Excited Electron Search in the $e^* \rightarrow ee\gamma$ Channel in ATLAS at $\sqrt{S} = 7$ TeV

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Abstract

The discovery of an excited electron would provide evidence for the theory of compositeness. In this analysis a search for excited electrons in the $e^* \rightarrow ee\gamma$ is performed with the ATLAS detector at the LHC, using 1 fb$^{-1}$ of data at an integrated luminosity of 7 TeV. This study implements the “best electron” selection method in the reconstruction of the $e^*$ resonant mass, and uses a data-driven fit for QCD background estimation. The mass region below 1248 GeV is excluded for excited electrons at a compositeness scale of $\Lambda = 5000$ GeV.

1 The Standard Model

The Standard Model is currently the most comprehensive and experimentally supported theory in existence in particle physics, incorporating all the particles that make up visible matter as well as three out of four fundamental forces. The Standard Model posits the existence of 6 quarks and 6 gluons pictured in figure 1, which together compose the 12 known fermions, spin-1/2 particles that each also have a corresponding antiparticle. Furthermore, the Standard Model describes 4 spin-1 bosons, (the photon, gluon, Z boson and W boson) which act as force carriers between the fermions. Finally, the Higgs Boson is a fifth boson in the Standard Model that is yet to be experimentally detected but in theory would explain the existence of mass in the universe.
2 Excited Electrons

2.0.1 Compositeness Model Compositeness models predict that quarks and leptons may share common constituent particles called preons. In particular, many models propose that a quark or lepton may be a bound state of three fermions or a fermion and a boson, suggesting that quarks and leptons are just the ground state of excited fermions. The discovery of an electron in an excited state would provide experimental evidence for the existence of quark and lepton substructures.

2.0.2 Contact Interactions Contact interactions that describe excited fermions can be described in terms of a Lagrangian \( L_{cl} = \frac{4\pi^2}{\Lambda^2} j_u^u j_u \), where \( j_u \) is the fermionic current. \[ ? \] The appropriate compositeness scale, \( \Lambda \), as well as the excited electron mass, must be determined experimentally.

2.0.3 Decay Process In this study, the excited electron is assumed to be produced through contact interactions between fermions in the following manner: \( pp \rightarrow ee^* \). Gauge particle mediated production must be considered at energy scales close to the probe scale, but represents less than 1% of the excited electron cross section mediated by contact interaction.\[3\] The excited electron is subject to the electroweak decay process: \( e^* \rightarrow e\gamma \), the most easily detected decay channel, and a particularly worthwhile focus because \( e^* \) can be directly reconstructed with high efficiency and good mass resolution, unlike the \( e^* \rightarrow eW \) decay channel in which a neutrino cannot be detected by ATLAS< or the \( e^* \rightarrow eZ \) channel in which the electron can only be reconstructed if the Z decays into an electron-positron pair. \[3\] The discovery of a quark or lepton in an excited state provides evidence for the theory of compositeness.

2.0.4 Previous Work Previous searches have set limits on the potential mass of the excited electron. the OPAL experiment excluded \( M_{e^*} < 207 \text{ GeV}/c^2 \) for \( f/\Lambda > 10^{-4} \text{ GeV}^{-1} \) and \( M_{e^*} < 103.2 \text{ GeV}/c^2 \) for any value of \( f/\Lambda \). the HERA experiment excluded \( M_{e^*} < 207 \text{ GeV} \) for \( f/\Lambda = .1 \text{ GeV} \). CDF has excluded \( 126 < M_{e^*} < 430 \text{ GeV}/c^2 \) for \( f/\Lambda \approx 0.01 \text{ GeV}^{-1} \) in the gauge interaction model, and has excluded \( 126 < M_{e^*} < 879 \text{ GeV}/c^2 \) for \( \Lambda = M_{e^*} \) in the contact interaction model, all at 95% confidence level. In a similar study, \( D\bar{O} \) set a lower limit of \( 879 \text{ GeV} \).\[3\] CMS has thus far set the tightest limit for excited electron production, excluding the region below 1070 GeV, using 36 \( fb^{-1} \) of data with a compositeness scale of \( \Lambda = M_{e^*} \) and below 780 GeV for \( \Lambda = 2000 \text{ GeV} \). \[5\]
3 Experiment

3.0.5 THE LHC The Large Hadron Collider (LHC) located at CERN in Switzerland in France will probe physical processes at previously uninvestigated energy levels. The LHC is a 27 km synchrotron running at a center of mass energy $\sqrt{s} = 7$ TeV at a peak luminosity of $10^{34} \text{ cm}^{-2}\text{ s}^{-1}$, confirming the accuracy of the Standard Model as well as potentially providing evidence for new Physics. It is designed to accurately collide bunches of protons using superconducting magnets. Six particle detector experiments are built around the detector to track particles produced as decay products of these proton collisions.

3.0.6 ATLAS ATLAS (“A Toroidal LHC ApparatuS”) is one of two primary general purpose experiments located at the LHC and is composed of a multilayered particle detection system. ATLAS uses a right-handed cylindrical coordinate system with $\theta$ defined with respect to the positive z-axis and pseudorapiditory defined as $\eta = -\log(\tan(\frac{\theta}{2}))$. Transverse momentum is defined as the momentum perpendicular to the axis of the LHC beam. The inner detector of ATLAS includes a pixel detector as well a silicon and radiation detector designed to measure the momentum, position, and vertex of particles. [2] The inner detector is surrounded by two calorimeters, as well as a muon detection and trigger system. This analysis uses track matching in the inner detector to reconstruct the position of electrons and the calorimeter to detect energy deposits of both electrons and photons.
3.0.7 The ATLAS Calorimeter

The electromagnetic liquid argon calorimeter is responsible for detecting photons and electrons. In ATLAS, the electromagnetic calorimeter has a high granularity (more than 200,000 channels) and longitudinal segmentation with layers of lead absorbers and liquid argon detection medium. [1] Photons and electrons interact with the absorbers of the calorimeter, creating a shower of secondary particles and ionized electrons that are released into the liquid argon, resulting in a detectable current signal. The calorimeter is composed of multiple layers, each with a different granularity, which is unique to ATLAS and allows for more precise reconstruction and identification of photons and electrons as they travel through the multiple layers. Furthermore, the presampler provides a method for recovering lost energy from particle showers. [2]

3.0.8 Electron and Photon Reconstruction

In this analysis the egamma reconstruction algorithm is used, which is designed to identify electrons as well as converted and unconverted photons. Electrons are identified by matching tracks to electromagnetic clusters, and converted and unconverted photons can be distinguished from one another by using tracking information: converted photons have at least one track originating from a vertex, whereas unconverted photons do not have such a track. There is ambiguity in distinguishing between electrons and photons. For example, an electron that passes through the crack may not have a track. In general, if there is no track match, the egamma signal is assumed to be a photon.

3.0.9 QCD Background

Proton-proton interactions are mediated by the strong force. Collisions will often result in a shower of quarks and gluons, which then recombine and produce a jet of energy. QCD background processes are particularly challenging to simulate, and thus a data-driven method for QCD background estimation is implemented as an alternative.
4 Analysis

4.1 Data/MC Samples

4.1.1 The data used is the skimmed dielectron data from 2011, periods B-H, (March 21st, 2011 to June 28th, 2011) tag p580, composed of 1.075 fb of data. Monte Carlo background samples are the officially produced SMWZ ntuples, tag p591, and the CompHEP was used for signal distributions, with a lambda values of 1200, 5000, and 7000 GeV.

4.2 Selections and Cuts

4.3 Best Electron Selection

4.3.1 A key task in reconstructing the excited electron’s invariant mass is determining which final state electron is a decay product of the excited electron. The excited electron’s invariant mass can be reconstructed by selecting the photon and one of the electrons as the excited electron’s decay products. The invariant mass of a particle is the same in all frames of reference and is related to the particle’s energy and momentum in the following manner: 

\[ \sqrt{E^2 - P^2} = \sqrt{(E_e + E_\gamma)^2 - (E_e + E_\gamma)^2} \]

A resonance detected in the \( e\gamma \) mass would suggest a possible \( e^* \) signal, and so a cut on the desired \( e\gamma \) mass should maximize the possibility for \( e^* \) detection. It is found experimentally that at lower mass values, the lower \( P_t \) electron tends to be the \( e^* \) decay product, whereas at higher probed masses the higher \( P_t \) electron tends to be the decay product.
4.3.2 However, rather than select the second highest $P_t$ electron for lower $e^*$ masses and the highest pT electron for greater $e^*$ masses, in this analysis the electron photon combination with an invariant mass closest to the $e^*$ mass in consideration is used as a basis for selecting the electron that is most likely a product of the $e^*$ decay process. A similar method was implemented in corresponding DØ studies [4] for probed masses > 200 GeV, but in this analysis in which the range of probed masses extends to 1500 GeV, 1000 GeV higher than dØ, the “best electron” selection method is implemented for the entire mass range studied. In addition, in line with the dØ analysis, the decay electron and the photon are expected to be separated by an angle in order to distinguish from $Z \rightarrow ee$ decay in which an electron emits a bremsstrahlung photon at a small $\Delta r$ value. In this analysis, a $\Delta r > 0.7$ cut is applied between the electron and photon. The analysis suggests that at all mass ranges studied, the “best electron selection” method will provide a stronger signal than either the highest pT or second highest pT electron selection, illustrated in figure 5.

4.3.3 When implementing the best electron selection method, the most substantial background processes to the $e^*$ decay process were also analyzed in order to ensure in simulation that the best electron selection method did not cause any previously unseen spikes in background. The results are shown in figure 6 with two different lambda values (5000 and 9000) plotted to compare signal strength. Background processes dominate at lower mass values (<400 GeV), and with the current cuts used, Wjet and ttbar backgrounds are nearly negligible. Furthermore, at lower theoretical lambda values, signal strength increases dramatically. The best analysis should help maximize the probability of detecting a signal should one be present in data.

4.4 QCD Background Studies

4.4.1 Data Driven Method The QCD background in this study is obtained by selecting events from the 2g20 trigger that pass the loose electron cut but fail the medium cut. From these events, a photon is required in order to satisfy the excited electron decay process final constituents, and the best electron selection method is used for selecting the electron that is the decay product of the excited electron. Finally, the resulting events are fit to an effective functional form: $p0\cdot x^{p1}\cdot x^{(p2\cdot \log(x))}$ which is then used as a template for modeling the QCD background for excited electrons at different mass trials.

4.4.2 Incorporating QCD Estimate The QCD background calculation is then added to the Monte Carlo simulated backgrounds and fit to the signal distribution. A scale factor for the QCD of 0.36457 is found from the fit, and a fixed scale factor of 1.0 is used for the Monte Carlo-generated backgrounds. Figure 7 illustrates the fit obtained. The black points are data, specifically the an invariant mass plot of electrons that pass the loose electron cut but fail the medium electron cut, and in which the best $e\gamma$ pair is selected. The lower smooth curve represents the QCD background estimate, and the binned plot is the total background. The resulting properly scaled and fitted QCD is then used as a background estimate and plotted with $1 fb^{-1}$ of data. The QCD background estimation is smooth and extends up to 1 TeV, useful for future studies.
Figure 5: A comparison of signal strength the higher pT, lower pT, and best electron selection methods for e* reconstruction at 200 GeV, 500 GeV, 700 GeV, 1000 GeV, 1200 GeV and 1500 GeV.
Figure 6: Best Electron signals with backgrounds plotted at 200, 500, 700, 1000, 1200 and 1500 GeV comparing lambda values of 5000 and 9000.
Figure 7: functional fit for data-driven QCD template generation at 700 GeV

Figure 8: QCD as well as all backgrounds plotted against signal for 700 GeV
Figure 9: Scaled and fitted QCD background plotted with MC-generated backgrounds against 1 fb\(^{-1}\) of data

<table>
<thead>
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<th>Mass</th>
<th>p0</th>
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</tr>
</tbody>
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QCD Fit Parameters at varying mass points
4.4.3 Verification of QCD Estimation Process with Z’ Dielectron Selection

In order to test the methodology and implementation of the excited electron QCD estimation described above, the procedure is replicated for Z’ dielectron selection. This can be compared to existing Z′ results from ATLAS.

4.4.4 Verification of ZVeto Cut

The ZVeto cut is meant to remove events near 90 GeV, the mass of Z, with the assumption that events near this mass point are highly likely to represent Z background. Out of 259,856 events, after basic selection cuts, only 194 remain. The ZVeto cut eliminates an additional 86 events. It is useful to analyze the effect of the ZVeto cut on the dataset, and so plots are generated for both the signal and dielectron selection without the Zveto cut. It is clear in the signal selection that the dielectron resonance peaks at 90 GeV, and the $Z \rightarrow ee$ peak is distinctly visible in the dielectron mass plot pictured. While QCD background is not considered in this analysis of the Zveto cut, the effect is known to be small. There is some assurance that a mass cut of $\pm 5 GeV$ around the Z resonant mass is effective in removing Z background events.

4.5 Results and Conclusion

4.5.1 Limit Setting

In order to set a limit on the current experimental sensitivity as well as a limit on the expected mass of the excited electron, a power-constrained one-sided 95% frequentist limit is used, implementing the standard ATLAS tool for limit setting.[8] Due to only six candidate events, a counting experiment is performed at this early stage of analysis in order to determine proper limits. Based on the results of this limit setting algorithm, no limit can be set at $\Lambda = 1500 GeV$. A limit of 1248 GeV can be set for $\Lambda = 5000 GeV$. In comparison with D∅ and CMS, these are the most stringent limits on the excited electron mass to date.

Figure 10: QCD estimation process reimplemented for Z’ Dielectron Selection as a cross check
4.5.2 Future Work An analysis framework has been set up to use both 2g20 and e60 trigger information to perform the QCD functional fit. Currently only 220 events out of 257,429 in consideration pass the e60 trigger but fail the 2g20 trigger, thus an analysis of the effect of a combined trigger fit on QCD background estimations will be postponed until more event statistics are available from ATLAS.

4.5.3 Event Candidate In total, 6 excited electron candidate events exist in this study. Of those, the highest energy event (331 GeV) is pictured in figure 13, in which three particles are reconstructed, two with clear track matches in the inner detector. $M_{ee} = 39.135$ which rules out the possibility of this being a $Z \rightarrow ee$ event.
Figure 12: Limit Setting Plots at $\Lambda = 1500\text{GeV}$ (above) and $\Lambda = 5000 \text{ GeV}$ (below). Shaded green region represents $1\sigma$ uncertainty, and shaded yellow region represents $2\sigma$ uncertainty. Red plot is expected value, and black plot is observed value.
Figure 13: Excited Electron Candidate, 331 GeV. Run Number 182424 Evt Num 86912141
References


[3] Search for Excited or Exotic

[4] Search for Excited Electrons in the eey Channel

[5] Search for Excited Leptons in PP Collisions at 7 TeV CMS

[6] Search for Excited/Exotic Electrons at CDF in Run 2
