Confronting dark matter co-annihilation of Inert two Higgs Doublet Model with a compressed mass spectrum

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Ref : arXiv:1912.08875

NCTS Dark Physics Workshop

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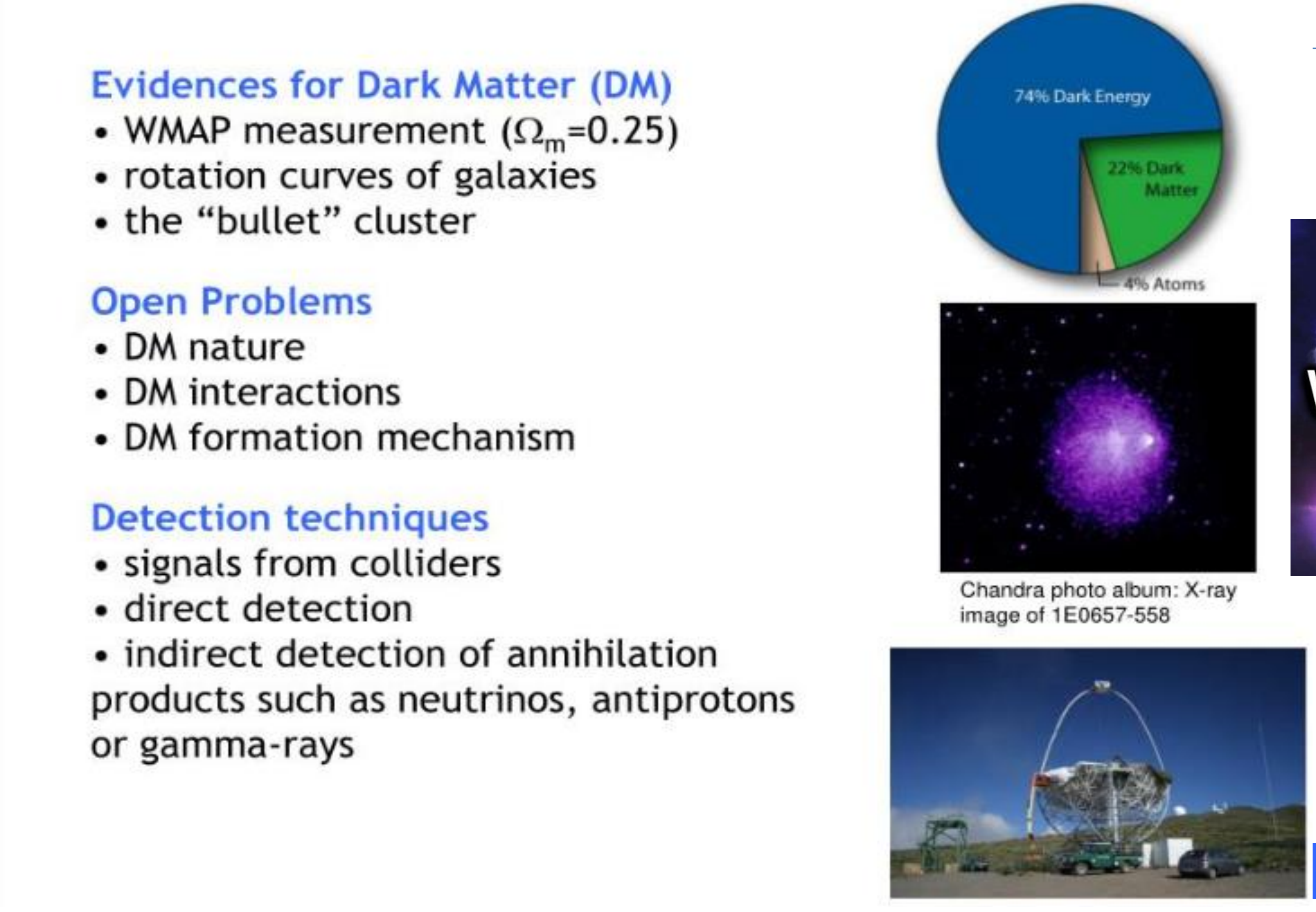
Contents

Contents

- **1. Introduction**
- 2. Brief review of inert two higgs doublet model (i2HDM)
- 3. Constraints on i2HDM
- 4. Results & Discussions
- 5. Summary and Future Prospect

Introduction – Dark Matter



Evidences for Dark Matter (DM)

- WMAP measurement (Ω_m=0.25)
- rotation curves of galaxies
- the “bullet” cluster

Open Problems

- DM nature
- DM interactions
- DM formation mechanism

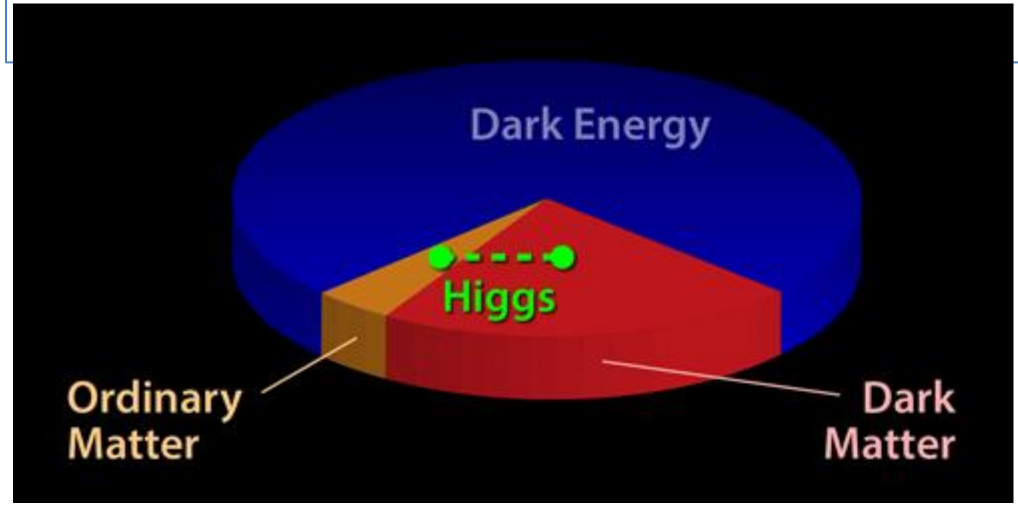
Detection techniques

- signals from colliders
- direct detection
- indirect detection of annihilation products such as neutrinos, antiprotons or gamma-rays

Chandra photo album: X-ray image of 1E0657-558

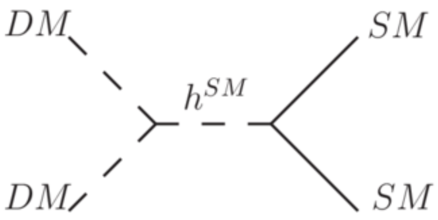
Mattia Fornasa and Marco Taoso

Introduction – Higgs Portal

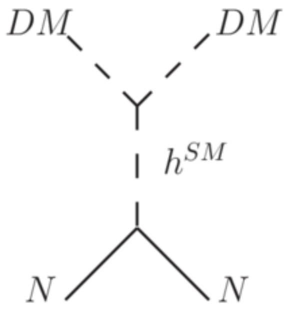


Hidden Sector DM and Higgs Portal

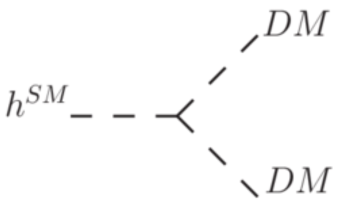
- The renormalizable Higgs can mediate the interaction between the SM and hidden sector



$\langle \sigma v \rangle$

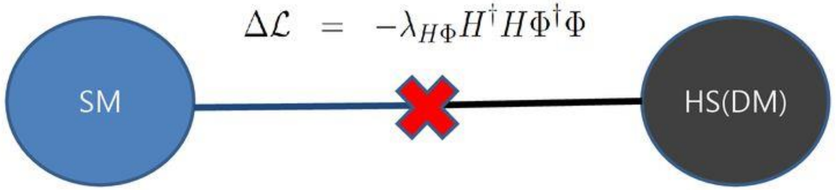


σ_{DM-N}



$\Gamma^{inv}_{h^{SM}}$

$$\Delta\mathcal{L} = -\lambda_{H\Phi} H^\dagger H \Phi^\dagger \Phi$$

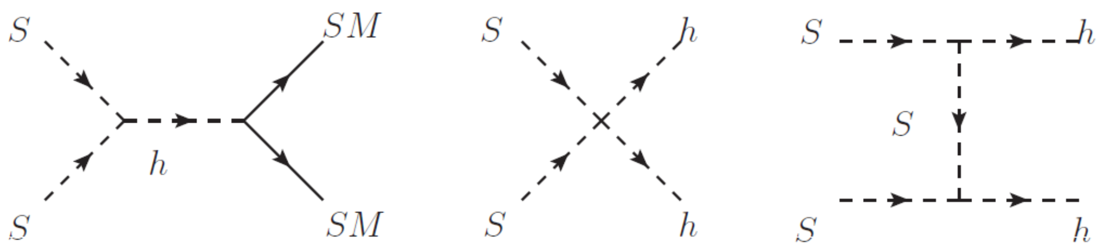


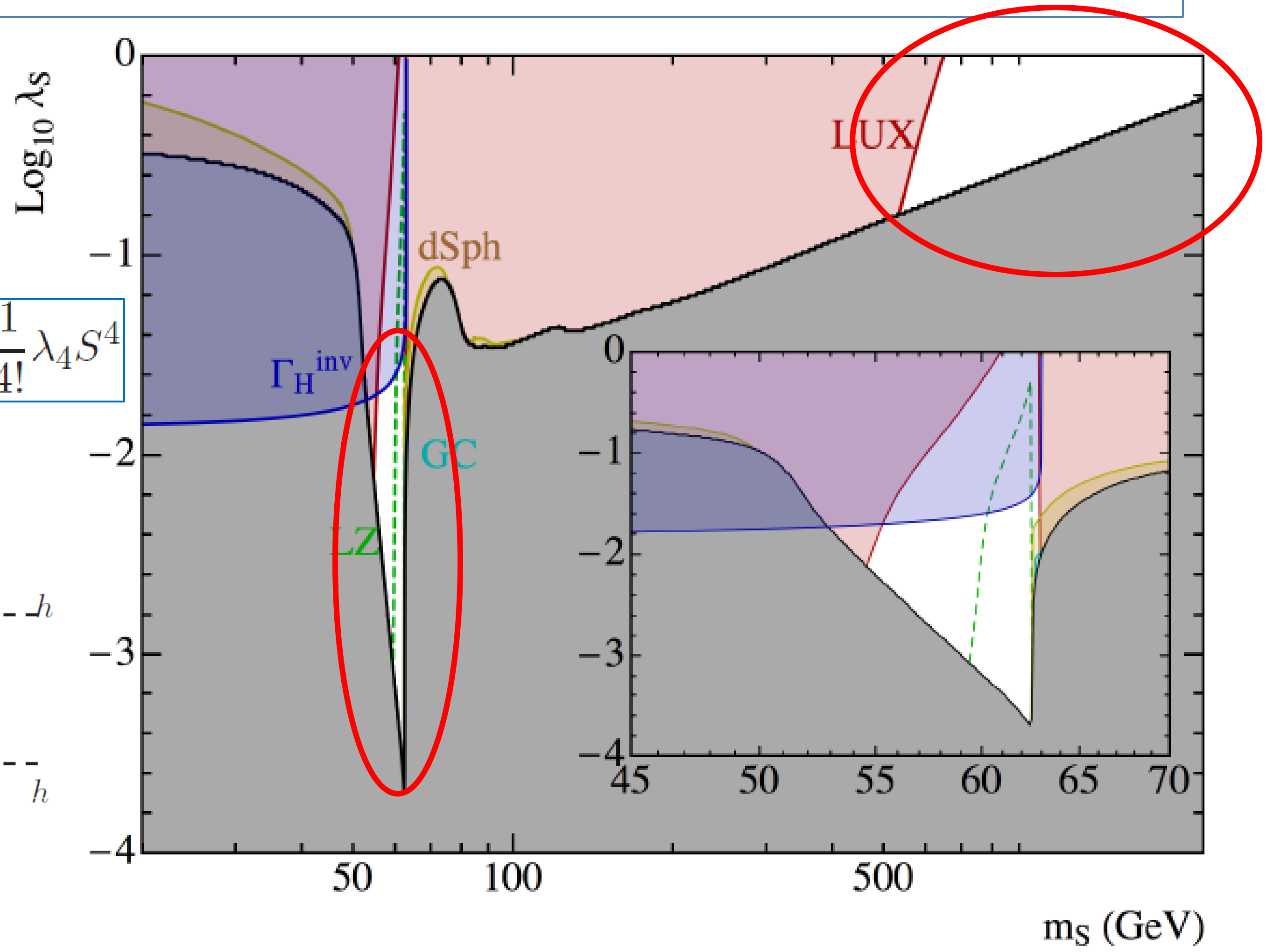
Introduction – Z2 odd scalar singlet DM

arXiv:1701.08134

JHEP 1705 (2017) 036

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





Introduction – Z2 odd scalar singlet DM

arXiv:1701.08134

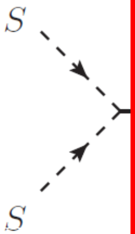
JHEP 1705 (2017) 036

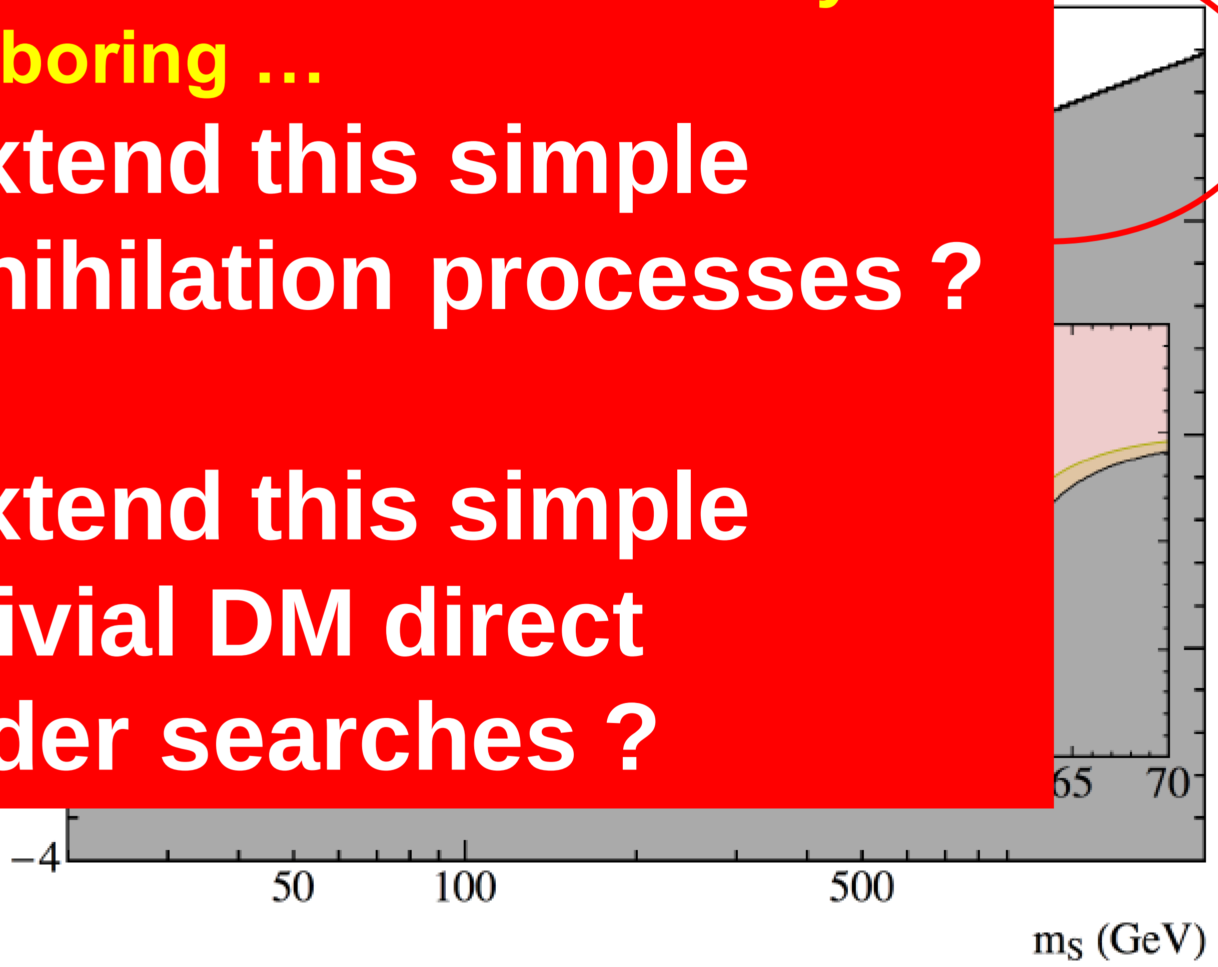
Even though this simple model has not been totally ruled out, but it's relatively boring …

1. Is it possible to extend this simple model with co-annihilation processes ?

2. Is it possible to extend this simple model with non-trivial DM direct detections & collider searches ?

$\mathcal{L}_{\mathrm{SHP}} =$

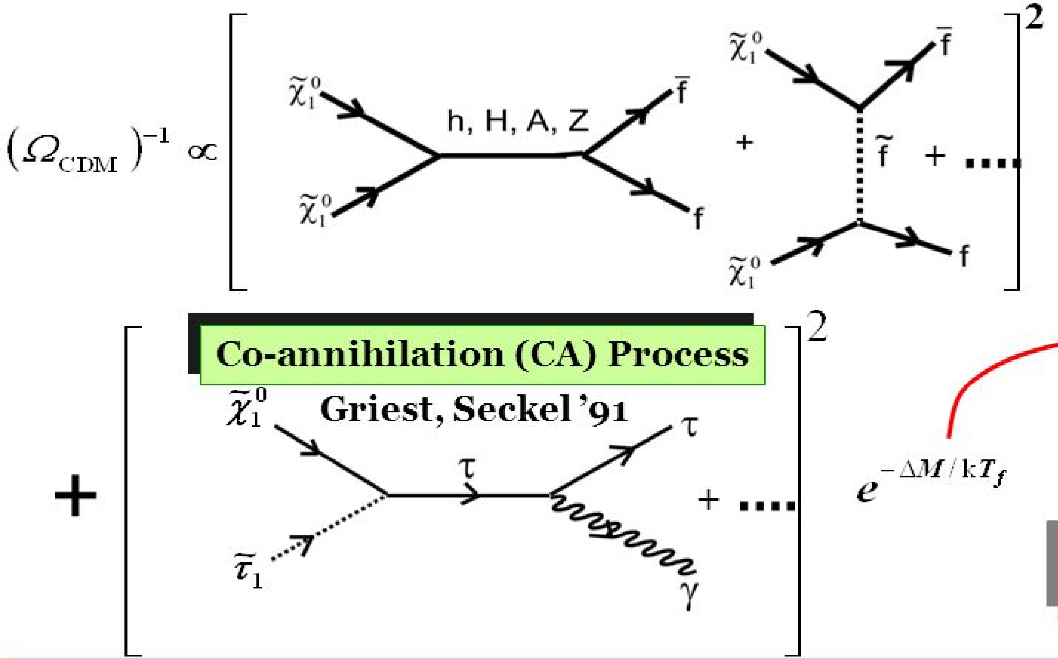




Introduction – Co-annihilation

Anatomy of σ_{ann}

$$\underbrace{\Omega_{\tilde{\chi}_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{ann} v \rangle} dx \qquad < \sigma_{ann} v > \sim \frac{\alpha^2}{M^2} \sim 1\, pb$$



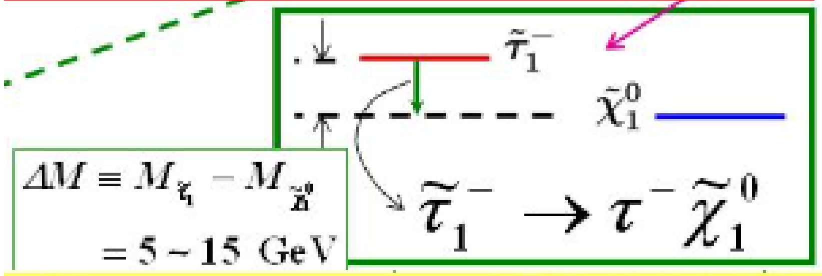
$e^{-\Delta M / kT_f}$

$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$

A near degeneracy occurs naturally for light stau in mSUGRA.

We need at least the 2nd particle inside the dark sector with mass close to DM candidate !

It's natural to connect the co-annihilation with compressed mass spectrum !



$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15$ GeV

$\tilde{\tau}_1^- \to \tau^- \tilde{\chi}_1^0$

Can we measure ΔM at colliders?

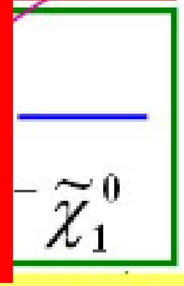
Introduction – Co-annihilation

One of the next non-trivial scalar dark matter model with co-annihilation processes is the inert two higgs doublet model (i2HDM).

N. G. Deshpande and E. Ma, Phys. Rev. D **18**, 2574 (1978).

I will focus on i2HDM with a compressed mass spectrum and its connection with dark matter co-annihilation in this talk !

essed



Can we measure ΔM at colliders?

Contents

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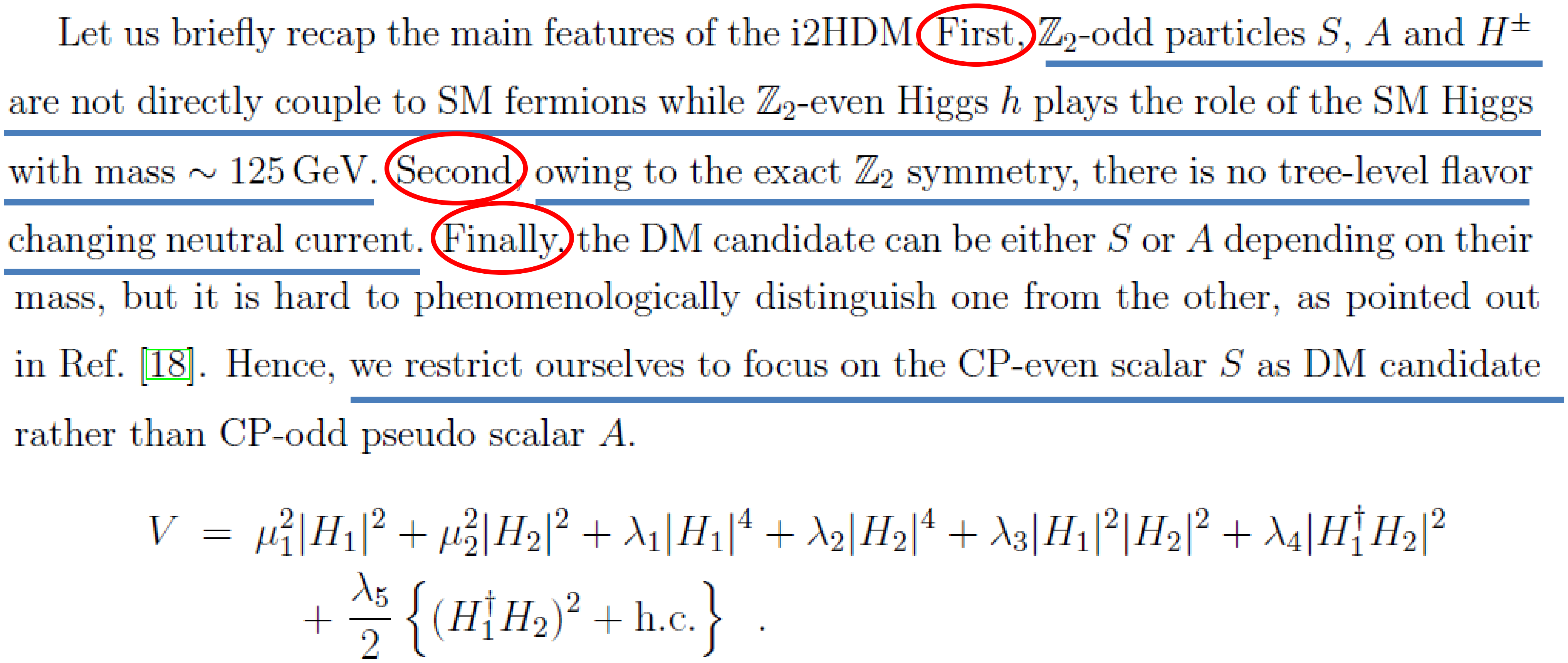
Brief review of inert two higgs doublet model (i2HDM)

The i2HDM [13] is the simplest version of DM model within the two Higgs doublets framework. Compared with the single scalar doublet in the SM, the i2HDM has two scalar doublets H_1 and H_2 under a discrete $\mathbb{Z}_2$ symmetry, $H_1 \to H_1$ and $H_2 \to -H_2$ which is introduced to maintain the stability of DM. The $\mathbb{Z}_2$ symmetry cannot be spontaneously broken, so that H_2 never develops a VEV. These two doublets are

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix}, \quad \text{and} \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{pmatrix}. \qquad (1)$$

Here, $G^\pm$ and G^0 are charged and neutral Goldstone bosons respectively. The symmetry breaking pattern for the doublets are $\langle H_1^T \rangle = (0,\ v/\sqrt{2})$ and $\langle H_2^T \rangle = (0,\ 0)$. In the end, we have five physical mass eigenstates: two CP-even neutral scalar h and S, one CP-odd neutral scalar A, and a pair of charged scalars $H^\pm$.

Brief review of inert two higgs doublet model (i2HDM)



Let us briefly recap the main features of the i2HDM. First, $\mathbb{Z}_2$-odd particles S, A and $H^\pm$ are not directly couple to SM fermions while $\mathbb{Z}_2$-even Higgs h plays the role of the SM Higgs with mass $\sim 125\,\mathrm{GeV}$. Second, owing to the exact $\mathbb{Z}_2$ symmetry, there is no tree-level flavor changing neutral current. Finally, the DM candidate can be either S or A depending on their mass, but it is hard to phenomenologically distinguish one from the other, as pointed out in Ref. [18]. Hence, we restrict ourselves to focus on the CP-even scalar S as DM candidate rather than CP-odd pseudo scalar A.

$$
\begin{aligned}
V \;=\; & \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 \\
& + \frac{\lambda_5}{2}\left\{(H_1^\dagger H_2)^2 + \text{h.c.}\right\} \quad .
\end{aligned}
$$

Brief review of inert two higgs doublet model (i2HDM)

Conventionally, it is more intuitive to adopt the physical mass basis as inputs

$$
\begin{aligned}
m_h^2 &= -2\mu_1^2 = 2\lambda_1 v^2, \\
m_S^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 = \mu_2^2 + \lambda_S v^2, \\
m_A^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 = \mu_2^2 + \lambda_A v^2, \\
m_{H^\pm}^2 &= \mu_2^2 + \frac{1}{2}\lambda_3 v^2,
\end{aligned}
$$

where we denote

$$\lambda_S = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5), \quad \text{and} \quad \lambda_A = \lambda_S - \lambda_5 = \lambda_S + \frac{m_A^2 - m_S^2}{v^2}.$$

Brief review of inert two higgs doublet model (i2HDM)

Conventionally, it is more intuitive to adopt the physical mass basis as inputs

For the scenario with the compressed mass spectra, the mass splitting parameters $\Delta^0 = m_A - m_S$ and $\Delta^\pm = m_{H^\pm} - m_S$ instead of m_A and $m_{H^\pm}$ are more useful. Hence, our input parameters are

$$\{m_S, \Delta^0, \Delta^\pm, \lambda_2, \lambda_S\}. \tag{6}$$

where we denote

$$\lambda_S = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5), \quad \text{and} \quad \lambda_A = \lambda_S - \lambda_5 = \lambda_S + \frac{m_A^2 - m_S^2}{v^2}.$$

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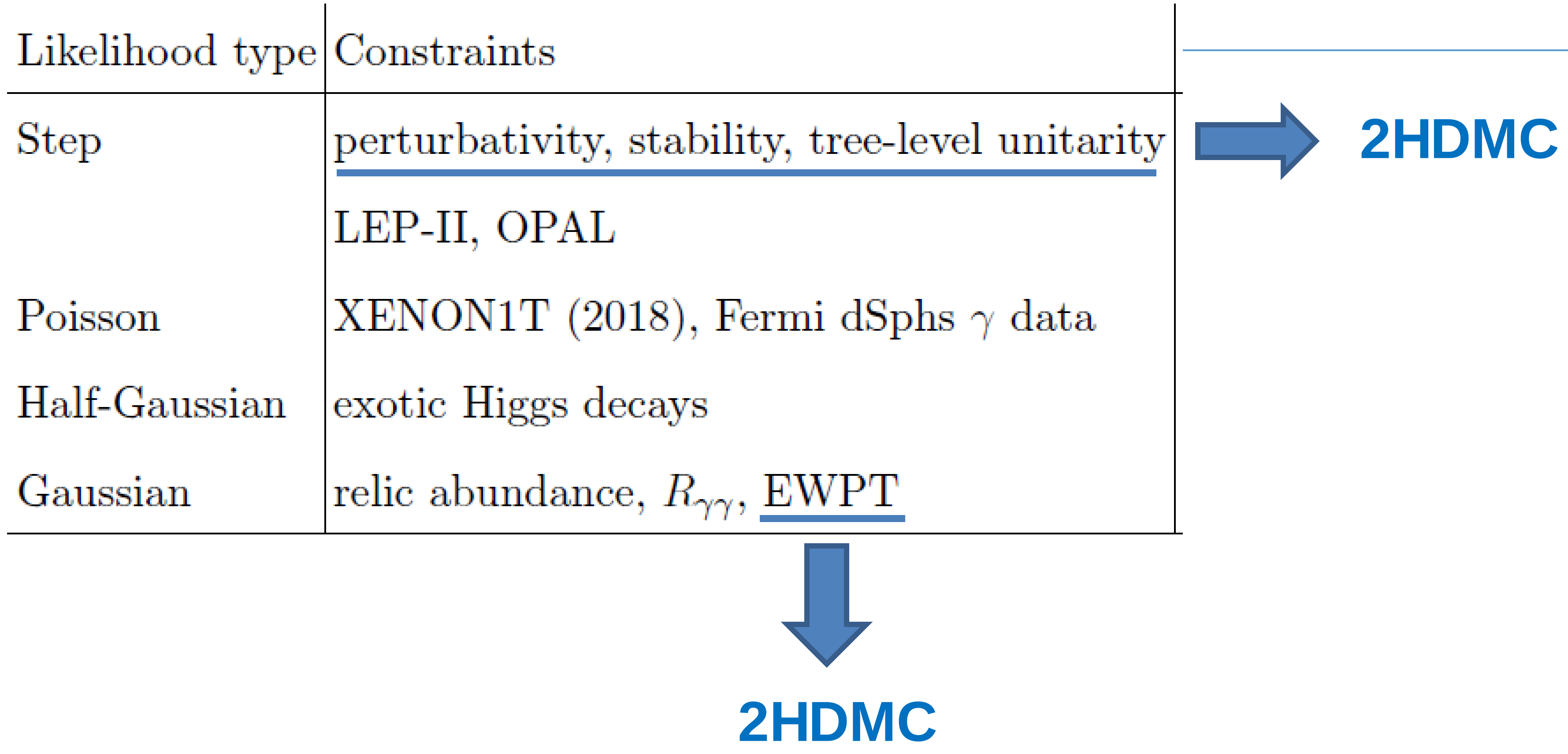
Constraints on i2HDM



Likelihood type	Constraints
Step	perturbativity, stability, tree-level unitarity
	LEP-II, OPAL
Poisson	XENON1T (2018), Fermi dSphs γ data
Half-Gaussian	exotic Higgs decays
Gaussian	relic abundance, $R_{\gamma\gamma}$, EWPT

2HDMC

2HDMC

Constraints on i2HDM

Phys. Rev. D 93, 035020 (2016)

Likelihood type	Constraints
Step	perturbativity, stability, tree-level unitarity
	LEP-II, OPAL
Poisson	XENON1T (2018), Fermi dSphs γ data
Half-Gaussian	exotic Higgs decays
Gaussian	relic abundance, $R_{\gamma\gamma}$, EWPT

$$\boxed{e^+e^- \to H^+H^-}$$

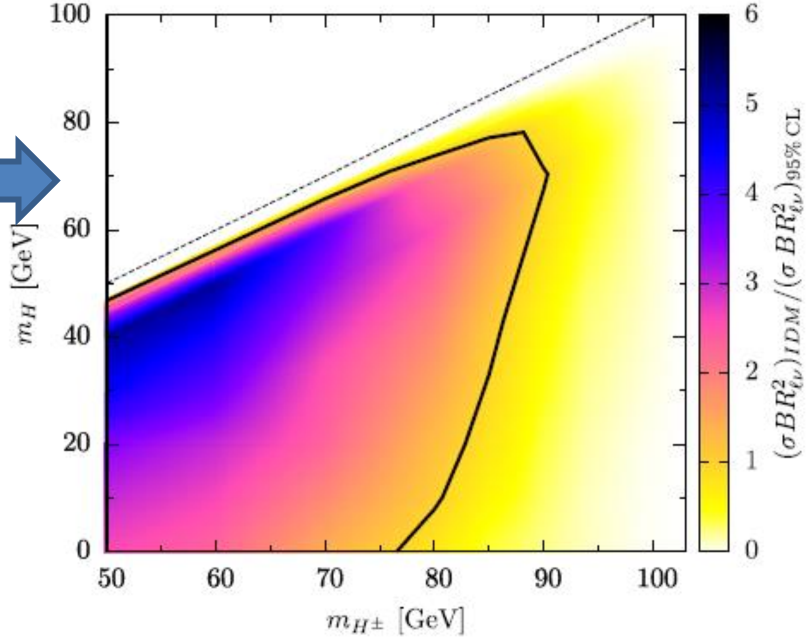
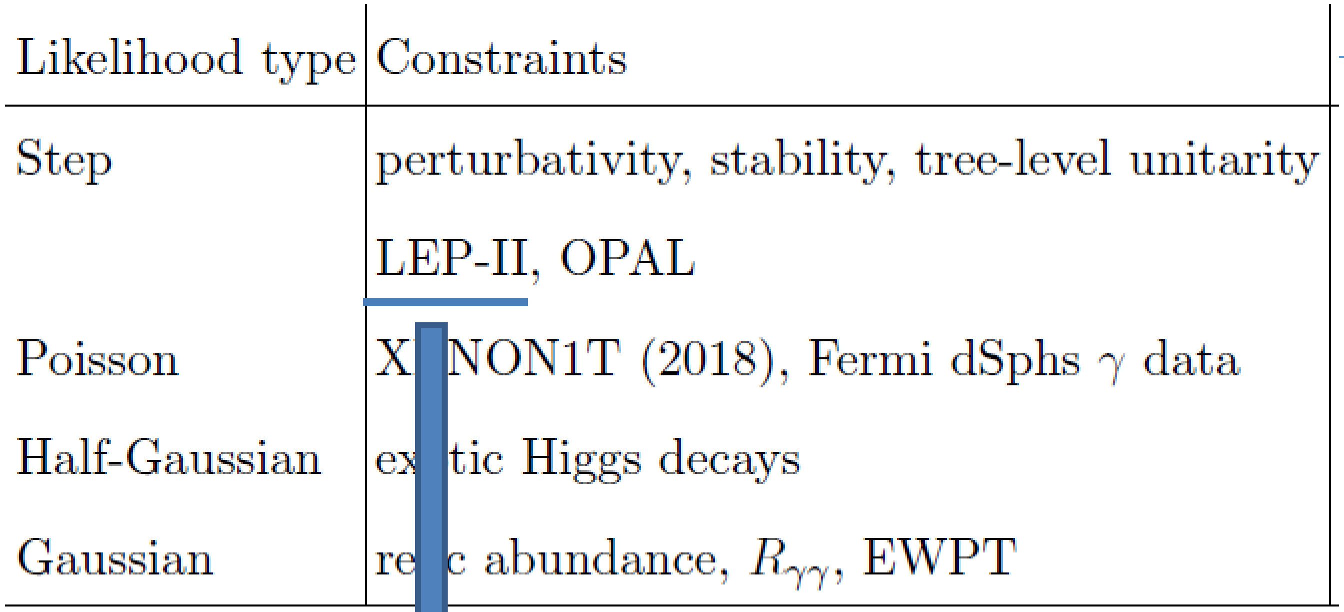


FIG. 5. Excluded region (95% C.L.) in the $m_{H^\pm} - m_H$ plane derived from the OPAL search for leptons and missing energy of Ref. [65]. The color map shows the magnitude of $(\sigma \mathrm{BR}^2_{\ell\nu})_{\mathrm{IDM}}/(\sigma \mathrm{BR}^2_{\ell\nu})_{95\%\,\mathrm{C.L.}}$.

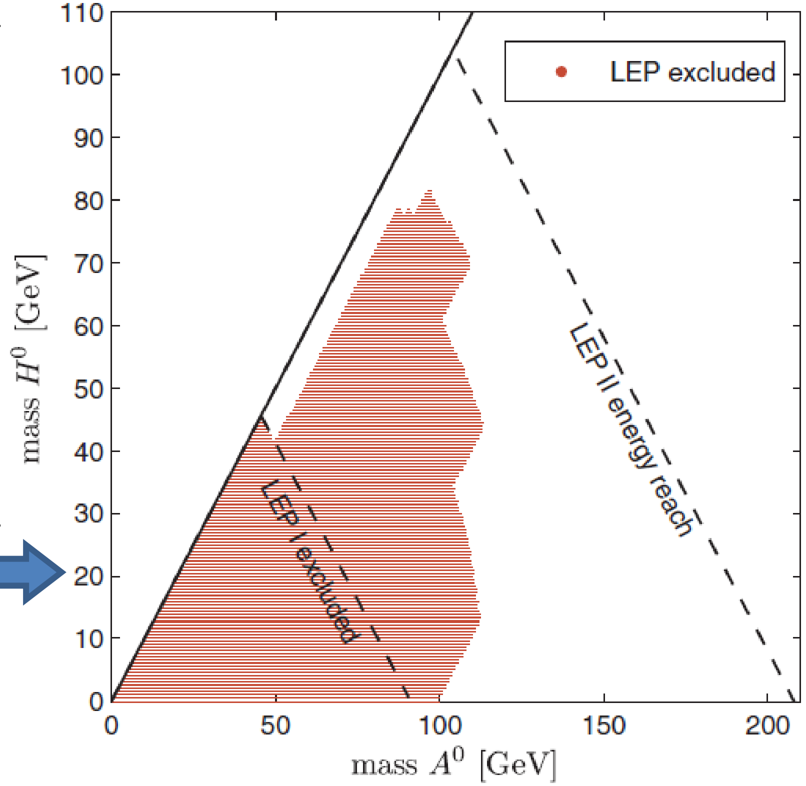
Constraints on i2HDM



Likelihood type	Constraints
Step	perturbativity, stability, tree-level unitarity LEP-II, OPAL
Poisson	X NON1T (2018), Fermi dSphs γ data
Half-Gaussian	ex tic Higgs decays
Gaussian	re c abundance, $R_{\gamma\gamma}$, EWPT

$$\boxed{e^+e^- \to SA}$$

Phys.Rev.D79:035013,2009



Constraints on i2HDM

Likelihood type	Constraints
Step	perturbativity, stability, tree-level unitarity
	LEP-II, OPAL
Poisson	XENON1T (2018), Fermi dSphs γ data
Half-Gaussian	exotic Higgs decays
Gaussian	relic abundance, $R_{\gamma\gamma}$, EWPT

$$\boxed{h \to SS/AA/H^+H^-}$$

CMS collaboration

$\boxed{\mathrm{BR}(h \to \texttt{inv.}) < 0.19}$ at 95% confidence level

In this work, we only use the latest ATLAS result $\boxed{R_{\gamma\gamma} = 1.08^{+0.13}_{-0.12}}$ to constrain the i2HDM parameter space.

$$\boxed{R_{\gamma\gamma} \equiv \frac{\sigma_h^{\gamma\gamma}}{\sigma_{h_{\mathrm{SM}}}^{\gamma\gamma}} \simeq \frac{\mathrm{BR}(h \to \gamma\gamma)^{\mathrm{i2HDM}}}{\mathrm{BR}(h \to \gamma\gamma)^{\mathrm{SM}}}.}$$

$$\boxed{\lambda_3 \sim hH^+H^-}$$

Constraints on i2HDM

Likelihood type	Constraints
Step	perturbativity, stability, tree-level unitarity
	LEP-II, OPAL
Poisson	XENON1T (2018), Fermi dSphs γ data
Half-Gaussian	exotic Higgs decays
Gaussian	relic abundance, $R_{\gamma\gamma}$, EWPT

DDCalc

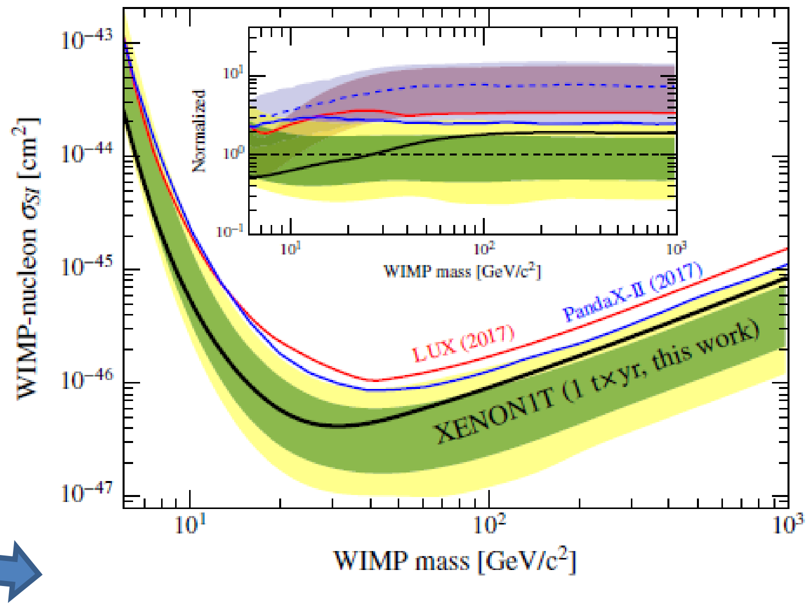


FIG. 5. 90% confidence level upper limit on σ_{SI} from this work (thick black line) with the 1σ (green) and 2σ (yellow) sensitivity bands. Previous results from LUX [6] and PandaX-II [7] are shown for comparison. The inset shows these limits and corresponding $\pm1\sigma$ bands normalized to the median of this work's sensitivity band. The normalized median of the PandaX-II sensitivity band is shown as a dotted line.

MicrOMEGAs

PLANCK
measurement

$$\boxed{\Omega_{\mathrm{CDM}}h^2 = 0.1199 \pm 0.0027.}$$

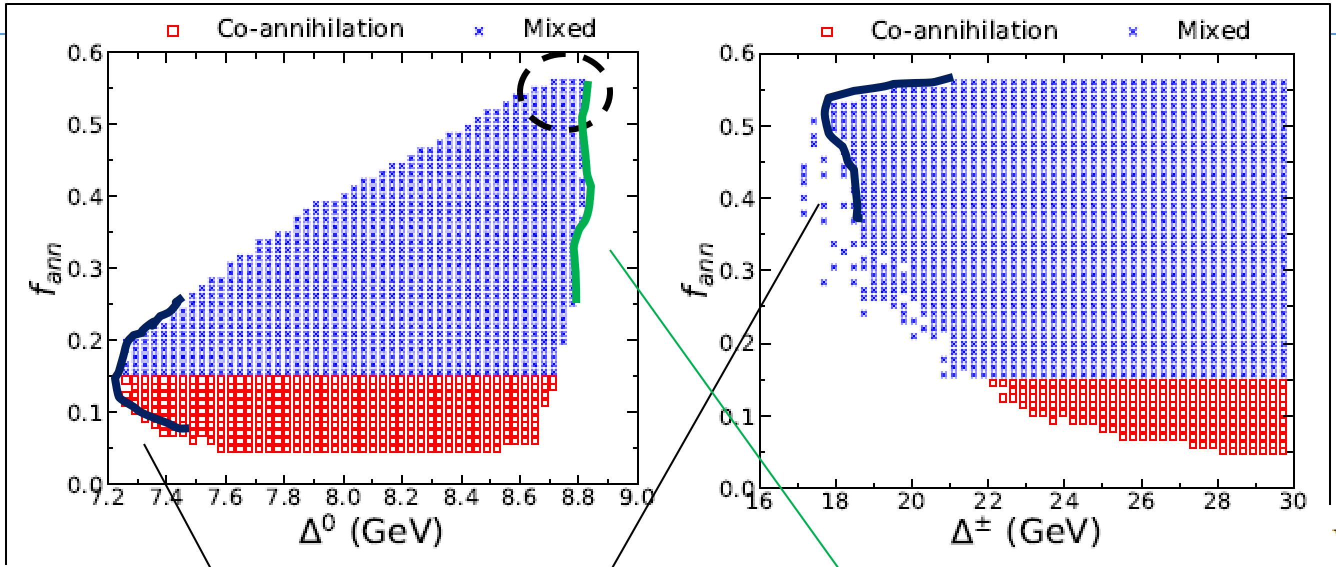
Contents

Results & Discussions

$$\begin{aligned} 5.0 &\leq m_S/\ \mathrm{GeV} \leq 100.0\,, \\ 10^{-3} &\leq \Delta^0/\ \mathrm{GeV} \leq 20\,, \\ 1.0 &\leq \Delta^\pm/\ \mathrm{GeV} \leq 30\,, \\ -2.0 &\leq \lambda_S \leq 2.0\,, \\ 0.0 &\leq \lambda_2 \leq 4.2\,. \end{aligned}$$

Likelihood type	Constraints
Step	perturbativity, stability, tree-level unitarity
	LEP-II, OPAL
Poisson	XENON1T (2018), Fermi dSphs γ data
Half-Gaussian	exotic Higgs decays
Gaussian	relic abundance, $R_{\gamma\gamma}$, EWPT

Co-annihilation and mixed scenarios



co-annihilation ($f_{ann} < 15\%$)

mixed regions ($f_{ann} > 15\%$)

$$f_{ann.} = \frac{\Gamma_{ann.}}{\Gamma_{tot.}},$$

where $\Gamma_{ann.}$ and $\Gamma_{tot.}$ are the annihilation and total interaction rate before freeze-out

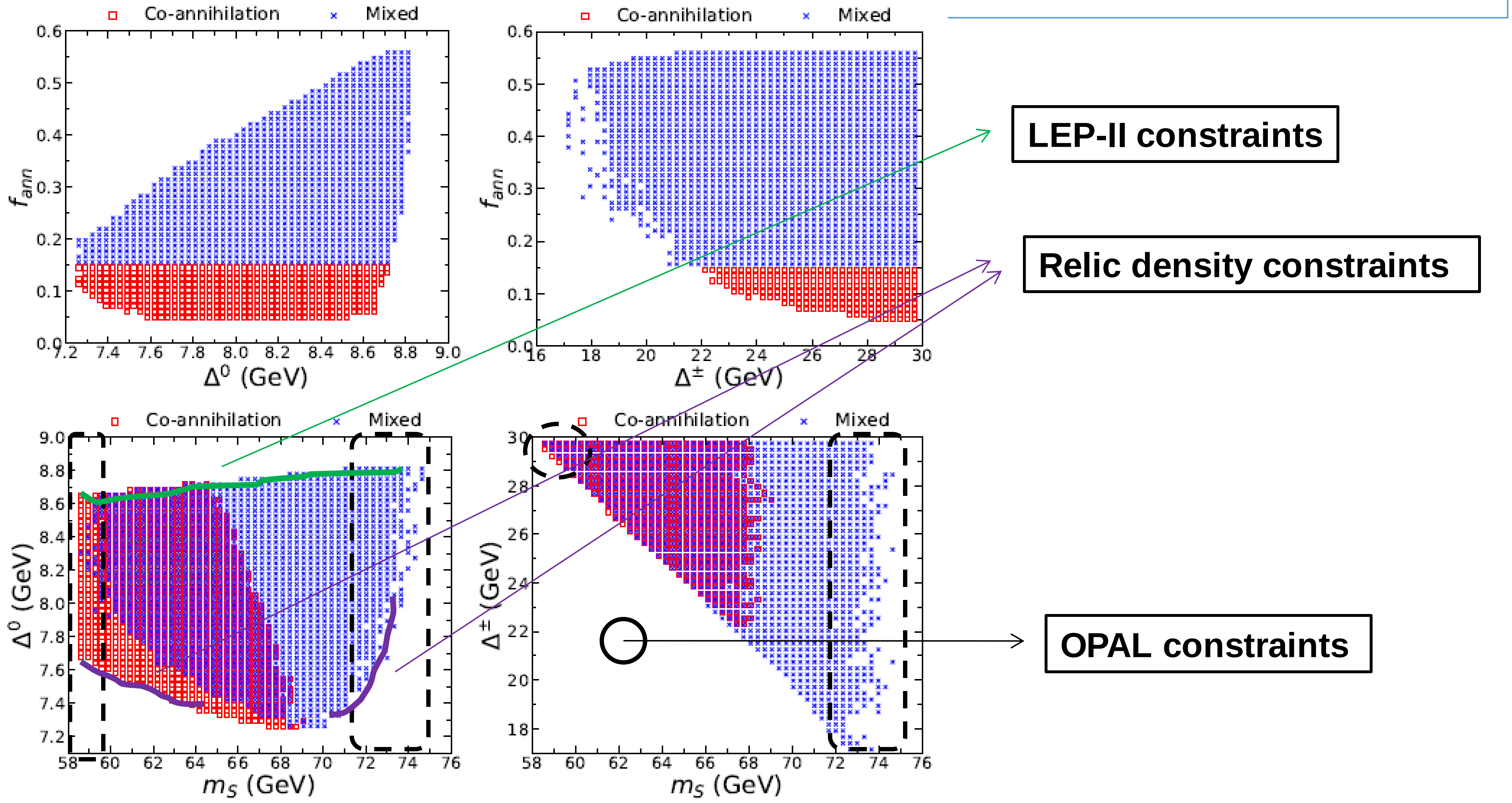
The allowed regions of theoretical conditions, LEP, and PLANCK 2σ projected on (Δ^0, $f_{ann.}$) and ($\Delta^{\pm}$, $f_{ann.}$) plane

Relic density constraints

LEP-II constraints

$$\Delta^0 < 8.7\,\mathrm{GeV}$$

Co-annihilation and mixed scenarios



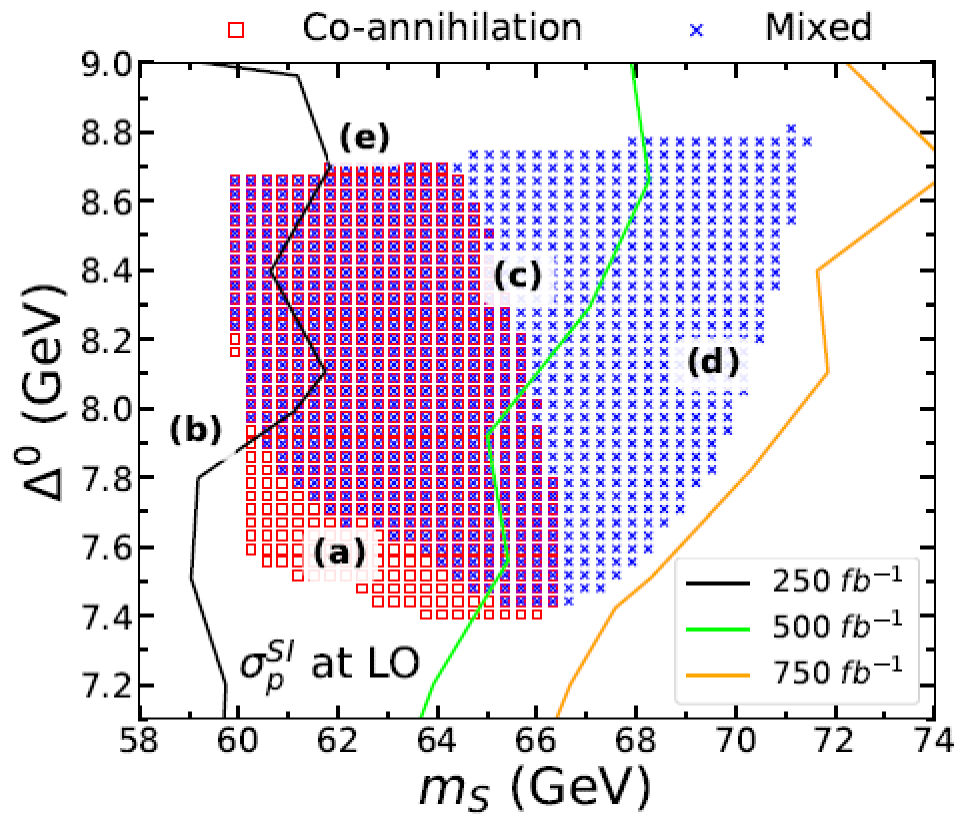
LEP-II constraints

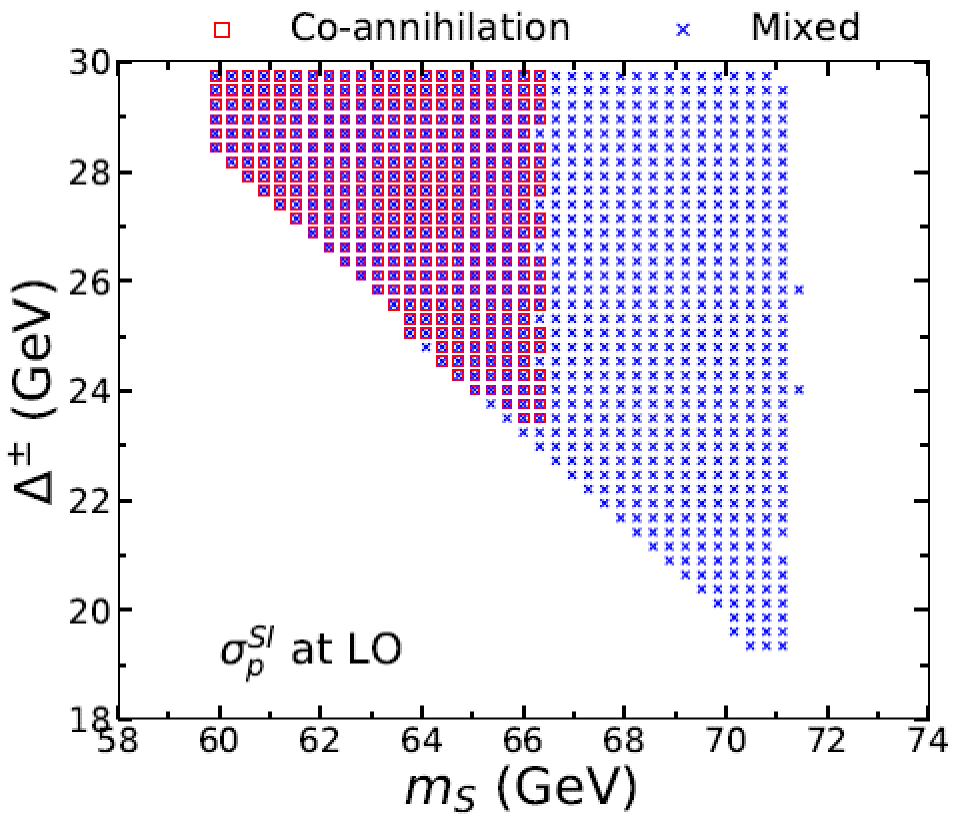
Relic density constraints

OPAL constraints

Results

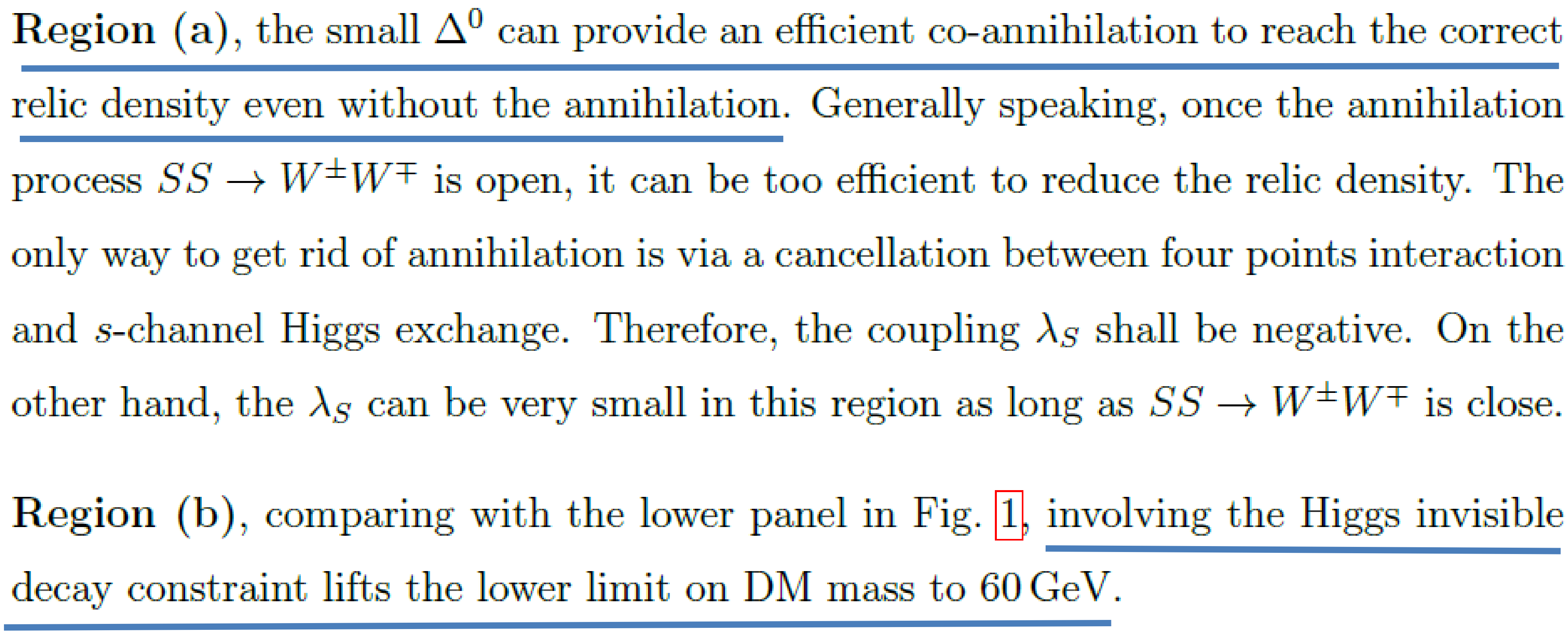
“all constraints”





$$60 < m_S / \text{GeV} < 72$$

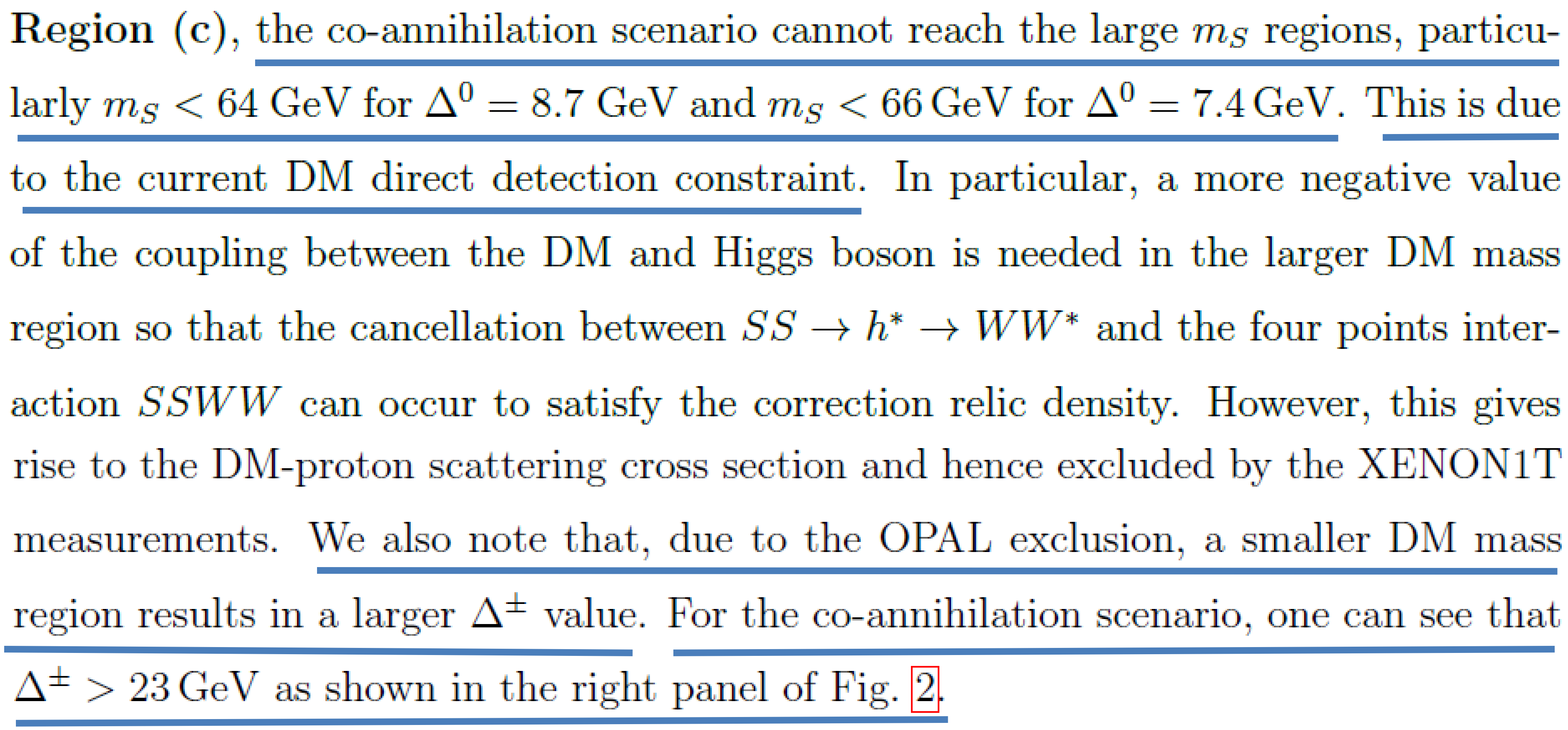
Results



Region (a), the small Δ^0 can provide an efficient co-annihilation to reach the correct relic density even without the annihilation. Generally speaking, once the annihilation process $SS \to W^\pm W^\mp$ is open, it can be too efficient to reduce the relic density. The only way to get rid of annihilation is via a cancellation between four points interaction and s-channel Higgs exchange. Therefore, the coupling λ_S shall be negative. On the other hand, the λ_S can be very small in this region as long as $SS \to W^\pm W^\mp$ is close.

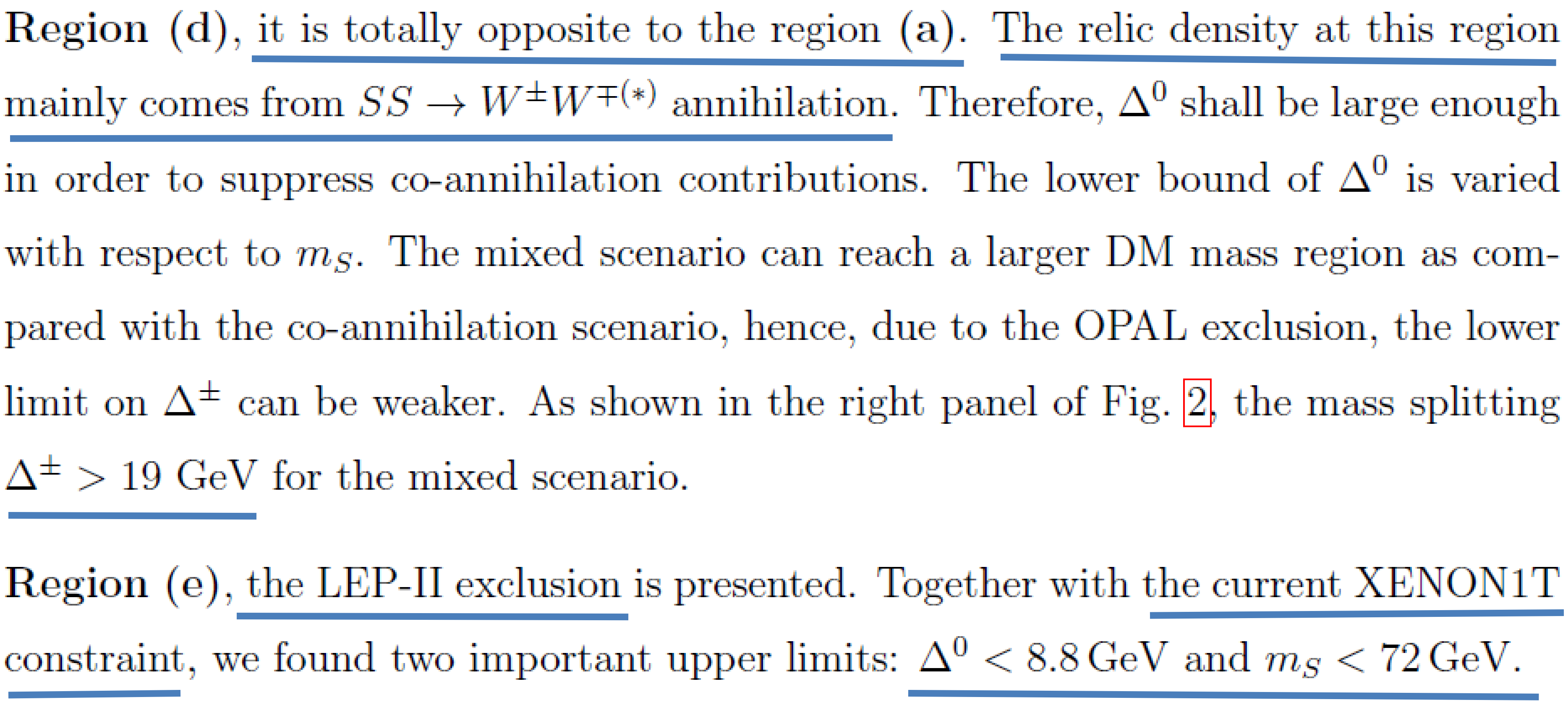
Region (b), comparing with the lower panel in Fig. 1, involving the Higgs invisible decay constraint lifts the lower limit on DM mass to 60 GeV.

Results



Region (c), the co-annihilation scenario cannot reach the large m_S regions, particularly $m_S < 64$ GeV for $\Delta^0 = 8.7$ GeV and $m_S < 66\,\text{GeV}$ for $\Delta^0 = 7.4\,\text{GeV}$. This is due to the current DM direct detection constraint. In particular, a more negative value of the coupling between the DM and Higgs boson is needed in the larger DM mass region so that the cancellation between $SS \to h^* \to WW^*$ and the four points interaction $SSWW$ can occur to satisfy the correction relic density. However, this gives rise to the DM-proton scattering cross section and hence excluded by the XENON1T measurements. We also note that, due to the OPAL exclusion, a smaller DM mass region results in a larger $\Delta^\pm$ value. For the co-annihilation scenario, one can see that $\Delta^\pm > 23\,\text{GeV}$ as shown in the right panel of Fig. 2.

Results

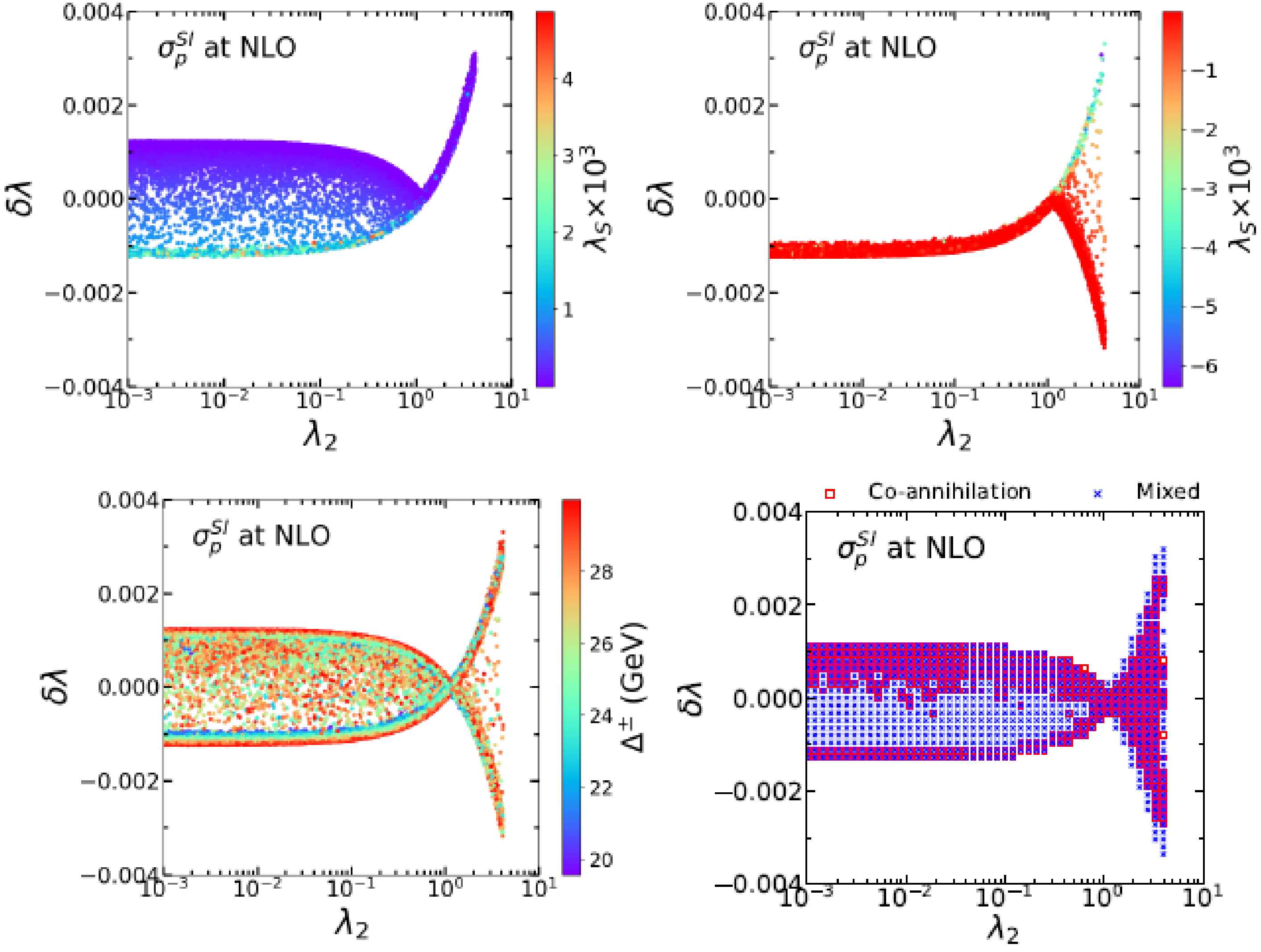


Region (d), it is totally opposite to the region (a). The relic density at this region mainly comes from $SS \to W^{\pm}W^{\mp(*)}$ annihilation. Therefore, Δ^0 shall be large enough in order to suppress co-annihilation contributions. The lower bound of Δ^0 is varied with respect to m_S. The mixed scenario can reach a larger DM mass region as compared with the co-annihilation scenario, hence, due to the OPAL exclusion, the lower limit on $\Delta^{\pm}$ can be weaker. As shown in the right panel of Fig. 2, the mass splitting $\Delta^{\pm} > 19$ GeV for the mixed scenario.

Region (e), the LEP-II exclusion is presented. Together with the current XENON1T constraint, we found two important upper limits: $\Delta^0 < 8.8\,\text{GeV}$ and $m_S < 72\,\text{GeV}$.

Results

$$R = \frac{\sigma_p^{\mathrm{SI}}(\texttt{tree+loop})}{\sigma_p^{\mathrm{SI}}(\texttt{tree})} = \left(\frac{\lambda_S + \delta\lambda}{\lambda_S}\right)^2 = \left(\frac{\lambda_S^{\mathrm{eff}}}{\lambda_S}\right)^2 .$$



JHEP 1503 (2015) 109

arXiv:1501.04161

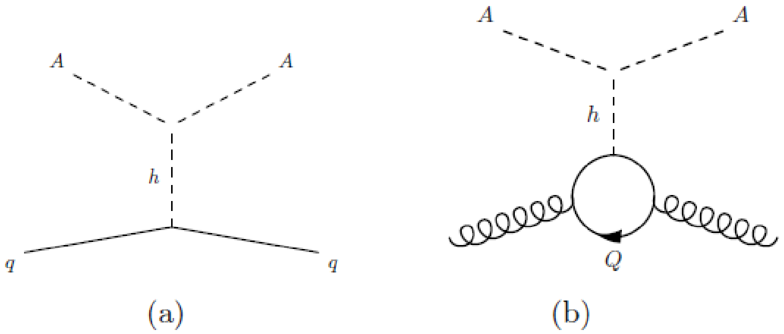


Figure 1. The diagrams which contribute to the spin-independent cross section at the leading order.

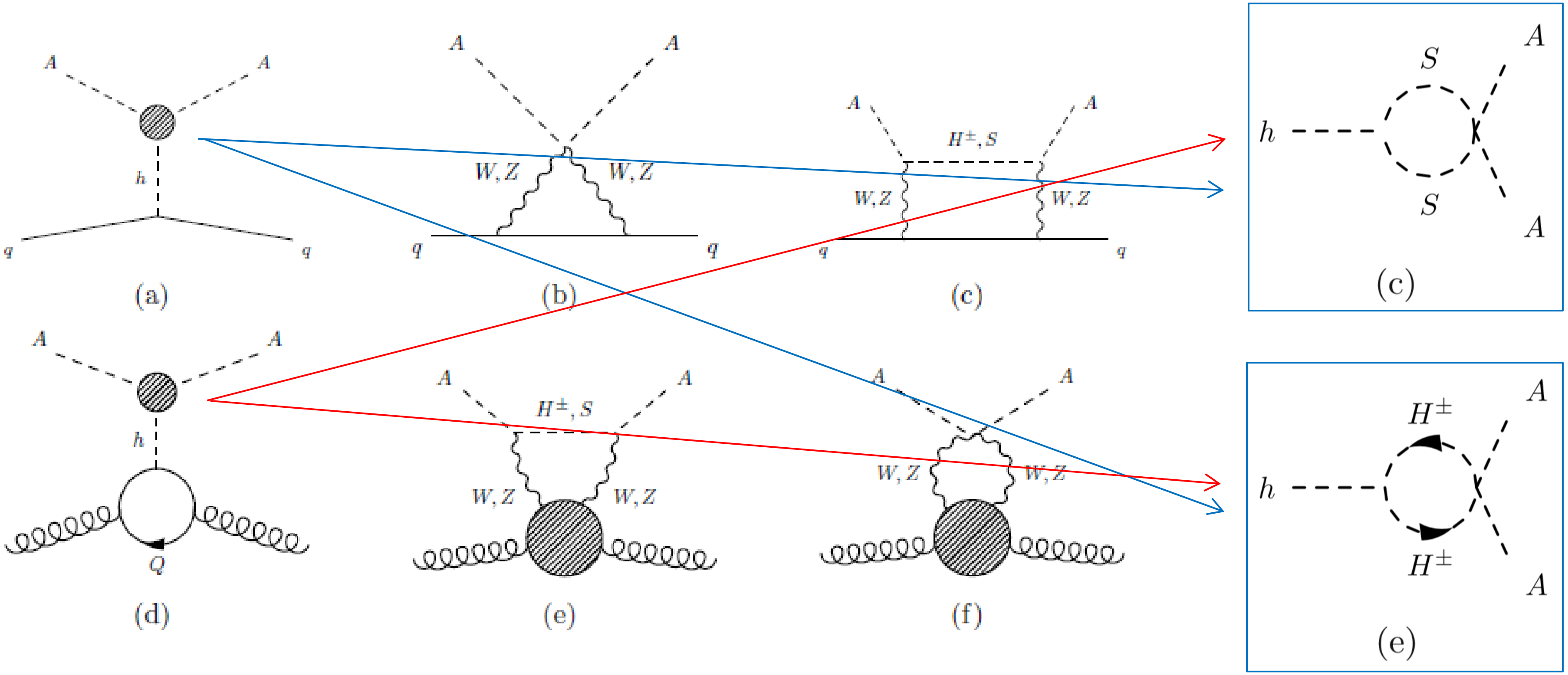
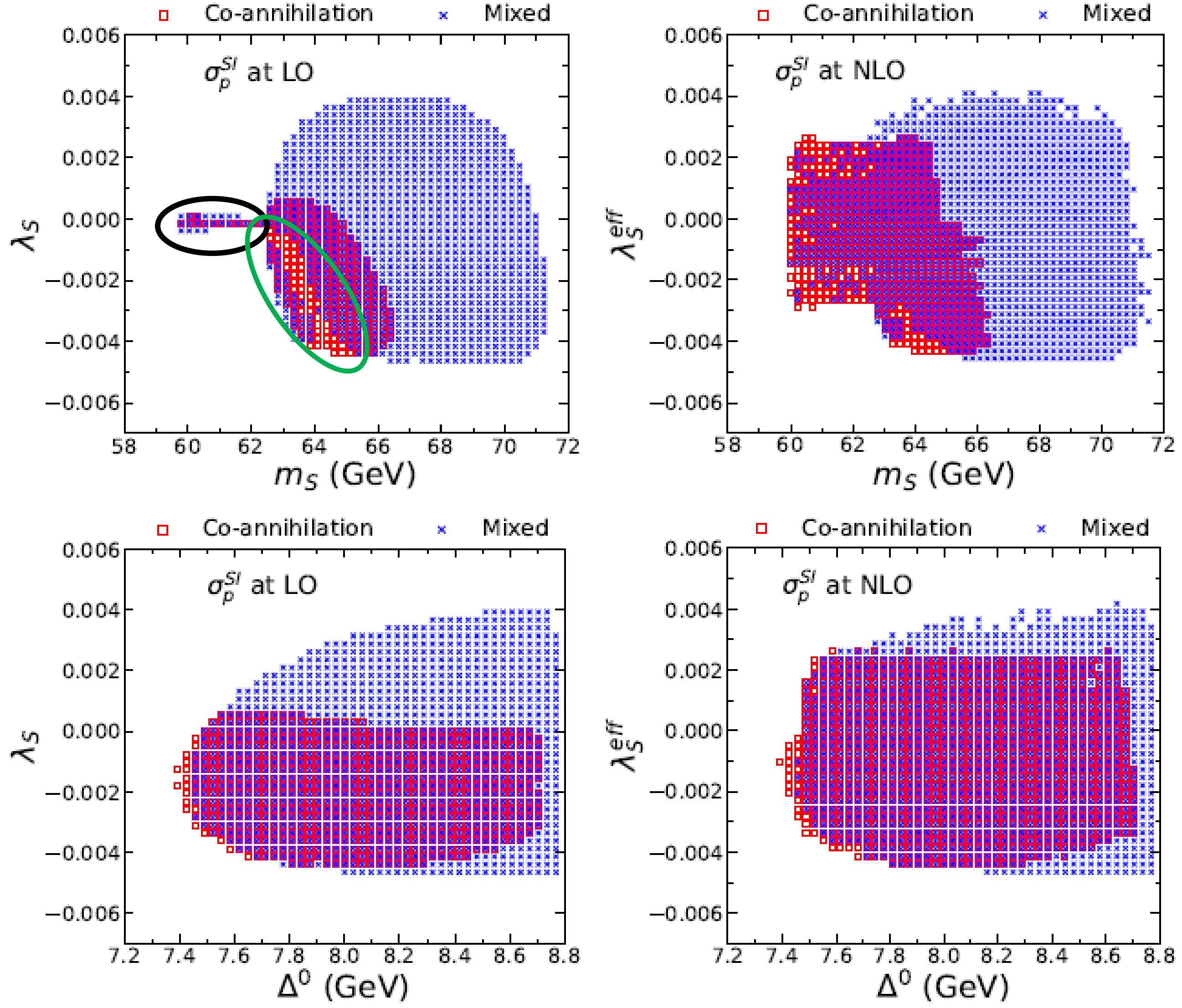


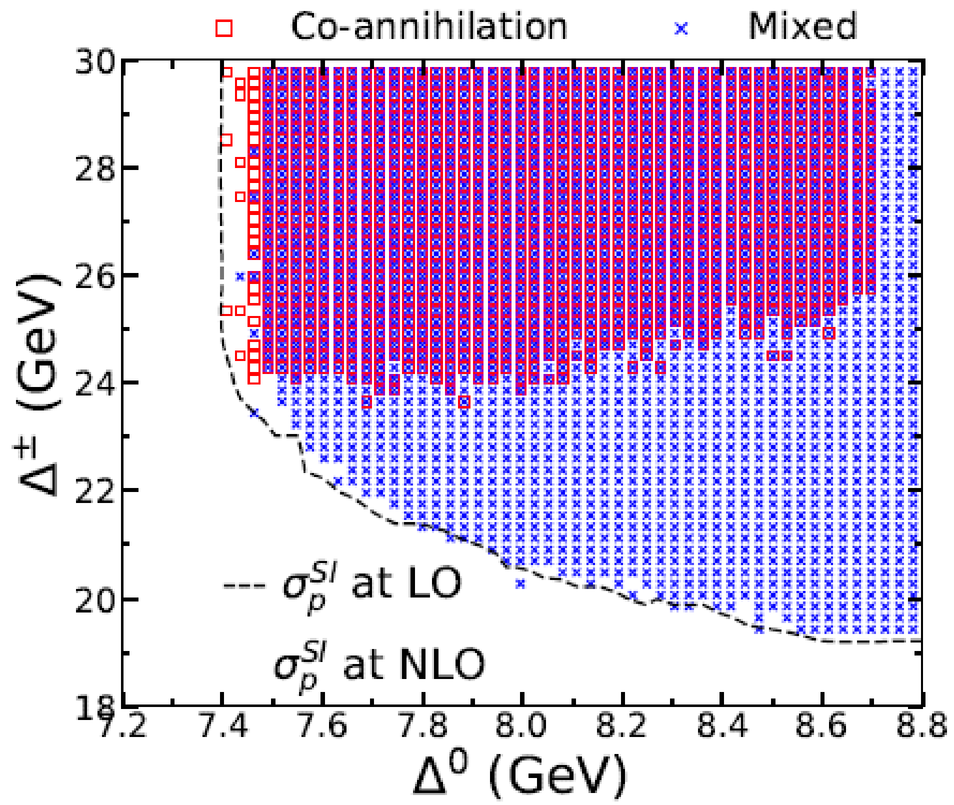
Figure 2. The diagrams we calculate. The shaded region is one-loop correction.

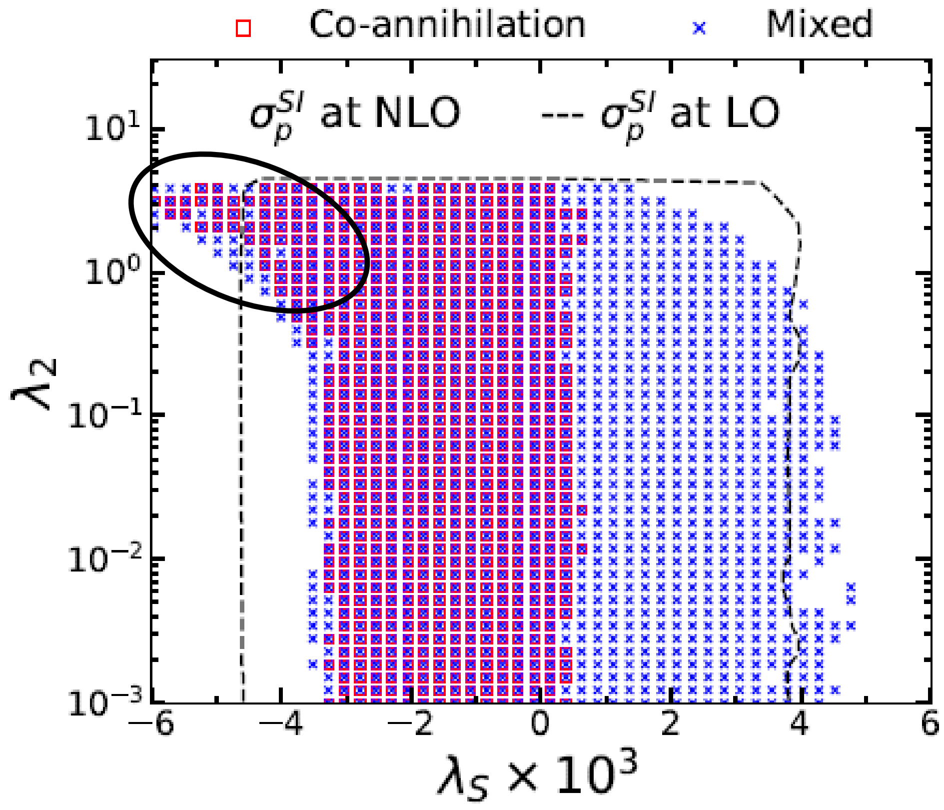
Results

$$R = \frac{\sigma_p^{\mathrm{SI}}(\texttt{tree+loop})}{\sigma_p^{\mathrm{SI}}(\texttt{tree})} = \left(\frac{\lambda_S + \delta\lambda}{\lambda_S}\right)^2 = \left(\frac{\lambda_S^{\mathrm{eff}}}{\lambda_S}\right)^2 .$$

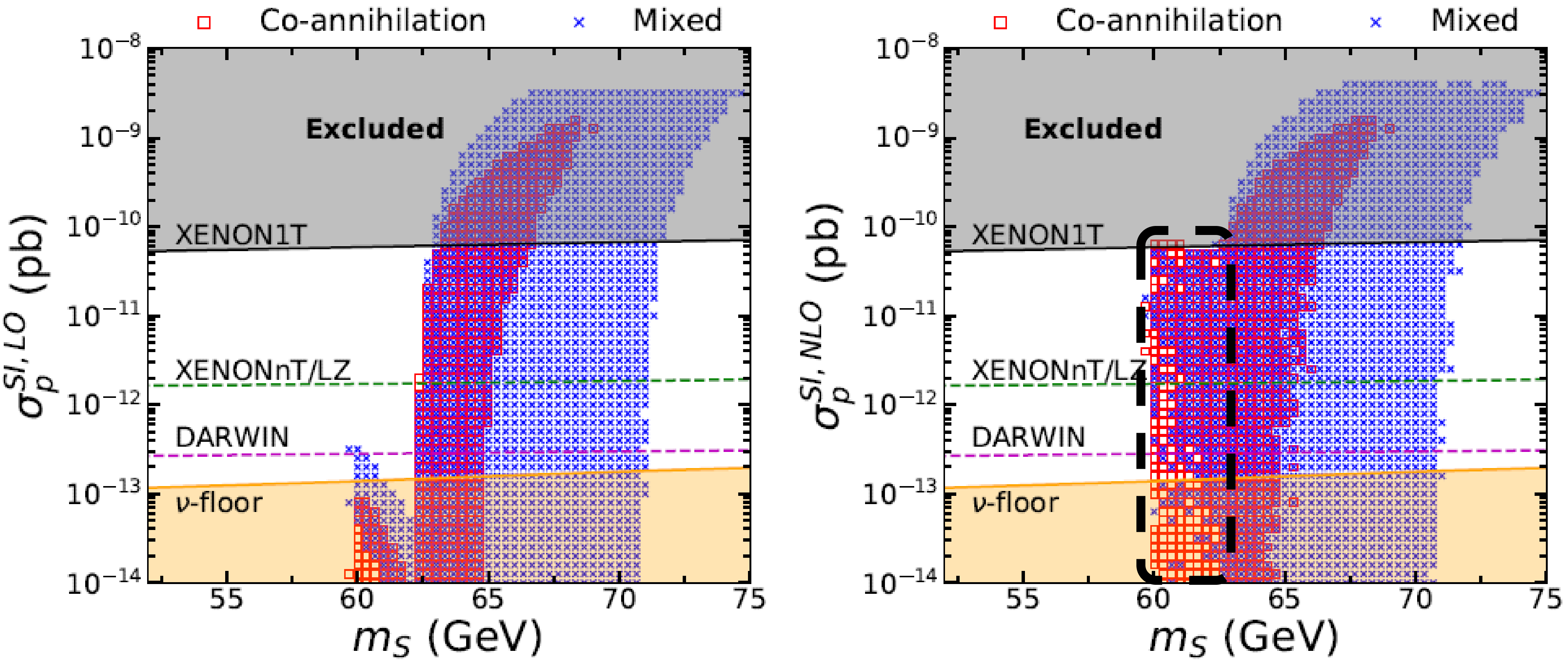


Results


□ Co-annihilation
× Mixed
--- σ_p^{SI} at LO
σ_p^{SI} at NLO
$\Delta^{\pm}$ (GeV)
Δ^0 (GeV)
18
20
22
24
26
28
30
7.2
7.4
7.6
7.8
8.0
8.2
8.4
8.6
8.8


□ Co-annihilation
× Mixed
σ_p^{SI} at NLO
--- σ_p^{SI} at LO
λ_2
$\lambda_S \times 10^3$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
−6
−4
−2
0
2
4
6

Results



□ Co-annihilation
× Mixed
Excluded
XENON1T
XENONnT/LZ
DARWIN
ν-floor
$\sigma_p^{SI,LO}$ (pb)
$\sigma_p^{SI,NLO}$ (pb)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
55
60
65
70
75
m_S (GeV)

Results

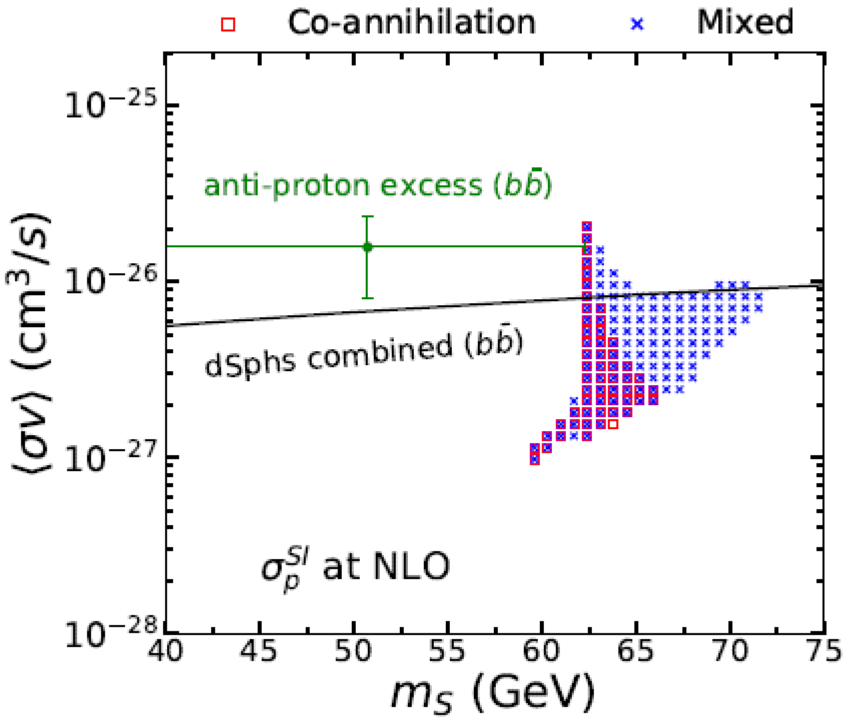


FIG. 7: The scatter plots in 2σ allowed region on the $(m_S, \langle\sigma v\rangle)$ plane. The color scheme for the co-annihilation (red square) and the mixed (blue cross) scenarios is the same as in Fig. 1. The solid black line represents the combined limit for DM annihilating into $b\bar{b}$ from observations of dSphs by Fermi-LAT, HAWC, HESS, MAGIC and VERITAS [79]. The green error bar is the 1σ signal region for anti-proton excess [80].

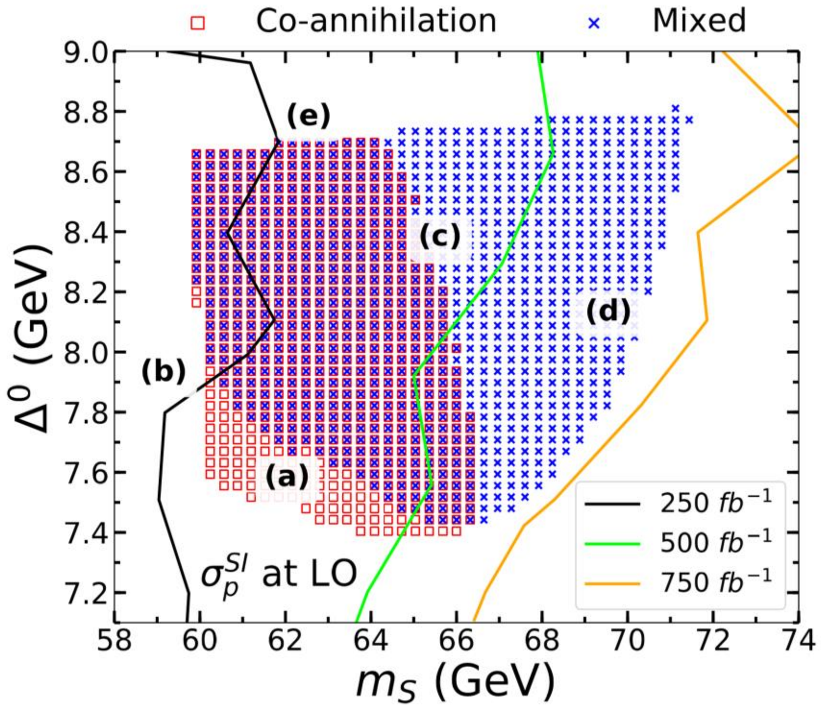
Contents

- 1. Introduction
- 2. Brief review of inert two higgs doublet model (i2HDM)
- 3. Constraints on i2HDM
- 4. Results & Discussions
- **5. Summary and Future Prospect**

Conclusions

- In this work, we have performed a global statistical analysis of the i2HDM with five parameters $(m_S, \Delta^0, \Delta^\pm, \lambda_2, \lambda_S)$ at the EW scale for compressed mass spectrum.
- By using the profile likelihood method, the survived parameter space were subjected to constraints from the theoretical conditions (perturbativity, stability, and tree-level unitarity), the collider limits (electroweak precision tests, LEP, and LHC), the relic density as measured by PLANCK, the $\sigma_p^{\rm SI}$ limit from XENON1T, and the $\langle\sigma v\rangle$ limit from Fermi dSphs gamma ray data.

- We found that the viable parameter space of co-annihilation scenario is located at $60\,\mathrm{GeV} \lesssim m_S \lesssim 66\,\mathrm{GeV}$, the $7.4\,\mathrm{GeV} \lesssim \Delta^0 \lesssim 8.8\,\mathrm{GeV}$, and $\Delta^\pm \gtrsim 23.0\,\mathrm{GeV}$.
- The allowed parameter space can be tested by the compressed mass spectra searches at the LHC. It can be partially probed with future luminosity $250\ fb^{-1}$ and mostly probed with luminosity $750\ fb^{-1}$



$$\lambda_S = 0,\ \lambda_2 = 1 \text{ and } \Delta^\pm = 28\,\mathrm{GeV}$$

Thank you
for your attention

경청해 주셨어 감사합니다