Complementarity of direct detections and Collider Search for Higgs portal DM

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TeVPA 2015, Kashiwa, Japan Oct. 26-30 (2015) Complementarity of direct detections and Collider Search for Higgs portal DM ???

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TeVPA 2015, Kashiwa, Japan Oct. 26-30 (2015) This is a special example of Beyond DM EFT/ Simplified Models: Higgs portal DMs as examples Only Higgs (~SM) and Nothing Else So Far at the LHC & Local Gauge Principle Works !

Based on the works

(with S.Baek, Suyong Choi, P. Gondolo, T. Hur, D.W.Jung, Sunghoon Jung, J.Y.Lee, W.I.Park, E.Senaha, Yong Tang in various combinations)

- Singlet fermion dark matter (1112.1847 JHEP)
- Higgs portal vector dark matter (1212.2131 JHEP)
- Vacuum structure and stability issues (1209.4163 JHEP)
- Higgs-portal assisted Higgs inflation, Higgs portal VDM for gamma ray excess from GC (1404.5257 JCAP; 1407.5492 JCAP ; 1407.6588, PLB in review)
- Invisible Higgs decay vs. DD (1405.3530 PRD)
- Work in progress

Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



(Direct detection)

Crossing & WIMP detection

Correct relic density \rightarrow Efficient annihilation then



Efficient scattering now (Direct detection)

DD vs. Monojet : Why complementarity breaks down in EFT ?

with S. Baek, Myeonghun Park, W.I.Park, Chaehyun Yu

arXiv:1506.06556

Why is it broken down in DM EFT ?

The most nontrivial example is the (scalar)x(scalar) operator for DM-N scattering

$$\mathcal{L}_{SS} \equiv \frac{1}{\Lambda_{dd}^2} \bar{q} q \bar{\chi} \chi \quad \text{or} \quad \frac{m_q}{\Lambda_{dd}^3} \bar{q} q \bar{\chi} \chi$$

This operator clearly violates the SM gauge symmetry, and we have to fix this problem

$$\overline{Q}_L H d_R$$
 or $\overline{Q}_L \widetilde{H} u_R$, OK $h \bar{\chi} \chi$, $s \bar{q} q$ Not OK

Both break SM gauge invariance !

$$s\bar{\chi}\chi \times h\bar{q}q \to \frac{1}{m_s^2}\bar{\chi}\chi\bar{q}q$$

Need the mixing between s and h

Higgs portal DM as examples

$$\mathcal{L}_{\text{scalar}} = \frac{1}{2} \partial_{\mu} S \partial^{\mu} S - \frac{1}{2} m_{S}^{2} S^{2} - \frac{\lambda_{HS}}{2} H^{\dagger} H S^{2} - \frac{\lambda_{S}}{4} S^{4} \qquad \begin{array}{l} \text{All invariant} \\ \text{under ad hoc} \\ \mathcal{L}_{\text{fermion}} = \overline{\psi} \left[i\gamma \cdot \partial - m_{\psi} \right] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^{\dagger} H \ \overline{\psi} \psi \\ \mathcal{L}_{\text{vector}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_{V}^{2} V_{\mu} V^{\mu} + \frac{1}{4} \lambda_{V} (V_{\mu} V^{\mu})^{2} + \frac{1}{2} \lambda_{HV} H^{\dagger} H V_{\mu} V^{\mu}. \end{array}$$

arXiv:1112.3299,1205.3169,1402.6287, to name a few







FIG. 2. Same as Fig. 1 for vector DM particles. FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV⁻¹.

Higgs portal DM as examples



- Scalar CDM : looks OK, renorm. .. BUT
- Fermion CDM : nonrenormalizable
- Vector CDM : looks OK, but it has a number of problems (in fact, it is not renormalizable)

Usual story within EFT

- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced in the full theories (renormalizable) however

Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847



This simple model has not been studied properly !!

Ratiocination

Mixing and Eigenstates of Higgs-like bosons

$$\mu_{H}^{2} = \lambda_{H}v_{H}^{2} + \mu_{HS}v_{S} + \frac{1}{2}\lambda_{HS}v_{S}^{2},$$

$$m_{S}^{2} = -\frac{\mu_{S}^{3}}{v_{S}} - \mu_{S}'v_{S} - \lambda_{S}v_{S}^{2} - \frac{\mu_{HS}v_{H}^{2}}{2v_{S}} - \frac{1}{2}\lambda_{HS}v_{H}^{2},$$

$$M_{\text{Higgs}}^{2} \equiv \begin{pmatrix} m_{hh}^{2} & m_{hs}^{2} \\ m_{hs}^{2} & m_{ss}^{2} \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_{1}^{2} & 0 \\ 0 & m_{2}^{2} \end{pmatrix} \begin{pmatrix} \cos\alpha - \sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_{1} = h\cos\alpha - s\sin\alpha,$$

$$H_{2} = h\sin\alpha + s\cos\alpha.$$
Mixing of Higgs and singlet

Ratiocination

• Signal strength (reduction factor)

$$r_{i} = \frac{\sigma_{i} \operatorname{Br}(H_{i} \to \operatorname{SM})}{\sigma_{h} \operatorname{Br}(h \to \operatorname{SM})}$$

$$r_{1} = \frac{\cos^{4} \alpha \ \Gamma_{H_{1}}^{\operatorname{SM}}}{\cos^{2} \alpha \ \Gamma_{H_{1}}^{\operatorname{SM}} + \sin^{2} \alpha \ \Gamma_{H_{1}}^{\operatorname{hid}}}$$

$$r_{2} = \frac{\sin^{4} \alpha \ \Gamma_{H_{2}}^{\operatorname{SM}}}{\sin^{2} \alpha \ \Gamma_{H_{2}}^{\operatorname{SM}} + \cos^{2} \alpha \ \Gamma_{H_{2}}^{\operatorname{hid}} + \Gamma_{H_{2} \to H_{1}H_{1}}}$$

$0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1$

Invisible decay mode is not necessary!

If r_i > I for any single channel,
 this model will be excluded !!

Constraints

EW precision observables

Peskin & Takeuchi, Phys.Rev.Lett.65,964(1990)



Constraints

• Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi} \mu^2 \lambda_p^2 \simeq 2.7 \times 10^{-2} \frac{m_p^2}{\pi} \left| \left(\frac{m_p}{v} \right) \lambda \sin \alpha \cos \alpha \left(\frac{1}{m_1^2} - \frac{1}{m_2^2} \right) \right|^2$$



Updates@LHCP

Signal Strengths







	ATLAS	CMS
Decay Mode	$(M_H=125.5~{ m GeV})$	$(M_H=125.7~{ m GeV})$
H ightarrow bb	-0.4 ± 1.0	1.15 ± 0.62
H ightarrow au au	0.8 ± 0.7	1.10 ± 0.41
$H ightarrow\gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H ightarrow WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H ightarrow ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\textbf{1.30} \pm \textbf{0.20}$	$\textbf{0.80} \pm \textbf{0.14}$

$\langle \mu angle = 0.96 \pm 0.12$



Higgs Physics



A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Low energy pheno.

- Universal suppression of collider SM signals [See 1112.1847, Seungwon Baek, P. Ko & WIP]
- If " $m_h > 2 m_{\phi}$ ", non-SM Higgs decay!
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_{\phi}^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{\rm SM}$$



Similar for Higgs portal Vector DM

$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- Stueckelberg mechanism ?? (work in progress)
- A complete model should be something like this:

$$\mathcal{L}_{VDM} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_{\mu}\Phi)^{\dagger} (D^{\mu}\Phi) - \frac{\lambda_{\Phi}}{4} \left(\Phi^{\dagger}\Phi - \frac{v_{\Phi}^2}{2}\right)^2 -\lambda_{H\Phi} \left(H^{\dagger}H - \frac{v_{H}^2}{2}\right) \left(\Phi^{\dagger}\Phi - \frac{v_{\Phi}^2}{2}\right) ,$$

$$\langle 0|\phi_X|0\rangle = v_X + h_X(x)$$

- There appear a new singlet scalar h_X from phi_X, which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model
- Important to consider a minimal renormalizable model to discuss physics correctly
- Baek, Ko, Park and Senaha, arXiv:1212.2131 (JHEP)



Figure 8. The vacuum stability and perturbativity constraints in the α - m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_{\Phi} = M_X/(g_X Q_{\Phi})$.

Figure 6. The scattered plot of σ_p as a function of M_X . The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ , while the red-(black-)colored points gives $r_1 > 0.7(r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity of the next XENON experiment, XENON1T.

 $M_X(\text{GeV})$

Comparison with the EFT approach

- SFDM scenario is ruled out in the EFT
- We may lose imformation in DM pheno.



FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and BR^{inv} = 10% for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

FIG. 2. Same as Fig. 1 for vector DM particles. FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV⁻¹.

With renormalizable lagrangian, we get different results !

 We don't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

$$\mathcal{L}_{\text{eff}} = \overline{\psi} \left(m_0 + \frac{H^{\dagger} H}{\Lambda} \right) \psi. \quad \text{or} \quad \widehat{\lambda h \psi \psi}$$
Breaks SM gauge sym

- Only one Higgs boson (alpha = 0)
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Is this any useful in phenomenology ?

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YES !

Talk by Yong Tang, Thu afternoon on GC gamma ray excess

Collider Implications



Crossing & WIMP detection

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(Direct detection)

Crossing & WIMP detection

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Efficient scattering now (Direct detection)

DD vs. Monojet : Why complementarity breaks down in EFT ?

arXiv: I 506.06556 with S. Baek, Myeonghun Park, W.I.Park, Chaehyun Yu, and longer version to appear

Why is it broken down in DM EFT ?

The most nontrivial example is the (scalar)x(scalar) operator for DM-N scattering

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$\overline{Q}_L H d_R$ or $\overline{Q}_L \widetilde{H} u_R,$ OK $h \bar{\chi} \chi,$ $s \bar{q} q$

Both break SM gauge invariance

$$s\bar{\chi}\chi imes h\bar{q}q o rac{1}{m_s^2}\bar{\chi}\chi\bar{q}q$$

Need the mixing between s and h

Full Theory Calculation

$$\chi(p) + q(k) \rightarrow \chi(p') + q(k')$$

$$\mathcal{M} = \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{v}\lambda_s \sin\alpha\cos\alpha \left[\frac{1}{t - m_{125}^2 + im_{125}\Gamma_{125}} - \frac{1}{t - m_2^2 + im_s\Gamma_2}\right]$$

$$\rightarrow \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{2v}\lambda_s \sin2\alpha \left[\frac{1}{m_{125}^2} - \frac{1}{m_2^2}\right]$$

$$\rightarrow \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{2v}\lambda_s \sin2\alpha \frac{1}{m_{125}^2} \equiv \frac{m_q}{\Lambda_{dd}^3}\overline{u(p')}u(p)\overline{u(q')}u(q)$$

$$\Lambda_{dd}^3 \equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha} \left(1 - \frac{m_{125}^2}{m_2^2}\right)^{-1}$$
$$\bar{\Lambda}_{dd}^3 \equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha}$$

Monojet+missing ET

Can be obtained by crossing : s <>t

$$\frac{1}{\Lambda_{dd}^3} \to \frac{1}{\Lambda_{dd}^3} \left[\frac{m_{125}^2}{s - m_{125}^2 + im_{125}\Gamma_{125}} - \frac{m_{125}^2}{s - m_2^2 + im_2\Gamma_2} \right] \equiv \frac{1}{\Lambda_{col}^3(s)}$$

There is no single scale you can define for collider search for missing ET

FIG. 1: In ATLAS 8TeV mono-jet+ \not{E}_T search [6] we plot $M_{\chi\chi}$ and the P_T of a hardest jet in a reconstruction level (after a detector simulation). Upper panels are with $m_{\chi} = 50 \text{ GeV}$ and lower panels are of $m_{\chi} = 400 \text{ GeV}$.

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3} \bar{q} q \bar{\chi} \chi$
- S.M.: Simple scalar mediator S of $\mathcal{L}_{int} = \left(\frac{m_q}{v_H} \sin \alpha\right) S \bar{q} q - \lambda_s \cos \alpha S \bar{\chi} \chi$
- H.M.: A case where a Higgs is a mediator $\mathcal{L}_{int} = -\left(\frac{m_q}{v_H}\cos\alpha\right)H\bar{q}q - \lambda_s\sin\alpha H\bar{\chi}\chi$
- H.P.: Higgs portal model as in eq. (2).

FIG. 1: We follow ATLAS 8TeV mono-jet+ $\not\!\!\!E_T$ searches [2]. For (a) we simulated various models for the

tl + missing El

FIG. 2: Parton level distributions of various variables in a $(t\bar{t}\chi\bar{\chi})$ channel for a dark matter's mass $m_{\chi} = 10 \text{ GeV}$ (above) and $m_{\chi} = 100 \text{ GeV}$ (below) for LHC 8TeV. As we can see here, due to a higgs propagator, even when $m_2 \to \infty$ case, a missing transverse energy $\not{\!\!E}_T$ of a higgs portal model shall be different from an effective operator operator case.

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FIG. 3: We follow CMS 8TeV $t\bar{t} + \not{\!\!\!E}_T$ search. For (a) we simulated various models for the

A General Comment

assume: $2m_{\chi} \ll m_{125} \ll m_2 \ll \sqrt{s}$

$$\begin{aligned} \sigma(\sqrt{s}) &= \int_0^1 d\tau \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s) \\ &= \left[\int_{4m_{\chi}^2/s}^{m_{125}^2/s} d\tau + \int_{m_{125}^2/s}^{m_{22}^2/s} d\tau + \int_{m_{2}^2/s}^1 d\tau \right] \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s) \end{aligned}$$

For each integration region for tau, we have to use different EFT

No single EFT applicable to the entire tau regions

Indirect Detection

$$\begin{aligned} \left| \frac{1}{\Lambda_{ann}^3} \right| &\simeq \left| \frac{1}{\Lambda_{dd}^3} \left| \frac{m_{125}^2}{4m_{\chi}^2 - m_{125}^2 + im_{125}\Gamma_{125}} - \frac{m_{125}^2}{4m_{\chi}^2 - m_{2}^2 + im_{2}\Gamma_{2}} \right| \\ &\to \left| \frac{1}{\Lambda_{dd}^3} \left| \frac{m_{125}^2}{4m_{\chi}^2 - m_{125}^2 + im_{125}\Gamma_{125}} \right| \neq \frac{1}{\Lambda_{dd}^3} \end{aligned} \end{aligned}$$

- Again, no definite correlations between two scales in DD and ID
- Also one has to include other channels depending on the DM mass

Conclusion

- Higgs portal DM : simple viable DM models (natural if one assumes dark gauge sym)
- EFT: not reliable for collider searches for DM, and one has to consider UV completions
- Full SM gauge symmetry, unitarity and renormalizability are important when constructing UV completions
- Search for Higgs portal DM at ILC, FCC-ee, LHC and FCC-hh, SPPC being studied