Reopening the Higgs Portal for Singlet Scalar Dark Matter

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In colaboración with A. Casas (IFT), J. Moreno (IFT) and D. Cerdeño (IPPP)

(Work in progress)

3rd IBS-MultiDark-IPPP Whorkshop

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- Higgs portal with a Real Singlet Scalar DM
- Higgs portal with two Real Singlet Scalars
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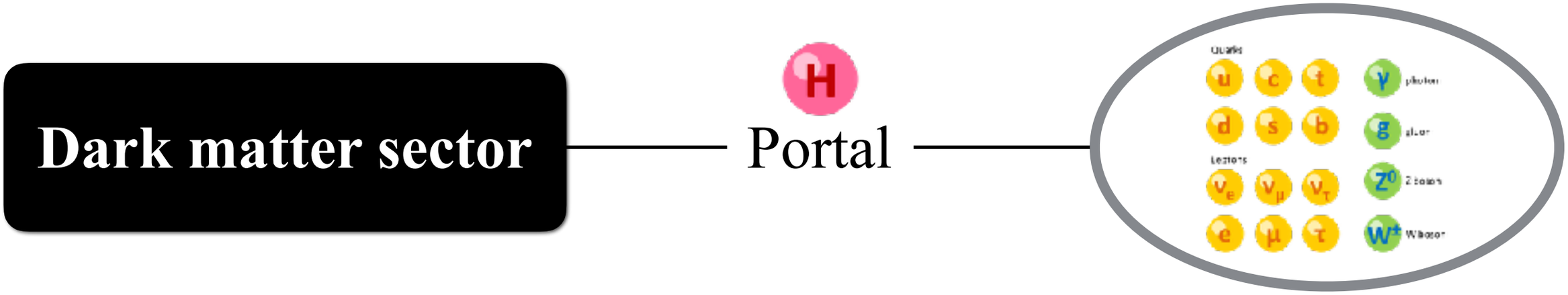
Introduction

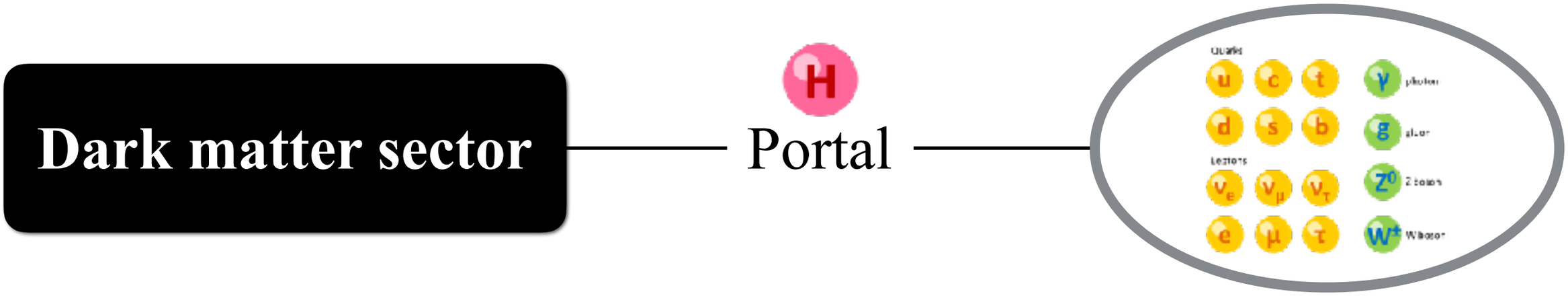
DM, portals and models

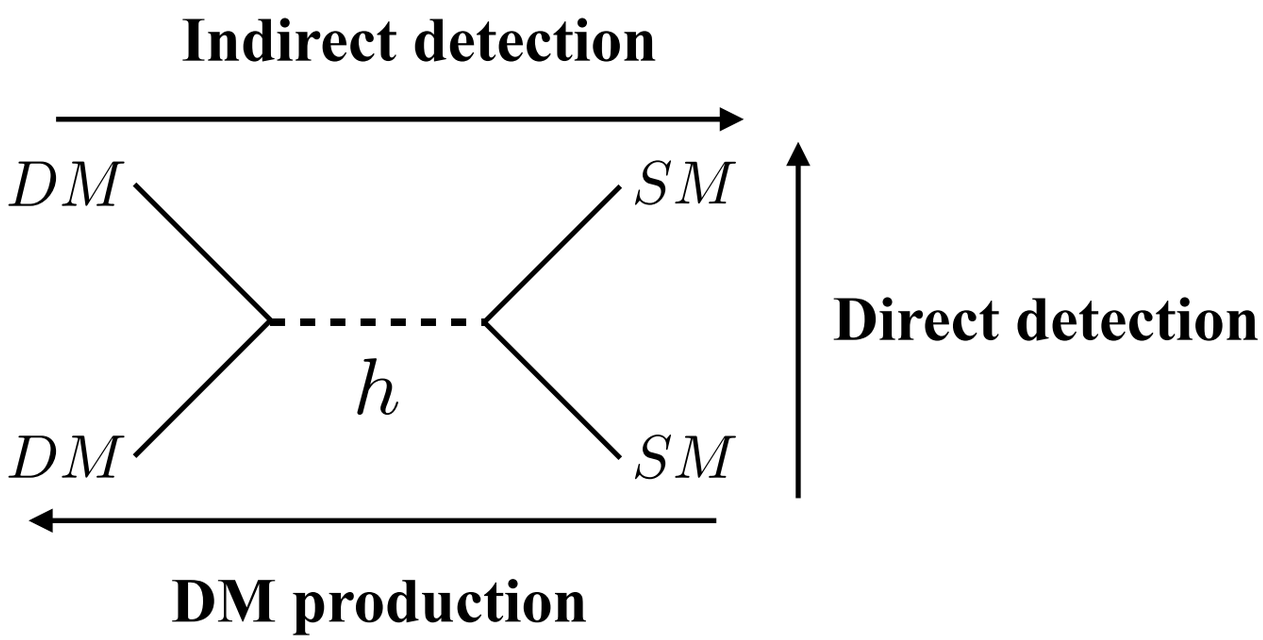
Relation between Dark sector and SM



DM, portals and models

Relation between Dark sector and SM

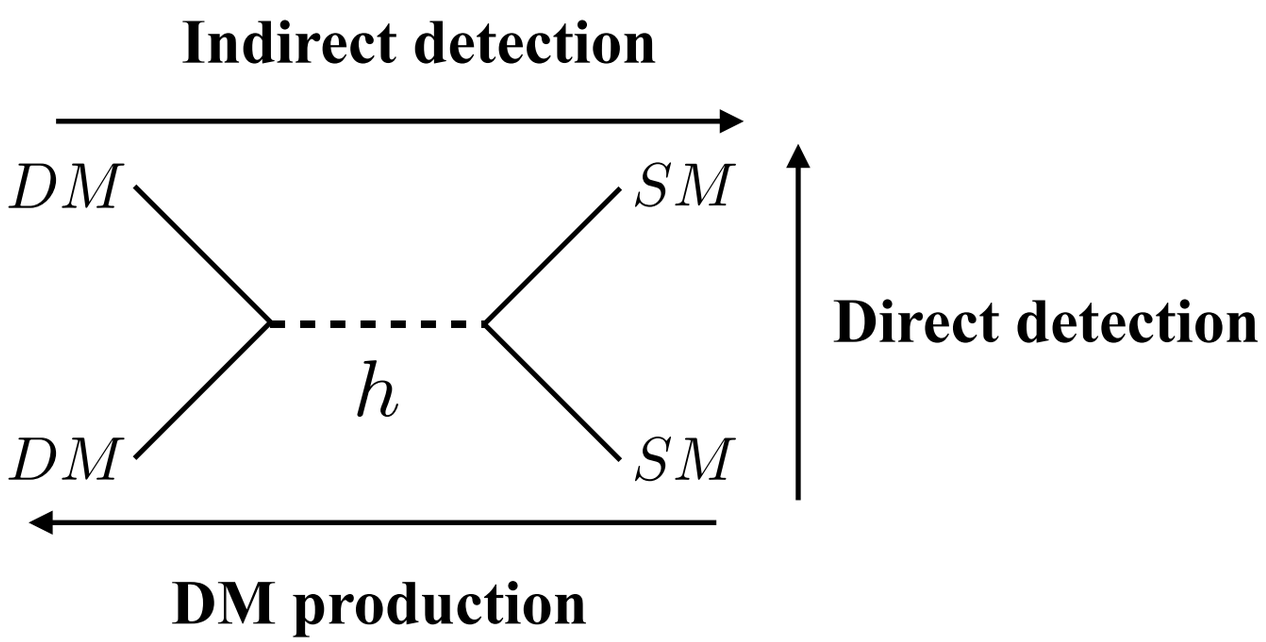




DM, portals and models

Relation between Dark sector and SM

Dark matter sector — Portal —



Many candidates

Singlet, Doublet…

Scalar, fermionic…

Simplest:

Real singlet scalar DM

Higgs portal with a Real Singlet Scalar DM

Higgs portal with a Real Singlet Scalar DM

$$Z_2 \text{ symmetry}$$

$$S \to -S \quad SM \to SM$$

Higgs portal with a Real Singlet Scalar DM

Z_2 symmetry

$S \to -S \quad SM \to SM$

Lagrangian

$$\mathcal{L}_{\mathrm{HP}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_0^2 S^2 - \frac{1}{2}\lambda_S |H|^2 S^2 - \frac{1}{4}\lambda_4 S^4$$

Renormalizable

Higgs portal with a Real Singlet Scalar DM

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Renormalizable

After EWSB

$$\mathcal{L}_{\rm HP} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \frac{1}{2}\lambda_S v h S^2 - \frac{1}{4}\lambda_S h^2 S^2 - \frac{1}{4}\lambda_4 S^4$$

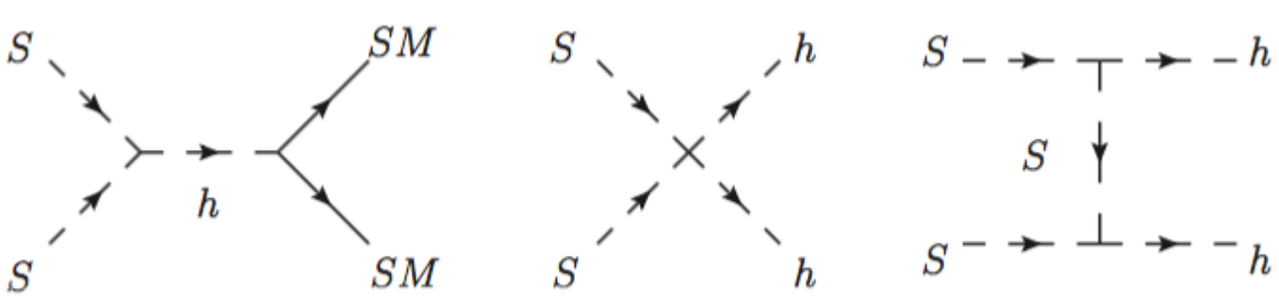
$(v = 175 \text{ GeV})$

Higgs portal with a Real Singlet Scalar DM

After EWSB

$$\mathcal{L}_{\rm HP} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \frac{1}{2}\lambda_S v h S^2 - \frac{1}{4}\lambda_S h^2 S^2 - \frac{1}{4}\lambda_4 S^4 \qquad (v = 175\ \text{GeV})$$

Processes DM-SM



Higgs portal with a Real Singlet Scalar DM

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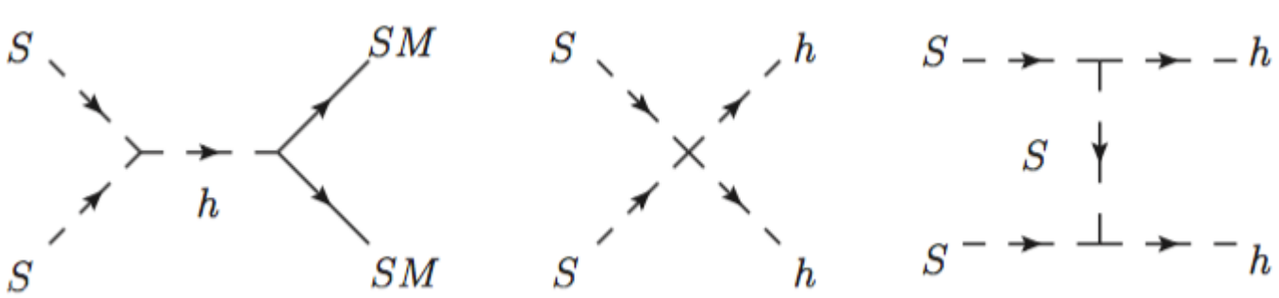


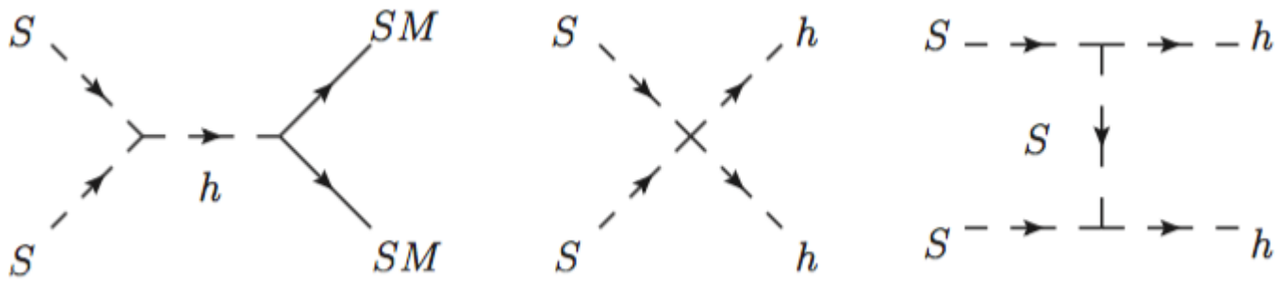
relevant parameters m_S λ_S

Higgs portal with a Real Singlet Scalar DM

After EWSB

$$\mathcal{L}_{\rm HP} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \frac{1}{2}\lambda_S v h S^2 - \frac{1}{4}\lambda_S h^2 S^2 - \frac{1}{4}\lambda_4 S^4 \qquad (v = 175\ \text{GeV})$$

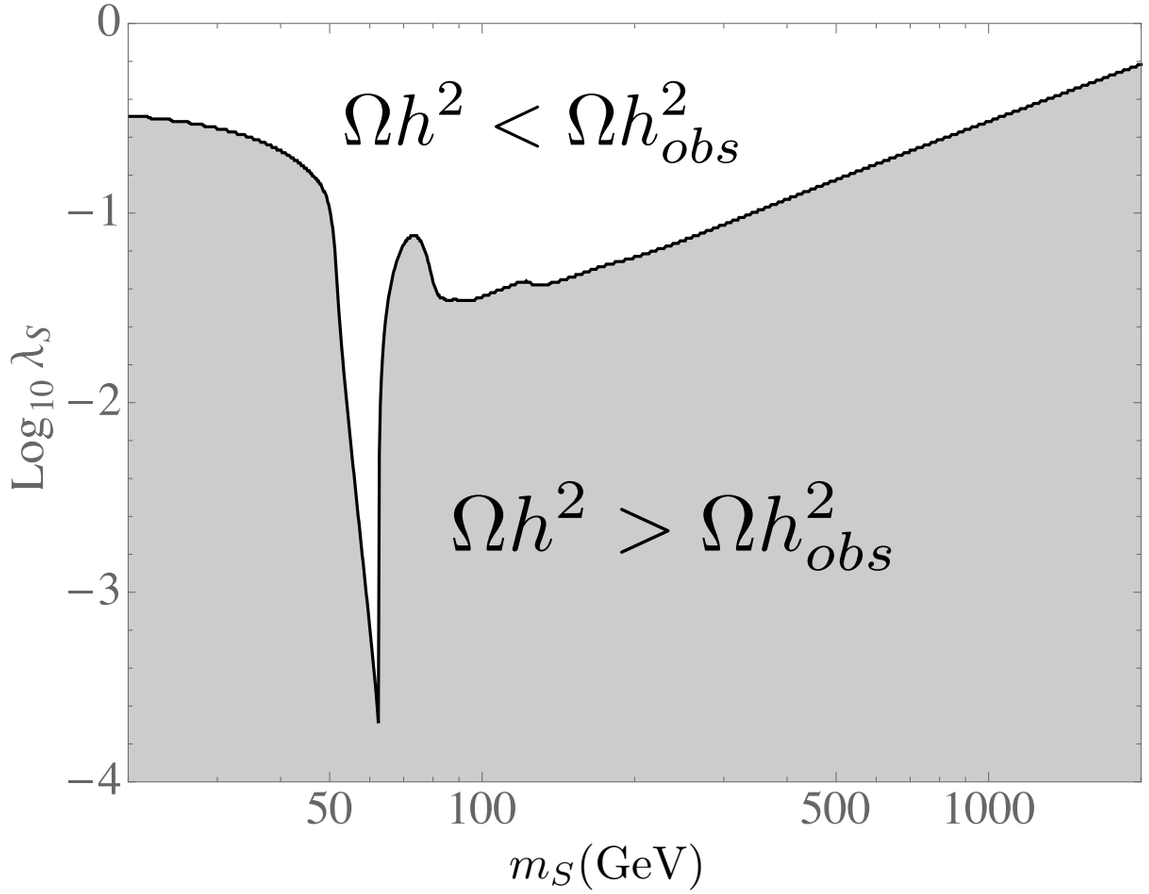
Processes DM-SM



relevant parameters

m_S λ_S

Relic density, Ωh^2



References on Real Singlet Scalar DM

[1] V. Silveira and A. Zee, *SCALAR PHANTOMS*, *Phys. Lett.* **B161** (1985) 136–140.

[2] J. McDonald, *Gauge singlet scalars as cold dark matter*, *Phys. Rev.* **D50** (1994) 3637–3649 [hep-ph/0702143].

[3] C. P. Burgess, M. Pospelov and T. ter Veldhuis, *The Minimal model of nonbaryonic dark matter: A Singlet scalar*, *Nucl. Phys.* **B619** (2001) 709–728 [hep-ph/0011335].

[4] W.-L. Guo and Y.-L. Wu, *The Real singlet scalar dark matter model*, *JHEP* **10** (2010) 083 [1006.2518].

[5] M. Duerr, P. Fileviez Perez and J. Smirnov, *Scalar Dark Matter: Direct vs. Indirect Detection*, 1509.04282.

[6] B. Li and Y.-F. Zhou, *Direct detection of dark matter with resonant annihilation*, *Commun. Theor. Phys.* **64** (2015), no. 1 119–126 [1503.08281].

[7] J. M. Cline, K. Kainulainen, P. Scott and C. Weniger, *Update on scalar singlet dark matter*, *Phys. Rev.* **D88** (2013) 055025 [1306.4710]. [Erratum: Phys. Rev.D92,no.3,039906(2015)].

[8] L. Feng, S. Profumo and L. Ubaldi, *Closing in on singlet scalar dark matter: LUX, invisible Higgs decays and gamma-ray lines*, *JHEP* **03** (2015) 045 [1412.1105].

[9] M. Duerr, P. Fileviez Perez and J. Smirnov, *Gamma-Ray Excess and the Minimal Dark Matter Model*, 1510.07562.

[10] H. Han and S. Zheng, *New Constraints on Higgs-portal Scalar Dark Matter*, *JHEP* **12** (2015) 044 [1509.01765].

References on Real Singlet Scalar DM

[11] A. Beniwal, F. Rajec, C. Savage, P. Scott, C. Weniger, M. White and A. G. Williams, *Combined analysis of effective Higgs portal dark matter models*, 1512.06458.

[12] H. Davoudiasl, R. Kitano, T. Li and H. Murayama, *The New minimal standard model*, *Phys. Lett.* **B609** (2005) 117–123 [hep-ph/0405097].

[13] S. W. Ham, Y. S. Jeong and S. K. Oh, *Electroweak phase transition in an extension of the standard model with a real Higgs singlet*, *J. Phys.* **G31** (2005) 857–872 [hep-ph/0411352].

[14] B. Patt and F. Wilczek, *Higgs-field portal into hidden sectors*, hep-ph/0605188.

[15] D. O'Connell, M. J. Ramsey-Musolf and M. B. Wise, *Minimal Extension of the Standard Model Scalar Sector*, *Phys. Rev.* **D75** (2007) 037701 [hep-ph/0611014].

[16] X.-G. He, T. Li, X.-Q. Li and H.-C. Tsai, *Scalar dark matter effects in Higgs and top quark decays*, *Mod. Phys. Lett.* **A22** (2007) 2121–2129 [hep-ph/0701156].

[17] S. Profumo, M. J. Ramsey-Musolf and G. Shaughnessy, *Singlet Higgs phenomenology and the electroweak phase transition*, *JHEP* **08** (2007) 010 [0705.2425].

[18] V. Barger, P. Langacker, M. McCaskey, M. J. Ramsey-Musolf and G. Shaughnessy, *LHC Phenomenology of an Extended Standard Model with a Real Scalar Singlet*, *Phys. Rev.* **D77** (2008) 035005 [0706.4311].

and many more….

Direct, indirect and Higgs Invisible Width constraints

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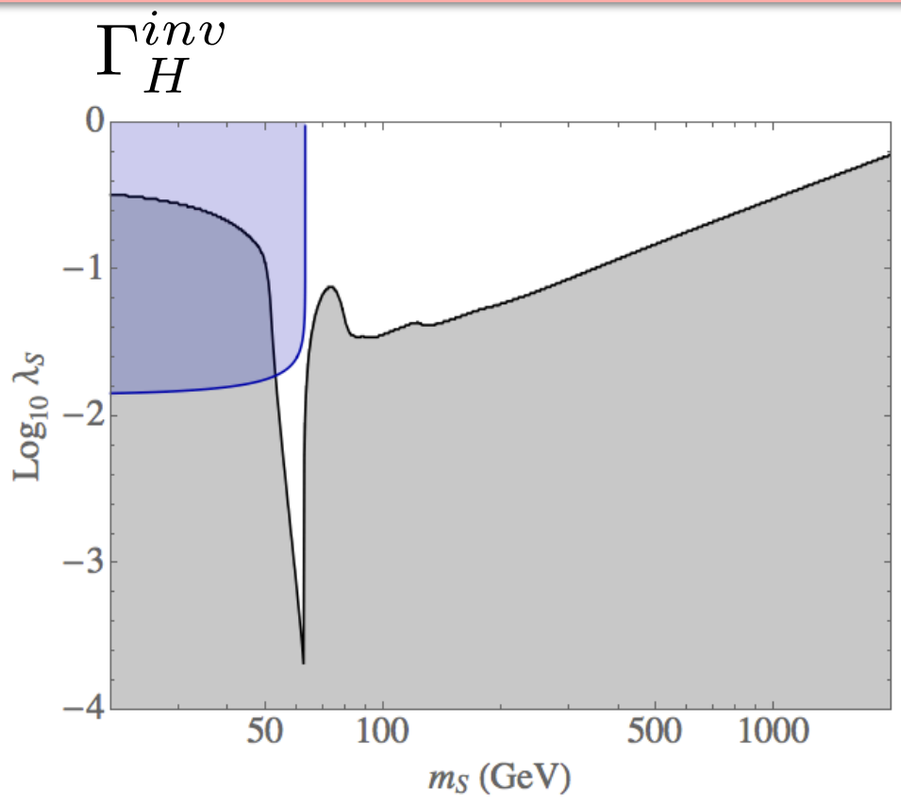
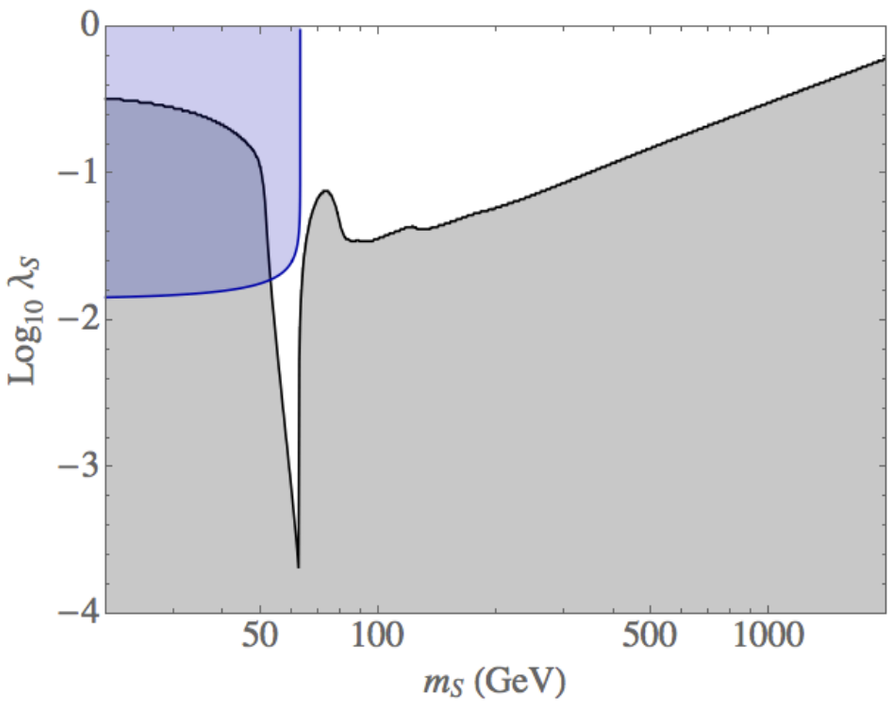
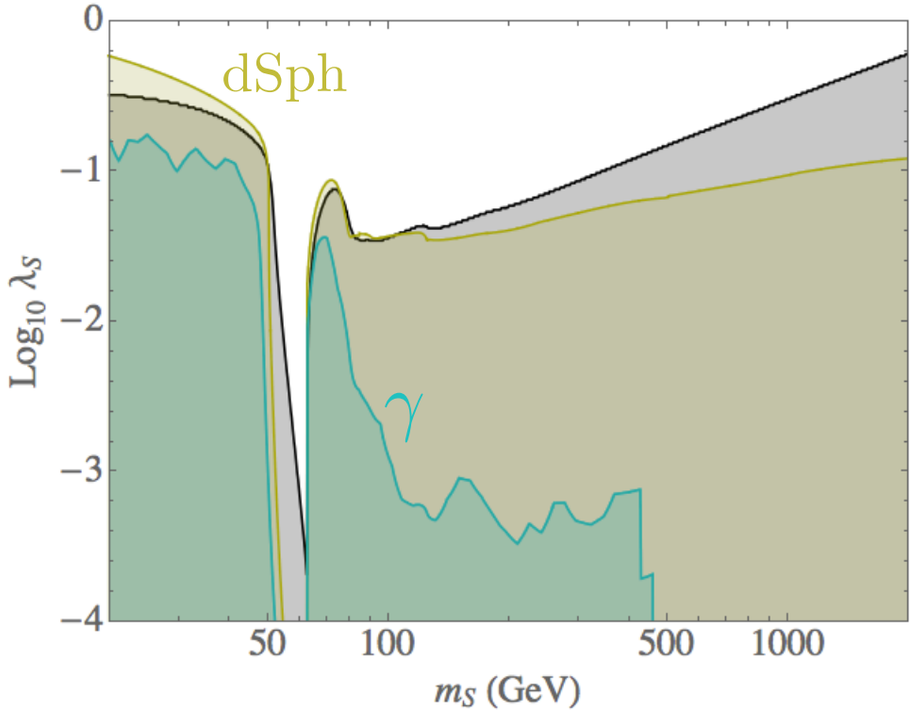


Direct, indirect and Higgs Invisible Width constraints

Γ_H^{inv}



Indirect detection



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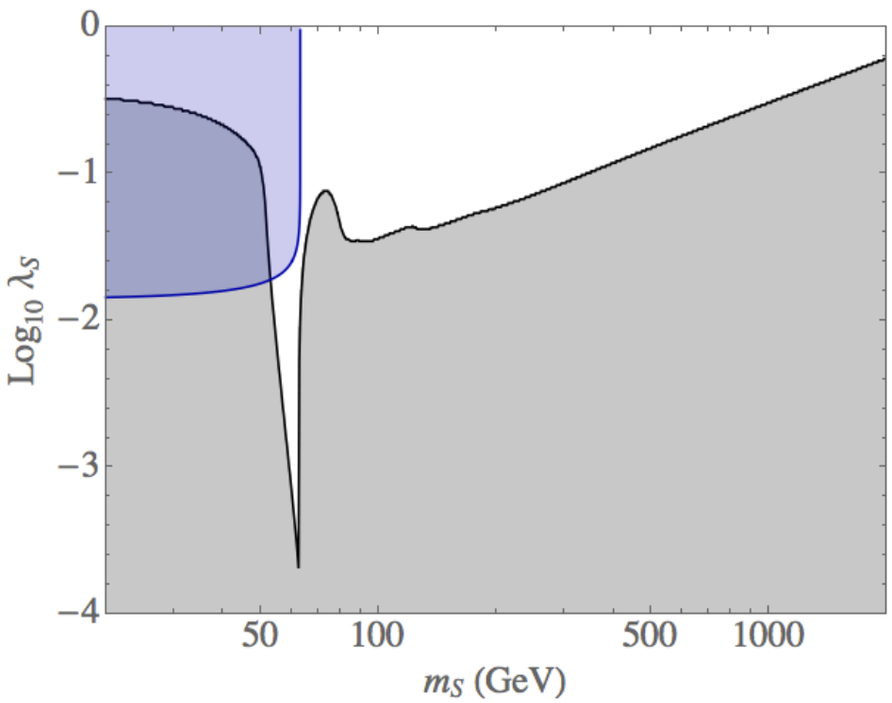

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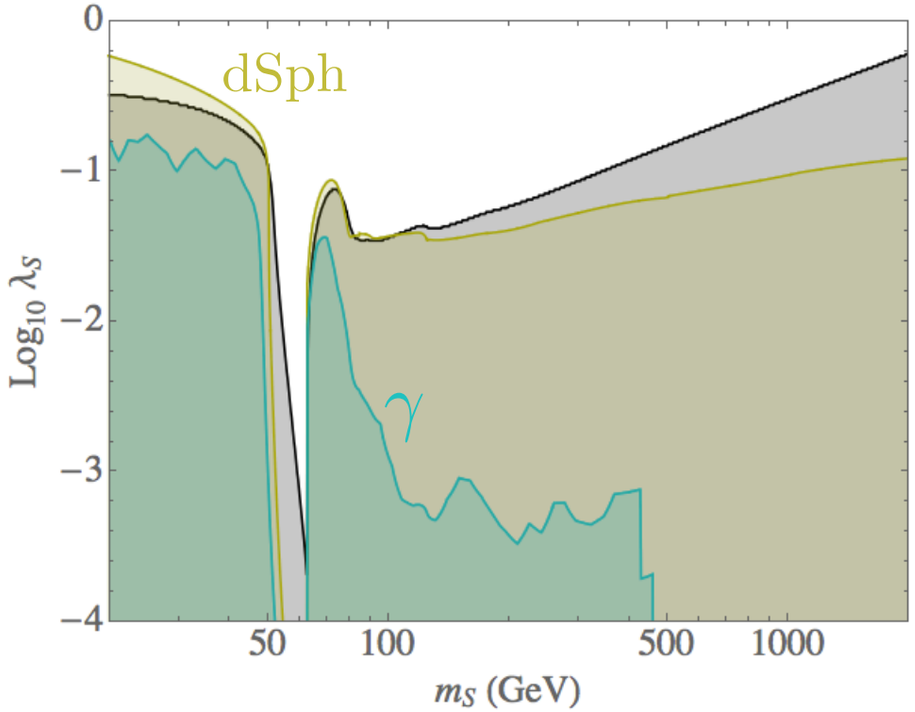
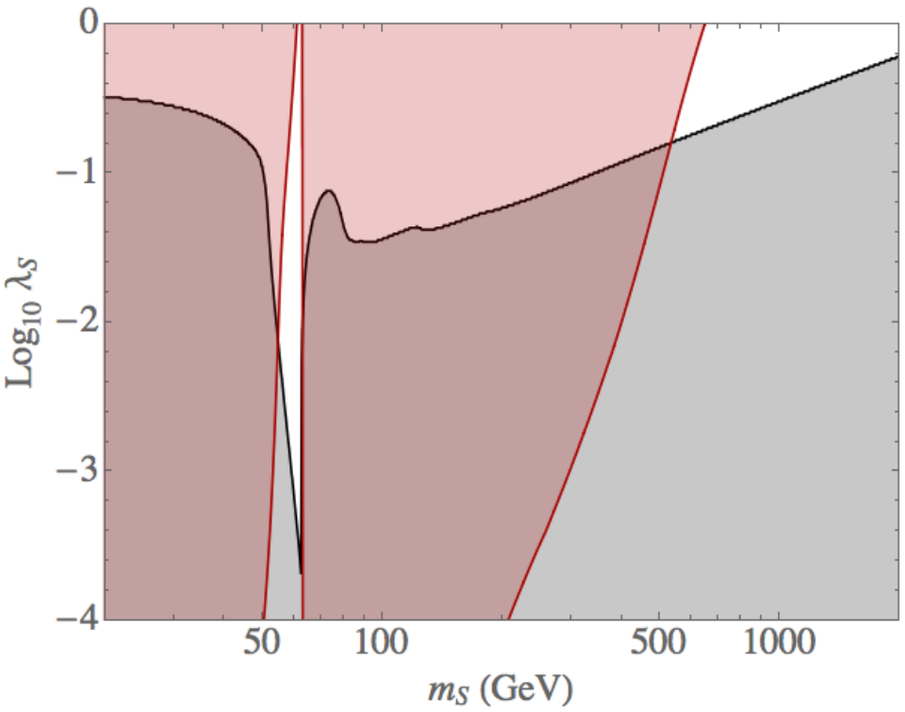
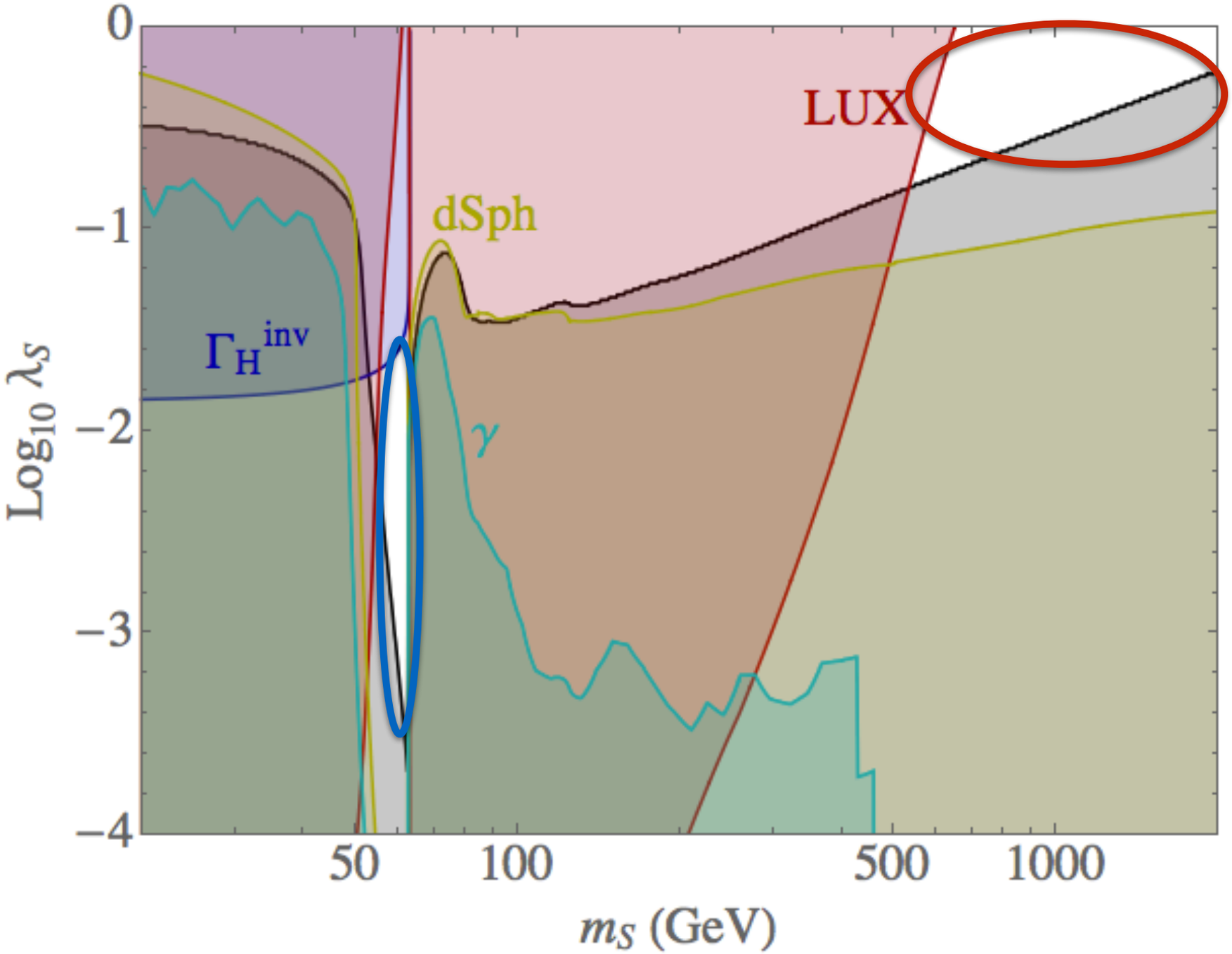


Direct detection: LUX



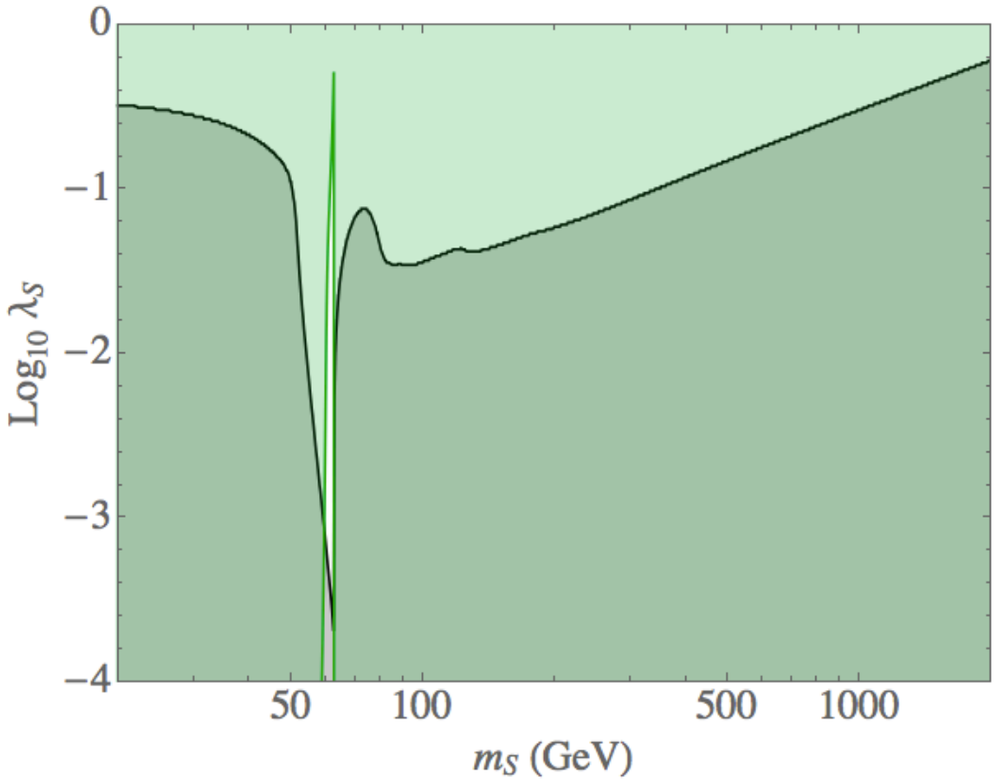
Direct, indirect and Higgs Invisible Width constraints



- **Masses over 500 GeV are allowed**
- **Small window in the resonance allowed**

Future constraints

Future Direct Detection: LZ



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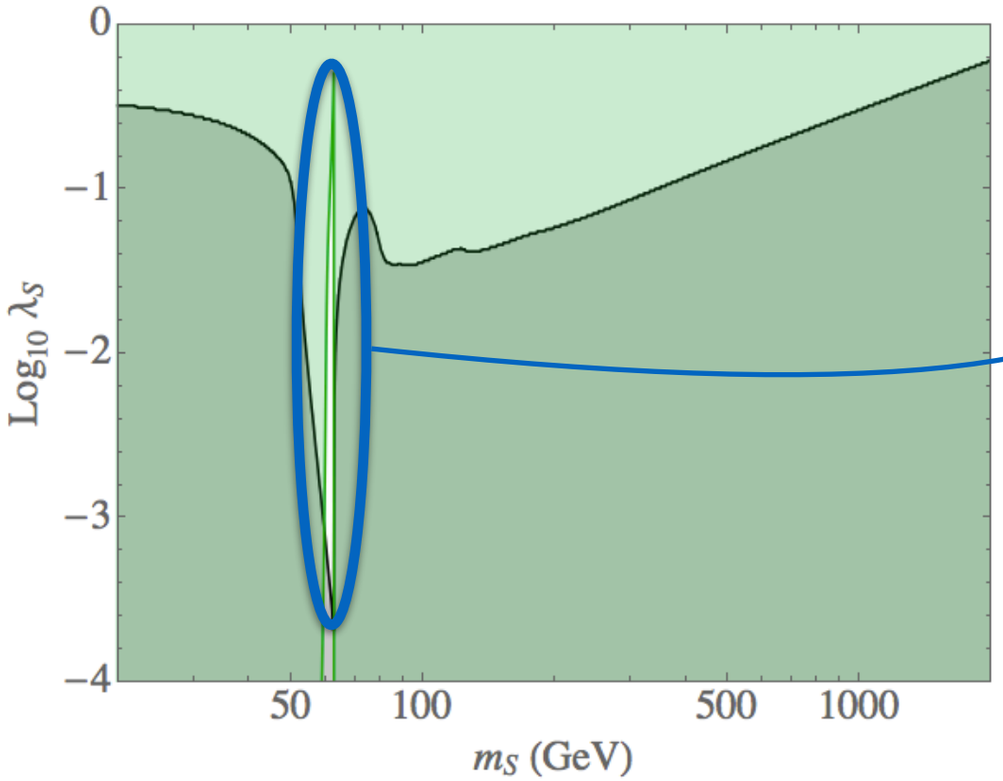

The only zone remaining will be the window in the **resonance**

Future constraints

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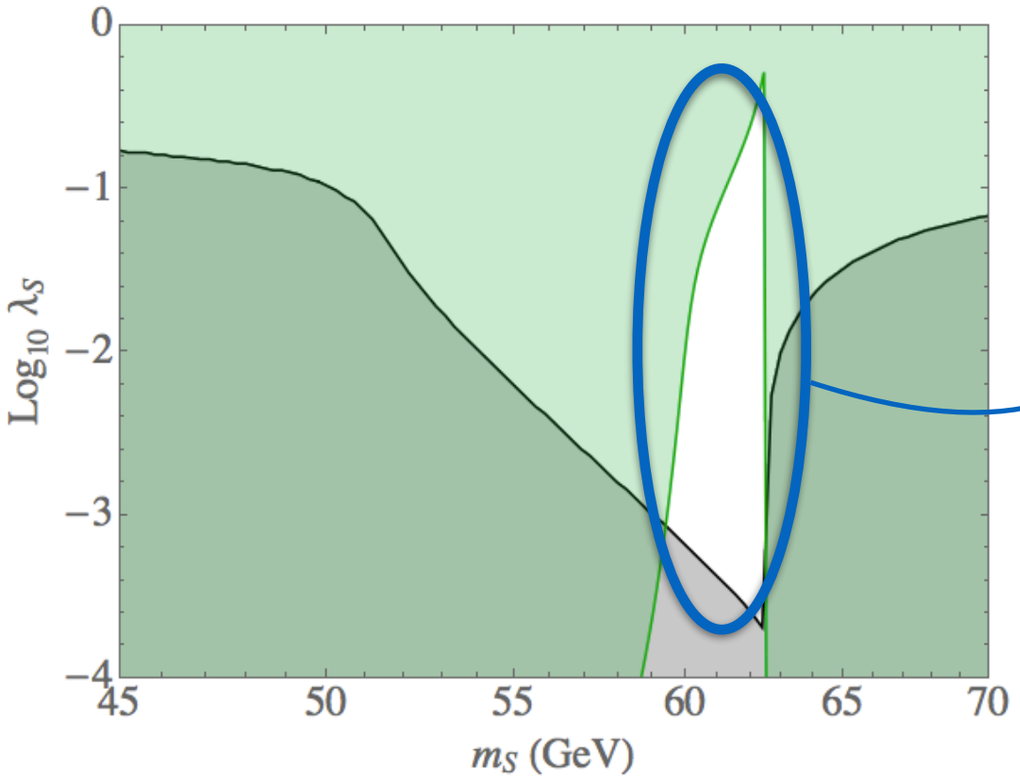

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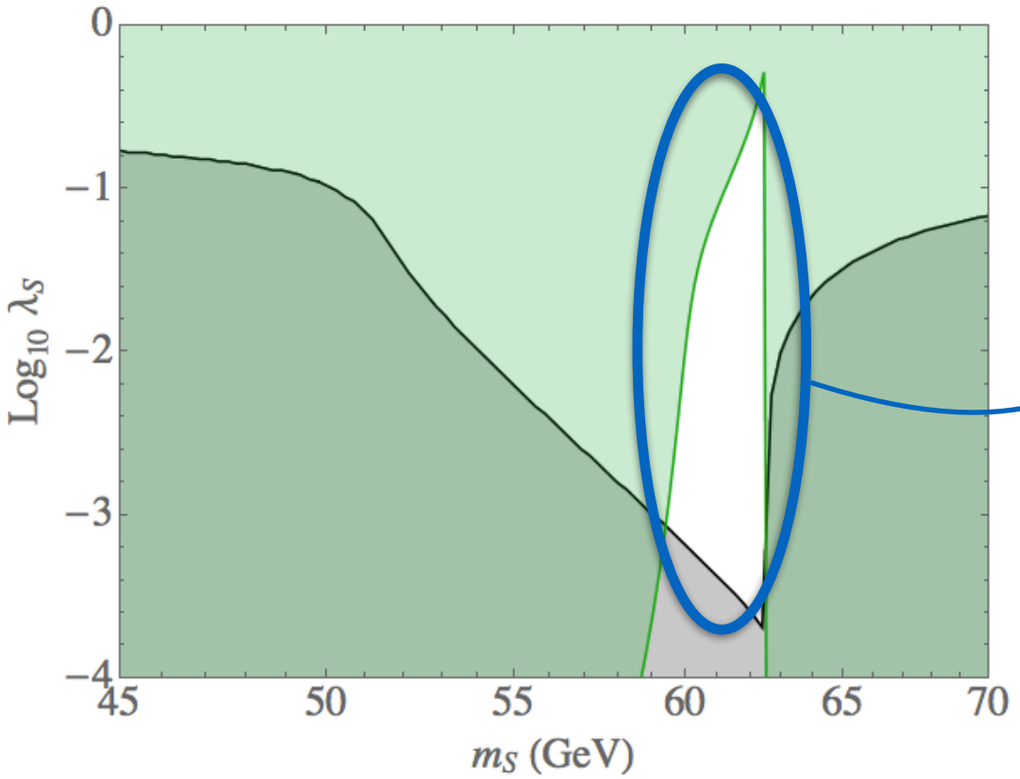


The only zone remaining will be the window in the **resonance**

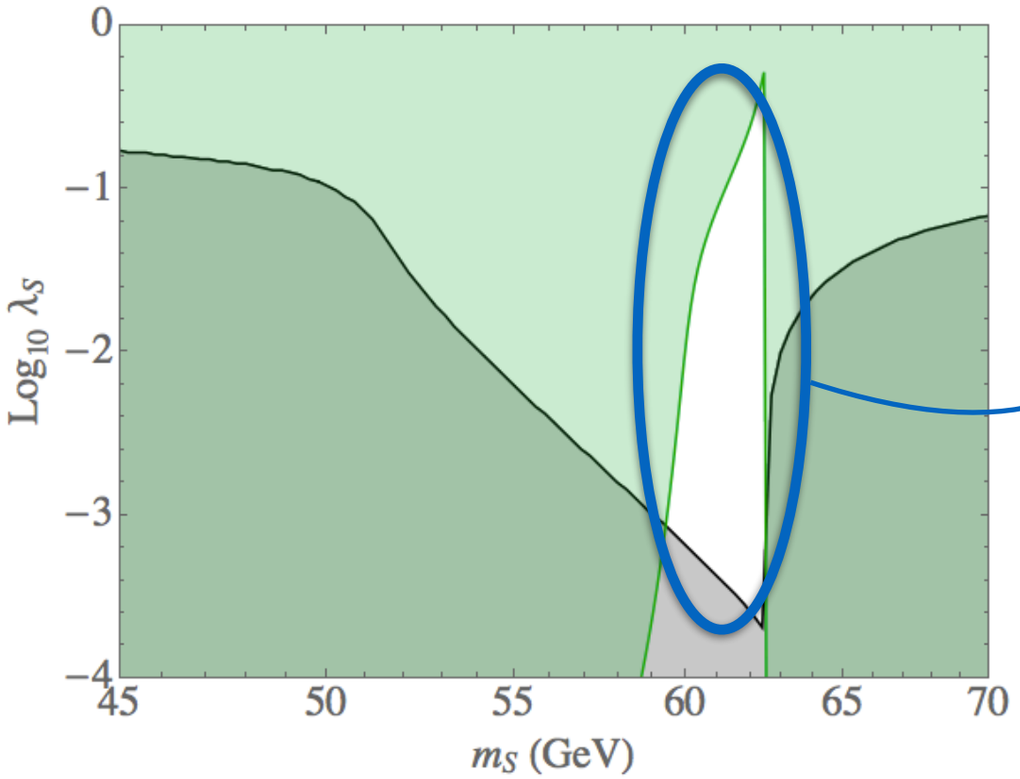
- We expect **indirect detection** experiments to explore that remaining window.

Feng et al: arXiv 1412:1105

Duerr et al: arXiv 1509.04282

Future constraints

Future Direct Detection: LZ



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No positive detection → Scalar Higgs portal

Future constraints

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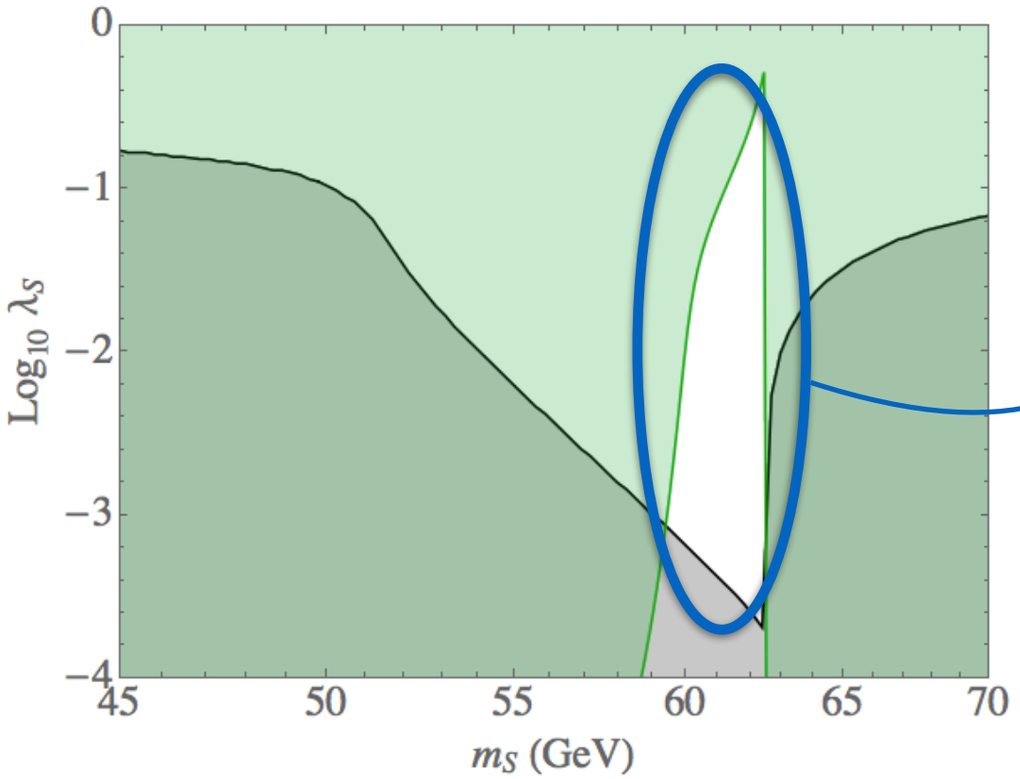

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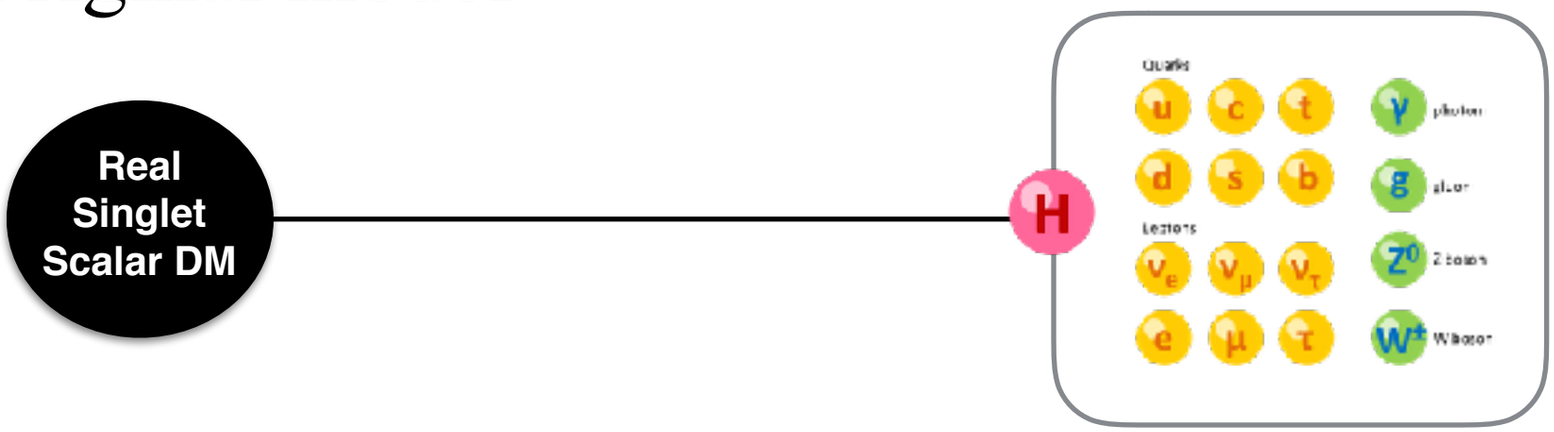
“Rescuing” the Higgs portal

Original model



“Rescuing” the Higgs portal

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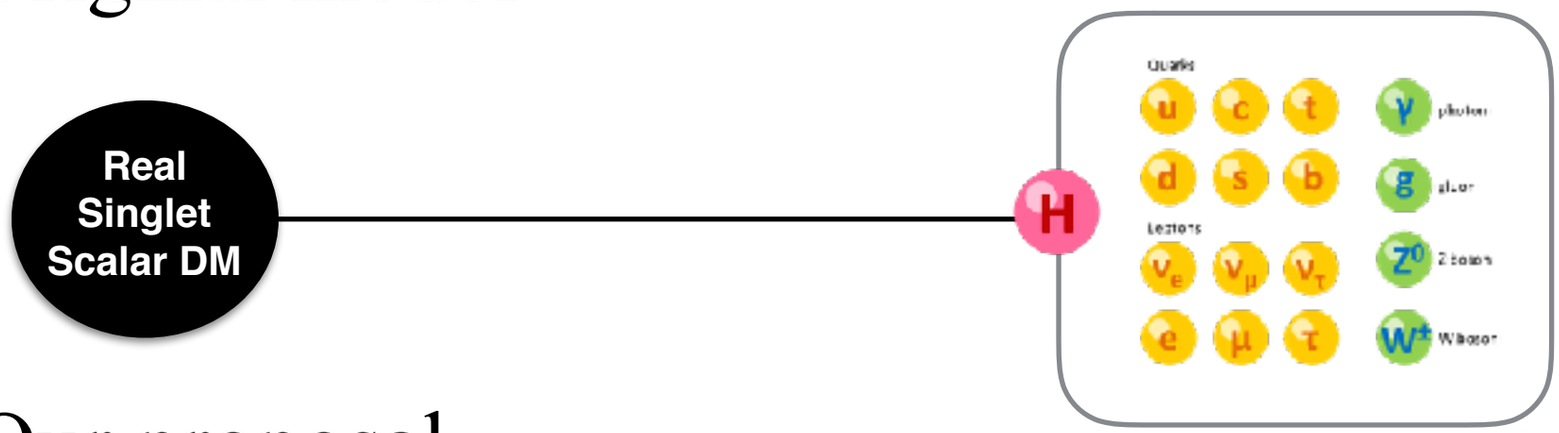
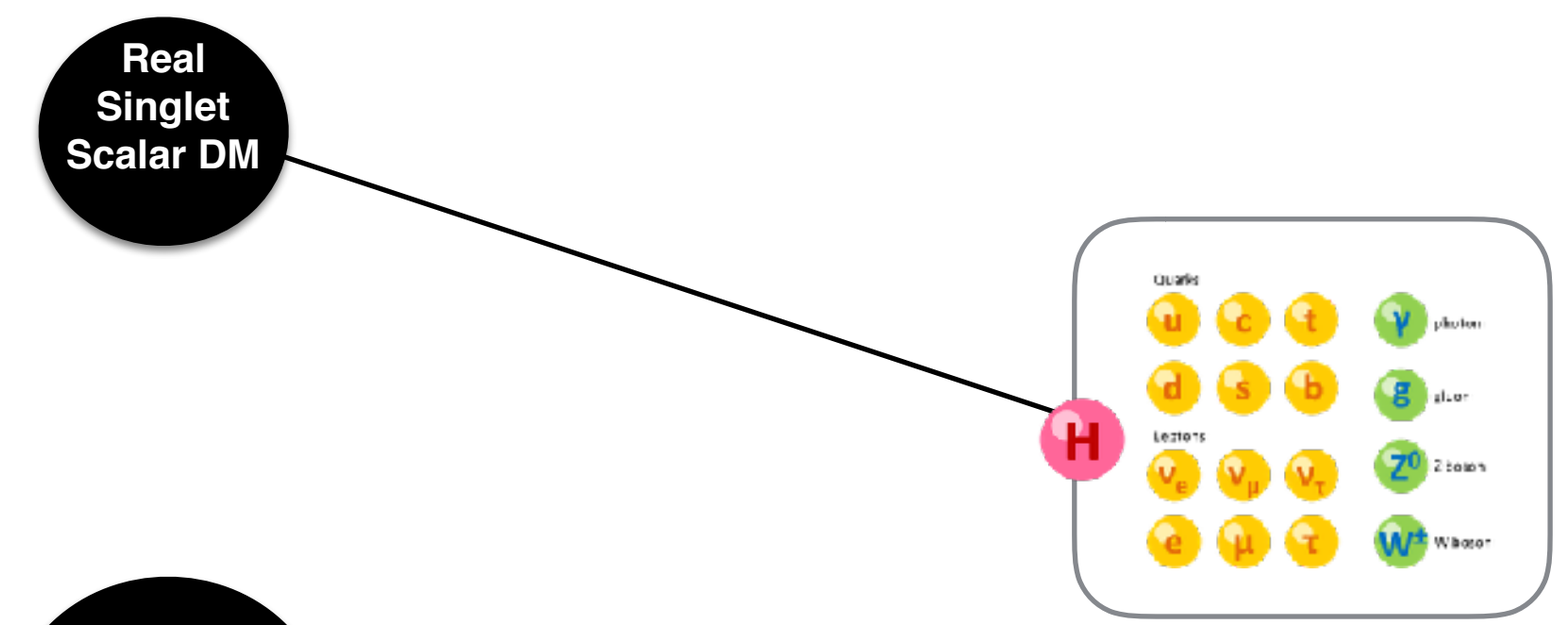


Our proposal



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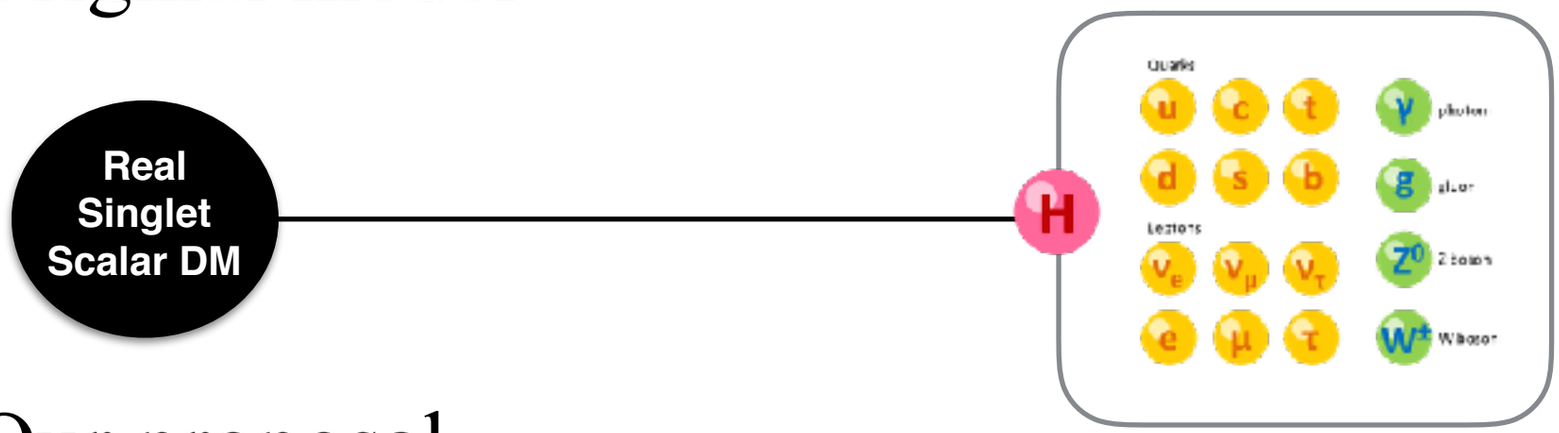

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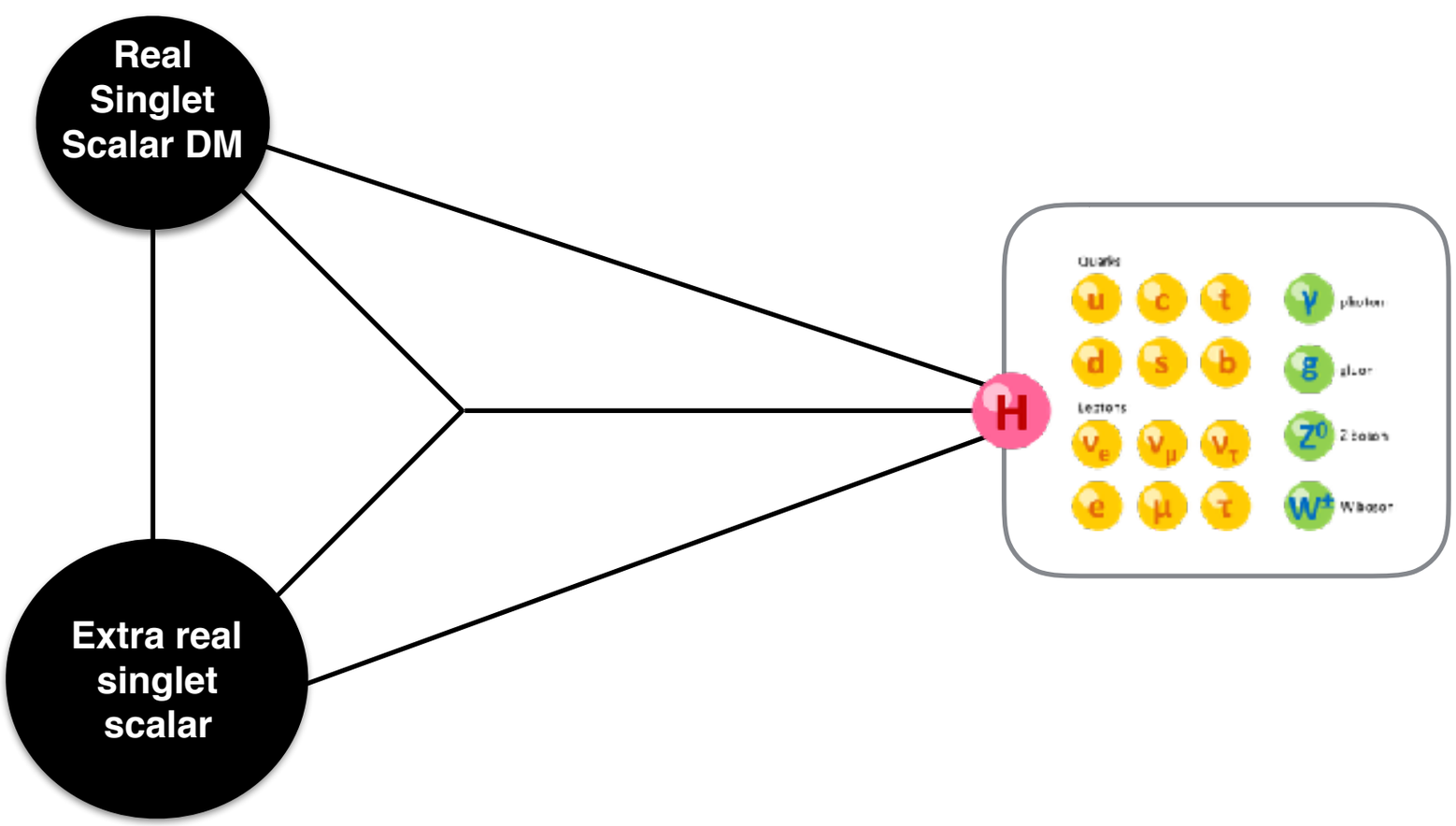

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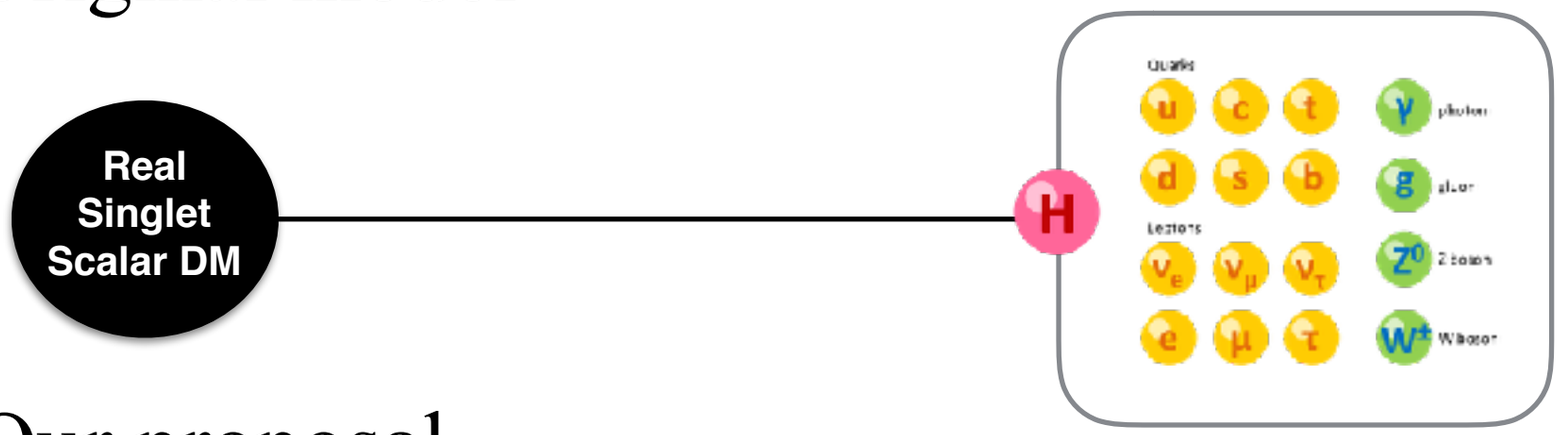

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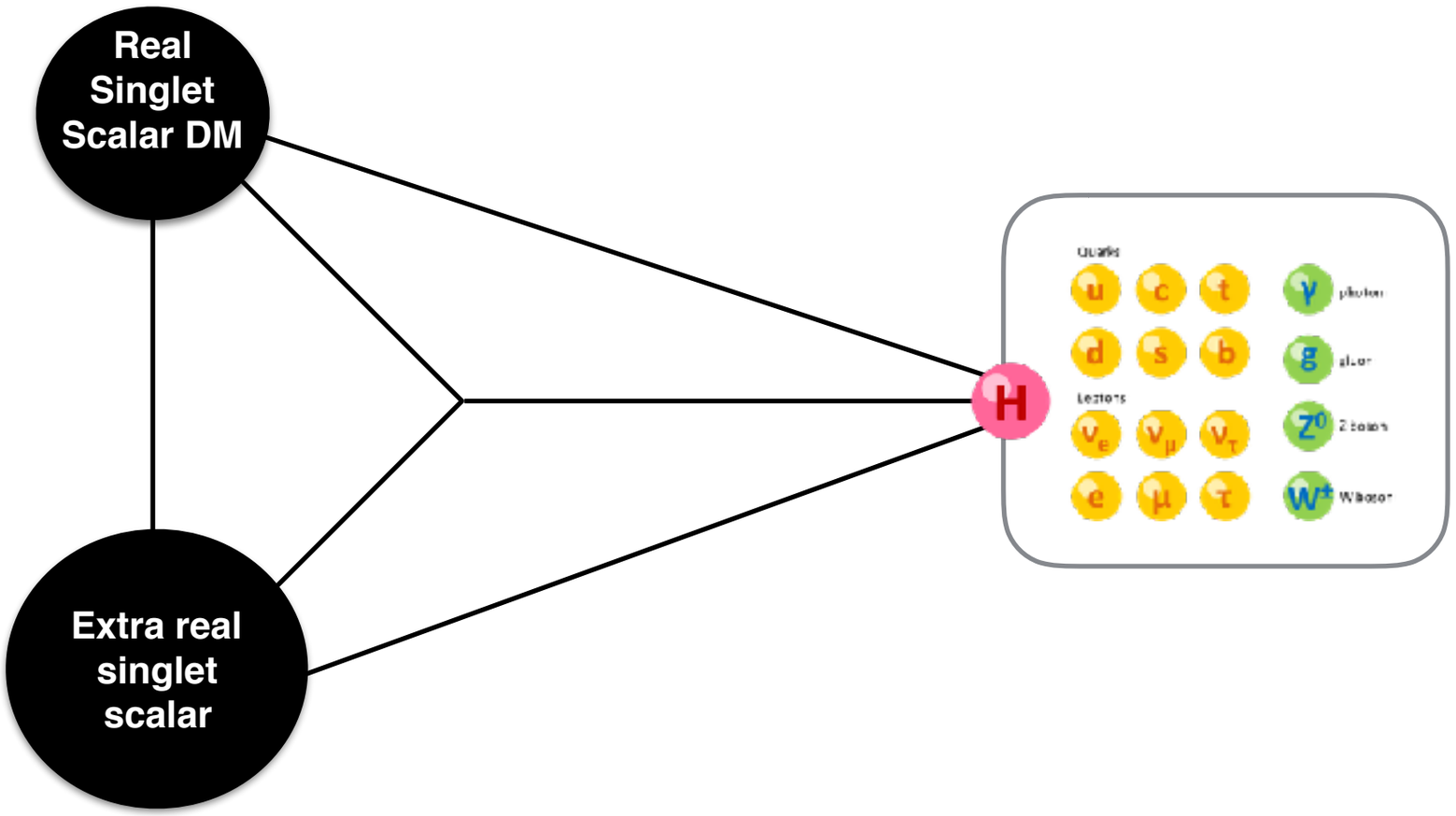
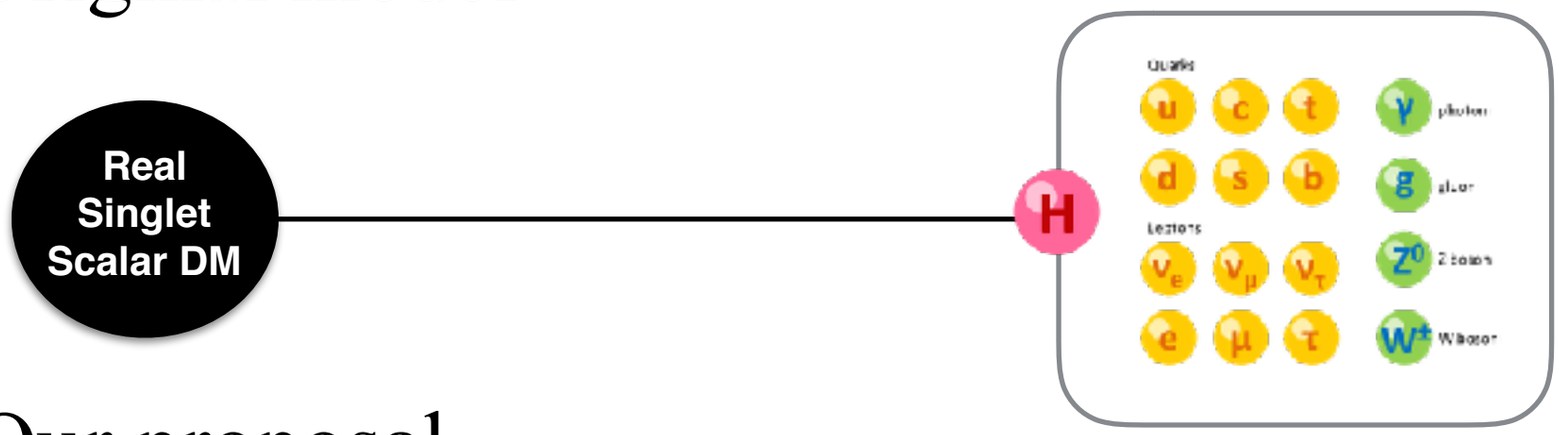


New scalar

- Heavier
- Decaying

“Rescuing” the Higgs portal

Original model



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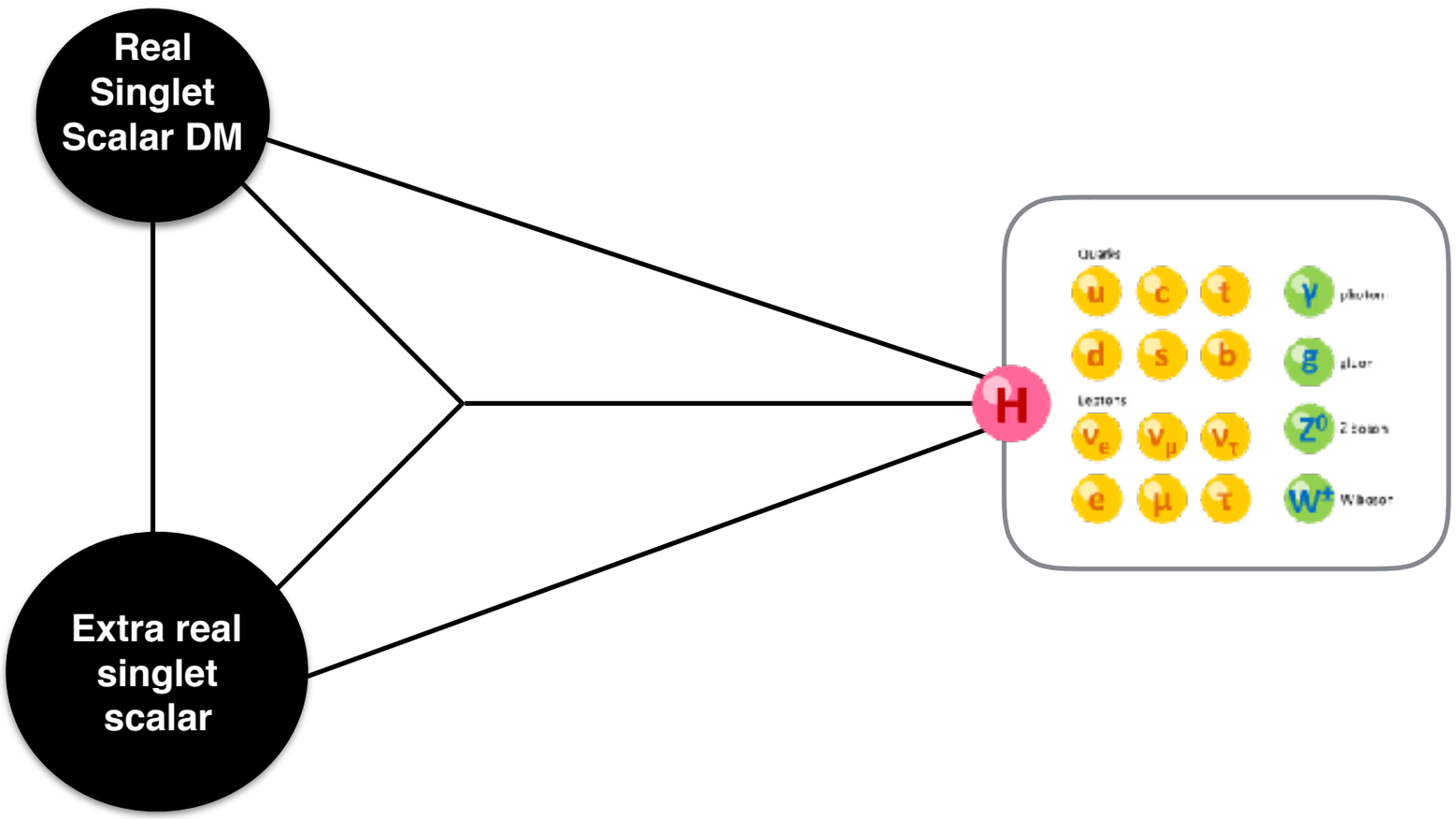

New scalar

- Heavier
- Decaying

Only
Singlet Scalar 1
remains

Higgs portal with two Real Singlet Scalars

Higgs portal with two Real Singlet Scalars

Global Z_2 symmetry

$S_1 \to -S_1 \quad S_1 S_2 \to S_1 S_2$

$S_2 \to -S_2 \quad SM \to SM$

S_1 DM candidate

S_2 Heavier scalar

Higgs portal with two Real Singlet Scalars

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Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\sum_{i=1,2}\left[(\partial_\mu S_i)^2 - m_i^2 S_i^2 - \frac{1}{12}\lambda_{i4} S_i^4\right] - \frac{1}{6}\lambda_{13} S_1 S_2^3 - \frac{1}{6}\lambda_{31} S_1^3 S_2 - \frac{1}{4}\lambda_{22} S_1^2 S_2^2$$

$$- \frac{1}{2}\lambda_1 S_1^2 |H|^2 - \frac{1}{2}\lambda_2 S_2^2 |H|^2 - \lambda_{12} S_1 S_2 \left(|H|^2 - \frac{v^2}{2}\right)$$

Renormalizable

Higgs portal with two Real Singlet Scalars

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Renormalizable

After EWSB

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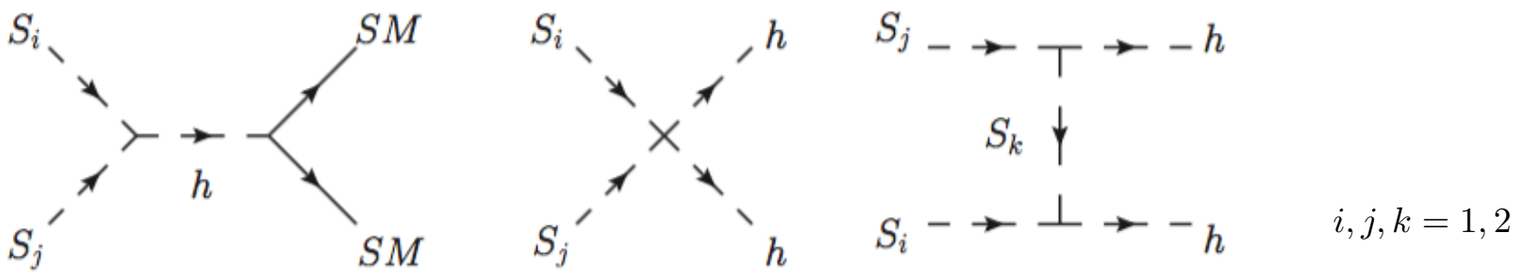
$$- \frac{1}{2}\lambda_1 v S_1^2 h - \frac{1}{2}\lambda_2 v S_2^2 h - \lambda_{12} v S_1 S_2 h - \frac{1}{4}\lambda_1 S_1^2 h^2 - \frac{1}{4}\lambda_2 S_2^2 h^2 - \frac{1}{2}\lambda_{12} S_1 S_2 h^2 \qquad (v = 175\ \text{GeV})$$

Higgs portal with two Real Singlet Scalars

After EWSB

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\sum_{i=1,2}\left[(\partial_\mu S_i)^2 - m_{S_i}^2 S_i^2 - \frac{1}{12}\lambda_{i4} S_i^4\right] - \frac{1}{6}\lambda_{13} S_1 S_2^3 - \frac{1}{6}\lambda_{31} S_1^3 S_2 - \frac{1}{4}\lambda_{22} S_1^2 S_2^2$$
$$- \frac{1}{2}\lambda_1 v S_1^2 h - \frac{1}{2}\lambda_2 v S_2^2 h - \lambda_{12} v S_1 S_2 h - \frac{1}{4}\lambda_1 S_1^2 h^2 - \frac{1}{4}\lambda_2 S_2^2 h^2 - \frac{1}{2}\lambda_{12} S_1 S_2 h^2 \qquad (v = 175\ \text{GeV})$$

Processes DM-SM



$i, j, k = 1, 2$

Coannihilation and eff. operator

To avoid constraints we need
low values of λ_1

$$-\frac{1}{2}\lambda_1 v S_1^2 h - \frac{1}{4}\lambda_1 S_1^2 h^2$$

Higgs portal with two Real Singlet Scalars

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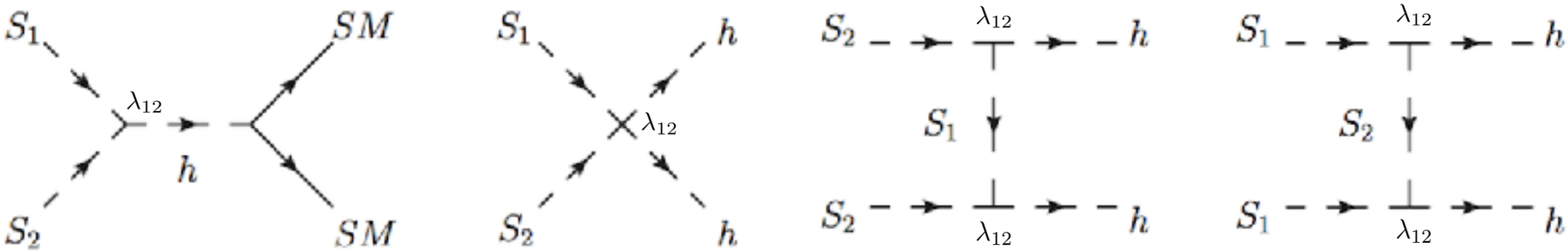
For low values of λ_1, λ_2 the coupling λ_{12} becomes relevant. $-\lambda_{12} v S_1 S_2 h - \frac{1}{2}\lambda_{12} S_1 S_2 h^2$



Higgs portal with two Real Singlet Scalars

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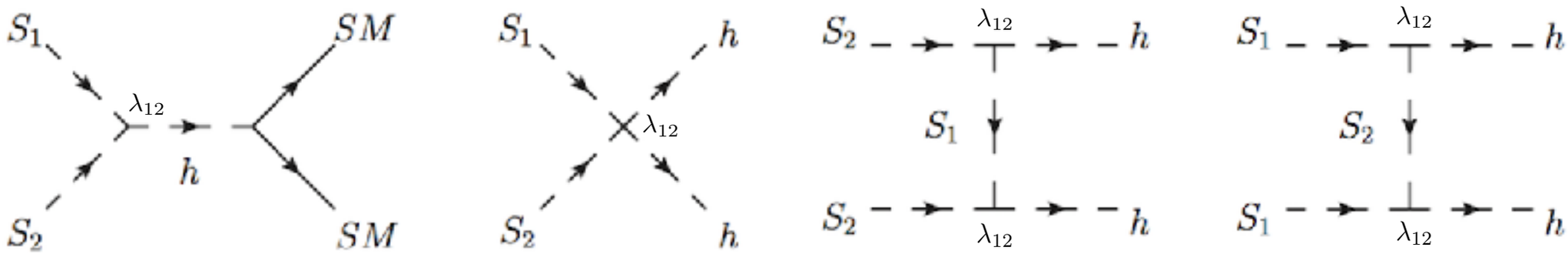


To analyze the effect of the coannihilation and effectives operators we set λ_1, λ_2 to

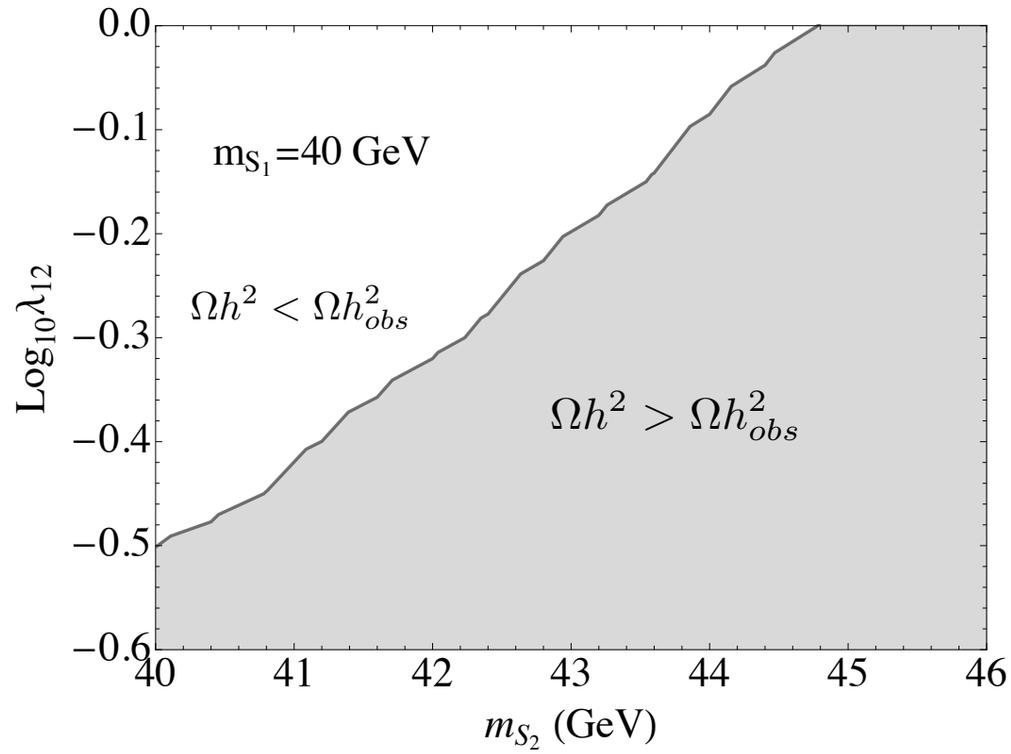
$\lambda_1 = \lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2}$ (radiative corrections), and we study the relevance of the coupling λ_{12}

Higgs portal with two Real Singlet Scalars

Coannihilation and eff. operator

$$\lambda_1 = \lambda_2 = \frac{\lambda_{12}^2}{(4\pi)^2}$$

The coupling λ_{12} is in charge of the annihilation of DM



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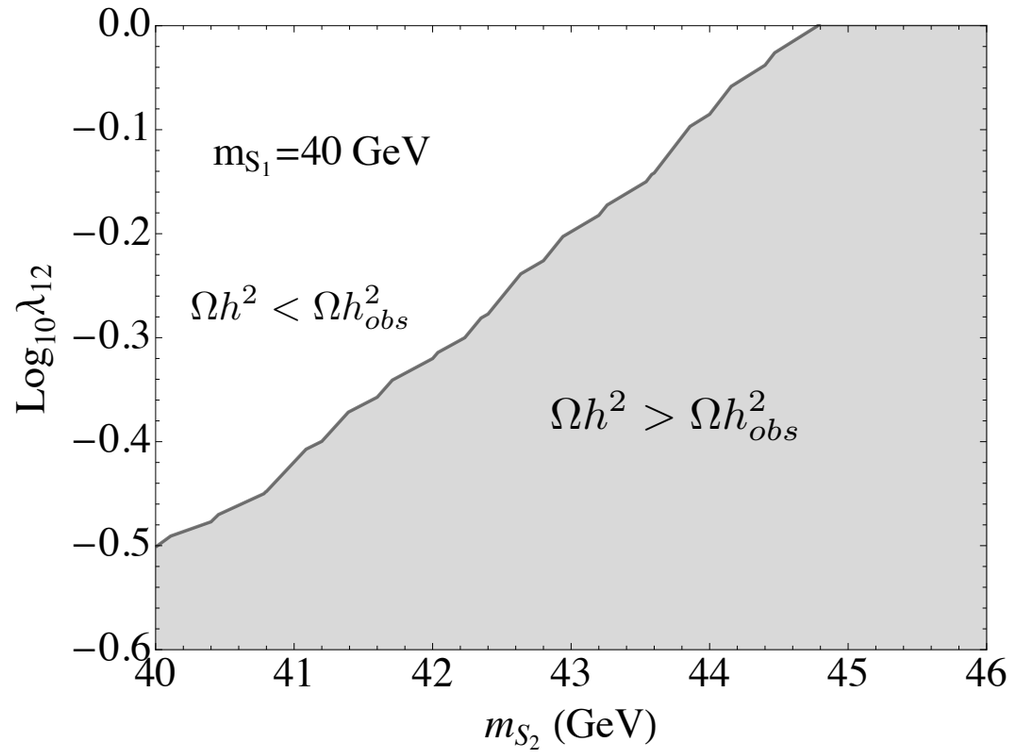

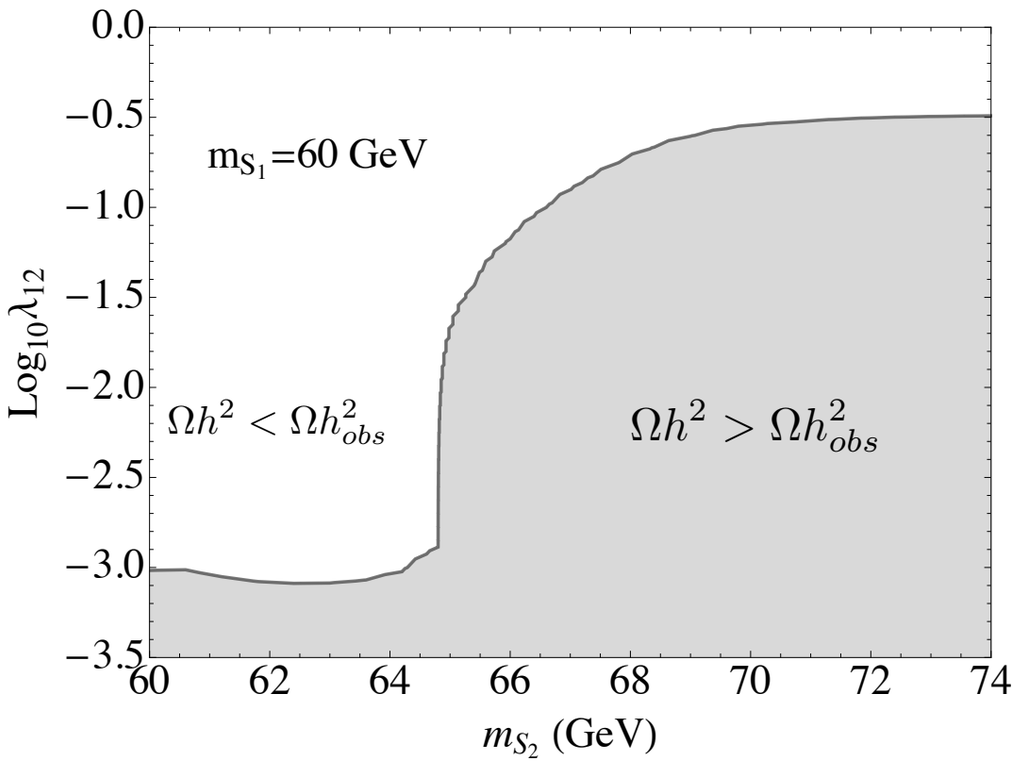

Higgs portal with two Real Singlet Scalars

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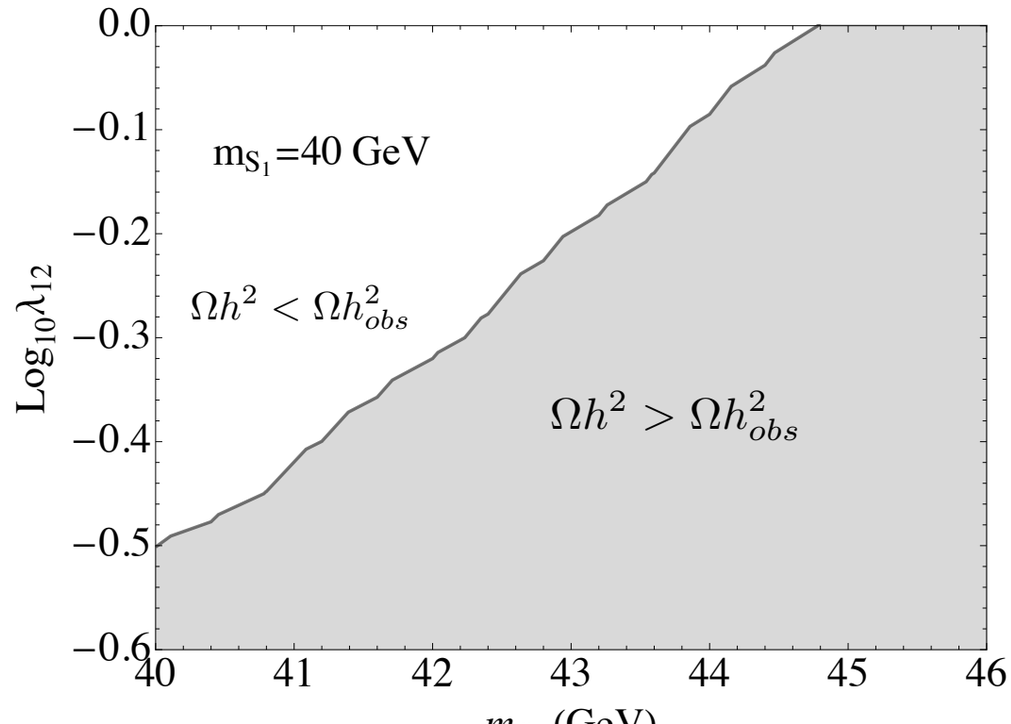

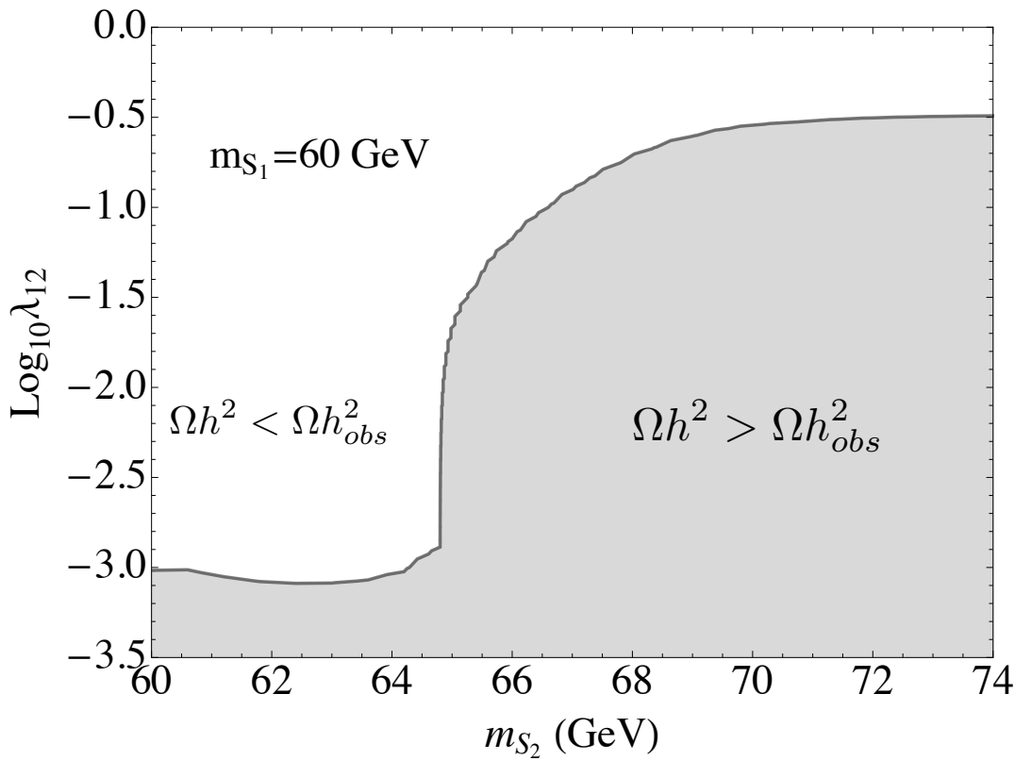

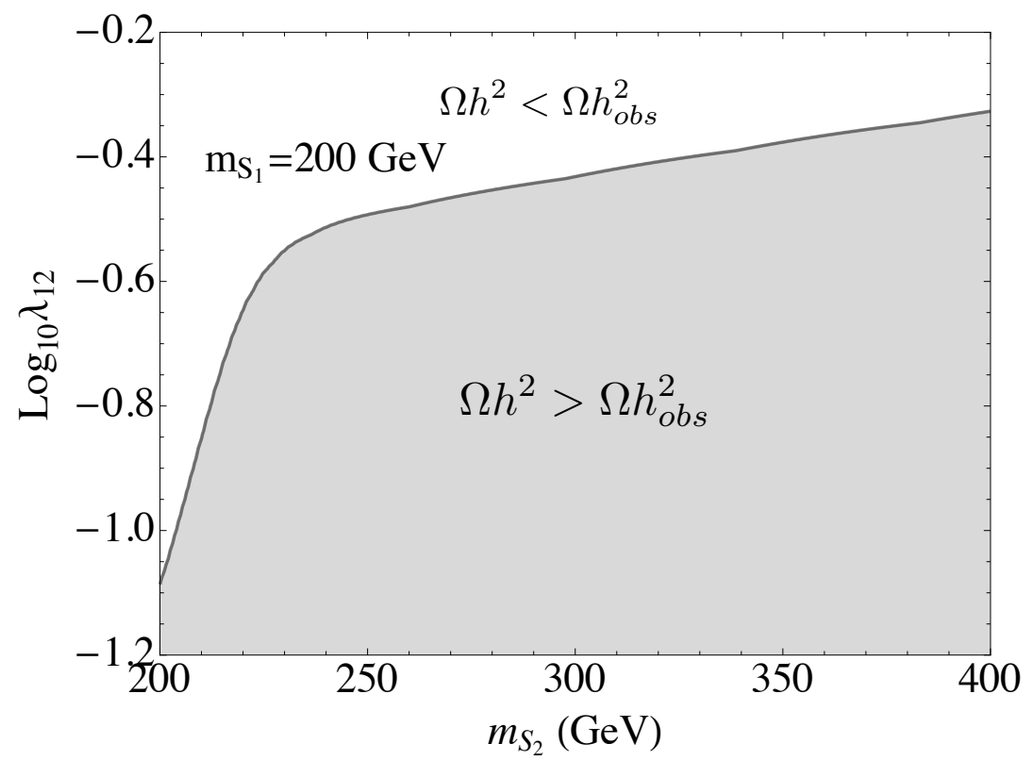

Parameter space of the new model

Random scan: $m_{S_1},\ m_{S_2},\ \lambda_1,\ \lambda_{12}$

Higgs portal with two Real Singlet Scalars

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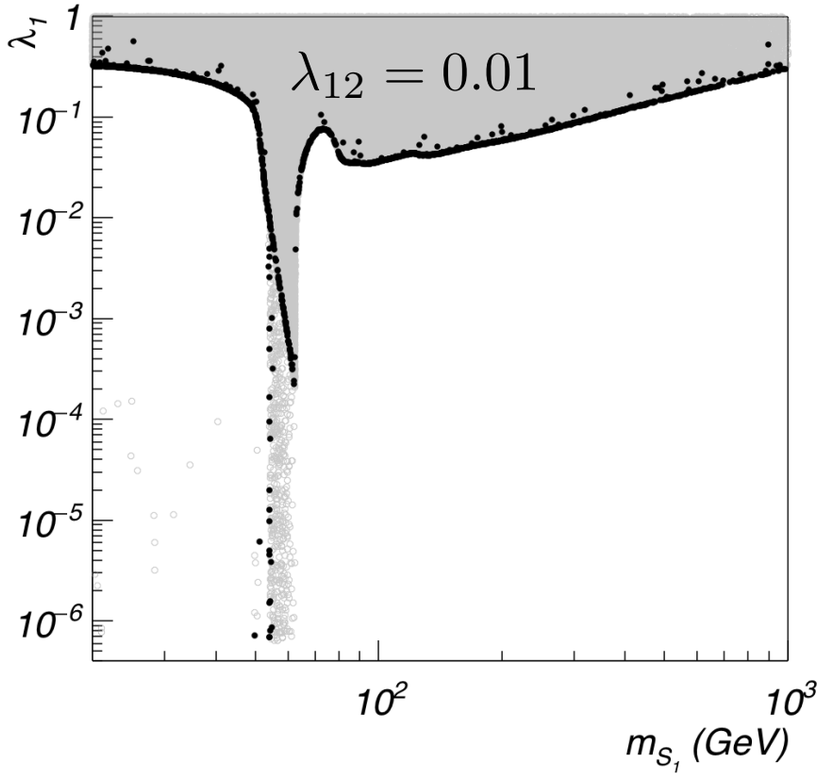

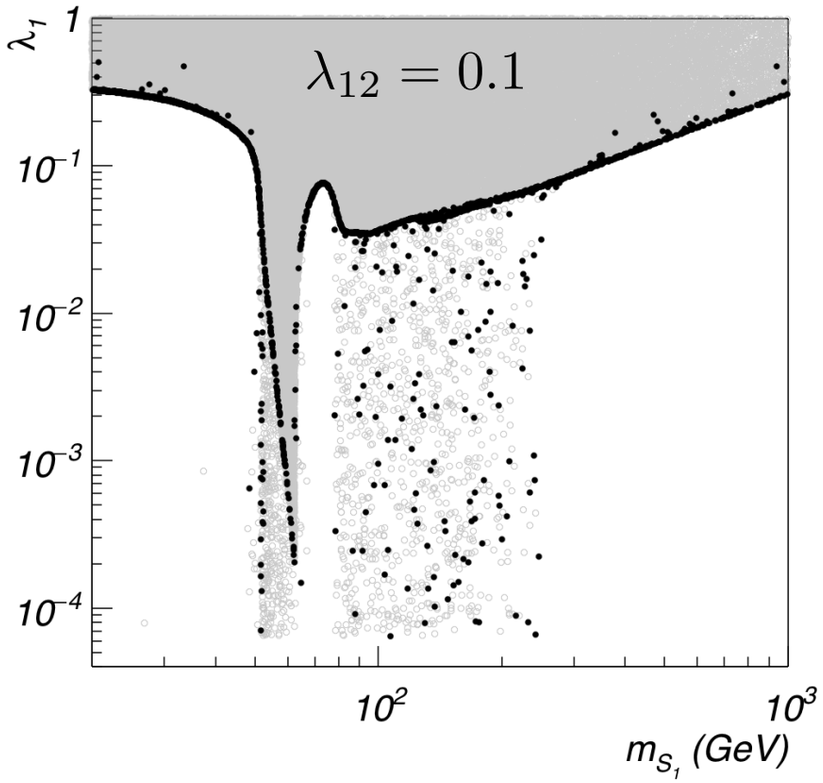

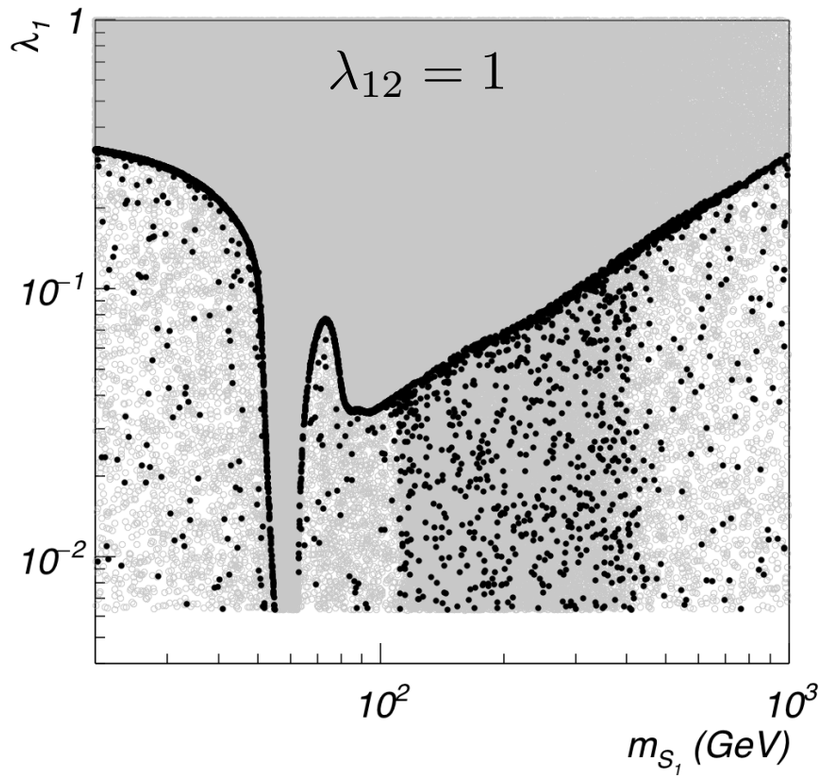

- ○ $0.116 > \Omega h^2$
- ● $0.116 < \Omega h^2 < 0.122$

Higgs portal with two Real Singlet Scalars

Constraints

- $\tau_{S_2} < 1s$ (BBN)
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- Γ_H^{inv}
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- gamma-ray

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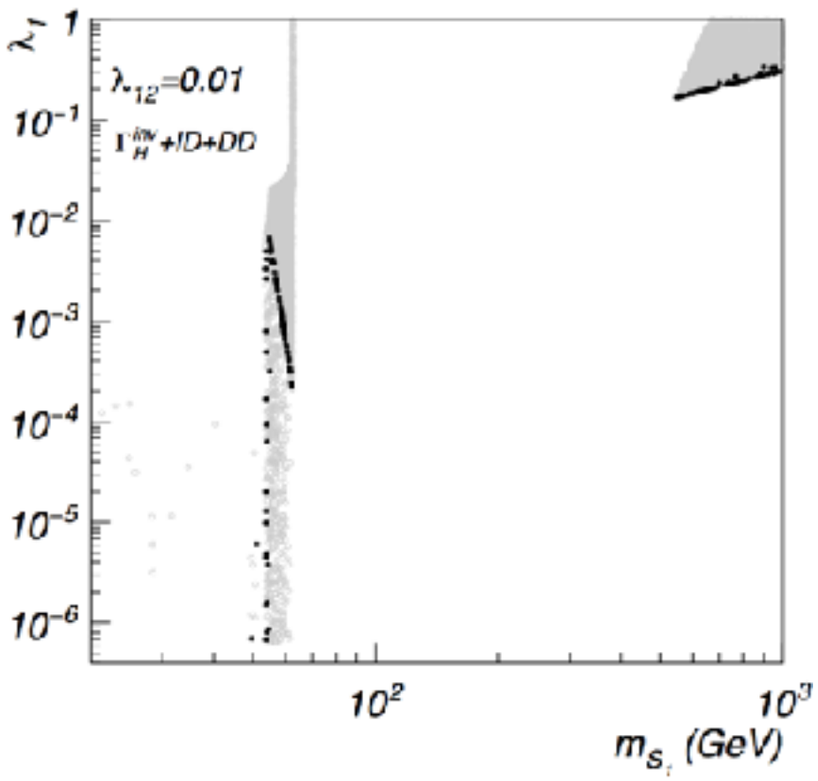

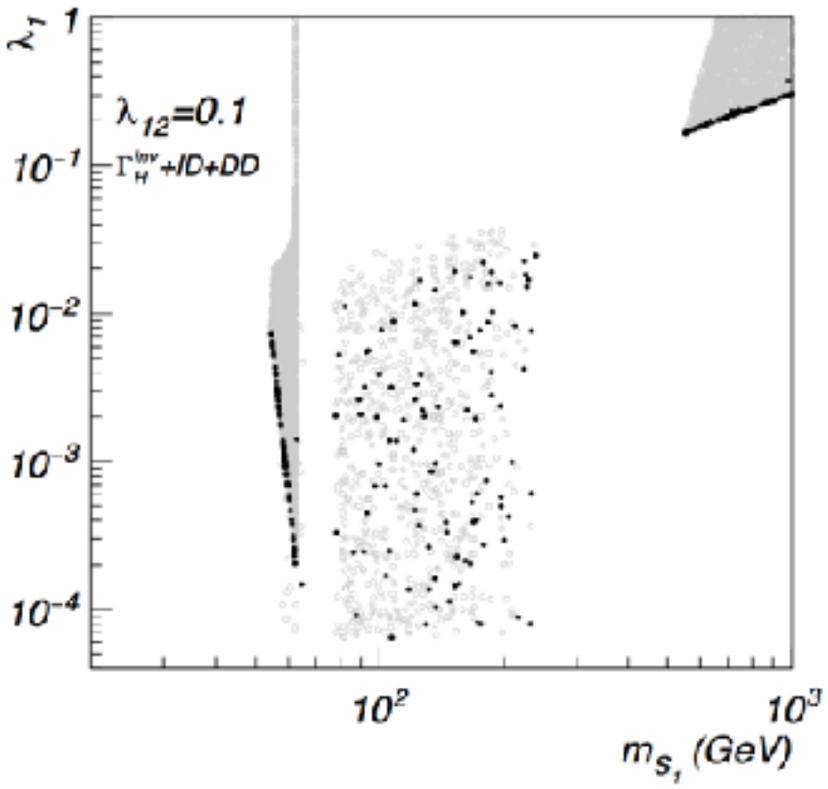

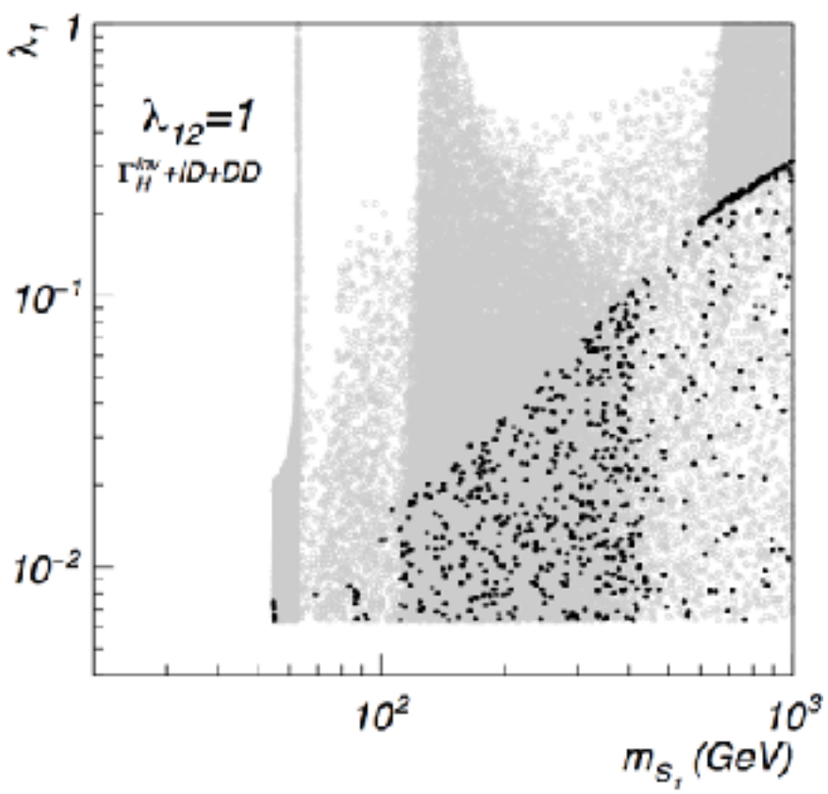

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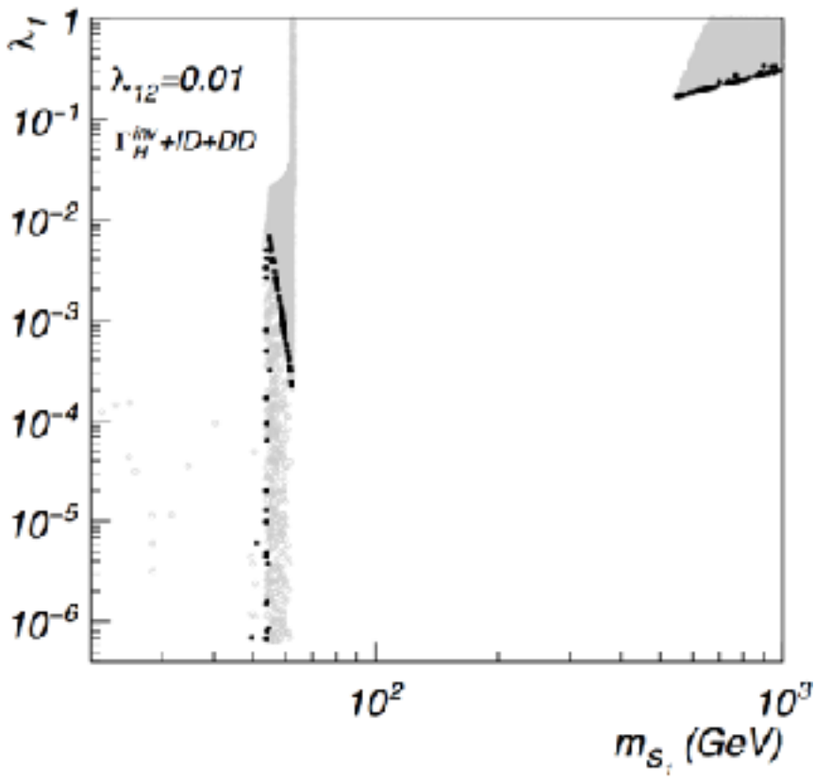

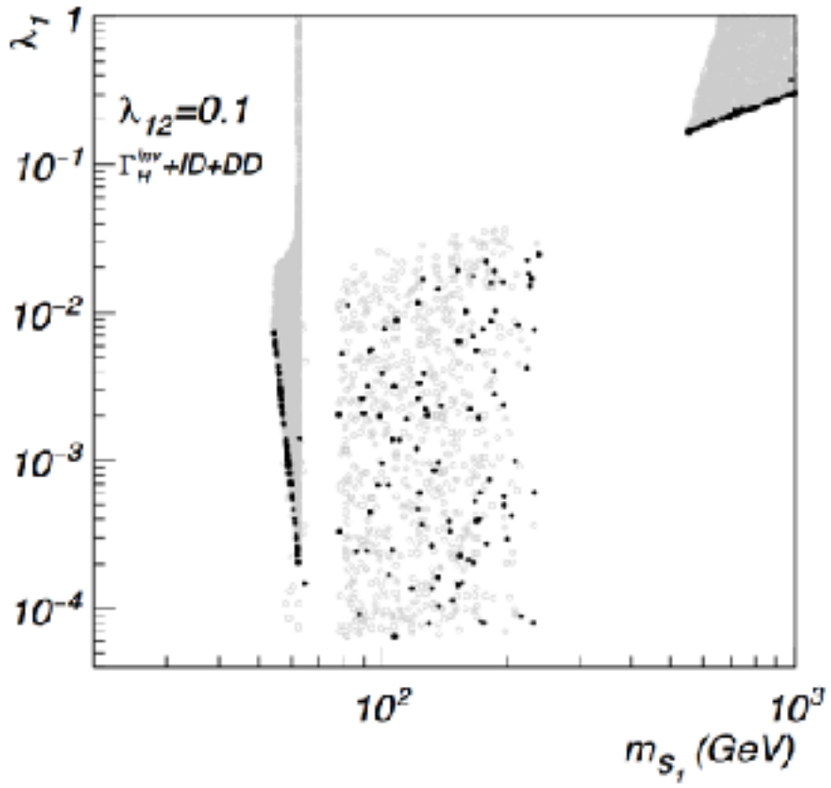

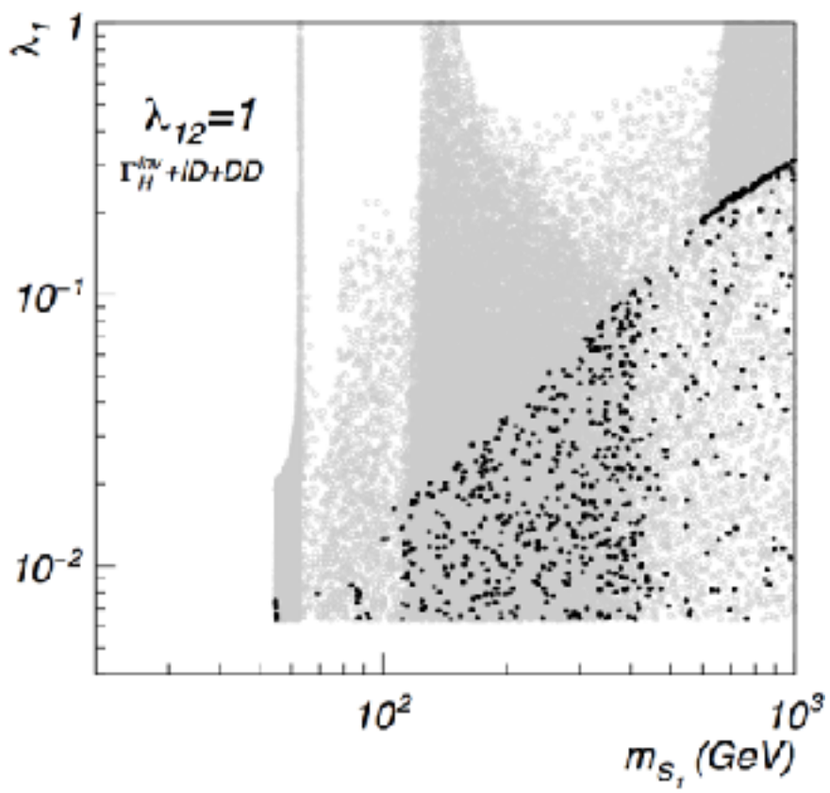

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For masses above 50 GeV we can find values of $m_{S_2},\ \lambda_1,\ \lambda_{12}$ with the correct relic density that survive all the constraints

Future DD constraints (LZ)

Higgs portal with two Real Singlet Scalars

Future DD constraints (LZ)

- $\tau_{S_2} < 1s$ (BBN)
- Γ_H^{inv}
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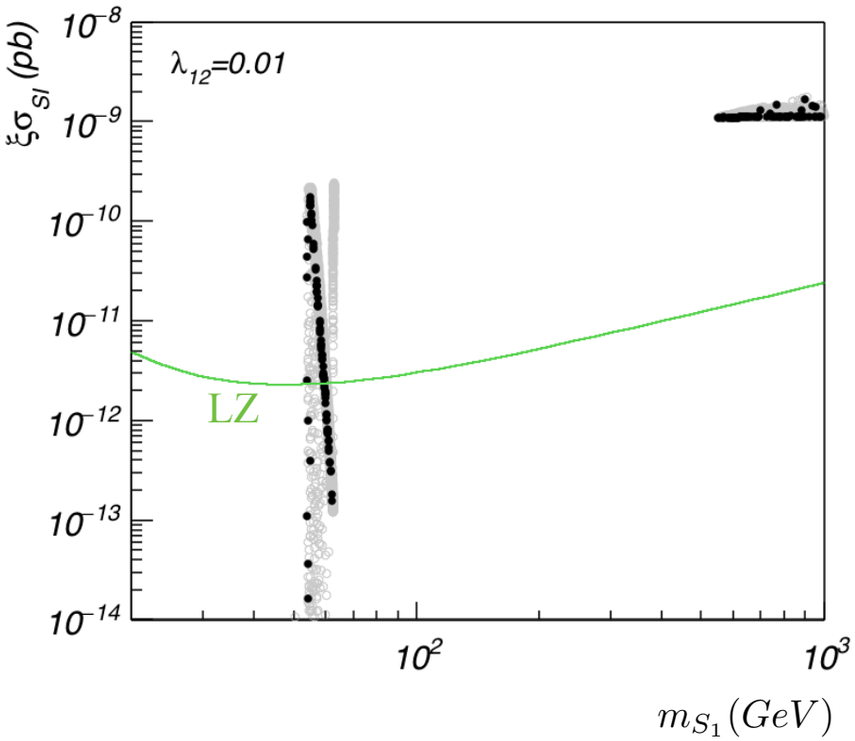
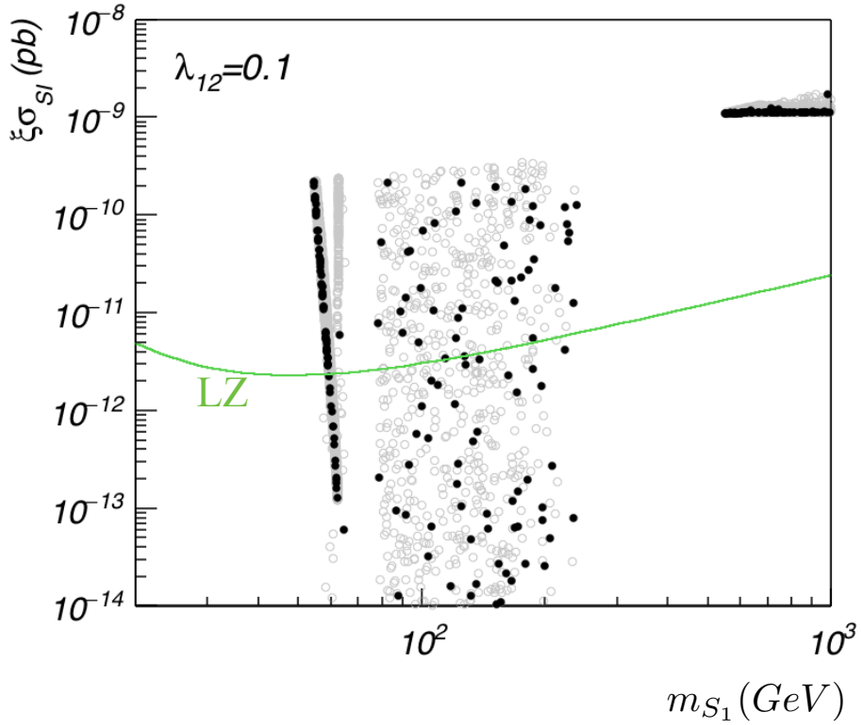
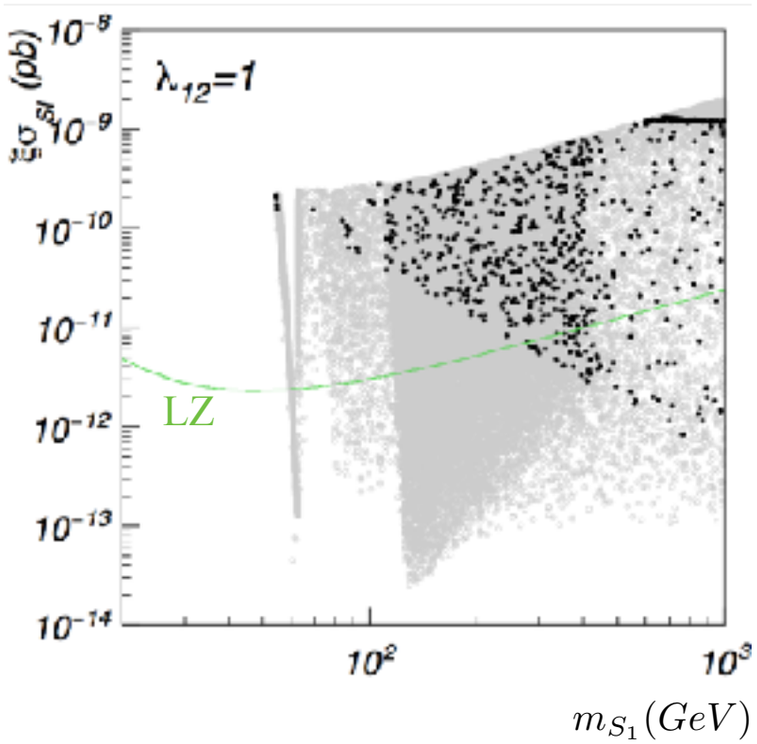
- LUX







$$\xi = \Omega h^2 / \Omega h^2_{obs}$$

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Higgs portal with two Real Singlet Scalars

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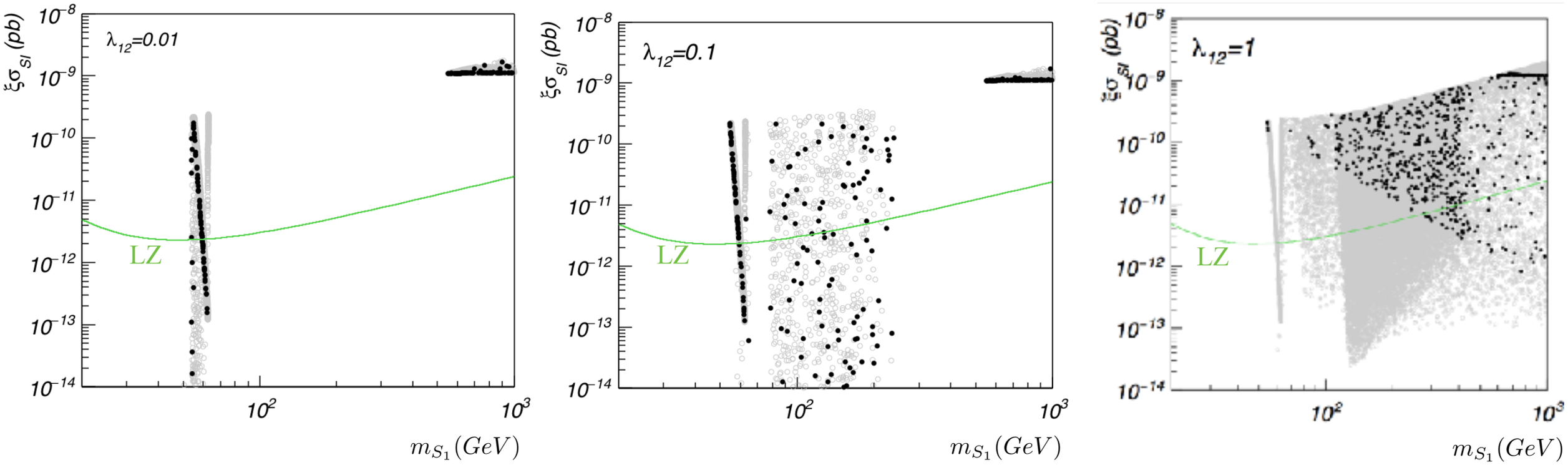

$\xi = \Omega h^2 / \Omega h^2_{obs}$

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There are points in the parameter space that avoid also future LZ constraints

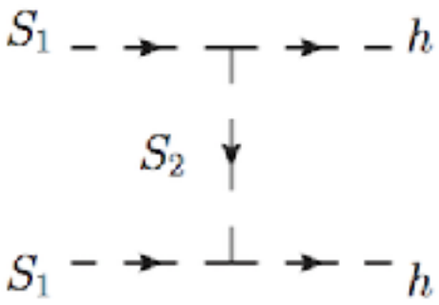
Summary

Summary

- 1 real scalar singlet Higgs portal has been almost completely explored
- Future DD and ID experiments will finish exploring the model
- A DM sector with two scalars can enlarge the allowed region in the parameter space
- If there is a positive detection in a zone where there would be more DM than the observed in the model with one scalar, could be allowed in this new model
- If the model with one scalar is completely ruled out by future DD and ID detection, the Higgs portal can live in this minimal extended version
- The model with 2 scalars is the most economical way to rescue the real singlet scalar model, which is the simplest model and renormalizable

Thanks for your attention!

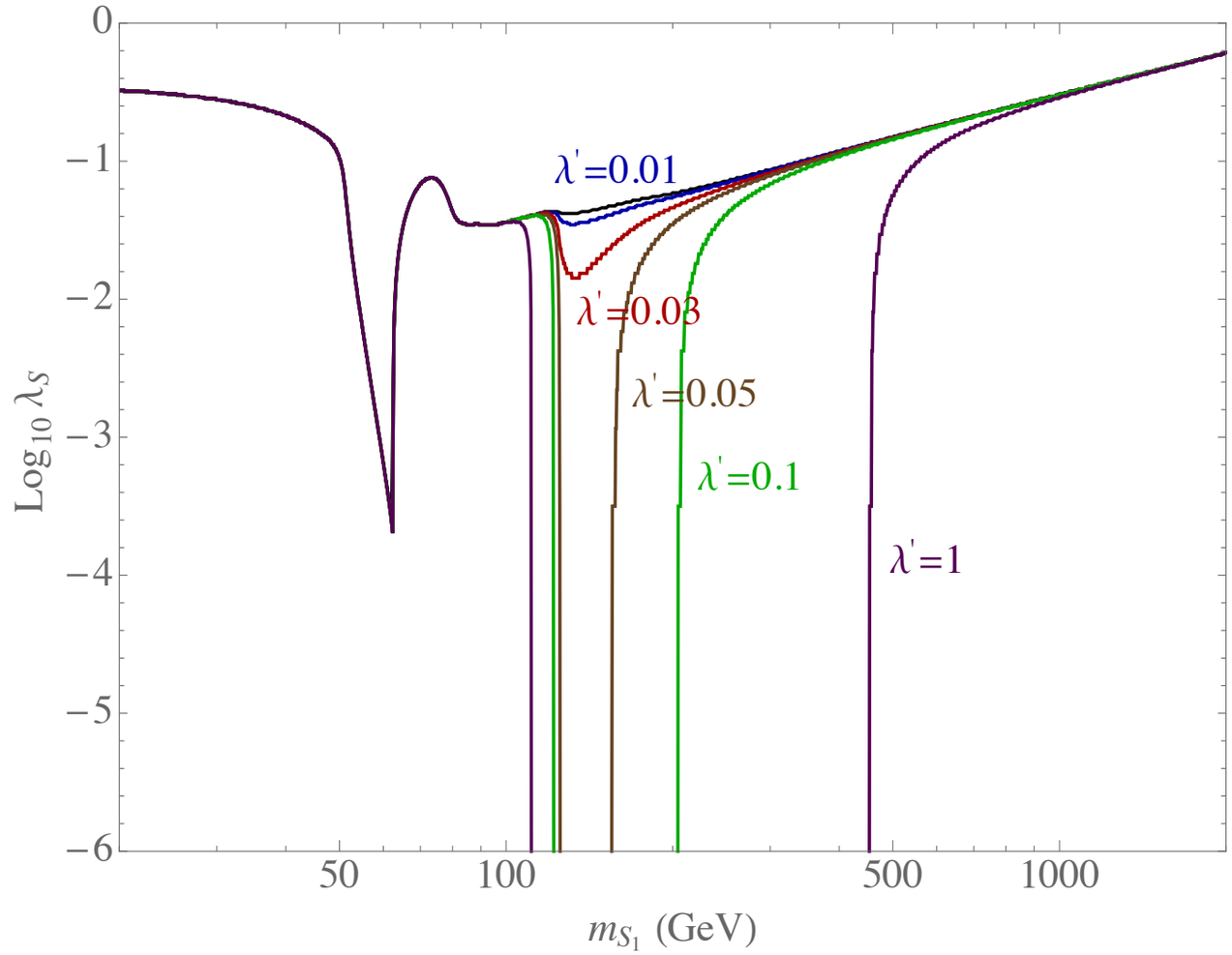
Effective operator

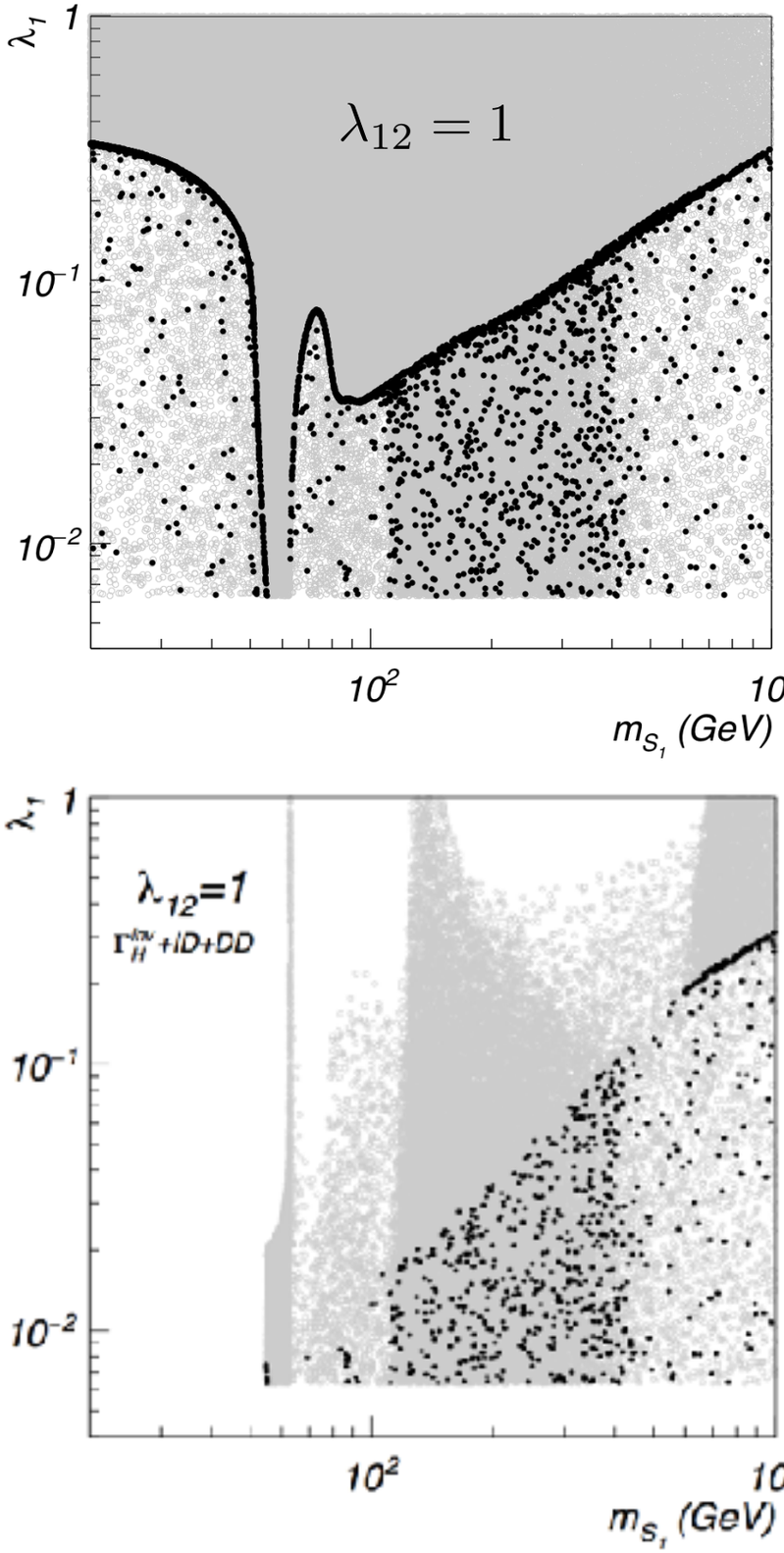


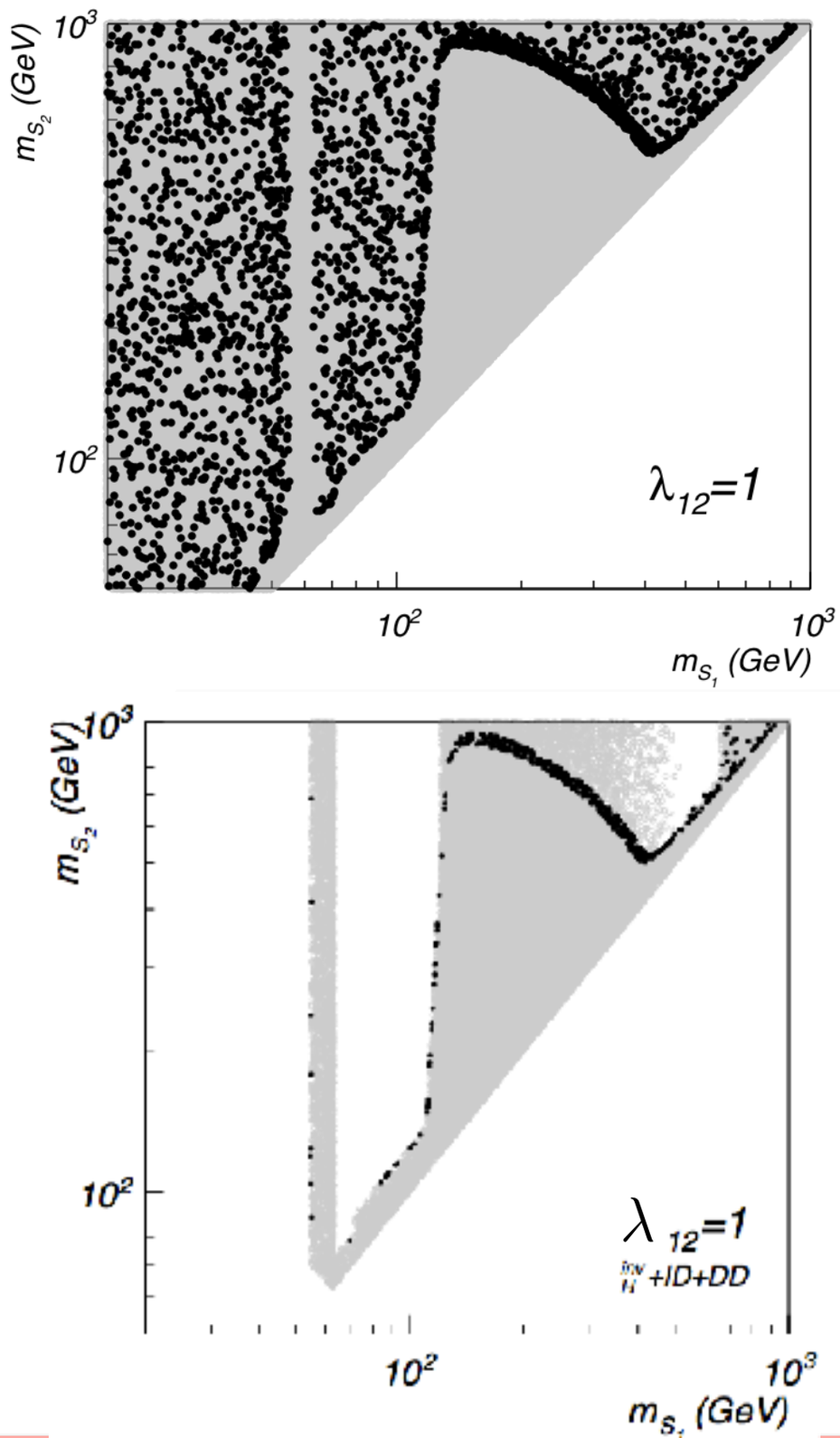
$$\Delta\mathcal{L}_{\text{eff}}(S_1, H) = -\frac{1}{2}\frac{\lambda_{12}^2}{m_{S_2}^2}\, S_1^2 \left(|H|^2 - \frac{v^2}{2}\right)^2 + \cdots$$

For large masses of S_2 we can integrate it out and the effective operator remains

$$\mathcal{L}_{\text{HP}}^{'} = \mathcal{L}_{\text{HP}} - \frac{1}{2}\frac{\lambda'}{m_{S_1}^2}\, S_1^2 \left(|H|^2 - \frac{v^2}{2}\right)^2$$




λ_1
1
10^{-1}
10^{-2}
$\lambda_{12} = 1$
10^2
10^3
m_{S_1} (GeV)


m_{S_2} (GeV)
10^3
10^2
λ_{12}=1
10^2
10^3
m_{S_1} (GeV)

λ_1
1
10^{-1}
10^{-2}
λ_{12}=1
Γ_H^{inv}+ID+DD
10^2
10^3
m_{S_1} (GeV)

m_{S_2} (GeV)
10^3
10^2
λ_{12}=1
Γ_H^{inv}+ID+DD
10^2
10^3
m_{S_1} (GeV)