LHC signals of vector-like down-type quarks in a $U(1)$ extension of SM.

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Motivation

- SM with Heavy fourth generation chiral fermion gives large yukawa coupling and hence nonperturbative.
- Perturbative SM with a 4th generation chiral fermions is excluded(EWPOs).
- Existance of elementary fermions are allowed if they are vector like with respect to SM gauge group. i.e Isosinglet quarks.

- Existing searches for a vector-like quark of charge -1/3 assume that it decays into $(W\,t,\ Z\,b, h\,b)$.

- 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.

- Such a scenario is possible in a TeV scale $U(1)'$ from a non SUSY version of E_6 model.

- TeV scale $U(1)'$ from :

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

- The unbroken $U(1)'$:

$$Q' = \cos\theta\ Q_\chi + \sin\theta\ Q_\psi, \quad \tan\theta = \sqrt{5/3}.$$

Model

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

$SO(10)$	$SU(5)$	Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y \times$U(1)'
16	10	Q_i	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6}, \mathbf{1})$
		U_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{2/3}, \mathbf{1})$
		E_i^c	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})$
	$\bar{5}$	D_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3}, \mathbf{7})$
		L_i	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2}, \mathbf{7})$
	1	N_i^c / T	$(\mathbf{1}, \mathbf{1}, \mathbf{0}, -\mathbf{5})$
10	5	XD_i	$(\mathbf{3}, \mathbf{1}, -\mathbf{1/3}, -\mathbf{2})$
		XL_i^c, H_u	$(\mathbf{1}, \mathbf{2}, \mathbf{1/2}, -\mathbf{2})$
	$\bar{5}$	XD_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3}, -\mathbf{8})$
		XL_i, H_d	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2}, -\mathbf{8})$
1	1	XN_i, S	$(\mathbf{1}, \mathbf{1}, \mathbf{0}, \mathbf{10})$

$$-\mathcal{L}_{\text{Yukawa}} \supset y_{ij}^{D} Q_i D_j^c H_d + \boldsymbol{y_{ij}^{TD} D_i^c XD_j T + y_{ij}^{SD} XD_i^c XD_j S} + y_{ij}^{TL} XL_i^c L_j T + y_{ij}^{SL} XL_i^c XL_j S + \mathrm{H.C.}$$

Model

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

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

- $-\mathcal{L}_{\text{Yukawa}} \supset y^D_{ij} Q_i D^c_j H_d + y^{TD}_{ij} D^c_i X D_j T + y^{SD}_{ij} X D^c_i X D_j S$

- Mass matrix in the (q_1, xq_1) basis :

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

- For $(M_{xd_1} = 640\,\text{GeV},\ v_s = 1.5\,\text{TeV}, v_t = 10\,\text{TeV},\ y_{11}^{TD} \sim 10^{-5})$

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

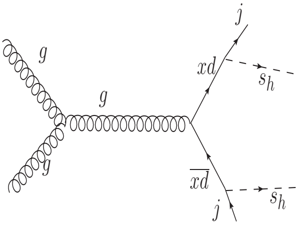
- For $(g_X = 0.5, v_s = 1\ \text{TeV},\ \boldsymbol{v_t = 20\ \text{TeV}},\ 0 \leq \frac{v_u}{v_d} \leq 200)$

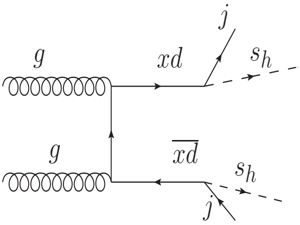
$$\implies \theta_{z-z'} \leq 10^{-4} \text{ and } M_Z' = 3.2\ \text{TeV}.$$

- Possible decay modes:
    - For $\boldsymbol{xd}$: $s_h\, d,\ t_h\, d,\ a_{h_1}\, d, a_{h_2}\, d, d\, Z',\ h\, d,\ d\, Z,\ u\, W^-$.
    - For $\boldsymbol{s_h}$: $\gamma\,\gamma,\ g\, g, x\bar{\ell}_i\, x\ell_j,\ x\bar{\ell}_i\, l_j,\ \bar{l}_i\, x\ell_j,\ \bar{l}_i\, l_j$.

Production and Decay

- The Channel





- Considered the scenario where :

  one s_h decays to $\gamma\,\gamma$

  another decays to $g\,g$

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

Benchmarks

- **Benchmark 1** : $M_{xd_1} = 640$ GeV, $M_{s_h} = 600$ GeV.

  final state : $2\gamma + 2j$ with $P_T(j) > 40$ GeV.

  $\sigma(pp \to xd_1\overline{xd_1}) = 0.339$ pb.

- **Benchmark 2** : $M_{xd_1} = 850$ GeV, $M_{s_h} = 600$ GeV.

  final state : $2\gamma + 4j$.

  $\sigma(pp \to xd_1\overline{xd_1}) = 0.056$ pb.

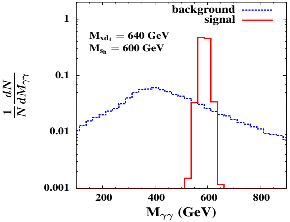
- For both the benchmarks : $M_{xl_i} = 500$ GeV,
  $M_{xd_2} = M_{xd_3} = 1.5$ TeV.

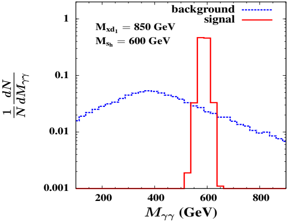
Analysis

	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	$p_T(j_1) \geq 150$ GeV $P_T(j_2) \geq 100$ GeV $p_T(\gamma_1) \geq 200$ GeV $P_T(\gamma_2) \geq 100$ GeV $M_{eff} \geq 800$ 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

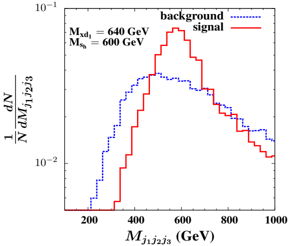
Analysis

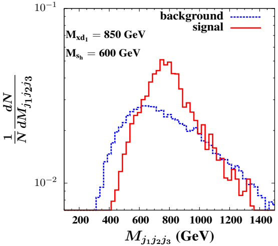
- Reconstruction of s_h from the two leading photons.



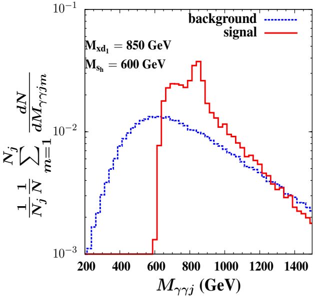


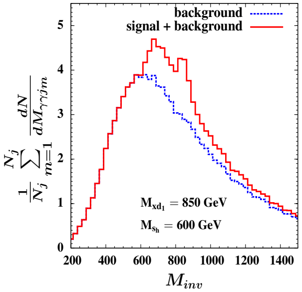
- Reconstruction of xd_1 from three leading jets.





- Reconstruction of xd_1 from the two leading photons and jets.$\left(\frac{1}{N_j}\frac{1}{N}\sum_{m=1}^{N_j}\frac{dN}{dM_{\gamma_1\gamma_2 jm}}\right)$ (Benchmark 2)





Summary

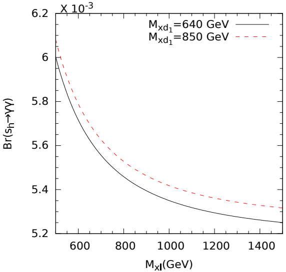
- Possibility of non-standard decay modes of a TeV scale vector-like quark exists in a E_6 inspired $U(1)$ extension of SM, where it can decay dominantly to a SM light jet and a SM singlet scalar.
- The SM singlet scalar can decay to two photons and the existence of such a scenario can be tested at LHC by analyzing the $2\gamma + \geq 4j$ final state.

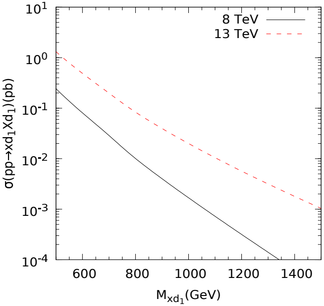
Future works

- $$-(L_{\text{Yukawa}})_{\text{neutrino}} = y^{N}_{ij} L_i N^c_j H_u + y^{XNd}_{ij} XL^c_i XN_j H_d + y^{XNu}_{ij} XL_i XN_j H_u + y^{TL}_{ij} XL^c_i L_j T + y^{SL}_{ij} XL^c_i XL_j S + y^{SN}_{ij} SN^c_i N^c_i + y^{TXNN}_{ij} T\, XN_i N^c_j + \text{H.C}$$
- $\nu_e \in L_1 \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}$, $xs_1 \in XL_1 \equiv \begin{pmatrix} xs_1 \\ xl_1 \end{pmatrix}$, $xs^c_1 \in XL^c_1 = \begin{pmatrix} xl^c_1 \\ xs^c_1 \end{pmatrix}$, N^c_1 and XN_1.
- Mass matrix in (ν_e, N^c_1) basis : $\begin{pmatrix} 0 & y^{N}_{11}\frac{v_u}{\sqrt{2}} \\ y^{N}_{11}\frac{v_u}{\sqrt{2}} & y^{SN}_{11}\frac{v_s}{\sqrt{2}} \end{pmatrix}$
- $y^{SN}_{11}\frac{v_s}{\sqrt{2}} = 1$ TeV, $v_u = 2v_d$, $m_1 \approx 0.01$ eV we have to take $y^{N}_{11} \approx 10^{-6}$ which gives $\theta \approx 10^{-7}$ and $m_2 \approx 1$TeV.

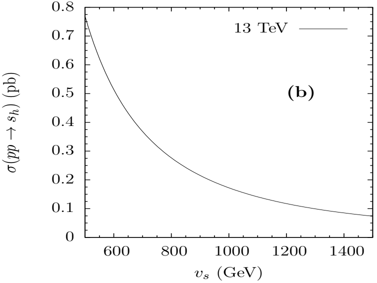
Thank You.

Back up Slides

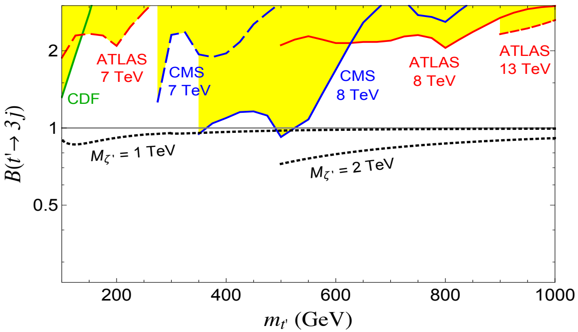

X 10-3
6.2
6
5.8
5.6
5.4
5.2
Br(s_h→γγ)
M_xd1=640 GeV
M_xd1=850 GeV
600
800
1000
1200
1400
M_xl(GeV)



10^1
10^0
10^-1
10^-2
10^-3
10^-4
σ(pp→xd1Xd1)(pb)
8 TeV
13 TeV
600
800
1000
1200
1400
Mxd1(GeV)



13 TeV
(b)
$\sigma(pp \to s_h)$ (pb)
v_s (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
600
800
1000
1200
1400



ATLAS
7 TeV
CMS
7 TeV
CDF
CMS
8 TeV
ATLAS
8 TeV
ATLAS
13 TeV
$M_{\zeta'}$ = 1 TeV
$M_{\zeta'}$ = 2 TeV
2
1
0.5
200
400
600
800
1000
$B(t' \to 3j)$
$m_{t'}$ (GeV)

Generation level cuts for Background

- Benchmark 1 : $pp \to 2\gamma + 2j$

$$P_T(j) > 20 \text{ GeV}, |\eta(j)| < 2.5,$$

$$P_T(\gamma) > 100 \text{ GeV}, |\eta(\gamma)| < 2.5,$$

$$\Delta R(j,j), \Delta R(\gamma,\gamma) \text{ and } \Delta R(\gamma,j) > 0.4.$$

$$\sigma(pp \to 2\gamma + 2j)_{13\,\text{TeV}} = 0.234 \text{ pb}.$$

- Benchmark 2 : $pp \to 2\gamma + 4j$

$$P_T(j_1) \text{ and } P_T(j_2) > 80 \text{ GeV},$$

$$P_T(j_3) \text{ and } P_T(j_4) > 40 \text{ GeV}, |\eta(j)| < 2.5,$$

$$P_T(\gamma) > 100 \text{ GeV}, |\eta(\gamma)| < 2.5,$$

$$\Delta R(j,j), \Delta R(\gamma,\gamma) \text{ and } \Delta R(\gamma,j) > 0.4.$$

$$\sigma(pp \to 2\gamma + 4j)_{13\,\text{TeV}} = 0.0121 \text{ pb}.$$

$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$	$4\sqrt{15}Q$
16	$10\ (Q_i, U_i^c, E_i^c)$	–1	1	1
	$\bar{5}\ (D_i^c, L_i)$	3	1	7
	$1\ (N_i^c/T)$	–5	1	-5
10	$5\ (XD_i, XL_i^c/H_u)$	2	–2	-2
	$\bar{5}\ (XD_i^c, XL_i/H_d)$	–2	–2	-8
1	$1\ (XN_i/S)$	0	4	10

Decomposition of the E_6 fundamental **27** representation under $SO(10)$, $SU(5)$, and the $U(1)_\chi$, $U(1)_\psi$ and $U(1)'$ charges.

- Particles and their charges under the

  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$ gauge symmetry.

Q_i	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6}, \mathbf{1})$	U_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{2/3}, \mathbf{1})$	D_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3}, \mathbf{7})$
L_i	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2}, \mathbf{7})$	E_i^c	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})$	N_i^c/T	$(\mathbf{1}, \mathbf{1}, \mathbf{0}, -\mathbf{5})$
XD_i	$(\mathbf{3}, \mathbf{1}, -\mathbf{1/3}, -\mathbf{2})$	$XL_i^c,\ H_u$	$(\mathbf{1}, \mathbf{2}, \mathbf{1/2}, -\mathbf{2})$	XD_i^c	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3}, -\mathbf{8})$
$XL_i,\ H_d$	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2}, -\mathbf{8})$	$XN_i,\ S$	$(\mathbf{1}, \mathbf{1}, \mathbf{0}, \mathbf{10})$		

  The $U(1)'$ charges are the $U(1)'$ charges in the Table divided by $4\sqrt{15}$.

- We consider the particles as simple exotics having anomaly-free $U(1)'$ charges.

- The Higgs potential essential for the extra $U(1)$ symmetry breaking is

$$V = - \mu_1^2 \, H_u^\dagger H_u - \mu_2^2 \, H_d^\dagger H_d + \lambda_1 \, (H_u^\dagger H_u)^2 + \lambda_2 \, (H_d^\dagger H_d)^2$$
$$+ \lambda_3 \, (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 \, [\epsilon_{ab}(H_u)_a(H_d)_b][\epsilon_{mn}(H_u^*)_m(H_d^*)_n]$$
$$- m_S^2|S|^2 - m_T^2|T|^2 + \lambda_S|S|^4 + \lambda_T|T|^4 + \lambda_{ST}|S|^2|T|^2$$
$$+ (\sigma S T^2 + H.C) + \lambda_5 \, H_u^\dagger H_u|S|^2 + \lambda_6 \, H_d^\dagger H_d|S|^2$$
$$+ \lambda_7 \, H_u^\dagger H_u|T|^2 + \lambda_8 \, H_d^\dagger H_d|T|^2$$
$$+ (M \, [\epsilon_{ab}(H_u)_a(H_d)_b]S + H.C.)$$
$$+ (\rho \, [\epsilon_{ab}(H_u)_a(H_d)_b] \, T^* T^* + H.C.) \ .$$

- The Yukawa sector is represented by

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

- All possible decay modes for VLQ :
$$xd \to s_h\, d,\; t_h\, d,\; a_h\, d,\; h\, d,\; d\, Z,\; d\, Z',\; u\, W^-.$$

- $t_h,\ a_h$ and Z' are taken to be heavier than xd.

- The mixing matrices which transform the the gauge eigen states(d^0, xd_1^0) to mass eigen states(d, xd_1) are given by
$$S_i = \begin{pmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{pmatrix}, \text{where } \ i = L, R,$$

- The mixings of the vectorlike quarks with the SM quark have been taken to be very small. This will ensure the decay modes $xd \to d\, Z,\ u\, W^-,\ h\, d$ are suppressed.

- The $Z - Z'$ mixing has also been taken to small, thus forbidding the decay to $d\, Z$ through this.

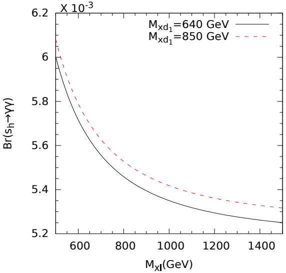
- All of the higgs bosons except h from the (H_u, H_d) sector are kept heavier than xd.

- Hence xd mostly decays to s_h and to a SM quark(through the term $y_{ij}^{TD} D_i^c X D_j T$).

- The existing bounds on VLQ mass around 800 GeV is significantly relaxed.

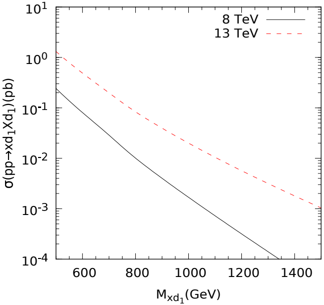
- Example: for the parameter set $(M_{xd_1} = 640\,\text{GeV},\ M_{s_h} = 600\,\text{GeV},\ v_s = 1.5\,\text{TeV},\ \sin\theta = 0.5,\ \sin\theta_R \sim 10^{-4},\ \sin\theta_L \sim 10^{-10},\ y_{11}^{TD} \sim 10^{-5})$ we get $\text{Br}(xd \to d\, s_h) \sim 1$ and a width for xd to be $\sim 10^{-10}$ GeV. $\sin\theta$ is the mixing in the CP even sector of (S, T) scalars.

- Possible decay modes for s_h
$$s_h \to \bar{l}_i\, l_j, x\bar{\ell}_i\, x\ell_j,\ x\bar{\ell}_i\, l_j,\ \bar{l}_i\, x\ell_j,\ \gamma\,\gamma,\ g\, g.$$
- Mixing between vectorlike leptons and SM leptons are taken to zero, and $M_{x\ell_i} > m_{s_h}/2$ condition is ensured.
- s_h can either decay to two gluons or to two photons through the $s_h gg$ and $s_h\gamma\gamma$ effective coupling.



- We have events with $2\gamma + 4j$, $4\gamma + 2j$ and $6j$ final states.

- We have tried to see the effect of only one VLQ on the $2\gamma + 4j$ final state. That VLQ is xd_1.
- Two benchmark scenarios, $M_{xd_1} = 640$ GeV and $M_{xd_1} = 850$ GeV. The other two VLQs are at 1.5 TeV.



- The crosssection for a 1.5 TeV VLQ is two orders of magnitude less compared to that of a 850 GeV VLQ.

- Object Identification :

  $|\eta(j)|,\ |\eta(\gamma)|,\ |\eta(l)| < 2.5$

  $P_T(j),\ P_T(\gamma) > 40$ GeV and $P_T(l) > 10$ GeV.

- Event selection :

  Benchmark 1:

  $N(l) = 0,\ N(j) \geq 2$ and $P_T(j_2) \geq 100$ GeV,

  $N(\gamma) \geq 2,\ P_T(\gamma_2) \geq 100$ GeV.

  $p_T(\gamma_1) \geq 200$ GeV, $p_T(j_1) \geq 150$ GeV,

  $M_{eff} \geq 800$ GeV.

  Benchmark 2:

  $N(l) = 0,\ N(j) \geq 4$ and $P_T(j_2) \geq 100$ GeV,

  $N(\gamma) \geq 2,\ P_T(\gamma_2) \geq 100$ GeV.

  $p_T(\gamma_1) \geq 200$ GeV, $M_{eff} \geq 1000$ GeV.

- With these cuts the crosssection for both the benchmarks

  Benchmark 1 : $\sigma_S = 2$ fb and $\sigma_B = 13.5$ fb.

  Benchmark 2 : $\sigma_S = 0.35$ fb and $\sigma_B = 3$ fb.

- With 100 fb^{-1} of integrated luminosity the Signal to background ratio for benchmark 1 is 5σ and for benchmark 2, it is 2σ.