Higgs Vacuum Stability
with
Vector-like Fermions

Shrihari Gopalakrishna

Institute of Mathematical Sciences (IMSc), Chennai

IMHEP

IOP Bhubaneswar Jan 2019

Vector-like Fermions (VLF)
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Higgs Effective Potential
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Vacuum Stability
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Talk Outline

- Vector-like Fermions (VLF) general aspects
- Vacuum decay basics
    - Bounce configuration
- Higgs Vacuum Stability
    - in the Standard Model
   - with VLFs present

BSM VLF

Vector-like fermions have both L and R chiralities charged under a gauge-group.
This allows a bare mass term.

- VLFs appear in many BSM extensions
    - they are sometimes the lightest BSM states

- We study VLF effects on Higgs vacuum stability
    - constraint on parameter space
    - but any other new states will alter conclusions!

Vector-like fermion (VLF) decoupling

- VLF has independent source of mass M (not given by $m = \lambda v$)

    - Can make M arbitrarily large

        - Yukawa coupling can be small; so perturbative

    - Nice decoupling behavior : $S, T, U, h \to \gamma\gamma, gg \to h, ...$
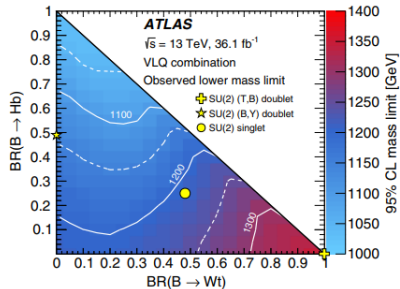
        - For instance $h\gamma\gamma$, ggh couplings
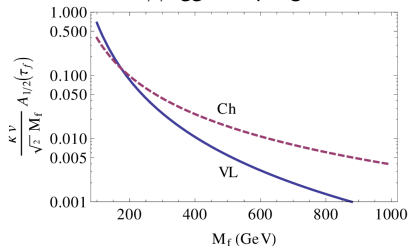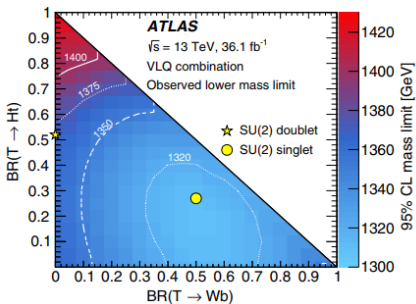
VLF signatures

Observables

- Precision Electroweak Probes
- LHC signals
    - Direct: $b' \to tW$,bZ; $t' \to bW, tZ, th$; $\chi \to tW$
    - Indirect: Higgs coupling modifications
- FCNC probes
- Vacuum stability implications
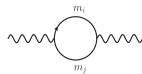
Vector-like fermion (t', b') search

[ATLAS: 1808.02343; PRL 2018]

EWPrecision $+$ Higgs Observables
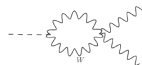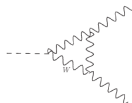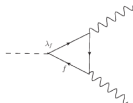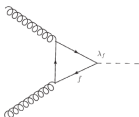
[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398, JHEP 2014]

Precision electroweak observables (S, T, U)

Modifications to hgg, $h\gamma\gamma$ couplings:

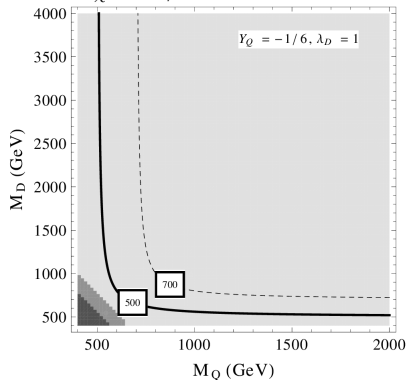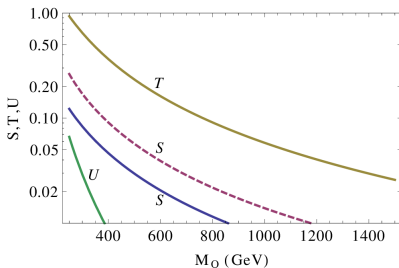$\sigma(gg \to h)$ $\Gamma(h \to \gamma\gamma)$

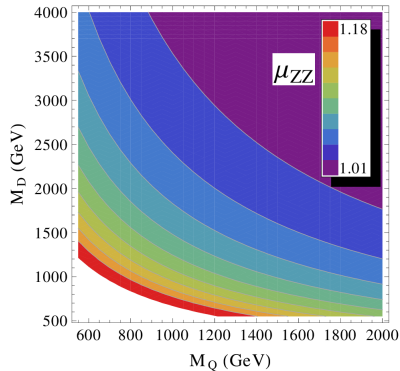We compute ratios $\frac{\Gamma_{h\to gg}}{SM}$, $\frac{\Gamma_{h\to\gamma\gamma}}{SM}$ using leading-order expressions

QCD corrections to ratios small: [Furlan '11] [Gori, Low '13]

$$\mu_{\gamma\gamma}^{VBF} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} \; ; \quad \mu_{ZZ}^{ggh} \approx \frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} \; ; \quad \mu_{\gamma\gamma}^{ggh} \approx \frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} \; ; \quad \frac{\mu_{\gamma\gamma}^{ggh}}{\mu_{ZZ}^{ggh}} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} \approx \mu_{\gamma\gamma}^{VBF}$$

$2\bar{2} + 1\bar{1}$ model

$Q + U$ model (ST Model like) : MVQD Model with $Y_\chi = -1/6$

$\lambda_D = 1$, $M_D = M_Q$, $Y_Q = (1/6, -1/6)$ (solid, dashed)

$Q + U$ model
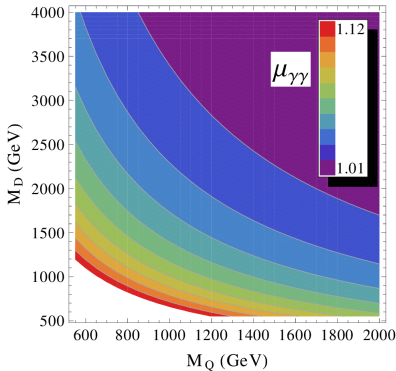
[Q+U model from MVQD model with $Y_\chi = -1/6$]

LHC constraints on Higgs couplings
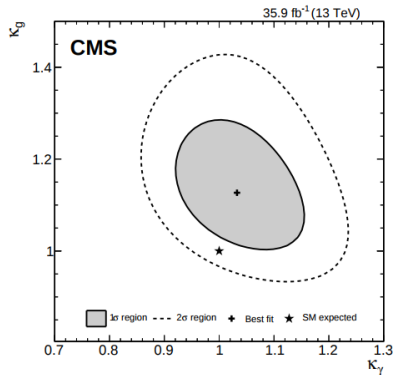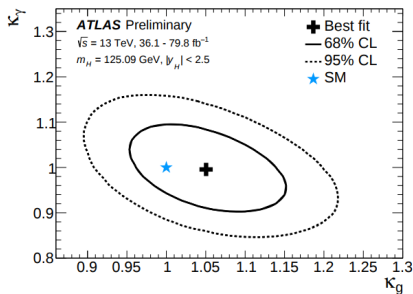
[ATLAS-CONF-2018-31] [CMS-HIG-17-031]

Vector-like Fermions (VLF)
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Higgs Effective Potential
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Vacuum Stability
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Higgs Effective Potential

HIGGS EFFECTIVE POTENTIAL

RG-Improved Higgs Effective Potential

Classical potential: $\mathcal{V} = \frac{m_h^2}{2} h^2 + \frac{\lambda}{4} h^4$

Quantum Effective Potential: $V_{\mathrm{eff}}(h) = \frac{m_{h\,\mathrm{eff}}^2}{2} h^2 + \frac{\lambda_{\mathrm{eff}}(h)}{4} h^4 \qquad \rightarrow \qquad \frac{\lambda_{\mathrm{eff}}(h)}{4} h^4$

Set $h \equiv \mu$; $\lambda_{\mathrm{eff}}(h) \equiv \lambda(\mu)$ obeys an RGE like evolution:
$$\frac{d\,\lambda(\mu)}{d\ln \mu} = \beta_\lambda \left(\lambda(\mu), y_t(\mu), g_3(\mu), g_2(\mu), g_1(\mu), ... \right)$$

1-loop SM RGE

$\beta_\lambda = \frac{1}{16\pi^2} \left[24\lambda^2 + 4N_c y_t^2 \lambda - 2N_c y_t^4 - 9g_2^2\lambda - \frac{9}{5}g_1^2\lambda + \frac{9}{8}\left(g_2^4 + \frac{2}{5}g_2^2 g_1^2 + \frac{3}{25}g_1^4\right)\right]$

$\beta_{y_t} = \frac{y_t}{16\pi^2} \left[\frac{(3+2N_c)}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2 \right]$

$\beta_{g_a} = \frac{g_a^3 b_a}{16\pi^2}$

[We include some significant 2-loop β-functions (not shown)]

Effective VLF model and 1-loop RGE

[SG, Arunprasath V: 1812.11303 [hep-ph]]

An effective model with one SU(2) doublet χ and one SU(2) singlet ξ

$$\mathcal{L} \supset -M_\chi \bar{\chi}\chi - M_\xi \bar{\xi}\xi - (\tilde{y}\,\bar{\chi}\cdot H^*\xi + h.c.)$$

Their contributions to the RGE is:

$$\beta_{g_3} = \frac{g_3^3}{16\pi^2}\left(\frac{2}{3}n_3\right)$$

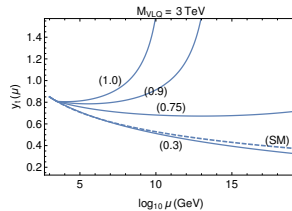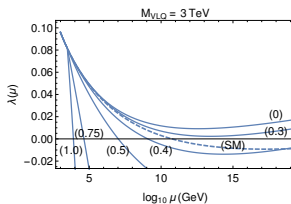$$\beta_{g_2} = \frac{g_2^3}{16\pi^2}\left(\frac{2}{3}N_c'n_2\right)$$

$$\beta_{g_1} = \frac{g_1^3}{16\pi^2}\left[\frac{4}{5}N_c'\left(2n_2 Y_\chi^2 + n_1 Y_\xi^2\right)\right]$$

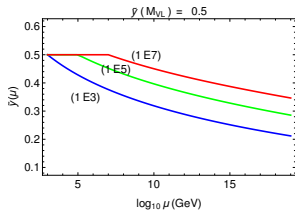$$\beta_\lambda = \frac{2n_F}{16\pi^2}\left(4N_c'\tilde{y}^2\lambda - 2N_c'\tilde{y}^4\right)$$

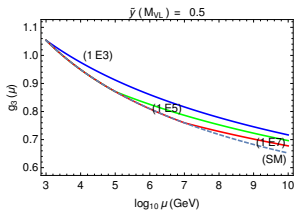$$\beta_{y_t} = \frac{n_F}{16\pi^2}y_t\left(2N_c'\tilde{y}^2\right)$$

$$\beta_{\tilde{y}} = \frac{\tilde{y}}{16\pi^2}\left[\frac{(3\tilde{y}^2 + 2N_c y_t^2 + 4n_F N_c'\tilde{y}^2)}{2} - 8\hat{n}_F^{VLQ}g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right]$$

Vector-like Fermions (VLF)
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Higgs Effective Potential
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Vacuum Stability
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Higgs Effective Potential

3 TeV VLQuark (VLQ) family ($\chi + \xi$)

VLQ family

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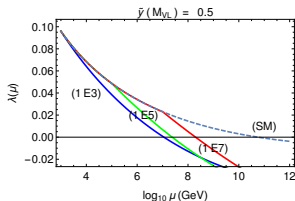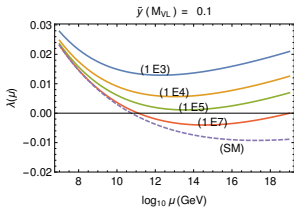
VACUUM STABILITY

Vacuum Stability
(Possible cases)

The Higgs Electroweak (EW) Vacuum can be:

Stable: EW vacuum is the global minium

Metastable: EW vacuum is a false vacuum with $\tau_{decay} > \tau_{universe}$

Unstable: EW vacuum is a false vacuum with $\tau_{decay} < \tau_{universe}$

Singlet VLQ, Doublet VLQ or a VLQ family (with small $\tilde{y}$) can render the Higgs EW vacuum stable for suitable parameters!

Eg: With a VLQ family with $\tilde{y} = 0.1$, $M_{VL} \lesssim 10^5$ GeV (example we considered earlier) the EW vacuum is absolutely stable.

Bounce configuration and Vacuum tunneling

Computing vacuum decay probability

[Coleman: Aspects of Symmetry] [M.Sher: Phys.Rep. 1989]

If Higgs EW vacuum is not the true vacuum, vacuum tunneling can occur via a **Bounce** configuration

To compute the tunneling probability, start with the Euclidean action:
$$S_E[h] = \int d^4\rho \left[\frac{1}{2}(\partial_i h)^2 + V_{\text{eff}}(h) \right]$$

Look for a stationary point of S_E that is $O(4)$ symmetric,

i.e. $h(\rho^i) = h_B(\rho)$, where $\rho = \sqrt{\rho^i \rho^i}$ [Coleman, Glasser, Martin 1978]

Equation of motion (EOM): $\frac{d^2 h}{d\rho^2} + \frac{3}{\rho}\frac{dh}{d\rho} = \frac{\partial V_{\text{eff}}}{\partial h}$

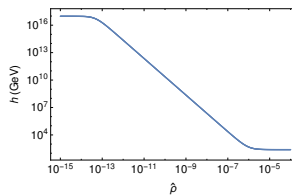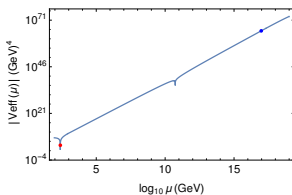**B.C.** $(dh/d\rho)(\rho=0) = 0$; $h(\rho \to \infty) = v$;   **(starting value h_0)**

EOM is that of a classical particle in a potential $-V_{\text{eff}}$ with friction
Solve this EOM to get $h_B(\rho)$

Probability that we would have tunneled into true vacuum in our Hubble volume:
$$P_{\text{tunl}} = (h_0/m_t)^4 \, e^{(404 - S_B)} \text{ where } S_B \equiv S_E[h_B]$$

If $P_{\text{tunl}} \sim \mathcal{O}(1)$, EW vacuum unstable and parameter disfavored!
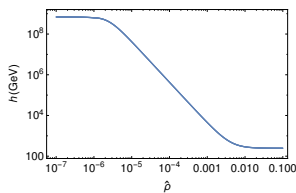
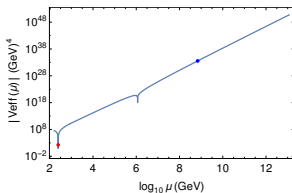# SM V_{eff}, Bounce and P_{tunl}

For the SM: $S_B = 2866 \quad \implies \quad P_{\mathrm{tunl}} \sim 10^{-1013}$
SM EW vacuum is **metastable**, with $\tau_{decay} \gg \tau_{universe}$

[compare with Buttazzo et al, 2013]

VLQ V_{eff}, Bounce and P_{tunl}

[SG, Arunprasath V: 1812.11303 [hep-ph]]
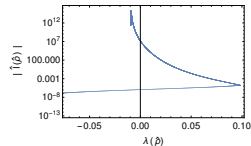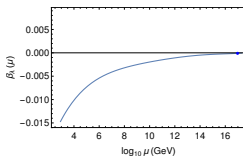

For VLQ family, $M_{VL} = 3$ TeV, $\tilde{y} = 0.57$: $S_B = 469 \implies P_{\mathrm{tunl}} \sim 10^{-4}$

If $\tilde{y} > 0.57$, $P_{\mathrm{tunl}} \sim \mathcal{O}(1)$, i.e. Higgs vacuum is **unstable**; such values are disfavored

An approximation

$$S_B^{\mathrm{approx}} = \frac{8\pi^2}{3(-\lambda(t))}$$

[Lee, Weinberg: NPB267, 1986]
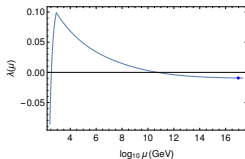
S_B^{approx} works well for the SM
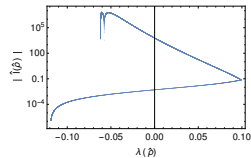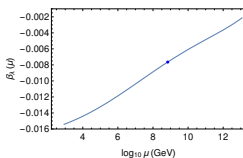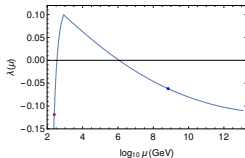
S_B^{approx} cannot be used for VLF

Aside: Application to Higgs Portal DM (VLL)

Can also apply to Higgs portal DM case: [SG. T.Mukherjee: AHEP 2017]
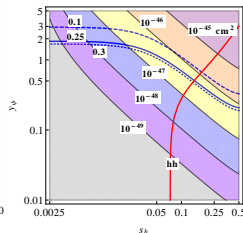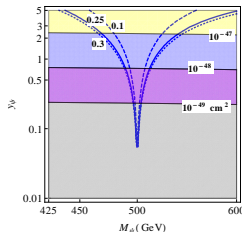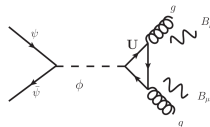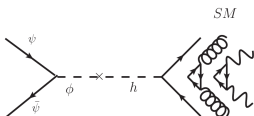
Constraint requires $s_h \ll 1$, so vacuum stability constraint is with VLL (DM)
effectively coupling with $\tilde{y} \equiv y_\psi s_h \ll 1$

Conclusions

- Higgs vacuum is metastable in the SM
    - life-time is much much larger than the age of the universe
- Many BSM theories include VLFs
    - fermions can destabilize the vacuum
    - we computed the renormalization group improved 1-loop Higgs effective potential with VLFs present
    - and analyzed their effects on Higgs vacuum stability

BACKUP SLIDES

Precision Electroweak Constraints

Precision Electroweak Constraints (S, T, $Zb\bar{b}$)

  (perturbatively calculable on the warped side)

W, Z, γ

- Bulk gauge symm - $SU(2)_L \times U(1)$ (SM ψ, H on TeV Brane)
- T parameter $\sim (\frac{v}{M_{KK}})^2 (k\pi R)$ [Csaki, Erlich, Terning 02]
  - S parameter also $(k\pi R)$ enhanced

- AdS bulk gauge symm $SU(2)_R$ $\Leftrightarrow$ CFT Custodial Symm

              [Agashe, Delgado, May, Sundrum 03]

  - T parameter - Protected; S parameter - $\frac{1}{k\pi R}$ for light bulk fermions
  - Implies heavy vector bosons: W'_μ, Z'_μ, ...
  - Problem: $Zb\bar{b}$ shifted

- 3rd gen quarks (2,2)   [Agashe, Contino, DaRold, Pomarol 06]
  - $Zb\bar{b}$ coupling - Protected
  - Precision EW constraints $\Rightarrow M_{KK} \gtrsim 1.5 - 2.5$ TeV
  - Implies top partners: t', b', χ, ...

                    [Carena, Ponton, Santiago, Wagner 06,07]

Warped Fermions

- SM fermions : $(+, +)$ BC $\to$ zero-mode
- "Exotic" fermions : $(-, +)$ BC $\to$ No zero-mode
    - 1st KK vectorlike fermion

- Typical c_{t_R}, c_{t_L} : $(-, +)$ top-partners "light"

  c : Fermion bulk mass parameter

  [Choi, Kim, 2002] [Agashe, Delgado, May, Sundrum, 03]

  [Agashe, Perez, Soni, 04] [Agashe, Servant 04]

    - Look for it at the LHC
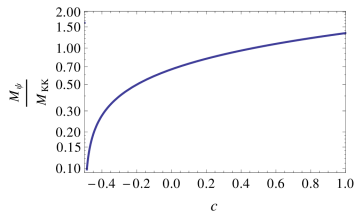
[Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08]
[Atre et al, '09, '11] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09]
[SG, Moreau, Singh, '10] [SG, Mandal, Mitra, Tibrewala, '11] [SG, Mandal, Mitra, Moreau : '13]

Fermion rep : $Zb\bar{b}$ not protected (DT model)

[Agashe, Delgado, May, Sundrum '03]

- Complete $SU(2)_R$ multiplet

    - $Q_L \equiv (\mathbf{2}, \mathbf{1})_{1/6} = (t_L, b_L)$
      $\psi_{t_R} \equiv (\mathbf{1}, \mathbf{2})_{1/6} = (t_R, b')$
      $\psi_{b_R} \equiv (\mathbf{1}, \mathbf{2})_{1/6} = (T, b_R)$

        - "Project-out" b', T zero-modes by $(-, +)$ B.C.
        - New $\psi_{VL} : b'$, T

- $b \leftrightarrow b'$ mixing

    - $Zb\bar{b}$ coupling shifted

        - So LEP constraint quite severe

Fermion rep : $Zb\bar{b}$ protected (ST & TT models)

- $Q_L = (2,2)_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$ [Agashe, Contino, DaRold, Pomarol '06]

  - $Zb_L\overline{b_L}$ protected by custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance
    Wt_Lb_L, Zt_Lt_L not protected, so shifts

Two t_R possibilities:

1. Singlet t_R (ST Model) : $(1,1)_{2/3} = t_R$ New ψ_{VL} : χ, T

2. Triplet t_R (TT Model) :

   $(1,3)_{2/3} \oplus (3,1)_{2/3} = \psi'_{t_R} \oplus \psi''_{t_R} = \begin{pmatrix} \frac{t_R}{\sqrt{2}} & \chi' \\ b' & -\frac{t_R}{\sqrt{2}} \end{pmatrix} \oplus \begin{pmatrix} \frac{t''}{\sqrt{2}} & \chi'' \\ b'' & -\frac{t''}{\sqrt{2}} \end{pmatrix}$

   New ψ_{VL} : χ, T, χ', b', χ'', t'', b''

Fermion rep : $Zb\bar{b}$ protected (ST & TT models)

- $Q_L = (2,2)_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$ [Agashe, Contino, DaRold, Pomarol '06]

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    $Wt_L b_L$, $Zt_L t_L$ not protected, so shifts

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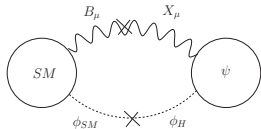
   New $\psi_{VL} : \chi$, T, χ', b', χ'', t'', b''
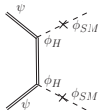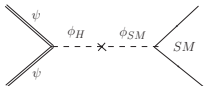
Hidden sector DM ψ

[SG, Lee, Wells 2009]

SM $\times U(1)_X$: $U(1)_X$ sector: X_μ, Φ_{hid}, ψ

$\mathcal{L} \supset -\alpha |H|^2 |\Phi_{hid}|^2 + \frac{\eta}{2} X_{\mu\nu} B^{\mu\nu} - \kappa \phi_{hid} \bar{\psi}\psi$

Higgs portal DM: Self-annihilation

Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

Hidden sector DM ψ

SM $\times U(1)_X$: $U(1)_X$ sector: X_μ, Φ_{hid}, ψ

$\mathcal{L} \supset -\alpha \, |H|^2 |\Phi_{hid}|^2 + \frac{\eta}{2} \, X_{\mu\nu} B^{\mu\nu} - \kappa \phi_{hid} \bar{\psi} \psi$

Higgs portal DM: Self-annihilation

Channels $\psi\psi \to b\bar{b}$, W^+W^-, ZZ, hh, $t\bar{t}$