Some non-standard signals of vector-like quarks at LHC

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- LHC is doing great ! History made with Higgs boson discovery !

- The full exploitation of the LHC is now the highest priority.

- Strongly interacting exotic particle searches are already pushing BSM validity thresholds; e.g. fourth generation chiral quarks, SUSY….

SM Extensions

- Gauge symmetries:
  - GUTs
  - Z', Left-Right Models, Top flavor, Top SU(5)...
  - Little Higgs models....

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  - Z’, Left-Right Models, Top flavor, Top SU(5)…
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The success of gauge symmetry in describing the SM suggests a natural extension.

SM Extensions

- Gauge symmetries:
  - GUTs
  - Z', Left-Right Models, Top flavor, Top SU(5)...
  - Little Higgs models....

- Matter fields and additional scalars:
  - 4th Generation, vector like quarks/leptons, heavy singlets, Higgs Triplet models

- SM quarks are chiral in nature. (Left handed and right handed components of a quark transform differently under $SU(2)_L \times U(1)_Y$).

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} : \text{Doublet under } SU(2)_L \quad \text{but,} \quad u_R \text{ and } d_R : \text{Singlet under } SU(2)_L.$$

$$Y_{u_L} = \frac{1}{6} \text{ but } Y_{u_R} = \frac{2}{3}.$$

- Vector-like quarks (Left handed and right handed components of a quark transform in the same way under $SU(2)_L \times U(1)_Y$).

Consider

$$\text{Case-I}: \begin{pmatrix} xu_L \\ xd_L \end{pmatrix} \text{ and } \begin{pmatrix} xu_R \\ xd_R \end{pmatrix} : \text{Both Doublet under } SU(2)_L.$$

$$Q = T_3 + Y \implies Y(xu_L) = Y(xu_R)$$

$$\text{Case-II}: xu_L, xd_L, xu_R, xd_R : \text{Singlet under } SU(2)_L$$

$$Y(xu_L) = Y(xu_R) = \tfrac{2}{3}.$$

- Neutral current : $\mathcal{L}_Z = \frac{g}{\cos\theta_w} J_z^\mu Z_\mu$
- SM quarks : $J_z^\mu = \overline{u_L}\,\gamma^\mu(\frac{1}{2} - Q\sin^2\theta_w)\ u_L + \overline{u_R}\,\gamma^\mu(0 - Q\sin^2\theta_w)\ u_R$
- Vector-like quarks :
  - Doublet :

$$J_z^\mu = \overline{xu_L}\,\gamma^\mu(\frac{1}{2} - Q\sin^2\theta_w)\ xu_L + \overline{xu_R}\,\gamma^\mu(\frac{1}{2} - Q\sin^2\theta_w)\ xu_R$$

$$= (\frac{1}{2} - Q\sin^2\theta_w)\ \overline{xu}\,\gamma^\mu\, xu \equiv V$$

Vector-like ?

Interactions with SM-gauge bosons

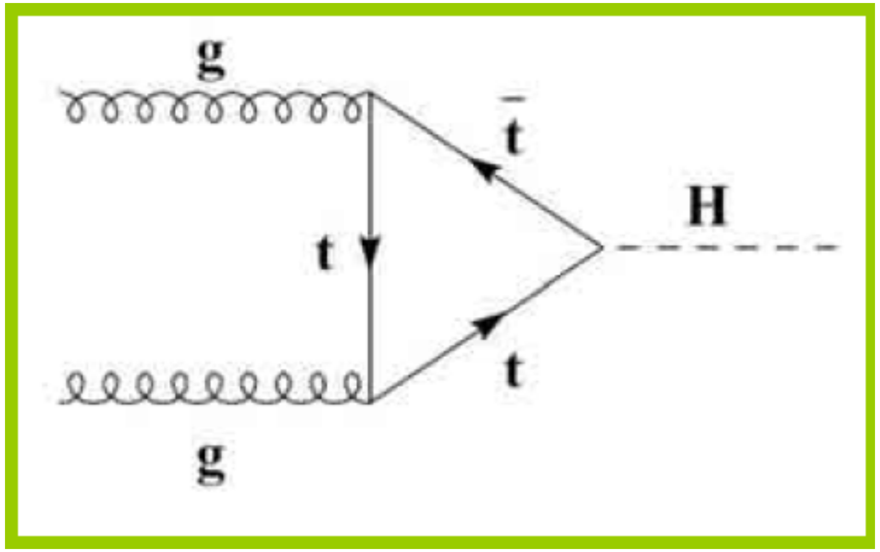
- Charged current : $\mathcal{L}_w = \frac{g}{\sqrt{2}}(J^{\mu +} W_\mu^+ + J^{\mu -} W_\mu^-)$
  - SM quarks : $J^{\mu +} = \overline{u}_L \gamma^\mu d_L = \frac{1}{2}\bar{u}\,\gamma^\mu (1 - \gamma^5)\, u \equiv V - A$
  - Vector-like quarks:

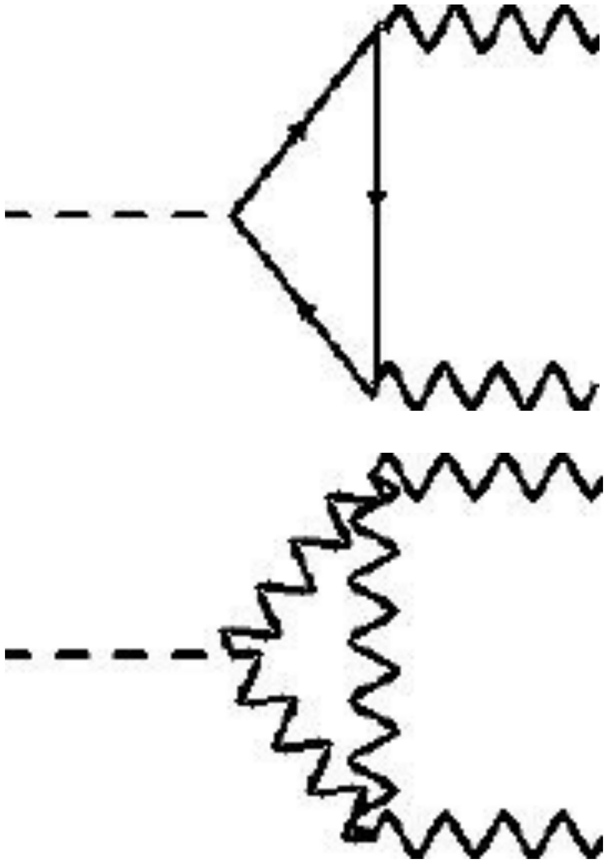
    $$J^{\mu +} = \overline{xu}_L \gamma^\mu xd_L + \overline{xu}_R \gamma^\mu xd_R = \overline{xu}\,\gamma^\mu\, xu \equiv V$$

$$y = \sqrt{2}\frac{m_f}{v}, \qquad v \sim 246 \text{ GeV}.$$

- SM with heavy fourth generation chiral fermions imply large Yukawa coupling and hence nonperturbative.
- The contribution from fermions to the loop induced Hgg and $H\gamma\gamma$ couplings do not vanish with increasing masses.
- Higgs production cross section via gluon fusion is enhanced by a factor of 9 due to the additional heavy quaarks in the loop.

New Particles in Loops can modify Higgs signals in a big way:





HTM

4^{th} Generation

VLQ

SUSY

…

…

…

4^{th} generation quarks practically ruled out from Higgs data !!!

- Perturbative SM with a 4th generation chiral fermions is excluded by combined fit of EWPOs and Higgs signal strengths in the decays to $\gamma\gamma$, WW, ZZ, bb and $\tau\tau$ (Eberhardt et al.).

- The cancellation of triangle anomalies in SM requires that leptons and quarks appear in complete multiplets $(E_L, e_R, Q_L, u_R, , d_R)$.
$tr[Y^3] = -2(-\frac{1}{2}^3) + (-1)^3 - 3[2(\frac{1}{6})^3 - (\frac{2}{3})^3 - (-\frac{1}{3})^3] = 0.$

- The contribution of a vector-like fermion to the triangle diagrams is zero, because both the left- and right- handed components contribute in same amount with a relative sign between them.

- Existence of elementary fermions are allowed if they are vector like with respect to SM gauge group.

- Unlike SM chiral quarks mass terms for vector-like quarks are allowed by gauge invariance.

$$\text{For a } SU(2)_L \text{ doublet : m } \begin{pmatrix} \overline{xu_L} & \overline{xd_L} \end{pmatrix} \begin{pmatrix} xu_R \\ xd_R \end{pmatrix}$$

$$\text{For a } SU(2)_L \text{ singlet : m } \overline{xu_L}\, xu_R$$

- SM extended with vector-like quarks will generate mixings between vector-like quarks and SM chiral quarks.

- Mixing generates tree level FCNCs including SM quarks. Mixing parameter is strongly constrained.

Observable effects of vector-like quarks

Indirect observations

- Rare top decays : $t \to Zq$ (FCNC)
- Meson mixings and decay.
- Modifications to CKM matrix.
- Modification of $Zc\bar{c}$, $Zb\bar{b}$, $Zu\bar{u}$, $Zd\bar{d}$ couplings.
- S, T, U parameters (VLQ in the loop.)
- Higgs coupling with gluons and photons.

Observable effects of vector-like quarks

Direct observations at LHC

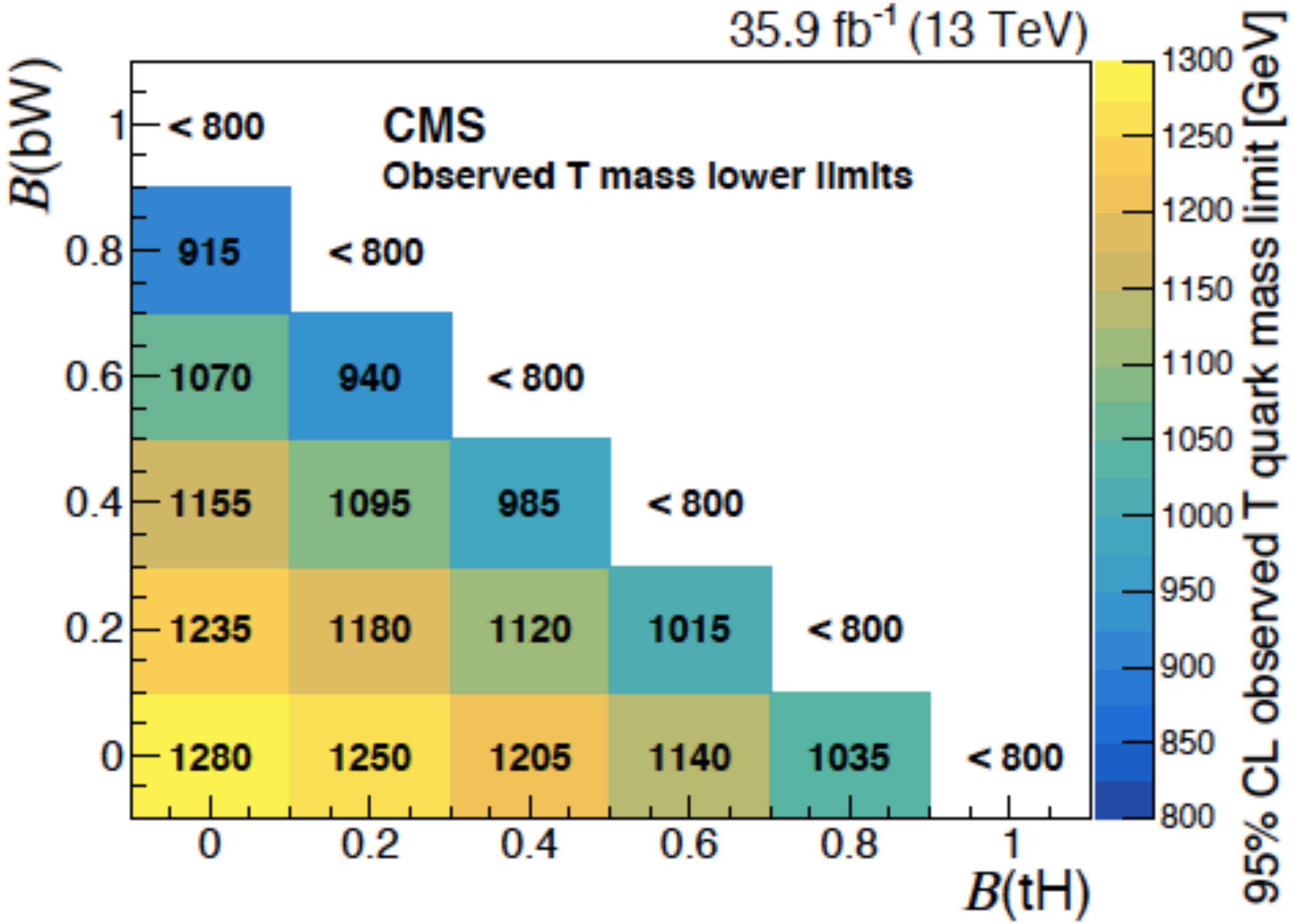
- As Colored particles they will be pair produced.
- Mixing with SM quarks opens up decay modes for VLQ :

$$xt \to W\,b,\; Z\,t,\; h\,t$$

$$xb \to W\,t,\; Z\,b,\; h\,b$$

- Existing searches at LHC assume that a VLQ decays into $(W\,t,\; Z\,b, h\,b)/(W\,b,\; Z\,t, h\,t)$.
- The existing lower bounds from LHC is around 800-1000 GeV.

one of the T quarks decays via T $\to$ tZ and the other via T $\to$ bW, tZ, or tH



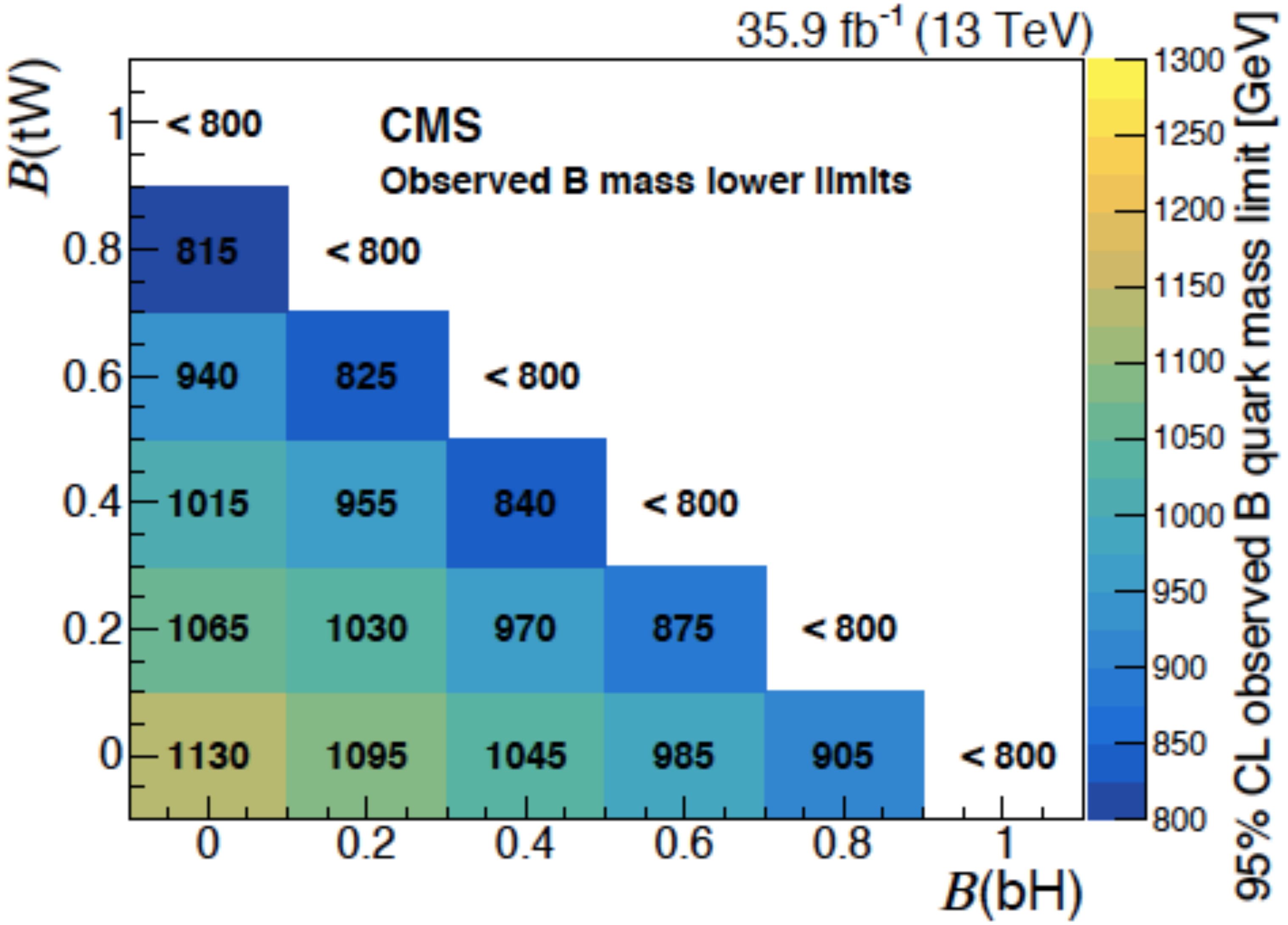
events with two oppositely charged leptons and jets

$$\mathcal{B}(T \to tZ) + \mathcal{B}(T \to tH) + \mathcal{B}(T \to bW) = 1$$

arXiv:1812.09768

CMS-B2G-17-012 ; CERN-EP-2018-290

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G one of the B quarks decays via B $\rightarrow$ bZ and the other B $\rightarrow$ tW, bZ, or bH.



$$\mathcal{B}(B \rightarrow bZ) + \mathcal{B}(B \rightarrow bH) + \mathcal{B}(B \rightarrow tW) = 1$$

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Non-minimal extensions of Standard Model with vector-like quarks may have other possible non-standard decay modes.

Mixing of a vectorlike quark with SM quarks can be negligibly small and it may have dominant decay modes other than the normal searched ones.

arXiv:1607.00810 Eur. Phys. J. **C78**, no. 1, 35 (2018)

- $U(1)$ gauge extension of Standard Model.

Phys. Rev. **D82** 055021, 2010 (arXiv:1006.5019)

- Leptophobic 221 Model.

arXiv:1807.08160

K. Das, **SKR** Phys. Rev. D **93**, no. 9, 095007, (2016)

K. Das, T. Li, S. Nandi, **SKR** Eur. Phys. J. **C78**, no. 1, 35 (2018)

K. Das, T. Li, S. Nandi, **SKR** arXiv:1607.00810

K. Das, T. Mondal, **SKR** arXiv:1807.08160

Vector-like quarks in a $U(1)$ extension of Standard Model.

- BSM quarks are vector-like under $\boxed{SU(3)_C \times SU(2)_L \times U(1)_Y}$

chiral under $U(1)'$.

vector-like under $U(1)'$.

The $U(1)'$ can be a TeV scale remnant $U(1)'$ from :

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$$

different versions of $U(1)'$ from E_6 have been considered in the literature

$$U(1)' = \cos\theta_{E_6} U(1)_\chi + \sin\theta_{E_6} U(1)_\psi,$$

Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$
Q_i	$(\mathbf{3}, \mathbf{2}, 1/6, 1)$
U_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3, 1)$
E_i^c	$(\mathbf{1}, \mathbf{1}, 1, 1)$
D_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3, 7)$
L_i	$(\mathbf{1}, \mathbf{2}, -1/2, 7)$
N_i^c / T	$(\mathbf{1}, \mathbf{1}, 0, -5)$
XD_i	$(\mathbf{3}, \mathbf{1}, -1/3, -2)$
$XL_i^c,\ H_u$	$(\mathbf{1}, \mathbf{2}, 1/2, -2)$
XD_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3, -8)$
$XL_i,\ H_d$	$(\mathbf{1}, \mathbf{2}, -1/2, -8)$
$XN_i,\ S$	$(\mathbf{1}, \mathbf{1}, 0, 10)$

$$Q' = \cos\theta_{E_6} Q_\chi + \sin\theta_{E_6} Q_\psi.$$

Normalize $U(1)'$ charges by $4\sqrt{15}$.

popular models are :

$$U(1)_\chi : \quad Q' = Q_\chi,\ \theta_{E_6} = 0,$$

$$U(1)_\psi : \quad Q' = Q_\psi,\ \theta_{E_6} = \frac{\pi}{2},$$

$$U(1)_\eta : \quad Q_\eta = Q'(\theta_{E_6} = \arctan(-\sqrt{5/3}) \approx -0.29\pi),$$

$$U(1)_S : \quad Q_S = Q'(\theta_{E_6} = \arctan(\sqrt{15}/9) \approx 0.13\pi),$$

$$U(1)_I : \quad Q_I = -Q'(\theta_{E_6} = \arctan\sqrt{3/5} \approx 0.21\pi),$$

$$U(1)_N : \quad Q_N = Q'(\theta_{E_6} = \arctan\sqrt{15} \approx 0.42\pi).$$

- Only down type vector-like quarks present (charge : $-\frac{1}{3}$).

$$
\begin{aligned}
-\mathcal{L}_{\mathcal{Y}} = \; & y_{ij}^{U} Q_i U_j^c H_u + y_{ij}^{D} Q_i D_j^c H_d + y_{ij}^{E} L_i E_j^c H_d + y_{ij}^{N} L_i N_j^c H_u \\
& + y_{ij}^{XNd} XL_i^c XN_j H_d + y_{ij}^{XNu} XL_i XN_j H_u + y_{ij}^{TD} D_i^c XD_j T \\
& + y_{ij}^{TL} XL_i^c L_j T + y_{ij}^{SD} XD_i^c XD_j S + y_{ij}^{SL} XL_i^c XL_j S \\
& + y_{ij}^{SN} S N_i^c N_j^c + y_{ij}^{TXNN} T XN_i^c N_j^c + \mathrm{H.C.}
\end{aligned}
$$

Mass matrix in the (q_1, xq_1) basis : (d, xd_1)

$$
\frac{1}{\sqrt{2}} \begin{pmatrix} y_{11}^{D} v_d & 0 \\ y_{11}^{TD} v_t & y_{11}^{SD} v_s \end{pmatrix}
$$

- $< H_d >= \begin{pmatrix} \frac{v_d}{\sqrt{2}} \\ 0 \end{pmatrix}$, $< H_u >= \begin{pmatrix} 0 \\ \frac{v_u}{\sqrt{2}} \end{pmatrix}$, $< T >= \frac{v_t}{\sqrt{2}}$, $< S >= \frac{v_s}{\sqrt{2}}$.

CP even Higgs : $h_1, h_2 \in (H_u, H_d)$ and $s_h, t_h \in (S, T)$,

CP odd Higgs: $a_1 \in (H_u, H_d)$ and $a_2 \in (S, T)$,

Charged Higgs : $h^+ \in (H_u, H_d)$.

For small Mixing

Eigenvalues : $m_d \sim \frac{y_{11}^{D} v_d}{\sqrt{2}}$ and $M_{xd_1} \sim \frac{y_{11}^{SD} v_s}{\sqrt{2}}$

Suppression of left mixing angle :

$\sin\theta_L \sim \frac{m_d}{M_{xd}} \sin\theta_R \quad (m_d \sim 5 \text{ MeV})$

- For $M_{xd_1} \sim 600\,\text{GeV}$, $v_s \sim 1.5\,\text{TeV}$, $v_t \sim 10\,\text{TeV}$, $y_{11}^{TD} \sim 10^{-5}$

$\implies \sin\theta_R \sim 10^{-4}$, $\sin\theta_L \sim 10^{-10}$.

Z' searches at LHC

$$\sigma\,(pp \to Z'\,X \to l^+ l^-\,X) \simeq \frac{\pi}{48\,s}\sum_q c_q\,w_q(s,\,M_{Z'}^2).$$

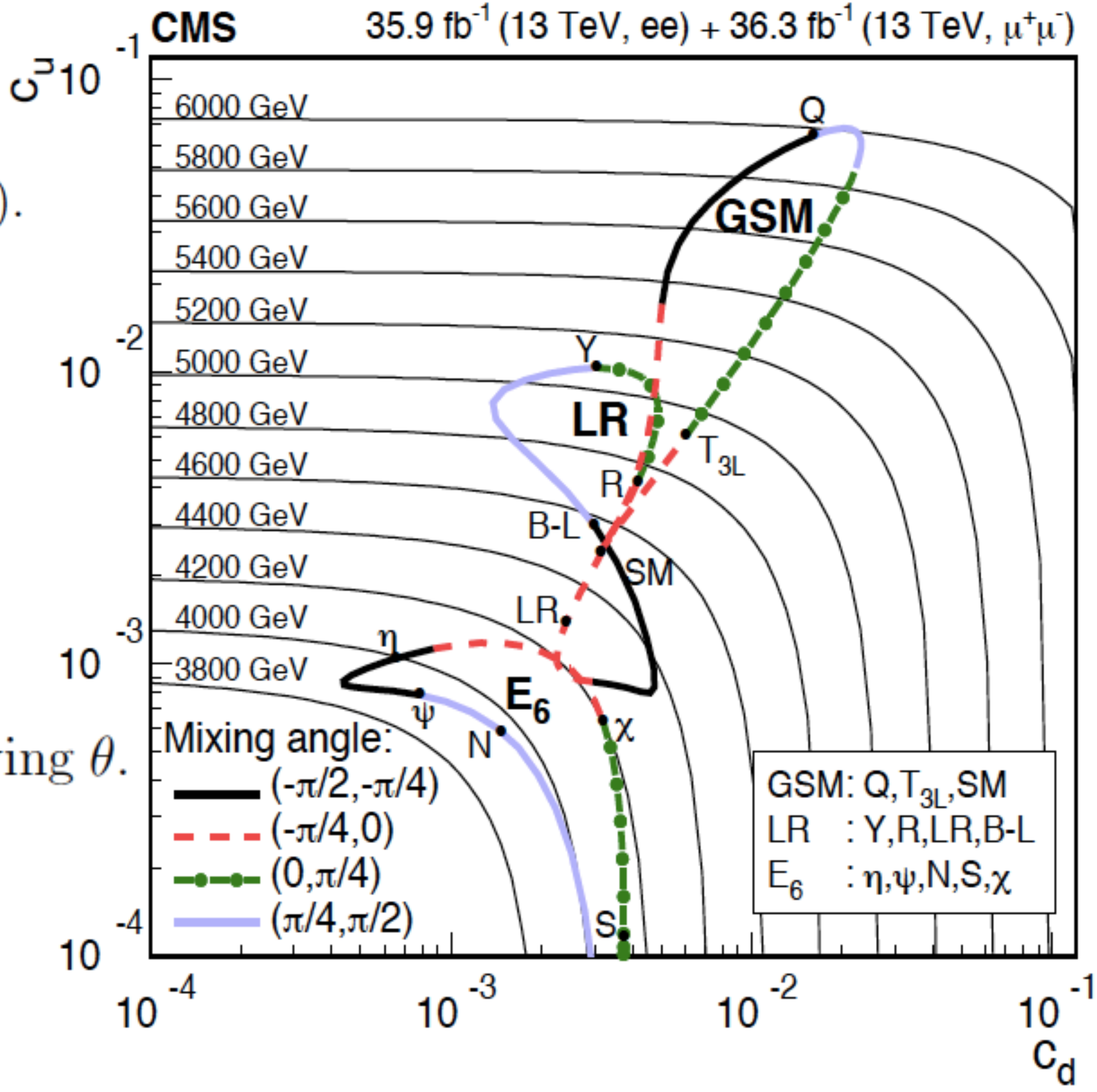
The coefficients are

$$c_q = [(g_{q_L})^2 + (g_{q_R})^2]\,Br(Z' \to l^+\,l^-),$$

the contour denoted by $\mathbf{E_6}$ is formed by varying θ.

In E_6 models the coupling g'

$$= \frac{e}{\cos\theta_W}\sqrt{5/3} \approx 0.462.$$



- Neutral Gauge Boson mass square matrix in (W_3, B, Z') basis is

$$\mathcal{M} = \begin{pmatrix} (\mathcal{M}_{SM})_{2\times 2} & & \mathcal{M}_{13} \\ & & \mathcal{M}_{23} \\ \mathcal{M}_{13} & \mathcal{M}_{23} & \mathcal{M}_{33} \end{pmatrix}$$

where

$$\mathcal{M}_{13} = \frac{g g_X}{8\sqrt{15}}(2v_u^2 - 8v_d^2), \qquad \mathcal{M}_{23} = -\frac{g' g_X}{8\sqrt{15}}(2v_u^2 - 8v_d^2)\ ,$$

and

$$\mathcal{M}_{33} = \frac{g_X^2}{240}(4v_u^2 + 64v_d^2 + 25v_t^2 + 100v_s^2)\ .$$

- $\tan 2\theta_{z-z'} = \frac{2\frac{\mathcal{M}_{13}}{g}\sqrt{g^2+g'^2}}{\mathcal{M}_{33}-M_{Z_0}^2}, \quad M_{Z_0}^2 = \frac{1}{4}(g^2 + g'^2)(v_u^2 + v_d^2)$

- $g_X \sim 0.5, v_s \sim 1$ TeV, $\boldsymbol{v_t} \sim$ **30 TeV**, $0 \leq \frac{v_u}{v_d} \leq 200$

$$\implies \theta_{z-z'} \leq 10^{-4} \text{ and } M_Z' \sim 4.8 \text{ TeV}.$$

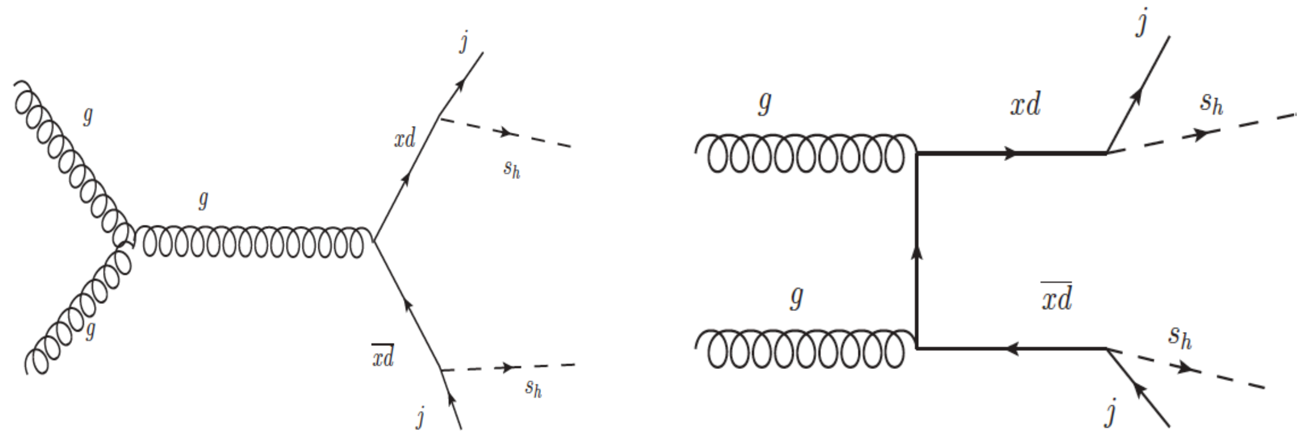
For $\boldsymbol{xd}$:

Standard Modes : $h\,d,\ d\,Z,\ u\,W^-$.

Non-standard modes : $s_h\,d,\ t_h\,d,\ a_{h_1}\,d,\ a_{h_2}\,d,\ d\,Z'$

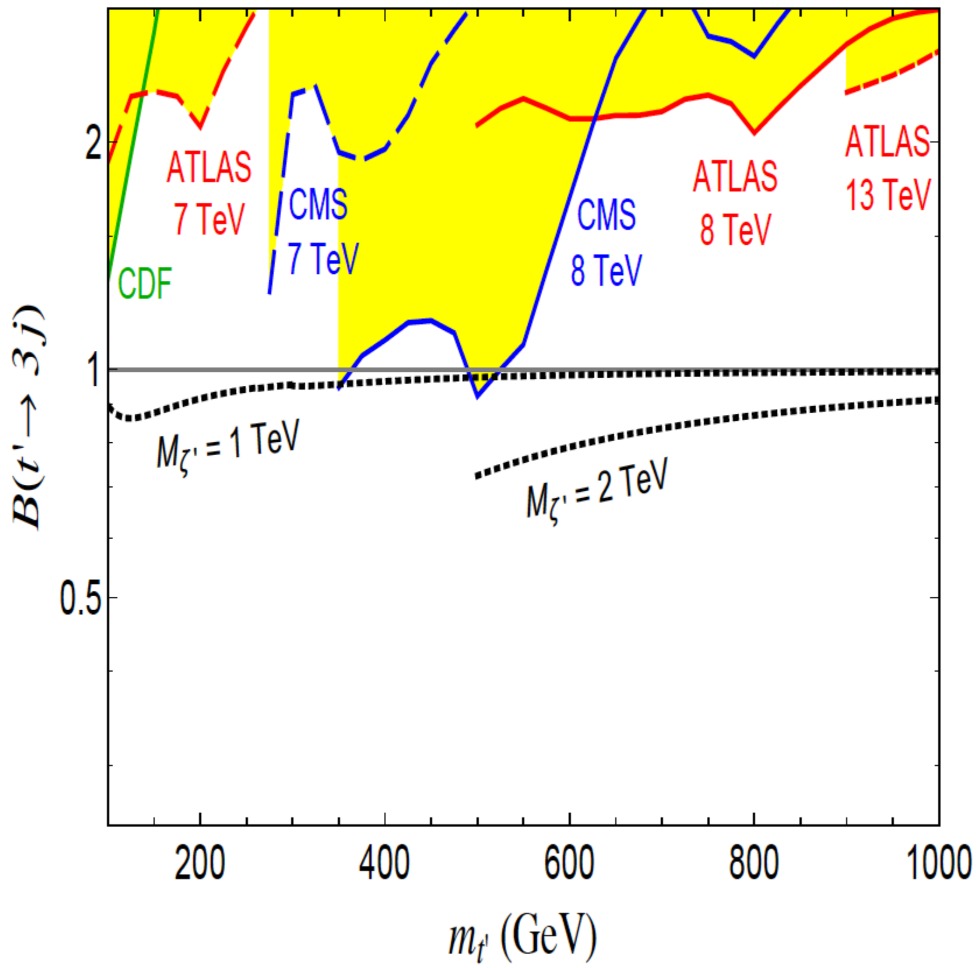
For $\boldsymbol{s_h}$: $\gamma\,\gamma,\ g\,g,\ x\bar{\ell}_i\,x\ell_j,\ x\bar{\ell}_i\,l_j,\ \bar{l}_i\,x\ell_j,\ \bar{l}_i\,l_j.$

Considered the scenario where after production each of the vector-like quark decays to the scalar s_h and a SM light jet. i.e. Br $(xd \to s_h j) \sim 1$.



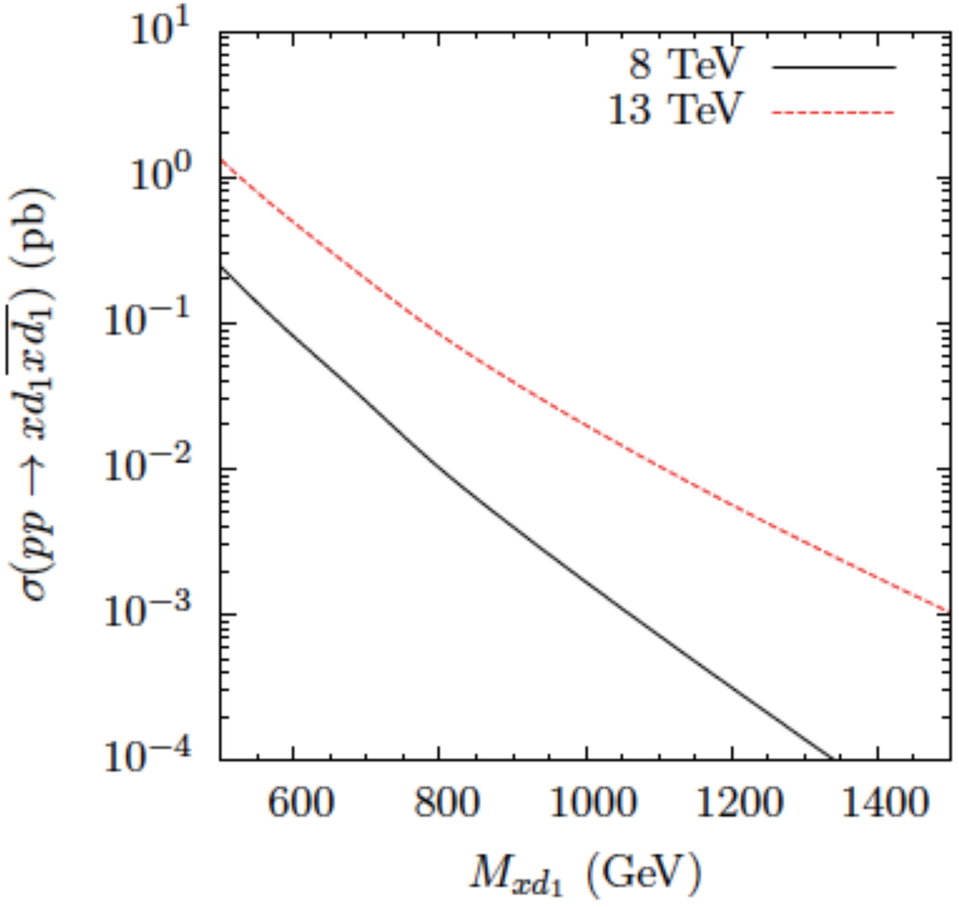
Final State : $\boldsymbol{2\gamma + 4j}$

Constraints from LHC



B.A. Dobrescu and F. Yu, 1612.01909

Signals



	$2\gamma + 2j$	$2\gamma + 4j$
	Benchmark 1	Benchmark 2
Masses	$\boldsymbol{M_{xd_1} = 640}$ **GeV** $\boldsymbol{M_{s_h} = 600}$ **GeV**	$\boldsymbol{M_{xd_1} = 850}$ **GeV** $\boldsymbol{M_{s_h} = 600}$ **GeV**
Selection	2γ, $\geq$ 2j, 0 leptons	2γ, $\geq$ 4j, 0 leptons
Cuts	$P_T(j_2) \geq 100$ GeV $p_T(\gamma_1) \geq 200$ GeV $P_T(\gamma_2) \geq 100$ GeV $M_{eff} \geq 800$ GeV	$P_T(j_2) \geq 100$ GeV $p_T(\gamma_1) \geq 200$ GeV $P_T(\gamma_2) \geq 100$ GeV $M_{eff} \geq 1000$ GeV
Crosssection	$\sigma_S = 2$ fb $\sigma_B = 13.5$ fb	$\sigma_S = 0.35$ fb $\sigma_B = 3$ fb
Significance with 100 fb^{-1} L	5σ	2σ

Direct observations

Reconstruction of xd_1 from the two leading photons and jets. $\left(\frac{1}{N_j}\frac{1}{N}\sum_{m=1}^{N_j}\frac{dN}{dM_{\gamma_1\gamma_2 j_m}}\right)$

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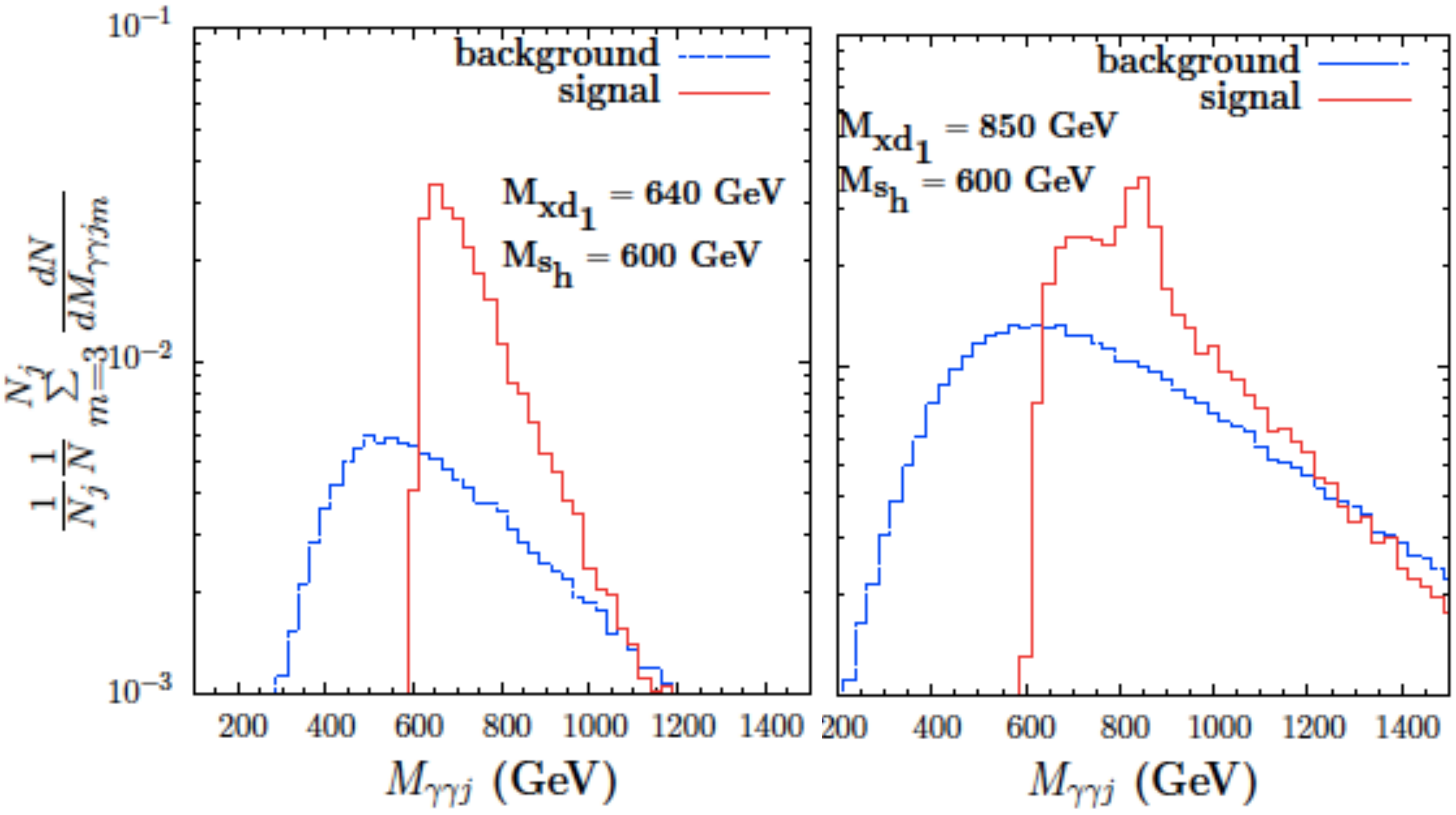
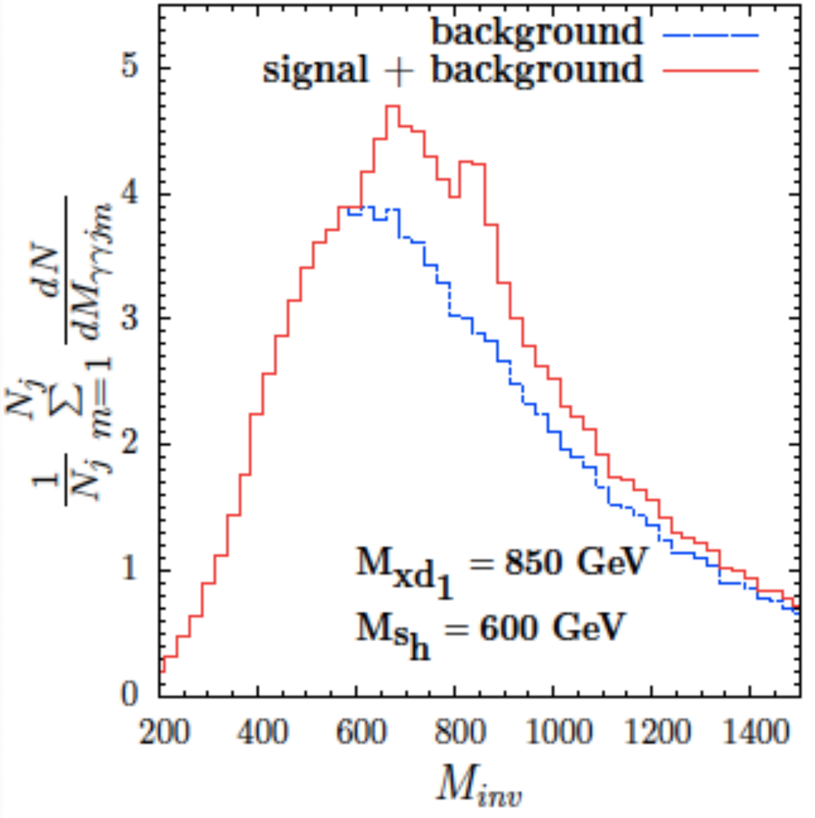




- Hidden $U(1)$: Standard Model fields are neutral under $U(1)'$.

  - New Weak singlet quarks: $D = D_L + D_R$
  - New EW singlet Higgs: S
  - New gauge boson: Z'_μ

Quantum numbers

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
b_R	3	1	$-\frac{1}{3}$	0
$D_L,\ D_R$	3	1	$-\frac{1}{3}$	-1
S	1	1	0	1

  - All SM particles are neutral under $U(1)'$

- Mixing between d-type quarks and exotic D

Phys. Rev. **D82** 055021, 2010 (arXiv:1006.5019)

Standard Modes

$$
pp \to D\overline{D} \to \begin{cases}
(Zb)(Z\bar{b}) & \Longrightarrow b\bar{b} + 2Z \\
(tW^-)(\bar{t}W^+) & \Longrightarrow t\bar{t} + W^+W^- \\
(tW^-)(Z\bar{b}) & \Longrightarrow t\bar{b} + ZW^- \\
(\phi_H b)(\phi_H \bar{b}) & \Longrightarrow b\bar{b} + 2\phi_H \quad \to b\bar{b} + 2(W^+W^-) \\
(\phi_H b)(\phi_H \bar{b}) & \Longrightarrow b\bar{b} + 2\phi_H \quad \to 3(b\bar{b}) \\
(\phi_H b)(\phi_S \bar{b}) & \Longrightarrow b\bar{b} + \phi_H\phi_S \quad \to b\bar{b} + 3\phi_H \quad \to 4(b\bar{b}) \\
(\phi_S b)(\phi_S \bar{b}) & \Longrightarrow b\bar{b} + 2\phi_S \quad \to b\bar{b} + 4\phi_H \quad \to 5(b\bar{b})
\end{cases}
$$

- Interesting multi b-jet final states

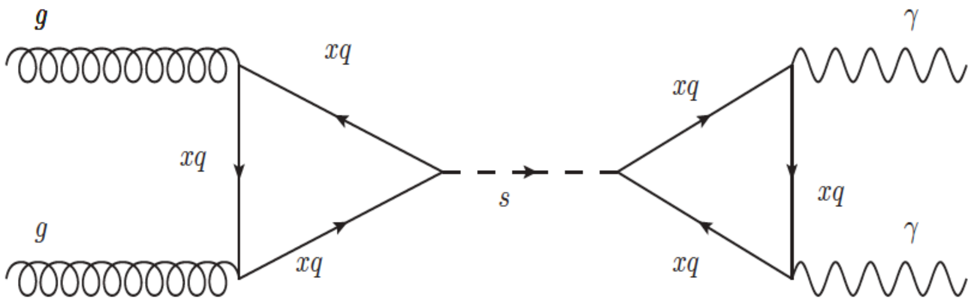
$$
\overline{D}D \to \begin{cases}
6b + X \\
4b + 2l + X \\
2b + 2l + X \\
nb + l + X \quad (n \geq 3)
\end{cases}
$$

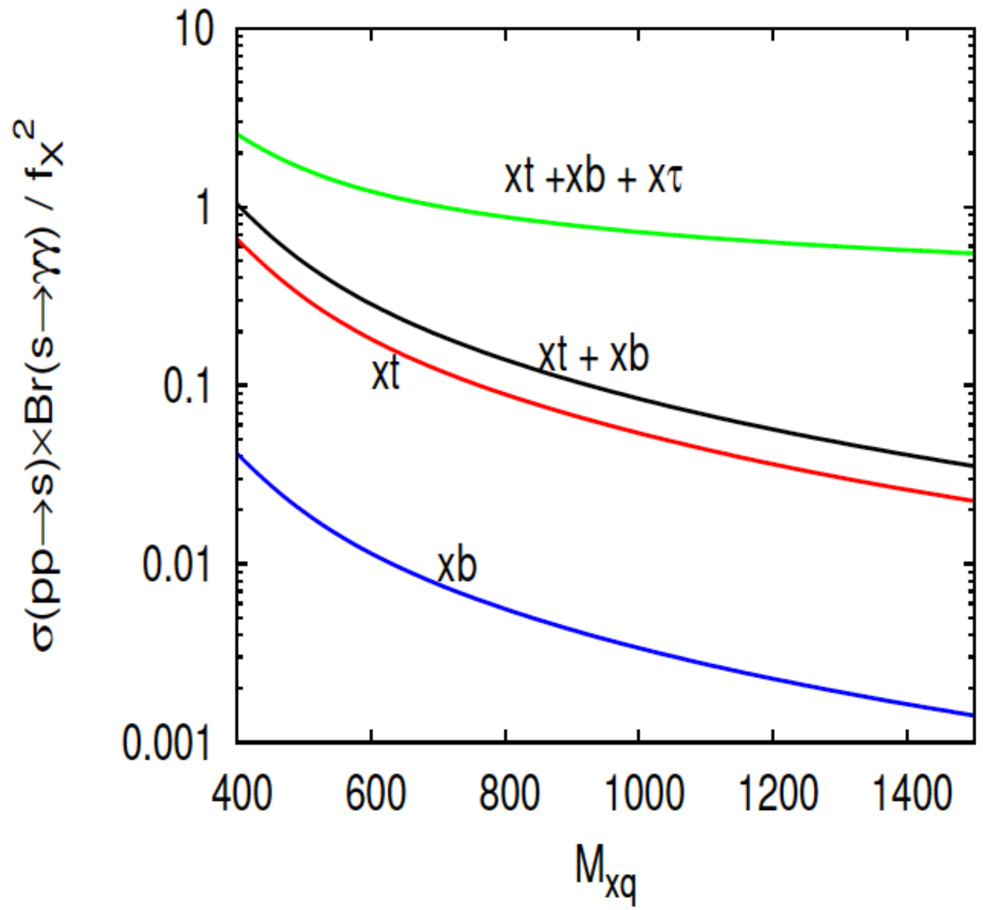
Phys. Rev. **D82** 055021, 2010 (arXiv:1006.5019)

Indirect

arXiv:1607.00810

$$\mathcal{L}_{s_h GG} = -\lambda_{sgg} s_h \; G_{\mu\nu} G^{\mu\nu}$$





$SU(3)_C \times SU(2)_L \times SU(2)_2 \times U(1)_X$. Leptophobic 221 Model.

$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$(3, 2, 1, \frac{1}{6})$	$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$(3, 1, 2, \frac{1}{6})$
$XQ_L = \begin{pmatrix} xu_L \\ xd_L \end{pmatrix}$	$(3, 1, 2, \frac{1}{6})$	xu_R xd_R	$(3, 1, 1, \frac{2}{3})$ $(3, 1, 1, -\frac{1}{3})$
$L_L = \begin{pmatrix} \nu_L \\ e^-_L \end{pmatrix}$	$(1, 2, 1, -\frac{1}{2})$	e^-_R	$(1, 1, 1, -1)$
Φ	$(1, 2, 2, 0)$	H_1 $\mathcal{H}_2$	$(1, 2, 1, -\frac{1}{2})$ $(1, 1, 2, -\frac{1}{2})$

Symmetry Breaking

Stage I : $SU(2)_2 \times U(1)_X \xrightarrow{\langle \mathcal{H}_2 \rangle} U(1)_Y$

vector-like nature : $Y(xu_L) = \frac{1}{2} + \frac{1}{6} = \frac{2}{3} = Y(xu_R)$

Stage II : $SU(2)_1 \times U(1)_Y \xrightarrow{\langle \Phi \rangle, \langle H_1 \rangle} U(1)_{EM}$.

- $-L_{Yukawa} = Y^{q}_{ij}\,\overline{Q_{iL}}\,\Phi\,Q_{jR} + Y^{qC}_{ij}\,\overline{Q_{iL}}\,\widetilde{\Phi}\,Q_{jR}$
  $$+ Y^{xqxu}_{ij}\,\overline{XQ_{iL}}\,xu_{jR}\,H_2 + Y^{qxu}_{ij}\,\overline{Q_{iL}}\,xu_{jR}\,H_1$$
  $$+ Y^{xqxd}_{ij}\,\overline{XQ_{iL}}\,xd_{jR}\,\widetilde{H_2} + Y^{qxd}_{ij}\,\overline{Q_{iL}}\,xd_{jR}\,\widetilde{H_1}$$
  $$+ \mu_{ij}\,\overline{XQ_{iL}}\,Q_{jR} + Y^{L}_{ij}\,\overline{L_{iL}}\,e_{jR}\,\widetilde{H_1} + \text{H.C.}$$
- $\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} \qquad H_1 = \begin{pmatrix} \chi^0 \\ \chi^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} \chi'^0 \\ \chi'^- \end{pmatrix}$
- Physical spectrum of the Model.
  - 4 neutral scalars, 2 pseudoscalars, 2 charged scalars. $h_1, h_2, h_3, h_4, A_1, A_2, h_1^+, h_2^+$
  - Gauge Bosons: Two charged(W, W'), Two neutral massive (Z, Z'), One massless(Photon).
  - Quarks : six up-type$(u, c, t, xu_1, xu_2, xu_3)$, six down-type $(d, s, b, xd_1, xd_2, xd_3)$.

- There is no FCNC if one vector-like quark mixes with only one linear combination of the SM quark gauge eigen states.

$$u_L = \cos\theta_L^u \left(\hat{A}_L^{u\,\dagger} \begin{pmatrix} u^0 \\ c^0 \\ t^0 \end{pmatrix} \right)_1 + \sin\theta_L^u \; xu_1^0,$$

$$xu_{1L} = -\sin\theta_L^u \left(\hat{A}_L^{u\,\dagger} \begin{pmatrix} u^0 \\ c^0 \\ t^0 \end{pmatrix} \right)_1 + \cos\theta_L^u \; xu_1^0,$$

$$\hat{A}_L^{u\,\dagger} \hat{A}_L^u = \mathbb{1}$$

- $V_{CKM} = C_L^u \hat{A}_L^{u\,\dagger} \hat{A}_L^d C_L^d$ With $C_L^u = diag(\cos\theta_L^u, \cos\theta_L^c, \cos\theta_L^t)$ and $C_L^d = diag(\cos\theta_L^d, \cos\theta_L^s, \cos\theta_L^b)$.

$$\begin{pmatrix} U^0 \\ XU^0 \end{pmatrix}_L = \begin{pmatrix} A_L^u & E_L^u \\ F_L^u & G_L^u \end{pmatrix} \begin{pmatrix} U \\ XU \end{pmatrix}_L$$

$$A_L^u = \hat{A}_L^u C_L^u,\ F_L^u = S_L^u,\ G_L^u = C_L^u,\ E_L^u = -\hat{A}_L^u S_L^u$$

$$\begin{aligned} \overline{U_L^0}\, \gamma^\mu\, U_L^0 &= \overline{U_L}\, A_L^{u\,\dagger} A_L^u\, \gamma^\mu\, U_L + \text{terms with xu} \\ &= \overline{U_L}\, C_L^{u\,2}\, \gamma^\mu\, U_L + \text{terms with xu} \end{aligned}$$

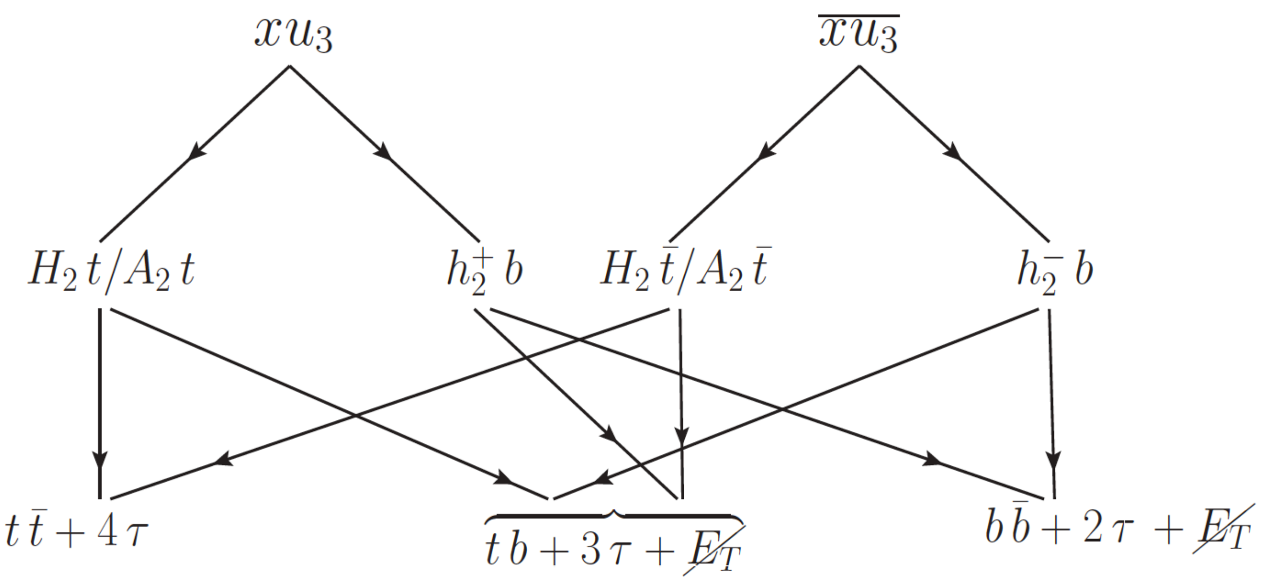
$C_L^{u\,2}$ is diagonal . No FCNC.

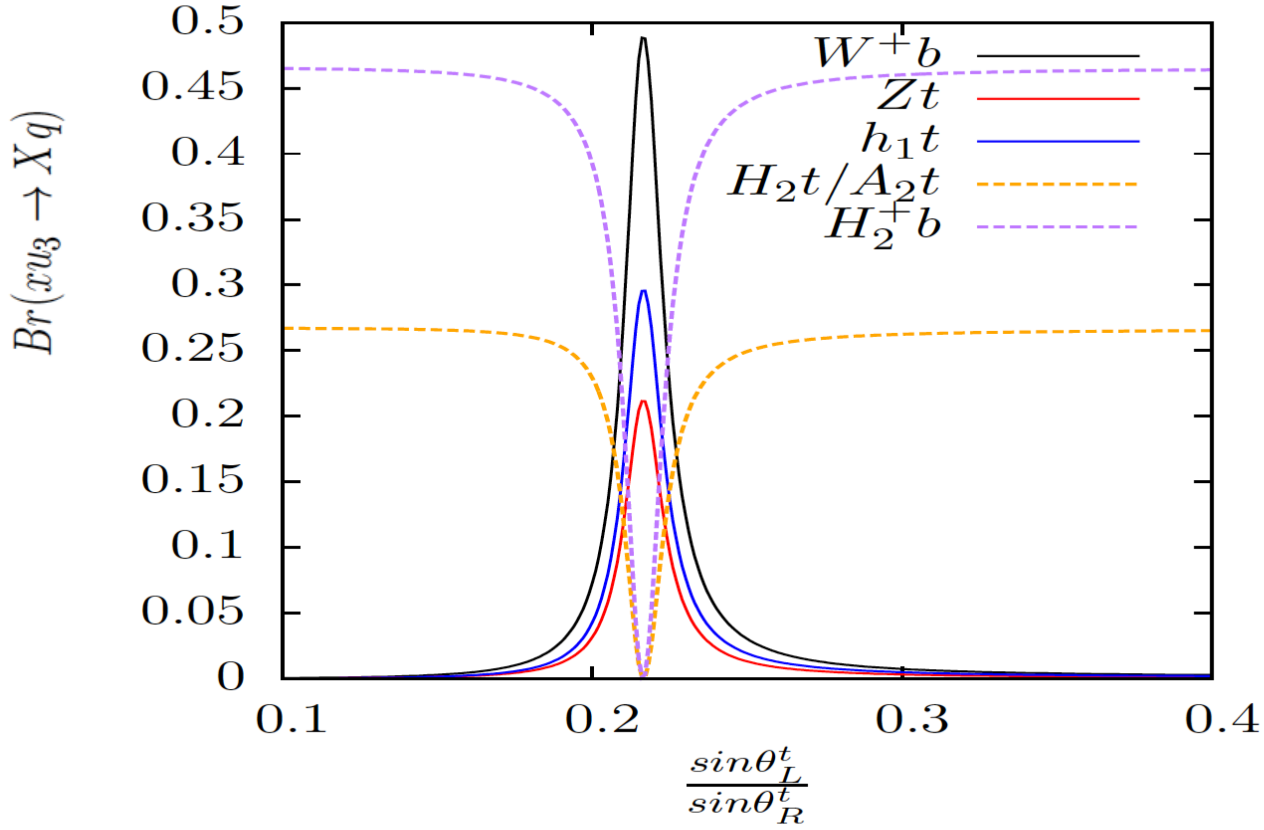
Signals at LHC

$$Y_{qxu} = 0 \implies \sin\theta_L^t = \frac{m_t}{m_{xu_3}} \sin\theta_R^t = \frac{173}{800} \sin\theta_R^t \simeq 0.22 \sin\theta_R^t$$

$$\text{Decay :} \quad xu_3 \to h_2^+\, b,\; H_2\, t, A_2\, t$$

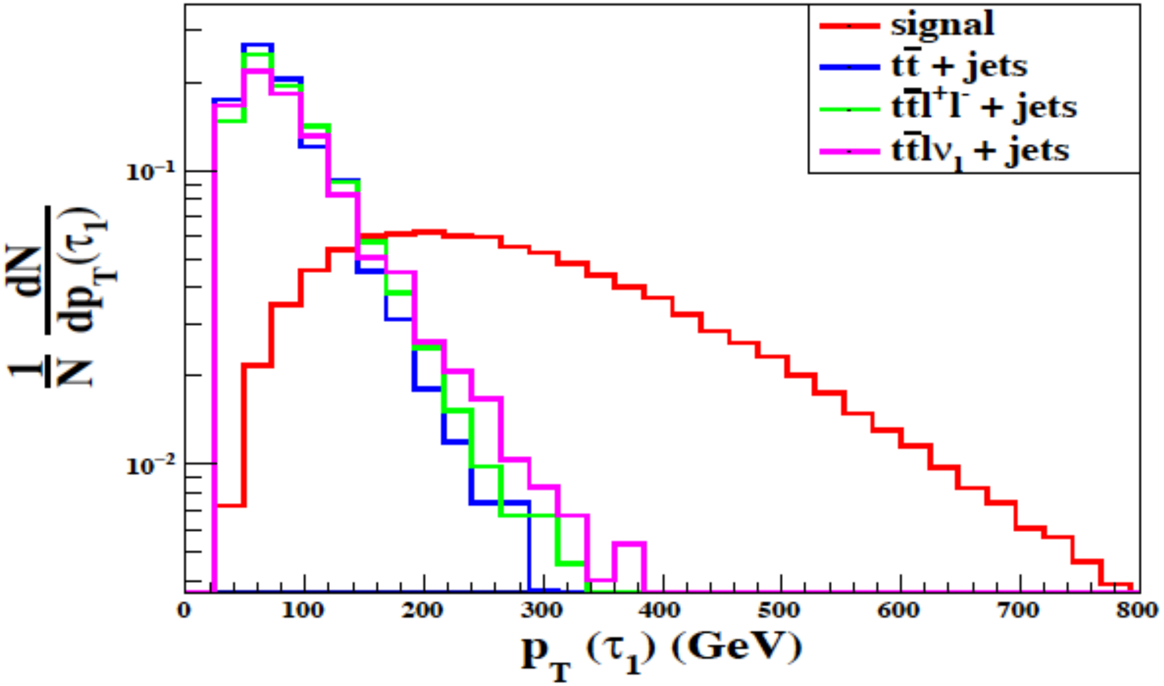
$$h_2^+ \to \tau^+ \nu_\tau \qquad H_2 \to \tau^+ \tau^- \qquad A_2 \to \tau^+ \tau^-$$

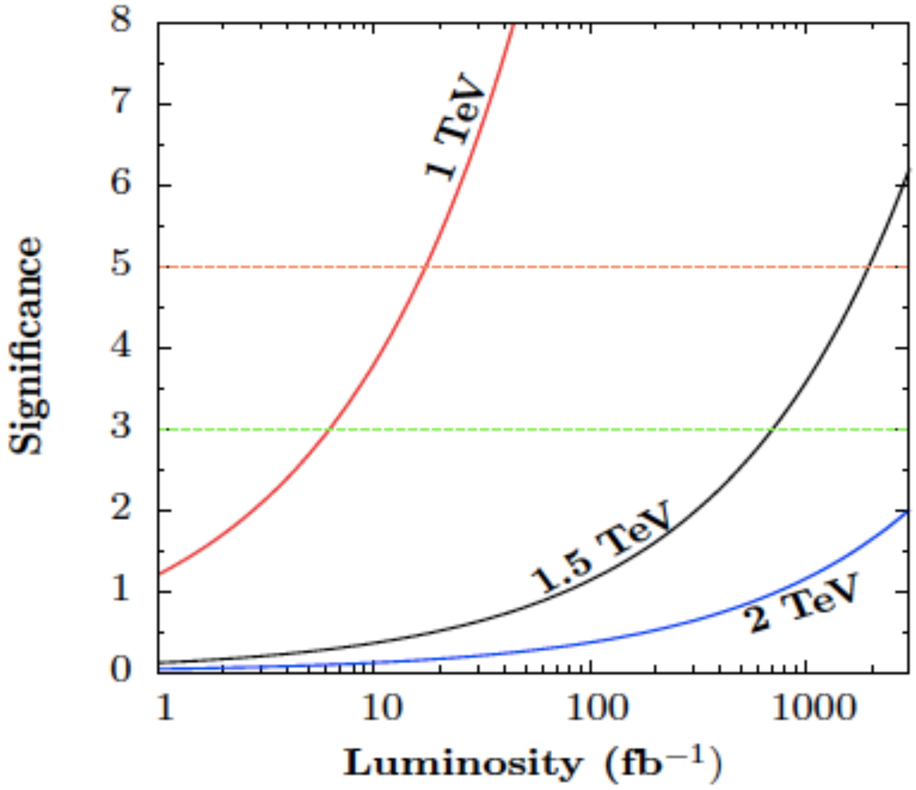




- $M_{xu_3} = 800$ GeV, $M_{h_2} = M_{A_2} = 300$ GeV, $M_{h_1^+} = 363$ GeV

Final State : $\geq 1b + \geq 2\tau + \geq 2j + \geq 1l$ $M_{H_2} = M_{A_2} = 300$ GeV, $M_{h_2^+} = 365$ GeV





$M_{xu_3} = 1200$ GeV

Cuts	Signal	Backgrounds
	96	16728
$P_T(j_1) > 150$ GeV	89	2526
$P_T(\tau_1) > 100$ GeV	72	678
$\not{E}_T > 100$ GeV	60	187

$\mathcal{S}(1200\text{GeV}) \sim 4\,\sigma$ $\mathcal{L} = 100\ fb^{-1}$

arXiv:1807.08160

Summary

- Vector-like quarks may have decay modes other than the normal decay modes ($xd \to bZ$, hb, tW^-).
- The current experimental limits for VLQ which do not decay directly to SM particles are very weak.
- These studies highlight an important point of caution for VLQ searches in the standard decay channels carried out at the LHC.
- Any new physics scenario which have additional gauge bosons and scalars can alter the VLQ searches in a significant way.
- Alternative channels of search should also be considered as the the VLQ mass limits crucially depend on them.

THANK YOU FOR YOUR ATTENTION

Back Up Slides

	Model Parameters	Particle Mass	$(\mathrm{Br}(s_h \to \gamma\gamma)$, $\mathrm{Br}(s_h \to gg))$	$\sigma(pp \to xd_1 \overline{xd_1})$
BP1	$\lambda_1 = 0.2$, $\lambda_2 = 0.04$, $\lambda_3 = \lambda_4 = 0$, $M = 0$, $\rho = 0.1$, $\frac{v_u}{v_d} = 2$, $v_s = 950$ GeV, $\lambda_S = 0.1$, $\lambda_T = 3 \times 10^{-3}$, $v_t = 30$ TeV, $\lambda_{ST} = 0.15$, $\sigma_1 = -5.14$ GeV , $\alpha = 51.17°$, $\theta_h = 153.43°$	$M_{xd_1} = 640$ GeV, $M_{x\ell_i} = 500$ GeV, $m_{s_h} = 600$ GeV, $m_{t_h} = 2.9$ TeV, $m_{h_1} = 125$ GeV, $m_{h_2} = 10$ TeV, $m_{h^-} = 10$ TeV, $m_{a_1} = 10$ TeV, $m_{a_2} = 1.9$ TeV	(0.006, 0.994)	339 fb
BP2	$\lambda_1 = 0.2$, $\lambda_2 = 0.04$, $\lambda_3 = \lambda_4 = 0$, $M = 0$, $\rho = 0.1$, $\frac{v_u}{v_d} = 2$, $v_s = 2.5$ TeV, $\lambda_S = 0.1$, $\lambda_T = 10^{-3}$, $v_t = 30$ TeV, $\lambda_{ST} = 0.06$, $\sigma_1 = -27.1$ GeV , $\alpha = 66.73°$, $\theta_h = 153.43°$	$M_{xd_1} = 850$ GeV, $M_{x\ell_i} = 500$ GeV, $m_{s_h} = 600$ GeV, $m_{t_h} = 3.1$ TeV, $m_{h_1} = 125$ GeV, $m_{h_2} = 10$ TeV, $m_{h^-} = 10$ TeV, $m_{a_1} = 10$ TeV, $m_{a_2} = 2.6$ TeV	(0.006, 0.994)	56.4 fb

Table 3.4: Two benchmark scenarios. The cross section is evaluated at the 13 TeV LHC. Note that $y_{ii}^{SD} = \sqrt{2}\, M_{xd_i}/v_s$, $y_{ii}^{TD} = 10^{-6}$ and we fix $M_{xd_2} = M_{xd_3} = 1.5$ TeV.