Exotic Higgs Decays - An Overview

Tao Liu

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A Potential Leading Window into New Physics

- Solving hierarchy problem requires Higgs to couple with new physics directly

- Higgs is one of the two SM fields that can have renormalizable couplings to SM singlet operators [Patt and Wilczek, arXiv:[hep-ph/0605188]]

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

Lorentz invariant gauge singlet

- Both couplings can modify the Higgs productions and decays at LHC.

- So we should study everything about it!

Many Possible Higgs Measurements

LHC (+ future colliders ...)

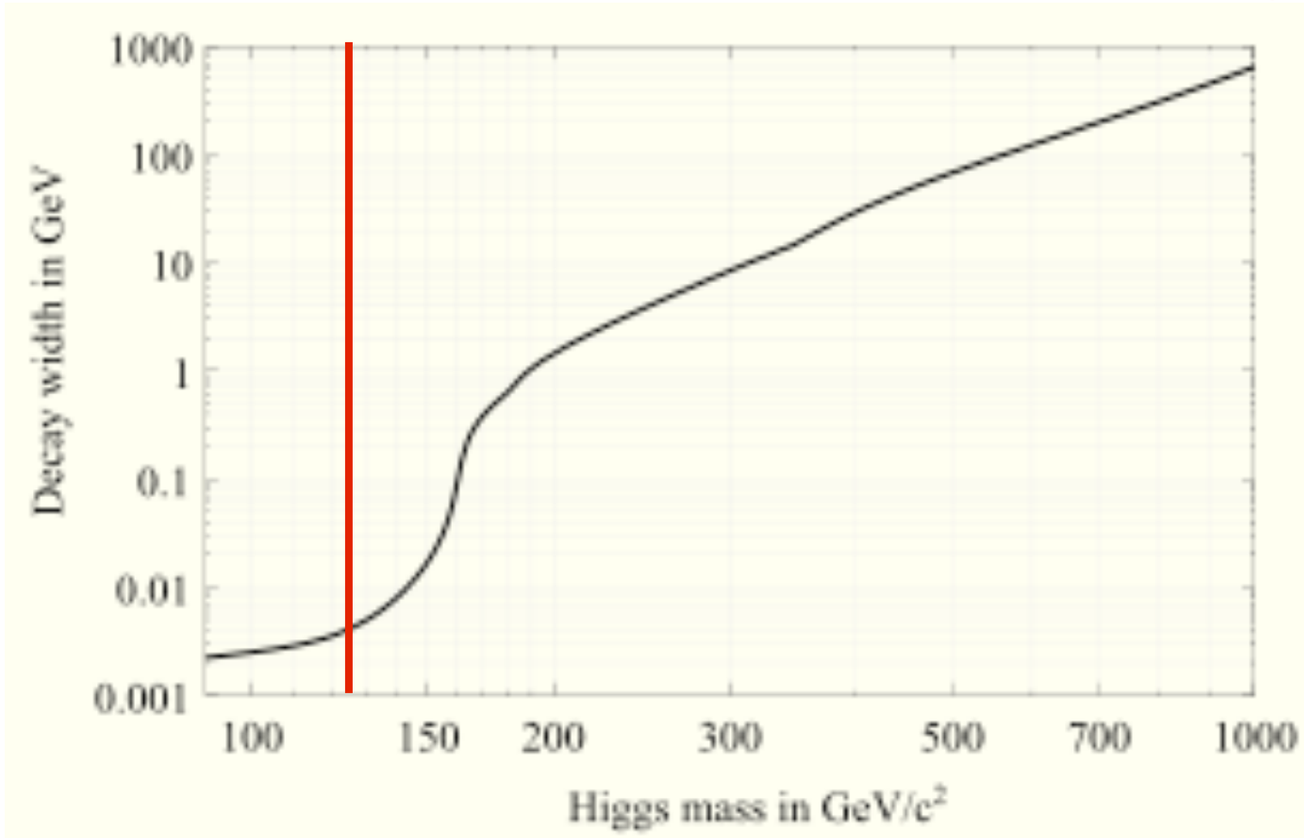
Measure the SM Higgs decays

Search for exotic Higgs decays (absent in the SM)

Search for non-standard Higgs production

Higgs Decay Width in the SM

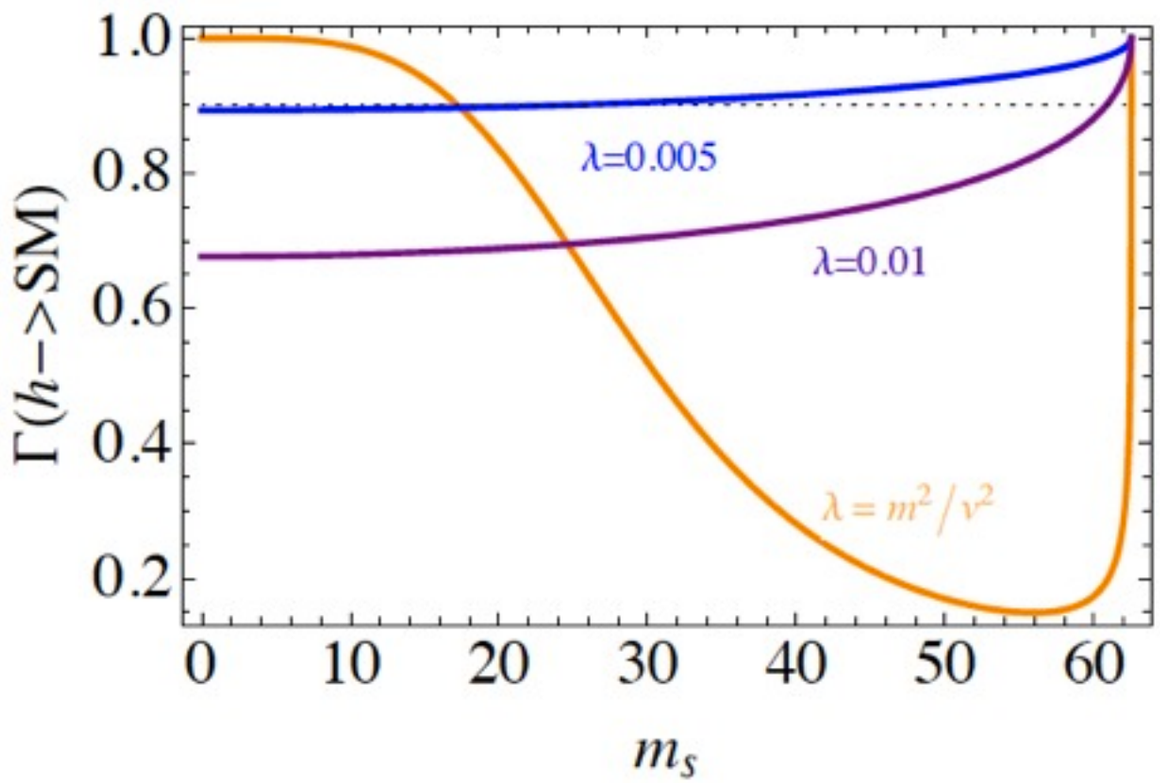
- The SM Higgs width is tiny for mH ~ 125 GeV
  - Decays into gauge bosons are either off-shell (WW*, ZZ*), or at loop level (di-photon, di-gluon)
  - Decays into fermions tend to be suppressed because of small Yukawa couplings (except tt*)
- About three orders smaller than the Z or W widths (~ 4MeV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



Exotic Higgs Decays

- A small non-standard Higgs coupling may lead to sizable effect.

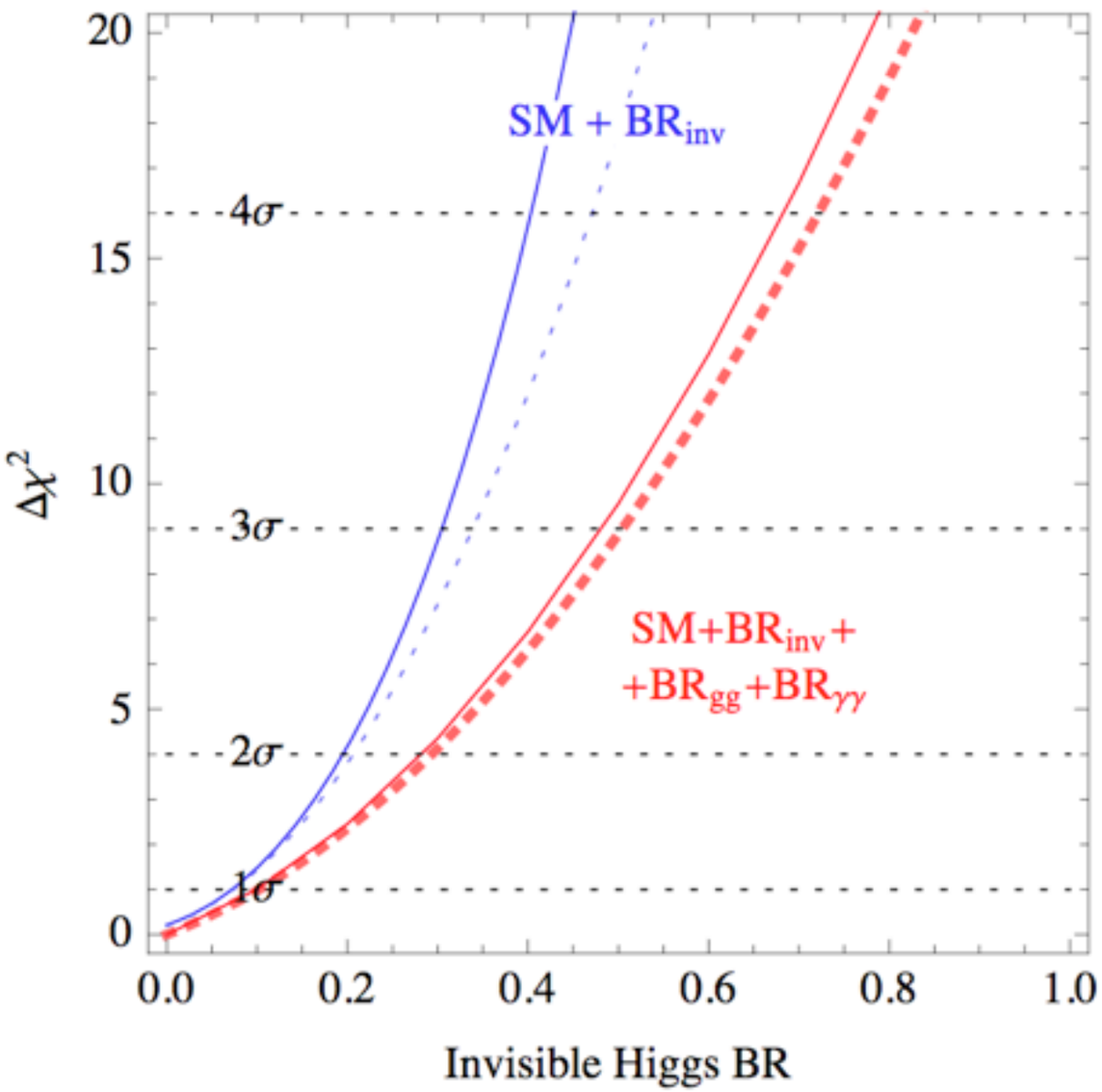
e.g., $\Delta\mathcal{L} = \lambda S^2|H|^2$ (common building block in extended Higgs sectors)



$\lambda \sim 0.005$ and $m_S < \frac{m_H}{2}$ can give $\mathrm{Br}(H \to SS) \sim 10\%$

- So exotic Higgs decays are a natural and very efficient way for probing BSM physics

``Invisible'' Higgs Width



- The currently allowed branching ratio for exotic Higgs decays is big

$$\mathrm{BR}_{\mathrm{exotic}} < 0.3 \text{ at } 95\% \text{ C.L.}$$

- As a comparison (for mh=125GeV)

$$\begin{aligned} \mathrm{Br}(h_{\mathrm{SM}} \to ZZ^*) &\sim 0.03 \\ \mathrm{Br}(h_{\mathrm{SM}} \to WW^*) &\sim 0.15 \\ \mathrm{Br}(h_{\mathrm{SM}} \to \tau\tau) &\sim 0.06 \end{aligned}$$

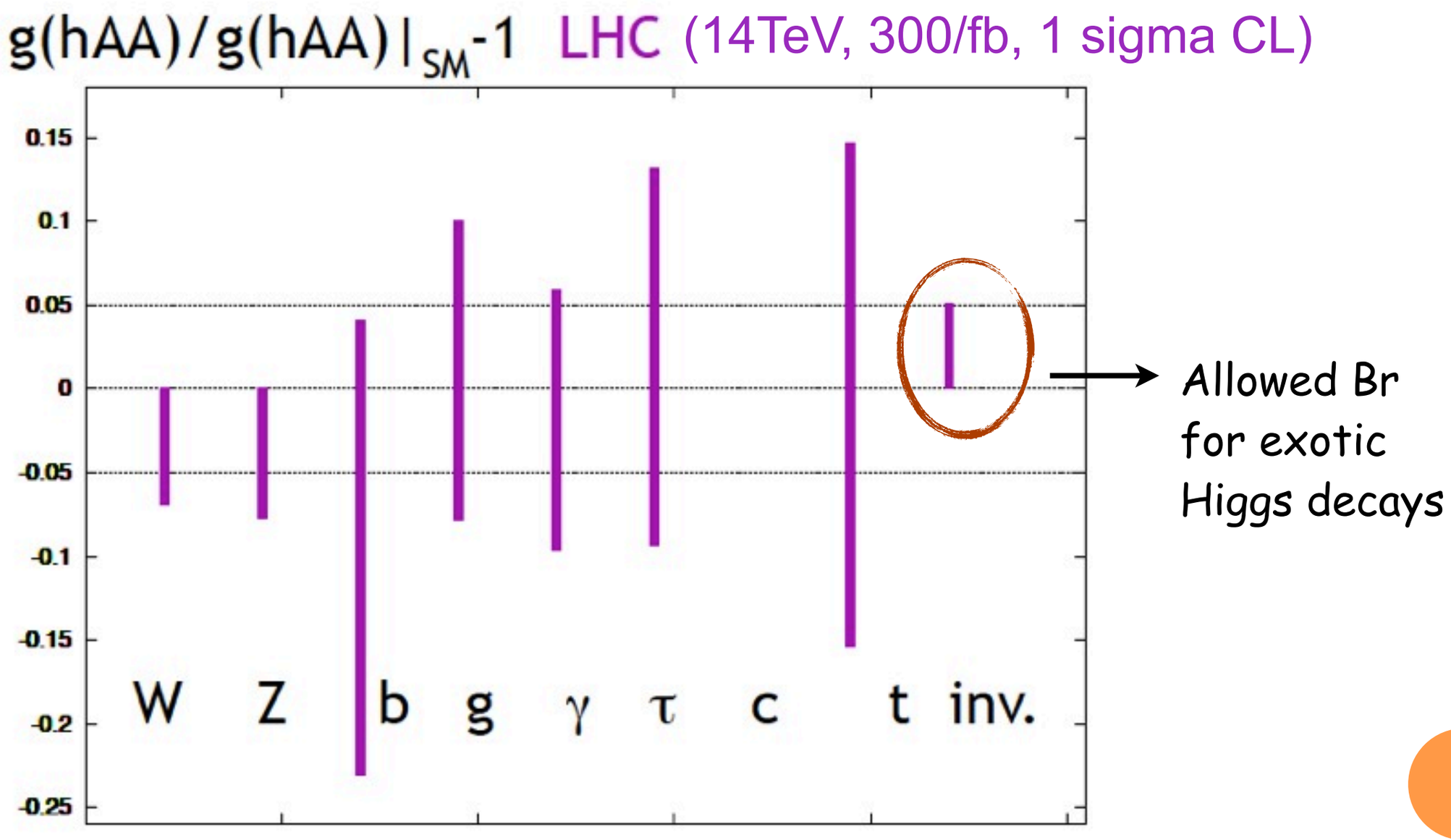
There exists a lot of room! (in a more general context, > 0.5 BR is allowed!)

Giardinoa, Kannike, Masina, Raidal, Strumia, 1303.3570

see e.g. Belanger, Dumont, Ellwanger, Gunion, Kraml; Espinosa, Muhlleitner, Grojean, Trott; Ellis

There Will Always Be Room for Exotic Decays

O(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]



How Many Exotic Decay Events Possible Right Now?

assume BR(h→new) = 10%, LHC8, 20/fb

channel	# events (raw)
ggF	39000
VBF	3150
W(ℓν)+h	280
Z(ℓℓ)+h	55
ttH	260

} Associated Production (AP)

Searching for them are not easy:

- Many events in ggF/VBF, but suitability depends on the Higgs decays
- Can always trigger w/ AP… but not many events
- Specific signature => dedicated search strategies are usually required
- => What is the discovery potential for exotic Higgs decays at LHC8 ? And at LHC14? And even at a future collider?

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 + future collider
- Assemble comprehensive summary document & website to inform experimental analyses (timescale of vol I ~ O(few weeks))

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Exotic Higgs Decays

David Curtin,[1] Rouven Essig,[1] Stefania Gori,[2,3] Prerit Jaiswal,[4] Andrey Katz,[5] Tao Liu,[6] Zhen Liu,[7] David McKeen,[7] Jessie Shelton,[5] Matthew Strassler,[7] Ze'ev Surujon,[1] Brock Tweedie,[8] and Yiming Zhong[1,*]

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The Website of ``Exotic Higgs Decays''

Non-Star

http://pheno11.physics.sunysb.edu/web/wopr/?page_id=6

News ▾ The official...IST & USNO) gnuplot / label (1E) Quark vs Gluon Plots

Non-Standard-Model h Decays

Much work has been done over the past twenty years on non-SM Higgs decays in different contexts. The purpose of this document is to assemble the motivations, models, and signatures of non-SM decays of *h* bosons that appear in the literature, and provide the necessary information for contextualizing, systematizing, and prioritizing LHC searches for such decays.

Please click here for the ***motivation*** *for the careful consideration of Non-Standard-Model h decays at the LHC.*

Please click here for the *list of possible decays, discussion of prioritization, and available studies*.

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Your email address will not be published. Required fields are marked *

Name *

The Website of ``Exotic Higgs Decays''

Decays to Standard Objects Without Missing Energy

1. $h \to 2 \to (2)+(1)$
   - $\gamma + Z$
   - $\gamma + Z'$
2. $h \to 2 \to (2)+(2)$
   - *via Spin-0 Bosons (S)*
     - $(b\bar{b})(b\bar{b})$
     - $(b\bar{b})(\tau^+\tau^-)$
     - $(b\bar{b})(\mu^+\mu^-)$
     - $(\tau^+\tau^-)(\mu^+\mu^-)$
     - $(b\bar{b})(\gamma\gamma)$
     - $(\tau^+\tau^-)(\gamma\gamma)$
     - $(\gamma\gamma)(\gamma\gamma)$
     - $(\gamma\gamma)(gg)$
   - *via Spin-1 Bosons (Z')*
     - $(l^+l^-)(l^+l^-)$
     - $(l^+l^-)(q\bar{q}$
3. $h \to 2 \to (3)+(3)$ or $(2+1)(2+1)$
   - *via Bosons*

Decays to Standard Objects With Missing Energy

(except for that from b's, c's, tau's)

1. $h \to 0$
   - MET (Invisible decay)
2. $h \to 2 \to 1 + 0$
   - γ + MET
3. $h \to 2 \to 2 + 0$
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     - $(\tau^+\tau^-)$ + MET
     - $(\mu^+\mu^-)$ + MET
     - $(\gamma\gamma)$ + MET
   - *via Spin-1 Bosons (Z')*
     - (l^+l^-) + MET
   - *via Spin-1/2 Fermions*
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purely visible or purely MET: familiar to us

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MET + visible : relatively less studied in the past

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These possibilities can be implemented in many NP scenarios. For benchmark selection, we will mainly focus on the NMSSM

R-limit vs. PQ Limit

R-symmetry

- a1 is singlet-like and light - pseudo-Goldstone boson of R-symmetry breaking.
- Singlet-like CP-even Higgs and singlino-like neutralino are typically not light

PQ-symmetry

- a_1, h_1 (singlet-like) and χ_1 (singlino-like) can be simultaneously light

[Draper, TL, Wagner, Wang and Zhang, Phys. Rev. Lett. 106 (2011)]

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

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

$$\begin{aligned} M_{H33}^2 &\sim \kappa(A_\kappa + 4\kappa s) \\ M_{A22}^2 &\sim -3\kappa A_\kappa s \\ M_{\chi_0 55} &\sim 2\kappa s \end{aligned}$$

- R-symmetry: Al, Ak -> 0, k is not small
- PQ-symmetry: k->0, Ak -> 0, Al is not small

R-limit vs. PQ Limit

R-symmetry

- h -> a1a1 is typically significant

[Dobrescu et al., Phys. Rev. D 63 (2001);
Dermisek et al., Phys. Rev. Lett. 95 (2005)]

PQ-symmetry

- h -> a1a1, h1h1 are generically suppressed
- $h_2 \to \chi_1\chi_2$ can be significant!

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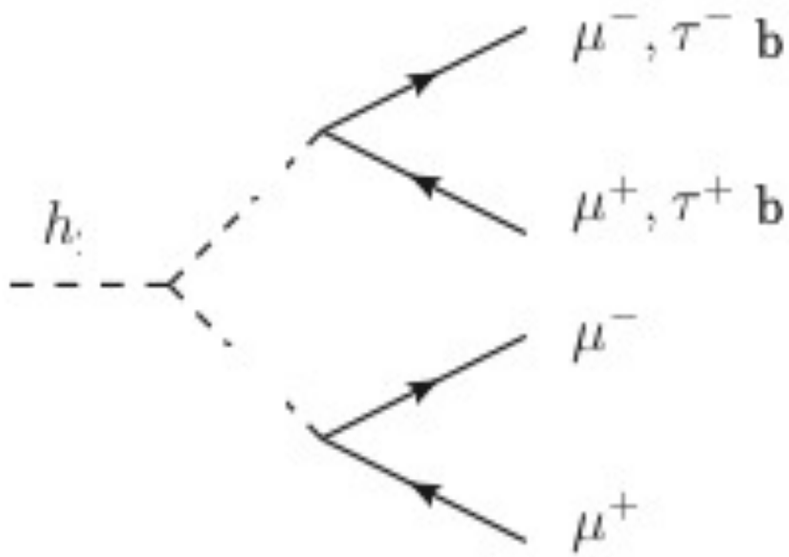

$$m_{h_1}^2 \approx -4v^2\varepsilon^2 + \frac{4\lambda^2 v^2}{\tan^2\beta} \Rightarrow \varepsilon^2 < \frac{\lambda^2}{\tan^2\beta}$$

$$y_{h_2 a_1 a_1} = -\sqrt{2}\lambda\varepsilon\frac{m_Z v}{\mu} + \sum_{i=0}^{4}\mathcal{O}\left(\frac{\lambda^{4-i}}{\tan^i\beta}\right),$$

$$y_{h_2 h_1 h_1} = -\sqrt{2}\lambda\varepsilon\frac{m_Z v}{\mu} + 2\sqrt{2}v\varepsilon^2 + \sum_{i=0}^{4}\mathcal{O}\left(\frac{\lambda^{4-i}}{\tan^i\beta}\right)$$

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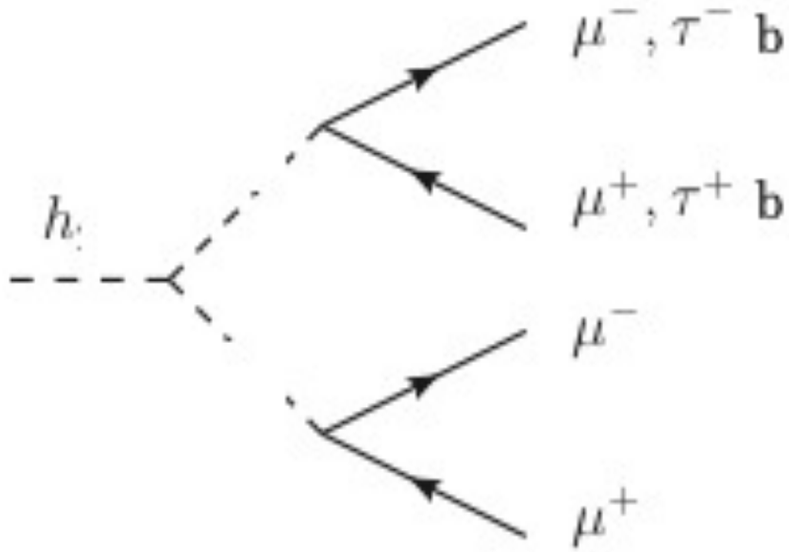

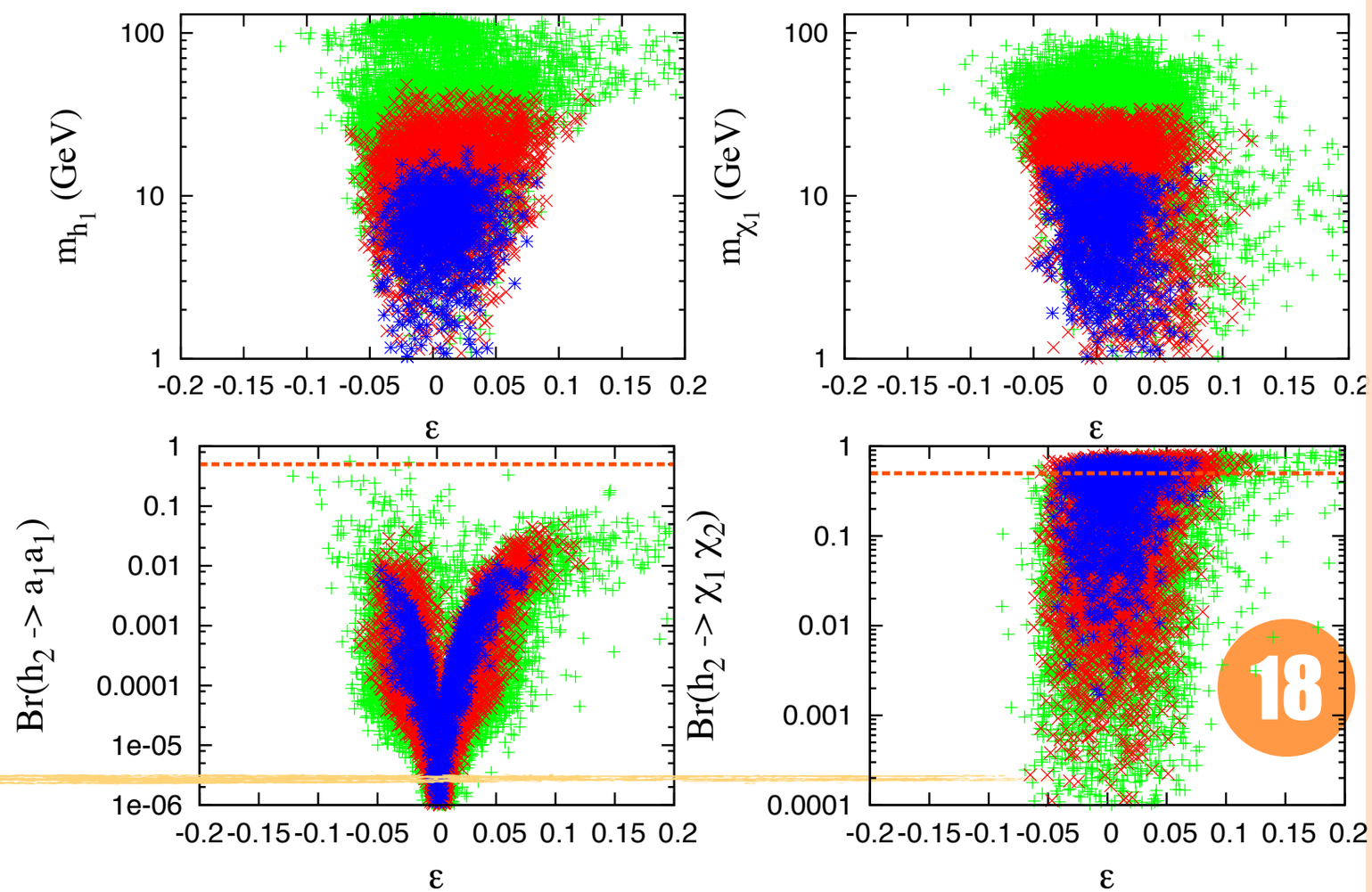

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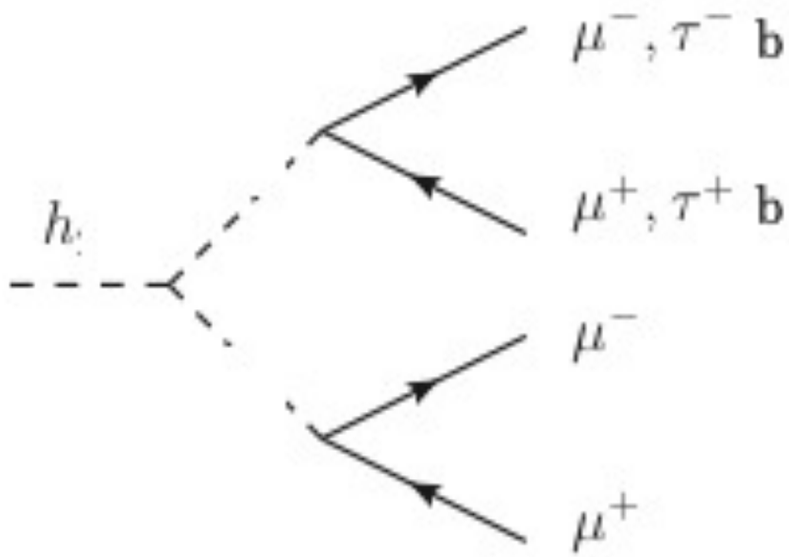

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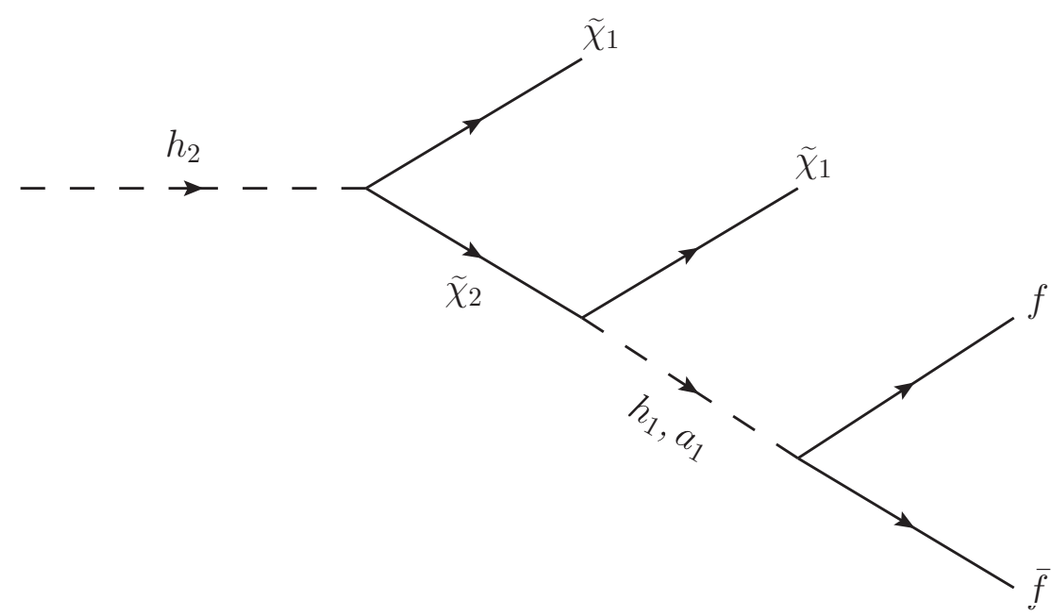

$\chi_2 \to \chi_1 h_1, \chi_1 a_1$ are typically dominant

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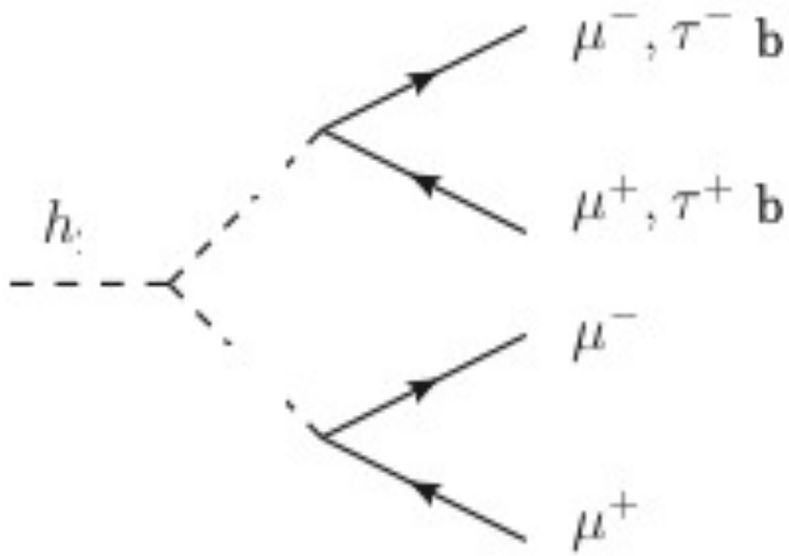

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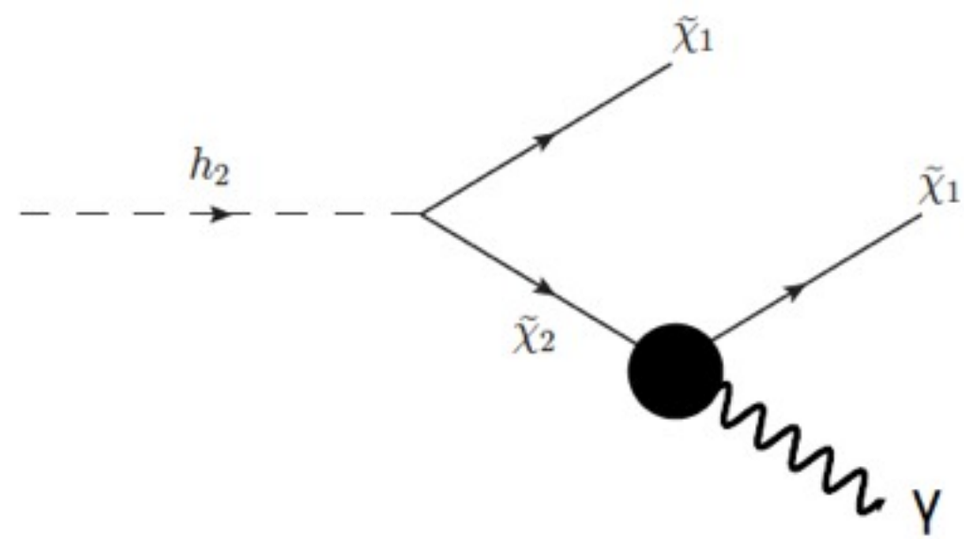
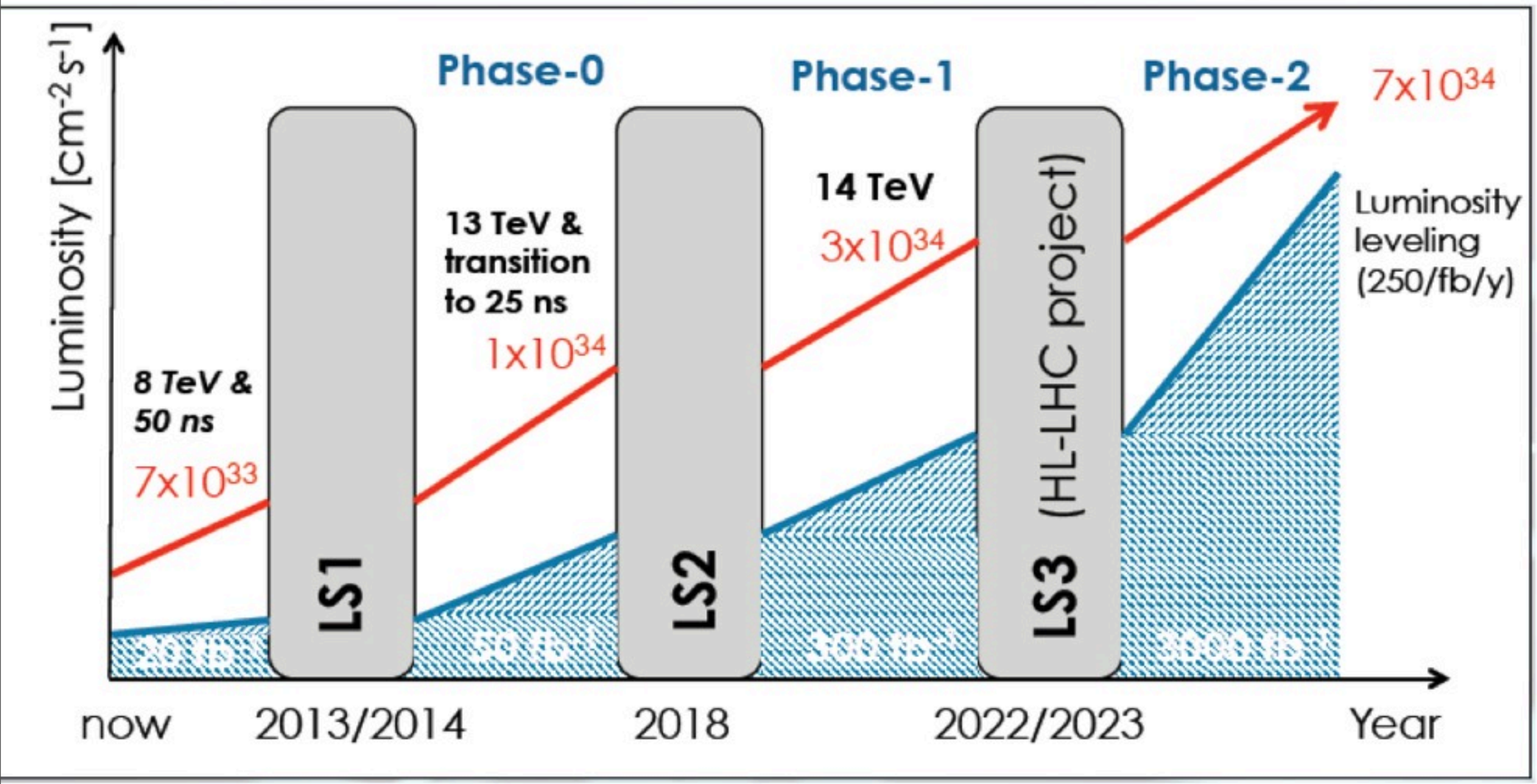


If mass splitting between χ_2 and χ_1 is small, $\chi_2 \to \chi_1 h_1, \chi_1 a_1$ become off-shell, Br($\chi_2 \to$ photon + χ_1) can be enhanced to O(0.1%-1%) level [S. Gori, TL and J. Shelton, arXiv: 13xx.xxxx]

LHC Upgrade Plan

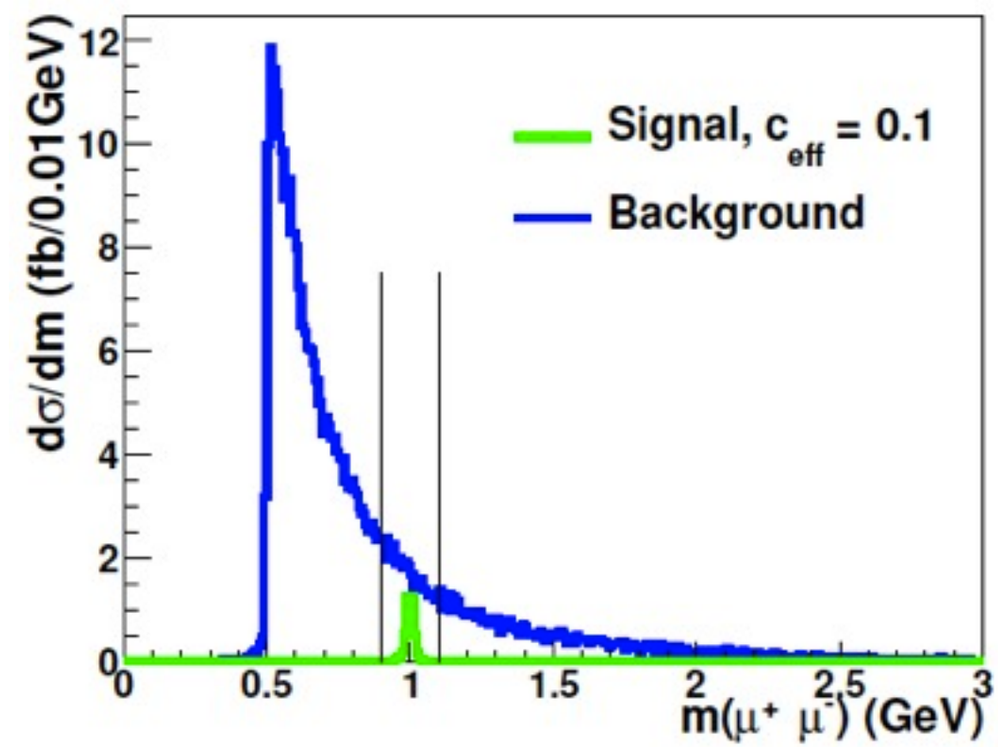


Many possibilities to explore during the whole LHC era. Next I will show some examples (preliminary results)

Example I: di-muon + MET

Stefania Gori, TL

m_{h_1}	m_{h_2}	m_{χ_1}	m_{χ_2}
1 GeV	125 GeV	10 GeV	80 GeV



- Trigger: W + h2
- Main background: W + gamma*/Z (after some specific isolation cut)

- With 13/fb data only at LHC8, $\frac{S}{\sqrt{B}} \sim 5\sigma$ can be achieved, with

$$C_{\rm eff} = \frac{\sigma(h_2)}{\sigma(h_{\rm SM})} \times {\rm Br}(h_2 \to \chi_1\chi_2) \times {\rm Br}(\chi_2 \to h_1\chi_1) \times {\rm Br}(h_1 \to f\bar{f}) = 0.1$$

[J.-R.Huang, TL, S.-F. Su, L.-T. Wang and F. Yu, arXiv: 1307.xxxx]

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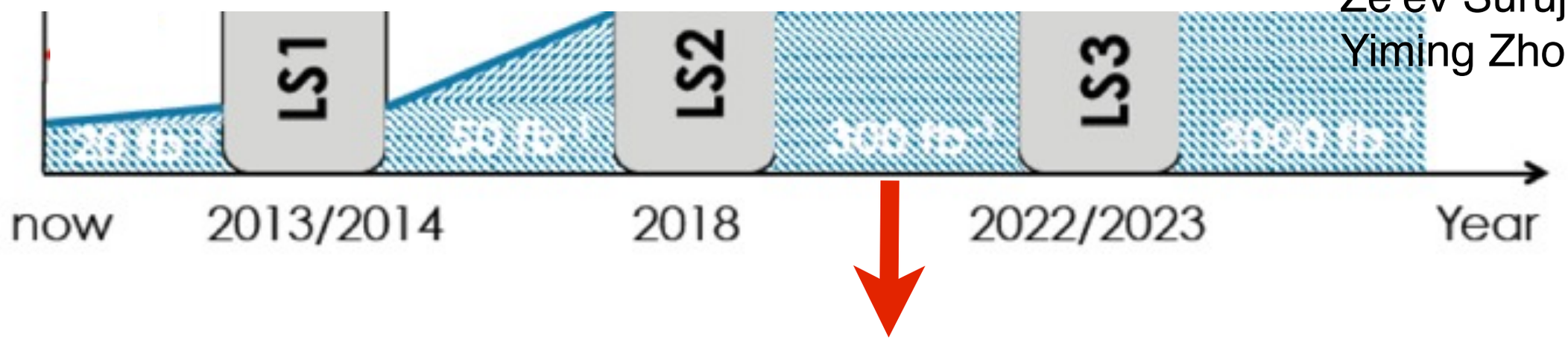
Example II: bbbb



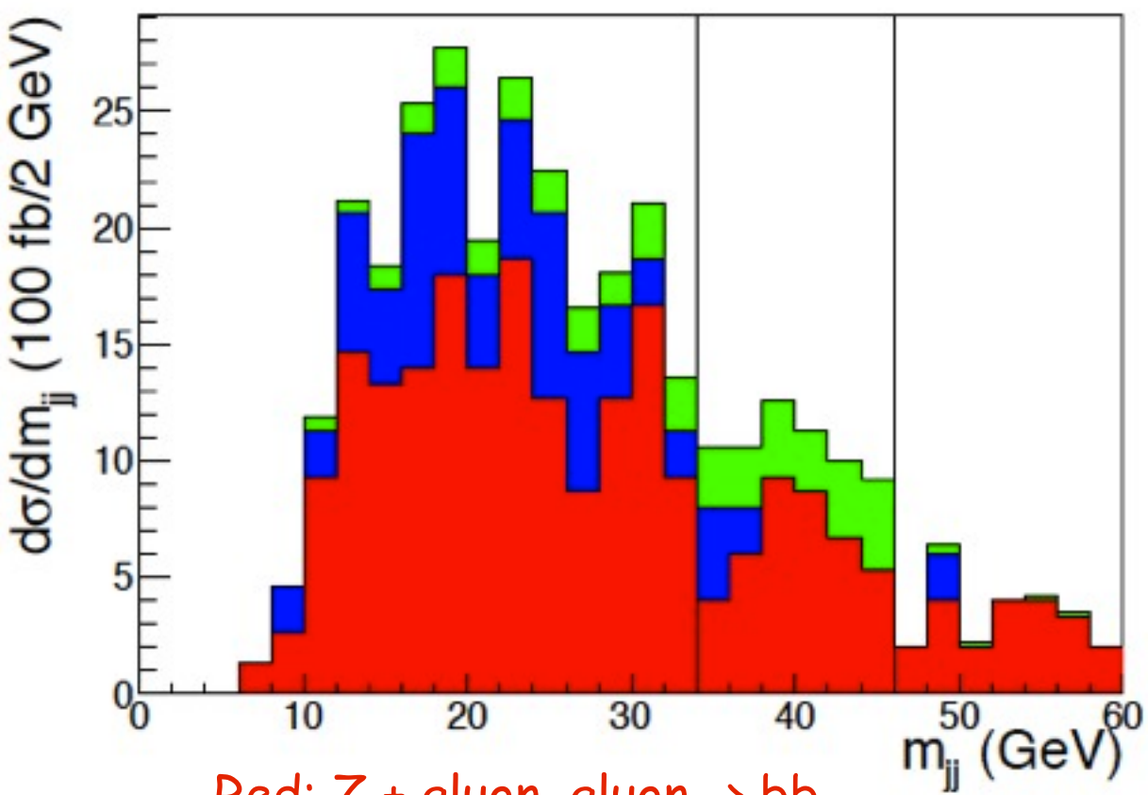
- Trigger: Wh + Zh
- Strategies: work in the boost regime, apply jet substructure tool + 2b-tags
- For 100/fb data at LHC14 and Ceff = 1

m_a(GeV)	*Signal*	s/b	σ
20	1.9	2%	0.18
30	37.4	33%	3.49
40	63.1	55%	5.89
50	61.0	53%	5.69

Carena, Han, Huang, Wagner (2007)
Cheung, Song, Yan (2007)
Kaplan, McEvoy (2011)

Example III: di-b + MET

TL



Red: Z + gluon, gluon -> bb

Blue: tt + jets

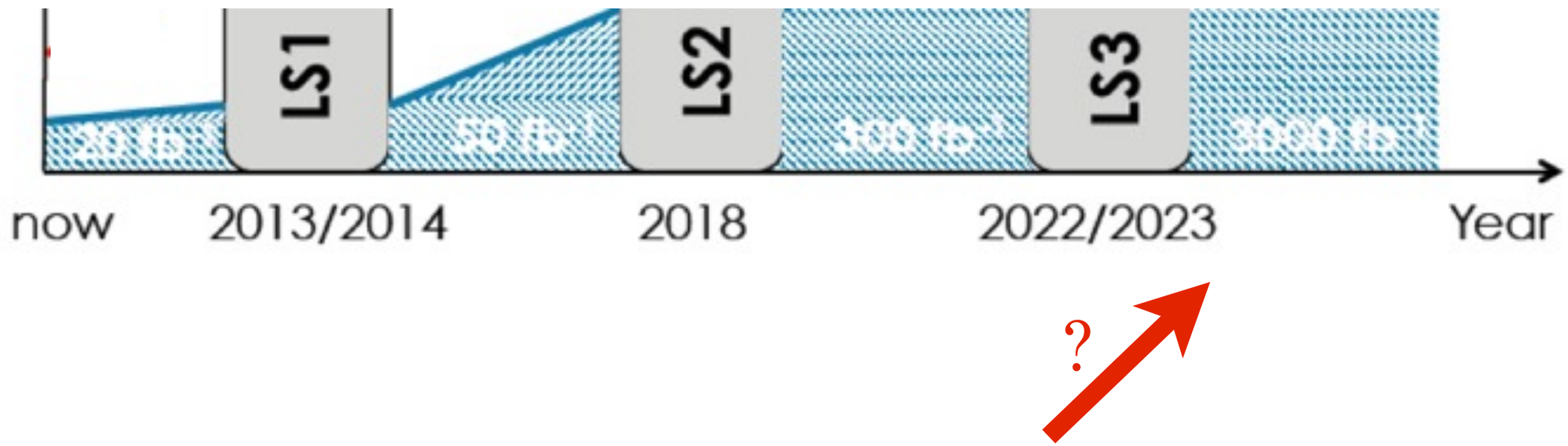
Green: signal X 20

m_{h_1}	m_{h_2}	m_{χ_1}	m_{χ_2}
45 GeV	125 GeV	10 GeV	80 GeV

- Trigger: Z + h2
- Main background: Z + gluon and tt + jets
- Strategies: Z ID + jet substructure tool
- With 300/fb data only at LHC14, $\frac{S}{\sqrt{B}} \sim 5\sigma$ can be achieved (Ceff = 0.5)

[J.-R.Huang, TL, S.-F. Su, L.-T. Wang and F. Yu, arXiv: 1307.xxxx]

Exotic Higgs Decays at a Higgs Machine?



Difficult cases at the LHC:

- Soft light jets in the final state
- The BR of exotic Higgs decay is of O(%) level

Question: can a future Higgs factory play a role as a discovery machine?

Chris Potter will try to address this question in the next talk.

Summary

- Higgs may be leading window to BSM physics => must look explicitly for exotic Higgs decays
- There are a large array of models, so we need to survey, systematize, prioritize possibilities, and assess their discovery potential
- R symmetry and PQ symmetry limits in the NMSSM provide supersymmetric benchmarks for a series of exotic Higgs decays with and without MET
- More results of collider analyses are coming soon ... ...


Thank you!

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[Dobrescu et al., Phys. Rev. D 63 (2001); Dermisek et al., Phys. Rev. Lett. 95 (2005)]

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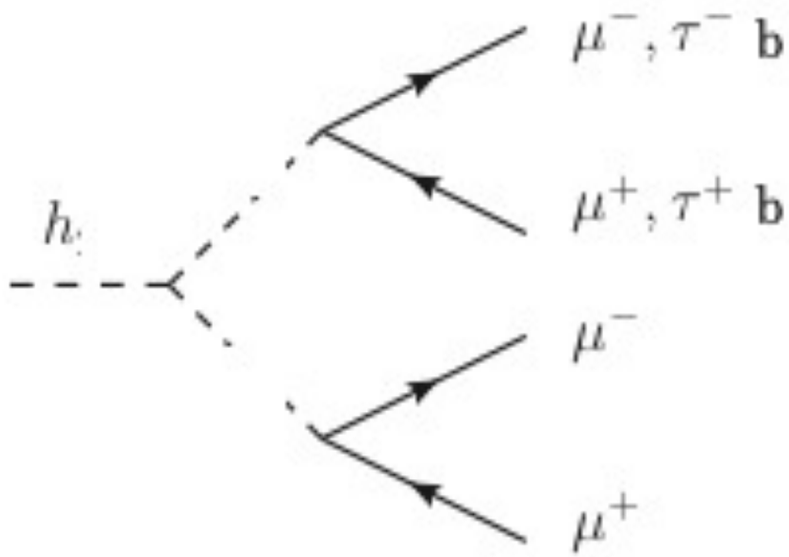

$$m_{h_1}^2 \approx -4v^2\varepsilon^2 + \frac{4\lambda^2 v^2}{\tan^2\beta} \Rightarrow \varepsilon^2 < \frac{\lambda^2}{\tan^2\beta}$$

$$y_{h_2 a_1 a_1} = -\sqrt{2}\lambda\varepsilon\frac{m_Z v}{\mu} + \sum_{i=0}^{4}\mathcal{O}\left(\frac{\lambda^{4-i}}{\tan^i\beta}\right),$$

$$y_{h_2 h_1 h_1} = -\sqrt{2}\lambda\varepsilon\frac{m_Z v}{\mu} + 2\sqrt{2}v\varepsilon^2 + \sum_{i=0}^{4}\mathcal{O}\left(\frac{\lambda^{4-i}}{\tan^i\beta}\right)$$

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%	–

SM decays ...
Well measured ...

$\Upsilon(1S)X+\Upsilon(2S)X+\Upsilon(3S)X$			(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

Rare and non-standard decays ...
limits ... but could have
something amazing ...