Identification of Extra Neutral Gauge Bosons at the LHC Using b and t Quarks

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New neutral gauge bosons (Z''s) are predicted by many models of physics beyond the standard electroweak theory. It is possible that a Z' will be discovered by the Large Hadron Collider program. The next step would be to measure its properties to identify the underlying theory that gave rise to the Z'. Heavy quarks have the unique property that they can be identified in the final states. In this Letter we demonstrate that measuring Z' decays to b- and t-quark final states can act as an effective means of discriminating between models with extra gauge bosons.

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In the coming years, it is anticipated that the CERN Large Hadron Collider (LHC), a pp collider with a center of mass energy $\sqrt{s} = 14$ TeV, will reveal a new level of understanding of the fundamental interactions when it starts to explore the TeV energy regime. For a number of reasons, including the quadratic sensitivity of the Higgs boson mass to radiative corrections, it is generally believed that the standard model (SM) is a low energy effective limit of a more fundamental theory, and numerous extensions of the SM have been proposed. Many of these extensions predict the existence of new neutral gauge bosons (Z') and other s-channel resonances [1–5]. If a kinematically accessible Z' exists, it is expected to be discovered very early in the LHC program. Once such an object is discovered, the immediate task would be to measure its properties and identify its origins. This is a difficult task and there is vast literature on Z' observables and analysis techniques.

A key ingredient in determining the nature of a new resonance is to measure its couplings to fermions. The Z' couplings to leptons can be measured using three observables: the cross section to leptons, the forward backward asymmetry, $A_{\rm FB}$, and the width, $\Gamma_{Z'}$ [6]. For quarks, studies have shown that rapidity distributions can be used to separate u-quark couplings from d-quark couplings [7,8]. However, these analyses are statistical in nature so there will always be contributions from the other type of quark. In contrast, the ability to identify b and t quarks in the final state can be a powerful tool to measure quark couplings that can be used to distinguish between models that give rise to Z' bosons.

Previous studies have pointed out that third generation fermions, top quarks, in particular, can be used to search for extra gauge bosons [9–15] and to distinguish between models [13,16]. While some have noted the possibility of using third generation t and b quarks to distinguish between models of extra neutral gauge bosons [3,15,17,18], this subject has not been fully explored. The ability to identify heavy quark flavors offers the unique opportunity to measure individual quark couplings that is not possible for light quarks. In what follows, we describe a method of using b- and t-quark final states to distinguish between models of new physics that predict extra neutral gauge bosons [17,19]. The primary challenges in these measurements will be the identification efficiencies for top and bottom quarks needed to make statistically meaningful measurements and the discrimination of the t's and b's coming from Z' decays from SM QCD backgrounds.

To distinguish between models, we propose to use the cross sections $\sigma(pp \to Z' \to b\bar{b})$ and $\sigma(pp \to Z' \to t\bar{t})$, as described by the Drell-Yan cross section with the addition of a Z' [6,20] at the LHC. We computed the cross sections using Monte Carlo phase space integration with weighted events, imposing a rapidity cut on the final state particles of $|\eta| < 2.5$ to take into account detector acceptances. We also included p_T and invariant mass distribution cuts with values chosen to reduce QCD backgrounds as described below. In our numerical results we take $\alpha = 1/128.9$, $\sin^2\theta_w = 0.231$, $M_Z = 91.188$ GeV, $\Gamma_Z = 2.495$ GeV, and $m_t = 172.5$ GeV [21]. We use the CTEQ6M parton distribution functions [22] and included a K factor to account for next-to-leading order (NLO) QCD corrections [23] while next-to-next-to-leading order (NNLO) are not numerically important to our results [24,25]. Final state QED radiation effects are important [26] but require a detailed detector level simulation that is beyond the scope of the present analysis. The Z' widths only include decays to standard model fermions. NLO QCD and electroweak radiative corrections were included in the width calculations [27].

An important challenge for this analysis will be to achieve sufficiently high b- and t-quark identification efficiencies to provide the statistics needed to distinguish between models. The ATLAS and CMS collaborations have worked hard at estimating these values, but experience with real data will be required to obtain reliable values. We therefore present results for two sets of values, distilled from the literature, that we expect to bound the values that will eventually be achieved by the LHC collaborations. Once the LHC experiments start to collect data, these values should be refined as experimenters gain experience and a better understanding of their detectors.

For b identification efficiency, the ATLAS technical design report (TDR) gives a value of $\epsilon_b = 60\%$ for low luminosity running and 50% for high luminosity running with 100 to 1 rejection against light and c jets [28]. We will use the latter value which is appropriate to the high luminosities we assume. The rejection of fakes arising from light and c jets can be improved considerably by requiring that both the b and $\bar{b}$ are seen. We therefore consider two cases for tagging $b\bar{b}$ events: 50% when only one b is observed and $\epsilon_{b\bar{b}} = 25\%$ when both the b and $\bar{b}$ are detected, independent of the dijet mass. Note that the $b\bar{b}$ detection efficiency is likely to be higher than simply using ϵ_b^2.

The understanding of t-quark identification efficiencies is evolving. The top quark almost always decays into a b quark and a W^+ boson ($t \to W^+ b$) with the W's subsequently decaying either into two leptons ($e\nu_e$, $\mu\nu_\mu$ or $\tau\nu_\tau$) or into a light quark-antiquark pair ($u\bar{d}$, $c\bar{s}$) that in turn hadronizes. The single lepton plus jets final state, where one W decays leptonically and the other W decays hadronically, $t\bar{t} \to WWb\bar{b} \to (l\nu)(jj)b\bar{b}$, has a branching ratio (BR) $\sim$30% of all $t\bar{t}$ events and is generally viewed as giving the best signal-to-background ratio. With suitable kinematic cuts and including the BR to $(l\nu)(jj)b\bar{b}$, a recent ATLAS study estimates $\epsilon_{t\bar{t}} \sim 4\%$ [14]. However, reconstructing the invariant mass of the $t\bar{t}$ system will reduce this number [14]. The ATLAS TDR is slightly more optimistic, claiming the efficiency for detecting a $M_{t\bar{t}} = 2$ TeV resonance of about 5% including the semileptonic mode BR while a CMS simulation obtains the lower value of $\epsilon_{t\bar{t}} \sim 2\%$ [29]. Baur and Orr [13,30] found that the t-quark identification efficiencies for this channel can be improved by using 2-jet and 3-jet final states with b tags. The fully hadronic modes have a combined BR $\sim$45%, so utilizing the hadronic modes has the potential of improving the $t\bar{t}$ identification efficiency significantly. A method has been suggested to distinguish top jets from standard model backgrounds using substructure of the top jet [31,32]. Kaplan *et al.* [31] estimated that high p_T dijets can be rejected with an efficiency of $\sim$99.99% while retaining $\sim$10% of the $t\bar{t}$ pairs. By combining the different top decay channels and identification strategies it should be possible to increase the overall $t\bar{t}$ identification efficiency. Given that the subject of t-quark identification at the LHC continues to evolve, we assume a wide range of values of $\epsilon_{t\bar{t}}$, taking 1% and 10% for the low and high efficiency scenarios, respectively.

Another challenge for making these measurements will be to distinguish the Z' signal from the large SM QCD backgrounds. The invariant mass distribution for $b\bar{b}$ final states is shown in Fig. 1 for the SM QCD background and the signal for a Z' with a mass of 2 TeV for several representative models. The QCD backgrounds were calculated using the WHIZARD package [33] with O'MEGA matrix element generation [34], and as an independent check we also calculated the QCD cross sections using a simple Monte Carlo event generator with tree level matrix elements. We use LO QCD cross sections in our background calculations. While it is known that higher order QCD corrections can be substantial [30,35], NLO corrections are highly dependent on the region of phase space being studied. As a crude estimate of the importance of NLO correction on our results, we rescaled the LO QCD backgrounds by a factor of 1.4 and found this to have little impact on our results.

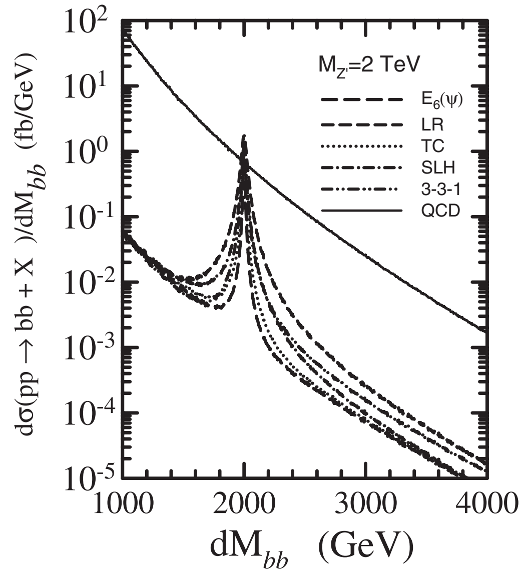

FIG. 1. Invariant mass distributions for the Drell-Yan process $pp \to b\bar{b}$ including a Z' with mass $M_{Z'} = 2$ TeV and the $b\bar{b}$ QCD backgrounds. The sets of curves correspond to $E_6(\psi)$ [1], left-right symmetric (LR, $g_R/g_L = 1$) [36], simplest little Higgs (SLH) [37,38], 3-3-1 model [39], and top color (TC) models ($\tan\theta = 0.577$) [9,40]. A kinematic cut of $P_T > 50$ GeV was imposed on the b quarks.

The p_T distributions are quite different for the signal and backgrounds with quarks coming from Z' decays having a much harder distribution than the background events. The background can be reduced considerably by imposing a transverse momentum cut on the reconstructed final state t and b's at some expense to the signal. The p_T cut was varied and it was found that the optimum cut is approximately $p_{T_Q} \geq 0.3M_{Z'}$, which reduces the background significantly compared to the signal. A stronger cut improves the signal-to-background ratio but decreases the total signal and therefore increases the statistical uncertainty. The invariant mass distribution for the signal and background are shown in Fig. 2 after applying the cut.

The QCD backgrounds can be further reduced by constraining the invariant mass of the final state fermions to $|M_{f\bar{f}} - M_{Z'}| \leq 2.5\Gamma_{Z'}$. The window was chosen to balance the total signal against the signal-to-background ratio. We examined the model independent choice of $|M_{f\bar{f}} - M_{Z'}| \leq 0.07M_{Z'}$, but found that our results were not very sensitive to the precise choice of $M_{f\bar{f}}$ window.

Fakes from gluon, light quark, and c jets are potentially problematic, but there is a trade off between heavy quark

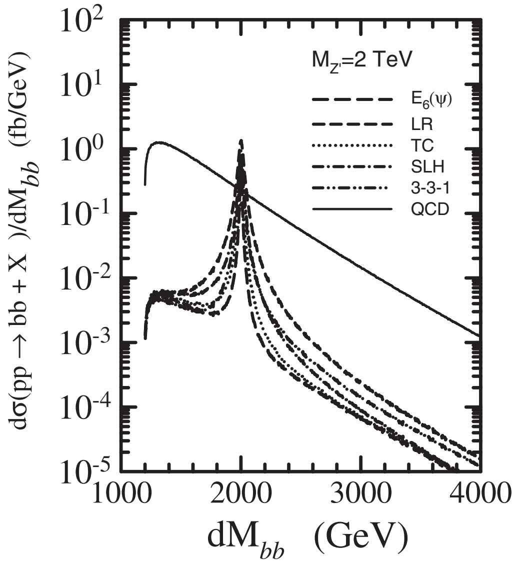

FIG. 2. Invariant mass distributions for the Drell-Yan process $pp \to b\bar{b}$ including a Z' with mass $M_{Z'} = 2$ TeV and the $b\bar{b}$ QCD backgrounds including a kinematic cut of $P_T > 0.3 M_{Z'}$ on the b quarks.

identification efficiencies and mistagging that requires detailed detector simulations. Likewise, we defer detector resolution effects to more detailed future studies. Other non-QCD SM backgrounds include $Wb\bar{b}$ + jets, $(Wb + W\bar{b})$, W + jets, etc. final states. Baur and Orr have shown that these can be controlled by constraining the cluster transverse mass and invariant mass of outgoing jets (and leptons) to be close to m_t [13,30].

In addition to the QCD backgrounds and the question of heavy quark identification efficiencies, there are additional theoretical uncertainties in the cross sections: higher order QCD and electroweak (EW) corrections to the cross sections, both initial and final state contributions, and uncertainties in the parton distribution functions. We can reduce some of these uncertainties by using ratios of heavy quark production to $\mu^+\mu^-$ production: $R_{b/\mu}$ and $R_{t/\mu}$. In particular, these ratios nearly eliminate the uncertainties originating in the parton distribution functions. The ratios are defined by

$$R_{b/\mu} \equiv \frac{\sigma(pp \to Z' \to b\bar{b})}{\sigma(pp \to Z' \to \mu^+\mu^-)} \approx \frac{3K_q(g_L^{b2} + g_R^{b2})}{(g_L^{\mu 2} + g_R^{\mu 2})} \quad (1)$$

$$R_{t/\mu} \equiv \frac{\sigma(pp \to Z' \to t\bar{t})}{\sigma(pp \to Z' \to \mu^+\mu^-)} \approx \frac{3K_q(g_L^{t2} + g_R^{t2})}{(g_L^{\mu 2} + g_R^{\mu 2})}, \quad (2)$$

where K_q is a constant depending on the QCD and EW correction factors, and the factor of 3 is due to summation over color final states. Each of these ratios depends on only four couplings from each model. An analysis based on the location of a measured Z' in the $R_{b/\mu} - R_{t/\mu}$ parameter space provides a means of distinguishing between models.

We assume that a Z' has been discovered and its mass and width measured [6,20] so that the appropriate $M_{Q\bar{Q}}$ cuts described above can be applied. It is expected that a Z' with $M_{Z'} \leq 2$ TeV can be discovered early in the LHC program with approximately 1–10 fb^{-1} of integrated luminosity depending on the specific model.

To obtain our results we calculate the expected number of events and statistical error for signal plus background for a given integrated luminosity and particle identification efficiencies, $\epsilon_{\mu^+\mu^-}$, $\epsilon_{b\bar{b}}$, and $\epsilon_{t\bar{t}}$. The expected number of SM QCD and electroweak events were similarly calculated and subtracted from the signal plus background events to give the predicted number of signal events. From these intermediate results we obtained the ratios given in Eqs. (1) and (2) with the errors calculated in the usual way by including both signal and background. We did not include uncertainties coming from luminosity and identification efficiencies. In the latter case there is simply too big a

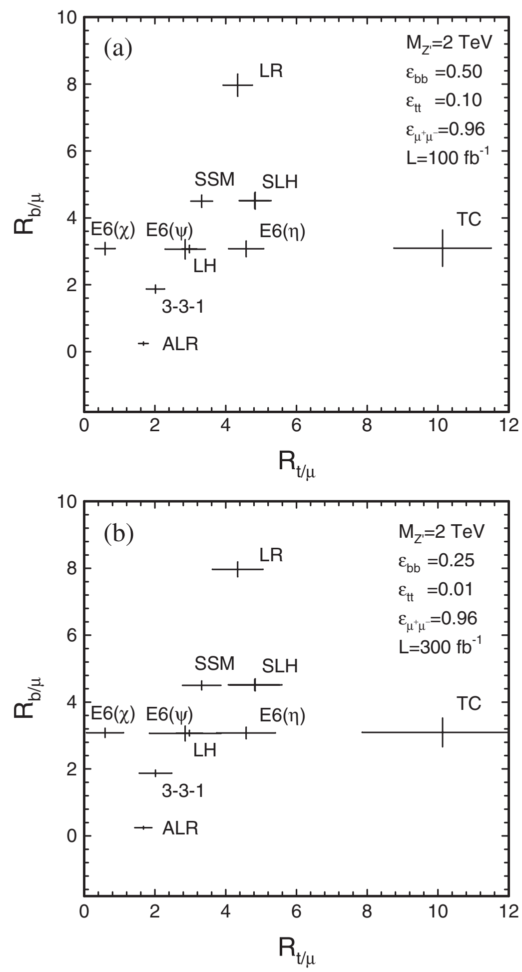

FIG. 3. $R_{b/\mu}$ vs $R_{t/\mu}$ for $M_{Z'} = 2$ TeV for the $E_6(\chi)$, $E_6(\psi)$, $E_6(\eta)$ [1]. LR symmetric model ($g_R/g_L = 1$) [36], Alternate left-right model (ALR, $g_R/g_L = 1$) [41], SLH model[37,38], littlest Higgs model (LH, $\cot\theta_H = 1$) [38,42], 3-3-1 2U1D model [39], TC model ($\tan\theta = 0.577$) [9,40]. The error bars are the statistical errors based on the integrated luminosity shown in the figure.

range to include in an error; rather, we show results for the two cases discussed above.

Our results for $R_{b/\mu}$ and $R_{t/\mu}$ are shown in Fig. 3 for $M_{Z'} = 2$ TeV. Figure 3(a) shows results for the high fermion identification efficiency values with 1σ statistical errors based on an integrated luminosity of $L = 100\ \mathrm{fb}^{-1}$. The low $\epsilon_{f\bar{f}}$ case would require higher integrated luminosity to distinguish between models, so in Fig. 3(b) we show statistical errors based on $L = 300\ \mathrm{fb}^{-1}$. The errors scale as $1/\sqrt{L}$ and very roughly like $1/\sqrt{\epsilon_{Q\bar{Q}}}$ so one can estimate how the errors will change with different integrated luminosities and heavy quark identification efficiencies.

It is clear that most models can be differentiated using heavy quark final states. However, some models such as the $E_6(\psi)$ and $SU(3) \times U(1)$ anomaly free little Higgs model give similar ratios so one would need additional input such as leptonic observables to distinguish between them.

In summary, we demonstrated that, in principle, the decay of a Z' boson into third generation quarks can be used to distinguish between models of physics beyond the SM. The main challenge would be to reduce the measurement errors sufficiently to discriminate between models and make accurate measurements of the b- and t-quark couplings to the Z'. The major unknown in the analysis is the detection efficiency of the t and b quarks. To account for this we considered two scenarios: an optimistic, high efficiency scenario using larger values for ϵ_t and ϵ_b given in the literature, and a pessimistic, low efficiency scenario which used more conservative values. We expect that the LHC experiments will attain values somewhere in between. Given the promise of this approach, a more detailed detector level study to see the effects of detector resolution is warranted.

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