Suppression of dark matter-nucleon scattering in singlet Higgs extension of the SM and its signature at collider experiments

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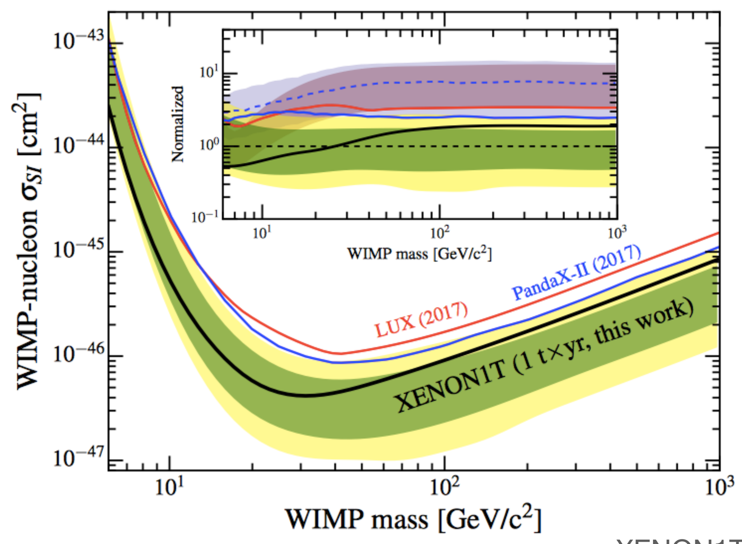
§0 Strong constraint on the DM models

Dark matter (DM) plays an important role in the galaxy formation and evolution / have not been found directly yet.
One of the most popular DM candidates is a Weakly Interacting Massive Particle (WIMP).
The DM direct-detection experiments give a severe upper bound on the DM-nucleon scattering cross section.



XENON1T (2018)

§1 Complex singlet extension of the SM (CxSM) w / softly broken global U(1)

$$V=\frac{m^2}{2}|H|^2+\frac{\lambda}{4}|H|^4+\frac{\delta_2}{2}|H|^2|S|^2+\frac{b_2}{2}|S|^2+\frac{d_2}{4}|S|^4+\left(a_1S+\frac{b_1}{4}S^2+\text{c.c.}\right)$$ V. Barger et al., PRD79, 015018 (2009)

$$H=\begin{pmatrix}0\\ \frac{v+h}{\sqrt{2}}\end{pmatrix}\qquad S=(v_S+s+i\chi)/\sqrt{2}$$

assumption : CP conservation

ATLAS, EPJC75 (2016) 476
CMS, PRD92, 012004 (2015)

CP-even scalars; $h, s \rightarrow h_1, h_2$ (mass eigenstates)

$$\begin{pmatrix}h_1\\ h_2\end{pmatrix}=\begin{pmatrix}\cos\alpha & \sin\alpha\\ -\sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}h\\ s\end{pmatrix}\qquad m^2_{h_1,h_2}=\frac{1}{2}\left(\frac{\lambda}{2}v^2+\Lambda^2\mp\sqrt{\left(\frac{\lambda}{2}v^2-\Lambda^2\right)^2+4\left(\frac{\delta_2}{2}vv_S\right)^2}\right)$$

$$M^2=\begin{pmatrix}\frac{\lambda}{2}v^2 & \frac{\delta_2}{2}vv_S\\ \frac{\delta_2}{2}vv_S & \Lambda^2\end{pmatrix}\qquad \tan 2\alpha=2\frac{\frac{\delta_2}{2}vv_S}{\frac{\lambda}{2}v^2-\Lambda^2}\qquad m_{h_1}=m_{h_{SM}}=125\,\text{GeV}\qquad \Lambda^2\equiv\frac{d_2}{2}v_S^2-\sqrt{2}\frac{a_1}{2v_S}$$

CP-odd scalar; χ (Goldstone boson) = DM

$$m_\chi^2=-b_1-\sqrt{2}\frac{a_1}{v_S}$$ (massive)

§2 Direct detection

scalar trilinear interactions

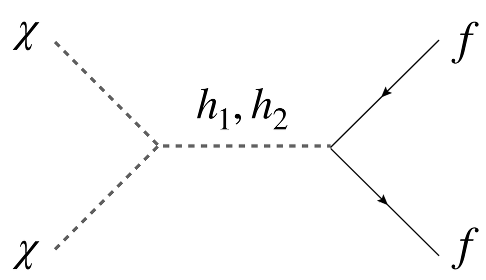
$$\mathcal{L}_S=g_{h_1\chi\chi}h_1\chi^2+g_{h_2\chi\chi}h_2\chi^2$$

$$g_{h_1\chi\chi}\equiv-\frac{m^2_{h_1}+\frac{\sqrt{2}a_1}{v_S}}{2v_S}\sin\alpha$$

$$g_{h_2\chi\chi}\equiv-\frac{m^2_{h_2}+\frac{\sqrt{2}a_1}{v_S}}{2v_S}\cos\alpha$$

yukawa interactions

$$\mathcal{L}_Y=\frac{m_f}{v}\bar{f}f\,(h_1\cos\alpha-h_2\sin\alpha)$$



$$i\mathcal{M}_{h_1}=-i\frac{m_f}{vv_S}\frac{m^2_{h_1}+\frac{\sqrt{2}a_1}{v_S}}{t-m^2_{h_1}}\sin\alpha\cos\alpha\;\bar{u}(p_3)\,u(p_1)$$

$$i\mathcal{M}_{h_2}=+i\frac{m_f}{vv_S}\frac{m^2_{h_2}+\frac{\sqrt{2}a_1}{v_S}}{t-m^2_{h_2}}\sin\alpha\cos\alpha\;\bar{u}(p_3)\,u(p_1)$$

$$i\left(\mathcal{M}_{h_1}+\mathcal{M}_{h_2}\right)\simeq i\frac{m_f}{vv_S}\sin\alpha\cos\alpha\;\bar{u}(p_3)\,u(p_1)\,\frac{\sqrt{2}a_1}{v_S}\left(\frac{1}{m^2_{h_1}}-\frac{1}{m^2_{h_2}}\right)$$

$$\frac{\sqrt{2}a_1}{v_S}\left(\frac{1}{m^2_{h_1}}-\frac{1}{m^2_{h_2}}\right)\simeq 0\iff a_1\to 0\ \text{ or }\ m_{h_1}\simeq m_{h_2}$$

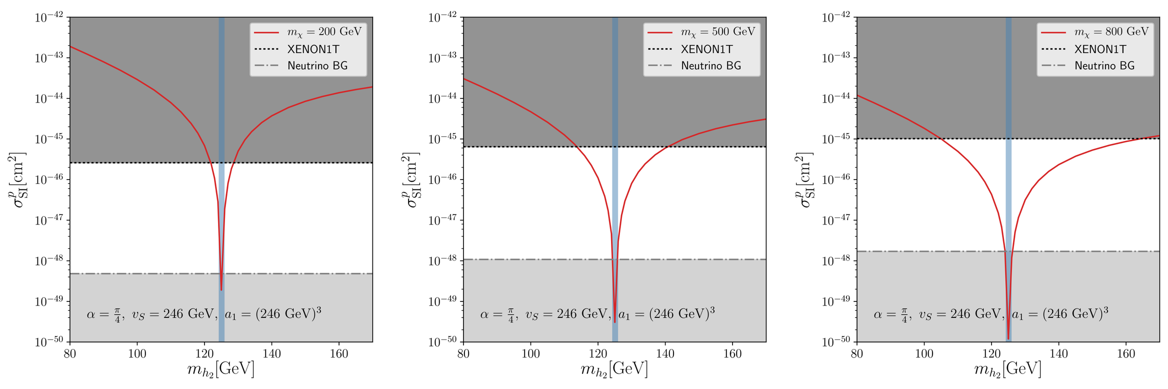
- $a_1\to 0$ Z2 symmetry : S → - S (domain wall problem) — Gross et al., PRL 119, 191801 (2017)
- $m_{h_1}\simeq m_{h_2}$ 2 degenerate 125 GeV Higgs bosons

assumption : degenerate within the uncertainty of the measurement

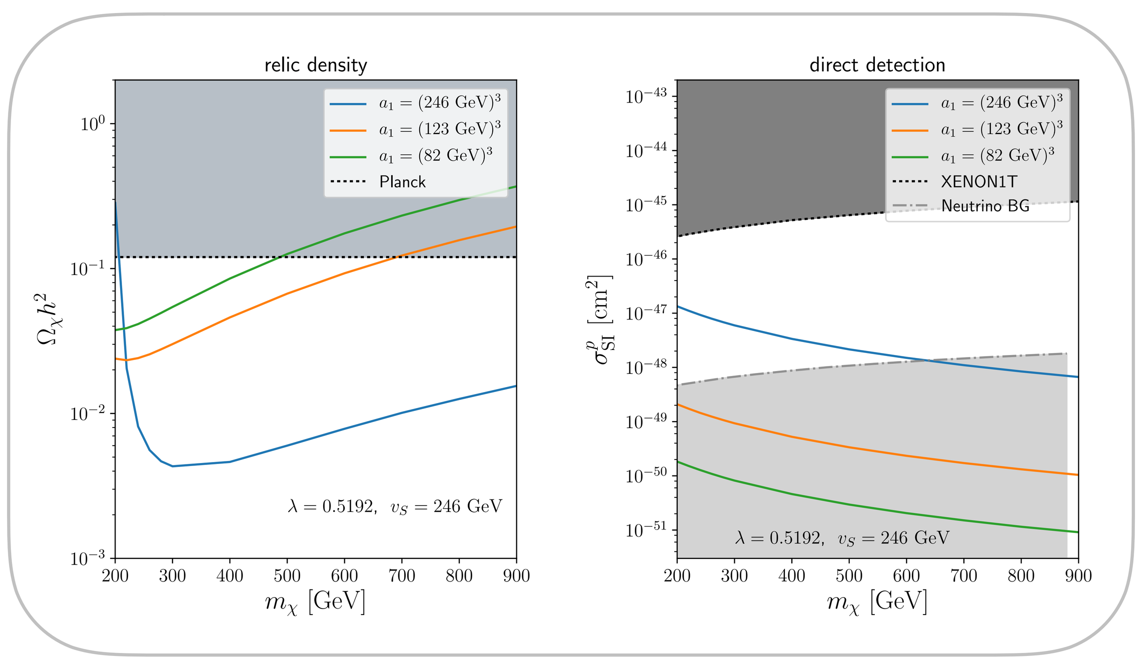
$m_H=125.09\pm0.24$ GeV ATLAS (Run1, 2) + CMS(Run1)

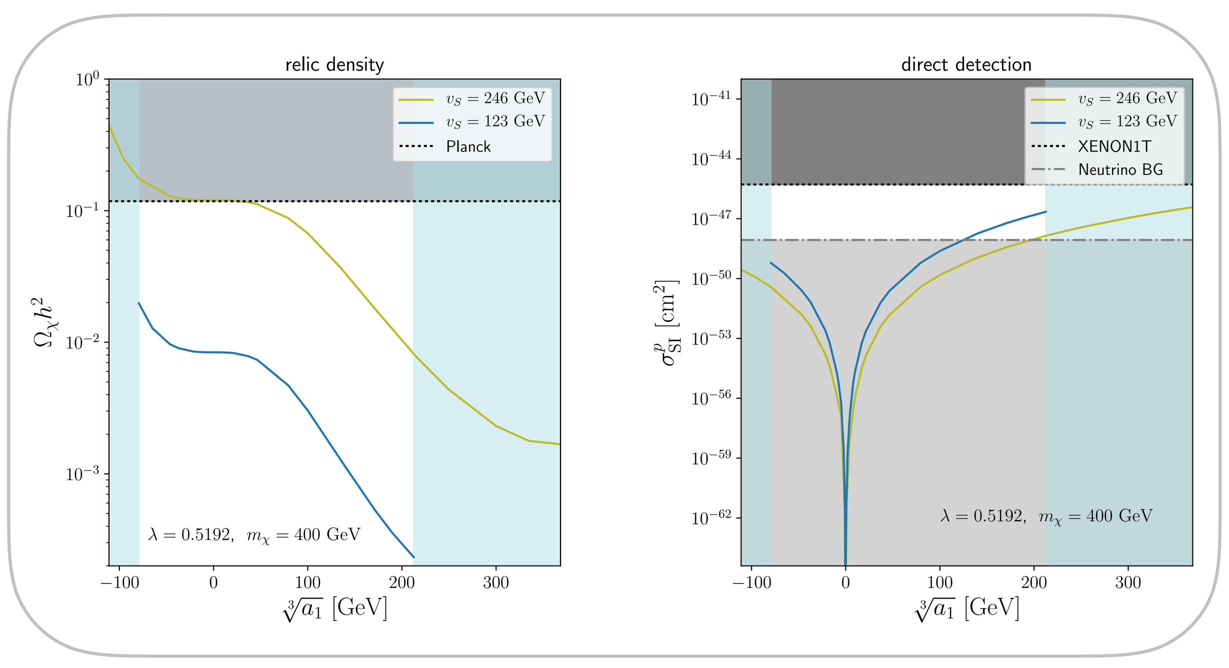
ATLAS Collaboration, PLD 784 (2018) 345

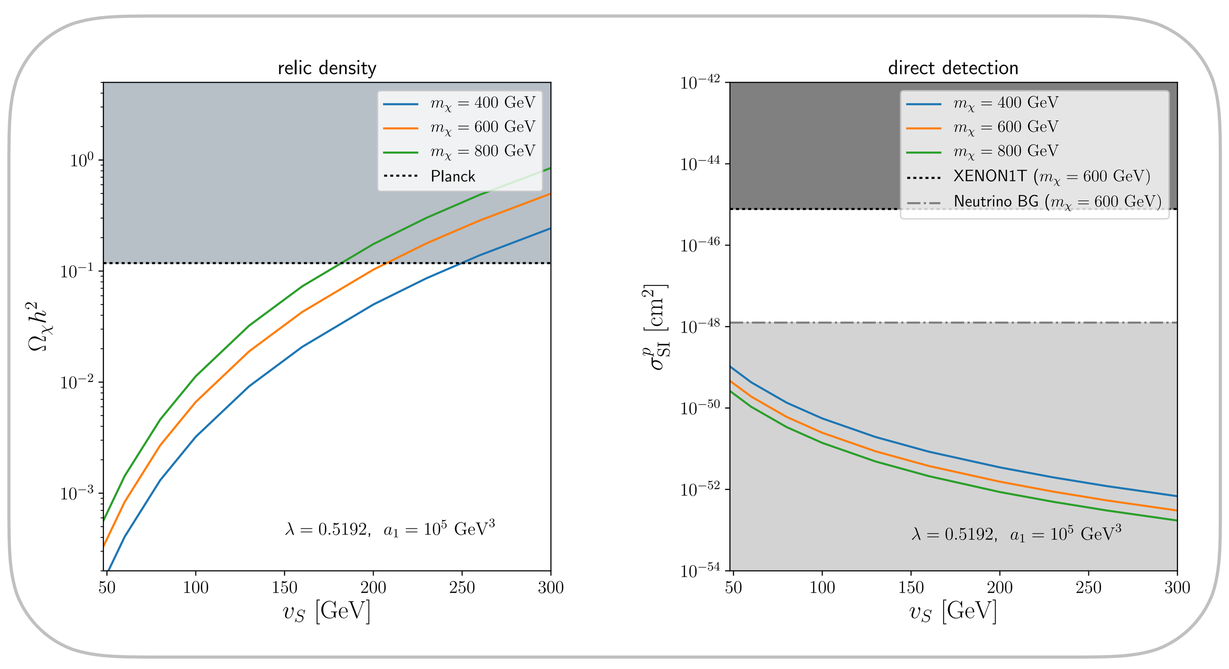
→ $\Delta m=|m_{h_1}-m_{h_2}|\leq 0.72$ GeV (blue bands in the graphs below)



§3 Parameter analysis





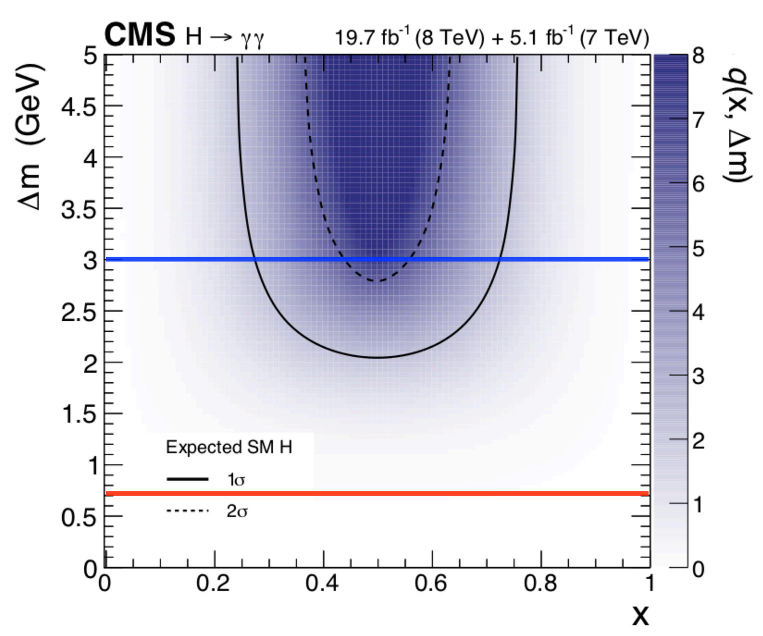


- : excluded by Planck observation — PLANCK 2018, arXiv 1807.06209
- : excluded by XENON1T experiment
- : Neutrino BG — J. Billard et al., PRD 89, 023524 (2014)

Other constraints : perturbativity / stability of the scalar potential

$$\lambda<\frac{16\pi}{3},\quad d_2<\frac{16\pi}{3},\quad \lambda\left(d_2+\frac{2\sqrt{2}a_1}{v_S^3}\right)>\delta_2^2$$

§4 Collider search for degenerate Higgs bosons

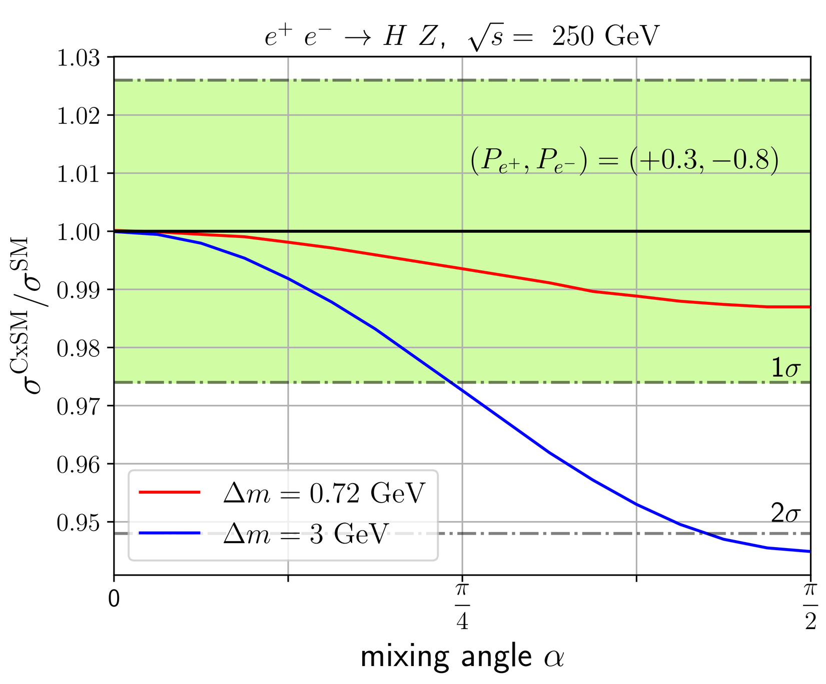


CMS Collaboration, EPJC 74 (2014) 3076

It is difficult to distinguish two degenerate ($\Delta m\lesssim 3$ GeV) Higgs produced at the Large Hadron Collider **(LHC)**.

→ How about at the **International Linear Collider (ILC)**?

compare cross sections of $e^+e^-\to H\ Z(\sqrt{s}=250\ \text{GeV})$ in the SM / CxSM



($h_1\to h_{SM}$ @α → 0)

precision of cross section : $\frac{\Delta\sigma}{\sigma}=2.6\%$

D.M. Asner et al., arXiv1310.0763

→ It is hard to distinguish two models at the ILC.