Testing Vector-like Quarks via Higgs Pair Production at NLO

Haiying Cai

IPNL, Universite Lyon 1

Work in preparation

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Motivation for VLQs

Vector-Like Quarks exist in several BSM scenarios: Little Higgs Models, Extra Dimensions, Strong dynamics and so on.

In Little Higgs model and Composite Higgs Model, vector-like top partners play the role of stabilising the Electroweak symmetry breaking.

Vector-like quarks may interplay with new coloured scalars, heavy vectors, possible to generate rich phenomenology.

The simplest scenario is vector-like quark mix with light SM quarks via Yukawa interaction, thus contribute to exotic Higgs pair production.

Types of VLQ and Yukawa Interactions

[Aguila, Victoria and Santiago, 2000]

	Singlet	Doublet			Triplet	
	$T \quad B$	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
$SU(2)_L$	1	2			3	
$U(1)_Y$	2/3 -1/3	1/6	7/6	-5/6	2/3 -1/3	
$\mathcal{L}_Y$	$-\frac{\lambda_u v}{\sqrt{2}}\bar{u_L}T_R$ $-\frac{\lambda_d v}{\sqrt{2}}\bar{d_L}B_R$	$-\frac{\lambda_u v}{\sqrt{2}}\bar{T_L}u_R$ $-\frac{\lambda_d v}{\sqrt{2}}\bar{B_L}d_R$			$-\frac{\lambda_u v}{\sqrt{2}}\bar{u_L}T_R$ $-\lambda_u v\bar{d_L}B_R$	

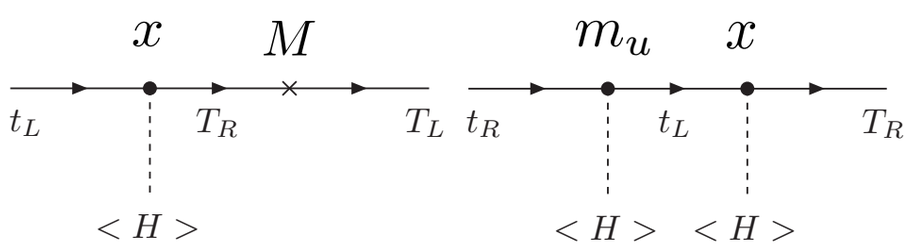
Yukawa mixing of T/B and SM quark

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix} = \begin{pmatrix} m_u & 0 \\ 0 & m_T \end{pmatrix}$$

M is the Dirac mass for vector-like quark

Mixing Patterns

Singlet/Triplet VLQ mixing



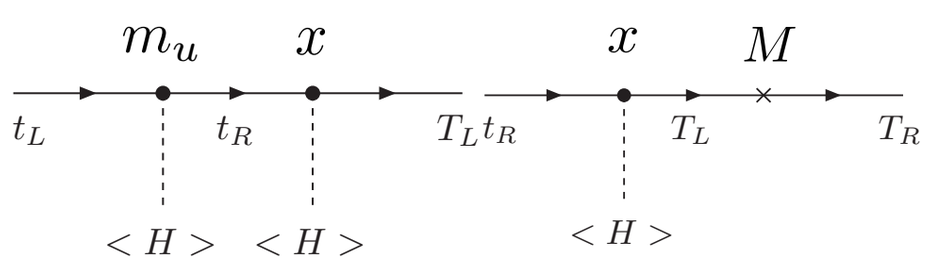
$\sim \frac{x}{M}$ $\sim \frac{m_u}{M}\frac{x}{M}$

$$\sin\theta_u^L = \frac{Mx}{\sqrt{(M^2-m_u^2)^2+M^2x^2}}$$

$$\sin\theta_u^R = \frac{m_u}{M}\sin\theta_u^L$$

mainly left handed mixing

(Non) SM Doublet VLQ mixing



$\sim \frac{m_u}{M}\frac{x}{M}$ $\sim \frac{x}{M}$

$$\sin\theta_u^R = \frac{Mx}{\sqrt{(M^2-m_u^2)^2+M^2x^2}}$$

$$\sin\theta_u^L = \frac{m_u}{M}\sin\theta_u^R$$

mainly right handed mixing

Interplay of 2 VLQs

Case A: 2 doublets mixing

$$\begin{pmatrix} m_u & & & & \\ & m_c & & & \\ & & m_t & & \\ y_1^1 & y_1^2 & y_1^3 & M_1 & \\ y_2^1 & y_2^2 & y_2^3 & & M_2 \end{pmatrix}$$

Left and right rotations exchanged

Case B: 2 singlets/triplets mixing

$$\begin{pmatrix} m_u & & & x_1^1 & x_2^1 \\ & m_c & & x_1^2 & x_2^2 \\ & & m_t & x_1^3 & x_2^3 \\ & & & M_1 & \\ & & & & M_2 \end{pmatrix}$$

Case C: 1 singlet/triplet and 1 doublet mixing

$$\begin{pmatrix} m_u & & & & x_2^1 \\ & m_c & & & x_2^2 \\ & & m_t & & x_2^3 \\ y_1^1 & y_1^2 & y_1^3 & M_1 & \omega \\ & & & \omega' & M_2 \end{pmatrix}$$

[Cacciapaglia, Deandrea, Gaur, Harada, Okada, Panizzi 2015]

Degenerate Bi-doublet Model

[Atre, Carena, Han and Santiago, 2000]

One special case is 2 vector-like quark $SU(2)_L$ doublets with hypercharges 1/6 and 7/6.

$$Q^{(0)}_{L,R} = \begin{pmatrix} T^1_{L,R} \\ B_{L,R} \end{pmatrix}_{1/6}, \quad \chi^{(0)}_{L,R} = \begin{pmatrix} X_{L,R} \\ T^2_{L,R} \end{pmatrix}_{7/6},$$

Defiining $T = \frac{1}{\sqrt{2}}\left(T^1 + T^2\right)$ and $T' = \frac{1}{\sqrt{2}}\left(T^1 - T^2\right)$

$$\mathcal{L}_m = \begin{pmatrix} \bar{u}_L & \bar{T}_L & \bar{T}'^{-}_L \end{pmatrix} \begin{pmatrix} \lambda_u \frac{v}{\sqrt{2}} & 0 & 0 \\ \lambda_Q v & m_Q & 0 \\ 0 & 0 & m_Q \end{pmatrix} \begin{pmatrix} u_R \\ T^+_R \\ T'^{-}_R \end{pmatrix} + h.c.$$

This model gives one heavy Top mainly couple to Higgs and another heavy Top mainly couple to Z-boson. Due to sole mixing with u-quark

Maximise the branching ratio of T decay into Higgs plus jet !

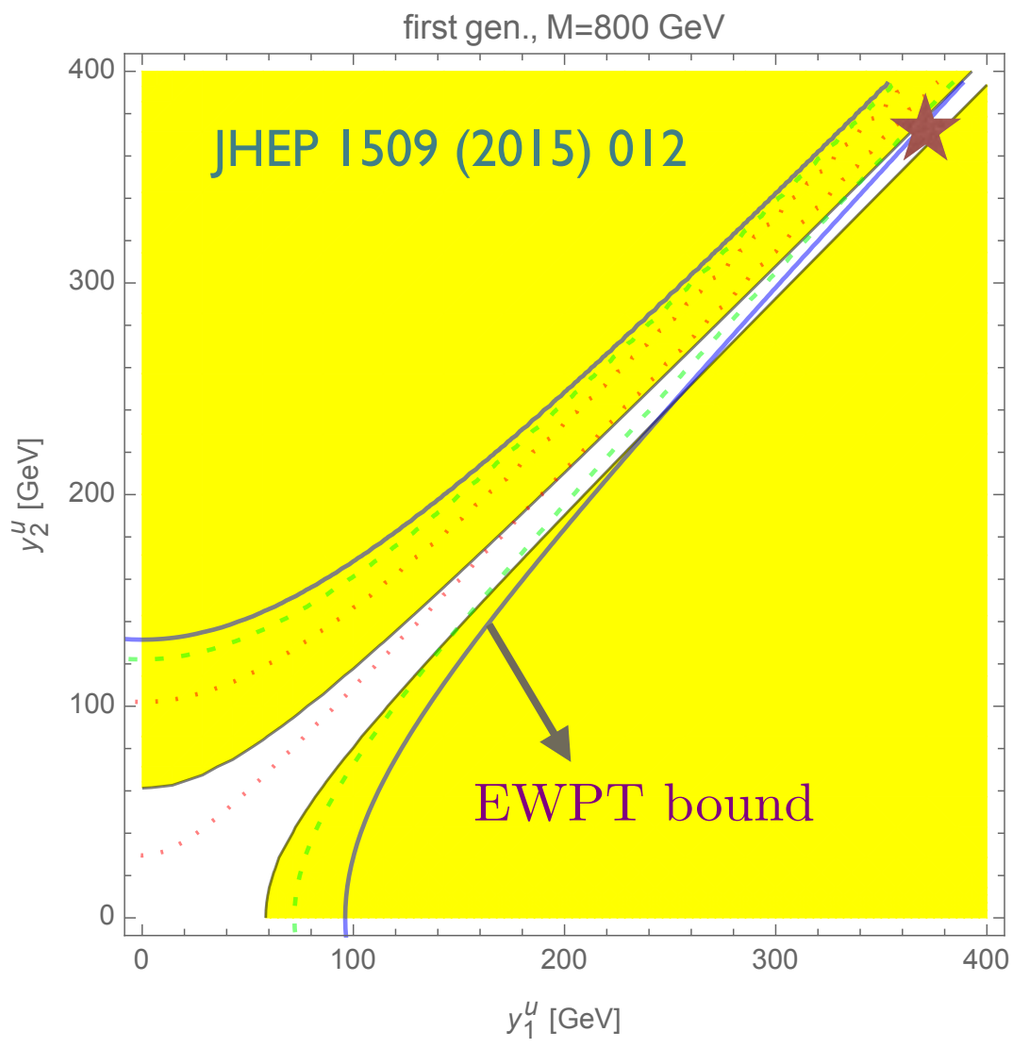
Effective Lagrangian

[Les Houches proceeding, 2015]

$$
\begin{aligned}
\mathcal{L}_{\rm eff} &= \frac{\sqrt{2}g}{2}\Big[\bar{Y}\not{W}\Big(\kappa_L^Y P_L + \kappa_R^Y P_R\Big)d + \bar{B}\not{W}\Big(\kappa_L^B P_L + \kappa_R^B P_R\Big)u \\
&+ \bar{T}\not{W}\Big(\kappa_L^T P_L + \kappa_R^T P_R\Big)d + \bar{X}\not{W}\Big(\kappa_L^X P_L + \kappa_R^X P_R\Big)u\Big] \\
&+ \frac{g}{2c_W}\Big[\bar{B}\not{Z}\Big(\tilde{\kappa}_L^B P_L + \tilde{\kappa}_R^B P_R\Big)d + \bar{T}\not{Z}\Big(\tilde{\kappa}_L^T P_L + \tilde{\kappa}_R^T P_R\Big)u\Big] \\
&- h\Big[\bar{B}\Big(\hat{\kappa}_L^B P_L + \hat{\kappa}_R^B P_R\Big)d + \bar{T}\Big(\hat{\kappa}_L^T P_L + \hat{\kappa}_R^T P_R\Big)u\Big] + \text{h.c.}\ ,
\end{aligned}
$$

For H-T-u and H-B-d, we parameterize $\hat{\kappa}_{L,R}^T = \kappa\frac{M_T}{v}$ and $\hat{\kappa}_{L,R}^B = \kappa'\frac{M_B}{v}$, to charactrize the linear mass dependence of the couplings.

Bounds on Kappa in Bi-doublet



Yellow band excluded by atomic parity violation

EWPT bound is more stringent

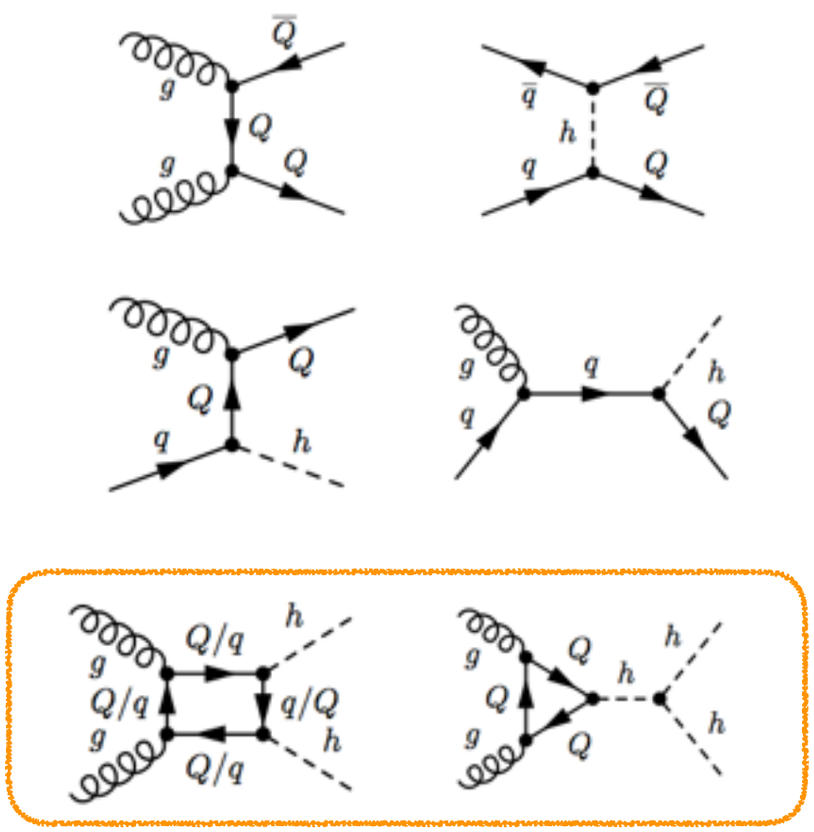
$\kappa \sim \sqrt{2}\frac{y}{M_T}$ constrained to be $\lesssim 1.0$

with only mild dependence on M_T

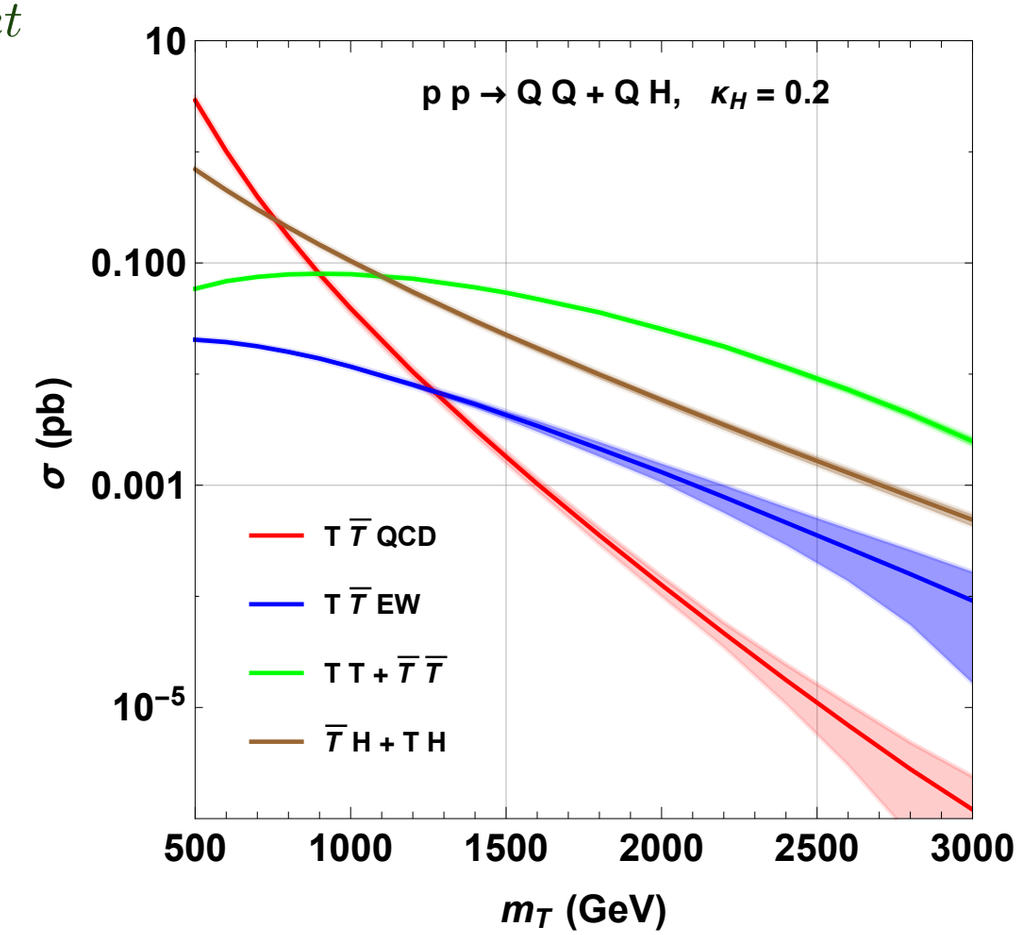
EW process competitive with QCD process !

NLO Cross Section at LHC Run II

VLQ induced di-Higgs production, $Q(\bar{Q}) \to h + jet$



very small compared with VLQ Induced signals

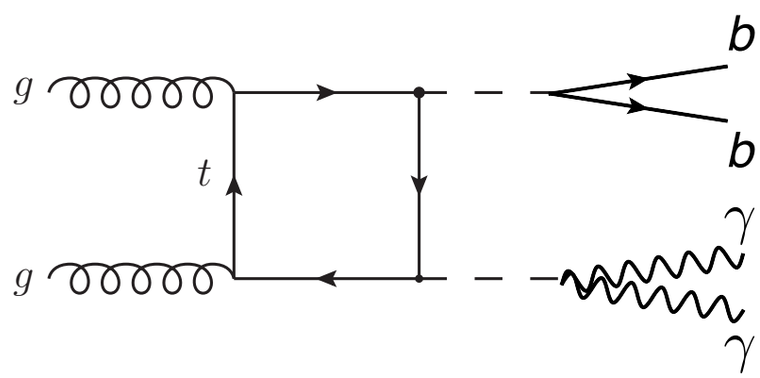


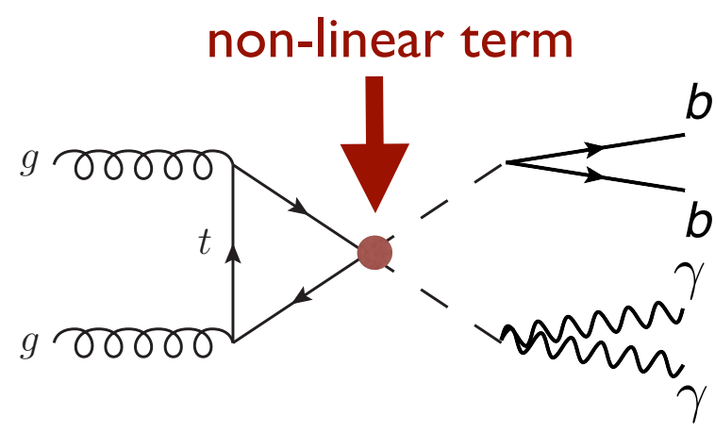
PDF uncertainty and scale uncertainty added in quadrature

QCD and EW interference effect in $q\bar{q} \to T\bar{T}$ ignored.

2b 2γ Channel

This channel benefits both from large $\mathcal{B}(h \to b\bar{b})$ and the clean di-photon signal, since the signal $m_{\gamma\gamma}$ will peak on top of a continuum spectrum.





2b 2γ is promising to explore the non-linear coupling from composite Higgs model.

[Contino, Ghezzi, Moretti, Panico, Piccinini and Wulzer, 2000]

VLQ model induce larger di-Higgs signals, at high luminosity LHC, for mT < 1 TeV
2b 2γ channel is more sensitive to BSM effects than other channels.

We generate signal events at QCD NLO by Madgraph5 and interface with pythia8 for parton shower, then use Fastjet package for jet clustering.

Signal vs. BKG I

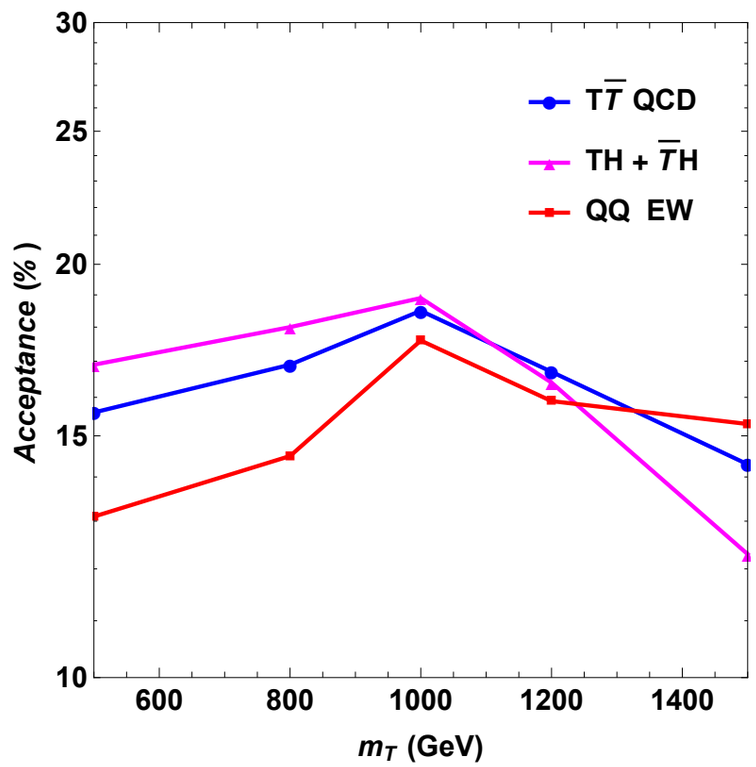
$m_T = 500$ GeV, 20.0fb^{-1}	$T\bar{T}$ (QCD)	QQ (EW)	$TH + \bar{T}H$	$gg \to HH$
$2b-$tagged, $\lvert\eta^b\rvert < 2.5$ $p_T^{b1(b2)} > 55(35)$ GeV	46.8	1.28	9.58	0.165
2γ, $\lvert\eta^\gamma\rvert < 2.37$ $E_T^{\gamma 1(\gamma 2)}/m_{\gamma\gamma} > 0.35(0.25)$	34.3	0.94	6.32	0.109
$95 < m_{bb} < 135$ GeV $105 < m_{\gamma\gamma} < 160$ GeV	23.74	0.68	4.75	0.087
Acceptance	15.6%	16.9%	13.1%	11.7%

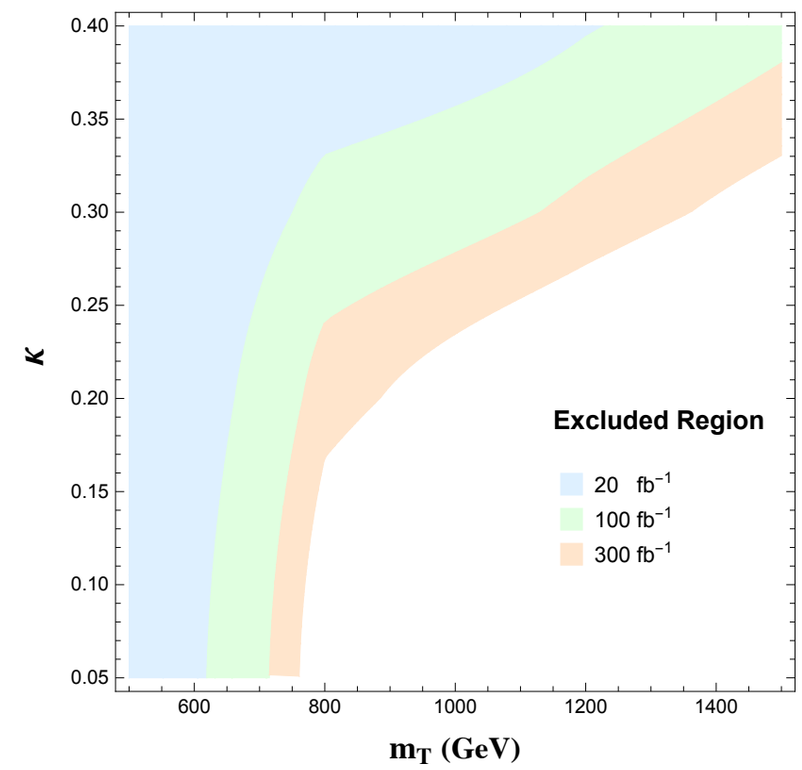
main BKG

	m_T (TeV)		$b\bar{b}\gamma\gamma$	$c\bar{c}\gamma\gamma$	$b\bar{b}H$	ZH
	0.5	1.0				
$2b-$tagged, $\lvert\eta^b\rvert < 2.5$ $p_T^{b1(b2)} > 55(35)$ GeV	57.8	3.77	1811	287	0.14	0.409
2γ, $\lvert\eta^\gamma\rvert < 2.37$ $E_T^{\gamma 1(\gamma 2)}/m_{\gamma\gamma} > 0.35(0.25)$	41.6	3.05	1320	220	0.081	0.244
$95 < m_{bb} < 135$ GeV $105 < m_{\gamma\gamma} < 160$ GeV	29.3	2.23	14.04	2.43	0.0055	0.0165
$S/\sqrt{B}$	7.28	0.55	—	—	—	—

Table : The significance of $S/\sqrt{B}$ at NLO with $\kappa = 0.2$, given for an integrated luminosity of $\int Ldt = 20.0$ fb^{-1} at a $\sqrt{s} = 13$ TeV LHC. The b-tag efficiency is set to be $\epsilon_b = 70\%$ and $\epsilon_{c\to b} = 10\%$.

Cut Efficiency and Sensitivity

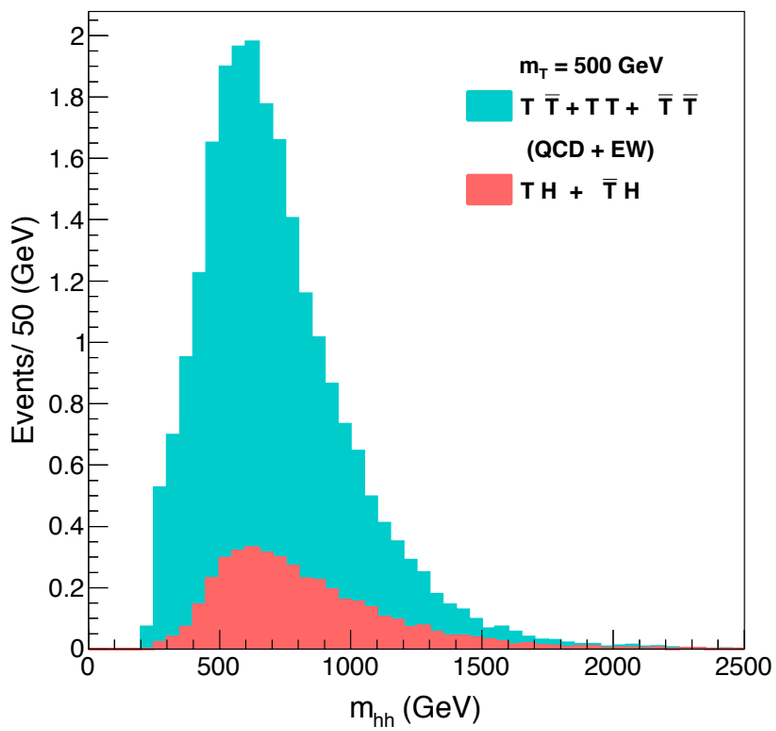


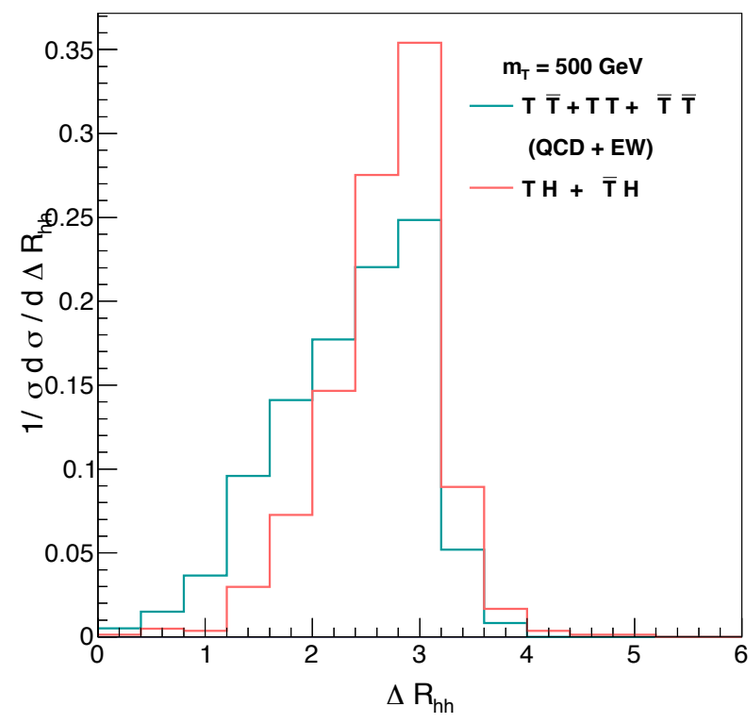


The cut efficiency is optimised at $m_T = 1000$ GeV.

The direct search (3 σ exclusion) puts a stronger bound than EWPT.

Kinematic distributions





The m_{hh} distribution at NLO peaks between m_T and 2 m_T

Additional cut $p_T^{h1} > 200$ GeV and $p_T^{h2} > 150$ GeV is imposed

4b Channel

The channel has the largest branching ratio around 33 %, yielding more events than other channels , but there is overwhelming b-enriched QCD backgrounds.

Higgs is decayed from a heavy VLQ, the b quark-antiquark pair collimates into a cone size of R ~ 2 mH/pT; for mT < 1 TeV, ATLAS resolved analysis is applicable.

- 4 b-tagged R=0.4 jets with $p_T > 40$GeV and $\eta < 2.5$, the b-tag effeciency is set to be 0.7.
- 2 di-bjets need to be reconstructed to be di-Higgs candidates, for the signal selection, we require $X_{hh} < 1.6$.
- $\Delta R_{bb} < 1.5$ and $p_T^{h1} > 200$ GeV, $p_T^{h2} > 150$ GeV.

$$X_{hh} = \sqrt{\left(\frac{m_{h1} - 124\ \mathrm{GeV}}{0.1\, m_{h1}}\right)^2 + \left(\frac{m_{h2} - 115\ \mathrm{GeV}}{0.1\, m_{h2}}\right)^2}$$

Signal vs. BKG II

Madgraph5 @ NLO / pythia8 / Fastjet

$M_T = 500$ GeV, 1.0fb^{-1}	$T\bar{T}$ (QCD)	QQ (EW)	$TH + \bar{T}H$	$gg \to HH$
$4b-$ tagged $p_T^b > 40$ GeV, $\lvert\eta^b\rvert < 2.5$	78.1	2.01	14.5	0.19
$\Delta R_{bb(h)} < 1.5$ $p_T^{h1(h2)} > 200(150)$ GeV	37.7	1.22	7.93	0.07
$x_{hh} < 1.6$	20.3	0.67	4.65	0.045
Acceptance	2.1%	2.6%	2.0%	1.0%

	m_T (GeV)			ATLAS BKG
	500	800	1000	
$4b-$ tagged $p_T^b > 40$ GeV, $\lvert\eta^b\rvert < 2.5$	303.4	44.8	20.86	—
$\Delta R_{bb(h)} < 1.5$ $p_T^{h1(h2)} > 200(150)$ GeV	150.1	32.37	15.58	—
$x_{hh} < 1.6$	82.12	18.49	8.95	47.6
$S/\sqrt{B}$	11.9	2.68	1.29	—

Table : The significance of $S/\sqrt{B}$ at NLO with $\kappa = 0.2$, given for an integrated luminosity of $\int Ldt = 3.2$ fb^{-1} at a $\sqrt{s} = 13$ TeV LHC. The b-tag efficiency is set to be $\epsilon_b = 70\%$.

Boost search

For large mass VLQ, the boost analysis is optimised, jet substructure technique is employed to reduce the QCD contamination.

The definition of N-subjettiness: [Thaler and Tilburg , JHEP 03 (2011)]

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

This quantity measures how close a fat-jet to be N-prong

For a fat-jet contains 2-prong, the ratio of $\tau_{21} = \tau_2/\tau_1$ is small.

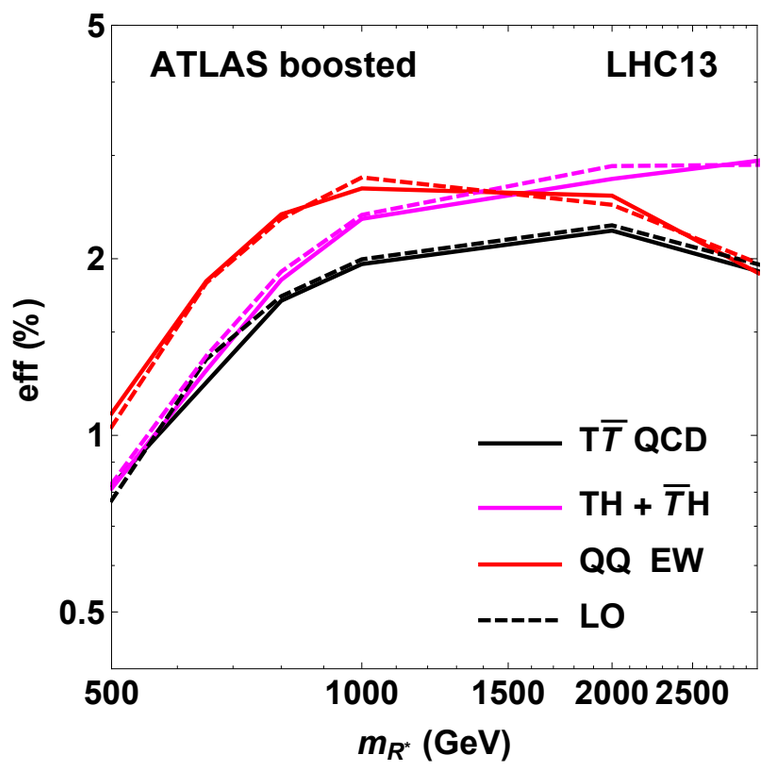
H. Cai, A.Carvalho, D.Majumder, work in progress

Following the large-R ATLAS analyses, we define a Higgs fat-jet J_H as anti-Kt jet with $R = 0.8$ that passes the following basic selection:

$$\eta_{J_H} < 2.4; \qquad 250 < p_T < 2500 \text{ GeV}; \qquad m_{J_H} > 50 \text{ GeV}$$

Large-R jet analysis

Madgraph5 @NLO, pythia8 and Delphes.



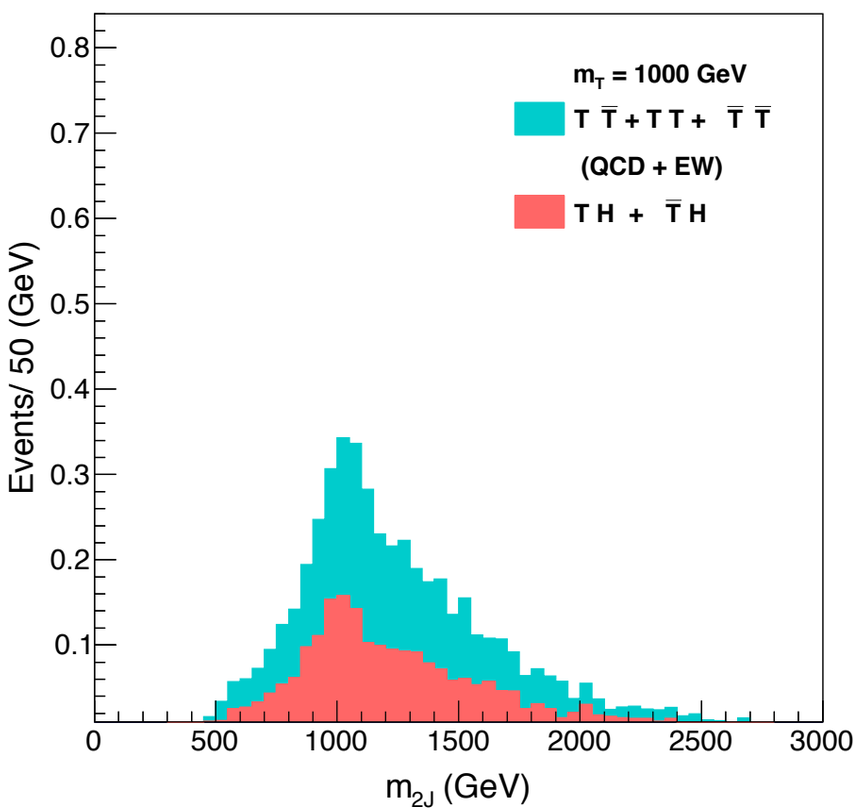
Using the ATLAS reconstruction

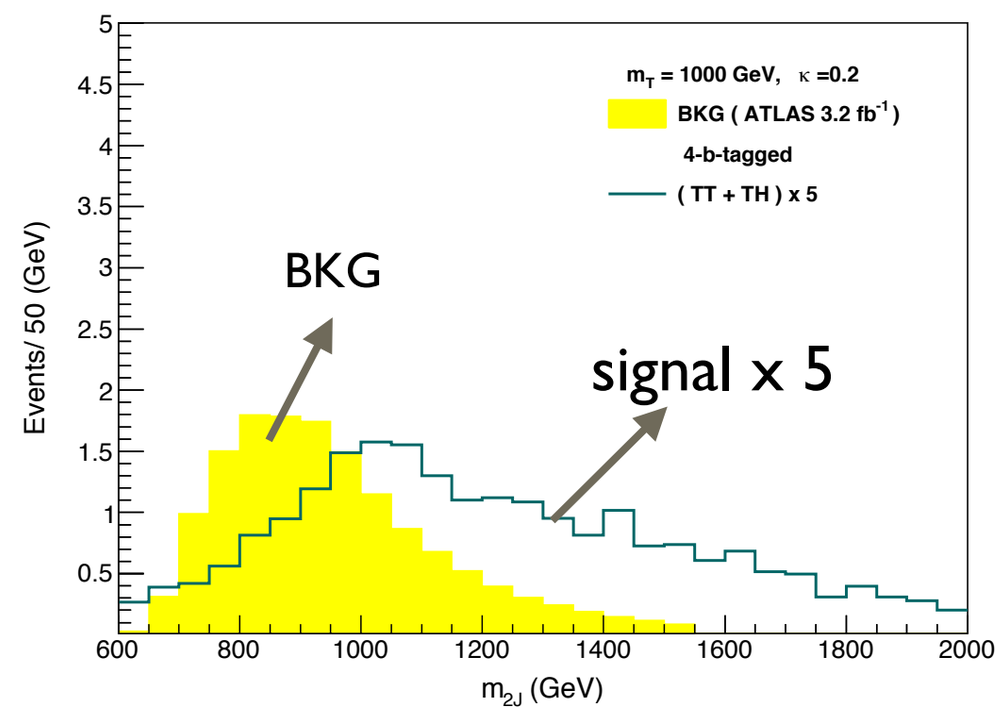
- 2 large-R jets satisfying ATLAS Higgs-jet pre-selection
- $\Delta\eta_{JJ} < 1.7$ as the Higgs-jet is mostly central production
- $\tau_{21} = \tau_2/\tau_1 < 0.6$, with 2-subjets
- $X_{hh} < 1.6$ as the signal region condition

Assume each Large-R jet contains 2 b-jets, with b-tag efficiency set to be 0.7

M_{2J} distribution

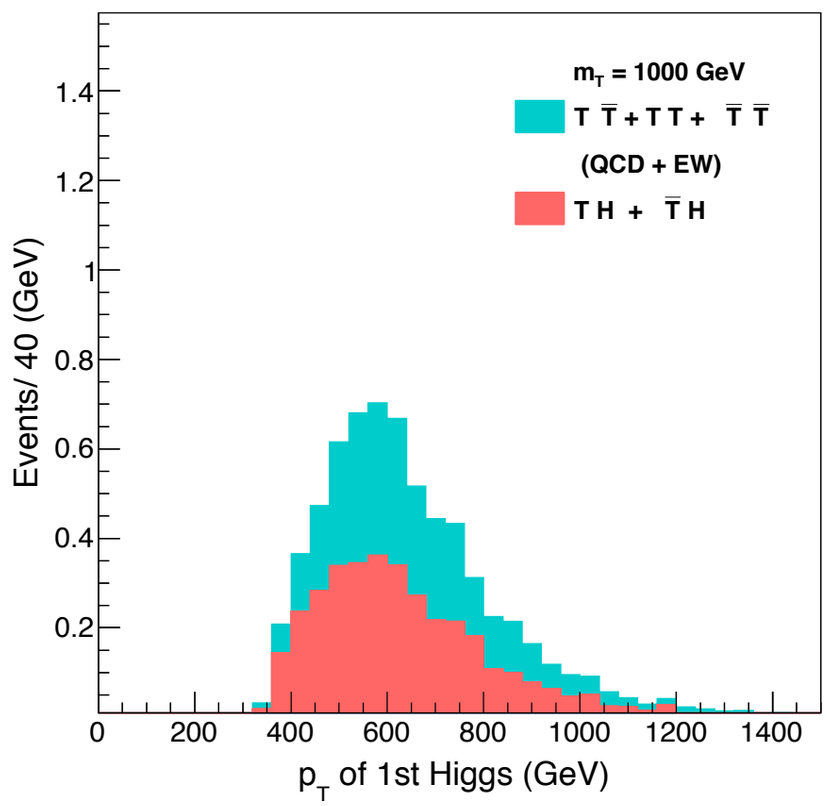
The Signal is compared with ATLAS BKG analysis in PRD. 94. 052002

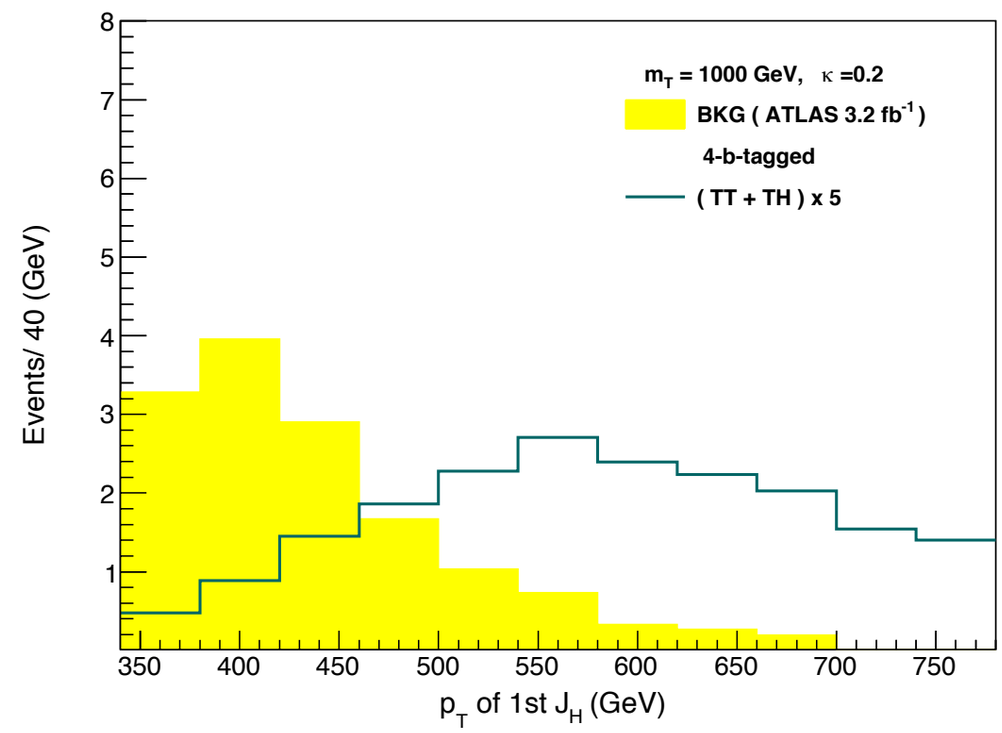




Leading H-Jet Pt distribution

The single VLQ + H EW production is important for large kappa value





Leading H-jet pT > 350 GeV

Conclusions

- We explore exotic di-Higgs production induced by vector-like quark (VLQ) mixing with light SM quarks, where the EW contribution can play an important role.
- For mT ~ 500 GeV, 2b 2 gamma channel has larger sensitivity than other channels due to the clean diphoton signal, put stronger exclusion limit on VLQ models than the EWPT constraint.
- For the 4b channel, the resolved analysis is applicable to the small VLQ mass region; while for high VLQ mass, boost effects make events have simple topology, we can use jet substructure for an effective analysis.
- The boost analysis applies to other processes, e.g. single VLQ plus jet production.