[Higgs Portal Fits to the Galactic Center Excess](https://indico.desy.de/abstractDisplay.py?abstractId=14&confId=11832)

[work in progress: Alessandro Cuoco, Benedikt Eiteneuer, JH, Michael Krämer]

Jan Heisig (RWTH Aachen University)

Meeting of the Research Unit **New Physics at the LHC** JGU Mainz - March 7th - 2016

Possible contribution: WIMP Dark Matter

Energy density of the universe:

WIMP Dark Matter: freeze-out

Example Standard cosmological history: Well motivated "production" mechanism

WIMP Dark Matter: freeze-out

 $T(GeV)$

- **Example Standard cosmological** history: Well motivated "production" mechanism
- **Exercise Conection between** cosmology and particles

WIMP Dark Matter: annihilation today

Searches for WIMP Dark Matter annihilation in the inner galactic region $\sum_{i=1}^{n} a_i$

Example 1 Subtract: Diffuse foregrounds + Point sources add. Dinabo ibi c_or barido

[see e.g. Calore, Cholis, Weniger]

 \Rightarrow Excess over the known foregrounds:

 \Rightarrow Excess over the known foregrounds:

Figure 17. Spectrum of the GCE emission, together with statistical and systematical errors, for model F (cf. figure 14). We show find the GCE with various spectral models. We emphasize that the GCE with various spectral models. We emphasize that the GCE with various spectral models. We emphasize the GCE with various Astrophysical explanation? [see e.g. 1405.7928, 1411.2980, 1506.05119]

fit quality, in table 4 (cf. figures 18 and 20). See text for details on the fitting procedure.

 \Rightarrow Excess over the known foregrounds:

Figure 17. Spectrum of the GCE emission, together with statistical and systematical errors, for model F (cf. figure 14). We show find the GCE with various spectral models. We emphasize that the GCE with various spectral models. We emphasize that the GCE with various spectral models. We emphasize the GCE with various Astrophysical explanation? Or signal of WIMP [see e.g. 1405.7928, 1411.2980, 1506.05119] fit quality, in table 4 (cf. figures 18 and 20). See text for details on the fitting procedure.

 \bigcap r cignal of $\bigwedge / \bigwedge / \bigwedge D$ **Panelists on the constraints on the fits with the fits with the fits with the fits with the ten GCE segments.** Dark Matter?

\Rightarrow Excess over the known foregrounds:

v" [cm3s−1]

Can the signal be explained by simple DM models? (taking into account further constraints)

This talk:

➔ "Simplest" Dark Matter model (Singlet Scalar) **→ Detailed numerical fit** ➔ Allow for additional DM components

Outline

- The Model

· Implementation

 The galactic center excess **Constraints**

- **Execute**
- **E** Conclusion

The Model

Scalar Singlet Higgs Portal Model can be searched for at colliders and through direct and indirect detection experiments [1–3]. The Scalar Singlet Higgs Port

[Burgess, Pospelov, Veldhuis: hep-ph/0011335, ...]

- \bullet Higgs bilinear $H^\dagger H$ unique (renormalizable) way to directly couple DM to the SM and all SM gauge groups. Imposing an additional *Z2* symmetry, would be seen as a symmetry, $\frac{1}{2}$ $\mathbf{f}_{\mathbf{q}}$ is the singlet Higgs portal model $\mathbf{f}_{\mathbf{q}}$
- Add Singlet Scalar *S* with *Z*2-symmetry: **E** Add Singlet Scalar S with Z_{as} cymmetry:

$$
\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2} \partial_{\mu} S \partial^{\mu} S - \frac{1}{2} m_{S,0}^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{2} \lambda_{HS} S^2 H^{\dagger} H
$$
\n(before EWSB)

(before EWSB)

Scalar Singlet Higgs Portal Model can be searched for at colliders and through direct and indirect detection experiments [1–3]. The model. The model comprises the Standard Model and a real scalar field, *S*, which is a singlet under all SM gauge groups. Imposing an additional *Z*² symmetry, *S* → −*S*, the scalar particle under all SM gauge groups. Imposing an additional *Z*² symmetry, *S* → −*S*, the scalar particle is Scalar Singlet Higgs Portal Model

[Burgess, Pospelov, Veldhuis: hep-ph/0011335, ...] $, \mathbb{I}$

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معن**اء** $\overline{=}$ ^λ*SS*⁴ [−] ¹
- Add Singlet Scalar *S* with *Z*2-symmetry: Add Singlet Scalar S with Zasymmetry breaking 2 *m*² *S* mmetry

\n- Add Singlet Scalar S with Z₂-symmetry:\n
$$
\mathcal{L} \supset -\frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{HS} h^2 S^2 - \frac{1}{4} \lambda_{HS} v h S^2,
$$
\n where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2 / 2.$ \n
\n- (after EWSB)
\n

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matter and model model is the minimal singlet scalar model is the minimal single specified by the model is the purpose of the purpos into account the constraints from invisible Higgs decays, direct dark matter searches and limits only two parameters between the scalar dark mass of the small matter particle, *matter particle*, *matter particle*, *matter particle*, *matter particle*, *matter particle, and matter particle, and matter particle, and mat* Γ and the strength of the strength of the dark matter and Higgs particles, *https://www.matter and Higgs particles*, Important for vacuum stability

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Contrary the model is the model in the purpose of the purpose of the purpose of the model is the model in the m into account the constraints from invisible Higgs decays, direct dark matter searches and limits only two parameters beyond those of the SM: the mass of the scalar dark matter particle, *mS*, θ parameters between the mass of the scalar mass of the SM: the scalar matter θ (IIIIpol tand for vacuum stability) (Important for vacuum stability)

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2 **■ Higgs bilinear** $H^{\dagger}H$ unique (renormaliz Couple DIT to the SIT $\mathbf{1}$ σ σ *S,*0*S*² [−] ¹ r $H^\dagger H$ uniq **9** *H* and *E H*^{α} *A* and *H*^{α} *A H*^{α} couple DM to the SM
- Add Singlet Scalar *S* with *Z*2-symmetry: Add Singlet Scalar S with Z_{as}symmetry: 2 *m*² *<u>Mmetry</u>*

(after EWSB) $\mathcal{L} \supset \mathcal{L} \supset \frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_S S$ in the various from the various potential \mathcal{I} . where $m_S \models m_{S,0}^2 + \lambda$ $\mathcal{L}_{\mathcal{A}}$ annihilation [11–21]. We will thus explore if the galactic center excess (GCE) can be explained in terms of dark matter and minimal singlet singlet singlet singlet singlet singlet scalar Higgs portal model, ta \overrightarrow{a} *L* ⊃ − 1 2 m_S^2 $\binom{2}{5} S^2 - \frac{1}{4}$ 4 $\lambda_S S^4 \left(\frac{1}{4} \right)$ $\overline{4}$ $\lambda_{HS}\,h^2S^2-\frac{1}{4}$ 4 $\lambda_{HS}\,vh S^2$ *,* (2) where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2 / 2$. (after EWSB) *S,*⁰ + λ*HSv*2*/*2. The scalar self coupling, λ*S*, is of importance for the stability of $\sqrt{2}$ R_{m} matter the purpose of the purpose of the model is the m only two parameters beyond those of the SM: the mass of the scalar dark matter particle, *mS*, \Rightarrow Only two parameters: m_S , λ_{HS} where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2/2$. The settler EWSB) *L* ⊃ − $\overline{2}$ ^λ*^S ^S*⁴ [−] ¹ $\frac{1}{2}$ ^λ*HS ^h*2*S*² [−] ¹ $\frac{2^{m}5^{D}}{4^{n}5^{D}}$ 4² \mathbf{f}_{max} data matter phenomenology. For this paper, the purpose of this paper, the model is the model is thus fully specified by \mathcal{A} only two parameters beyond those of the SM: the mass of the scalar dark matter particle, *mS*, and the strength of the strength of the coupling between the dark matter and Higgs particles, *https://www.matter and Higgs particles, and Higgs particles, and Higgs particles, and Higgs particles,* λ Important for this work ^λ*HS ^h*2*S*² [−] ¹ $\frac{1}{\sqrt{2}}$ $\mathcal{L} \supset \left\{ \frac{1}{2} m_S^2 S^2 \right\} - \frac{1}{4} \lambda_S S^4 \left(\frac{1}{4} \lambda_{HS} h^2 S^2 \right)$ where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2 / 2$. *S,*⁰ + λ*HSv*2*/*2. The scalar self coupling, λ*S*, is of importance for the stability of the electroweak vacuum and the perturbativity of the model, see e.g. [24], but does not affect 노
-
- $\frac{2}{n^2}S^2 - \frac{1}{n} \lambda_0 S$ \mathcal{S} $\sqrt{1}$ $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $\frac{1}{2}$ where $m^2 = m^2 + \lambda \pi c v^2/2$ (after FWSB $S_{\rm S}$ ³ $S_{\rm S}$ ¹ the electroweak vacuum and the perturbativity of the perturbativity of the model, see e.g. μ dark matter phenomenology. For the purpose of this paper, the model is the model is the model is thus fully specified by

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Dark matter annihilation in the scalar Higgs portal model proceeds through *s*-channel Higgs, *t*-channel scalar exchange, and the *S*2*h*² interactions, see Fig. 1. 3.2 Scalar Singlet Higgs Por Scalar Singlet Higgs Portal Model

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Implementation

Implementation: Galactic center excess

- Need gamma-ray spectrum
- **Example Slow in fit** \Rightarrow **Pre-compute spectra for all channels** (as function of DM mass) with MadGraph/Pythia 8
- During fit: Combine spectra according to contribution

Implementation: Galactic center excess 50 100 150 200 *Implementation: Galactic center excess m^S* [GeV] \blacksquare $\sqrt{2}$ d*E* lactic center excess plarily in Fig. (ref to Spectra). Here, *R* denotes the fraction of annihilating dark matter to the

- \blacksquare Take measured spectrum d_i and covariance matrix ℓ from [Calore, Cholis, Weniger: 1409.0042] d_i and covariance matrix Σ_{ij} **from** [Calore, Cholis, Weniger: 1409.0042] **Take measured spectrum** d_i **and covariance matrix** Σ_{ij} λ*HS* = 0*.*01 (right panel). Below *m^S* = *m^h* the contributions are independent of λ*HS*. $F = \frac{1}{2}$ fig. 2 $\frac{1}{2}$ for $\frac{1}{2}$ and $\frac{1}{2}$ for $\frac{1}{2}$ and $\frac{1}{2}$ for $\frac{1}{$ τ data matter content which is discussed in section τ \blacksquare iake ineasured spect **Reference to Fig. 2.**
- **E** Additional uncertainty on the theoretical prediction \bullet of the spectrum $\Sigma_{ij}\to \Sigma_{ij}+\Sigma_{ij}\delta_{ij}t_i^2\sigma_t^2\,,~~\sigma_t=10\%$ [Achterberg et al. 1502.05703] \rightarrow 2 $_{ij} + \Sigma_{ij} \delta_{ij} t_i^2 \sigma_t^2$ λ*HS* = 0*.*01 (right panel). Below *m^S* = *m^h* the contributions are independent of λ*HS*. dΦ α ^{*f*} the spectrum</sub> p **Incertainty o** \sum $\begin{array}{rcl} \textsf{ty} \textsf{ on the the}\ \textsf{m}\ \textsf{b} \ \textsf{c} \ \textsf{b} \ \textsf{c} \ \textsf{d} \ \textsf{d} \ \textsf{c} \end{array} \end{array}$ aratir $\zeta_{\cdot\cdot}$ $\Sigma_{ij} \rightarrow \Sigma_{ij} + \Sigma_{ij} \delta_{ij} t_i^2 \sigma_t^2$, $\sigma_t = 10\%$ and **prediction**
	- **Large theoretical uncertainties on DM distribution in galaxy:** eoret ■ Large theoretical uncertainties on DM distribu

Non-WIMP contribution to Dark Matter plan *MIMD* contribution to Dark Matter total dark matter content which we being integral over the integral over the integral over the line of sight o **IMP** contribution to

- **Allow for additional unspecified DM component** $\overline{}$ $\overline{}$ $\overline{}$ $\overline{}$ $\overline{}$ *m* Alio
- **Example 1 Fraction of WIMP component:** Reference to Fig. 2. Figure 2: Relative contribution to the dark matter annihilation today, exemplarily for λ*HS* = 1 (left panel) and

 $R = \rho_{\mathrm{WIMP}}/\rho_{\mathrm{DM, \, total}}$

- **E** Assumption: same distribution
- \Rightarrow Rescaling of flux:

$$
\phi \to R^2 \phi \quad \Longleftarrow \quad \text{For indirect} \quad \text{detection}
$$

Implementation: Constraints

Implementation: Constraints Dark matter annihilation in the scalar Higgs portal model proceeds through *s*-channel Higgs, *t*-channel scalar exchange, and the *S*2*h*² interactions, see Fig. 2.

 $J_{40\degree\times40\degree}/J_{40\degree\times40\degree}$, nom \sim 40 $\,\times$ 40 $\,\degree$ \sim 40 $\,\times$ 40 $\,\degree$ and \sim 40 $\,\degree$

Implementation: Fitting tools plarily in Fig. (ref to Spectra). Here, *R* denotes the fraction of annihilating dark matter to the

- **Use MultiNest (nested sampling algorithm)** is discussed function 3.3.06.2144] a MultiNest (nested sampling algorithm)
- **4 scan parameters:**

mS: 5 *...* 220 GeV λ_{HS} : 3×10^{-5} \dots 4π $\ln (\bar{J}/\bar{J}_{\rm nom})$: $-4\sigma_{\xi} \ldots 4\sigma_{\xi}$ *R*: 10^{−3} ...1

- **EXPLOSE SECTIONS AND BRS: micrOMEGAS**
- **Example 1 Frequentist interpretation**

Fit results

Limits from gamma lines further tighten range for $\ln(\bar{J}/\bar{J}_{\mathrm{nom}})$

Summary

- **WIMP DM intriguing explanation of GCE**
- **Higgs Portal: Unique coupling to minimal DM models**
- **E** Singlet Scalar Model: Good fit!
- **After constraints: Only Higgs-resonance remains**
- **E** Allow for additional non-WIMP DM component
- Non-trivial implications for WIMP fraction near resonance (for large velocity dependence)

Backup slides: Spectrum for best-fit point (after all constraints)

Explain final result and R-factor

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ToDo

Best-fit points raussuchen

 \blacksquare

Parametric fits and theoretical uncertainties with the covariance matrix of the covariance matrix of the covariance matrix \sim Parametric fits and theoretical uncertainties Lassum the total direct the the 10% degrees in 10% and 20% levels and the 10% degrees on the 20% of the 20% deg
Level 20% degrees with a concern parallel concern and the 20% degrees on 20% degrees with 20% degrees on 20% d shift of all data points up or down, as illustrated by the black dots. Secondly, the black article particles in the predicted physics in the predicted photon spectrum in the predicted photon spectrum, w

- \bullet Take measured spectrum d_i and covariance matrix i from [Calore, Cholis, Weniger: 1409.0042] **Figure 7 axists running Ferrum** d_i **and covariance matrix** Σ_{ij} from [Calore, Cholis, Weniger: 1409.0042]
- **Example 2 Additional uncertainty on the theoretical prediction** of the spectrum $\Sigma_{ij} \rightarrow \Sigma_{ij} + \delta_{ij} d_i^2 \sigma_s^2, \ \sigma_s\,=\,10\%$ ertainty on the theoretical prediction

— ¹⁰ ...⁰ ...⁰ 0%
057031 **Solutional uncertainty on the theoretical prediction**
As $\frac{1007}{\pi}$ $\Sigma_{ij} \rightarrow \Sigma_{ij} + \delta_{ij} d_i^2 \sigma_s^2$, $\sigma_s = 10\%$
- **Example 1** Compute χ^2 via: (24×24) covariance matrix accounting for empirical model systematics, and Σ*ij,* res the resid- α A^{\bullet} Denote Density A^{\bullet} Denote be and A^{\bullet} are described with semi-empirical models with semi-empirical $\frac{1}{2}$, $\frac{1}{2}$ $\frac{1}{2}$ (*dⁱ* [−] ¹⁰ξ*mi*)(Σ*ij*) [Achterberg et al. 1502.05703]

$$
\chi^{2} = \sum_{i,j} (d_{i} \sqrt{10^{\xi}} h_{i})(\Sigma_{ij})^{-1} (d_{j} \sqrt{10^{\xi}} h_{j}) \sqrt{\frac{\xi^{2}}{(\log_{10} 2)^{2}}}
$$
\nwhere $\xi = \log \left(\frac{\bar{J}}{\sqrt{10^{\xi}}}$ Takes into account

where
$$
\xi = \log_{10} \left(\frac{\bar{J}}{\bar{J}_{\text{best fit}}^{\text{NFW}}} \right)
$$
 The uncertainty of the function $\bar{J}_{\text{best fit}}^{\text{NFW}}$ represents the function of the function.

 \mathcal{L} , weinger. Footback are performed using the minimizer \mathcal{L} $\bar{J}^\mathrm{NFW}_{\mathrm{best\,fit}}$ from [Calore, Cholis, Weniger: 1409.0042] \sim 0.000 and K

LICS

 $\frac{1}{2}$

b and *δ*

Parametric fits to the Galactic center excess *M*1*, M*2*, µ,*tan β*, MA, d* !3*, Q*!3*, At.*

Table 4. Results of spectral fits to the GCE emission as shown in figure 14, together with *±*1σ

0*.*0

, (5.1)

Higgs Portal Model \overline{H} H₂ \overline{g} \overline{g} \overline{g} \overline{g} *Drtal* P P P Q Q P P $-$ Higgs $Port$ z **z z P** z **P** z *d* z *d* ² ^ξ*^s ^s*² *^R* [−] *^V* (*s*2*, H†* where *L*SM is the SM Lagrangian density minus the purely Higgs doublet terms, *m*^P is the

[Burgess, Pospelov, Veldhuis: hep-ph/0011335, ...]

where L_{out} is the SM Lagrangian density method is the purely minus the purely minus the purely minus of the smallet terms, L_{out} is the smallet term of the smallet terms, L_{out} is the smallet term of the small **Extend Higgs sector by a scalar singlet s:** reduced Direction mass and Γ '2 $1 \cdot 100$ $1 \cdot 100$ $1 \cdot 100$ $1 \cdot 100$ $1 \cdot 100$

$$
V(s^2, H^{\dagger}H) = \lambda_h \left[\left(H^{\dagger}H \right) - \frac{v^2}{2} \right]^2 + \frac{1}{2} \lambda_{hs} s^2 H^{\dagger}H + \frac{1}{4} \lambda_s s^4 + \frac{1}{2} m_{s_0}^2 s^2
$$

[also interesting in the context of WIMP Inflation, see e.g. Kahlhoefer, McDonald: 1507.03600 for a recent analysis] Laiso interesting in the context of VVIIYIP Inflation, see e.g. Kahihoefer,
McDonald: 1507.03600 for a recent analysis] transformation to the Einstein frame, where the non-minimal coupling to gravity disappears.

Implementation: Constraints

■ Collider constraints: Higgs invisible BR

▪ Constraints on the parameter space:

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E GCE fits versus constraints:

Figure 42: Scan points in terms of CMB observables. *Left panel:* XXX *Right panel:* XXX [see also Duerr, Pérez, Smirnov:1509.04282]

Example 1 GCE fits versus constraints:

Best fit point:

GCE fits:

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Dark Matter → WIMP

