Dark Matter at the Higgs Resonance

Daniele Massaro

based on arXiv:2305.11937

https://dimauromattia.github.io/SingletScalar_DM

In collaboration with:
M. Di Mauro, C. Arina, N. Fornengo, J. Heisig

Invisibles23 Workshop
29th September 2023

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

UCLouvain

Singlet Scalar Higgs Portal Model

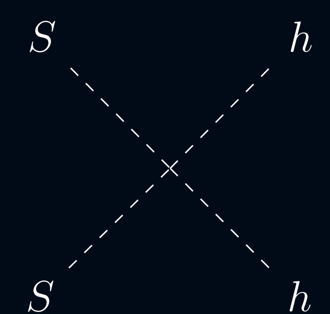
- DM candidate is a scalar S, with an Higgs portal to the SM.
- Protected by a Z_2 symmetry. [V. Silveira and A. Zee. Physics Letters B 161.1 (1985), pp. 136–140]
- Depends on only 2 parameters: m_S and λ_{HS}.

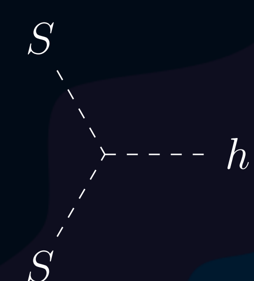
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HS} h^2 S^2 - \frac{1}{2} v_0 \lambda_{HS} h S^2$$

4-legs vertex

3-legs vertex

- Model extensively studied and constrained. [P. Athron et al. Eur. Phys. J. C 77.8 (2017), p. 568]
- Focus on the **resonance region** $m_S \approx m_h / 2$.





Dark matter freeze-out

- Compute dark matter relic density solving the Boltzmann equation:

$$E(\partial_t - H\boldsymbol{p}\cdot\boldsymbol{\nabla}_{\boldsymbol{p}})f_S = \mathcal{C}[f_S]$$

In canonical freeze-out **kinetic equilibrium is maintained during chemical decoupling**

Approximate the Boltzmann equation:

$$\frac{\mathrm{d}n_S}{\mathrm{d}t} + 3Hn_S = -\langle\sigma v\rangle_T(n_S^2 - n_{S,\,\mathrm{eq}}^2)$$

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! Does not work on the resonance region.

[T. Binder, T. Bringmann, M. Gustafsson, and A. Hryczuk. Eur. Phys. J. C 81 (2021), p. 577]

Dark matter freeze-out

In the resonance region:
kinetic equilibrium is not maintained

[T. Binder, T. Bringmann, M. Gustafsson, and A. Hryczuk. Eur. Phys. J. C 81 (2021), p. 577]

- Annihilation (s-channel) are enhanced → Initiate chemical decoupling

- Scatterings (t-channel) are **not** enhanced
- Couplings h-SM depends on small yukawa couplings: **suppressed**

→ Can not maintain kinetic eq.

- Solve the **full** Boltzmann equation:

$$E(\partial_t - H\boldsymbol{p} \cdot \boldsymbol{\nabla}_{\boldsymbol{p}}) f_S = \mathcal{C}[f_S]$$

Dark matter freeze-out: relic density

- Use the code DRAKE and find:

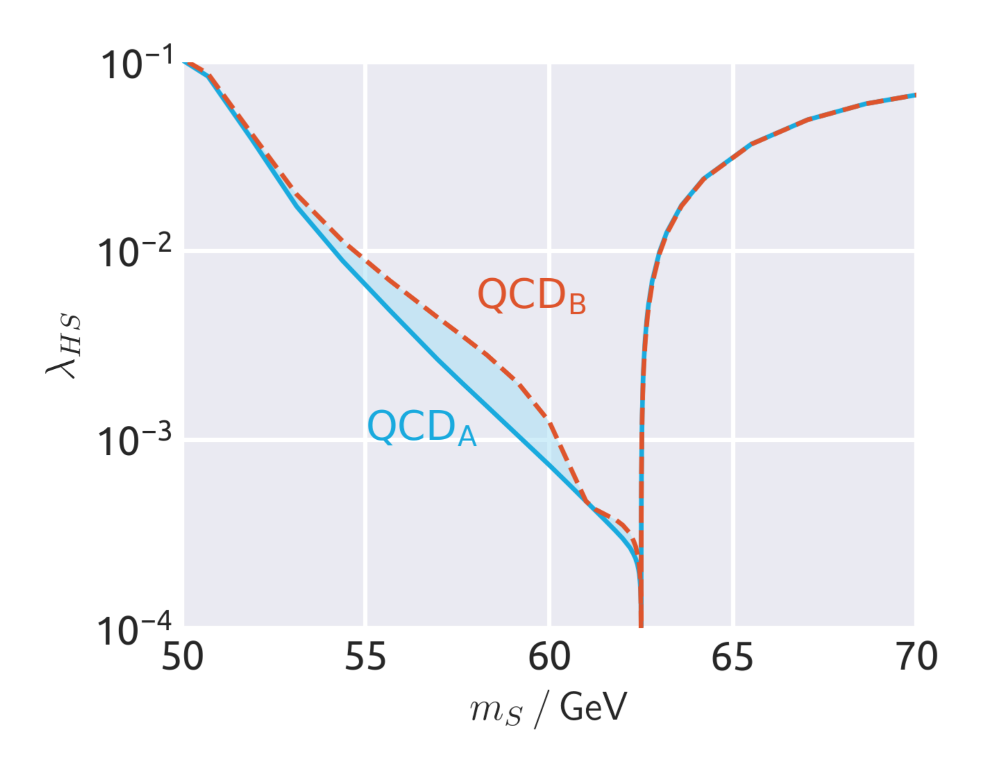
[T. Binder, T. Bringmann, M. Gustafsson, and A. Hryczuk. Eur. Phys. J. C 81 (2021), p. 577]

$$T_{\mathrm{fo}} \approx \mathcal{O}(1)\ \mathrm{GeV}$$

Close to the QCD phase transition...

$\mathrm{QCD_A}$
All quarks are free and present in the plasma. Maximize elastic scattering.

$\mathrm{QCD_B}$
Only light quarks (u, d, s) can contribute. Minimize elastic scattering.



$$\Omega_{\mathrm{DM}} h^2 = 0.120$$

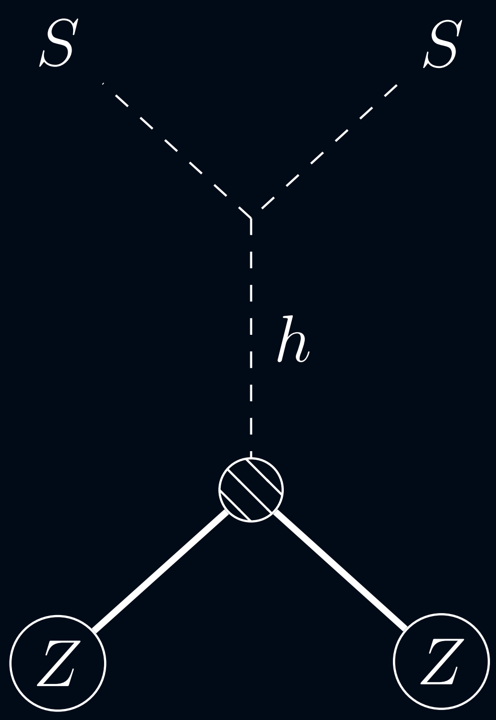
[N. Aghanim et al. Astron. Astrophys. 641 (2020)]

Direct detection

- Spin-independent elastic scatterings off nucleons.
- LZ (2022) upper limit and Darwin projections.

$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \frac{\sigma_{\mathrm{SI}}\rho_0}{m_S}$$

[J. Aalbers et al. Phys. Rev. Lett. 131.4 (2023), p. 041002]
[J. Aalbers et al. JCAP 11 (2016), p. 017]

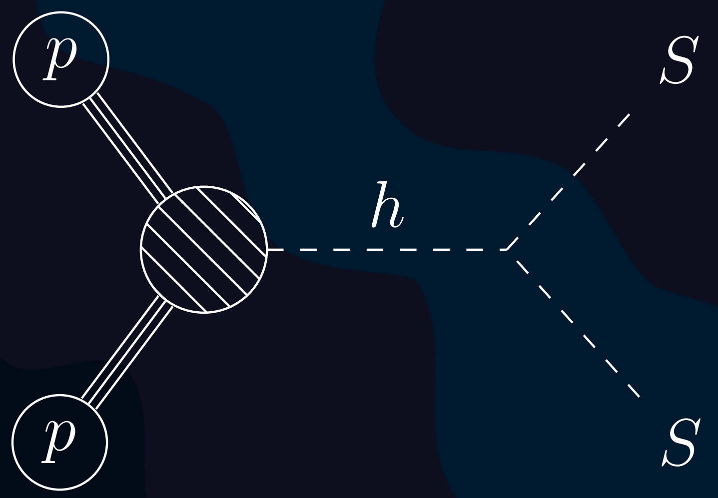


Collider searches

- S can be produced in colliders.
- $m_S < m_h / 2$

→ Higgs can decay invisibly to S (ATLAS 2020).

$$\mathcal{B}_{h,\text{inv}} = \frac{\Gamma_{h,\text{inv}}}{\Gamma_{h,\text{inv}} + \Gamma_{h,\text{SM}}}$$

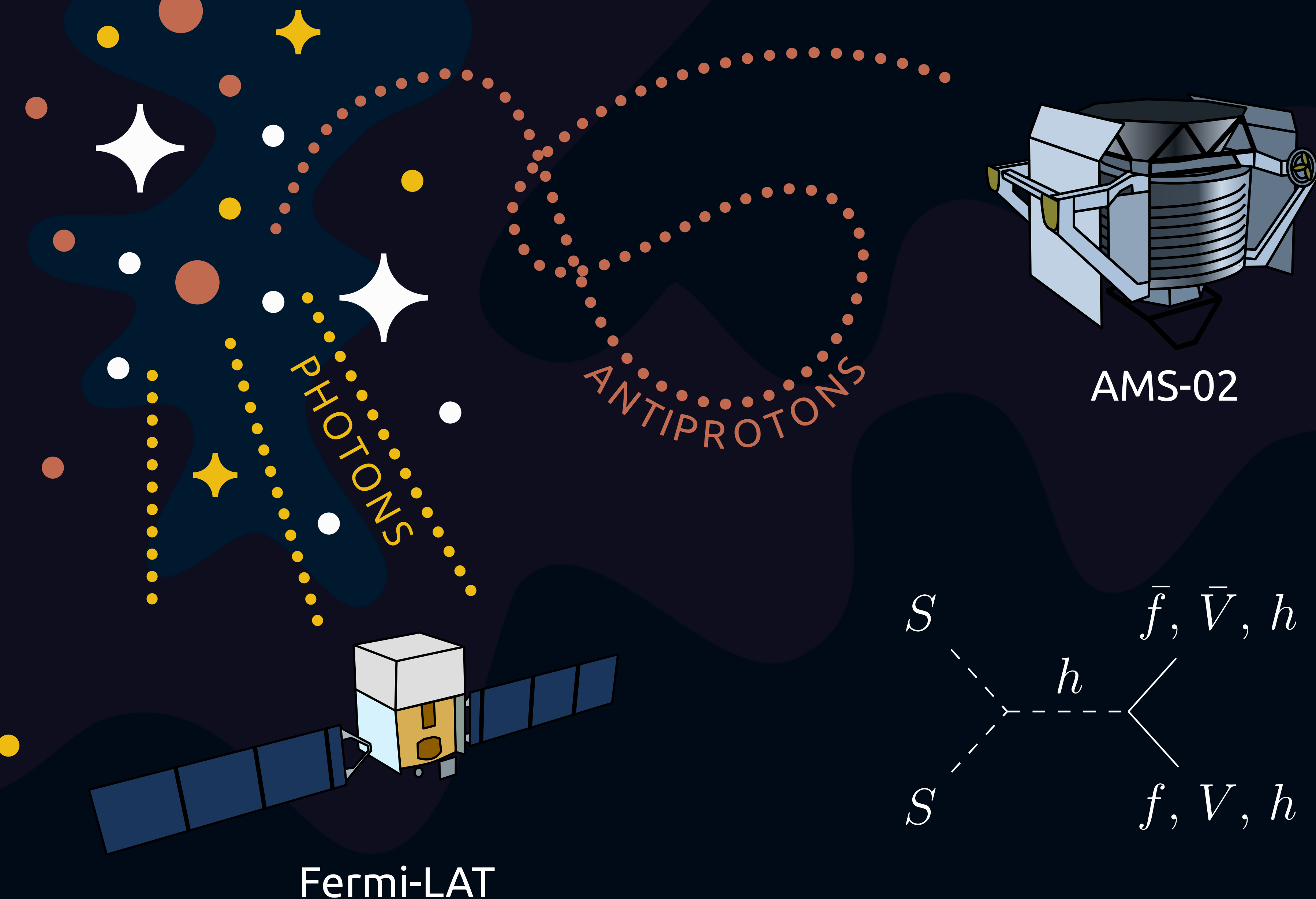


- Resonance region **requires special care**:
  - Higgs's width can become a rapidly varying function.
  - Relevant off-shell Higgs contribution.

Extend the procedure assuming S production via on-shell Higgs-like scalar with $m = \sqrt{s}$

[J. Heisig, M. Krämer, E. Madge, and A. Mück. JHEP 03 (2020), p. 183]

Indirect detection



Fermi-LAT

Photons

Galactic Centre

- Only prompt (direct) emission, secondary (indirect) is negligible;
- Fit **Galactic Centre Excess** energy distribution assuming the SHP model.

$$\frac{dN}{dE d\Omega} = \frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_S}\right)^2 J \times \langle \sigma v \rangle \sum_f \mathcal{B}_f \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_f$$

Geometrical factor
affected by ρ uncertainties

MIN	MED	MAX
J	←——→	7 J

[M. Di Mauro. Phys. Rev. D 103.6 (2021), p. 063029]

[M. Di Mauro and M. W. Winkler. Phys. Rev. D 103.12 (2021), p. 123005]

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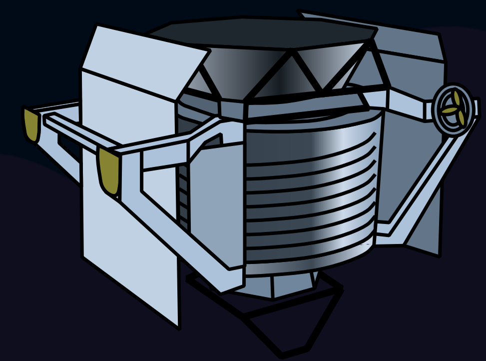
Dwarves spheroidal galaxies

Study a sample of 48 dwarfes galaxies and fit fluxes for a DM origin.

[M. Di Mauro, M. Stref, and F. Calore. Phys. Rev. D 106.12 (2022), p. 123032]

Antiprotons

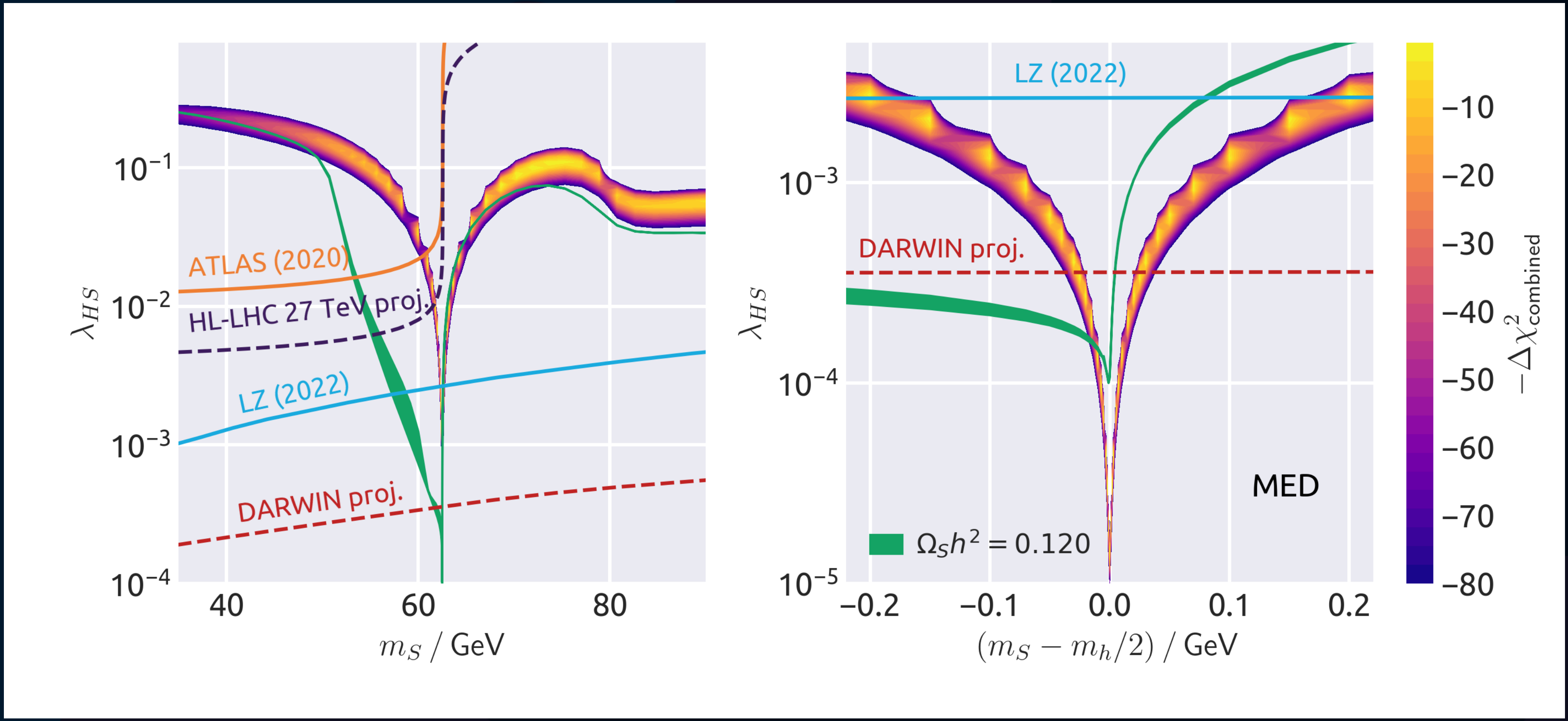


AMS-02

$$\mathcal{Q}(E,\boldsymbol{r}) = \left(\frac{\rho(\boldsymbol{r})}{\rho_{\odot}}\right)^2 \sum_f \mathcal{B}_f \left(\frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}E}\right)_f$$

- Study **primary** and **secondary** productions and fit for a DM origin.
  [F. Kahlhöfer, M. Korsmeier, M. Krämer, S. Manconi, and K. Nippel. JCAP 12.12 (2021), p. 037]
  [S. Balan, F. Kahlhöfer, M. Korsmeier, S. Manconi, and K. Nippel. JCAP 08 (2023), p. 052]
  [M. Aguilar et al. Physics Reports 894 (2021), pp. 1–116]
- **Propagation model**: diffusion, reacceleration, energy losses, secondary production/fragmentation, solar modulation.

Putting it all together

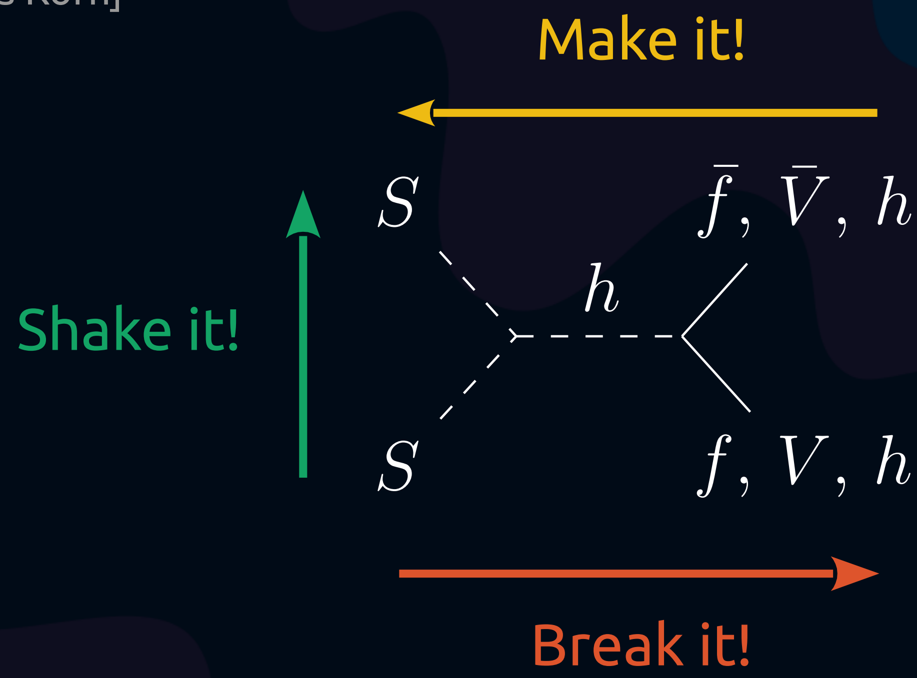


$$m_S = m_h/2 - (10 \div 20)\ \text{MeV}$$
$$\lambda_{HS} = (1.4 \div 1.7) \times 10^{-4}$$

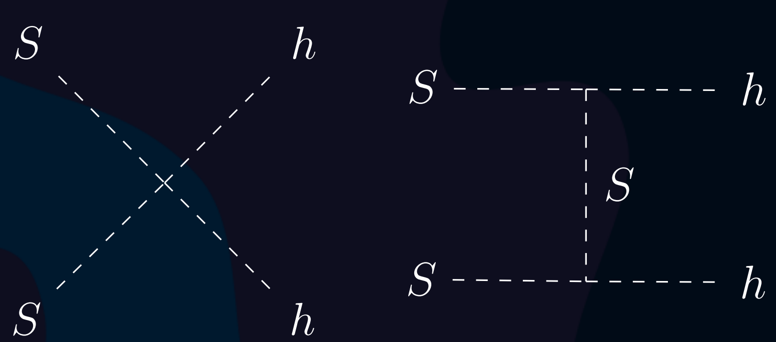
Backup slides

Phenomenology

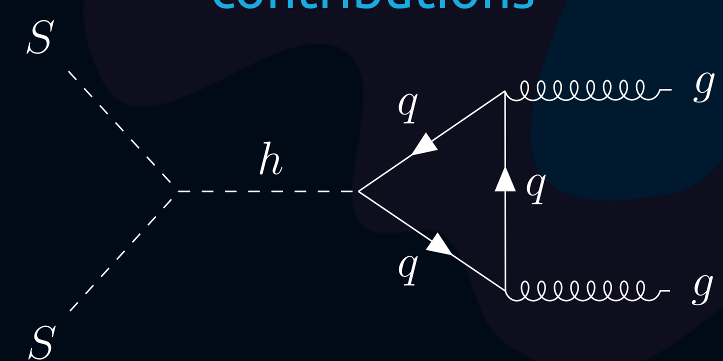
[Quote by Andreas Korn]



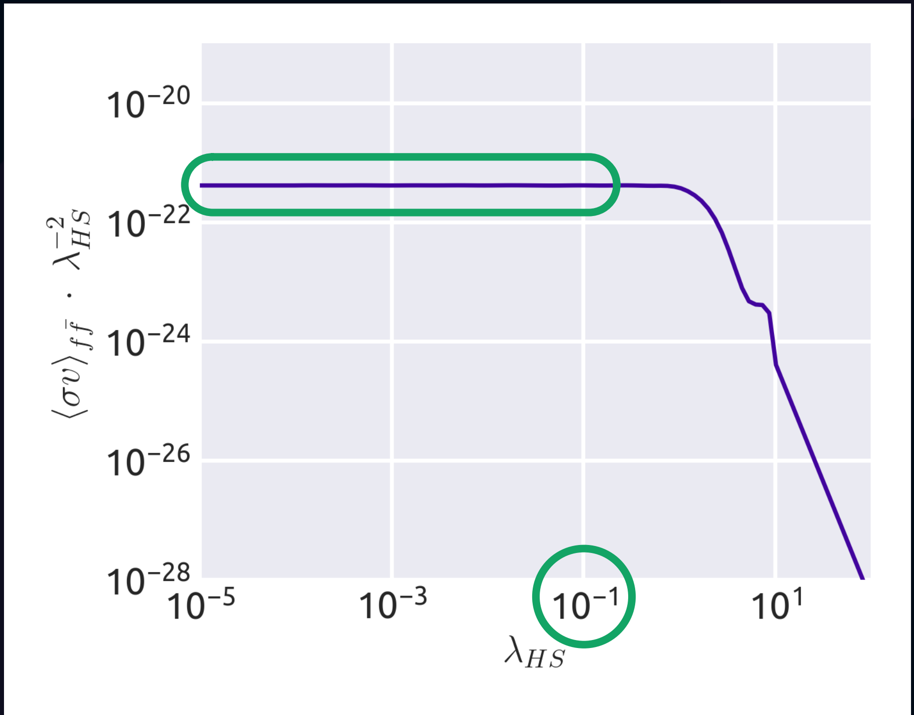
Annihilations kinematically available only for $m_S > m_h$

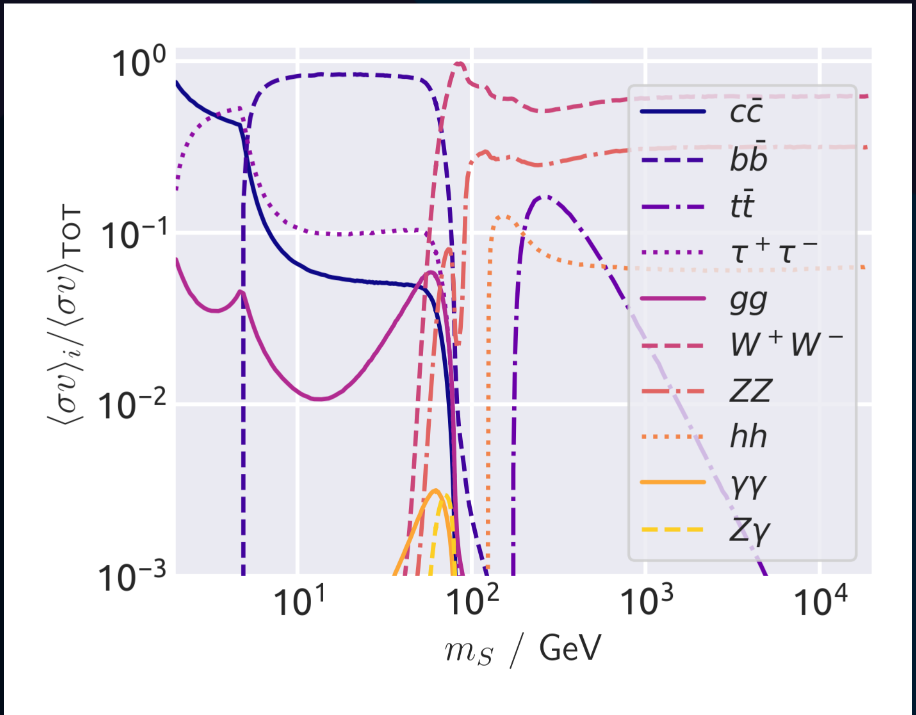


Also loop-induced contributions

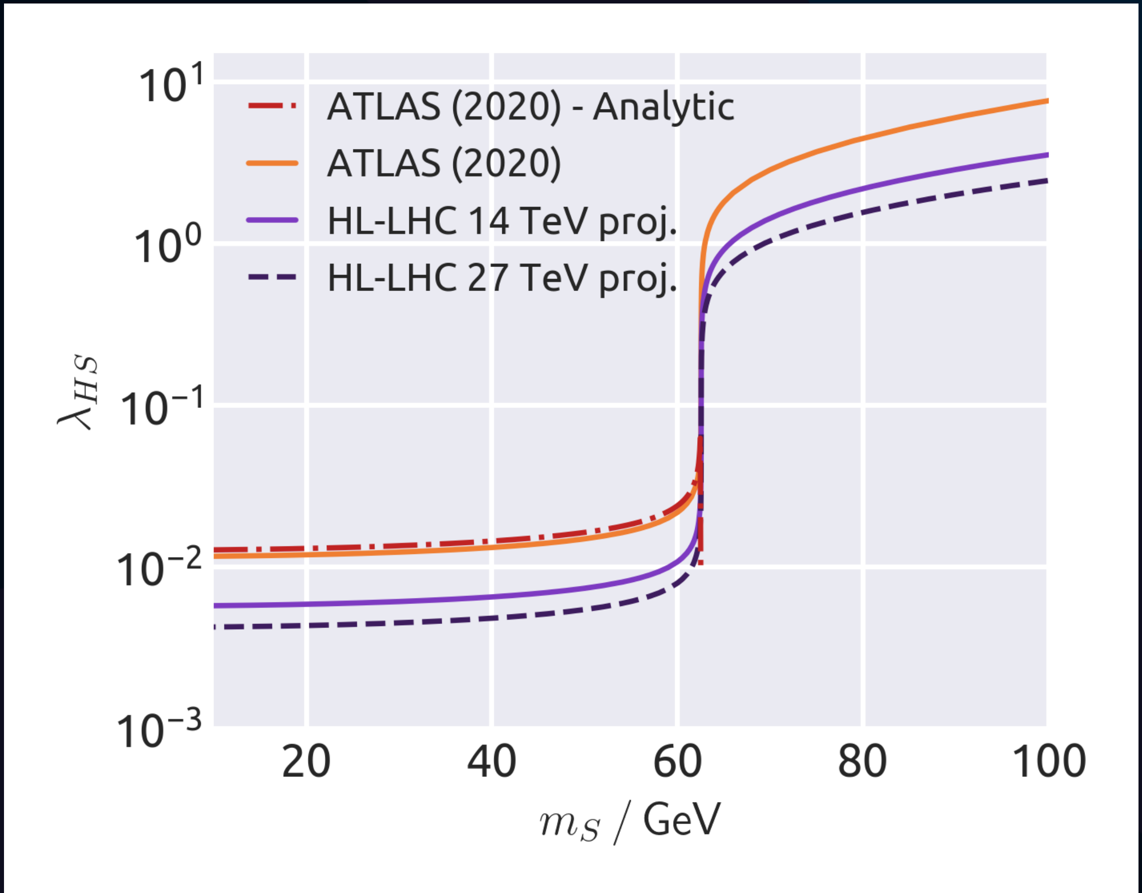


Annihilation cross section

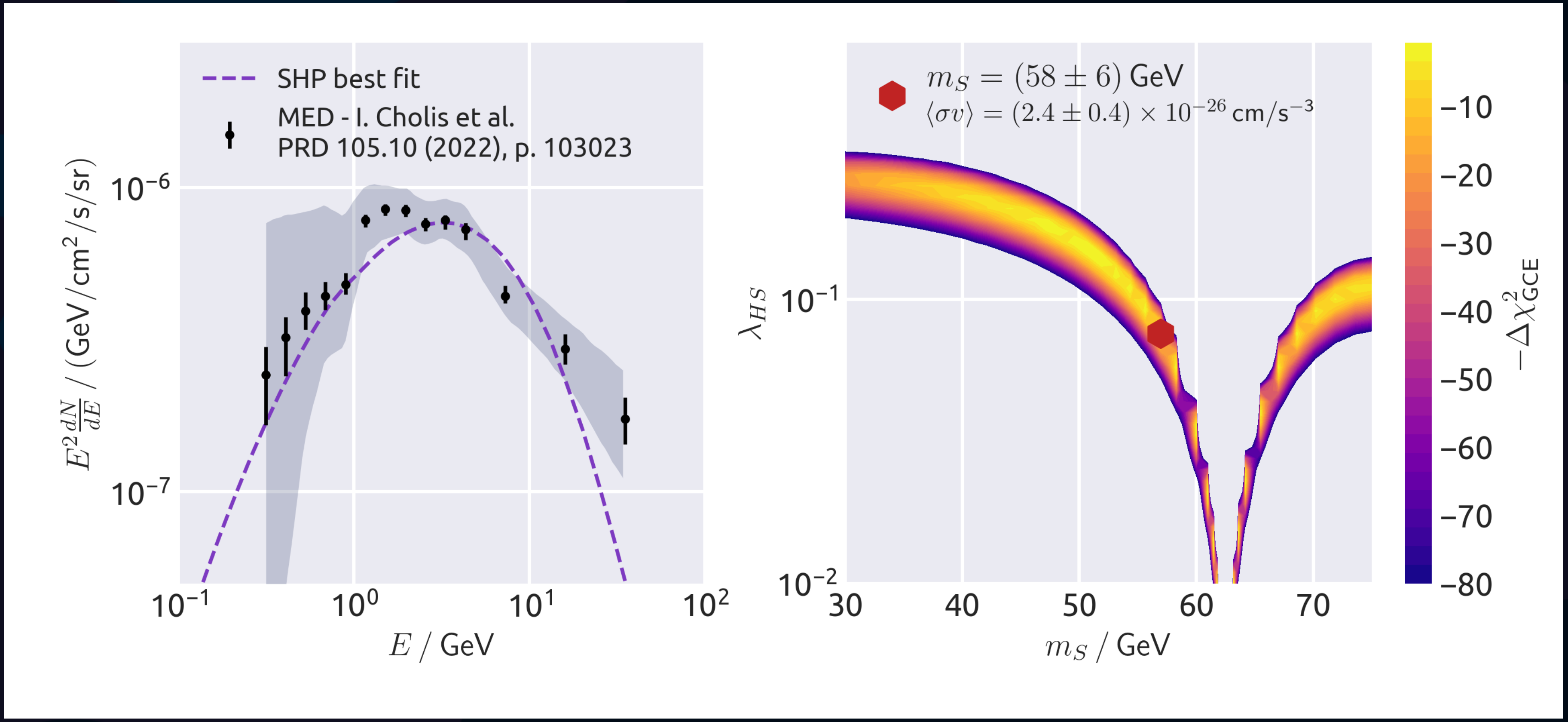




Collider searches



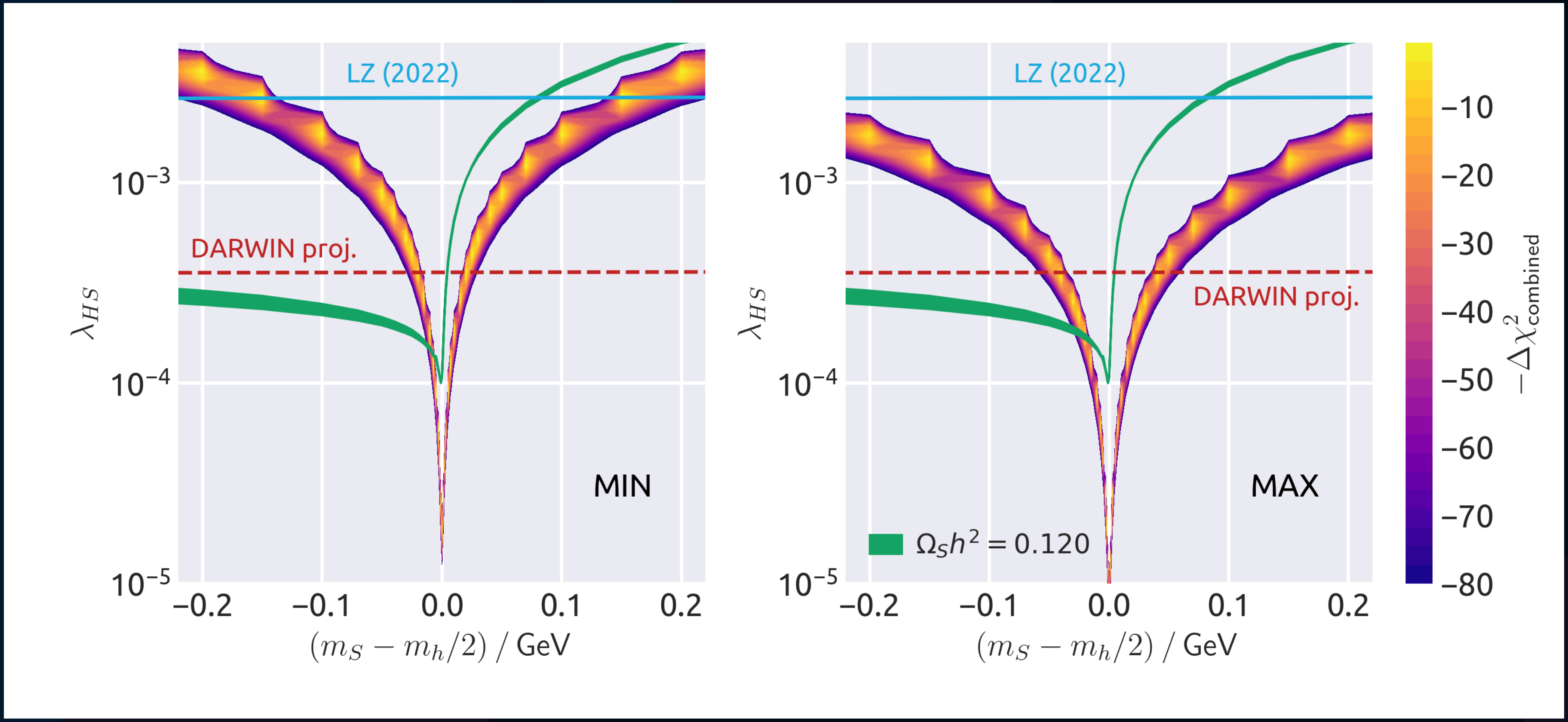
GCE fit



Annihilations spectra computed with MadDM and Pythia.

[C. Arina, J. Heisig, F. Maltoni, DM, and O. Mattelaer. Eur. Phys. J. C 83.3 (2023), p. 241]
[C. Bierlich et al. SciPost Phys. Codebases (Mar. 2022), p. 8]

Putting it all together (MIN and MAX)



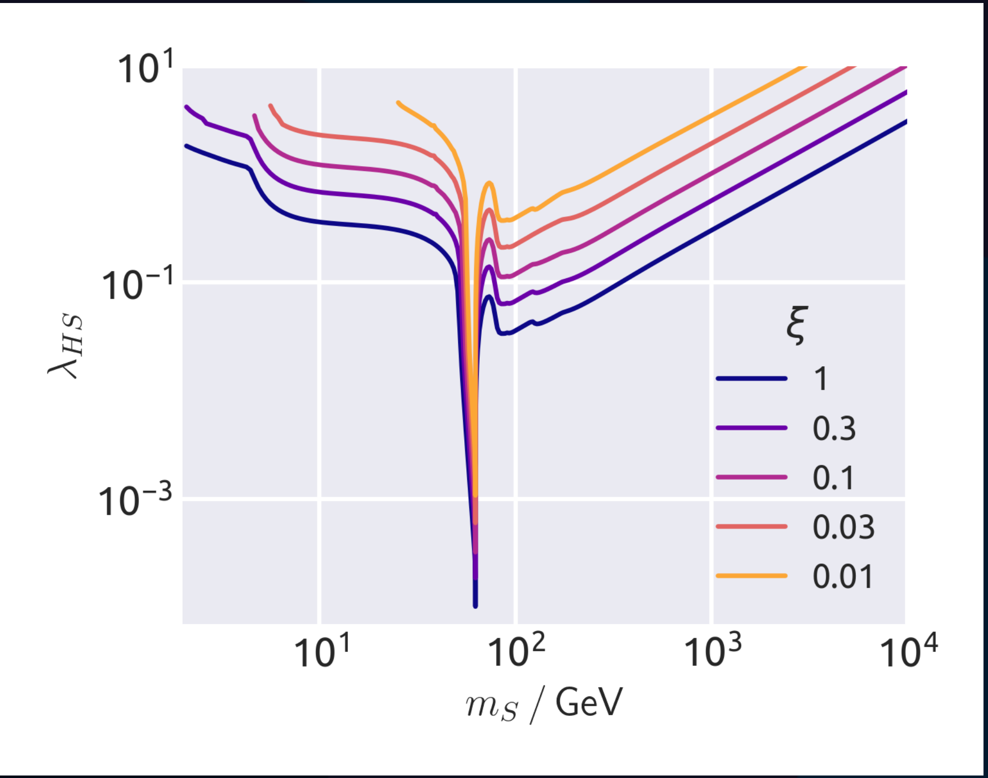
What if S is not alone?

- Consider also the case S **makes up only a fraction** of the total dark matter density:

$$\xi = \frac{\Omega_S h^2}{\Omega_{\rm DM} h^2}$$

- On the resonance, for $\lambda_{HS} < 0.1$:

$$\Omega_S h^2 \propto \frac{1}{\langle \sigma v \rangle} \propto \frac{1}{\lambda_{HS}^2}$$



$$\lambda_{HS} \to \frac{\lambda_{HS}}{\sqrt{\xi}}$$

What if S is not alone?

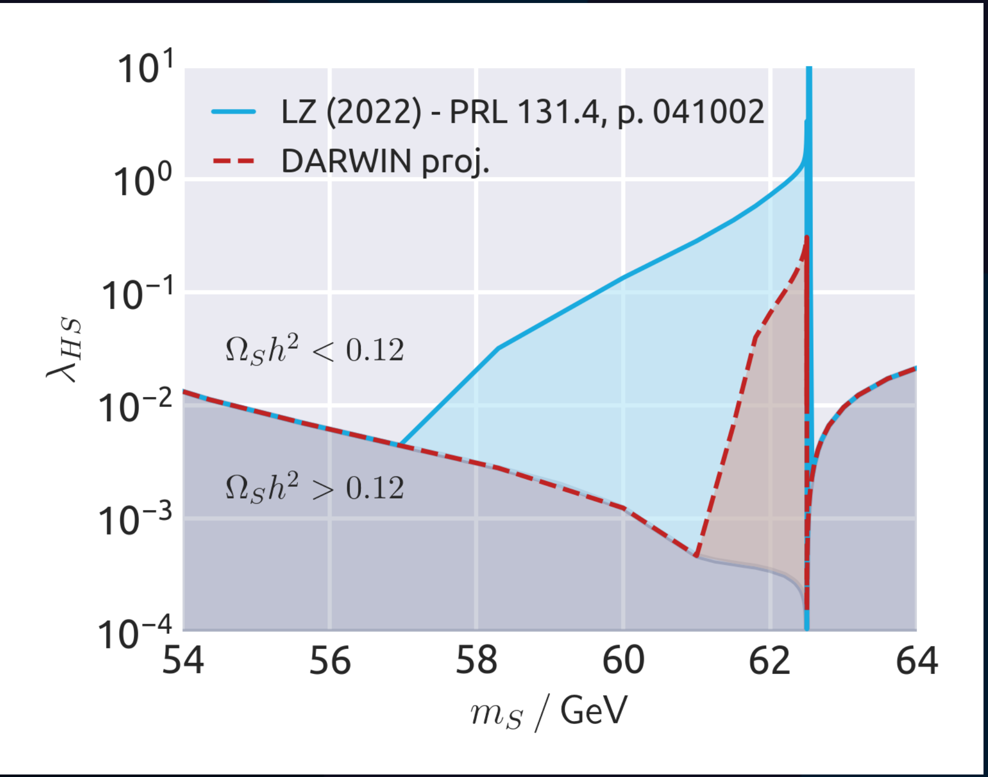
- Direct detection: it modifies local DM density ρ_0. **Recompute the bound (rescale λ_{HS}):**

$$\xi \sigma_{\rm SI}(m_S, \lambda_{HS}) \leq \sigma_{\rm UL}$$

$$\lambda_{HS} \to \frac{\lambda_{HS}}{\sqrt{\xi}}$$

- Collider searches bounds are **unaffected**.
- Indirect detection: affects local DM density, translating into a different geometrical factor J, absorbed by a **rescale of λ_{HS}:**

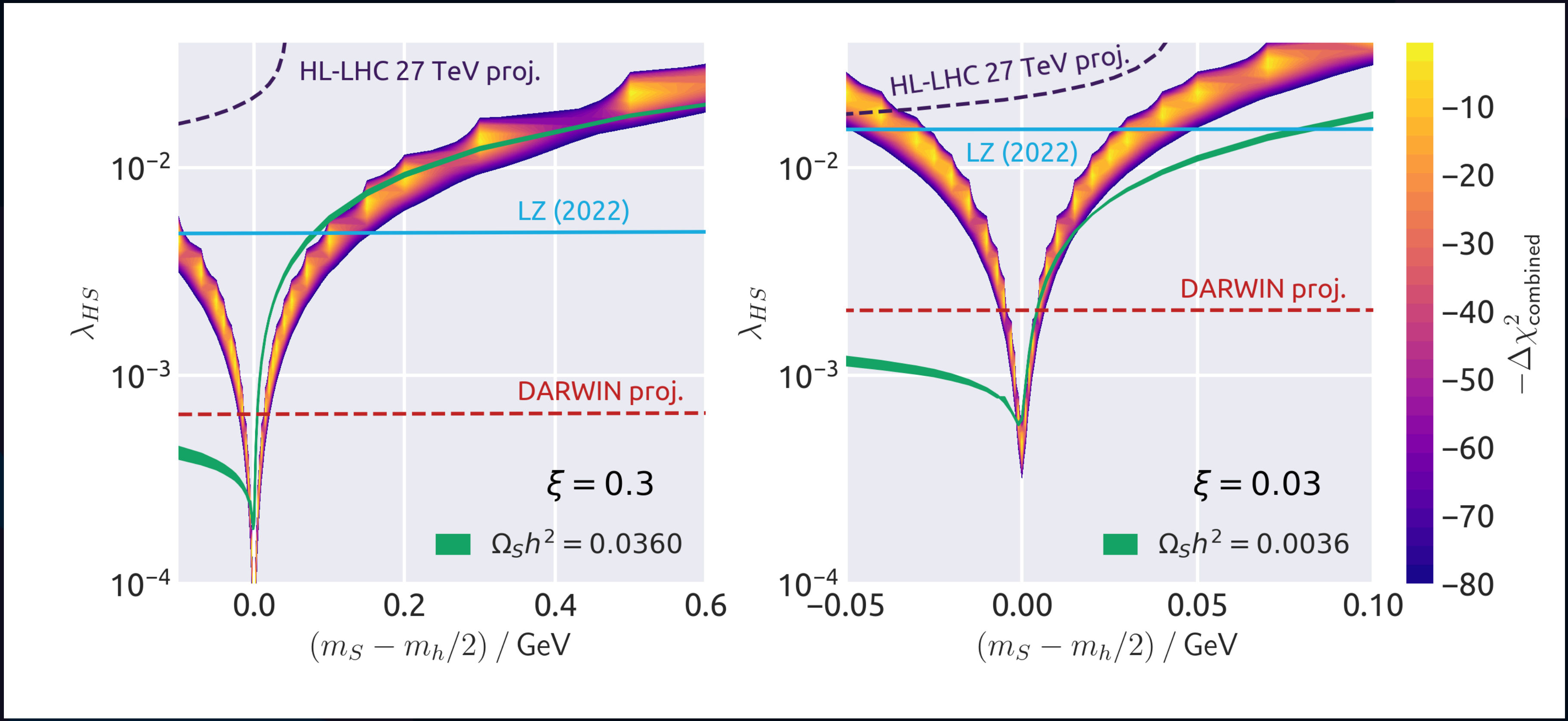
$$\rho \to \xi\, \rho \Rightarrow \mathcal{J} \propto \xi^2 \Rightarrow \lambda_{HS} \to \frac{\lambda_{HS}}{\xi}$$



Direct detection rates computed with MicrOMEGAs.

[G. Alguero, G. Belanger, S. Kraml, and A. Pukhov. SciPost Phys. 13 (2022), p. 124]

Results for ξ < 1



MED model.

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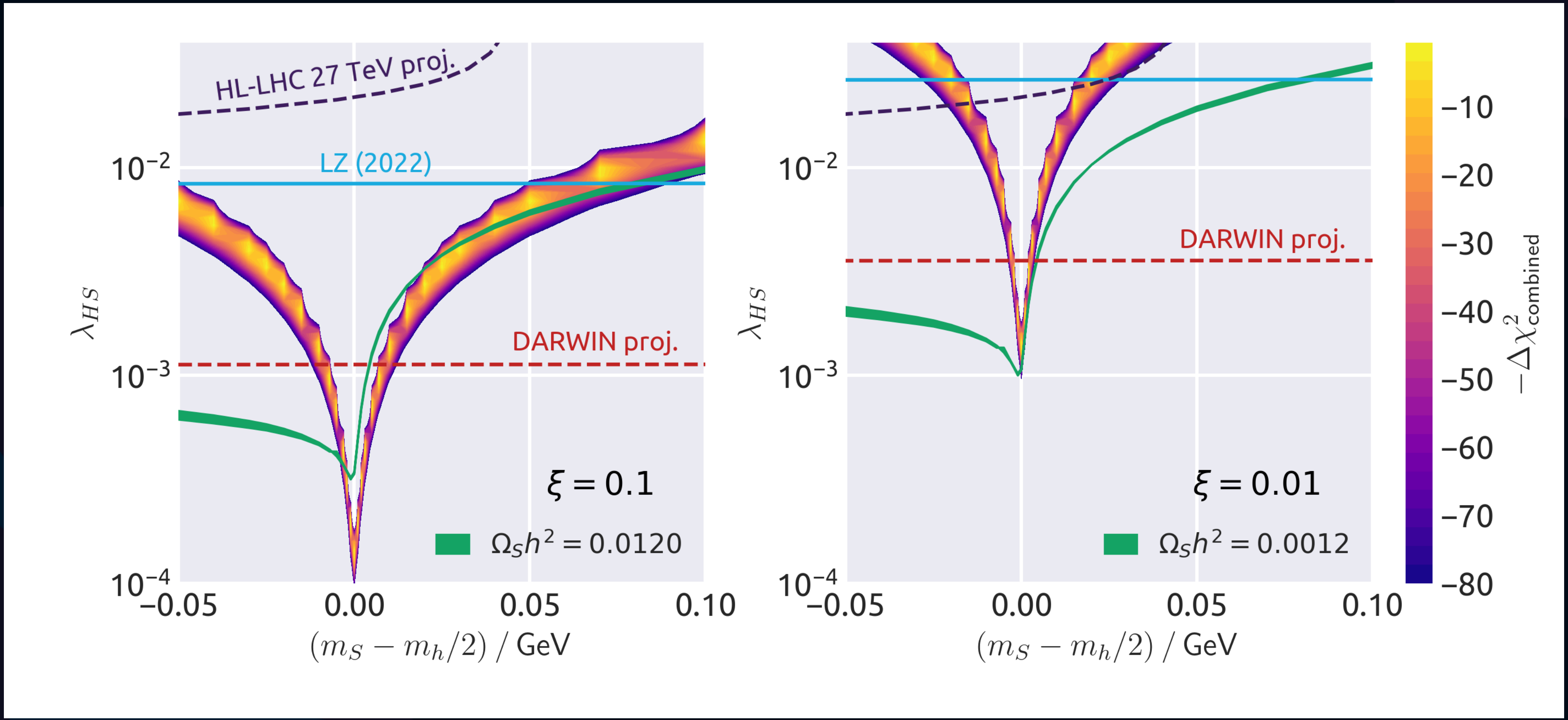
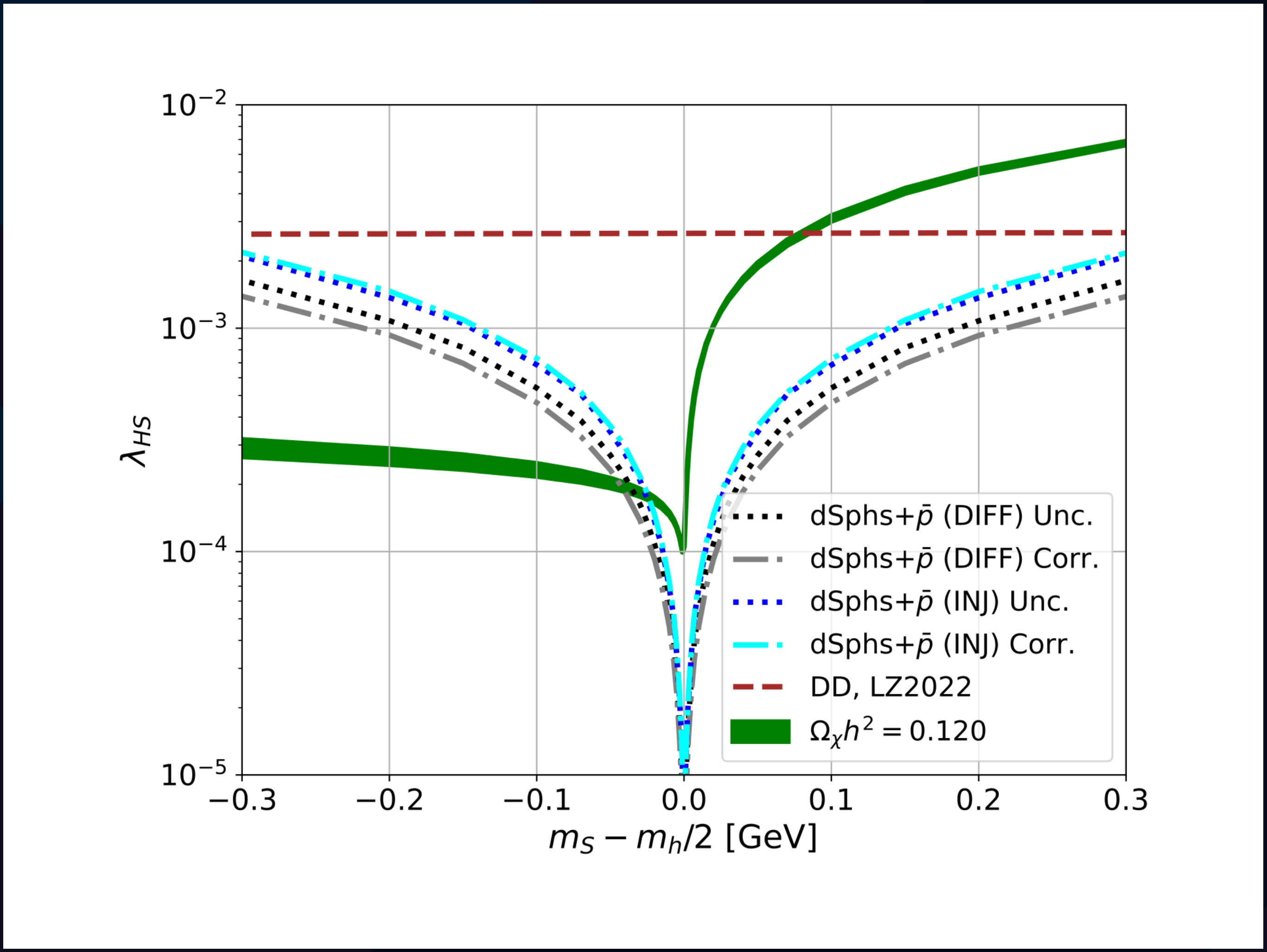


MED model.

What if there is no DM?



[S. Balan, F. Kahlhöfer, M. Korsmeier, S. Manconi, and K. Nippel. JCAP 08 (2023), p. 052]