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

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(move to Niels Bohr Institute (Copenhagen) next week)

SUSY 2015, Tahoe, CA
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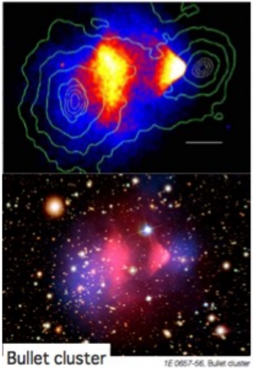
- A. Drozd, B. Grzadkowski, J. F. Gunion and Y.J., JHEP **1411** (2014) 105; 1509.XXXXX (appear soon).

Outline

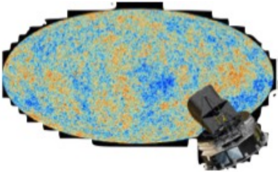
1. Preliminary Background
    - Dark matter direct detection
    - Isospin-violating mechanism
2. Model building

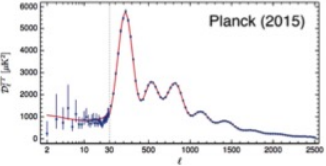
    (The discussion in this talk is mainly limited in the Higgs-portal models)
    - minimal singlet extension
    - go beyond the minimal (e.g., 2HDM plus a real scalar singlet)
3. DM phenomenology
4. Collider search signature
5. Conclusion

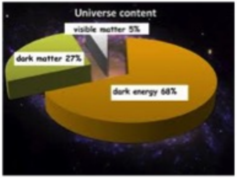
Existence of dark matter?

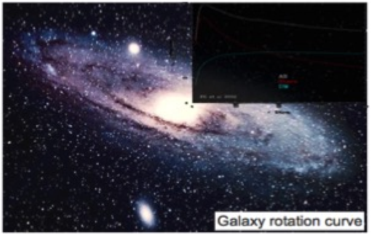

Bullet cluster

1E 0657-56, Bullet cluster



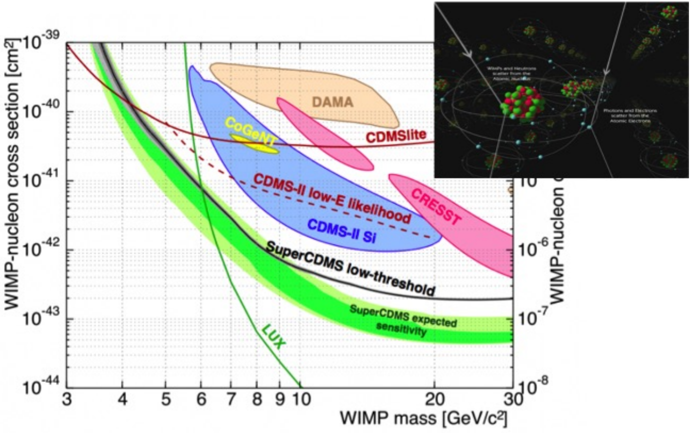





Galaxy rotation curve

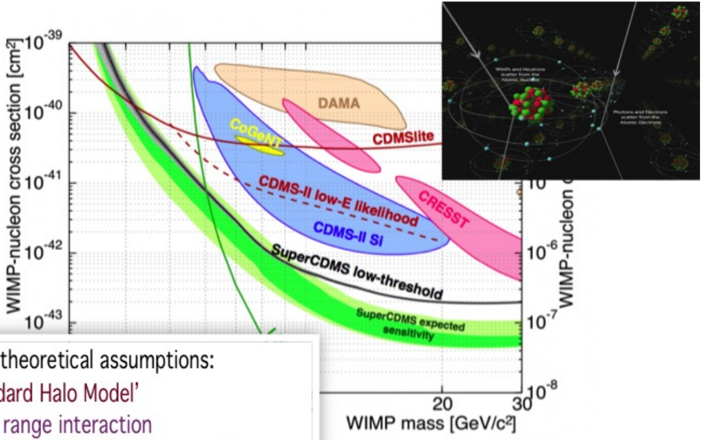
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 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

Messages from DM direct detection



- 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

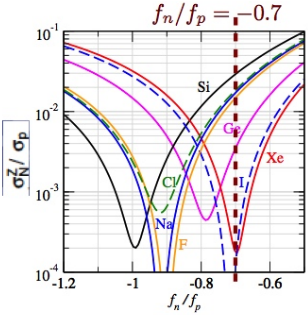
Are they all true?

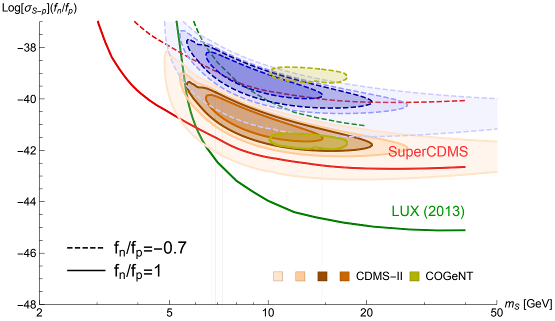
If f_n/f_p is NOT equal to one?

J.Feng et.al., PLB703(2011)124, 1307.1758

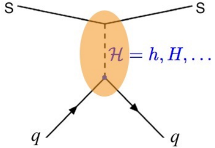
$$\sigma_N^Z = \sigma_p \frac{\sum_i \eta_i \mu_{A_i}^2 [Z - (A_i - Z) f_n/f_p]^2}{\sum_i \eta_i \mu_{A_i}^2 A_i^2}$$

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

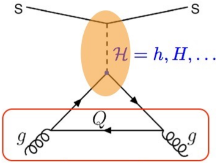




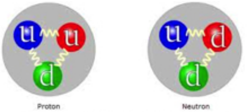
Isospin-violating mechanism

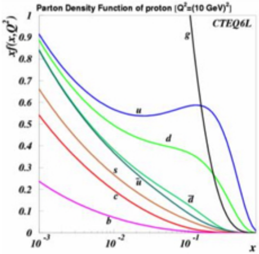


light quarks



heavy quarks





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

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

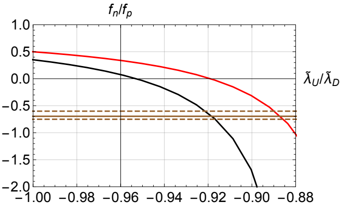
where the combined form factors (including the QCD NLO) are

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

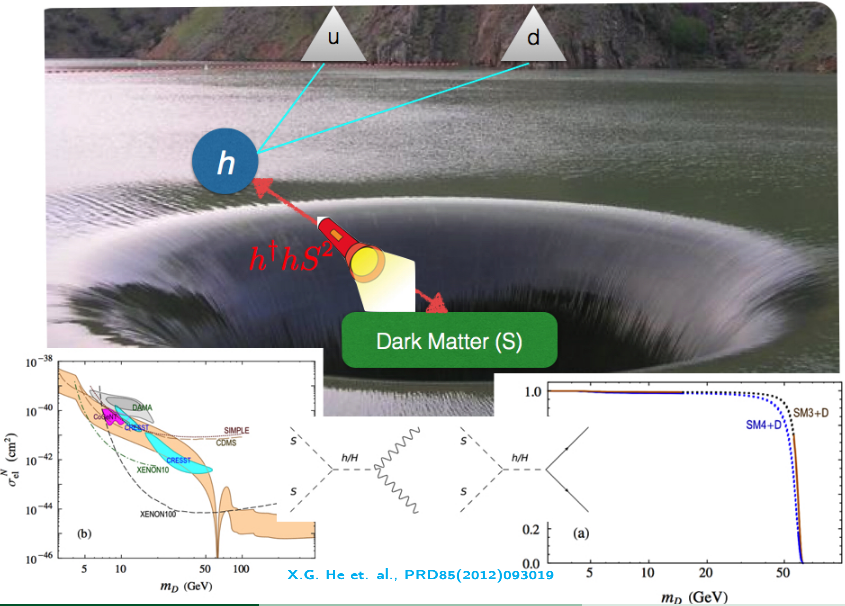
$$F_d^N = f_{Td}^N + f_{Ts}^N + \frac{2}{27} f_{TG}^N \left(1 + \frac{35}{36\pi}\alpha_S(m_b)\right)$$

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

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

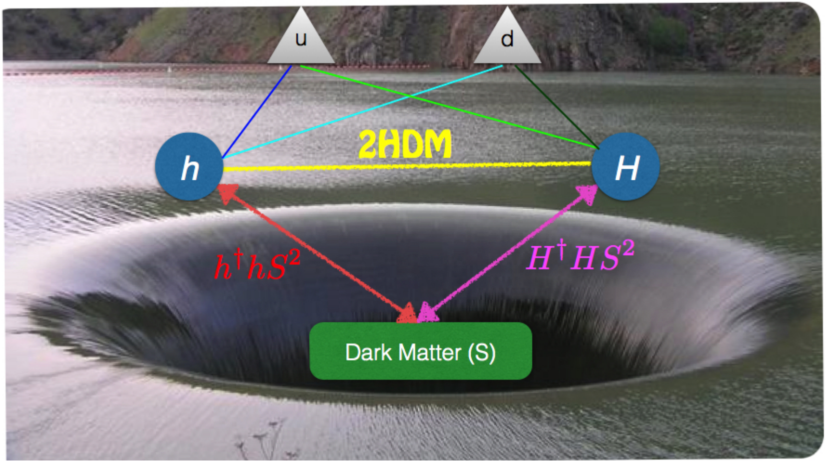


Model building: SM+Singlet (FAILED)



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

$$m_S^2 = m_0^2 + (\kappa_1 \cos^2\beta + \kappa_2 \sin^2\beta) v^2 \tag{3}$$
$$\lambda_h = -\kappa_1 \sin\alpha \cos\beta + \kappa_2 \cos\alpha \sin\beta \tag{4}$$
$$\lambda_H = \kappa_1 \cos\alpha \cos\beta + \kappa_2 \sin\alpha \sin\beta \tag{5}$$
$$\lambda_{AA} = \frac{1}{2}\lambda_{H^+H^-} = \frac{1}{2}(\kappa_1 \sin^2\beta + \kappa_2 \cos^2\beta) \tag{6}$$
$$\lambda_{hh} = \frac{1}{2}(\kappa_2 \cos^2\alpha + \kappa_1 \sin^2\alpha) \tag{7}$$
$$\lambda_{HH} = \frac{1}{2}(\kappa_1 \cos^2\alpha + \kappa_2 \sin^2\alpha) \tag{8}$$
$$\lambda_{hH} = \frac{1}{2}(\kappa_2 - \kappa_1) \sin 2\alpha\,. \tag{9}$$

Remarks

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

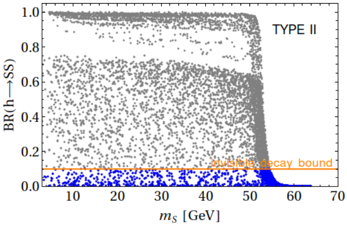
Experimental constraints

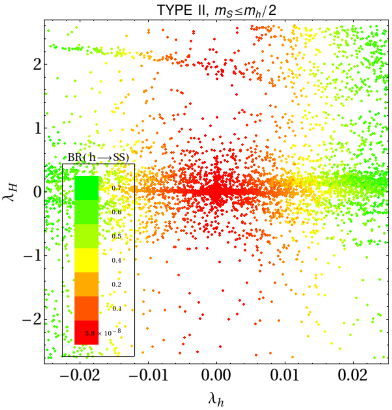
Our focus: light dark matter

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

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.

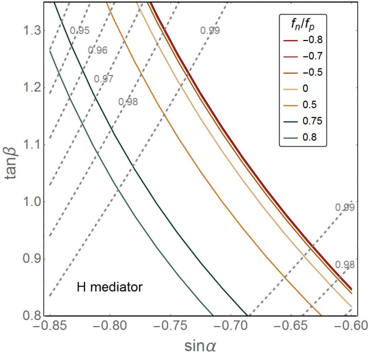
Finding a IVDM, a really challengeable job

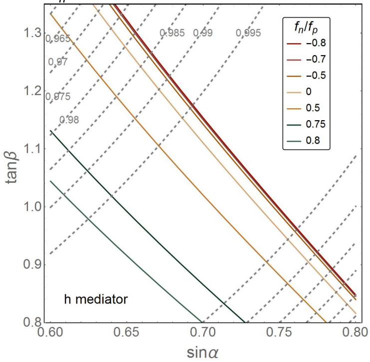
Applying the Higgs-quark coupling pattern into the generic f_n/f_p already derived yields

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 $w = \frac{\lambda_h}{\lambda_H}\frac{m_H^2}{m_h^2}$

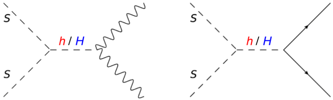




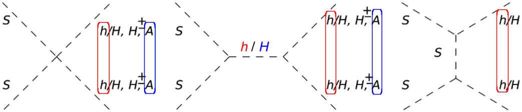
The solution is very tuned and occurs in the vicinity of $\tan\beta \simeq 1$!

Dark matter physics

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



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



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

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

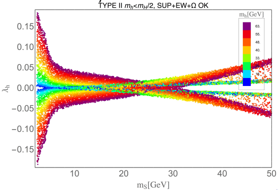
Light DM ($m_S \le 50$ GeV)

$m_h \sim 125$ 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 $m_S \simeq m_h/2$.

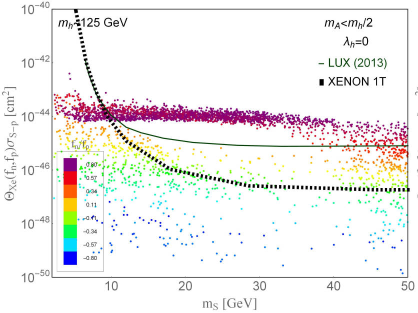


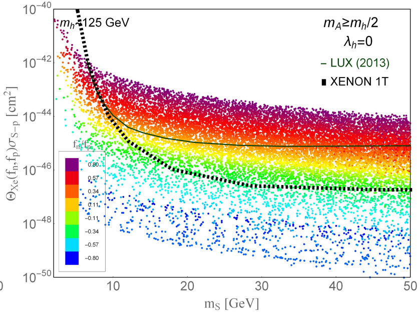
Numerical analysis (h-125 scenario as an example for illustration)

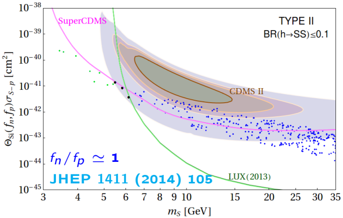
In fact both h-125 and H-125 scenarios could fit very well with cosmological observation.

- 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)

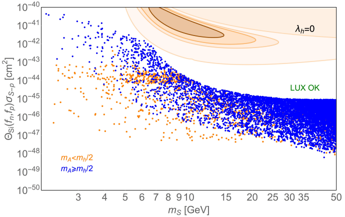




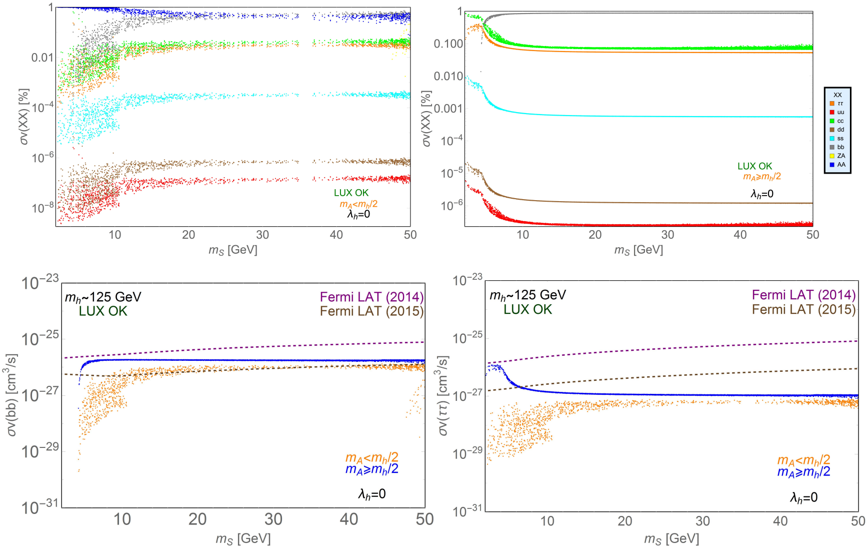


$f_n/f_p \simeq 1$

JHEP 1411 (2014) 105

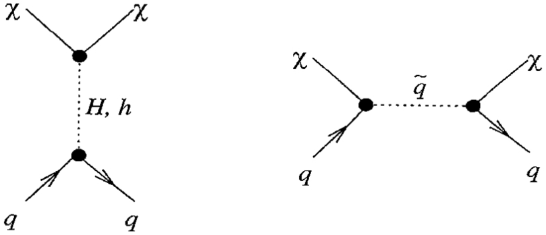


Indirect detection (h-125 case for example)



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)

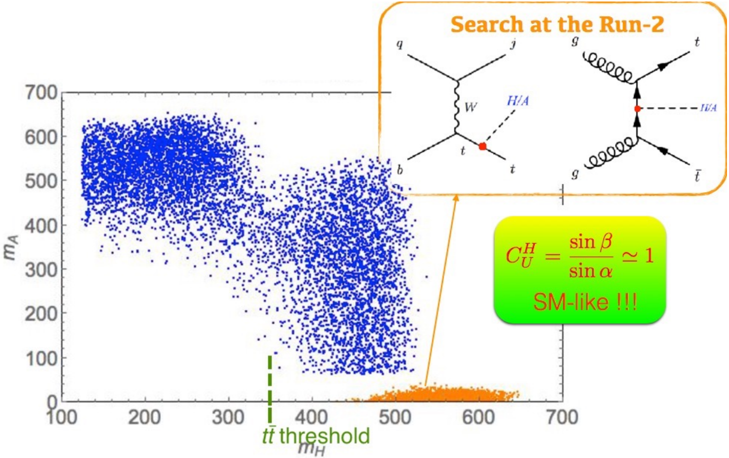


- SM-like Higgs exchange (mostly unlikely)
- Non SM-like (light and heavy) Higgs exchange
- SM-like Higgs and light squark exchange
- Generic Higgs and light squark exchange

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

Collider search signature

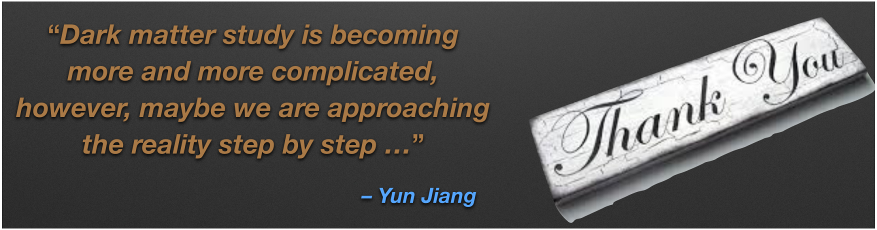
- Alignment without decoupling: $m_H, m_A \lesssim 650$ GeV.
- Top-quark coupling for H, A is enhanced at low $\tan\beta \sim 1$.



Which final state shall we look for?

Remarks

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. It is of interest to explore some of the implications of recent developments in hunting for Higgs and detecting DM in the context of as simple framework as possible.
3. The seemingly last mission: baryogenesis?



"Dark matter study is becoming more and more complicated, however, maybe we are approaching the reality step by step ..."

– Yun Jiang