# Physics Beyond the Standard Model

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Lecture 1: The reasons for BSM and the agnostic approach
→ Lecture 2: Simple extensions of the Standard Model
Lecture 3: Naturalness guided BSM

We will only be convinced of NP by direct evidence: finding new particles!

This is the main motivation of LHC.

We will first explore simple extensions of the SM. Many aspects of these simple models are common to more complete and better motivated BSM,

Adopt a “bottom-up” approach: no grand principle invoked.

# The simplest extension

The Higgs boson may be the first scalar particle found in Nature.

It is conceivable that there are more scalar particles out there in a “hidden sector”

They may communicate to us only via the Higgs: the Higgs acts like a portal between the SM and this new sector.

# The simplest extension

The simplest possibility is to extend the SM by adding one real scalar particle (S) singlet under the SM and hence interacting only with the Higgs doublet in a renormalizable potential.

We have 2 choices (with different phenomenology) in writing the potential:
allow or not for S to have a vacuum expectation value.

$\langle S \rangle \neq 0 \Longrightarrow$ Mixing between H and S

$\langle S \rangle = 0 \Longrightarrow$ S is a dark matter candidate

# The simplest extension $\langle S \rangle \neq 0$

See, eg, Falkowiski, Gross and Lebedev (1502.01361)
Robens and Stefaniak (1501.02234)

Write a general scalar potential respecting a $Z_2$ (S-> -S) symmetry
Write Higgs doublet in unitary gauge: $H = \begin{pmatrix} 0 \\ h/\sqrt{2} \end{pmatrix}$

$$V(h,S) = \frac{1}{2}\mu_h h^2 + \frac{1}{2}\mu_S S^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_S S^4 + + \frac{1}{4}\lambda_{hS} h^2 S^2$$

5 parameters (3 more than in SM)

# The simplest extension $\langle S \rangle \neq 0$

Minimizing the potential:

$$\left.\frac{\partial V(h,S)}{\partial h}\right|_{h=v,S=w} = \left.\frac{\partial V(h,S)}{\partial S}\right|_{h=v,S=w} = 0$$

one finds the vev's v and w:

$$v^2 = \frac{2\lambda_{hS}\mu_S^2 - 4\lambda_S\mu_h^2}{4\lambda_h\lambda_S - \lambda_{hS}^2} \qquad w^2 = \frac{2\lambda_{hS}\mu_h^2 - 4\lambda_h\mu_S^2}{4\lambda_h\lambda_S - \lambda_{hS}^2}$$

Assuming both fields develop vev's at the minimum requires

$$v^2 > 0, \quad w^2 > 0$$

# The simplest extension $\langle S \rangle \neq 0$

NB: spontaneous breaking of a discrete symmetry results in a cosmological problem: domain walls!

# The simplest extension $\langle S \rangle \neq 0$

Masses and mixings: one must use fields with zero vev's

$$h = v + \tilde{h}, \; S = w + \tilde{S}$$

The mass terms arise from the quadratic terms in the potential

$$V^{(2)}(\tilde{h}, \tilde{S}) = \frac{1}{2}(\tilde{h} \; \tilde{S})\mathcal{M}(\tilde{h} \; \tilde{S})^T$$

where the mass matrix is given by

$$\mathcal{M} = \begin{pmatrix} 2\lambda_h v^2 & \lambda_{hS} v w \\ \lambda_{hS} v w & 2\lambda_S w^2 \end{pmatrix}$$

# The simplest extension $\langle S \rangle \neq 0$

The mass matrix is not diagonal: there is a mixing between the fields from the term in the potential

$$\lambda_{hS}\, vw\, \tilde{h}\tilde{S}$$

Physical fields are linear combinations that diagonalize the mass matrix and hence are mass eigenstates.

# The simplest extension $\langle S \rangle \neq 0$

Physical fields $H_1$ and $H_2$:

$$H_1 = \cos\theta \; \tilde{h} - \sin\theta \; \tilde{S}$$
$$H_2 = \cos\theta \; \tilde{S} + \sin\theta \; \tilde{h}$$

with mixing angle

$$\tan 2\theta = \frac{\lambda_{hS} v w}{\lambda_S w^2 - \lambda_h v^2}$$

# The simplest extension $\langle S \rangle \neq 0$

Masses of physical fields $H_1$ and $H_2$:

$$m^2_{H_1,H_2} = \lambda_h v^2 + \lambda_S w^2 \pm \frac{\lambda_h v^2 - \lambda_S w^2}{\cos 2\theta}$$

# The simplest extension $\langle S \rangle \neq 0$

Conditions on parameters:

$$\lambda_h > \frac{\lambda_{hS}^2}{4\lambda_S}, \ \lambda_S > 0$$

**from mass matrix positive-definite**

$$\lambda_{hS}\mu_S^2 - 2\lambda_S\mu_h^2 > 0$$

$$\lambda_{hS}\mu_h^2 - 2\lambda_h\mu_S^2 > 0$$

**from $v^2>0$, $w^2>0$**

# The simplest extension $\langle S \rangle \neq 0$

Identify $H_1$ with the physical 125 GeV scalar found at the LHC and require v=246 GeV. 3 free parameters left.

Since in the SM lagrangian one has couplings such as

$$\frac{\tilde{h}}{v}\left(2m_W^2 W_\mu^+ W^{\mu -} + m_Z^2 Z_\mu Z^\mu - \sum_f m_f \bar{f} f\right) \Longrightarrow$$

$$\frac{H_1 \cos\theta + H_2 \sin\theta}{v}\left(2m_W^2 W_\mu^+ W^{\mu -} + m_Z^2 Z_\mu Z^\mu - \sum_f m_f \bar{f} f\right)$$

# The simplest extension $\langle S \rangle \neq 0$

Physical consequences:

• all Higgs couplings are reduced by a common factor of cos $\theta$ and hence all Higgs widths are reduced by $\cos^2\theta$

• couplings of $H_2$ to gauge bosons and fermion are the same of a SM Higgs reduced by sin $\theta$

• new processes (depending on mass of $H_2$):

$$H_2 \to H_1 H_1 \ \text{for} \ m_{H_2} > 250 \text{ GeV}$$

$$H_1 \to H_2 H_2 \ \text{for} \ m_{H_2} < 62.5 \text{ GeV}$$

# The simplest extension $\langle S \rangle \neq 0$

## Bounds on the model:

- perturbativity of couplings ($\lambda_i < 4\pi^2$)
- vacuum stability (potential bounded from below, $\lambda_i > 0$)
- EW precision measurements

modified couplings, new loop contributions from $H_2$
(depend only on $H_2$ mass and $\theta$)

- LEP direct searches (low mass $H_2$)
- LHC direct searches (high mass $H_2$)
- Higgs couplings at LHC ($H_1 \to \gamma\gamma$, 4f)

modification of widths ($\theta$), possible new contribution to $H_1$ width for light $H_2$($\lambda_{hS}$)

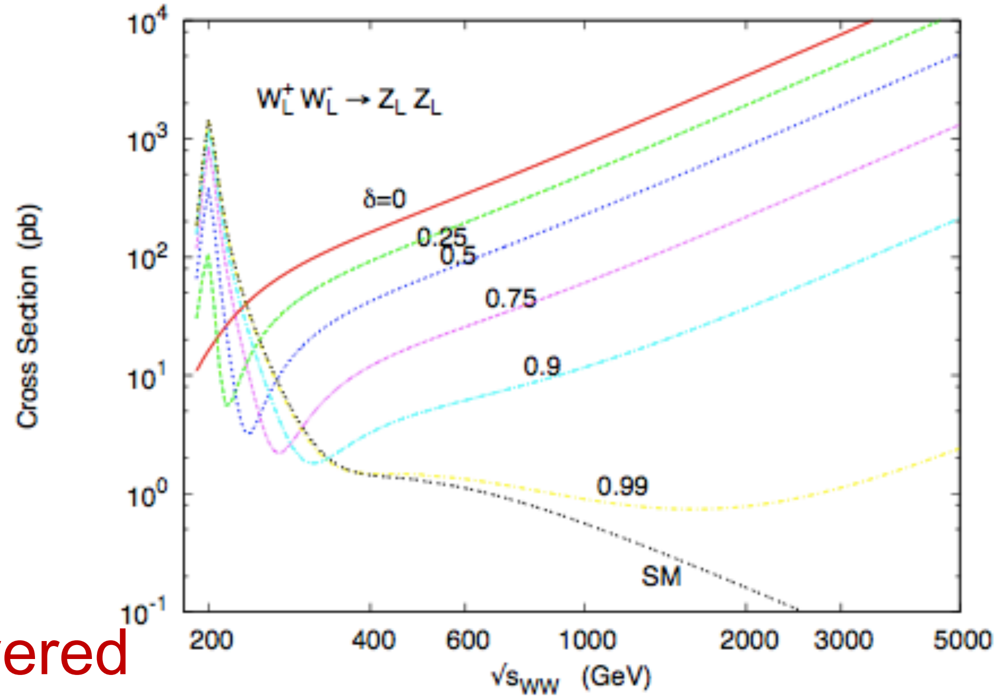
- Partial unitarization

# The simplest extension $\langle S \rangle \neq 0$

Partial unitarization:

$$\delta = \left( \frac{g_{HWW}}{g_{HWW}^{SM}} \right)^2$$

Cheung, Chiang and Yuan, 0803.2661




(b)

Unitarity must be recovered after the 2nd Higgs threshold!

FIG. 1: Scattering cross sections for (a) $W_L^+W_L^- \to W_L^+W_L^-$ and (b) $W_L^+W_L^- \to Z_L Z_L$ versus $\sqrt{s_{WW}}$. Various values of $\delta$ are shown, where $\delta$ denotes the size of the Higgs amplitude relative to the SM one. An angular cut of $|\cos\theta_{WW}| < 0.8$ is applied and the light Higgs boson mass $m_h = 200$ GeV is assumed.

# The simplest extension $\langle S \rangle \neq 0$

Some results:

Falkowiski, Gross and Lebedev (1502.01361)

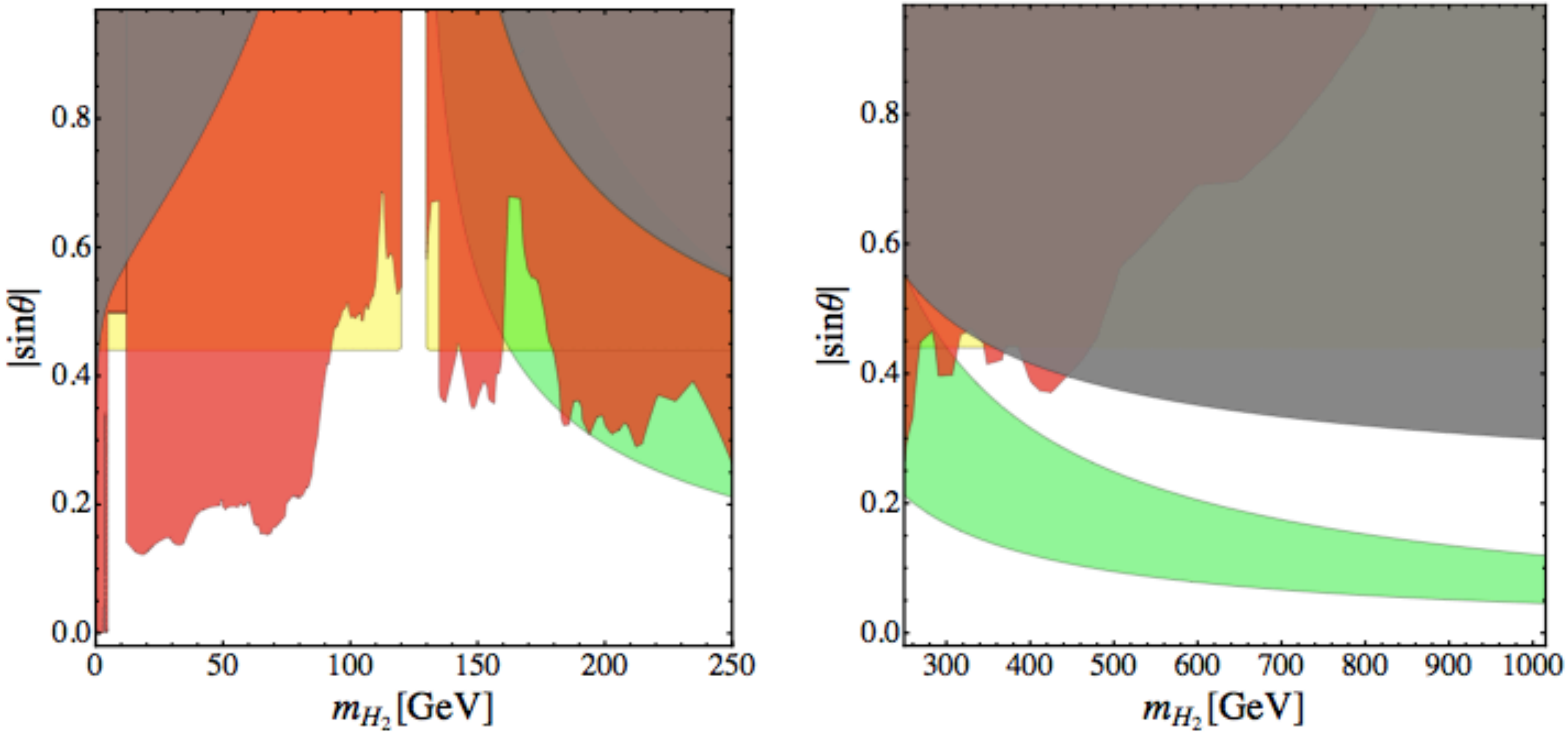



**Figure 3:** Left: Parameter space (for $m_{H_2} \leq 2m_{H_1}$) excluded at 95 % CL by direct searches (red), precision tests (gray), and $H_1$ couplings measurements (yellow). For $m_{H_2} < m_{H_1}/2$, the limit from the $H_1$ couplings is marginalised over $\lambda_{hs}$, otherwise it does not depend on $\lambda_{hs}$. The green region is preferred by stability of the scalar potential up to the Planck scale at $\lambda_{hs} = 0.01$; for other $\lambda_{hs}$, it is either very similar or smaller and contained within the green region. Right: Same for $m_{H_2} > 2m_{H_1}$.

# The simplest extension $\langle S \rangle \neq 0$

Falkowiski, Gross and Lebedev (1502.01361)

It seems that $\sin\theta \leq \mathcal{O}(0.2)$ is allowed so far.

How about the prospects of directly finding a heavy $H_2$ at the LHC?

Resonant double Higgs production:

$$pp \to H_2 \to H_1 H_1$$

# The simplest extension $\langle S \rangle \neq 0$

Resonant double Higgs production is a signal in many BSM extensions but difficult to detect.

Final states with 4 b's or 2b's+2 γ's

$$pp \to H_2 \to H_1 H_1 \to \bar{b}b\bar{b}b,\ \gamma\gamma\bar{b}b$$

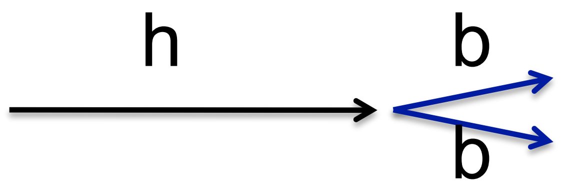
**CMS-PAS-HIG-14-013** **CMS-PAS-HIG-13-032**

# The simplest extension $\langle S \rangle \neq 0$

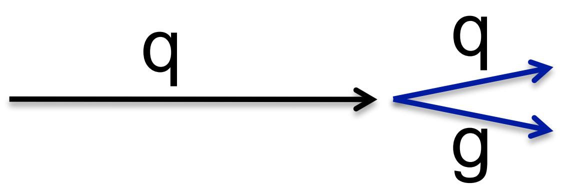
Final states with 4 b's: huge QCD backgrounds
For heavy $H_2$: boosted b's
Feasibility study using boosted jet techniques

Gouzevitch, Oliveira, Rojo, RR, Salam, Sanz (JHEP 2013)

QCD jets are different from Higgs jets:

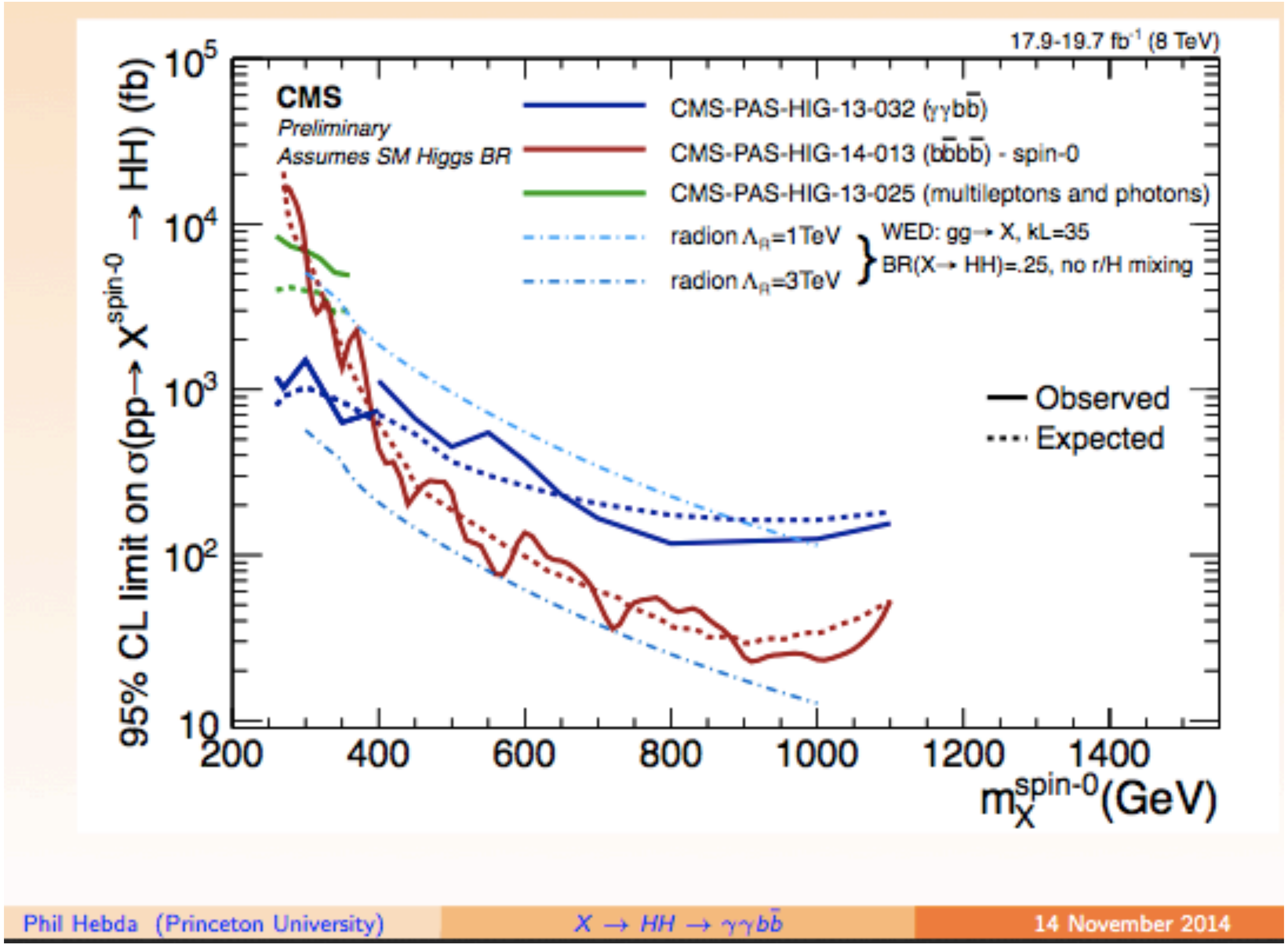



2 b's tend to share same momentum




Gluon radiation is soft - asymmetry

# CMS limits on resonant double Higgs production



# The simplest extension $\langle S \rangle = 0$

$Z_2$ symmetry is unbroken: scalar S does not mix with Higgs and is stable.

Simplest model of dark matter!
Actually, self-interacting dark matter.

Higgs can decay invisibly.

Eg, Bento, Bertolami, RR, Teodoro (2000)

# The simplest extension $\langle S \rangle = 0$

Mixing term $\lambda_{hS}\, h^2 S^2$ controls:

- S S -> SM SM processes (DM relic abundance)
- S N -> S N (direct detection)
- h -> S S (invisible Higgs decay)

Term $\lambda_S\, S^4$ controls DM self-interactions.

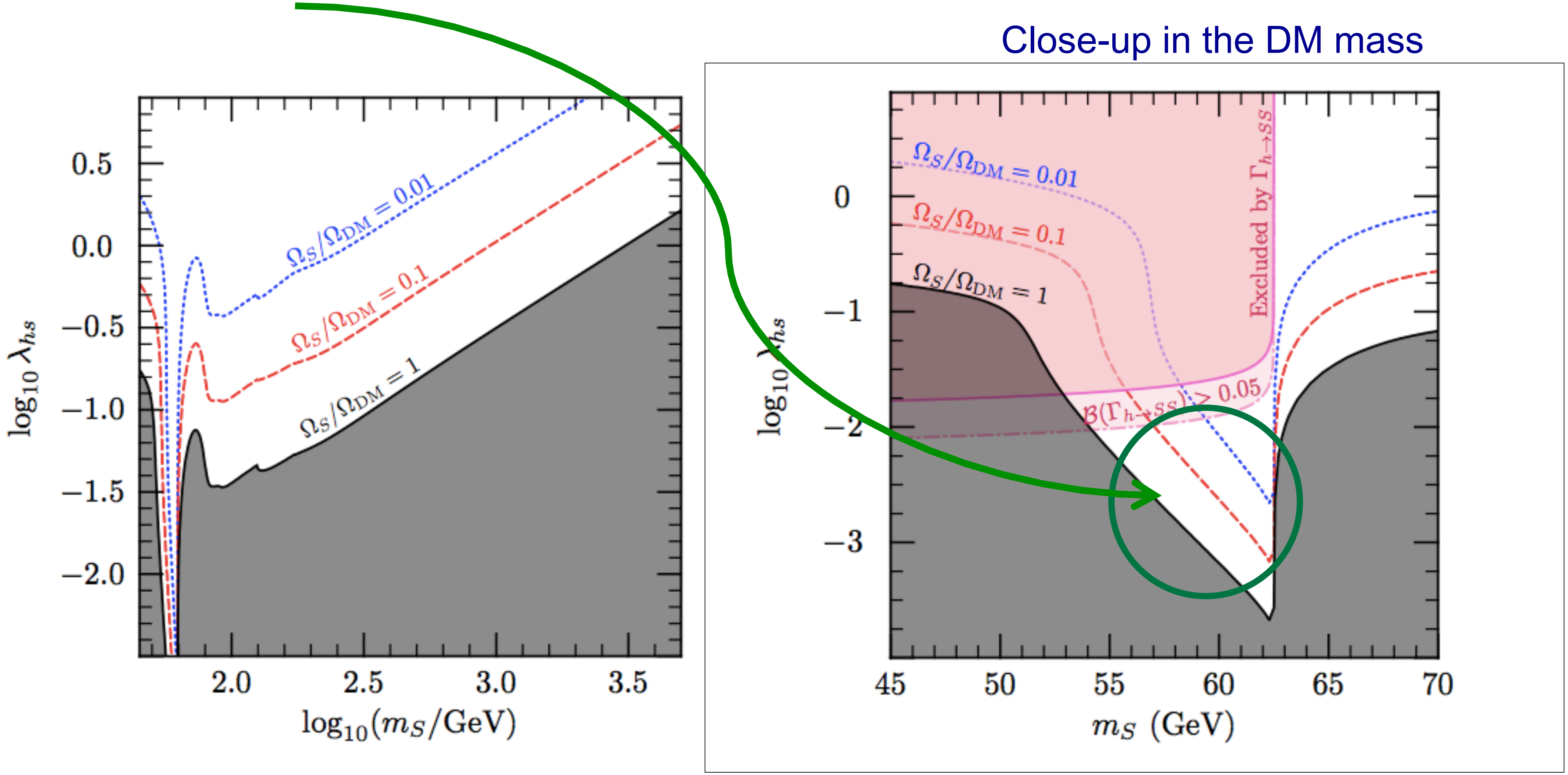
# The simplest extension $\langle S \rangle = 0$

## Latest constraints on parameters $m_S$ and $\lambda_{hS}$:

Allowed region for $m_S < m_h/2$

Cline, Scott, Kainulainen, Weniger (1306.4710)

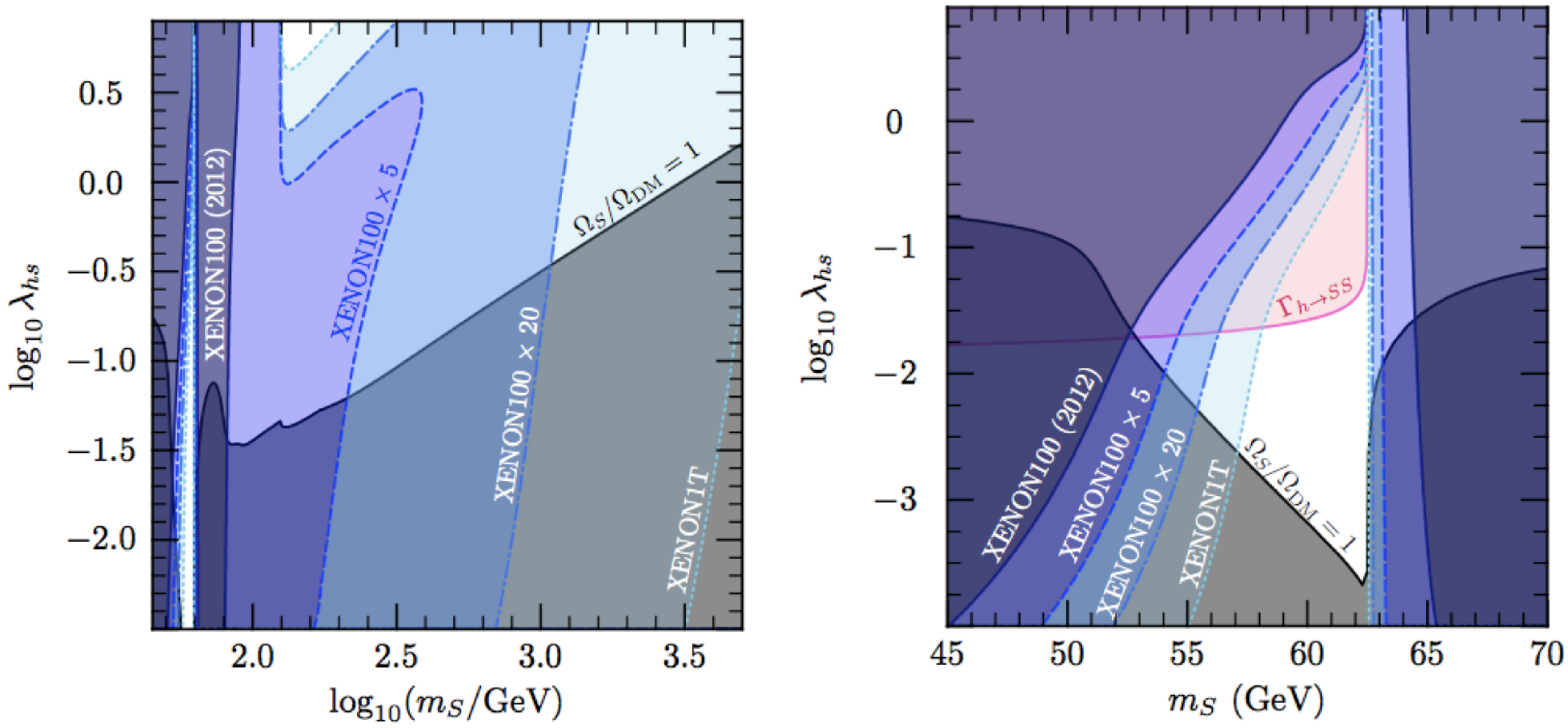
Close-up in the DM mass



# The simplest extension $\langle S \rangle = 0$

Model is very constrained when direct detection is included:

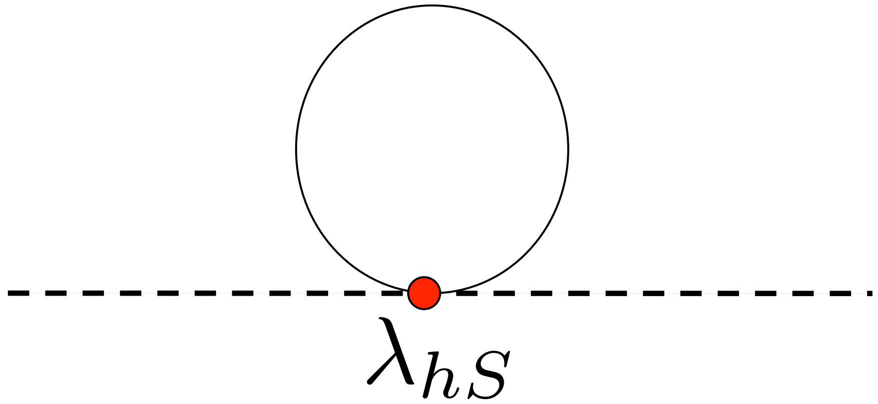
Cline, Scott, Kainulainen, Weniger (1306.4710)



# Naturalness in the simplest extension

Mass of new scalar particle (a new scale) may introduce a hierarchy problem.

The contribution of S to the higgs mass is:




$$\delta M_h^2 = \frac{\lambda_{hS}}{16\pi^2} M_S^2$$

# Naturalness in the simplest extension

To avoid fine-tunig one should either have masses ~ (TeV) or small couplings.Naturalness implies:

$$M_S^2 < \frac{16\pi^2}{\lambda_{hS}} M_h^2$$

Typical tension between naturalness and experimental searches (common in many models):
Not finding new physics imply larger masses – make theories less natural (unless couplings are very small).

# The simplest extension

This concludes the discussion on the simplest extension of the SM: adding a singlet scalar field.

Many of its consequences (modifications of Higgs couplings through mixing, Higgs invisible decays, possibility of resonant double Higgs production, possible DM candidates) are common to other BSM extensions.

Many BSM's build on this simple class, adding more scalar fields: complex singlet (e.g., axion models), 2-Higgs doublets (inert or active, SUSY), Higgs triplets .....

# The simplest extension

Even though the vacuum stability issue at high energies can be ameliorated, these models were not built to avoid the naturalness problem, which is arguably the guiding principle to BSM.

We will next study models that were motivated by the hierachy problem.

# Addendum (if time permits)

It is possible to capture the basic features of collider phenomenology of more complicated models by studying the mixing of SM particles to particles in the BSM sector (heavy particles with typical mass M).

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM} + \mathcal{L}_{mix}$$

Contino, Kramer, Son, Sundrum (06)

# Addendum (if time permits)

- Higgs-S mixing

$$V(h,S) = \frac{1}{2}\mu_h h^2 + \frac{1}{2}\mu_S S^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_S S^4 + + \frac{1}{4}\lambda_{hS} h^2 S^2$$

- Fermion mixing

$$\mathcal{L}_{mix} \propto \mu\, \bar{\psi}_L \chi_R + h.c.$$

- Vector mixing (ρ-γ mixing in QCD)

$$\mathcal{L}_{mix} \propto M^2\, \tilde{W}_\mu \tilde{\rho}^\mu$$

Pheno: diagonalize lagrangian, write it in terms of eigenstates and mixing angles.