Exotic Decays of the 125 GeV Higgs Boson

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based on 1312.4992

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US ATLAS Workshop on LHC Searches at LBNL, 1/27/2014

Post discovery

- 125 GeV state is a new particle discovered at LHC

$\Longrightarrow$ must study *everything* about it

- Important to e.g.
  - measure SM decays
  - look for non-SM production
  - look for Higgs partners
  - look for non-standard decays

e.g. *h* → *invisible* Suzuki, Shrock

$h \to 4\gamma, 4b, \gamma + \not{E}_T, \ldots$

Is there any room for exotic decays?

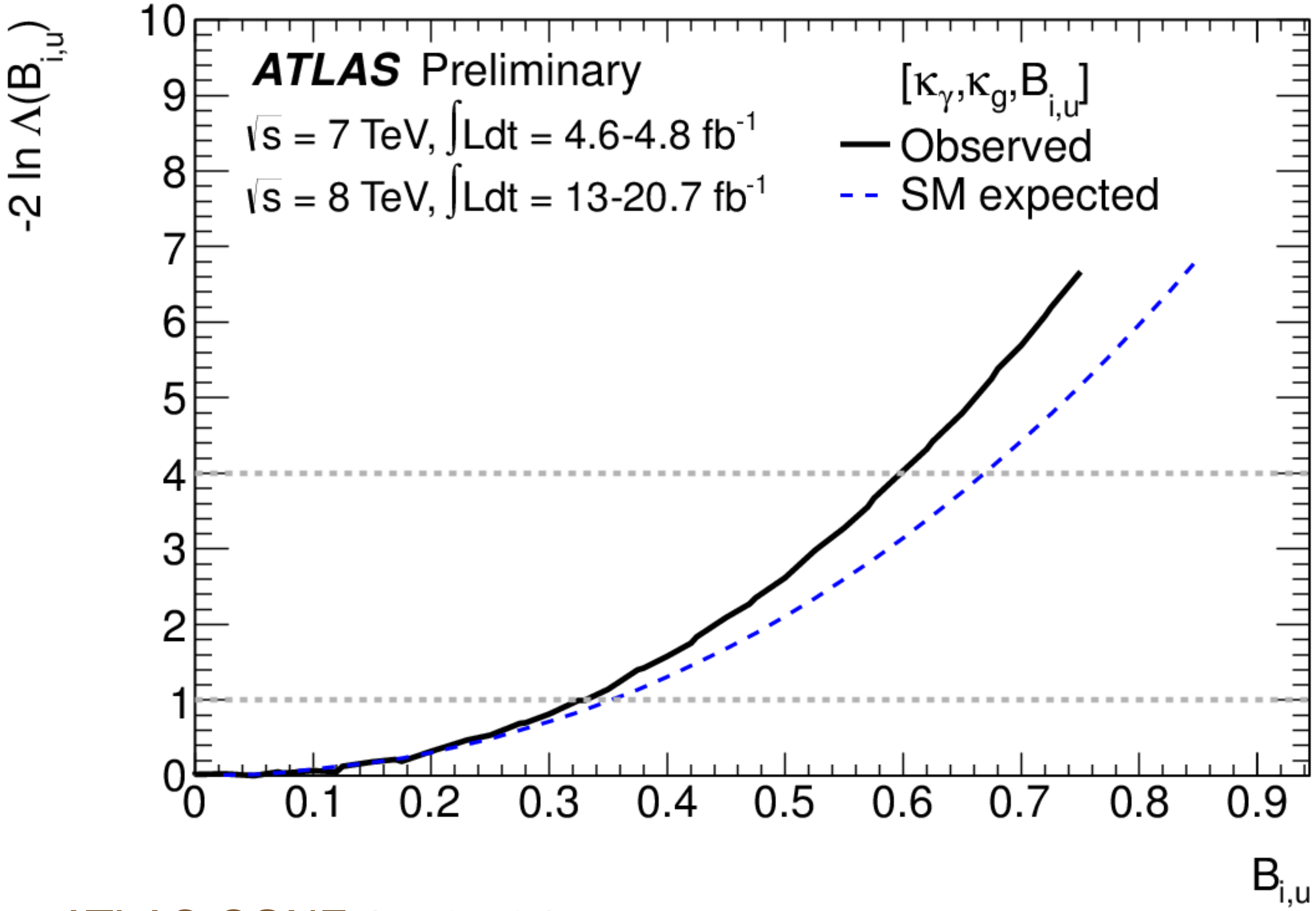
Even though Higgs is SM-like,
the answer is a resounding:

Yes!

invisible/undetected Higgs decay modes

$\mathrm{BR}_{\mathrm{inv,undet}} < 0.6$ at 95% C.L.

(no constraint on total width; result different under other assumptions)



ATLAS-CONF-2013-034

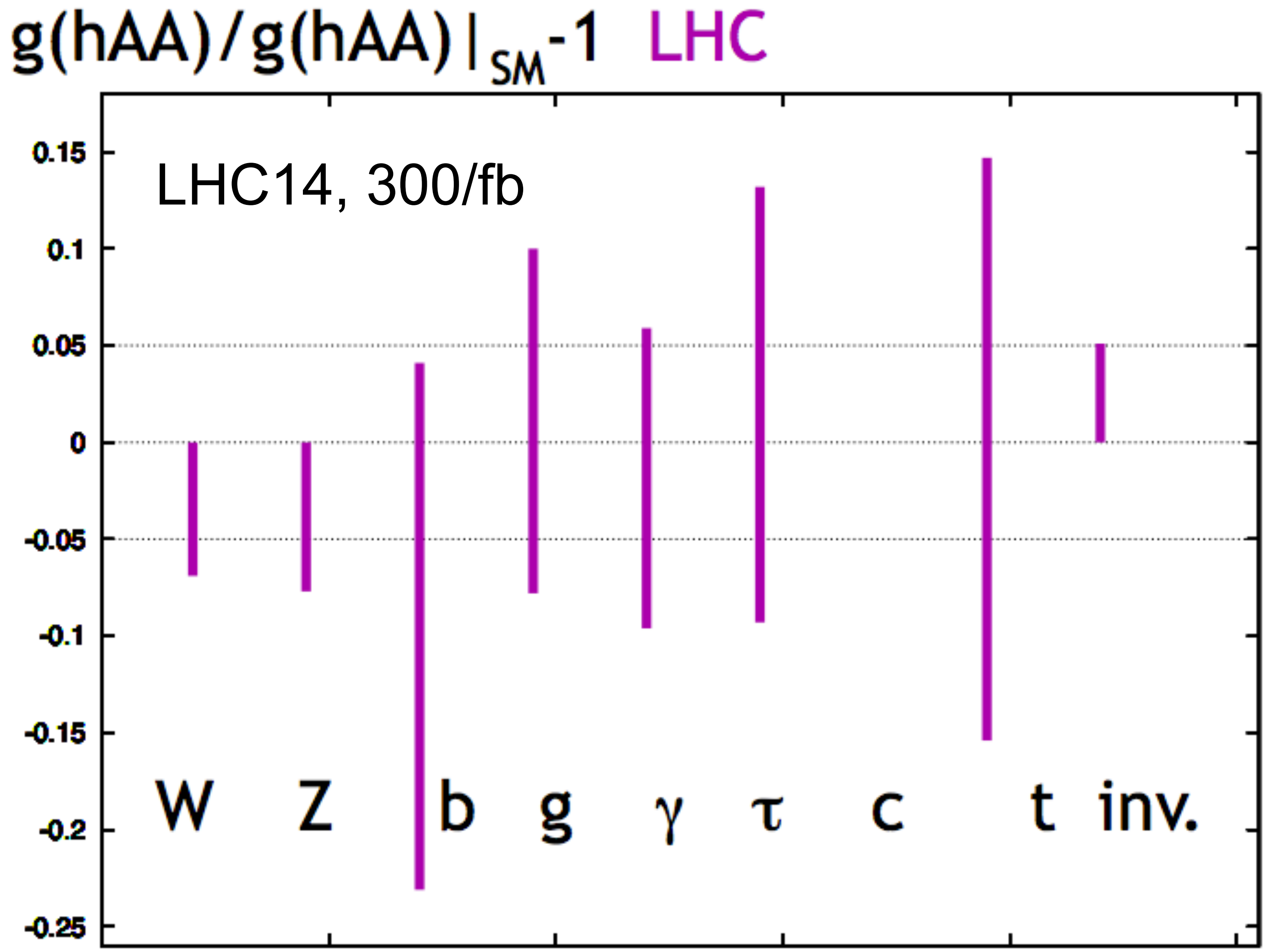
plenty of room for exotic decays

could be much more common than $h \to \gamma\gamma$, $h \to ZZ^*$

see e.g. also CMS, Giardinoa et.al., Belanger et.al., Espinosa et.al., ,Muhlleitner et.al.

Even after LHC there will be room

LHC measurements will never determine Higgs couplings to SM particle better than 5-10%, e.g.



M. Peskin, 1207.2516 (see also Snowmass proceedings)

How many exotic decay events possible right now?

assume BR($h \to$ new) = 10%, **LHC7+8**, 25/fb

channel	# events (raw)
ggF	46,000
VBF	3,800
$W(\ell\nu)$+h	360
$Z(\ell\ell)$+h	70
ttH	300

} Associated Production (AP) — $W(\ell\nu)$+h, $Z(\ell\ell)$+h

Many events in ggF/VBF, but suitability depends on *h* decays

Can always trigger w/ AP… but not many events

How many exotic decay events possible in future?

assume BR($h \rightarrow$ new) = 10%, LHC14, 300/fb

channel	# events (raw)
ggF	1.5 million
VBF	125,000
$W(\ell\nu)+h$	9,600
$Z(\ell\ell)+h$	1,800
ttH	18,300

} Associated Production (AP) — $W(\ell\nu)+h$, $Z(\ell\ell)+h$

lots of events possible!

Why study exotic Higgs decays?

SM Higgs width is tiny

- SM Higgs decays suppressed by small Yukawa couplings, loops, or multi-body phase space:

$$\Gamma_h \sim 4.07 \text{ MeV} \qquad \frac{\Gamma_h}{m_h} \sim 3.3 \times 10^{-5}$$

- dominant decay to b-quarks suppressed by tiny coupling

$$y_b \sim 0.017$$

$\Longrightarrow$ even a small coupling to another light state can open up additional sizable decay modes

The Higgs as a "portal" to dark sectors

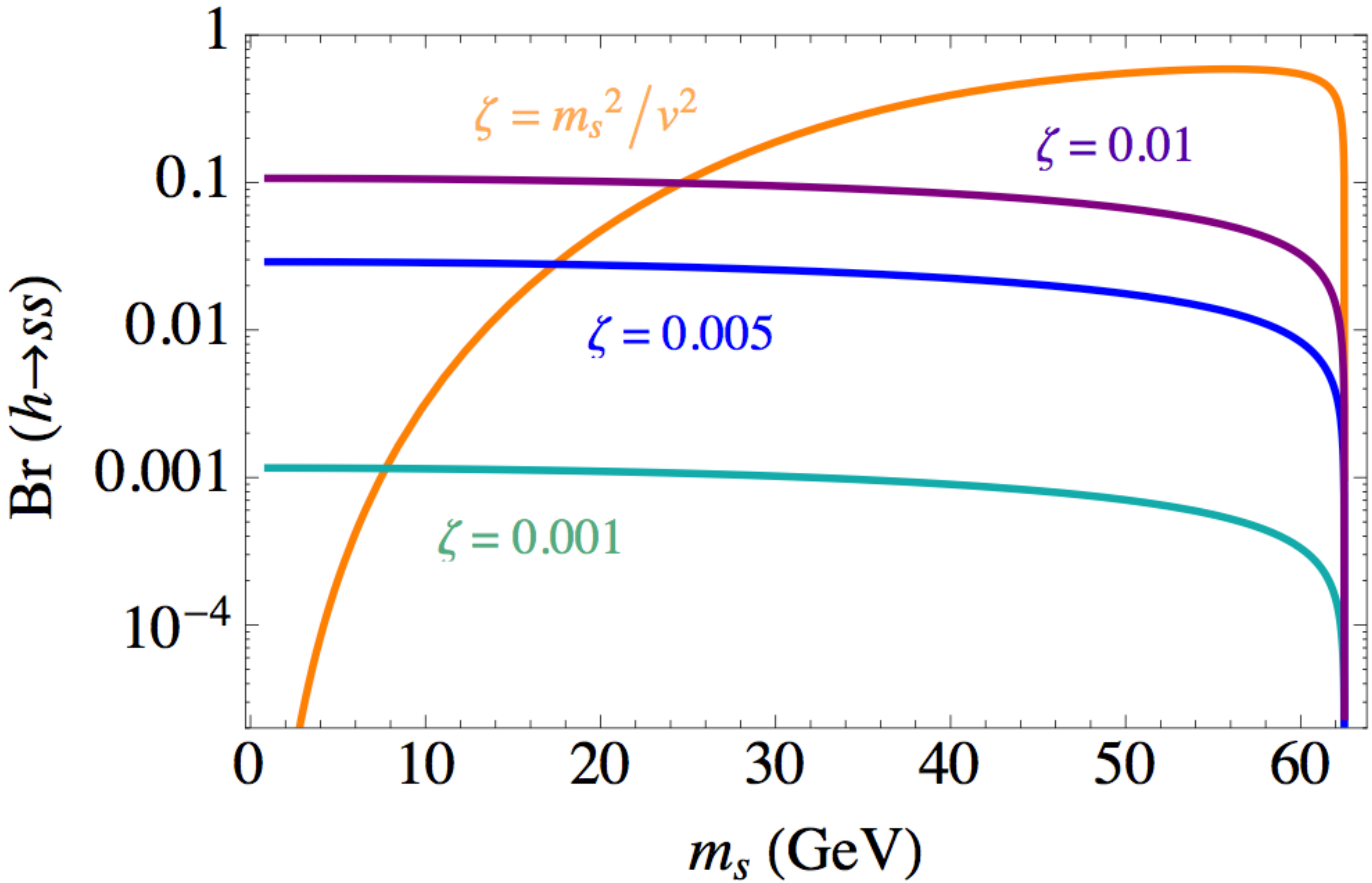
- Higgs is one of only a few SM fields that can have renormalizable couplings to SU(3)xSU(2)xU(1) singlet fields

$\Longrightarrow$
- Higgs may be leading window into BSM physics
- trivial to have allowed, exotic decays

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

can give BR($h \rightarrow ss$)~O(10%) for ζ *as small as* 0.01 !

The Higgs as a “portal” to dark sectors



(orange curve is when interaction on previous slide generates mass of s)

exotic Higgs decays…

- could easily be missed by *all* other searches

  e.g., p_T of h-decay products is often softer than other new-physics searches

- require dedicated analyses

- deserve study *now* as there is discovery potential w/ existing data

Aim of our work

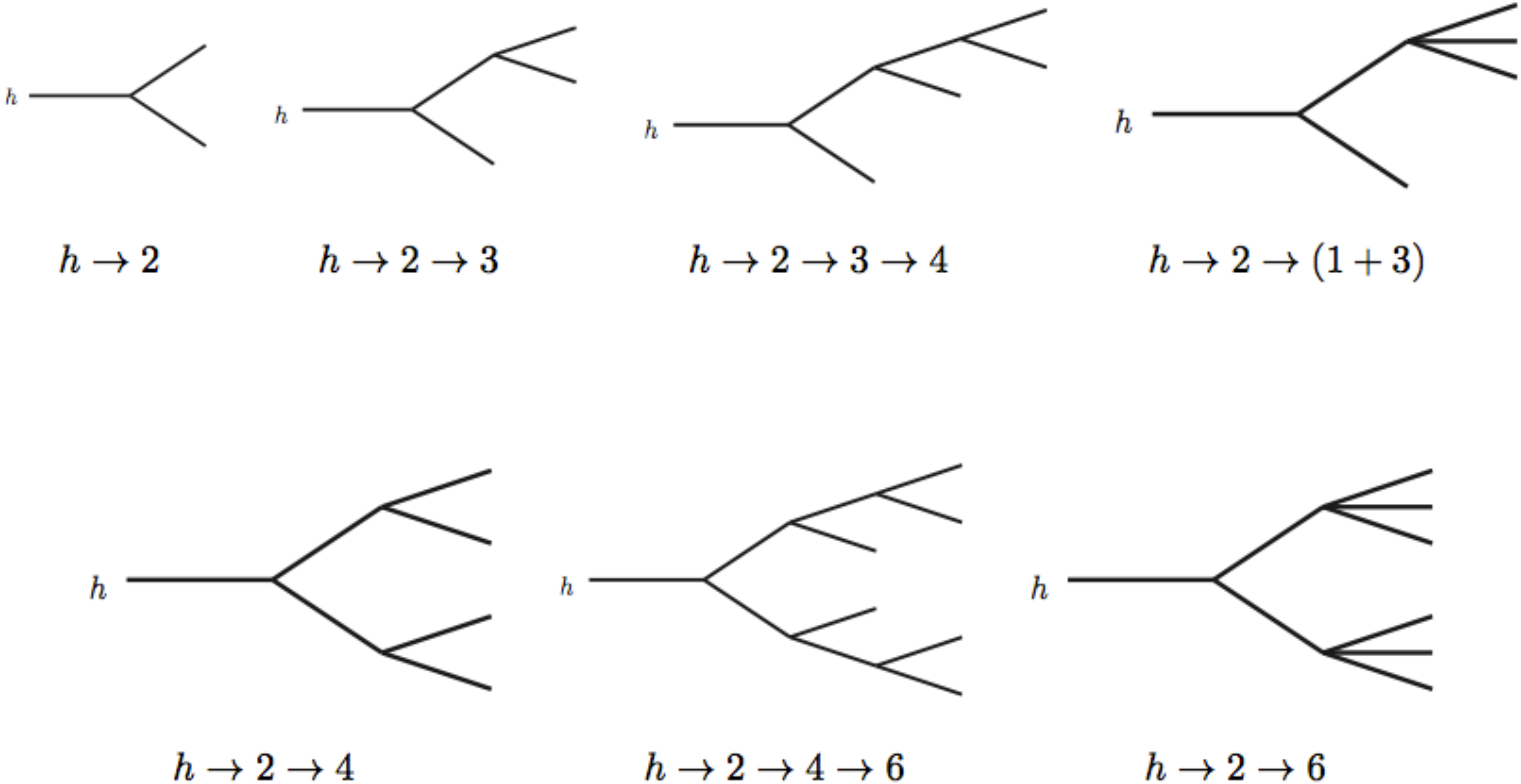
- survey, systematize, prioritize exotic decays
- extensive literature exists, but models need reassessment: what BR can be probed? how maximize sensitivity?
- to some extent, develop search strategies, provide viable benchmark models/points, inform LHC14 trigger selection
- provide website that will be updated regularly (exotichiggs.physics.sunysb.edu)

Overview of possible exotic Higgs decays

We make 3 assumptions:

- observed 125 GeV state is primarily responsible for EWSB
  - usually requires "decoupling" limit
  - h production close to SM
  - other scenarios possible, but this is generic and minimal
- 125 GeV state decays to new BSM particles
  - these BSM particles could primarily/only be produced through h decays
  - do not consider rare or nonstandard decays directly to SM particles
- initial decay is 2-body
  - >3-body js possible, but requires new light states w/ substantial coupling to h to overcome phase space suppression

Decay Topologies



Many exotic decays are possible

1. h→2

e.g. h decays to detector-stable particles: h→invisible

2. h→2→3

e.g. h decays to one detector stable particle and another particle that decays promptly or w/ displaced vertex

$$h \to X_1 X_2$$

$$X_1 \to \not{E}_T, X_2 \to \bar{f} f + \not{E}_T$$

$$X_1 \to \not{E}_T, X_2 \to \bar{f} f$$

$$X_2 \to \gamma X_1$$

etc.

$$h \to \gamma + \not{E}_T, (bb) + \not{E}_T, (\tau\tau) + \not{E}_T, \gamma\gamma + \not{E}_T, (\ell\ell) + \not{E}_T$$

Many exotic decays are possible

3. h→2→4

e.g. $\left.\begin{array}{l} h \to 4x \\ h \to 2x2y \end{array}\right\} x, y = e, \mu, \tau, \gamma, b, j, \not{E}_T, \ldots$

1. $(b\bar{b})(b\bar{b})$
2. $(b\bar{b})\ (\tau^+\tau^-)$
3. $(b\bar{b})\ (\mu^+\mu^-)$
4. $(\tau^+\tau^-)\ (\tau^+\tau^-)$
5. $(\tau^+\tau^-)\ (\mu^+\mu^-)$
6. $(jj)(jj)$
7. $(jj)\ (\gamma\gamma)$
8. $(\ell^+\ell^-)\ (\ell^+\ell^-)$
9. $(\gamma\gamma)\ (\gamma\gamma)$
10. $\gamma\gamma + \not{E}_T$

Many exotic decays are possible

4. h→2→4→6

e.g. w/ NMSSM neutralinos

$$h \to \chi_2 \chi_2, \ \text{w/} \ \chi_2 \to \chi_1 a, \ a \to f\bar{f}$$

5. h→2→6

e.g. $h \to \tilde{\chi}_1 \tilde{\chi}_1 \to 6 \text{ SM particles}$ (w/ R-parity violation)

6. h→2→many

e.g. lepton-jets, photon-jet, … (e.g. in Hidden Valleys)

7. any of above w/ displaced vertex

etc.!

Many exotic decays are possible

can map decay topologies to various popular theoretical models or scenarios, including:

- SM + Scalar
- 2HDM (+ Scalar)
- SM + Fermion
- SM + 2 Fermions
- SM + Vector
- MSSM
- NMSSM with exotic Higgs decay to scalars
- NMSSM with exotic Higgs decay to fermions
- Little Higgs
- Hidden Valleys

Two basic lessons:

There is no shortage of "simplified" and well known theoretical models that have exotic decays

Need broad array of searches!

A few examples in more detail to show rich possibilities

SM + singlet scalar

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

S = real scalar

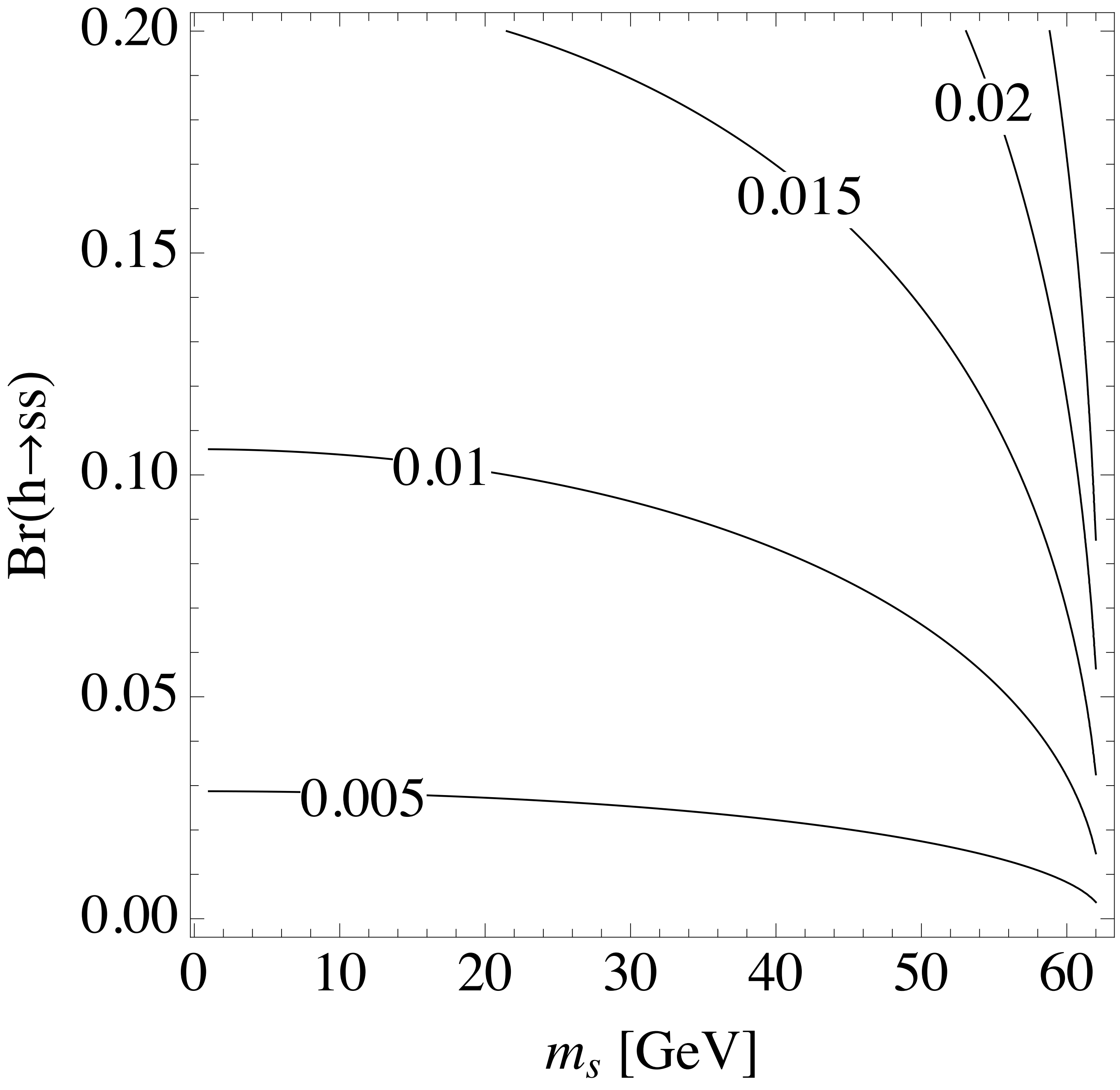
$$\mathcal{L}_{\text{eff}} \supset \mu_v\,h\,s\,s \qquad\qquad h \to ss$$

- if Z_2 symmetry $(S \to -S)$ unbroken: s stable & h→invisible
- otherwise $s \to f\,\bar{f}$
- can extend to complex scalar w/ approximate global U(1) symmetry, giving rise to light pseudo-scalar, *a*

$$h \to aa$$ (similar phenomenology)

SM + singlet scalar

$$\mathcal{L}_{\text{eff}} \supset \mu_v \, h \, s \, s$$

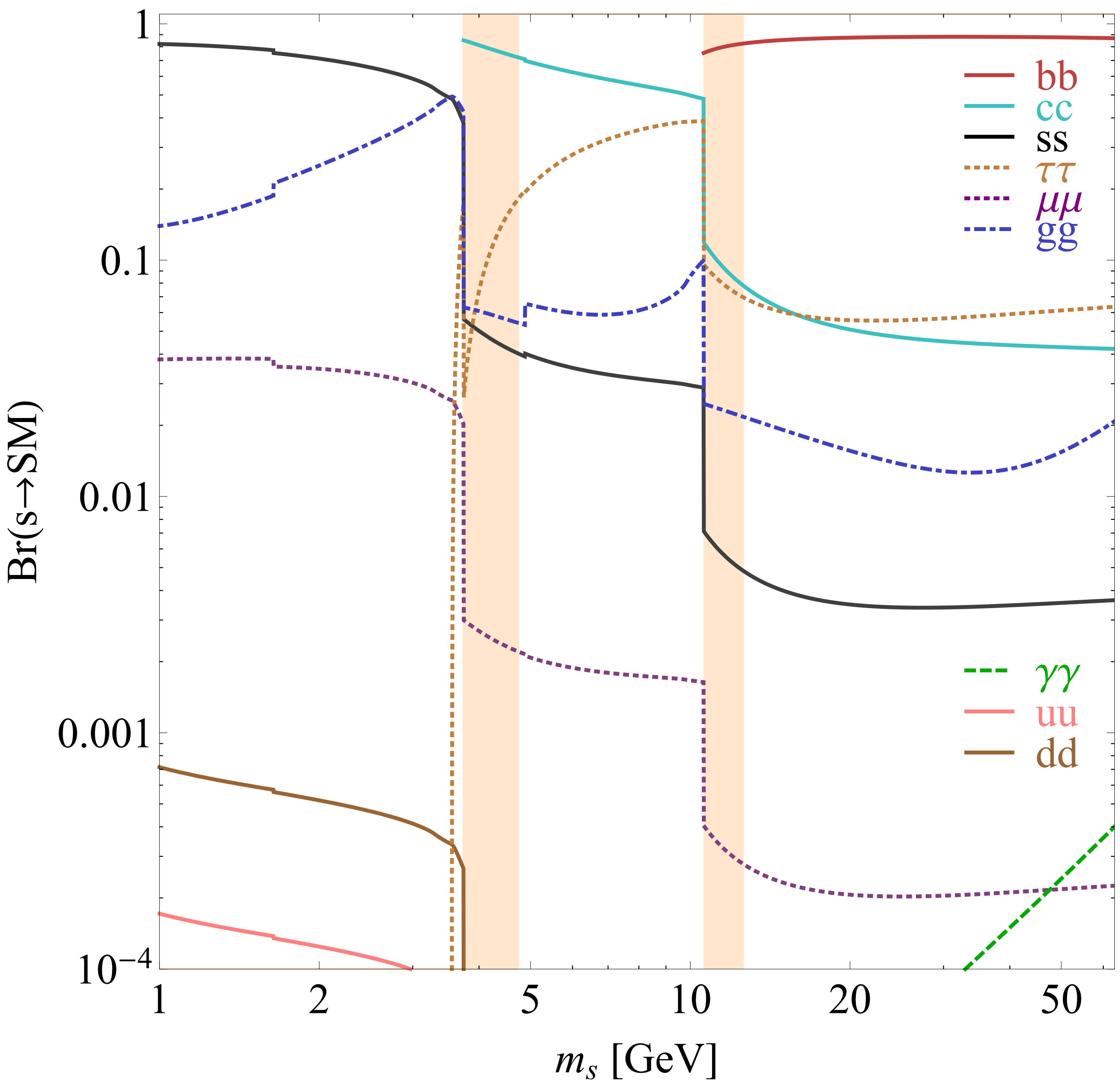


easy to get
BR = 10%

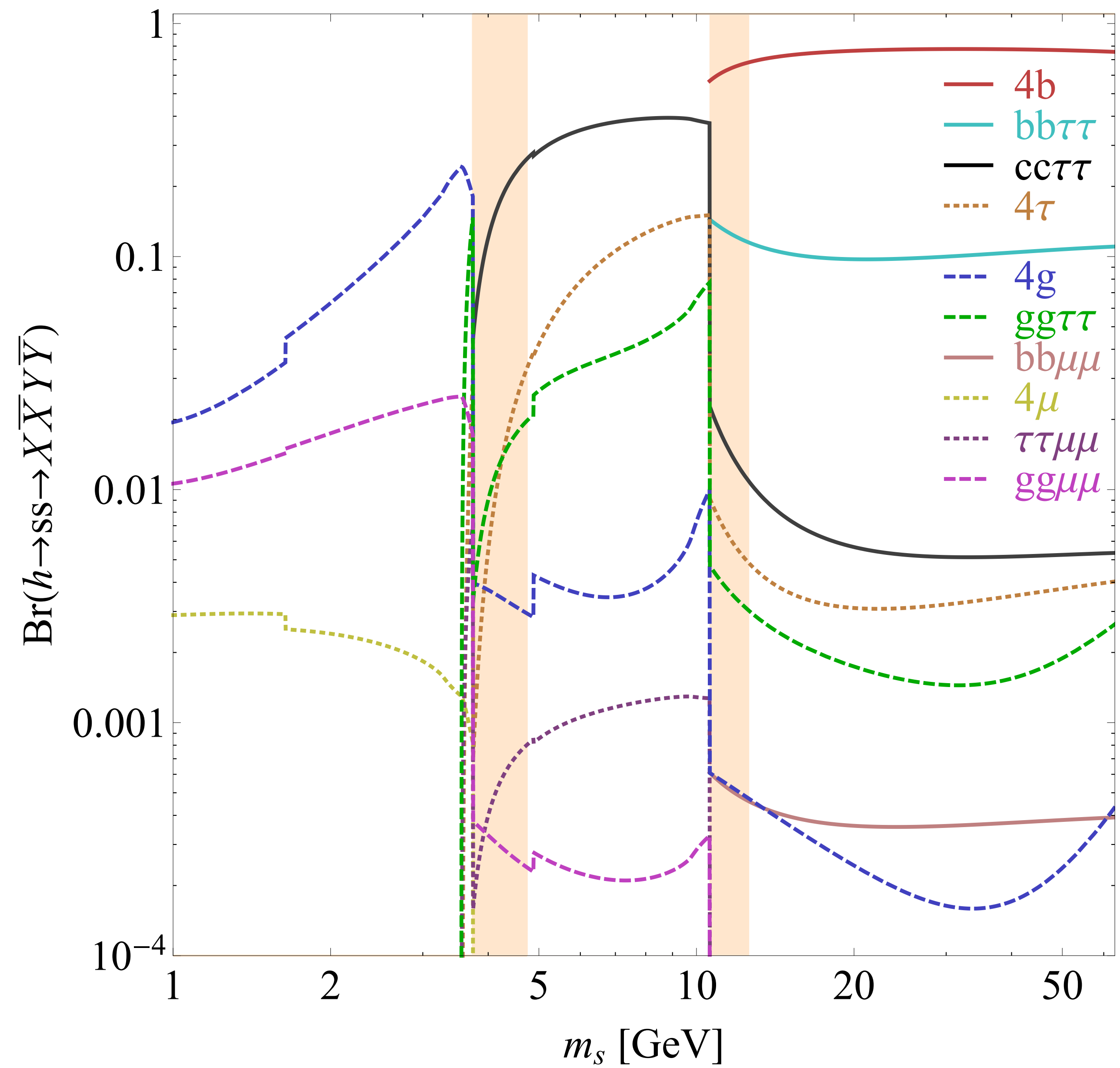
contours show μ_v in units of v

SM + singlet scalar

$s \to \mathrm{SM}$



$h \to s \to X\,\bar{X}\,Y\,\bar{Y}$



simple model, w/ lots of possibilities already

4b dominates, then 2b2τ

2HDM + S

Two-Higgs-Doublet-Models (2HDM)

w/ CP and flavor conservation, 4 popular types:

	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
		MSSM-like	lepton-specific	flipped

see e.g. recent review by Craig et.al., Branco et.al.…

viable in e.g. the "decoupling limit" where one Higgs is SM-like

(important to search for Higgs partners)

2HDM + S

Now add a singlet w/ small mixing w/ Higgs

allows $h \to aa$ &/or $h \to ss$ ($h \to Za$ also possible)

(pseudo-scalar) (scalar)

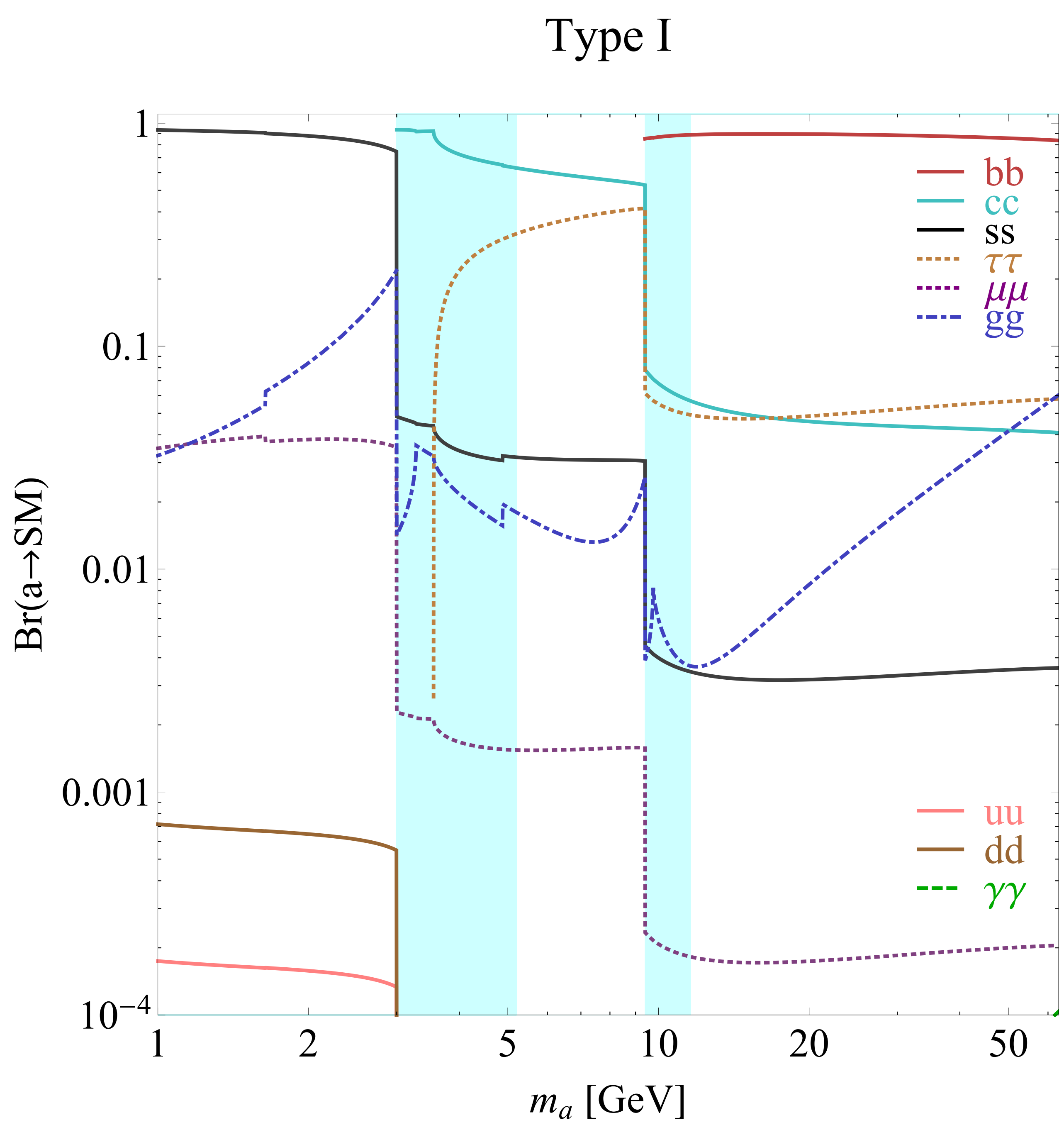
easily get BR < 10-20%

pseudo-scalar (a) and scalar (s) inherit a mixture of H_u and H_d couplings to fermions

get *rich* set of 125 GeV Higgs exotic decay modes

(much richer than pure NMSSM!)

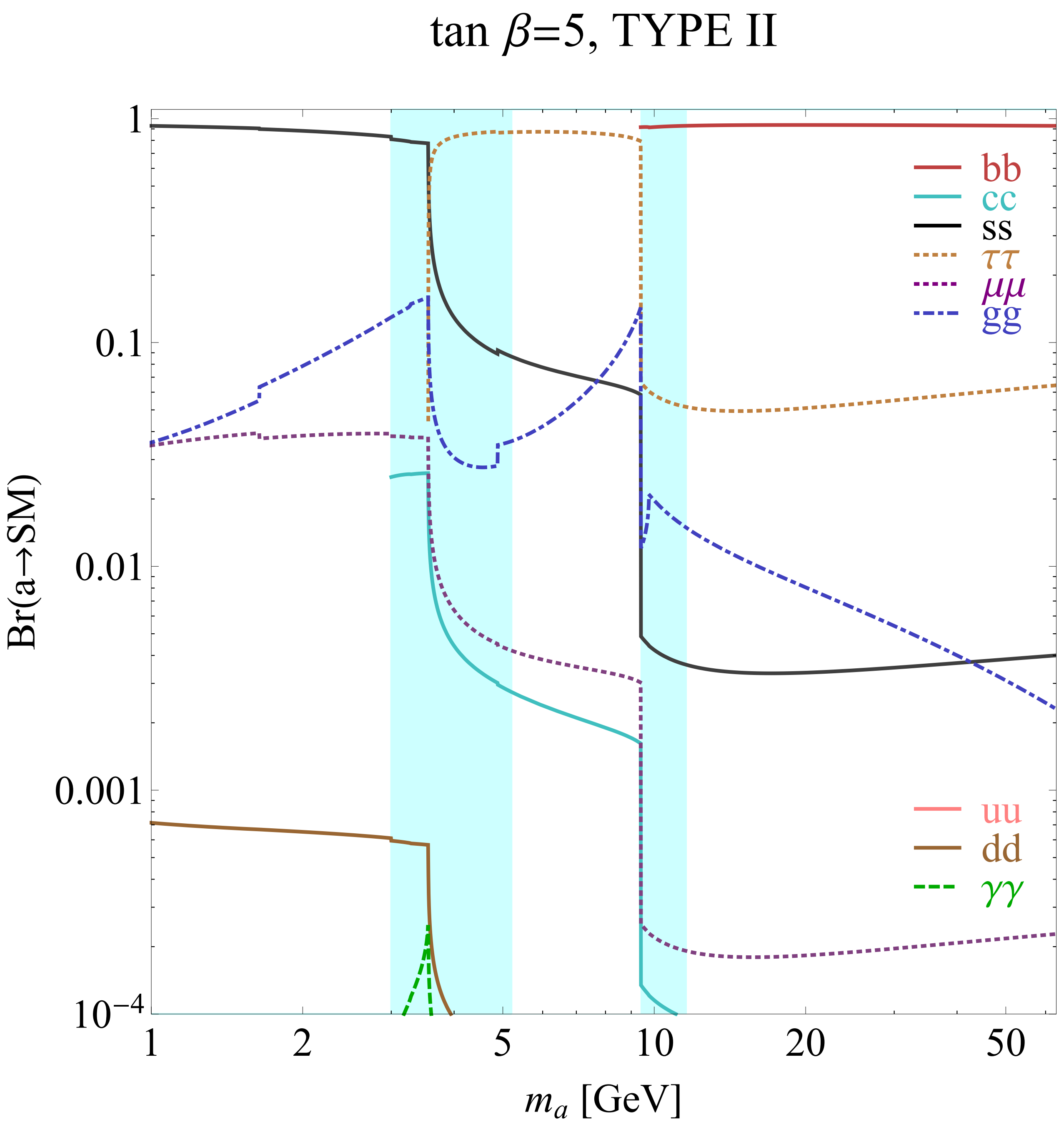
2HDM + S (pseudoscalar)



2b (>10 GeV)

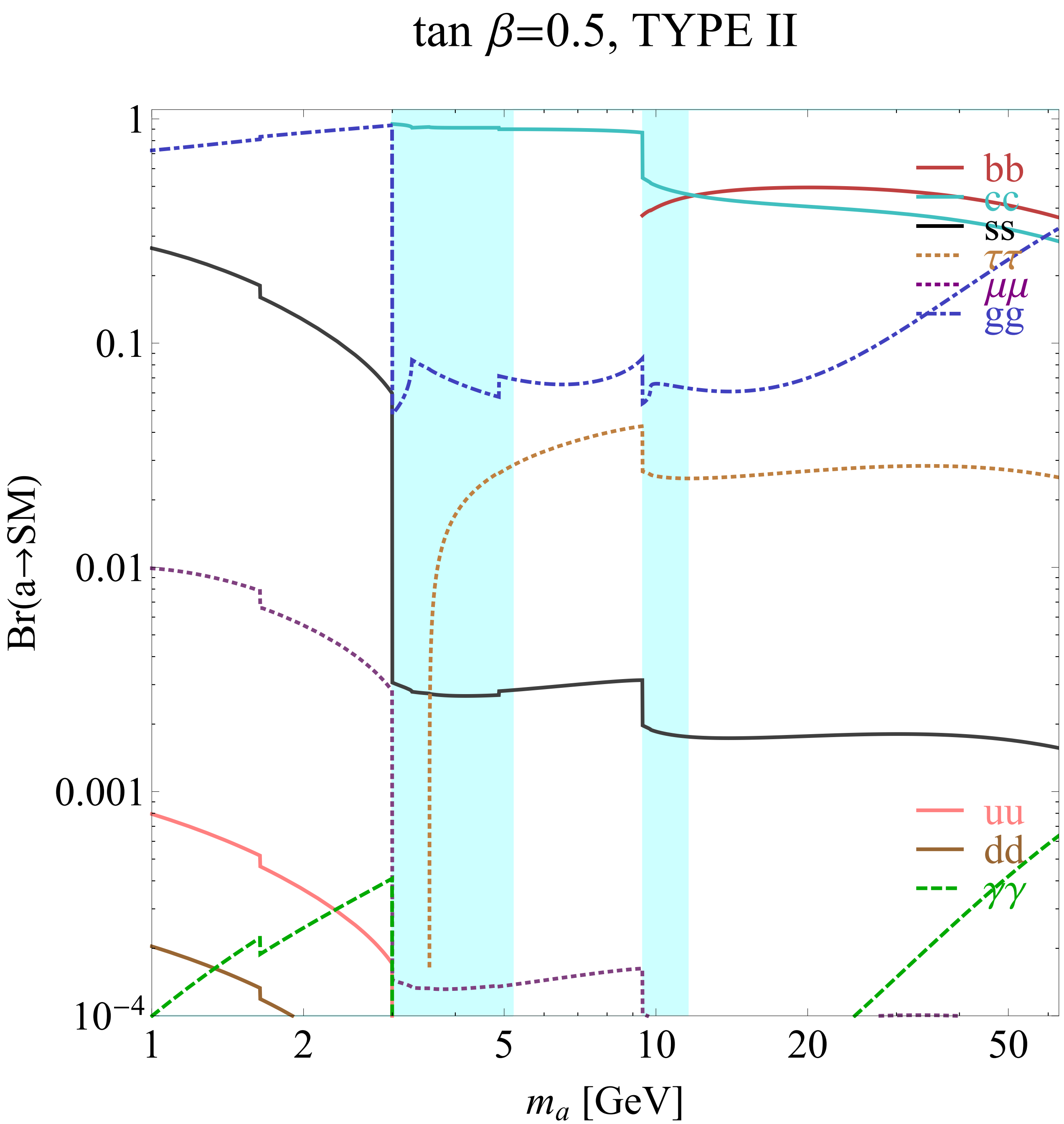
2c or 2s (<10 GeV)

2HDM + S (pseudoscalar)



2b (>10 GeV)

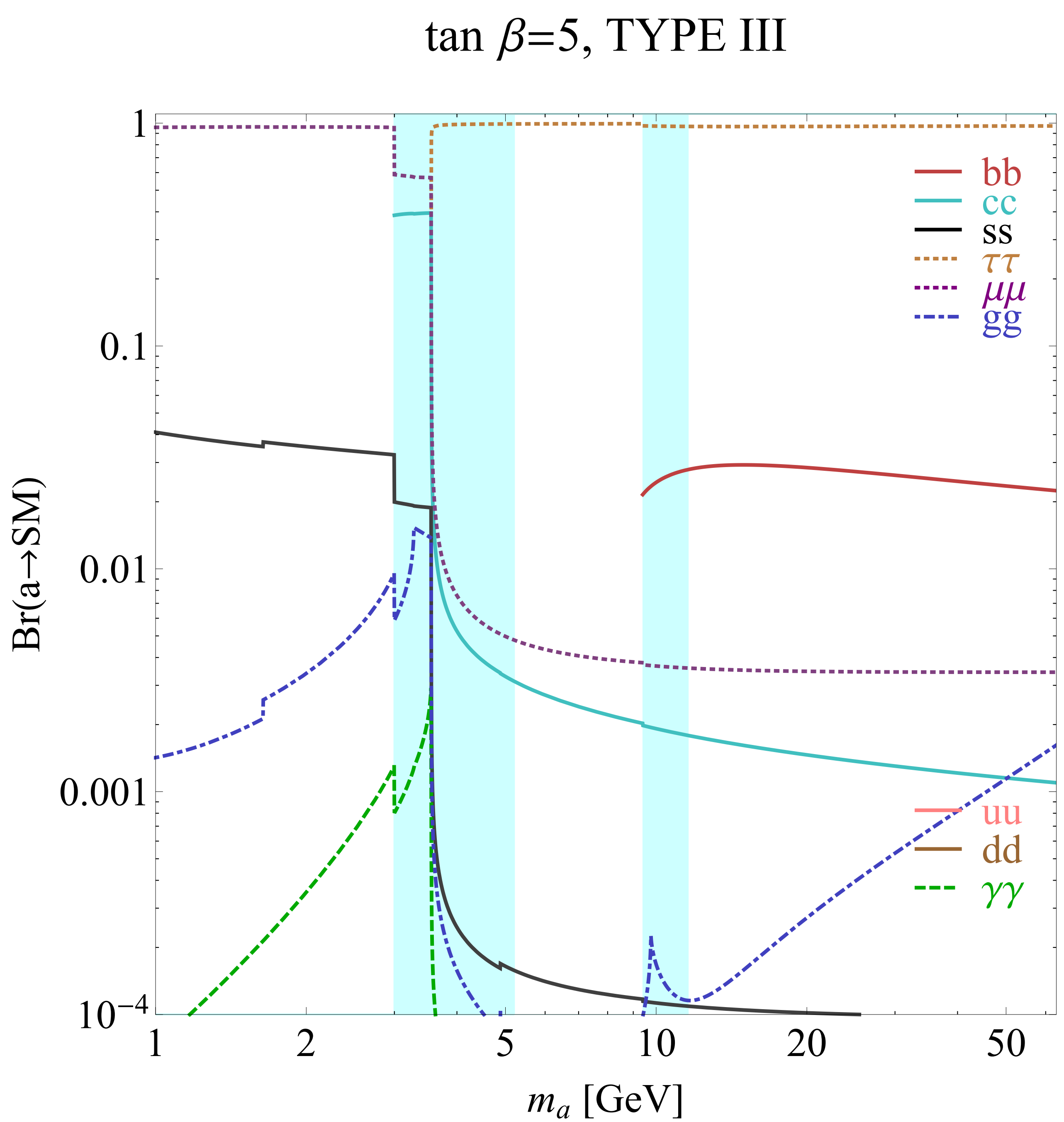
2τ or 2s (<10 GeV)



equal 2b, 2c (>10 GeV)

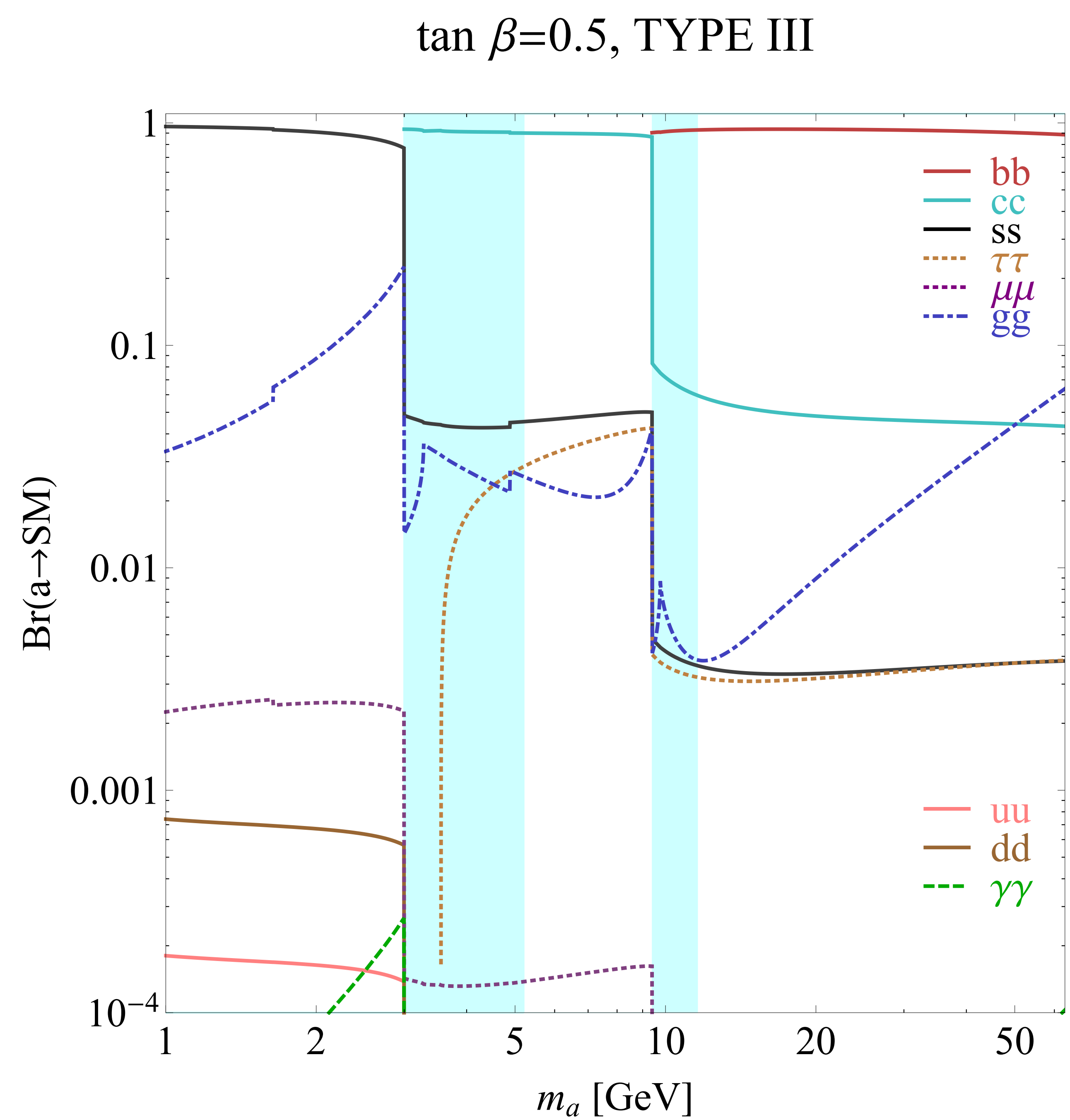
2c or 2g (<10 GeV)

2HDM + S (pseudoscalar)



2τ (>3.4 GeV) !

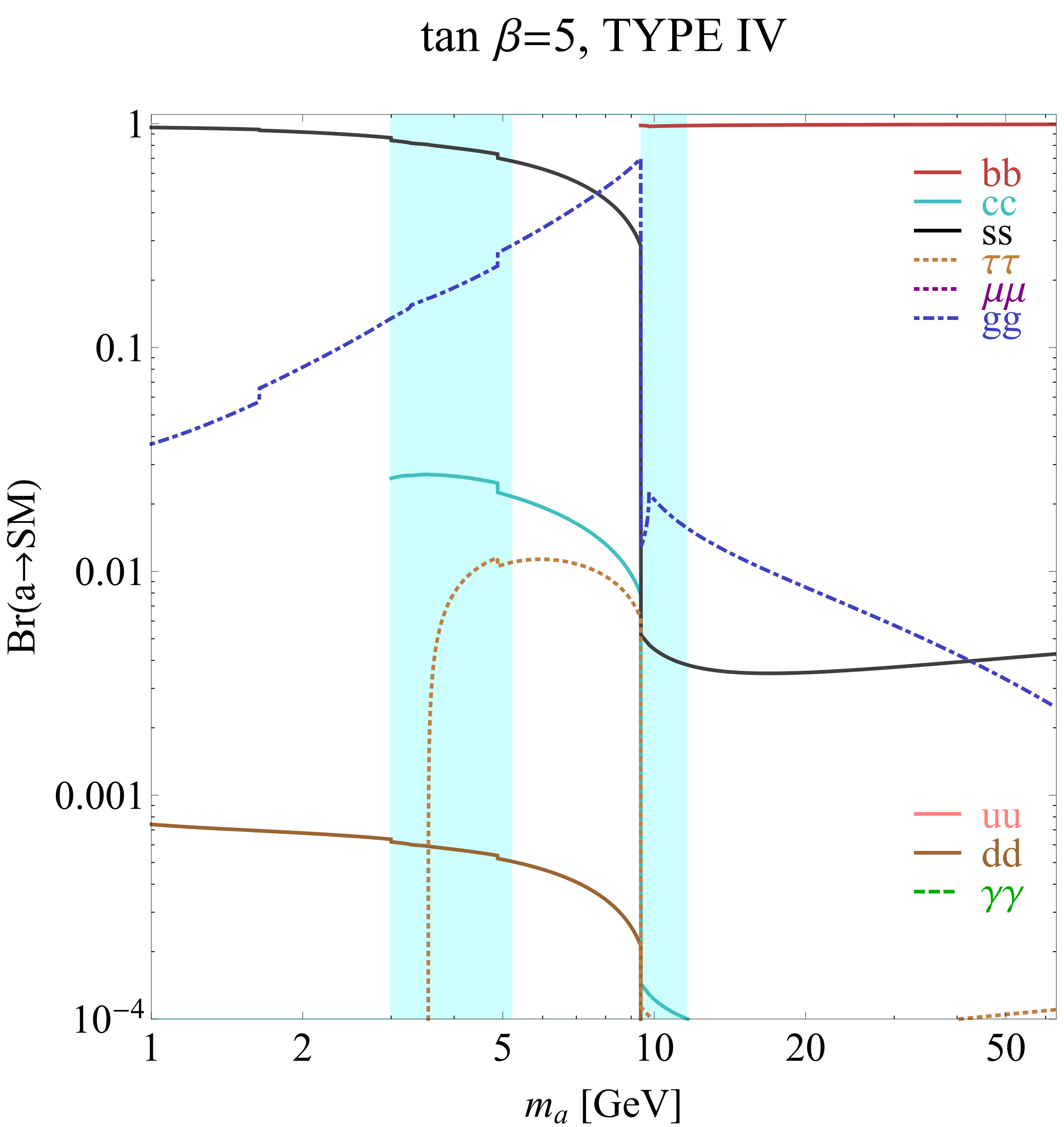
2μ (<3.4 GeV)

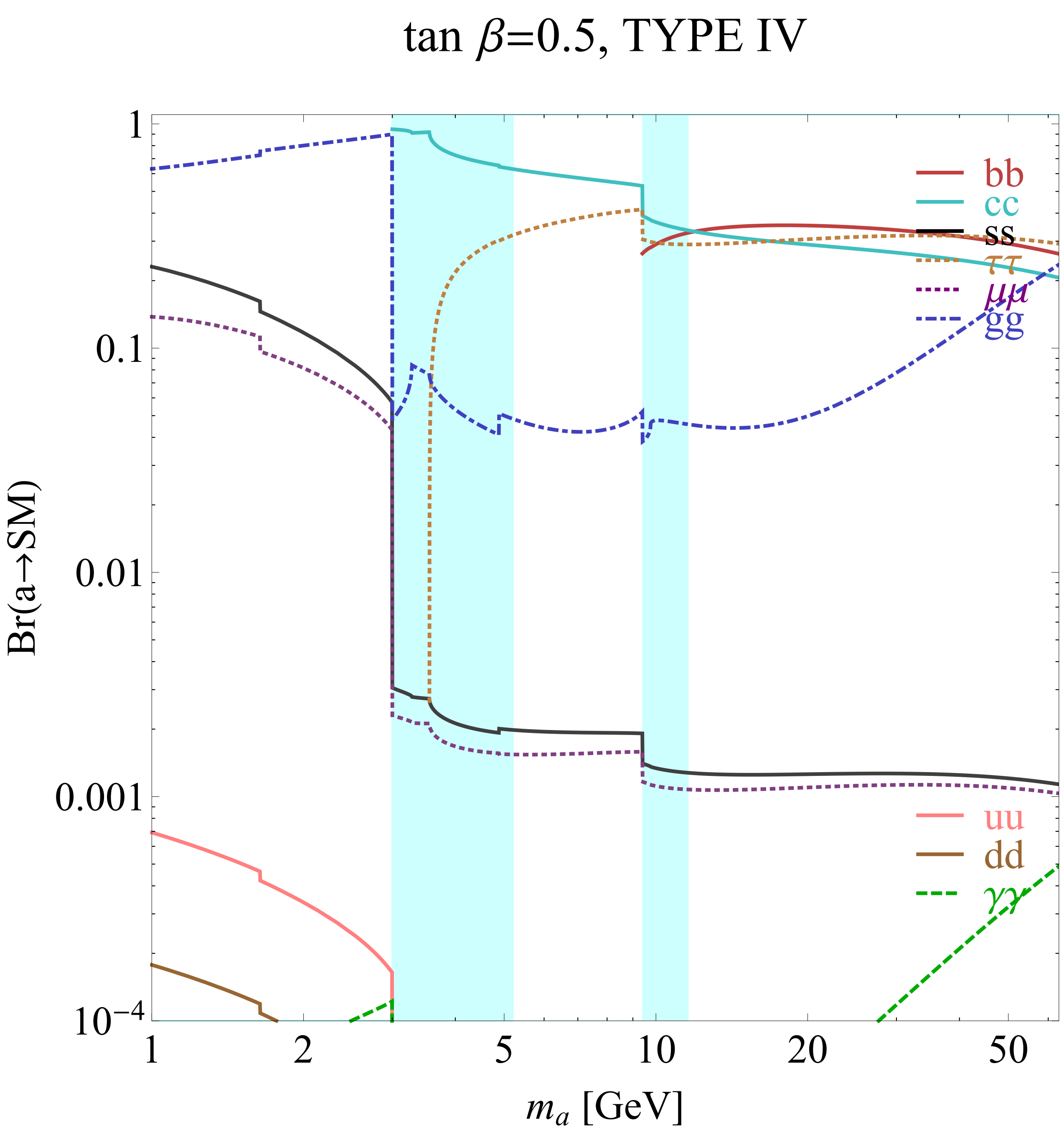


2b (>10 GeV)

2c or 2s (<10 GeV)

2HDM + S (pseudoscalar)

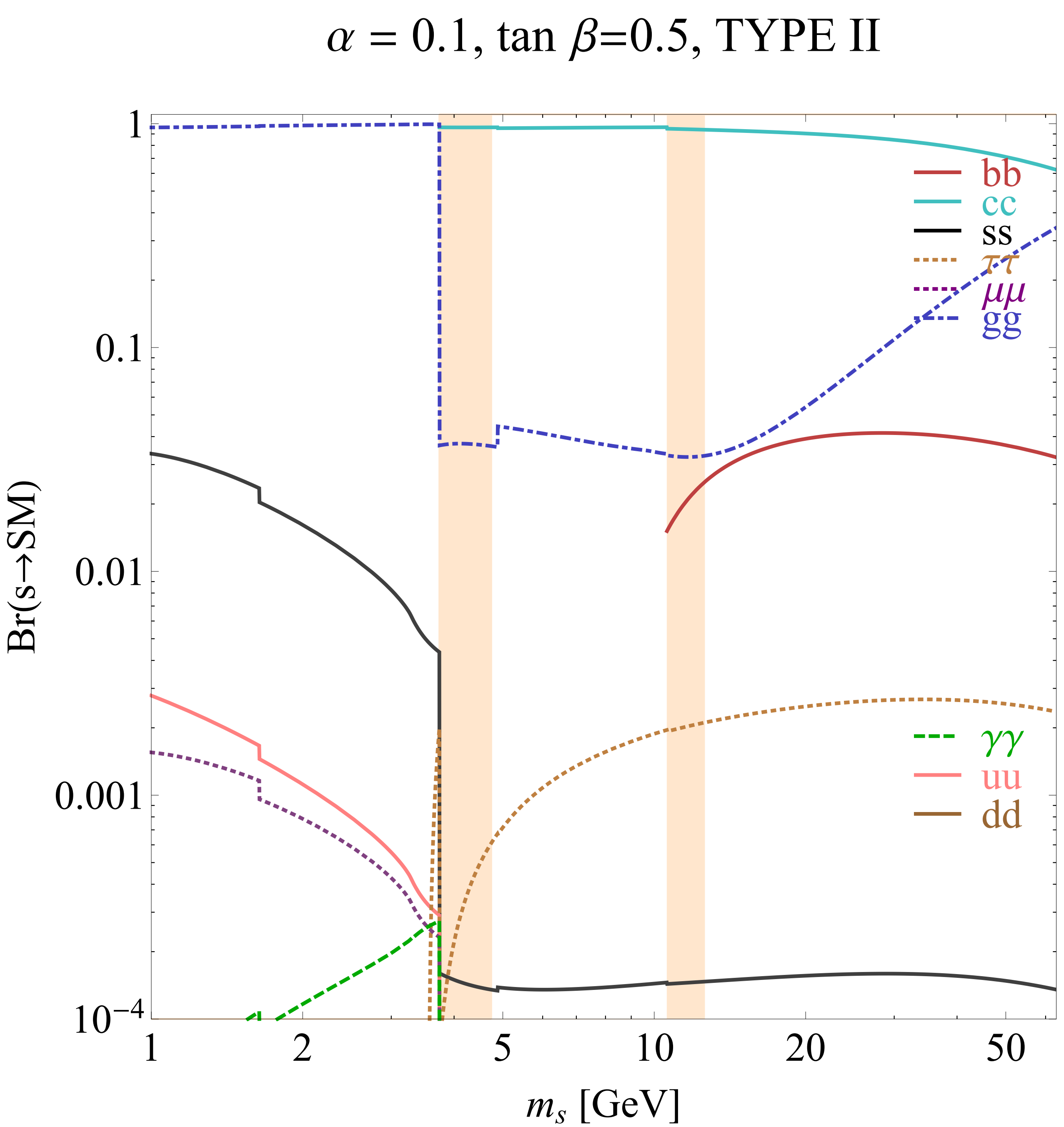


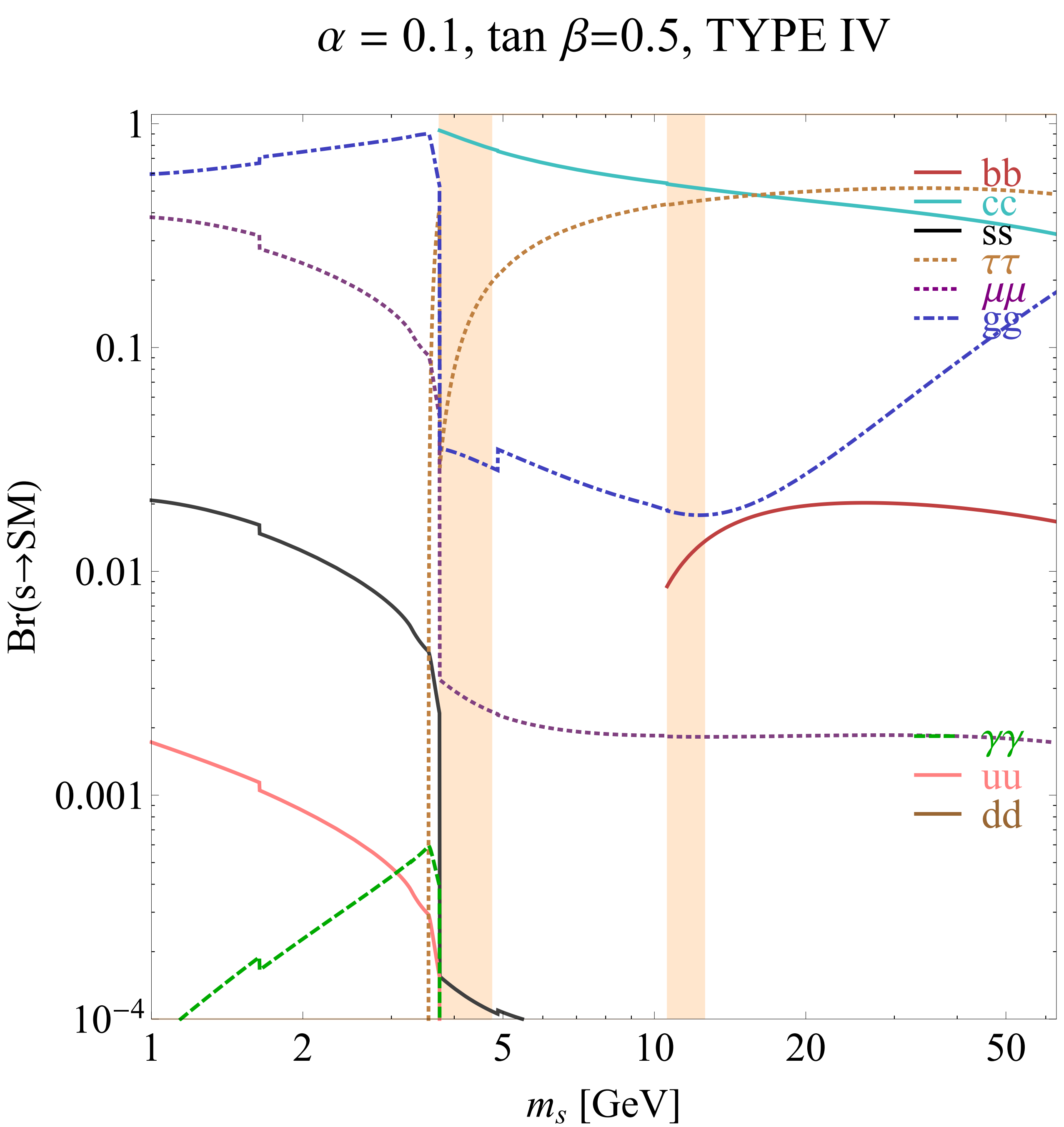


2b (>10 GeV)
2g or 2s (<10 GeV)

equal 2b, 2c, 2τ (>10 GeV)
2c or 2g (<10 GeV)

2HDM + S (scalar)





2c (>3 GeV)

2g (<3 GeV)

equal 2c, 2τ (>3 GeV)

2g (<3 GeV)

SM + Vector

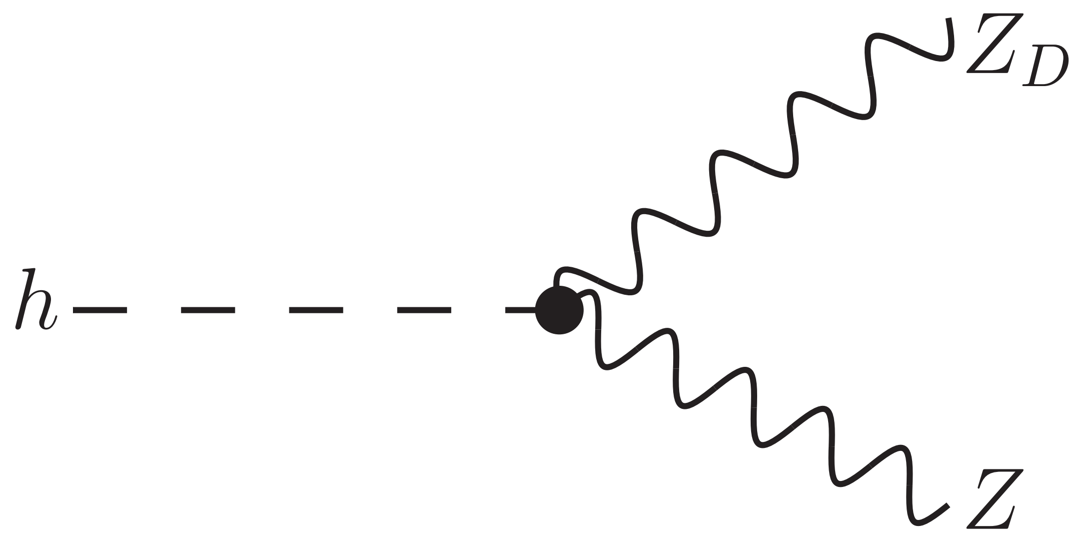
- add to SM a $U(1)_D$ "dark" gauge symmetry (mediator Z_D), broken by a "dark" Higgs, S
- $U(1)_D$ mixes with $U(1)_Y$ (kinetic mixing), strength ε
- S can mix w/ ordinary Higgs H, strength ζ

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}Z_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}\hat{B}_{\mu\nu}\hat{Z}_D^{\mu\nu}$$

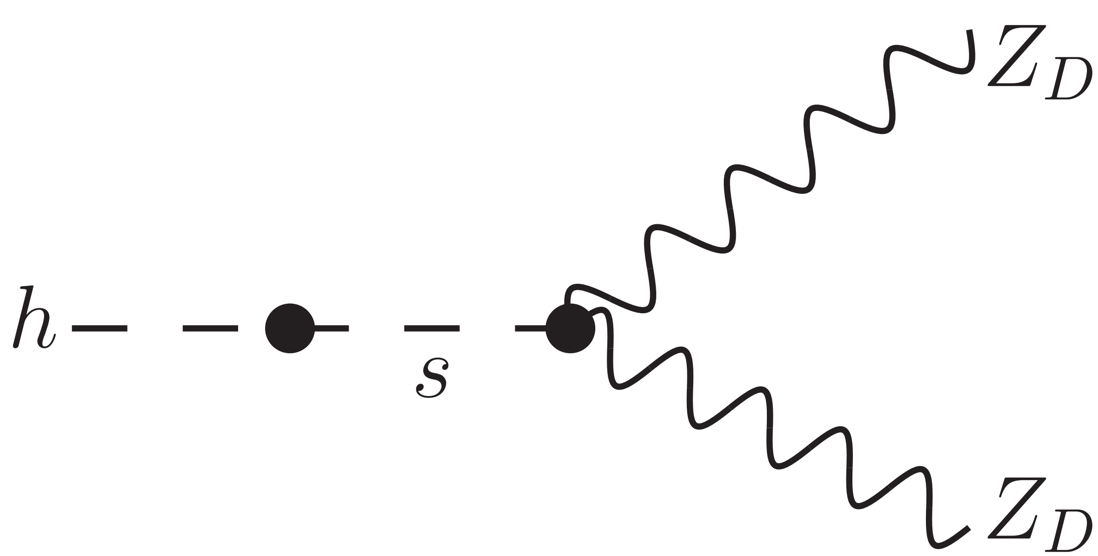
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 - \mu_D^2|S|^2 + \lambda_D|S|^4 + \zeta|S|^2|H|^2$$

SM + Vector

- e.g.



$\propto \epsilon$

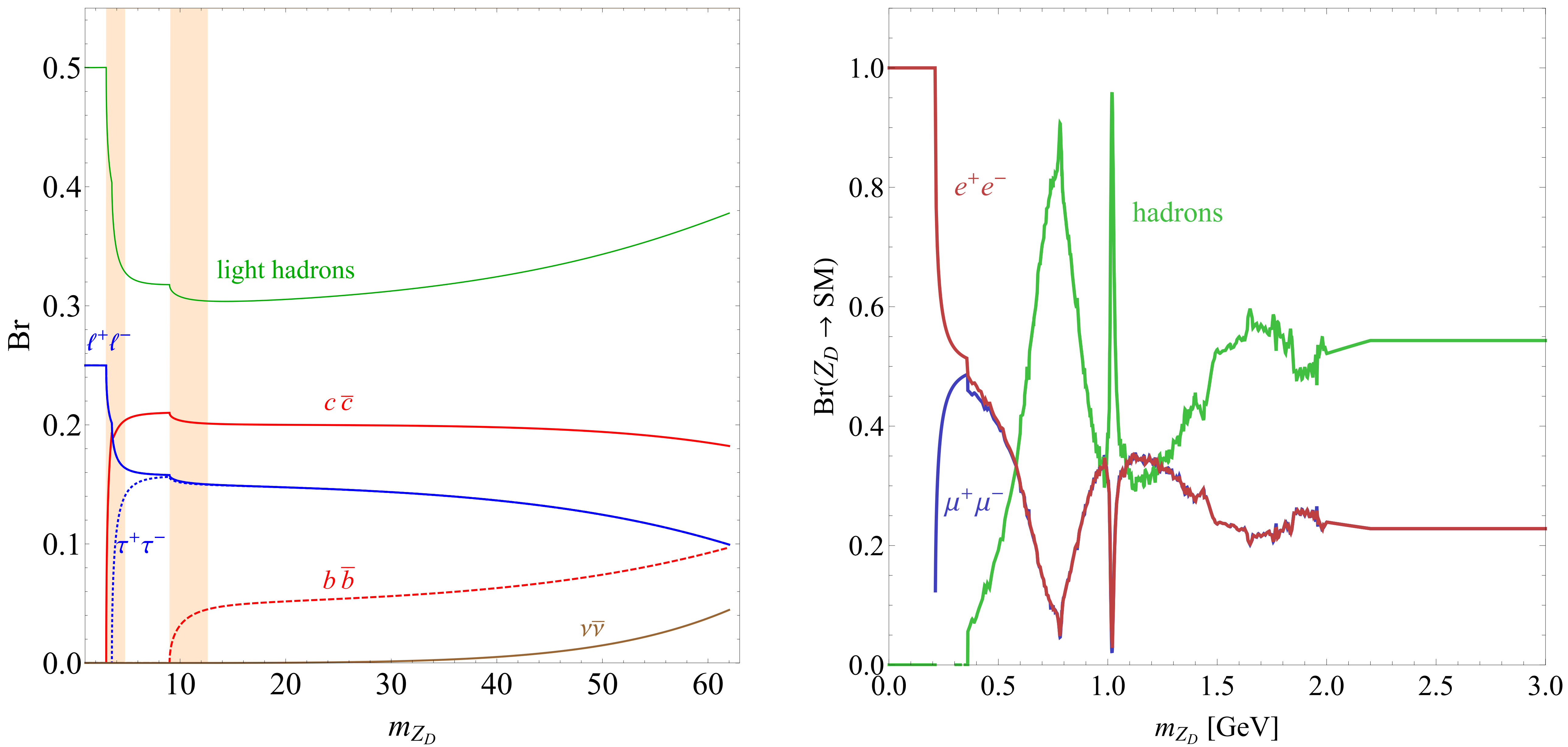


$\propto \zeta$

either could dominate, leading to different phenomenology

SM + Vector

$$Z_D \to \mathrm{SM}$$



could easily get signatures w/ many leptons

Some lessons and suggestions of what to focus on

- reasonably detailed discussion of many decay modes in paper (worth reading once you've picked your favorite final state)
- in the following I will *briefly* summarize only a *few* lessons
- please read detailed summary of paper as it contains more info and important caveats

Some lessons and suggestions of what to focus on

- in a particular model, important to know which of the various decay modes offers the best sensitivity to the existence of the exotic decays; i.e., given various

$$\mathrm{Br}(h \to \mathcal{F}_i)$$

which gives strongest limit on

$$\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br}(h \to \mathrm{non-SM\ decays}) = \frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \sum_i \mathrm{Br}(h \to \mathcal{F}_i) \ ?$$

$h \to aa^{(\prime)} \to$ fermions

couplings of *a* to SM fermions are weighted by mass, possibly separately for up-type quarks, down-type quarks, and leptons

$h \to aa^{(\prime)} \to$ fermions

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	quarks suppressed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^T $[0.2^L]$	W	0.8	0.9 [0.2]	0	–
$b\bar{b}\tau\tau$	> 1 $[0.15^L]$	V	0.1	> 1 [1]	0	–
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.5-1$ $[0.2-0.8]$	0	–
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]	1	$0.2-0.4$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]	0.007	$0.04-0.1$ [U]
$\mu\mu\mu\mu$	$1\cdot 10^{-4\ R}$ [U]	G	$1\cdot 10^{-7}$	1000 [U]	$1\cdot 10^{-5}$	10 [U]

projection/limit based on theory estimate in literature (L), our theory estimate (T), our re-interpretation of an LHC limit (R), or is unknown (U)

$h \to aa^{(\prime)} \to$ fermions

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	quarks suppressed: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^T $[0.2^L]$	W	0.8	0.9 [0.2]	0	–
$b\bar{b}\tau\tau$	> 1 $[0.15^L]$	V	0.1	> 1 [1]	0	–
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.5-1$ $[0.2-0.8]$	0	–
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]	1	$0.2-0.4$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]	0.007	$0.04-0.1$ [U]
$\mu\mu\mu\mu$	$1\cdot 10^{-4\ R}$ [U]	G	$1\cdot 10^{-7}$	1000 [U]	$1\cdot 10^{-5}$	10 [U]

Conclusion: bbμμ & ττμμ searches well motivated in *Run I* & *Run II*; scan w/o prejudice for m_a; consider also *a* different from *a′*

$h \to aa^{(\prime)} \to \gamma\gamma$ or gg

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\text{Br}(a \to \gamma\gamma) \approx 0.004$: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	$\text{Br}(a \to \gamma\gamma) \approx 0.004$: Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV	$\text{Br}(a \to \gamma\gamma) \approx 0.04$: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	$\text{Br}(a \to \gamma\gamma) \approx 0.04$: Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV
$jjjj$	> 1 $[0.1^{L*}]$	W	0.99	> 1 $[0.1^*]$	0.92	> 1 $[0.1^*]$
$\gamma\gamma jj$	0.04 $[0.01^{L*}]$	W	0.008	5 $[1^*]$	0.08	0.5 $[0.1^*]$
$\gamma\gamma\gamma\gamma$	$2 \cdot 10^{-4\ T}$ $[3 \cdot 10^{-5\ L*}]$	G	$1 \cdot 10^{-5}$	20 $[1^*]$	0.001	0.2 $[0.03^*]$

Conclusion: search for 4γ in Run I and for 4γ, 4j, 2γ2j in Run II; keeping triggers for multiple photons is well-motivated

$h \to Z_D Z_D$

couplings of Z_D to SM fermions are weighted by SM gauge charge

(i.e. generally enhanced couplings to leptons compared to pseudo-scalar *a*)

$h \to Z_D Z_D$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br}(\text{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br}(\text{non-SM})$ 7+8 [14] TeV
$jjjj$	> 1 $[0.1^{L*}]$	W	0.25	> 1 $[0.4^{*}]$
$\ell\ell\ell\ell$	$4 \cdot 10^{-5}$ ^{R} [U]	G	0.09	$4 \cdot 10^{-4}$ [U]
$jj\mu\mu$	$0.002 - 0.008$ ^{T} [U] $[(5-20) \times 10^{-4}$ $^{T}]$	G	0.15	$0.01 - 0.06$ $[0.003 - 0.01]$
$b\bar{b}\mu\mu$	$(2-7) \cdot 10^{-4}$ ^{T} $[(6-20) \cdot 10^{-5}$ $^{T}]$	G	0.015	$0.01 - 0.05$ $[0.003 - 0.01]$

strong constraint on 4ℓ from published results on Higgs results & $Z^{(*)}Z^{(*)}$

Conclusion: dedicated 4ℓ search can improve on this result and is highly motivated in *Run I* & *Run II*; extend to low Z_D masses

see more examples in
backup & paper

Summary of highly motivated searches

- $h \to Z_D Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $h \to Z Z_D \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $h \to \ell^+\ell^- + \not{E}_T$
- $h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
- $h \to aa^{(\prime)} \to (b\bar{b})(\mu^+\mu^-)$
- $h \to aa^{(\prime)} \to (\tau^+\tau^-)(\mu^+\mu^-)$
- $h \to aa^{(\prime)} \to (\gamma\gamma)(\gamma\gamma)$
- $h \to \gamma\gamma + \not{E}_T$

- search across full kinematic range, including regimes where leptons are collimated or (b-)jets merge
- in some cases, re-interpret search for same final state but w/ small MET by relaxing invariant mass = 125 GeV

Summary

Higgs may be our (only)
window to new physics

must look *explicitly* for non-standard decays

Backup

$h \to ZZ_D, Za$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$ZZ_D \to \ell\ell\ell\ell$	$4 \cdot 10^{-5}$ ^{R} [U]	G	0.02	0.002 [U]
$Za \to \ell\ell\mu\mu$	$4 \cdot 10^{-5}$ ^{R} [U]	G		
$\mathrm{Br}(a \to b\bar{b}) \sim 0.9$			$2 \cdot 10^{-5}$	2 [U]
$\mathrm{Br}(a \to q\bar{q}) = 0$			$2 \cdot 10^{-4}$	0.2 [U]

Conclusion: Za and ZZ_D searches well motivated in *Run I* & *Run II*; scan w/o mass-prejudice

$h \to \psi\psi'$ w/ $\psi \to \psi' a$, $a \to f\,f$, $\psi' \to$ invisible

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV	quarks suppressed: $\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	quarks suppressed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV
$(b\bar{b})\ \not{E}_T$	$> 1^T\ [0.2^{L*}]$	Z	0.9	$> 1\ [0.2^*]$	0	–
$(\tau\tau)\ \not{E}_T$	$> 1\ [> 1^{L*}]$	Z	0.1	$> 1\ [> 1^*]$	1	$> 1\ [> 1^*]$
$\mu\mu\ \not{E}_T$	0.1^R [U]	G	0.003	40 [U]	0.03	4 [U]

(numbers assume no muon resonance, i.e. are pessimistic)

$h \to \psi\psi^{(\prime)}$ w/ $\psi \to \psi' Z_D$, $Z_D \to f\,f$, $\psi' \to$ inv.

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$h \to \psi\psi' \to \bar{f}f + \not{E}_T$: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	$h \to \psi\psi' \to \bar{f}f + \not{E}_T$: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV	$h \to \psi\psi \to \bar{f}_1 f_1 + \bar{f}_2 f_2 + \not{E}_T$: $\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br(non\text{-}SM)}}$	$h \to \psi\psi \to \bar{f}_1 f_1 + \bar{f}_2 f_2 + \not{E}_T$: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br(non\text{-}SM)}$ 7+8 [14] TeV
$(b\bar{b})\ \not{E}_T$	$> 1^T$ [0.2^{L*}]	Z	0.05	> 1 [4*]	0.1	> 1 [2*]
$(\tau\tau)\ \not{E}_T$	> 1 [$> 1^{L*}$]	Z	0.15	> 1 [> 1*]	0.28	> 1 [> 1*]
$\ell\ell\ \not{E}_T$	0.07^R [U]	G	0.30	0.2 [U]	0.51	0.1 [U]
$\ell\ell\ell\ell\ \not{E}_T$	$5 \cdot 10^{-4\ R}$ [U]	G, V	–	–	0.09	0.005 [U]

(numbers assume no lepton resonance, i.e. are pessimistic)

Conclusion: MET + 2 or 4 lepton searches in *Run I* is well-motivated, both w/ and w/o pair-wise resonances

$h \to \psi\psi^{(\prime)}$ w/ $\psi \to \psi^{\prime}+\gamma$, $\psi^{\prime} \to$ inv.

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit Limit on $\text{Br}(\mathcal{F}_i)$	Production Mode
$\gamma\ \not{E}_T$	$> 1^R$ [U]	G
$\gamma\gamma\ \not{E}_T$	$.04^R$ [U]	G

(numbers assume no photon resonance, i.e. are pessimistic)

Conclusion: MET + $\gamma\gamma$ search in *Run I* is well-motivated as a meaningful limit could be obtained

$h \to \psi\psi^{(\prime)}$ w/ $\psi \to \psi' a$, $a \to \gamma\gamma$, $\psi' \to$ inv.

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\text{Br}(a \to \gamma\gamma) \approx 0.004$		$\text{Br}(a \to \gamma\gamma) \approx 0.04$	
			$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV	$\frac{\text{Br}(\mathcal{F}_i)}{\text{Br(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \text{Br(non-SM)}$ 7+8 [14] TeV
$\gamma\gamma \not{E}_T$	$.04^R$ [U]	G	0.004	10 [U]	0.04	1 [U]

(numbers assume no photon resonance, i.e. are pessimistic)

Conclusion: MET + γγ search in *Run I* is well-motivated as a meaningful limit could be obtained and an enhancement in $a \to \gamma\gamma$ decay is a reasonable possibility

Small MET

- Searches w/o MET can probe scenarios w/ *small* MET if certain kinematic requirements are relaxed
- Example: h → *aa′*, w/ *a′* → invisible, *a* → f f, and

$$m_h \sim m_a \gg m_h - m_a \sim m_{a'}$$

Conclusion: searches should not only be done assuming that invariant mass of observed objects equals Higgs mass; search for lower masses too (and higher, since there may be Higgs partners as well)

Collimated objects in pairs

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode
$\{\mu\mu\}\{\mu\mu\}$	$1 \cdot 10^{-5}$ $(5 \cdot 10^{-3})$ [U]	G
$\{ee\}\{ee\}$	limit unclear [U]	W, G
$\{\mu\mu\}X$	1 [U]	G
$\{\mu\mu\}\ \not{E}_T$	0.03^L [U]	W
$\{\mu\mu\}\{\mu\mu\}\ \not{E}_T$	$1 \cdot 10^{-5}$ $(5 \cdot 10^{-3})$ [U]	G
$\{ee\}\{ee\}\ \not{E}_T$	limit unclear [U]	W, G
$\{\tau\tau\}\{\mu\mu\}$	$(3-7) \cdot 10^{-4\ T}$ [U]	G
$\{\gamma\gamma\}\{\gamma\gamma\}$	0.01 [U]	G
$\{\gamma\gamma\}\ \not{E}_T$	U[U]	
$\{gg\}\{gg\}$	> 1 $[0.7^L]$	W
$\{b\bar{b}\}\{b\bar{b}\}$	0.7^T $[0.2^L]$	W

Conclusion:

Some LHC searches exist for "lepton-jets", but not always w/ full data set;

also, a much more comprehensive search is warranted and highly motivated

Various additional studies are needed, e.g.

$$h \to XY \to \gamma YY = \gamma + \not{E}_T$$

$$h \to aa \to (b\bar{b})(b\bar{b})$$

$$h \to aa \to (b\bar{b})(\tau^+\tau^-)$$

Trigger implications for Run II

- it is highly motivated to keep one-lepton and VBF di-jet trigger thresholds as low as possible to trigger on Associated Higgs production or VBF for those channels with difficult decays
- a combination of a VBF di-jet + soft leptons + MET is needed for e.g. $h \to \ell^+\ell^- + \not{E}_T$ w/ large MET
- ditto for photons

Data “parking”

- ATLAS: lower p_T-thresholds for some objects may help
- CMS: VBF production (M_{jj} > 650 GeV, $|\Delta\eta|$ > 3.5)