Scalar dark matter from a double-Higgs portal and the role of isospin-violating/dependent effect

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HAP Dark Matter workshop 2015
Karlsruhe, Germany

09/22/2015

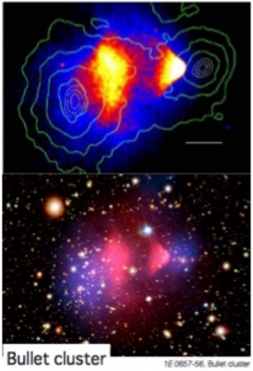
- A. Drozd, B. Grzadkowski, J. F. Gunion and Y.J., JHEP **1411** (2014) 105; 1510.XXXXX (appear soon).

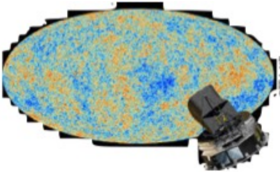
Outline

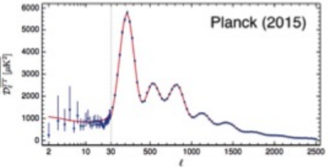
1. Preliminary Background
   - Dark matter direct detection
   - Isospin-violating mechanism
2. Model building

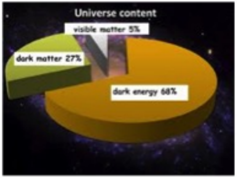
   (The discussion in this talk is mainly limited in the Higgs-portal models)
   - minimal singlet extension
   - go beyond the minimal (e.g., 2HDM plus a real scalar singlet)
3. DM phenomenology
4. Collider search signature
5. Conclusion

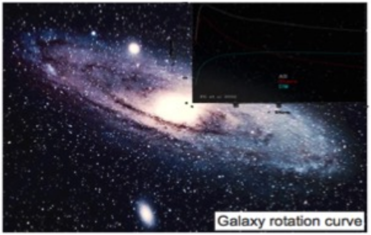
Existence of dark matter?



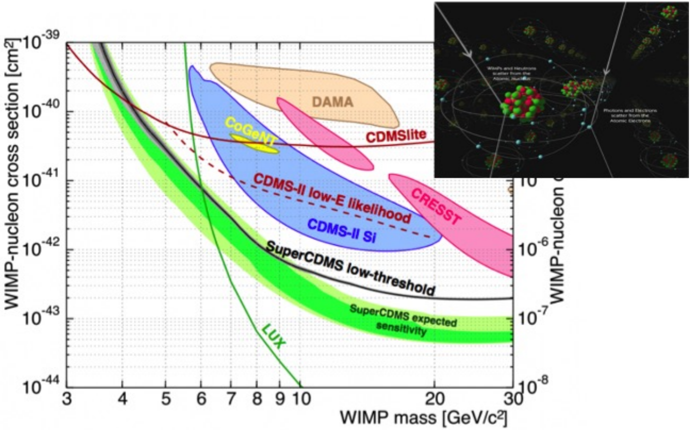






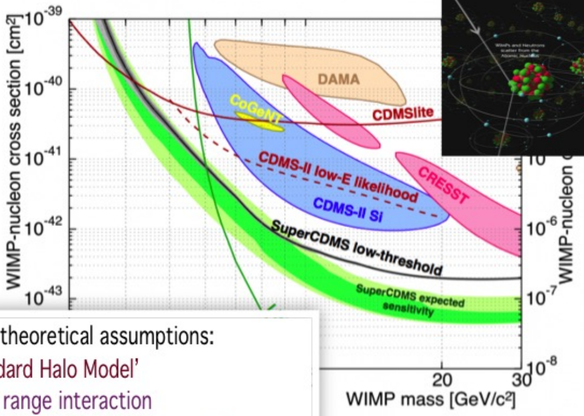


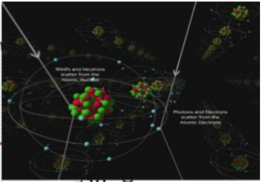
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010



- The strongest of those limits is currently a result of the LUX and the superCDMS in the very-low mass regime.
- In particular, the lower energy threshold of LUX allows a significant improvement in constraints at small WIMP mass where positive signals are reported by other collaborations (CDMS II, CoGeNT and etc.).

Messages from DM direct detection





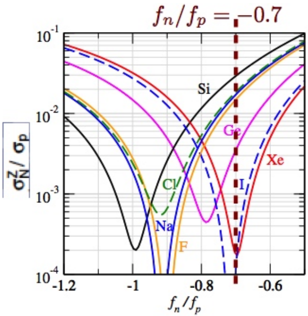
Standard theoretical assumptions:

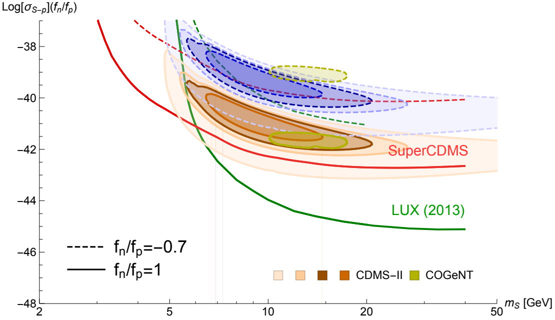
1. 'Standard Halo Model'
2. Short range interaction
3. Equal couplings to protons and neutrons
4. Elastic scattering

Are they all true?

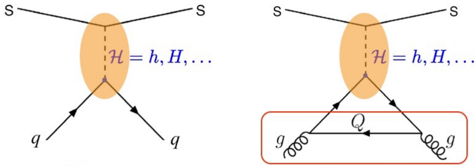
$$\sigma_N^Z = \sigma_p \frac{\sum_i \eta_i \mu_{A_i}^2 [Z - (A_i - Z) f_n/f_p]^2}{\sum_i \eta_i \mu_{A_i}^2 A_i^2}$$

where σ_p: DM-proton cross section (as a function of f_n/f_p)
σ_N^Z: DM-nucleon cross section assuming $f_n/f_p = 1$
η: relative abundance of an isotope
μ_A: reduced nucleon-DM mass

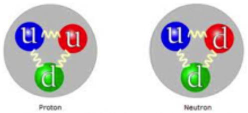


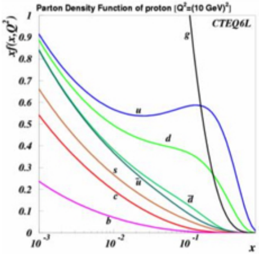


Isospin-violating mechanism



light quarks heavy quarks





The ratio of DM-nucleon (N) (proton (p), neutron (n)) couplings:

$$\boxed{\frac{f_n}{f_p} = \frac{F_u^n \tilde{\lambda}_U + F_d^n \tilde{\lambda}_D}{F_u^p \tilde{\lambda}_U + F_d^p \tilde{\lambda}_D}}$$

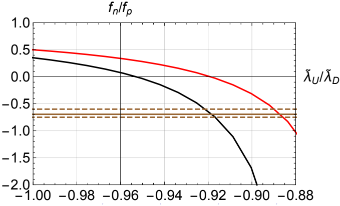
where the combined form factors (including the QCD NLO) are

$$F_u^N = f_{Tu}^N + \frac{2}{27} f_{TG}^N \left(1 + \frac{35}{36\pi}\alpha_S(m_c)\right) + \frac{2}{27} f_{TG}^N \left(1 + \frac{35}{36\pi}\alpha_S(m_t)\right)$$

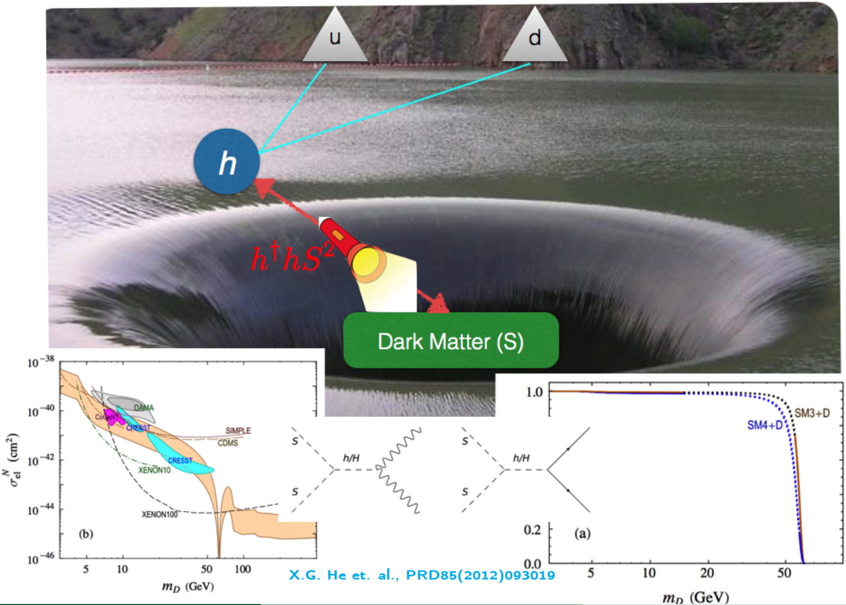
$$F_d^N = f_{Td}^N + f_{Ts}^N + \frac{2}{27} f_{TG}^N \left(1 + \frac{35}{36\pi}\alpha_S(m_b)\right)$$

for which the nucleon form factor has the relation defined as $f_{TG}^N = 1 - \sum_{q=u,d,s} f_{Tq}^N$ and the DM-quark effective couplings

$$\tilde{\lambda}_U = \sum_{\mathcal{H}} \frac{\lambda_{\mathcal{H}}}{m_{\mathcal{H}}^2} C_U^{\mathcal{H}}, \qquad \tilde{\lambda}_D = \sum_{\mathcal{H}} \frac{\lambda_{\mathcal{H}}}{m_{\mathcal{H}}^2} C_D^{\mathcal{H}}$$

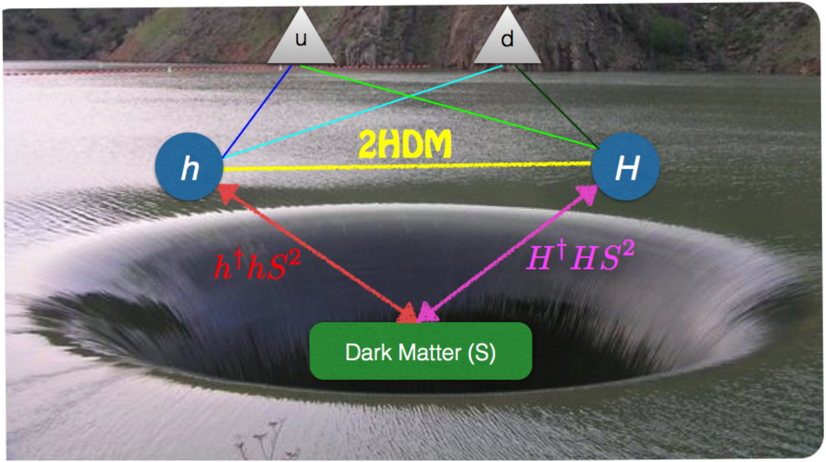


Model building: SM+Singlet (FAILED)



X.G. He et. al., PRD85(2012)093019

Model building: go beyond the minimal



1. one Higgs → 125 GeV, small invisible decay
2. the other Higgs → responsible for dark matter physics
3. Type II: generate the isospin violation

2HDM+Singlet model (2HDMS)

Adding a **real** gauge singlet scalar S to the two-Higgs-double model (2HDM)

$$
\begin{aligned}
V(H_1, H_2, S) = {} & m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - \left[m_{12}^2 H_1^\dagger H_2 + h.c. \right] \\
& + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2 \\
& + \left[\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \lambda_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \lambda_7 (H_2^\dagger H_2)(H_1^\dagger H_2) + h.c. \right] \\
& + \frac{1}{2} m_0^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \kappa_1 S^2 (H_1^\dagger H_1) + \kappa_2 S^2 (H_2^\dagger H_2) + S^2 (\kappa_3 H_1^\dagger H_2 + h.c.)
\end{aligned}
\tag{1}
$$

Symmetry: $\mathbb{Z}_2 \times \mathbb{Z}_2'$

- $\mathbb{Z}_2 : H_1 \to H_1, H_2 \to -H_2$
- $\mathbb{Z}_2' : H_1 \to H_1, H_2 \to H_2, S \to -S$

S is stable and thus could be a dark matter candidate.

2HDM+Singlet model (2HDMS)

the S-dependent part (after the EWSB)

$$\begin{aligned} V_S = & \frac{1}{2} m_S^2 S^2 + \frac{1}{4!} \lambda_S S^4 + \lambda_h v h S^2 + \lambda_H v H S^2 \\ & + S^2 (\lambda_{HH} HH + \lambda_{hH} hH + \lambda_{hh} hh + \lambda_{AA} AA + \lambda_{H^+H^-} H^+ H^-) \end{aligned} \tag{2}$$

where

$$m_S^2 = m_0^2 + (\kappa_1 \cos^2\beta + \kappa_2 \sin^2\beta) v^2 \tag{3}$$

$$\lambda_h = -\kappa_1 \sin\alpha \cos\beta + \kappa_2 \cos\alpha \sin\beta \tag{4}$$

$$\lambda_H = \kappa_1 \cos\alpha \cos\beta + \kappa_2 \sin\alpha \sin\beta \tag{5}$$

$$\lambda_{AA} = \tfrac{1}{2} \lambda_{H^+H^-} = \tfrac{1}{2} (\kappa_1 \sin^2\beta + \kappa_2 \cos^2\beta) \tag{6}$$

$$\lambda_{hh} = \tfrac{1}{2} (\kappa_2 \cos^2\alpha + \kappa_1 \sin^2\alpha) \tag{7}$$

$$\lambda_{HH} = \tfrac{1}{2} (\kappa_1 \cos^2\alpha + \kappa_2 \sin^2\alpha) \tag{8}$$

$$\lambda_{hH} = \tfrac{1}{2} (\kappa_2 - \kappa_1) \sin 2\alpha \,. \tag{9}$$

Remarks

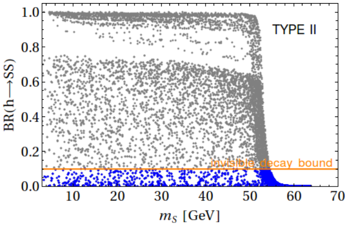
- NO AS^2 term!
- The set of independent inputs: $m_S, \lambda_h, \lambda_H, \lambda_S$ (only 4 !!!)

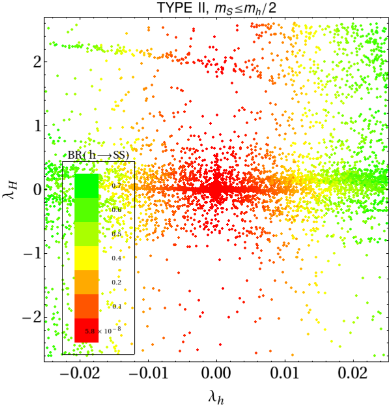
Our focus: light dark matter

$$m_S < 50\ \text{GeV}$$

The invisible decay width for the SM-like Higgs $\mathcal{H}$ is

$$\Gamma(\mathcal{H} \to SS) = \frac{1}{2\pi} \frac{4\lambda_{\mathcal{H}}^2 v^2}{m_{\mathcal{H}}} \sqrt{1 - \frac{4m_S^2}{m_{\mathcal{H}}^2}}$$





Portal coupling $\lambda_{\mathcal{H}}$ for the SM-like Higgs being constrained very small.

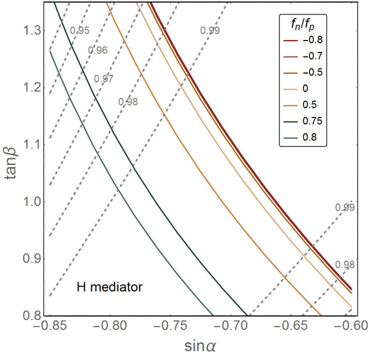
Finding a IVDM, a really challengeable job

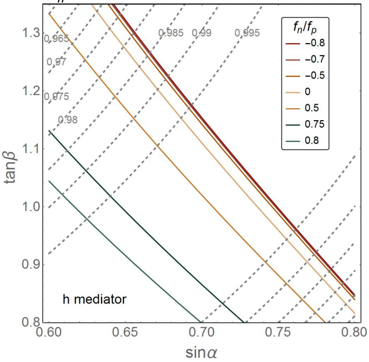
Applying the Higgs-quark coupling pattern into the generic f_n/f_p already derived yields

Higgs	C_V	C_U	C_D
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

$$\tan\beta = -\frac{\frac{f_n}{f_p}F_u^p - \frac{m_n}{m_p}F_u^n}{\frac{f_n}{f_p}F_d^p - \frac{m_n}{m_p}F_d^n}\,\frac{w+\tan\alpha}{1-w\tan\alpha}$$

where the weight parameter is defined by $w = \frac{\lambda_h}{\lambda_H}\frac{m_H^2}{m_h^2}$

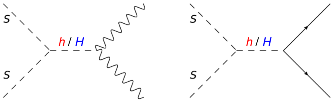




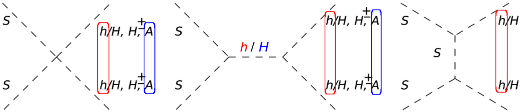
The solution is very tuned and occurs in the vicinity of $\tan\beta \simeq 1$!

Dark matter physics

$$\boxed{\Omega_S \simeq 1.07 \times 10^9 \frac{m_S/T_f}{\sqrt{g_*}\, M_{\rm Pl} \langle \sigma_{\rm ann} v_{\rm rel} \rangle} \ \mathrm{GeV}^{-1}}$$



$$\langle \sigma_{SS\to X\bar{X}} v_{\rm rel} \rangle = \sum_{\mathcal{H}=h,H} \left| \frac{g_{\mathcal{H}SS}\, C_X^{\mathcal{H}}}{4m_S^2 - m_{\mathcal{H}}^2 + i\Gamma_{\mathcal{H}} m_{\mathcal{H}}} \right|^2 \frac{\Gamma_{\rm SM}(\mathcal{H}^* \to X\bar{X})}{2m_S}$$



$$\langle \sigma_{SS\to H_iH_j} v_{\rm rel} \rangle = \frac{1}{32(1+\delta_{ij})\pi m_S^2} \left(1 - \frac{m_{H_i}^2 + m_{H_j}^2}{2m_S^2} + \frac{(m_{H_i}^2 - m_{H_j}^2)^2}{16 m_S^4} \right)^{1/2}$$

$$\times \left| g_{H_iH_jSS} + \sum_{\mathcal{H}=h,H} \frac{g_{\mathcal{H}SS}\, g_{\mathcal{H}H_iH_j}}{4m_S^2 - m_{\mathcal{H}}^2 + i\Gamma_{\mathcal{H}} m_{\mathcal{H}}} + 2\delta_{CP} \frac{g_{H_iSS}\, g_{H_jSS}}{\frac{1}{2}(m_{H_i}^2 + m_{H_j}^2) - 2m_S^2} \right|^2$$

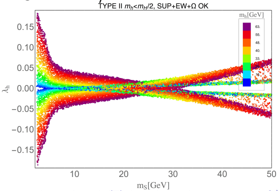
Light DM ($m_S \leq 50$ GeV)

$m_h \sim 125$ GeV

1. the ratio $\frac{\lambda_H}{m_H^2}$ is crucial.
2. A could be light, so $SS \to AA$ opens.

$m_H \sim 125$ GeV

1. the ratio $\frac{\lambda_h}{m_h^2}$ is crucial.
2. h could be light, so $SS \to hh$ opens.
3. Additionally, the pole resonance structure is hit when $m_S \simeq m_h/2$.

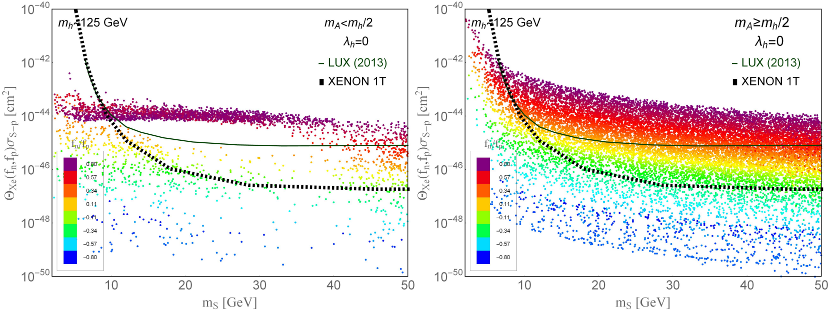


Numerical analysis (h-125 scenario as an example for illustration)

In fact both h-125 and H-125 scenarios could fit very well with cosmological observation.

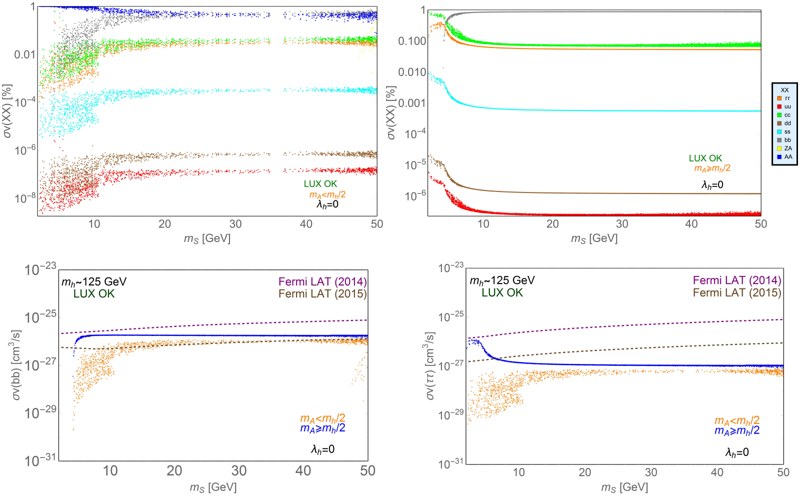
- Fully suppressed the invisible decay for the SM-like Higgs.
- Produce proper relic abundance
- direct detection
- indirection detection

Direct detection (h-125 case for example)



- Due to an isospin-violating cancellation between up-type and down-type quark interactions with the DM, one can achieve a DM-nucleon cross section as low as possible so that typical WIMP models will be ruled out by the projected exclusion limits at the future experiments.
- In reserve, the exclusion limits of dark matter direct detection will place a limit on the value of f_n/f_p.

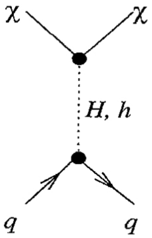
Indirect detection (h-125 case for example)

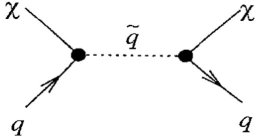


- Fermi-LAT (2015) data (arXiv: 1503.02641, see Anderson's talk) did exclude the $m_A \geq m_h/2$ solution (bb and $\tau\tau$ modes in combination).
- Due to the presence of the DM annihilation into the BSM mode $SS \to AA$, the $m_A < m_h/2$ solution is allowed. (To produce a proper relic density, $m_A > m_S$ for all the points in our analysis.)

What about the possibility for the supersymmetric dark matter?

Consider the SI $\tilde{\chi}_0^1$-nucleon scattering in the MSSM (the minimal SUSY model)



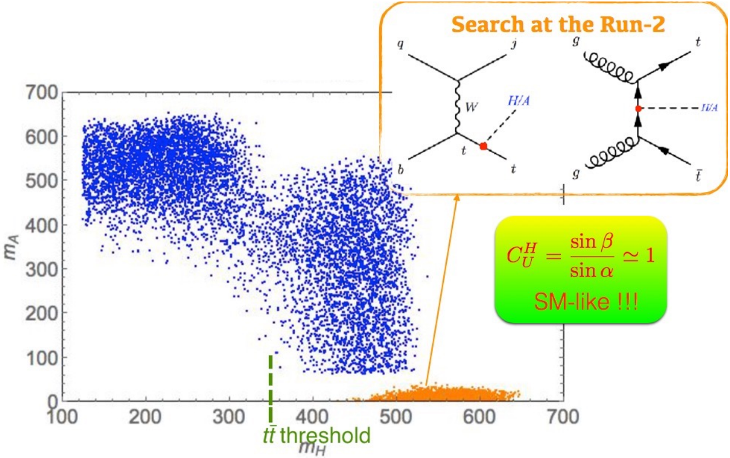


- SM-like Higgs exchange (probably unlikely)
- Non SM-like (light and heavy) Higgs exchange
- SM-like Higgs and light squark exchange
- Generic Higgs and light squark exchange

The recent paper 1503.03478 investigated all these scenarios but they restrict the $m_{\tilde{\chi}_0^1} > 50$ GeV.

Collider search signature (for $m_A < m_h/2$ only)

- Alignment without decoupling: $420 \lesssim m_H, m_{H^\pm} \lesssim 650$ GeV (very little impact by the new limit from $b \to s\gamma$).
- At low $\tan\beta \sim 1$, so the predicted cross section will no longer have large variation.



Which final state shall we look for? (tt is a good idea.

Conclusion

1. The Higgs and DM sectors may be intimately connected. If so, detecting the signs of one of sectors could shine light on still hidden elements of the other.

2. Isospin-violating effect is possible in many (but not ALL) models and dramatically changes the analysis of dark matter direct detection.

3. However, if DM were discovered in the future, our fine study of the IVDM scenario will determine the DM coupling strength and provide an efficient way for experiments to discover the nature of particle DM.