Exotic Higgs Decays

Jessie Shelton
U. Illinois at Urbana-Champaign

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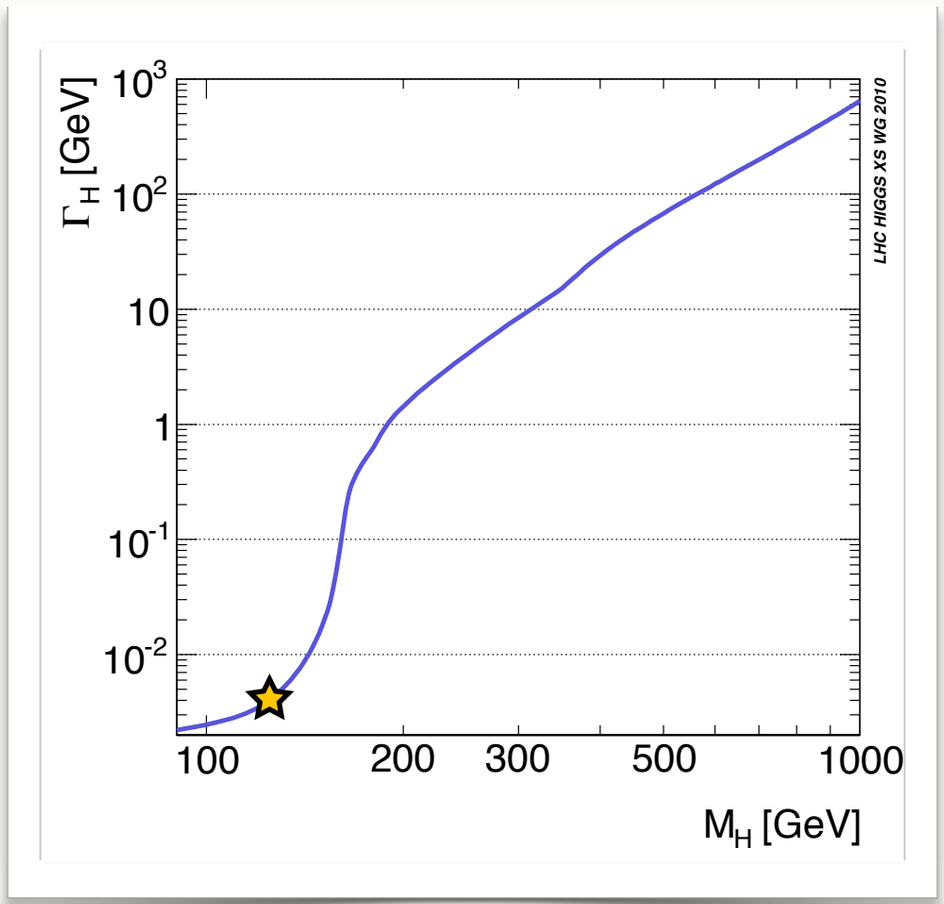
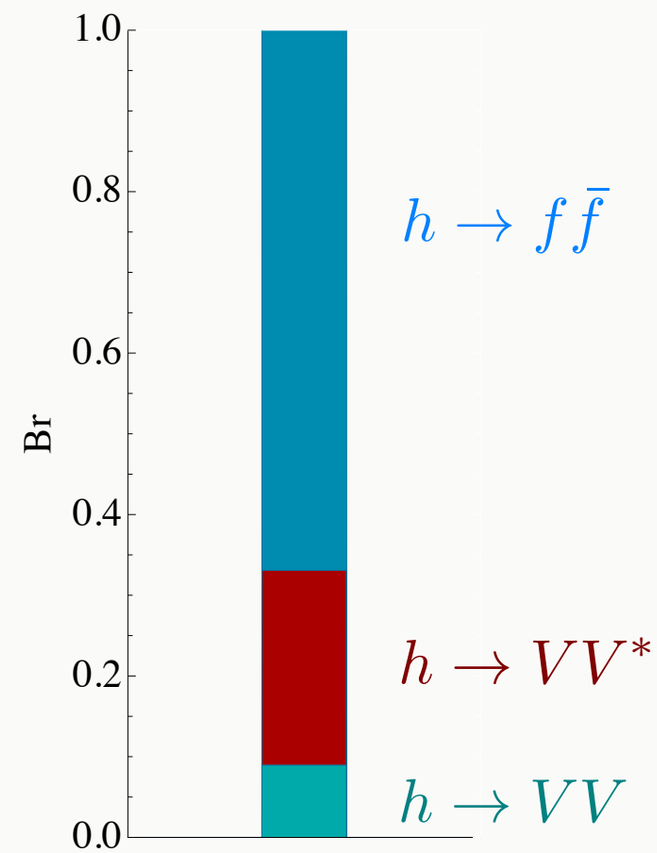
The SM-like Higgs boson

- A light SM-like Higgs is narrow:

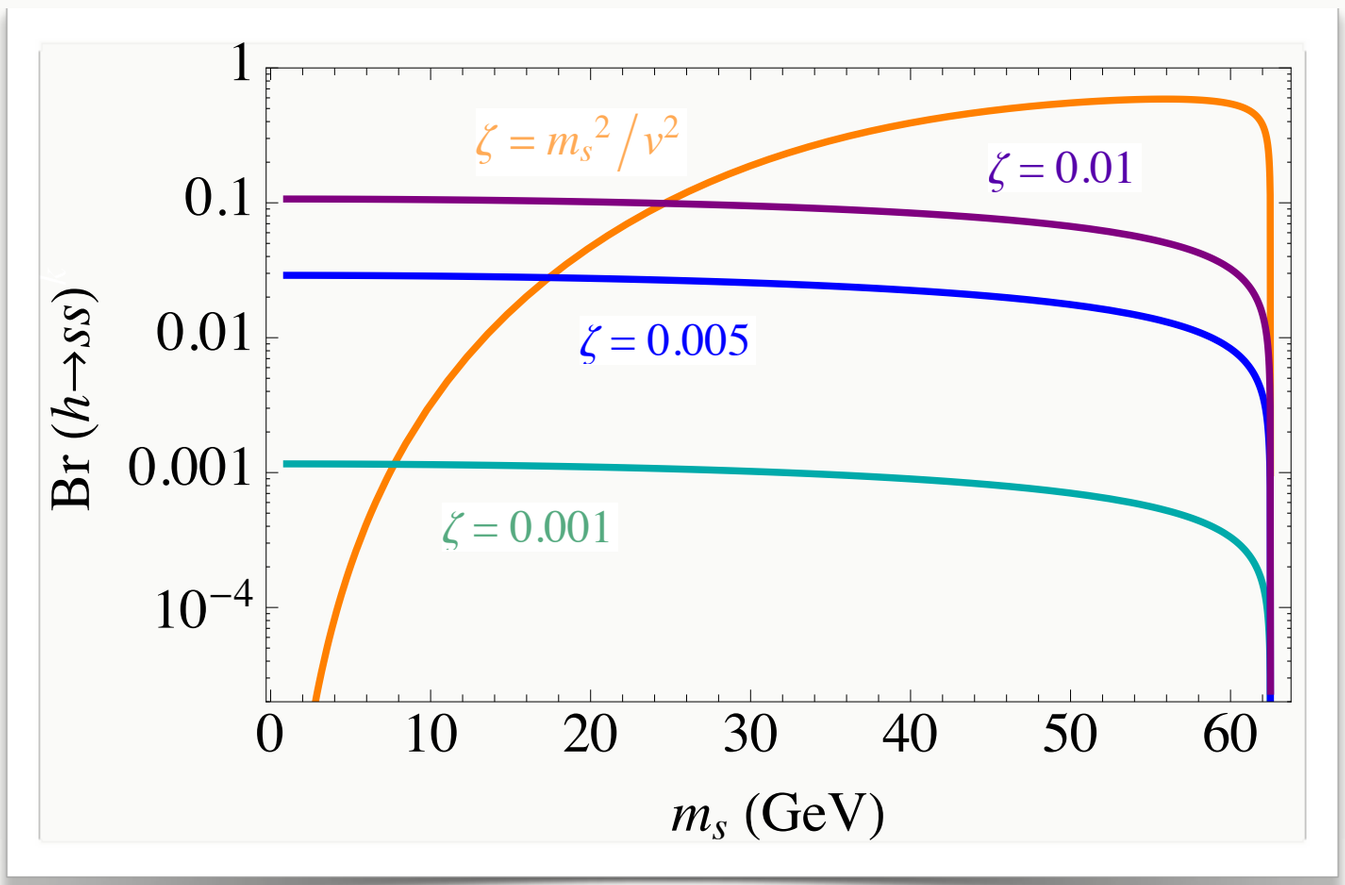




$$\Gamma_h(125\ \text{GeV}) = 4.1\ \text{MeV}$$

Exotic decays of the SM-like Higgs

- Presence of new light degrees of freedom can distort Higgs *Br*s 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 generating it
  - stabilize it
  - thermal dark matter
  - …why not?

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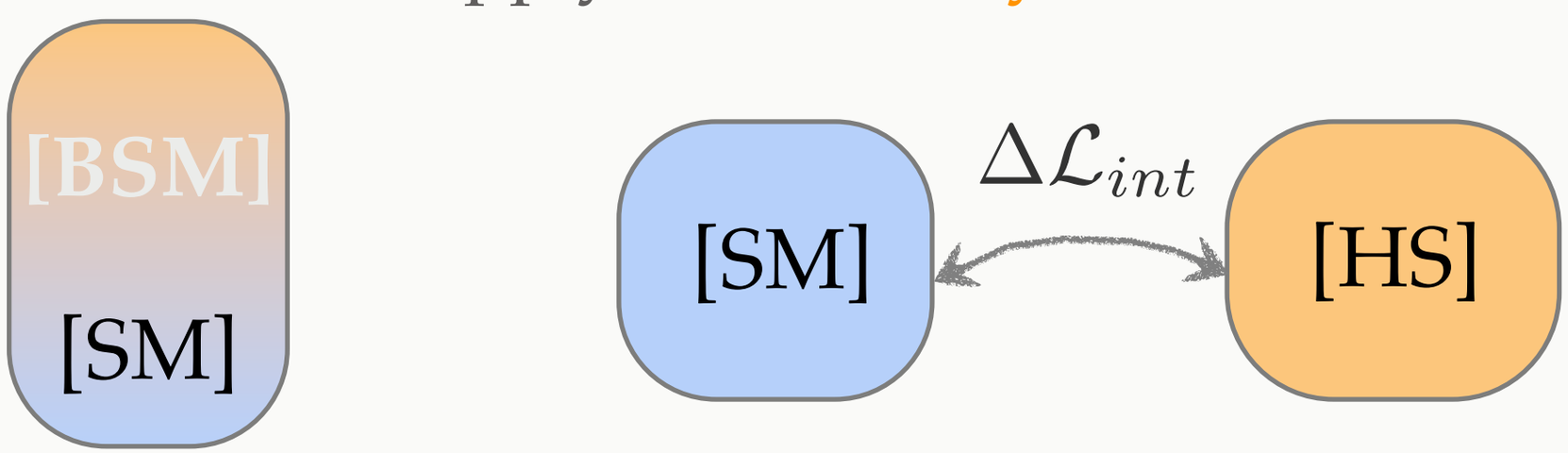
  - …why not?
- These motivations apply horizontally as well as vertically

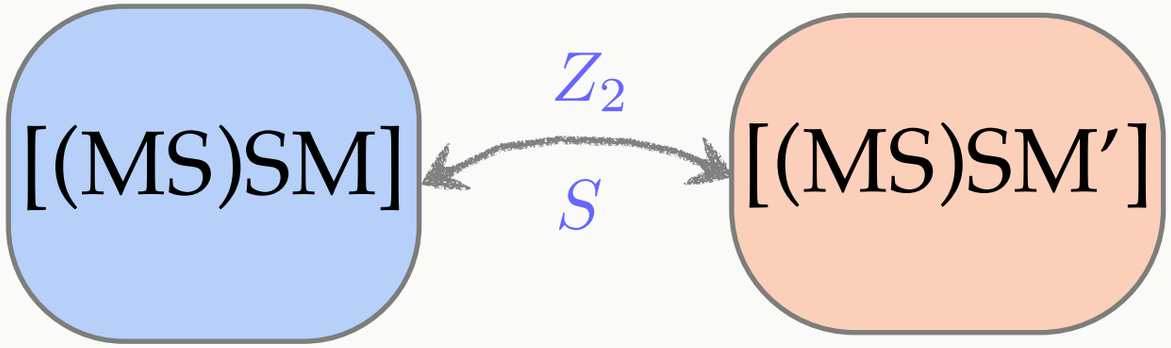


Why exotic Higgs decays?

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

Why exotic Higgs decays?

- Naturalness
  - Twin Higgs and related models:

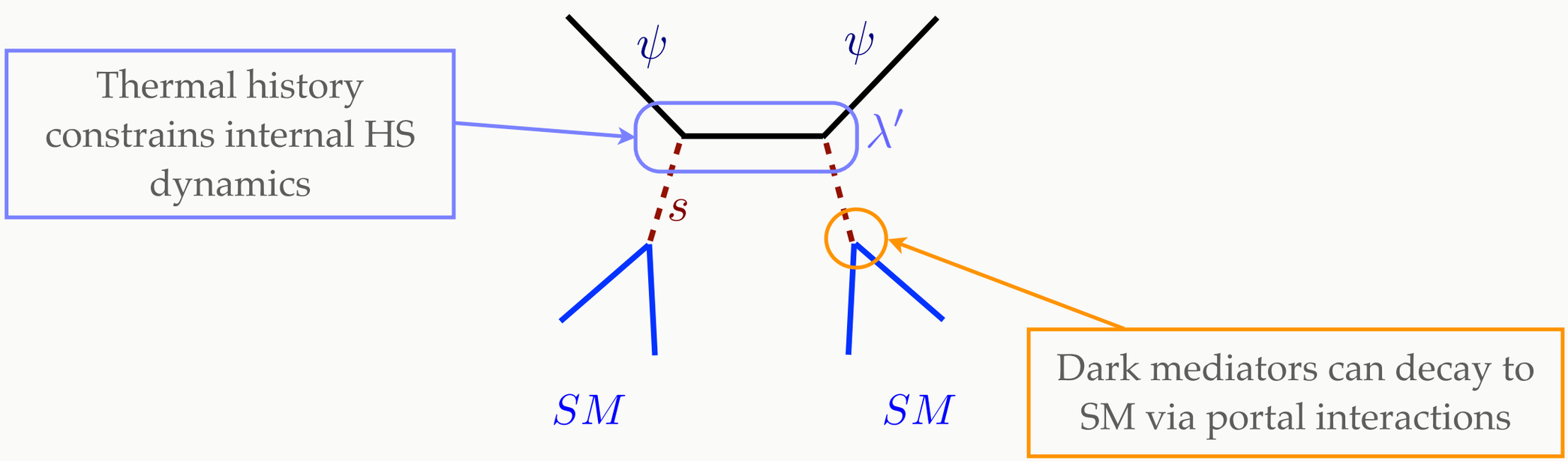


  - light weak-scale states needed for naturalness can be SM singlets
    - Higgs portal interactions by construction; also possibly hypercharge

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

Why exotic Higgs decays?

- Dark matter:
  - First work on exotic Higgs decay: $h \to$ dark matter
  - "WIMP miracle": a statement about cold dark matter freezing out via perturbative interactions
  - Hidden sector freezeout:



[Suzuki, Shrock; Pospelov, Ritz, Voloshin]

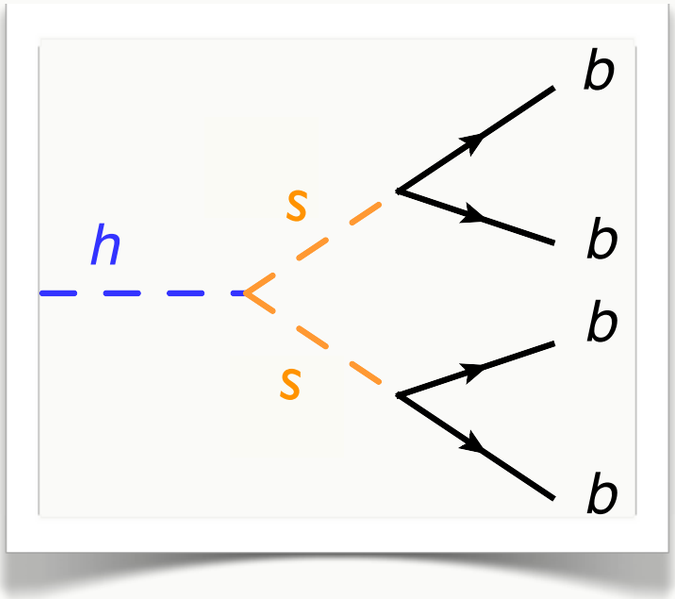
Why exotic Higgs decays?

- 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 leading operators mediating SM-HS interactions
    - Higgs portal: unique possibilities at LHC: direct Higgs production, small SM width

Example: $h \longrightarrow 4\ b$

- Generic prediction of Higgs-portal (pseudo-)scalars:

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



mass, couplings related to phase transitions

- Electroweak baryogenesis:
  - couplings of new (complex) scalar singlet to SM Higgs can drive EWPT to be strongly first-order
  - If $m_s < 2\ m_h$: $h \longrightarrow ss$ unavoidable, same operator gives $s \longrightarrow bb$
  - Higgs properties and in particular Br ($h \longrightarrow$SM) leading constraints

[Profumo, Ramsey-Musolf, Shaughnessy; ...]

Example: $h \longrightarrow 4\,b$

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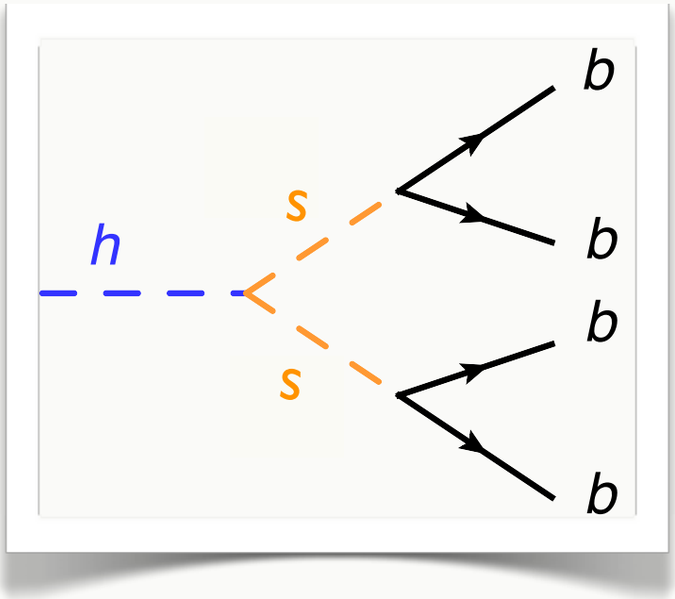

dark mediator properties may be related to other DM signals

- Dark matter:
  - Thermal WIMP: $XX \longrightarrow a \longrightarrow$ SM, $XX \longrightarrow ss\ (aa)$
  - Leading signatures: indirect detection*, direct detection*, exotic Higgs decays*
  - Branching ratio bounded by BBN constraints on mediator lifetime: effectively free parameter (and can be very small)

[Ipek, McKeen, Nelson; Unwin, Martin, JS; Evans, Gori, JS (to appear); ...]

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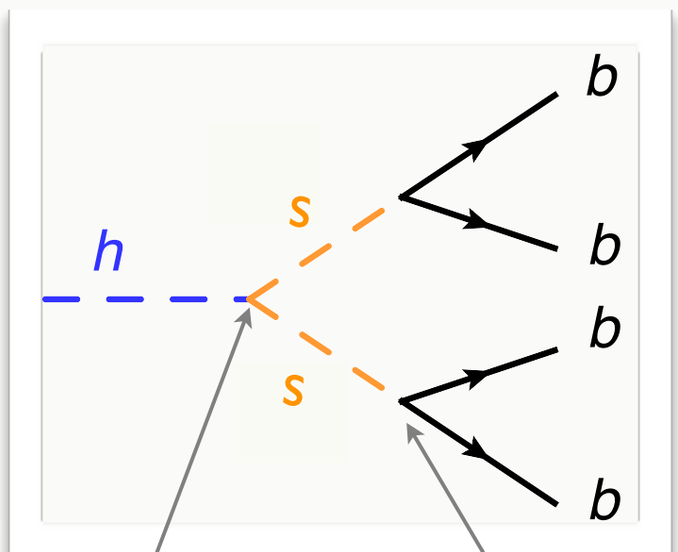
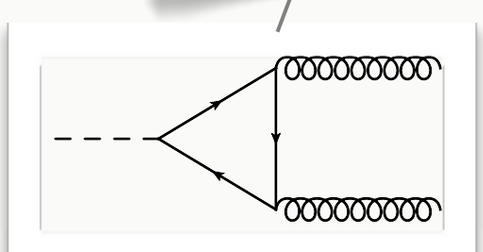




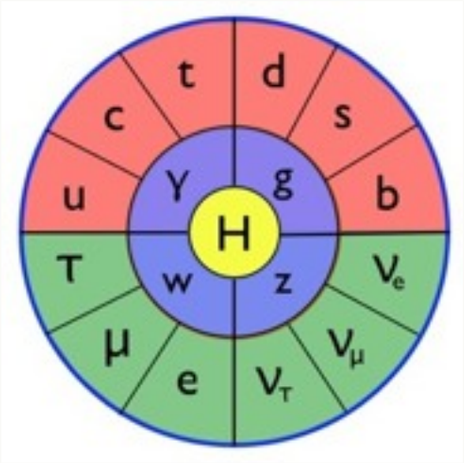
composite glueballs decay via Higgs mixing

- Neutral naturalness
  - s is composite: dark glueballs
  - Leading signatures: Higgs properties, especially Br ($h \longrightarrow$ SM)
  - Composite: decays can be parametrically separated from production $\Longrightarrow$ displacement

[Craig, Katz, Strassler, Sundrum; ...]

Lessons for collider searches

- Signature-based approach: typically, many models yield the same final state
  - relatively few ways to couple SM singlet new physics to the SM
  - helps inform searches: Yukawa ordered, gauge-ordered, ...
- Minor changes or additions to the BSM physics can lead to $O(1)$ changes in signatures
  - nature does not guarantee minimality!
  - important to cast a wide net

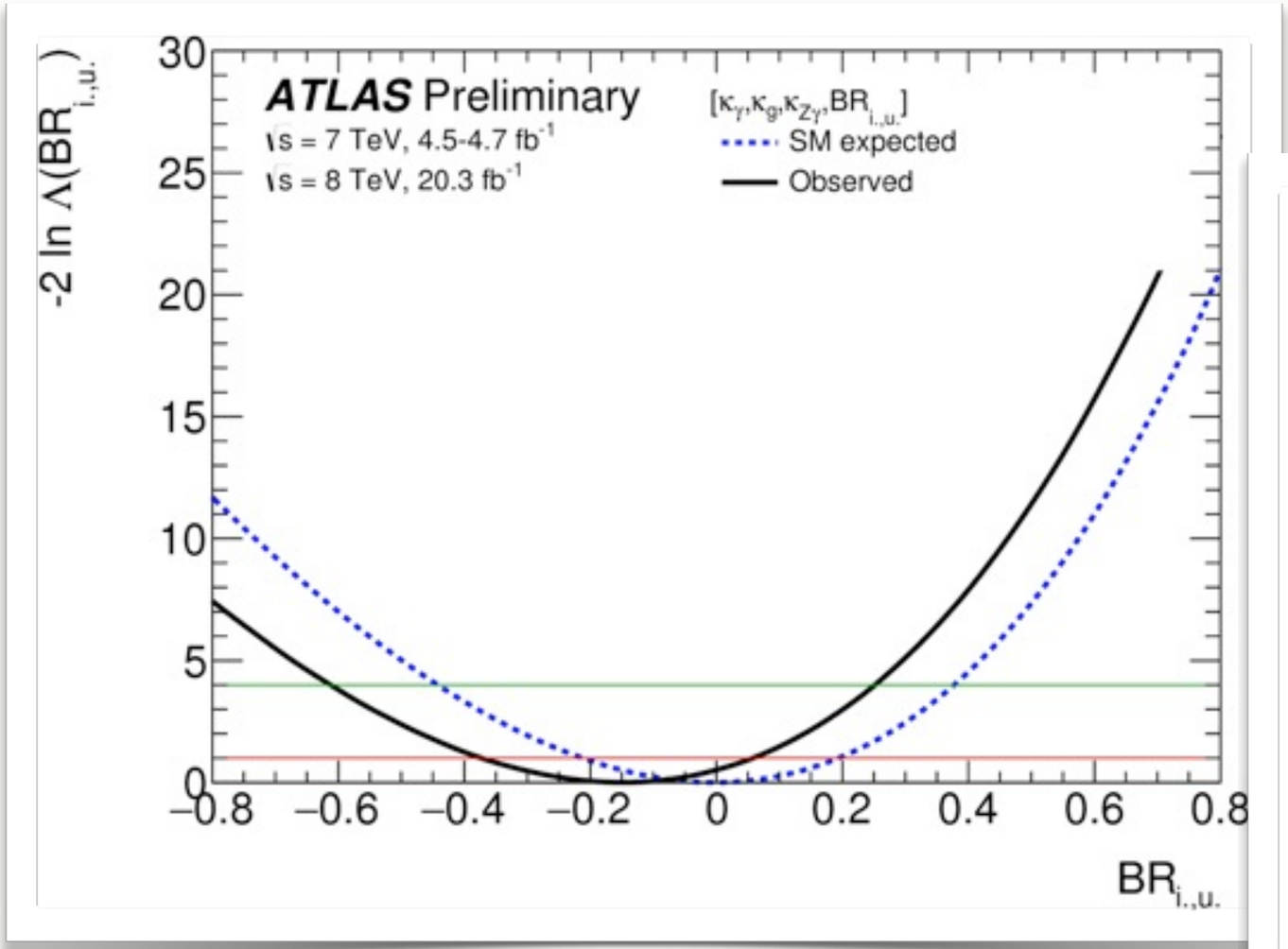


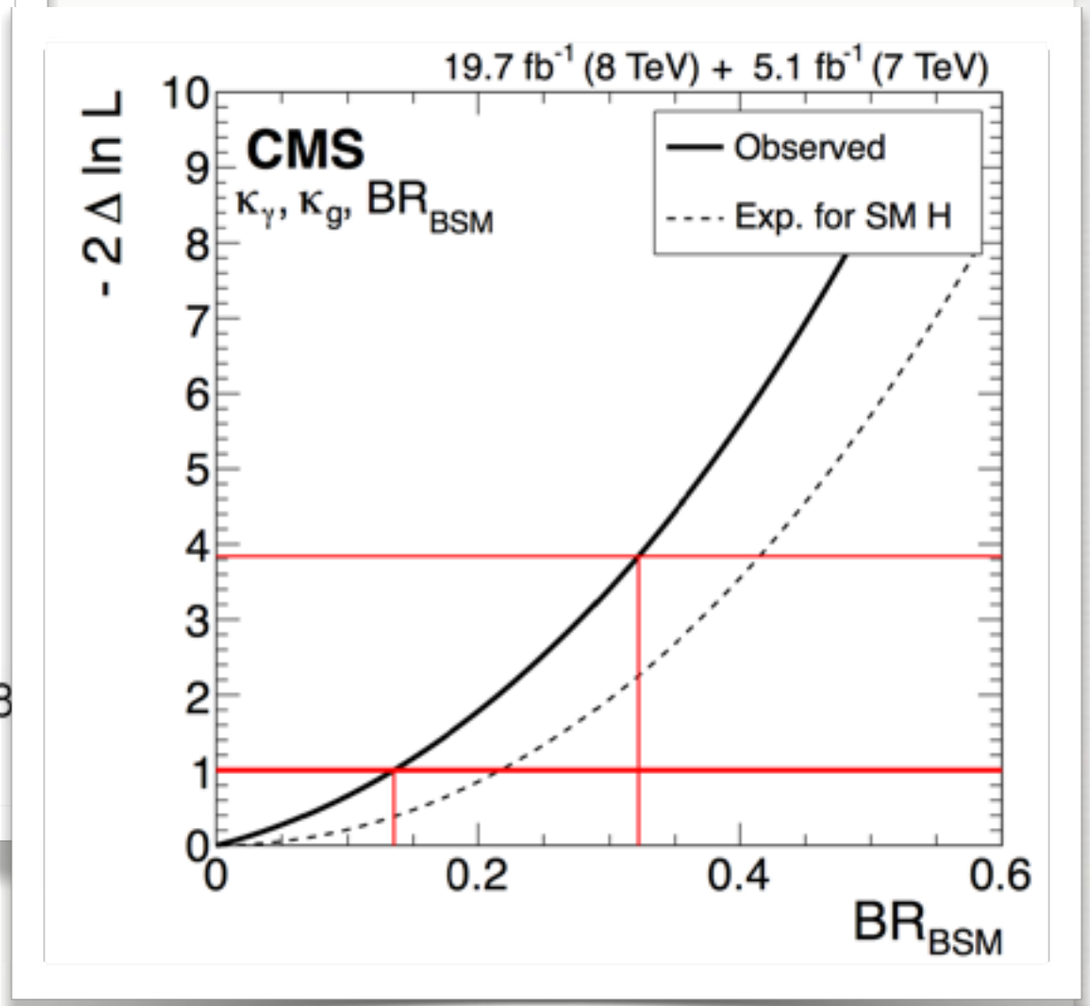
Exotic Higgs decays at the LHC

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

Exotic Higgs decays at the LHC

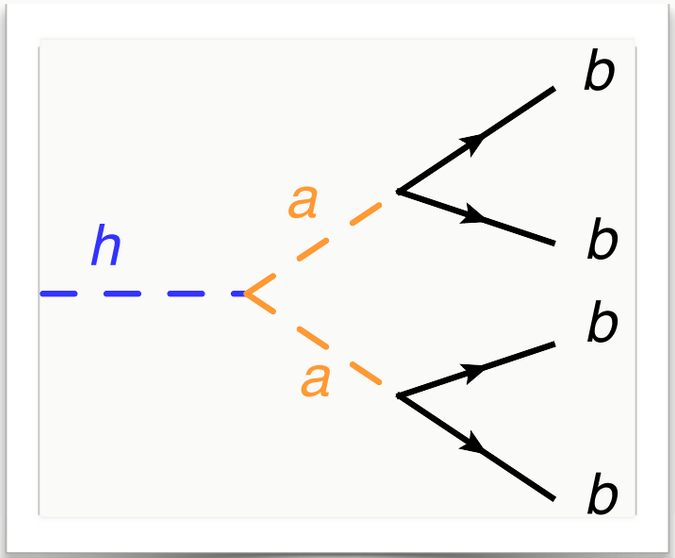
- Indirect limits: observation of SM modes





Higgs decays to (pseudo-)scalars

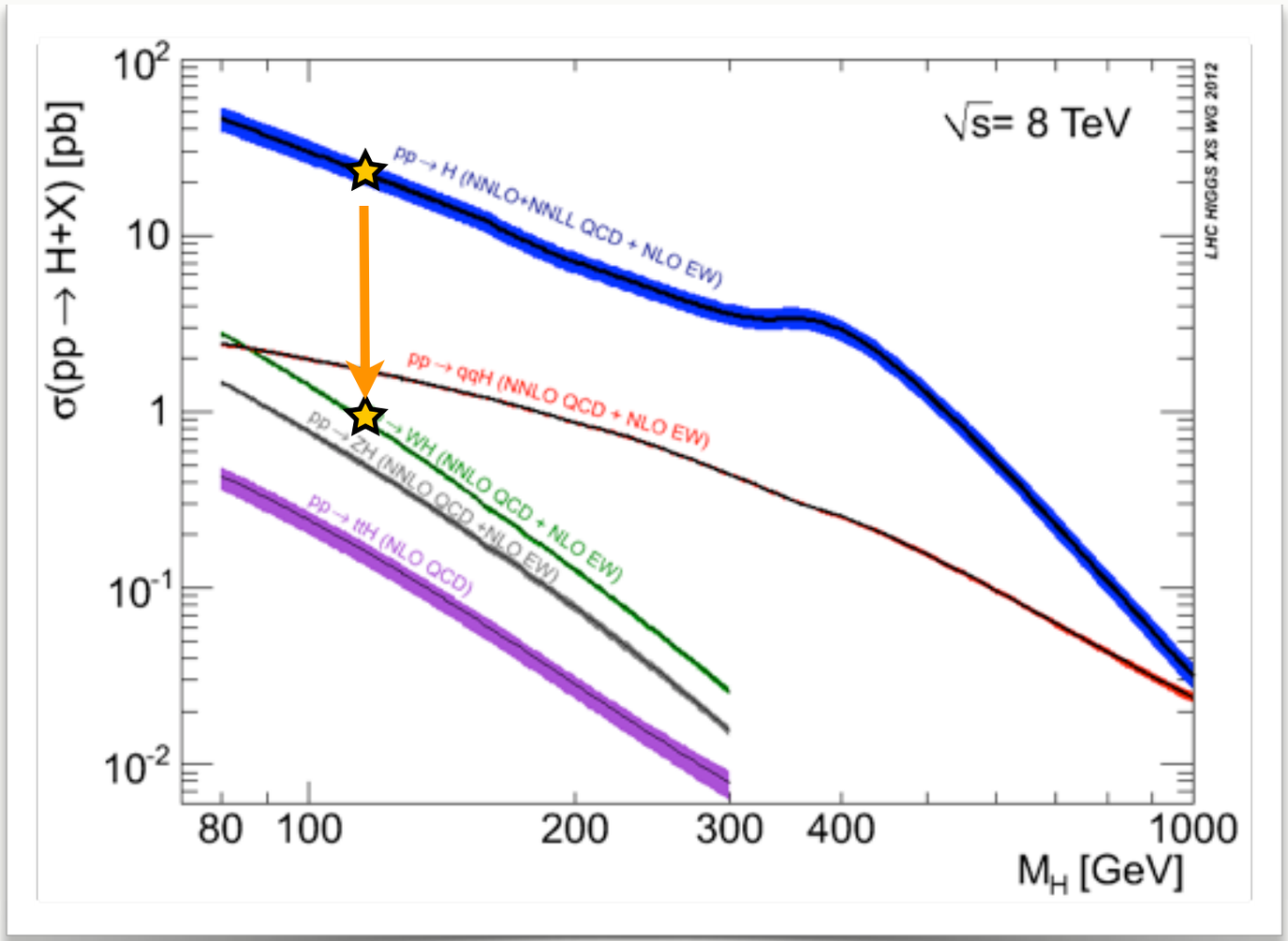
- Our example process $h \to ss(aa) \to 4b$



Four soft b-jets:

$p_T \lesssim 30$ GeV

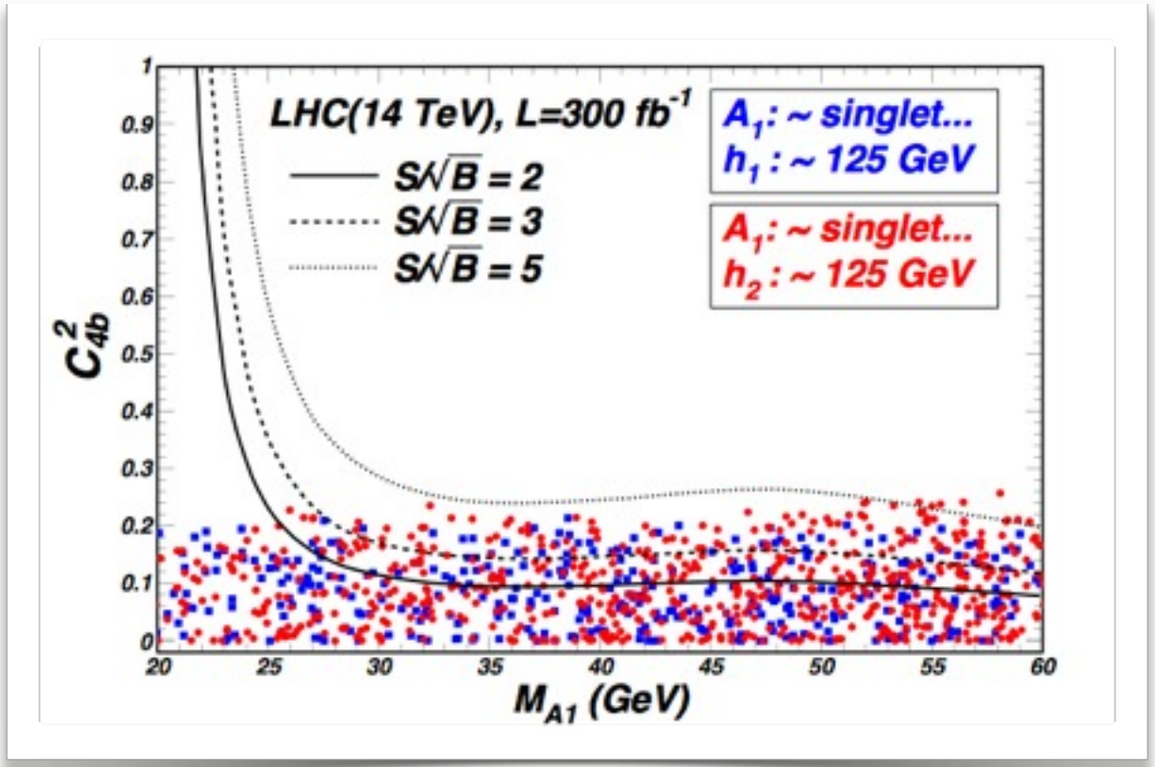
use VH associated production



Higgs decays to (pseudo-)scalars

- Current status: mass-dependent efficiency for an $h \to 4b$ event to pass SM $h \to 2b$ search criteria
  - For light (~ 15 GeV) scalars: $Br(h \to 4b) \lesssim 0.7$
  - Heavier scalars: no limit
- Future prospects:
  - analyses with, without jet substructure
  - ultimate 95% CL sensitivity in both cases *estimated* to be

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

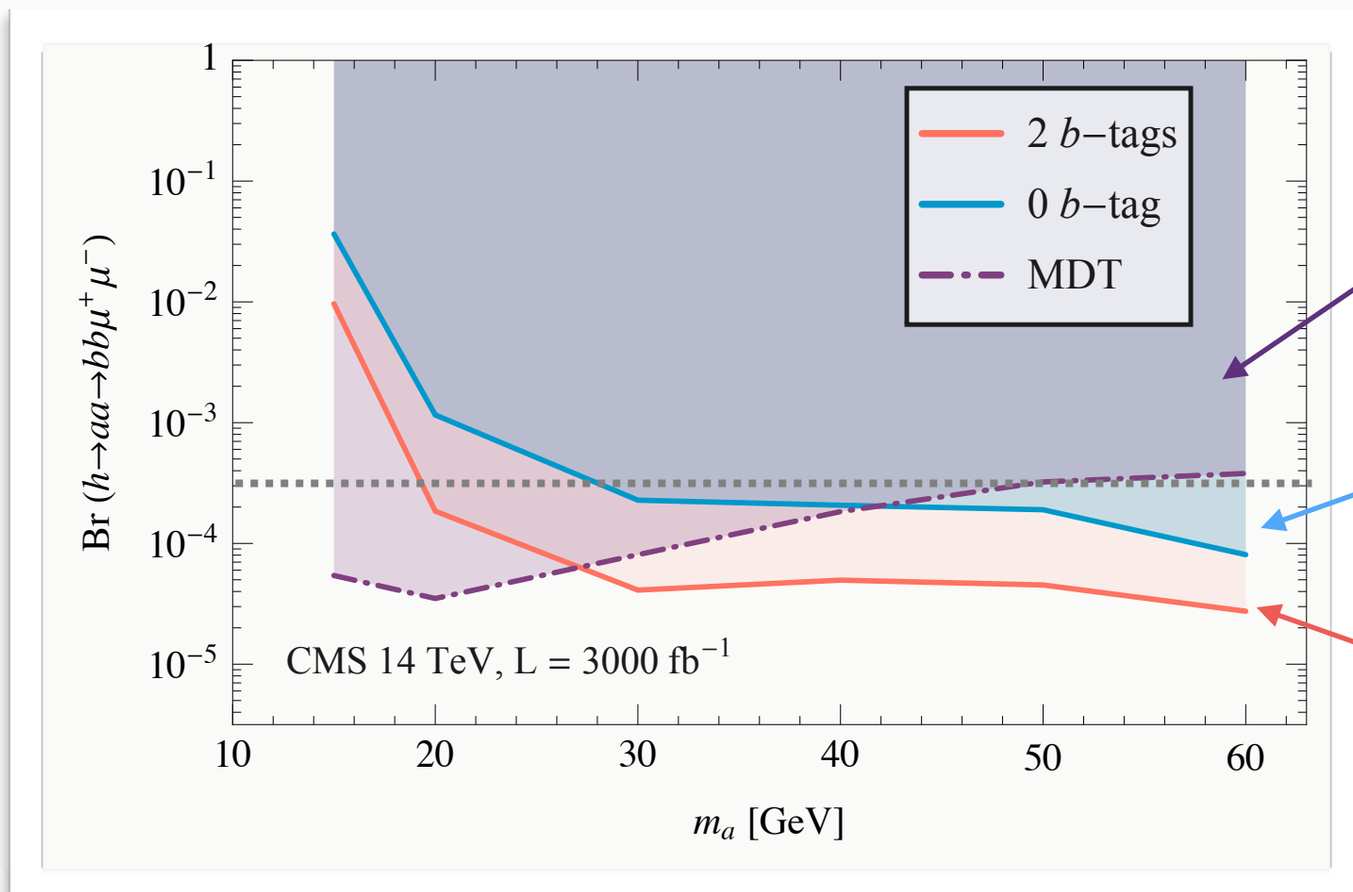


[Exotic Higgs Decay Working Group: 1312.4992; Cao, Ding, Han, Yang, Zhu; Kaplan, McEvoy; …]

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

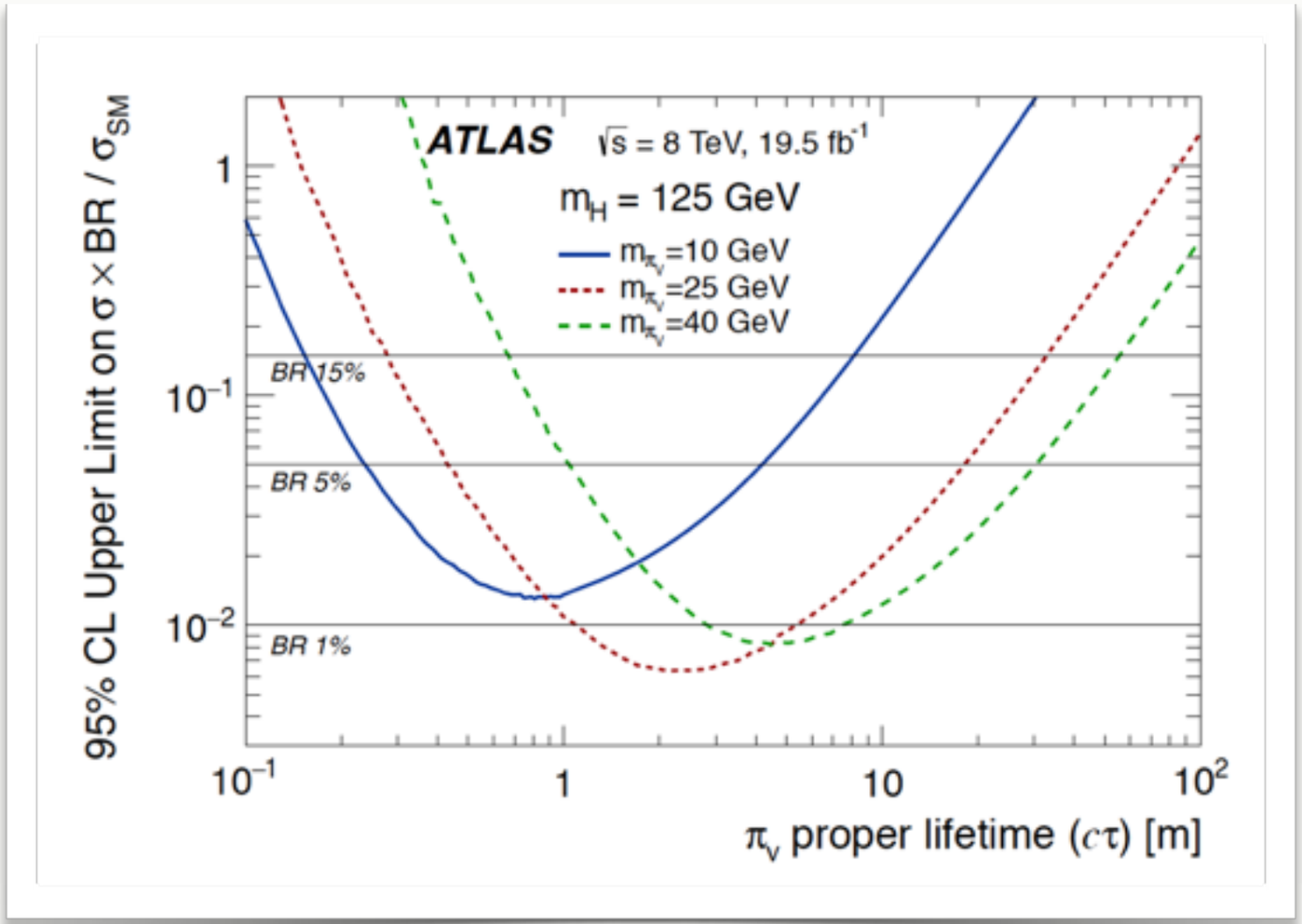
$2j$ (m_{jj}, $m_{jj\mu\mu}$ consistent with resonant origin)

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

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

Higgs decays to (pseudo-)scalars

- Displaced decays are in some ways easier: S/B

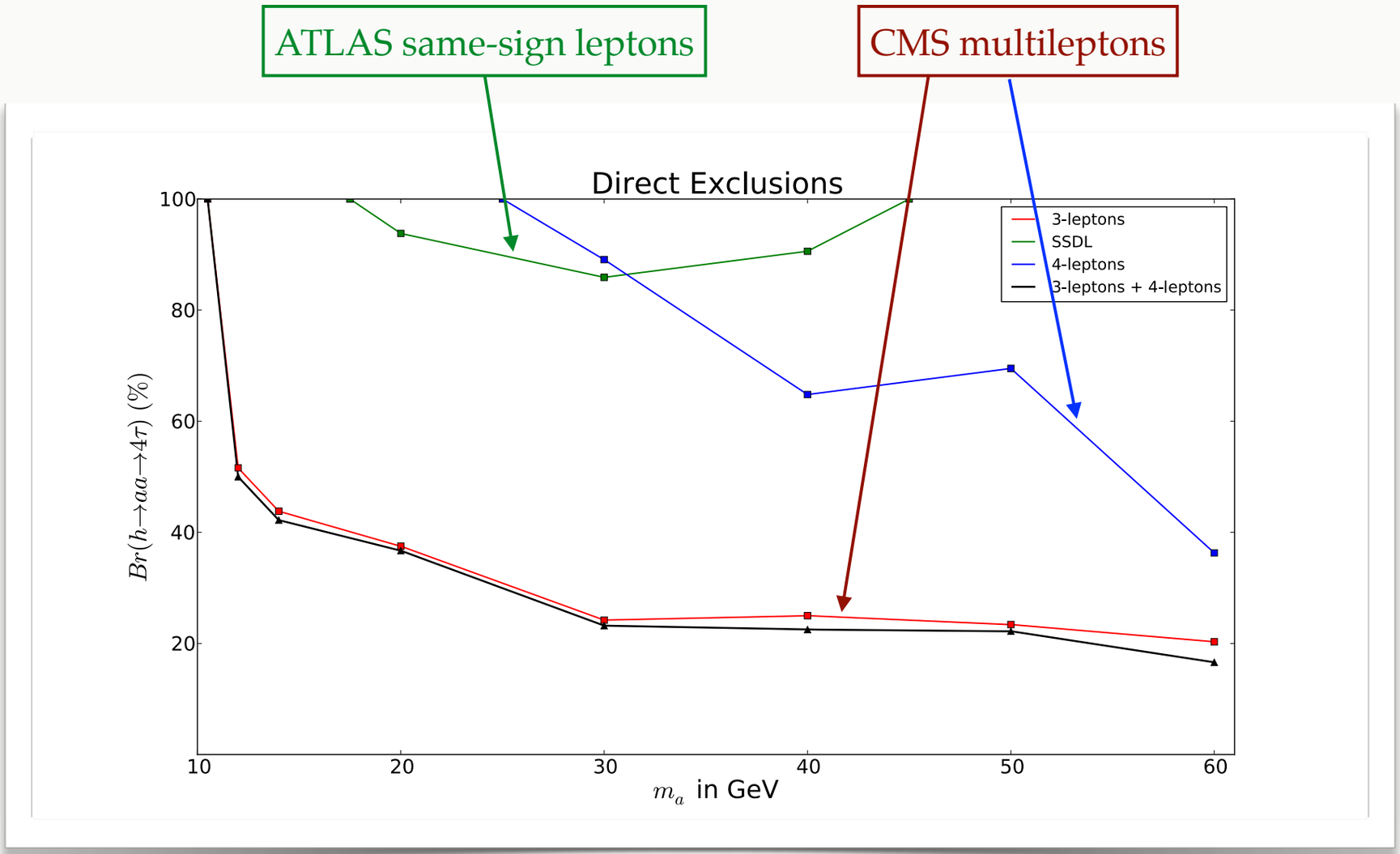


two objects decaying in muon chambers and HCAL

- but triggering and reconstruction are highly nontrivial

Higgs decays to (pseudo-)scalars

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

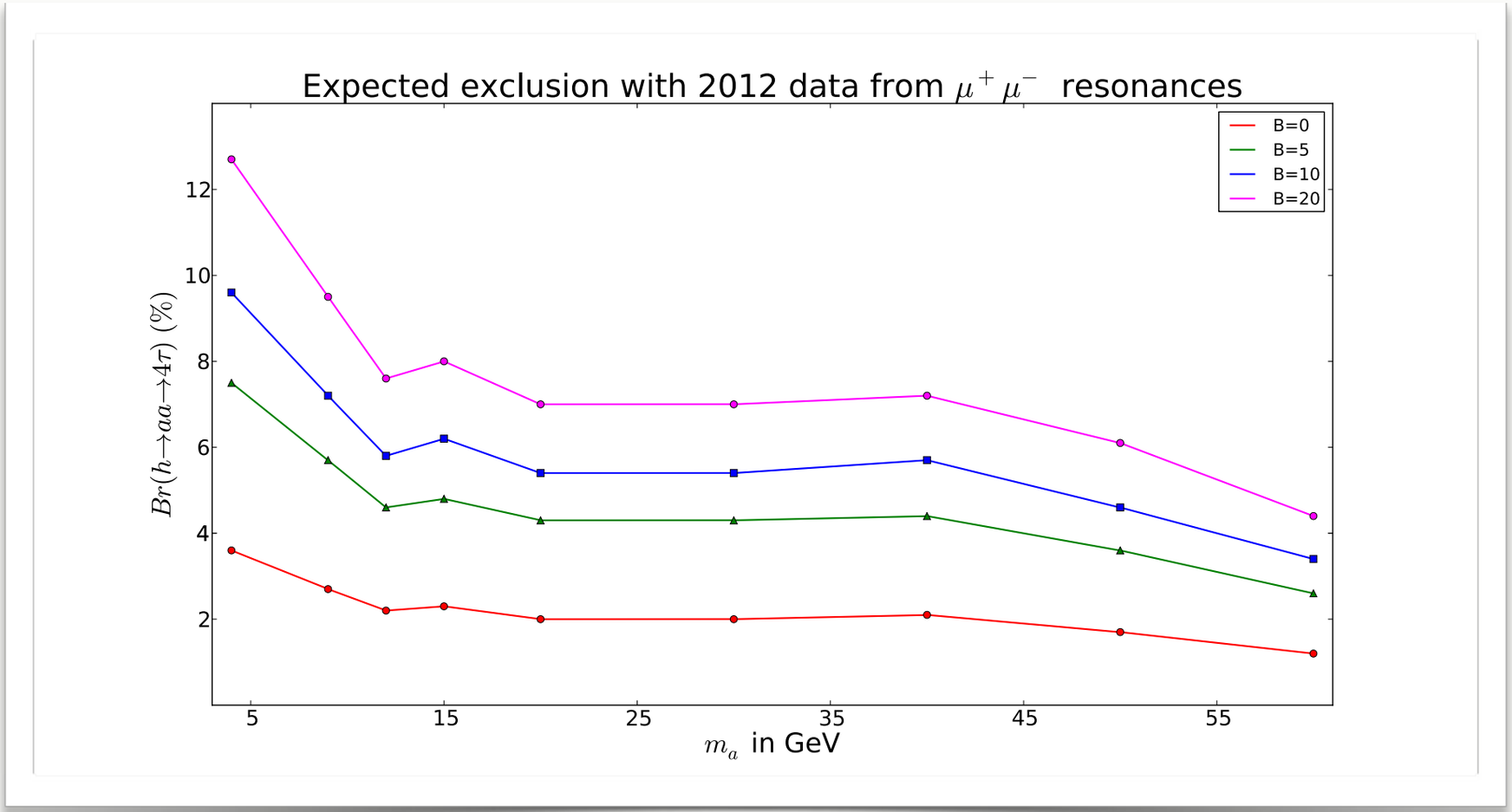


gluon fusion via leptons; binned event rates alone

[Exotic Higgs Decay Working Group: 1312.4992]

Higgs decays to (pseudo-)scalars

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

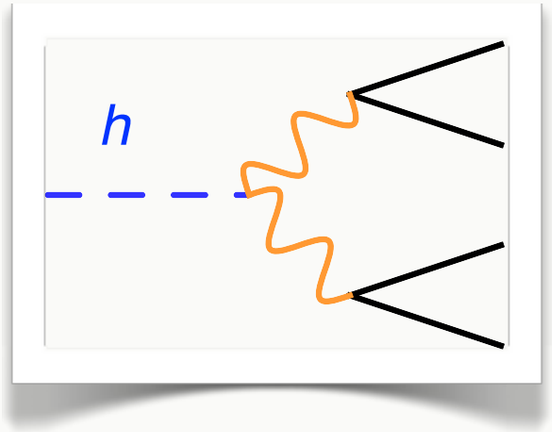


estimate of current sensitivities in a CMS-like multilepton analysis extended to incorporate dimuon mass

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

Non-minimal dark sectors

- BSM states will often prefer to decay to other dark states, if such decays are available
- A weakly-coupled example: Higgsed dark *U(1)*



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

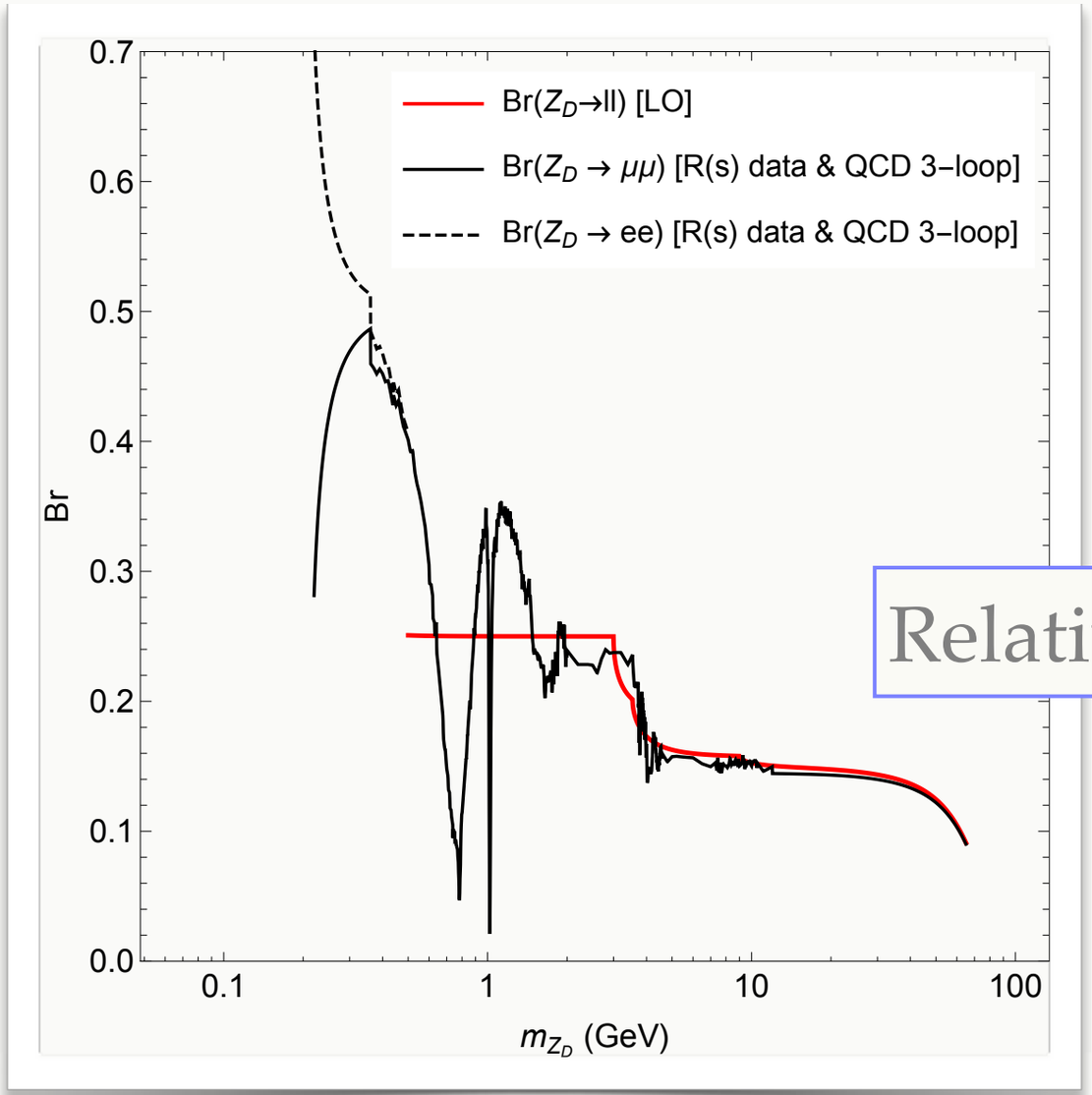
- Higgs mixing: $h \to ss$, but now $s \to Z_D Z_D$,

  $h \to Z_D Z_D$

[Gopalakrishna, Jung, Wells; ...]

A dark U(1)

- Kinetic mixing determines branching ratios of Z_D:

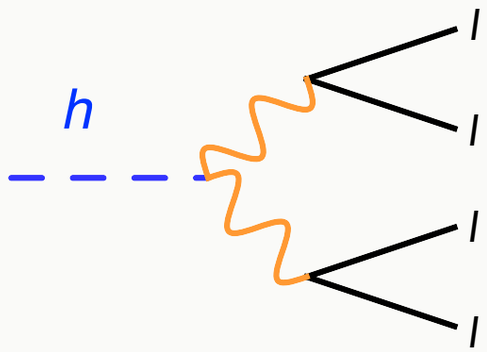


Relatively leptophilic

[Curtin, Essig, Gori, JS]

Lessons from LHC8 recasts

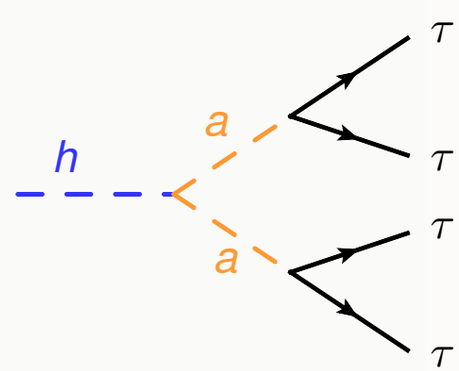
- In general prospects depend in detail on final state and range from spectacular to very hard

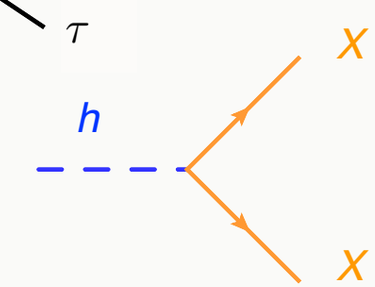


Easy: multiple resonant light leptons

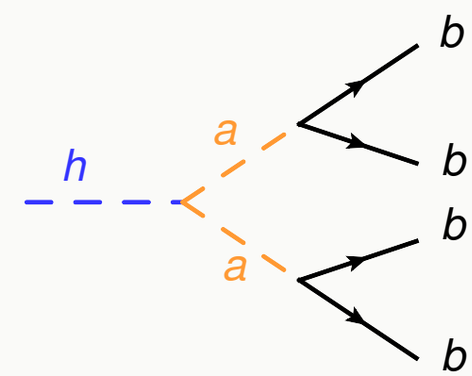
$\mathrm{Br} \lesssim 4 \times 10^{-4}$

Moderate: multiple electroweak objects, poor mass resolution





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



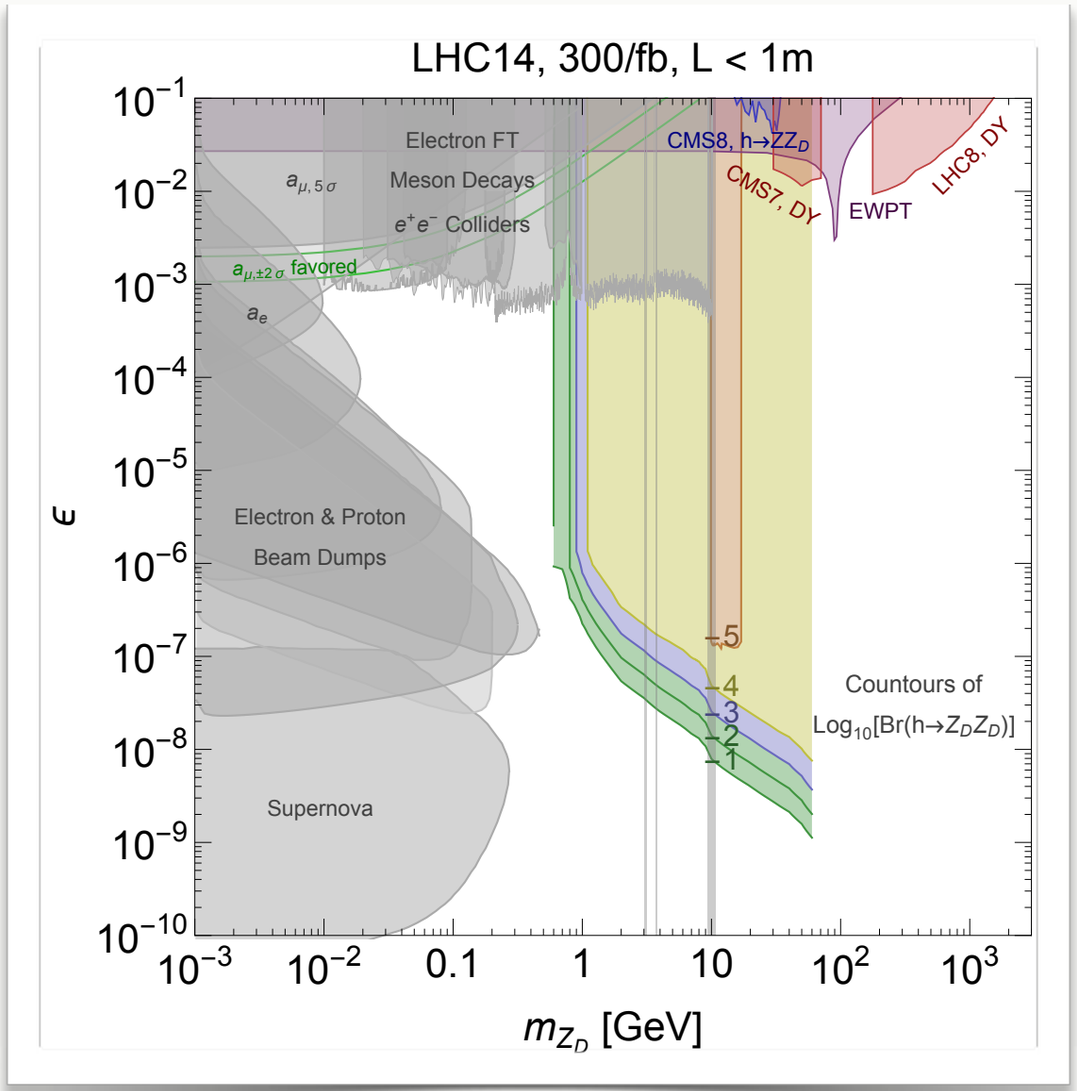
Hard: all-hadronic

$\mathrm{Br} \lesssim 0.9$

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

A dark U(1)

- Higgs portal coupling is a powerful window into dark sectors



[Curtin, Essig, Gori, JS]

Summary and conclusions

- The observed 125 GeV Higgs boson is highly sensitive to the potential existence of new light degrees of freedom
- Higgs portal couplings + BSM at weak scale are vital ingredients of many theories of cosmology, naturalness
- Already in LHC Run 1: interesting results and prospects for many exotic decay modes
- Looking forward to LHC Run 2
  - Programmatic effort: LHC Higgs Cross-section Working Group