EXOTIC HIGGS DECAYS

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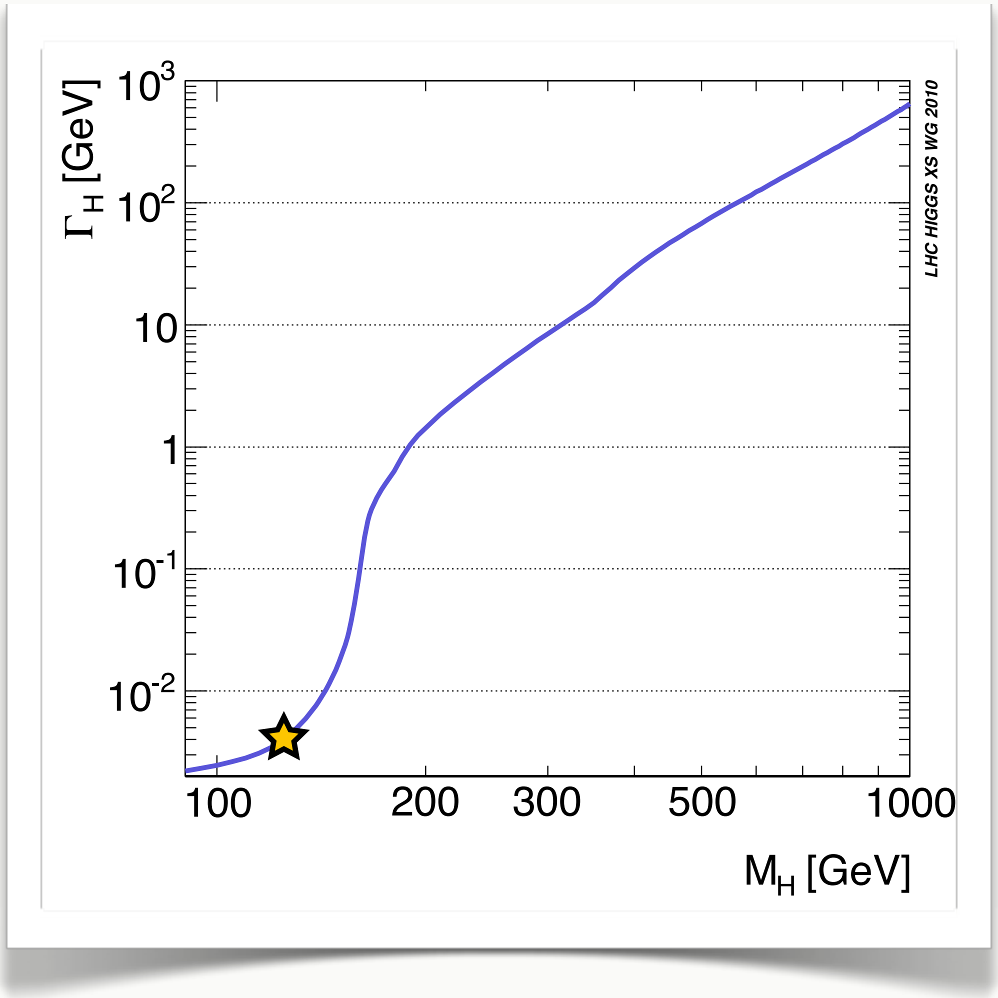
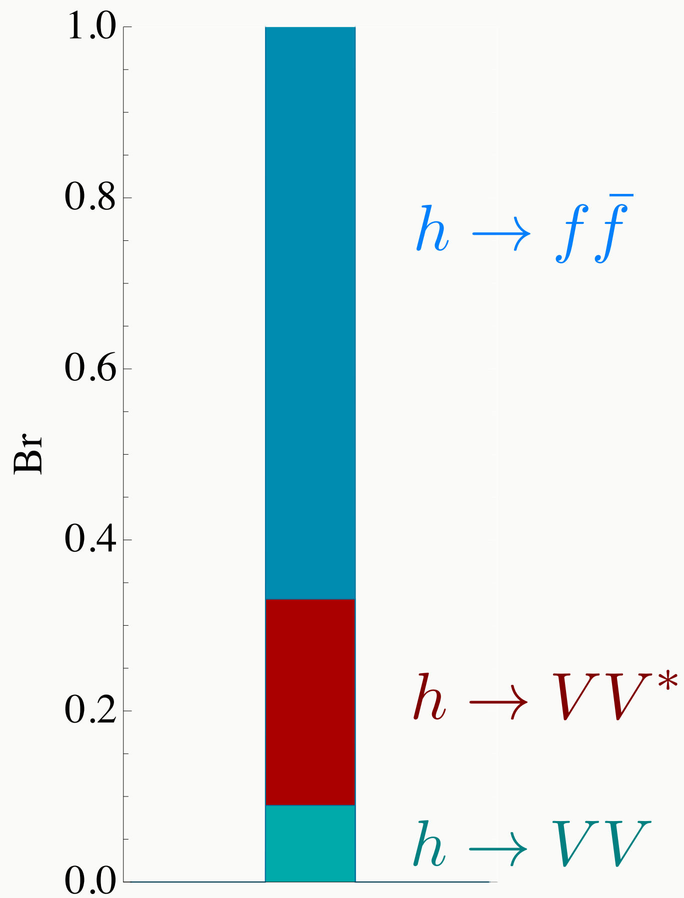
BSM Higgs @ LHC workshop, Fermilab

November 5, 2014

The SM-like Higgs boson

- A light SM-like Higgs is narrow:

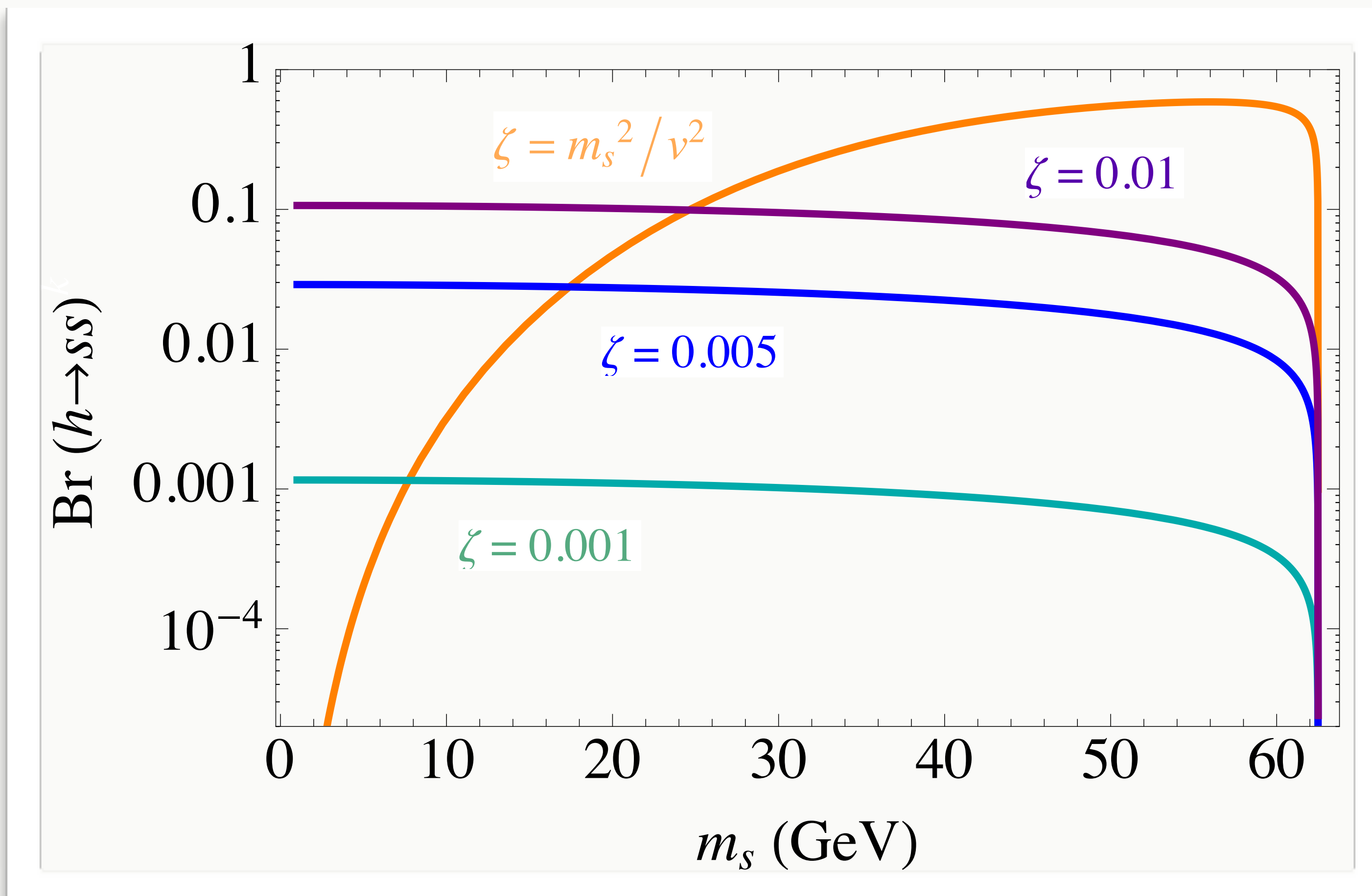




$$\Gamma_h(125\ \text{GeV}) = 4.1\ \text{MeV}$$

Exotic decays of the SM-like Higgs

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



Simple example: one new scalar

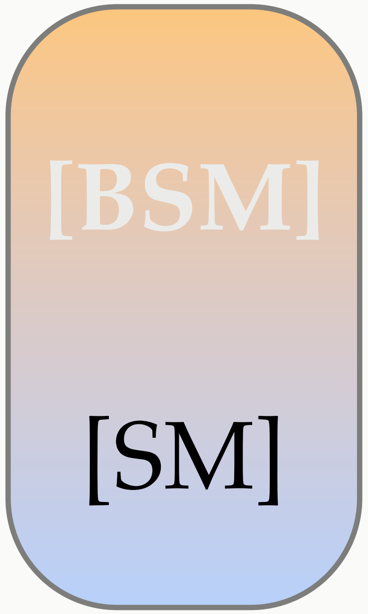
$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

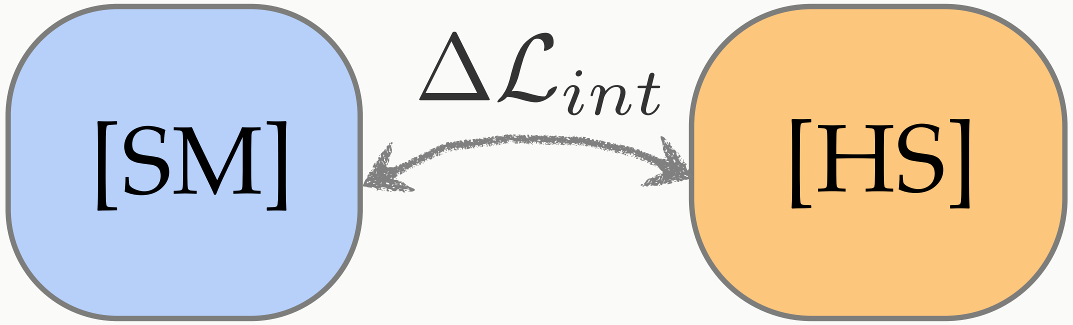
Why exotic Higgs decays?

- Motivations for new physics at the weak scale:
  - co-responsible for electroweak symmetry breaking
  - stabilize weak scale
  - dark matter
  - …why not?

Why exotic Higgs decays?

- The same motivations apply horizontally as well as vertically





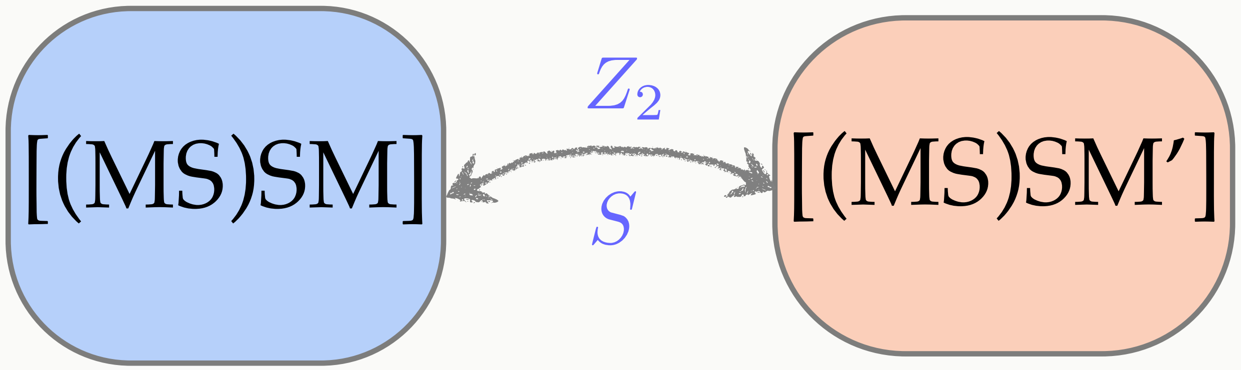
- Hidden sector signatures: driven by size and structure of leading interactions
  - portals: $|H|^2$, $B_{\mu\nu}$, HL_L $\ldots$

Why exotic Higgs decays?

- Extended Higgs sectors: SM + s, MSSM + S
  - simplest realization of Higgs portal coupling: $|S|^2|H|^2$
  - NMSSM: dynamically generate μ, relax phenomenological constraints on $V(H)$, neutralino dark matter
  - electroweak baryogenesis: first-order phase transition

Why exotic Higgs decays?

- Naturalness
  - Twin Higgs and related models:

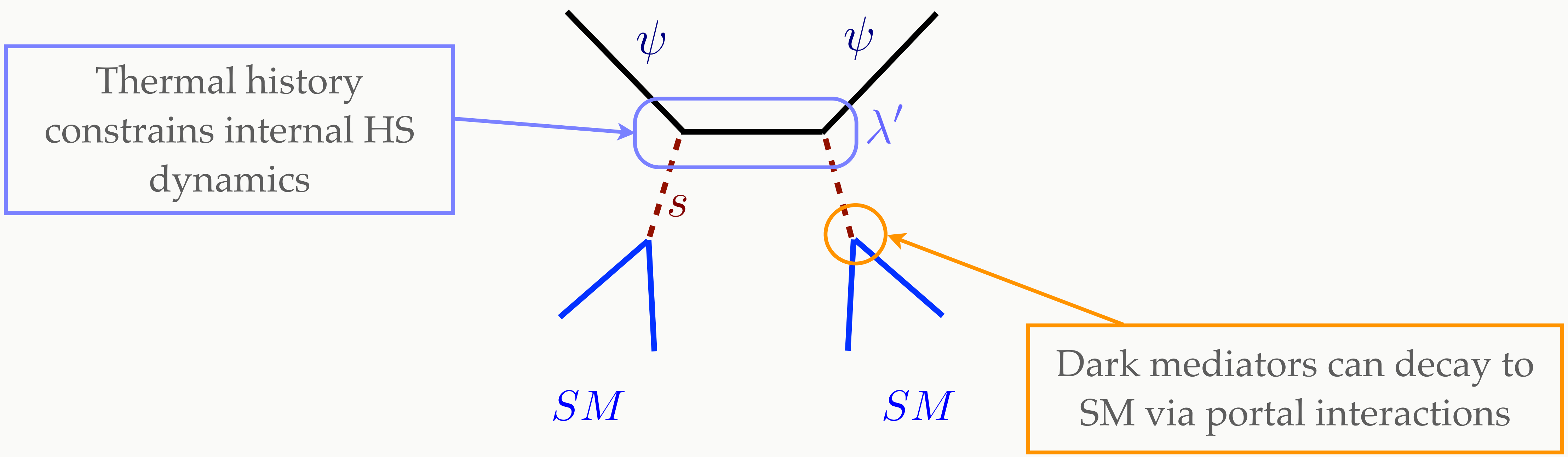


  - light weak-scale states needed for naturalness can be SM singlets
    - Higgs portal interactions by construction; also possibly hypercharge

[Chacko, Goh, Harnik; Craig, Howe; Craig, Knapen, Longhi]

Why exotic Higgs decays?

- Dark matter:
  - "WIMP miracle": a statement about cold dark matter freezing out via perturbative interactions
  - Hidden sector freezeout:



[Pospelov, Ritz]

Why exotic Higgs decays?

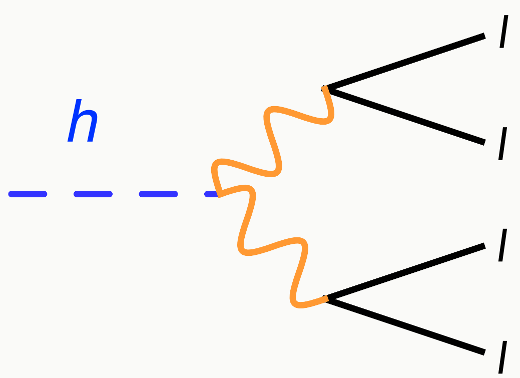
- Why not?
  - Hidden sectors are a generic ingredient in UV theories: e.g., SUSY-breaking
  - Generic signatures of new physics may be light, weakly coupled states just as well as heavier, SM-charged states
  - Characterize signatures by portals mediating SM-HS interactions
    - Higgs portal: unique possibilities at LHC: direct Higgs production, small SM width

Exotic Higgs decays at the LHC

- The LHC as an intensity frontier machine
  - Higgs production cross-section at 8 TeV: ~20 pb
  - Integrated luminosity, ~20 ifb
    - → ~400000 Higgs bosons served
    - If: reasonable reconstruction efficiency, good S/B: statistics for branching fractions $\sim 10^{-4}$

Lessons from LHC8 recasts

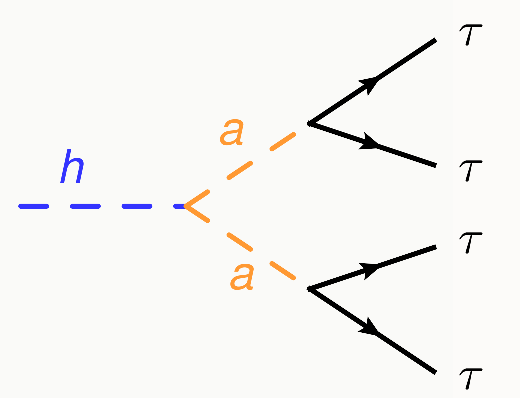
- Prospects depend in detail on the particles in the final state, and range from spectacular to very hard

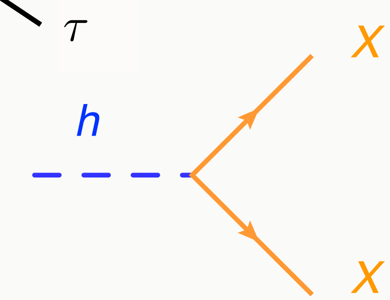


Easy: multiple resonant light leptons

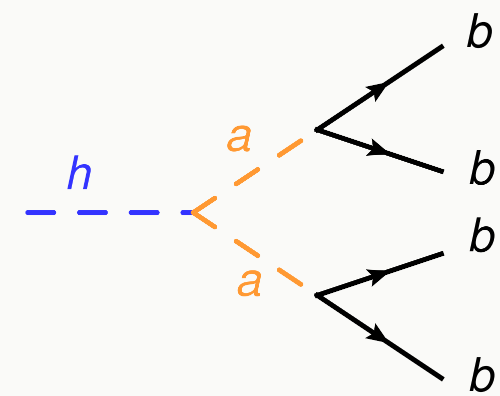
$\text{Br} \lesssim 4 \times 10^{-4}$

Moderate: multiple electroweak objects, poor mass resolution





$\text{Br} \lesssim 0.1 - 0.6$



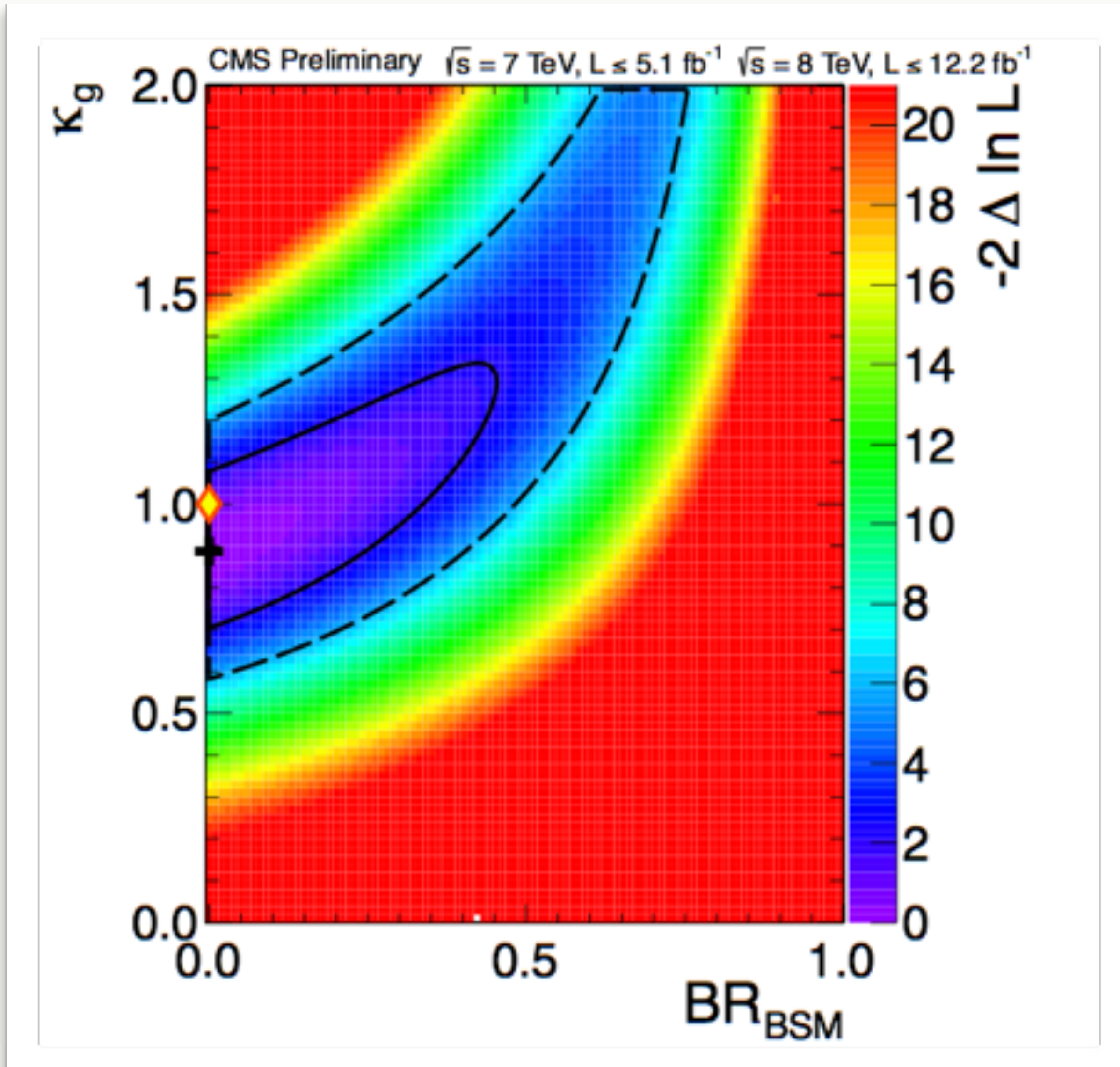
Hard: all-hadronic

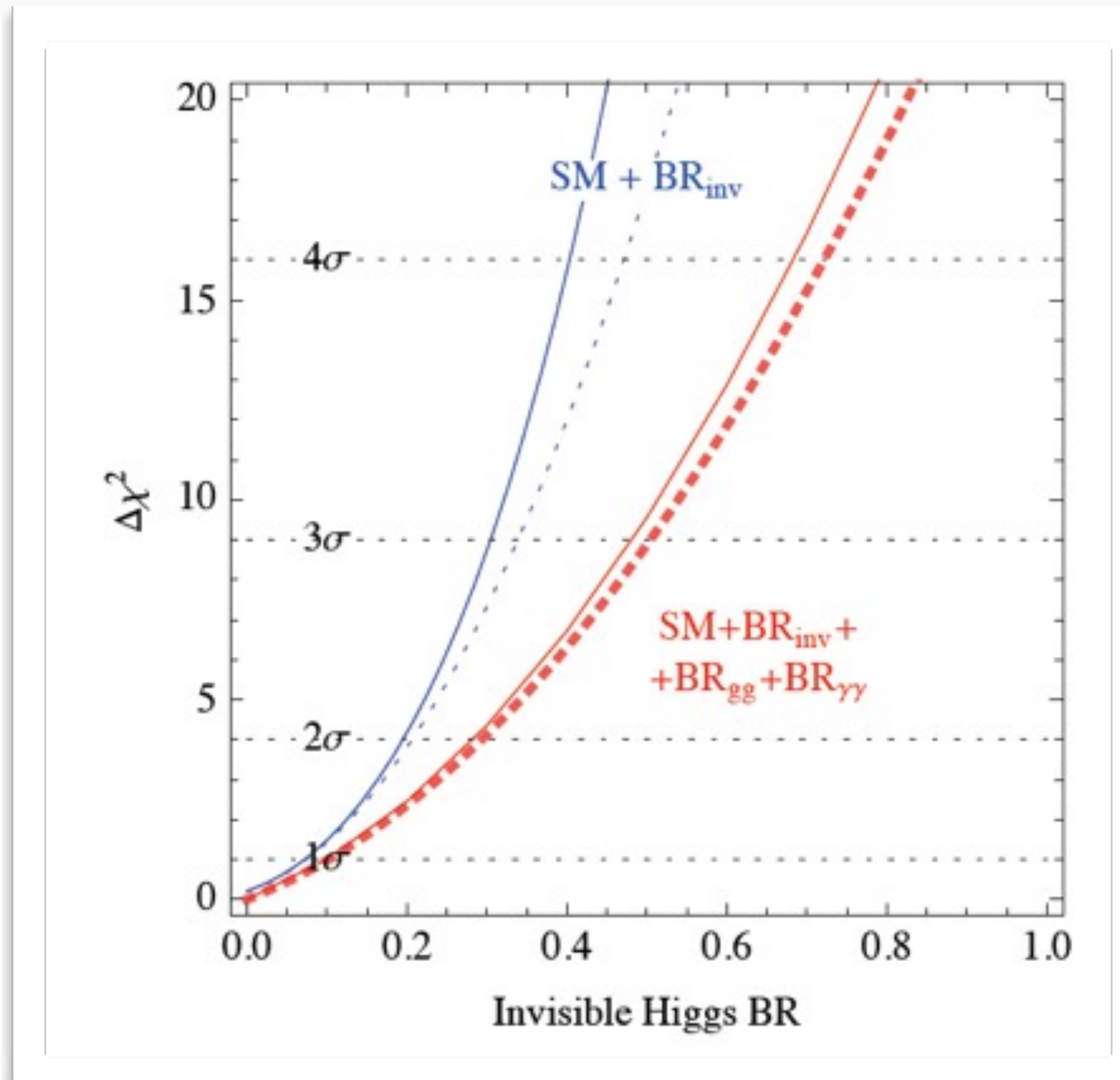
$\text{Br} \lesssim 0.9$

[Curtin, Essig, Gori, Jaiswal, Katz, Liu, Liu, McKeen, JS, Strassler, Surujon, Tweedie, Zhong]

Exotic Higgs decays at the LHC

- Indirect limits: observation of SM modes





[Giardino et al; see also Ellis, You; Belanger et al]

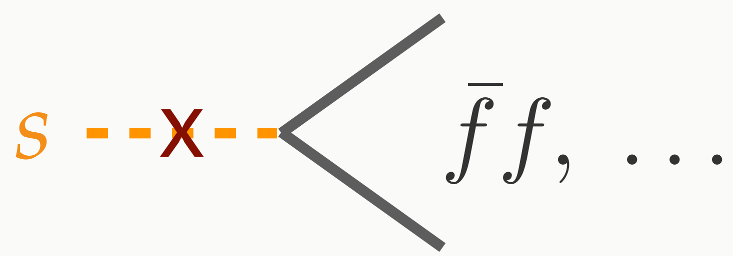
Direct searches for exotic Higgs decays

- Example: a scalar field coupled to the SM via the Higgs portal:

$$V(H,S) = V(H) + V(S) + \frac{1}{2}\zeta S^2 |H|^2$$

$$\Rightarrow \Delta\mathcal{L} = \frac{1}{2}\kappa h s^2$$

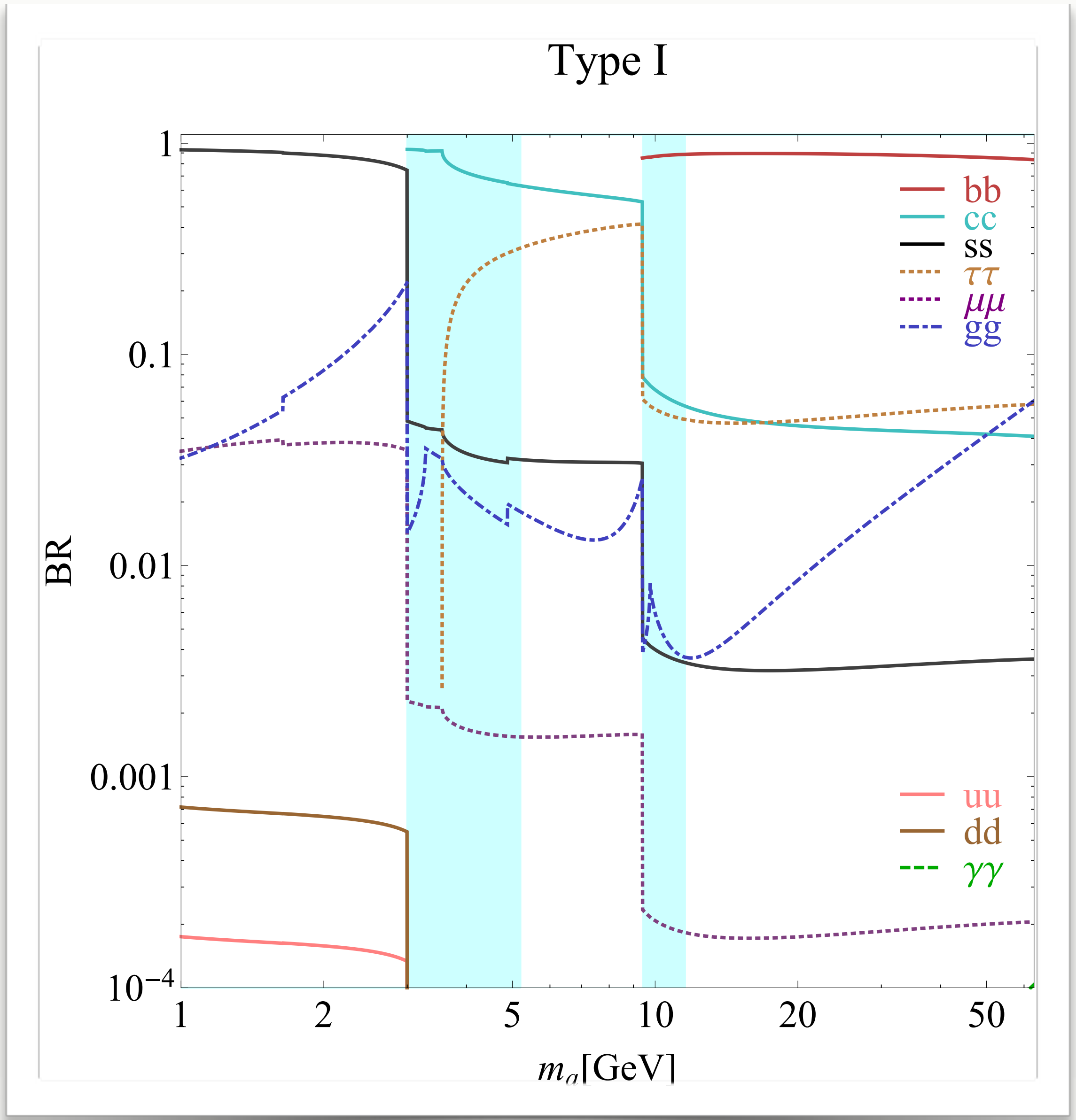
- Same coupling controls s decay: *Br*s of SM Higgs of given mass



An example: (pseudo-)scalars

- Two Higgs doublet models + S:
  - light pseudoscalar mixing with A^0
  - altered Yukawa couplings

Type 1: SM



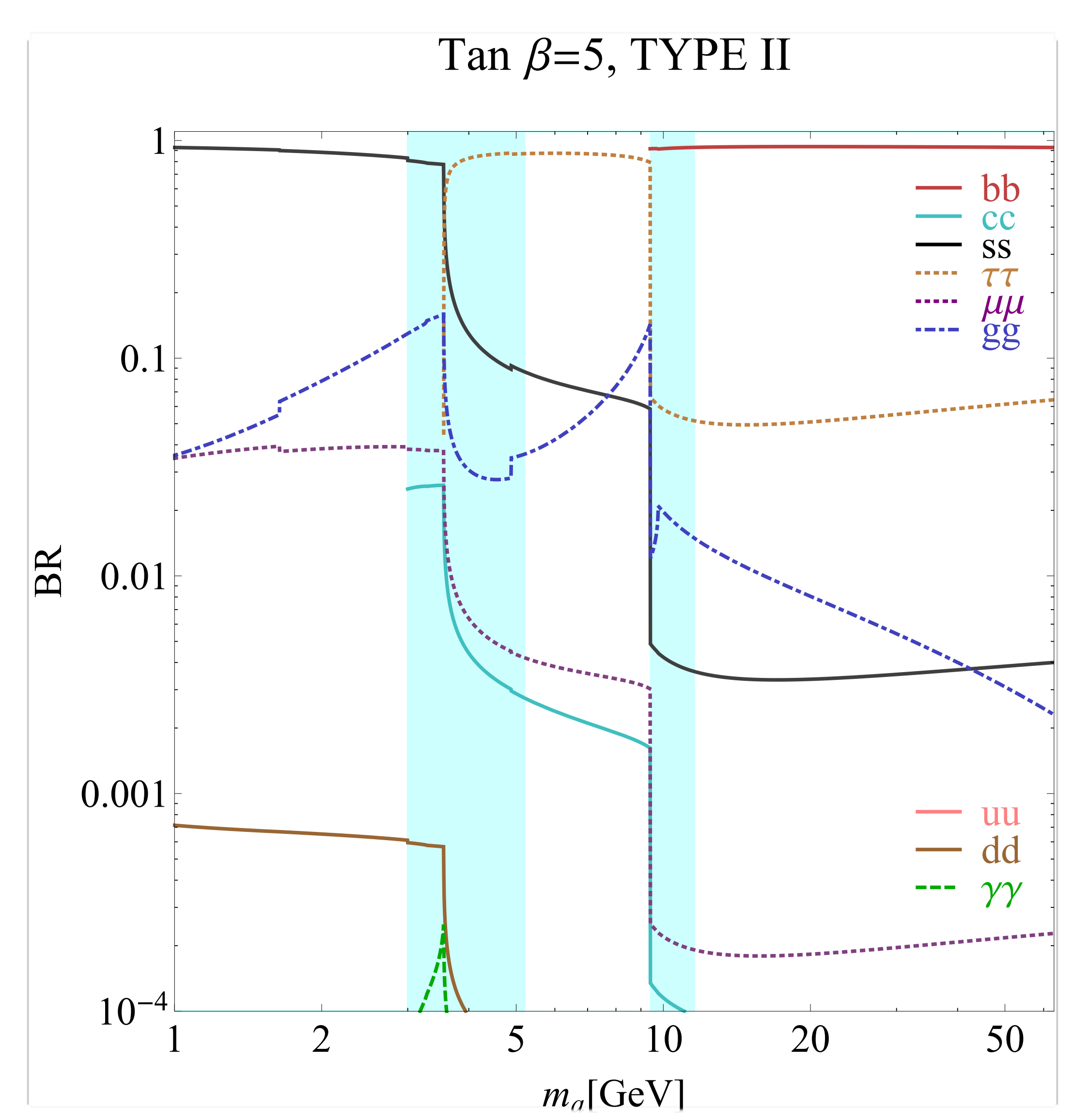
Singlet pseudoscalar Br: SM Yukawas

[Exotic Higgs Decay Working Group: 1312.4992]

An example: (pseudo-)scalars

- Two Higgs doublet models + S:
  - light pseudoscalar mixing with A^0
  - altered Yukawa couplings

Type 1: SM
Type II: NMSSM-like



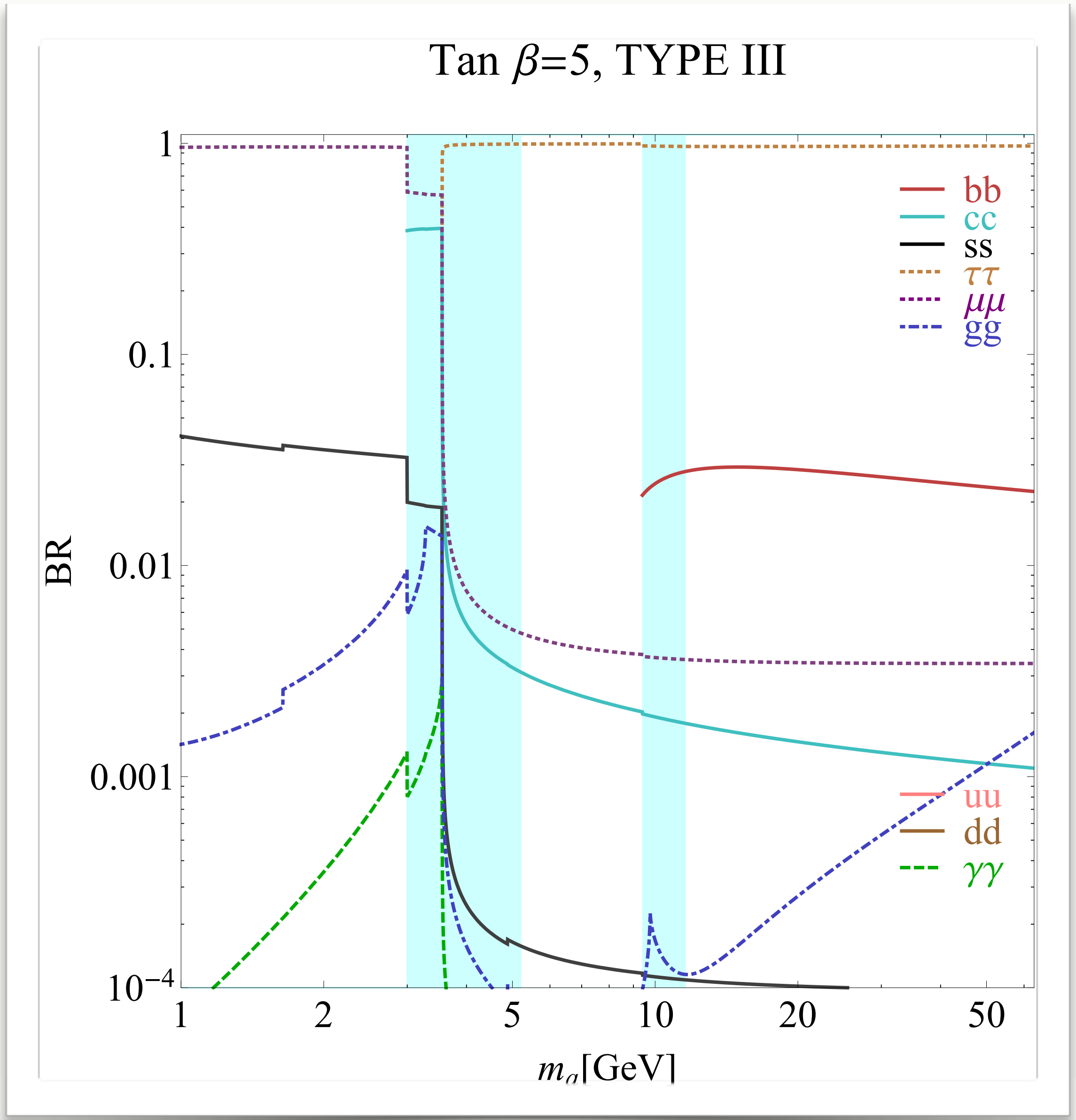
Singlet pseudoscalar Br: Type II Yukawas

[Exotic Higgs Decay Working Group: 1312.4992]

An example: (pseudo-)scalars

- Two Higgs doublet models + S:
  - light pseudoscalar mixing with A^0
  - altered Yukawa couplings

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



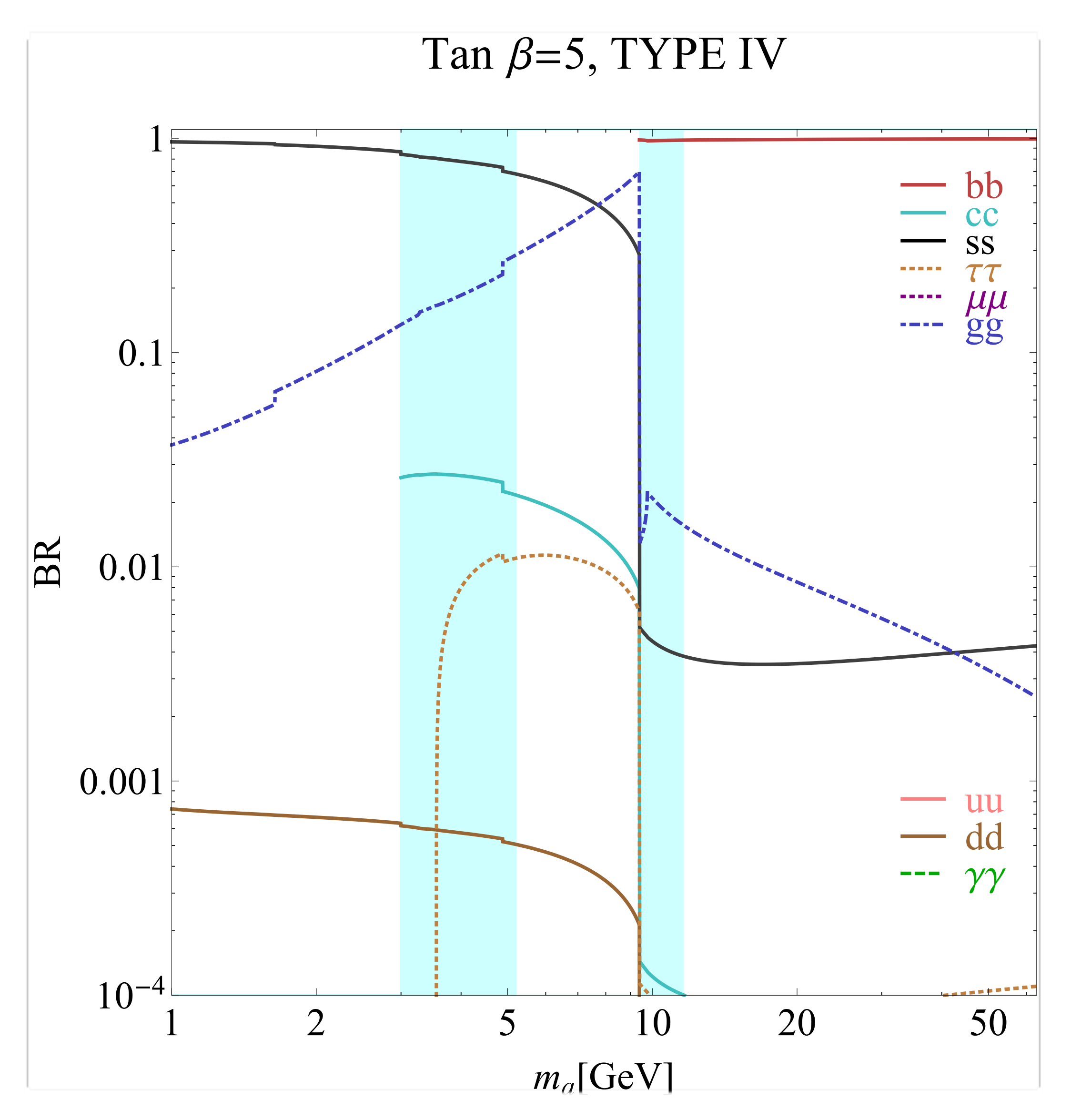
Singlet pseudoscalar Br: Type III Yukawas

[Exotic Higgs Decay Working Group: 1312.4992]

An example: (pseudo-)scalars

- Two Higgs doublet models + S:
  - light pseudoscalar mixing with A^0
  - altered Yukawa couplings

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



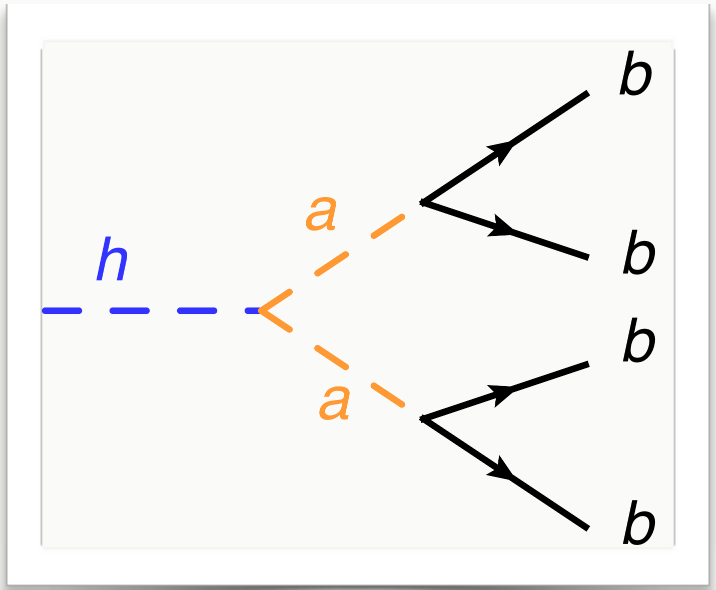
Singlet pseudoscalar Br: Type IV Yukawas

[Exotic Higgs Decay Working Group: 1312.4992]

Higgs decays to (pseudo-)scalars

- Most generic prediction of Higgs-portal scalars:

$$h \to ss(aa) \to 4b$$



Four soft b-jets:

$p_T \lesssim 30$ GeV

use VH associated production

- Current status:
  - mass-dependent efficiency for an $h \to 4b$ event to pass SM $h \to 2b$ search criteria
  - For light ($\sim$ 15 GeV) scalars:

    $$Br(h \to 4b) \lesssim 0.7$$

  - Heavier scalars: no limit

[Exotic Higgs Decay Working Group: 1312.4992]

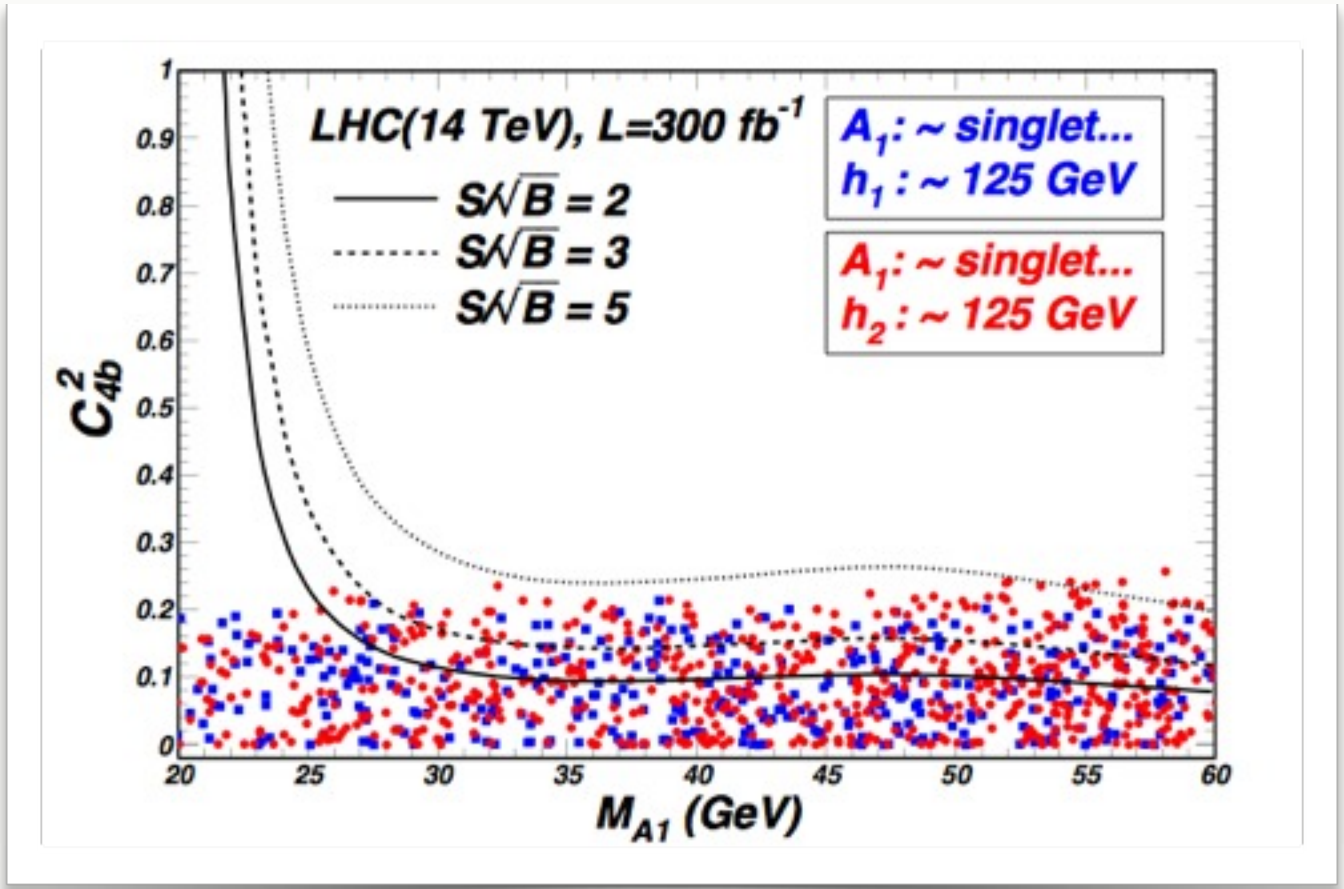
Higgs decays to (pseudo-)scalars

- Most generic prediction of Higgs-portal scalars:

$$h \to ss(aa) \to 4b$$

- Future prospects:
  - analyses with, without jet substructure
  - ultimate 95% CL sensitivity in both cases *estimated* to be

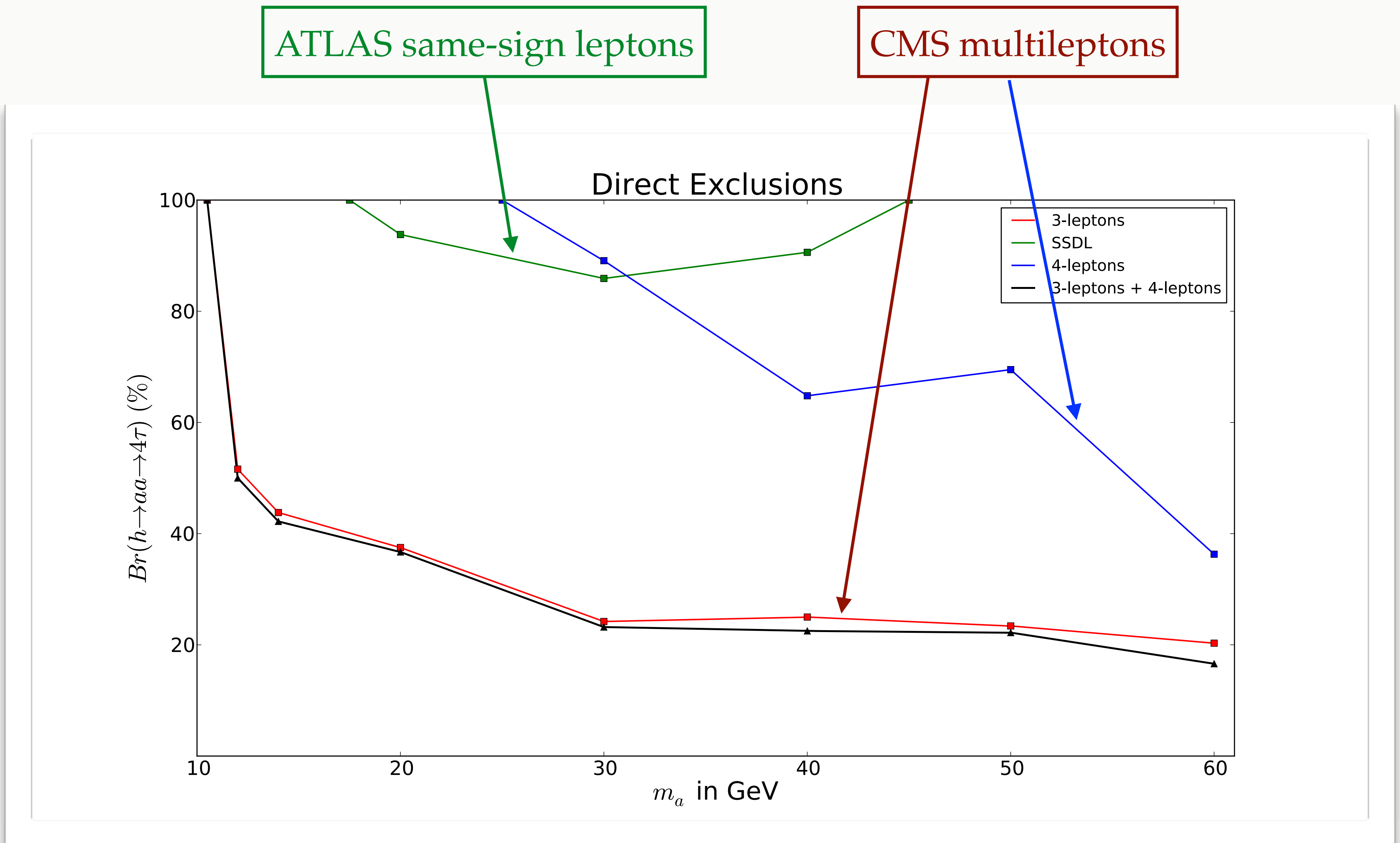
$$Br(h \to 4b) \approx 0.1$$



[Cao, Ding, Han, Yang, Zhu; Kaplan, McEvoy; …]

Higgs decays to (pseudo-)scalars

- If a is light or leptophilic: $h \to ss(aa) \to 4\tau$

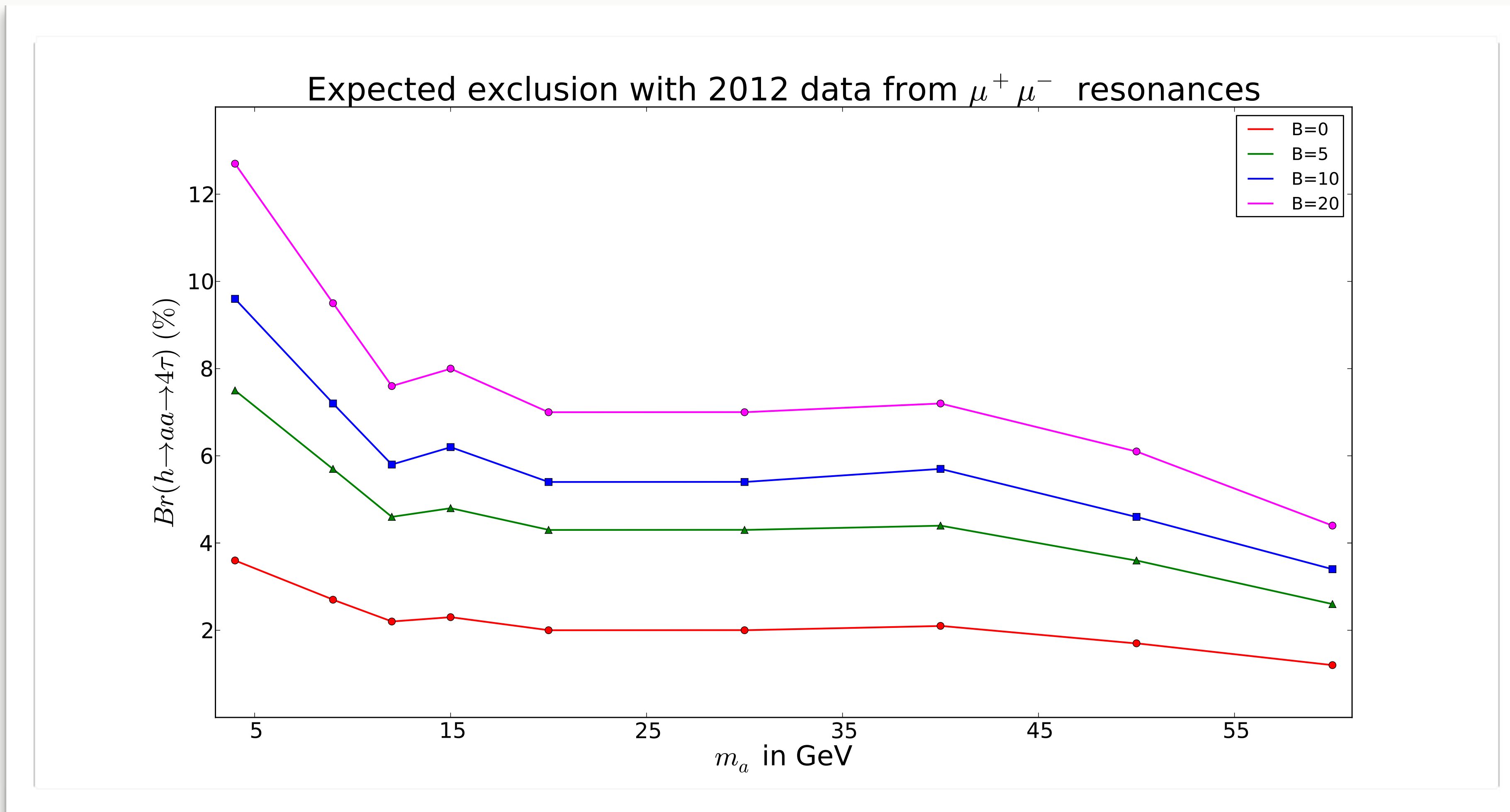


gluon fusion via leptons; binned event rates alone

[Exotic Higgs Decay Working Group: 1312.4992]

Higgs decays to (pseudo-)scalars

- Gain from sharp resonance in subdominant $a \to 2\mu$, despite smaller rate:



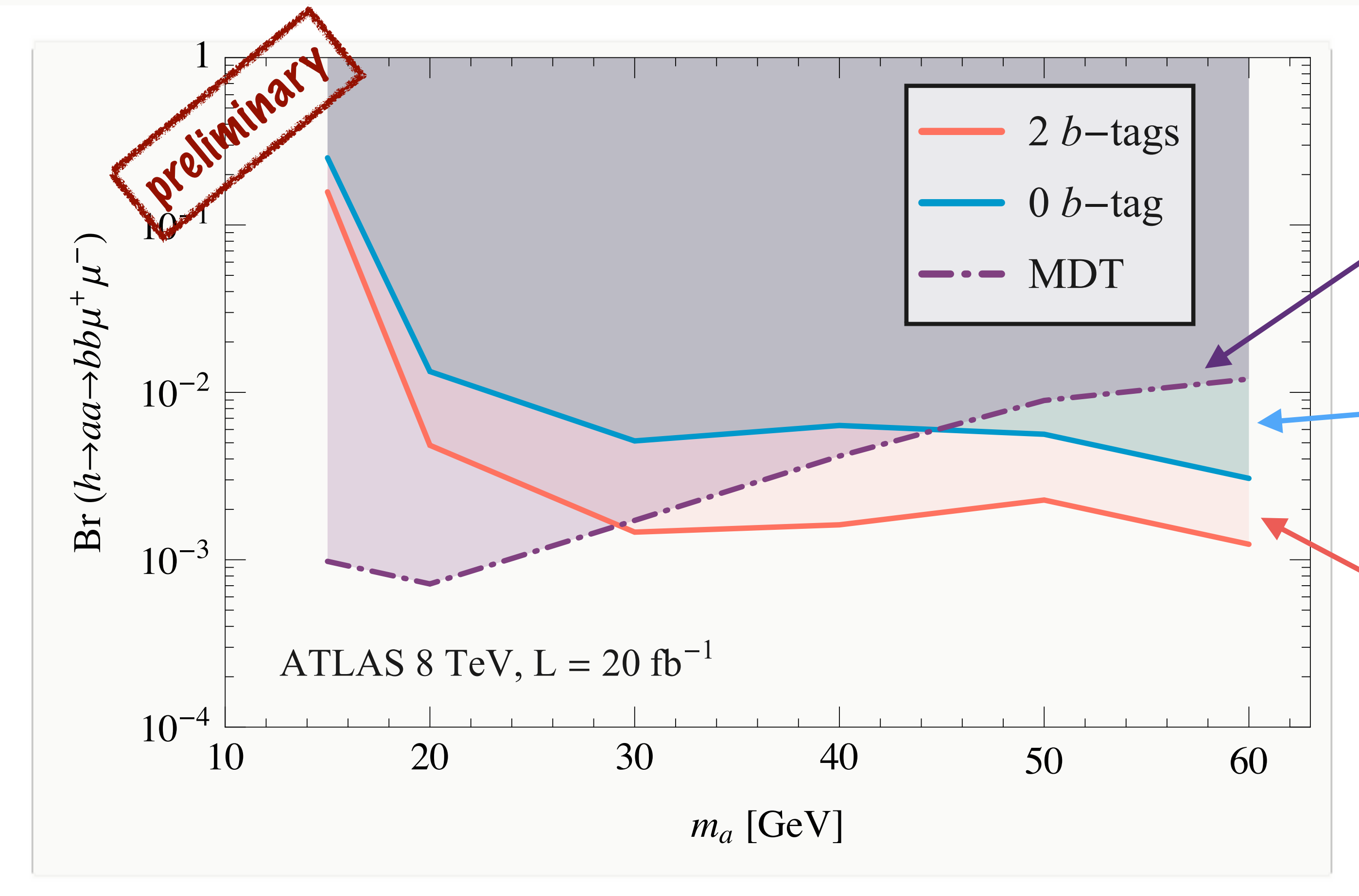
estimate of current sensitivities in a CMS-like multilepton analysis extended to incorporate dimuon mass

[Lisanti, Wacker; Exotic Higgs Decay Working Group: 1312.4992]

Higgs decays to (pseudo-)scalars

- Power of clean dimuon resonance: $h \to ss(aa) \to 2b2\mu$

$$\frac{Br(a \to 2\mu)}{Br(a \to 2b)} \sim \frac{m_\mu^2}{3m_b^2} \approx 2 \times 10^{-4}$$



resonant dimuon pair plus:

mass-drop + b-tag

$2j$ (m_{jj}, $m_{jj\mu\mu}$ consistent with resonant origin)

$2b$ (m_{bb}, $m_{bb\mu\mu}$ consistent with resonant origin)

[Curtin, Essig, Zhong, to appear; Exotic Higgs Decay Working Group: 1312.4992]

Higgs decays to (pseudo-)scalars

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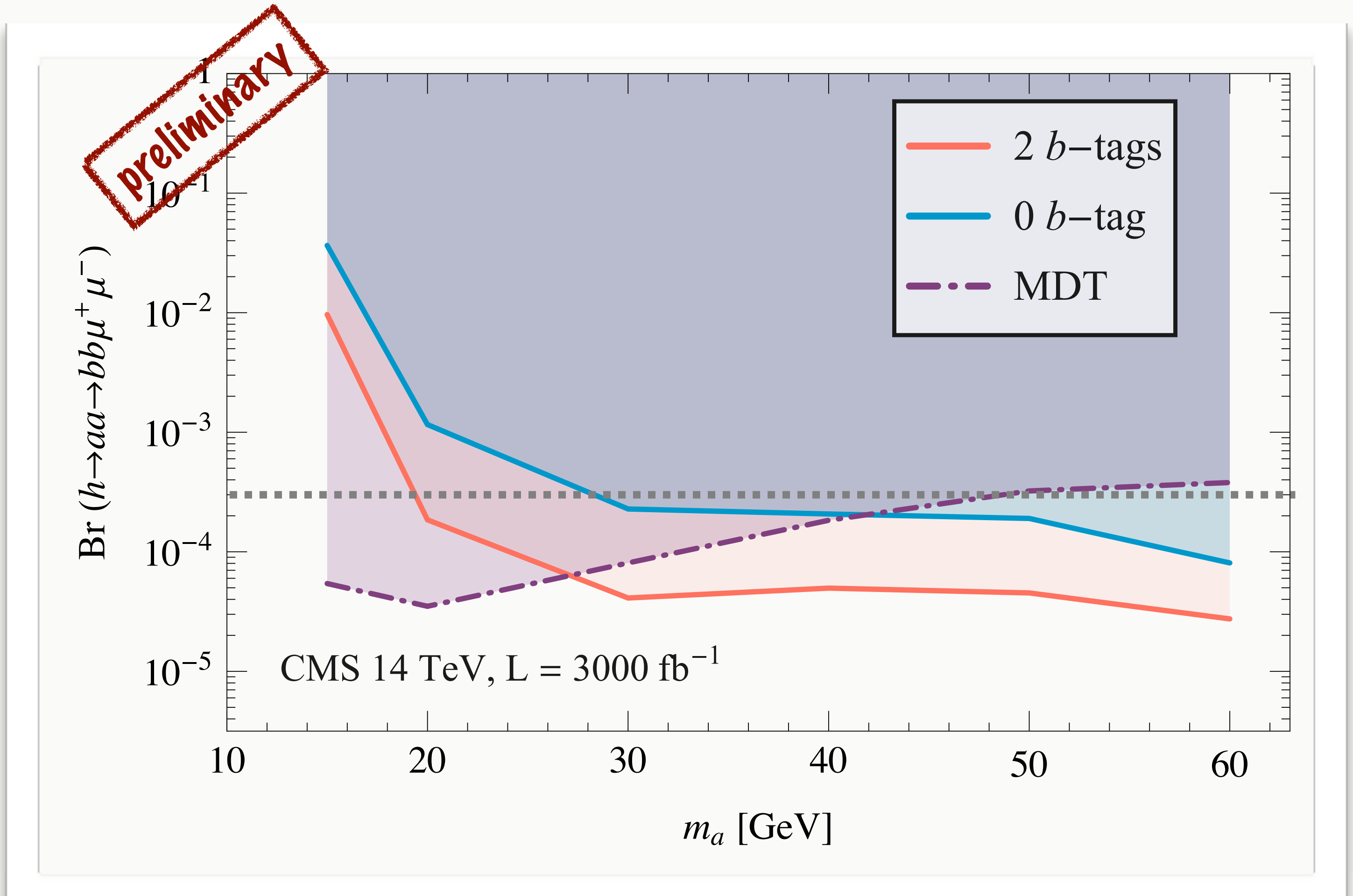

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Direct searches

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	Produc-tion 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]

[Curtin, Essig, Gori, Jaiswal, Katz, Liu, Liu, McKeen, JS, Strassler, Surujon, Tweedie, Zhong]

Direct searches

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[Curtin, Essig, Gori, Jaiswal, Katz, Liu, Liu, McKeen, JS, Strassler, Surujon, Tweedie, Zhong]

Beyond the simple examples

- Recast LHC8 limits: dependence on (electroweak) object acceptance
- More general theories easily yield longer hidden sector showers/cascades, often some detector-stable states
    - more objects! …and thus softer
- Displaced decays: often clean, great statistical reach
- Triggering: *VH*? VBF?

Summary and conclusions

- The observed 125 GeV Higgs boson is highly sensitive to the potential existence of new light degrees of freedom
- Already in LHC8 data: interesting results and prospects for many exotic decay modes
- Great statistical power from LHC14: Higgs factory
  - but reduced acceptance for low-p_T objects may limit the gains
- See Stefania Gori's talk for more!