Looking through the Higgs portal with exotic Higgs decays

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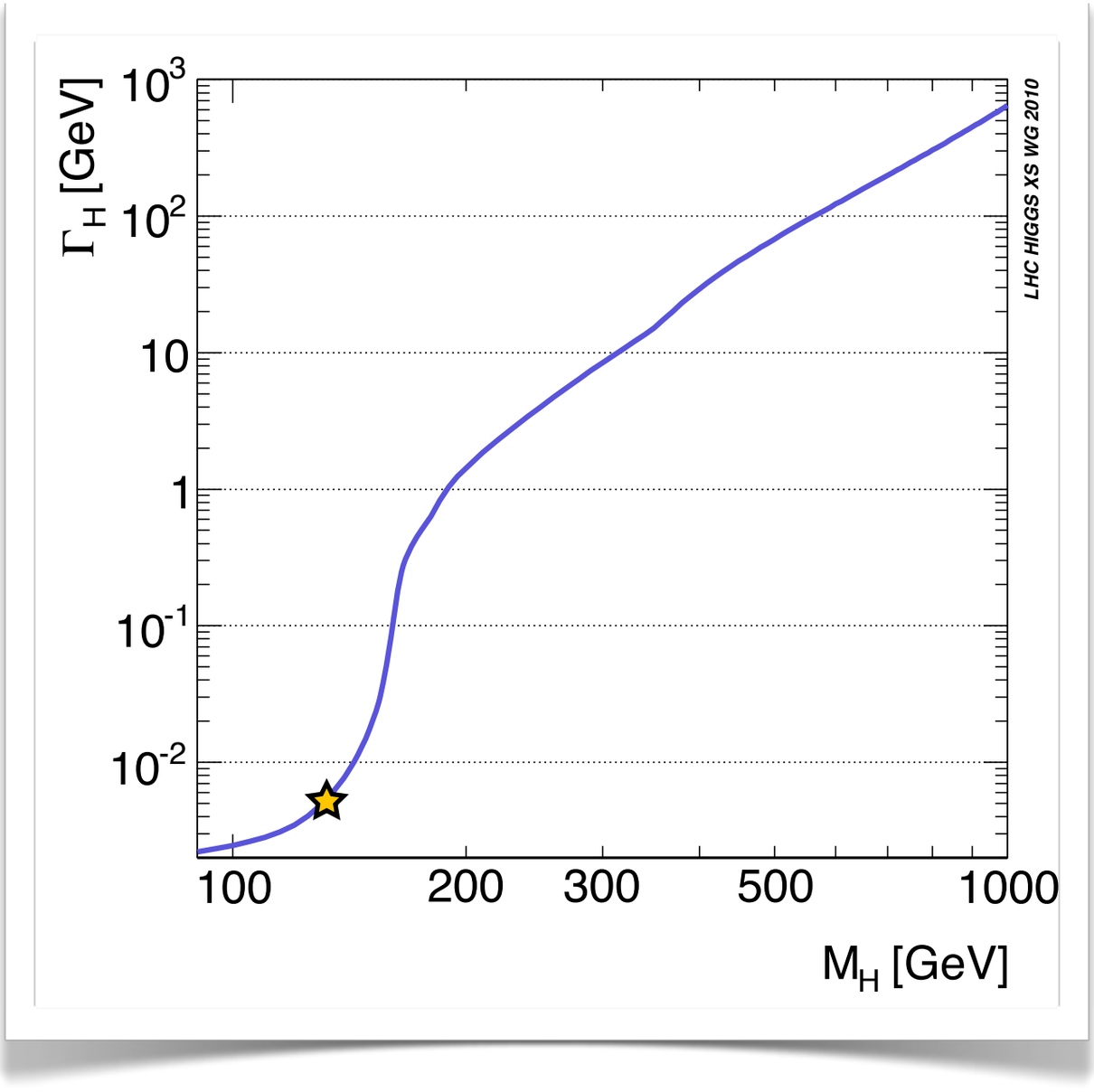
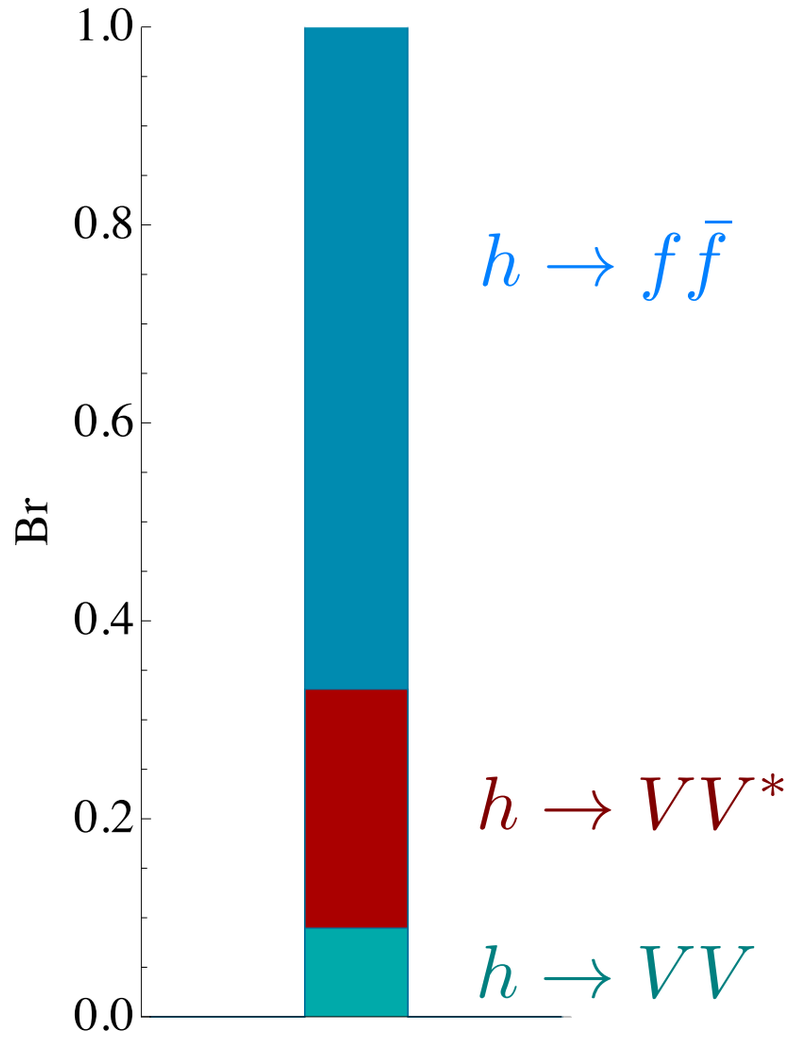
Unlocking the Higgs Portal (U. Mass. Amherst)
May 1, 2014

A light SM-like Higgs is narrow

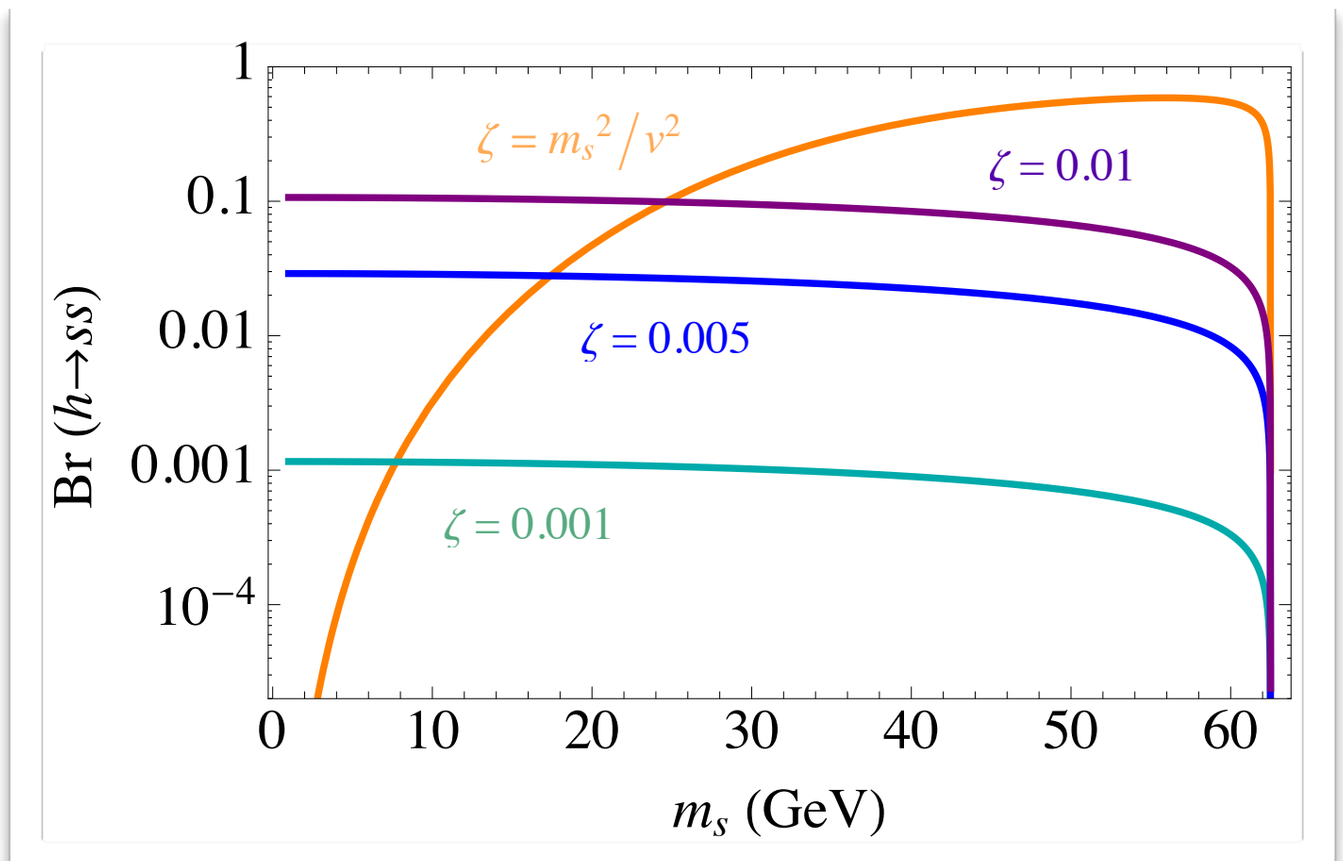




$$\Gamma_h(125\ \text{GeV}) = 4.1\ \text{MeV}$$

A light SM-like Higgs is narrow

- Presence of new light degrees of freedom can distort Higgs *Br*s by *O*(1) even for small couplings



Simple example: one new scalar

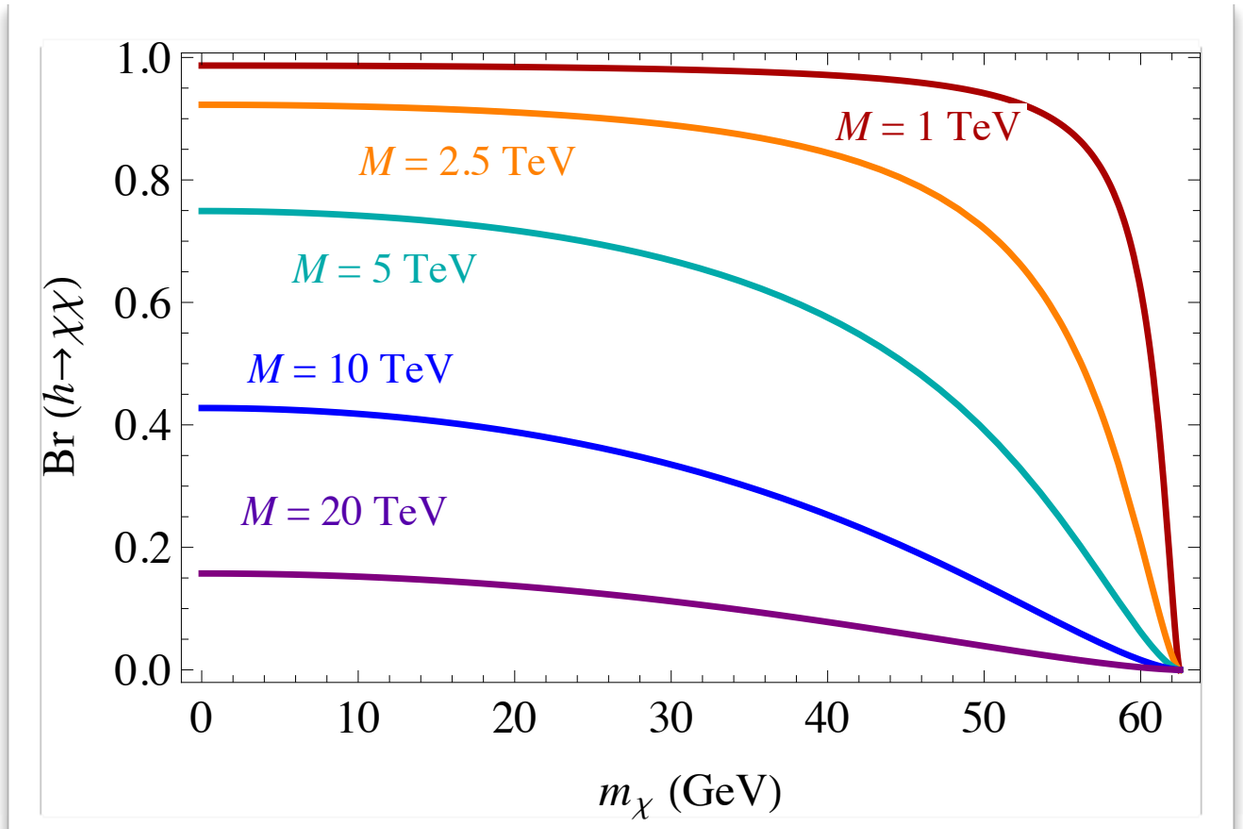
$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

A light SM-like Higgs is narrow

- Exotic Higgs decay modes easily sensitive to new physics scales significantly above a TeV

Simple dim-5 interaction

$$\Delta\mathcal{L} = \frac{1}{M}\bar{\psi}\psi|H|^2$$



Exotic Higgs Decays at the LHC

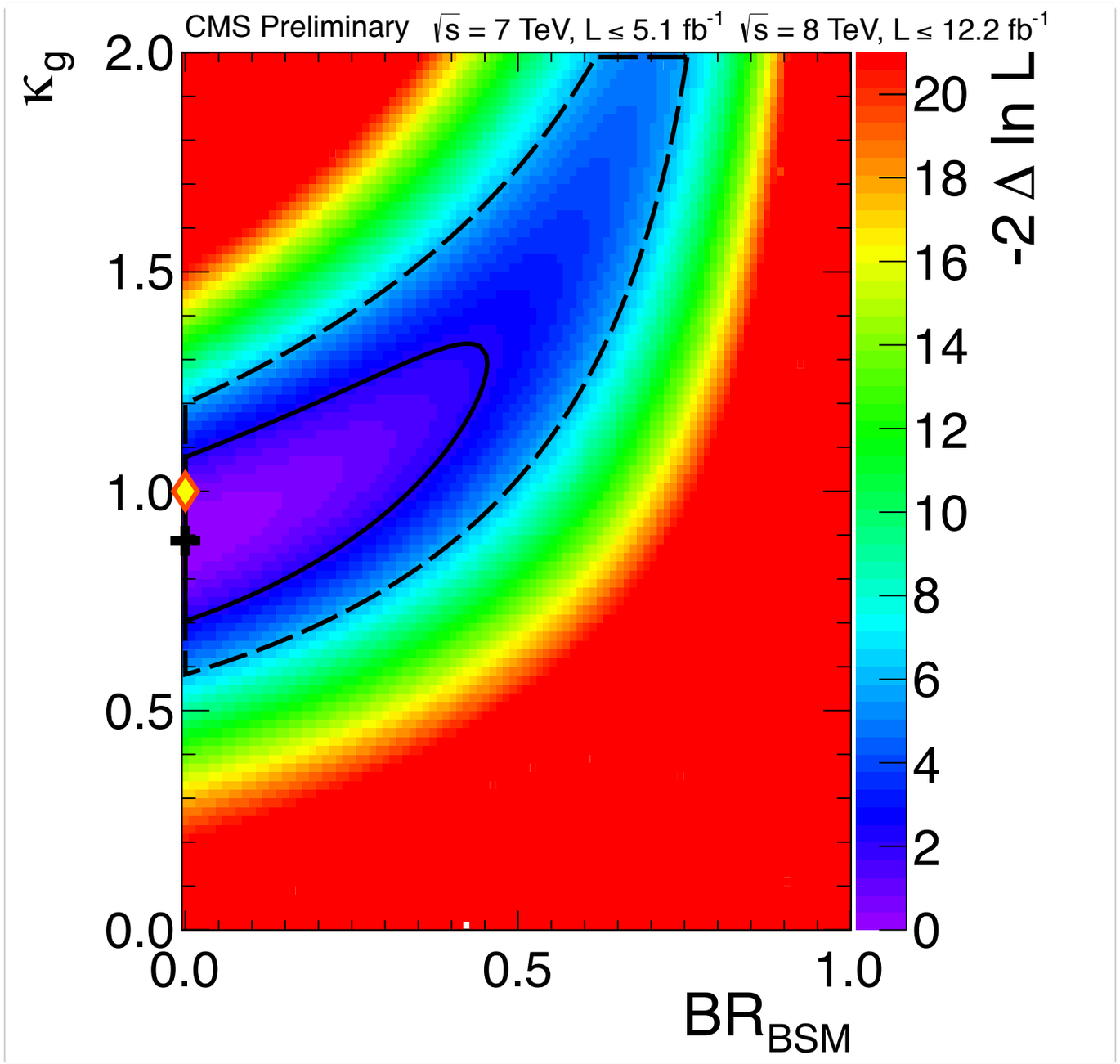
Higgs production in gluon fusion (8 TeV): 20 pb

Accumulated data at 8 TeV: 20 ifb

~400,000 Higgs bosons served

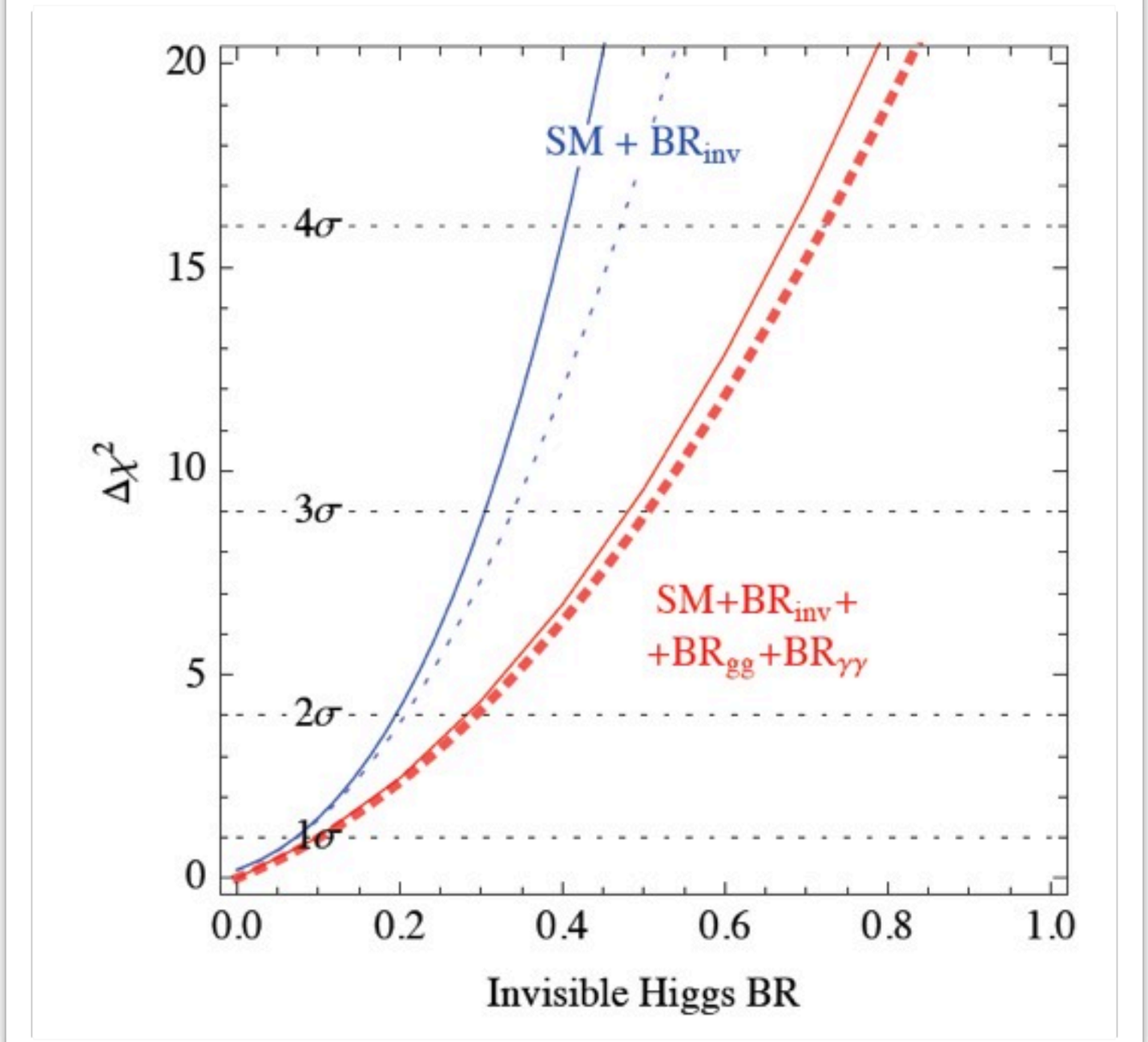
If: order one acceptance, good *S*/*B*:
statistics for branching fractions ~10^{-4}

Exotic Higgs Decays at the LHC



CMS *indirect* limits on BSM Higgs width

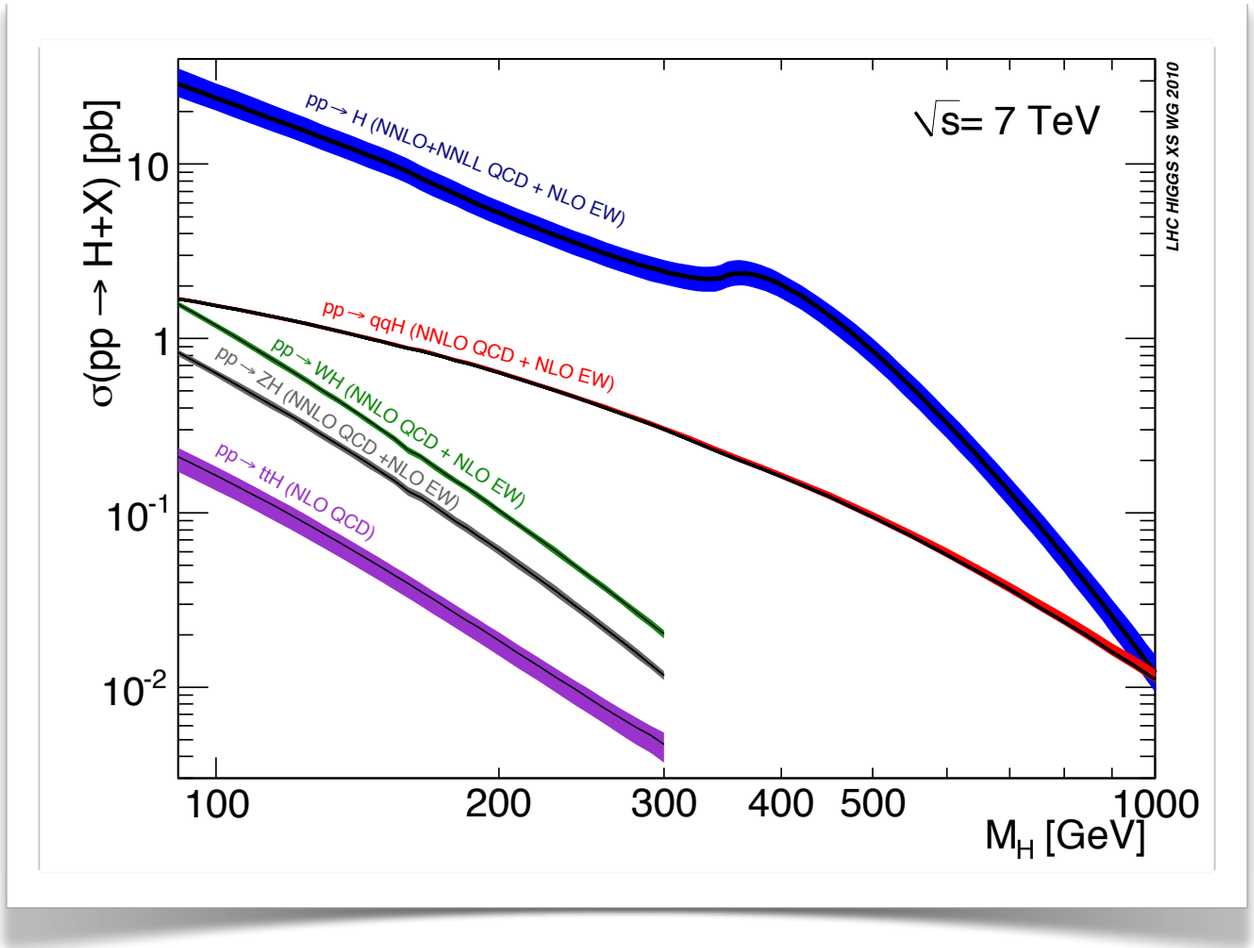
Exotic Higgs Decays at the LHC

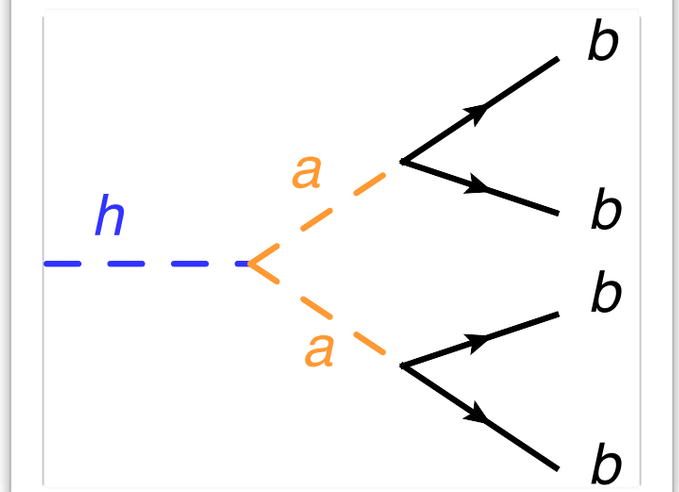


Unofficial combination of ATLAS and CMS (Giardino et al.);
(see also Ellis, You; Belanger et al.)

Exotic Higgs Decays at the LHC

A tough signal for a hadron machine like LHC:





Four soft *b*-jets:

$$p_T \lesssim 30 \text{ GeV}$$

...but also, many searches have not yet been done

Immense landscape of possibilities

- Higgs portal couplings:

$$\mathcal{L}_{int} = \sum_i \frac{1}{\Lambda_i^{d_i-2}} |H|^2 \mathcal{O}_i^{(d_i)} + \dots$$

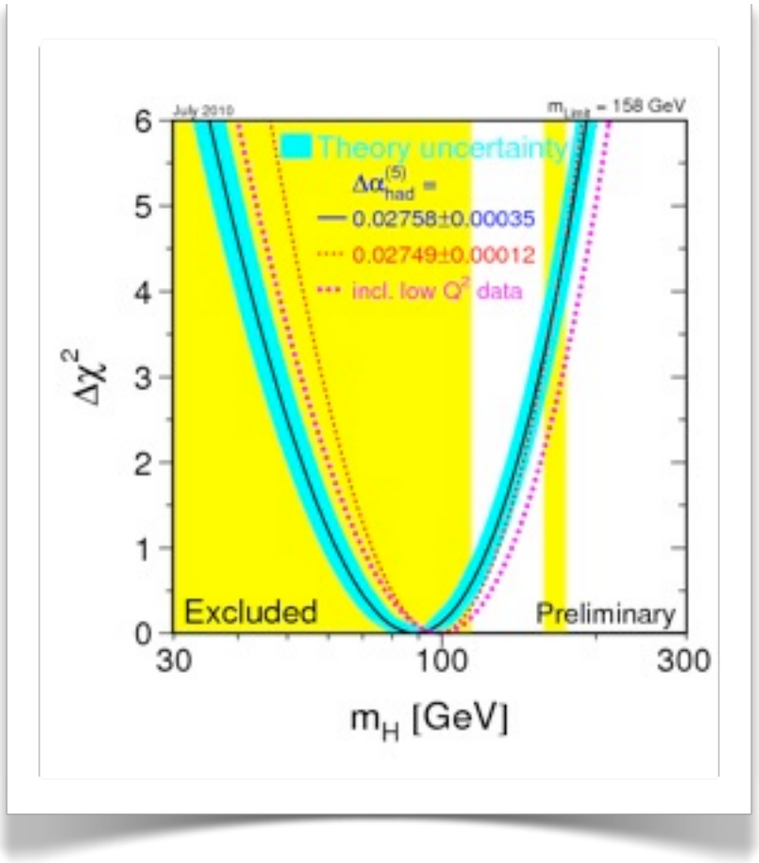
- Signatures depend on how HS states decay: to further HS states, back to SM
- May be: NMSSM-like, semi-invisible, high multiplicity, displaced, ...

Exotic Decays of the 125 GeV Higgs Boson, arXiv:1312.4992

D. Curtin, R. Essig, S. Gori, P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen, JS, M. Strassler, Z. Surujon, B. Tweedie, Y-M. Zhong

Theories for Exotic Higgs Decays

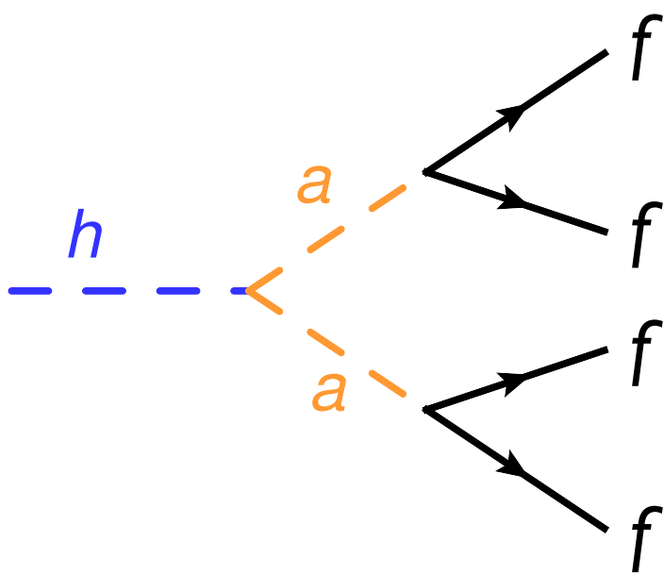
- Long-standing body of work on exotic Higgs decays, much driven by precision EW preference for a Higgs below the LEP bound



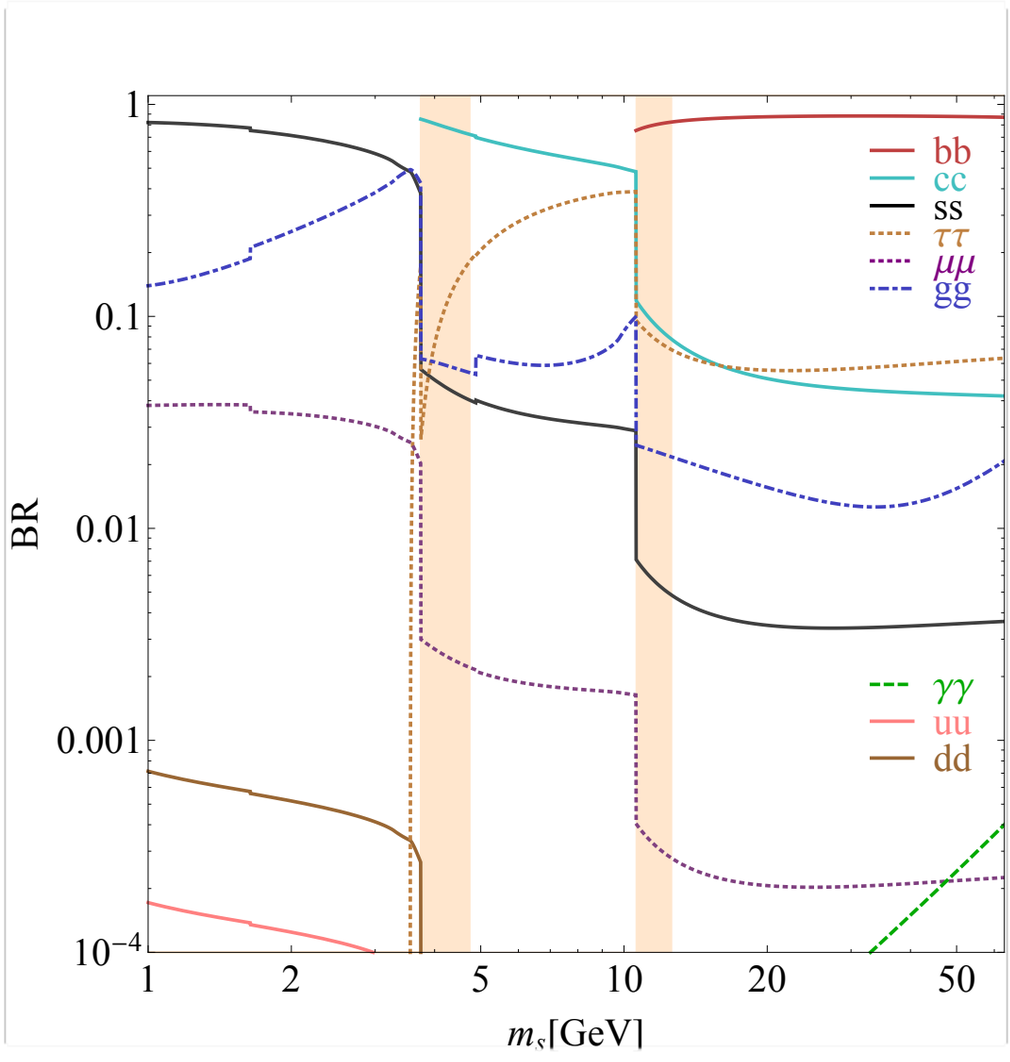
- Many examples fall out naturally from extended Higgs sectors: NMSSM, EW baryogenesis, ...
- Others come from DM model building
- Genericity of Higgs portal: what are light degrees of freedom?

Theories for Exotic Higgs Decays

1. Higgs decay to scalars



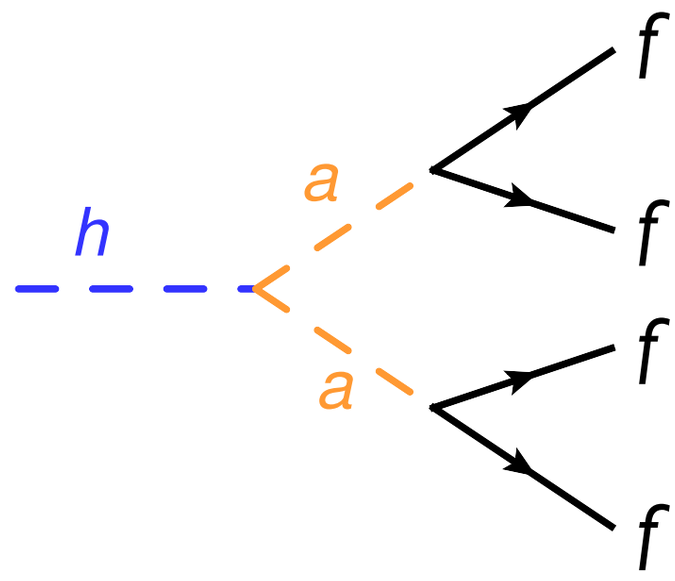
$$\Delta\mathcal{L} = V(a) + \frac{\lambda}{4}a^2|H|^2$$



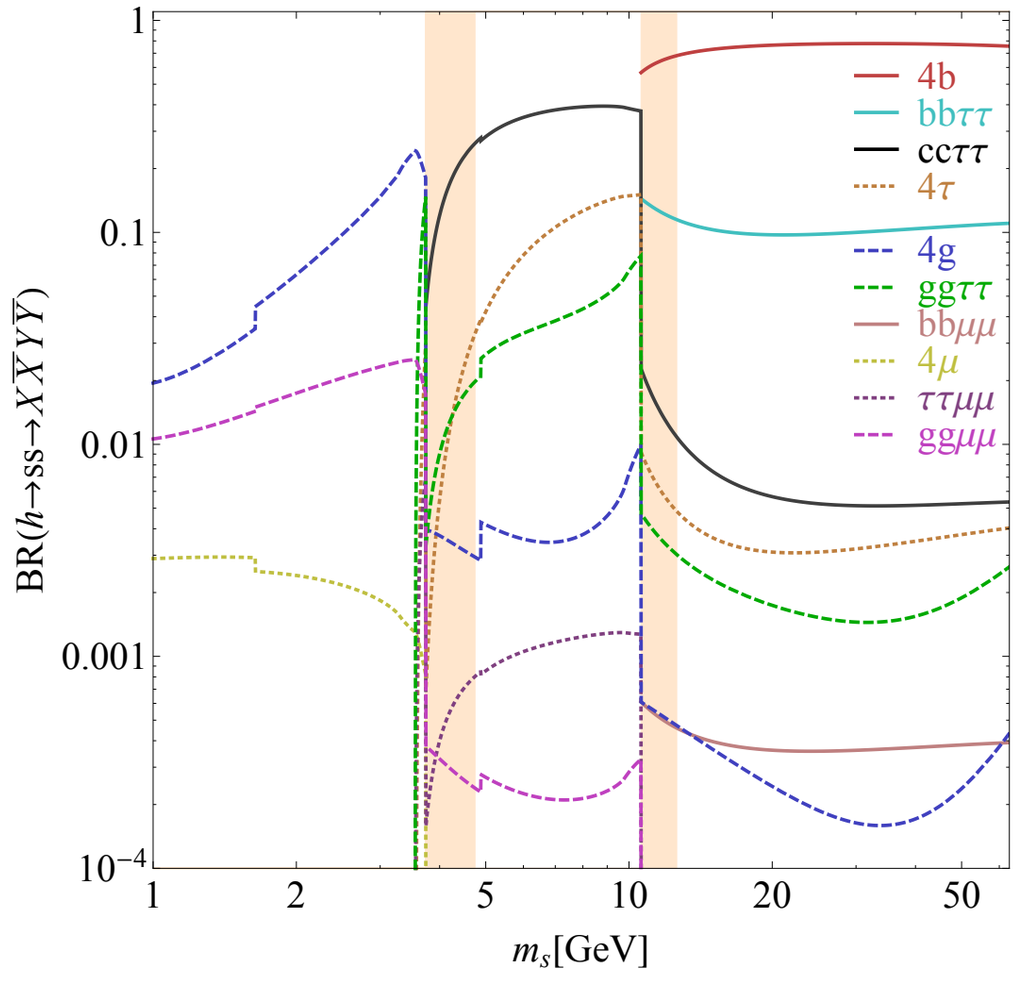
Singlet Br: SM Yukawas

Theories for Exotic Higgs Decays

1. Higgs decay to scalars



$$\Delta\mathcal{L} = V(a) + \frac{\lambda}{4}a^2|H|^2$$



Singlet *pair* Br: SM Yukawas

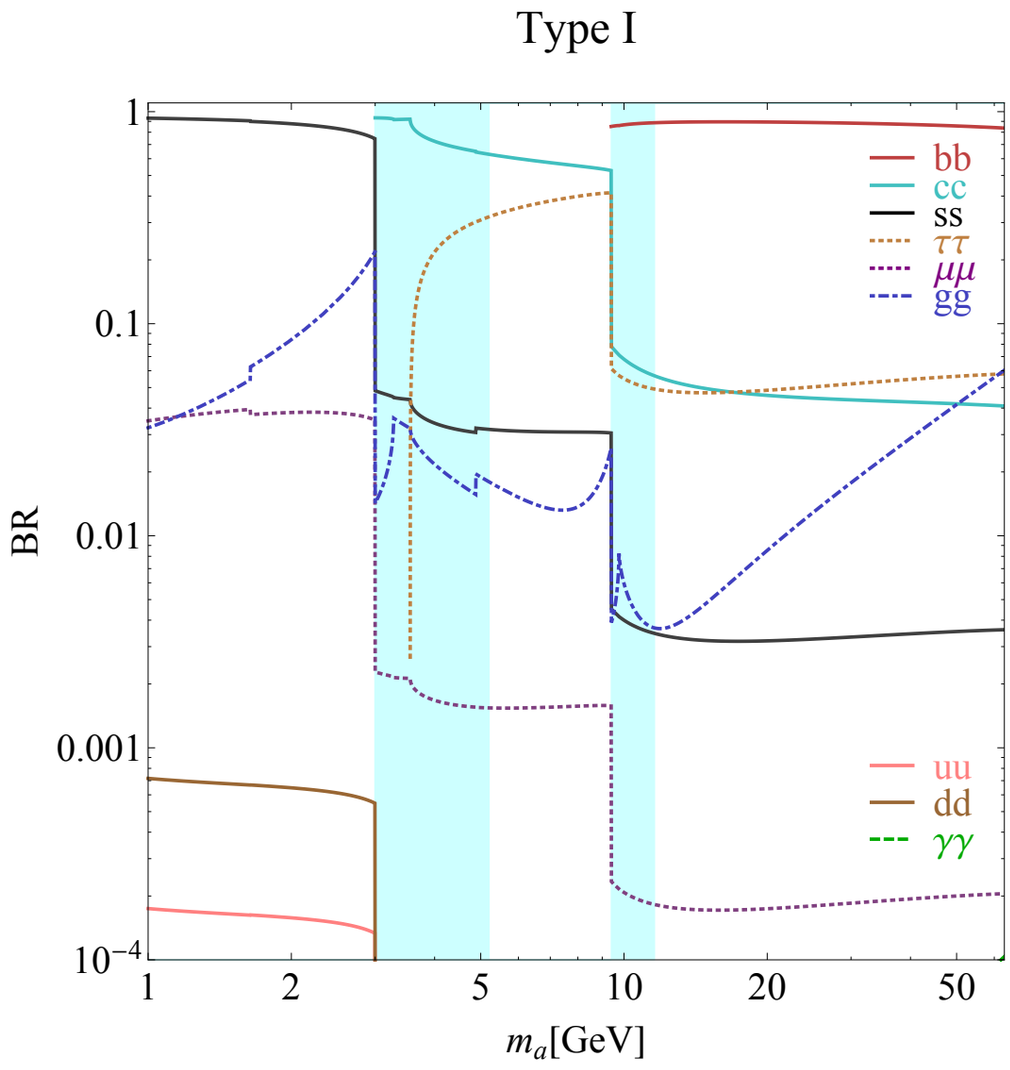
Theories for Exotic Higgs Decays

1. Higgs decay to scalars

Extended Higgs sectors alter Yukawas:

consider 2HDM + complex singlet S

Type 1: SM



Singlet pseudoscalar Br: SM Yukawas

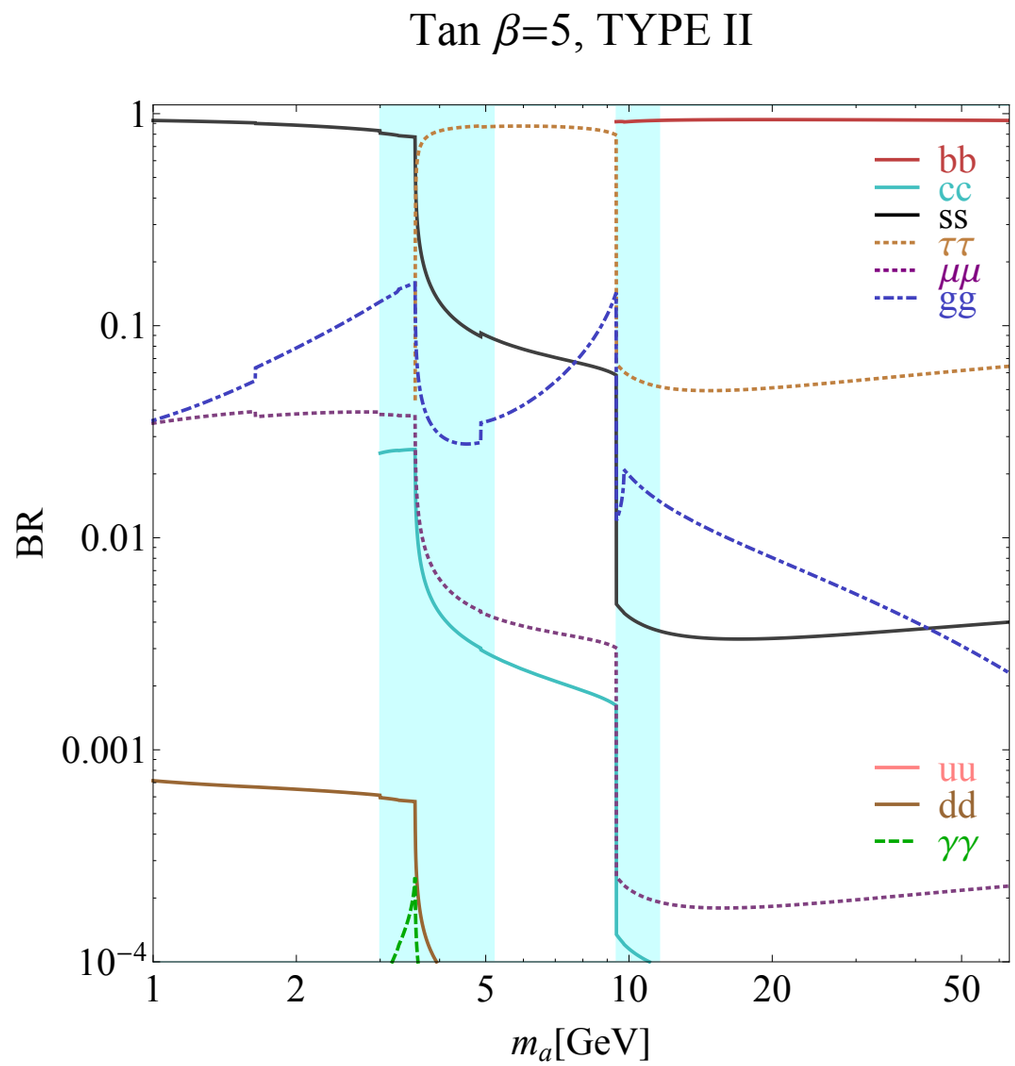
Theories for Exotic Higgs Decays

1. Higgs decay to scalars

Extended Higgs sectors alter Yukawas:

consider 2HDM + complex singlet *S*

Type 1: SM
Type II: NMSSM-like



Singlet pseudoscalar Br: Type II Yukawas

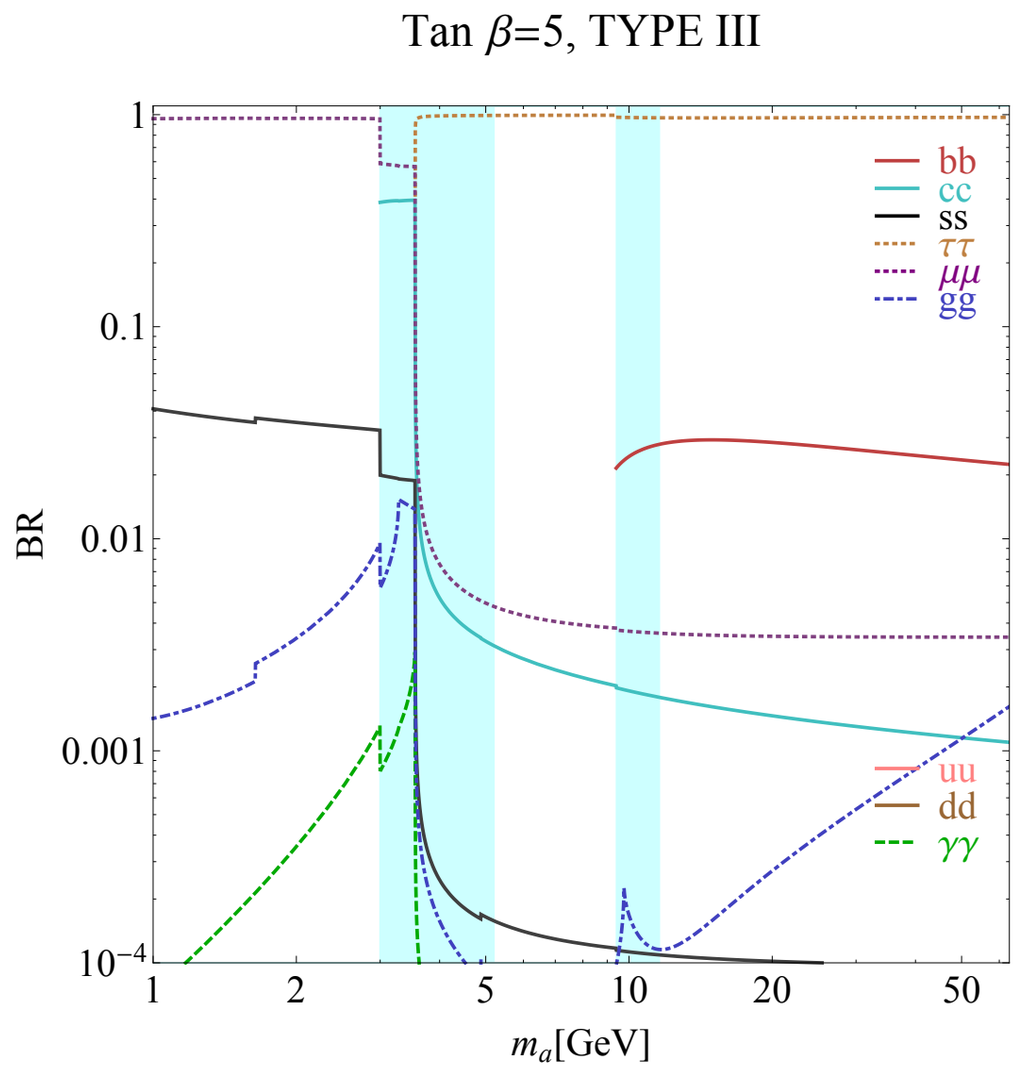
Theories for Exotic Higgs Decays

1. Higgs decay to scalars

Extended Higgs sectors
alter Yukawas:

consider 2HDM +
complex singlet *S*

Type 1: SM
Type II: NMSSM-like
Type III: lepton-specific



Singlet pseudoscalar Br: Type III Yukawas

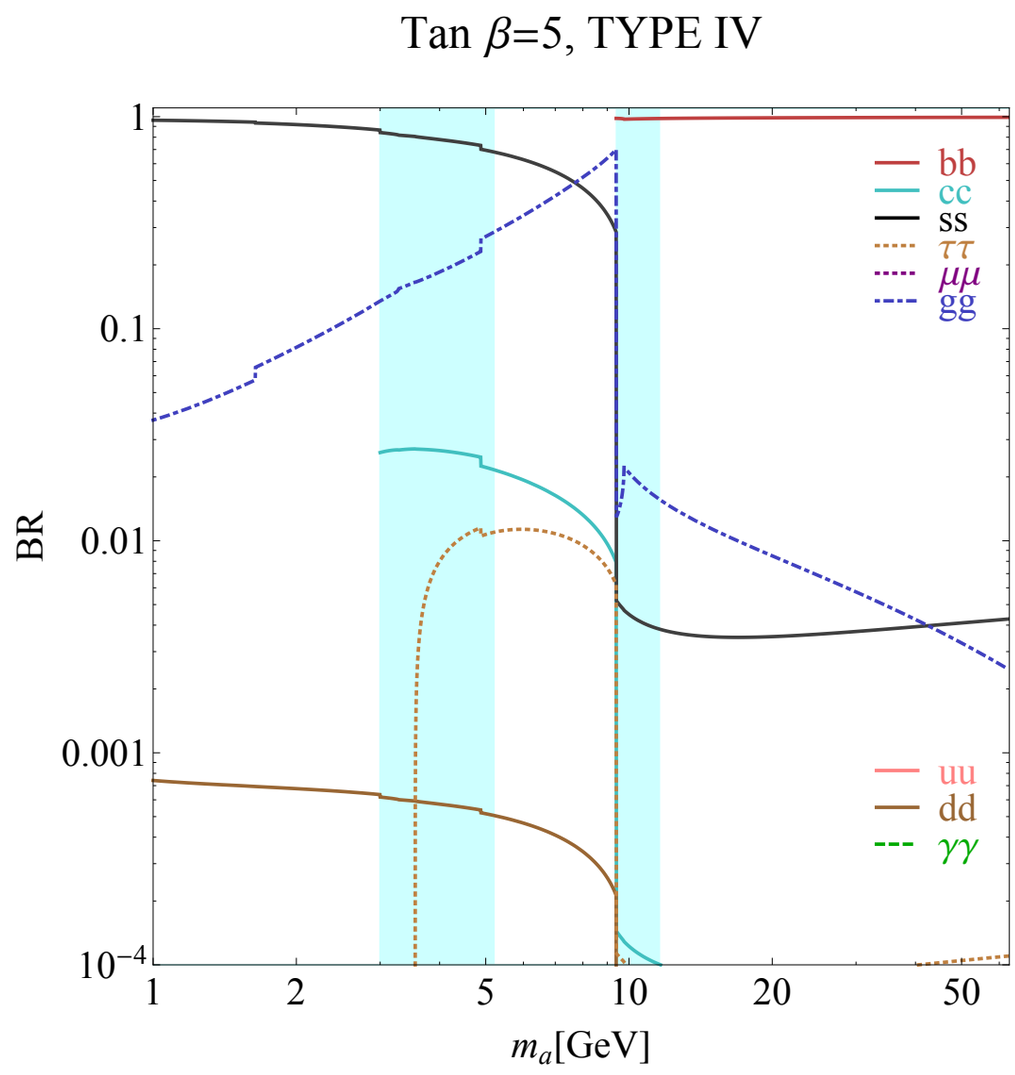
Theories for Exotic Higgs Decays

1. Higgs decay to scalars

Extended Higgs sectors alter Yukawas:

consider 2HDM + complex singlet *S*

Type 1: SM
Type II: NMSSM-like
Type III: lepton-specific
Type IV: flipped



Singlet pseudoscalar Br: Type IV Yukawas

Theories for Exotic Higgs Decays

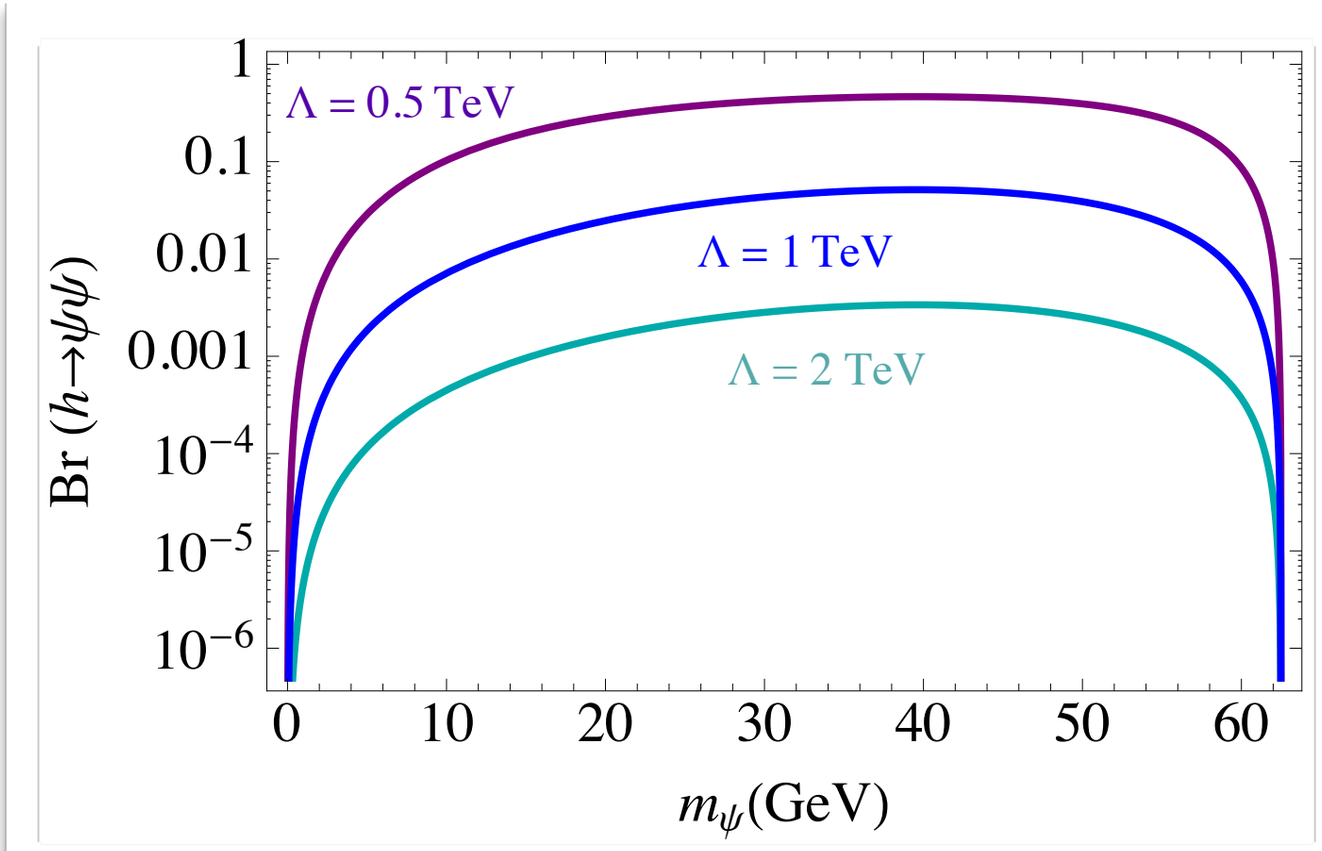
2. Higgs decay to fermions

Lepton number violation

$$\Delta\mathcal{L} = \lambda\chi HL$$

Nonrenormalizable

$$\Delta\mathcal{L} = \frac{1}{M}\chi^\dagger\chi|H|^2$$

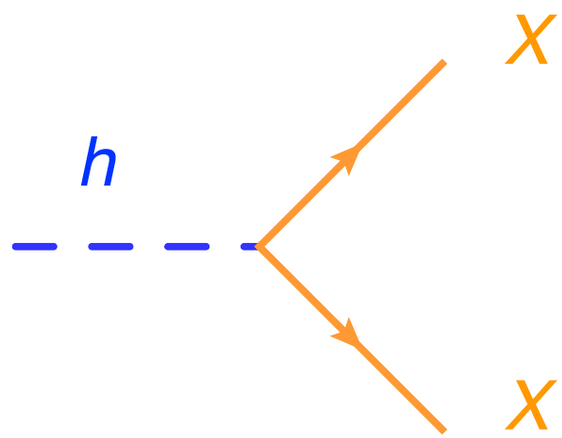


Chiral symmetry:
can be effective dim-6

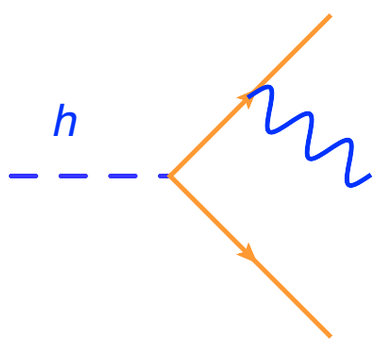
Theories for Exotic Higgs Decays

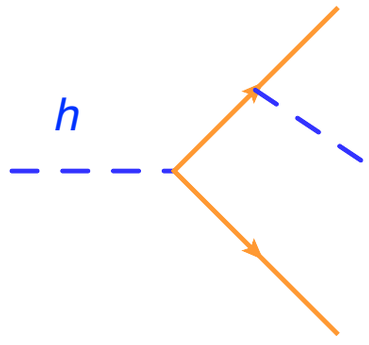
2. Higgs decay to fermions

Signatures depend on further fermion couplings: parameters largely independent of Higgs couplings

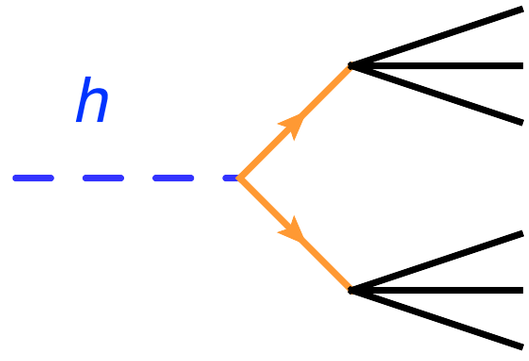


invisible: DM, SUSY





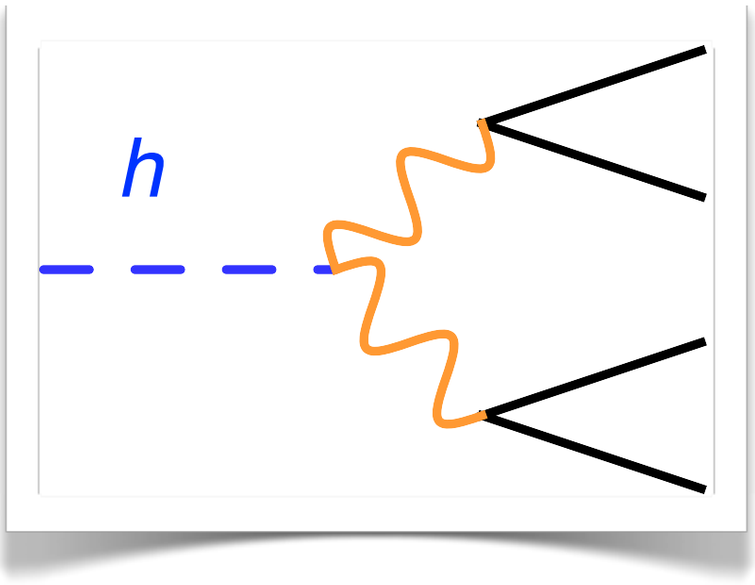
light bosonic dofs?



flavored 3-body decays

Theories for Exotic Higgs Decays

3. Higgs decay to vectors

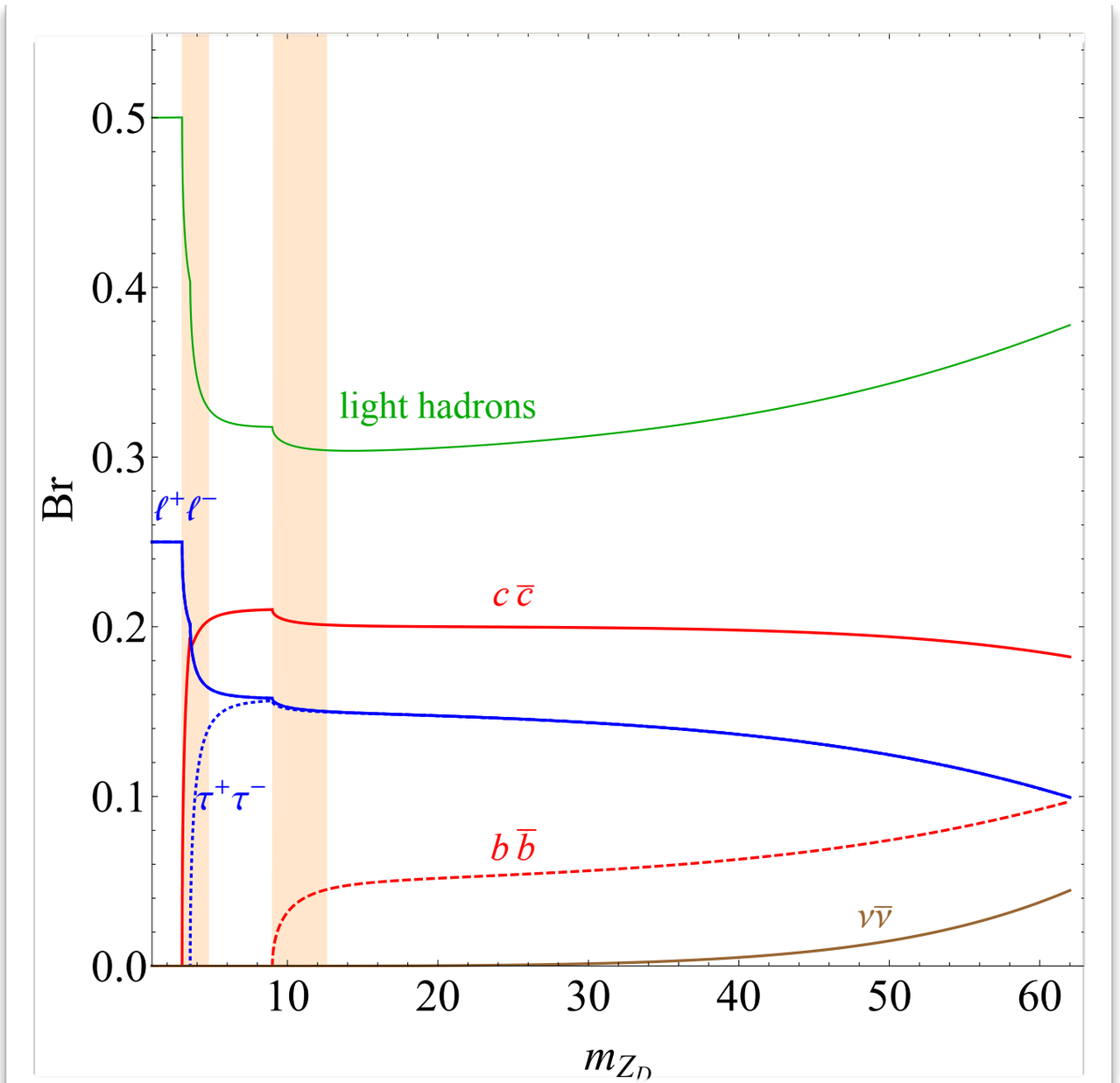


$$\Delta\mathcal{L} = V(S) + \frac{\kappa}{4} S^2 |H|^2$$
$$+\epsilon B_{\mu\nu} V^{\mu\nu}$$

- Photon and Higgs portal couplings with independent strengths
- Higgs mixing: $h \to V_D V_D$, $h \to aa$
- Kinetic mixing: $h \to V_D Z$

Theories for Exotic Higgs Decays

3. Higgs decay to vectors



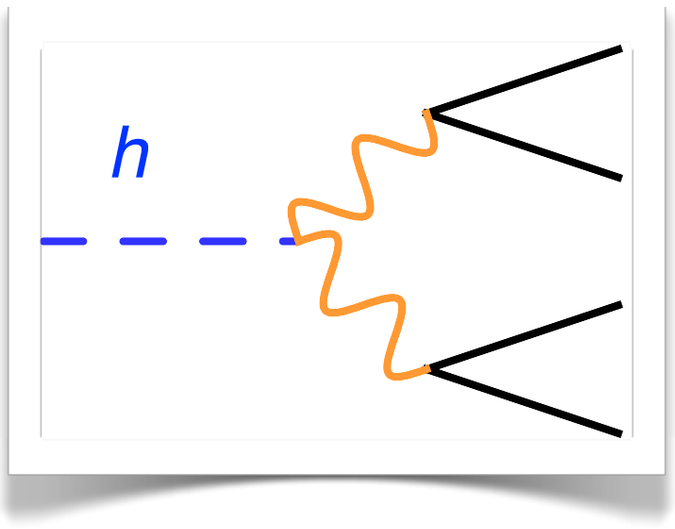
Relatively leptophilic!

Direct searches for exotic Higgs decays

- Each final state requires its own strategy.
- General observations:
  - Leptonic resonances especially powerful
  - Recast LHC8 analyses already place interesting limits on final states with multiple electroweak objects
  - ...but results depend very sensitively on acceptance thresholds
  - gluon fusion: powerful but limited
- A range of possibilities from spectacular to very hard

Direct searches for exotic Higgs decays

Example 1: $h \to V_D V_D \to 4\ell$



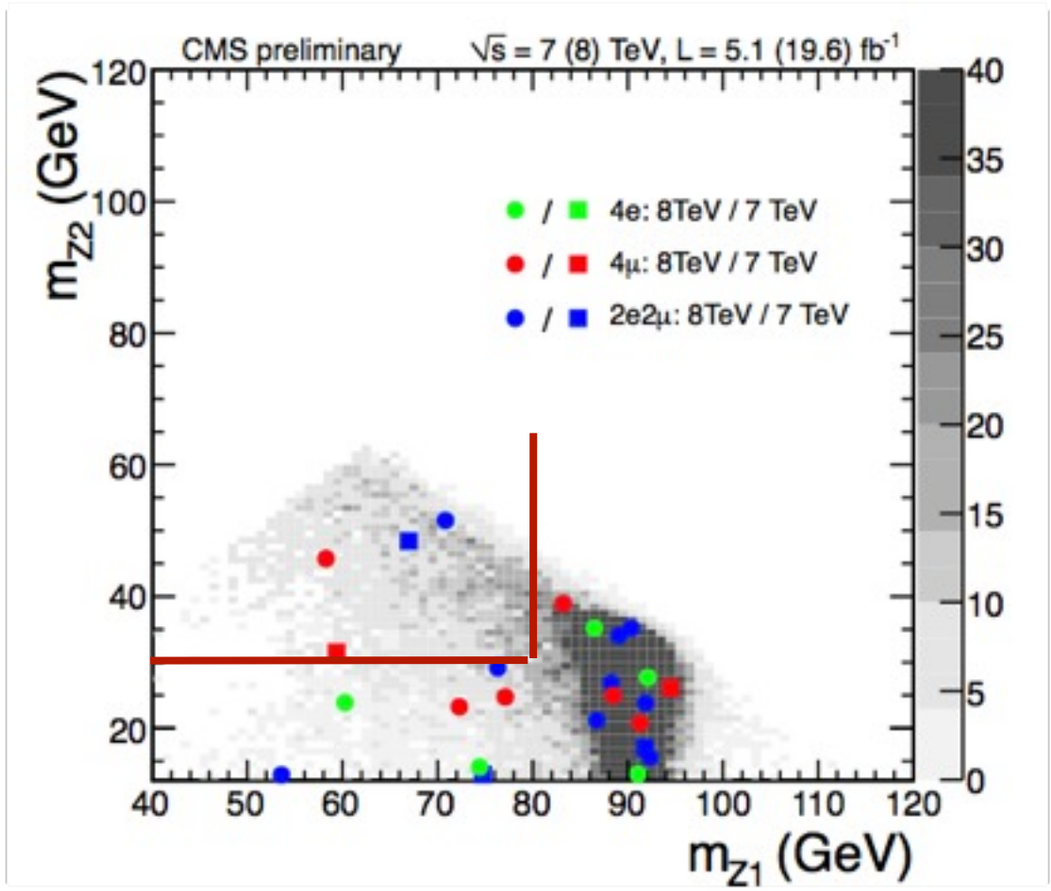
Resonant 4-lepton signal: spectacular

...just need to look for it!

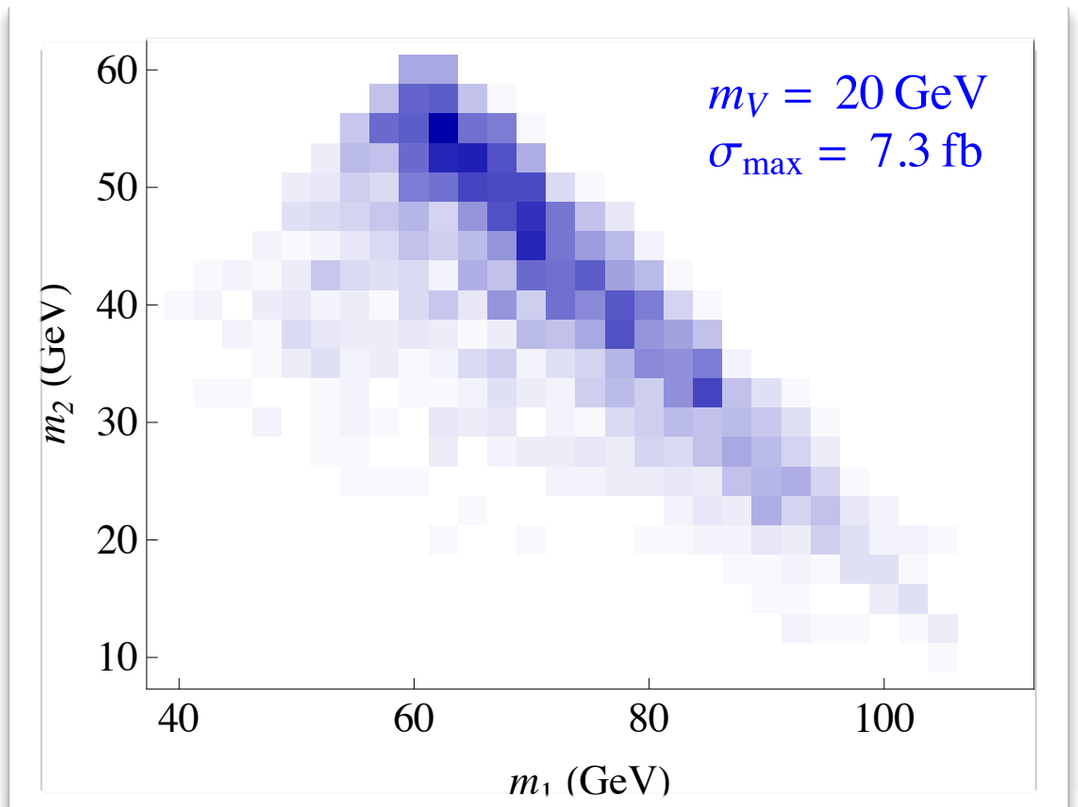
- NMSSM-motivated 4-muon searches stop at 5 GeV
- Scrape data from Higgs searches, ZZ calibration regions

Direct searches for exotic Higgs decays

Example 1: $h \to V_D V_D \to 4\ell$



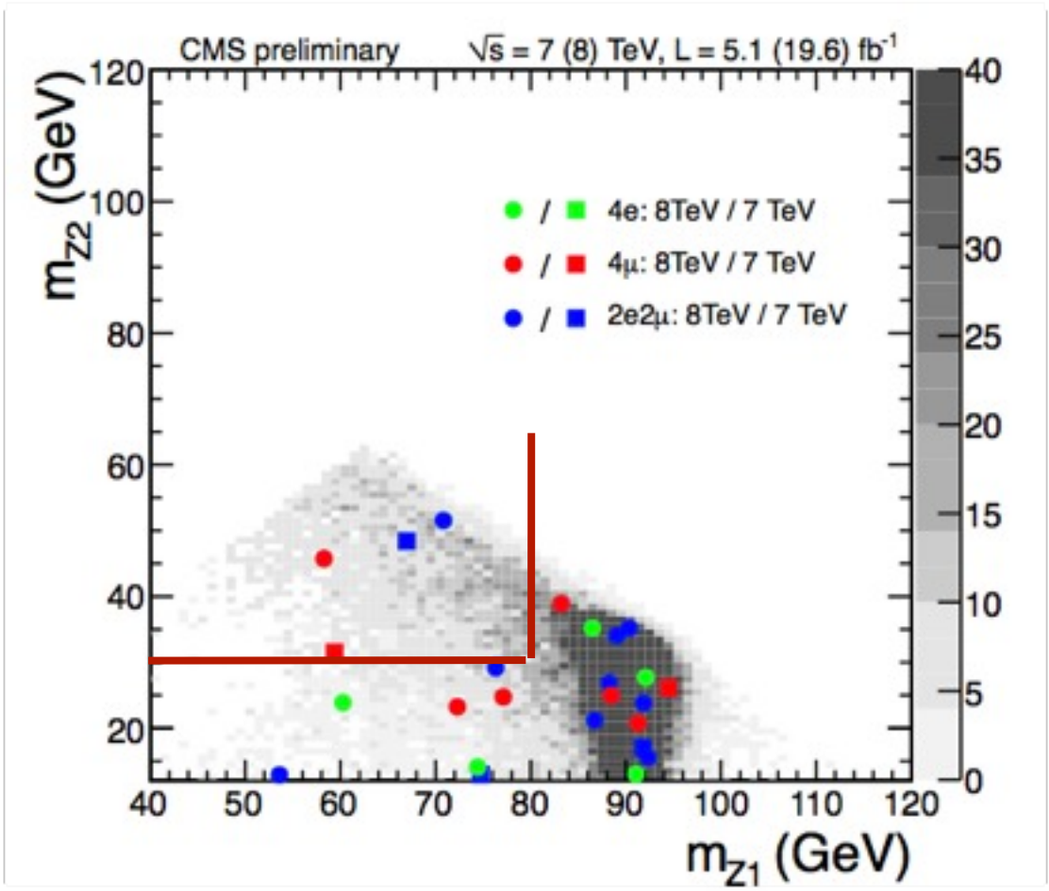
CMS data, SM background: ZZ*



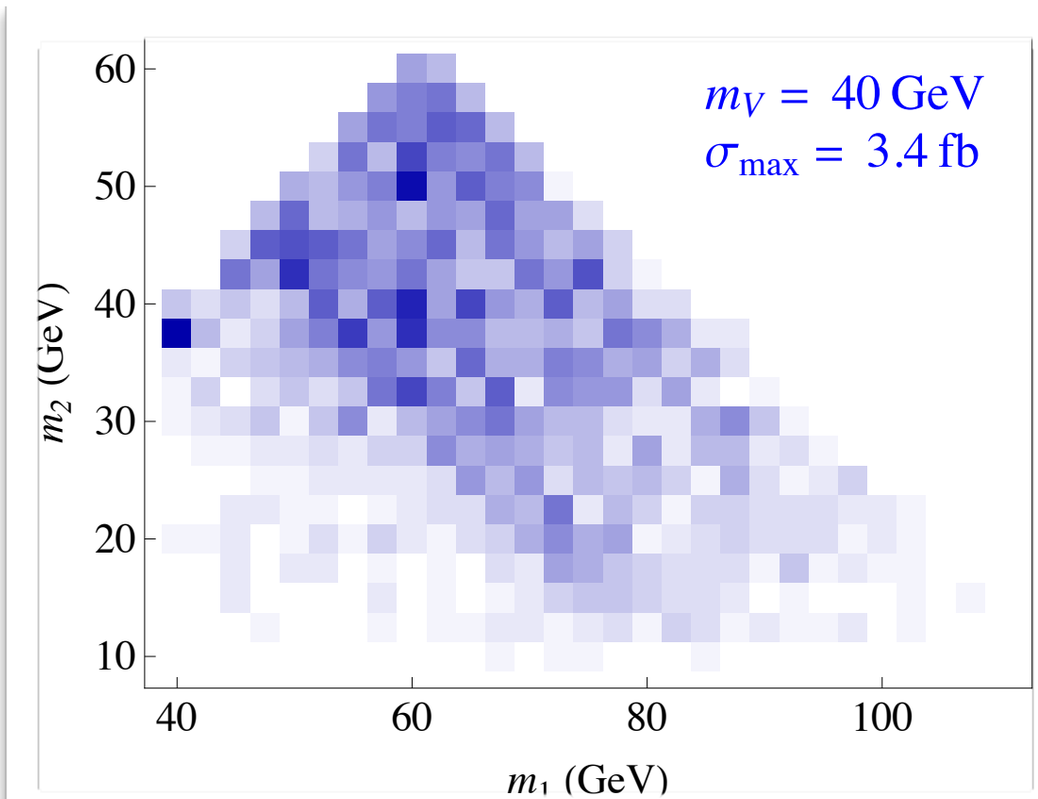
Exotic contribution

Direct searches for exotic Higgs decays

Example 1: $h \to V_D V_D \to 4\ell$



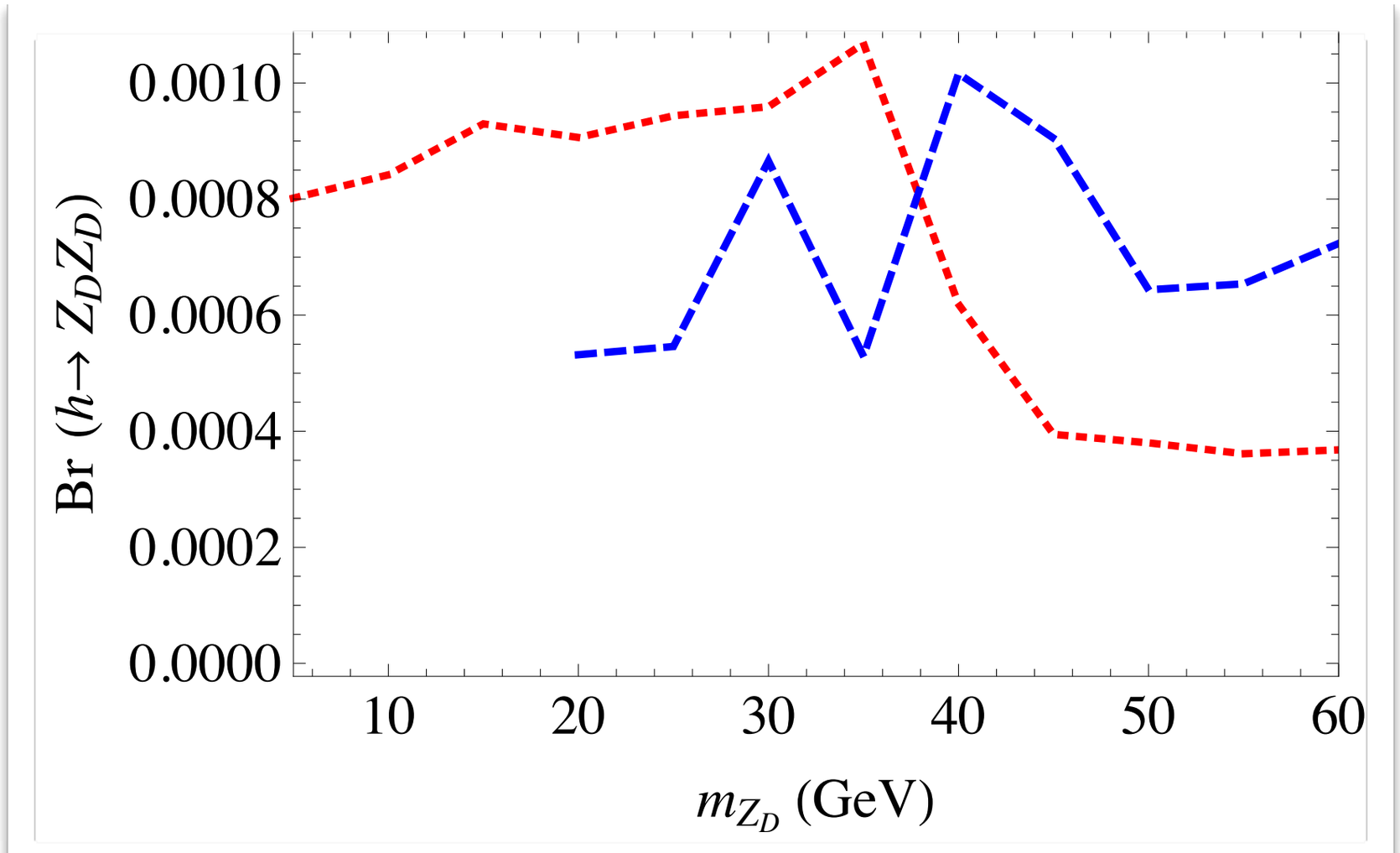
CMS data, SM background: ZZ*



Exotic contribution

Direct searches for exotic Higgs decays

Example 1: $h \to V_D V_D \to 4\ell$



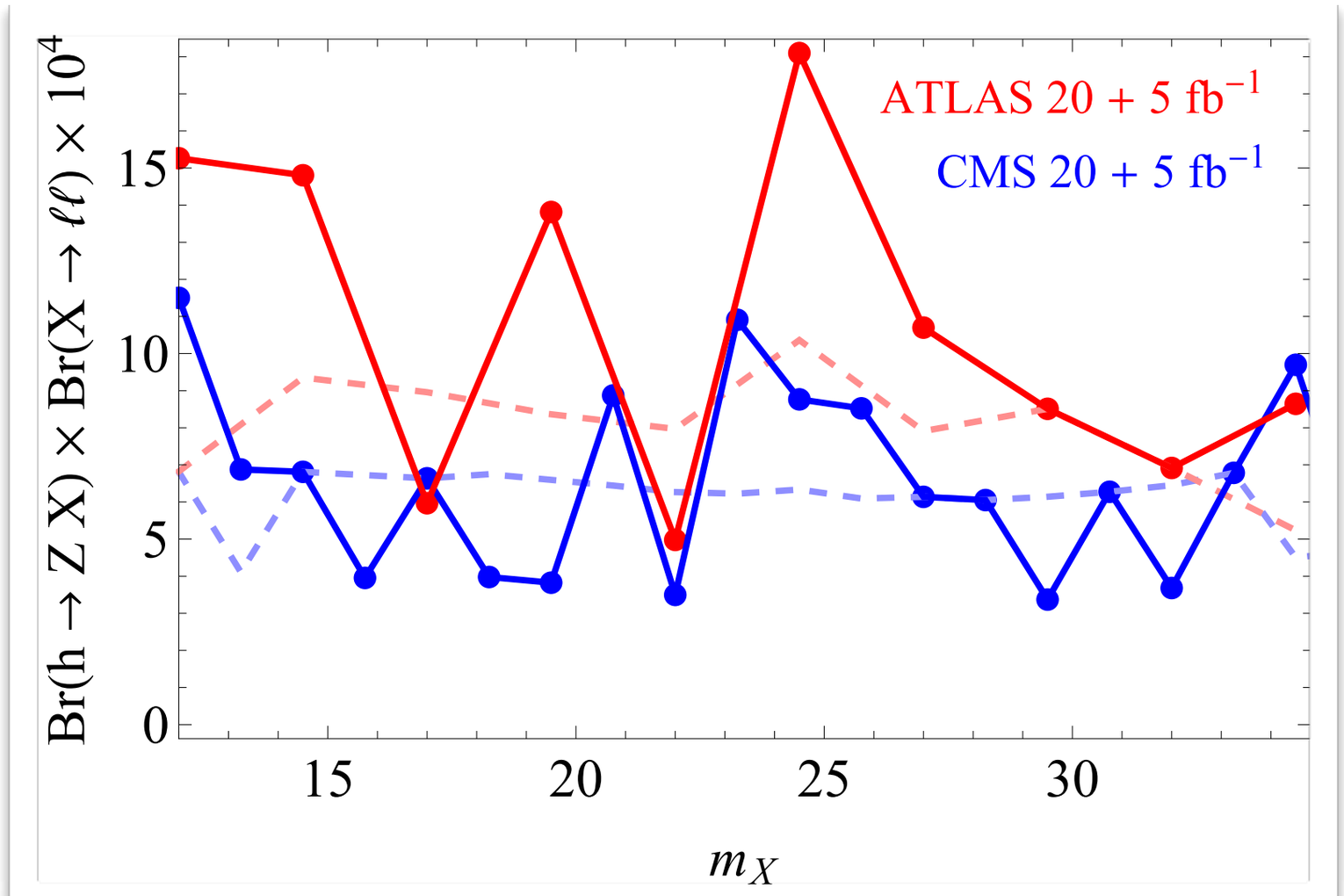
ATLAS ZZ control region

CMS Higgs

95% CL limits

Direct searches for exotic Higgs decays

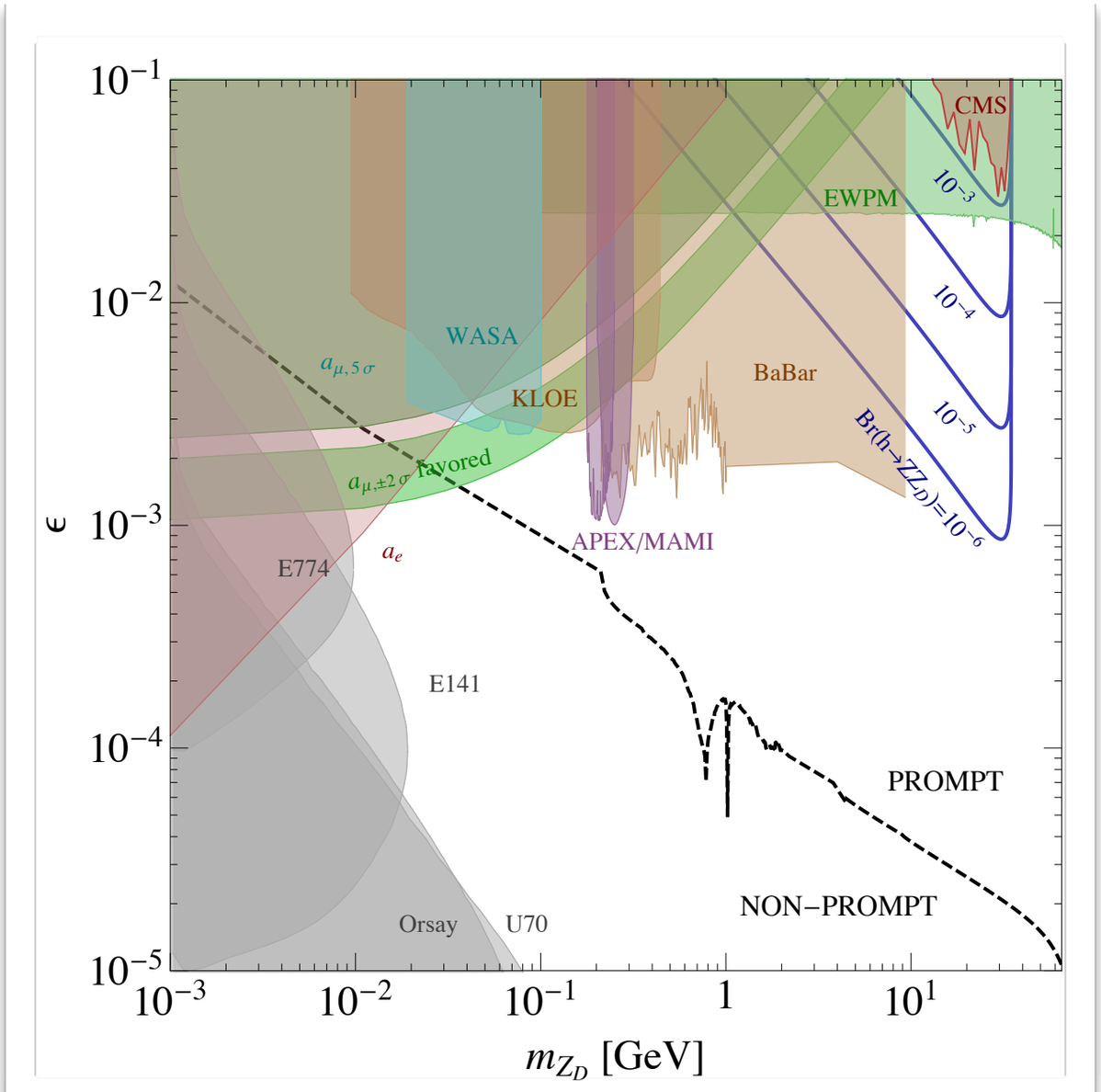
Example 1A: $h \to Z V_D \to 4\ell$



95% CL limits

Direct searches for exotic Higgs decays

Example 1A: $h \to Z V_D \to 4\ell$

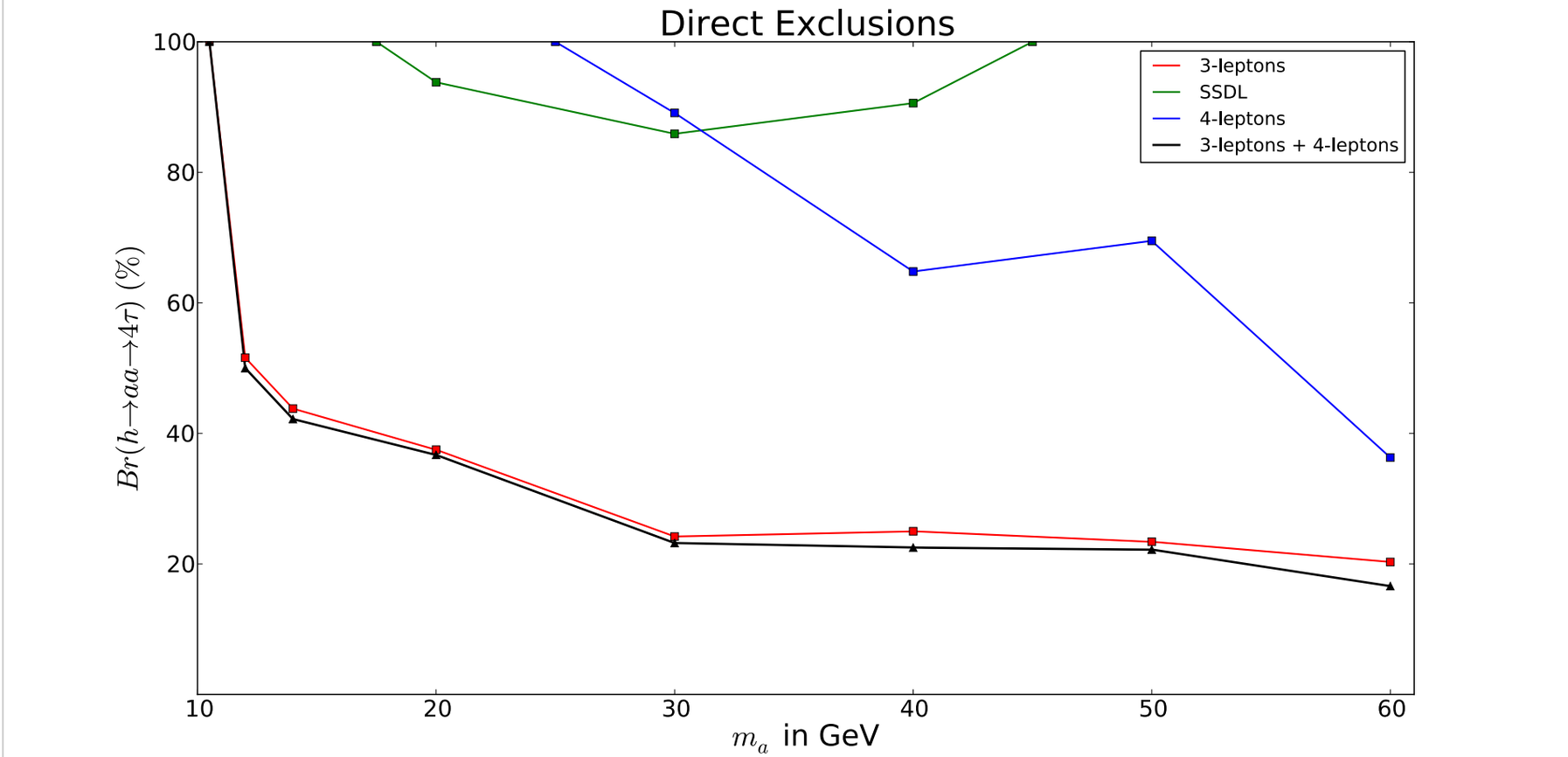


Further possibilities:

- $h \to ss \to 4Z_D$
- $h \to Z_D Z_D \to$ exotic
- more complicated HS cascades...

Direct searches for exotic Higgs decays

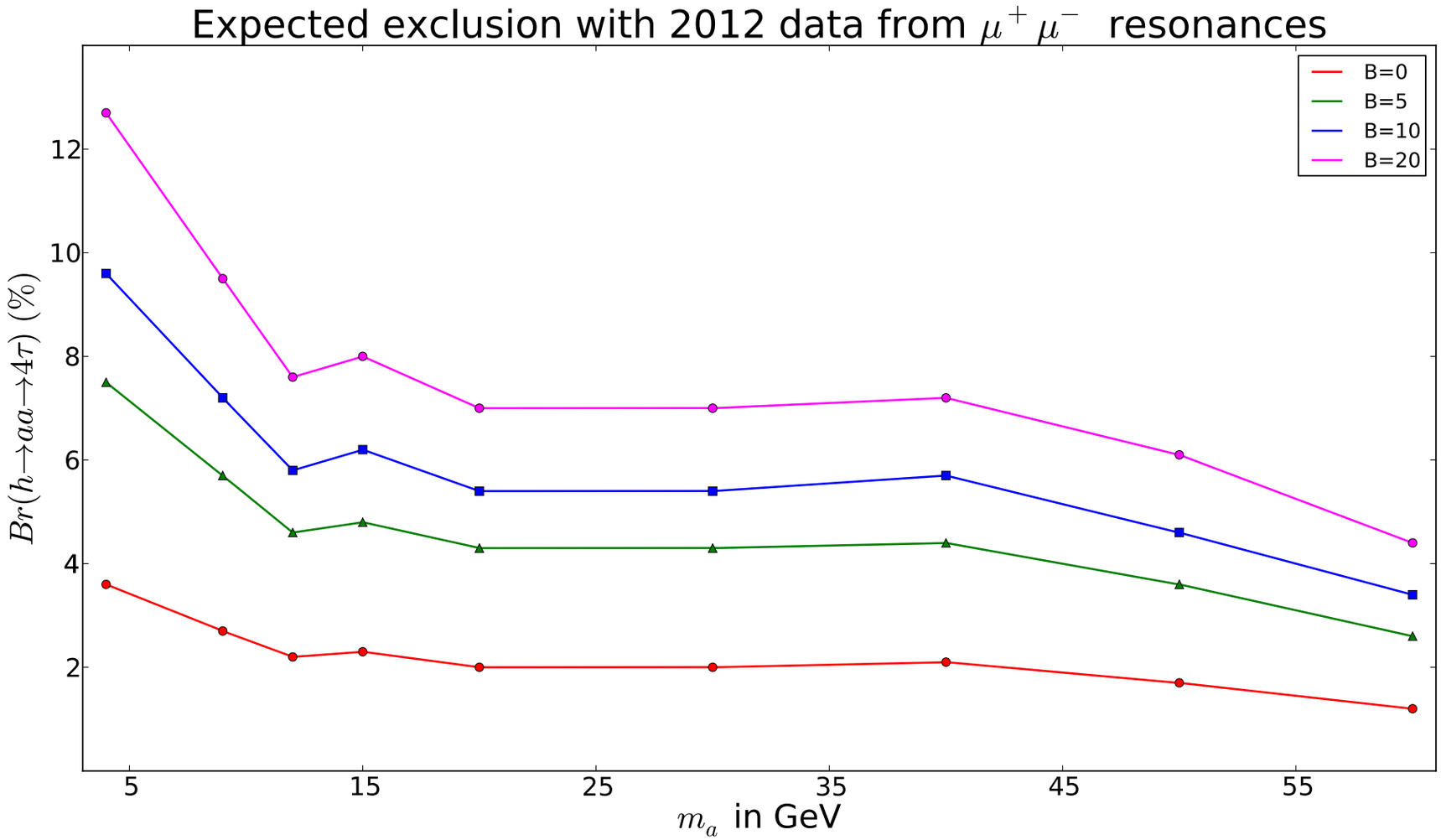
Example 2: $h \to aa \to 4\tau,\ 2\tau 2\mu$



Exclusions from multilepton searches

Direct searches for exotic Higgs decays

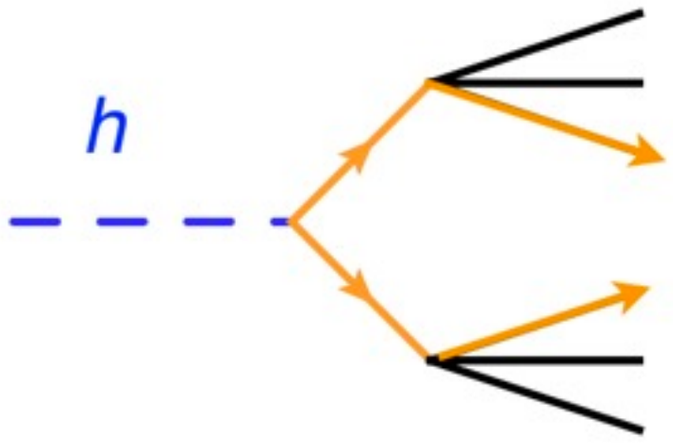
Example 2: $h \to aa \to 4\tau,\ 2\tau 2\mu$



Gain from sharp resonance in muons, despite lower *BR* [Lisanti & Wacker]

Direct searches for exotic Higgs decays

Example 2A: $h \to \chi_2\chi_2 \to 4\ell +$ *MET*



RPV neutralinos
off-shell Z or HV meson decay

Best existing limits from inclusive many-bin CMS multi-lepton searches:

$$Br(h \to \chi_2\chi_2) < 12\%$$

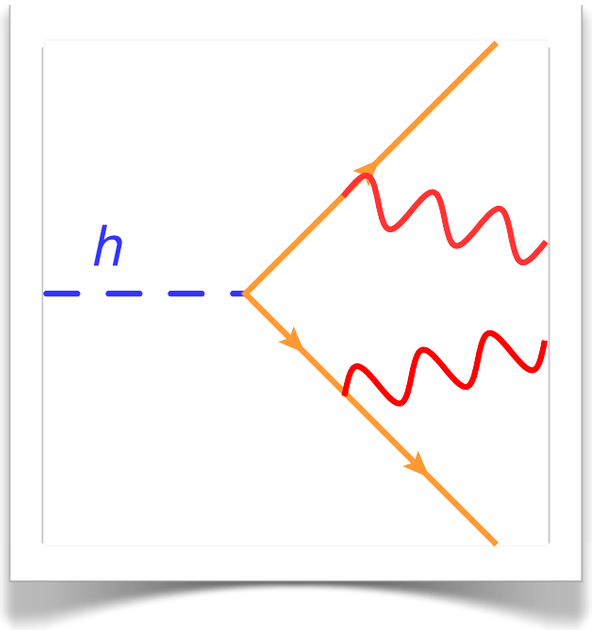
(SUS-12-027, SUS-13-010)
(includes Z Br and is highly spectrum-dependent)

- Most multi-lepton analyses specialized for high-p_T signals
- Can further target analyses to Higgs kinematics

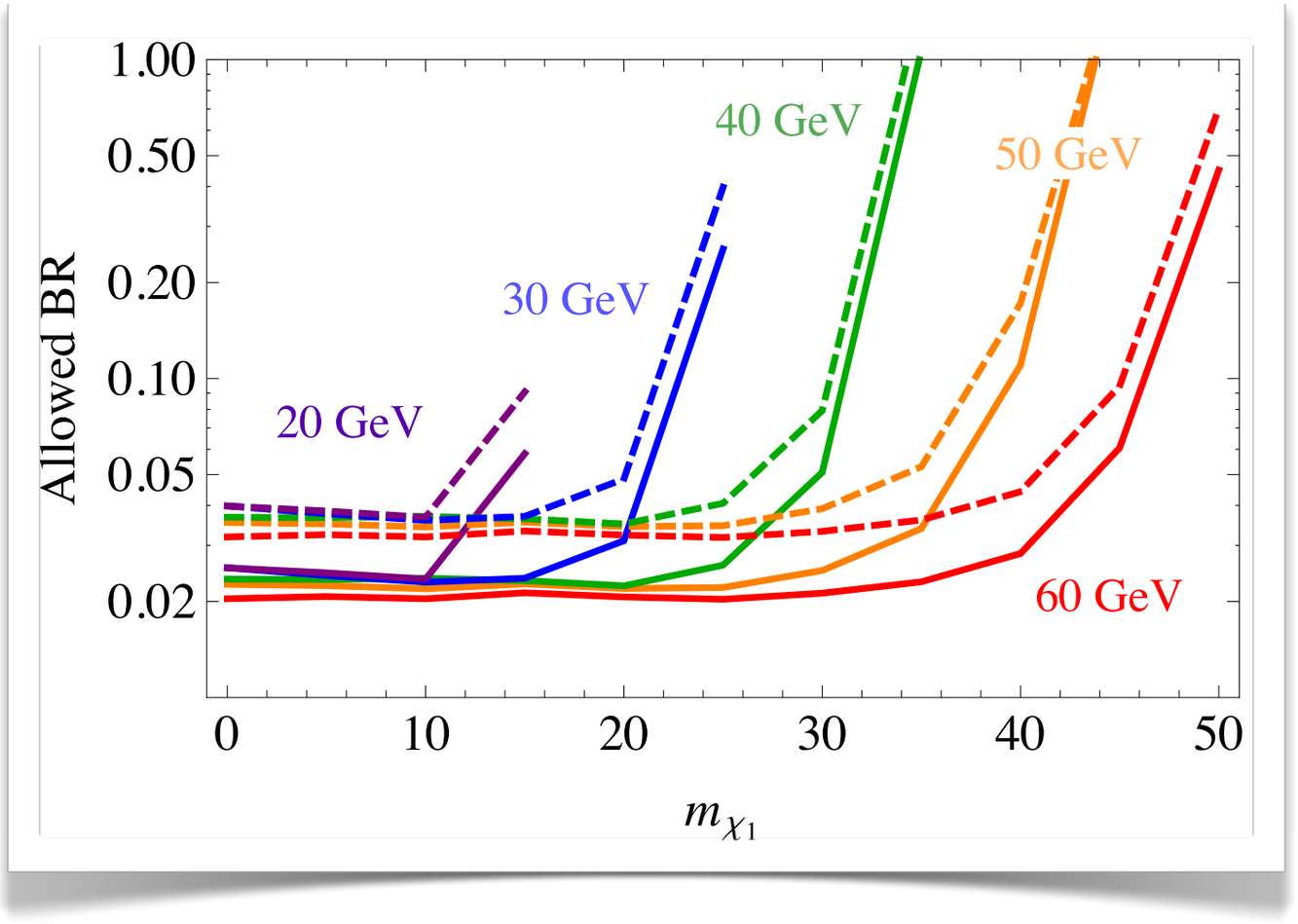
Direct searches for exotic Higgs decays

Example 2B: $h \to \chi_2\chi_2 \to 2\gamma + MET$

GMSB neutralinos
extended DM sector with dipole



Estimated 95% CL limits on allowed Br



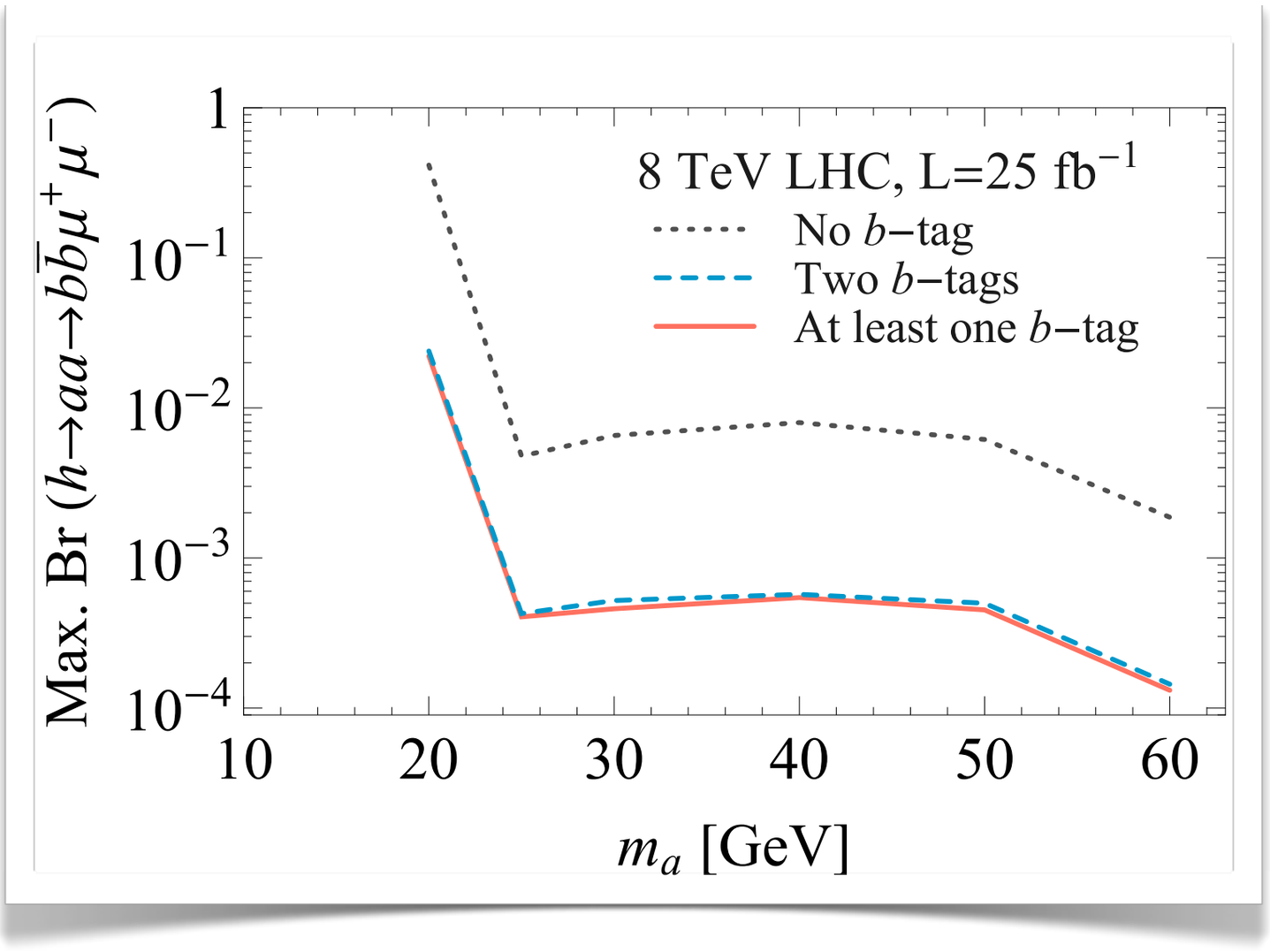
Best limits: GMSB search (CMS SUS-12-018)

- 4 ifb, not optimized for Higgs signal

Direct searches for exotic Higgs decays

Example 3: $h \to ss \to 2b2\mu$

$$\frac{2m_\mu^2}{3m_b^2} = 4 \times 10^{-4}$$



Estimated 95% CL reach

Direct searches for exotic Higgs decays

LHC prospects for $h \to ss, aa$

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^R $[0.2^L]$	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}	$0.7-1$ $[0.2-0.7]$	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]

Direct searches for exotic Higgs decays

LHC prospects for $h \to ss, aa$

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
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$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.7-1$ $[0.2-0.7]$	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]

Direct searches for exotic Higgs decays

LHC prospects for $h \to ss, aa$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	quarks allowed		quarks suppressed	
			$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br}(\text{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br}(\text{non-SM})$ 7+8 [14] TeV	$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br}(\text{non-SM})}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{Br}(\text{non-SM})$ 7+8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^R $[0.2^L]$	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}	$0.7-1$ $[0.2-0.7]$	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]

Summary and Conclusions

- The observed 125 GeV Higgs boson is highly sensitive to the potential existence of new light degrees of freedom
- Many interesting results/prospects at LHC8 already
  - Light (pseudo-)scalars: still difficult
- Great statistical power from LHC 14: Higgs factory
  - but reduced acceptance for low-p_T objects may limit reach
- Important to remember for LHC 14: many physics opportunities at low p_T