``After the Discovery: Hunting for a Non-Standard Higgs Sector''
Benasque, Spain; April, 2014

EXOTIC DECAYS OF THE 125 GEV HIGGS BOSON - A THEORETICAL OVERVIEW

``Supersymmetric Exotic Decays of the 125 GeV Higgs'',
J. Huang, TL, L-T Wang and F. Yu,
arXiv: 1309.6633, to be published in Phys. Rev. Lett

``Exotic Decays of the 125 GeV Higgs'',
D. Curtin, R. Essig, S. Gori, P. Jaiswal, A. Katz, TL, Z. Liu,
D. McKeen, J. Shelton, M. Strassler, Z. Surujon, B. Tweedie, Y. Zhong,
arXiv: 1312.4992, submitted to Phys. Rev. D

Tao Liu

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125 GeV Higgs - a Leading Window into New Physics

- If new physics (NP) manifests itself as SM singlet operators, $H^\dagger H$ is one of the two dim-2 operators in the SM which can couple with it via either renormalizable coupling or non-renormalizable coupling at leading level [Patt and Wilczek, arXiv:[hep-ph/0605188]]

$$\mathcal{L} \supset \lambda H^\dagger H \mathcal{O}_{\rm NP}$$

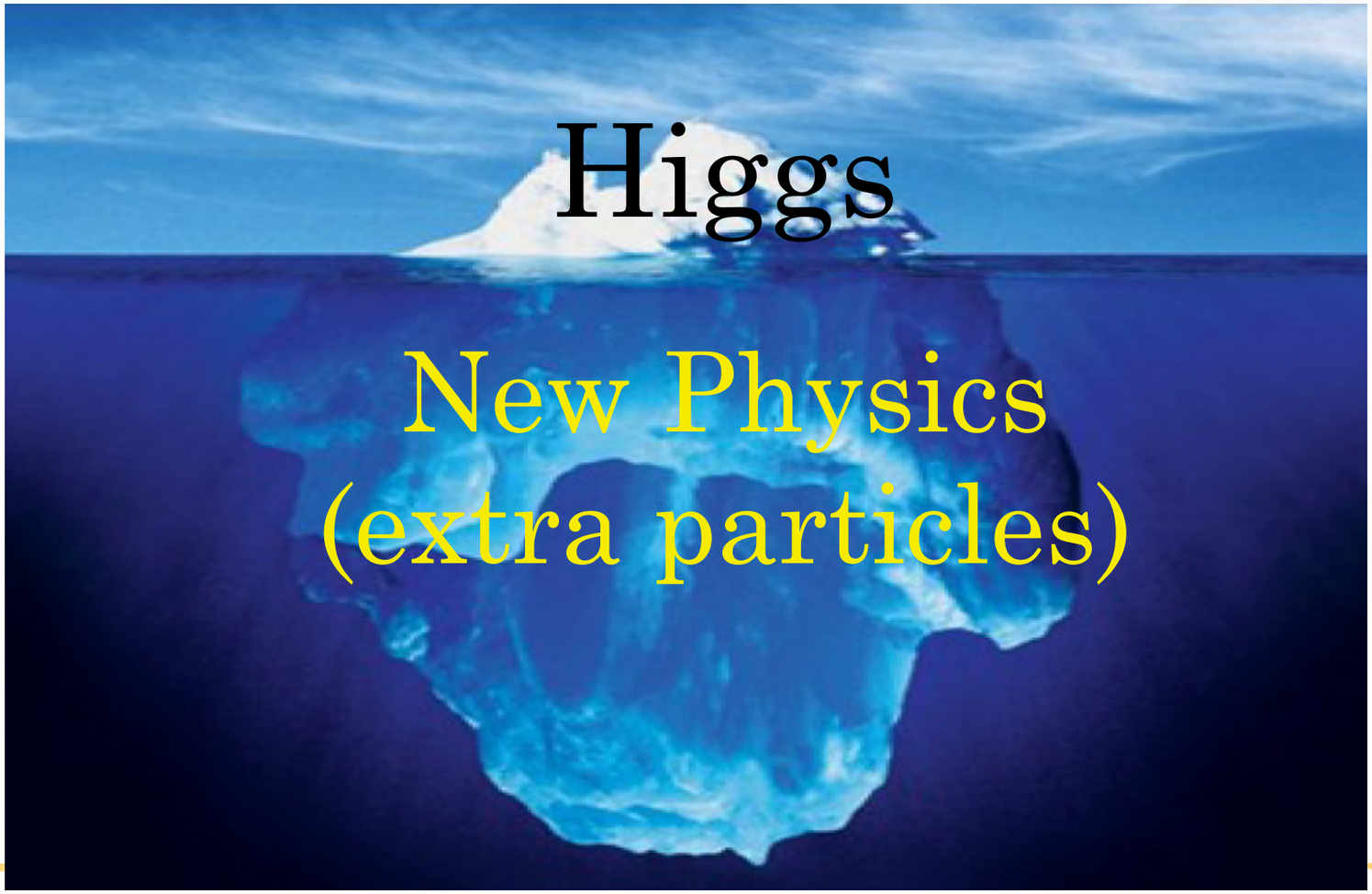
Lorentz invariant gauge singlet

- If NP serves as a mechanism for dynamically stabilizing the Higgs mass (e.g., SUSY), then the Higgs needs to couple with the NP directly

- Both types of couplings can modify the Higgs productions and decays at colliders in a significant way.

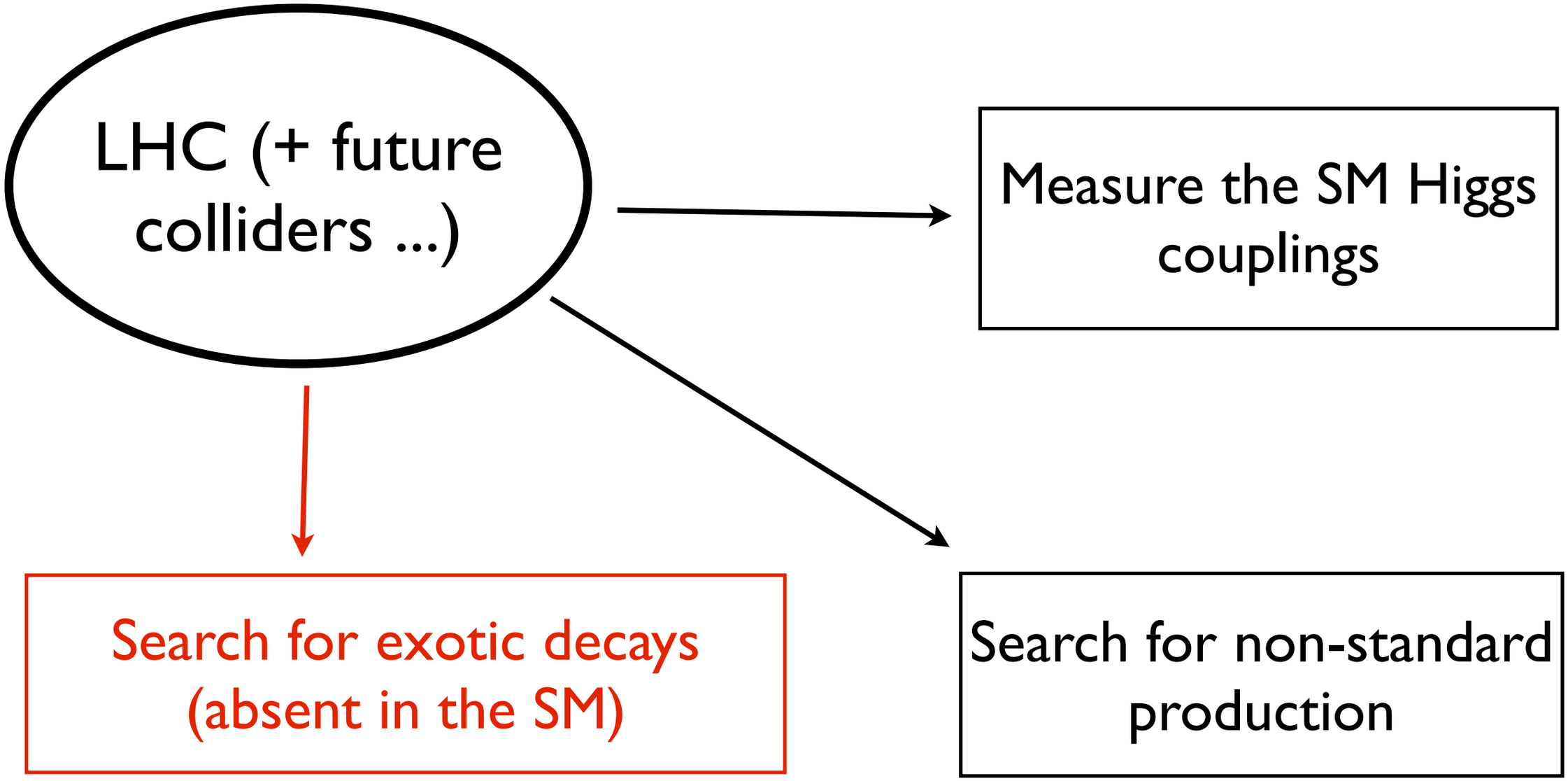
Where is New Physics?

"The world is full of things which nobody by any chance ever observes."
- Sherlock Holmes



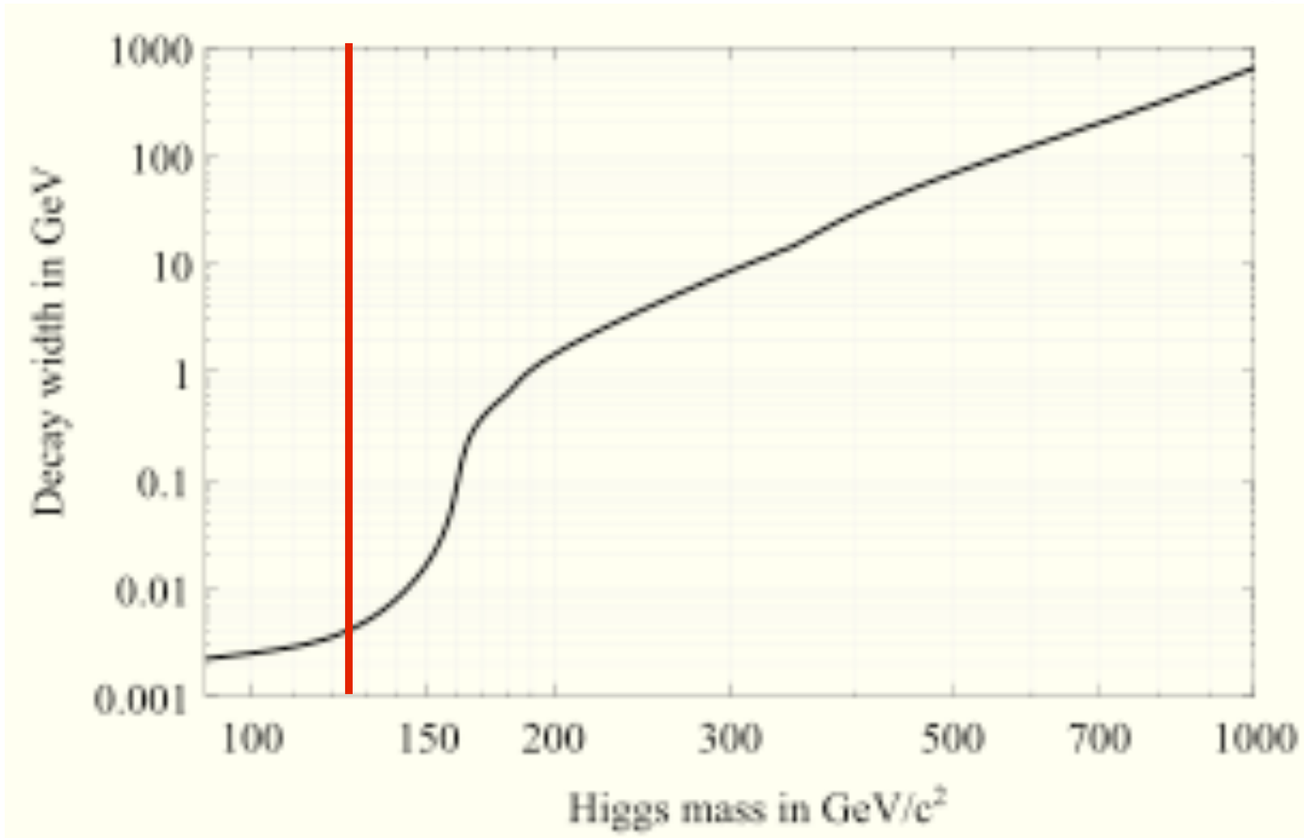
We should study everything about the 125 GeV Higgs !

Several Ways to Do That



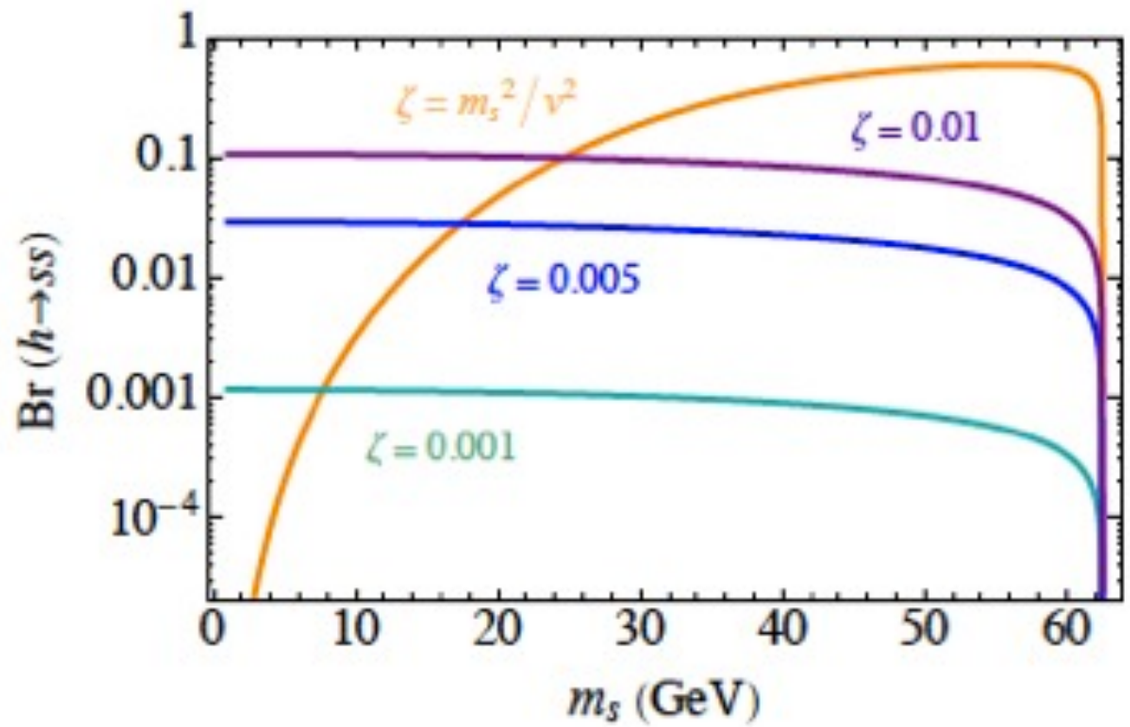
EHD - Sensitive to NP

- The SM Higgs width is tiny for mh ~ 125 GeV
  - Its decays into gauge bosons are either off-shell (WW*, ZZ*), or at loop level (di-photon, di-gluon)
  - Its decays into fermions tend to be suppressed because of small Yukawa couplings (except t*t*)
- About three orders smaller than the Z or W widths (~ 4MeV only) !



EHD - Sensitive to NP

- A small non-standard Higgs coupling or a higher-dim operator of high new physics scale (> TeV) may lead to sizable effect.



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

- So exotic decays of the 125GeV Higgs provide a natural and efficient way for probing new physics

EHD - Sizable Room

Limit on Invisible Decay BR_{inv}

- Consider effective loop couplings: κ_γ, κ_g
- Fix the SM Higgs couplings for κ_V and κ_f
- Define the invisible branching ratio BR_{inv}

$\Gamma_H = \Gamma_{SM} + \Gamma_{inv}$ $\quad$ $BR_{inv} = \Gamma_{inv}/\Gamma_H$

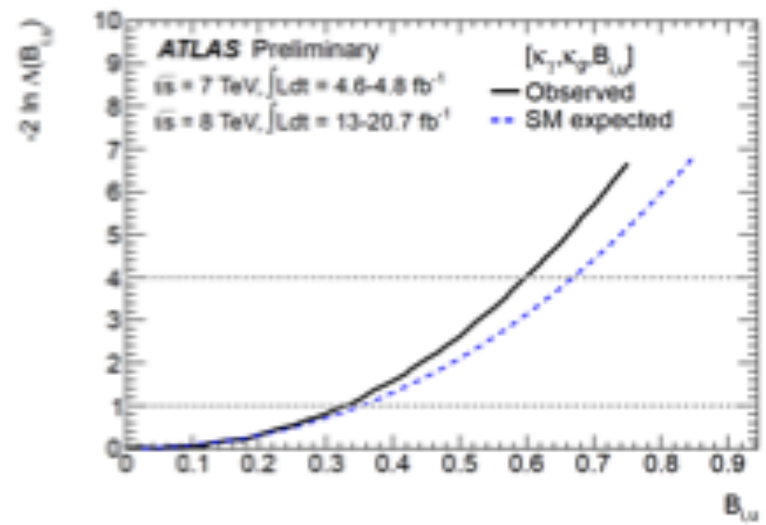
Parameterization on modified Higgs width:

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})}\Gamma_H^{SM}$$

- Three fitted parameters:

κ_γ, κ_g + BR_{inv}

ATLAS-CONF-2013-34



BR_{inv} < 58% at 95% C.L.

$$\kappa_g = 1.08^{+0.32}_{-0.14}$$
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$

42

Bin Zhou, ``International Syposium for Higgs Physics", 08/2013, IHEP, Beijing

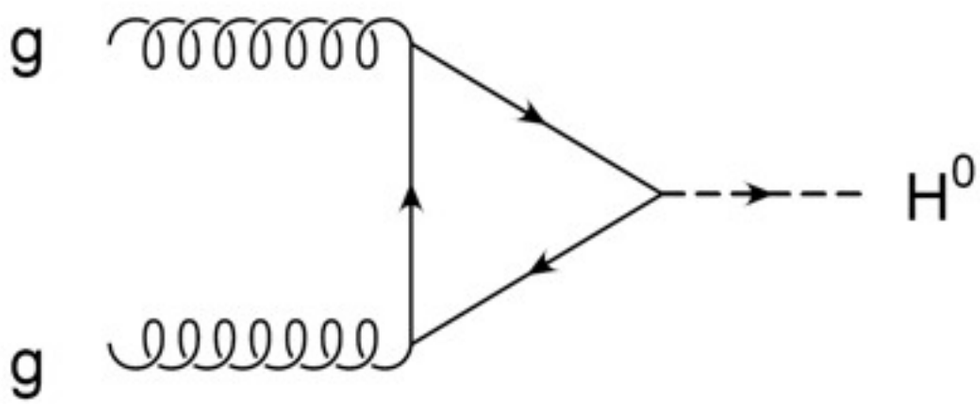
A big room for exotic Higgs decays: > 50% BR at 2 sigma C.L. !

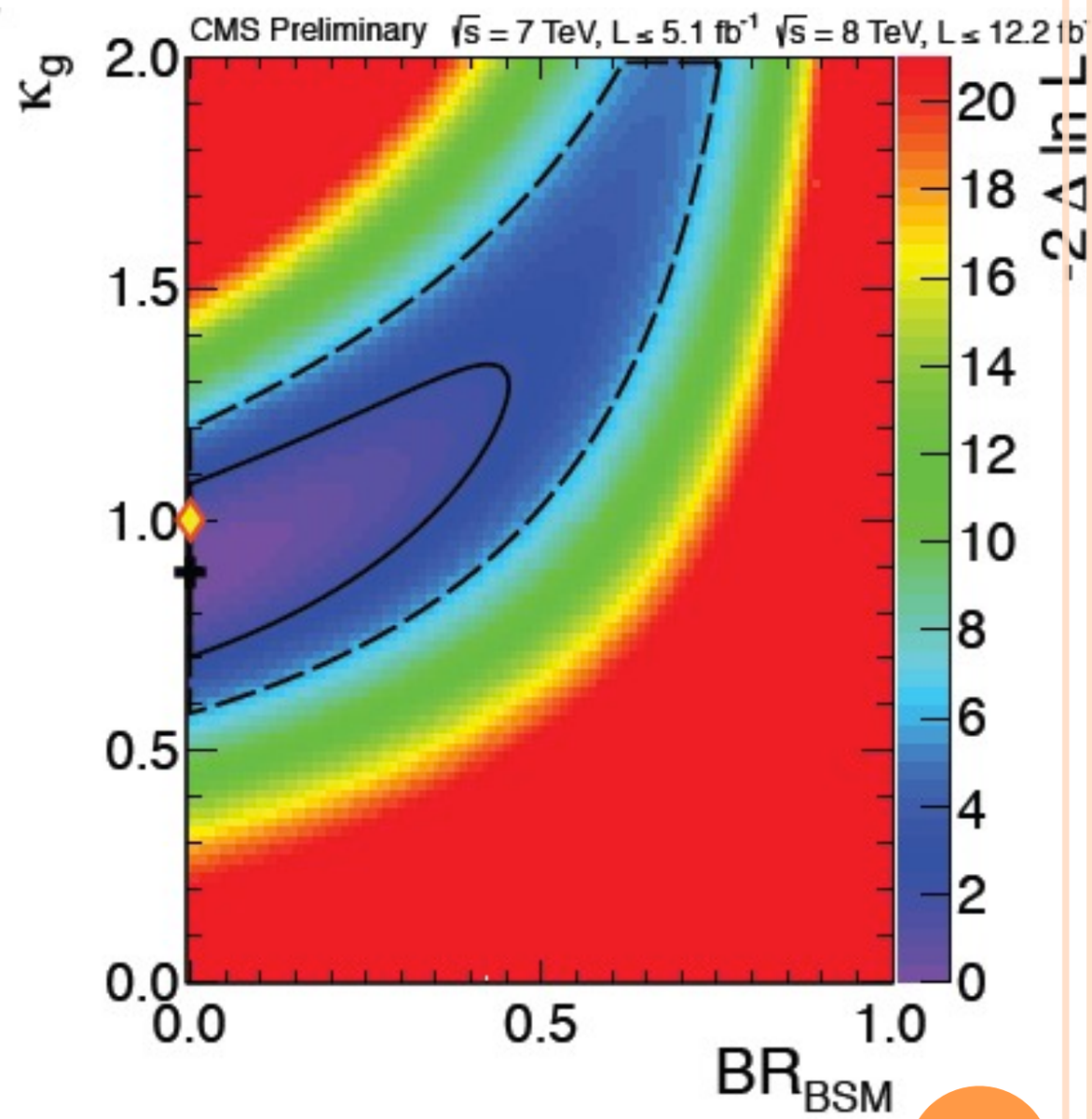
EHD - Sizable Room

Simply because the LHC has no sensitivity to measure the Higgs-glue-glue coupling

$$\text{Signal rate}_{\gamma\gamma,ZZ^*} = \sigma_{h_{\rm SM}} \times \text{Br}(h \to \gamma\gamma, ZZ^*)$$

$$\text{Br}(h \to \gamma\gamma, ZZ^*) = \frac{\Gamma_{h\to\gamma\gamma,ZZ^*}}{\Gamma_{h\to\text{SM}} + \Gamma_{h\to\text{exotic}}}$$





As a comparison (for mh=125GeV)

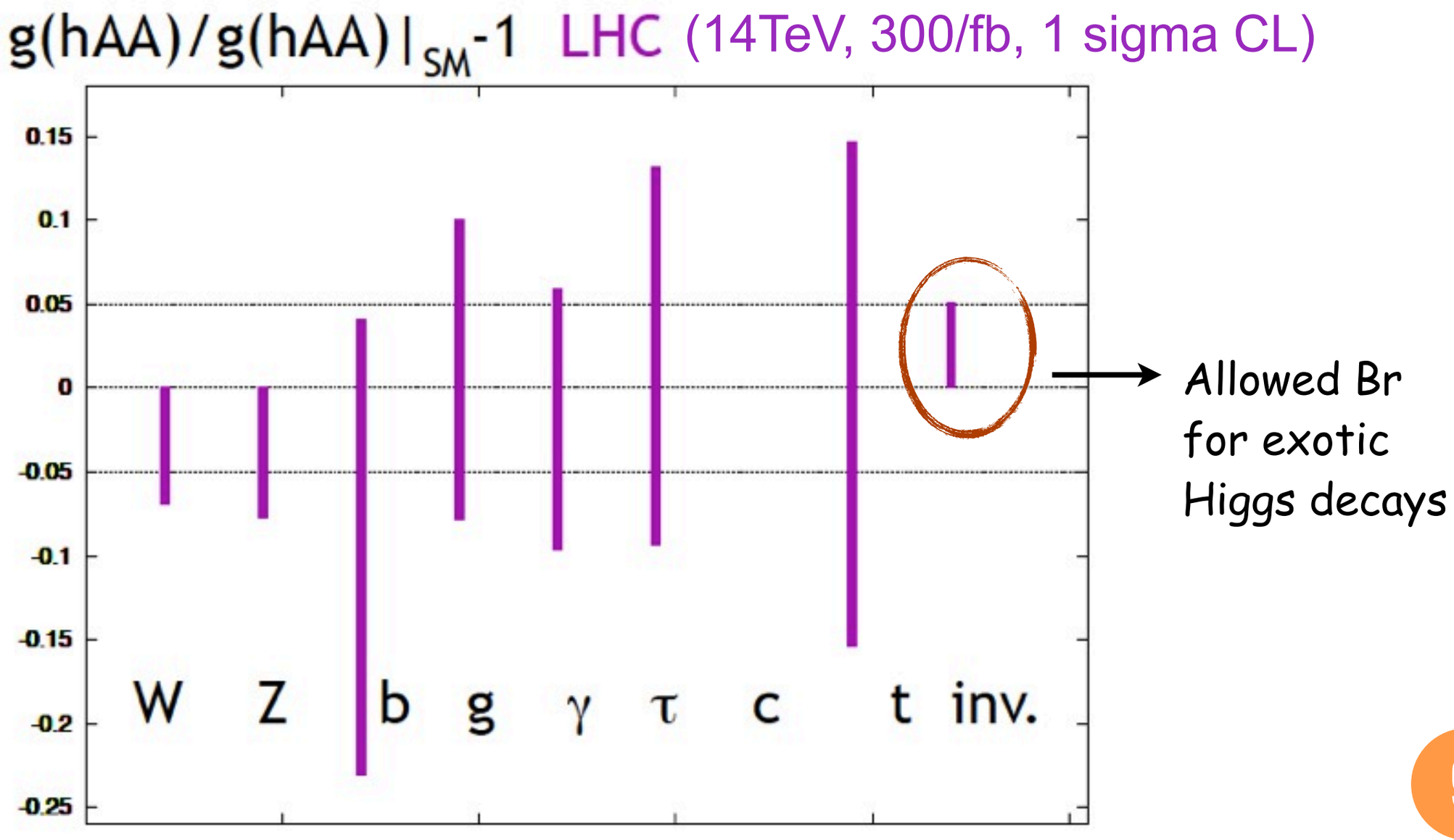
$$\text{Br}(h_{\rm SM} \to ZZ^*) \sim 0.03$$

$$\text{Br}(h_{\rm SM} \to WW^*) \sim 0.15$$

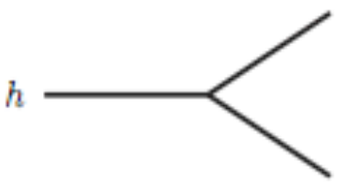
$$\text{Br}(h_{\rm SM} \to \tau\tau) \sim 0.06$$

EHD - Sizable Room

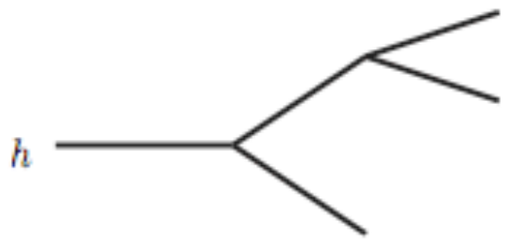
O(5-10%) BR into exotic decay modes are not only allowed by existing data, but will remain reasonable targets for the duration of the LHC program [M. Peskin, 2013]



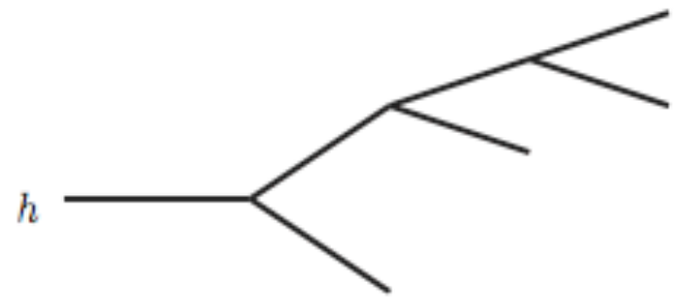
EHD - Various Decay Topologies



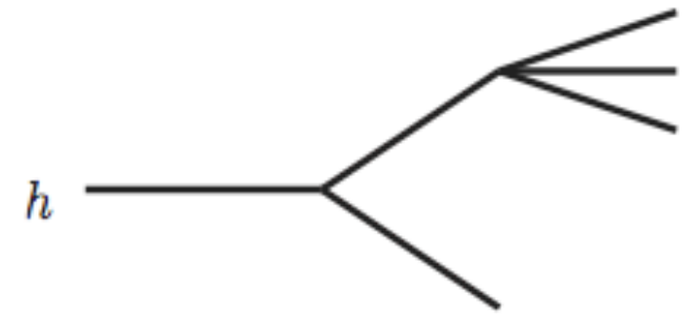
$h \to 2$



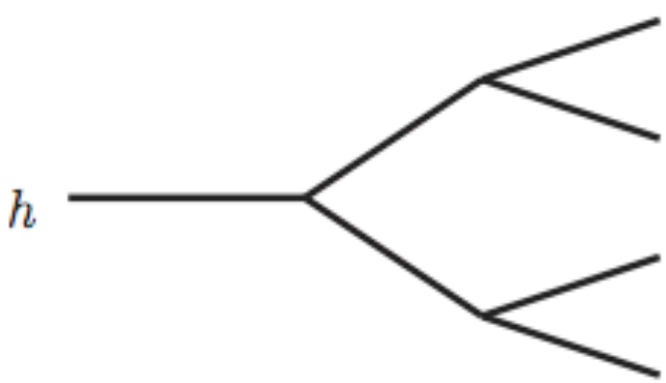
$h \to 2 \to 3$



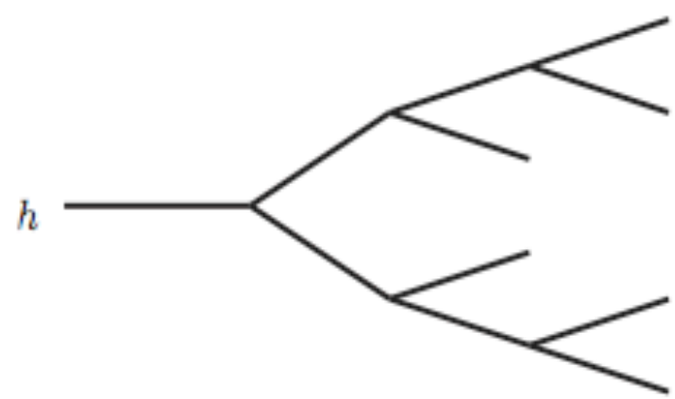
$h \to 2 \to 3 \to 4$



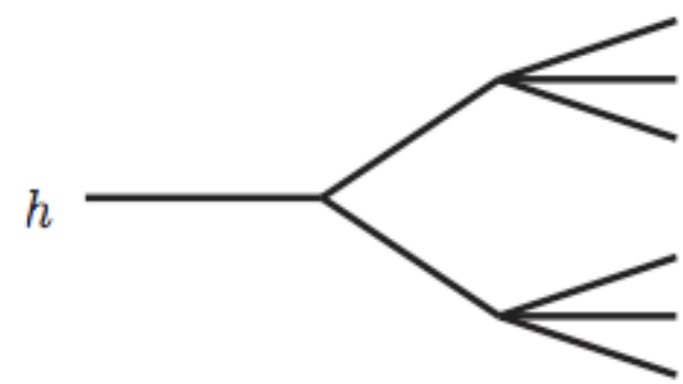
$h \to 2 \to (1+3)$



$h \to 2 \to 4$

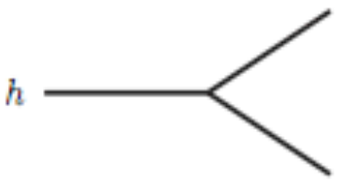


$h \to 2 \to 4 \to 6$

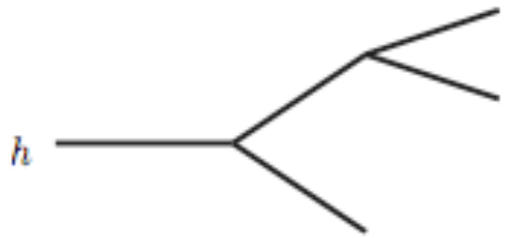


$h \to 2 \to 6$

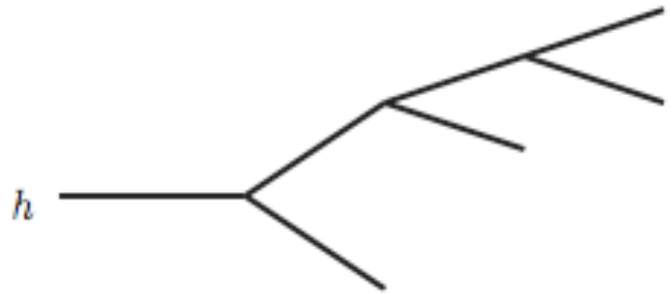
EHD - Various Decay Topologies



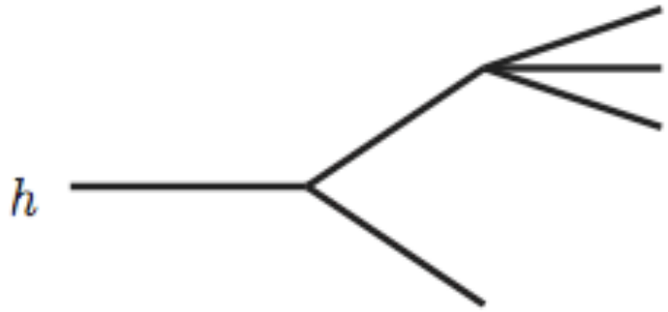
$h \to 2$



$h \to 2 \to 3$

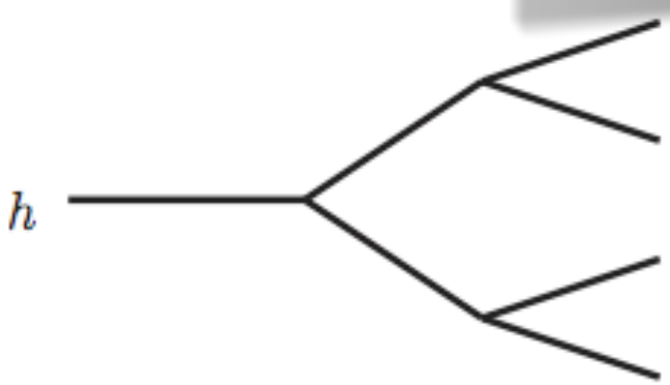


$h \to 2 \to 3 \to 4$

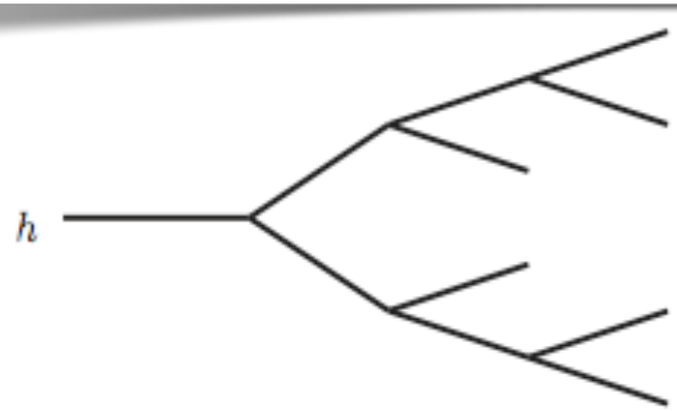


$h \to 2 \to (1+3)$

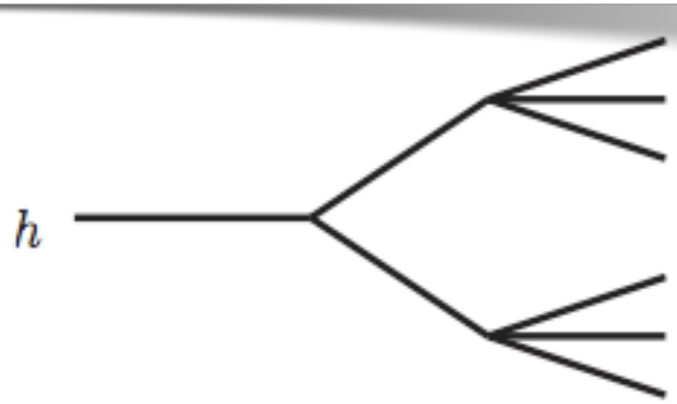
Note: here initial decay is assumed to be 2-body, since 3-body usually suffers a phase space suppression



$h \to 2 \to 4$

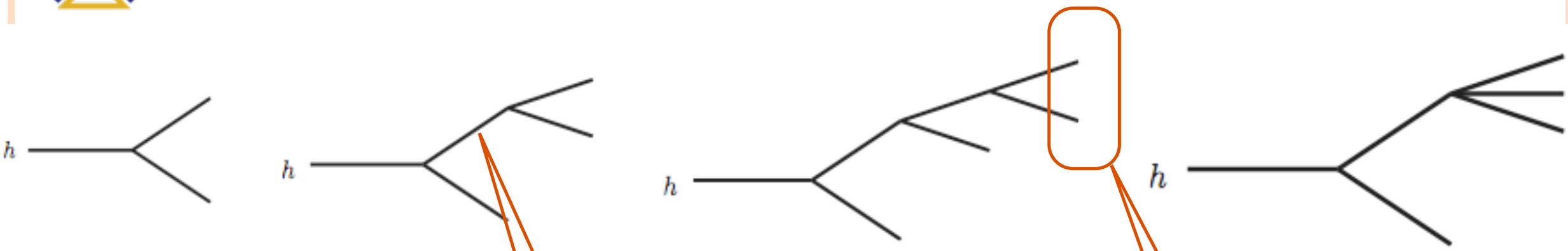


$h \to 2 \to 4 \to 6$



$h \to 2 \to 6$

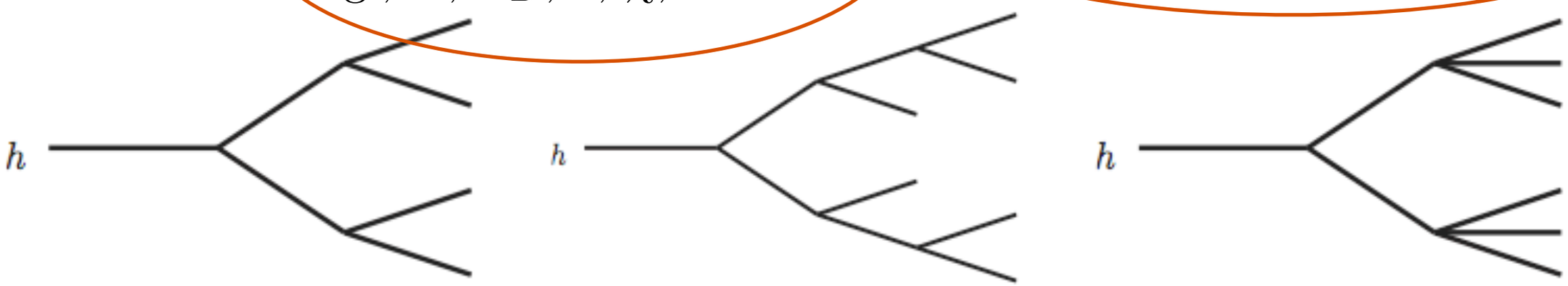
EHD - Various Decay Topologies



$h \to 2$ $\quad$ $h \to 2 \to 3$ $\quad$ $h \to 2 \to 3 \to 4$ $\quad$ $h \to 2 \to (1+3)$

Typically neutral,
either bosonic or fermionic,
e.g., Z, Z_D, s, χ, ...

$e,\ \mu,\ \tau,\ b,\ j,\ \gamma,\ \not{E}_{\mathrm{T}}, \ldots\ldots$



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

EHD - Various Decay Topologies

h -> invisible, semi-visible, visible

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

Can these decay topologies be mapped to various popular theoretical models or scenarios?

EHD - Rich Theories

Simple extensions of the SM:

- SM + singlet scalar
- SM + vector
- SM + singlet fermion

More complicated ones:

- Supersymmetry
- 2HDM + singlet scalar
- Little Higgs
- … …

SM + Singlet Scalar

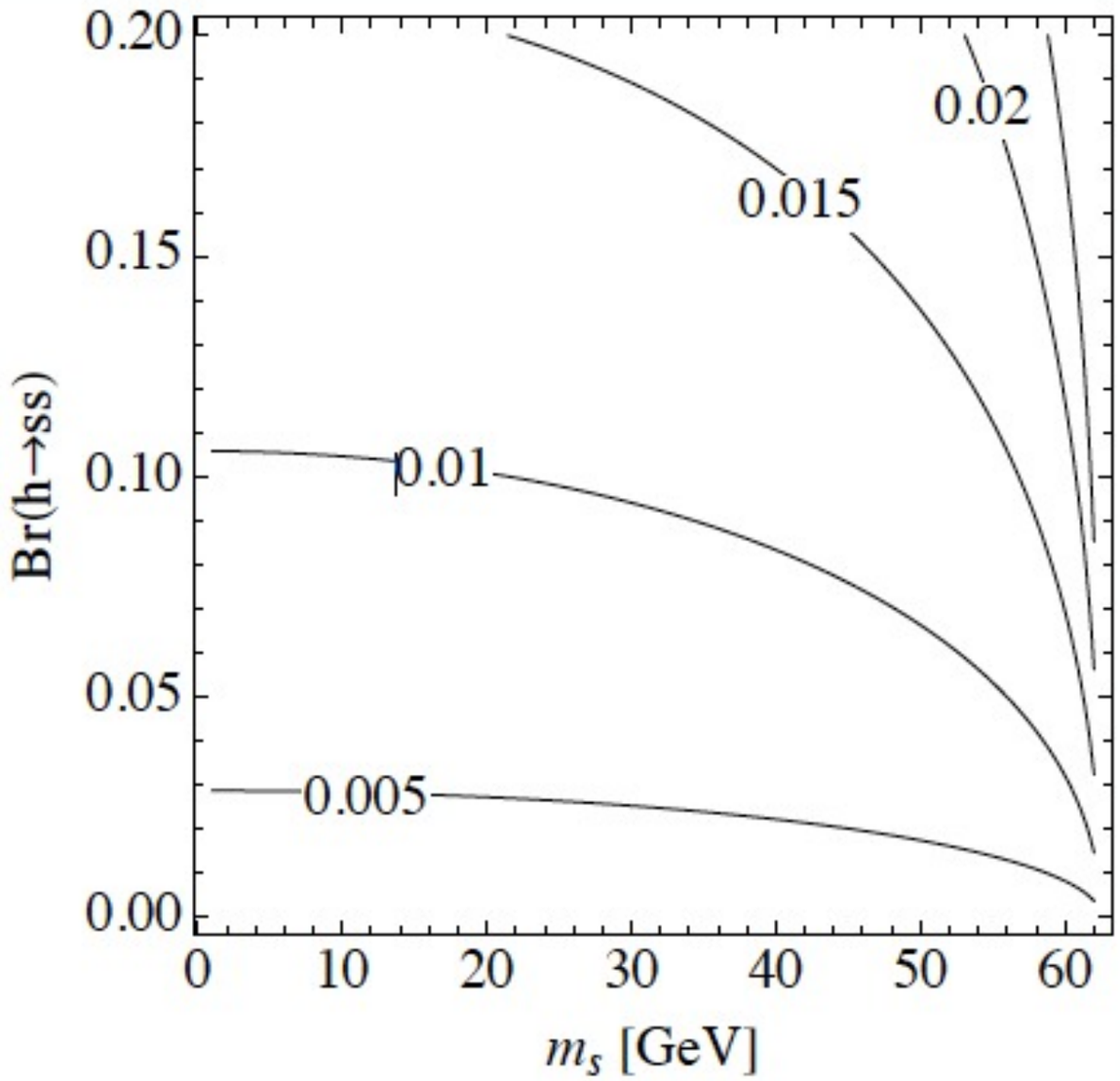
$$V(H,S) = -\mu^2 |H|^2 - \frac{1}{2}\mu'^2 S^2 + \lambda |H|^4 + \frac{1}{4}\kappa S^4 + \frac{1}{2}\zeta S^2 |H|^2$$

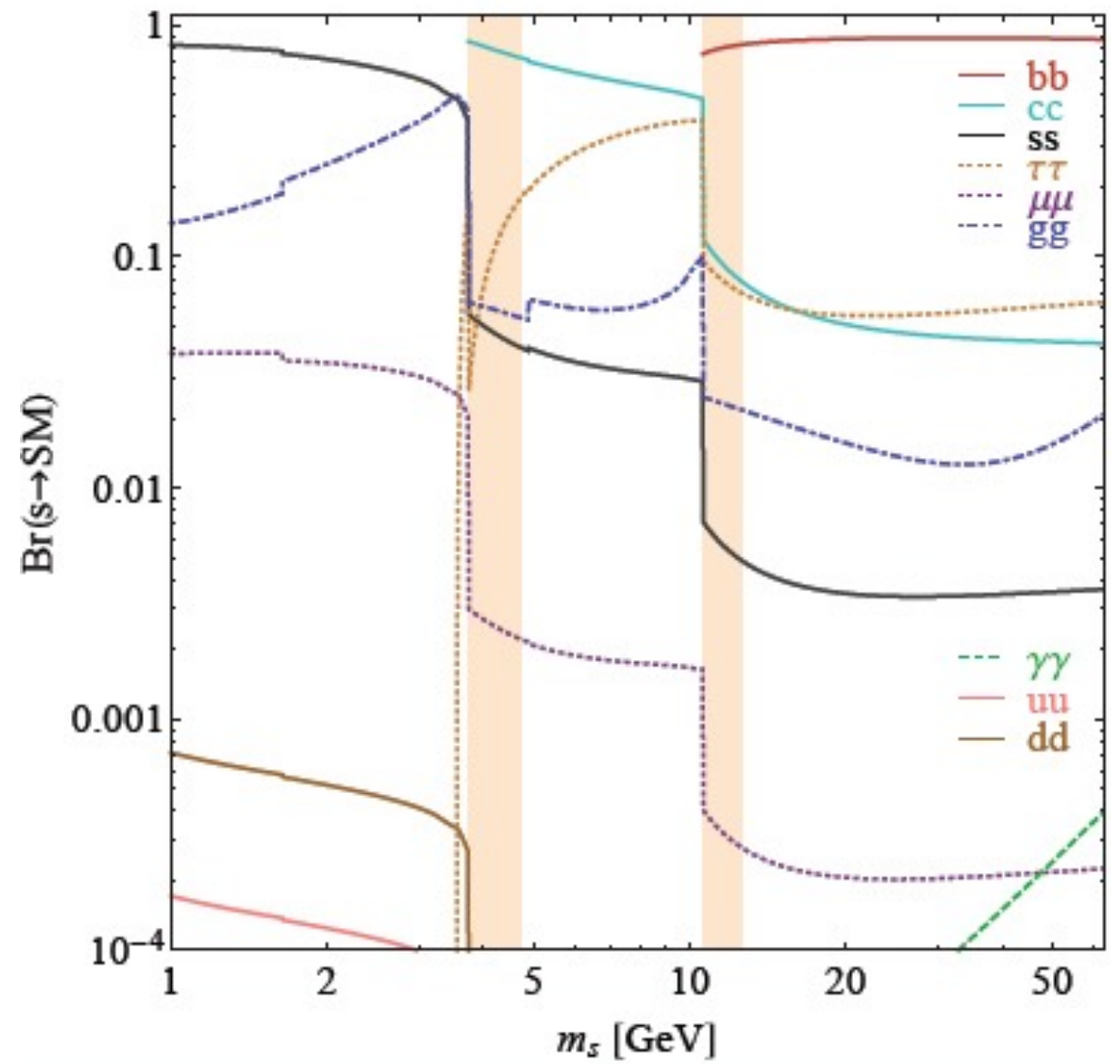
$$\Rightarrow \mathcal{L}_{\rm eff} \sim \mu_v h s s$$

- S is real:
  - If there is a Z2 symmetry under S -> -S, then s is stable, h -> ss = invisible
  - If there is no Z2 symmetry under S -> -S, we have h -> ss -> 4f
- S is complex:
  - there may exist an approximate global U(1) symmetry, giving rise to light pseudo-scalar a, with h -> aa -> 4f

SM + Singlet Scalar

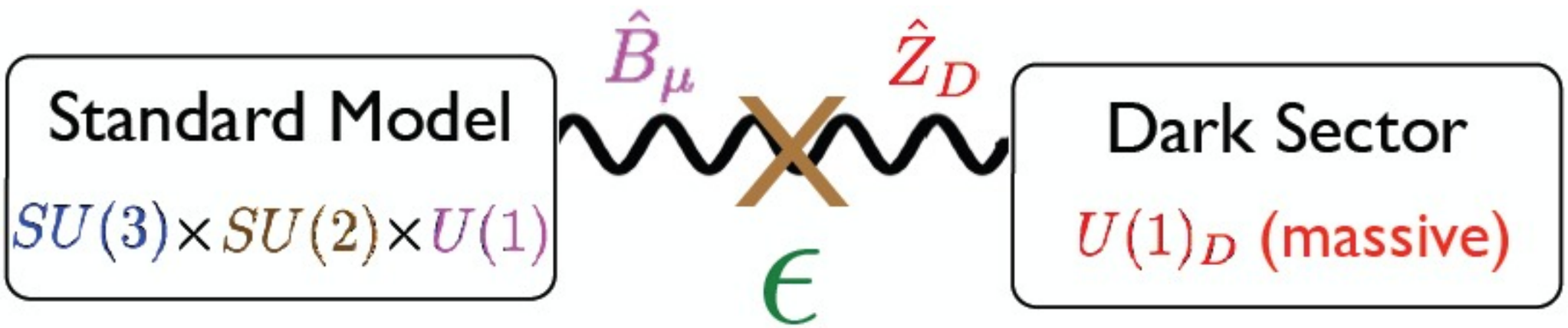
$$V(H,S) = -\mu^2 |H|^2 - \frac{1}{2}\mu'^2 S^2 + \lambda |H|^4 + \frac{1}{4}\kappa S^4 + \frac{1}{2}\zeta S^2 |H|^2$$





- A zeta as small as O(0.01) can lead to a BR as large as 10%
- The BR of s decay is controlled by Yukawa couplings at leading order

SM + Vector

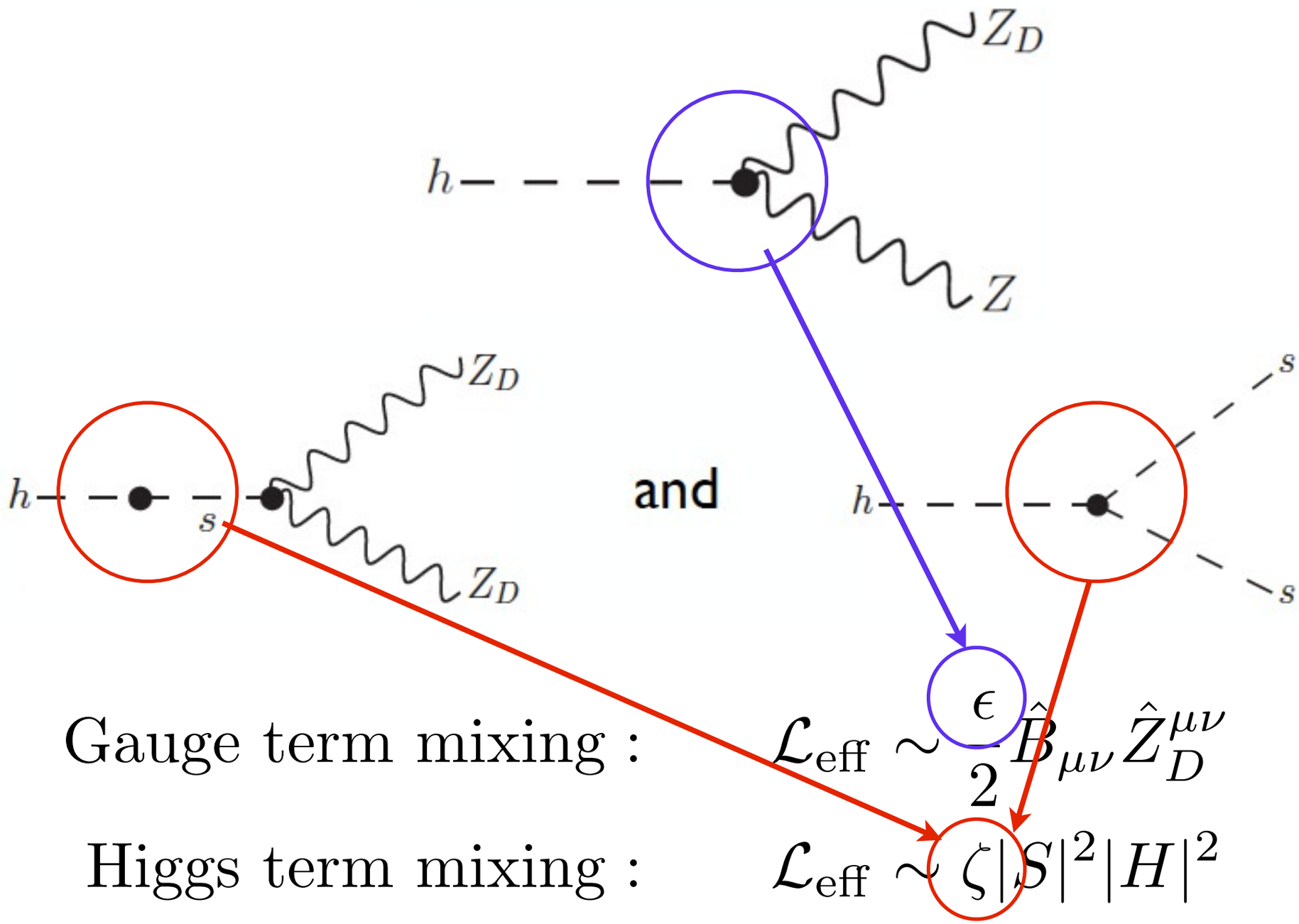


- Dark U(1)D gauge symmetry, broken by a "dark" Higgs, S
- The SM sector and the dark sector can be mixed in two ways:

$$\text{Gauge term mixing}: \qquad \mathcal{L}_{\text{eff}} \sim \frac{\epsilon}{2}\hat{B}_{\mu\nu}\hat{Z}_D^{\mu\nu}$$

$$\text{Higgs term mixing}: \qquad \mathcal{L}_{\text{eff}} \sim \zeta|S|^2|H|^2$$

SM + Vector



$$\text{Gauge term mixing}: \quad \mathcal{L}_{\text{eff}} \sim \frac{\epsilon}{2} \hat{B}_{\mu\nu} \hat{Z}_D^{\mu\nu}$$

$$\text{Higgs term mixing}: \quad \mathcal{L}_{\text{eff}} \sim \zeta |S|^2 |H|^2$$

The relative magnitude of epsilon and zeta determines which one is dominant

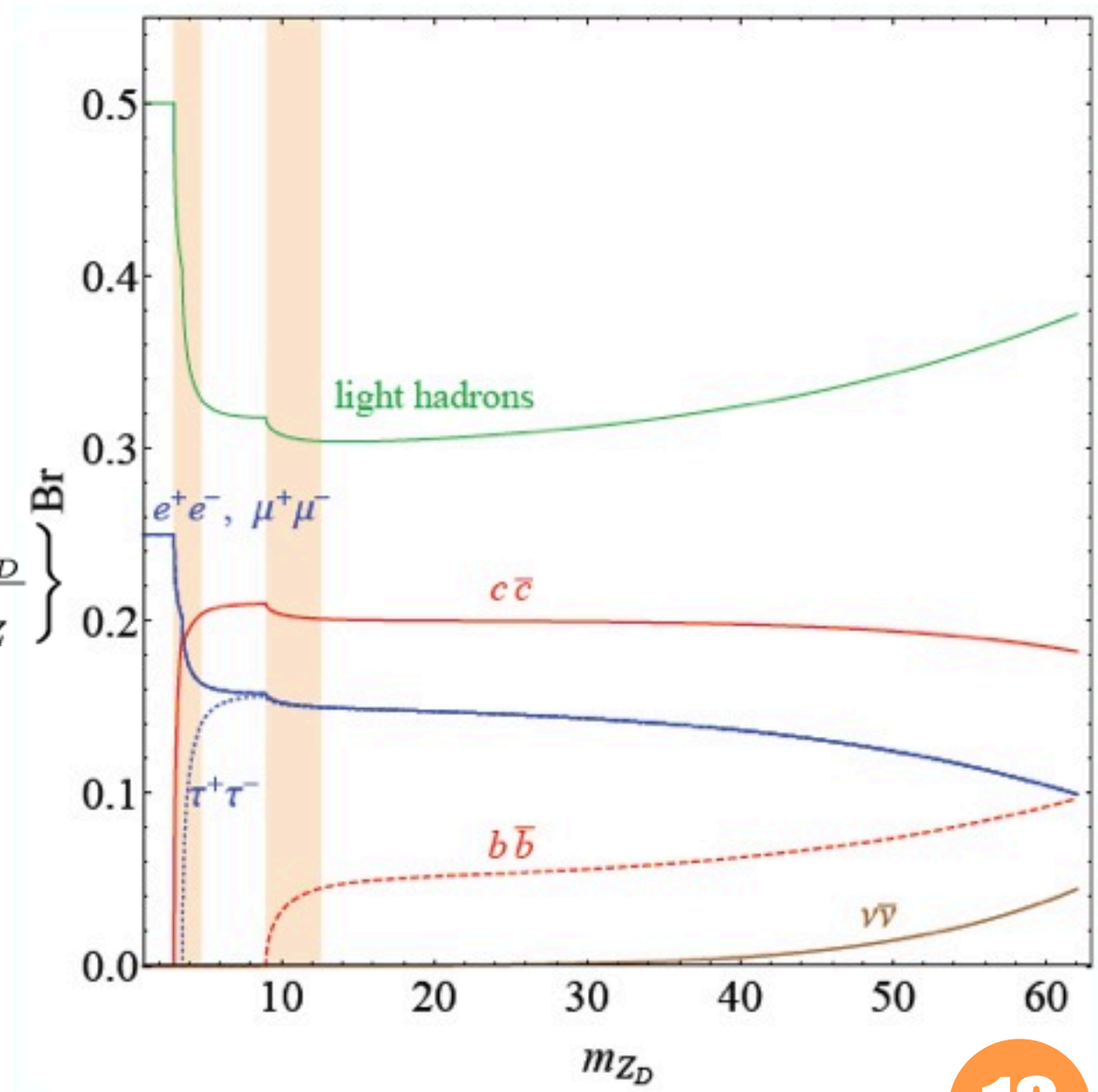
SM + Vector

- Dark photon Z_D is massive. It couples to the SM fermions via gauge term mixing

$$\mathcal{L}_{\rm eff} \sim \frac{\epsilon}{2}\hat{B}_{\mu\nu}\hat{Z}_D^{\mu\nu}$$

- The coupling is given by

$$g_{Z_D ff} \simeq \epsilon\, g' \left\{ -Q\cos\theta_W \left(1+\frac{m_{Z_D}^2}{m_Z^2}\right) + \frac{Y}{\cos\theta_W}\frac{m_{Z_D}^2}{m_Z^2} \right\}$$



- As a comparison, BR to leptons are sizable within a wide mass range of Z_D, since it is controlled by gauge coupling !

SM + Singlet Fermion

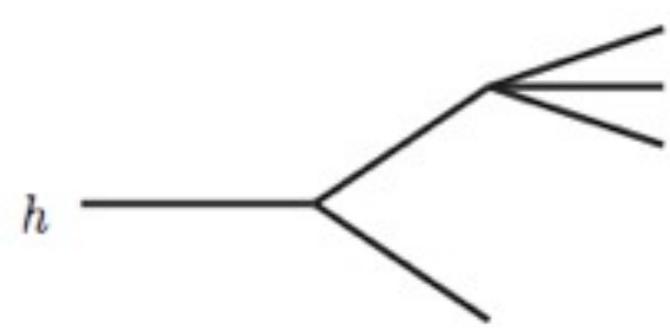
Renormalizable (e.g., nuSM) $\mathcal{L} \sim y\chi HL$

$$\Gamma(h \to \nu\chi) = \frac{|y|^2}{8\pi} m_h \left(1 - \frac{m_\chi^2}{m_h^2}\right)^{3/2}$$

Neutrino data still allow this decay mode to dominate over the bb mode in the SM. In the region of parameter space for which the active-sterile mixing angle is close to its phenomenological upper bound, chi decays promptly into

$$\chi \to \nu Z^* \to \nu f \bar{f}$$

$$\chi \to \ell W^* \to \ell f f'$$



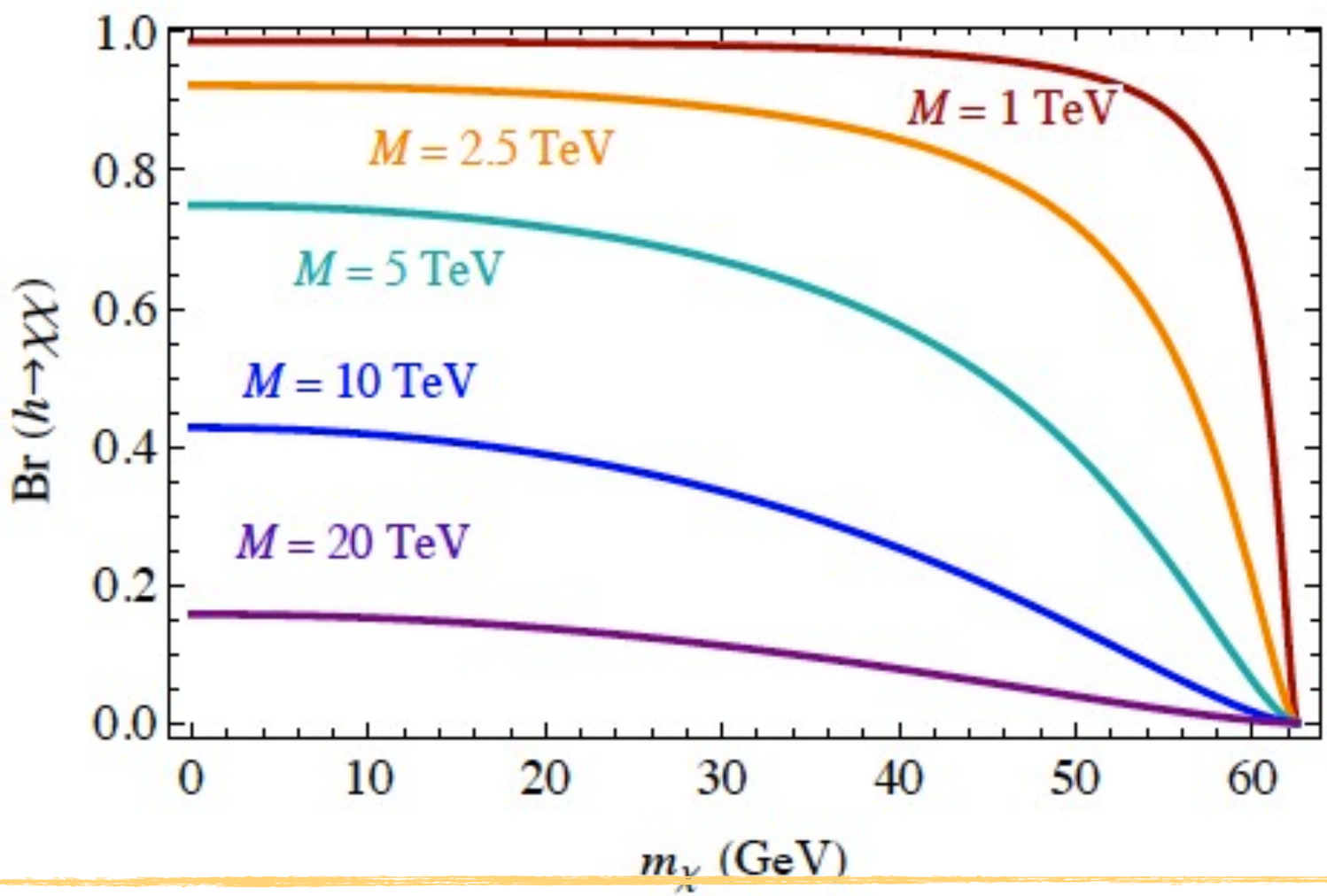
A. de Gouvea, 2007

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

SM + Singlet Fermion

Non-renormalizable

$$\text{Fermionic} : \mathcal{L} \sim \frac{1}{M}\chi\chi|H|^2 \qquad \text{Bosonic} : \mathcal{L} \sim \frac{\zeta\mu}{M^2}\chi\chi|H|^2$$



SM + Singlet Fermion

- If there exists a Z2 symmetry, under

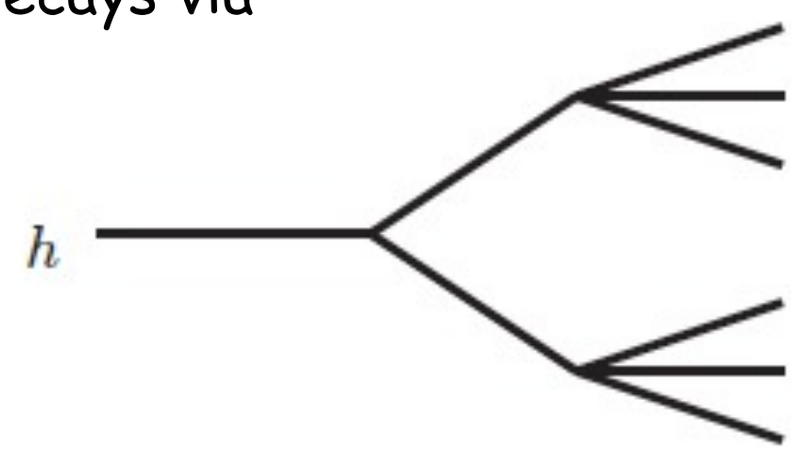
$$\chi \to -\chi$$

then the Higgs decays to invisible

- If Z2 is violated by a dimension-six operator of the form

$$\mathcal{L}_f = \frac{1}{\Lambda^2}\chi f_1 f_2 f_3$$

then the Higgs decays via



$$h \to 2 \to 6$$

Supersymmetric Benchmarks

- Extensively exist: MSSM and its various extensions, with or without R-parity ...
- For illustration, consider the NMSSM with R-parity conservation:

$$W_{NMSSM} = Y_U \mathbf{Q}\mathbf{H}_u\mathbf{U}^c - Y_D \mathbf{Q}\mathbf{H}_d\mathbf{D}^c - Y_E \mathbf{L}\mathbf{H}_d\mathbf{E}^c + \lambda \mathbf{N}\mathbf{H}_u\mathbf{H}_d + \frac{1}{3}\kappa \mathbf{N}^3$$

$$V_{soft} = m_{H_d}^2|H_d|^2 + m_{H_u}^2|H_u|^2 + m_N^2|N|^2 - (\lambda A_\lambda H_u H_d N + \text{h.c.}) + \left(\frac{\kappa}{3}A_\kappa N^3 + \text{h.c.}\right)$$

- h -> light pseudoscalar: R-symmetry limit (Al, Ak -> 0)

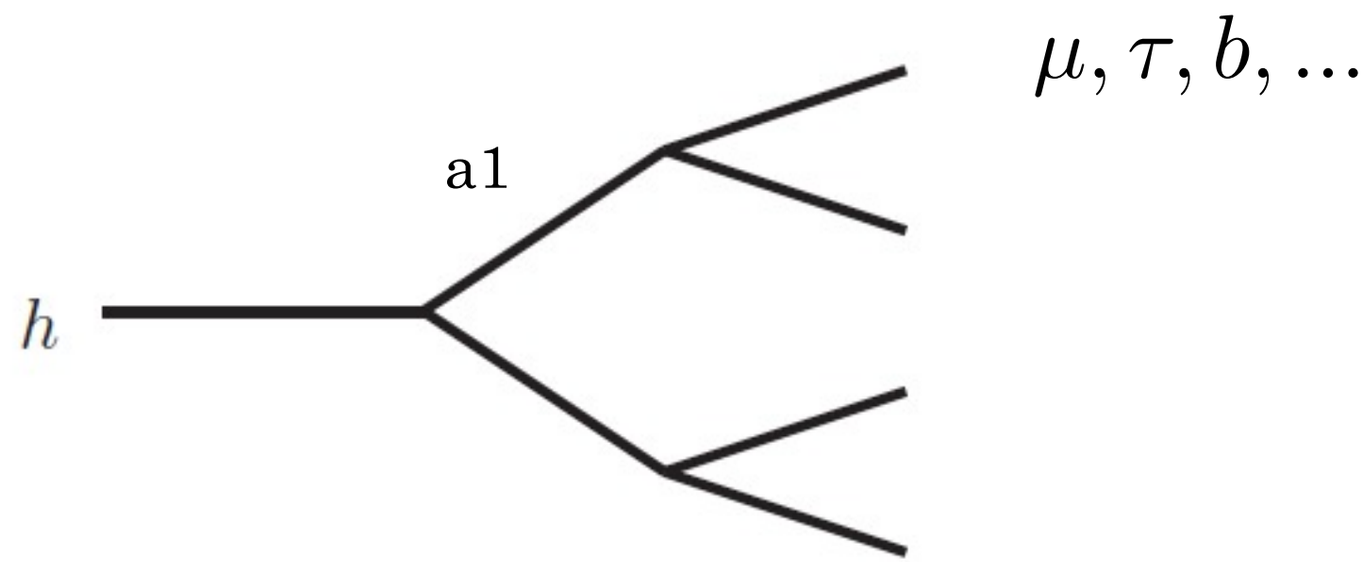
  [B. Dobrescu and K. Matchev, JHEP 0009 (2000) 031; B. Dobrescu, G. Landsberg and K. Matchev, Phys. Rev. D 63 (2001); R. Dermisek, J. Gunion, Phys. Rev. Lett. 95 (2005),...]

- h -> fermions: Peccei-Quinn limit (k -> 0, Ak -> 0)

  [P. Draper, TL, C. Wagner, L-T Wang and H. Zhang, Phys. Rev. Lett. 106 (2011); J. Huang, TL, L-T Wang and F. Yu, to be published in Phys. Rev. Lett., ...]

R-symmetry Limit

- There exists a light singlet-like R-axion a1
- h -> a1a1 is kinematically allowed and typically significant
- Extensive studies were done in the past decade

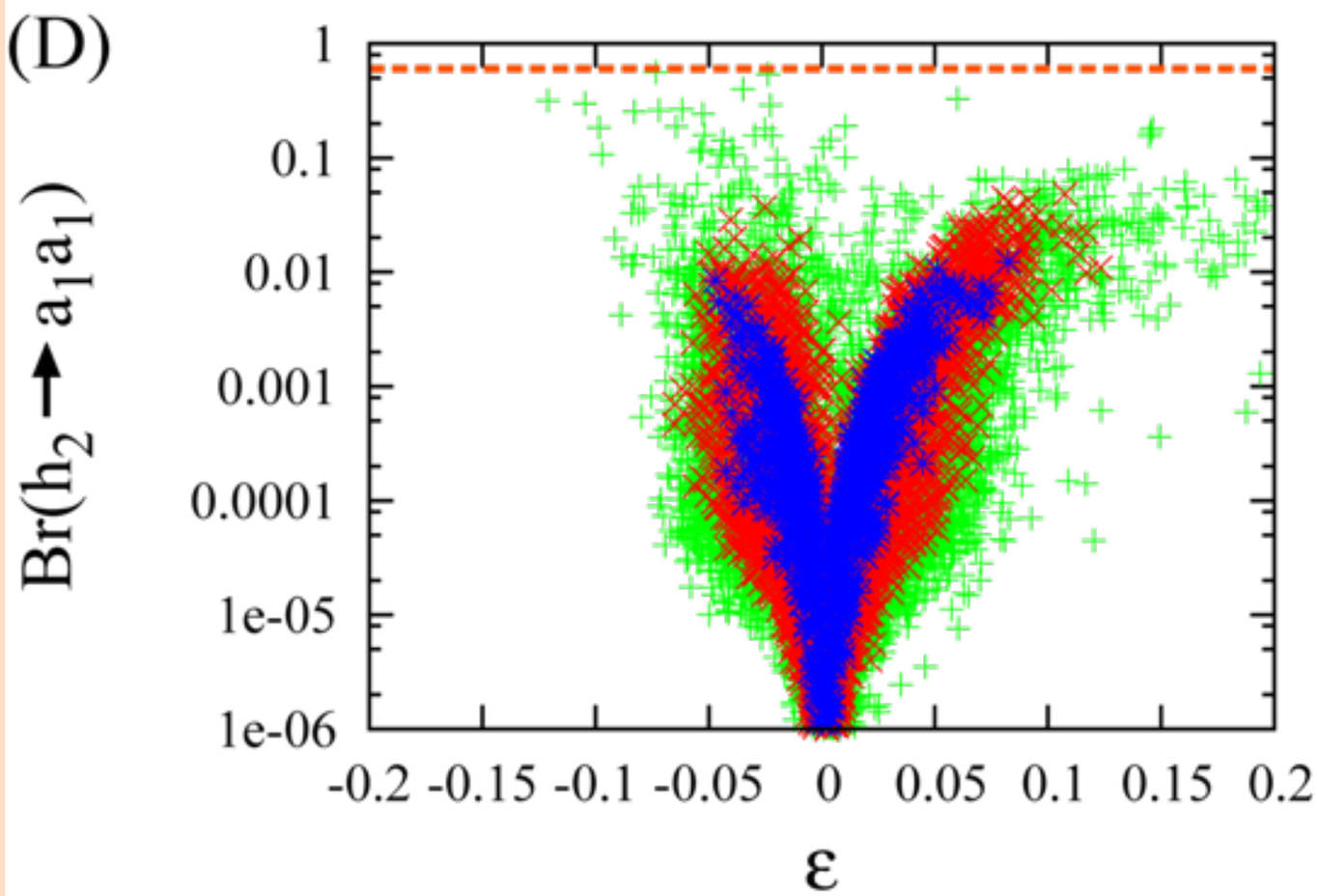


$$h \to 2 \to 4$$

- This possibility can be generalized to 2HDM + S

PQ-symmetry Limit

- There exists a light singlet-like PQ-axion a1
- h -> a1a1 is kinematically allowed but generically suppressed



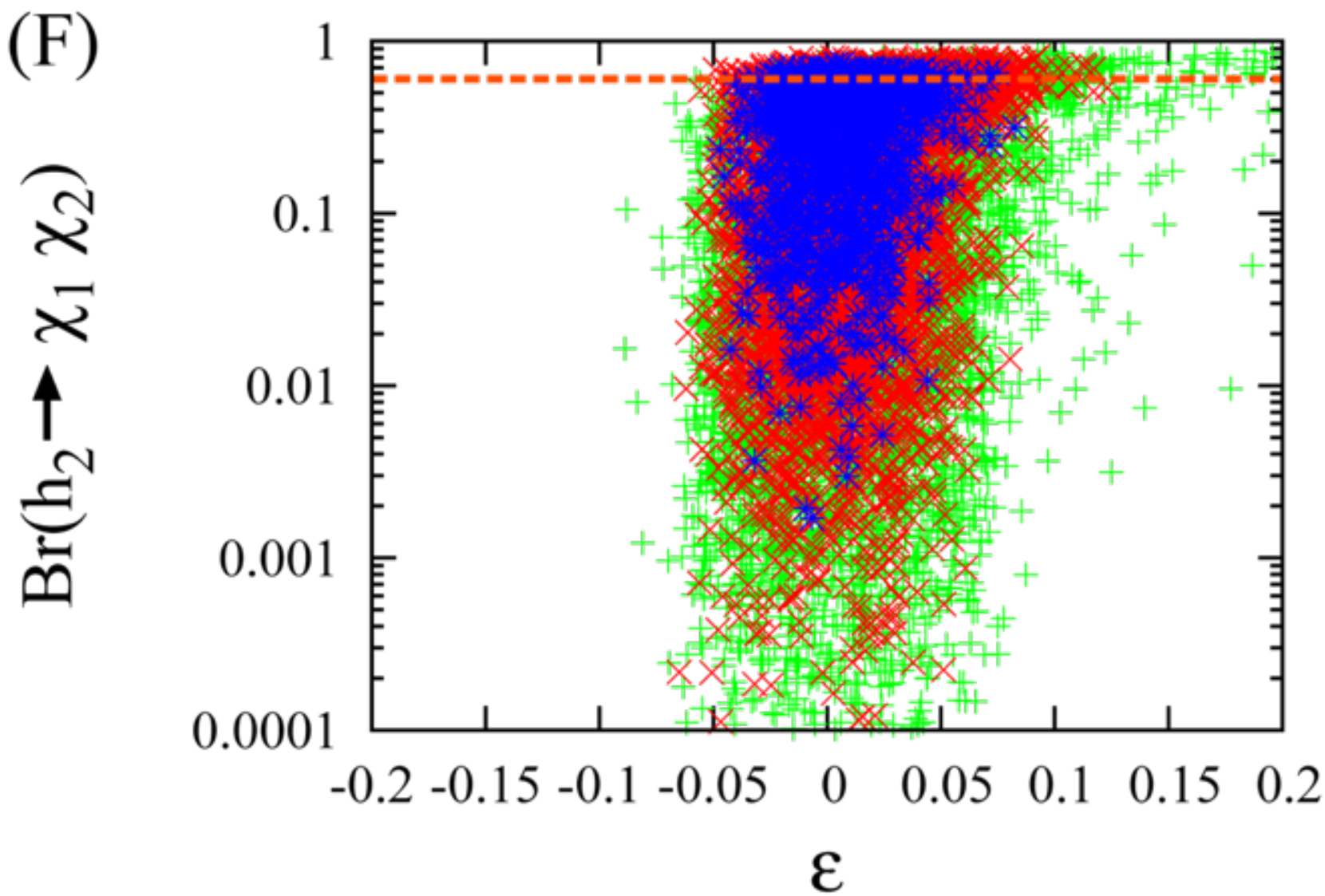
$$m_{h_1}^2 \approx -4v^2\varepsilon^2 + \frac{4\lambda^2 v^2}{\tan^2\beta} \Rightarrow \varepsilon^2 < \frac{\lambda^2}{\tan^2\beta}$$

$$\varepsilon \propto \left(\frac{A_\lambda}{\mu\tan\beta} - 1\right)$$

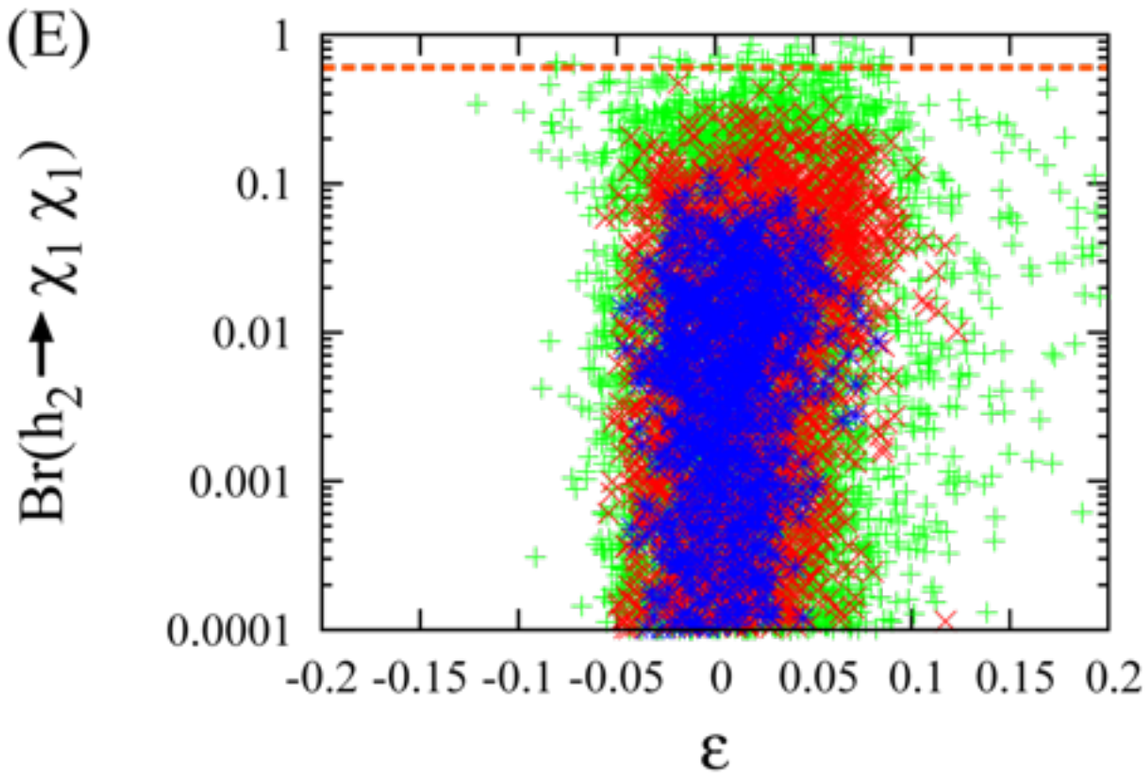
$$y_{h_2 a_1 a_1} \sim -\sqrt{2}\lambda\varepsilon\frac{m_Z v}{\mu}$$

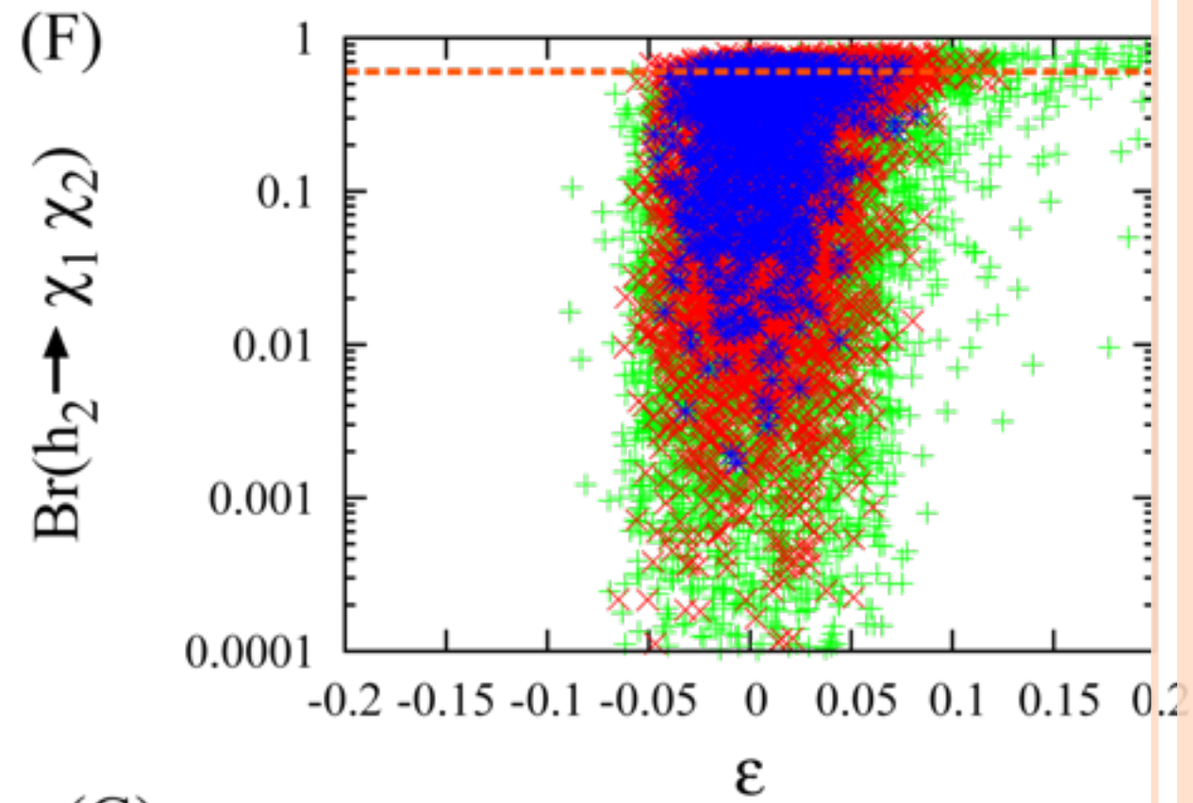
PQ-symmetry Limit

- $h \to \chi_1\chi_2$, $\chi_2\chi_2$ becomes significant, if kinematically allowed!
- It is typical: χ_1 is singlino-like, light in PQ limit (small contribution from the cubic term due to small kappa, different from the R limit) + bino-like χ_2



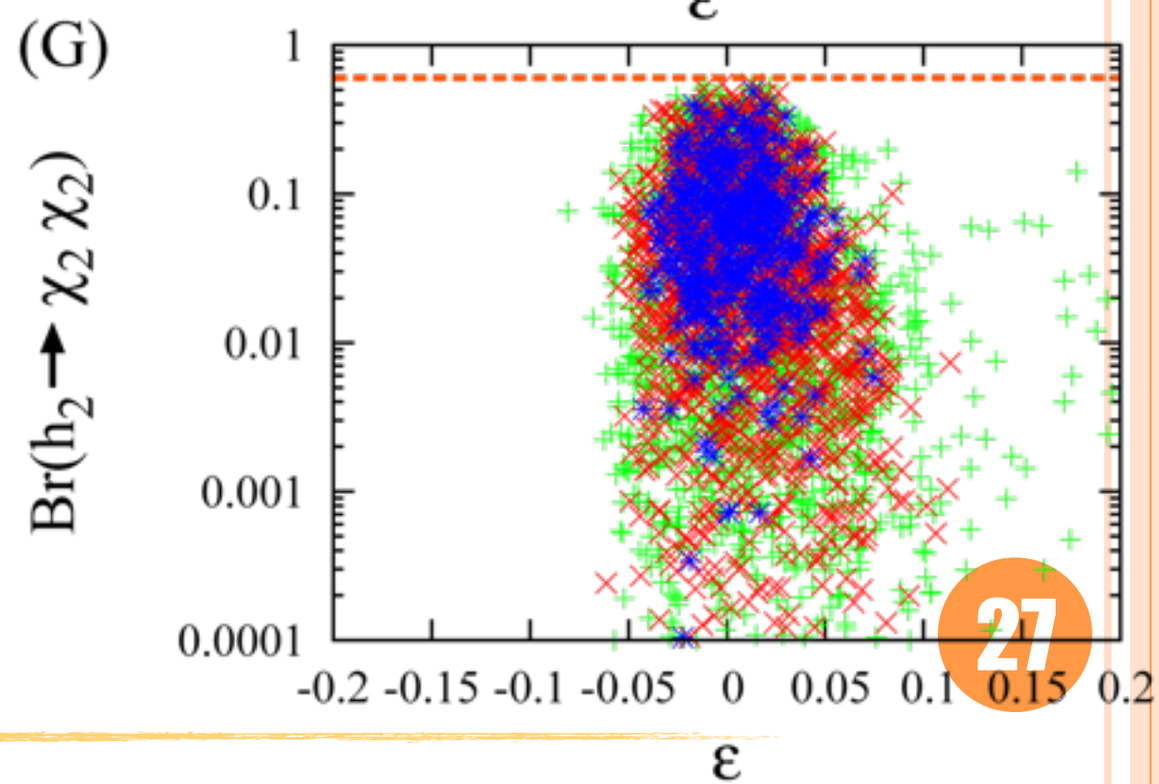
PQ-symmetry Limit



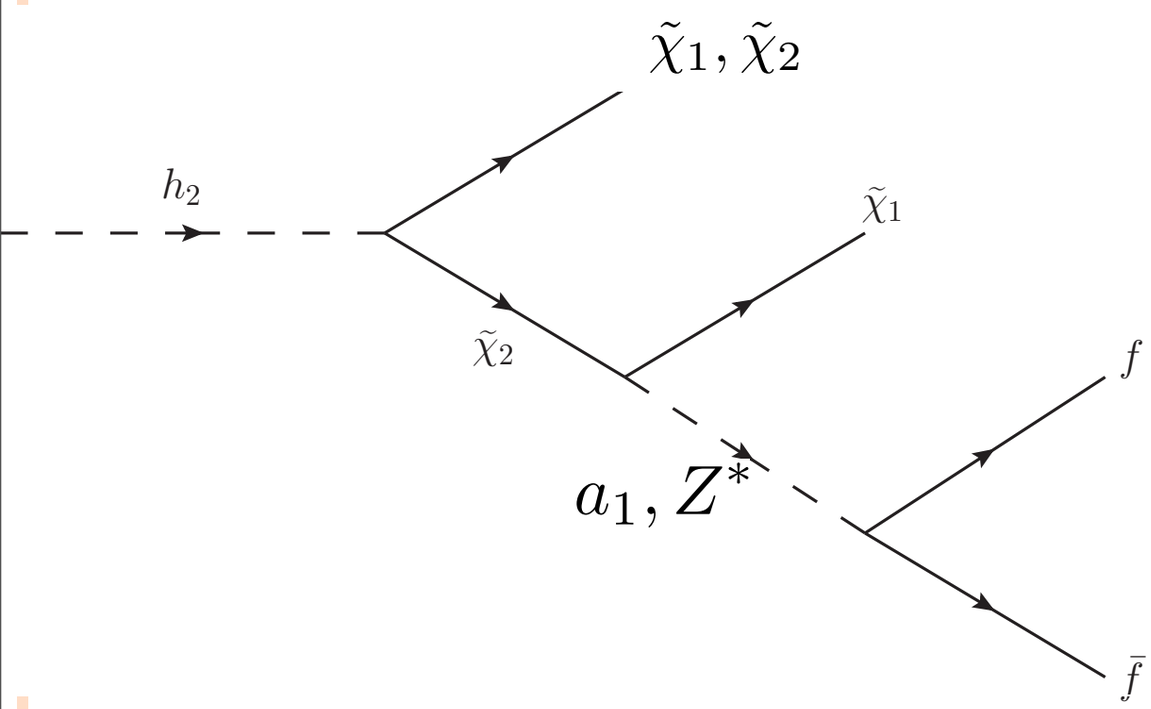


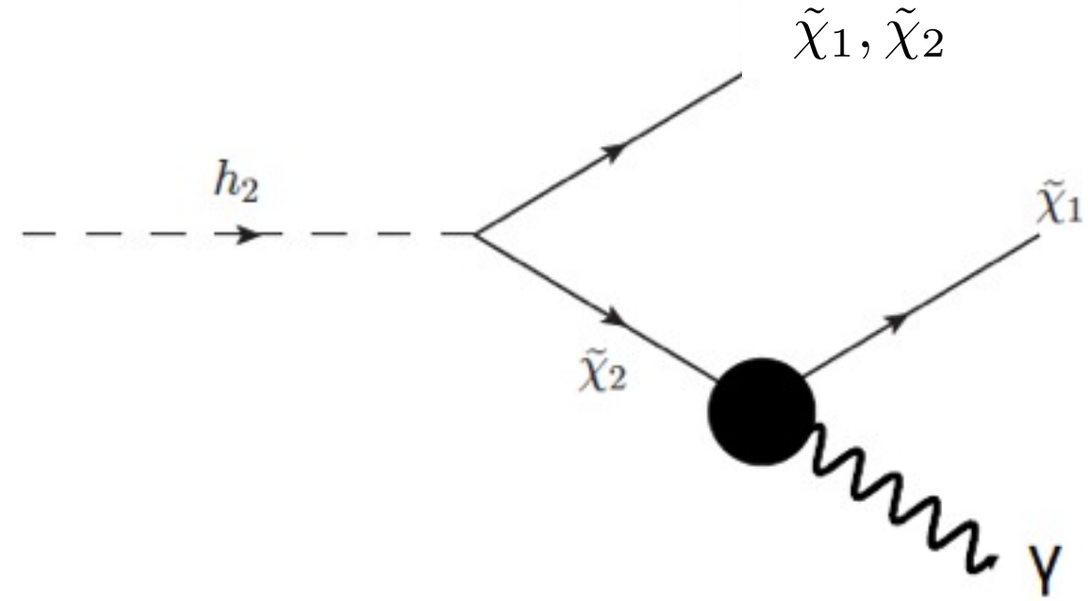
$$y_{h\chi_1\chi_1} \sim \mathcal{O}\left(\frac{\lambda^2 v}{\mu \tan\beta}\right)$$

$$y_{h\chi_1\chi_2} \sim \mathcal{O}\left(\frac{\lambda g_1 v}{\mu}\right)$$



PQ-symmetry Limit

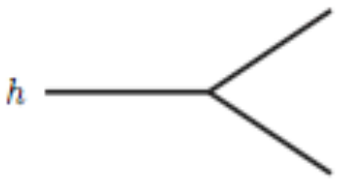




Collider phenomenology: characterized by moderate MET + visible objects

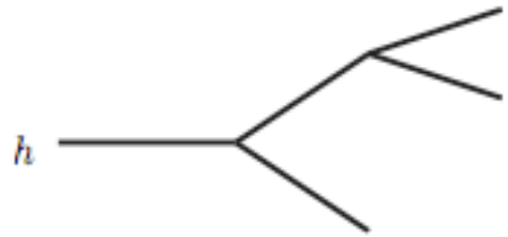
$$h \to \not{E}_{\mathrm{T}} + 2l, 4l, \text{lepton jets}, \tau\bar{\tau}, b\bar{b}, \gamma, \ldots\ldots$$

An Incomplete Summary



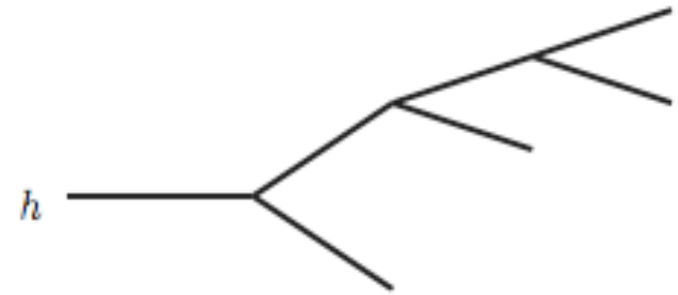
$h \to 2$

e.g., DM models, ...



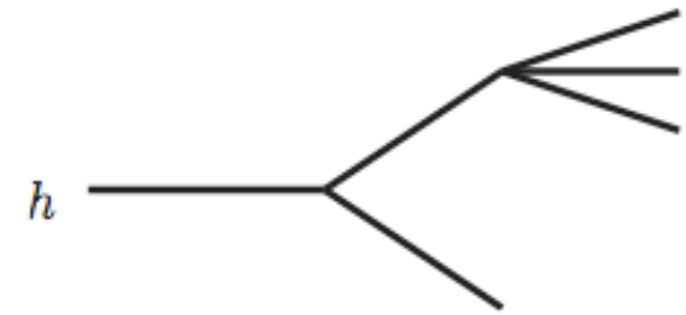
$h \to 2 \to 3$

e.g., SUSY(gauge-mediation),. ..



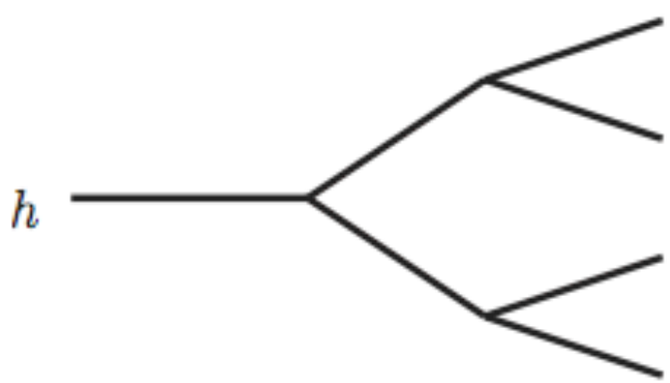
$h \to 2 \to 3 \to 4$

e.g., SM+F, NMSSM(PQ), ...



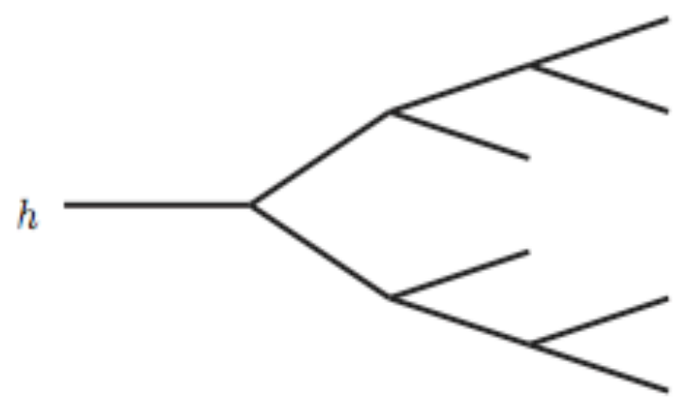
$h \to 2 \to (1+3)$

e.g, SM+F, NMSSM(PQ),...



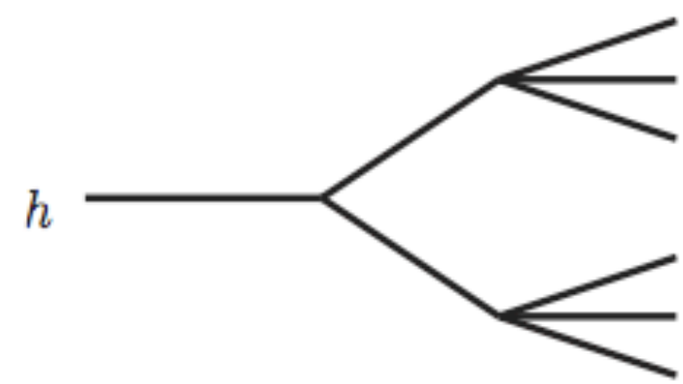
$h \to 2 \to 4$

e.g., SM+S, SM+V, NMSSM(R), 2HDM+S, ...



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

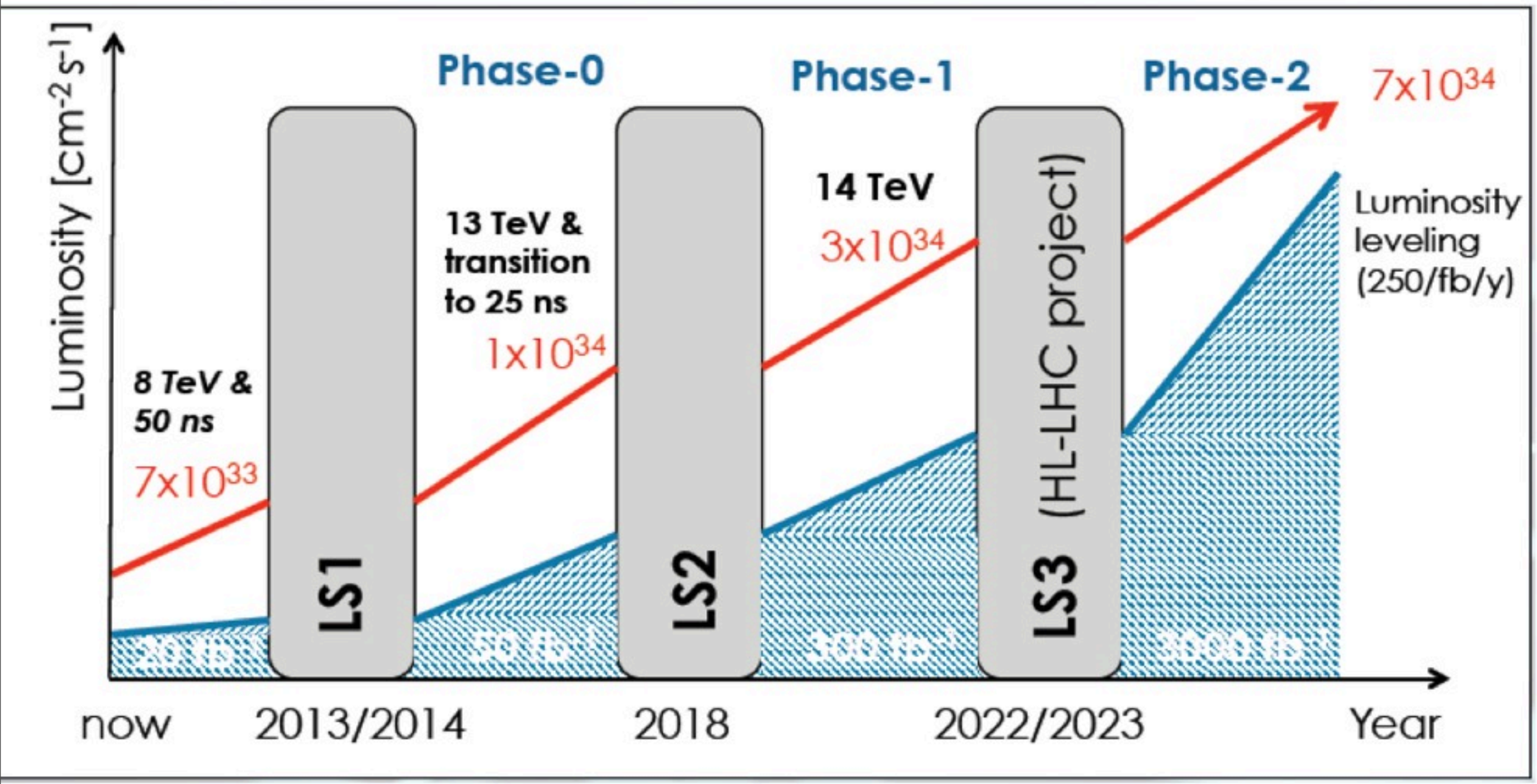
e.g., SM+F, NMSSM(PQ), ...



$h \to 2 \to 6$

e.g., SM+F, ...

LHC Upgrade Plan



The LHC provides an opportunity to explore the rich phenomenology of exotic Higgs decays.

How Many Exotic Decay Events Generated?

Production	$\sigma_{7\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 5 fb^{-1}	$\sigma_{8\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 20 fb^{-1}	$\sigma_{14\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 300 fb^{-1}
ggF	15.13	7,600	19.27	38,500	49.85	1.5×10^6
VBF	1.22	610	1.58	3,200	4.18	125,000
$hW^{\pm}$	0.58	290	0.70	1,400	1.5	45,000
$hW^{\pm}(\ell^{\pm}\nu)$	$0.58 \cdot 0.21$	62	$0.70 \cdot 0.21$	300	$1.5 \cdot 0.21$	9,600
hZ	0.34	170	0.42	830	0.88	26,500
$hZ(\ell^+\ell^-)$	$0.34 \cdot 0.067$	11	$0.42 \cdot 0.067$	56	$0.88 \cdot 0.067$	1,800
$t\bar{t}h$	0.086	43	0.13	260	0.61	18,300

- Many events in ggF/VBF, but only suitable for searches for some of the exotic decay modes
- Can always trigger w/ AP… but statistics is low
- Specific signature: decay products are typically soft, sometimes collimated

  => dedicated search strategies are required

How Many Exotic Decay Events Generated?

Production	$\sigma_{7\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 5 fb^{-1}	$\sigma_{8\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 20 fb^{-1}	$\sigma_{14\ \mathrm{TeV}}$ (pb)	$N_{ev}^{10\%}$, 300 fb^{-1}
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$t\bar{t}h$	0.086	43	0.13	260	0.61	18,300

What is their discovery potential at LHC8 ? At LHC14? And even at a future Higgs factory?

The ``Exotic Higgs Decay Working Group''

D. Curtin, R. Essig, S. Gori, P. Jaiswal,
A. Katz, TL, Z. Liu,
D. McKeen, J. Shelton, M. Strassler,
Z. Surujon, B. Tweedie, Y. Zhong

Self-formed group of theorists. Our aims are:

- Survey, systematize, prioritize exotic Higgs decays
- Develop search strategies, assess discovery potential, provide viable benchmark models/points
- Inform trigger selection for LHC14
- Assemble comprehensive summary document & construct a website to inform experimental analyses

Eventually, … …

arXiv.org > hep-ph > arXiv:1312.4992

Search or

High Energy Physics - Phenomenology

Exotic Decays of the 125 GeV Higgs Boson

David Curtin, Rouven Essig, Stefania Gori, Prerit Jaiswal, Andrey Katz, Tao Liu, Zhen Liu, David McKeen, Jessie Shelton, Matthew Strassler, Ze'ev Surujon, Brock Tweedie, Yi-Ming Zhong

(Submitted on 17 Dec 2013)

We perform an extensive survey of non-standard Higgs decays that are consistent with the 125 GeV Higgs-like resonance. Our aim is to motivate a large set of new experimental analyses on the existing and forthcoming data from the Large Hadron Collider (LHC). The explicit search for exotic Higgs decays presents a largely untapped discovery opportunity for the LHC collaborations, as such decays may be easily missed by other searches. We emphasize that the Higgs is uniquely sensitive to the potential existence of new weakly coupled particles and provide a unified discussion of a large class of both simplified and complete models that give rise to characteristic patterns of exotic Higgs decays. We assess the status of exotic Higgs decays after LHC Run 1. In many cases we are able to set new nontrivial constraints by reinterpreting existing experimental analyses. We point out that improvements are possible with dedicated analyses and perform some preliminary collider studies. We prioritize the analyses according to their theoretical motivation and their experimental feasibility. This document is accompanied by a website that will be continuously updated with further information: this http URL

Comments: 172 pages + references and appendices, 34 figures, 20 tables. Enjoy!
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:1312.4992 [hep-ph]
(or arXiv:1312.4992v1 [hep-ph] for this version)

Summary I: Highly Motivated Searches at LHC7 + LHC8

- Search for $h \to Z_D Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$ .....
- Search for $h \to Z Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$ .....
- Search for $h \to \ell^+\ell^- +$ MET, including regimes where the leptons are collimated, and including the cases where there is a resonance in $m_{\ell\ell}$. Benchmark models include $h \to XY \to aYY$ or Z^*YY, $h \to XX \to aa^{(\prime)}YY$ for $m_a < 2m_\tau$, $h \to XX \to Z^*Z^*YY$, where Y is invisible and Z^* is an off-shell Z boson.
- Search for $h \to \ell^+\ell^-\ell^+\ell^- +$ MET .....
- Search for $h \to aa \to (b\bar{b})(\mu^+\mu^-)$ .....
- Search for $h \to aa \to (\tau^+\tau^-)(\mu^+\mu^-)$ .....
- Search for $h \to aa \to (\gamma\gamma)(\gamma\gamma)$ .....
- Search for $h \to \gamma\gamma +$ MET .....

Summary II: Further Studies

- $h \to 2 \to 6$ e.g. decays of the Higgs to neutralinos that decay via R-parity violation to three jets, etc.
- h to complex lepton jets (*i.e.* with > 2 tracks), including both purely electronic, purely muonic, purely leptonic with a mix of muons and electrons, and mixed leptonic/hadronic jets.
- Decays to one or more photonic jets (consisting of ≥ 2 collimated photons) need more experimental study.
- h decaying to long-lived particles with decays in flight.
- It is urgent that further studies be done on the more difficult channels, such as $b\bar{b}\tau\tau$, $b\bar{b}+$ MET, $\tau\tau+$ MET, $jj\gamma\gamma$, in the context of VBF production. If such studies reveal VBF can yield significant improvements in sensitivity, then developing triggers for 2015 aimed at these final states may be crucial.
- Sensitivities at future colliders: ILC, TLEP, CEPC-SppC, ...
- ... ...

Indeed, exotic Higgs decays look exotic … …

But behind that, there might exist a landscape
that we have never seen before ... ...

"The Future of High Energy Physics", Hong Kong IAS, Jan, 2015

International Organizing Committee: John Ellis, David Gross, Peter Jenni, Hitoshi Murayama*, Nigel Lockyer, Yifang Wang, Shing-Tung Yau

Local Coordinators: Nima Akani-Hamed, Ming-Chung Chu, Hong-Jian He, Tao Liu, Kam Biu Luk, Xinchou Lou*, Qing Qin*

Golden Research Conference, "Physics at 14 TeV LHC", Hong Kong IAS, June, 2015

Chair: John Ellis, Vice-chairs: Hitoshi Murayama, Tao Liu

Thank you!

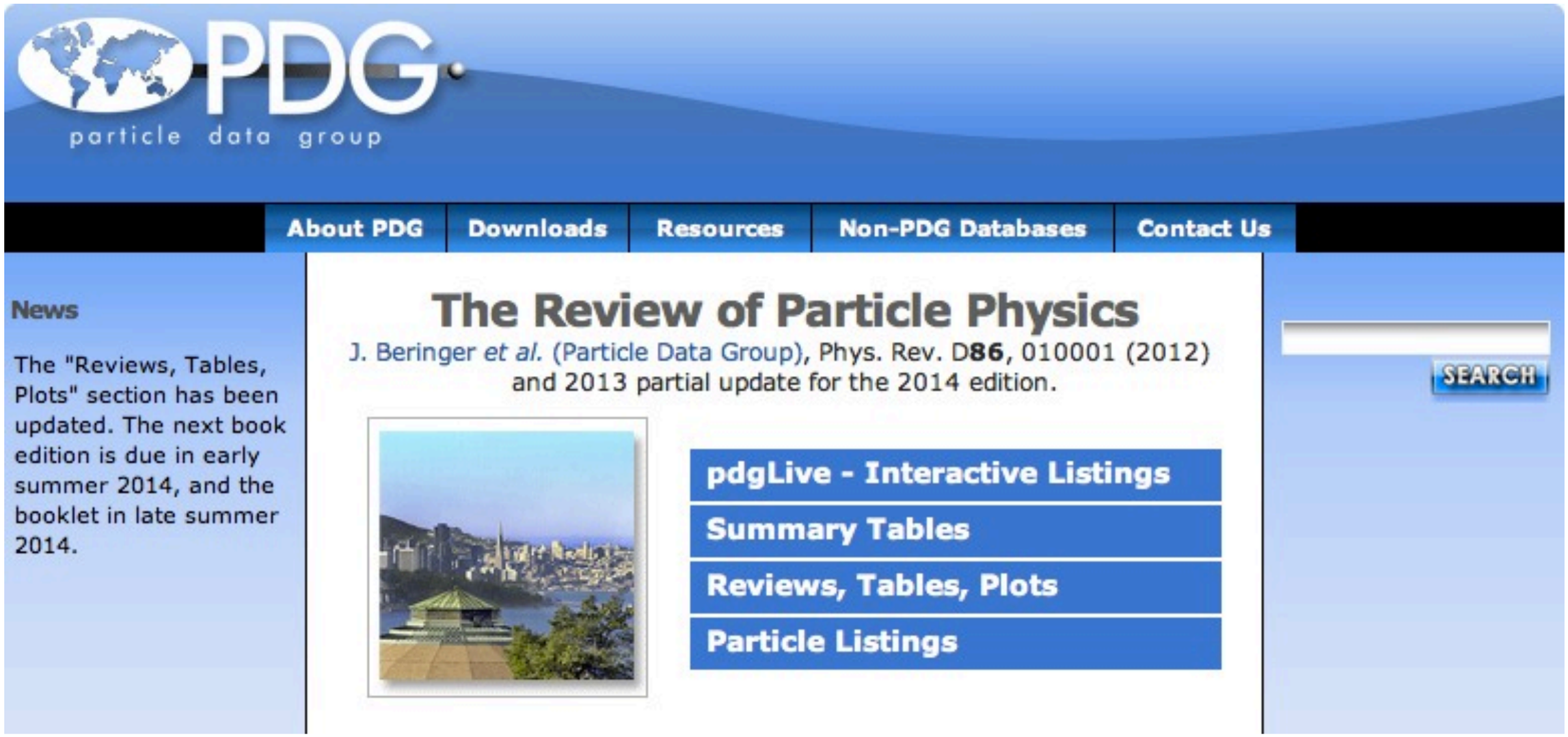
Z Boson Measurements (from PDG)

Z DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
e^+e^-		(3.363 ±0.004) %		45594
$\mu^+\mu^-$		(3.366 ±0.007) %		45594
$\tau^+\tau^-$		(3.370 ±0.008) %		45559
$\ell^+\ell^-$	[b]	(3.3658±0.0023) %		–
invisible		(20.00 ±0.06) %		–
hadrons		(69.91 ±0.06) %		–
$(u\bar{u}+c\bar{c})/2$		(11.6 ±0.6) %		–
$(d\bar{d}+s\bar{s}+b\bar{b})/3$		(15.6 ±0.4) %		–
$c\bar{c}$		(12.03 ±0.21) %		–
$b\bar{b}$		(15.12 ±0.05) %		–
$b\bar{b}b\bar{b}$		(3.6 ±1.3) $\times 10^{-4}$		–
ggg		< 1.1 %	CL=95%	–
$\pi^0\gamma$		< 5.2 $\times 10^{-5}$	CL=95%	45594
$\eta\gamma$		< 5.1 $\times 10^{-5}$	CL=95%	45592
$\omega\gamma$		< 6.5 $\times 10^{-4}$	CL=95%	45590
$\eta'(958)\gamma$		< 4.2 $\times 10^{-5}$	CL=95%	45589
$\gamma\gamma$		< 5.2 $\times 10^{-5}$	CL=95%	45594
$\gamma\gamma\gamma$		< 1.0 $\times 10^{-5}$	CL=95%	45594
$\pi^\pm W^\mp$	[h]	< 7 $\times 10^{-5}$	CL=95%	10162
$\rho^\pm W^\mp$	[h]	< 8.3 $\times 10^{-5}$	CL=95%	10136
$J/\psi(1S)X$		(3.51 $^{+0.23}_{-0.25}$) $\times 10^{-3}$	S=1.1	–
$\psi(2S)X$		(1.60 ±0.29) $\times 10^{-3}$		–
$\chi_{c1}(1P)X$		(2.9 ±0.7) $\times 10^{-3}$		–
$\chi_{c2}(1P)X$		< 3.2 $\times 10^{-3}$	CL=90%	–
$\Upsilon(1S)X+\Upsilon(2S)X+\Upsilon(3S)X$		(1.0 ±0.5) $\times 10^{-4}$		–
$\Upsilon(1S)X$		< 4.4 $\times 10^{-5}$	CL=95%	–
$\Upsilon(2S)X$		< 1.39 $\times 10^{-4}$	CL=95%	–
$\Upsilon(3S)X$		< 9.4 $\times 10^{-5}$	CL=95%	–
$(D^0/\bar{D}^0)X$		(20.7 ±2.0) %		–
$D^\pm X$		(12.2 ±1.7) %		–
$D^*(2010)^\pm X$	[h]	(11.4 ±1.3) %		–
$D_{s1}(2536)^\pm X$		(3.6 ±0.8) $\times 10^{-3}$		–
$D_{sJ}(2573)^\pm X$		(5.8 ±2.2) $\times 10^{-3}$		–
$D^{*\prime}(2629)^\pm X$		searched for		–
B^+X	[i]	(6.08 ±0.13) %		–
B^0_sX	[i]	(1.59 ±0.13) %		–
B^+_cX		searched for		–
Λ^+_cX		(1.54 ±0.33) %		–
Ξ^0_cX		seen		–
Ξ_bX		seen		–
b-baryon X	[i]	(1.38 ±0.22) %		–
anomalous $\gamma+$ hadrons	[j]	< 3.2 $\times 10^{-3}$	CL=95%	–
$e^+e^-\gamma$	[j]	< 5.2 $\times 10^{-4}$	CL=95%	45594
$\mu^+\mu^-\gamma$	[j]	< 5.6 $\times 10^{-4}$	CL=95%	45594
$\tau^+\tau^-\gamma$	[j]	< 7.3 $\times 10^{-4}$	CL=95%	45559
$\ell^+\ell^-\gamma\gamma$	[k]	< 6.8 $\times 10^{-6}$	CL=95%	–
$q\bar{q}\gamma\gamma$	[k]	< 5.5 $\times 10^{-6}$	CL=95%	–
$\nu\bar{\nu}\gamma\gamma$	[k]	< 3.1 $\times 10^{-6}$	CL=95%	45594
$e^\pm\mu^\mp$	LF [h]	< 1.7 $\times 10^{-6}$	CL=95%	45594
$e^\pm\tau^\mp$	LF [h]	< 9.8 $\times 10^{-6}$	CL=95%	45576
$\mu^\pm\tau^\mp$	LF [h]	< 1.2 $\times 10^{-5}$	CL=95%	45576
pe	L,B	< 1.8 $\times 10^{-6}$	CL=95%	45589
$p\mu$	L,B	< 1.8 $\times 10^{-6}$	CL=95%	45589

SM decays

Non-standard decays

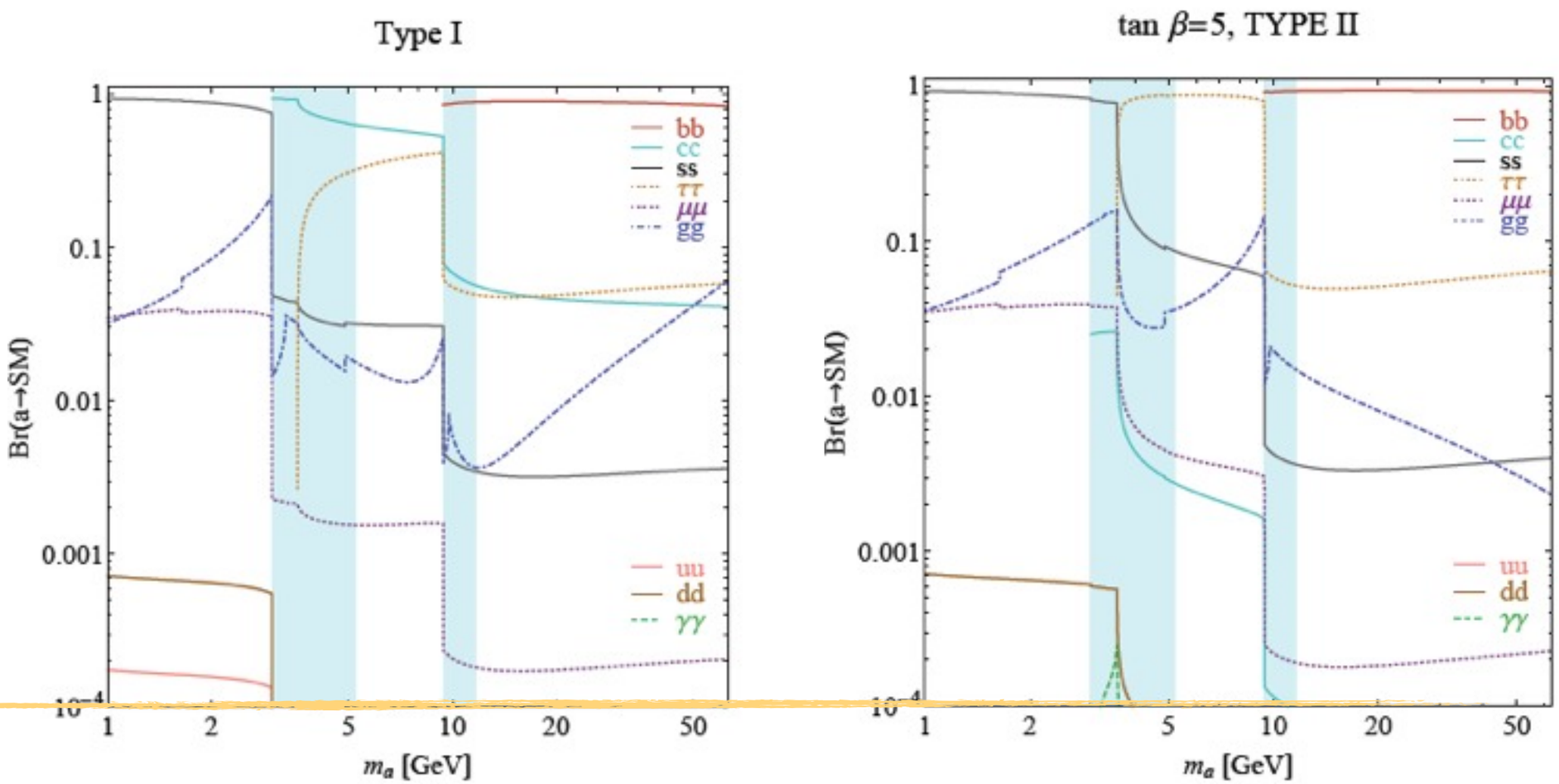
Particle Data Group



Hopefully in the near future similar entries will be created for the 125GeV Higgs boson

2HDM + Singlet Scalar

- This can be generalized to 2HDM + S, with

	2HDM I	2HDM II	2HDM III	2HDM IV
u	H_u	H_u	H_u	H_u
d	H_u	H_d	H_u	H_d
e	H_u	H_d	H_d	H_u

- The pseudo-scalar inherits a mixture of Hu or Hd couplings to fermions => different Br for the same decay mode