Optimization of search variables for the pair production of first generation scalar leptoquarks at CMS

Viraj Thakkar*

Tata Institute of Fundamental Research, Mumbai

(Dated: July 2,2017)

Abstract

As possible signature of new physics beyond the standard model (SM), we search for hypothetical particles called "leptoquarks" that have the dual properties of both leptons and quarks. We search for such particles in the final states of two electrons and two hadronic jets using proton-proton collision data events recorded at 13 TeV with the CMS detector at the LHC. We optimize the value of various search variables to obtain an optimal significance for a leptoquark mass of 250 GeV/c^2 from various SM background processes. The optimization is performed using Monte Carlo simulated data, which can be later applied to collision data. Further, the same procedure can be repeated for higher leptoquark masses.

CONTENTS

STANDARD MODEL AND BEYOND STANDARD MODEL

The SM is a successful theory which describes the interaction of known elementary particles with three out of four fundamental forces in nature: Strong, Electromagnetic and Weak.

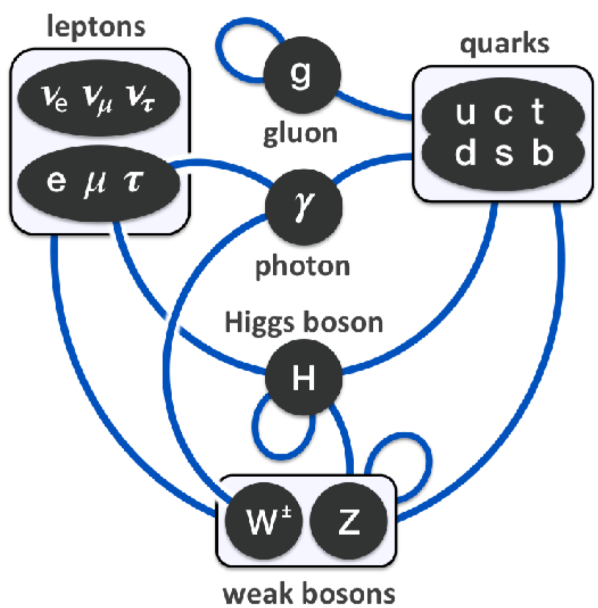

FIG. 1. Summary of interactions between particles described by the Standard Model.

Limitations of Standard Model

Despite its success, the SM does not account for gravity, one of the fundamental force in the universe.

Experimental results from astrophysics tell us that roughly one quarter of the energy density of the universe is composed of “dark matter” and nearly three quarters is composed of “dark energy”. However, the Standard Model makes no predictions for such a matter and it has no such dark matter candidate particles .

It fails to account for neutrino mass and explain phenomenon such as neutrino oscillations.

Due to such limitations of the SM, it seems that the standard model is a low energy remnant of a much larger theory. Hence, the scientific community look for existence of theories beyond standard model or Standard Model "extensions" such the study of dark matter and dark energy, matter–antimatter asymmetry , neutrino oscillations, Supersymmetry (SUSY) and existence of new particle.

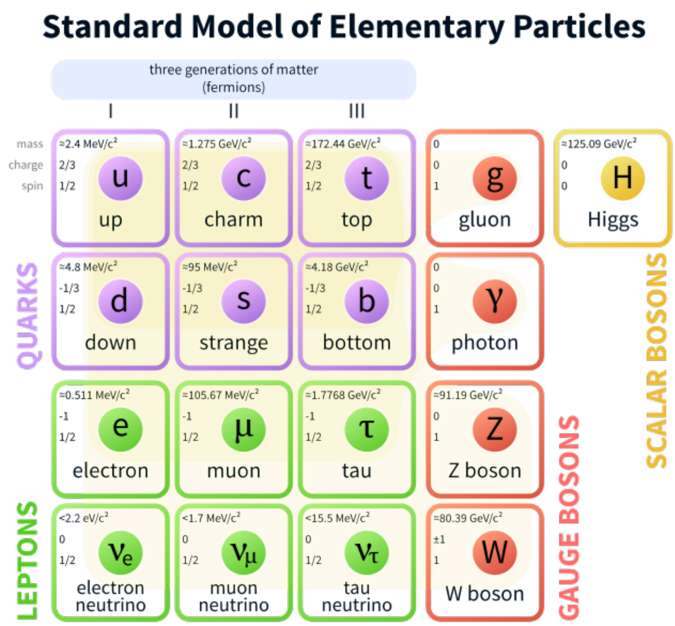

FIG. 2. The Standard Model of elementary particles , with the three generations of matter, gauge bosons in the fourth column, and the Higgs boson in the fifth

LEPTONS AND QUARKS

Fundamentally we are made up of two types of particles: leptons and quarks. In the Standard Model, leptons and quarks are formally independent from each other.

Motivation for the leptoquark model

Leptons and quarks naturally fit into three generations of doublets based on the way they interact with the weak force. Also the masses of leptons and quark increase as we move on from generation one to three. We do not know why both types of particles conform to the same pattern.

The Leptoquark model, possible candidate for physics beyond the SM, predicts the existence of hypothetical particles called "leptoquarks" that have dual properties of both leptons and quarks.

LEPTOQUARK PRODUCTION

Leptoquarks are usually formed by pair production rather than single production as the cross sections predicted for pair production are significantly larger than single production for leptoquark with mass less than 1.2 TeV . Leptoquark pair production in pp collisions occurs primarily through quark-antiquark annihilation and gluon-gluon fusion processes, with gluon-gluon fusion dominating.

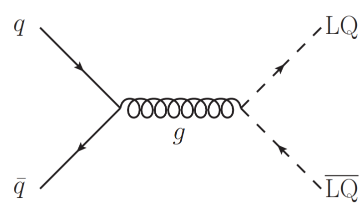

FIG. 3. Example of Leptoquark pair production through quark-antiquark annihilation

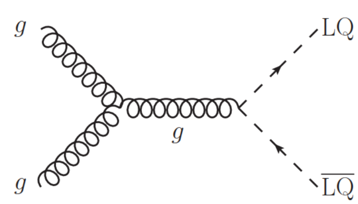

FIG. 4. Example of Leptoquark pair production through gluon gluon fusion.

LEPTOQUARK DECAY

As Leptoquark is composed of leptons and quarks, it can decay into any combination of leptons and quarks. We will deal with first generation of scalar leptoquarks and assume there is no inter generation mixing. Let β denote the branching fraction for a Leptoquark to decay into a quark and a lepton (electron) $\beta =$ BR (LQ$\rightarrow$ $l^{\pm}q$). We get the possibilities as shown in the Fig. 5.

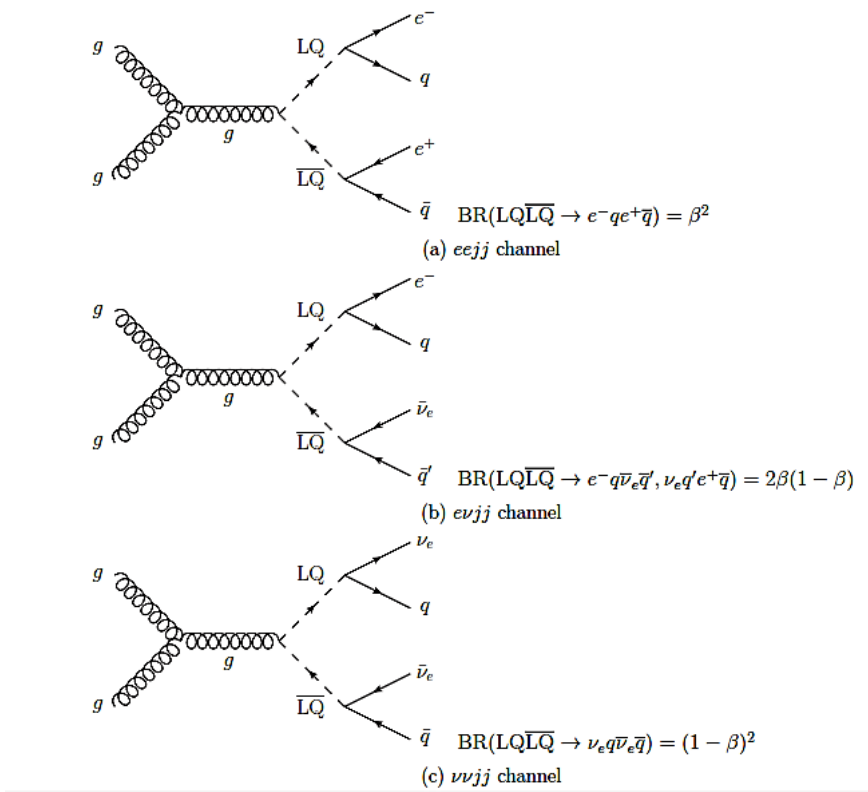

FIG. 5. Possible final states for a decay of a pair of first-generation scalar leptoquarks. q denotes either an up or down quark.

The final states for leptoquark pair production are : two charged leptons and two quarks; one charged lepton, one neutrino, and two quarks; and two neutrinos and two quarks. For experimental purposes, this corresponds to the following final state : two charged leptons and two jets; one charged lepton, two jets, and missing transverse energy (as neutrino passes through the CMS detector undetected) ; and two jets and missing transverse energy. We consider $\beta = 1$ for our analysis, thus eliminating the second and third possibility.

SELECTION OF EEJJ EVENTS

We have information on the electrons and the jets produced in the final state of pp collisions through Monte-Carlo simulated data. As the final state of leptoquark decay consists of two leptons(electrons) and two jets , We want to filter out events satisfying following criteria:

- The events should contain exactly two electrons

- The event final state should contain at least two jets. We select the two jets with the highest and the next highest p_T

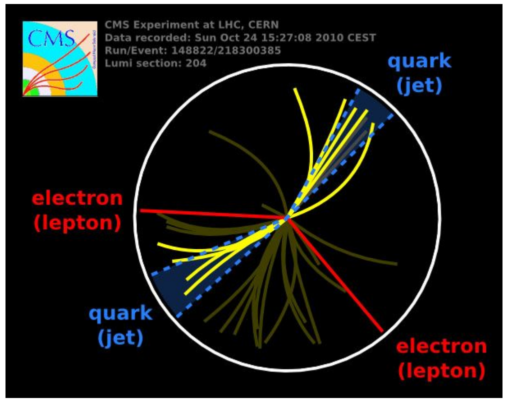

FIG. 6. eejj final state in CMS detector.

INVARIANT MASS RECONSTRUCTION OF Z BOSON

The W and Z bosons are together known as the weak or more generally as the intermediate vector bosons. These elementary particles mediate the weak interaction. They also form a part of our SM background processes in the final state eejj events. As the final state of our events include two electrons along with at least two jets, we first learn to calculate invariant mass reconstruction of Z boson (M_{ee}) as it decays into an electron and a positron. See Fig.7

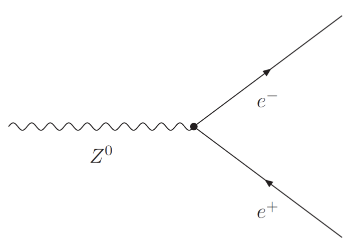

FIG. 7. Decay of Z boson into an electron and a positron.

Let us denote the four momenta of the two electrons as P_{e1} and P_{e2} whose components are $P_{e1} = (E_1, P_{x1}, P_{y1}, P_{z1})$ and $P_{e2} = (E_2, P_{x2}, P_{y2}, P_{z2})$. According to the law of conservation of 4-momentum , The Z boson four vector is then given by

$$P_Z = P_{e1} + P_{e2}$$

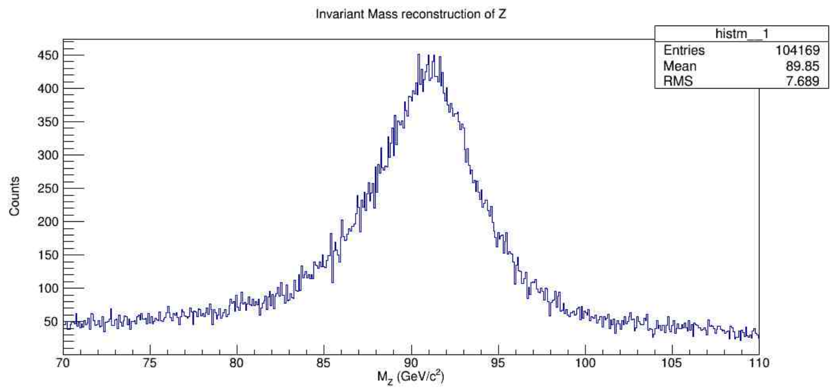

FIG. 8. Invariant Mass reconstruction of Z boson. The calculated mass is approximately in agreement with the theoretical value.

The invariant mass of Z boson (M_{ee}) is calculated as follows :

$$M_{ee} = \left[(E_1 + E_2)^2 - (P_{x1} + P_{x2})^2 - (P_{y1} + P_{y2})^2 - (P_{z1} + P_{z2})^2\right]^{1/2} \tag{1}$$

RECONSTRUCTION OF LEPTOQUARK OF MASS 250 GEV

As a leptoquark decays into an electron and hadronic jet, we have to reconstruction the invariant mass of leptoquark (M_{ej}) from the signal data. We consider LQ-250 GeV in this project.

Selection cuts

- Electron $p_T > 50$ GeV
- Jet $p_T > 50$ GeV
- Angular separation between selected electrons and jets $\triangle R > 0.4$ where $\triangle R$ is calculated as

  $$\triangle R = \sqrt{(\triangle\eta)^2 + (\triangle\phi)^2}$$

  where η is the pseudorapidity and ϕ is the azimuthal angle.

Selecting Leptoquark mass with minimum mass difference of particle-antiparticle pair

After selecting events with at least two electrons (say e_1 and e_2) and two leading p_T jets (say j_1 and j_2) , we have two possible combinations :

1. Case 1: $e_1 j_1$ and $e_2 j_2$

2. Case 2: $e_1 j_2$ and $e_2 j_1$

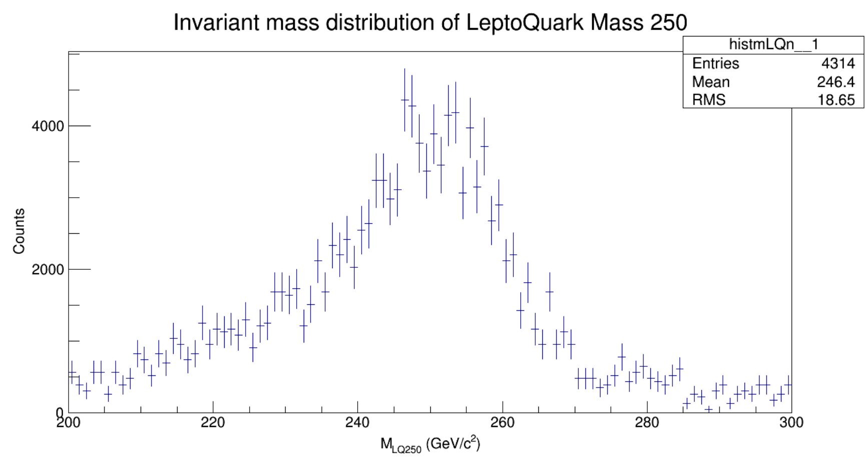

FIG. 9. Invariant mass distribution of LQ-250 GeV

Corresponding to these combinations, we get four possible Leptoquark masses. $LQ1$ and $LQ2$ in Case 1. $LQ3$ and $LQ4$ in Case 2. As $LQ1$ and $LQ2$ (similarly $LQ3$ and $LQ4$) are particle antiparticle pair , they must have the same mass. So we select the pair with the minimum difference in mass among $LQ1$ and $LQ2$ (or $LQ3$ and $LQ4$). The final mass of LQ is taken to be the average of the pair. Thus, the Leptoquark mass (M_{ej}) is reconstructed from two electron and at least two jets events.Fig.9

The invariant mass M_{ej} is calculated as

$$M_{ej} = \left[(E_e + E_j)^2 - (P_{xe} + P_{xj})^2 - (P_{ye} + P_{yj})^2 - (P_{ze} + P_{zj})^2\right]^{1/2} \quad (2)$$

where electron four momentum is $P_e = (E_e, P_{xe}, P_{ye}, P_{ze})$
and Jet four momentum is $P_j = (E_j, P_{xj}, P_{yj}, P_{zj})$

BACKGROUND PROCESSES

We consider background processes which have similar final state as our signal i.e eejj events. Some of the background processes considered are $t\bar{t}$ decay, Drell- Yan, $\gamma+$ Jets, diboson decays (WW,WZ and ZZ) etc. The dominant ones being $t\bar{t}$ decay and Drell-Yan process.

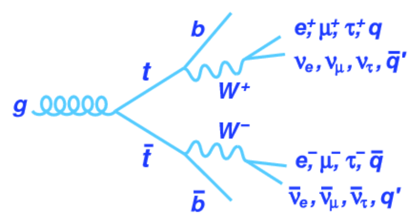

FIG. 10. $t\bar{t}$ decay.

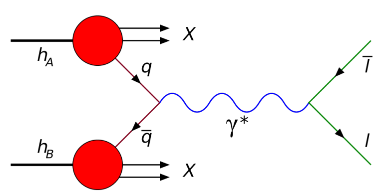

FIG. 11. Drell-Yan process.

OPTIMIZATION OF SEARCH VARIABLES TO GET THE MAXIMUM SIGNIFICANCE

Definition of optimization variables

We select the following variables for optimizing the significance ($s/\sqrt{b}$, where s is the number of signal events and b is the total number of background processes) for leptoquark mass 250 GeV . These three variable are varied independently over a range of values(in steps of 5 GeV) and the thresholds which give the maximum significance is obtained. These variables are chosen as they are weakly correlated.

- S_T : Sum of p_T of two electrons and two leading jets

- M_{ee} : Invariant mass of the two electrons. See Eq.1
- M_{ej} : Average mass of the LQ pairs with minimum mass difference. See Eq.2

Cuts on various variables

We apply a few preliminary cuts to the electron and jet related observables to eliminate low energy processes and to reduce background:

Variable	Barrel Threshold	Endcap Threshold
η	$\|\eta_{SC}\| < 1.4442$	$1.566 < \|\eta_{SC}\| < 2.5$
isEcalDriven	yes	yes
Inner layer lost hits	≤ 1	≤ 1
$\|d_{xy}\|$ [cm]	<0.02	<0.05
$\|\Delta\eta_{in}^{seed}\|$	<0.004	<0.006
$\|\Delta\phi_{in}\|$	<0.06	<0.06
H/E	$< 1/E + 0.05$	$< 5/E + 0.05$
$\sigma_{i\eta i\eta}^{full5\times5}$	n/a	<0.03
Shower shape	$E^{2\times5}/E^{5\times5} > 0.94$ OR $E^{1\times5}/E^{5\times5} > 0.83$	-
Calo iso. [GeV]	$< 2 + 0.03 \times E_T + 0.28 \times \rho$	$\begin{cases} < 2.5 + 0.28 \times \rho & \text{if } E_T < 50 \\ < 2.5 + 0.28 \times \rho + 0.03 \times (E_T - 50) & \text{if } E_T \geq 50 \end{cases}$
Tracker iso. [GeV]	<5	<5

FIG. 12. Preselection cuts for electrons.

- At least two jets with $p_T > 50$ GeV and $|\eta| < 2.1$
- $M_{ee} > 50$ GeV
- $S_T > 300$ GeV

Optimization of S_T

The significance is calculated for various values of S_T for fixed M_{ee} and M_{ej}. We get the maximum significance plot as shown in Fig.13

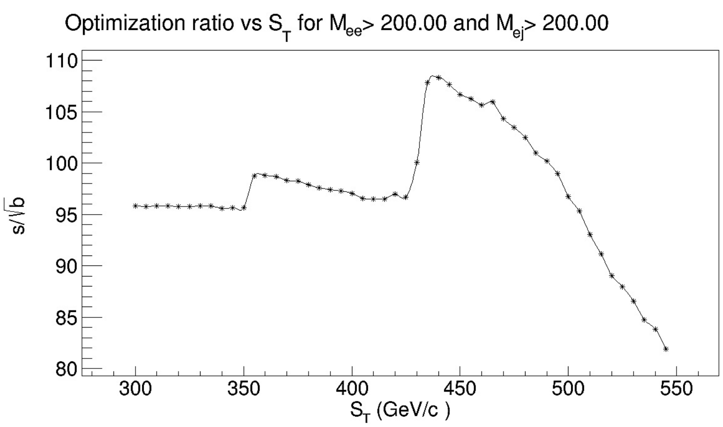

FIG. 13. S_T optimization.

Optimization of M_{ee}

The significance is calculated for various values of M_{ee} for fixed S_T and M_{ej}. We get the maximum significance plot as shown in Fig.14

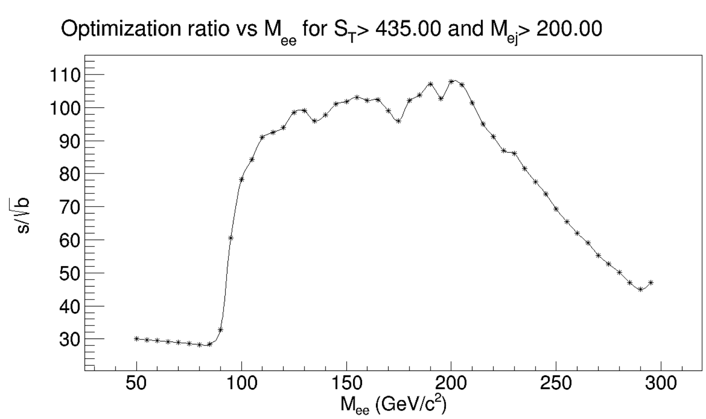

FIG. 14. M_{ee} Optimization.

Optimization of M_{ej}

The significance is calculated for various values of M_{ej} for fixed S_T and M_{ee}. We get the maximum significance plot as shown in Fig.15

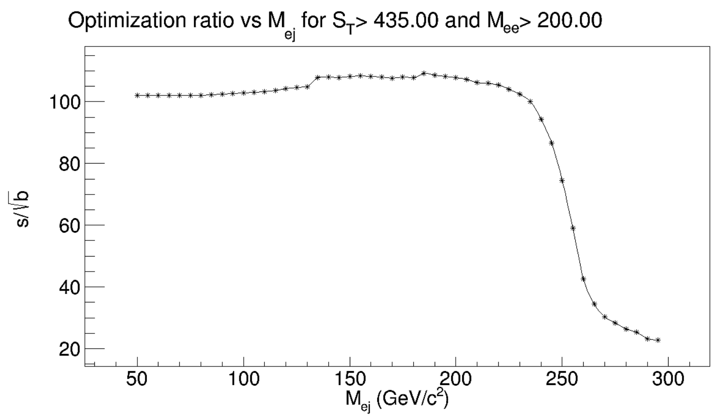

FIG. 15. M_{ej} Optimization.

Visualization of maximum significance

A 3D plot can be made for visualization purposes to see the maximum significance peak on the mountain like surface. This is a plot of significance on the z axis, with varying values of S_T and M_{ee} at fixed $M_{ej} > 200$ GeV. It can clearly be seen that the significance is maximum around the peak point.

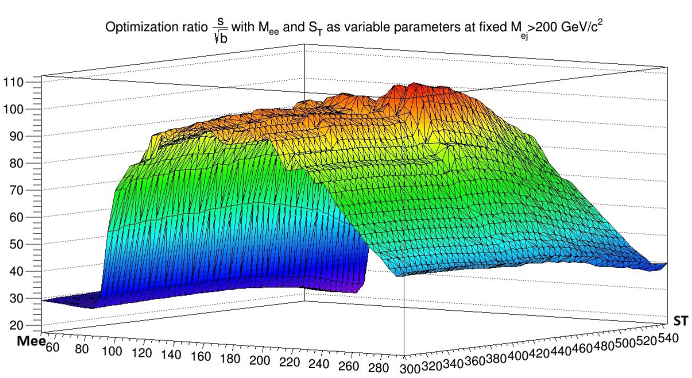

FIG. 16. Significance($s/\sqrt{b}$) plot on z-axis vs S_T and M_{ee} on x and y axis respectively at fixed M_{ej} cut of 200 GeV .

RESULT

The maximum value of significance is obtained at

$$\mathbf{S_T} > \mathbf{435} \text{ GeV} \ ; \ \mathbf{M_{ee}} > \mathbf{200} \text{ GeV} \ ; \ \mathbf{M_{ej}} > \mathbf{200} \text{ GeV}$$

CONCLUSION

We thus obtain an optimal significance for leptoquark mass 250 under the above mentioned cuts for the search parameters S_T, M_{ee} and M_{ej}. The physical importance of this optimization is that the signal for Leptoquark Mass 250 (if it exists) can be best observed under these cuts in the CMS detector at LHC.

Future Prospects

- b-tagging of jets can be introduced and Optimization values can be found out.
- The same procedure can be repeated for higher Leptoquark masses.

ACKNOWLEDGMENTS

Supervisor:
Dr. Gagan Mohanty
Thanks to:
Muzamil Ahmad Bhat

* viraj.thakkar@niser.ac.in

[1] Search for the Pair Production of First Generation Scalar Leptoquarks with the CMS Detector ,Edmund A. Berry

[2] http://cms.web.cern.ch/news/hunt-platypus-particle

[3] Griffiths, David. Introduction to elementary particles. John Wiley & Sons, 2008.

[4] The CMS Experiment at CERN