Electroweak Testing of Vector-like Quarks and Higgs-boson Pair Production at NLO

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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 quarks 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 interaction is determined by EW Symmetry

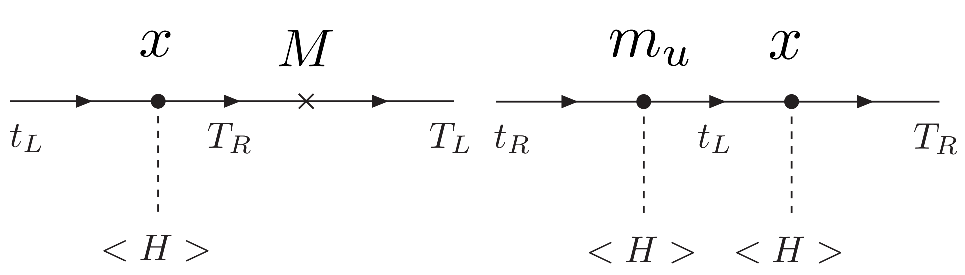
Yukawa mixing of T/B and SM quark

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

M is the Dirac mass for vector-like quark

Mixing Patterns

Singlet/Triplet VLQ mixing



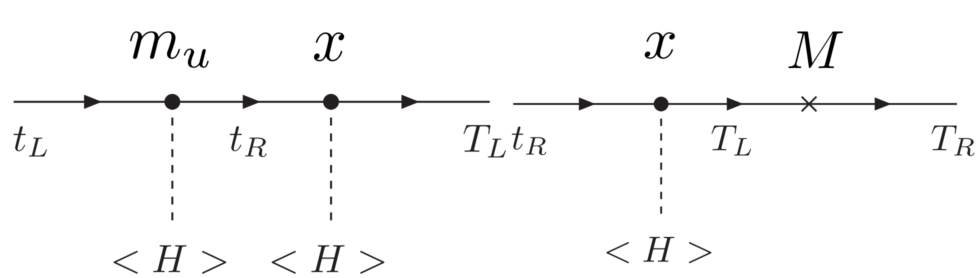
$\sim \frac{x}{M}$ $\sim \frac{m_u}{M}\frac{x}{M}$

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

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

mainly left handed mixing
right handed mixing suppressed

(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

In a realistic set-up, there exit more than one VLQ multiplets, which change branching ratio and loosen the corresponding experimental constraints.

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]

Effective Lagrangian

[Les Houches proceeding, 2015]

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

These interactions give decay channels: $T/B \to Wq, Zq, Hq$, $X/Y \to Wq$.

For H-T-u and H-B-d, we parameterise $\hat{\kappa}_{L/R}^{T/B} = \sqrt{2}\frac{M_{T/B}}{v_{\rm SM}}\kappa_{T/B}\sqrt{\zeta^i/2\Gamma_h^0}$, $2\Gamma_h^0 \sim 1$ for $M_{T/B} \sim \mathcal{O}(\text{TeV})$, to characterise the linear mass dependence, so that $\kappa_{T/B}$ is proportional to mixing angle between VLQ and SM quarks.

Degenerate Bi-doublet Model

Atre, Carena, Han and Santiago, 2009 (Original Model)

One special case is 2 vector-like quark $SU(2)_L$ doublets carrying hypercharges of 1/6 and 7/6, with mixing terms of $\bar{Q}_L^{(0)}(y_1 \;\; 0)^T u_R + \bar{\chi}_L^{(0)}(0 \;\; y_2)^T u_R$:

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

New parameter in a generalised bi-doublet model

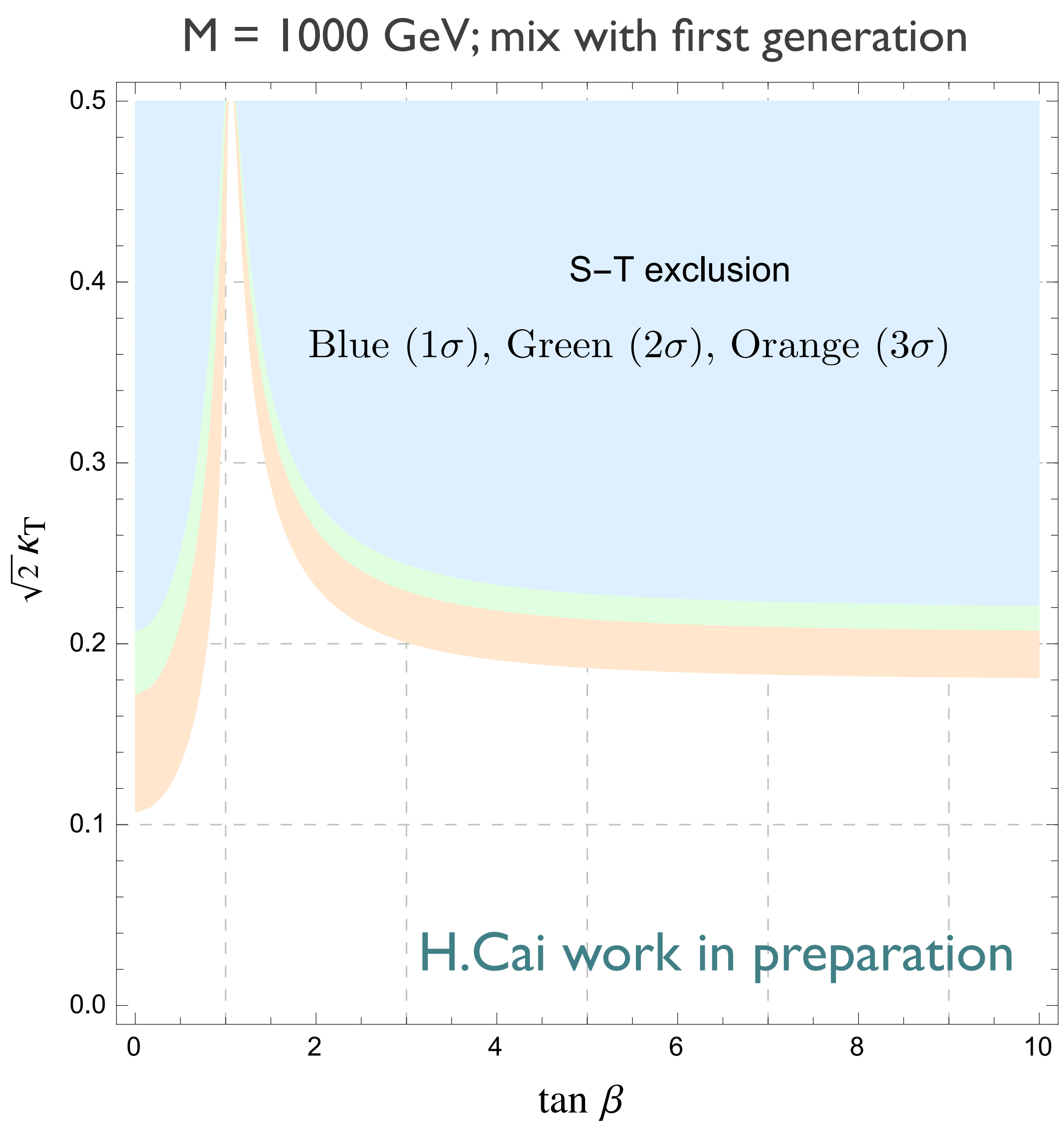
Defiine $T = \cos\beta T^1 + \sin\beta T^2$, $T' = \sin\beta T^1 - \cos\beta T^2$, with $\tan\beta = y_2/y_1$.

$$\mathcal{L}_m = \begin{pmatrix} \bar{u}_L & \bar{T}_L & \bar{T}'_L \end{pmatrix} \begin{pmatrix} \frac{m_u^{(0)}}{\sqrt{y_1^2 + y_2^2}} & 0 & 0 \\ & m_Q & 0 \\ 0 & 0 & m_Q \end{pmatrix} \begin{pmatrix} u_R \\ T_R \\ T'_R \end{pmatrix} + h.c.$$

In the case of $y_1 = y_2$, this model gives one top partner mainly couple to Higgs and one top partner mainly couple to Z-boson. Due to sole mixing with u-quark

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

S and T Bound for Bi-doublet



T-u-h: $\hat{\kappa}_R^T = \sqrt{2}\frac{M_T}{v}\kappa_T$, $\sqrt{2}\kappa_T = \sin\phi_R \cos\phi_R$.

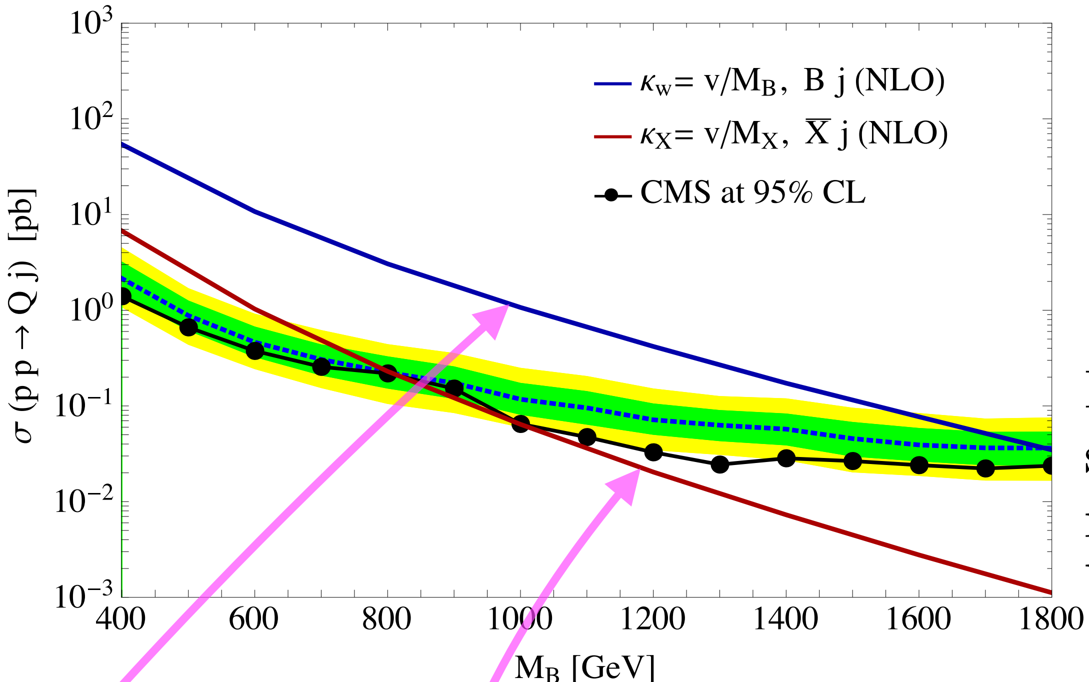
For $\tan\beta \neq 1$, EWPT bound is stringent, with only mild dependence on VLQ bare mass M_Q.

In special case $\tan\beta = 1$: $\Delta T \sim 0$ and the $\log(m_u^2/M^2)$ term disappears in ΔS, EWPT bound is very loose.

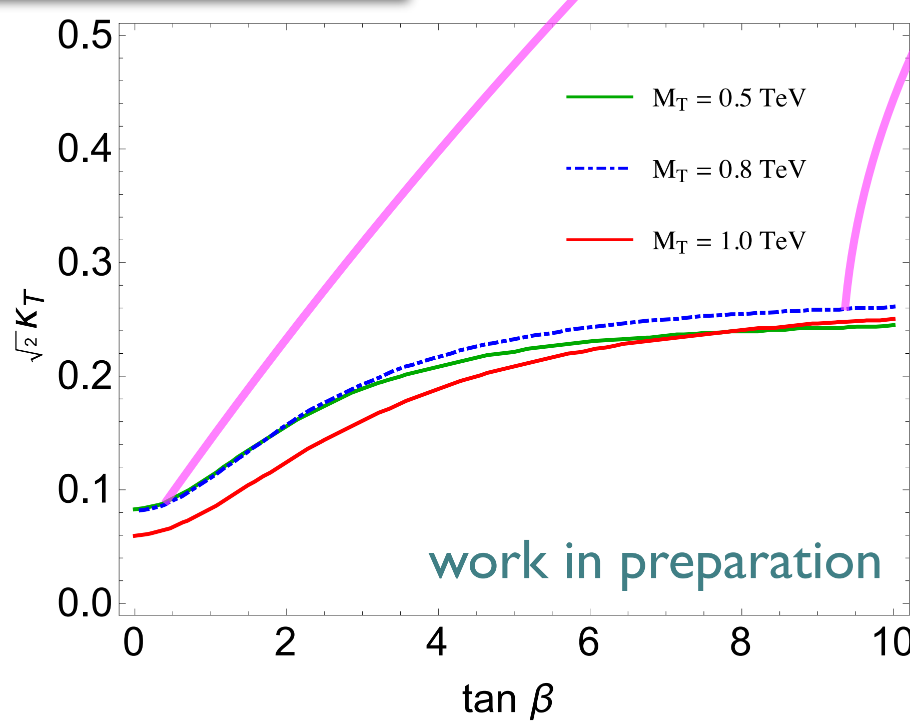
consider merely S-T bound, κ_T could be large; EW process competitive with QCD process !

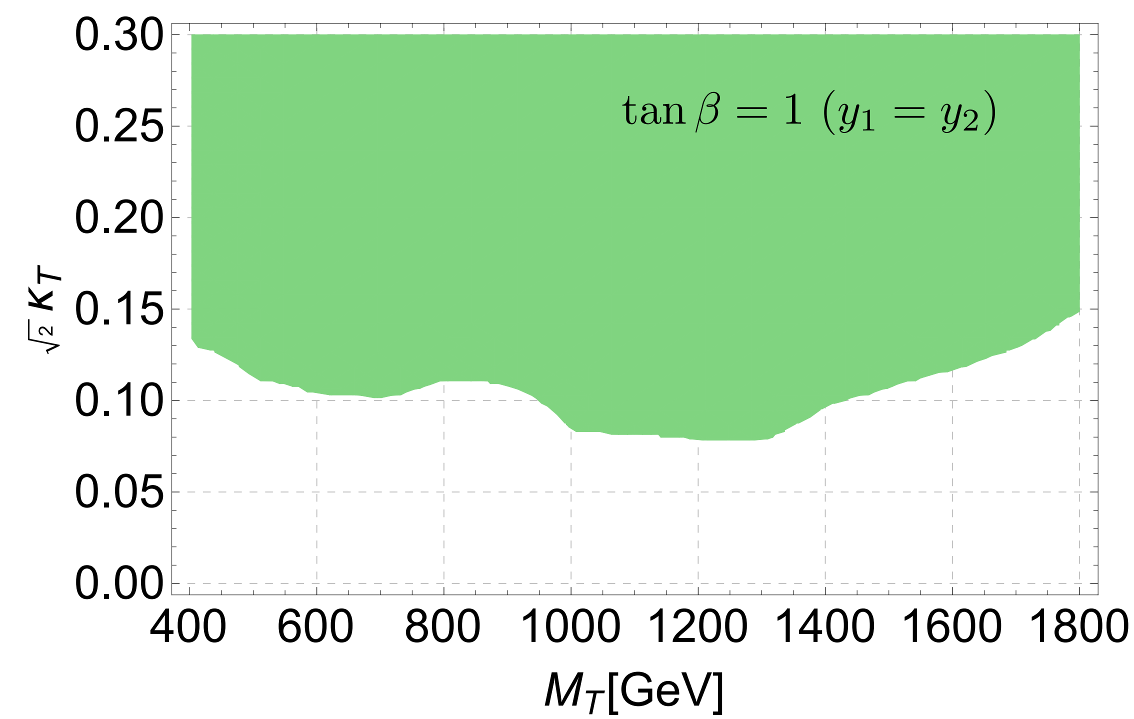
LHC Bound from W+2jets

For small beta ~ 0, kappa is mainly constrained by B +jet production; while for beta ~ Pi/2, kappa is mainly bounded by X+jet production.



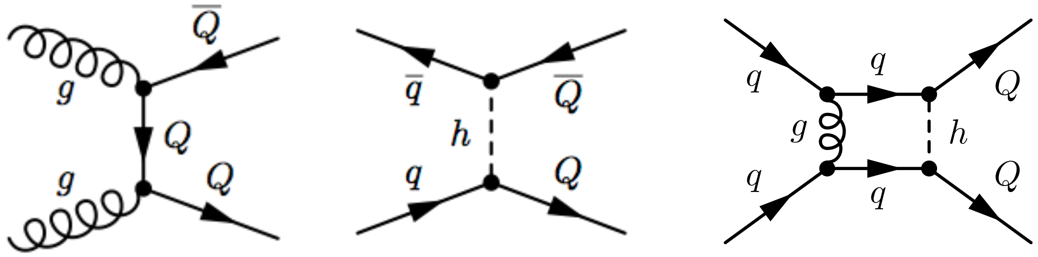
For $\tan\beta = 1$, the LHC direct search puts stronger bound, requires the T-u-h coupling to be less than 0.1 M_T/v.

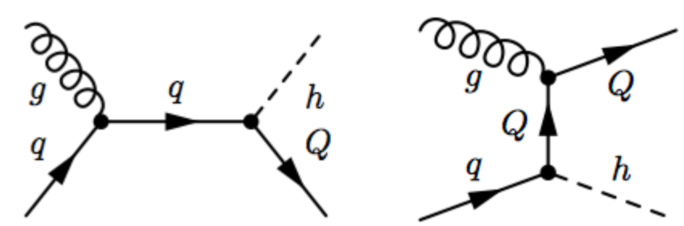




VLQ induced Higgs Pair Production

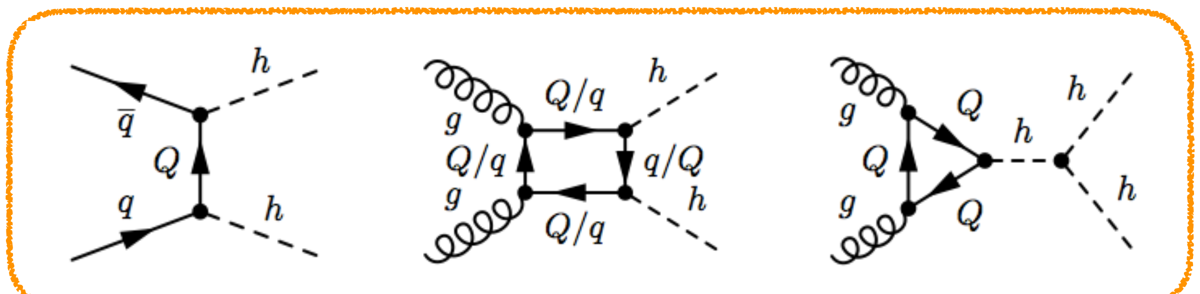
We consider non-resonant di-Higgs production, induced by a pair of VLQs or a single VLQ associated with a Higgs boson. Through $Q(\bar{Q}) \to h + j$, the final states are $2h$+jets.





QQ EW pair production scales as κ_T^4 $\qquad$ Qh single production scales as κ_T^2

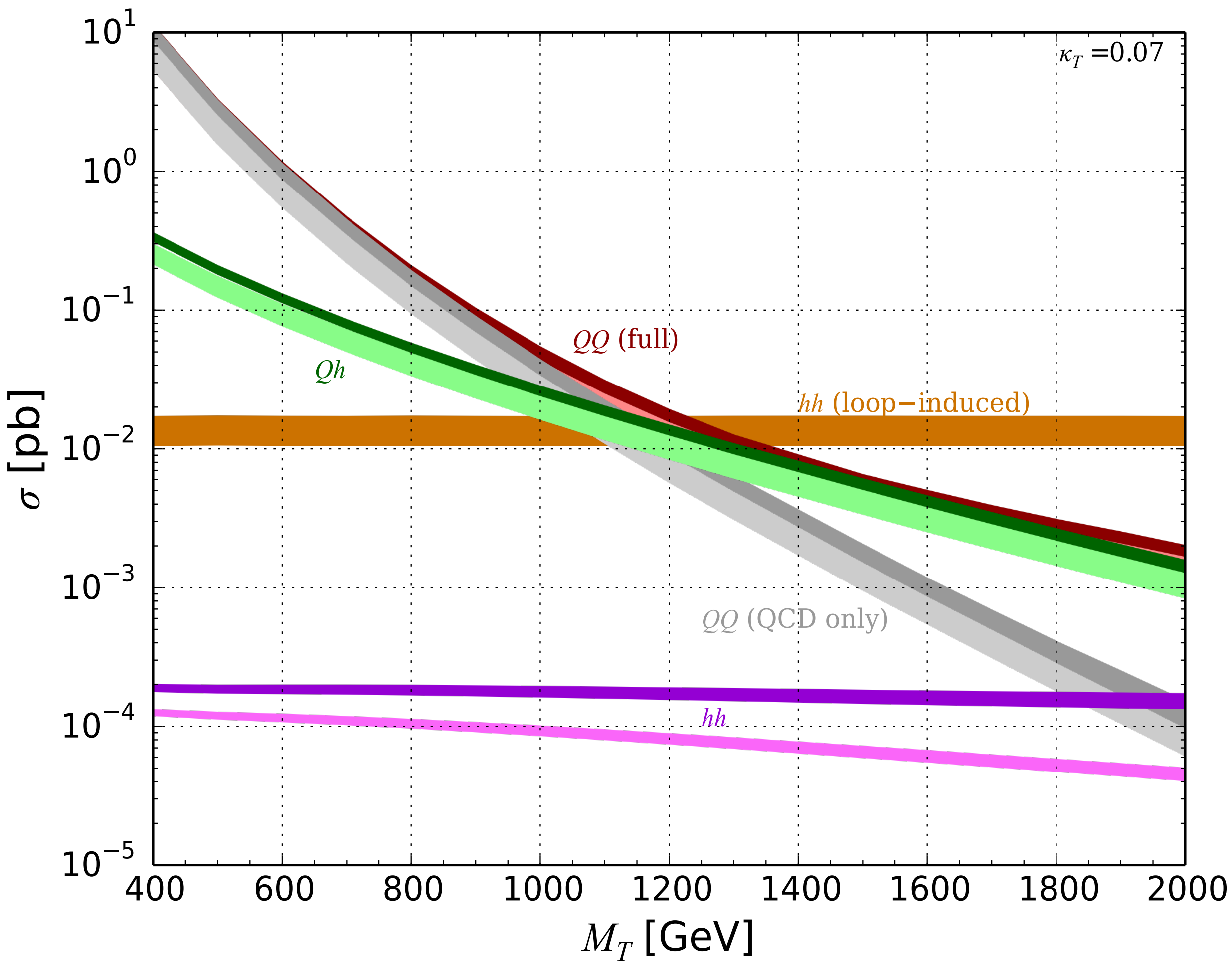
For the pure 2 h process the loop one is dominant:



At the Next-To-Leading order (NLO): $d\sigma = d\sigma^{(0)} + \alpha_s \sigma^{(1)}$, with $\sigma^{(1)}$ including contribution from field renormalisation, vertice correction and real emission.

Why NLO $\Rightarrow$ more precise theoretical prediction and better constraint on new physics.

NLO Cross Section at LHC Run II



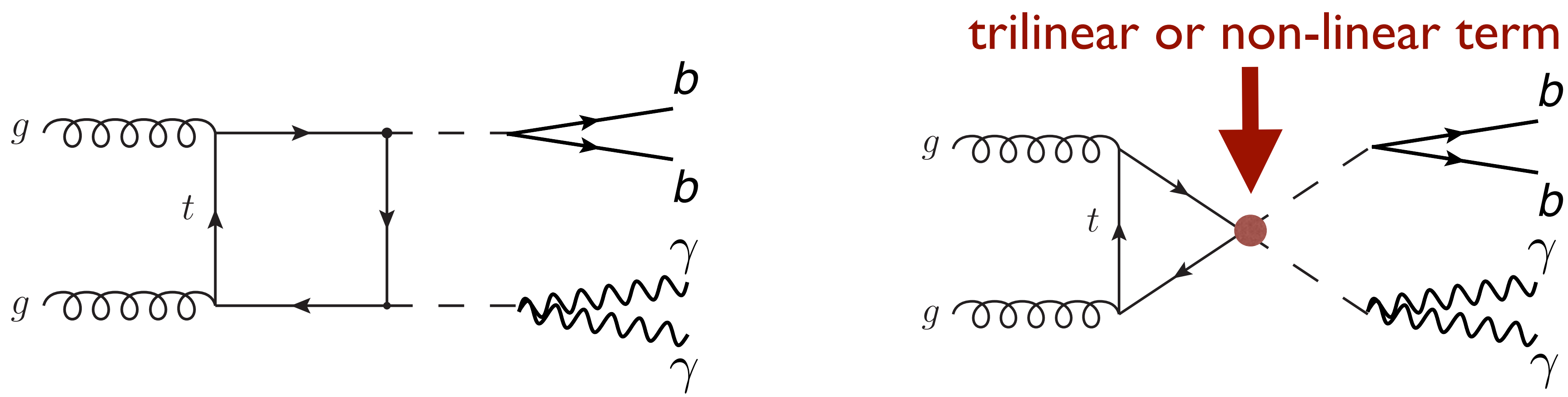
arxiv:1703.10614, Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, Fuks, Majumder and Shao

- QCD-induced $Q\bar{Q}$ is model independent, dropping quickly with the VLQ mass.
- T-channel EW QQ production is included, may start to dominate for $M_T > 1$ TeV.
- Qh production benefits from smaller phase space suppression, and only dominates over the QQ mode for intermediate VLQ mass.
- T-channel VLQ exchanged hh production is negligible, but the K-factor is large due to the quark-gluon-initiated contribution at NLO.

LO result in light colours and NLO result in dark colours; PDF uncertainty and scale uncertainty added in quadrature

2b 2γ Channel

This channel benefits both from large branching ratio of Higgs into bb and well identified di-photon signal, since the signal from a Higgs decay peaks on top of a continuum spectrum.



$2b2\gamma$ is promising to explore the trilinear h-h-h coupling or the non-linear h-h-t-$\bar{t}$ coupling from Beyond Standard models, normally without boost effects.

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

For $m_T < 1$ TeV, $2b2\gamma$ is sensitive to BSM effects from VLQs at high luminosity LHC.

Signal vs. BKG

Madgraph5 @ NLO / pythia8 / Fastjet   work in preparation

$m_T = 500$ 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%

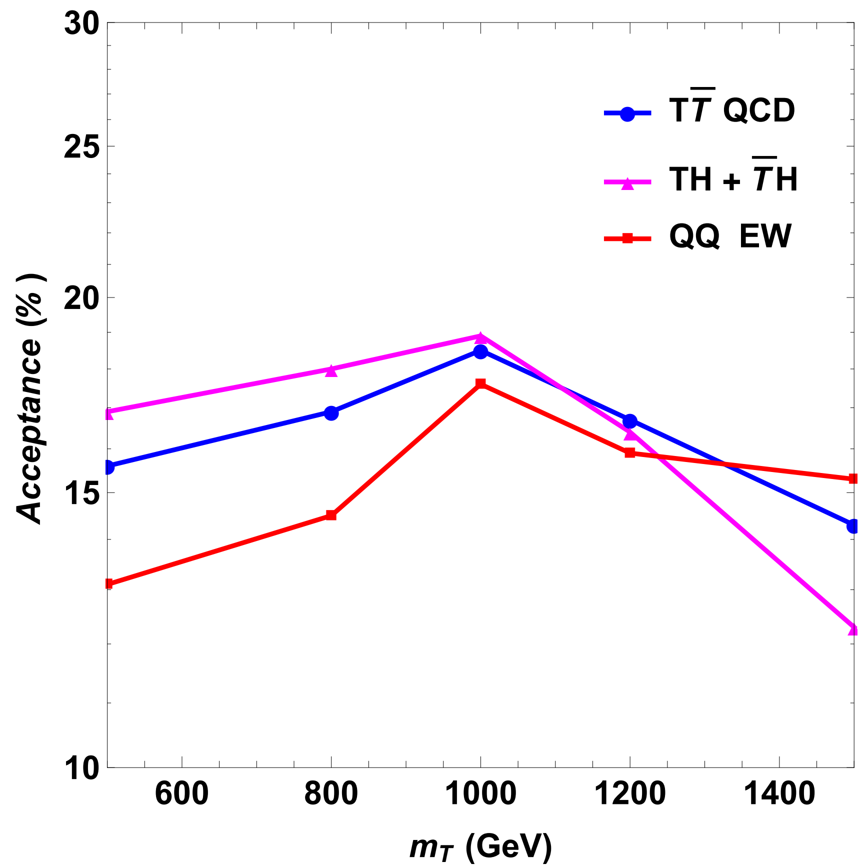
other BKG $b\bar{b}\gamma j$, $c\bar{c}\gamma j$ need be included, with j mimic one photon.

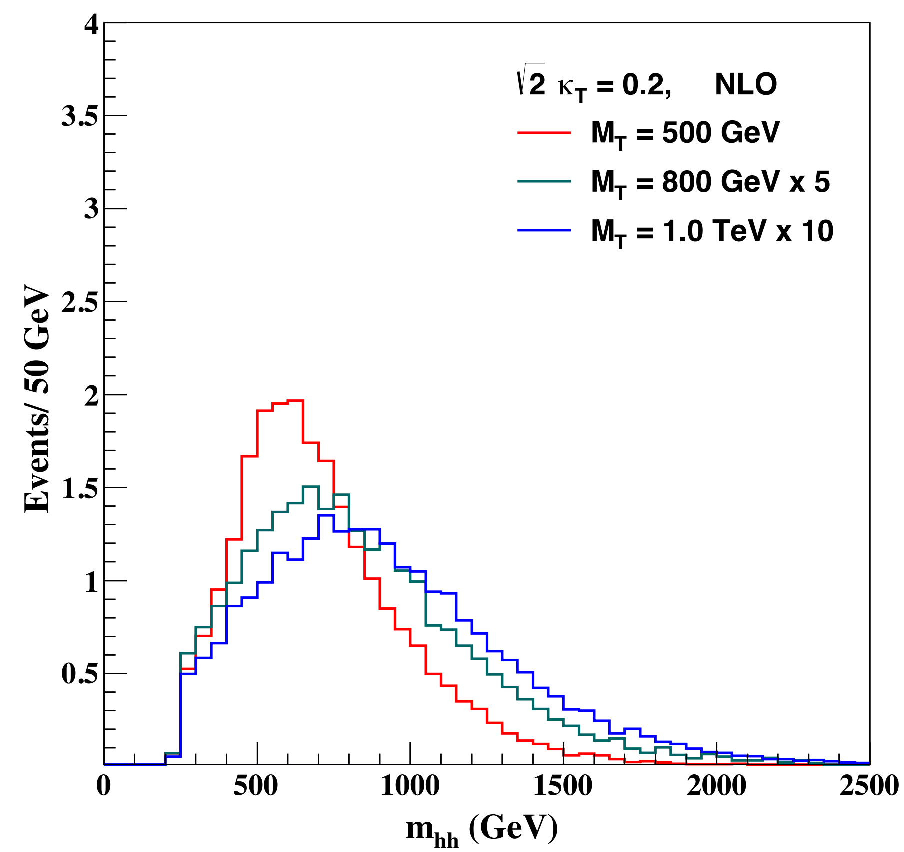
The significance shows sufficient sensitivity to light vector-like quarks

	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
$S/\sqrt{B}$	7.20	0.55	—	—	—	—

Table : The significance of $S/\sqrt{B}$ at the NLO with $\sqrt{2}\kappa_T = 0.2$, given for an integrated luminosity of $\int Ldt = 20.0\ \text{fb}^{-1}$ 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 M_{hh} spectrum





- The cut efficiency is $\sim 15\%$ for those channels, optimised near $m_T = 1.0$ TeV.
- For the invariant mass m_{hh} spectrum, additional cuts $p_T^{h1} > 200$ GeV and $p_T^{h2} > 150$ GeV are put to remove most of QCD background.

4b Channel

This 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 $b\bar{b}$ pair collimates into a small cone size $R \sim 2m_H/p_T$; for $m_T < 1$ TeV, the resolved analysis is applicable, e.g. ATLAS cuts:

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

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

$\Rightarrow$ For a large mass VLQ, in order to account the boost effect, jet substructure is employed to reduce the QCD contamination.

CMS search (AK8 jet)

CMS-like 'fat jet' is reconstructed by means of the anti-k_t algorithm with a distance parameter $R = 0.8$, and further satisfies:

$$\left|\eta^{J_h^C}\right| < 2.4 \ , \qquad \tau_{21}^{J_h^C} < 0.6 \qquad \text{and} \qquad m_{\text{pruned}}^{J_h^C} \subset [105, 135] \ \text{GeV}$$

The τ_{21} is the ratio of N=2 and N=1 N-subjettiness defined to measure how close a fat-jet to be N-prong. [Thaler and Tilburg , JHEP 03 (2011)]

We require two clustered fat-jets to be Higgs candidates, passing those pseudo rapidity, large p_T, and reduced mass cuts:

$$|\eta(h_{1,2})| < 2.4 \ , \quad p_T(h_{1,2}) > 200 \ \text{GeV} \ , \quad |\Delta\eta(h_1, h_2)| < 1.3 \ , \quad m_{\text{red}} > 1 \ \text{TeV}$$

$$m_{\text{red}} = m_{4j} - (M_{h1} - 125 \ \text{GeV}) - (M_{h2} - 125 \ \text{GeV})$$

ATLAS search (Large-R jet)

Following the large-R ATLAS analyses, we define a Higgs fat-jet J_H as anti-Kt jet with $R = 1.0$, trimmed by Delphes 3, that passes the basic selection:

$$\eta_{J_H} < 2.0; \qquad 250 < p_T < 2500 \text{ GeV}; \qquad m_{J_H} > 50 \text{ GeV}$$

The signal region is defined by imposing extra constraints on 2 large-R jets:

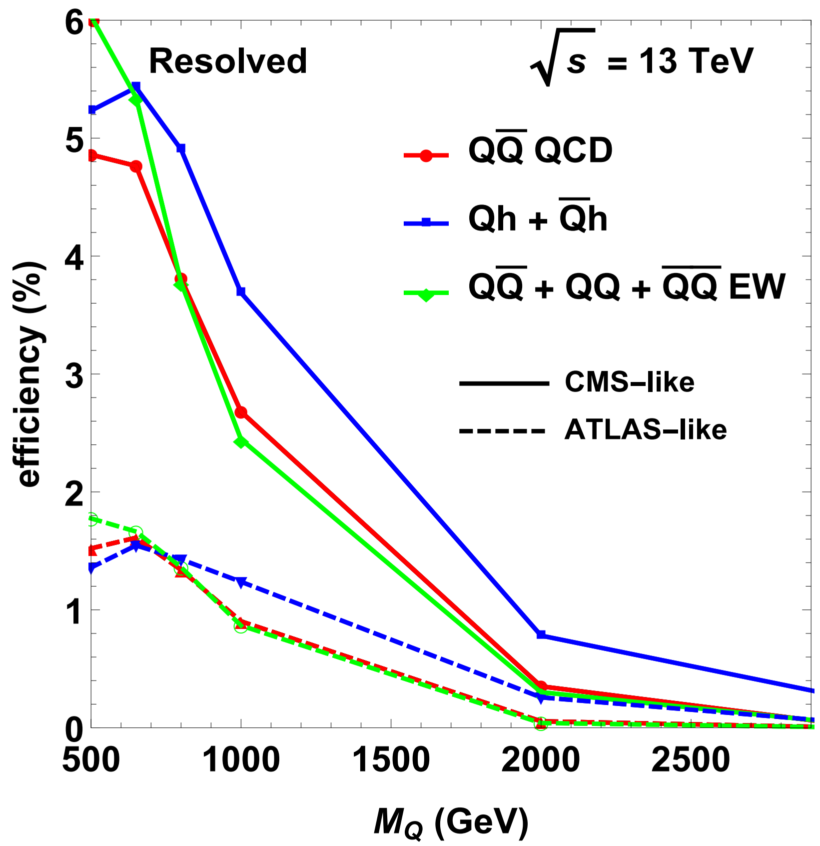
$$p_T(h_1) > 350 \text{ GeV} , \quad p_T(h_2) > 250 \text{ GeV} , \quad |\Delta\eta(h_1, h_2)| < 1.7 , \quad \chi^2_{\rm hh} < 2.56 .$$

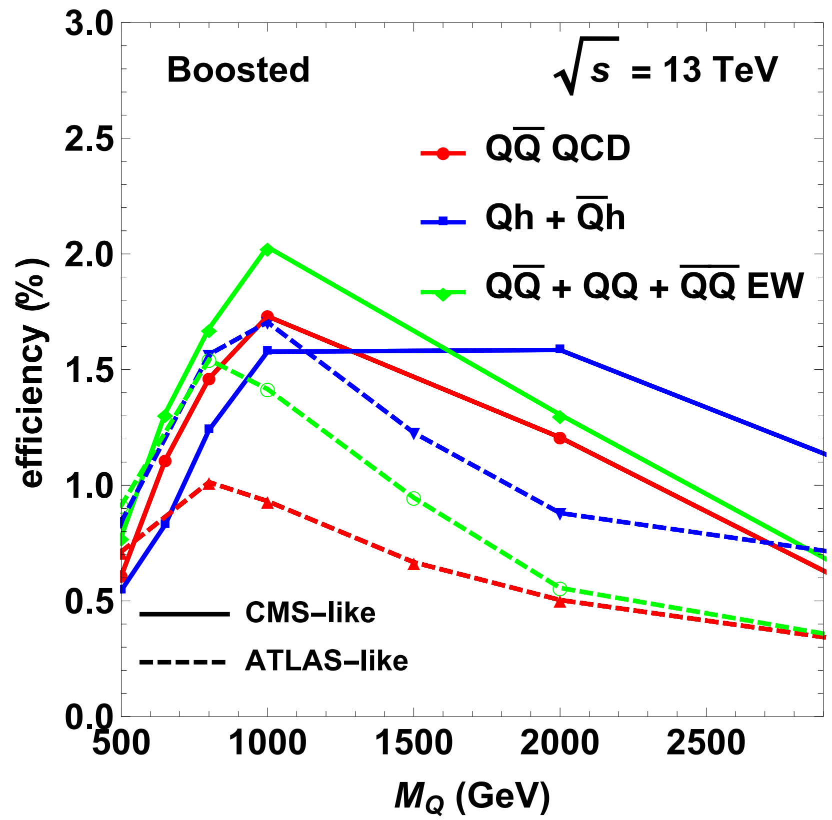
We optimistically assume that each large-R jet contains 2 b-jets, and each b-jet carries $1/2 p_T$ of the large-R jet, so that the b-tag efficiency is mapped into the ATLAS table.

Selection Efficiency

Madgraph5 @NLO, pythia8 and Delphes.

arxiv:1703.10614, Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, Fuks, Majumder and Shao





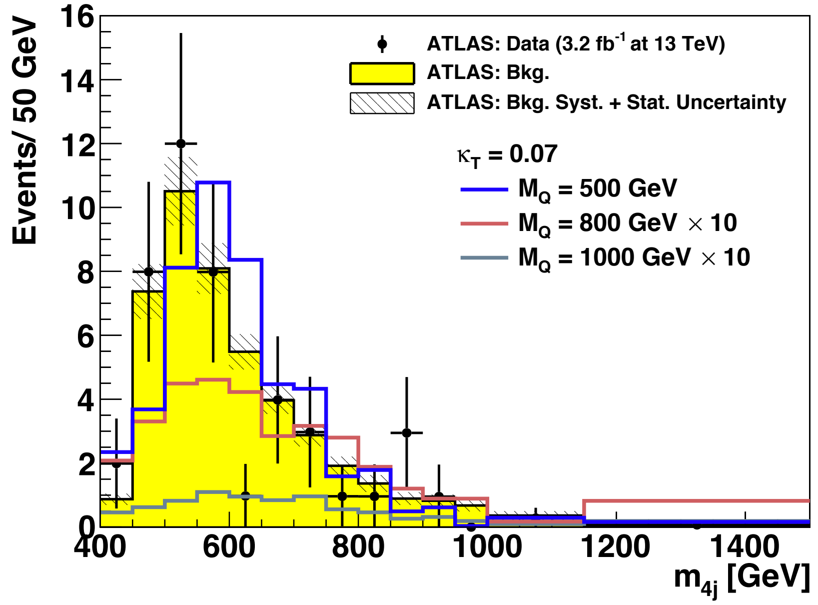
For the resolved analysis, the efficiency is maximal for the light VLQ mass, and single VLQ production channel leads to higher efficiency than pair production.

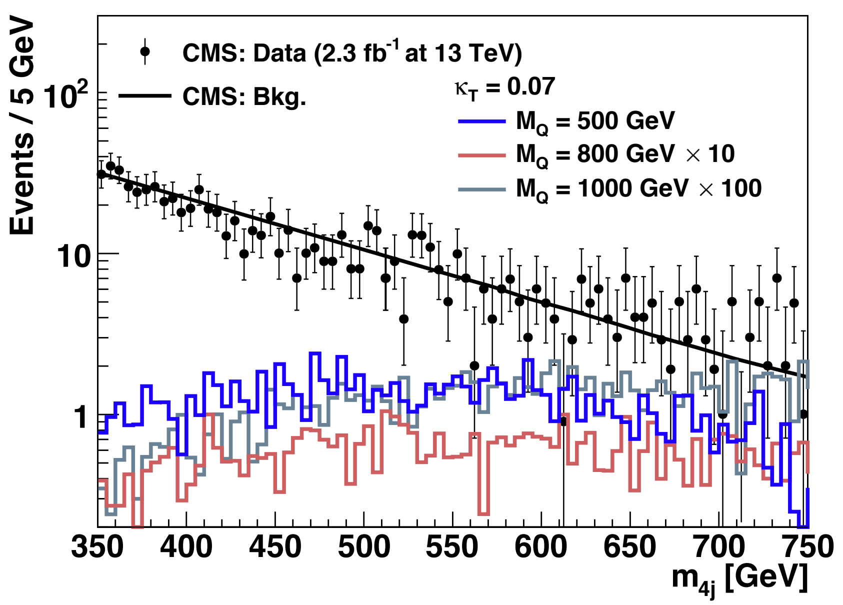
For the boosted analysis, selection efficiency show difference in each channel, since these processes lead to different jet topology, to which boost jet tagger is sensitive to.

M_{4j} distribution and signal yields

Compared with data obtained by ATLAS PRD. 94. 052002 and CMS-PAS-HIG-16-002

[arxiv:1703.10614]





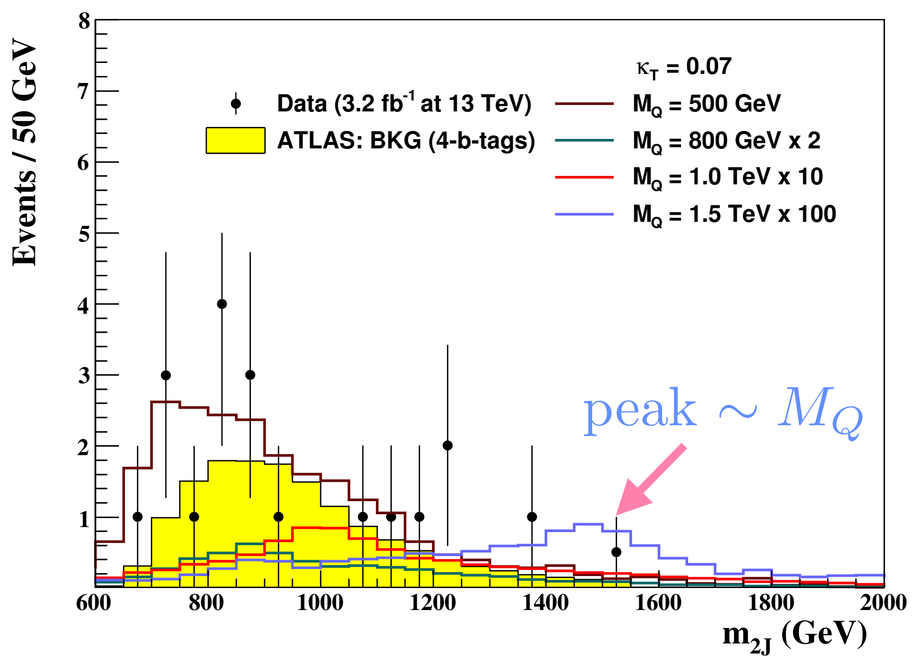
Analysis	Data	SM	Signals (for given VLQ masses)			
			0.5 TeV	0.8 TeV	1 TeV	2 TeV
ATLAS-resolved (3.2 fb^{-1})	44	47.6 ± 3.8	47.0	3.34	0.78	-
ATLAS-boosted (3.2 fb^{-1})	20	14.6 ± 2.4	23.5	2.82	0.933	0.024
CMS-resolved (2.3 fb^{-1})	797	n.a.	120	7.27	1.68	-
CMS-boosted (2.7 fb^{-1})	15	n.a.	17.6	2.99	1.10	0.04

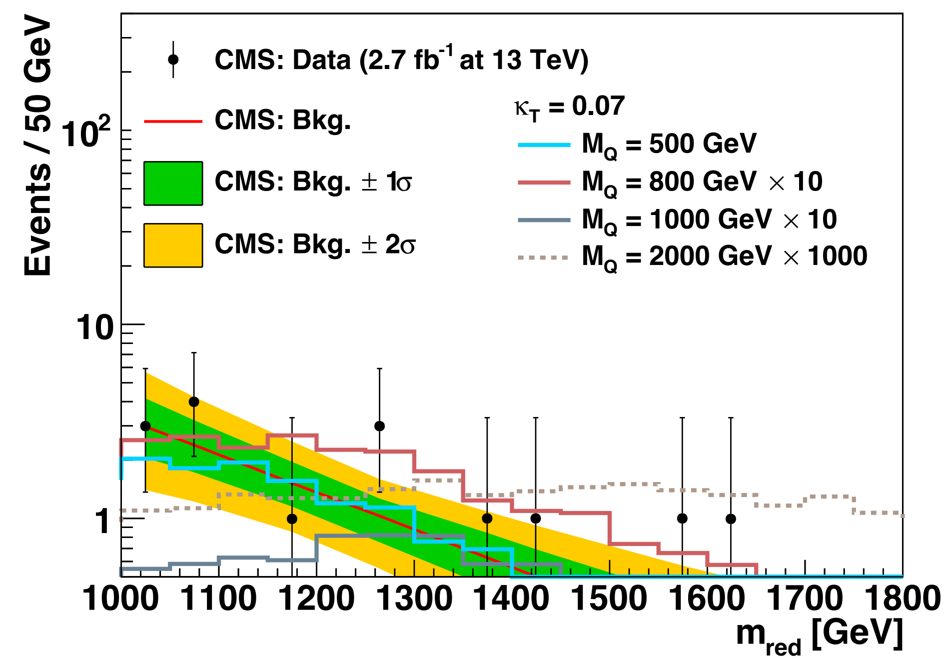
The ATLAS resolved analysis is sensitive to VLQ mass $\sim$ 500GeV, although the current strategy is not designed for a VLQ-induced di-Higgs search.

M_{2J} distribution for boosted case

Compared with data obtained by ATLAS PRD. 94. 052002 and CMS-PAS-HIG-16-008

[arxiv:1703.10614]





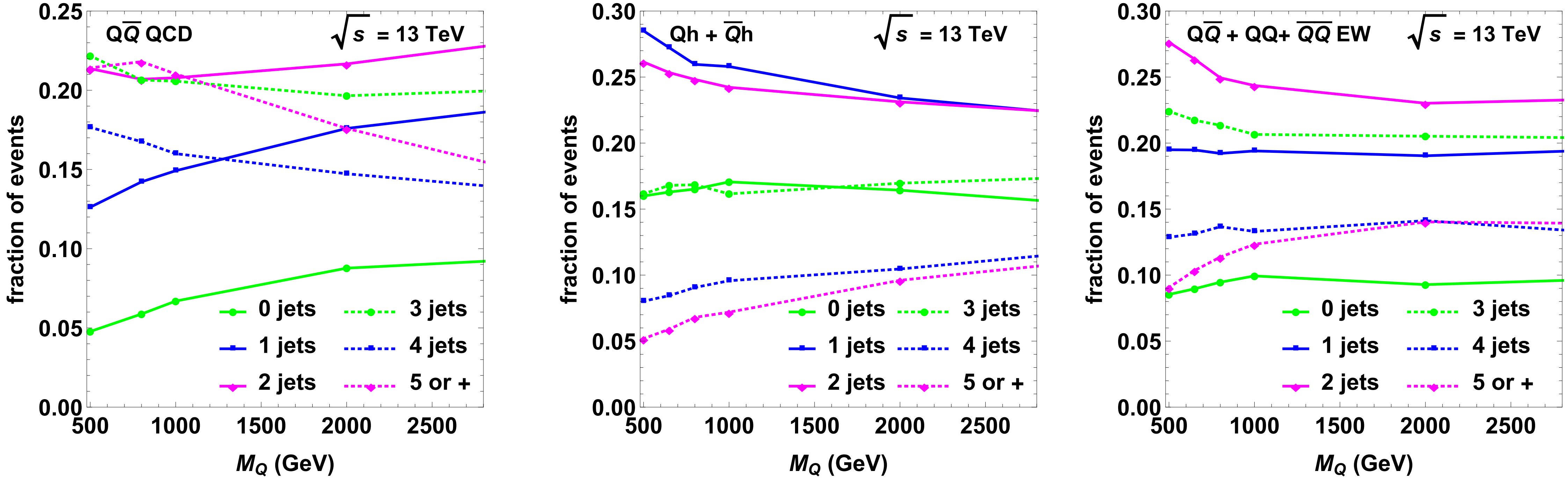
⇒ The boosted analysis in principle offer better handles to TeV scale VLQs. Even for 500 GeV benchmark, the boosted technique benefits from the much more reduced QCD background.

⇒ In the ATLAS large-R analysis, the peak of M_{2J} distribution shows a good property, shifting with the VLQ mass.

Counting additional Jets

Fraction of signal events containing the number of AK4 jets not from a Higgs decay.

[arxiv:1703.10614]



⇒ di-higgs events from VLQ (QCD and EW) pair production feature mostly one to three extra jets.

⇒ signal events from single Qh mode in general lead to one or two extra jets.

This information help discriminate VLQ-induced scenario from direct hh production channel.

Conclusions

- We explore Higgs pair production induced by vector-like quark (VLQ), where the EW contribution can play an important role. The general bi-doublet VLQ models deserve a further investigation.

- For mT ~ 500 GeV, 2b 2gamma channel has larger sensitivity than other channels due to the clean $\gamma\gamma$ signal. In order to put accurate exclusion limit on VLQ models, higher luminosity is needed.

- For the 4b channel, we apply both resolved and boosted analyses to VLQ-induced Higgs pair signals. For a large VLQ mass, we show that boost effects lead to simple event topology, so that jet substructure offers an effective analysis.

- The boost analysis applies to other processes, e.g. single VLQ plus jet production.