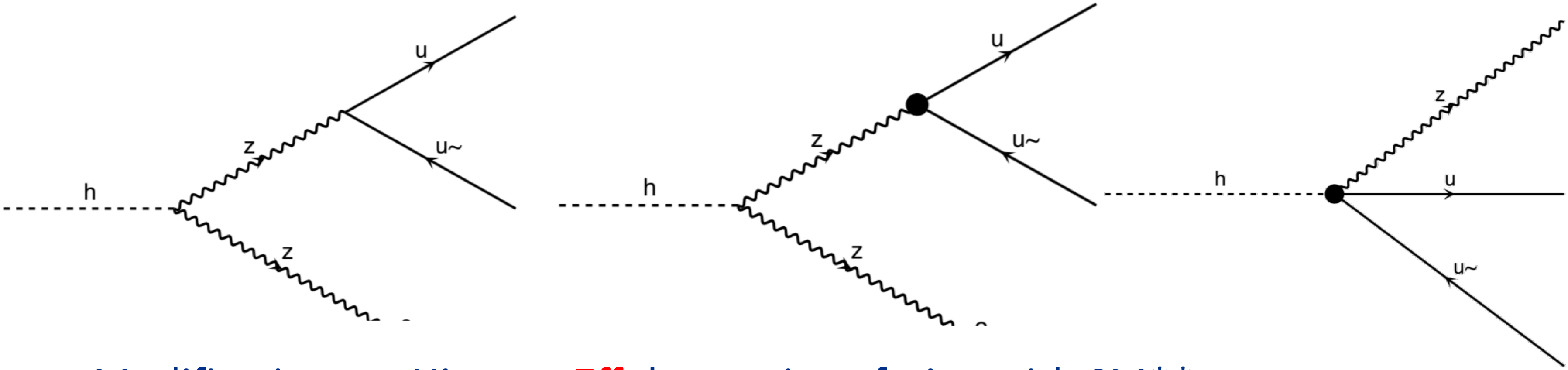
S. Alioli, M. Farina, D. Pappadopulo, J. Ruderman, 17'



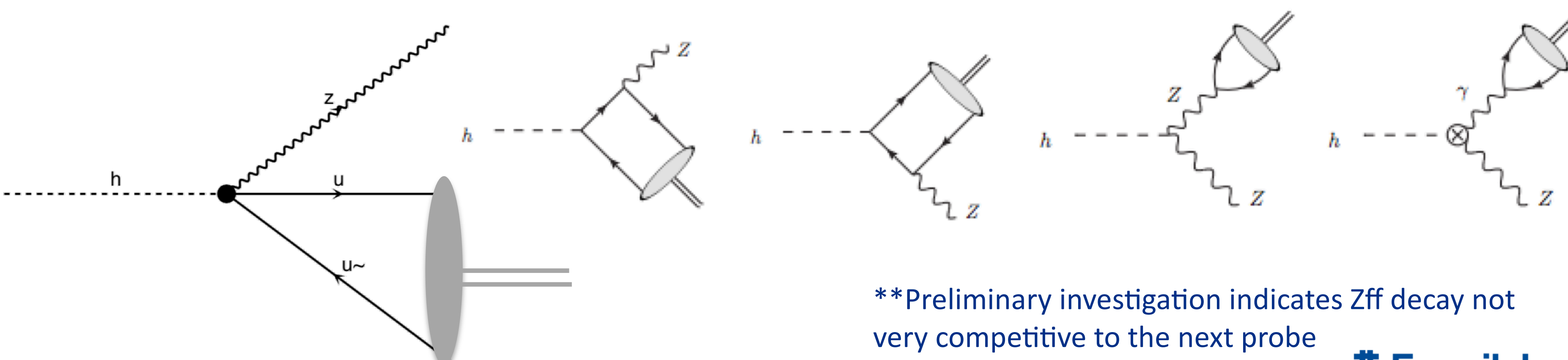
- Low mass, explicit search dominant;
- Higher masses, EFT and UV model agrees well;
- Beat EWPT at high masses;
- Four-fermi operators, can be translated to our operators*, already see **complementarity between Z-pole and High energy tails**

* common complexity and dependences on other operators during translation

Higgs exotic decays



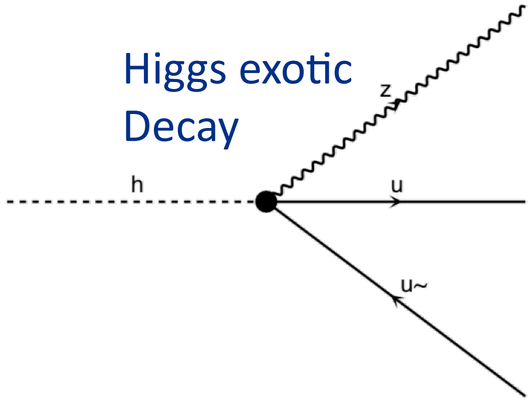
- Modifications to Higgs to Zff decays, interfering with SM**
- Modifying and interfering with the Z+meson decays, could change the rate significantly and make an early discovery.
- No existing analysis yet from both the SM group or the exotic group (exotic group always do the equal mass assumption) for either decay modes

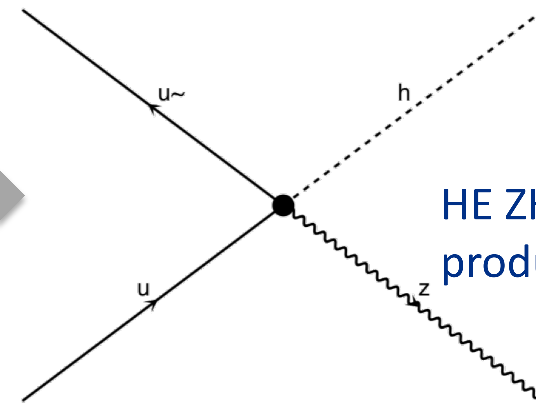


**Preliminary investigation indicates Zff decay not very competitive to the next probe

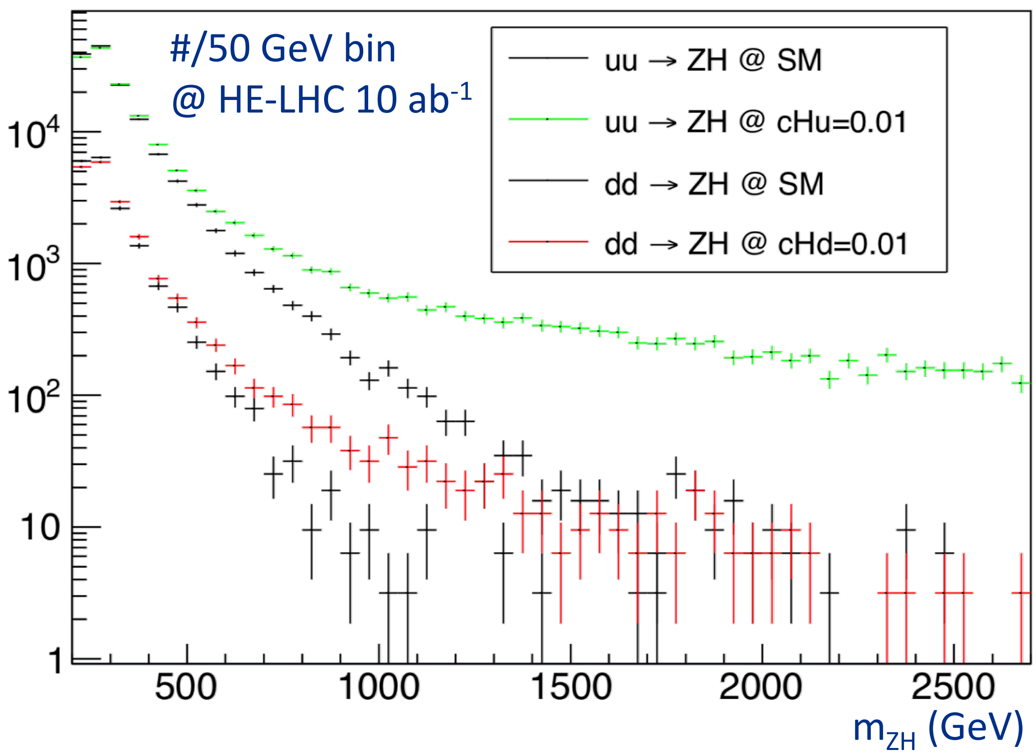
Higgs and Z boson at High Energies

Higgs exotic Decay

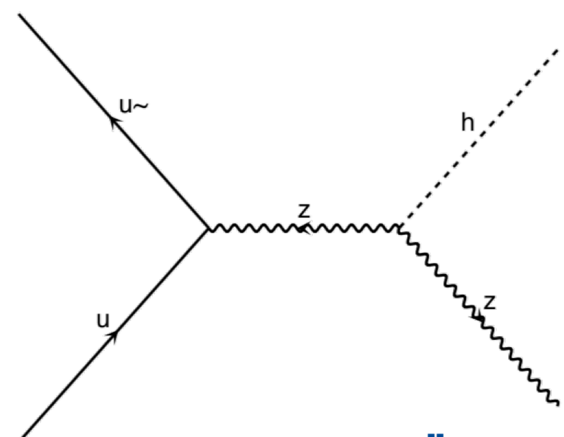




HE ZH production



$\frac{v\sqrt{s}}{\Lambda^2}$ Growing faster than the SM (interfering) process $\frac{v}{\sqrt{s}}$

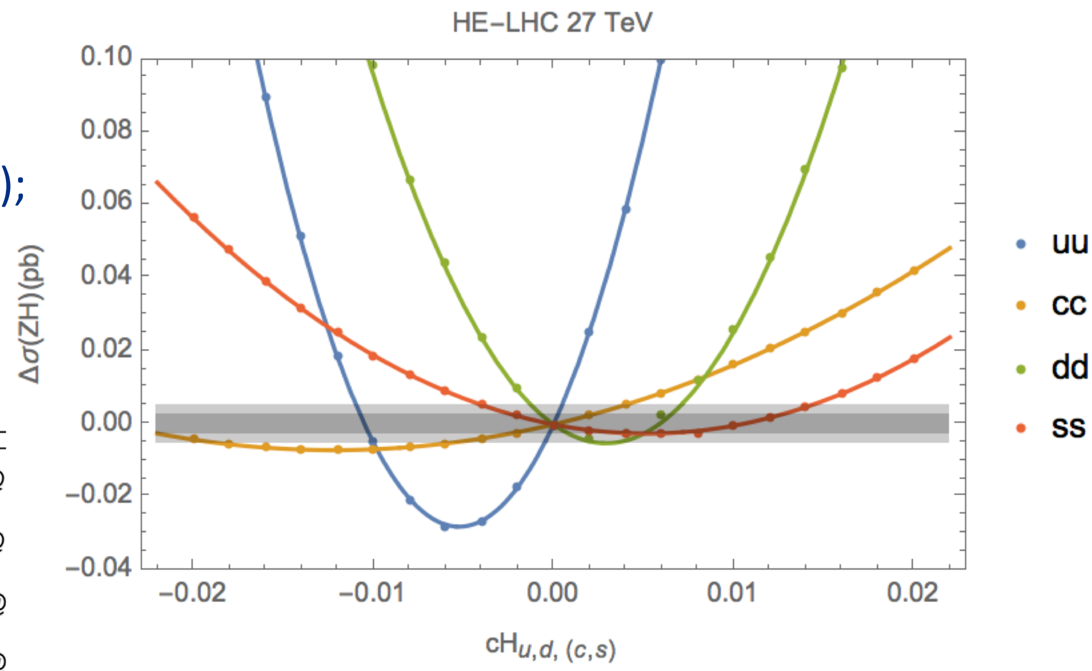


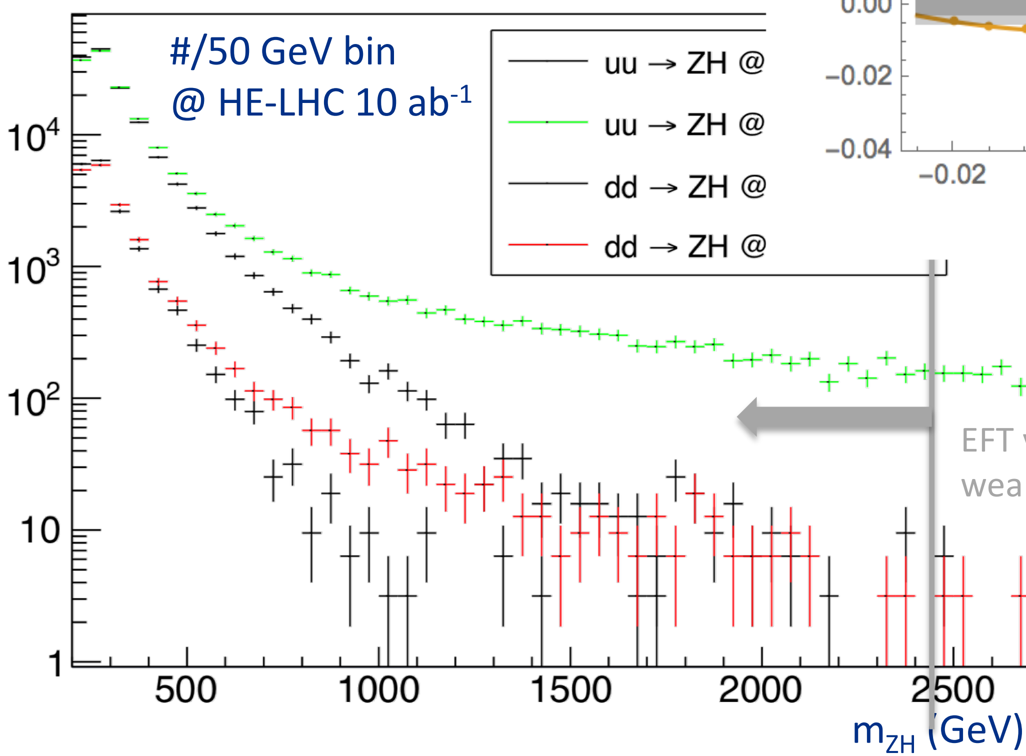
Also see similar study on high energy tail in Franceschini, Panico, Pomarol, Riva, Wulzer17’

Higgs and Z boson at High Energies

Constraints on Wilson coefficients to O(0.001), corresponding to O(10 TeV);

Lots of room to improve;





$$pp \to ZH \to (l^+l^-)(b\bar{b})$$

- 50% signal efficiency.
- Statistical dominance (true for current LHC)
- S/B ratio around 1/3
- Not yet the differential information analysis
- Angular analysis

**well within linear regime

Summary and outlook

- HE and HL will push our knowledge of the Higgs boson rare and exotic decays to new territory by two orders of magnitude or more;
- A lot of new search channels to be covered, especially those with missing energy;
- Will achieve some very interesting benchmarks with the improved precision, e.g., probing Higgs decays to mesons, providing non-trivial tests to SM, QCD, and interferences;
- An example where Z-pole, H-pole (rare and exotic decays) and High energy tails complements each other to provide coherent pictures of the gauge coupling shifting operators for quarks;
- Higgs CPV, Flavor-violating, (a zoo of) Long-lived signatures to be explored (see many talks in this workshop);

Summary and outlook

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We should also fully exploit the new features of our new detector to achieve more.

Thank you!

HE-LHC Higgs cross section

	M_H=125 GeV				
Process	**Cross section**	**Scale uncertainty**		**PDF+α_s uncertainty**	
ggF [a]	50.35 pb	+7.5%	-8.0%	+7.2%	-6.0%
VBF [b]	4.172 pb	+0.4%	-0.3%	+1.9%	-1.5%
WH [c]	1.504 pb	+0.3%	-0.6%	+3.8%	-3.8%
ZH [c]	0.8830 pb	+2.7%	-1.8%	+3.7%	-3.7%
ttH [c]	0.6113 pb	+5.9%	-9.3%	+8.9%	-8.9%
bbH [d]	0.5805 pb	+13.0%	-24.0%	+6.1%	-6.1%

PDF+α_s uncertainties are according to PDF4LHC recipe.

HE-LHC Higgs cross section

	M_H=125 GeV				
Process	**Cross section**	**Scale uncertainty**		**PDF+α_s uncertainty**	
ggF [a]	178.32 pb	+7.8%	-8.2%	+7.4%	-7.2%
VBF [b]	15.47 pb	+0.6%	-0.6%	+1.7%	-1.4%
WH [c]	4.272 pb	+0.2%	-0.7%	+2.4%	-2.4%
ZH [c]	2.780 pb	+4.8%	-3.2%	+2.5%	-2.5%
ttH [d]	4.377 pb	+8.1%	-8.9%	+5.4%	-5.4%
bbH [e]	2.132 pb	+7.0%	-34.0%	+5.9%	-5.9%

PDF+α_s uncertainties are according to PDF4LHC recipe.

Organizing the study (Prompt)

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]

- 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 (captured in precision program, including angular distributions)
- 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