Exotic Decays of the 125 GeV Higgs Boson

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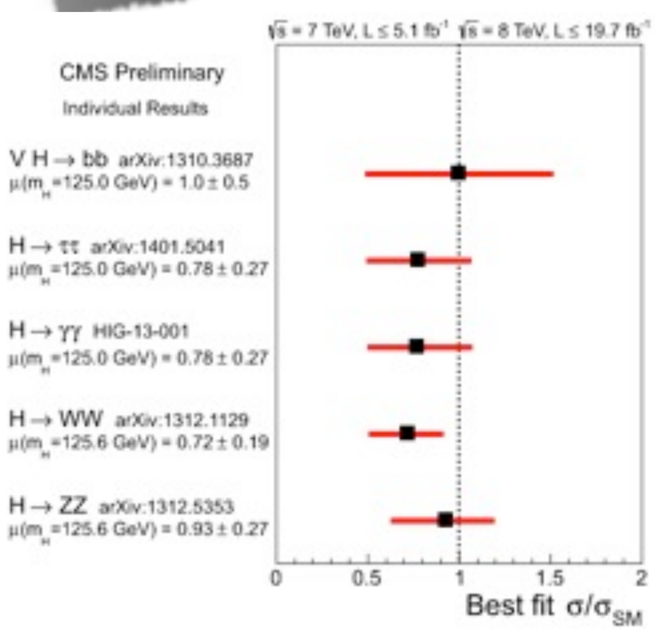
26th Rencontres de Blois
May 21st, 2014

Post-Higgs Discovery

Measurement of the SM Higgs couplings

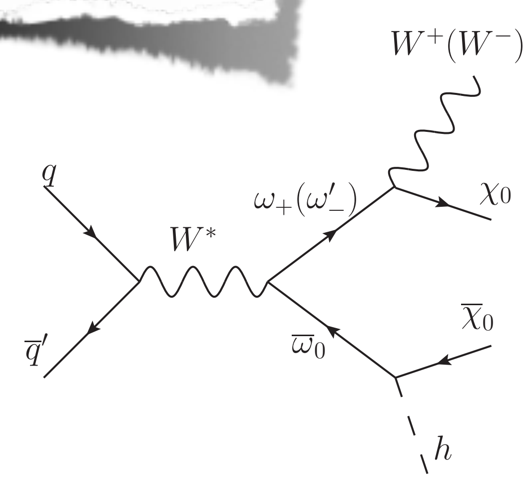


(*covered in Monday's talk by Sally Dawson*)

Exotic Production Modes

- SUSY
- Displaced Higgs

(*PJ, T. Okui arXiv: 1303.1181*)

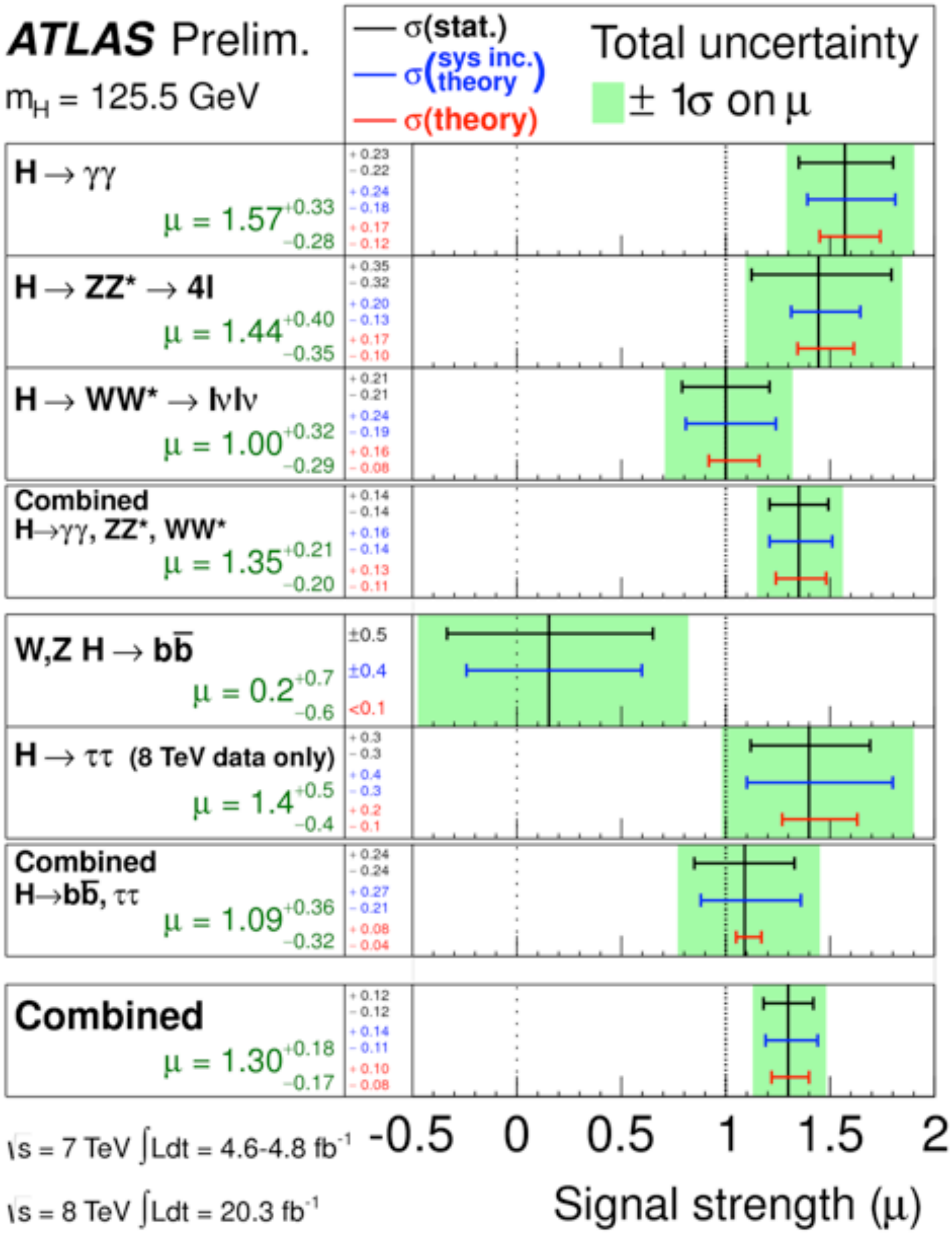


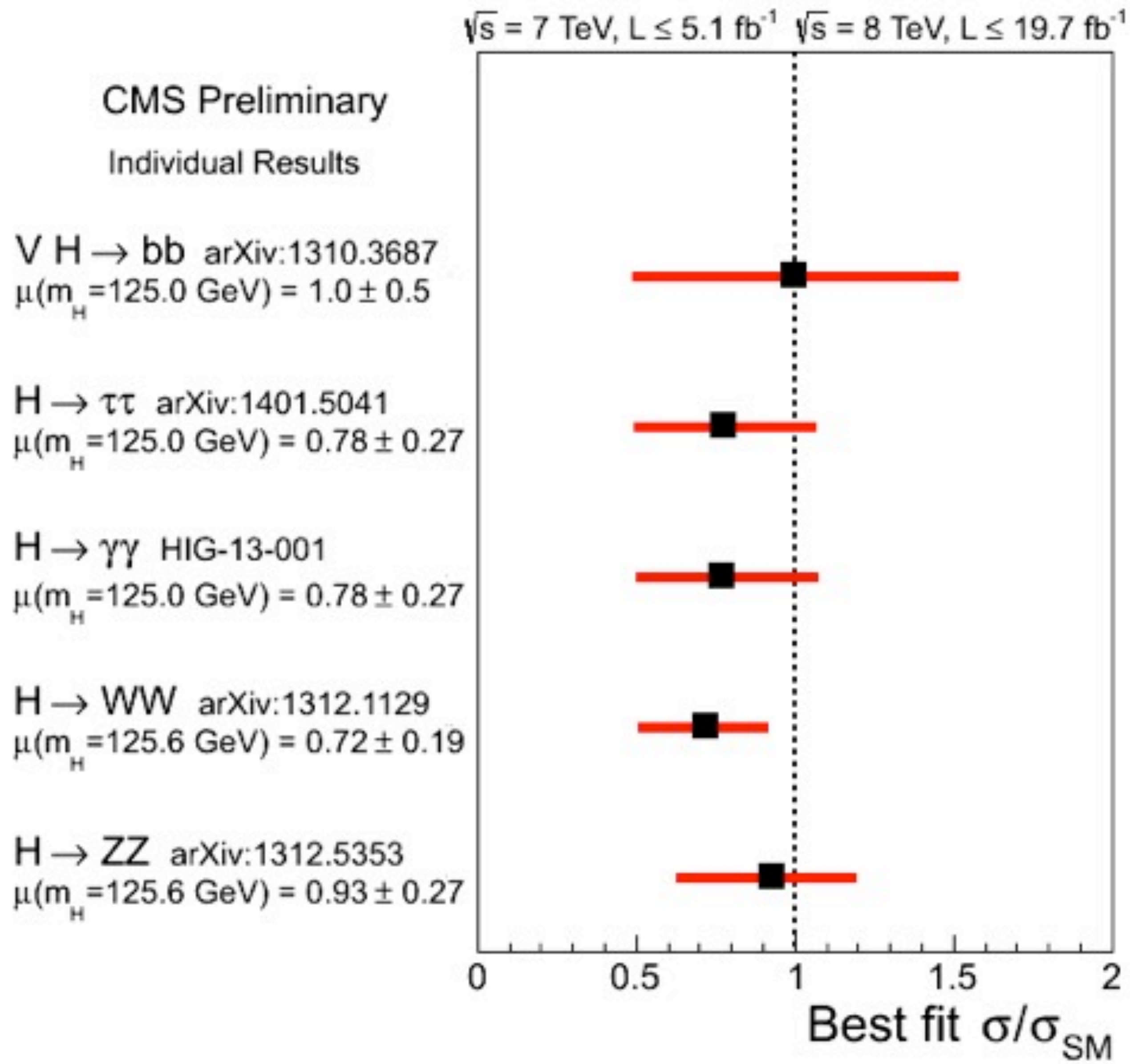
Exotic Decay Modes

(this talk)

- The Higgs boson as we know of :

Higgs Couplings to SM particles are SM-like.

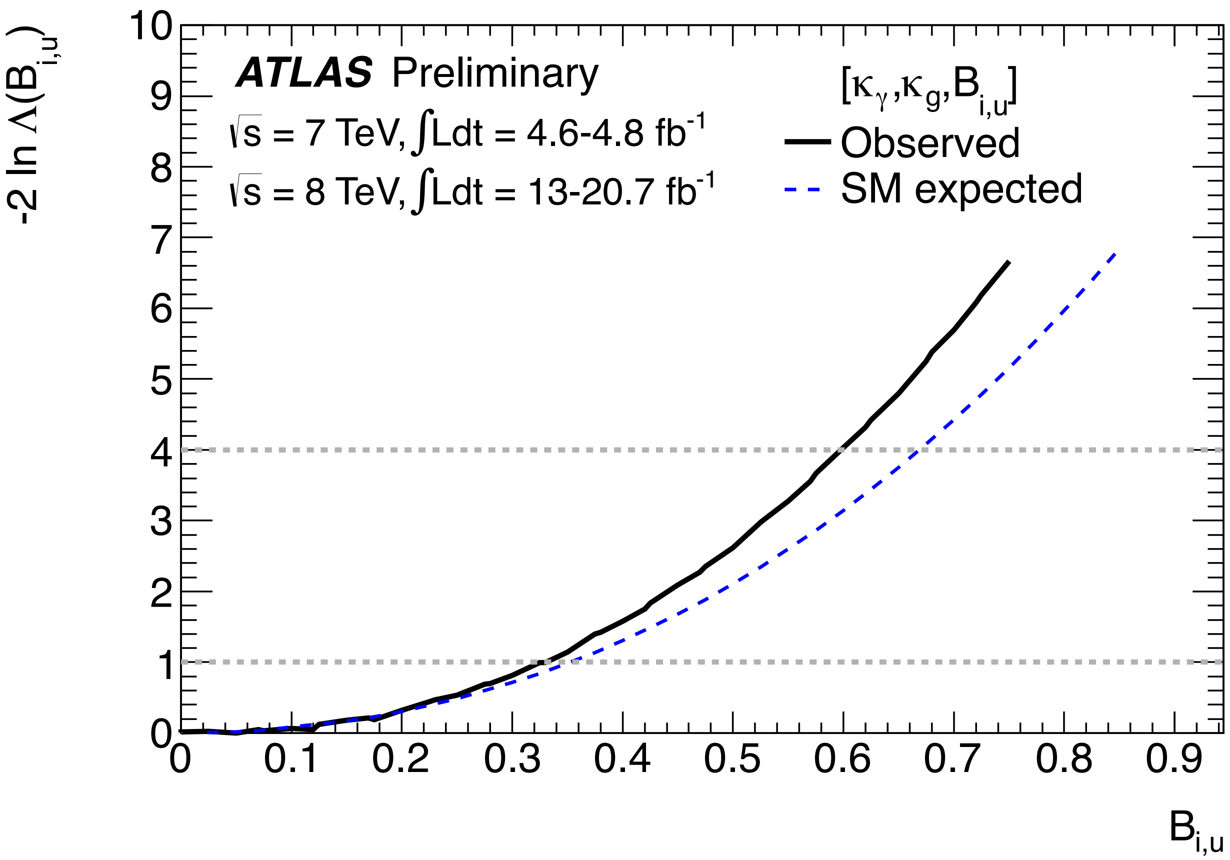




- Are exotic decays of the Higgs allowed by <u>current</u> experimental constraints?

Br(h → invisible/undetected)

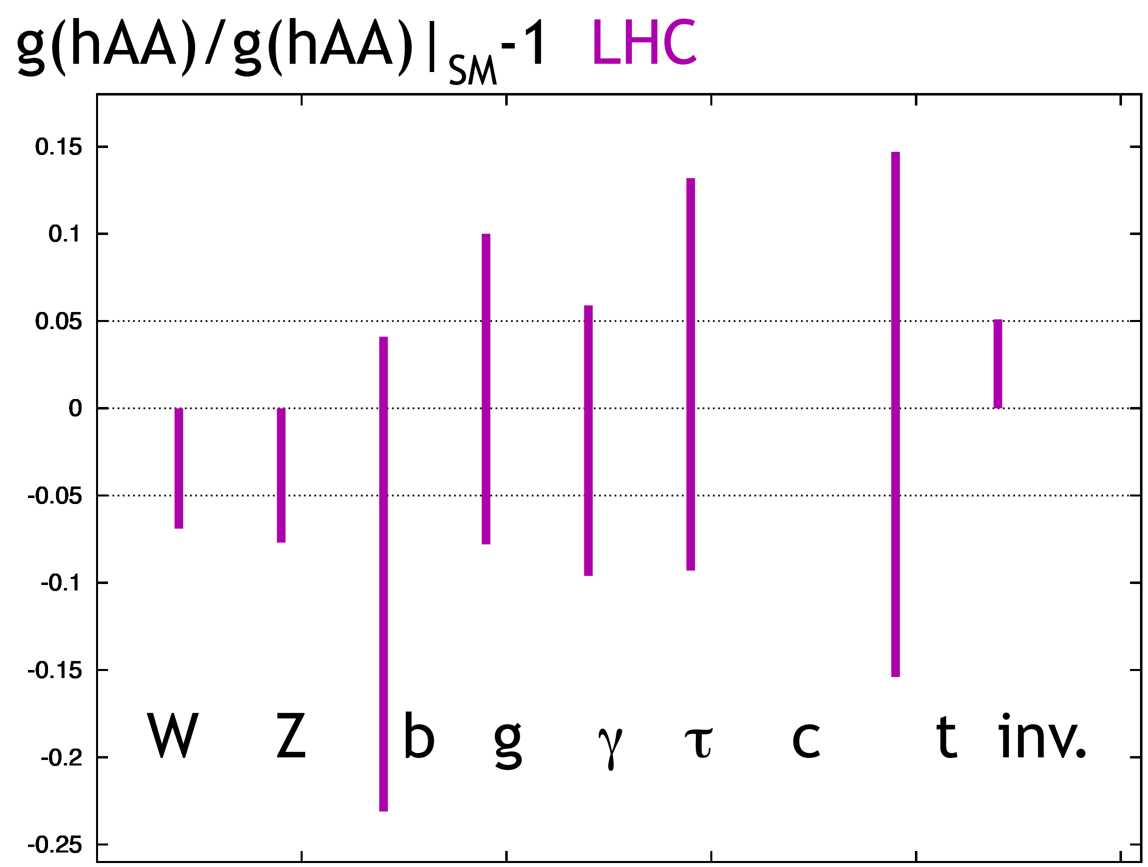
< 60 % at 95% C.L.



ATLAS-CONF-2013-034

- Will exotic decays of the Higgs be allowed by <u>future</u> experimental constraints?

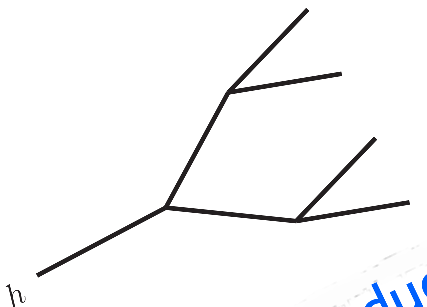
Even with 300^{-1} fb @ 14 TeV LHC, uncertainties are at least 5-10 %.



Peskin, arXiv:1207.2516

Assumption : Br(h →inv/undet) = 10 %

Production	8 TeV: $N_{\text{ev}}^{10\%}$, 20 fb^{-1}	14 TeV: $N_{\text{ev}}^{10\%}$, 300 fb^{-1}
ggF	38,500	1.5×10^6
VBF	3,200	125,000
$hW^\pm$	1,400	45,000
$hW^\pm(\ell^\pm\nu)$	300	9,600
hZ	830	26,500
$hZ(\ell^+\ell^-)$	56	1,800
$t\bar{t}h$	260	18,300



Triggering issues due to soft final states?

Use W/Z associated production

... some events may already be on the tape

And possibly many more to come in the future runs...

But why study exotic decays of the Higgs?

- It is a likely possibility.

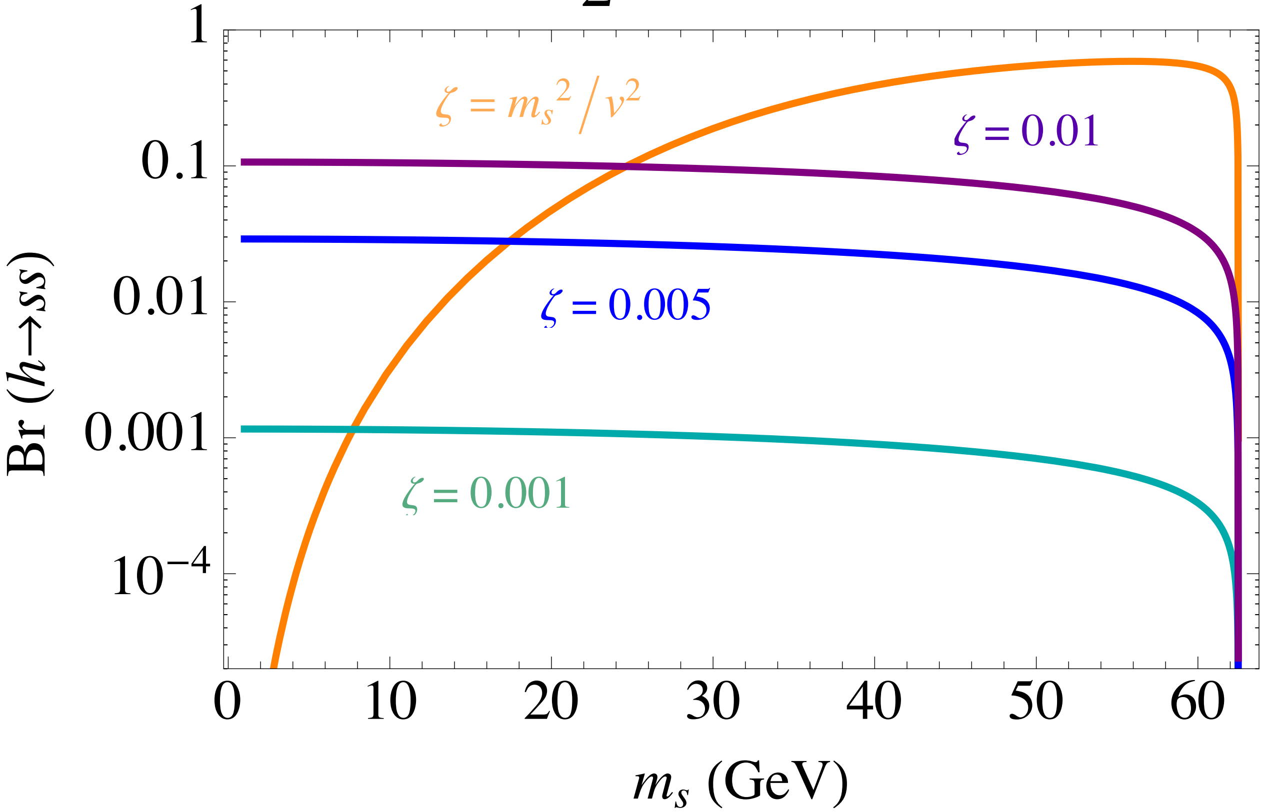
  SM Higgs decay width, Γ_h = 4.07 MeV

  Even a small coupling to new particles can give sizable BR.

- Higgs as Portal to New Physics / Dark Sector

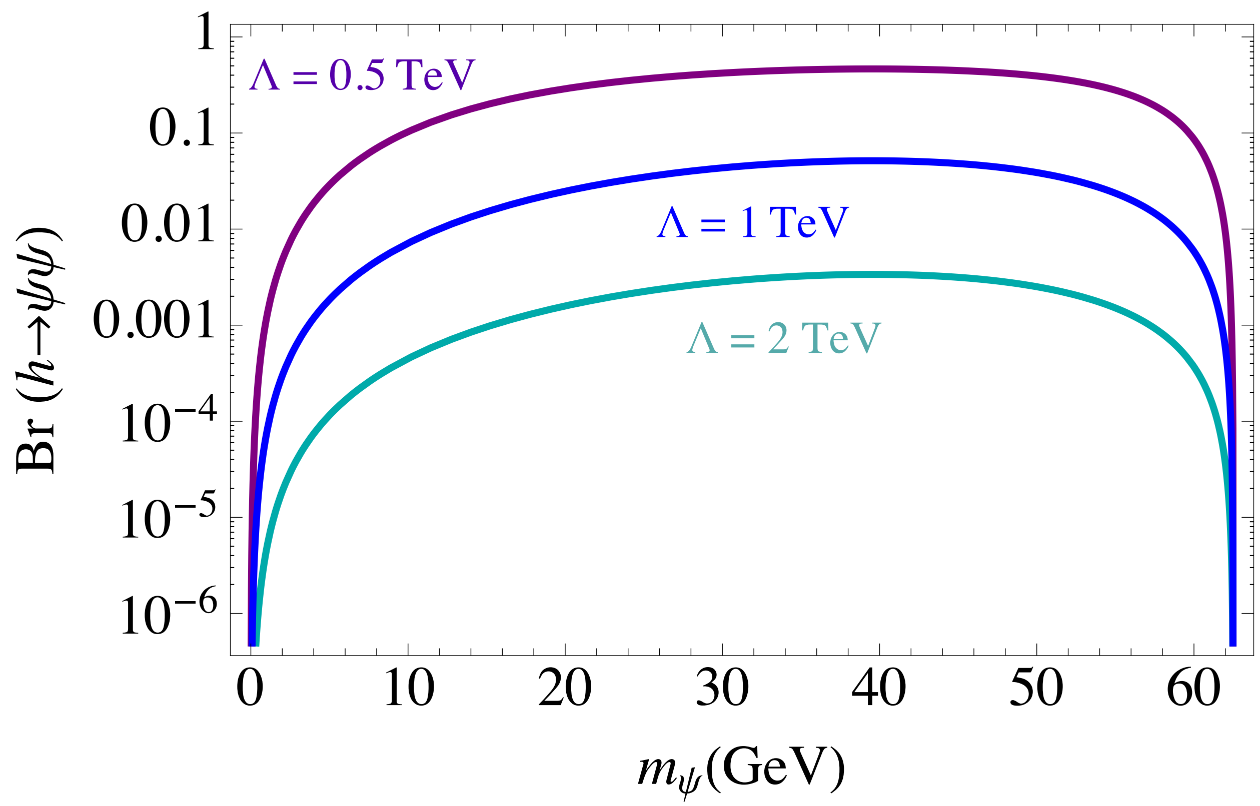
  - Renormalizable couplings to SM singlet states

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$



  - Probing NP scales > 1 TeV

$$\Delta\mathcal{L} = \frac{\mu}{\Lambda^2} |H|^2 \bar{\psi}\psi$$



Existing Experimental Searches

- $h \to$ invisible

CMS PAS HIG-13-013 (8 TeV)

CMS PAS HIG-13-018 (7+8 TeV)

CMS PAS HIG-13-028 (8 TeV)

ATLAS: 1402.3244 (7+8 TeV)

- $h \to$ light pseudoscalars

$h \to 2a \to 4\gamma$: ATLAS-CONF-2012-079 (7 TeV)

$h \to 2a \to 4\mu$: CMS PAS HIG-13-010 (8 TeV)

- $h \to$ lepton-jets

muon-jets : CMS PAS HIG-13-010 (8 TeV)

electron-jets : ATLAS 1302.4403 (~2/fb, 7 TeV)

displaced muon-jets : ATLAS 1210.0435 (~2/fb, 7 TeV)

Exotic Higgs Decay Working Group

D. Curtin, R. Essig, S. Gori, PJ, A. Katz, T. Liu, Z. Liu, D. McKeen, J. Shelton,

M. Strassler, Z. Surujon, B. Tweedie, Y. Zhong

Main Document : arXiv: 1312.4992

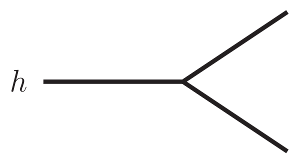
Aim of our work

- 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

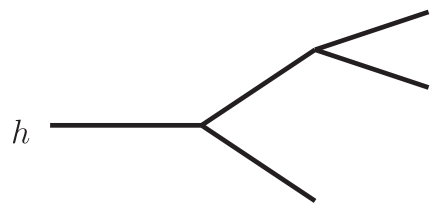
www.exotichiggs.physics.sunysb.edu

Assumptions

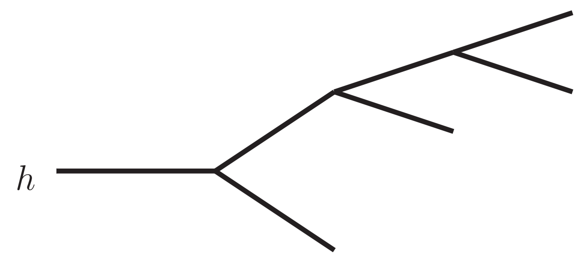
- Observed 125 GeV state is primarily responsible for EWSB
- 125 GeV state decays to new BSM particles
- Initial decay is 2-body



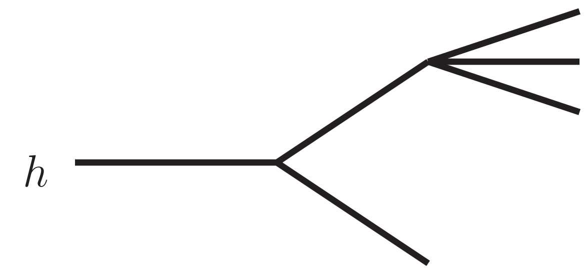
$h \to 2$



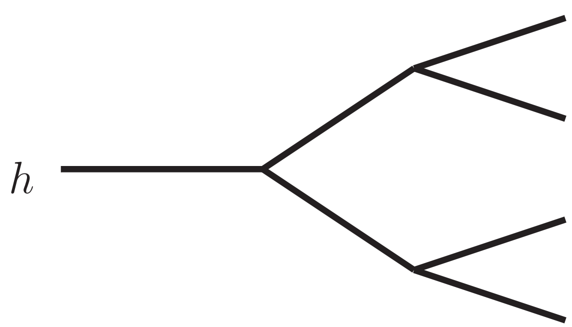
$h \to 2 \to 3$



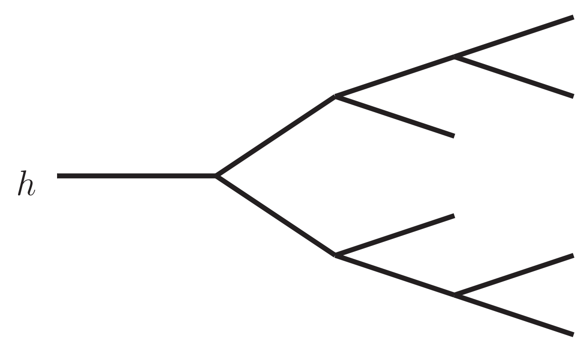
$h \to 2 \to 3 \to 4$



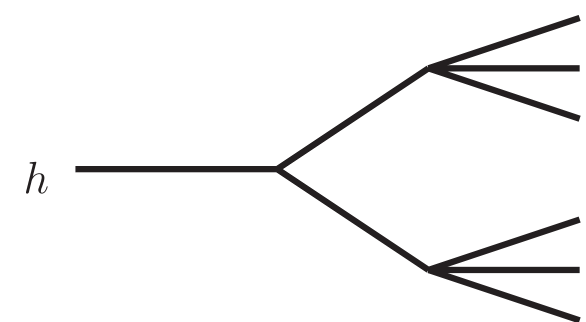
$h \to 2 \to (1+3)$



$h \to 2 \to 4$



$h \to 2 \to 4 \to 6$



$h \to 2 \to 6$

Decay Modes we studied → Theoretical Models

- $h \to$ MET
- $h \to 4b$
- $h \to 2b2\tau$
- $h \to 2b2\mu$
- $h \to 4\tau, 2\tau2\mu$
- $h \to 4j$
- $h \to 2\gamma2j$
- $h \to 4\gamma$
- $h \to ZZ_D \to 4l$
- $h \to Z_DZ_D \to 4l$
- $h \to \gamma$+MET
- $h \to 2\gamma$+MET
- $h \to 4l$+MET
- $h \to 2l$+MET
- $h \to$ one lepton jet
- $h \to$ two lepton jets
- $h \to bb$+MET
- $h \to \tau\tau$+MET

SM + Scalar

2HDM (+ Scalar)

SM + Fermion

SM + 2 Fermions

SM + Vector

MSSM

NMSSM with exotic Higgs decay to scalars

NMSSM with exotic Higgs decay to fermions

Little Higgs

Hidden Valleys

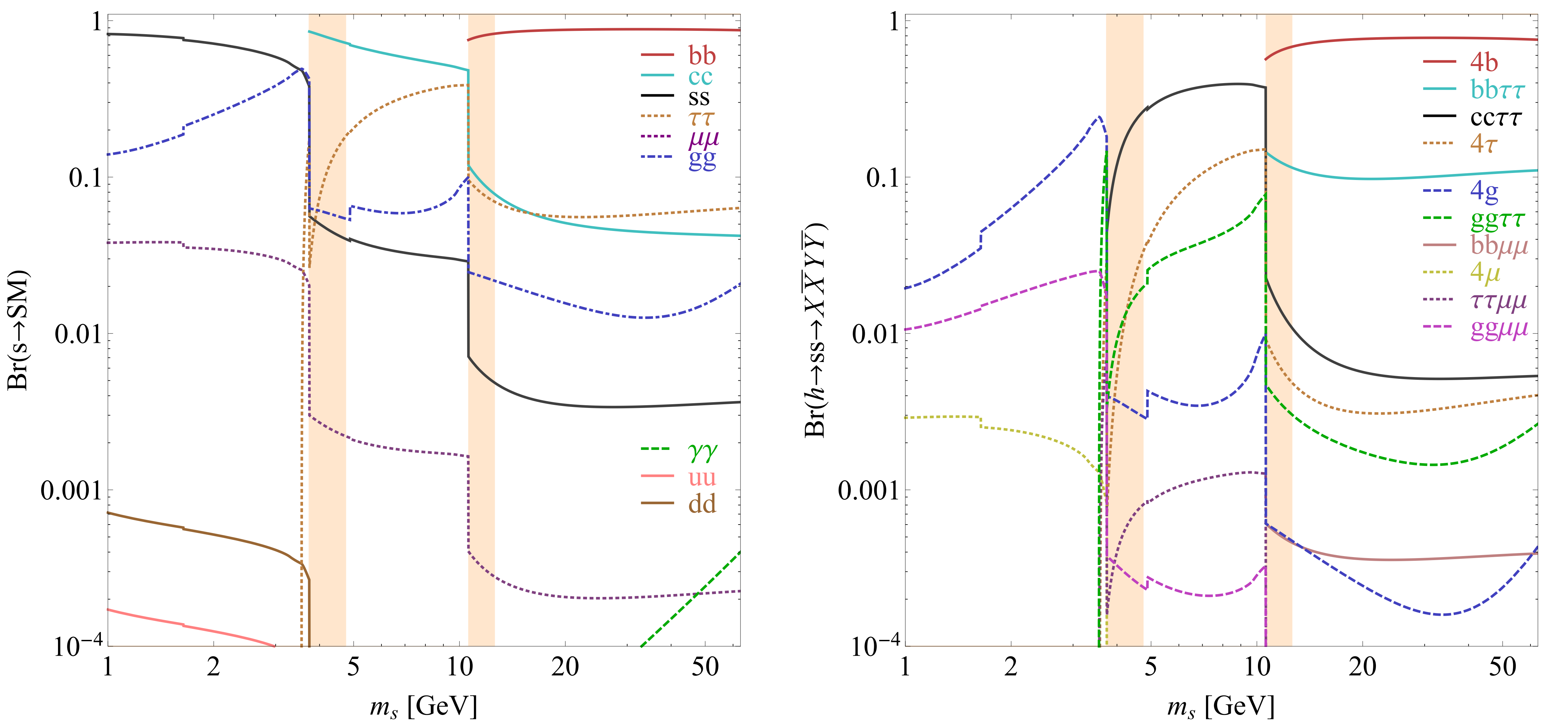
Need Simplified Model Approach!

Exotic Higgs Decays : Rich Phenomenology

- Example 1 : SM + Singlet

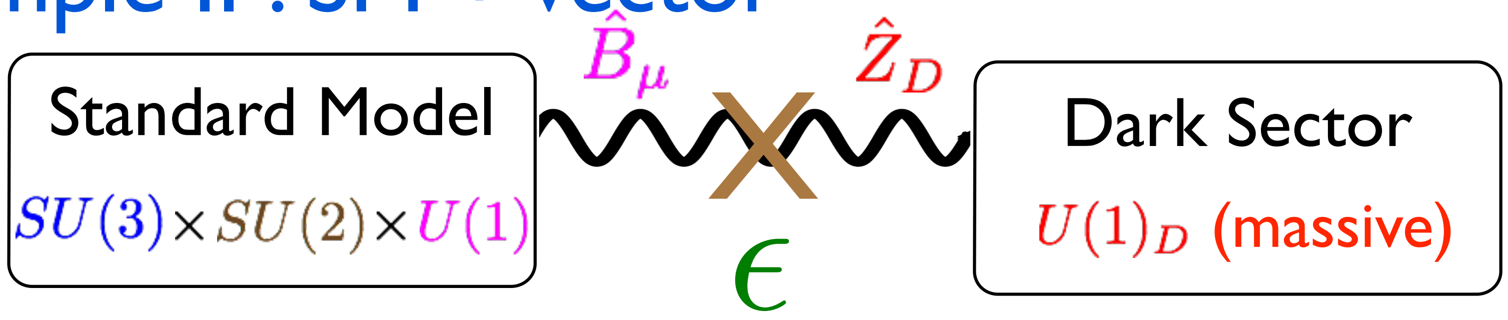
$$V(H,S) = -\mu^2\,|H|^2 - \frac{1}{2}\,\mu'^2\,S^2 + \lambda\,|H|^4 + \frac{1}{4}\,\kappa\,S^4 + \frac{1}{2}\,\zeta\,S^2\,|H|^2.$$

- If unbroken Z_2 symmetry $\Rightarrow$ stable S $\Rightarrow$ invisible Higgs decays
- If Z_2 is broken $\Rightarrow h \to s\,s \to X\,\bar{X}\,Y\,\bar{Y}$

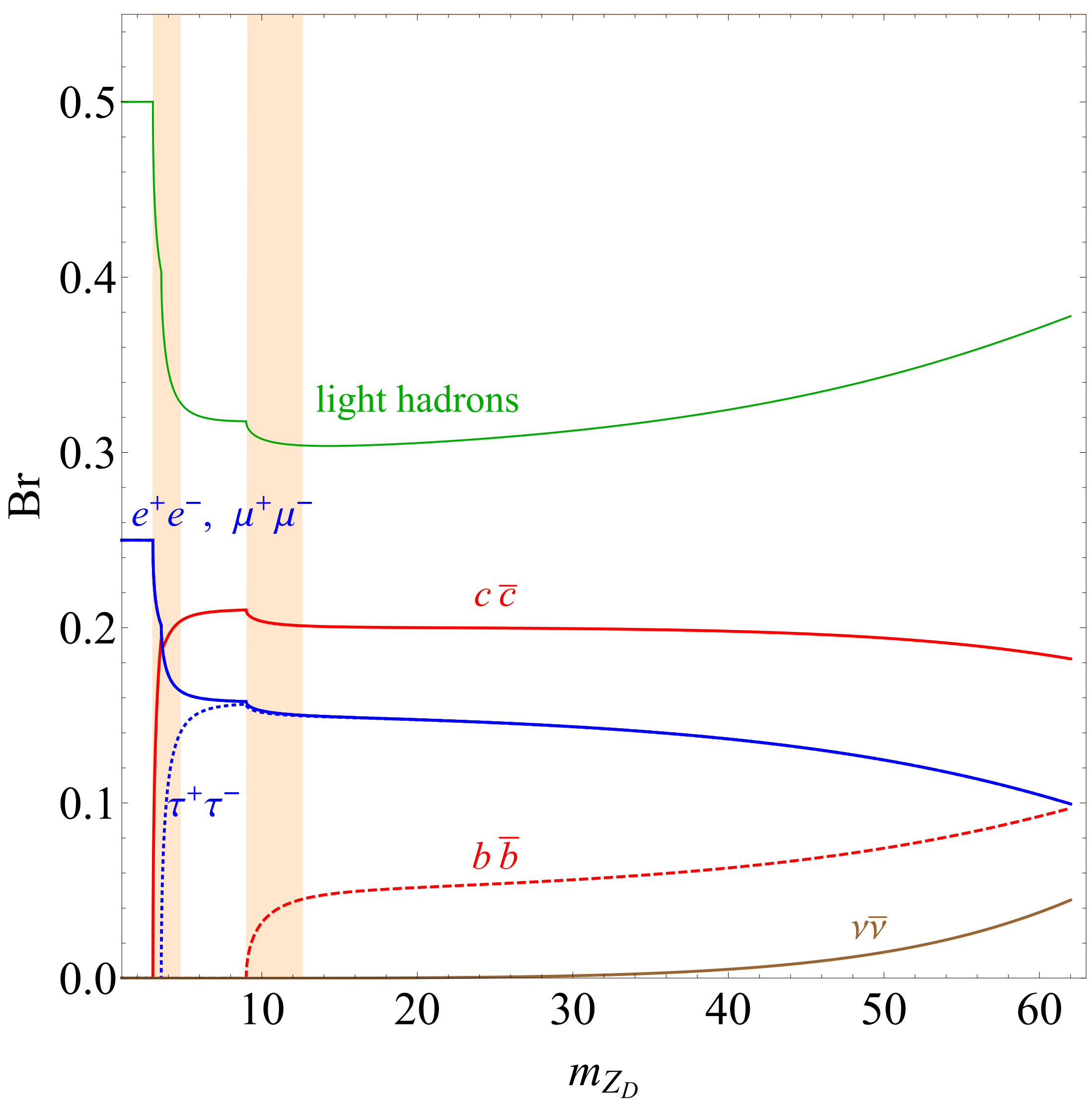


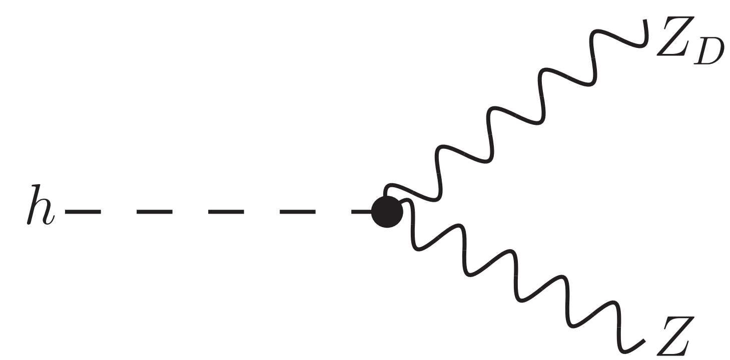
Exotic Higgs Decays : Rich Phenomenology

- Example II : SM + Vector



$$\Delta\mathcal{L} \sim \frac{\epsilon}{2}\,\hat{B}_{\mu\nu}\,\hat{Z}_D^{\mu\nu}$$ kinetic mixing





$\mathcal{M} \propto \epsilon$

Unlike previous example,
NOT Yukawa weighted

Results

h → a a(') → fermions

h → 4b | a a → 4b (Yukawa weighted) | h → aa

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	quarks suppressed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^R $[0.2^L]$	W	0.8	0.9 [0.2]	0	–
$b\bar{b}\tau\tau$	> 1 $[0.15^L]$	V	0.1	> 1 [1]	0	–
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.7-1$ $[0.2-0.7]$	0	–
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]	1	$0.2-0.4$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]	0.007	$0.04-0.1$ [U]
$\mu\mu\mu\mu$	$1\cdot 10^{-4\ R}$ [U]	G	$1\cdot 10^{-7}$	1000 [U]	$1\cdot 10^{-5}$	10 [U]

projection/limit based on theory estimate in literature (L), our theory estimate (T), our re-interpretation of an LHC limit (R), or is unknown (U)

$h \to a\, a^{(\prime)} \to$ fermions

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	quarks suppressed $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^R [0.2^L]	W	0.8	0.9 [0.2]	0	–
$b\bar{b}\tau\tau$	> 1 [0.15^L]	V	0.1	> 1 [1]	0	–
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ [$(0.6-2)\cdot 10^{-4\ T}$]	G	3×10^{-4}	$0.7-1$ [$0.2-0.7$]	0	–
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]	1	$0.2-0.4$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]	0.007	$0.04-0.1$ [U]
$\mu\mu\mu\mu$	$1 \cdot 10^{-4\ R}$ [U]	G	$1 \cdot 10^{-7}$	1000 [U]	$1 \cdot 10^{-5}$	10 [U]

bbμμ & ττμμ searches well motivated in *Run I* & *Run II*

Example : Limits on $h \to a\, a \to 4b$

Theory estimates for 14 TeV LHC from existing literature

Carena et al. - arXiv:0712.2466
Kaplan, McEvoy - arXiv:1102.0704
(Use of jet-substructure techniques)

Limits from recasting $h \to 2\, b$ LHC searches (7/8 TeV)

For $m_a < 15$ GeV, b-pair highly collimated.
$\Rightarrow$ Efficiency of SM $h \to bb$ analysis is high

$Br(h \to 4b) < 0.7$

$h \rightarrow a\, a^{(\prime)} \rightarrow \gamma\gamma / gg$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\mathrm{Br}(a \to \gamma\gamma) \approx 0.004$: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	$\mathrm{Br}(a \to \gamma\gamma) \approx 0.004$: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	$\mathrm{Br}(a \to \gamma\gamma) \approx 0.04$: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	$\mathrm{Br}(a \to \gamma\gamma) \approx 0.04$: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$jjjj$	$> 1\ [0.1^{L*}]$	W	0.99	$> 1\ [0.1^*]$	0.92	$> 1\ [0.1^*]$
$\gamma\gamma jj$	$0.04\ [0.01^{L*}]$	W	0.008	$5\ [1^*]$	0.08	$0.5\ [0.1^*]$
$\gamma\gamma\gamma\gamma$	$2 \cdot 10^{-4\ T}\ [3 \cdot 10^{-5\ L*}]$	G	$1 \cdot 10^{-5}$	$20\ [1^*]$	0.001	$0.2\ [0.03^*]$

search for 4γ in Run I and for 4γ, 4j, 2γ2j in Run II

$h \to Z_D Z_D$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$jjjj$	> 1 $[0.1^{L*}]$	W	0.25	> 1 $[0.4^{*}]$
$\ell\ell\ell\ell$	$4 \cdot 10^{-5\ R}$ [U]	G	0.09	$4 \cdot 10^{-4}$ [U]
$jj\mu\mu$	$0.002 - 0.008\ ^{T}$ [U] $[(5 - 20) \times 10^{-4\ T}]$	G	0.15	$0.01 - 0.06$ $[0.003 - 0.01]$
$b\bar{b}\mu\mu$	$(2 - 7) \cdot 10^{-4\ T}$ $[(6 - 20) \cdot 10^{-5\ T}]$	G	0.015	$0.01 - 0.05$ $[0.003 - 0.01]$

search for 4 ℓ highly motivated in Run I and Run II

Summary of highly motivated searches

- $h \to Z_D Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $h \to Z Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $h \to \ell^+\ell^- + \not{E}_T$
- $h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
- $h \to aa^{(\prime)} \to (b\bar{b})(\mu^+\mu^-)$
- $h \to aa^{(\prime)} \to (\tau^+\tau^-)(\mu^+\mu^-)$
- $h \to aa^{(\prime)} \to (\gamma\gamma)(\gamma\gamma)$
- $h \to \gamma\gamma + \not{E}_T$

- Search across full kinematic range, including regimes where leptons are collimated or (b-)jets merge
- Relaxing invariant mass = 125 GeV