# Probing the invisible at the LHC

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# Introduction

Many evidence for **Dark Matter (DM)**:

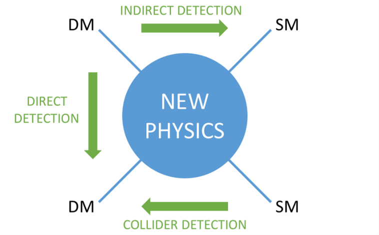
- Rotational velocity curves of galaxies
- Bullet cluster
- Large scale structure

The **Standard Model (SM) does not have a DM candidate**.
So, we must look for (**at least**) one new particle.

# Introduction

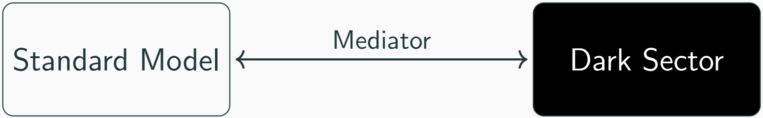
Ways of **detecting DM**:

- Indirect detection
- Direct detection
- Collider detection




At the **LHC** we would detect a **lot of missing transverse energy/momentum**.

# Introduction

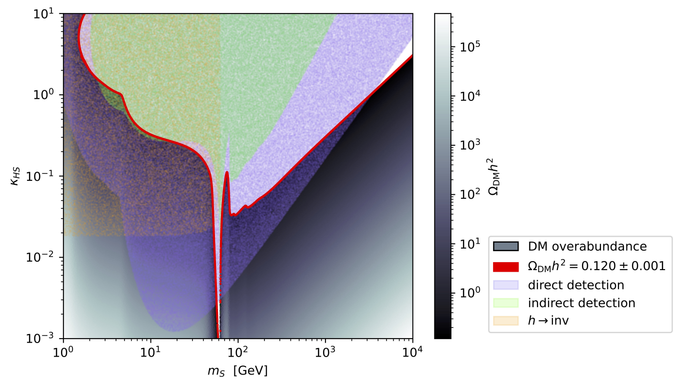



One approach is to consider the **Higgs to be the mediator** between the two sectors (**Higgs Portal models**).

The simplest case is to assume that **DM is a real singlet scalar (RSS) particle**.

# Introduction - Singlet Scalar Model

For a **freeze-out DM** candidate, the Singlet Scalar model (SM+RSS) is **highly constrained**, only allowed for masses starting at $\approx 3500$ GeV or at the Higgs resonance region.

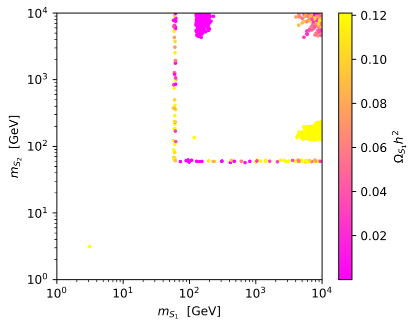


The **Two Singlets Scalar model (SM+2RSS)** is an extension of the SM, its Lagrangian is given by,

$$\mathcal{L}_{\mathsf{SM+2RSS}} = \mathcal{L}_{\mathsf{SM}} + \frac{1}{2}(\partial_\mu S_1)\partial^\mu S_1 - \frac{1}{2}\mu_1^2 S_1^2 + \frac{1}{2}(\partial_\mu S_2)\partial^\mu S_2 - \frac{1}{2}\mu_2^2 S_2^2 - \frac{\lambda_1}{4!}S_1^4 - \frac{\lambda_2}{4!}S_2^4 \underbrace{-\frac{\lambda_{12}}{4}S_1^2 S_2^2}_{=\mathcal{L}_{\mathsf{int}(1,2)}} \underbrace{-\frac{\kappa_{H1}}{2}S_1^2\Phi^\dagger\Phi}_{=\mathcal{L}_{\mathsf{portal}(1)}} \underbrace{-\frac{\kappa_{H2}}{2}S_2^2\Phi^\dagger\Phi}_{=\mathcal{L}_{\mathsf{portal}(2)}},$$

Each DM field has its own $\mathcal{Z}_2$ symmetry:
$\mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)} : S_r(x) \to -S_r(x)$ ($r = 1$ or $r = 2$).

Both $S_1$ and $S_2$ do not acquire VEVs, *i.e.* $\langle 0| S_{1,2} |0\rangle = 0$.

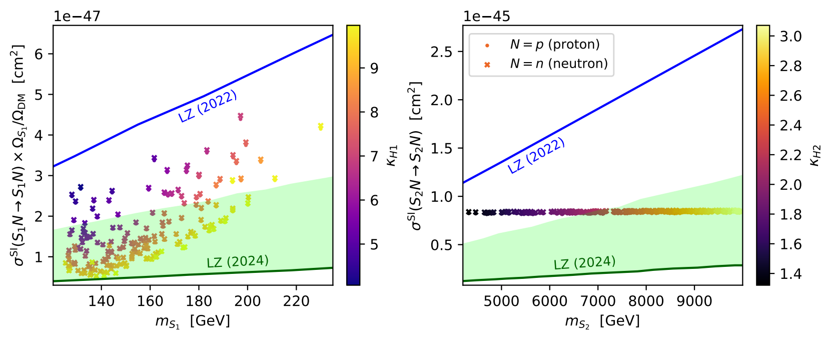



**Region allowed by DD:**

$m_{S_1} \in [124.8, 230.0]$ GeV
$m_{S_2} \in [4321.0, 9977.0]$ GeV
$\kappa_{H1} \in [4.066, 9.986]$
$\kappa_{H2} \in [1.321, 3.074]$
$\lambda_{12} \in [2.940 \times 10^{-6}, 0.7093]$

At $\approx$ 125 GeV the **channel $\mathbf{S_1 S_1} \rightarrow$ hh opens**, thus, the **relic density decreases** making the points **not constrained by DD**.

However, points **close to exclusion by LZ 2024 data**.



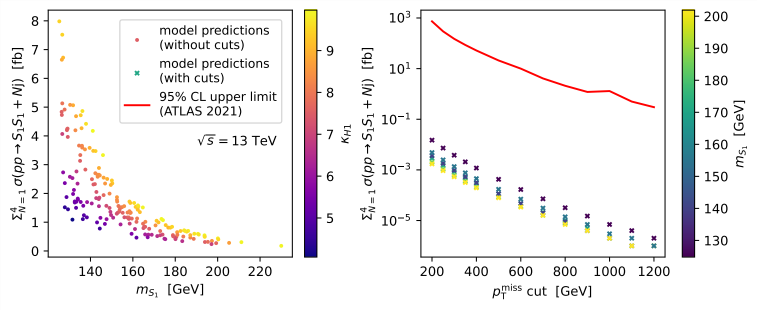
For **monojet searches**, we used data from the ATLAS Collaboration [arXiv:2102.10874] where they found **model-independent 95% CL limits on visible cross sections for monojet processes** at a center-of-mass energy of 13 TeV.

| **Selection** | $\langle\sigma\rangle^{95}_{\text{obs}}$ [fb] | $S^{95}_{\text{obs}}$ | $S^{95}_{\text{exp}}$ |
|---|---|---|---|
| $p_T^{\text{recoil}} > 200$ GeV | 736 | 102 274 | $83\,000^{+22\,000}_{-23\,000}$ |
| $p_T^{\text{recoil}} > 250$ GeV | 296 | 41 158 | $33\,800^{+11\,300}_{-9400}$ |
| $p_T^{\text{recoil}} > 300$ GeV | 150 | 20 893 | $15\,400^{+5900}_{-4300}$ |
| $p_T^{\text{recoil}} > 350$ GeV | 86 | 11 937 | $8300^{+3100}_{-2300}$ |
| $p_T^{\text{recoil}} > 400$ GeV | 52 | 7214 | $4700^{+1800}_{-1300}$ |
| $p_T^{\text{recoil}} > 500$ GeV | 21 | 2918 | $1930^{+730}_{-540}$ |
| $p_T^{\text{recoil}} > 600$ GeV | 10 | 1391 | $940^{+360}_{-260}$ |
| $p_T^{\text{recoil}} > 700$ GeV | 4.1 | 574 | $490^{+190}_{-140}$ |
| $p_T^{\text{recoil}} > 800$ GeV | 2.1 | 298 | $277^{+106}_{-77}$ |
| $p_T^{\text{recoil}} > 900$ GeV | 1.2 | 164 | $168^{+65}_{-47}$ |
| $p_T^{\text{recoil}} > 1000$ GeV | 1.3 | 186 | $119^{+45}_{-33}$ |
| $p_T^{\text{recoil}} > 1100$ GeV | 0.5 | 73 | $75^{+28}_{-21}$ |
| $p_T^{\text{recoil}} > 1200$ GeV | 0.3 | 40 | $49^{+19}_{-14}$ |

# Two Singlets Scalar Model - Monojet Searches

**Considerations:**

- up to 4 jets
- a leading jet with $p^T > 150$ GeV
- up to 3 additional jets with $p^T > 30$ GeV



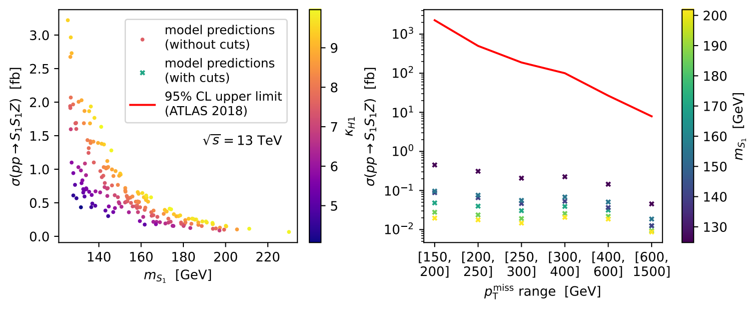
For **mono-Z searches**, we also used ATLAS data [arXiv:1807.11471] where they found results for the **model-independent upper limits at 95% CL on the visible cross section**.

| $E_{\mathrm{T}}^{\mathrm{miss}}$ range [GeV] | Upper limit at 95% CL [fb] $\sigma_{\mathrm{vis}}^{\mathrm{obs}}$ | $\sigma_{\mathrm{vis}}^{\mathrm{exp}}$ | $-1\sigma$ | $+1\sigma$ | $A \times \varepsilon$ |
|---|---|---|---|---|---|
| $Z$+DM, $Z \to q\bar{q}$ | | | | | |
| [150, 200] | 313 | 225 | 162 | 314 | 20% |
| [200, 250] | 69 | 60 | 43 | 83 | 20% |
| [250, 300] | 39 | 29 | 21 | 40 | 30% |
| [300, 400] | 31.1 | 18.5 | 13.3 | 25.7 | 45% |
| [400, 600] | 9.2 | 9.1 | 6.5 | 12.6 | 50% |
| [600, 1500] | 3.0 | 2.6 | 1.9 | 3.6 | 55% |

# Two Singlets Scalar Model - Mono-Z Searches

The results are expressed in terms of:

$$\sigma_{Z+DM}(E_T^{miss}) = \frac{\sigma_{vis,Z+DM}(E_T^{miss})}{B_{Z\to q\bar{q}} \times (A \times \epsilon)(E_T^{miss})}$$



# Three Singlets Scalar Model

What happens **if we add another RSS**?

Now, for the **Three Singlets Scalar model (SM+3RSS)**, the Lagrangian is given by,

$$\mathcal{L}_{\text{SM+3RSS}} = \mathcal{L}_{\text{SM}} + \sum_{r=1}^{3} \left[ \frac{1}{2}(\partial_\mu S_r)\partial^\mu S_r - \frac{1}{2}\mu_r^2 S_r^2 - \frac{\lambda_r}{4!} S_r^4 \underbrace{- \frac{\kappa_{Hr}}{2} S_r^2 \Phi^\dagger \Phi}_{= \mathcal{L}_{\text{portal}(r)}} \right]$$

$$\underbrace{- \frac{\lambda_{12}}{4} S_1^2 S_2^2}_{= \mathcal{L}_{\text{int}(1,2)}} \underbrace{- \frac{\lambda_{23}}{4} S_2^2 S_3^2}_{= \mathcal{L}_{\text{int}(2,3)}} \underbrace{- \frac{\lambda_{31}}{4} S_3^2 S_1^2}_{= \mathcal{L}_{\text{int}(3,1)}}$$

Each DM field has its own $\mathcal{Z}_2$ symmetry:
$\mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)} \times \mathcal{Z}_3^{(2)} : S_r(x) \to -S_r(x)$ ($r = 1$, $r = 2$ or $r = 3$).

Both $S_1$, $S_2$ and $S_3$ do not acquire VEVs, *i.e.* $\langle 0 | S_{1,2,3} | 0 \rangle = 0$.

# Three Singlets Scalar Model

Considerations about the 3RSS model:

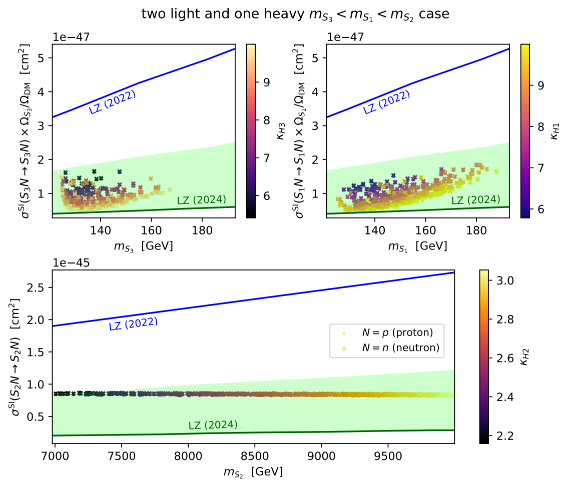
- Large parameter space
- More allowed regions could appear

We found **two cases** so far:

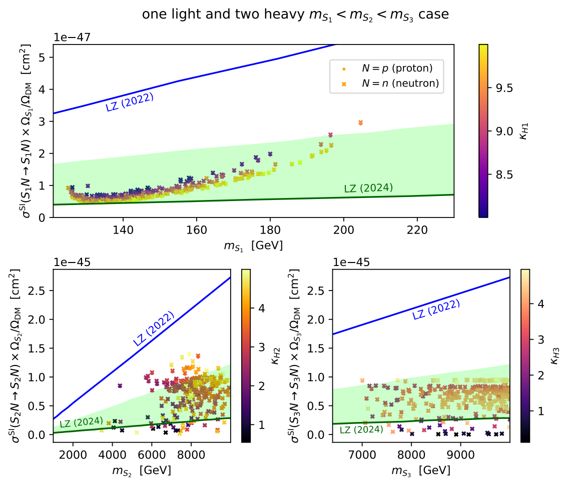
- $m_{S_3} < m_{S_1} < m_{S_2}$
- $m_{S_1} < m_{S_2} < m_{S_3}$

# Three Singlets Scalar Model - LZ (2024)

Case: $\mathbf{m_{S_3} < m_{S_1} < m_{S_2}}$



Case: $\mathbf{m_{S_1} < m_{S_2} < m_{S_3}}$



# Final Remarks

- 2RSS less constrained than 1RSS
- $S_1$ visible at colliders
- $S_2$ cannot be visible at colliders
- Collider constraints on the 2RSS may be important in the next LHC run
- 3RSS can be promising, but additional regions are hard to find

**Thank you!**