Exotic decays of SM & BSM Higgs bosons

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UC Santa Cruz

Higgs couplings 2019

Oxford University
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Exotic Higgs signatures & open problems in particle physics

Exotic Higgs signatures & open problems in particle physics

Origin of flavor hierarchies

Higgs flavor violating decays (and productions)

1.

Origin of neutrino masses;
Origin of baryon anti-baryon asymmetry;
…

Higgs hierarchy problem

SUSY;

neutral naturalness; …

Heavy Higgs decays to new particles

3.

Origin of DM

Possible existence of a dark sector

Higgs decays to dark particles

2.

A broad topic. Apology for the omissions…

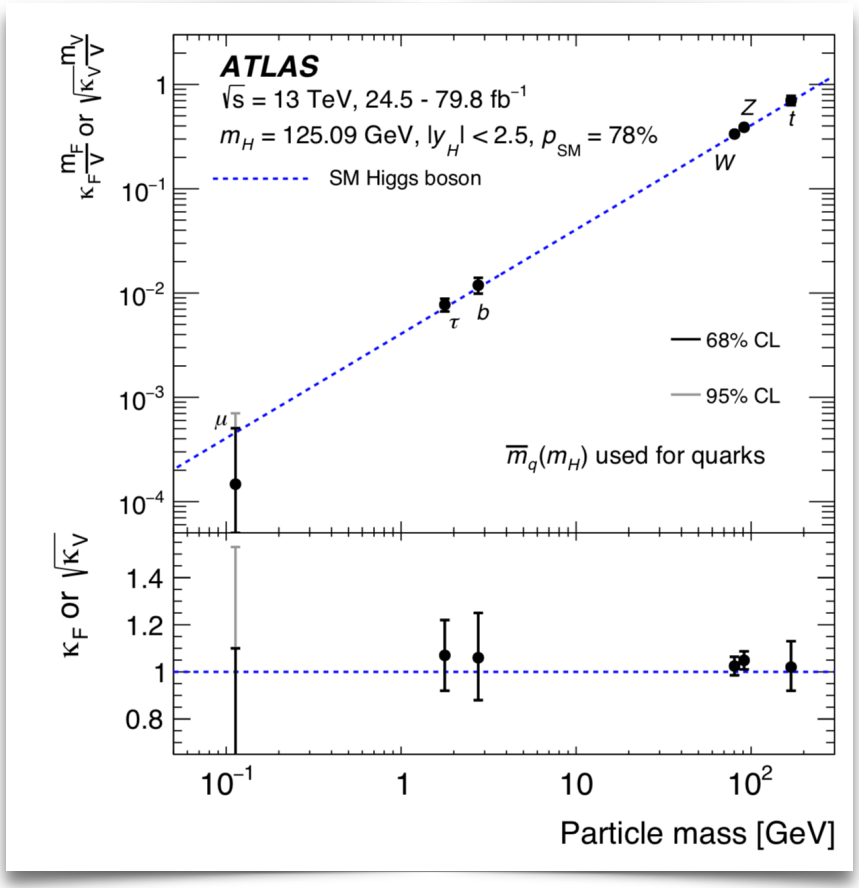
1.

Higgs and flavor

In the SM, the Higgs couplings to fermions are highly hierarchical.

Experimentally, we do not yet know if the Higgs gives mass to all quarks and leptons!

The couplings to **light generation quarks/leptons** are still very much un-known
(hee (BR ~ $5*10^{-9}$), hmumu (BR ~ $2*10^{-4}$), hcc (BR ~ 3%), hss (BR ~ $2*10^{-4}$), …)



1909.02845

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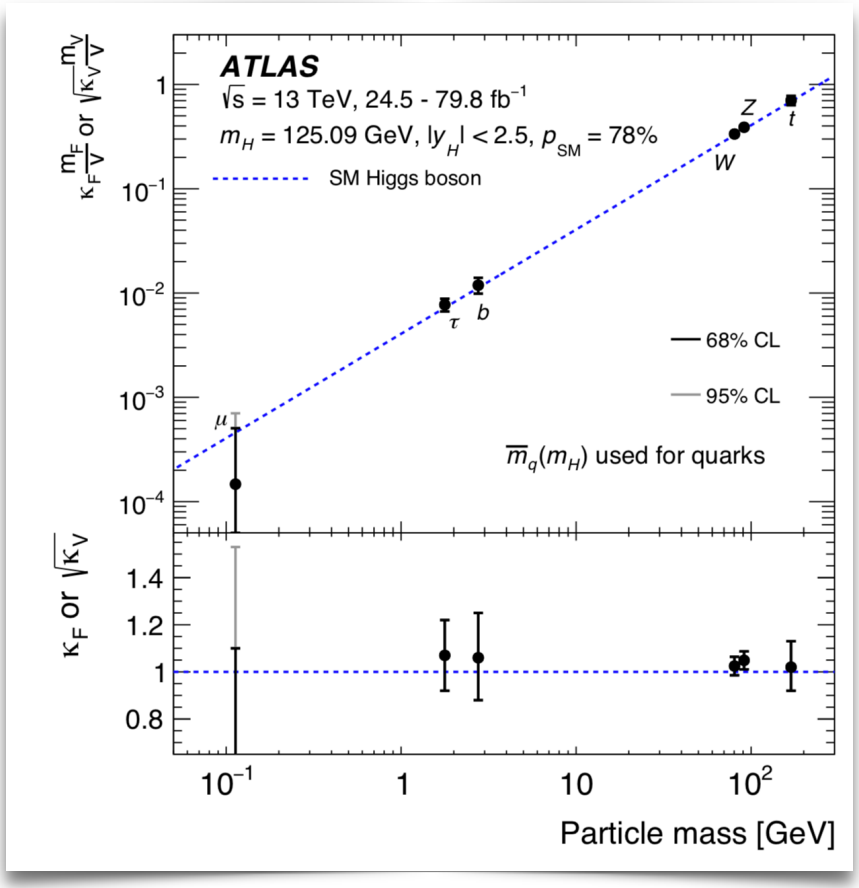

1909.02845

Flavor puzzle:

what is the origin of the large hierarchies between quark and lepton masses, as well as mixing angles?

- Is the 3rd generation special?
- Is there an approximate U(2) symmetry in Nature?
- Breaking of flavor universality?

e.g. $\frac{Y_{hcc}}{Y_{htt}} \neq \frac{m_c}{m_t}$

1.

New flavorful structures

Models with an extended Higgs sector that
- break flavor universality
- naturally generate (some) mass hierarchies

can be consistent with low energy flavor measurements

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Example

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H' \rightarrow \mathcal{M} = vY + v'Y'$$

125 Higgs (h) — Additional Higgses (H, A, $H^{\pm}$)

$(\mathcal{M}_0 + \Delta\mathcal{M})$

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927;

see also Ghosh, Gupta, Perez, 1508.01501

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

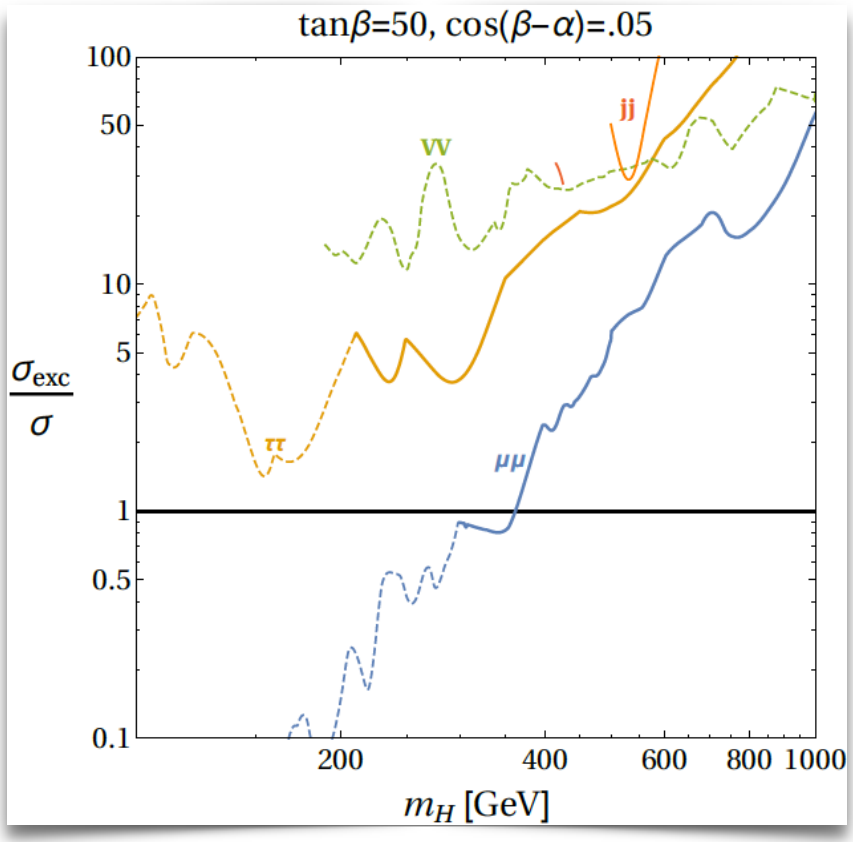
(analogous structure in the quark sector)

see also talk by G.G.Ross

- Hierarchies obtained through v>>v'
- Flavor constraints under control thanks to an approximate U(2) symmetry
- New Higgs exotic decays (flavor violating decays)

New flavorful signatures

Experimental bounds are mild



No bound beyond LEP for tanβ ≤ 12!

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

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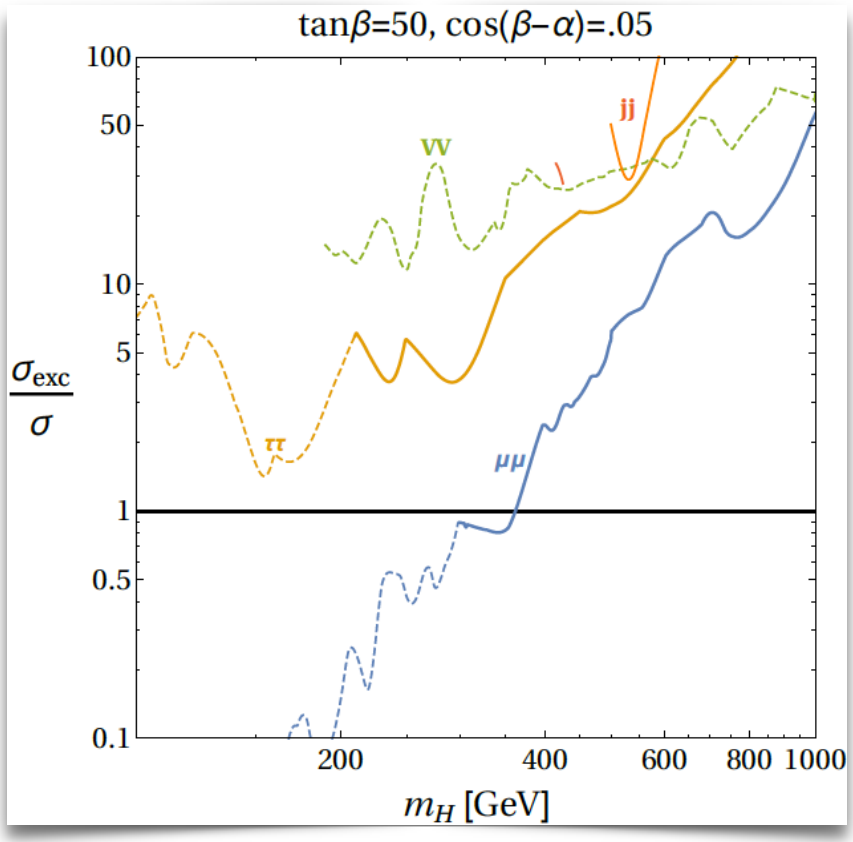

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Plenty of new signatures for the additional Higgs bosons…

Quark-quark fusion:

$$pp \to H \to cc$$
$$pp \to H \to tc$$

Top-Higgs production:

$$pp \to t(c)H,\ H \to tc$$
$$pp \to t(c)H,\ H \to cc$$
$$pp \to t(c)H,\ H \to \tau\mu$$

Charged Higgs:

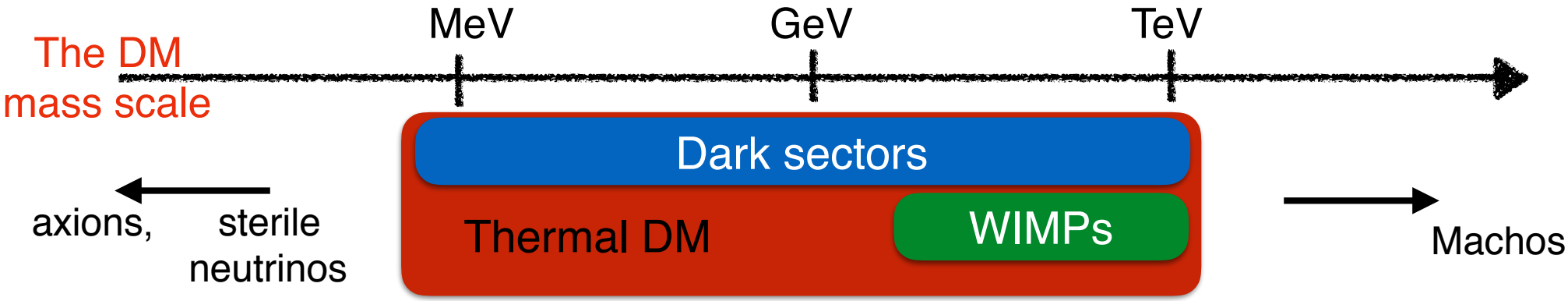
$$pp \to H^\pm \to Wh$$
$$pp \to H^\pm \to cs,\ cb$$
$$pp \to tH^\pm,\ H^\pm \to cs,\ cb$$

…and of the SM-like Higgs

$$pp \to h \to \tau\mu$$

2.

(Thermal) dark matter



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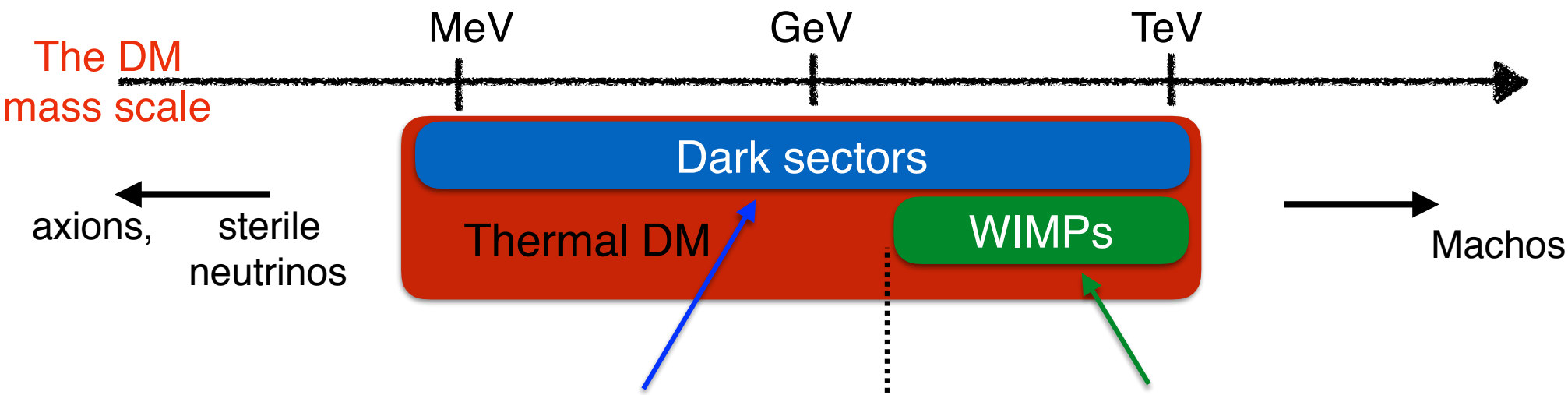


Neutral under the SM interactions.
Annihilate through **new interactions**

Annihilate through
weak interactions

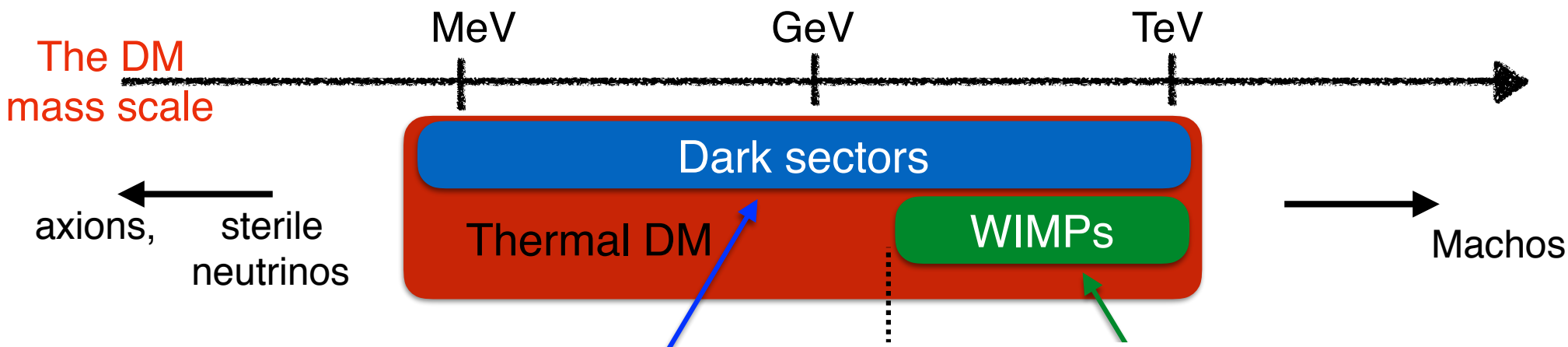
Lee-Weinberg bound
(~ few GeV)

Need for new particles in addition to DM

dark sector

2.

(Thermal) dark matter



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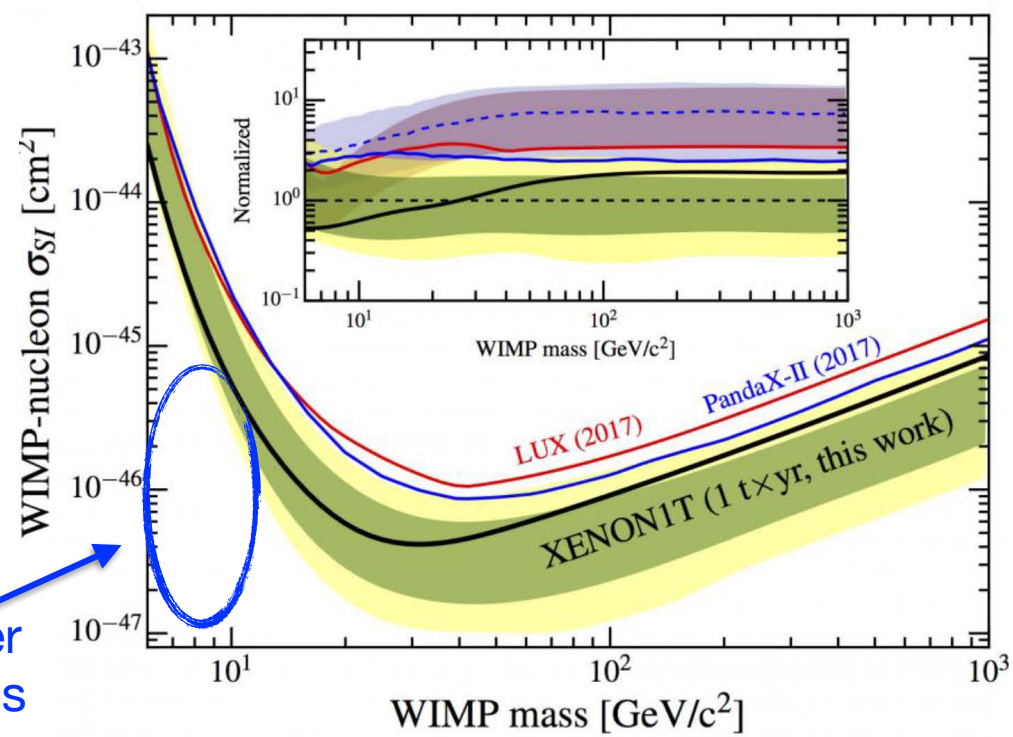

weaker bounds

A typical signature: Higgs exotic decays

2.

We can write down only a limited set of renormalizable operators connecting SM particles to dark particles:

$$B_{\mu\nu}F'_{\mu\nu},\ |H|^2|S|^2,\ HLN$$

dark photon, dark Higgs, dark neutrino

A typical signature: Higgs exotic decays

2.

We can write down only a limited set of renormalizable operators connecting SM particles to dark particles:

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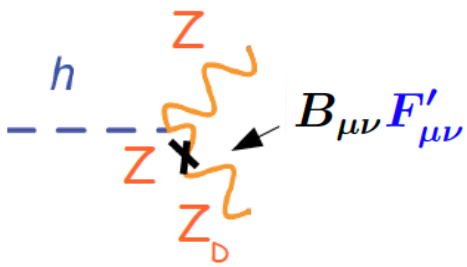
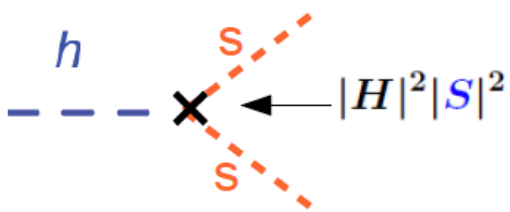
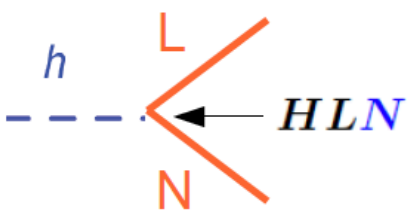
$h \to ZZ_D$



$h \to ss$



$h \to LN$



Typical signatures:

Multi-(resonant) leptons
Multi-(resonant) leptons + MET

Multi-quark/lepton resonances, typically involving heavy flavor

(Multi) lepton + MET

Easy to obtain sizable branching ratios (SM Higgs width is tiny!)

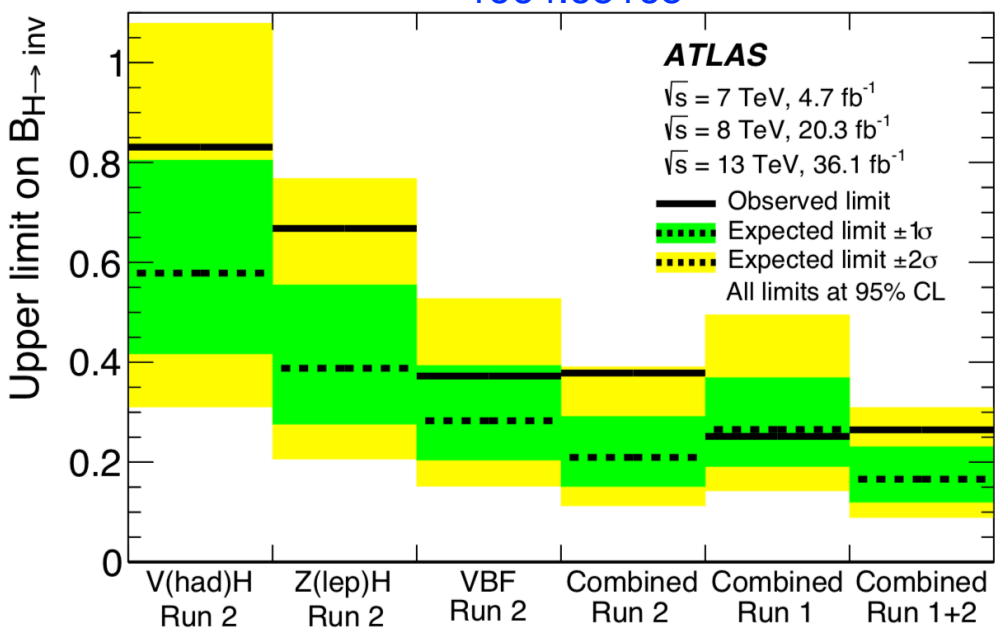
Crucial to cast a wide net of searches!

2.

Higgs invisible signatures

$h \to$ dark particles $\to$ MET

1904.05105



BR Higgs decay to invisible particles (DM?) is constrained to be <~ 25%

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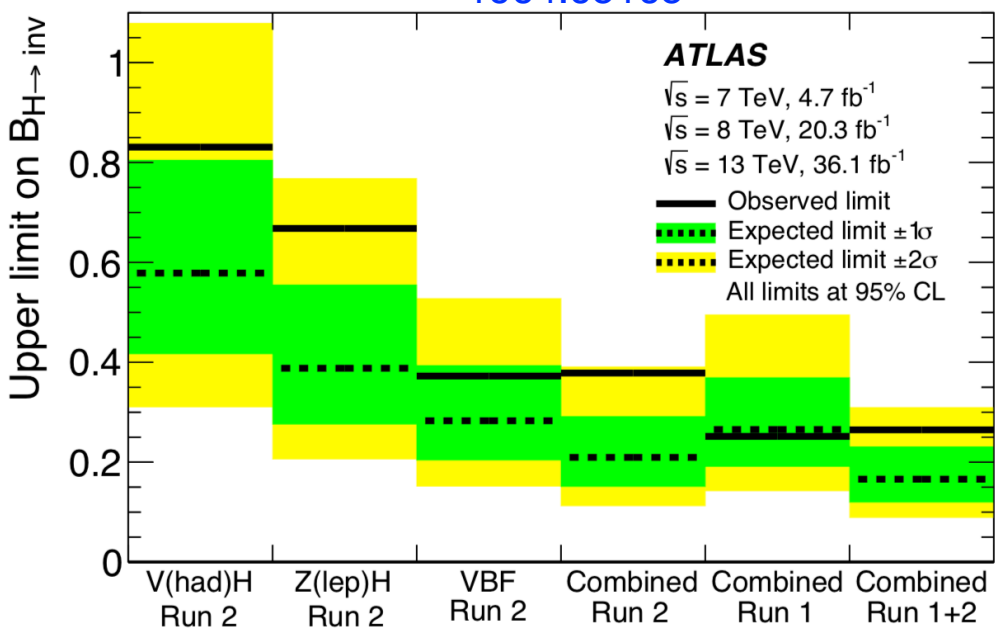
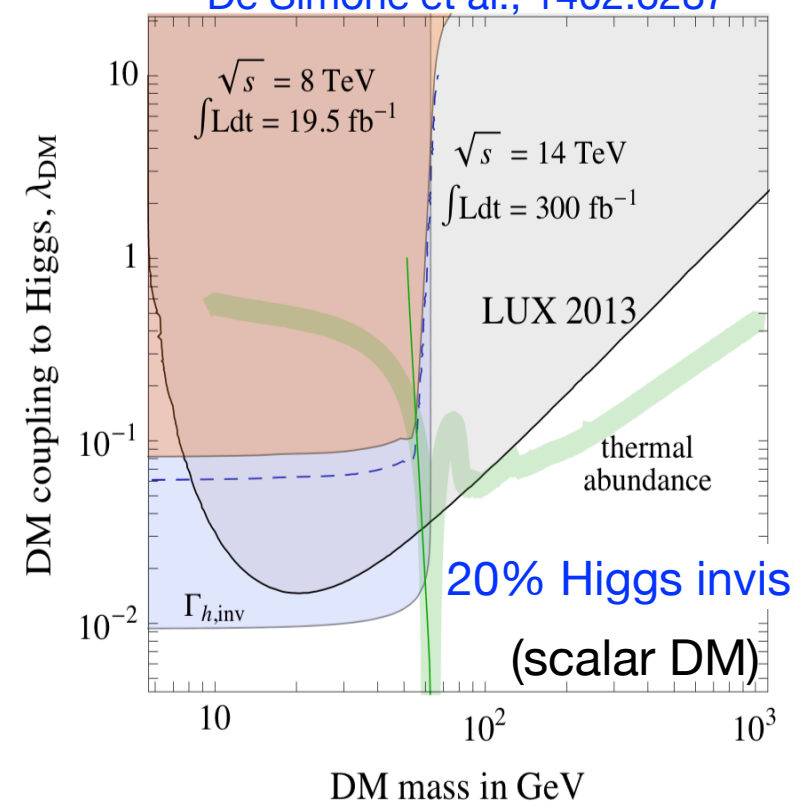


BR Higgs decay to invisible particles (DM?) is constrained to be <~ 25%

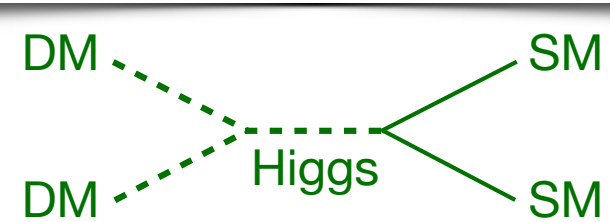
This result fully constrains purely Higgs-mediated DM models!

De Simone et al., 1402.6287



20% Higgs invisible BR

(scalar DM)



Characterizing prompt visible channels

2.

For a comprehensive list of 2-body decays leading to prompt signatures + present/future LHC bounds:

Exotic decays of the 125 GeV Higgs boson 1312.4992

David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

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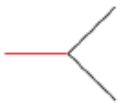
1312.4992

$h \to$ dark particle dark particle $\to$ visible



Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
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	$h \to (\tau^+\tau^-) + \not{E}_T$
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	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
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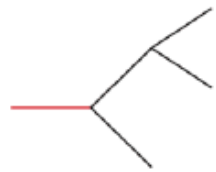

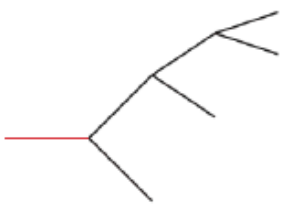

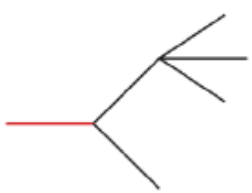

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	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
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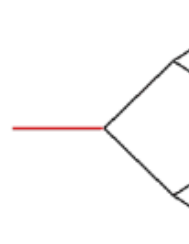
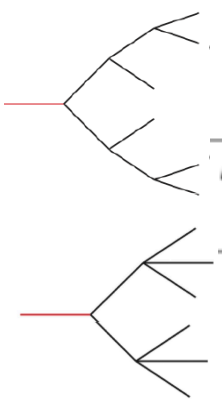
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$





From Z. Liu

Characterizing prompt visible channels

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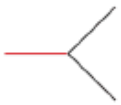
1312.4992

$h \to$ dark particle dark particle $\to$ visible



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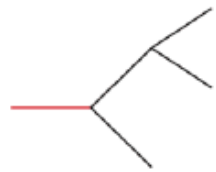

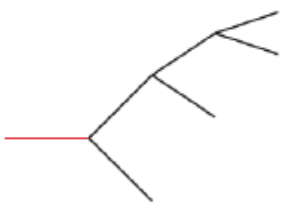

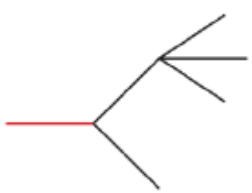

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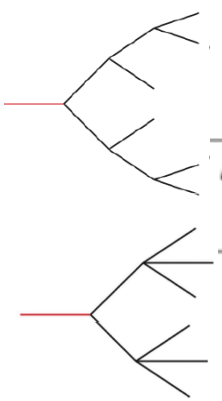


Great reach at the LHC/future hadron colliders (clean signatures)

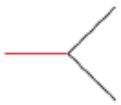
From Z. Liu

Characterizing prompt visible channels

2.

1312.4992

$h \to$ dark particle dark particle $\to$ visible



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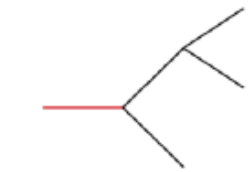

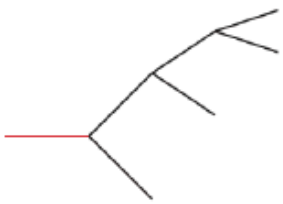

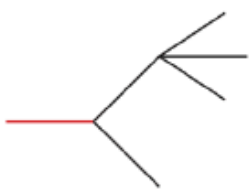

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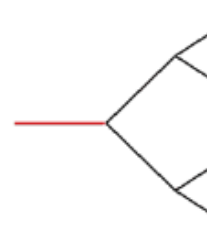
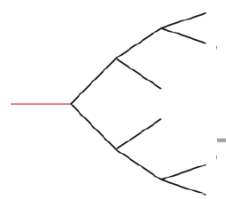
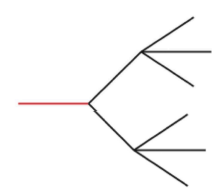
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$







From Z. Liu

Great reach at the LHC/future hadron colliders (clean signatures)

Background limited signatures (hadronic/with MET). Interplay with future e^+e^- colliders

2.

Decays to long-lived particles

Depending on the strength of the interaction between the dark sector and the SM, the dark sector particle can be long-lived.

Nothing so exotic. We have plenty of long-lived particles in the SM.

$h \to XX$ (+ MET), X = long-lived

Challenging decays to search for.

Low trigger thresholds needed and/or sub-leading Higgs production modes.

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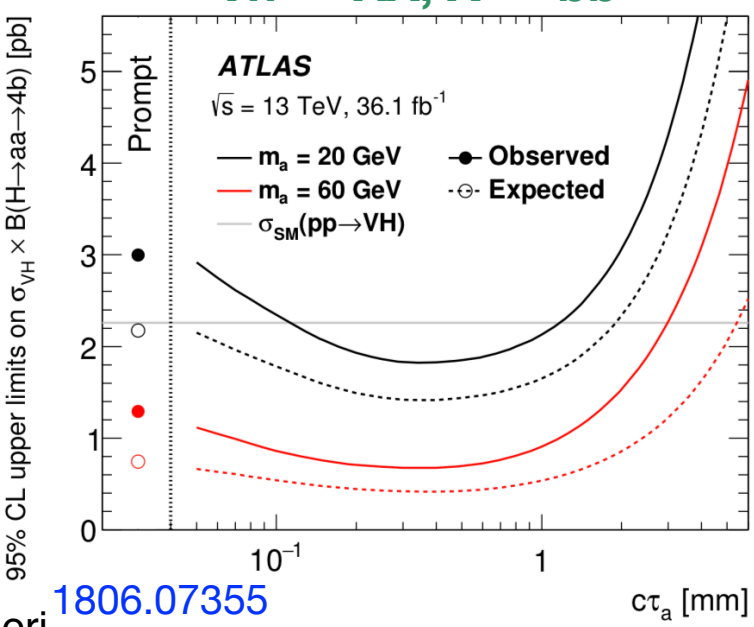
A few searches have been already performed.

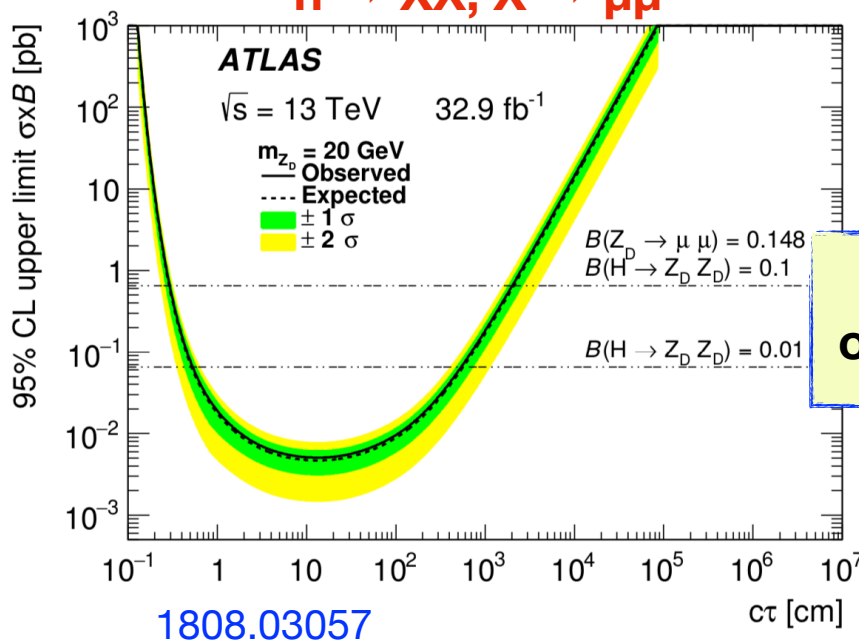
For example:

Vh → XX, X → bb



1806.07355

h → XX, X → μμ



1808.03057

Many more opportunities!

The hierarchy problem & new Higgs bosons

Many models that can (at least partially) address the hierarchy problem contain several Higgs bosons:

- SUSY: MSSM: 2 charged scalars, 1 pseudoscalar, 2 scalars; NMSSM: …
- Neutral naturalness models: fraternal twin Higgs: 2 scalars; …

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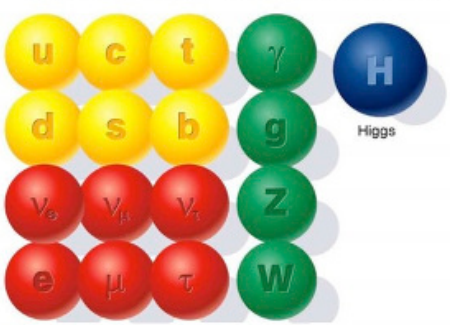
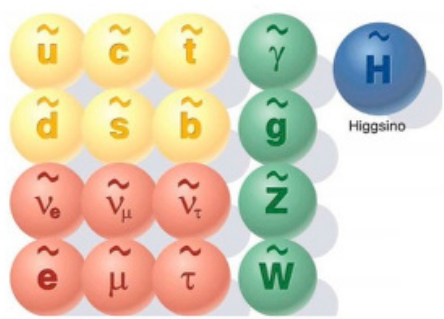
- Neutral naturalness models: fraternal twin Higgs: 2 scalars; …

+ several additional new particles:
stops, sleptons, charginos, neutralinos, …; twin tops, twin Z, glue-balls, …

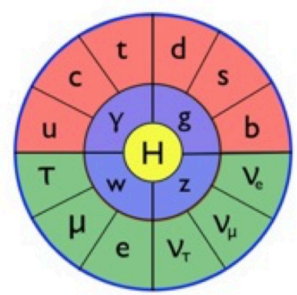
SM



MSSM

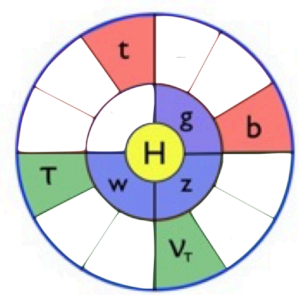


SM



SU(3) × SU(2)

Fraternal twin



SU(3)' × SU(2)'

S.Knapen

Some of these particles are relatively hidden to experimental searches for direct production. Examples: staus, glue-balls, …

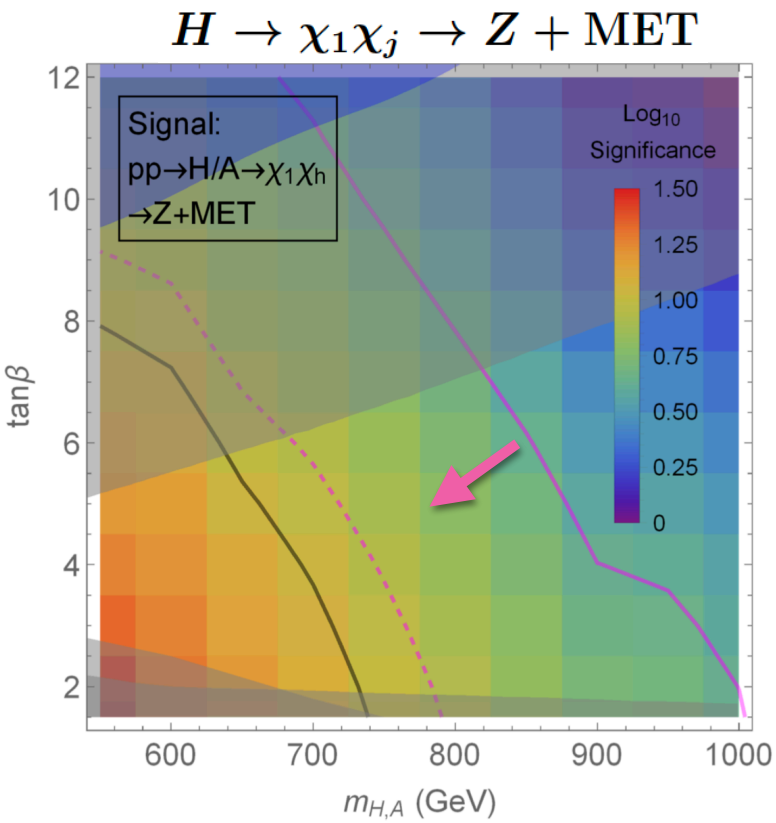
Can these particles be copiously produced from the decay of the new Higgs bosons?

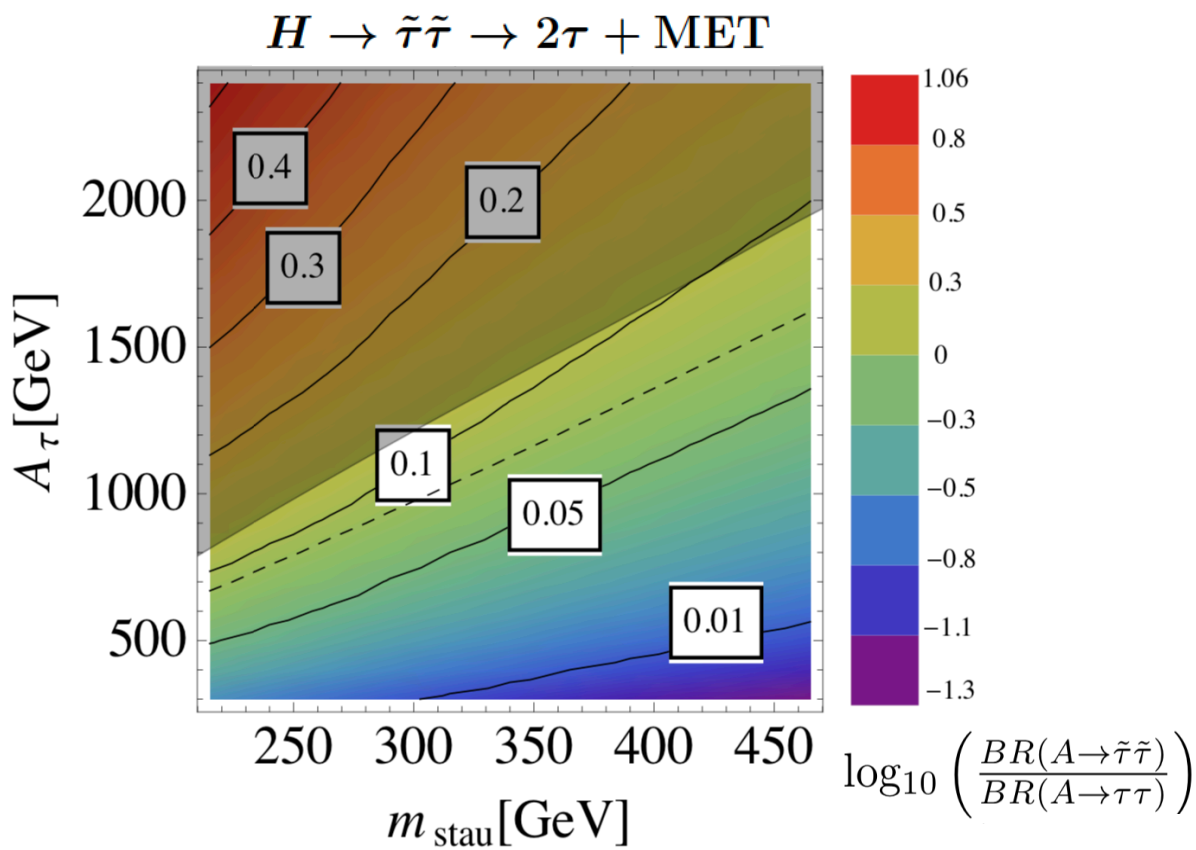
The heavy H portal to SUSY EW particles

Extensive literature. What are the most promising channels?

A couple of examples…

SG, Liu, Shakya, 1811.11918





More room to study exotic SUSY signatures of H, especially in extended SUSY models

+ “Higgs to higgs decays”. e.g. H → h A, …

3.

Twin Higgs exotic decays

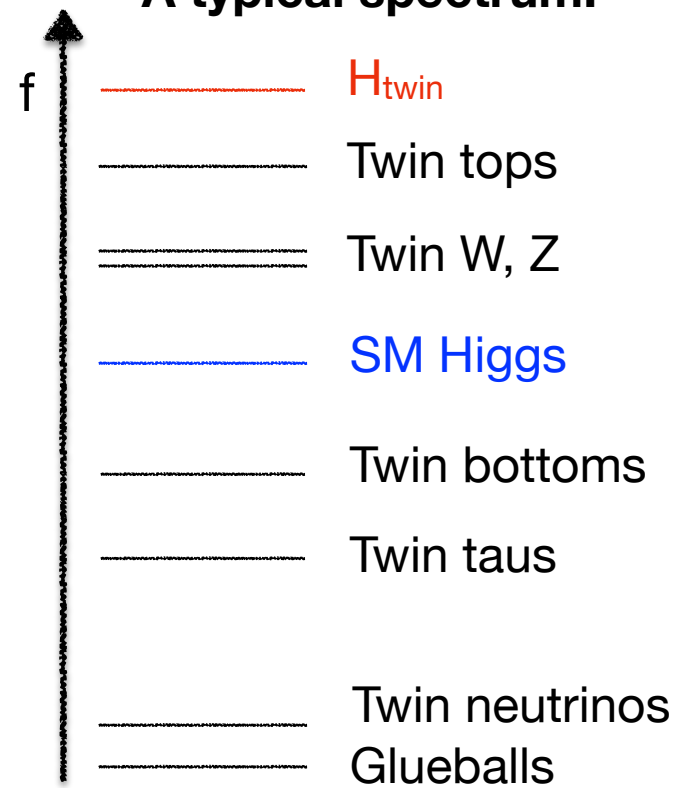
$SM_A \times SM_B \times Z_2$

$$V = \lambda \left(|H_A|^2 + |H_B|^2\right)^2 - m^2 \left(|H_A|^2 + |H_B|^2\right) + \kappa \left(|H_A|^4 + |H_B|^4\right) + \tilde{\mu}^2 |H_A|^2 + \rho |H_A|^4$$

~ SM doublet

$$|\langle H_A \rangle|^2 + |\langle H_B \rangle|^2 = f^2$$

A typical spectrum:



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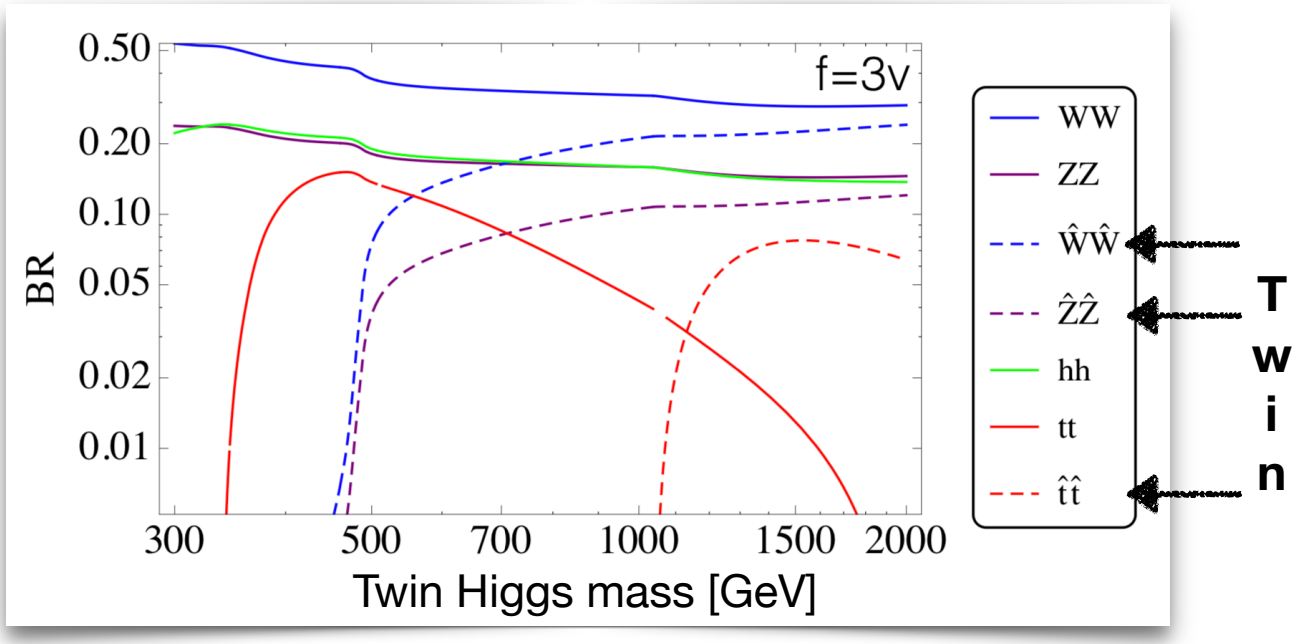
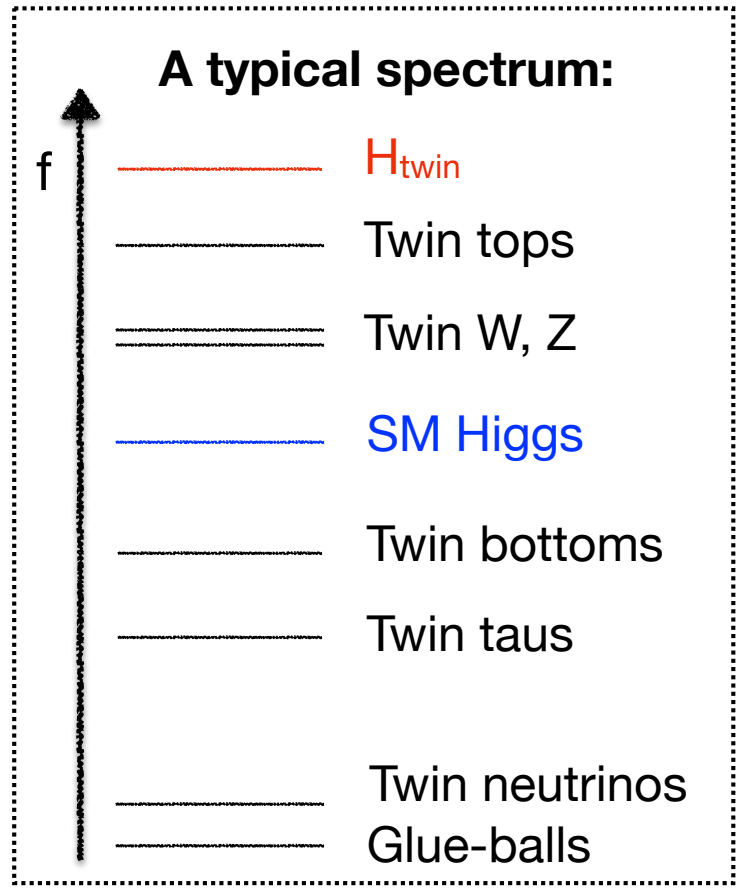


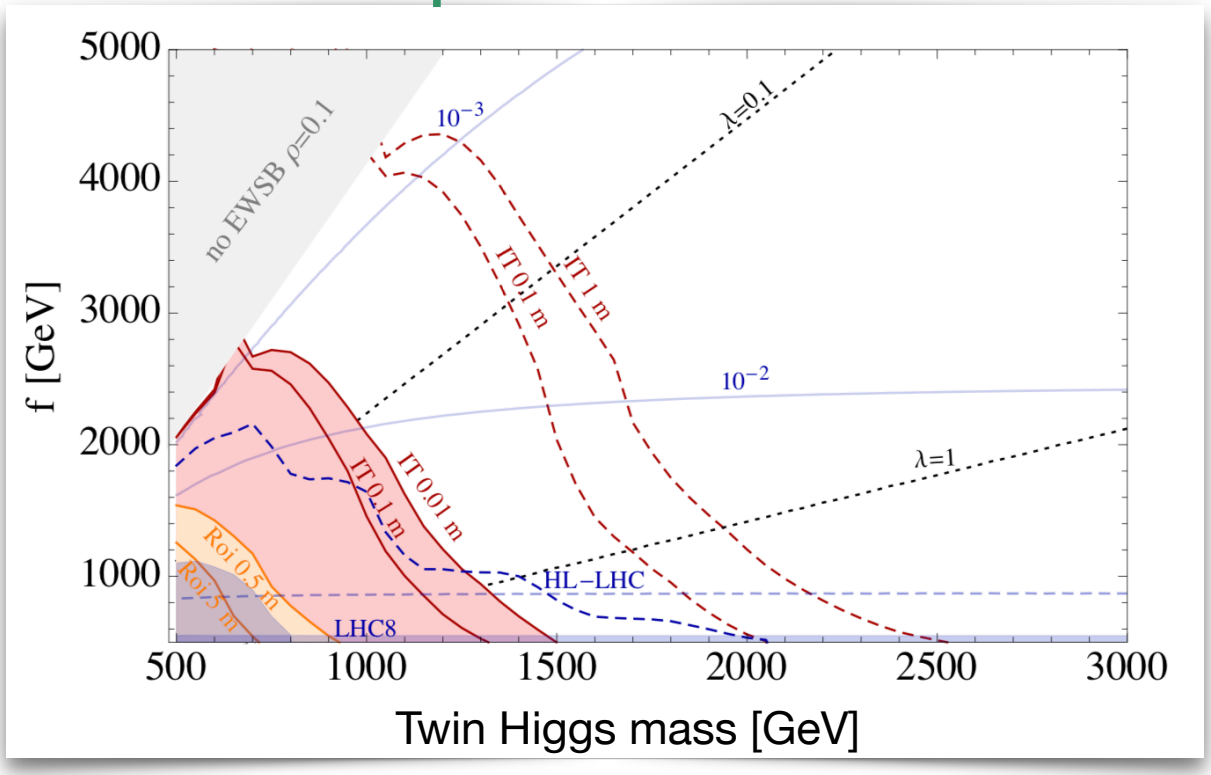
N.Craig



Twin particles undertake cascade decays to (typically) long lived glue-balls

Prompt vs. long-lived decays

Prospects for the HL-LHC



Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

Prompt vs. long-lived decays

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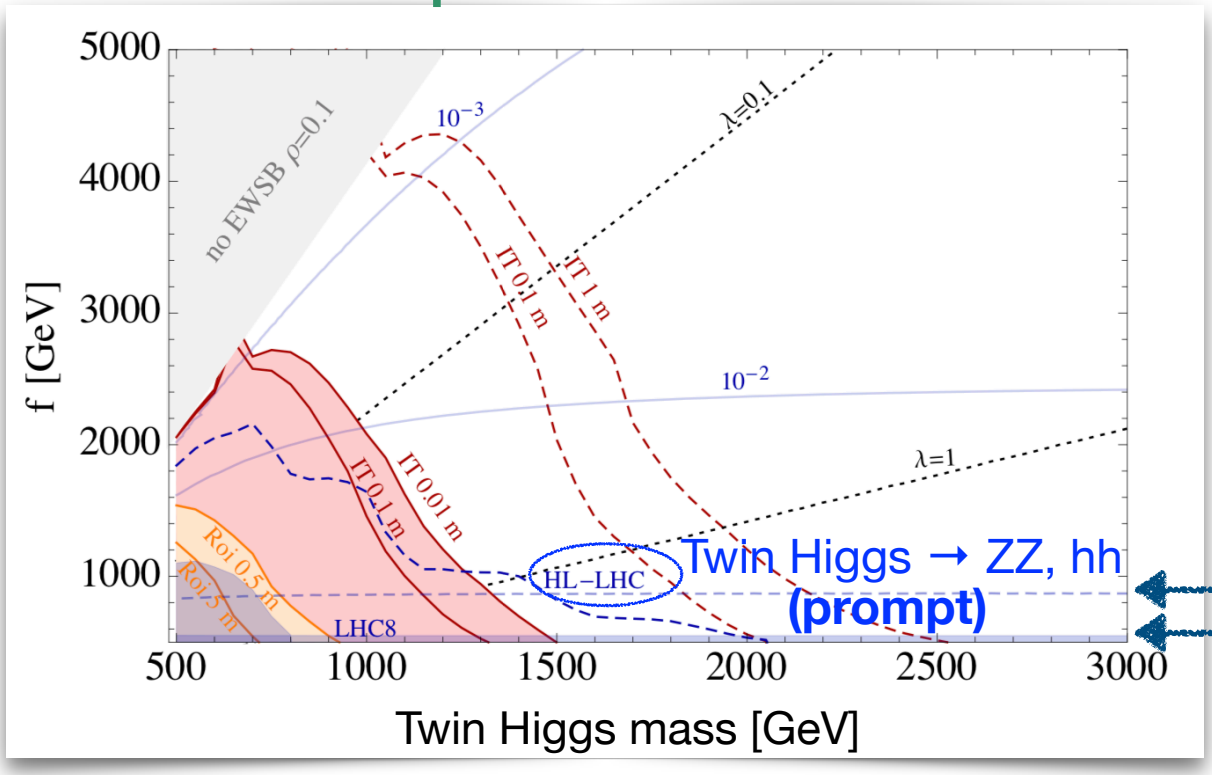
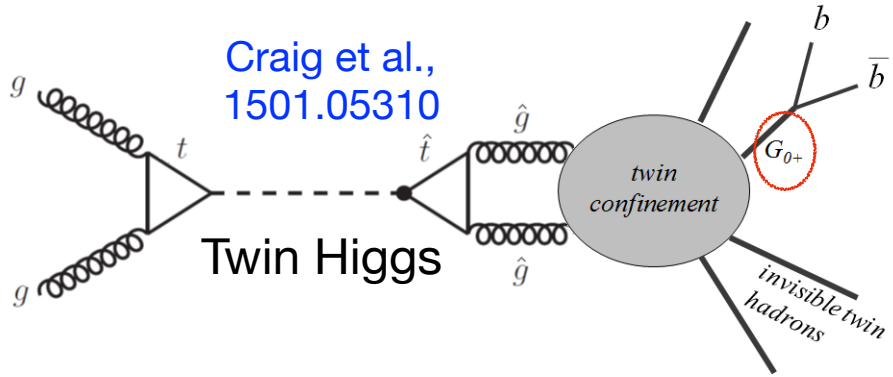


125 GeV Higgs coupling measurements

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

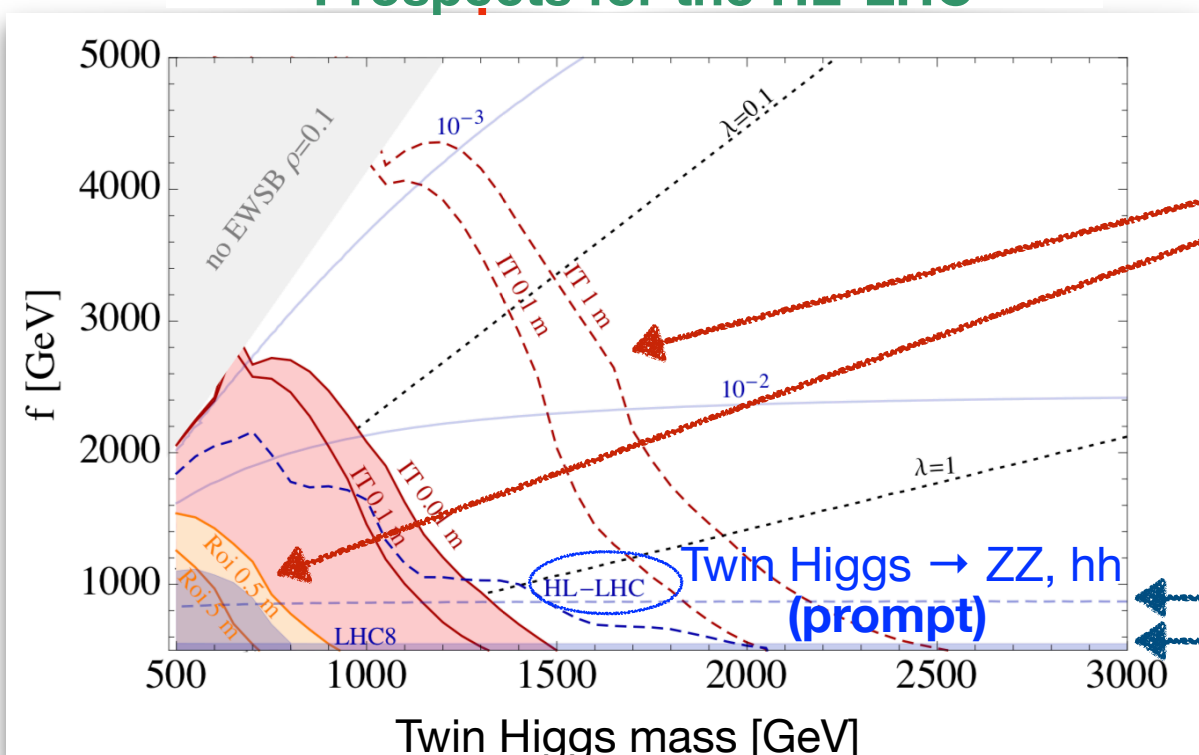
Prompt vs. long-lived decays



Glue-ball.
0^{++} mixes with the 125 GeV Higgs and decays typically displaced.

Theory: more work to be done to compute rates!

Prospects for the HL-LHC



Twin Higgs → glue-balls:
(long lived)
CMS inner tracker analysis;
ATLAS muon spectrometer analysis

125 GeV Higgs coupling measurements

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

Conclusions & outlook

The most important open problems in particle physics motivate models that naturally predict exotic decays of the 125 GeV Higgs / additional Higgs bosons.

Flavor puzzle

Dark Matter

Neutrino masses;
Baryon anti-baryon asymmetry;
…

Higgs hierarchy problem

- Higgs flavor violating decays.
- 125 GeV Higgs decay to light dark particle.
- Heavy Higgs bosons decaying to SUSY/twin particles.

Many experimental opportunities to discover exotic signatures.

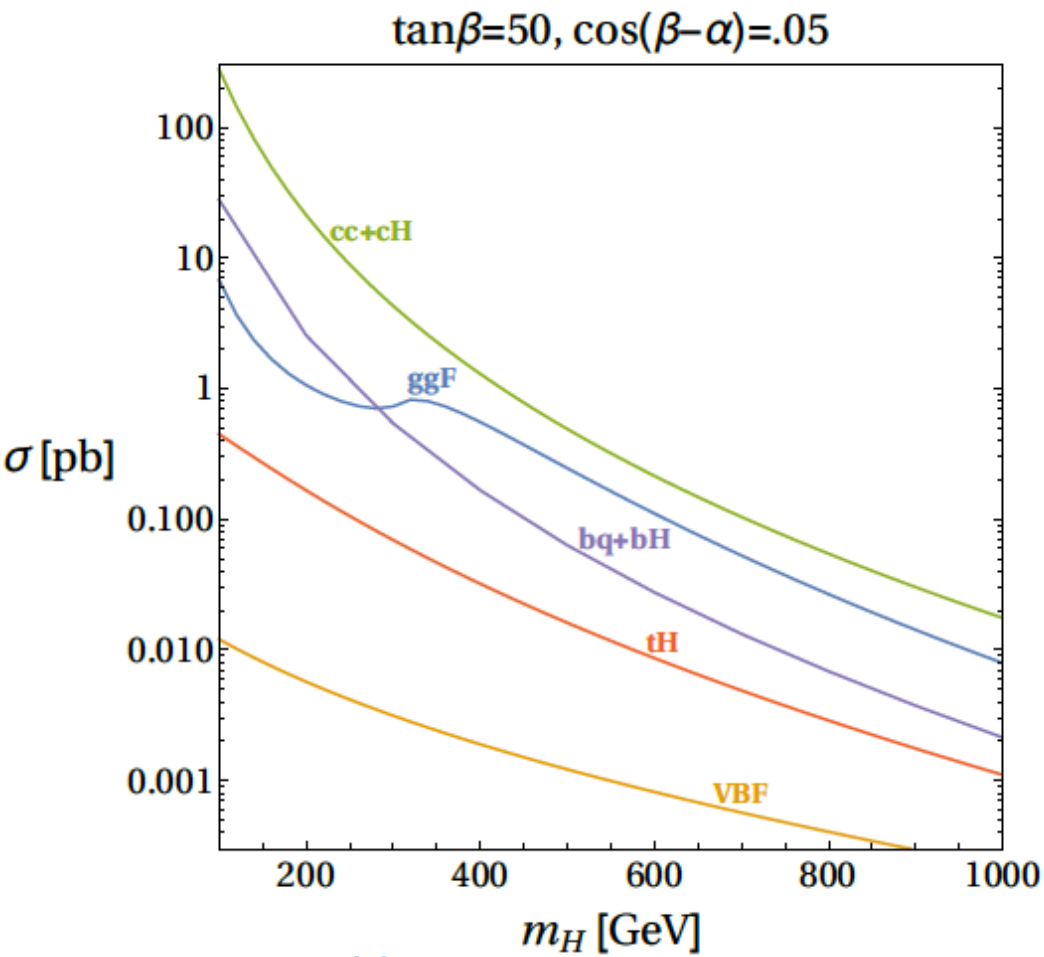
Flavor non universality

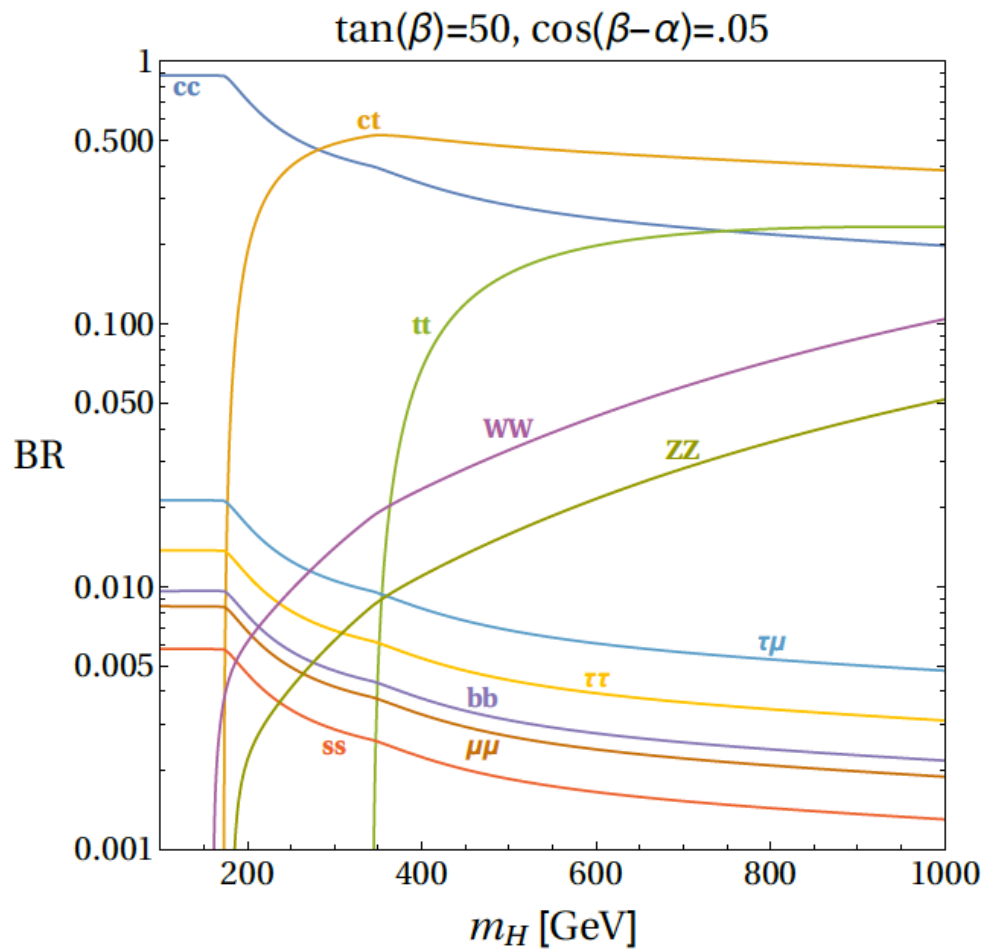
Comparing to the other flavor structures…

	W,Z κ_V^H	up quarks $\kappa_t^H,\ \kappa_c^H,\ \kappa_u^H$	down quarks $\kappa_b^H,\ \kappa_s^H,\ \kappa_d^H$	leptons $\kappa_\tau^H,\ \kappa_\mu^H,\ \kappa_e^H$
2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
Flavorful 2HDM	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$

In the flavorful 2HDM there are additional corrections to the κ's of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$

Production & decays of the scalar H



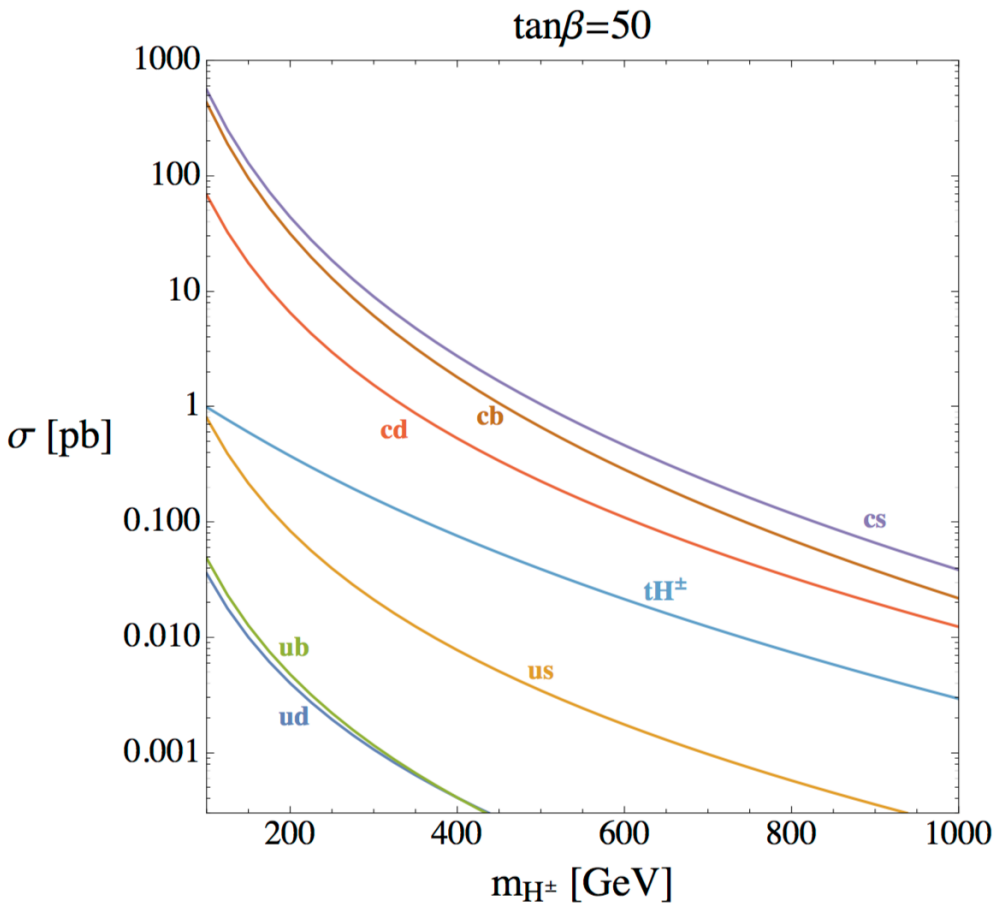


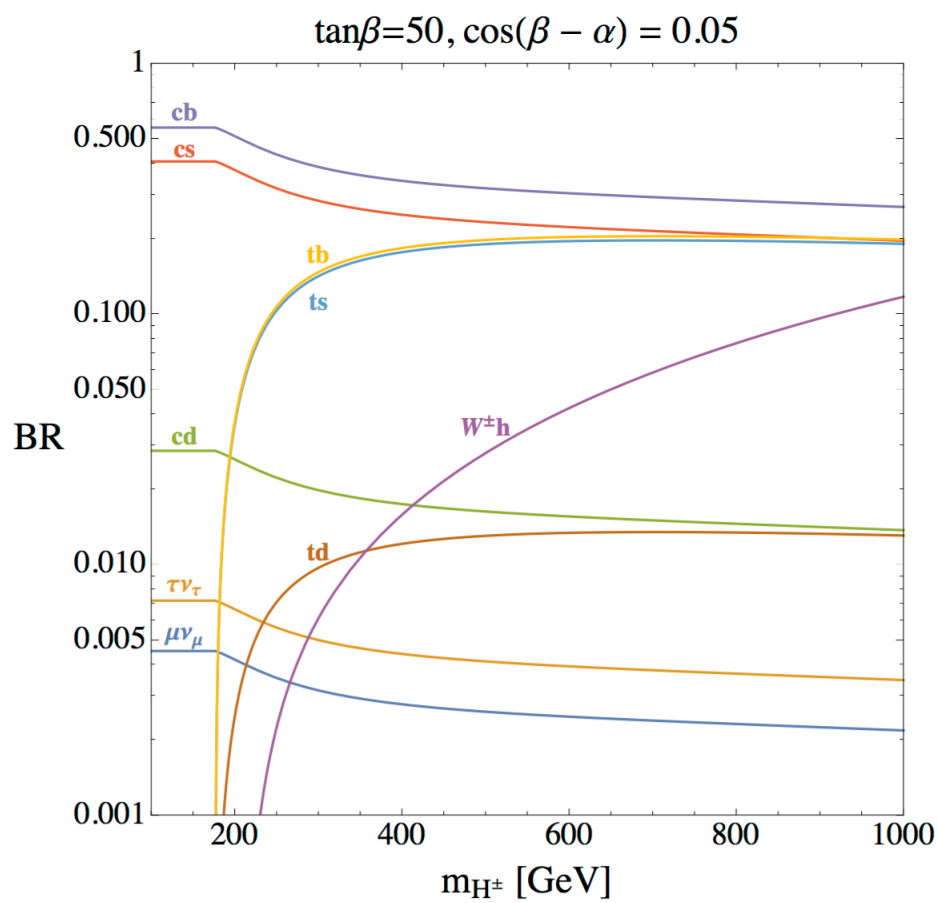
Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

bH typically suppressed, if compared to Type II 2HDMs

The branching ratio to the "golden" channel, τ τ, is suppressed

Production & decays of the scalar H±





Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

s-channel production (quark-quark fusion) is the dominant one

The branching ratio to the "golden" channels, tb, τν, are suppressed

Higgs width and exotic decays

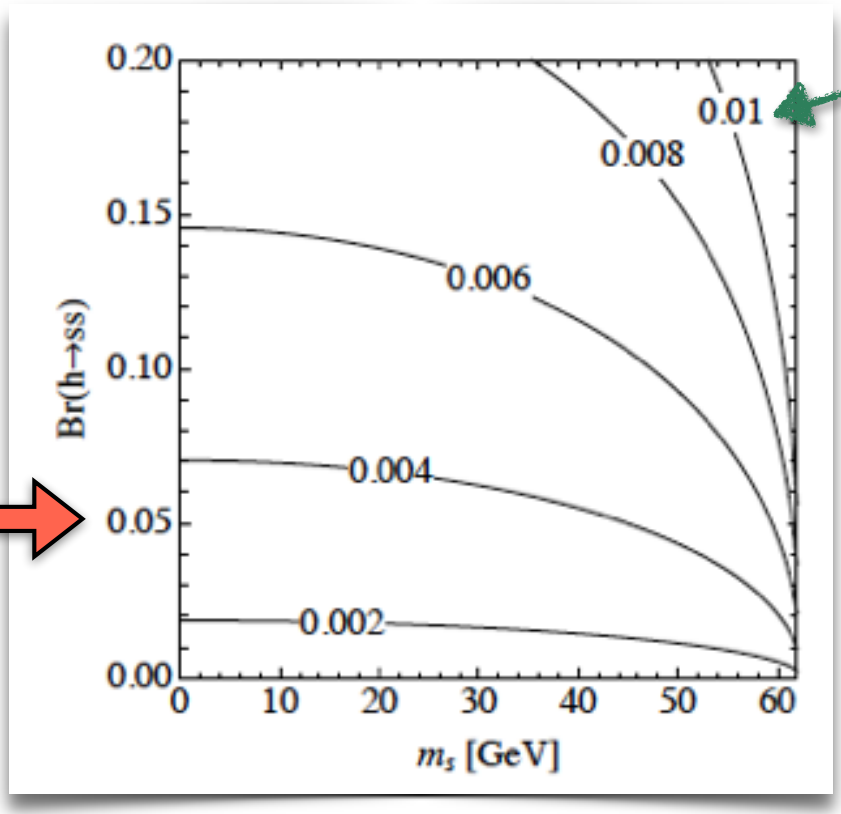
The SM Higgs width is tiny: ~4 MeV

(and challenging to measure directly at hadron colliders)

If a BSM theory contains light dark particles, sizable branching ratios for the Higgs decaying into dark particles is a generic prediction

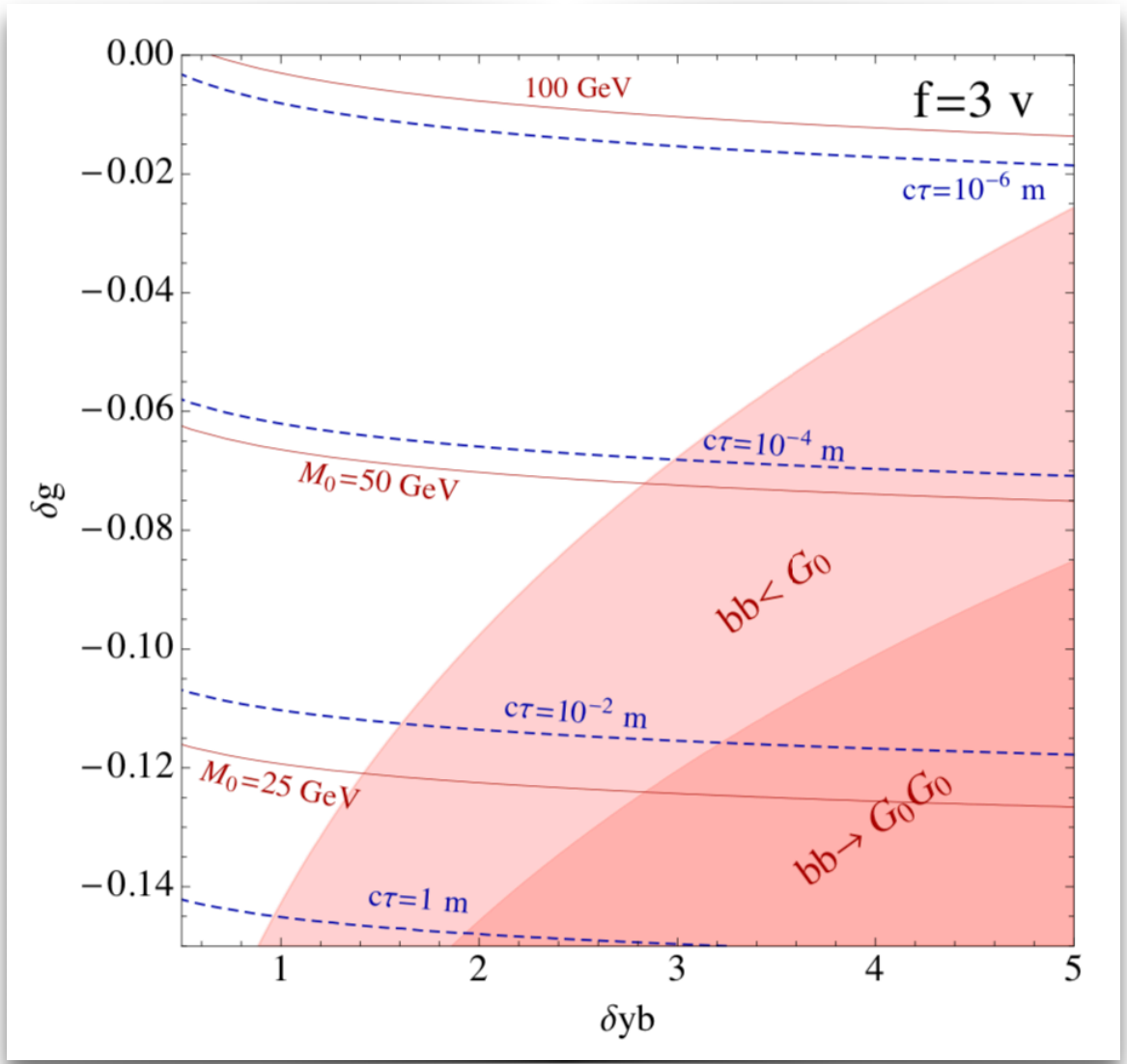
Example:

$$\frac{\xi}{2}|S|^2|H|^2$$



Value of ξ needed for the corresponding BR

Glue-balls in twin Higgs

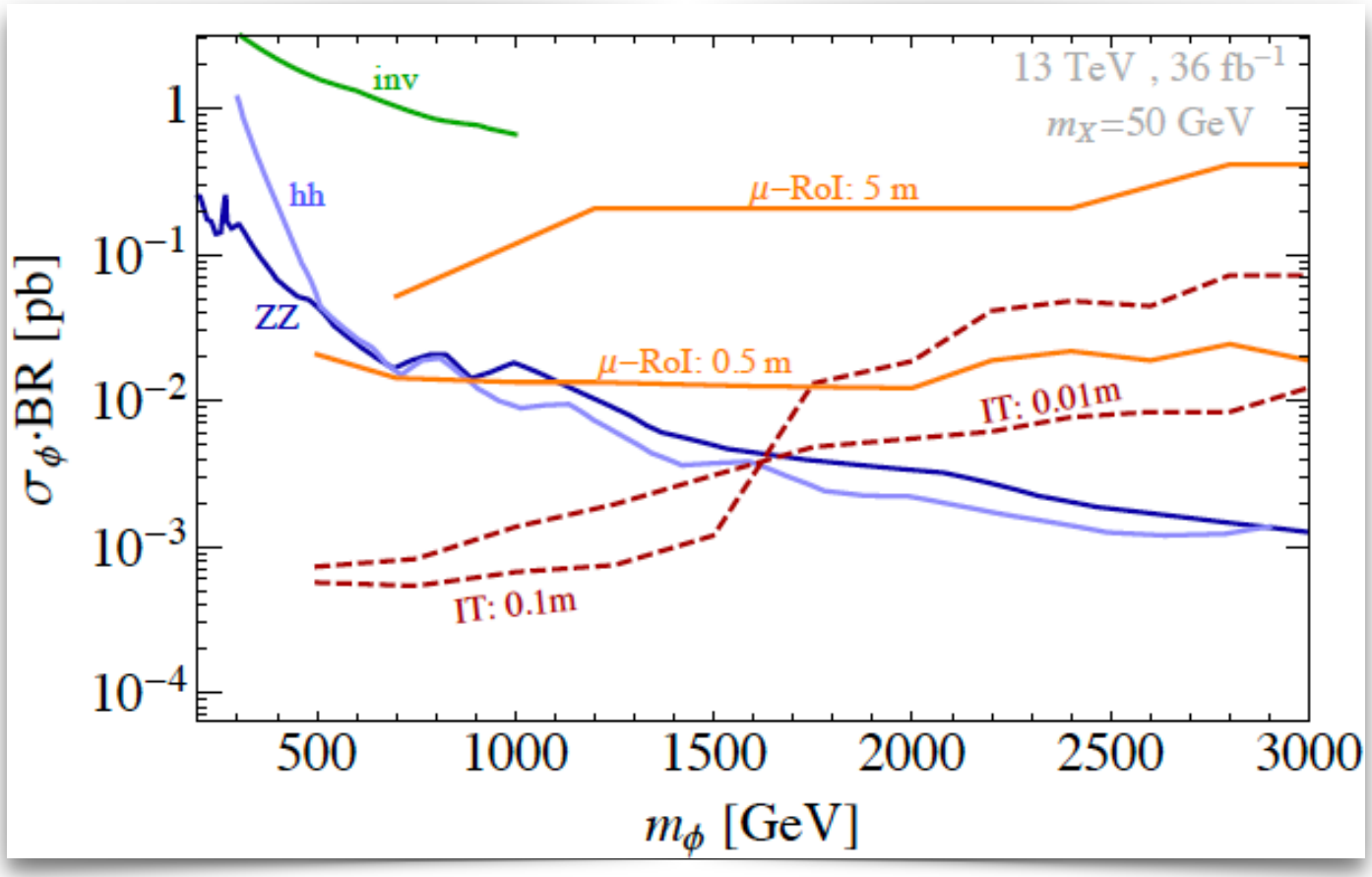


$$g_s^B(\Lambda) = g_s^A(\Lambda) + \delta g$$

$$y_b \left(H_A b_A^l b_A^r + \delta y_b H_B b_B^l b_B^r \right).$$

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

Displaced vs. prompt searches



Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315