# Scalar portal and its connection to Higgs physics from a theory viewpoint

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UC Santa Cruz


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# The scalar portal & open problems in particle physics

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


# The scalar portal & open problems in particle physics

**Baryon anti-baryon asymmetry**
Electroweak phase transitions

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

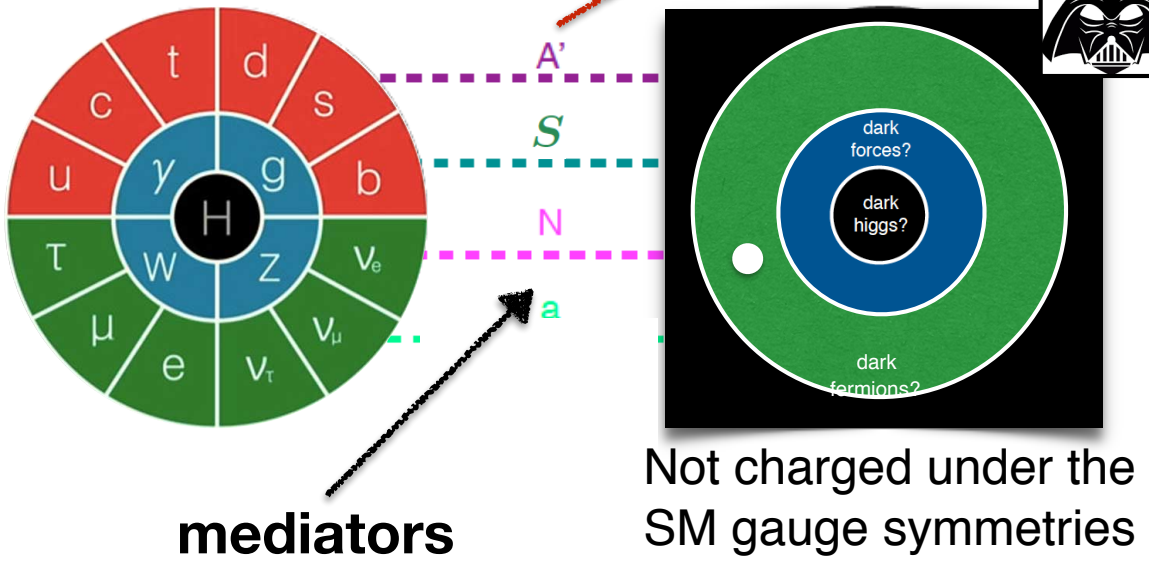

**Origin of neutrino masses;**
**Flavor puzzle;**
**…**

**Origin of DM**
Possible existence of a dark sector
Dark scalar responsible of DM mass

**Higgs hierarchy problem**
SUSY;
Neutral naturalness;
Relaxion models; …

A broad topic. Apology for the omissions…

# Dark sectors & the Higgs portal




**mediators**

Not charged under the SM gauge symmetries

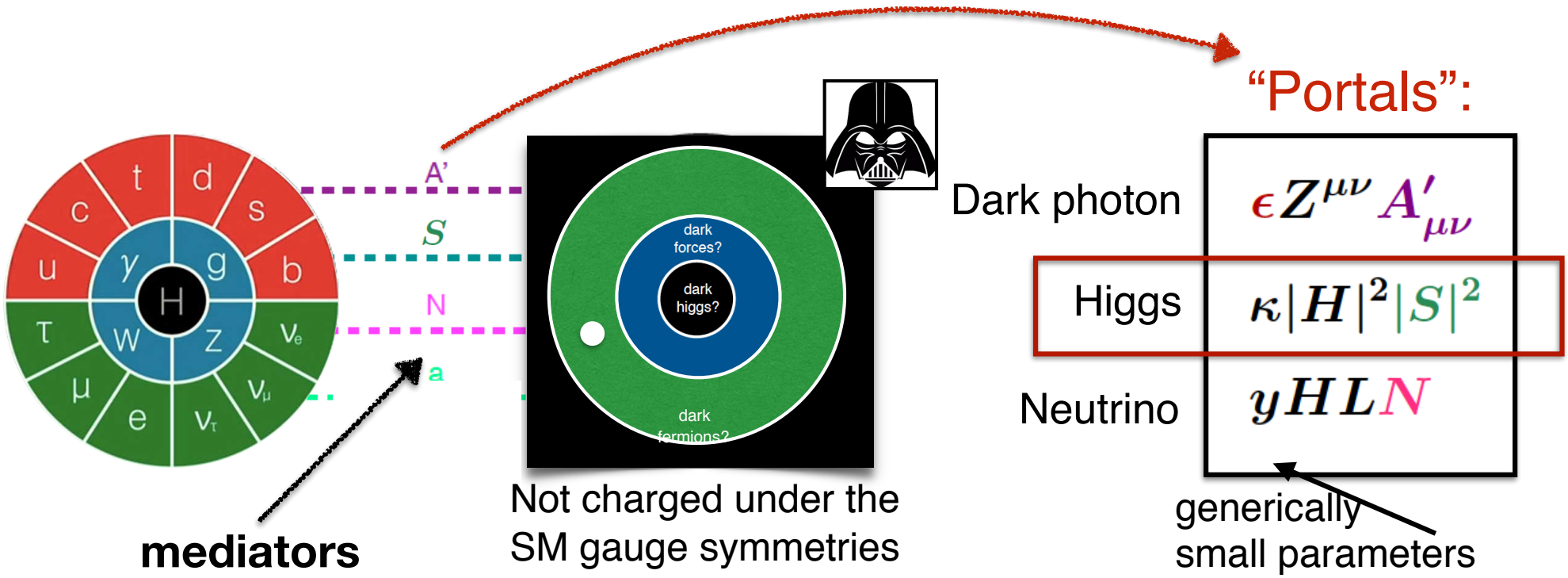
"Portals":

| | |
|---|---|
| Dark photon | $\epsilon Z^{\mu\nu} A'_{\mu\nu}$ |
| Higgs | $\kappa \lvert H \rvert^2 \lvert S \rvert^2$ |
| Neutrino | $y H L N$ |

generically small parameters

**The Higgs portal is one of the three renormalizable portals connecting the SM to the dark sector**

# Dark sectors & the Higgs portal




**The Higgs portal is one of the three renormalizable portals connecting the SM to the dark sector**

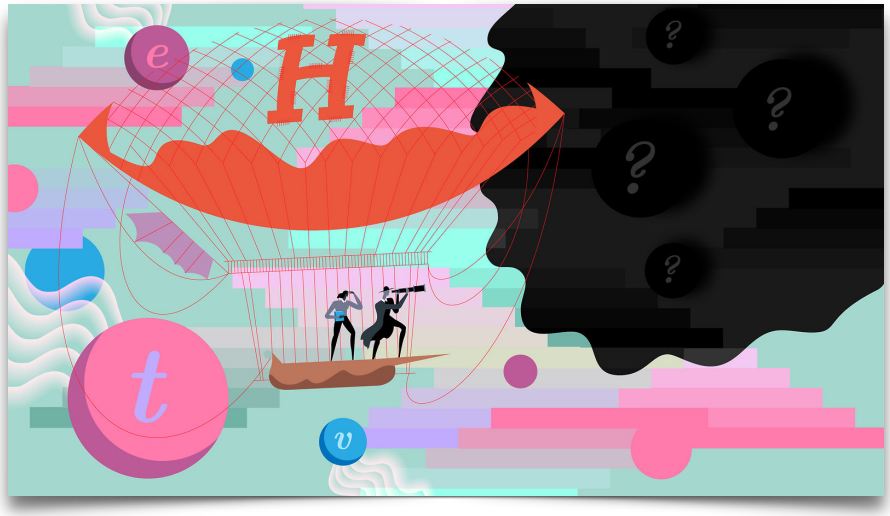
In this talk, we will discuss the phenomenology of three simplified models:

Minimal model (SM+S): **1)** $m_s < m_h / 2$; **2)** heavy $m_s$; **+** more complete theories

**3)** Non minimal model (SM+S+DM): $m_s > 2m_{DM}$

# Simplified models

Minimal model (SM+S): **1)** $m_s < m_h / 2$; **2)** heavy $m_s$;
**3)** Non minimal model (SM+S+DM): $m_s > 2m_{DM}$




from symmetry magazine

1)

$m_s < m_h / 2$

# How to probe the Higgs portal (light $m_s$)?

Higgs portal interaction

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

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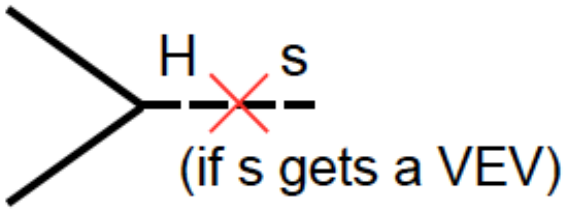


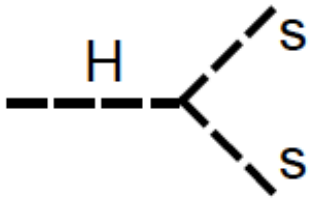

(same production mechanisms as for the SM Higgs)

**$Z_2$ breaking**
(S →-S)

Higgs portal interaction
$\frac{\xi}{2}|H|^2 s^2$

Interplay of LHC searches

(125 GeV) Higgs decays: 2.

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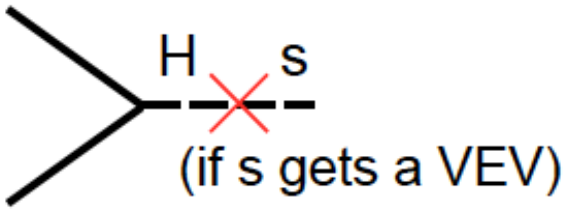


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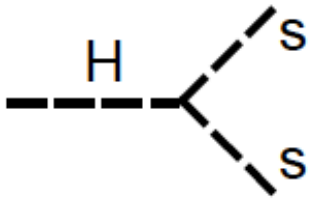
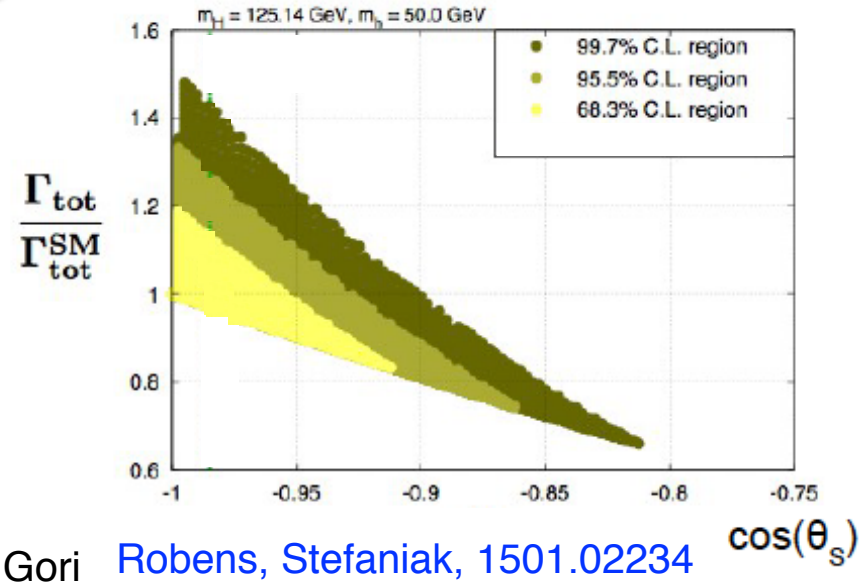


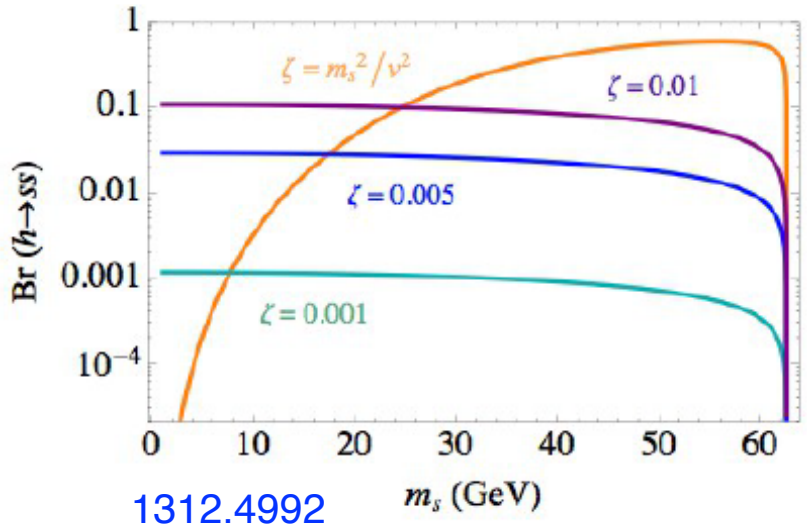

It does not depend on the mixing, $\theta_s$

3. The Higgs couplings to SM particles are reduced by a factor of $\cos(\theta_s)$




Robens, Stefaniak, 1501.02234

The Higgs has some "exotic" signatures




1312.4992

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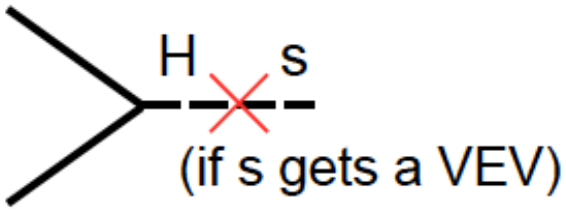


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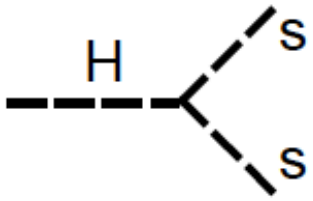


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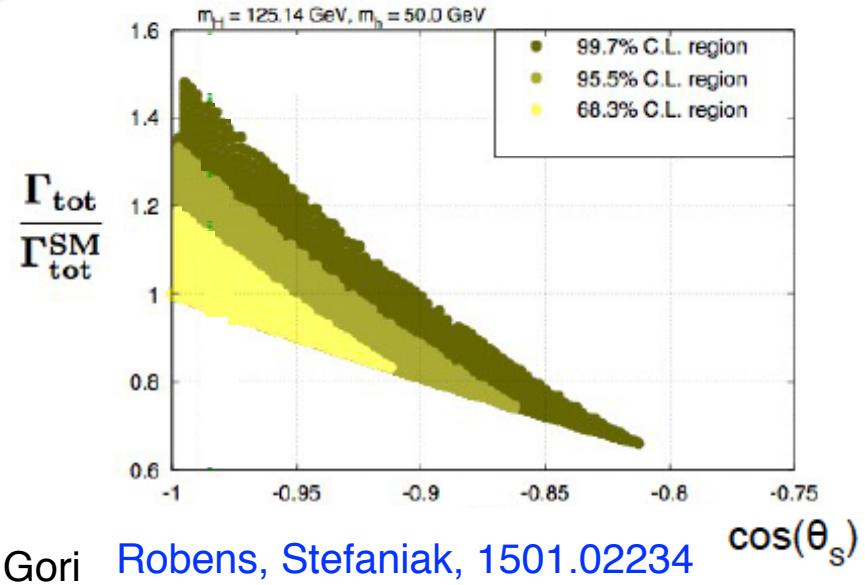


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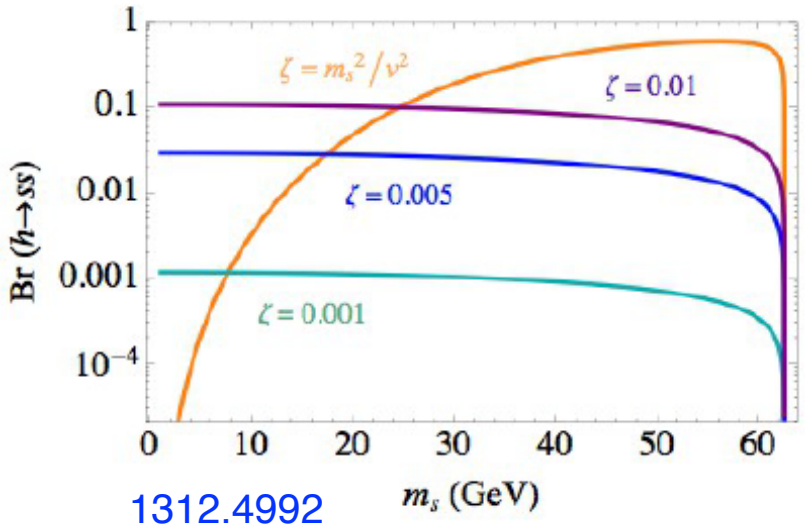



1312.4992

# Decays of the dark scalar

**If the scalar is heavier than ~10 GeV:**

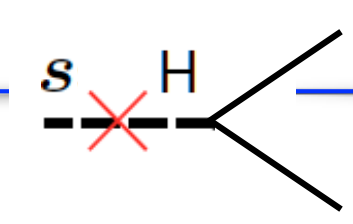
- If $\theta_s = 0$, s is stable
  - ➡ S invisible
- If $\theta_s \neq 0$, s will decay to SM particles

$$\Gamma(s \to f\bar{f}) = \sin^2\theta_S \frac{N_c}{8\pi} \frac{m_s m_f^2}{v^2} \beta_f^3$$

Main BRs: bb, ττ, cc, ...

$\mathrm{Sin}(\theta_s) \geq O(10^{-5})$
S decays promptly

$\mathrm{Sin}(\theta_s) \leq O(10^{-5})$
S has displaced decays



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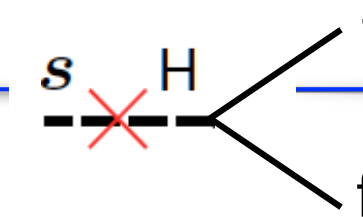
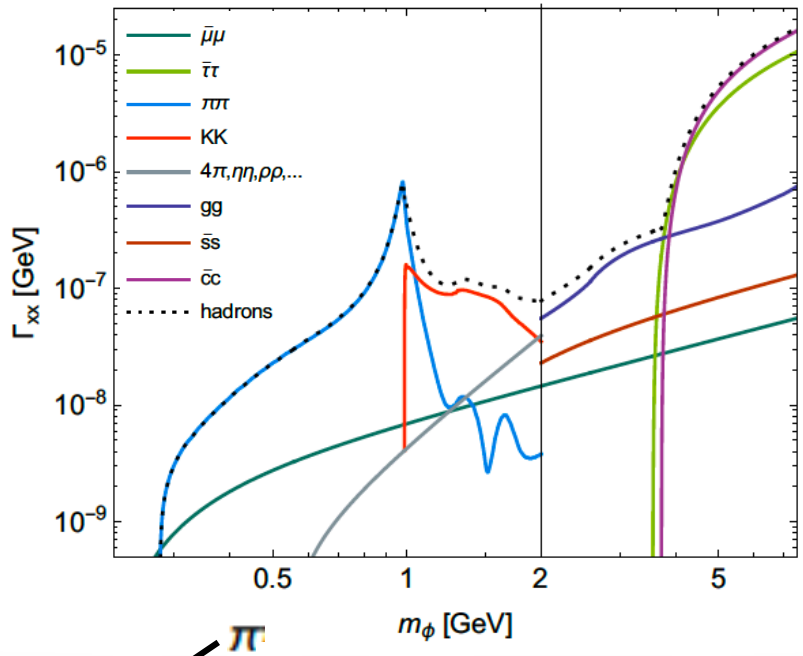


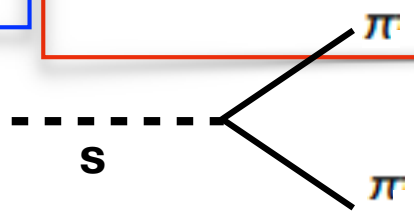

## If the scalar is lighter than ~10 GeV:

The calculation of the widths has large theory uncertainties

Several different theoretical methods in the literature.

Winkler, 1809.01876




Particularly relevant for long-lived scalars

1.

# Direct production of a new scalar (LHC)

1)
$m_s < m_h / 2$

The production cross section$_s$ = production$_{SM\ Higgs}$*$\sin^2(\theta_S)$
Same production modes as for the SM Higgs

Only a few LHC searches have been performed.
Examples are bbS, S →μμ
ggS, S →μμ, (also searched for by LHCb)
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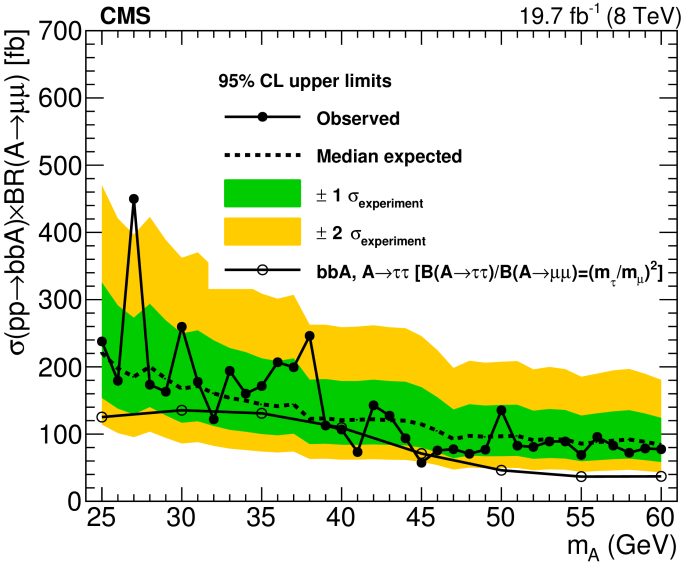


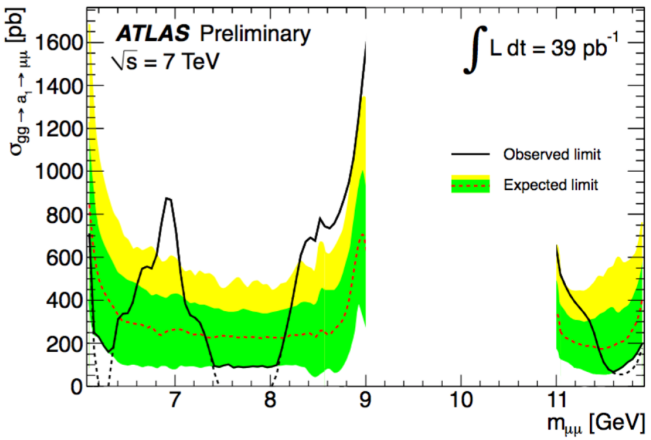


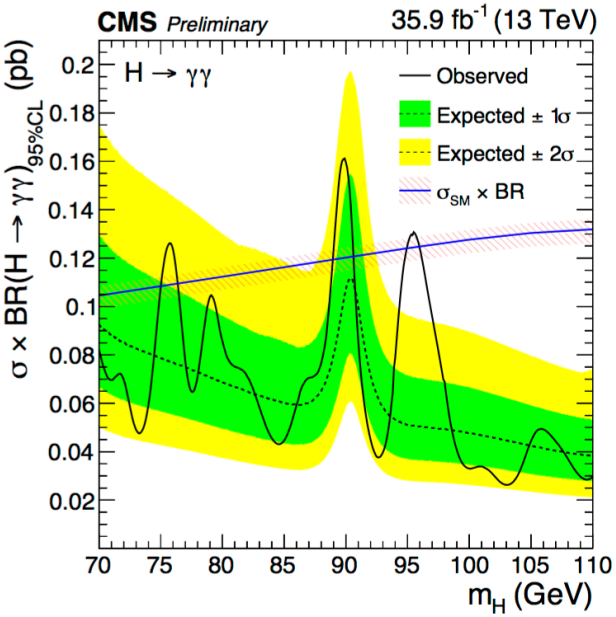


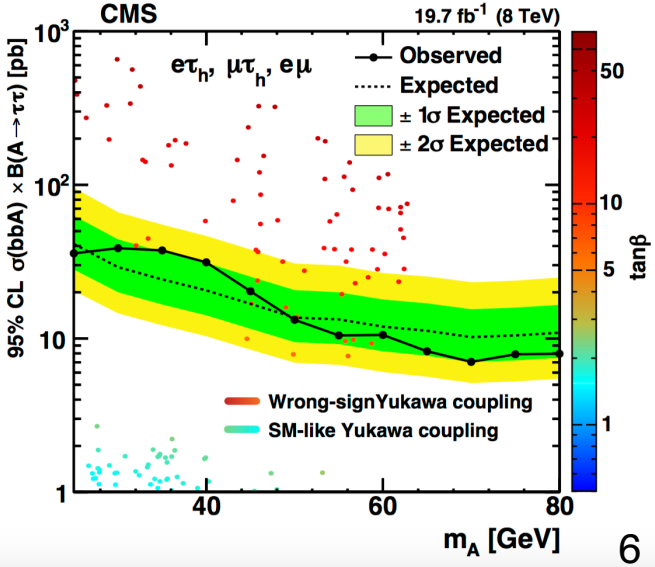

1.

# Direct production of a new scalar (low energy)

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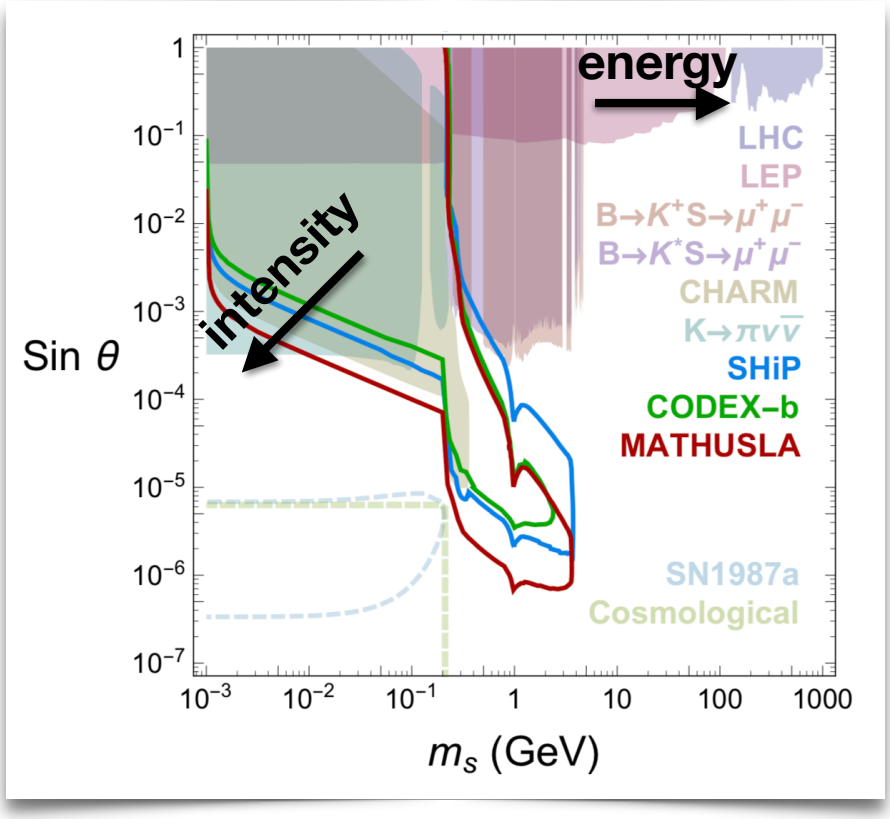
In addition to the LHC, high intensity (low energy experiments) can produce the dark scalar through its mixing with the Higgs.

e.g. B decays, Kaon decays, Bremsstrahlung, gluon fusion, …

Evans, SG, Shelton, 1712.03974



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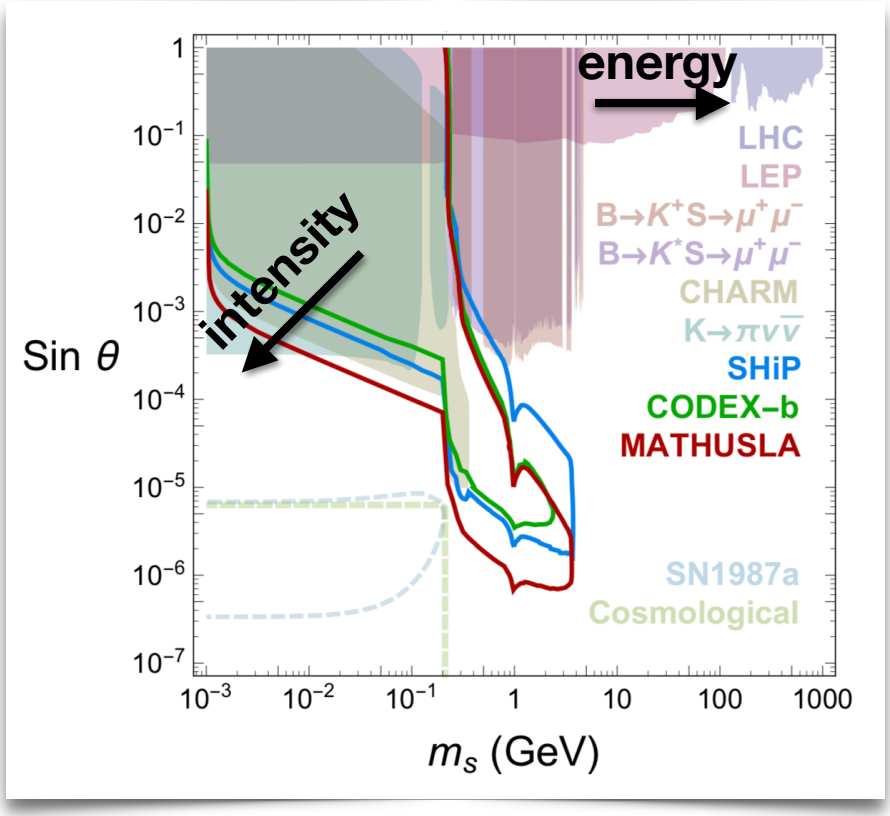
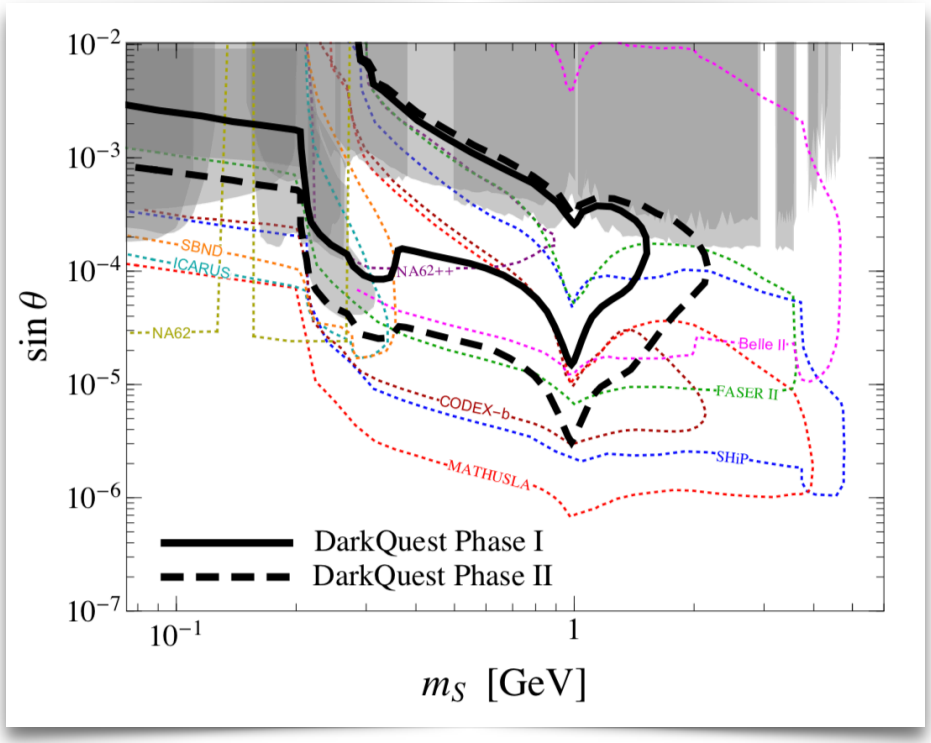
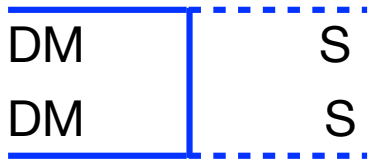



Batell, Evans, SG, Rai, 2008.08108




Upgrade of the SeaQuest experiment at Fermilab
(see talks by T.Nelson & J.C.Swallow)

The entire region of parameter space is well motivated by **thermal secluded DM models**.
The requirement of thermalization leads to **Sinθ >~$10^{-7}$**



2.

# A program for searches for h → ss

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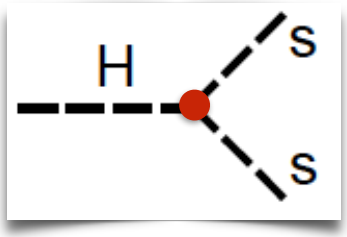
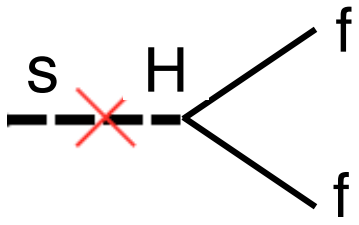



The scalar can decay thanks to its mixing with the Higgs




Note: the BR(h) does not depend on the mixing! We are probing a different parameter, if compared to pp→s

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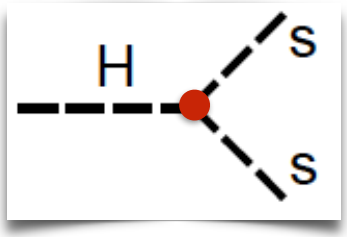


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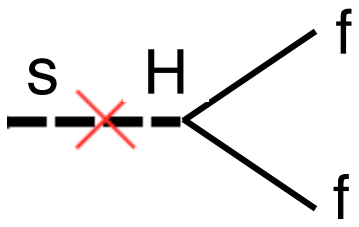


Many possible signatures to look for

gg → h → ss → 4b
gg → h → ss → 4γ
gg → h → ss → 2b 2μ
gg → h → ss → 2γ2j
gg → h → ss → 4μ
gg → h → ss → 2tau 2μ
…

both prompt & displaced (or invisible)

+ sub-leading production modes of the Higgs boson

e.g. qq → Zh → Z(ss) → Z(4b) …

see talks by
V. Martinez Outschoorn, M. Cepeda

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# A program for searches for h → ss

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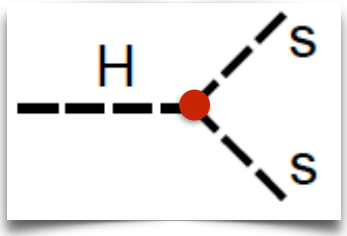


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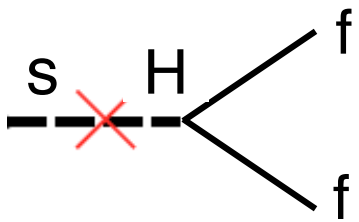


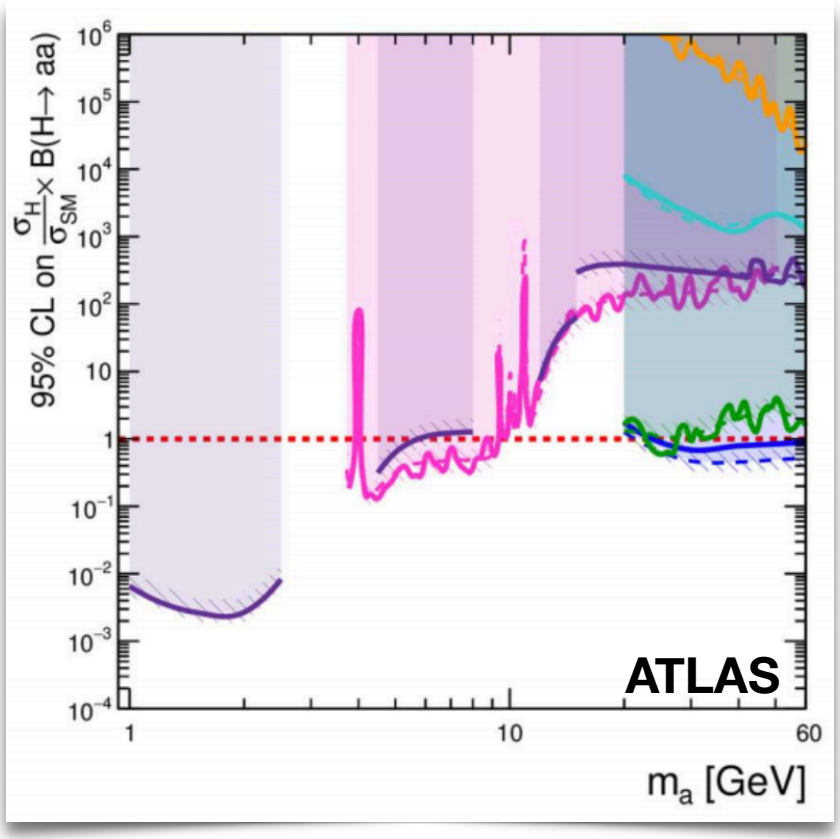


Broader mass range?

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gg → h → ss → 4γ
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$m_s > m_h$

# How to probe the Higgs portal (heavy $m_s$)?

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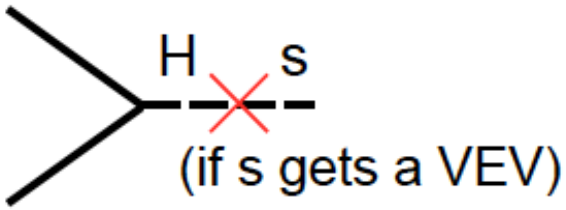


(same production mechanisms as for the SM Higgs)

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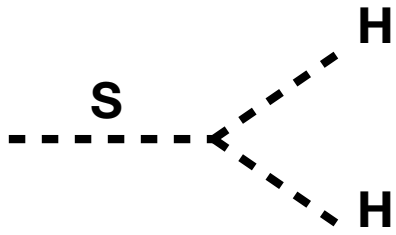
Interplay of LHC searches

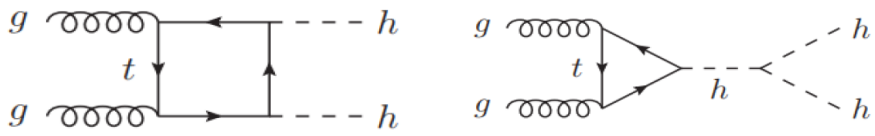
2. Di-Higgs production




NEW

**$Z_2$ breaking**
(S →-S)

The SM di-Higgs production cross section is rather small at the LHC: ~37 fb (@14 TeV)




Large enhancements are possible in Higgs portal models.

3. Higgs coupling measurements

**$Z_2$ breaking**
(S →-S)

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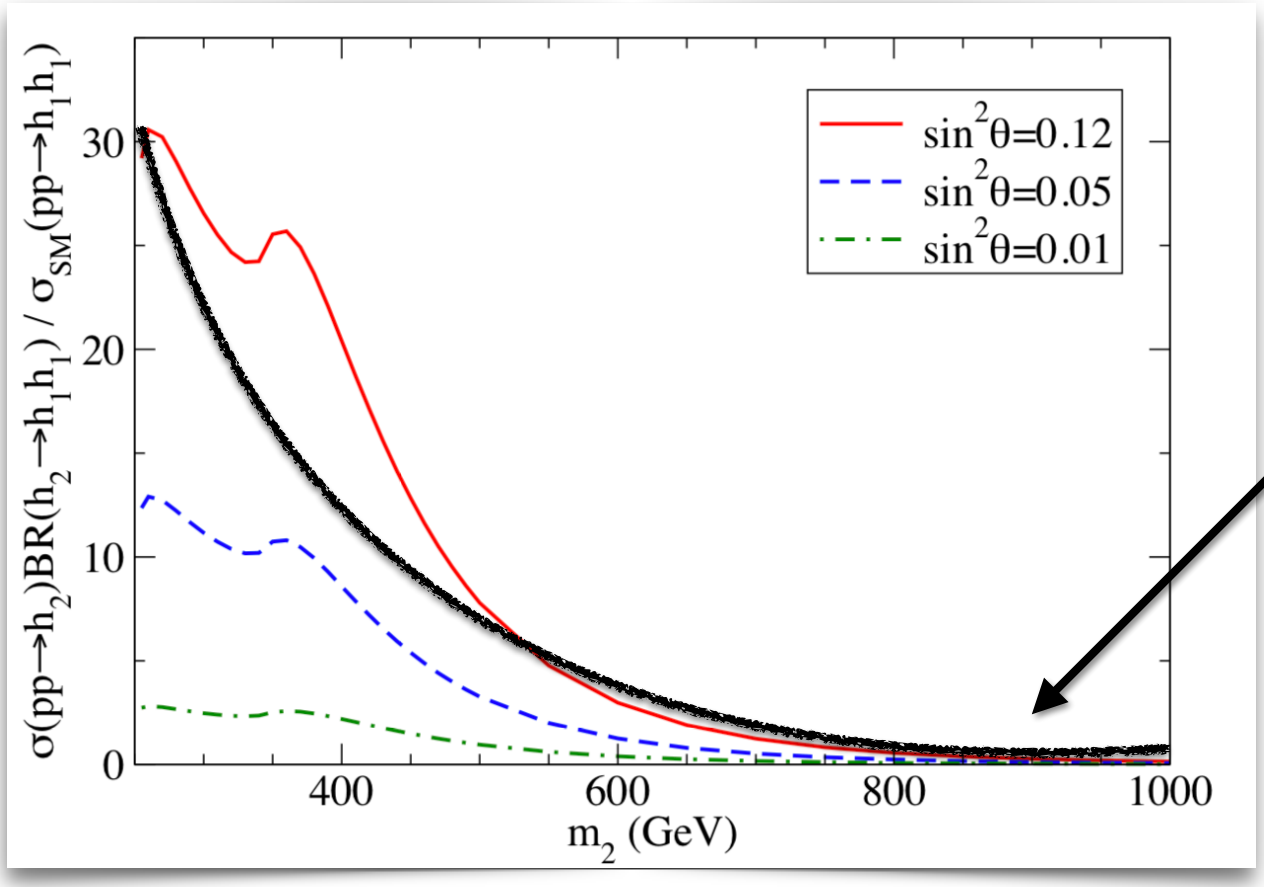
# Di-Higgs production & the Higgs portal




Lewis, Sullivan, 1701.08774

Constraint from the present ATLAS & CMS resonant di-Higgs production searches

**Note:**

Dawson, Lewis, 1508.05397
Carena, Liu, Riembau, 1801.00794

to obtain a more precise bound, one should consider interference effects between the resonant decay and the SM diagrams

# Extended Higgs portal simplified models

DM models can have the DM state lighter than the scalar mediator, $m_s > 2m_{DM}$.
If so, the dark scalar can be produced through the Higgs portal and decay invisibly to DM. ⇨ Different signatures at high energy and high intensity

**2 different parameters for production and decay**

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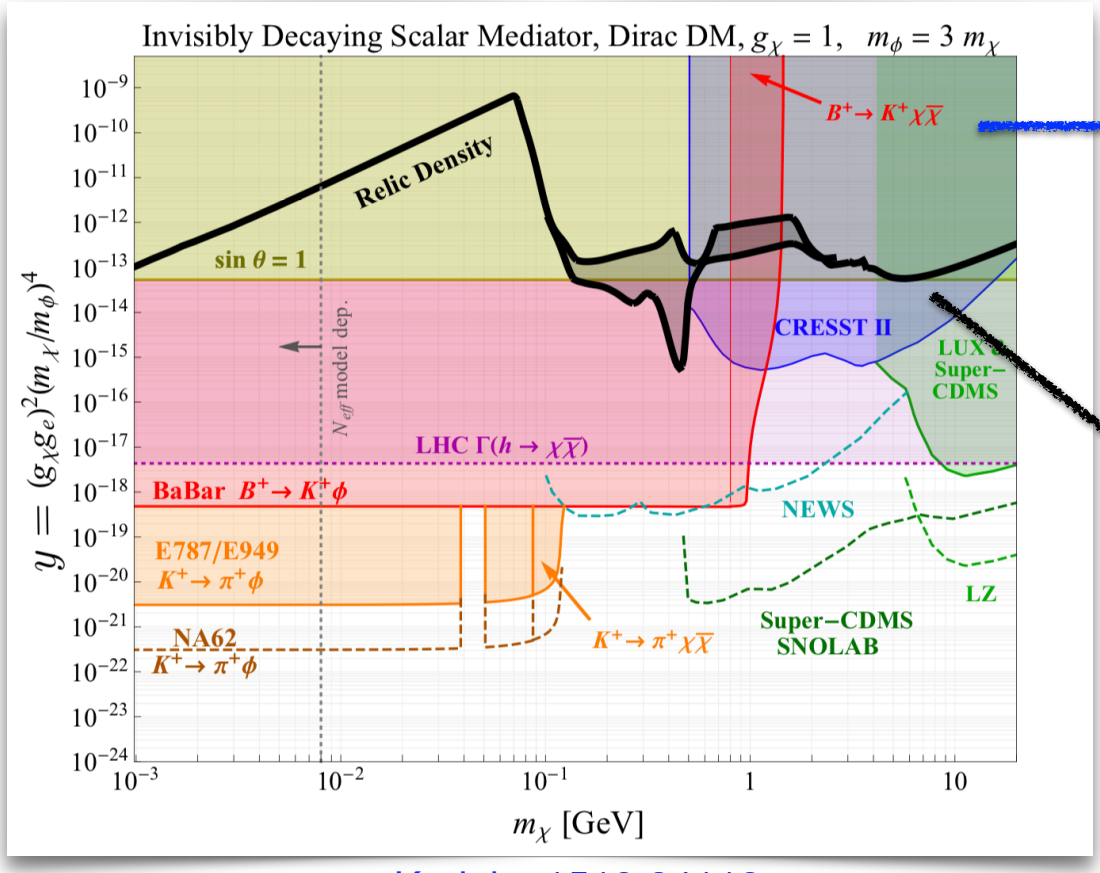
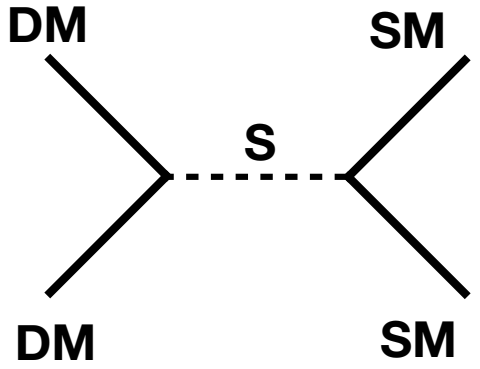


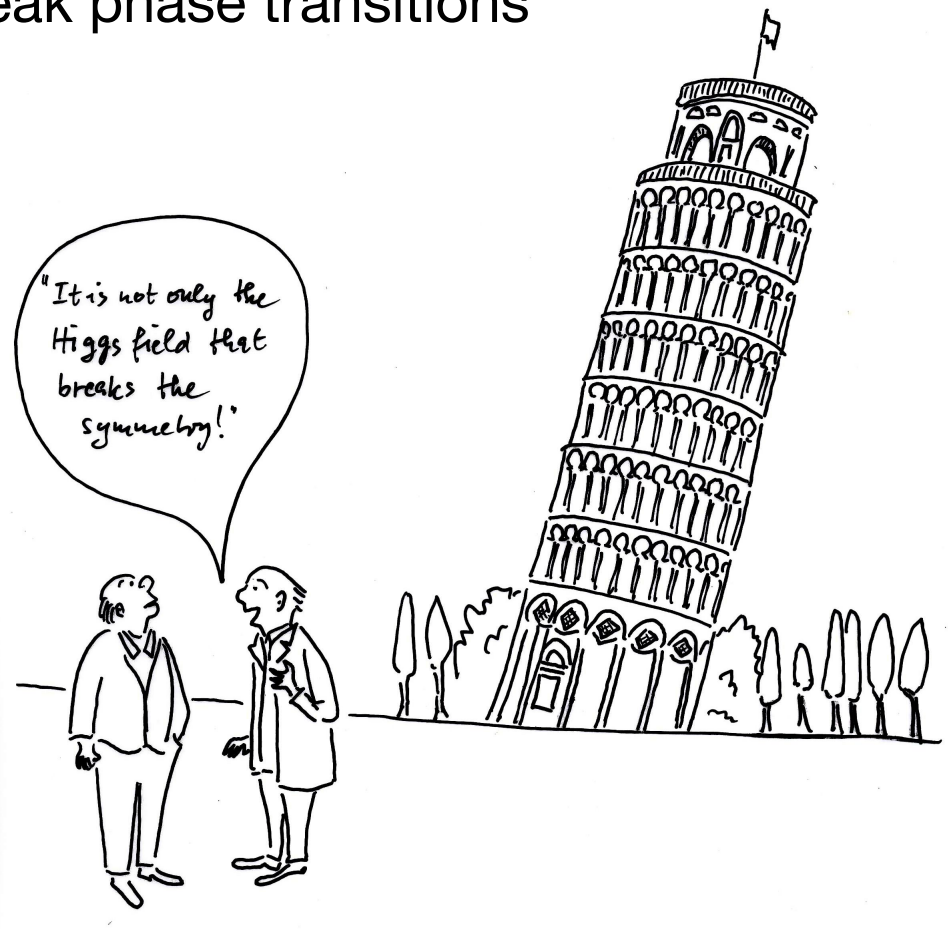

**LHC mono-X searches**




Krnjaic, 1512.04119

# (More complete) models:

- Twin Higgs models
- Models for electroweak phase transitions



# Twin Higgs models & the hierarchy problem

**$SM_A$ x $SM_B$ x $Z_2$**

Global symmetry of the scalar potential (e.g. SU(4))

➡ The SM Higgs is a (massless) Nambu-Goldstone boson

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

~SM Higgs doublet

Twin Higgs doublet

$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

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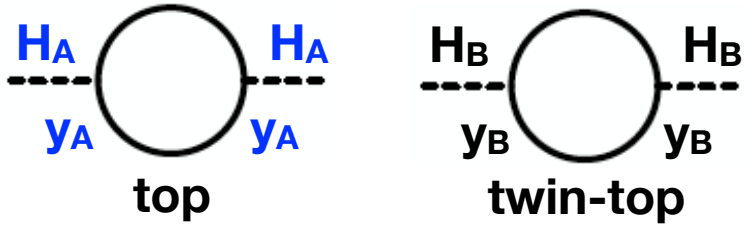
$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Loop corrections to the Higgs mass: $\frac{3}{8\pi^2}\Lambda^2 (y_A^2 H_A^\dagger H_A + y_B^2 H_B^\dagger H_B)$




$$Z_2 \Rightarrow y_A = y_B$$

Loop corrections to mass are SU(4) symmetric

➡ no quadratically divergent corrections!

# Twin Higgs models & the hierarchy problem

**$SM_A$ x $SM_B$ x $Z_2$**

Global symmetry of the scalar potential (e.g. SU(4))

➡ The SM Higgs is a (massless) Nambu-Goldstone boson

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

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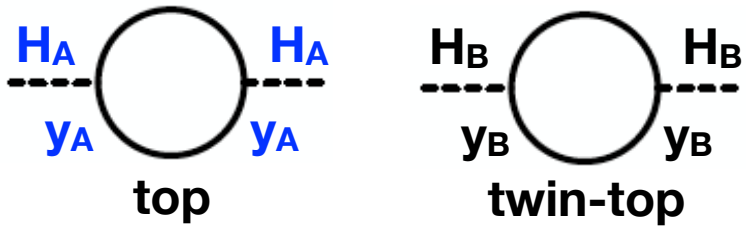



$Z_2 \Rightarrow y_A = y_B$

SU(4) and $Z_2$ are (softly) broken:

$v_A \neq v_B$

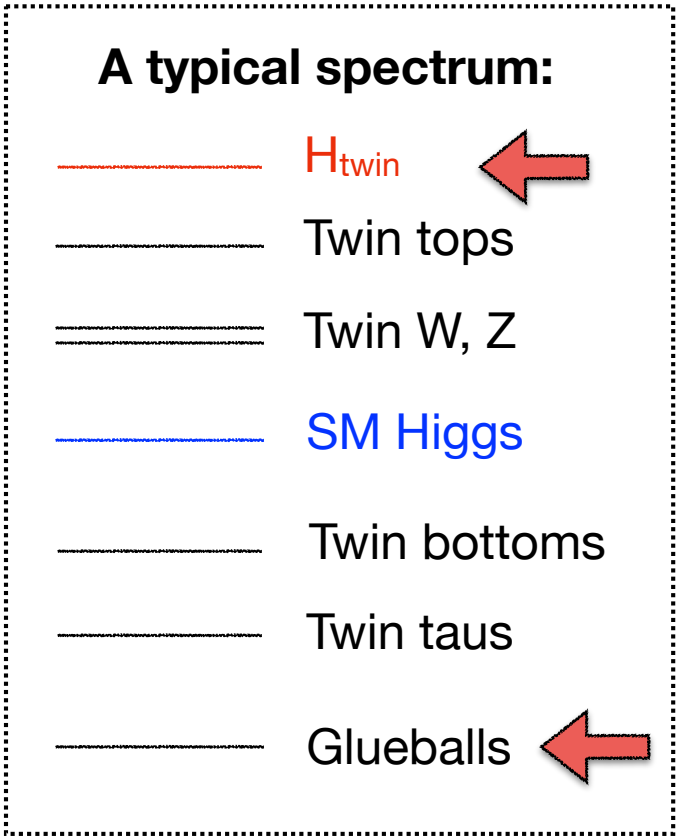
$(f^2 \equiv v_A^2 + v_B^2 \gg 246\ \mathrm{GeV})$

$\sin\theta \sim \frac{v}{f}$ mixing between the SM and the twin Higgs

Loop corrections to mass are SU(4) symmetric

➡ no quadratically divergent corrections!

# Phenomenology of the twin Higgs



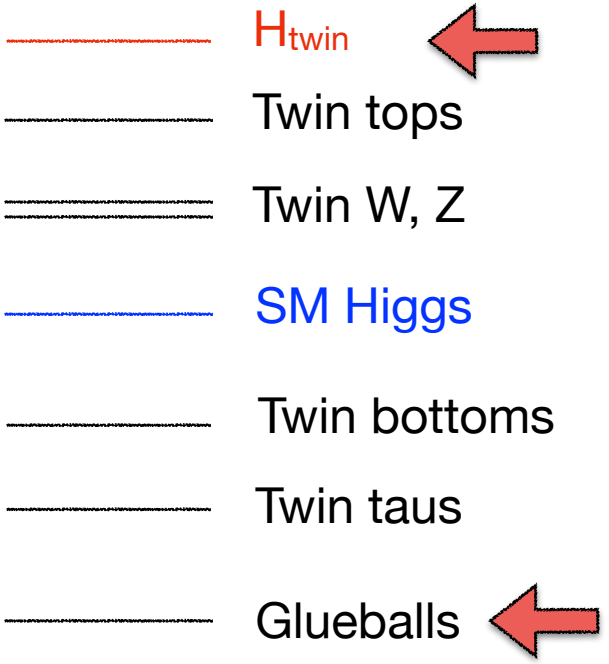
# Phenomenology of the twin Higgs

1. **Production of the twin Higgs**

   The twin Higgs will mix with the 125 GeV Higgs with a mixing angle ~v/f

   Because of this mixing, it can be produced as a SM Higgs boson (reduced rates!)

**A typical spectrum:**



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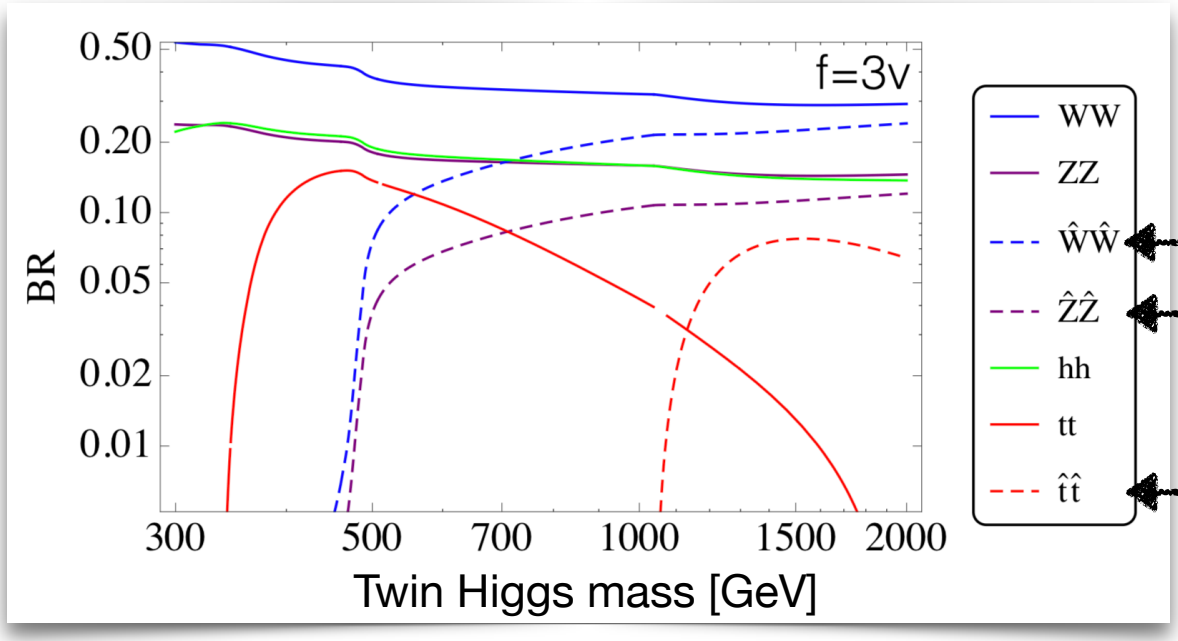
2. **Decay of the twin Higgs**



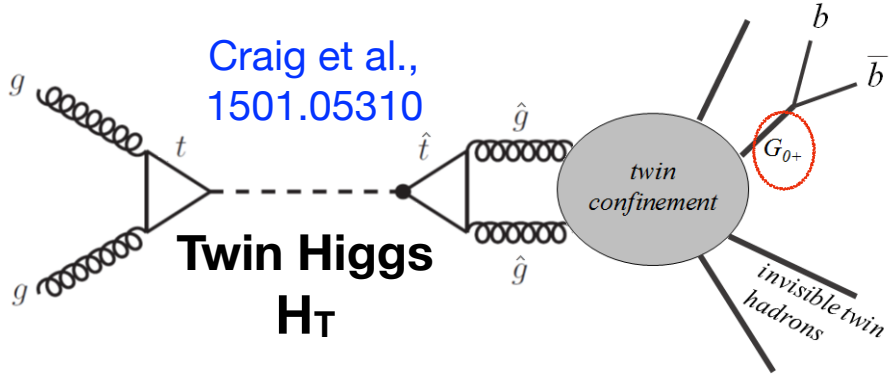

N.Craig

**A typical spectrum:**

- $H_{twin}$
- Twin tops
- Twin W, Z
- SM Higgs
- Twin bottoms
- Twin taus
- Glueballs

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

# Long-lived signatures from twin Higgs decays




Craig et al., 1501.05310

**Twin Higgs $H_T$**

Glue-ball.

$O^{++}$ mixes with the 125 GeV Higgs and decays typically displaced.

$$\frac{\alpha_s^{\mathrm{B}}}{3\pi}\left[\frac{y^2}{M^2}\right]|H|^2\, G_{\mu\nu}^{(\mathrm{B})} G^{(\mathrm{B})\mu\nu}$$

**Signature: $H_T \rightarrow$ >= 2 displaced**

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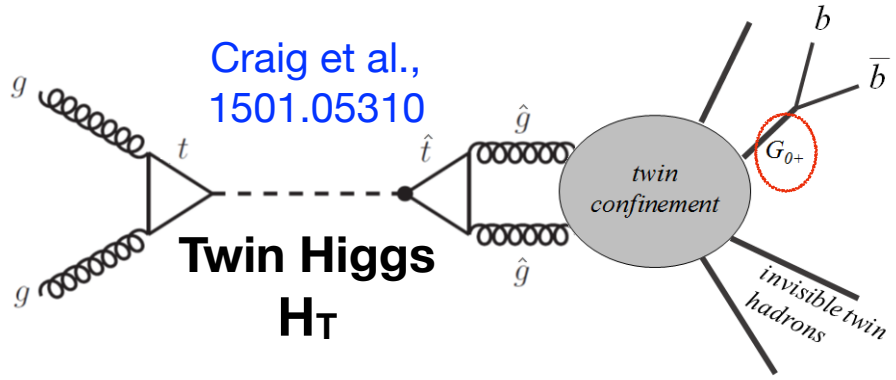


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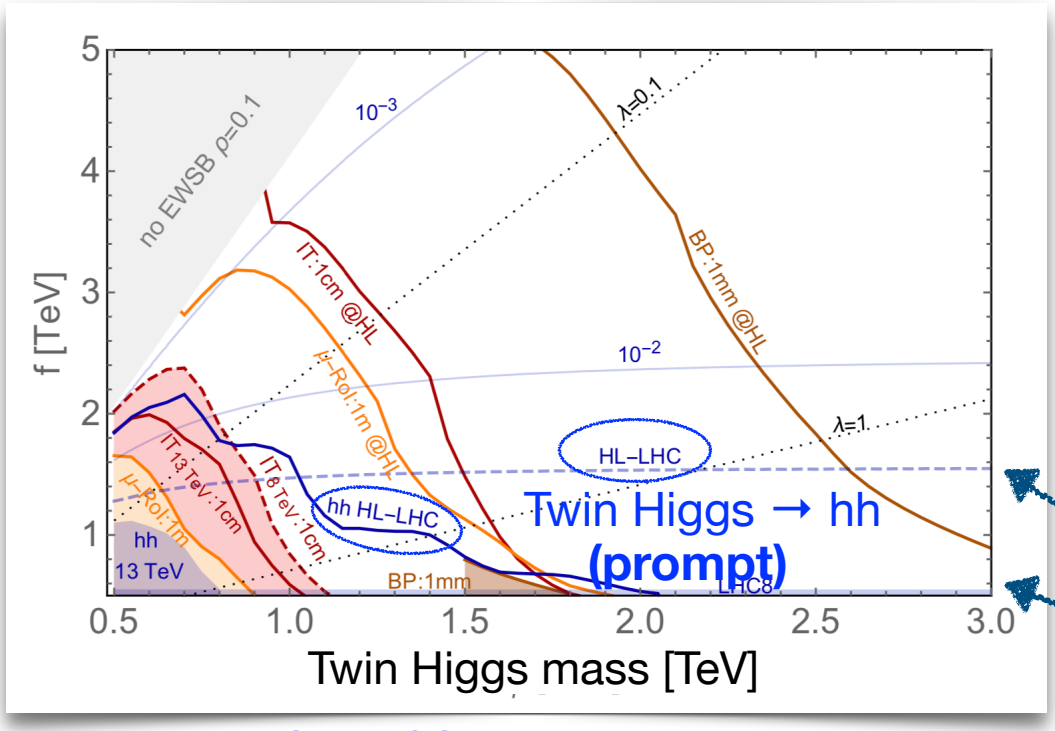
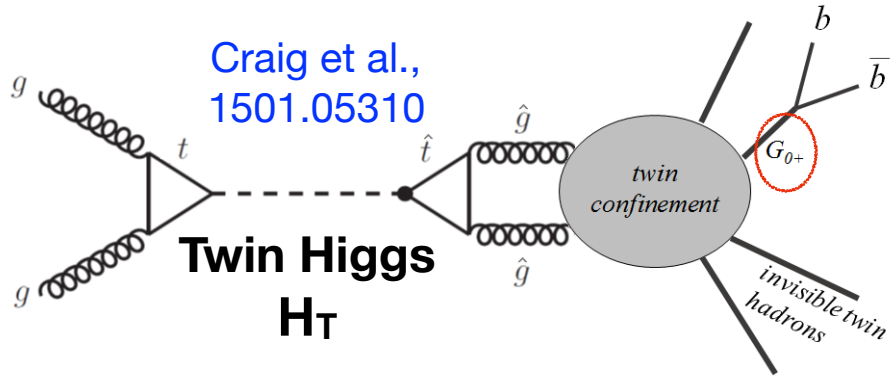



125 GeV Higgs coupling measurements

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

# Long-lived signatures from twin Higgs decays

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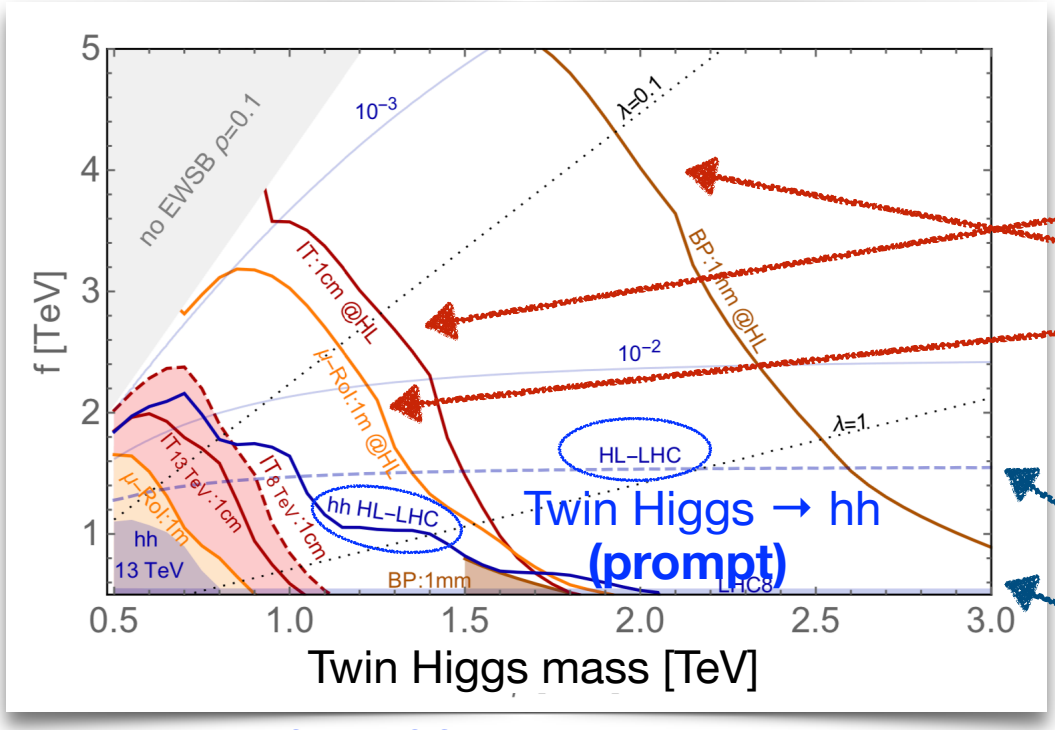



Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

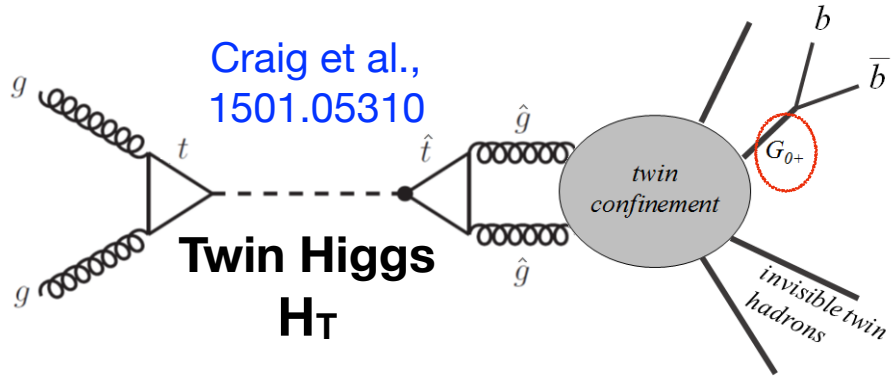
Twin Higgs → glue-balls:
**(long lived)**

CMS inner tracker analysis;
CMS beam pipe analysis;
ATLAS muon spectrometer analysis

The relative strength depends on other parameters of the theory

125 GeV Higgs coupling measurements

# Long-lived signatures from twin Higgs decays

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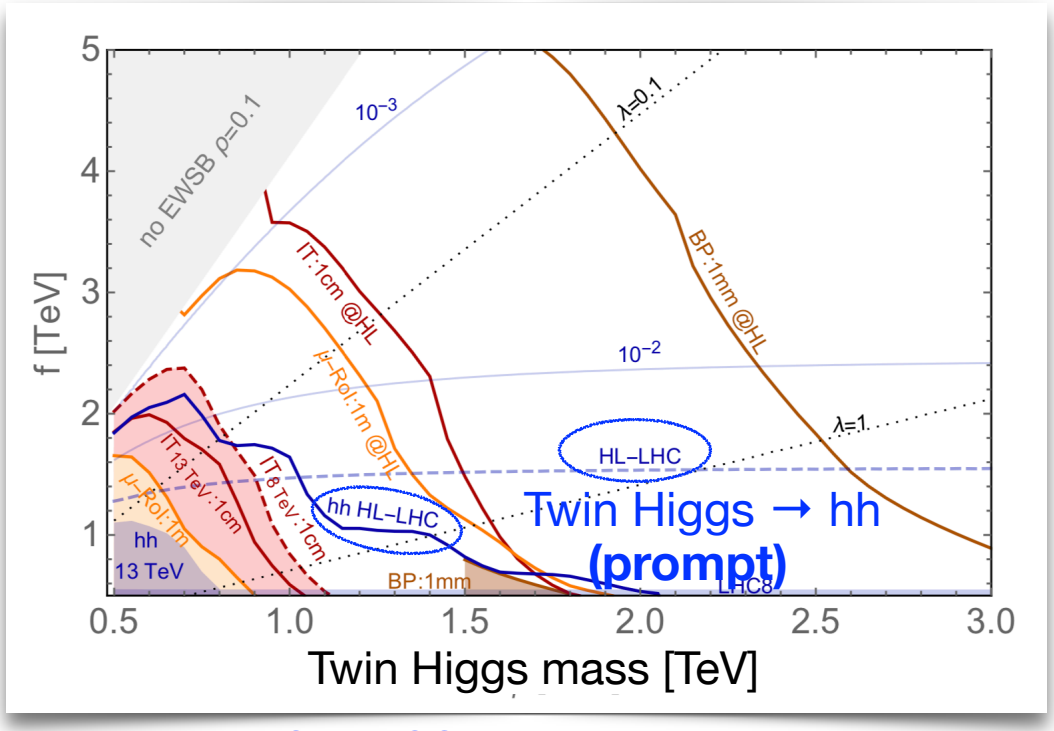


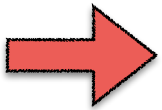

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

Many additional opportunities!

- study the pheno of the heavier glue-balls (some mix with the pseudo scalar Higgs)
- displaced + invisible signatures
- sub-leading twin Higgs production mechanisms?
- Even more rich pheno in SUSY twin Higgs models

# Effects on the 125 GeV Higgs pheno

The 125 GeV Higgs will mix with the twin Higgs with a mixing angle ~ v/f



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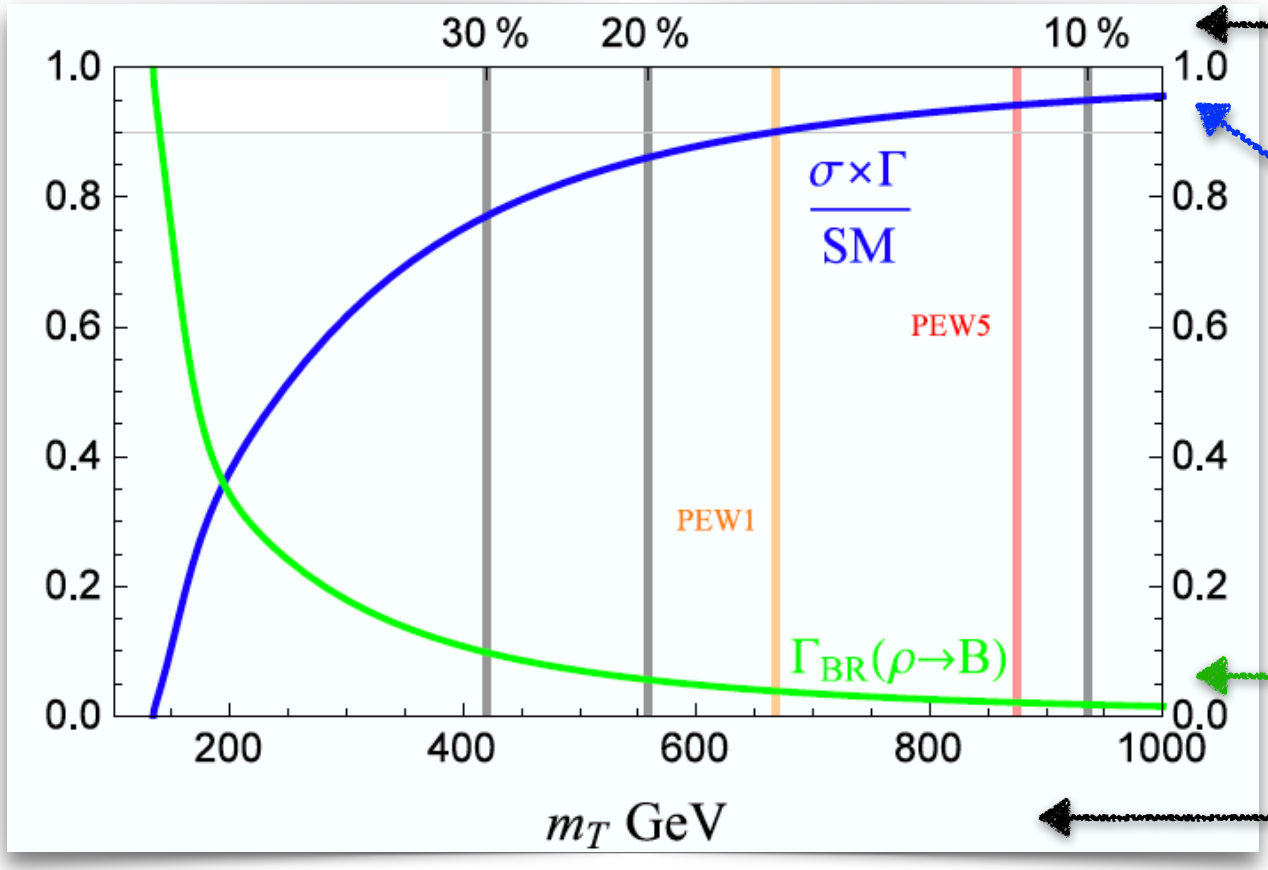


**Amount of fine tuning**

**Higgs rates into SM particles**

**Width into the twin-sector** (either invisible or displaced signatures)

**Mass of the top-partner**

Burdman et al, 1411.3310

# Higgs portal and electroweak phase transitions

Light new physics weakly coupled to the Higgs can induce a strong first-order electroweak phase transition

To have a strong first order phase transition ($v_c/T_c >= 1$), one needs a sizable value for the hSS coupling.
In particular:

Analysis of the finite-temperature effective potential of SM+S

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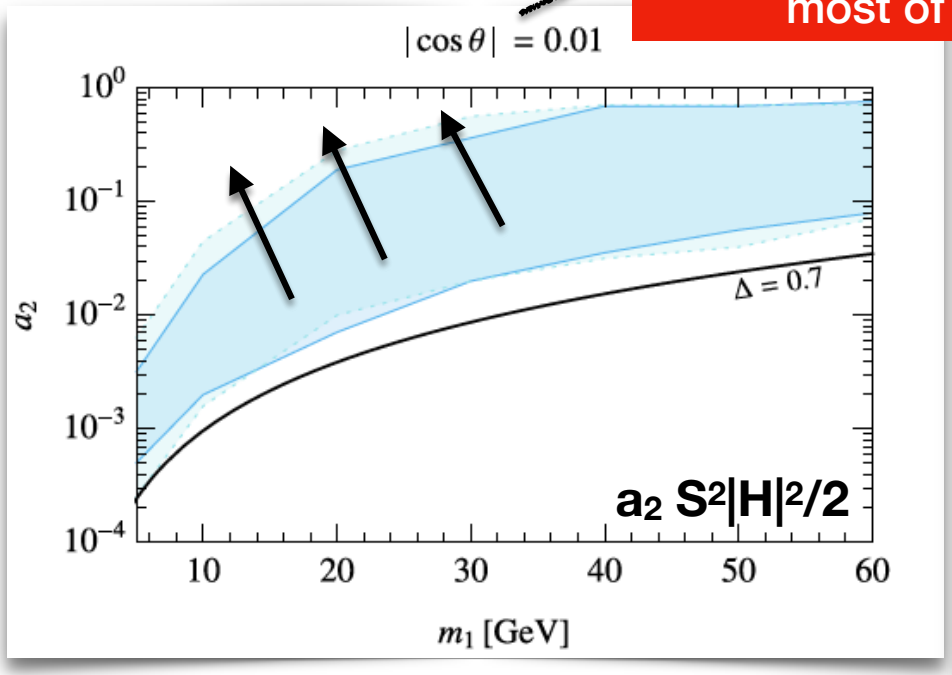
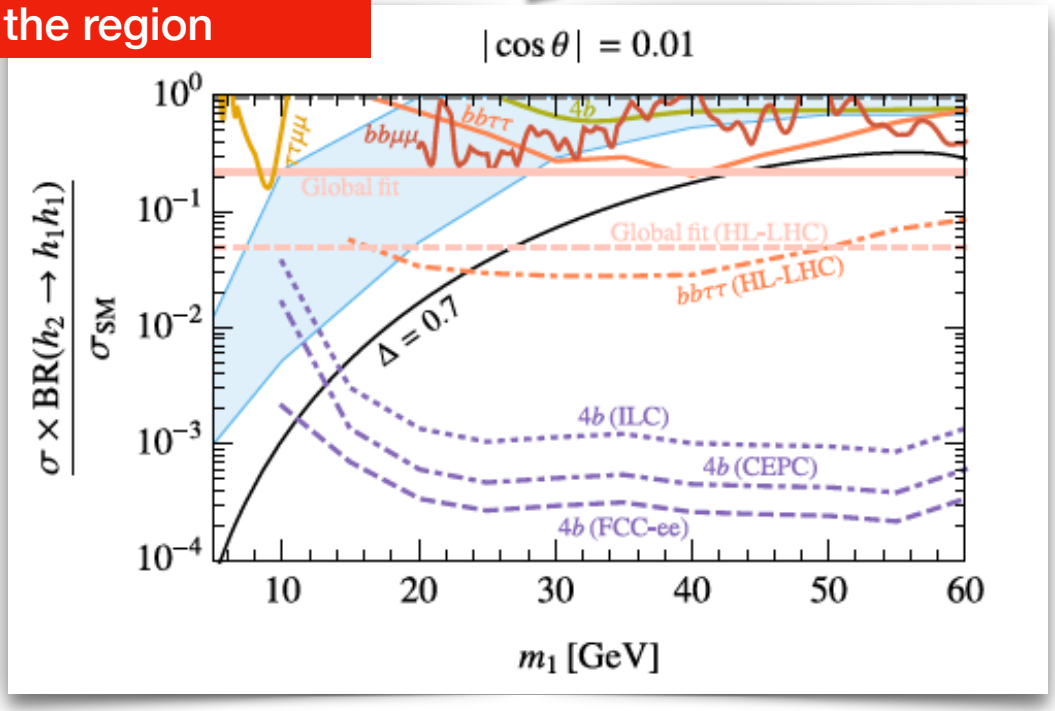
Higgs exotic decays can probe most of the region




Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210

See also Curtin, Meade, Yu, 1409.0005

# Conclusions and outlook

Complementarity of…

- Higgs coupling measurements
- Higgs exotic decays
- Direct production of new scalars (LHC & high intensity experiments)
- Di-Higgs searches

…in probing the Higgs portal

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

Many future experimental opportunities

An (incomplete set of) theory targets:

- Thermal Dark sector (lower bound on Sinθ) for secluded DM models
- Thermal line for non-secluded DM models
- Strong first order electroweak phase transition