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Observing Heavy Top Quarks with charge 5/3 and Heavy B quarks with the CMS detector: A Feasibility Study

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Abstract

In this note, we present a feasibility study for searches for two exotic particles - a heavy top quark with a fractional charge of 5/3, $T_{5/3}$, and its partner, the heavy B quark. These particles decay to a top quark and a W boson, leading to very busy events with multi-leptons and multi-jets. We consider the event signatures where same-sign dileptons are likely to be produced. The backgrounds are predominantly from standard model signatures due to $t\bar{t}WW$, $t\bar{t}W$ and multiple-W+jets production. We conclude that it is possible to observe these exotic particles with masses around 500 GeV, in data samples ranging from a few hundred inverse pico-barns to about 1 fb^{-1} of integrated luminosity.

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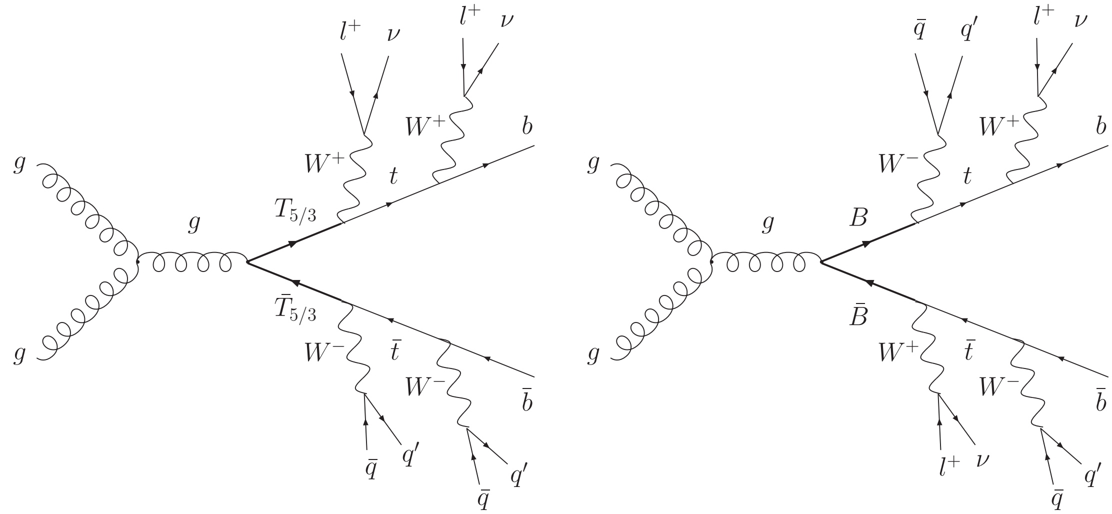

Figure 1. Pair production of $T_{5/3}$ and B quarks and decay to same-sign dilepton final states. Figures taken from Ref. [1].

1 Introduction

The Large Hadron Collider (LHC) with a collision center of mass energy of $\sqrt{s} = 14$ TeV will allow the LHC experiments to probe particle interactions up to the TeV scale, making it extremely likely that they will be able to detect some signatures of new physics. In order to make progress in developing our understanding of particle physics beyond the standard model experimental evidence of such physics is essential.

During the first year of LHC running, we expect to collect about one fb^{-1} of integrated luminosity. Recently, Contino and Servant, have suggested a model which predicts the existence of an exotic heavy top quark partner with fractional charge 5/3, $T_{5/3}$, and a heavy B quark [1]. These particles are predicted in models where the Higgs is a pseudo-Goldstone boson and the $T_{5/3}$ is the prediction of a LR custodial parity invariance of the electroweak symmetry breaking sector.

Their study suggests that we can observe these particles, if they exist, with datasets corresponding to relatively small integrated luminosity, of the order of a few hundred inverse pico-barns. Both the $T_{5/3}$ quark and B quark can have masses around 500 GeV to a TeV or so and are predominantly pair produced. They both decay to a top quark and a W boson and hence have final state signatures based on the decays of the top quarks and the W boson. One of the decay signatures of both the heavy $T_{5/3}$ quark and the heavy B quarks is shown is Fig. 1, and involves same sign-dileptons in the final state.

In this note, we perform a feasibility study on observing the $T_{5/3}$ quark and B quark with the CMS detector during the early running of the LHC. We consider the multi-W event signature with same sign dilepton final states as shown in Fig. 1.

The major sources of backgrounds that contribute to the same-sign di-leptonic channel are: $t\bar{t}W$, $t\bar{t}WW$, WWW, and WW in association with jets. Table 1 summarizes the data used with cross sections for the signal and background events. The cross sections quoted are computed to leading-order (LO). The masses of $T_{5/3}$ and B are taken to be 500 GeV for this study. Note that they do not necessarily have to be degenerate.

	σ(fb)	$\sigma \times BR(\ell^{\pm}\ell^{\pm})$(fb)
$T_{5/3}\bar{T}_{5/3}$ (M=500 GeV)	2500	104
$B\bar{B}$ (M=500 GeV)	2500	104
$t\bar{t}W^{\pm}$+jets	595	18.4
$W^{\pm}W^{+}W^{-}$	603	18.7
$t\bar{t}W^{\pm}W^{\pm}$	121	5.1
$W^{\pm}W^{\pm}$	340	15.5

Table 1. Cross Sections for the Signal and Background Samples.

2 Event Samples and Simulation

The signal and background event samples are generated using the MadGraph[2] event generator. For all these samples PYTHIA[3] is used to fragment and hadronize quarks and gluons. For the background evnets, a jet-matching algorithm, following the MLM prescription[4] is employed to ensure that there is no double counting due to the parton showering in PYTHIA.

These samples are then processed via a dedicated fast simulation processor (FAMOS) of the CMS detector. We use CMSSW version 1_6_8 for this purpose. Jets with cone size $\Delta R = 0.5$ were reconstructed with the iterative cone algorithm. Generic jet energy corrections (jet_corrections_16X) are applied to the cone jets.

3 Event Selection

The distributions for basic kinematic properties of the signal and background events, such as p_T of the first and second leading leptons, the p_T of the first two leading jets, and the missing E_T in the events are shown in Figs. 2 through 4. They show that the transverse momenta of the lepton and the jets in the signal sample are harder compared to those from the background. The number of jets above p_T of 30 GeV in both the signal and background samples, normalized to unit area, are shown in Fig. 5 (left). The same distributions but with all the backgrounds summed together and weighted by their expected theoretical cross sections are shown in Fig. 5 (right). One notices a clear separation between the signal and background in these distributions.

In order to enhance the signal to background ratio, we select events with the following kinematic properties:

1. At least 5 jets with $p_T > 30$ GeV.
2. $p_T > 100$ GeV for the leading jet.
3. $p_T > 80$ GeV for the second leading jet.
4. Two same-sign isolated leptons (electron or muons).
5. Electrons or muons with $|\eta| < 2.4$.
6. $p_T > 50$ GeV for the leading lepton.
7. $p_T > 25$ GeV for the second leading lepton.
8. Missing transverse energy $>$ 20 GeV.

Tracker-based isolation is used for both electrons and muons with the isolation for electrons being defined as:

$$\sum_{track}\left(\frac{p_T^{track}}{p_T^{ele}}\right)^2 < 0.02$$

where all tracks with $p_T^{track} > 1.5$ GeV, within an $\eta - \phi$ annular isolation cone centered on the reconstructed electron, are summed. The cone has limits, $0.02 < \Delta R < 0.6$ where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and p_T^{ele} is the momentum of the reconstructed electron. In addition ΔR between the electron and its closest jet is required to be greater than 0.4. For muon isolation the sum of p_T of tracks in a cone of radius $\Delta R = 0.3$ is required to be less than 3.0.

A distribution of H_T, computed using the scalar sum of all jet p_Ts in events passing the selection cuts listed above is shown in Fig. 6. We note that the H_T of the background peaks at lower values compared to that expected from $T_{5/3}$ and B samples with mass of 500 GeV.

Table 2 list the efficiencies for the above kinematic cuts for the various samples. The last row of the table also corresponds to the number of events expected after the basic selection in our data sample with an integrated luminosity of 1.0 fb^{-1}, which is anticipated to be collected during the first year of LHC running. The H_T distribution normalized to 1.0 fb^{-1} is shown in Fig. 7.

In addition to the physics backgrounds listed in Table 2, we expect instrumental backgrounds mainly due to charge mis-identification, leading to same-sign dileptons in the event. The charge mis-reconstruction probability is expected to be less than 0.1% in the case of 100 GeV muons, while slightly larger values are expected for electrons [5]. Thus a SM process with large cross sections, for example $t\bar{t}+ \geq$3 jets, $Z+ \geq 5$ jets are potential

	$T_{5/3}\bar{T}_{5/3}$ (M=500 GeV)	$B\bar{B}$ (M=500 GeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
Efficiencies (ϵ_{main})	0.55	0.53	0.15	0.06	0.02	0.03
Expected number of events per fb^{-1}	57.2	55.1	2.76	0.30	0.374	0.46

Table 2. Efficiencies for the main kinematic cuts.

sources of instrumental background and may give rise to same-sign dilepton backgrounds at the level estimated from $t\bar{t}W$+jets, or $t\bar{t}WW$+jets. However, the event selection efficiency of these background processes are expected to be smaller as the first and second lepton p_T, as well as jet p_T distributions are much softer compared to those for $t\bar{t}W, t\bar{t}WW$+jets. Given a couple of percent charge mid-identification probability for electrons in the CMS detector, we estimate this instrumental background, after the basic selection cuts, to be around 1 to 1.5 events. They can be further drastically reduced by making a di-lepton invariant mass cut around the Z mass, or by reconstructing the top quark in the event. Since a realistic estimate of the charge mis-reconstruction probability as a function of the lepton p_T and pseudo-rapidity is not publicly available, we decide not to include this instrumental background in our analysis at this time. We note that for the future an accurate estimate of this background is required to validate our results.

4 Reconstruction of the Exotic Top Quark

The heavy top quark, $T_{5/3}$, with fully hadronic decay signature in the event can be fully reconstructed by reconstructing the two W bosons and the top quark in its decay chain.

In addition to the basic selection described above, we require that at least two of the jets are b-tagged. In order to reconstruct the hadronic $T_{5/3}$, the b-jet associated with the di-leptonic $T_{5/3}$ needs to be identified. The closest jet identified as a b-jet to the second leading lepton in the event is marked as being part of the di-leptonic decay chain. It is then removed from consideration for the list of jets in the hadronic decay chain.

Next the two W bosons and the top quark are reconstructed:

- Reconstructing the W boson from top decay:
  - Two jets with invariant mass consistent within 20 GeV of W boson are assigned to this W boson.
  - The two jets are required to have $\Delta R < 1.5$
  - The p_T of the reconstructed W is required to be greater than 50 GeV.
  - We find an efficiency of 84% to get the correct W assignment using this procedure.
- Reconstructing the W boson from $T_{5/3}$ decay:
  - Remove jets associated with the first W boson.
  - Two jets that have an invariant mass consistent with a W boson (within 25 GeV) are assigned to the second W.
  - The two jets are required to have $\Delta R < 2.0$.
  - The p_T of the reconstructed W is required to be greater than 30 GeV.
- Reconstructing the top quark from $T_{5/3}$ decay:
  - Discard the four jets that were assigned to the two W bosons.
  - Combine the b-tagged jet with one of the two W bosons to compute the top quark mass. The combination which gives an invariant mass closest to the top quark mass, within 40 GeV, is taken.
- Finally, the top quark candidate is combined with the other W boson to yield the mass of the heavy top $T_{5/3}$ in the event.

Table 3 lists the efficiencies for reconstructing events with two W candidates and a top quark candidate.

Fig. 8(left panel) shows the tW invariant mass distributions obtained using the procedure described above. The same distributions but stacked on top of each other can be seen in Fig. 8(right panel).

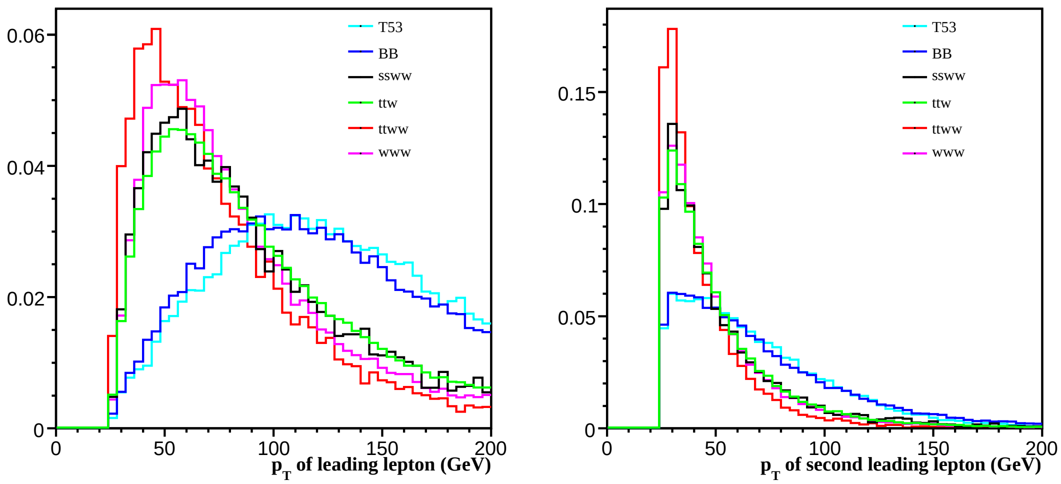

Figure 2. Distributions of leading lepton p_T (left) and second leading lepton p_T (right) for signal and background samples. The distributions are normalized to unit area.

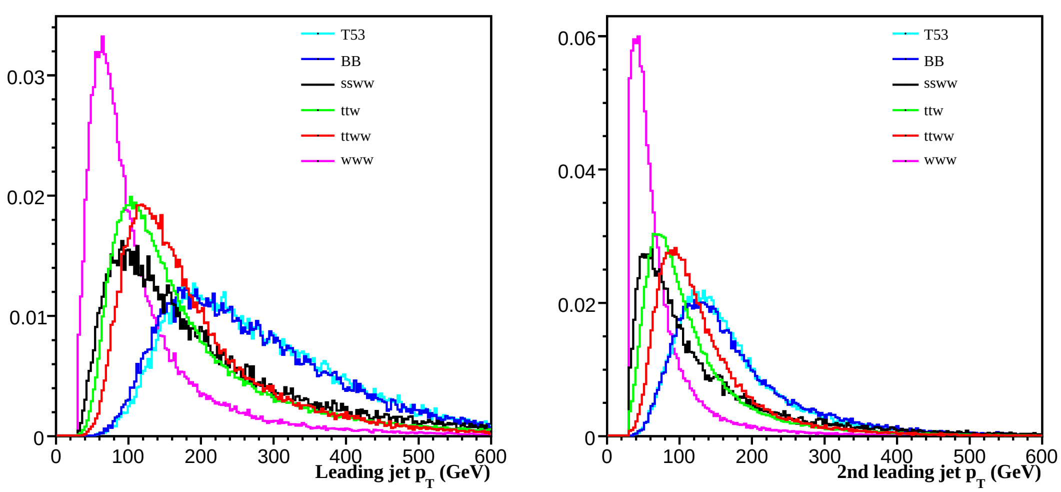

Figure 3. Leading jet p_T (left) and second leading jet p_T distributions for signal and background samples. The distributions are normalized to unit area.

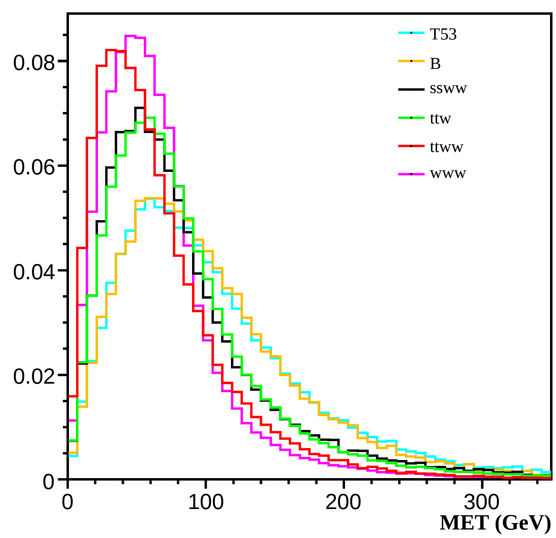

Figure 4. Missing E_T distributions for signal and background samples. The distributions are normalized to unit area.

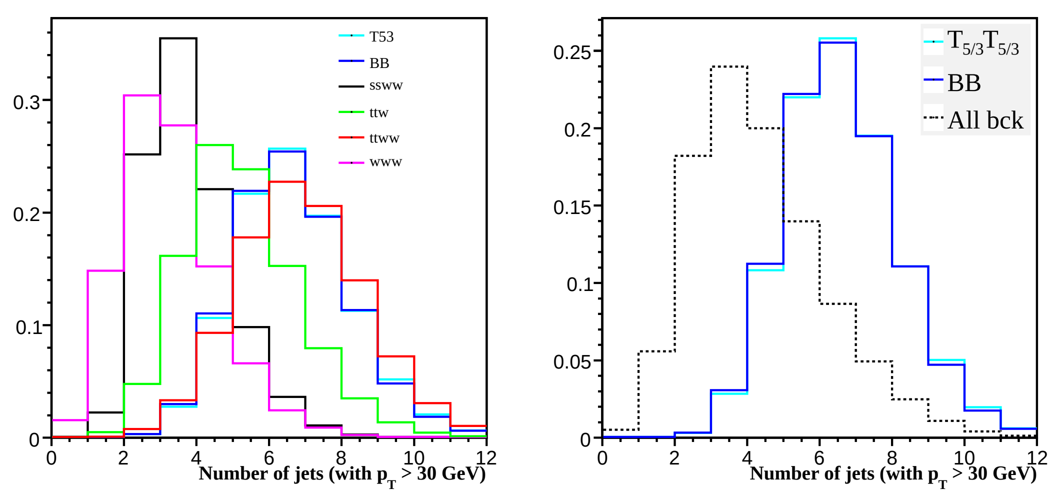

Figure 5. Left panel: Number of jets for signal and individual background samples. The distributions are normalized to unit area. Right panel: Number of jets for signal and cross-section weighted background sample.

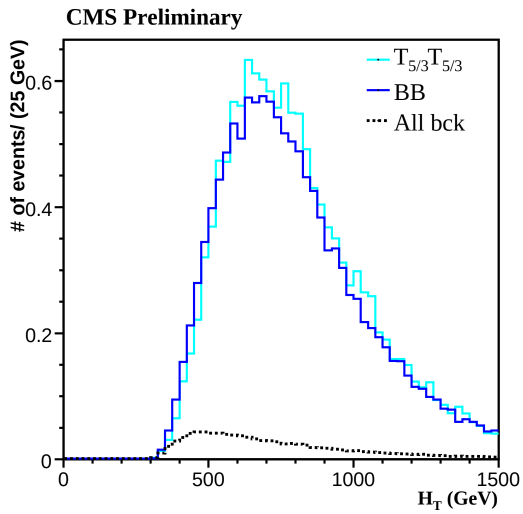

Figure 6. H_T distributions for signal and background events. A dataset corresponding to an integrated luminosity of 240 pb^{-1} was used.

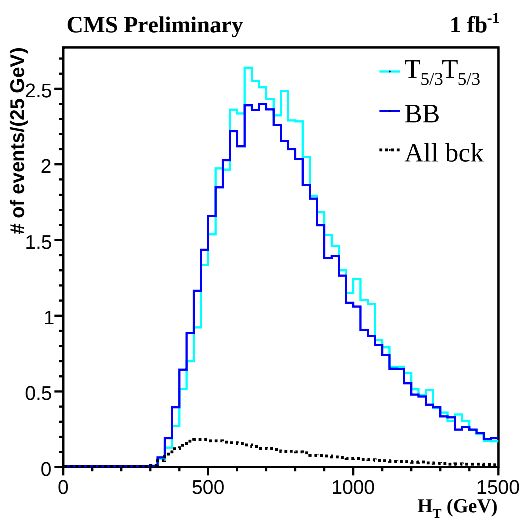

Figure 7. H_T distributions for signal and background events. A dataset corresponding to an integrated luminosity of 1 fb^{-1} was used.

	$T_{5/3}\bar{T}_{5/3}$ (M=500 GeV)	$B\bar{B}$	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
ϵ_{2W}	0.64	0.65	0.51	0.63	0.50	0.40
ϵ_{top}	0.54	0.53	0.54	0.56	0.13	0.12

Table 3. Efficiencies for reconstructing two W candidates and one top quark candidate.

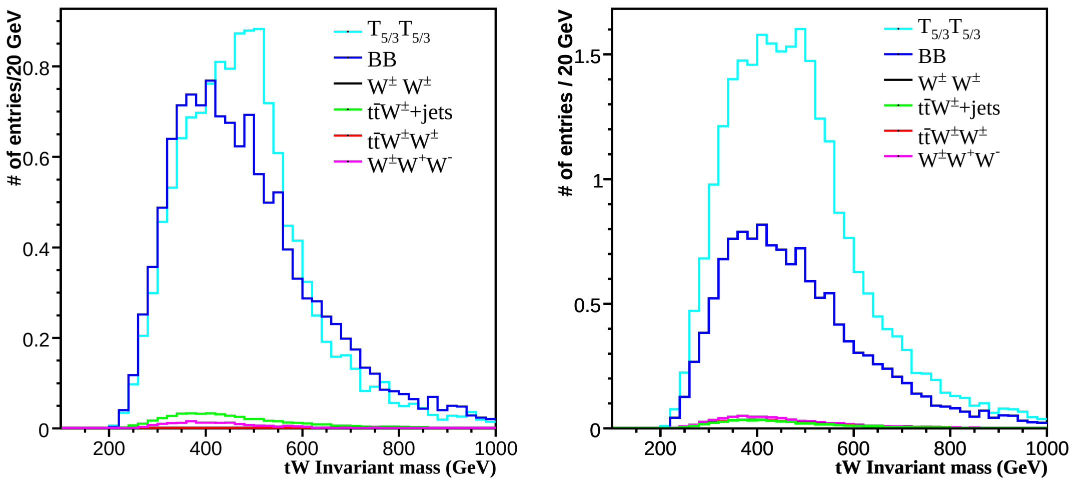

Figure 8. tW invariant mass distributions, corresponding to heavy top quark $T_{5/3}$ mass distribution, for signal and background samples (left panel). Stacked tW invariant mass distributions for signal and background samples (right panel). A dataset corresponding to an integrated luminosity of 650 pb^{-1} was used.

5 CMS Discovery Potential for Exotic Top Quark and the Heavy B quark

Two techniques are used to estimate the sensitivity for observing a signal corresponding to the exotic heavy top quark $T_{5/3}$ and its partner, the heavy B quark. From both Tables 1 and 2, we note that the number of background events expected are relatively small and hence it is easy to control the backgrounds.

A simple event counting technique (using $S/\sqrt{S+B}$) after the first set of event selection cuts leads to an estimate of $\approx$ 230 pb^{-1} of integrated luminosity for a 5σ observation of the $T_{5/3}$ and heavy B combination. If we include an 100% uncertainty on the estimate of the background events, the required integrated luminosity goes up to ≈ 240 pb^{-1}.

We can also estimate the sensitivity from signal and background yields under the tW mass peak. The efficiency for reconstructing $T_{5/3}$ needs to be taken into account in this procedure. Following this prescription, the first evidence at 3σ level for the $T_{5/3}+B$ combination could come with ≈ 250 pb^{-1} of data and 5σ significance can be reached with ≈ 650 pb^{-1}. No systematic uncertainties have been applied yet.

6 Conclusion

We have performed the first sensitivity study for the search for an exotic heavy top quark with charge 5/3, $T_{5/3}$ and its partner the heavy B quark. We find that it is possible to observe a low mass exotic top quark (M=500 GeV) and its partner in a data sample corresponding to a few hundred pb^{-1} of integrated luminosity. This analysis can be pursued with the data accumulated during the first year of LHC running. Our conclusion is similar to that reached by Contino and Servant [1], who are the original proposers of this model.

We should note that we present a feasibility study using fast simulation and hence this should be considered a work in progress. Additional analysis improvements are underway: full detector simulations of the signal and background samples, better jet energy corrections, jet cleaning, fake removal etc. These should further enhance the sensitivity. This updated version of the analysis will also include a detailed study of systematic uncertainties.

7 Acknowledgment

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