Exotic Higgs Decays

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Higgs: Questions After Discovery

- Is it really the Higgs Boson?

  Probably **Yes** (coupling to $W^{\pm}, Z^{0}$; spin , parity)

- Is it the Standard-Model Higgs?

  Maybe, but still need to…

  - *measure* SM couplings → Look for deviations in SM-like decays
  - *discover* non-SM couplings → Look for new production modes

  Look for new decay modes

Exotic Higgs Decay Modes

are

Modes which do not exist / are very rare in the SM

Examples:

$h \to$ invisible (Shrock+Suzuki 1982)

$h \to$ flavor violating (e.g.: Harnik+Kopp+Zupan,…)

$h \to XX \to (\ell\ell)(\ell\ell)$

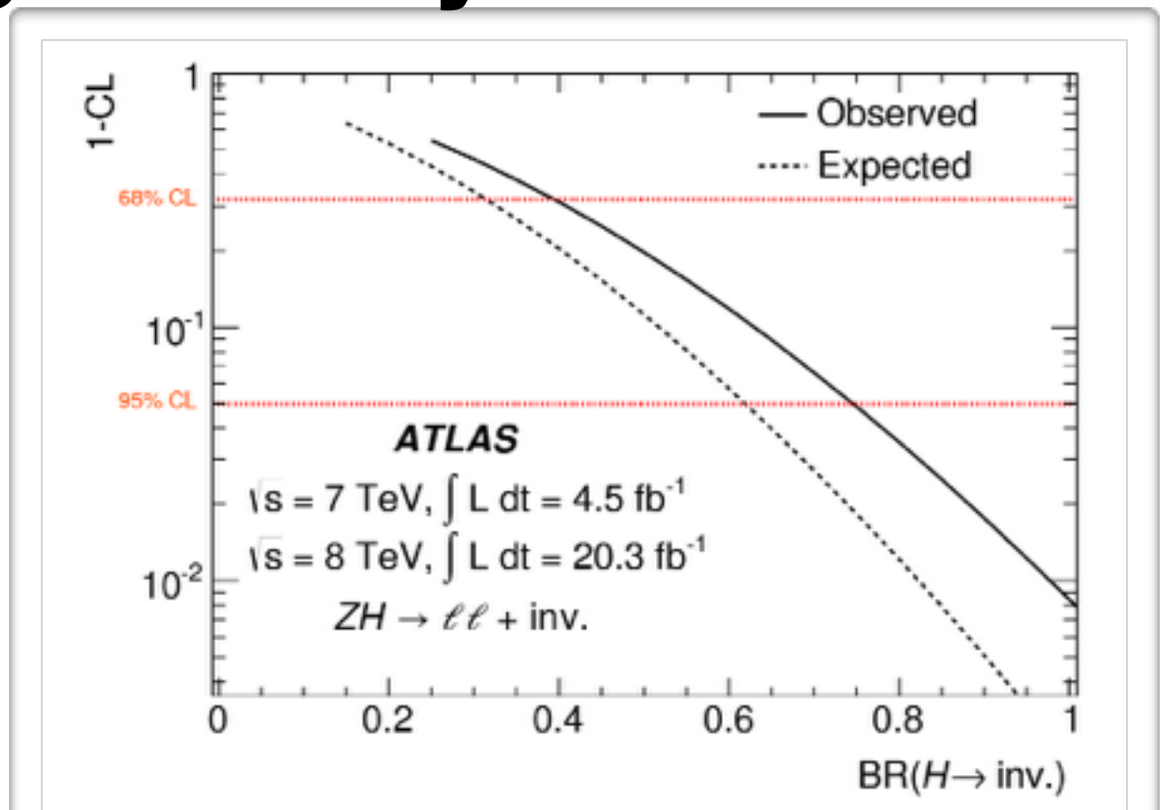
$h \to$ displaced

$h \to$ …

Exotic Higgs Decays

Why is it important?

1. Higgs Width in the SM ~ 4 MeV



Experimental Resolution ~ GeV $\quad \mathrm{BR(inv)} \lesssim 1$

New CMS Width Measurement: ~17 MeV $\quad \mathrm{BR(inv)} \lesssim 0.8$

Invisible Higgs (both ATLAS, CMS) $\quad \mathrm{BR(inv)} < 0.75$

Couplings fits (Belanger et al. 1302.5694) $\quad \mathrm{BR(inv)} \lesssim 0.2 - 0.8$

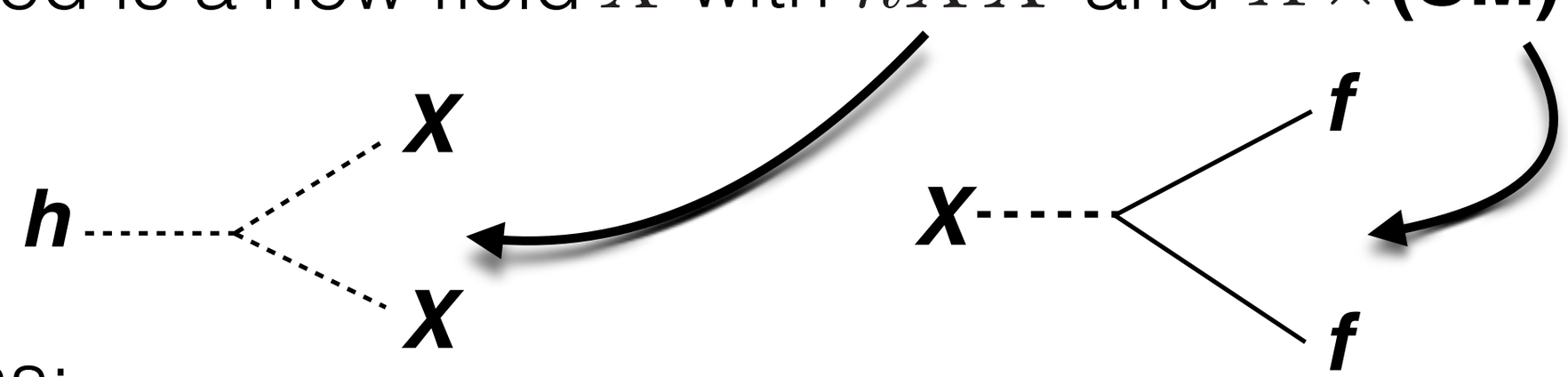
Still a lot of room for exotic decay modes

Exotic Higgs Decays

Why is it important?

2. Theoretically easy:

All we need is a new field X with hXX and $X\times$**(SM)**



Concerns:

Is it ruled out due to hXX coupling being too strong?

No! This coupling only competes with $y_b \simeq 0.02$

Is it ruled out due to $X\times$ (SM) coupling being too strong?

No! can be tiny, e.g. if ***X*** decays only to SM

Exotic Higgs Decays

***3. Potentially spectacular*:**

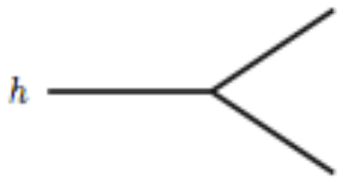
- Often little or no irreducible background
- High multiplicity

***4. Easy to miss if not looked for* (especially in ggF)**

5. Very common: NMSSM, DM models, Little Higgs,…

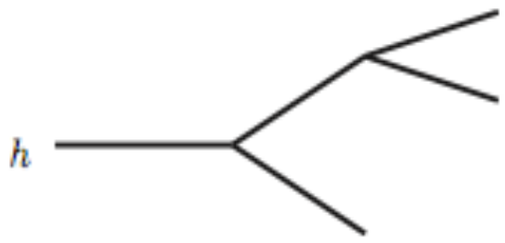
It may be the first/primary signal of new physics!

Decay topologies



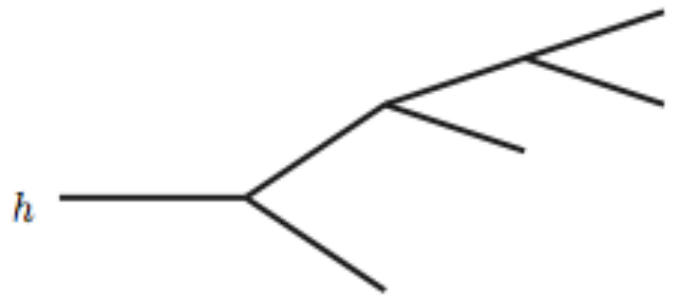
$h \to 2$

$h \to \not{E}_T$



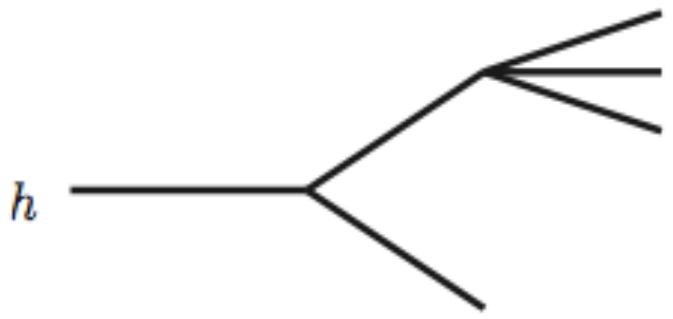
$h \to 2 \to 3$

$h \to \tilde{\chi}\tilde{G},\ \tilde{\chi} \to \gamma\tilde{G}$

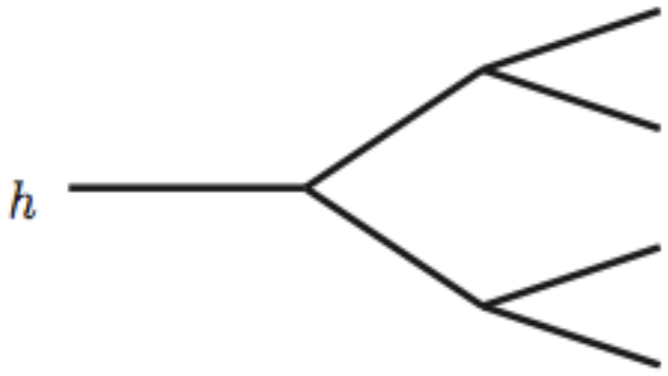


$h \to 2 \to 3 \to 4$

$h \to \chi_1\chi_2,\ \chi_2 \to a\chi_1$



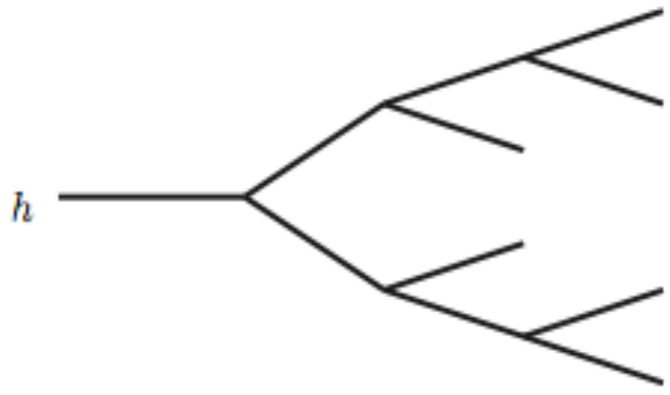
$h \to 2 \to (1+3)$



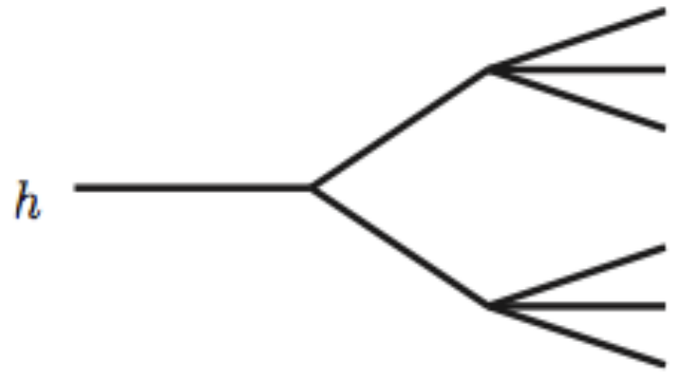
$h \to 2 \to 4$

$h \to (xx)(yy)$

$x, y = \ell, \gamma, b, j, \not{E}_T$



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



$h \to 2 \to 6$

RPV

Exotic Decay Modes

We studied:

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau$

$h \to 2\tau 2\mu$

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

$h \to ZZ_D(Za) \to 4\ell$

$h \to Z_D Z_D \to 4\ell$

$h \to \gamma + \not{E}_T$

$h \to 2\gamma + \not{E}_T$

$h \to 4$ isolated leptons $+ \not{E}_T$

$h \to 2\ell + \not{E}_T$

$h \to \text{lepton} - \text{jet(s)} + X$

$h \to 2b + \not{E}_T$

$h \to \tau^+\tau^- + \not{E}_T$

Simple Prototype Theories

1. Standard Model + Singlet

$$V(H,S) = V(H) + V(S) + aSH^\dagger H + \frac{1}{2}\kappa S^2 H^\dagger H$$

κ ⟶ $h \to SS$

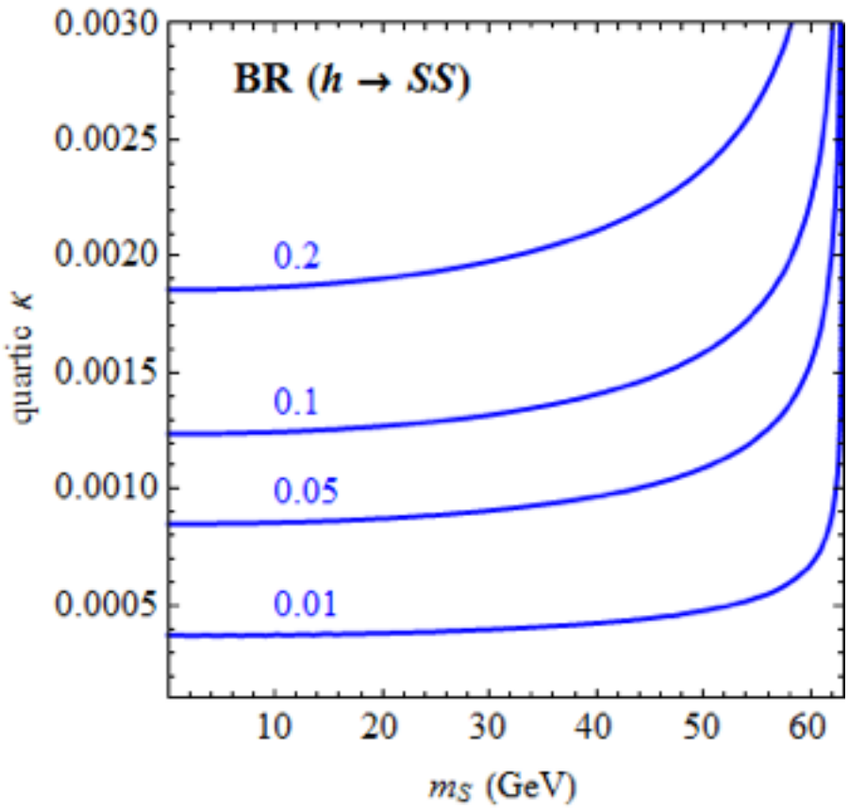
a ⟶ $S \leftrightarrow h$ mixing ⟶ S decays to SM

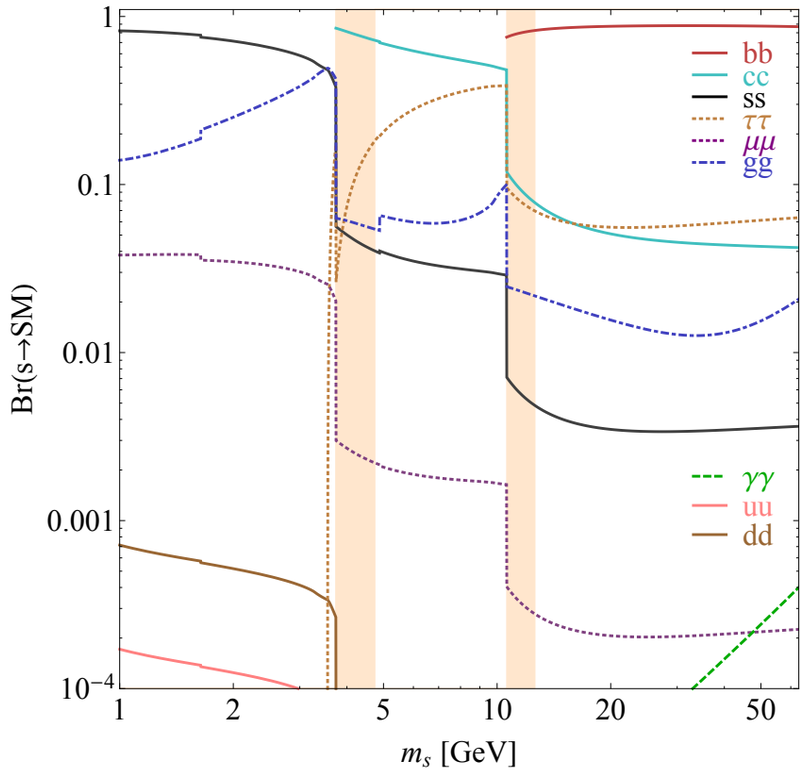
Very predictive:

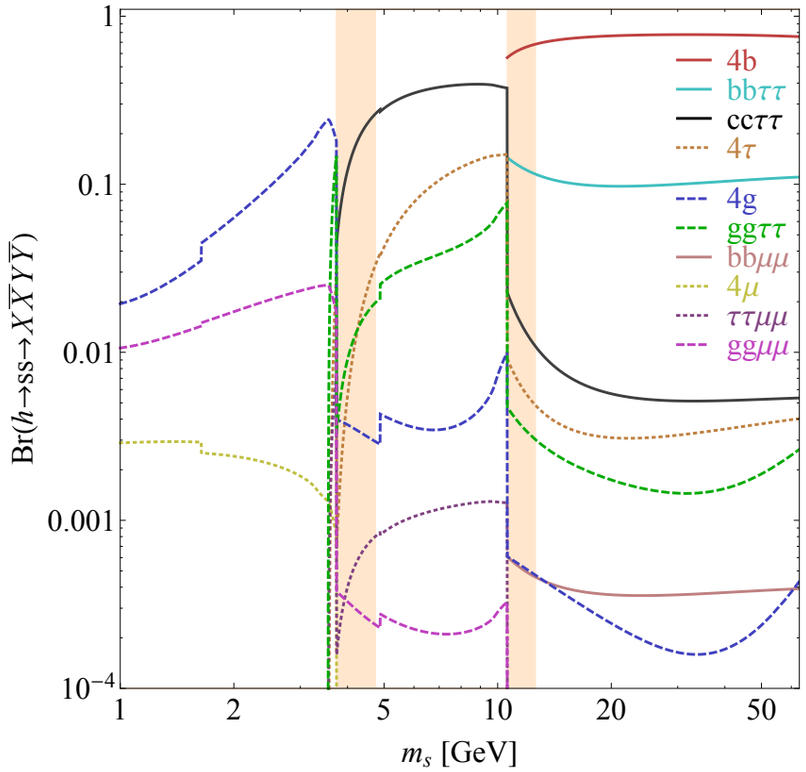
- Induced couplings of ***S*** to SM fermions are inherited from SM
- κ determines overall exotic BR
- Mass m_S affects $S \to \mathrm{SM}$ decays through kinematic thresholds
- Mixing ($\theta \sim a/m_h$) determines overall width (and lifetime)

Simple Prototype Theories

1. Standard Model + Singlet







Simple Prototype Theories

2. 2HDM + Singlet

	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
	Inert	**MSSM**	**lepton-specific**	**flipped**

Extra Singlet mixes with Higgses

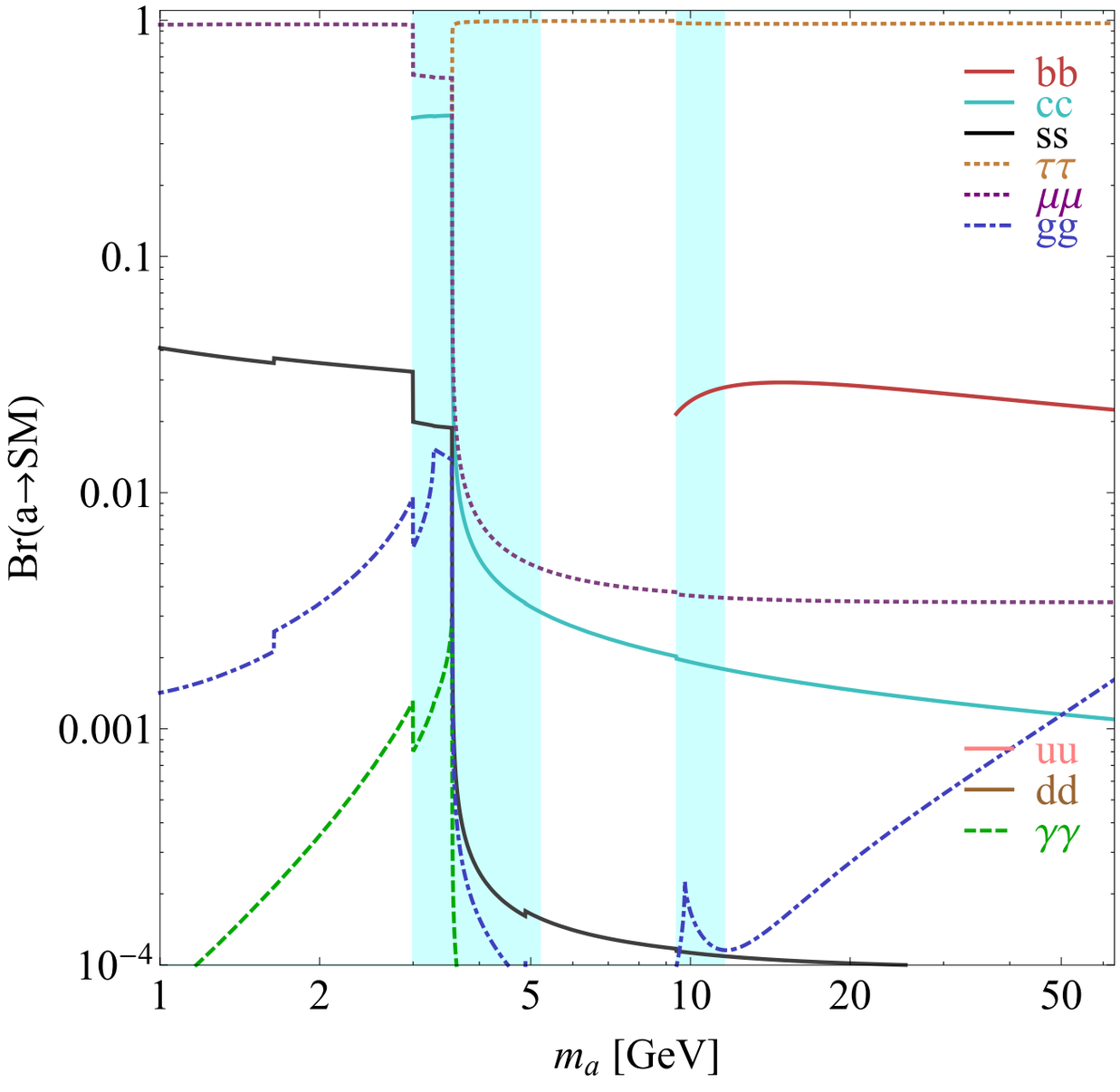
BRs controlled by:

1) $\tan\beta \equiv v_u/v_d$, 2) singlet-Higgs mixing angle, 3) mass (thresholds), 4) scalar or pseudoscalar

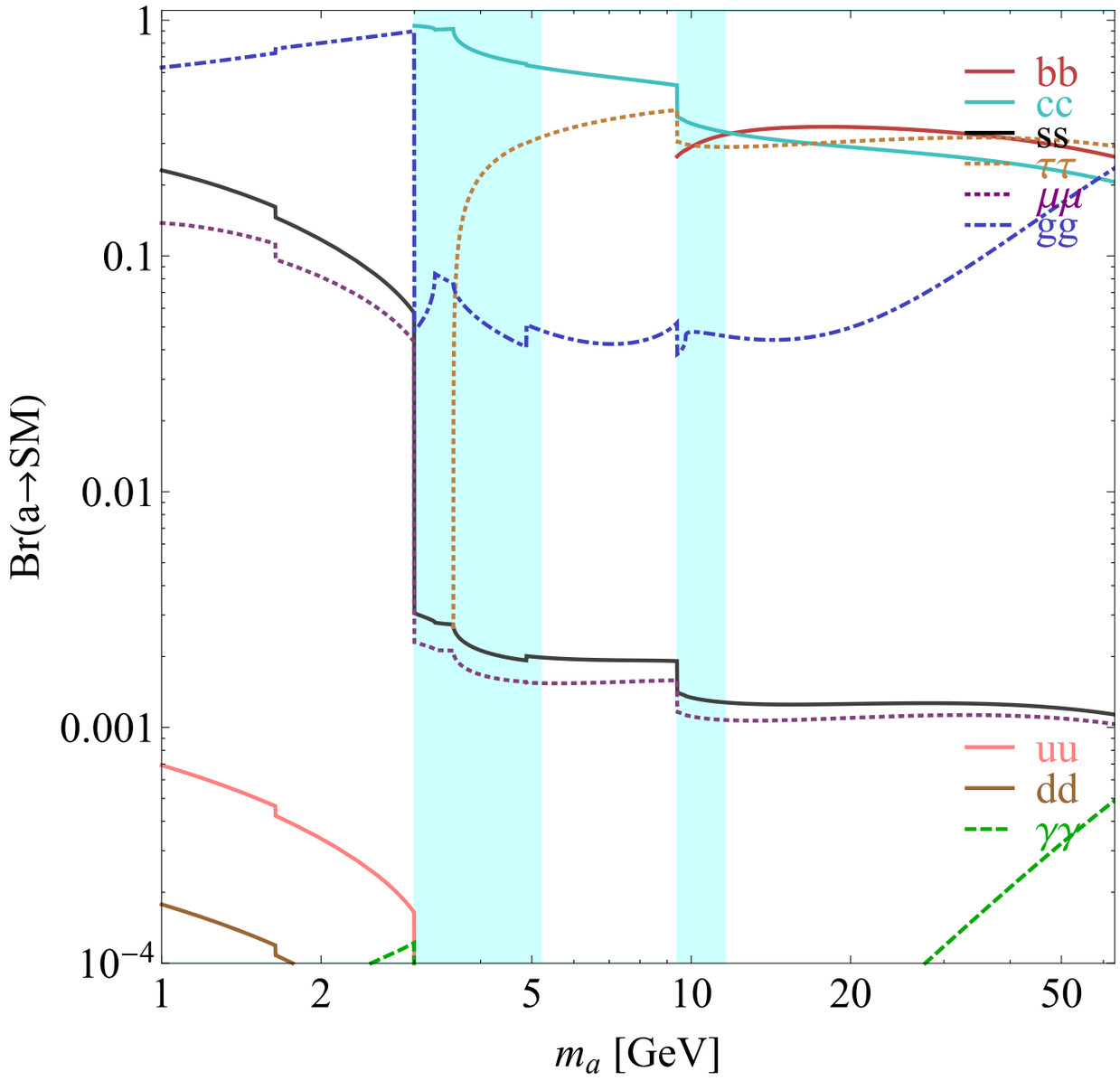
Simple Prototype Theories

2. 2HDM + Singlet

tan β=5, TYPE III



tan β=0.5, TYPE IV

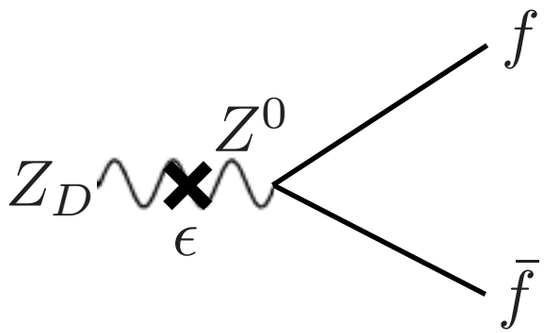


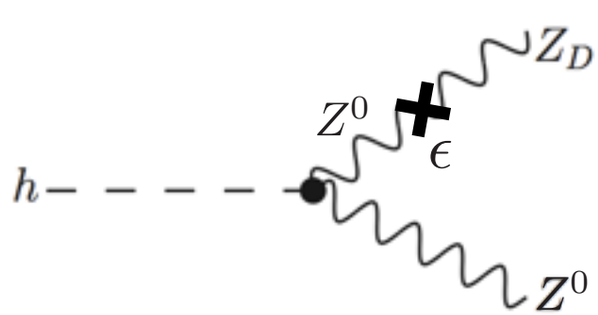
Simple Prototype Theories

3. SM + Vector

Add U(1)' with gauge field Z_D^μ

Kinetic mixing $\epsilon B_{\mu\nu} Z_D^{\mu\nu}$ → Z_D mixes with Z^0

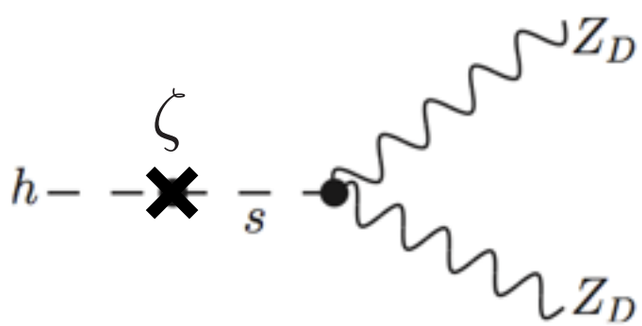


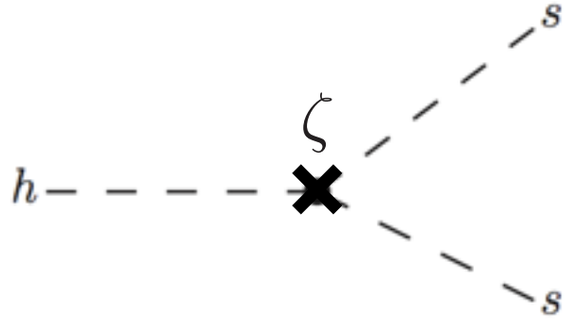


$\propto \epsilon$

Dark Higgs *S* breaks U(1)'

Mixing via Higgs Portal $\zeta H^\dagger H S^\dagger S$ → ***S*** mixes with ***H***

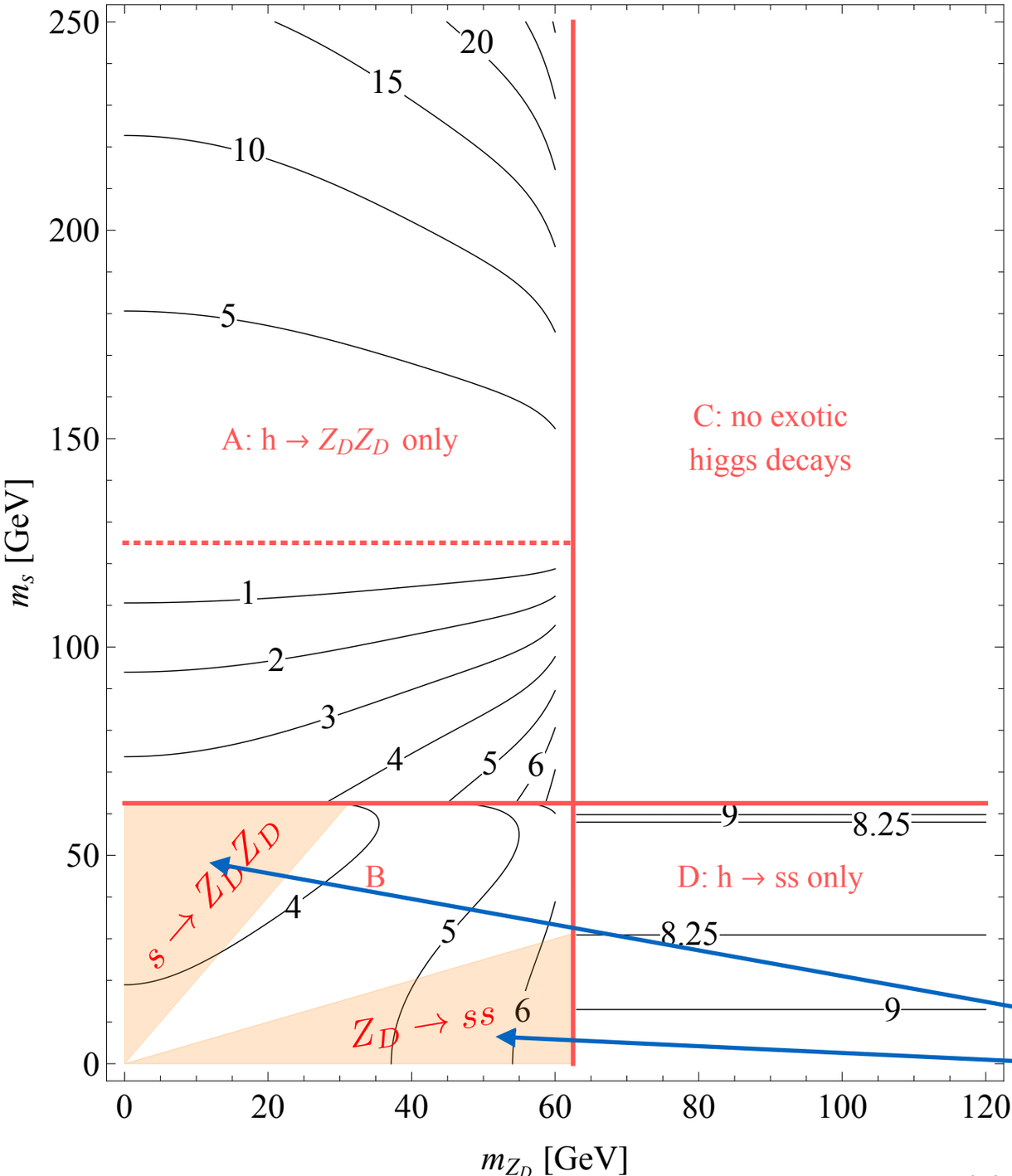


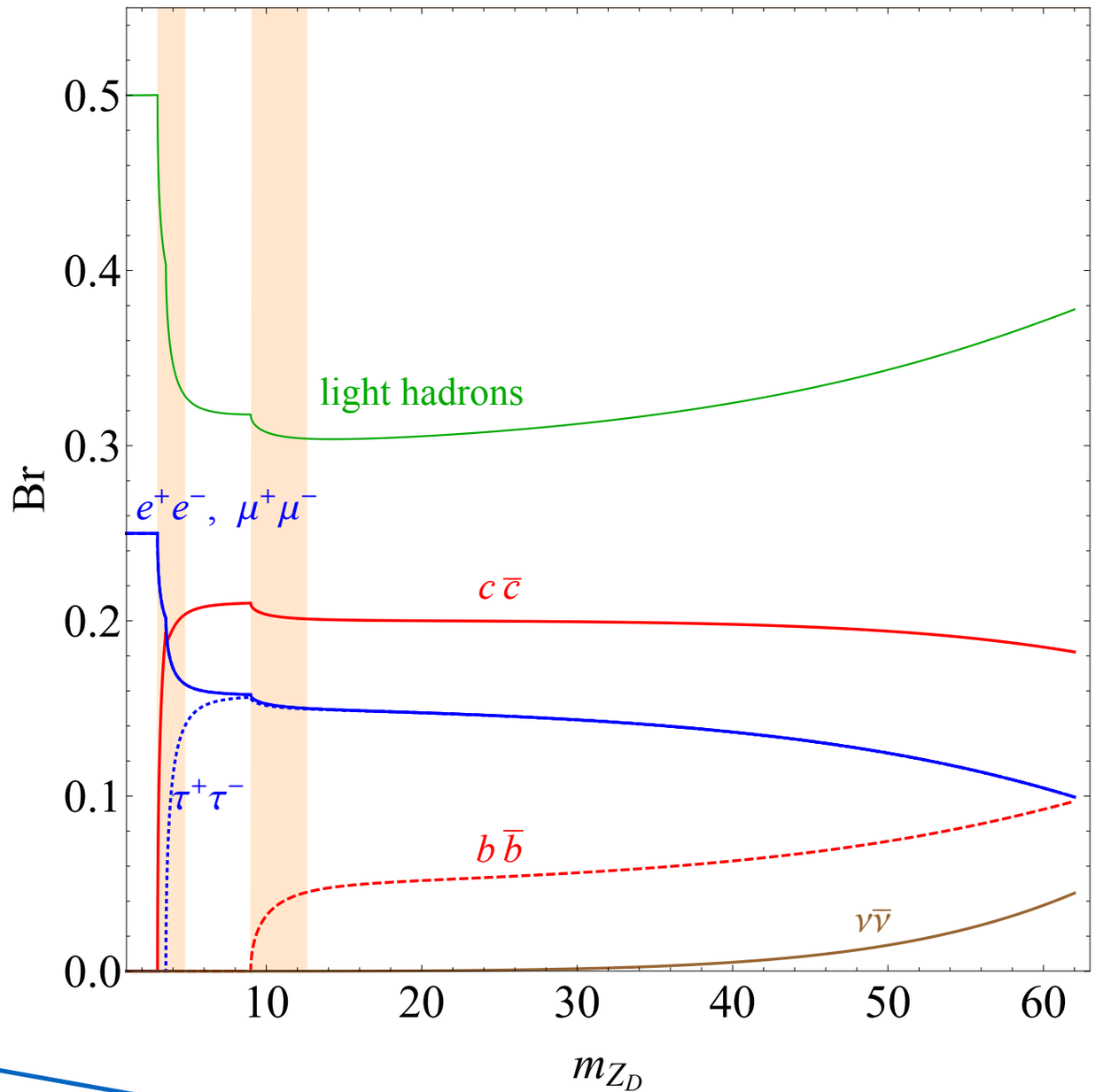


$\propto \zeta$

Simple Prototype Theories

3. SM + Vector





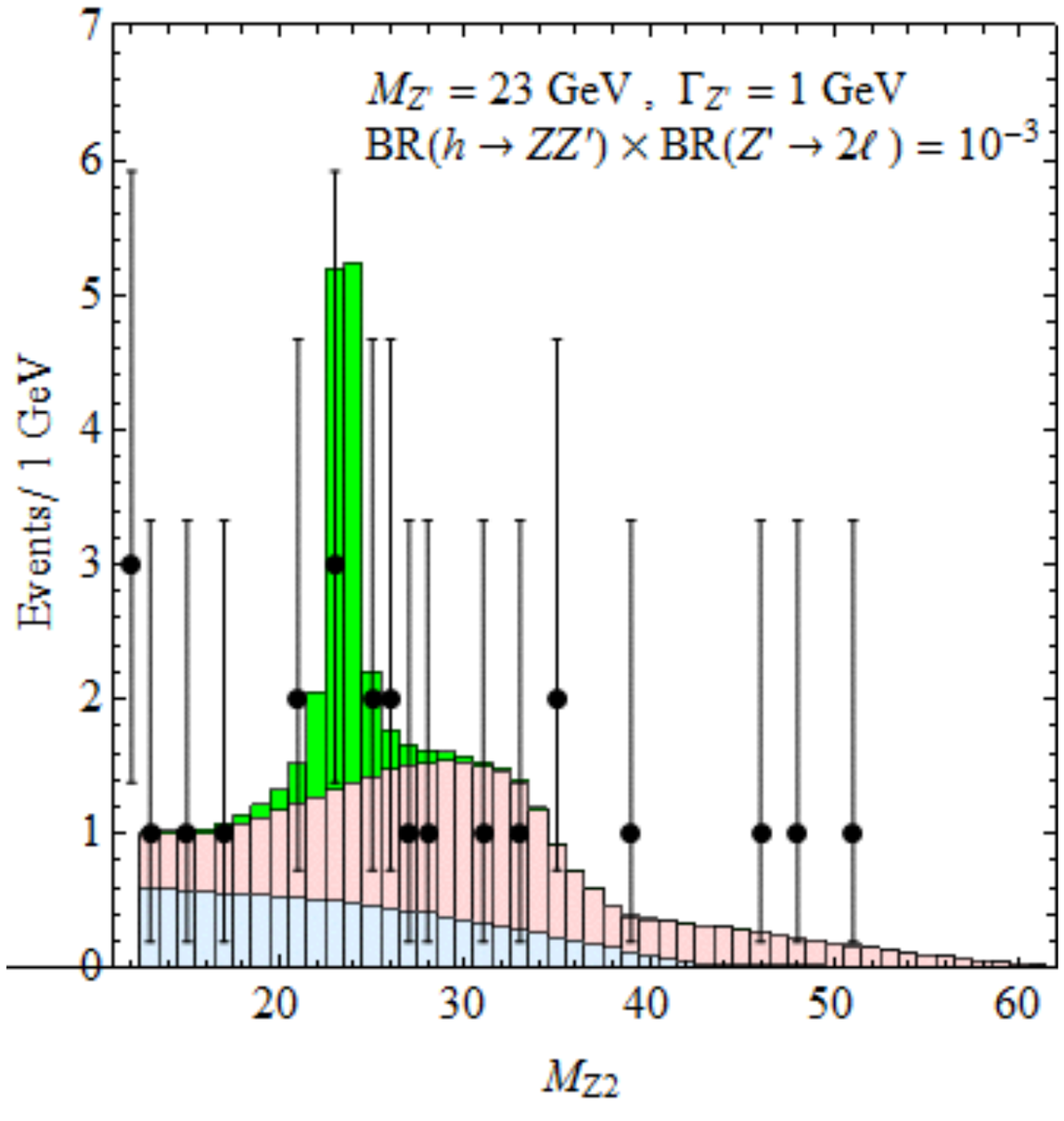
$h \to 8$ fermions

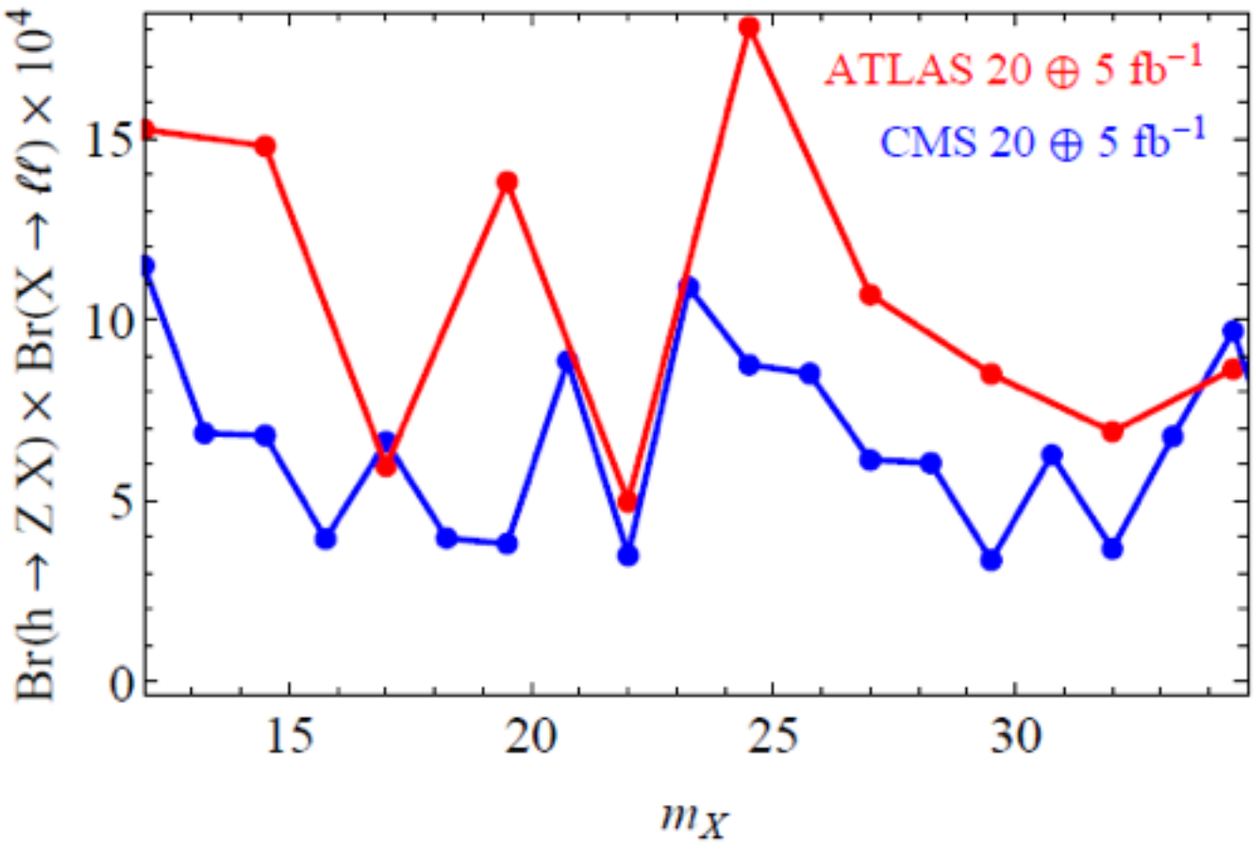
A Few Results

1. $h \to Z Z_D (Za) \to 4\ell$

(SM+V with $\epsilon \gg \zeta$)

Z_D would be interpreted as off-shell Z^0 in $h \to ZZ^*$

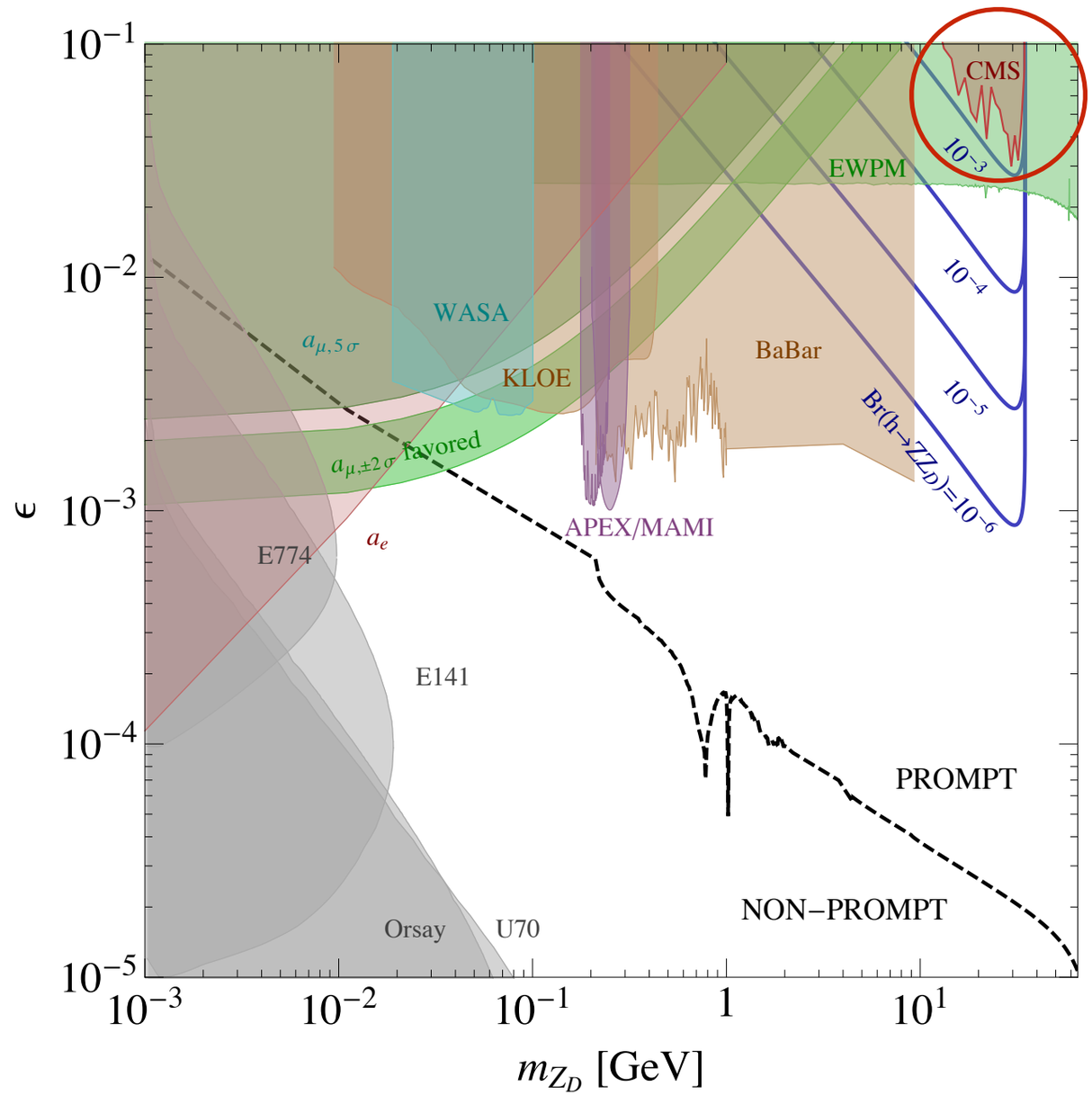




A Few Results

1. $h \to Z Z_D (Za) \to 4\ell$

(SM+V with $\epsilon \gg \zeta$)

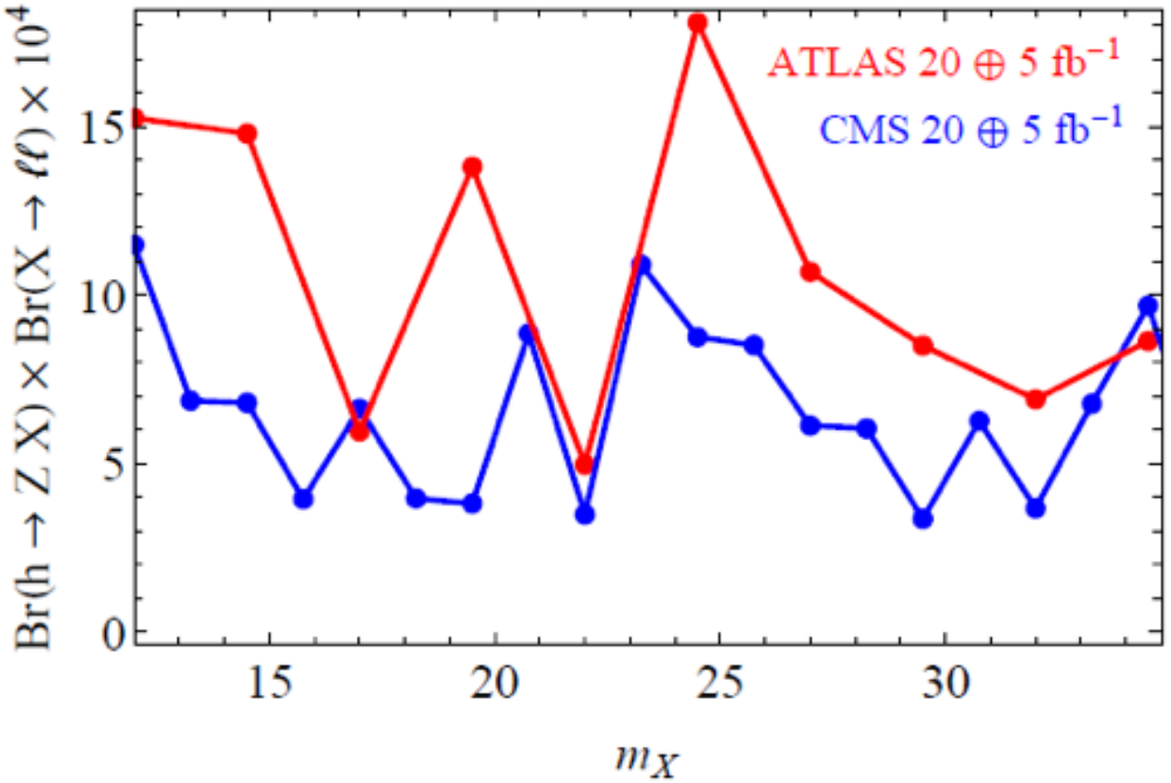


from $h \to Z Z_D$

A Few Results

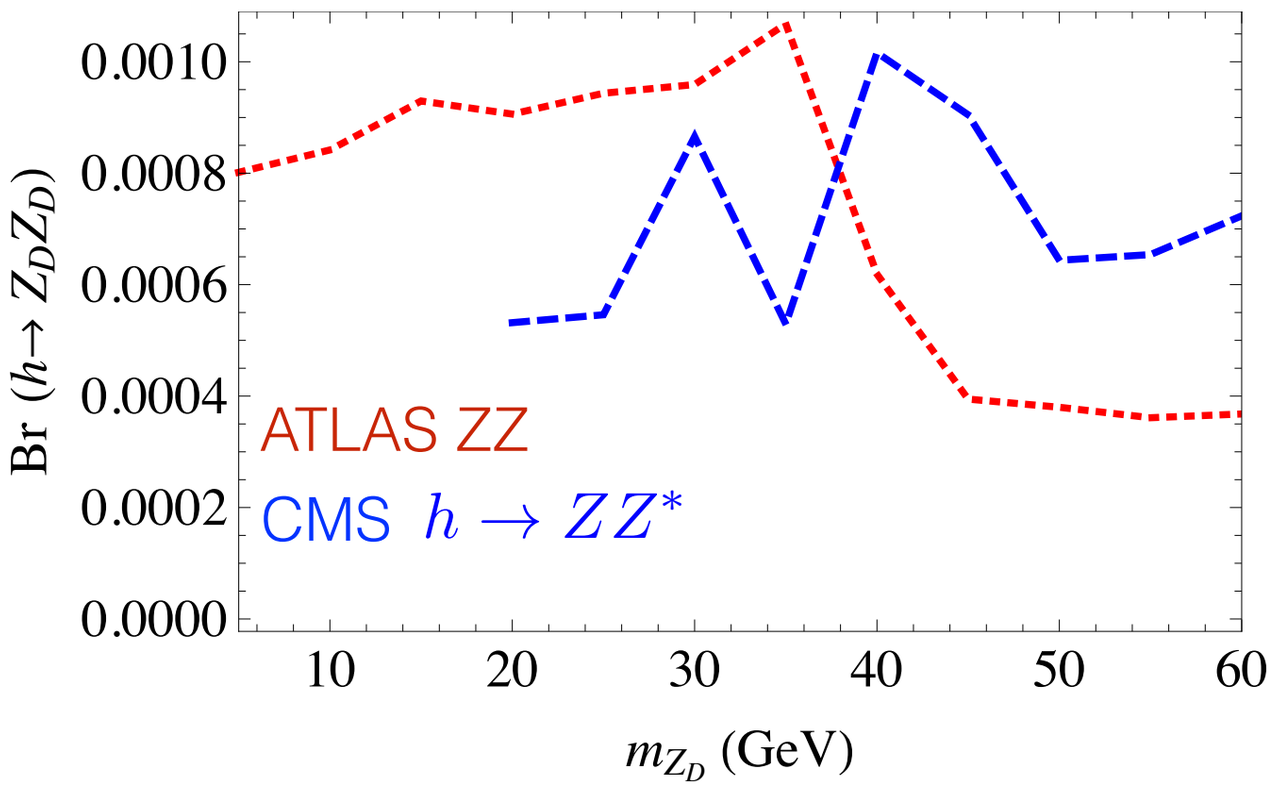
1. $h \to Z Z_D(Za) \to 4\ell$

(SM+V with $\epsilon \gg \zeta$)



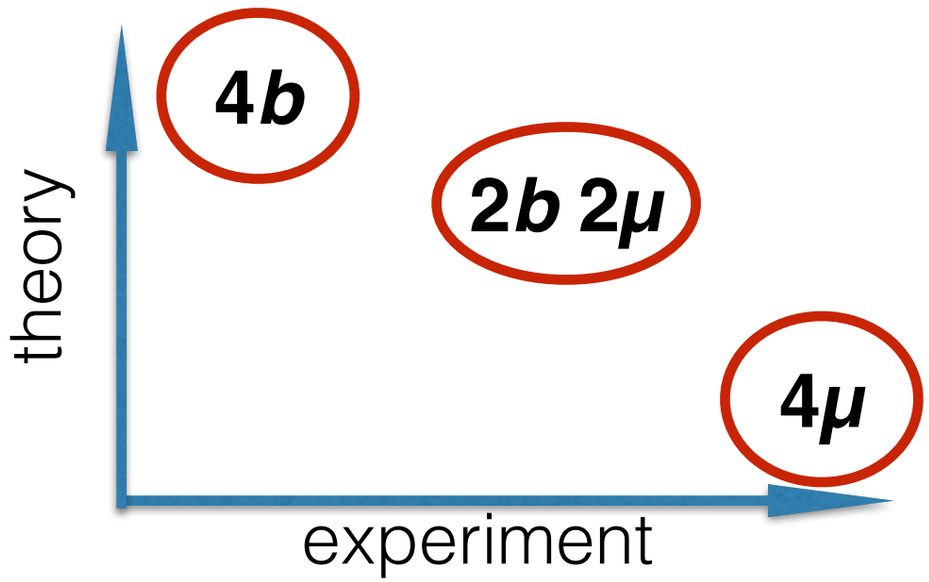
2. $h \to Z_D Z_D \to 4\ell$

(SM+V with $\epsilon \ll \zeta$)



A Few Results

3. $h \to (b\bar{b})(\mu^+\mu^-)$



need (pseudo)scalar ***a***

heavy enough (10 GeV)

that couples to both ***b*** and ***μ***

SM+S: BR(2***μ***)/BR(2***b***)~$m_\mu^2/3m_b^2 \approx 2 \times 10^{-4}$

or two (pseudo)scalars ***a*** , ***a'***

Parton-Level Study with Madgraph (*Yi-Ming Zhong, Stony Brook*)

Background: *Zbb* , *Zcc* , *Zjj* , *WW*+jets, *tt*

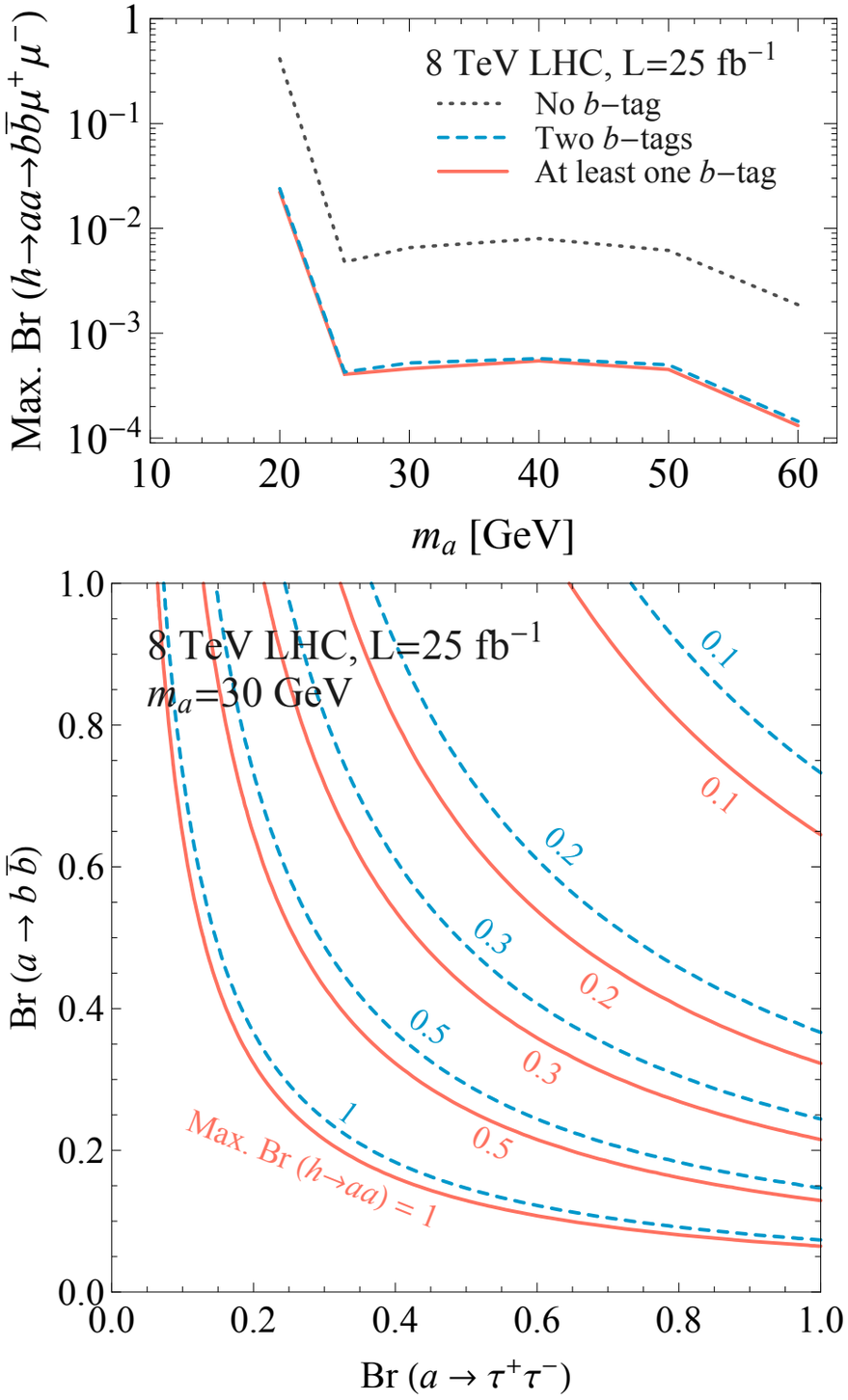
Signal: only ggF

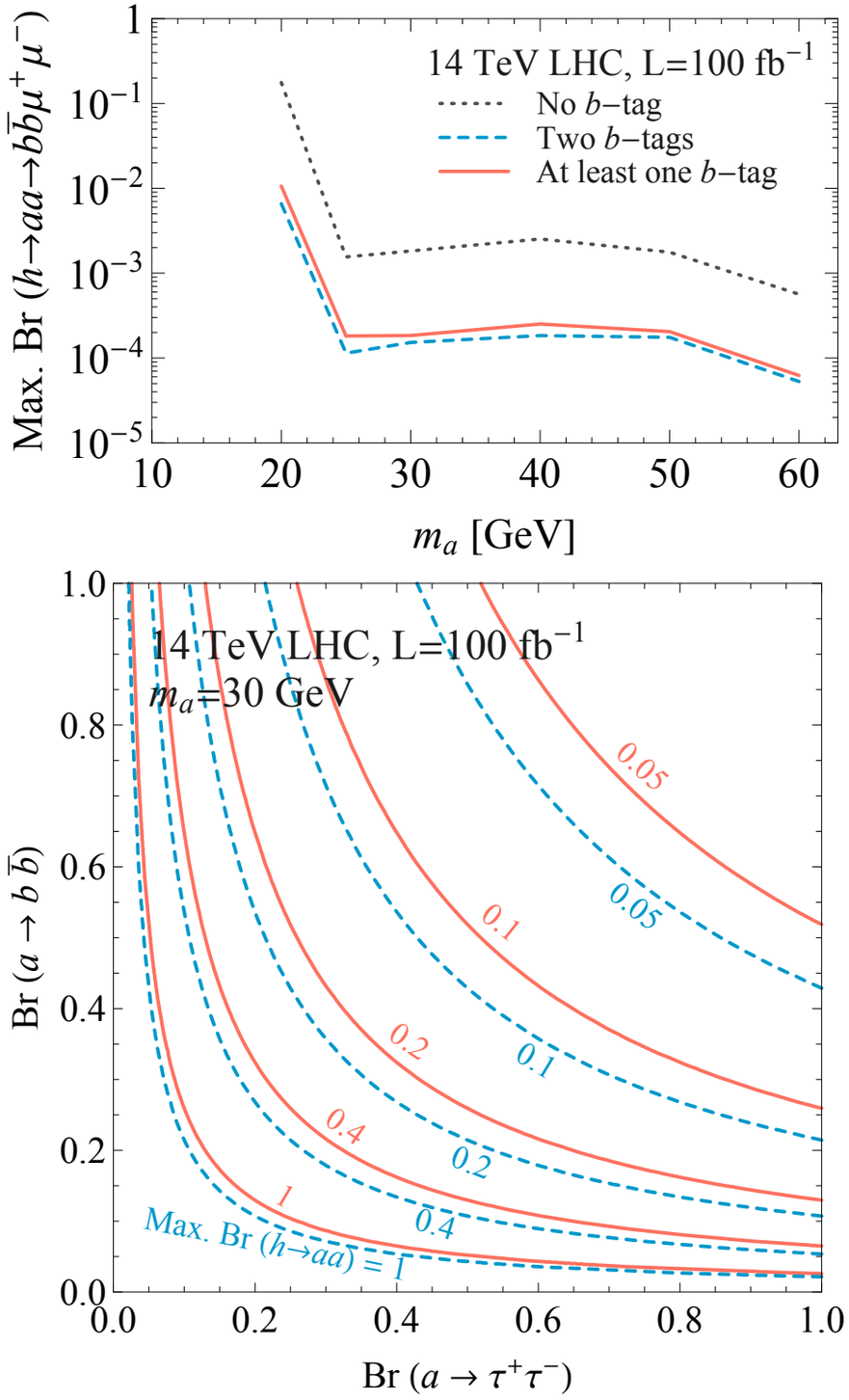
Cuts: 2 leading jets w/ pT>25 GeV, 2 OS muons w/ pT>17,8 GeV,
b-tag efficiency, invariant mass cuts (resonance search)

Resulting Efficiencies: ~10^{-2} for the signal, 10^{-5} for background

A Few Results

3. $h \to (b\bar{b})(\mu^+\mu^-)$





Exotic Higgs Decays

Wish List

$h \to Z_D Z_D \to$ leptons

$h \to Z Z_D \to$ leptons

$h \to \ell^+\ell^- + \not{E}_T$

$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$

$h \to 2\tau 2\mu$

$h \to 4\gamma$

$h \to 2\gamma + \not{E}_T$

Exotic Higgs Decays

Summary

- Exotic Higgs decays may be our main window to new physics
- Common / motivated in new physics scenarios
- Challenges: existing triggers, especially in ggF
- Can be easy to find, but also easy to miss...
- Need more experimental and theory work

Thank You