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EXOTIC DECAYS OF THE 125 GEV HIGGS

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``BREAKTHROUGH of the YEAR (2012)'' - Science

Mosaic of the CMS and ATLAS detectors (as in 2007), part of the Large Hadron Collider at CERN. In 2012, research teams used these detectors to fingerprint decay products from the long-sought Higgs boson and determine its mass, successfully testing a key prediction of the standard model of particle physics.

Photos: Maximilien Brice and Claudia Marcelloni/CERN

The discovery of the Higgs-like particle at the LHC announced that a new era of particle physics, the Higgs era, has begun.

Leading Window into New Physics ?

- If new physics (NP) manifests itself as SM singlet operators, the 125 GeV Higgs is one of the two fields in the SM which may couple with it via renormalizable couplings [Patt and Wilczek, arXiv:[hep-ph/0605188]]

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

Lorentz invariant gauge singlet

- If NP serves as a solution to the hierarchy problem (e.g., SUSY), the 125 GeV Higgs must couple with the NP directly
- Both types of couplings can modify the Higgs productions and decays at colliders.
- So the 125 GeV Higgs can be a leading window into NP and we should study everything about it within the next years or decades!

Several Ways to Do That

LHC (+ future colliders ...) → Measure the SM Higgs couplings

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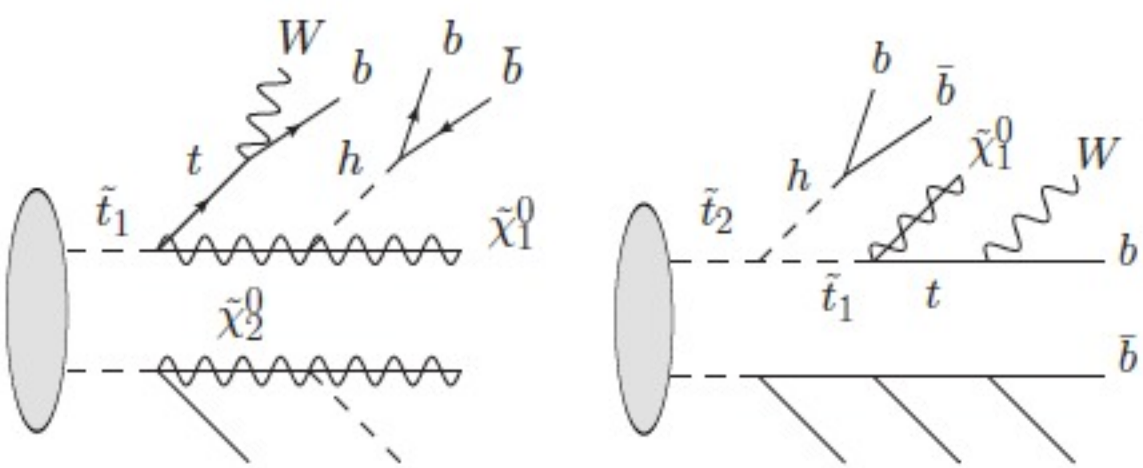
→ Measure the SM Higgs couplings

→ Search for non-standard production



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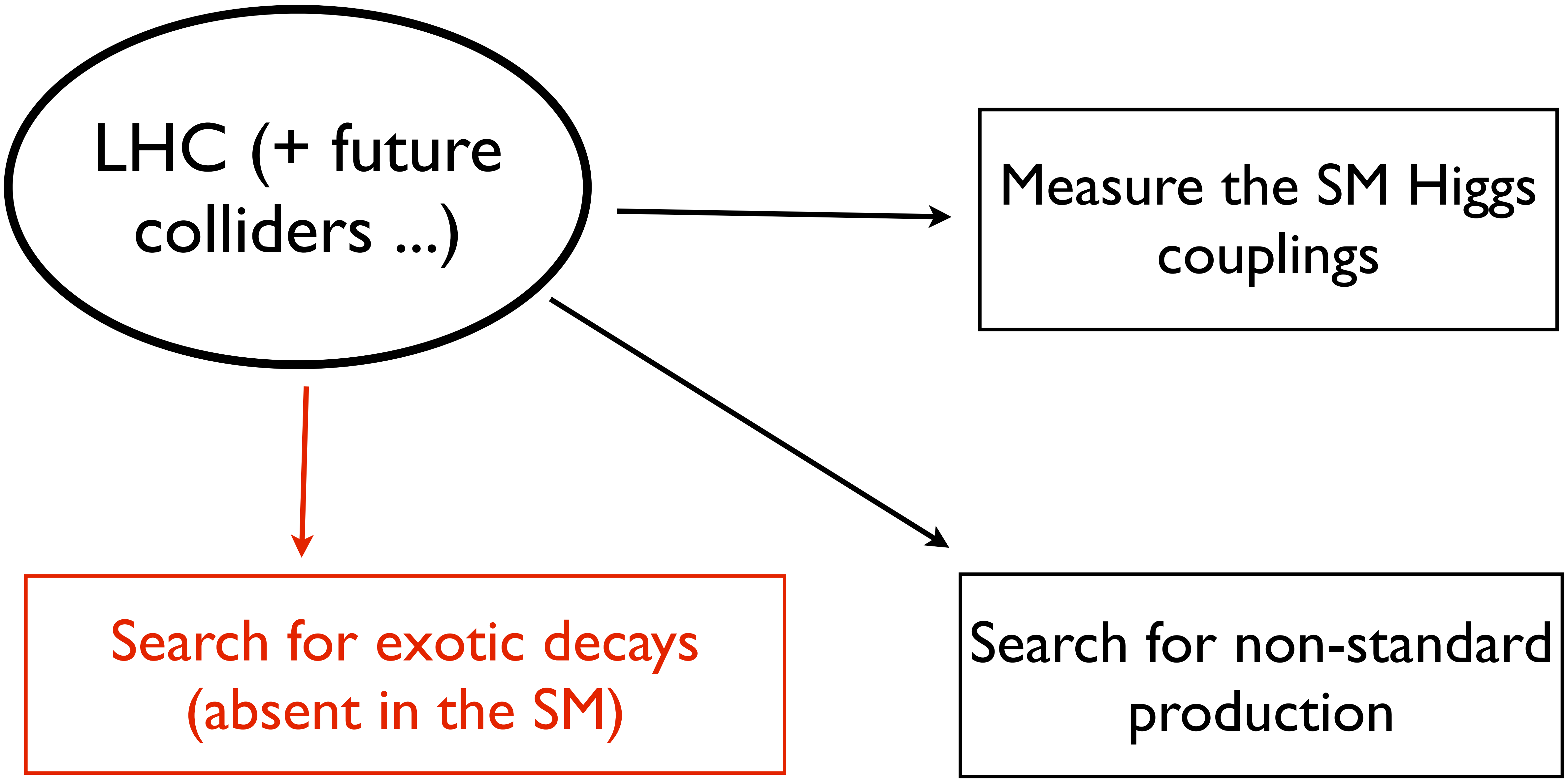
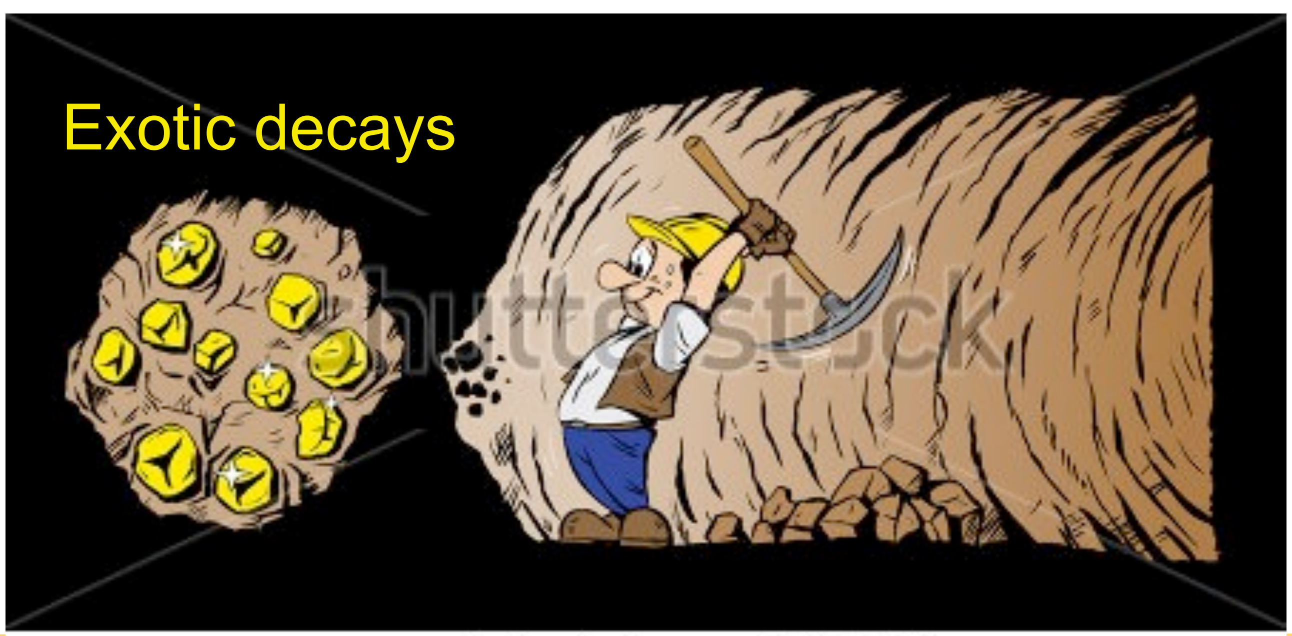


Several Ways to Do That

LHC (+ future colliders ...)

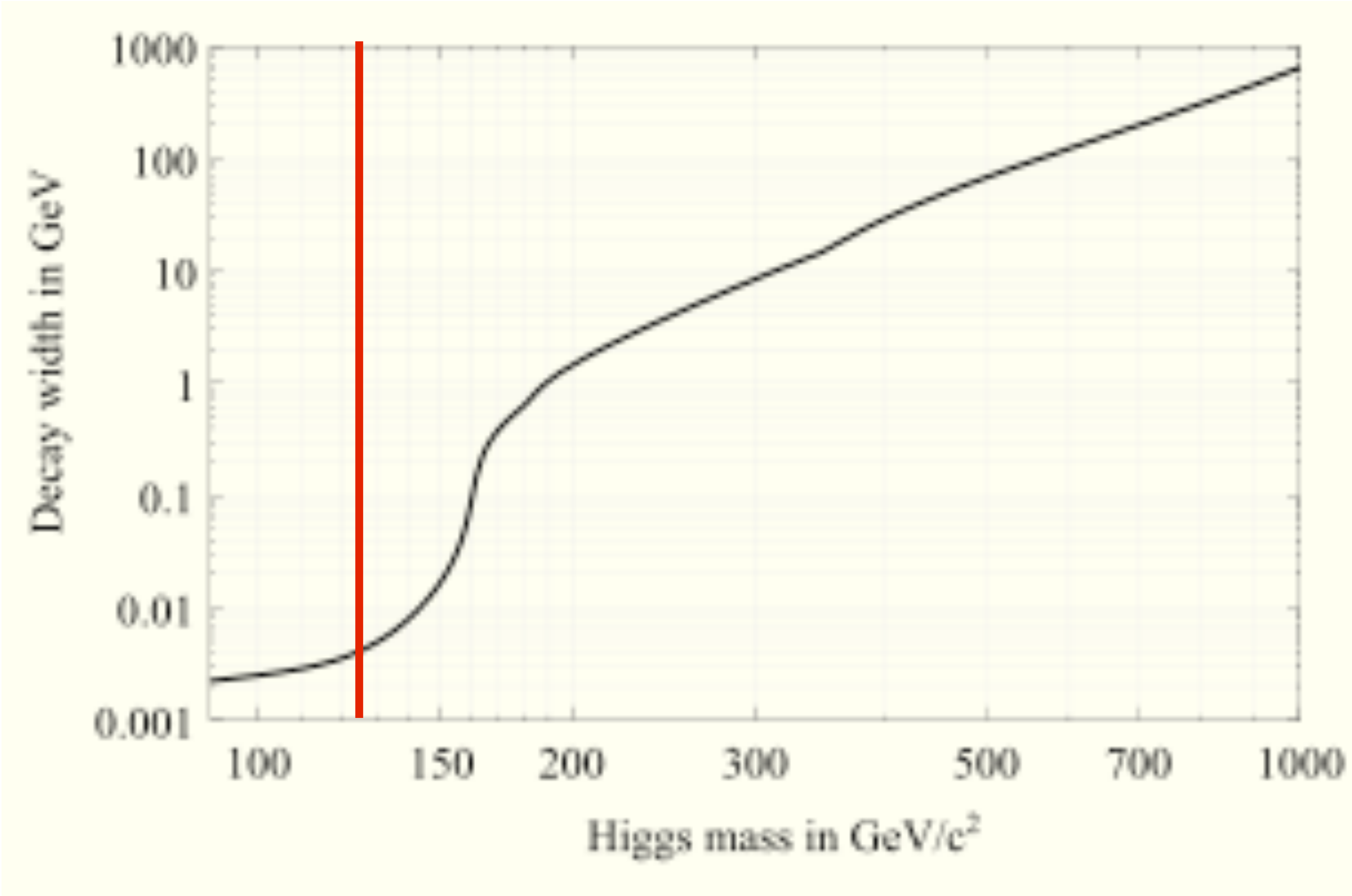
Measure the SM Higgs couplings

Search for non-standard production



Higgs Decay Width in the SM

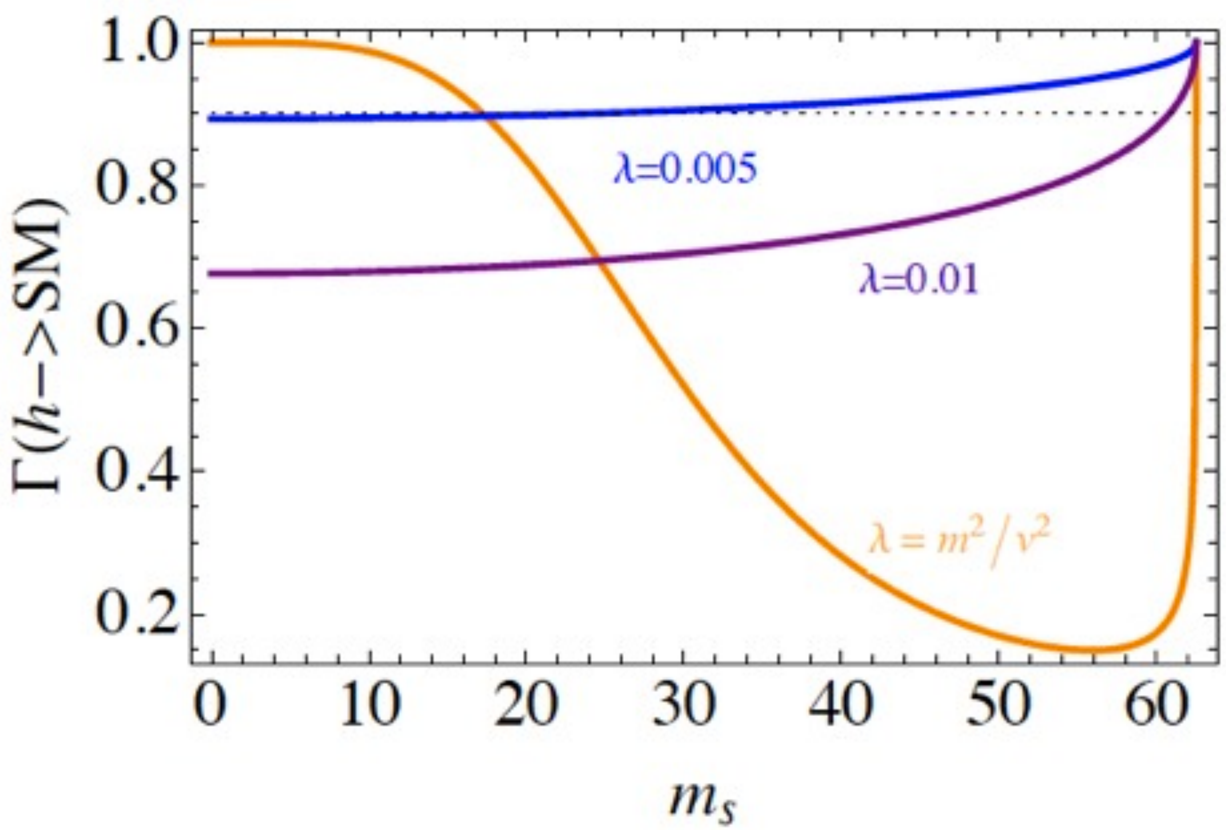
- The SM Higgs width is tiny for mh ~ 125 GeV
  - Its decays into gauge bosons are either off-shell (WW*, ZZ*), or at loop level (di-photon, di-gluon)
  - Its decays into fermions tend to be suppressed because of small Yukawa couplings (except tt*)
- About three orders smaller than the Z or W widths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



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

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

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) %		–
$(u\overline{u}+c\overline{c})/2$		(11.6 ±0.6) %		–
$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ±0.4) %		–
$c\overline{c}$		(12.03 ±0.21) %		–
$b\overline{b}$		(15.12 ±0.05) %		–
$b\overline{b}b\overline{b}$		(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

$\Upsilon(1S)$ 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%	–
$(D^0/\overline{D}^0)$ 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 γ+ 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%	–
$q\overline{q}\gamma\gamma$		[k]	< 5.5 $\times 10^{-6}$	CL=95%	–
$\nu\overline{\nu}\gamma\gamma$		[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

``Invisible'' Higgs Width

Limit on Invisible Decay BR_{inv}

ATLAS-CONF-2013-34

- 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}

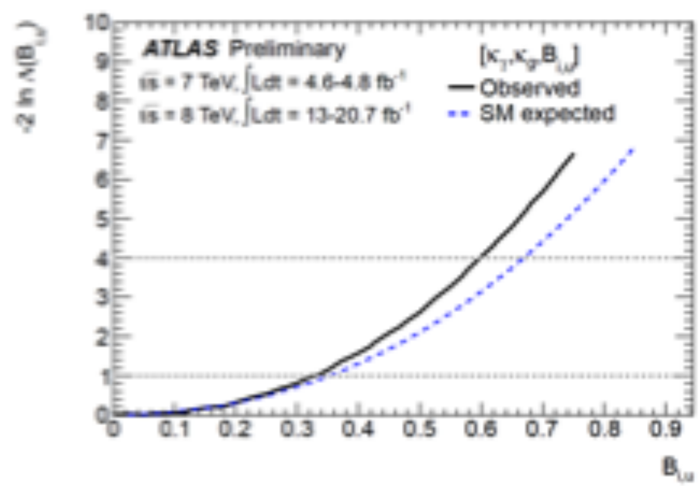
$\Gamma_H = \Gamma_{SM} + \Gamma_{inv}$ $\quad BR_{inv} = \Gamma_{inv}/\Gamma_H$

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}



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

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

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Bing Zhou's talk

As a comparison (for mh=125GeV)

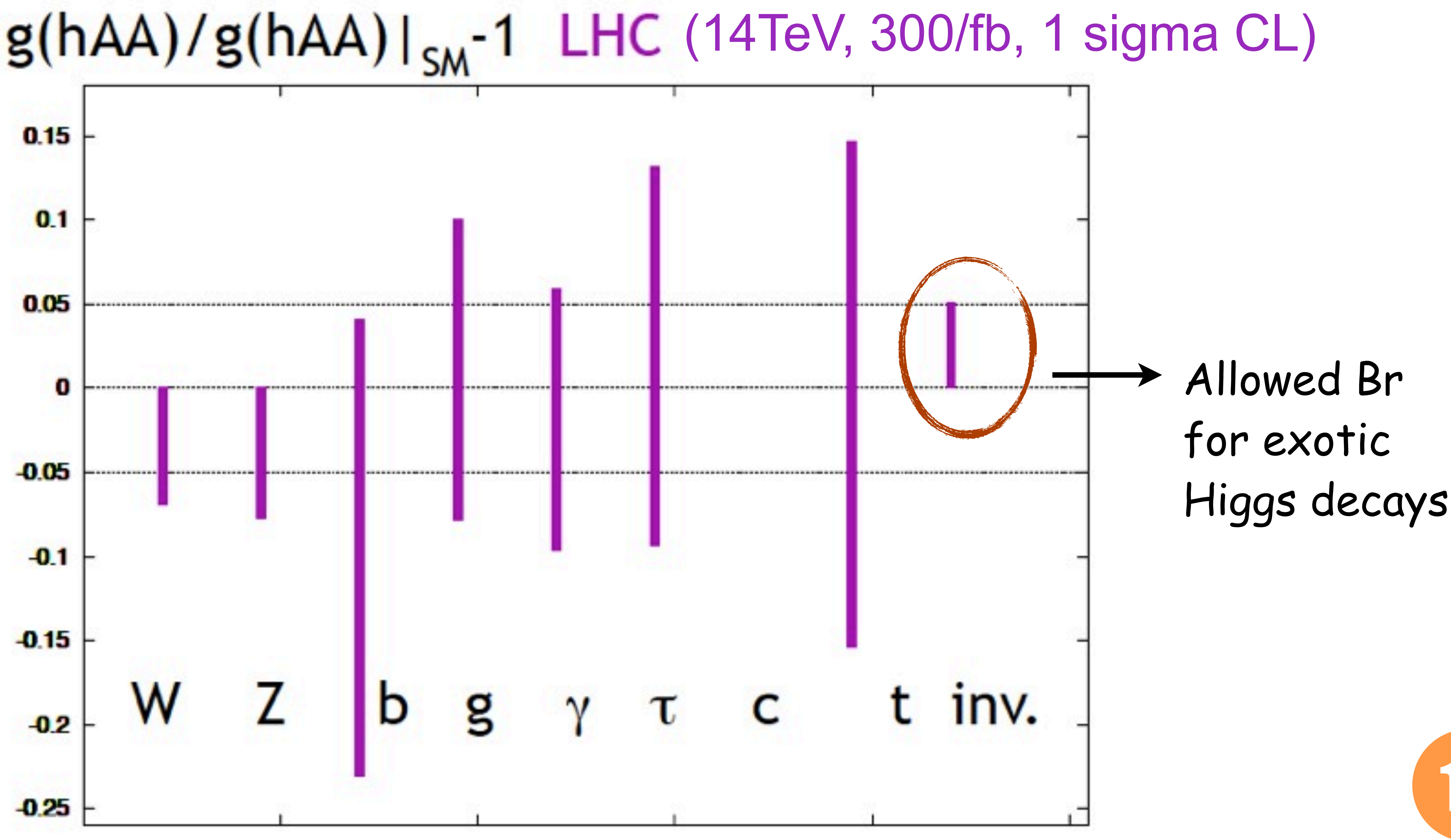
$$\mathrm{Br}(h_{\rm SM} \to ZZ^*) \sim 0.03$$
$$\mathrm{Br}(h_{\rm SM} \to WW^*) \sim 0.15$$
$$\mathrm{Br}(h_{\rm SM} \to \tau\tau) \sim 0.06$$

see also Belanger, Dumont, Ellwanger, Gunion, Kraml; Espinosa, Muhlleitner, Grojean, Trott; Ellis; Strumia

There exists a lot of room for exotic Higgs decays: > 50% BR is allowed! (exotic and invisible decays are not distinguished here)

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($h \to new$) = 10%, LHC8, 20/fb

channel	# events (raw)
ggF	39000
VBF	3150
W($\ell\nu$)+h	280
Z($\ell\ell$)+h	55
ttH	260

} Associated Production (AP)

Searching for them are not so easy:

- Many events in ggF/VBF, but suitability depends on the Higgs decays
- Can always trigger w/ AP... but not many events
- Usually specific signature => dedicated search strategies are required

How Many Exotic Decay Events Possible Right Now?

What is the discovery potential for exotic Higgs decays 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,
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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
- Eventually, assemble comprehensive summary document & construct website to inform experimental analyses (timescale ~ 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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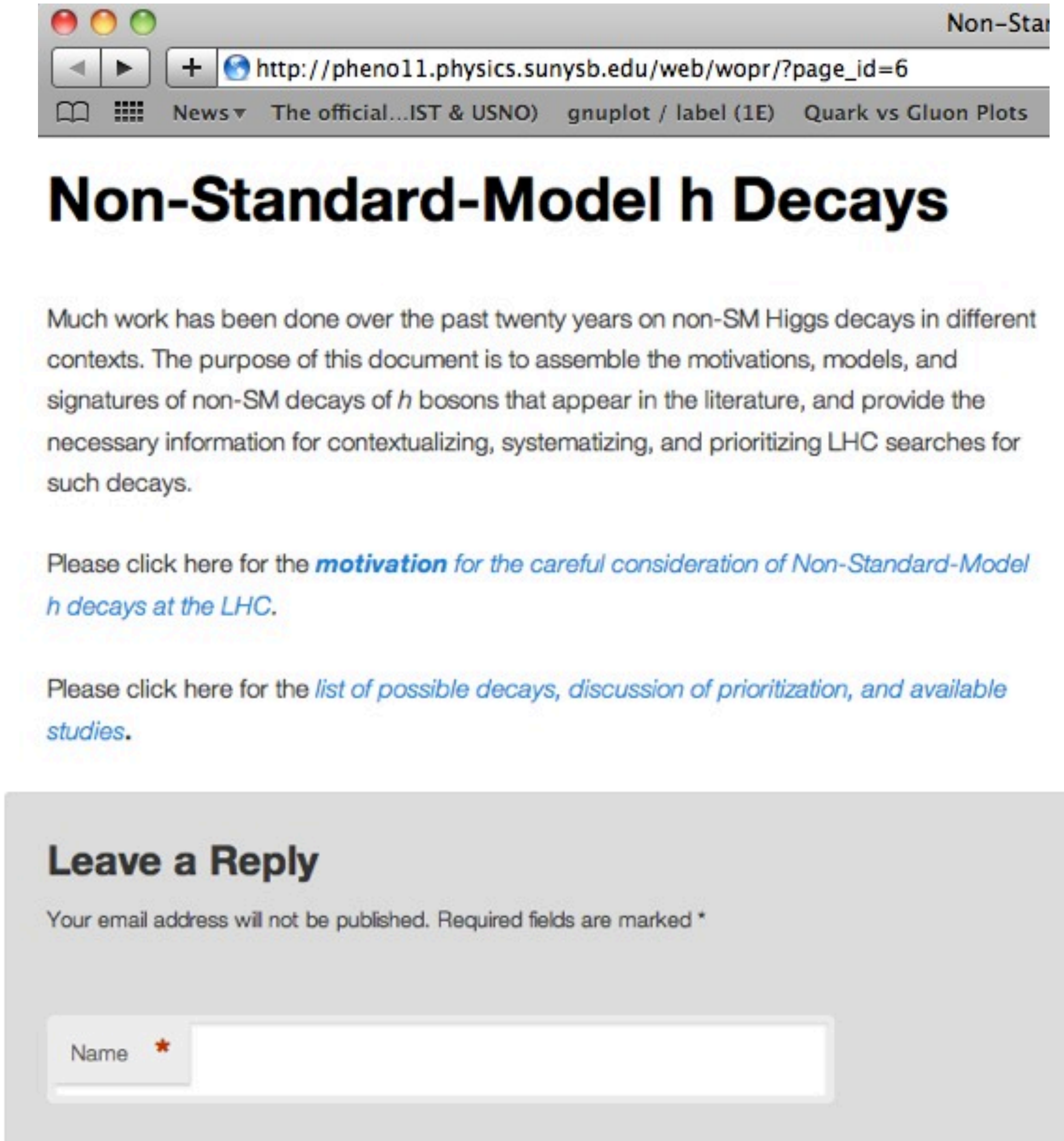
The Website of ``Exotic Higgs Decays''


Non-Star
http://pheno11.physics.sunysb.edu/web/wopr/?page_id=6
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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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The Website of ``Exotic Higgs Decays''

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

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Motivation for Studying Non-Standard-Model h Decays

1. **The decays of any newly discovered particle need to be thoroughly characterized, and this is especially true of the *h*, for several reasons.** For any new particle, including most recently the *b* and *t* quarks, the *W* boson and especially the *Z* boson, the study of its decays represents a powerful strategy for seeking and constraining BSM physics. Specifically, searches for decays that are expected to be small or absent in the SM (e.g. $b \to s\gamma$, $B_s \to \mu\mu$, $t \to cZ$, $Z \to 4\tau$) --- in short, null experiments --- are especially sensitive, because often these decays are suppressed by exact or approximate symmetries of the SM that are absent in many BSM contexts. Since the *h* interacts with all SM particles proportional to their masses, but often interacts differently with BSM particles, which often do not get any or all of their mass from the Higgs field, many of its decays that are allowed by symmetries, but are highly suppressed in the SM, are greatly enhanced in BSM contexts. (The same is true of its production modes, though this lies beyond our scope.)

… … … …

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. $h \to 2 \to 2+0$
   - *via Spin-0 Bosons (S)*
     - $(b\bar{b})$ + MET
     - $(\tau^+\tau^-)$ + MET
     - $(\mu^+\mu^-)$ + MET
     - $(\gamma\gamma)$ + MET
   - *via Spin-1 Bosons (Z')*
     - (l^+l^-) + MET
   - *via Spin-1/2 Fermions*
     - $\gamma\gamma$ + MET
     - $[\gamma\gamma]$ + MET
     - $[l^+l^-]$ + MET

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Decays into purely visible or purely MET are familiar to us

The Website of ``Exotic Higgs Decays''

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     - (l^+l^-) + MET
   - *via Spin-1/2 Fermions*
     - $\gamma\gamma$ + MET
     - $[\gamma\gamma]$ + MET
     - $[l^+l^-]$ + MET

Decays into MET + visible are less studied in the past

The Website of ``Exotic Higgs Decays''

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   - $\gamma + Z'$
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     - $(\tau^+\tau^-)(\gamma\gamma)$
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     - $\gamma\gamma$ + MET
     - $[\gamma\gamma]$ + MET
     - $[l^+l^-]$ + MET

Can be found in many NP scenarios: SUSY, little Higgs, SM+X, ... we build up benchmarks in the Next-Minimal-Supersymmetric-SM (NMSSM)

NMSSM: R-symm limit vs. PQ-symm Limit

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

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

R-symmetry

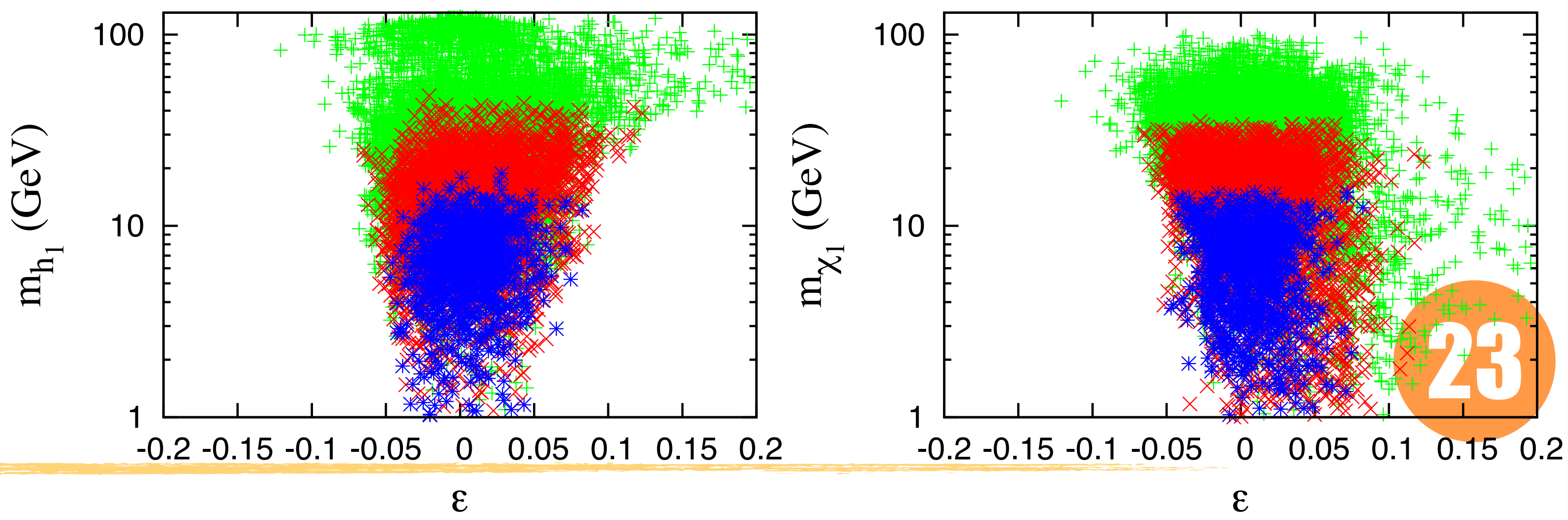
- R-symmetry: Al, Ak -> 0, k is not small
- a1 is singlet-like and light: R-axion.
- Singlet-like CP-even Higgs and singlino-like neutralino are typically not light

$$M^2_{H33} \sim \kappa(A_\kappa + 4\kappa s)$$
$$M^2_{A22} \sim -3\kappa A_\kappa s$$
$$M_{\chi^0 55} \sim 2\kappa s$$

PQ-symmetry

- PQ-symmetry: k -> 0, Ak -> 0, Al is not small
- a_1, h_1 (singlet-like) and χ_1 (singlino-like) tend to be simultaneously light

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

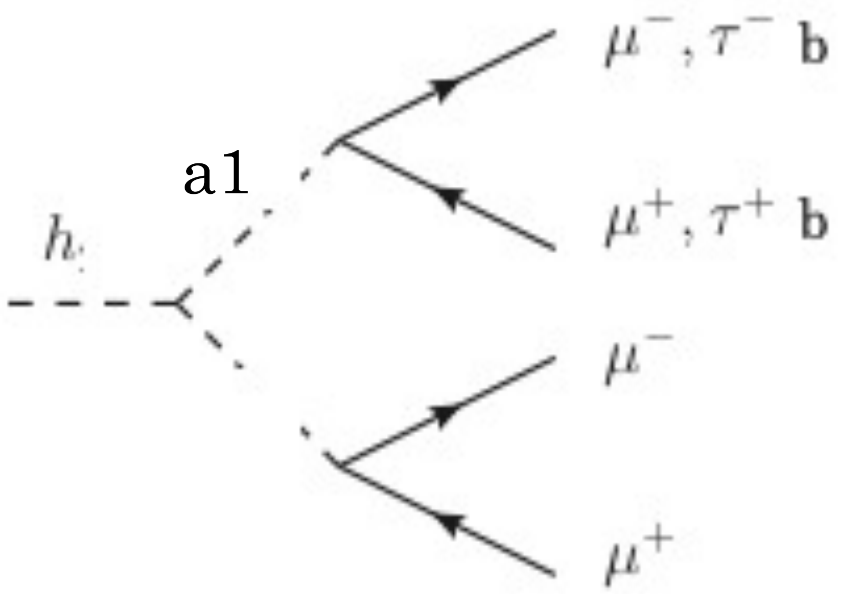


NMSSM: R-symm limit vs. PQ-symm Limit

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
- $h \to \chi_1\chi_2$ becomes significant, if kinematically allowed!

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

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

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

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

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

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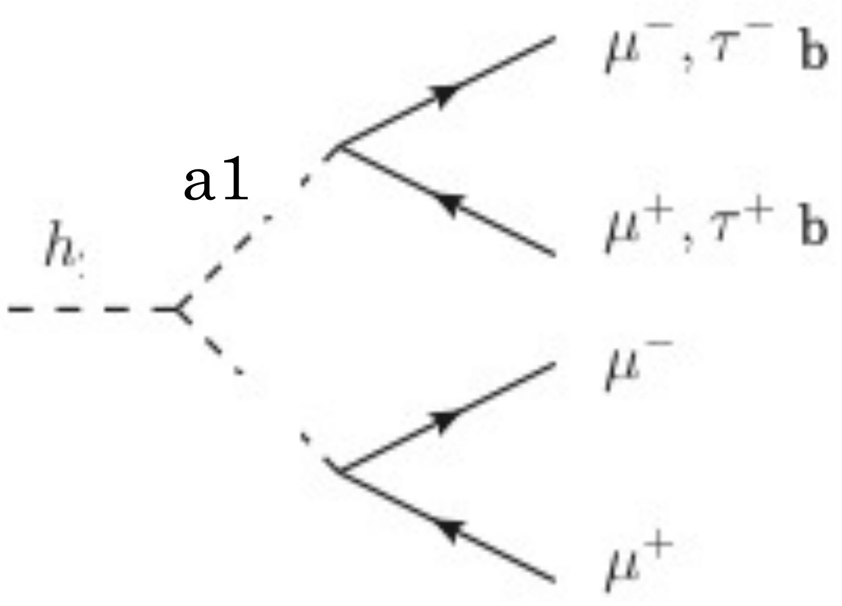

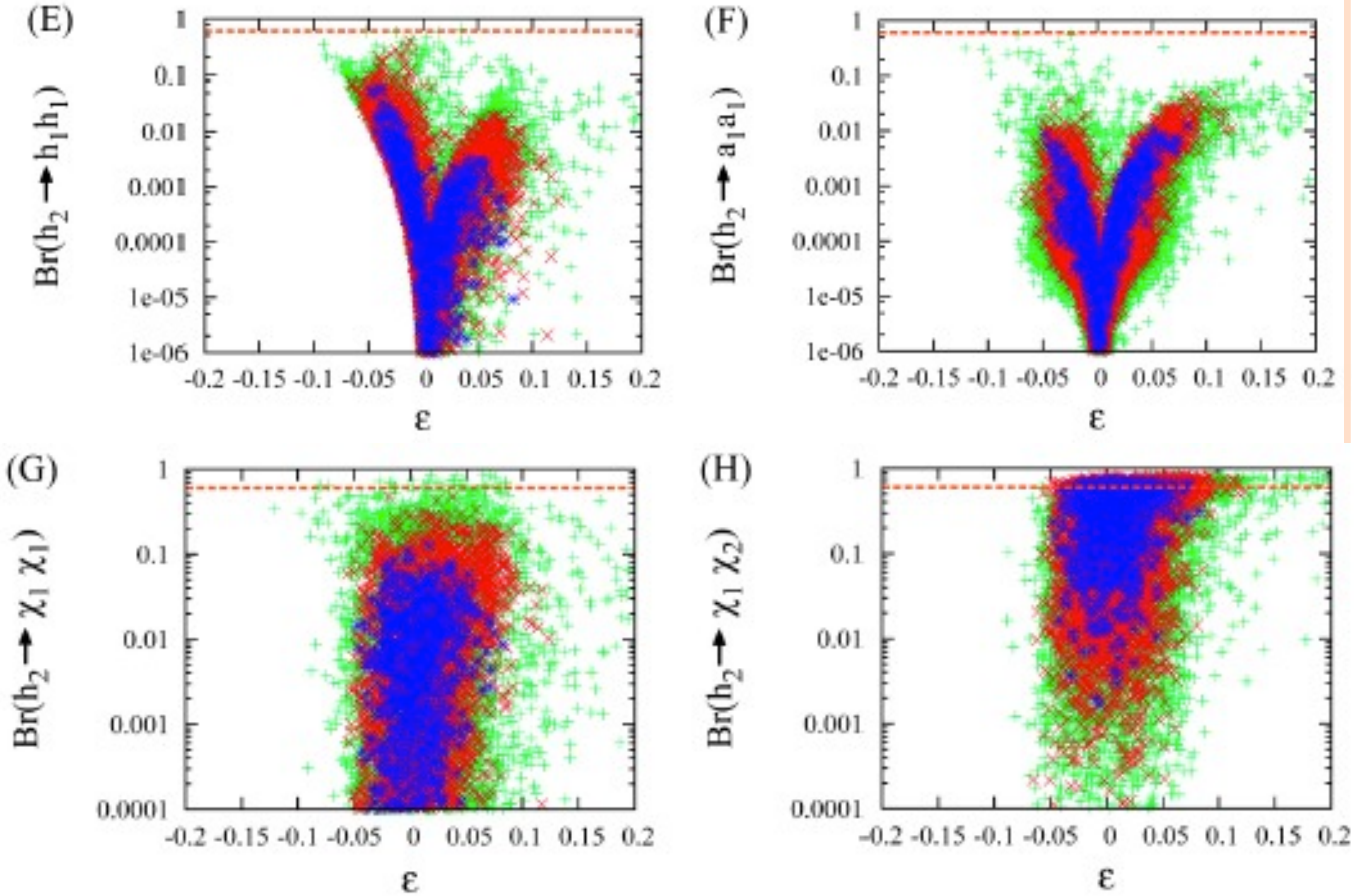

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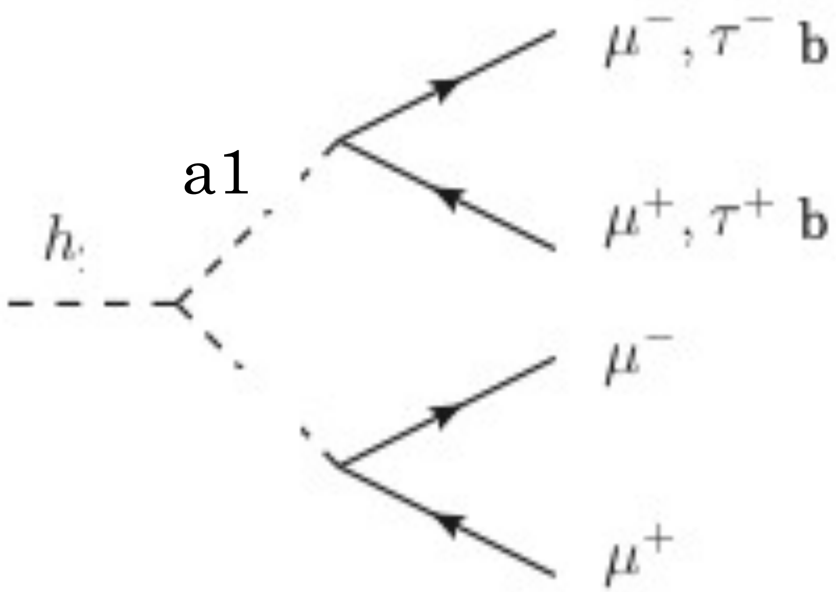
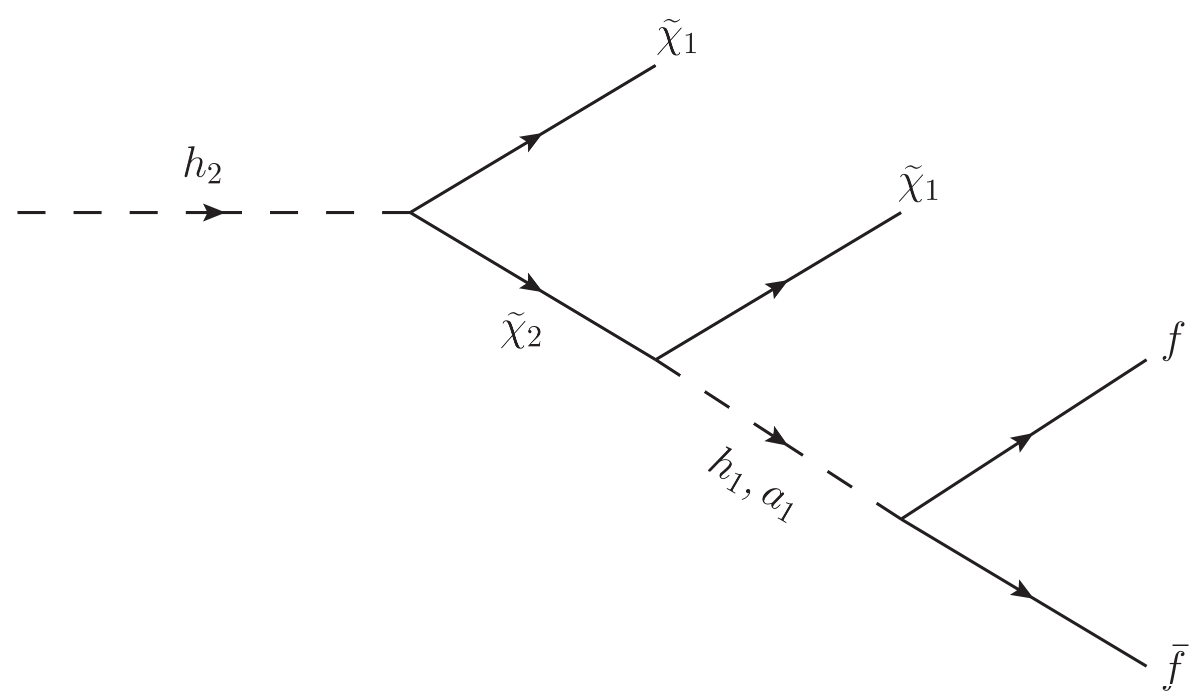
[Dobrescu et al., Phys. Rev. D 63 (2001); Dermisek et al., Phys. Rev. Lett. 95 (2005)]



PQ-symmetry

- h -> a1a1, h1h1 are generically suppressed
- $h \to \chi_1\chi_2$ becomes significant, if kinematically allowed!

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



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

NMSSM: R-symm limit vs. PQ-symm Limit

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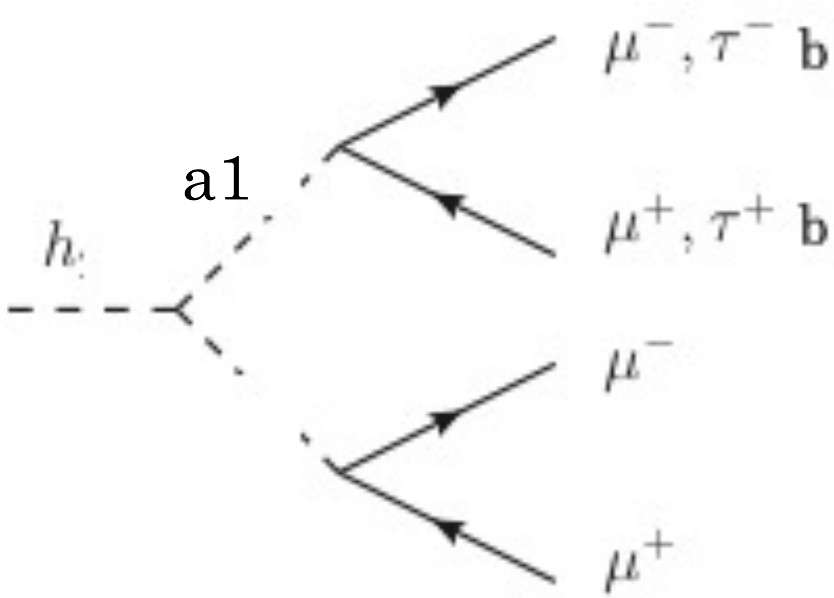
[Dobrescu et al., Phys. Rev. D 63 (2001); Dermisek et al., Phys. Rev. Lett. 95 (2005)]



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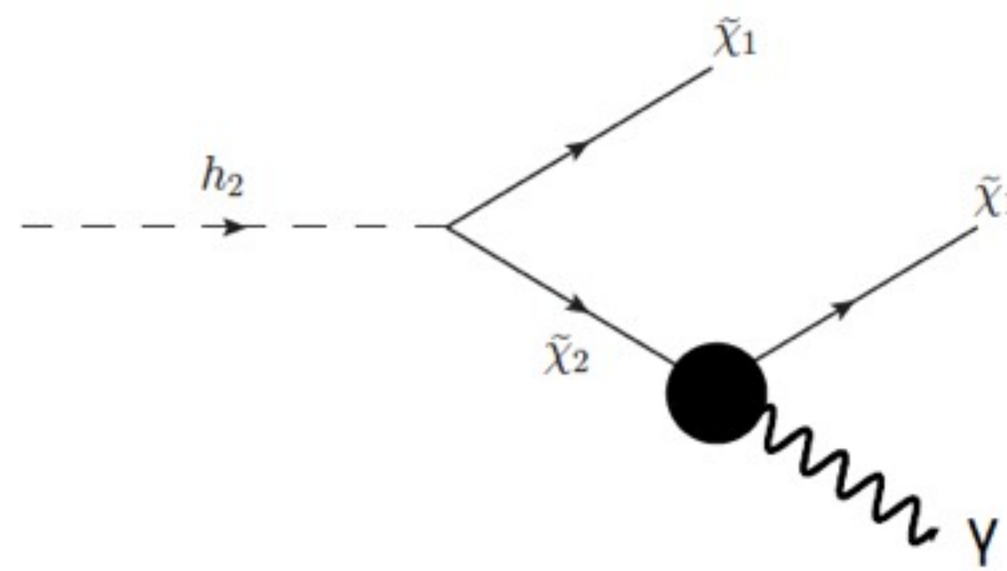

If mass splitting between χ_2 and χ_1 is small, $\chi_2 \to \chi_1 h_1, \chi_1 a_1$ become off-shell and Br($\chi_2 \to$ photon + χ_1) can be enhanced to O(1)% level

[S. Gori, TL and J. Shelton, arXiv: 13xx.xxxx]

NMSSM: R-symm limit vs. PQ-symm Limit

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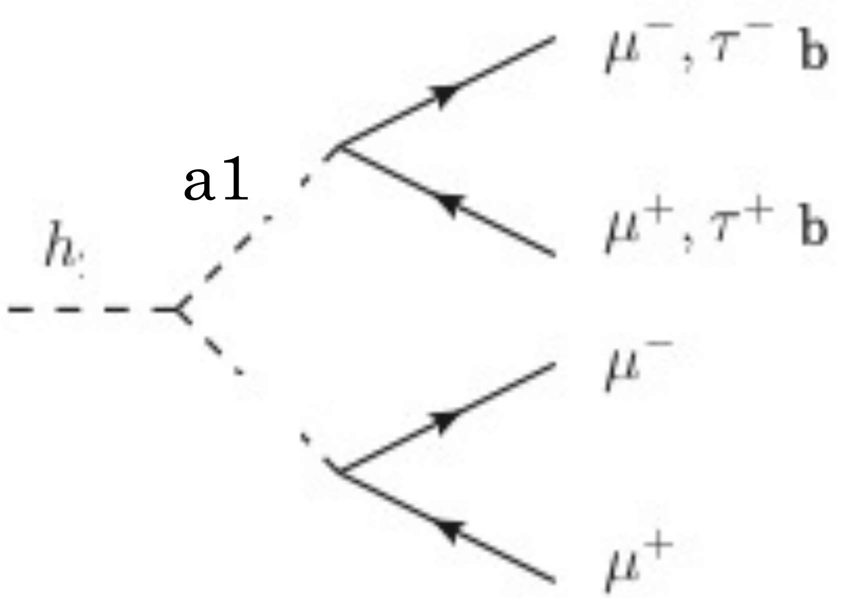
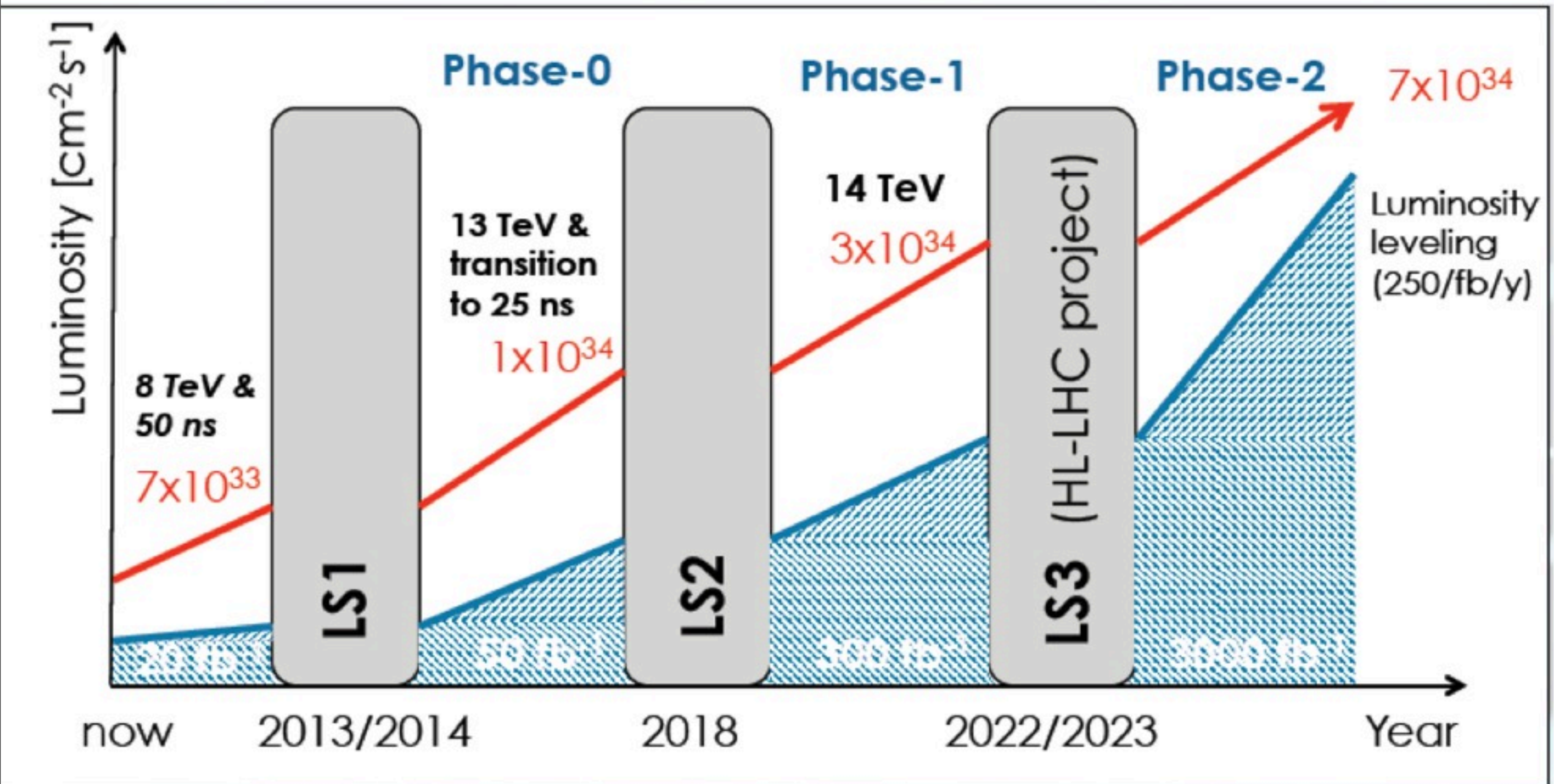


PQ-symmetry

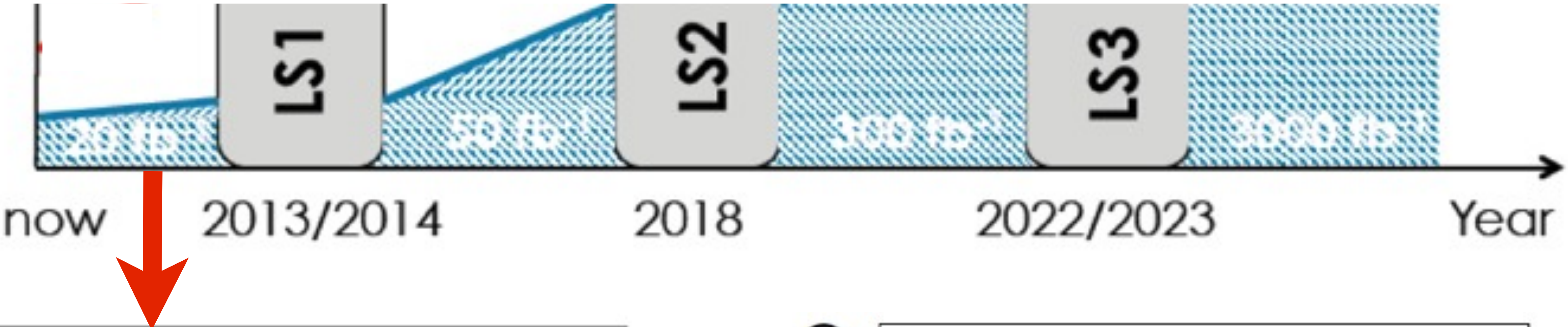
Benchmarks	$h \to \chi_1\chi_2$	$h \to \chi_1\chi_2$	$h \to \chi_2\chi_2$
λ	0.18	0.064	0.02
κ	3.4×10^{-3}	9.0×10^{-3}	1.2×10^{-3}
$\tan\beta$	9.0	12.5	10
μ(GeV)	326	138	160
A_λ(GeV)	2960	1700	1800
A_κ(GeV)	-43.5	-17	-7
M_1(GeV)	85	80	55
m_{h_1}(GeV)	23.0	34.6	17.4
m_{h_2}(GeV)	124.7	125.3	124.9
m_{a_1}(GeV)	28.7	31.6	14.2
m_{χ_1}(GeV)	12.7	39.1	19.7
m_{χ_2}(GeV)	80.8	66.4	47.3
BR($h_2 \to a_1a_1$)	< 0.01	< 0.01	< 0.01
BR($h_2 \to \chi_1\chi_1$)	< 0.01	0.04	< 0.01
BR($h_2 \to \chi_1\chi_2$)	0.28	0.27	0.05
BR($h_2 \to \chi_2\chi_2$)	< 0.01	< 0.01	0.31
BR($\chi_2 \to \chi_1 h_1 + \chi_1 a_1$)	0.92+0.08	< 0.01	0.09 + 0.60
BR($\chi_2 \to \chi_1 X^*$)	< 0.01	0.96	0.30
BR($\chi_2 \to \chi_1\gamma$)	< 0.01	0.04	0.01

LHC Upgrade Plan

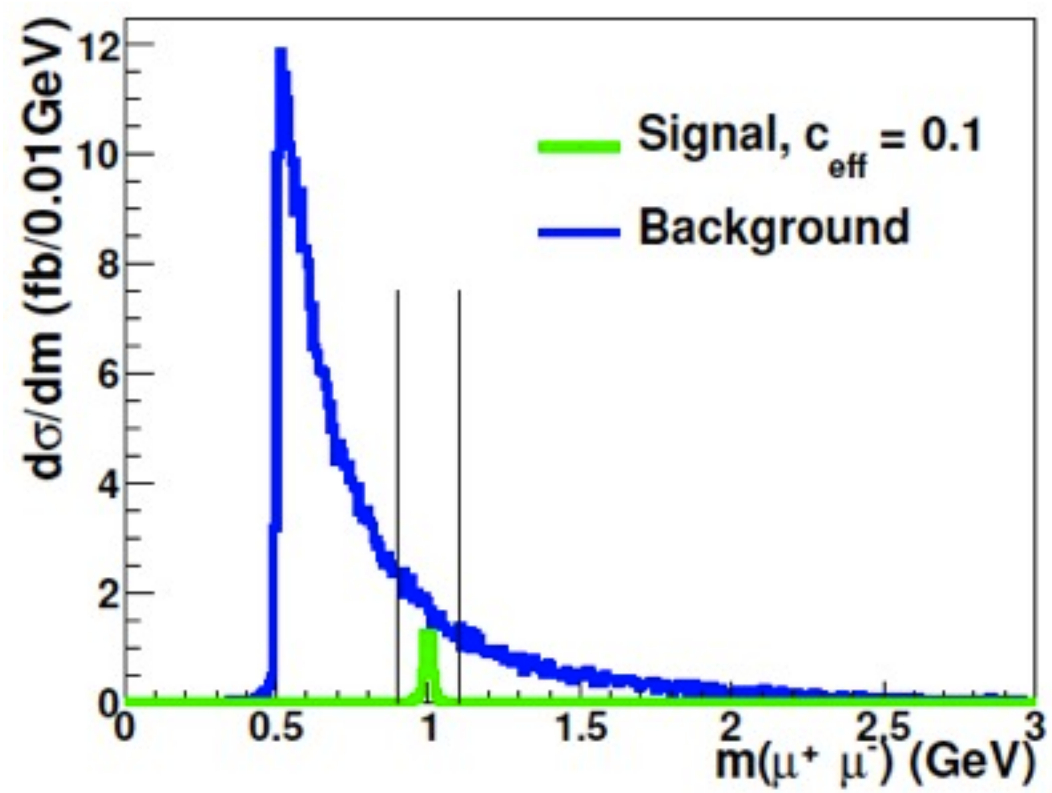


Many things to explore during the whole LHC era. Next I will show some examples (preliminary results)

Example I: di-muon + MET



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

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

[Huang, TL, Wang et. al., arXiv: 13xx.xxxx]

Example II: bbbb

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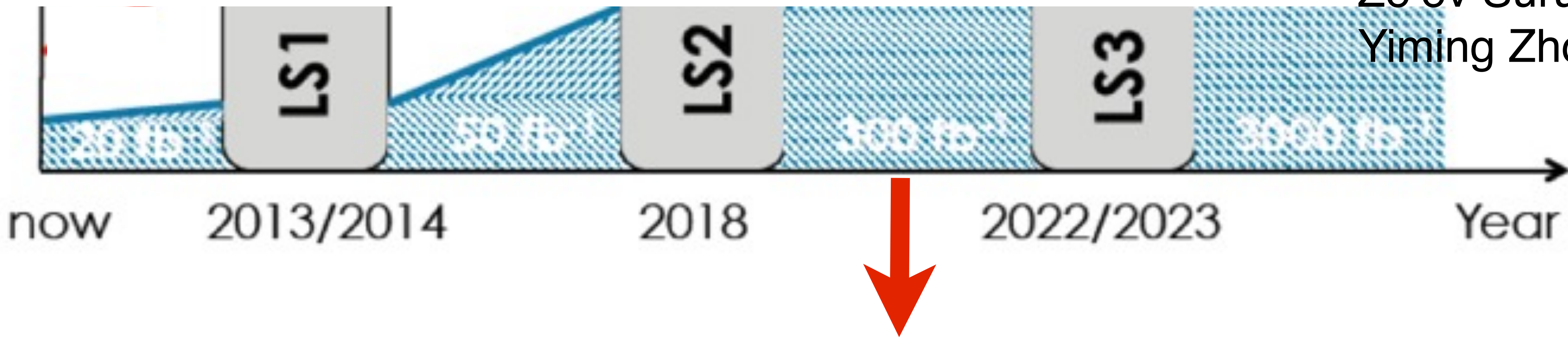
Yiming Zhong



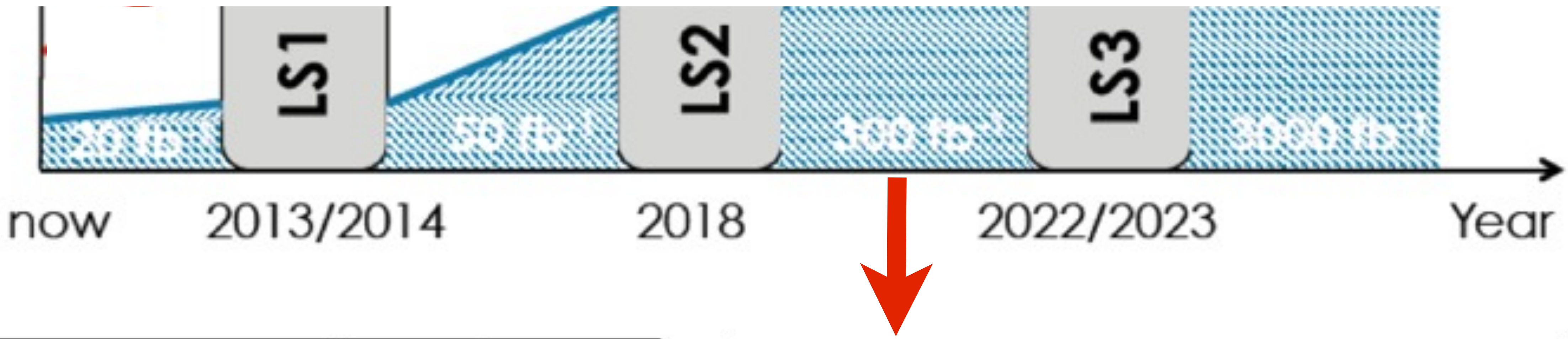
- Trigger: Wh + Zh
- Strategies: work in the boost regime, apply jet substructure tool + 2b-tags
- For 100/fb data at LHC14 and Ceff = 1

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

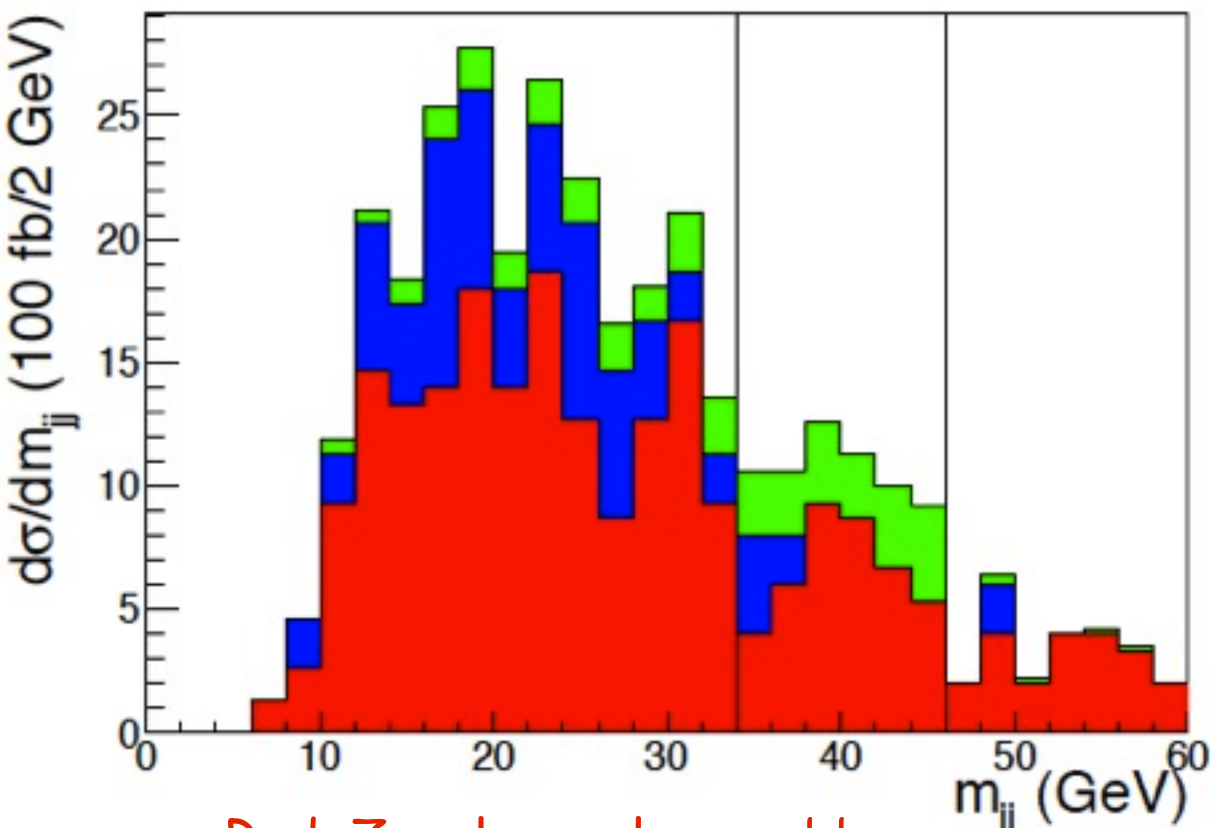
Carena, Han, Huang, Wagner (2007)
Cheung, Song, Yan (2007)
Kaplan, McEvoy (2011)

Example III: di-b + MET

TL



m_{h_1}	m_{h_2}	$m_{\chi 1}$	$m_{\chi 2}$
45 GeV	125 GeV	10 GeV	80 GeV



Red: Z + gluon, gluon -> bb

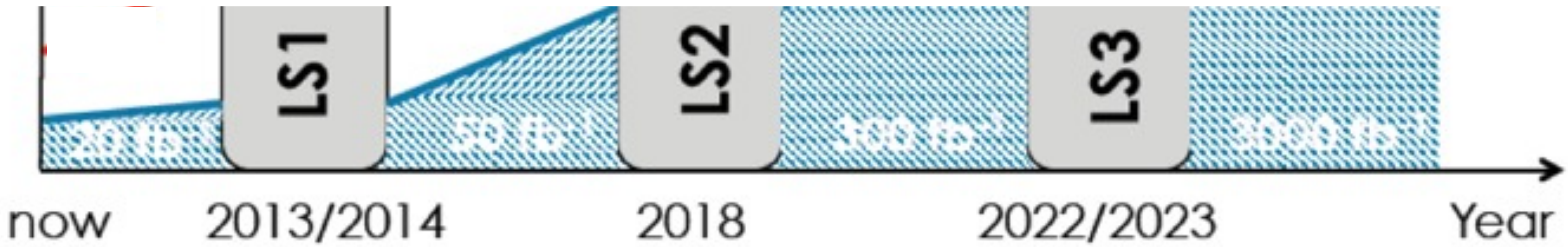
Blue: tt + jets

Green: signal X 20

- 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)

[Huang, TL, Wang et. al., arXiv: 13xx.xxxx]

LHC vs. Higgs Factory



?

Difficult cases at the LHC:

The final state is purely MET or soft jets (with or without MET), given the BR for the exotic Higgs decay below 10%

Question: can a Higgs factory play a role in discovering exotic decays which are challenging at the LHC?

[TL, Chris Potter, arXiv: 13xx.xxxx]

Summary

- The 125 GeV Higgs can be a leading window into BSM physics => must look explicitly for its exotic decays
- There exist many possibilities for its exotic decays, so we need to survey, systematize, prioritize them, and assess their discovery potential
- R- and PQ-symmetry limits in the NMSSM provide supersymmetric benchmarks for various exotic Higgs decays with and without MET
- The LHC and a future Higgs factory can play a crucial role in searching for them ... ...


Thank you!