IAS Workshop on ``New Perspectives on Cosmology”
HKIAS, MAY, 2014

PROBING FOR DM PHYSICS VIA EXOTIC DECAYS OF THE 125 GEV HIGGS BOSON

Tao Liu

Hong Kong University of Science and Technology

``Dark Light Higgs Boson'',

P. Draper, TL, C. E.M. Wagner, L.-T. Wang and H. Zhang,

Phys. Rev. Lett. 106 (2011)

``Supersymmetric Exotic Decays of the 125 GeV Higgs Boson'',

J. Huang, TL, L-T Wang and F. Yu,

arXiv: 1309.6633, to be published in Phys. Rev. Lett

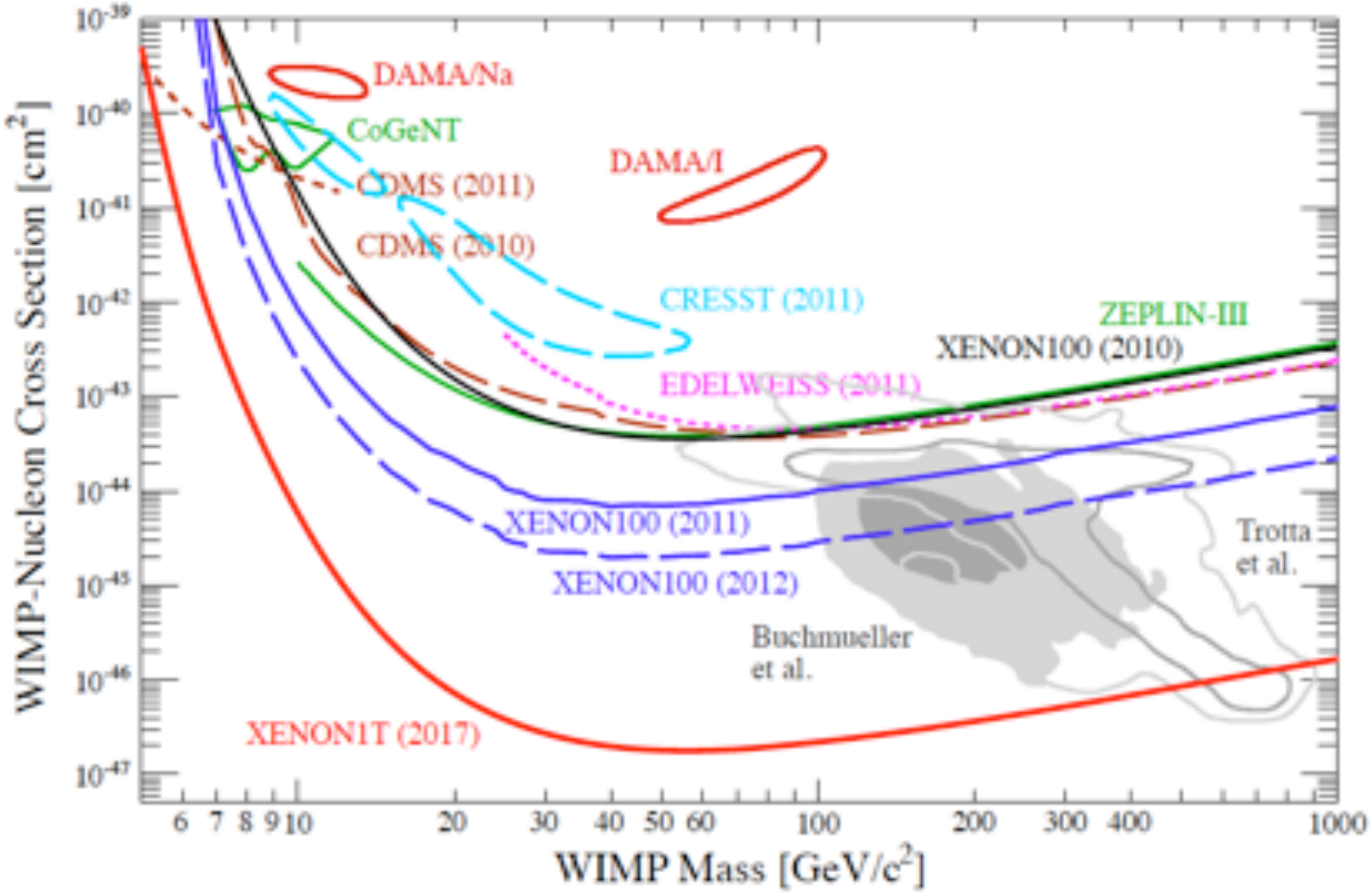
``Exotic Decays of the 125 GeV Higgs Boson'',

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,

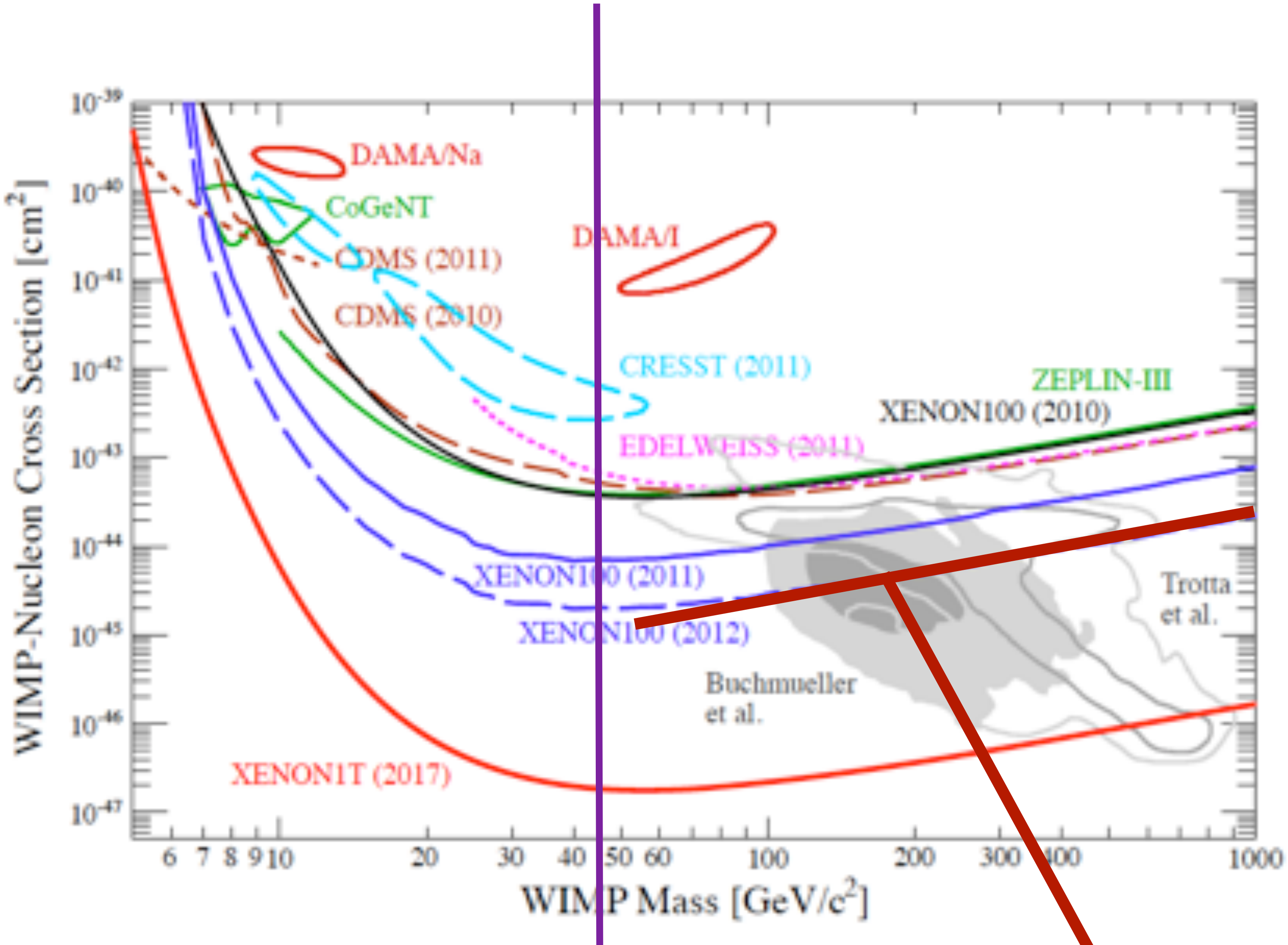
arXiv: 1312.4992, submitted to Phys. Rev. D

WIMP Miracle



$$\Omega_X h^2 \propto \frac{1}{\langle \sigma v \rangle} \propto \frac{m_X^2}{g_X^4} \sim \frac{(100\mathrm{GeV})^2}{g_{SU(2)_L}^4}$$

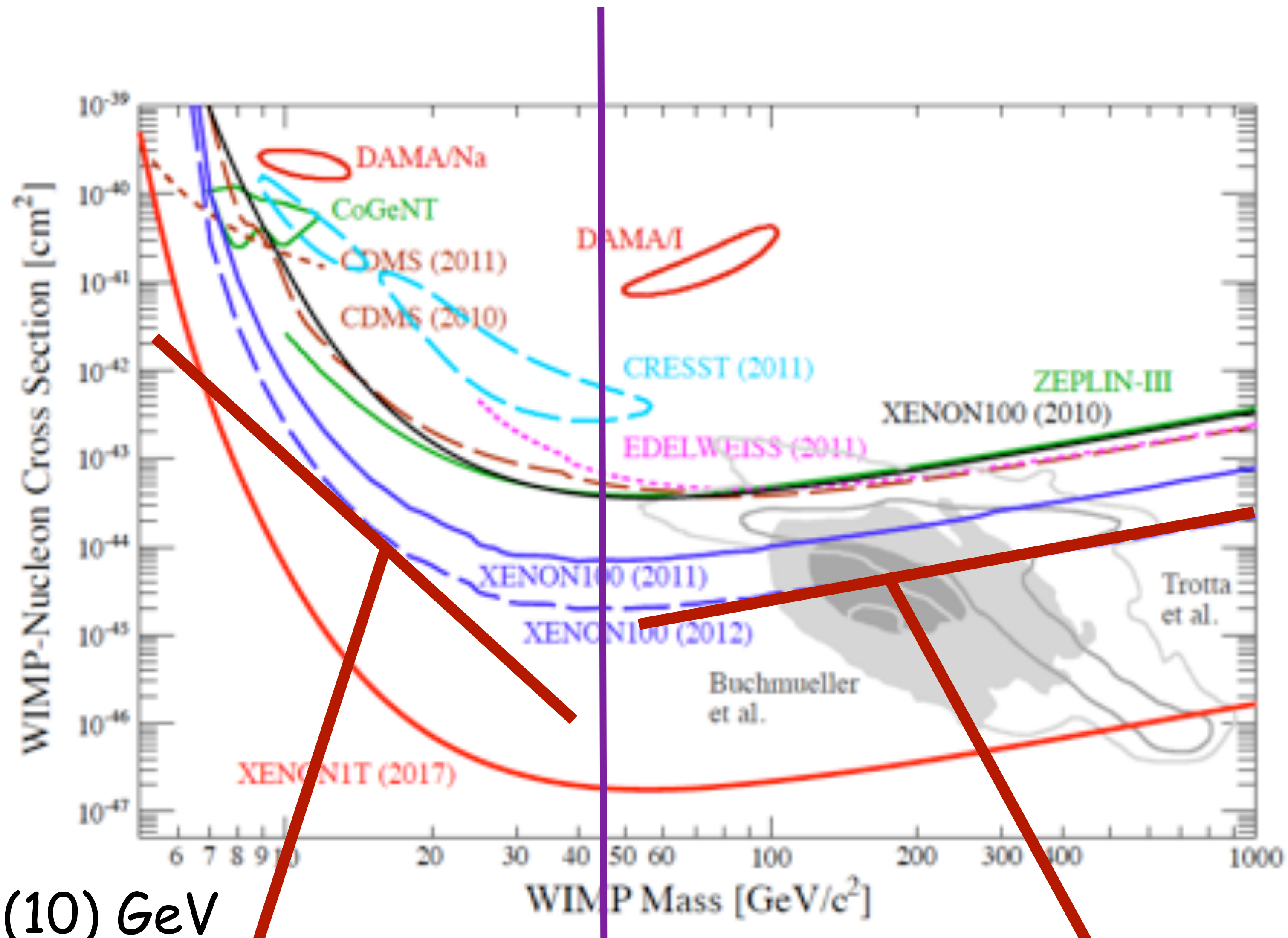
Dark Matter - Direct Detection



$M_{DM} \sim O(100)$ GeV

Well-studied in UV-complete theories

Dark Matter - Direct Detection



M_{DM} ~ O(1) or O(10) GeV

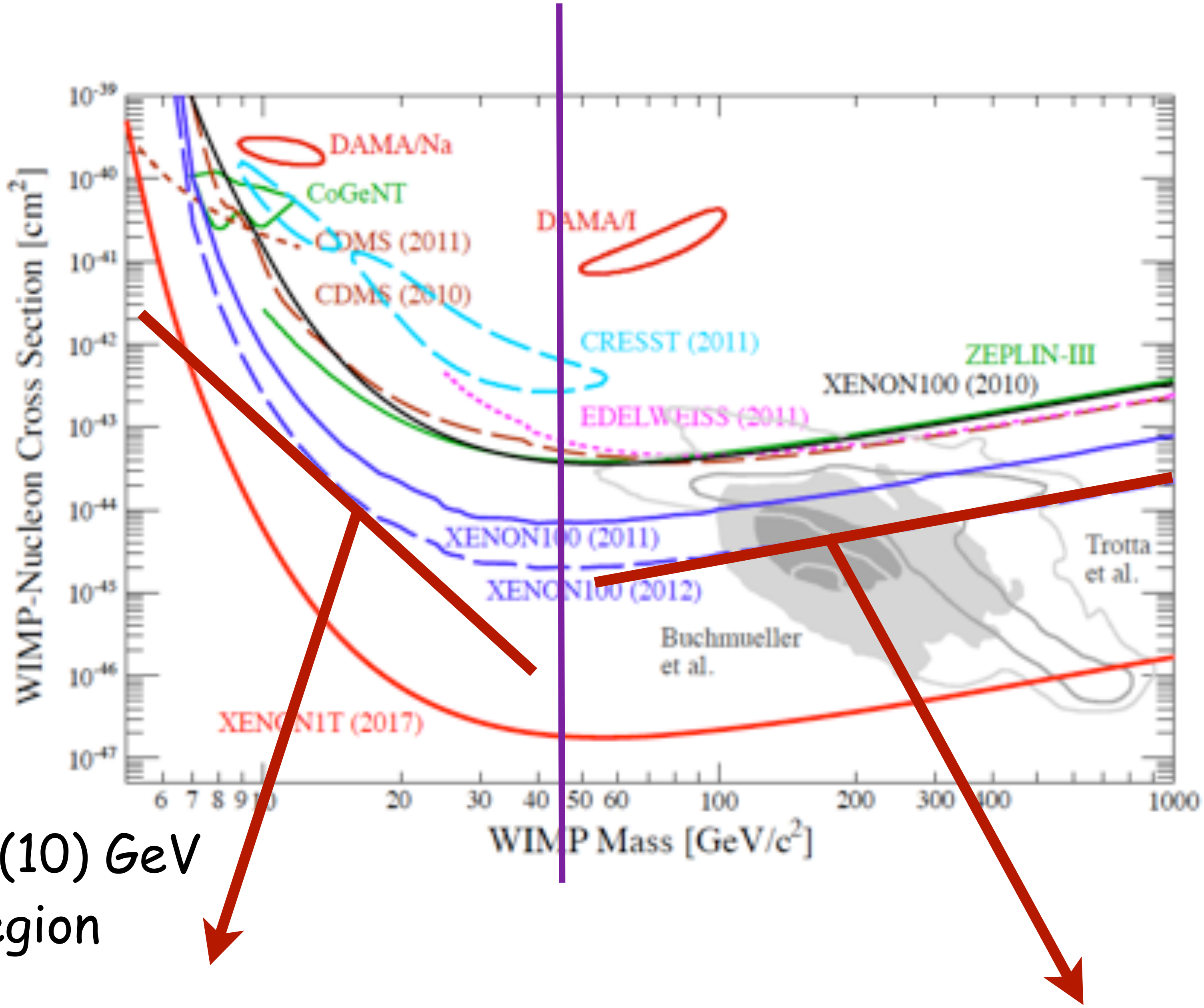
``Messy'' region

Controversial results from both direct detections and indirect detections (for recent progress of the latter, e.g., see [D. Hooper etc. arXiv: 1402.6703])

M_{DM} ~O(100) GeV

Well-studied in UV-complete theories

Dark Matter - Direct Detection



M_{DM} ~ O(1) or O(10) GeV
``Messy" region

Are there any supersymmetric benchmark scenarios for light or sub-EW scale (thermal) DM?

M_{DM} ~O(100) GeV

Well-studied in UV-complete theories

A Toy Model: SM + Singlet Scalar

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

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

- S is real and doesn't get a VEV during EW phase transition (hence no mixing between H and S)
- There is a Z_2 under transformation S -> -S, so s is stable
- Then ms ~ 10 GeV, zeta ~ 0.1 can lead to acceptable relic density

Thermal Light DM Particle in Supersymmetry?

$$\chi_1 = \tilde{B} + \tilde{W} + \tilde{h}_u + \tilde{h}_d + \tilde{s}$$

Thermal Light DM Particle in Supersymmetry?

$$\chi_1 = \tilde{B}\,? + \tilde{W} + \tilde{h}_u + \tilde{h}_d + \tilde{s}\,?$$

- Wino or Higgsino-like? No, due to bounds for charginos
- Bino-like? Probably okay, but GUT is gone; also difficult to get correct relic density in the MSSM
- Singlino-like? Very likely, in singlet extensions of the MSSM like the NMSSM.

Thermal Light DM Particle in Supersymmetry?

$$\chi_1 = \tilde{B}? + \tilde{W} + \tilde{h}_u + \tilde{h}_d + \tilde{s}?$$

- Wino or Higgsino-like? No, due to bounds for charginos
- Bino-like? Probably okay, but GUT is gone; also difficult to get correct relic density in the MSSM
- Singlino-like? Very likely, in singlet extensions of the MSSM like the NMSSM.

Nearly Peccei-Quinn symmetry limit of of the singlet-extensions of the MSSM

P. Draper, TL, C. E.M. Wagner, L.-T. Wang and H. Zhang, Phys. Rev. Lett. 106 (2011)

Nearly PQ-limit in the NMSSM

- For illustration, consider the NMSSM with R-parity conservation:

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

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

- Peccei-Quinn limit (k -> 0, Ak -> 0), to keep invariant under the transformation

$$H_u \to H_u \exp(i\phi_{PQ}),\ \ H_d \to H_d \exp(i\phi_{PQ}),\ \ N \to N \exp(-2i\phi_{PQ})$$

- Why is the singlino mass small? $m_{\chi_1} \approx v^2\lambda^2 \sin 2\beta/\mu + 2\kappa\mu/\lambda$
  - contribution from self-interaction term is small (due to kappa -> 0)
  - contribution from mixing term is also small (avoiding Landau pole problem requires lambda < 0.5)

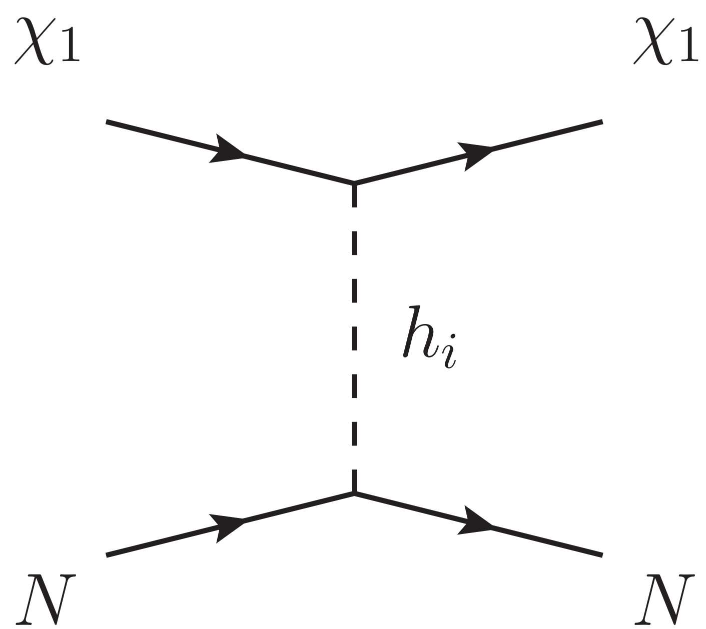
Nearly PQ-limit in the NMSSM

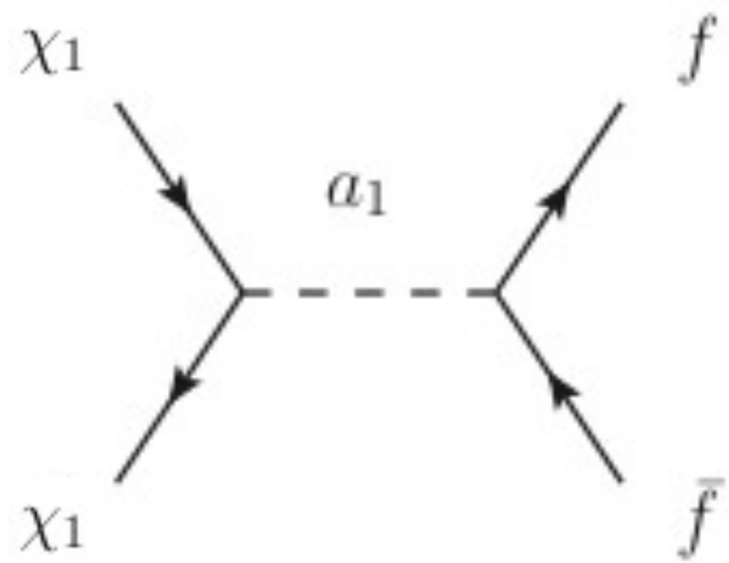
$$
\begin{aligned}
M^2_{H33} &\sim \kappa s (A_\kappa + 4\kappa s) \\
M^2_{A22} &\sim -3\kappa A_\kappa s \\
M_{\chi_0 55} &\sim 2\kappa s
\end{aligned}
$$

$$\Rightarrow M^2_{\chi_0 55} \sim M^2_{H33} + \frac{1}{3} M^2_{A22}$$

Simultaneously light: singlino, singlet-like CP-even and CP-odd Higgs boson!

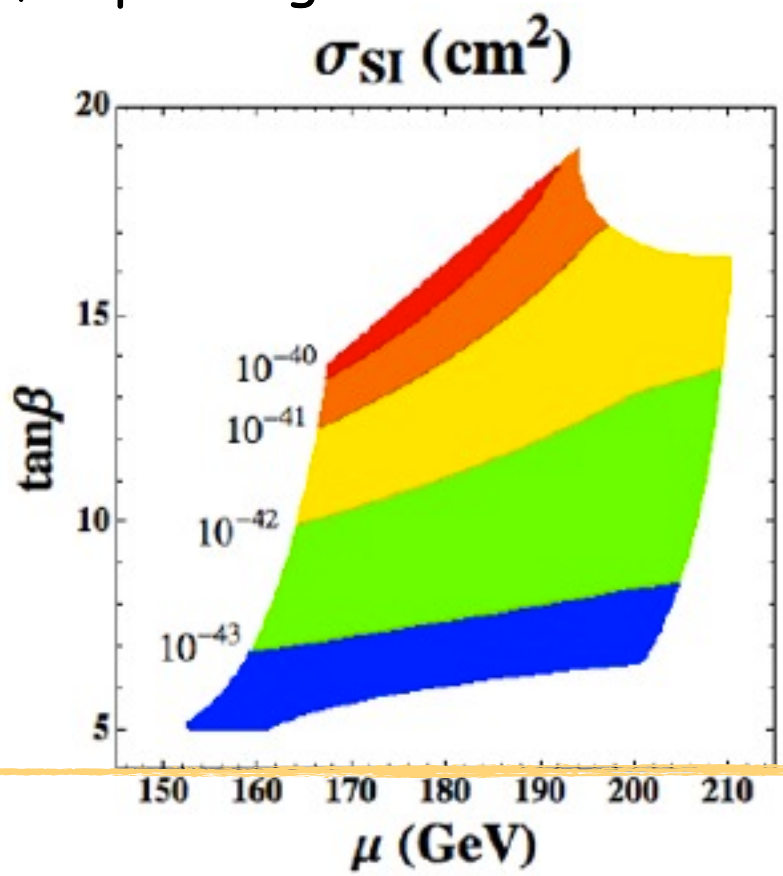
DM Physics in the Nearly PQ-limit of the NMSSM

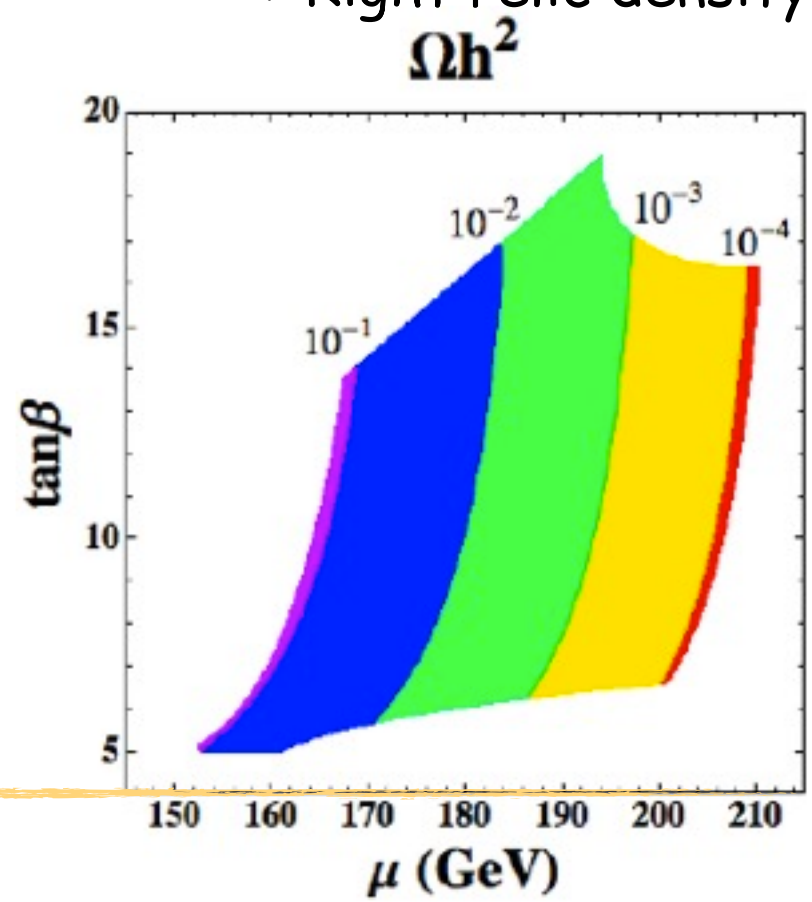




Direct detect cross section varying within a big range, depending on the mediator mass

Breit - Wigner enhancement effect ! -> Right relic density





Questions to Address

In DM physics

Can we probe for DM physics of sub-EW scale via Higgs measurements?

125 GeV Higgs - a Leading Window into New Physics

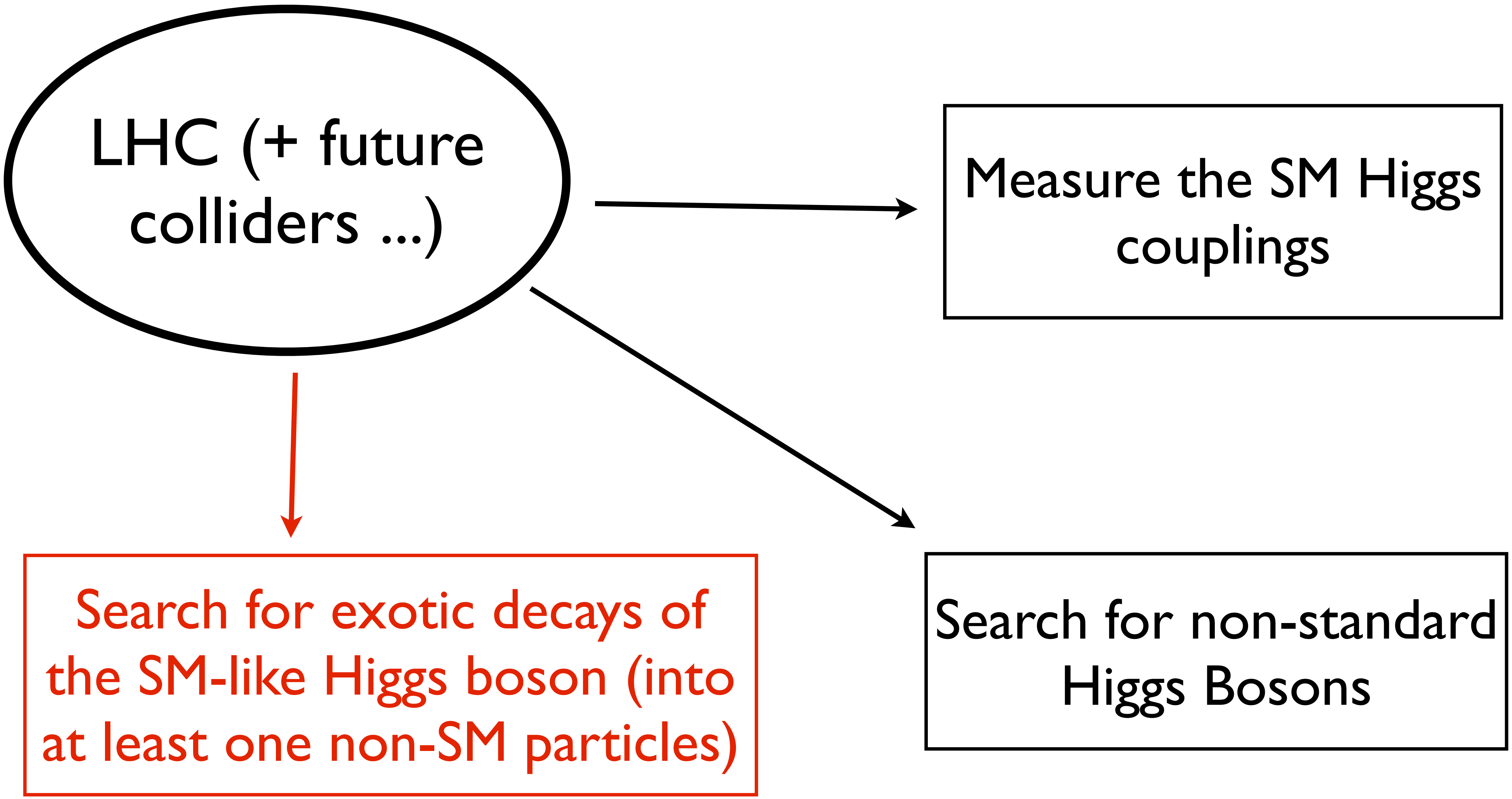
- If new physics (NP) manifests itself as SM singlet operators, $H^\dagger H$ is one of the two dim-2 operators in the SM which can couple with it via either renormalizable coupling or non-renormalizable coupling at leading level [Patt and Wilczek, arXiv:[hep-ph/0605188]]

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

Lorentz invariant gauge singlet

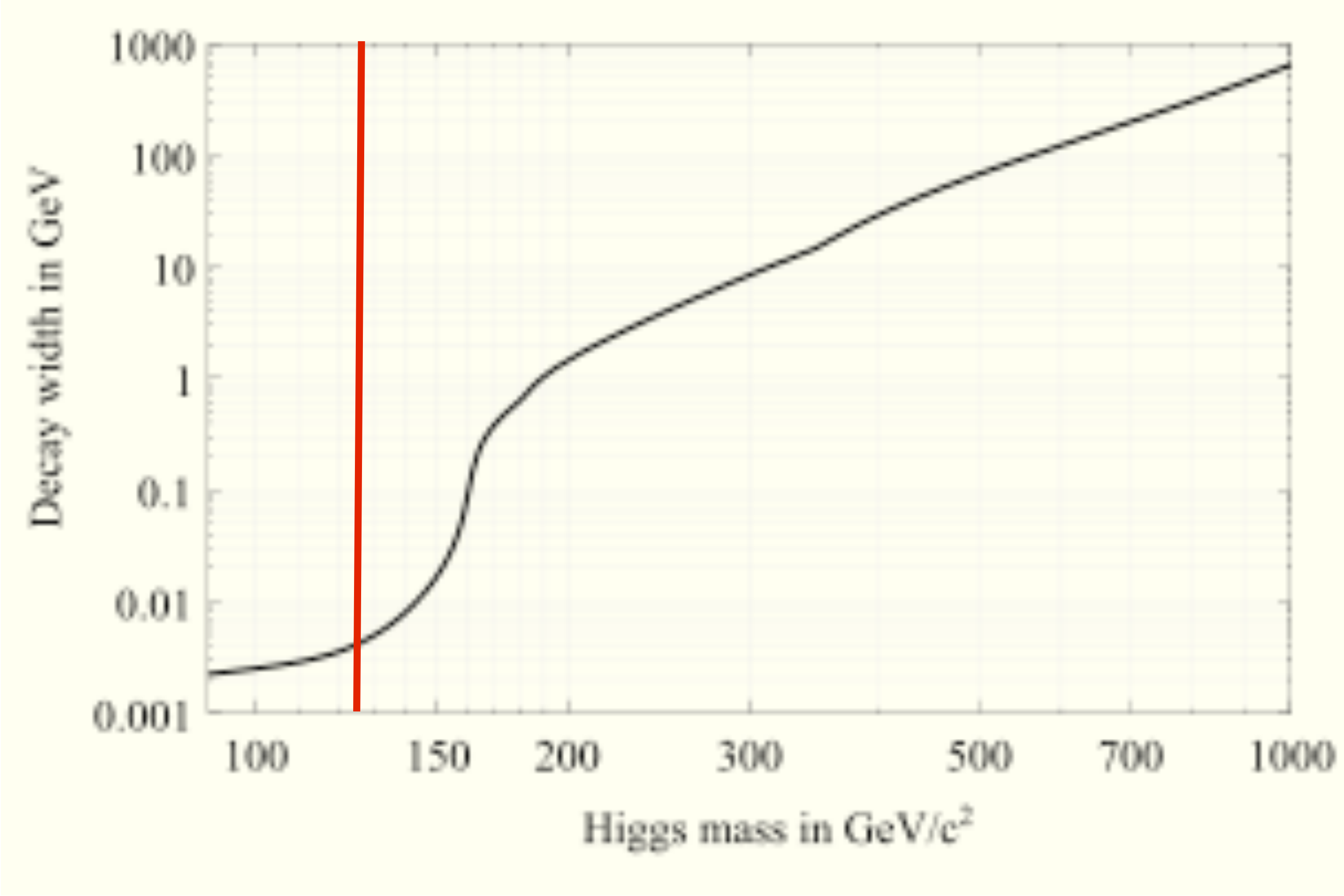
- If NP serves as a mechanism for dynamically stabilizing the Higgs mass (e.g., SUSY), then the Higgs needs to couple with the NP directly
- Both types of couplings can modify the Higgs productions and decays at colliders in a significant way.

Searching for New Physics via Higgs Measurements

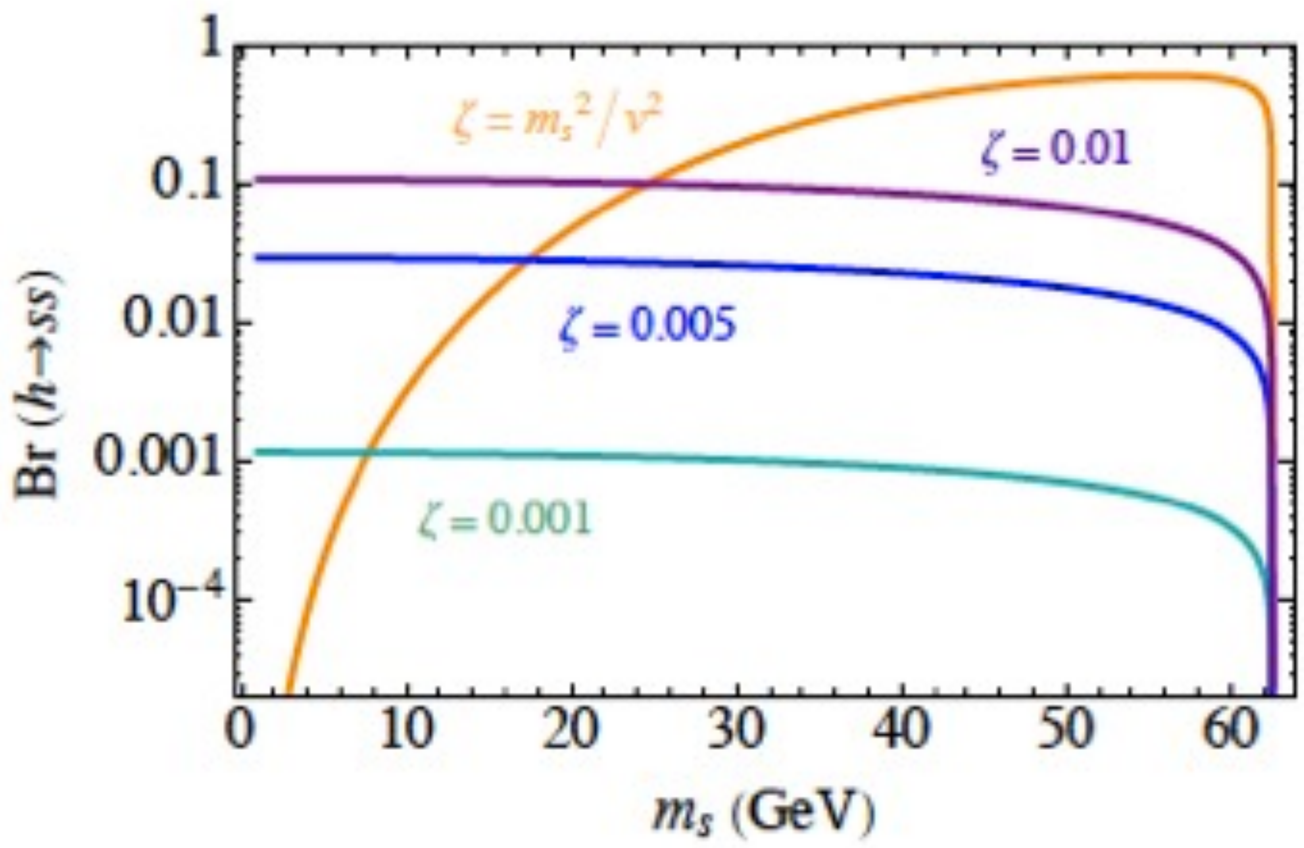


EHD - Sensitive to NP

- Higgs width is small: about three orders smaller than the Z or W widths (~ 4MeV only) !
- A small non-standard Higgs coupling => sizable effect.



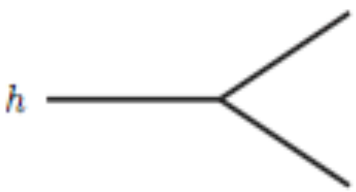
EHD - Sensitive to NP



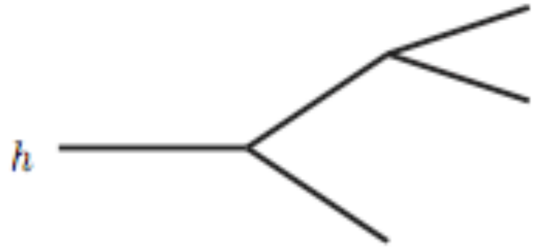
$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

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

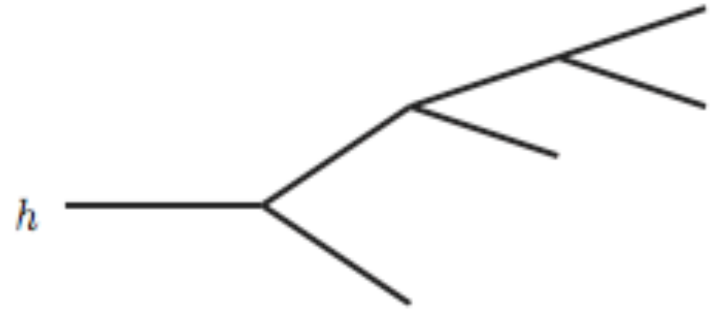
EHD - Various Decay Topologies



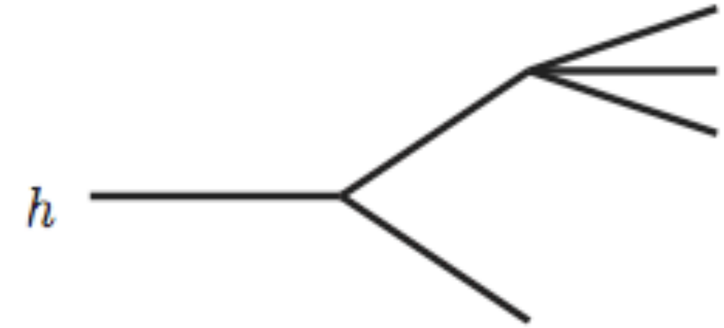
$h \to 2$



$h \to 2 \to 3$

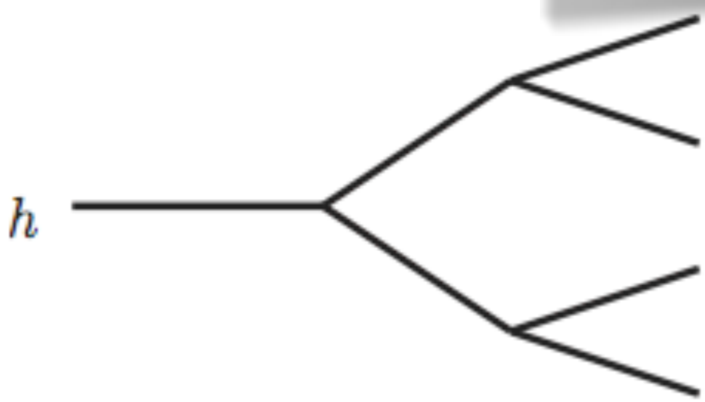


$h \to 2 \to 3 \to 4$

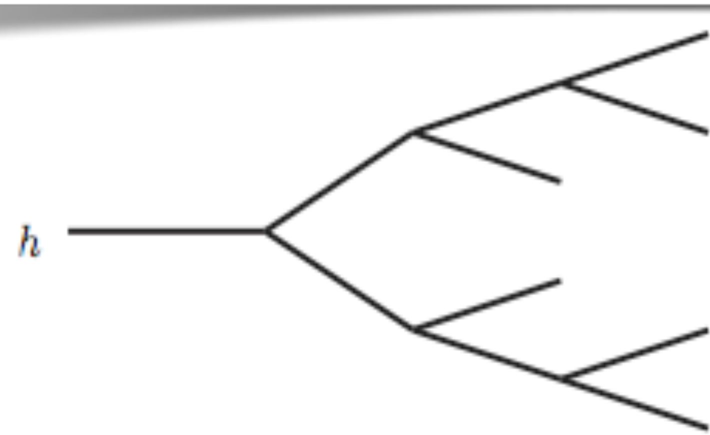


$h \to 2 \to (1+3)$

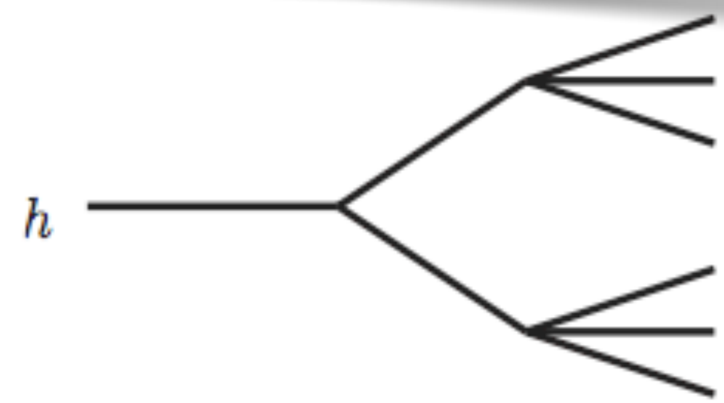
Note: here initial decay is assumed to be 2-body, since 3-body usually suffers a phase space suppression



$h \to 2 \to 4$

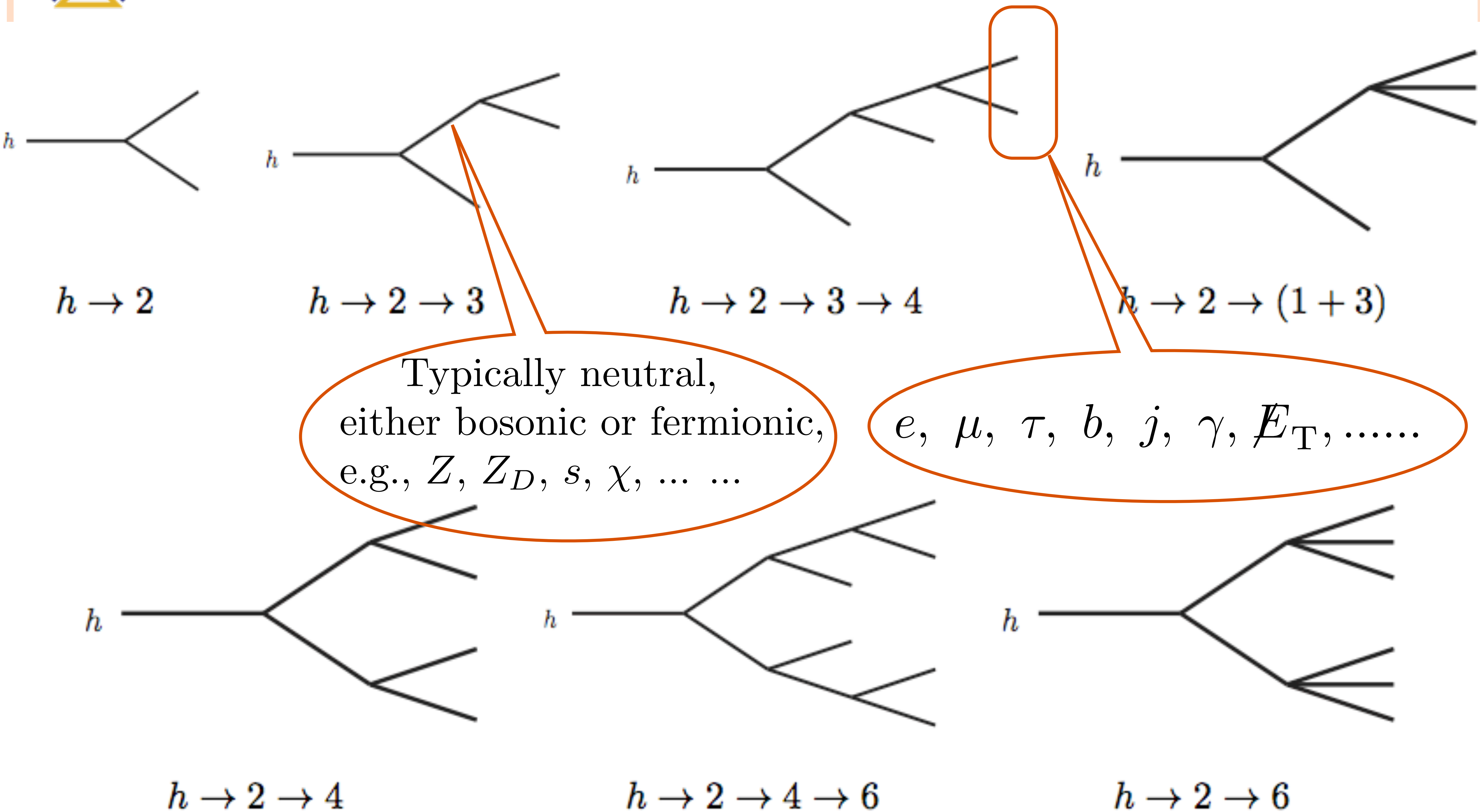


$h \to 2 \to 4 \to 6$



$h \to 2 \to 6$

EHD - Various Decay Topologies



=> Various Collider Signatures

$$h \rightarrow \text{MET}$$
$$h \rightarrow \gamma + \text{MET}$$
$$h \rightarrow 2\gamma + \text{MET}$$
$$h \rightarrow 2l + \text{MET}$$
$$h \rightarrow 4l + \text{MET}$$
$$h \rightarrow 1\text{lepton} - \text{jet} + \text{MET}$$
$$h \rightarrow 2\text{lepton} - \text{jets} + \text{MET}$$
$$h \rightarrow 2b + \text{MET}$$
$$h \rightarrow 2\tau\text{MET}$$

$$h \rightarrow 4b$$
$$h \rightarrow 2b2\tau$$
$$h \rightarrow 2b2\mu$$
$$h \rightarrow 4\tau, 2\tau 2\mu$$
$$h \rightarrow 4j$$
$$h \rightarrow 2\gamma 2j$$
$$h \rightarrow 4\gamma$$
$$h \rightarrow Z Z_D \rightarrow 4l$$
$$h \rightarrow Z_D Z_D \rightarrow 4l$$

h -> invisible, semi-visible, visible

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}

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

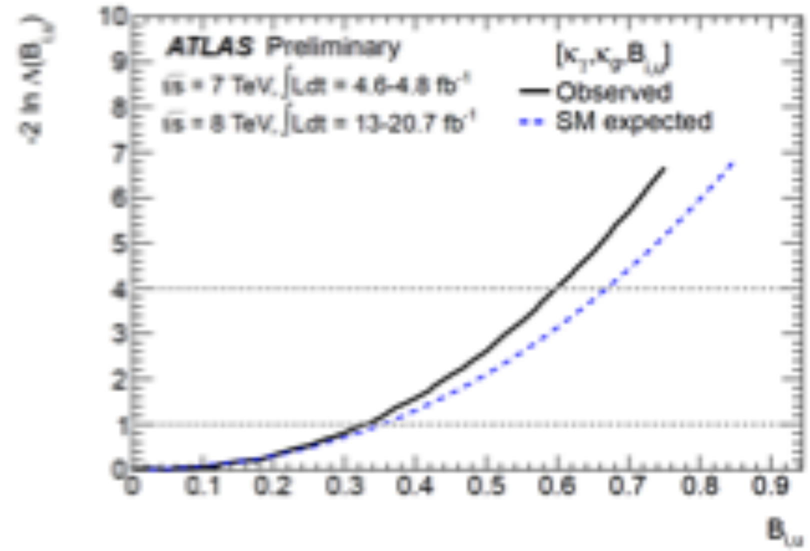
Parameterization on modified Higgs width:

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

- Three fitted parameters:

$\kappa_\gamma, \kappa_g + BR_{inv}$

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

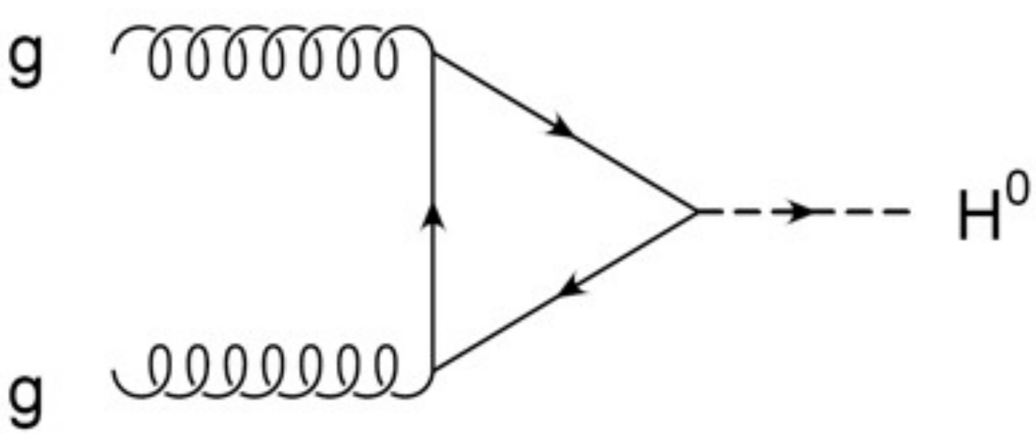
In a general context, a big room for exotic Higgs decays is allowed:
> 50% BR at 2 sigma C.L. !

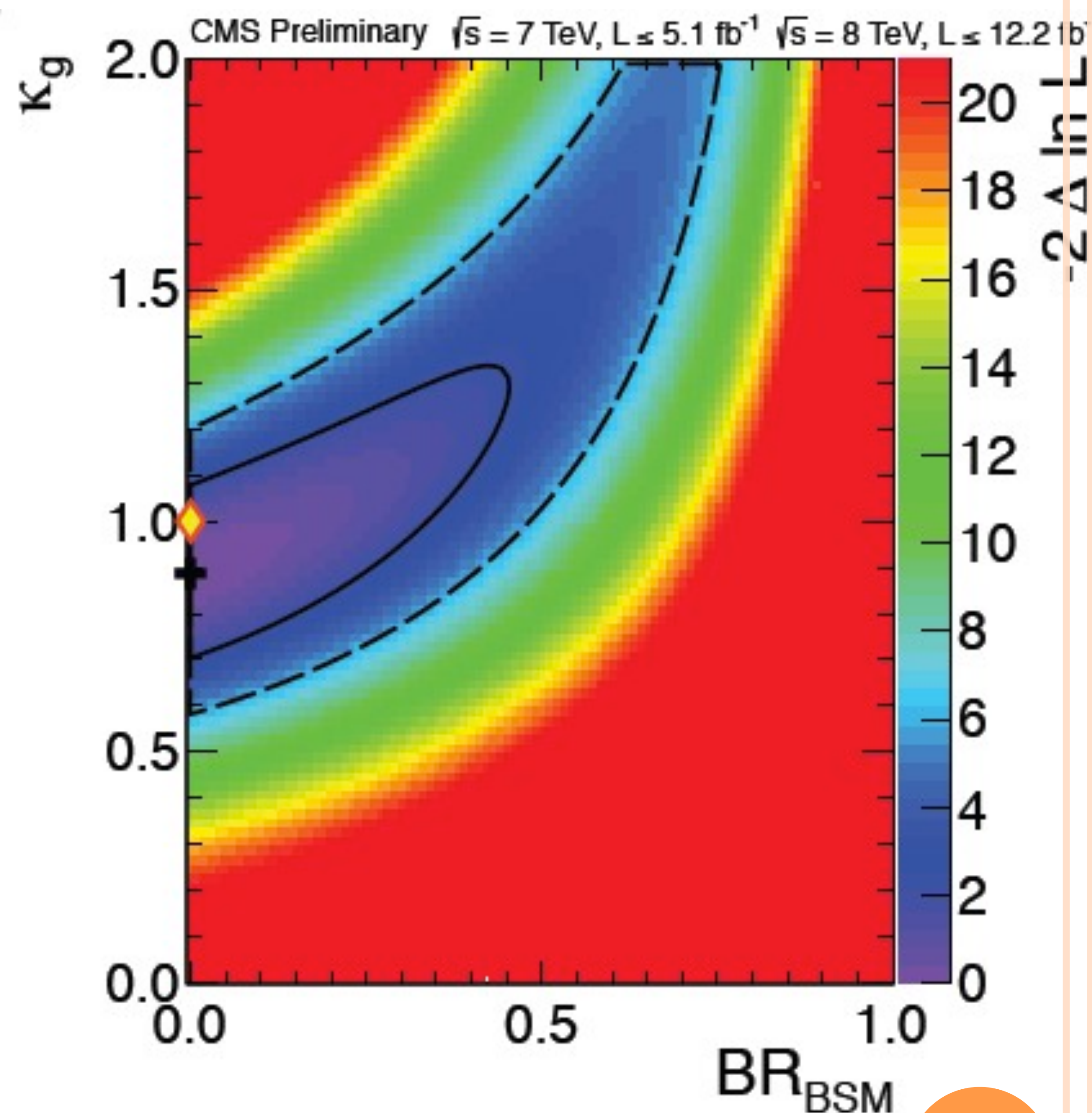
EHD - Sizable Room

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

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

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



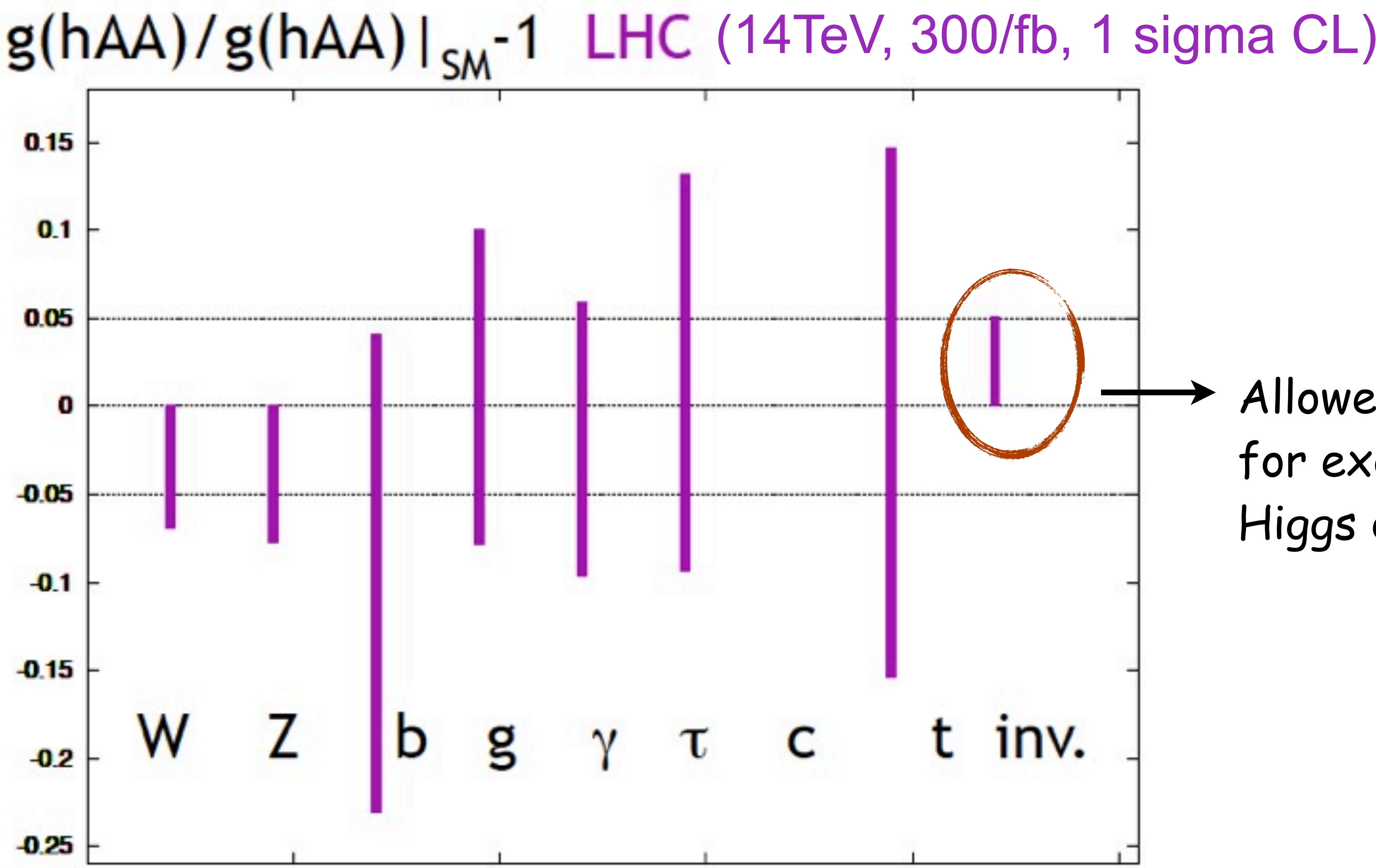


As a comparison (for mh=125GeV)

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

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]



Allowed Br for exotic Higgs decays

How Many Exotic Decay Events Generated at LHC8?

Production	$\sigma_{7\ \mathrm{TeV}}$ (pb)	$N_{\mathrm{ev}}^{10\%}$, 5 fb^{-1}	$\sigma_{8\ \mathrm{TeV}}$ (pb)	$N_{\mathrm{ev}}^{10\%}$, 20 fb^{-1}	$\sigma_{14\ \mathrm{TeV}}$ (pb)	$N_{\mathrm{ev}}^{10\%}$, 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

Will motivate many experimental searches. Very exciting!
But in the regard of theory, we need more inputs!

Questions to Address

In DM physics

Can we probe for DM physics of sub-EW scale via Higgs measurements?

In Higgs physics

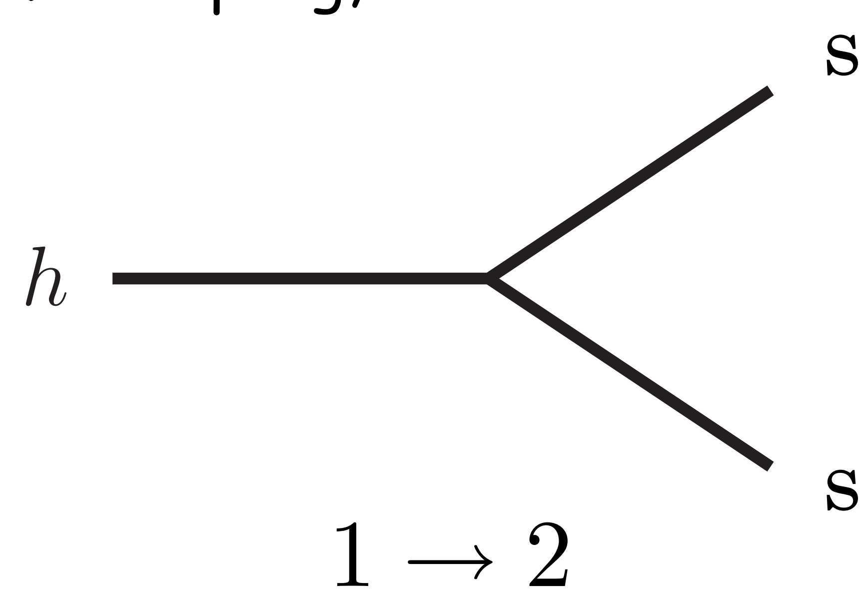
Can these decay topologies be mapped to well-motivated theoretical models or scenarios, such as supersymmetry?

Case I: SM + Singlet Scalar

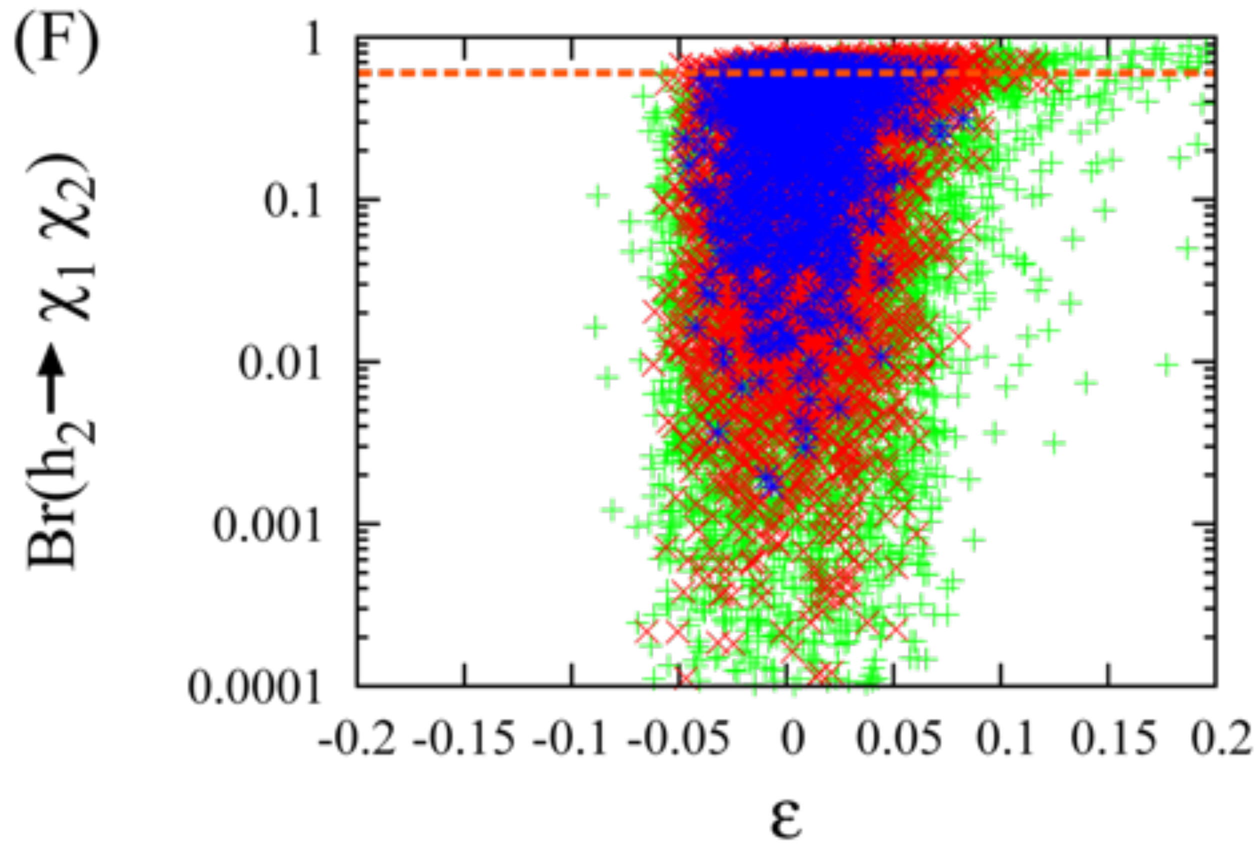
$$V(H,S) = -\mu^2\,|H|^2 - \frac{1}{2}\,\mu'^2\,S^2 + \lambda\,|H|^4 + \frac{1}{4}\,\kappa\,S^4 + \frac{1}{2}\,\zeta\,S^2\,|H|^2$$

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

- S is real and doesn't get a VEV during EW phase transition (hence no mixing between H and S)
- There is a Z_2 under transformation S -> -S, so s is stable
- Then ms ~ 10 GeV, zeta ~ 0.1 can lead to acceptable relic abundance
- Because of the same coupling, h -> ss = invisible

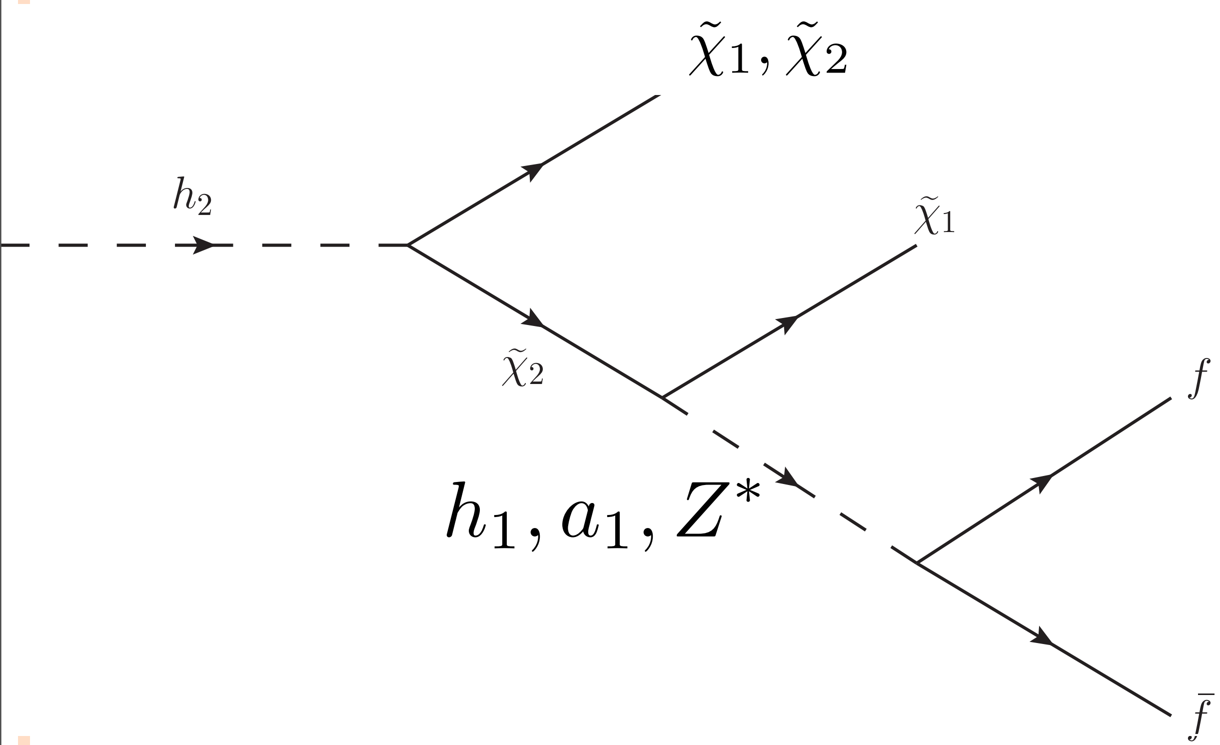


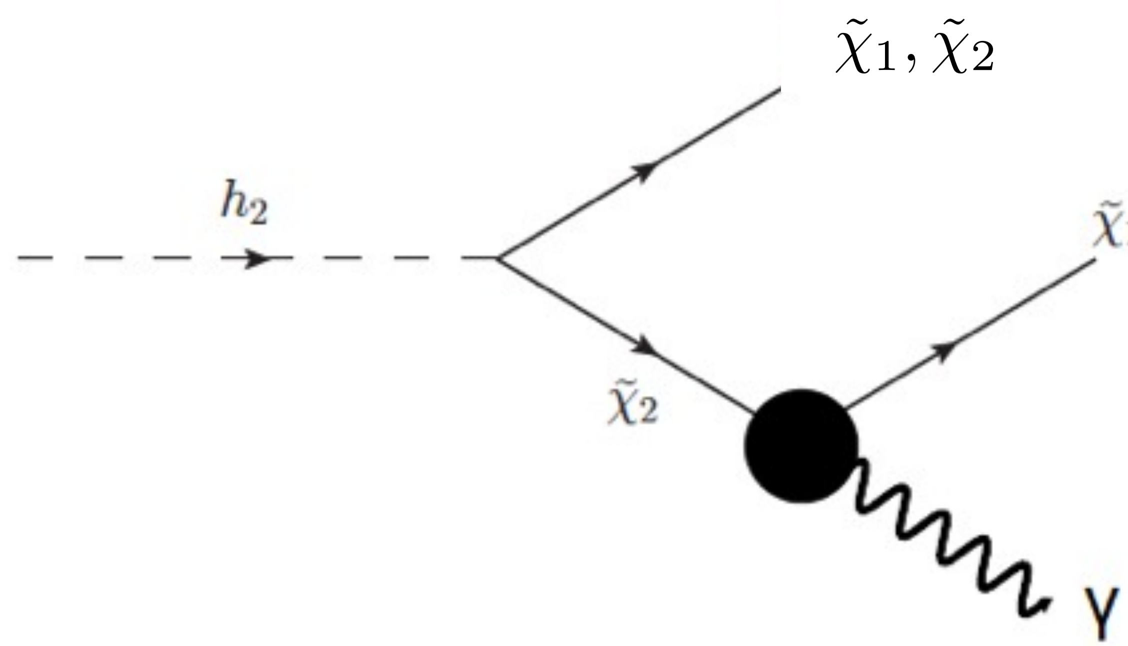
Case II: PQ-symmetry Limit in the NMSSM



- $h \to \chi_1\chi_2$ is significant, if kinematically allowed!
- Recall: in PQ-limit, χ_1 is singlino-like, and typically light
- If χ_2 is bino-like and has a mass of EW scale or below, then such decays are kinematically turned on !

Case II: PQ-symmetry Limit in the NMSSM





Collider phenomenology: characterized by moderate MET + visible objects

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

Nearly PQ-limit of the NMSSM provides supersymmetric benchmark for almost all possible semi-invisible exotic Higgs decays

[J. Huang, TL, L-T Wang and F. Yu,
arXiv: 1309.6633, to be published in Phys. Rev. Lett.]

More Theories ... ...

Simple extensions of the SM:

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

More complicated ones:

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

Take-home Messages

In DM physics

Can we probe for DM physics of sub-EW scale via Higgs measurements?

In Higgs physics

Can these decay topologies be mapped to well-motivated theoretical models or scenarios, such as supersymmetry?

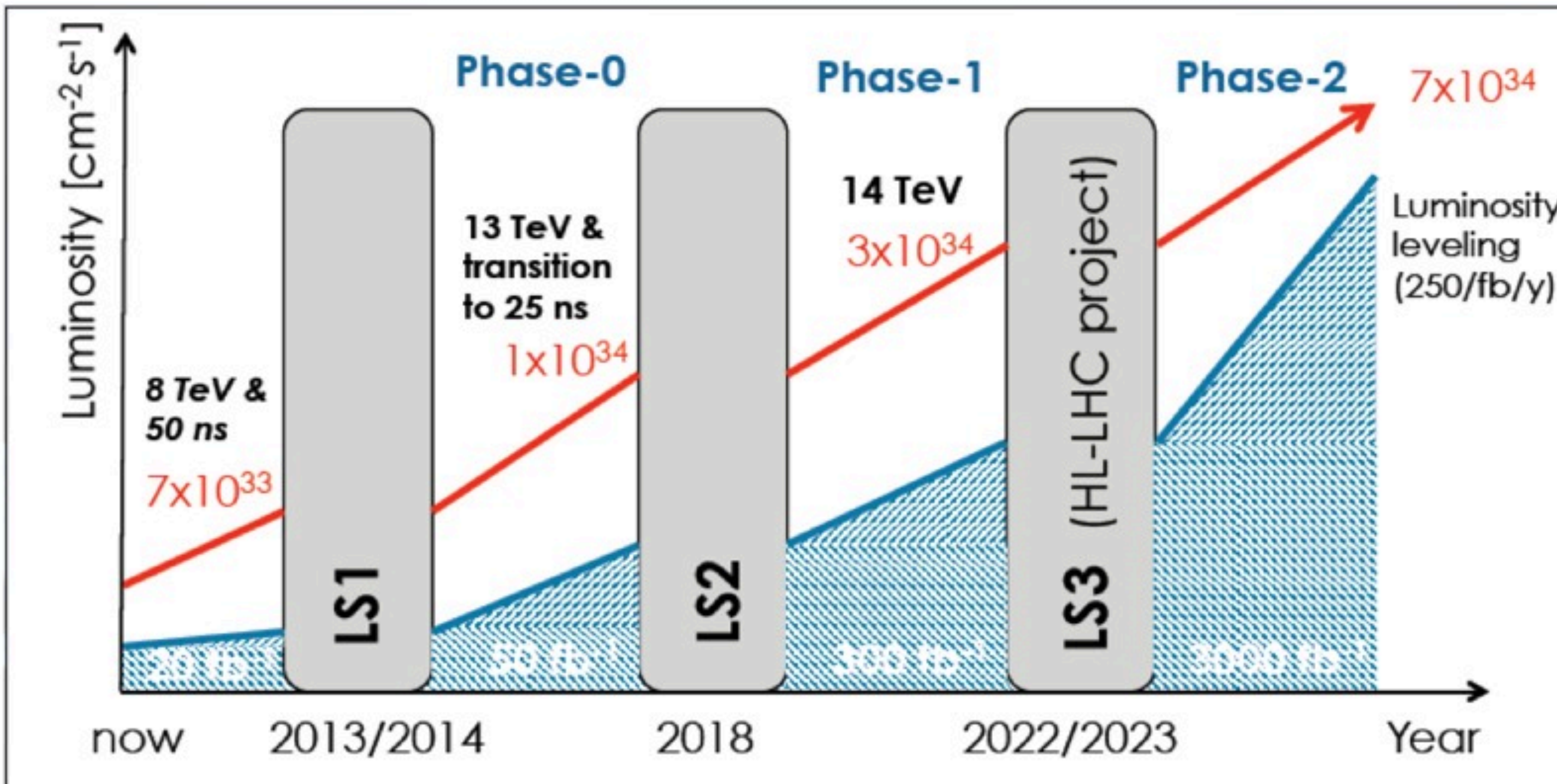
- Exotic Higgs decays provide a powerful tool for probing for DM physics of sub-EW scale
- DM physics provides one of the most important theoretical motivations for searching for exotic Higgs decays

How Many Exotic Decay Events Generated LHC8?

Production	$\sigma_{7\text{ TeV}}$ (pb)	$N_{\text{ev}}^{10\%}$, 5 fb^{-1}	$\sigma_{8\text{ TeV}}$ (pb)	$N_{\text{ev}}^{10\%}$, 20 fb^{-1}	$\sigma_{14\text{ TeV}}$ (pb)	$N_{\text{ev}}^{10\%}$, 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

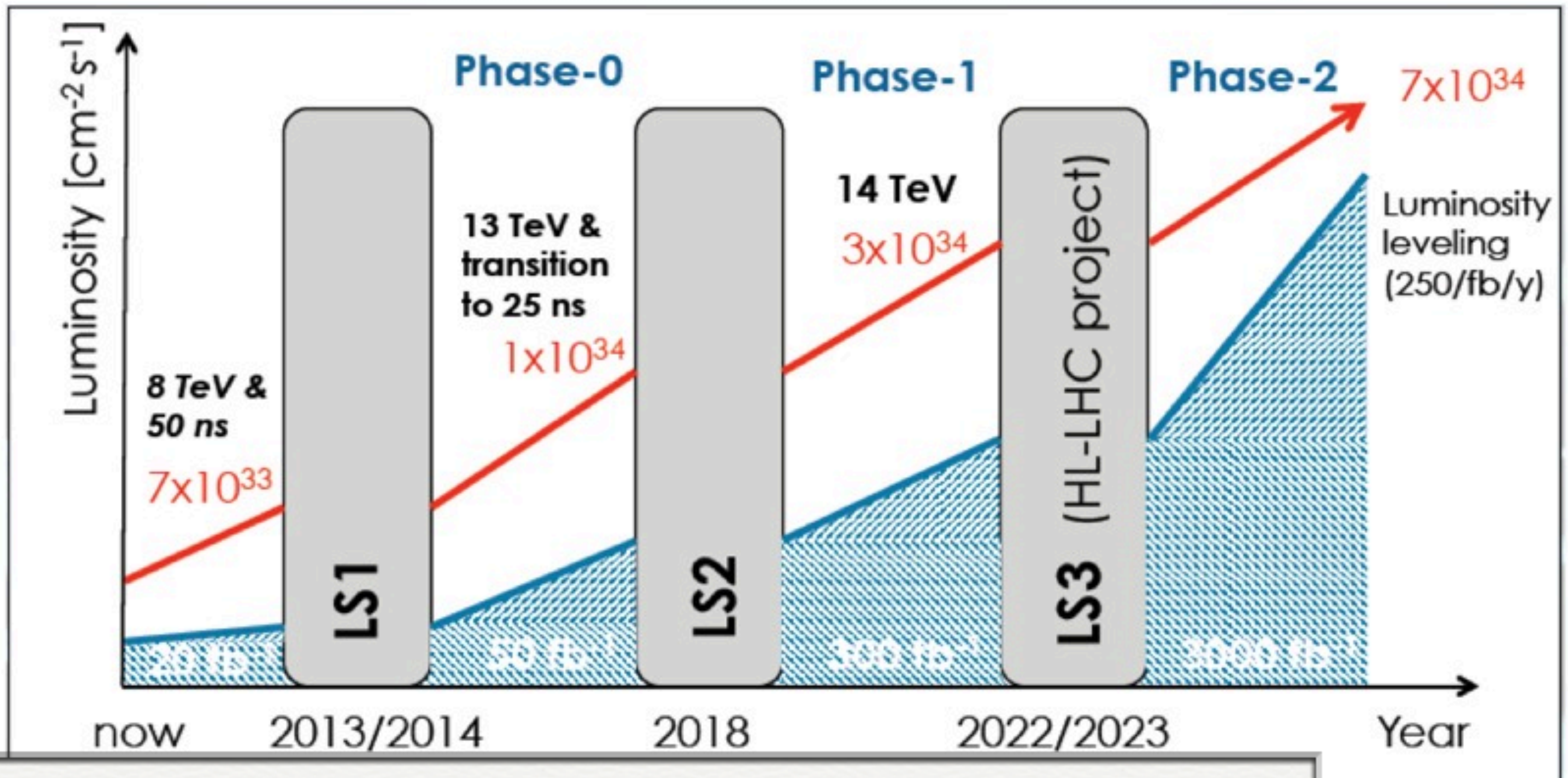
How Many Exotic Decay Events Generated LHC8?

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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$hW^\pm$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$hW^\pm(\ell^\pm\nu)$	0.5[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
hZ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$hZ(\ell^+\ell^-)$	0.34[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$t\bar{t}h$	0[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



How Many Exotic Decay Events Generated LHC8?

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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$hW^{\pm}$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$hW^{\pm}(\ell^{\pm}\nu)$	0.5[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
hZ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$hZ(\ell^{+}\ell^{-})$	0.34	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$t\bar{t}h$	0[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



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, ...
- ... ...

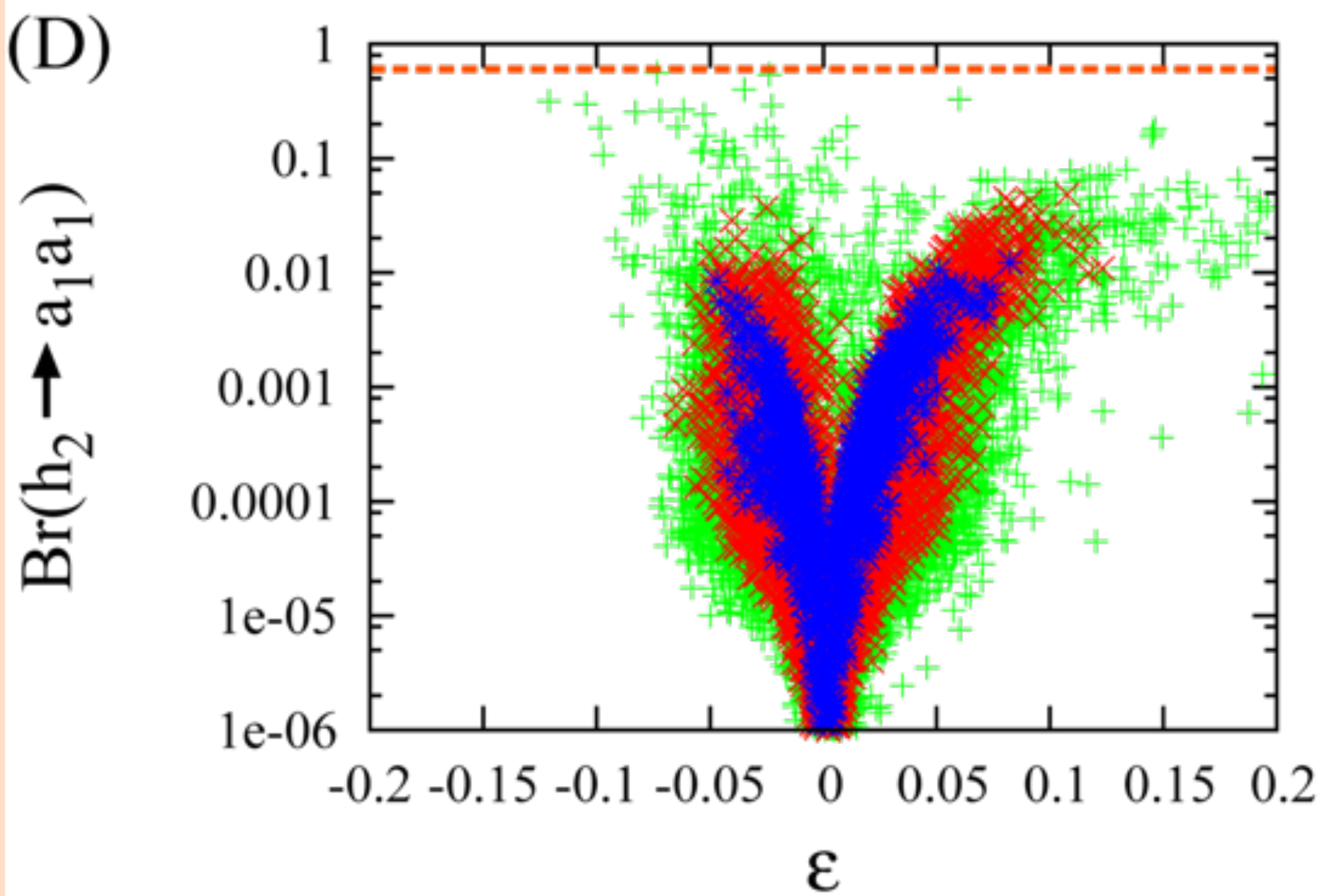
Indeed, exotic Higgs decays look exotic ... ...


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


Thank you!

PQ-symmetry Limit

- There exists a light singlet-like PQ-axion a1
- h -> a1a1, h1h1 are kinematically allowed but generically suppressed



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

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

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