Search for scalar production through vector-like top quark loop at e^-e^+ colliders

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Overview

What are vector-like quarks?

- Left and right handed chiralities transform under the same way under the SM symmetries.
- Dirac mass term is allowed:

$$\mathcal{L}_M = -M\bar{\psi}\psi$$

- why they are called vector?
- A SM chiral quark couples only to left-handed charge current (V-A) interaction

$$J_L^{\mu+} = \bar{u}_L \gamma^\mu d_L = \bar{u}\gamma^\mu (1-\gamma^5) d = V - A$$
$$J_R^{\mu+} = 0$$

- Vector like quarks would couple to both the left-handed and right-handed charge current

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u}\gamma^\mu d = V$$

- They can mix with SM quarks

$$t' \to \times \to u_i \qquad b' \to \times \to d_i$$

VLQs appear in many beyond standard models

- **Composite Higgs models**
  VLQ appear as excited resonances of the bounded states which form SM particles
- **Little Higgs models**
  partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- **Non-minimal SUSY extensions**
  VLQs increase corrections to Higgs mass without affecting EWPT
- **extra-dimensions**
- **and so on.....**

Representations and lagrangian terms

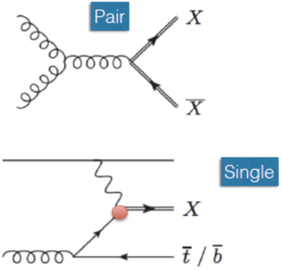
Assumption: vector-like quarks couple with SM quarks through Yukawa interactions

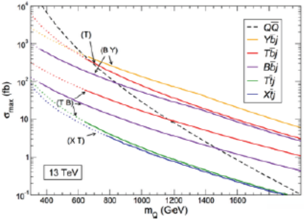
	SM	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(U)	(D)	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	-1/3	7/6	1/6	-5/6	2/3	-1/3
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	

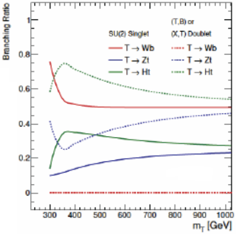
Luca Panizzi

How do they appear at colliders?

Production:







Limits depend on the branching ratios
—a function of mass and multiplet

Sadia Khalil,HEP Seminar, Mar 14, 2016

The Model

- Introduce gauge singlet scalar: S
- Introduce $SU(2)_L$ singlet vector-like top partner: T
- Only consider interactions with 3rd generation SM quarks: $Q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R$

$$\mathcal{L} \supset \mathcal{L}_{scalar} + \mathcal{L}_{Yukawa} + \mathcal{L}_{gauge}$$

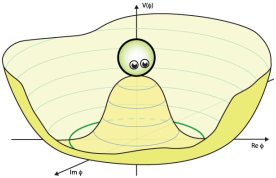
$$\begin{aligned} \mathcal{L}_{\rm scalar} &= \frac{1}{2}(D_\mu H)^\dagger (D^\mu H) + \frac{1}{2}\partial_\mu S\, \partial^\mu S - \mu^2 H^\dagger H + \lambda_H (H^\dagger H)^2 \\ &+ \frac{a_1}{2} H^\dagger H\, S + \frac{\lambda_{SH}}{2} H^\dagger H\, S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{\lambda_S}{4} S^4, \end{aligned}$$

$$\mathcal{L}_{\rm Yukawa} = y_M S \overline{T}_L^{\rm int} T_R^{\rm int} + y_t \overline{Q}_L^{\rm int} \widetilde{H} t_R^{\rm int} + y_b \overline{Q}_L^{\rm int} H b_R + y_T \overline{Q}_L^{\rm int} \widetilde{H} T_R^{\rm int}$$

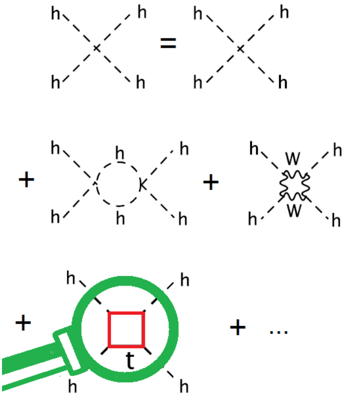
arXiv:1601.07208[hep-ph]

After electroweak symmetry breaking

- parameters a_1, b_1, b_3 are set to be zero.
- Two scalar mass eigenstates : h_1 , h_2
  with: $m_{h_1} = 125$ GeV$< m_{h_2}$ and $v_H = 246$ GeV$< v_S$
- Scalar mixing angle: θ
- Two fermion mass eigenstates : t, T with mass: $m_t = 173$GeV$< m_T$
- One independent fermion mixing angle : θ_L
  as $\tan\theta_R = \frac{m_t}{m_T}\tan\theta_L$

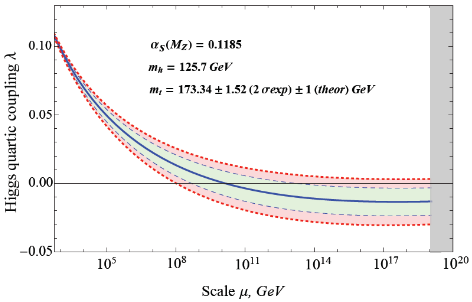


Vacuum stability in SM



$$V(\phi) = \mu^2(\phi^*\phi) + \lambda_H(\phi^*\phi)^2$$

$$\frac{d\lambda_H}{d\ln\mu^2} = \beta_{\lambda_H}^{\mathrm{SM}} = \frac{3}{4\pi^2}\left[\lambda_H^2 + \frac{1}{2}\lambda_H y_t^2 - \frac{1}{4}y_t^4 + \mathcal{B}(g,g')\right]$$

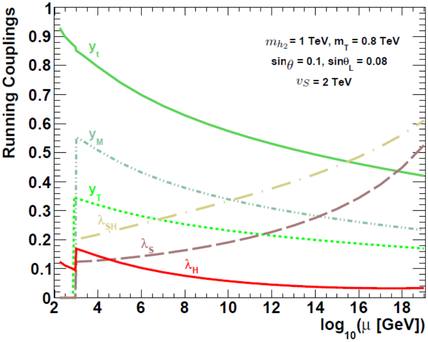


arXiv:1512.01222[hep-ph]

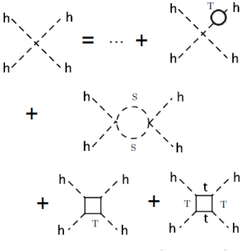
Vacuum stability in simplified model

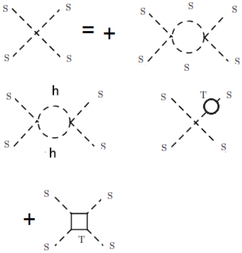
$$\frac{d\lambda_H}{d\ln\mu^2} = \beta_\lambda^{\rm SM} + \frac{1}{(4\pi)^2}\left[6\lambda_H y_T^2 + \frac{1}{4}\lambda_{SH}^2 - 3y_T^4 - 6y_t^2 y_T^2\right]$$

$$\frac{d\lambda_S}{d\ln\mu^2} = \frac{1}{(4\pi)^2}\left[9\lambda_S^2 + \lambda_{SH}^2 + 6y_M^2\lambda_S - 3y_M^4\right]$$

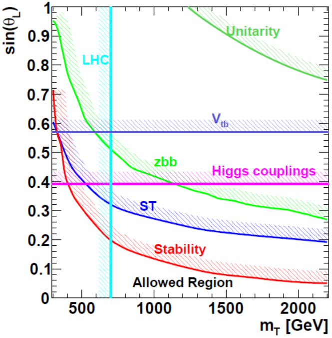


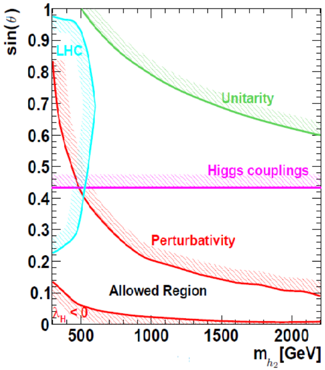
arXiv:1404.0681[hep-ph]





Constrain on parameter of the model

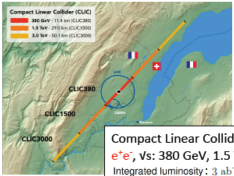




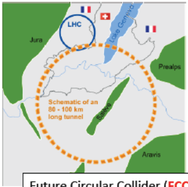
arXiv:1404.0681[hep-ph]

Proposed e^-e^+ colliders

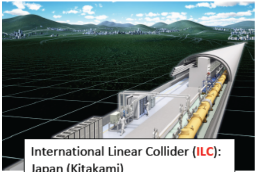
- With well-understood initial beam properties, the scattering kinematics is well-constrained.
- low backgrounds
- The e^-e^+ interaction is well understood within the standard model electroweak theory.



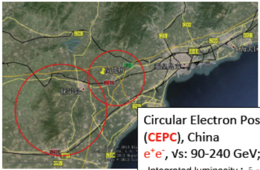
Compact Linear Collider (**CLIC**): CERN
e^+e^-, √s: 380 GeV, 1.5 TeV, 3 TeV
Integrated luminosity : $3\ \mathrm{ab}^{-1}$



Future Circular Collider (**FCC-ee**): CERN
e^+e^-, √s: 90 - 350 GeV: FCC-hh pp
Integrated luminosity : $5\ \mathrm{ab}^{-1}$



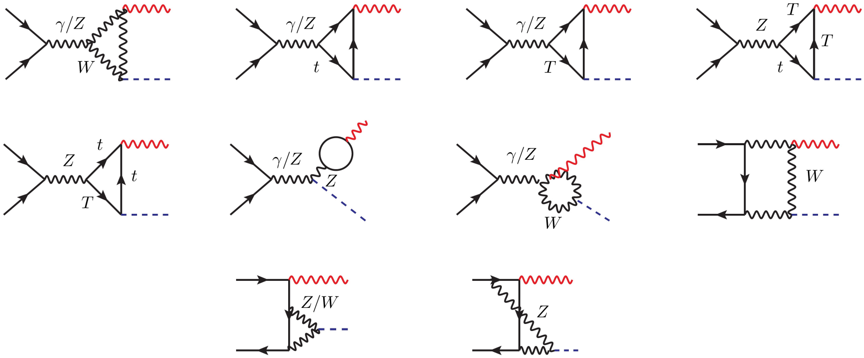
International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, √s: 250 – 500 GeV (1 TeV)
Integrated luminosity : $2\ \mathrm{ab}^{-1}$



Circular Electron Positron Collider (**CEPC**), China
e^+e^-, √s: 90-240 GeV; SPPC pp,
Integrated luminosity : $5\ \mathrm{ab}^{-1}$

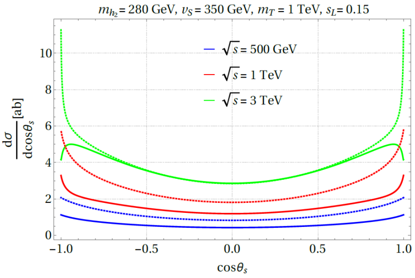
Lucie Linssen

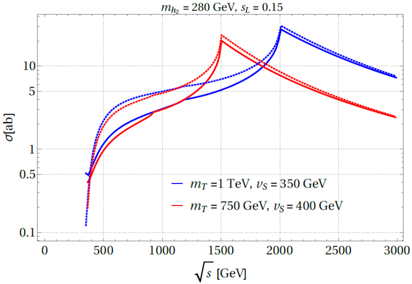
$e^- e^+ \to h_2 \gamma$



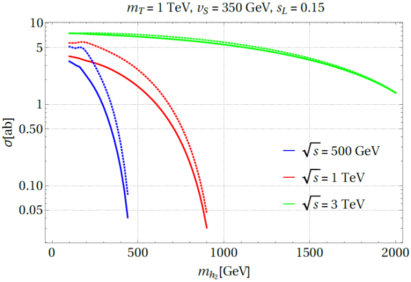
Cross section of $e^- e^+ \to h_2\gamma$

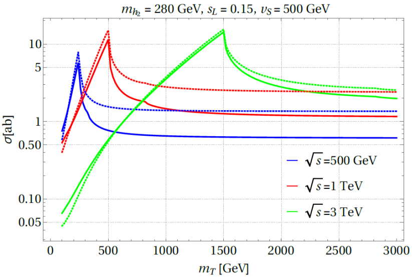
- Solid$\to$ $s_\theta = 0.15$ and Dotted$\to$ $s_\theta = -0.15$
- The distribution is forward-backward symmetric
- Cross section is maximal near the TT threshold



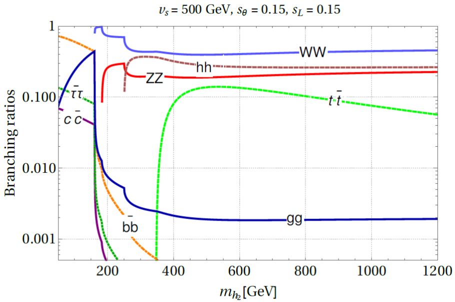


Cross section of $e^- e^+ \to h_2 \gamma$





Branching ratios of h_2



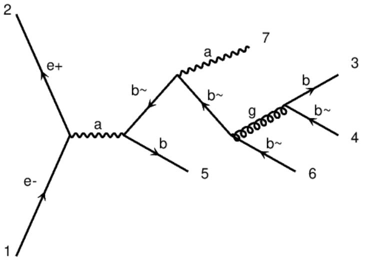
ZZ mode [Br %]	$t\bar{t}$ mode [Br %]	WW mode [Br %]	hh mode [Br %]
$(ll)(l'l')$[1%]	$(l\nu_l b)(q\bar{q}'b)$[44%]	$(l\nu_l)(q\bar{q}')$[44%]	$(b\bar{b})(b\bar{b})$[34%]
$(ll)(q\bar{q})$[14%]	$(l\nu_l b)(l'\nu_{l'}b)$[10%]	$(l\nu_l)(l'\nu_{l'})$[10%]	$(b\bar{b})(ll)$[7%]
$(ll)(\nu_{l'}\nu_{l'})$[4%]	$(q\bar{q}'b)(q\bar{q}'b)$[46%]	$(q\bar{q}')(q\bar{q}')$[46%]	$(ll)(ll)$[0.4%]
$(q\bar{q})(q'\bar{q}')$[49%]	.....	.....	$(b\bar{b})(\gamma\gamma)$[0.3%]
$(q\bar{q})(\nu\bar{\nu})$[28%]	.....	.....	$(ll)(\gamma\gamma)$[0.03%]
$(\nu\bar{\nu})(\nu\bar{\nu})$[4%]	.....	.....	$(WW)(WW)$[5%]

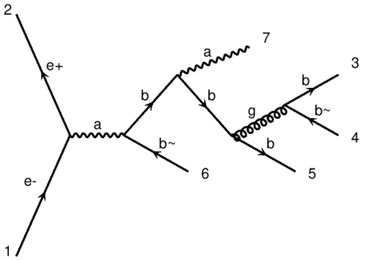
- We consider $e^-e^+ \to h_2\gamma \to hh\gamma \to (b\bar{b})(b\bar{b})\gamma$.

Backgrounds

Main backgrounds:

- $e^+e^- \to 4b + \gamma$.
- $e^+e^- \to 2b + 2j + \gamma$ $(j = u, d, s, c, g)$.
- $e^+e^- \to 4j + \gamma$ $(j = u, d, s, c, g)$.





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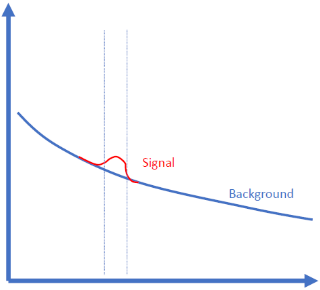
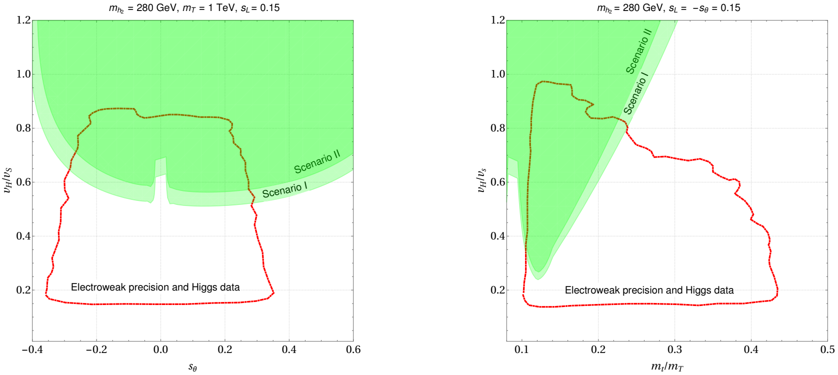


Cuts:

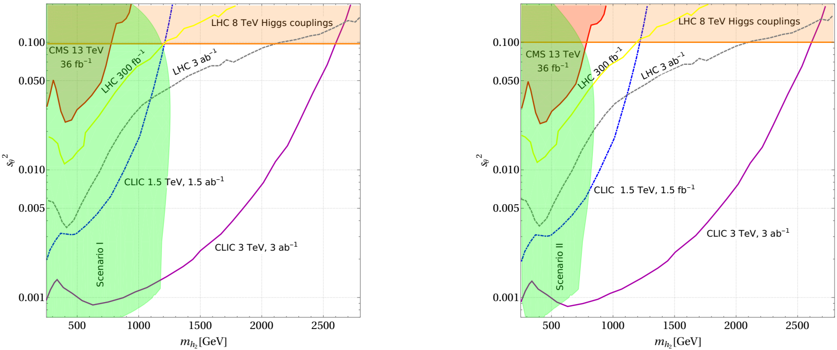
- $p_{T,jet} > 20$ GeV, $|\eta| < 2.5$.
- $\Delta R(i,j) > 0.4$
- $p_{T\gamma} > 300$ GeV, $|\eta| < 2.5$.
- $m_h - 25 \leq m_{b\bar{b}} \leq m_h + 25$GeV,

$\sigma_{BG}|_{\text{After cut}} \sim 10^{-5}\sigma_{BG}|_{\text{Before cut}}$

95% C.L. probed regions of s_θ vs v_H/v_s and m_t/m_T vs v_H/v_s at $\sqrt{s} = 3$ TeV and $\mathcal{L} = 3\,\mathrm{ab}^{-1}$



95% C.L. probed regions of m_{h_2} vs s_θ^2 at $\sqrt{s} = 3$TeV and $\mathcal{L} = 3\,\mathrm{ab}^{-1}$



Summary

- The model is well-motivated as it provide the posibility to stabilize the electroweak vacuum
- Larger signal efficiency can probe a bulk of allowed parameter space by the LHC data.
- We can improve the sensitivity by:
  - Considering other decay modes of the particles.
  - Considering the other decay channels of h_2.
  - Using various kinematic variables and multivariate techniques.
- scalar plus photon production at lepton collider would be a complementary channel to the results obtained from the combination of electroweak precision tests and LHC Higgs data.

Thank you