# Higgs Vacuum Stability with Vector-like Fermions

Shrihari Gopalakrishna

Institute of Mathematical Sciences (IMSc), Chennai

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# Talk Outline

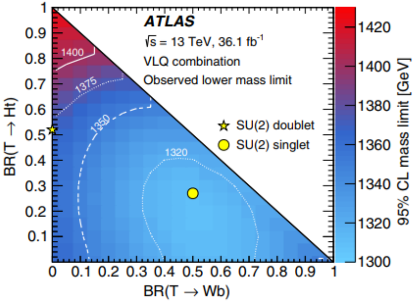
- Vector-like Fermions (VLF) general aspects
- Vacuum decay basics
  - Bounce configuration
- Higgs Vacuum Stability
  - in the Standard Model
  - with VLFs present

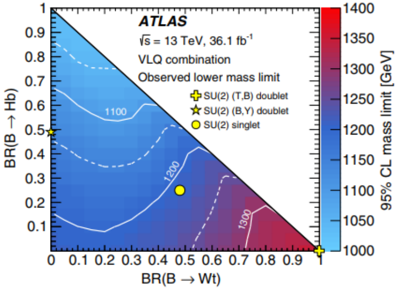
# BSM Vector-like Fermions (VLF)

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
  (Eg: composite-Higgs theories, Extra-dimensional theories)
  - 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 $(t', b')$ search




[ATLAS: 1808.02343; PRL 2018]

# 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: $V_{\rm eff}(h) = \frac{m_{h\,\rm eff}^2}{2} h^2 + \frac{\lambda_{\rm eff}(h)}{4} h^4 \quad \rightarrow \quad \frac{\lambda_{\rm eff}(h)}{4} h^4$

Set $h \equiv \mu$; $\lambda_{\rm eff}(h) \equiv \lambda(\mu)$ obeys an RGE like evolution:

$$\frac{d\,\lambda(\mu)}{d \ln \mu} = \beta_\lambda \left(\lambda(\mu), y_t(\mu), g_3(\mu), g_2(\mu), g_1(\mu), \ldots\right)$$

# 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 significant 2-loop $\beta$-functions (not shown)]

# Effective VLF model and 1-loop RGE

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

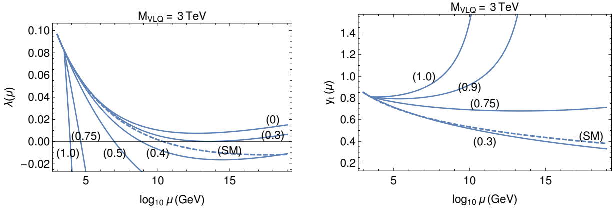
An effective model with one SU(2) doublet $\chi$ and one SU(2) singlet $\xi$

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

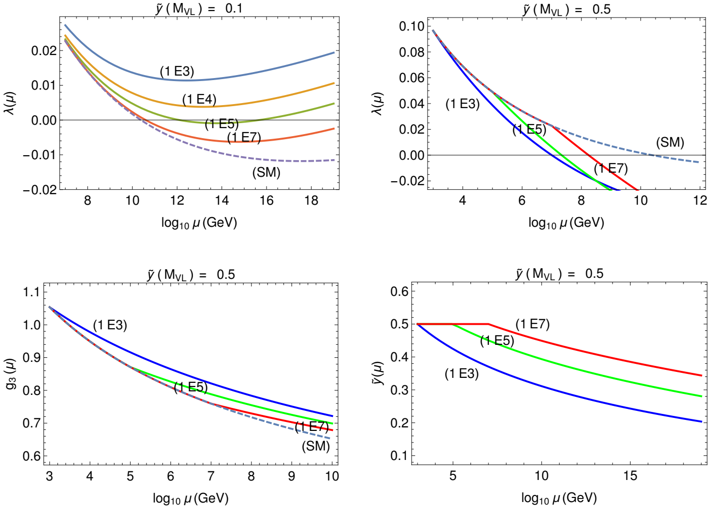
Their contributions to the RGE is:

$$\begin{aligned}
\beta_{g_3} &= \frac{g_3^3}{16\pi^2}\left(\frac{2}{3}n_3\right)\\
\beta_{g_2} &= \frac{g_2^3}{16\pi^2}\left(\frac{2}{3}N_c' n_2\right)\\
\beta_{g_1} &= \frac{g_1^3}{16\pi^2}\left[\frac{4}{5}N_c'\left(2n_2 Y_\chi^2 + n_1 Y_\xi^2\right)\right]\\
\beta_\lambda &= \frac{2n_F}{16\pi^2}\left(4N_c'\tilde{y}^2\lambda - 2N_c'\tilde{y}^4\right)\\
\beta_{y_t} &= \frac{n_F}{16\pi^2}y_t\left(2N_c'\tilde{y}^2\right)\\
\beta_{\tilde{y}} &= \frac{\tilde{y}}{16\pi^2}\left[\frac{(3\tilde{y}^2+2N_c y_t^2+4n_F N_c'\tilde{y}^2)}{2} - 8\hat{n}_F^{VLQ}g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right]
\end{aligned}$$

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



# VLQ family



$\tilde{y}(M_{VL}) = 0.1$
$\lambda(\mu)$
(1 E3)
(1 E4)
(1 E5)
(1 E7)
(SM)
$\log_{10}\mu$ (GeV)
$\tilde{y}(M_{VL}) = 0.5$
$\lambda(\mu)$
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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.

# 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:

$$S_E[h] = \int d^4\rho \left[\frac{1}{2}(\partial_i h)^2 + V_{\rm eff}(h)\right]$$

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): $\frac{d^2h}{d\rho^2} + \frac{3}{\rho}\frac{dh}{d\rho} = \frac{\partial V_{\rm eff}}{\partial h}$

**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 $-V_{\rm eff}$ with friction

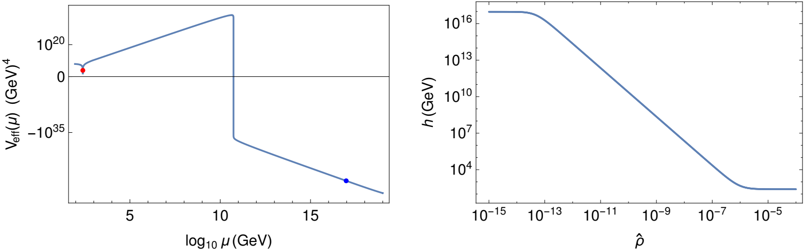
Solve this EOM to get $h_B(\rho)$

Probability that we would have tunneled into true vacuum in our Hubble volume:

$P_{\rm tunl} = (h_0/m_t)^4\, e^{(404-S_B)}$ where $S_B \equiv S_E[h_B]$

If $P_{\rm tunl} \sim \mathcal{O}(1)$, EW vacuum unstable and parameter disfavored!

# SM $V_{\rm eff}$, Bounce and $P_{\rm tunl}$

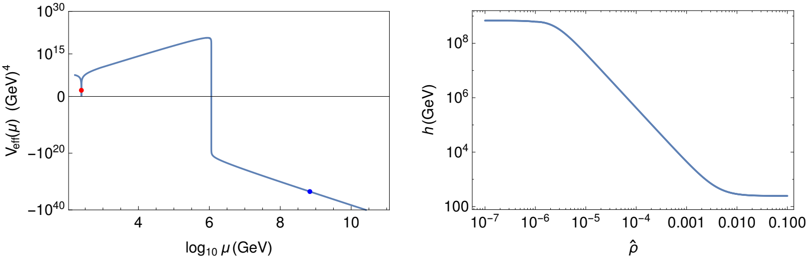



For the SM: $S_B = 2866 \quad \Longrightarrow \quad P_{\rm tunl} \sim 10^{-1013}$
SM EW vacuum is **metastable**, with $\tau_{decay} \gg \tau_{universe}$

[compare with Buttazzo et al, 2013]

# VLQ $V_{\rm eff}$, Bounce and $P_{\rm tunl}$

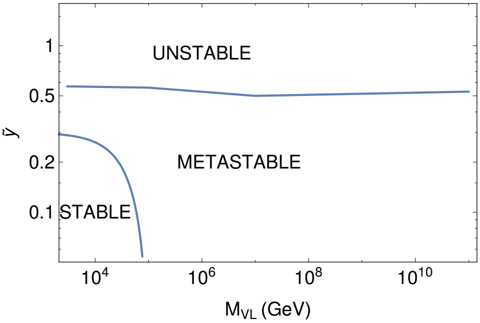
[SG, Arunprasath V: 1812.11303 [hep-ph]]




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

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

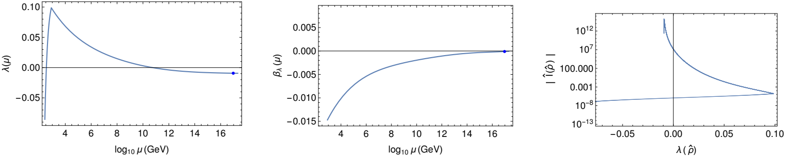
# VLQ stability regions



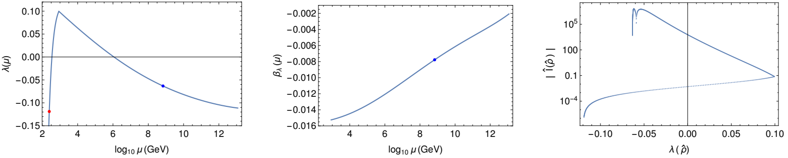
# Compare with analytical approximation

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

[Lee, Weinberg: NPB267, 1986]




$S_B^{\mathrm{approx}}$ works well for the SM




$S_B^{\mathrm{approx}}$ cannot be used for VLF

# Conclusions

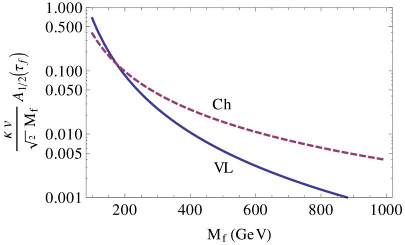
- Higgs vacuum is metastable in the SM
  - life-time is much much larger than the age of the universe
- Many BSM theories include VLFs
  - fermions can destabilize the vacuum (some interesting exceptions!)
  - we computed the renormalization group improved Higgs effective potential with VLFs present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

# BACKUP SLIDES

BACKUP SLIDES

# 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 : $S, T, U, h \to \gamma\gamma, gg \to h, \ldots$
    - 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

# Precision Electroweak Constraints

Precision Electroweak Constraints (S, T, $Zb\bar{b}$)
(perturbatively calculable on the warped side)


- Bulk gauge symm - $SU(2)_L \times U(1)$ (SM $\psi$, 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: $W'_\mu$, $Z'_\mu$, ...
  - 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: $t'$, $b'$, $\chi$, ...

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

# Warped Fermions

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

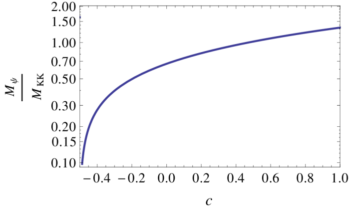
- Typical $c_{t_R}, c_{t_L}$ : $(-,+)$ top-partners "light"

  $c$ : 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 $\psi_{VL}$ : $\chi$, $T$
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 $\psi_{VL}$ : $\chi$, $T$, $\chi'$, $b'$, $\chi''$, $t''$, $b''$

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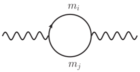
New $\psi_{VL}$ : $\chi$, $T$, $\chi'$, $b'$, $\chi''$, $t''$, $b''$

# EWPrecision + Higgs Observables

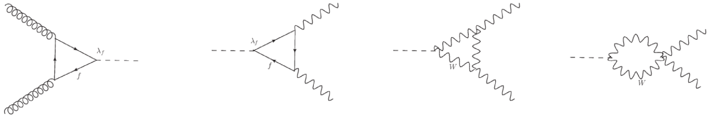
[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398, JHEP 2014]

Precision electroweak observables $(S, T, U)$




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

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



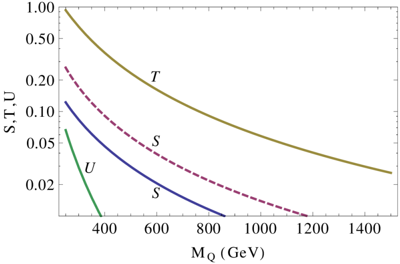

We compute ratios $\frac{\Gamma_{h\to gg}}{SM}$, $\frac{\Gamma_{h\to\gamma\gamma}}{SM}$ using leading-order expressions

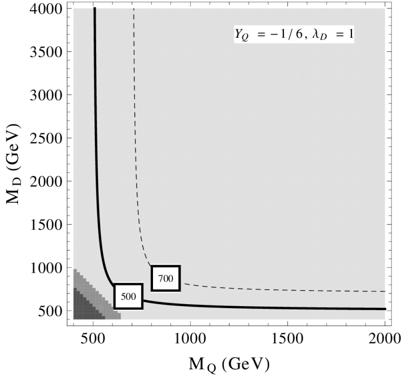
QCD corrections to ratios small: [Furlan '11] [Gori, Low '13]

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

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

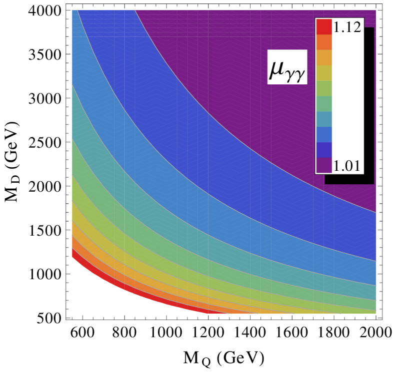
$Q + U$ model (ST Model like) : MVQD Model with $Y_\chi = -1/6$



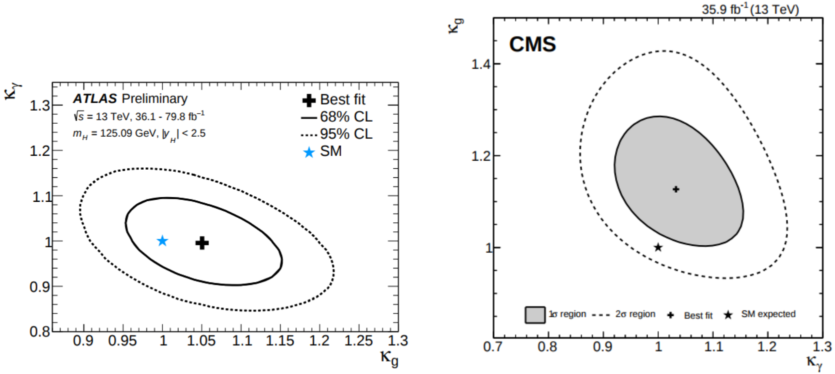

$\lambda_D = 1,\ M_D = M_Q,\ Y_Q = (1/6, -1/6)$ (solid, dashed)

# $Q + U$ model




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

# LHC constraints on Higgs couplings



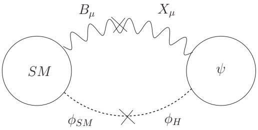

[ATLAS-CONF-2018-31] [CMS-HIG-17-031]

# Hidden sector DM $\psi$

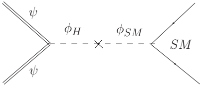
[SG, Lee, Wells 2009]

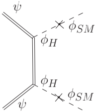
SM $\times U(1)_X$ :  $U(1)_X$ sector: $X_\mu, \Phi_{hid}, \psi$

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




**Higgs portal DM**: Self-annihilation




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

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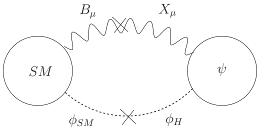


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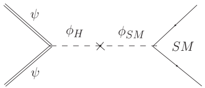
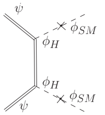
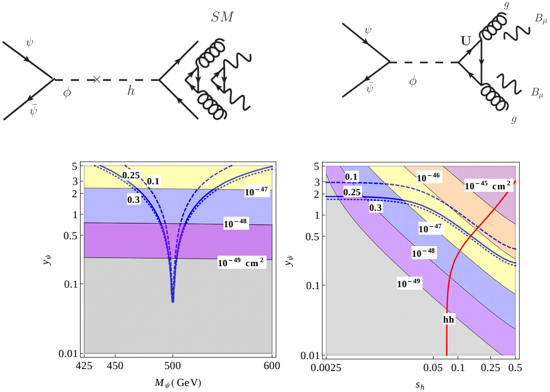



Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

# 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 $\tilde{y} \equiv y_\psi s_h \ll 1$