Production of a Z boson and photon via a Randall-Sundrum-type graviton at the Large Hadron Collider

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Abstract. In extra dimensional models with Kaluza-Klein graviton states that are well separated in mass, such states may be observed as resonances in collider experiments. We extend previous works on such scenarios by considering the one-loop resonant production of a Z boson in association with a photon. We find the production rate to be negligible in conservative scenarios, and small for reasonable luminosity in less conservative scenarios.

Key words. Beyond Standard Model, Phenomenology of Field Theories in Higher Dimensions

1 Introduction

A number of models, most notably the Randall-Sundrum 1 class models [1], predict the possibility of discrete TeV-scale graviton resonances. The coupling of the Kaluza-Klein graviton states to matter is enhanced when compared with the coupling of the ground state graviton to matter [2]. As a result, phenomenologically reasonable regions of parameter space exist in which resonant tree-level production of Standard Model particles via a Kaluza-Klein graviton excitation is observable [3, 4]. In a previous work [5] we extended an argument of Nieves and Pal [6] to calculate the amplitude for the one-loop decay of a Z boson to a photon and a Kaluza-Klein graviton, in a form applicable to an effectively continuous spectrum of graviton excitations [7] in the ADD model [8,9,10,11]. With minimal additional calculation it is possible to derive from this an amplitude that can be used in calculations pertaining to the process $pp \rightarrow G \rightarrow Z\gamma$, where $G$ is the first Kaluza-Klein excitation of a graviton in a Randall-Sundrum model.

It will turn out that the one-loop suppression of this process is sufficient to render the process negligible for most accessible regions of parameter space. Further investigation of this process for purposes of discovery or parameter constraint is therefore not warranted, although observation of the process at high luminosity would act as a consistency check on any claim of observation of a Randall-Sundrum-type scenario. Observation of the process at very low luminosity could not be explained by such a scenario.

This note is organised as follows. We first outline the theoretical adjustments to our previous work required in order to calculate $\Gamma(G \rightarrow Z\gamma)$. We then describe results obtained for the cross-section $\sigma(pp \rightarrow G \rightarrow Z\gamma)$, both analytically and using a modified version of HERWIG [12,13]. We make a brief mention of the angular distribution of the process.

2 Amplitude for the process $G \rightarrow Z\gamma$

The amplitude for $G \rightarrow Z\gamma$ is closely related to the amplitude for the process $Z \rightarrow \gamma G$ calculated in reference [5], with the following choices/modifications:

- We choose $n = 1$ extra dimensions, and consider only a single spin-2 Kaluza-Klein graviton excitation (i.e. we do not sum over excited states);
- We set the gravitational coupling $\kappa$ equal to $1/A_\pi$, where $A_\pi = M_{KK}/((k/M_{Pl})x_1)$, $x_1$ is the first root of the Bessel equation of order 1, $M_{KK}$ is the mass of the first Kaluza-Klein excitation of the graviton, and $k/M_{Pl}$ is the ratio of the Randall-Sundrum warp factor to the reduced Planck mass, for consistency with [3] chosen to satisfy $k/M_{Pl} = 0.01$ unless stated otherwise (this represents the value satisfying conservative theoretical constraints [2] that is most likely to give rise to detectable phenomena);
- In this resonant production $M_{kk} \geq M_Z$, and we need to review one approximation in the analytic calculation, which was based on the assumption $M_Z \geq M_{kk}$;
- The polarisation averaging is over the five polarisation states of the massive graviton, rather than the three of the Z boson.
2.1 The analytic approximation

Reference [5] gives the amplitude for the $GZ\gamma$ interaction in the form

$$M(q,k) = E^{\lambda\rho}(q)\varepsilon^{\ast\nu}(k)\varepsilon_{Z}^{\mu\nu}(p)F_{\lambda\rho\mu\nu}(q,k),$$  \hspace{1cm} (1)$$

with $E^{\lambda\rho}(q)$ and $q$ the polarisation tensor and momentum respectively of the graviton, $\varepsilon^{\ast}(k)$ and $k$ the polarisation tensor and momentum respectively of the photon, and $\varepsilon_{Z}^{\mu\nu}(p)$ and $p$ the polarisation tensor and momentum respectively of the Z boson. From Ward-like identities, it can be shown [5] that

$$F_{\lambda\rho\mu\nu} = \{(k\lambda q_{\nu} - k \cdot q_{\lambda\nu})(k_{\rho} q_{\mu} - k \cdot q_{\rho\mu})F_{\lambda\rho\mu\nu} +$$

$$+ \varepsilon_{\lambda\rho\alpha\beta}k^{\alpha}k^{\beta}(k_{\rho} q_{\mu} - k \cdot q_{\rho\mu})F_{1}\lambda\rho\mu\nu +$$

$$(k\lambda q_{\nu} - k \cdot q_{\lambda\nu})\varepsilon_{\rho\mu\alpha\beta}q^{\alpha}k^{\beta}F_{2}\} + (\lambda \leftrightarrow \rho),$$

\hspace{1cm} (2)$$
in which

$$F = \frac{\kappa e g}{4\pi^{2}\cos\theta_{W}} \times$$

$$\times \left[ \cos^{2}\theta_{W}\left(6 - \frac{1}{\cos^{2}\theta_{W}}\right)J(M_{W}, M_{kk}, M_{Z}) -$$

$$-2\sum_{j}Q_{f}X_{j}J(m_{f}, M_{kk}, M_{Z}) \right],$$

\hspace{1cm} (3)$$
F_{1} = 0,$$
\hspace{1cm} (4)$$
F_{2} = 0,$$
\hspace{1cm} (5)$$
and

$$J(X,Y,Z) = \int_{0}^{1}dx \int_{0}^{1-x}dy \frac{x^{2}y(1-x-y)}{X^{2} - y(1-x-y)Y^{2} - xyZ^{2}}.$$  \hspace{1cm} (6)$$

The integral of equation (6) is not analytically tractable, but can be solved by means of an approximation. The approximate solutions derived in reference [5] rely upon the assumption $M_{Z} \geq M_{kk}$ (i.e. $Z \geq Y$), but it is not hard to replace this assumption with the assumption $M_{kk} \geq M_{Z}$. To make the integral analytically tractable, we need either to neglect the factor X in the denominator of the integrand (equivalent to assuming $X/(Y + Z) \ll 1/4$, or to neglect the factors Y and Z in that denominator (equivalent to assuming $X/(Y + Z) \gg 1/4$). For each integral in equation (3) the most appropriate choice is to neglect the factor X, but we note that this produces the constraint that the result is valid only in the region $M_{kk} \gg 4m_{t}$.

We therefore approximate each integral $J(M_{X}, M_{kk}, M_{Z})$ by $J(0, M_{kk}, M_{Z})$ (where $M_{X} = M_{W}$ or $m_{f}$), and as in reference [5] this integral may be evaluated to obtain

$$J(0, M_{kk}, M_{Z}) = \frac{1}{12(M_{Z}^{2} - M_{kk}^{2})^{2}} - \frac{M_{Z}^{2}}{8(M_{Z}^{2} - M_{kk}^{2})^{2}} +$$

$$+ \frac{M_{Z}^{2}M_{kk}^{2}}{4(M_{Z}^{2} - M_{kk}^{2})^{3}} +$$

$$+ \frac{M_{Z}^{4}}{4(M_{Z}^{2} - M_{kk}^{2})^{4}} \log \left(\frac{M_{kk}^{2}}{M_{Z}^{2}}\right).$$

\hspace{1cm} (7)$$

We must perform a different series expansion of the logarithm from that in reference [5], in order to get a convergent series, and the appropriate result is

$$J(0, M_{kk}, M_{Z}) = -\frac{1}{4} \sum_{j=0}^{\infty} \frac{1}{(j + 3)(j + 4)} \times$$

$$\times M_{kk}^{4j - 2}(M_{Z}^{2} - M_{kk}^{2})^{j}.$$  \hspace{1cm} (8)$$

This result agrees with the expansion obtained in reference [5] in the case $M_{kk} = M_{Z}$.

Returning now to equation (3) we can substitute to obtain

$$F = \frac{\kappa e g}{4\pi^{2}\cos\theta_{W}} \times$$

$$\times \left[ \cos^{2}\theta_{W}\left(6 - \frac{1}{\cos^{2}\theta_{W}}\right) - 12 + 32\sin^{2}\theta_{W} \right] \times$$

$$\times \left[ -\frac{1}{4M_{kk}^{2}} \sum_{j=0}^{\infty} \frac{1}{(j + 3)(j + 4)} \left(1 - \frac{M_{Z}^{2}}{M_{kk}^{2}}\right)^{j} \right].$$

\hspace{1cm} (9)$$

This expression is valid for $M_{kk} \gg 4m_{t}$, and should be used with caution for smaller graviton excitation masses.

Using the polarisation sum formulae quoted in reference [5], we obtain

$$|M|^{2} = |F|^{2} \left(\frac{(M_{Z}^{2} - M_{kk}^{2})^{4}(7M_{Z}^{2} + 3M_{kk}^{2})}{60M_{Z}^{2}}\right),$$

\hspace{1cm} (10)$$
and hence

$$\Gamma(G \to Z\gamma) = \frac{1}{960\pi^{2}M_{Z}^{2}M_{kk}^{2}}(M_{kk}^{2} - M_{Z}^{2})^{5} \times$$

$$\times (7M_{Z}^{2} + 3M_{kk}^{2})|F|^{2}.$$  \hspace{1cm} (11)$$

3 The process $pp \to G \to Z\gamma$

In order to investigate the process $pp \to G \to Z\gamma$, we may follow one of two procedures:

1. Use a numerical calculation of $\sigma(pp \to G)$ and a numerical calculation of $\Gamma(G)$ in order to derive a cross-section for a given $M_{kk}$ via $\sigma(pp \to G \to Z\gamma) = \sigma(pp \to G)\Gamma(G \to Z\gamma)/\Gamma(G)$;

2. Use the expression for the amplitude for the process $G \to Z\gamma$ to make a narrow width approximation for the overall process, which may be used either directly for angular distribution calculations or via a numerical simulation to obtain values for $\sigma(pp \to G \to Z\gamma)$.
We explore both possibilities. To perform the algebra necessary to obtain the amplitude for the narrow width approximation, we use FORM [14], and for the numerical simulation, we use HERWIG 6.5 [12, 13], modified to be HERWIG default of taking into account the contributions from tree-level decays to partons, leptons and bosons.)

Table 1 contains results for the benchmark value of $k/M_{Pl} = 0.01$. The row printed in bold type corresponds to the lightest Kaluza-Klein graviton mass not significantly above 800 GeV: see the text for discussion.

![Table 1](image)

We assume that this channel would be used as a consistency check following discovery in another channel. The most favourable Kaluza-Klein mass considered in Table 2 that is not already excluded (900 GeV) yields an event rate too small for observation at the LHC, but an event rate that with 3000 fb$^{-1}$ of data from a sLHC upgrade needs slightly more careful consideration ($\sim 35$). However, the number of background events at this integrated luminosity is relatively high in comparison with the signal: a very rough estimate using ALPGEN [18] gives an approximate background cross-section of 4.0 $\times$ 10$^{-5}$ pb ($\sim 121$ events with 3000 fb$^{-1}$ of data), and when one additionally takes into account detector effects and the necessity of only looking at a subset of Z decay channels for event tagging, one is led to the conclusion that it would be very difficult to observe this process at the LHC, even with a luminosity upgrade.

### 3.1 Angular distributions

Although moot in many regions of accessible parameter space, the angular distributions of the process may be relevant in particularly favourable regions of parameter space. It is possible to calculate the angular distributions algebraically given the general form of the $GZ\gamma$ vertex given in equation (2), together with equations (4) and (5), and expressions for the $q\bar{q}G$ and $ggG$ vertices and graviton propagator, obtainable from references [19, 20], for example.

The angular distributions are given in Table 3 and are plotted for the high-M$_{KK}$ limit in Figure 1.

1 The parameters used were: events with 1 photon, 1 Z boson (all decay modes – for comparison with the all-decays $pp \rightarrow G \rightarrow Z\gamma$ cross-section), and no additional hard jets, with a $p_T$ cut on the Z boson of 40% of the relevant graviton mass $M_{KK}$. This is merely a very rough indicative estimate of background – but is sufficient to demonstrate that with a significant number of background events it would be very difficult to infer the existence of a signal.
Table 3. Angular distributions for the hard subprocesses of resonant Zγ production via a Kaluza-Klein graviton. θ* is the polar angle of the outgoing particle in the graviton rest frame; β' is equal to 1 − M_KK^2/M_Z^2 (so in most cases we can take β' = 1).

| Process | Distribution |
|---------|--------------|
| gg → G → Zγ | 2(1 + cos^2 θ*) − β'(1 + cos^2 θ')^2 |
| q̅q → G → Zγ | 3 − cos^2 θ* − 2β'(1 + cos^2 θ* − 2cos^2 θ*) |

Both Zγ decay subprocesses differ in angular distribution from the respective γγ and ZZ decay subprocesses (see reference [4]). This should not be surprising, given that the γγ and ZZ decay subprocesses differ in angular distribution from each other, owing to the additional polarisation states of the Z bosons.

4 Conclusions

We have evaluated branching ratios and cross-sections for the hadronic production of a Z boson and a photon via a single Kaluza-Klein graviton excitation, applicable to scenarios that lead to discrete graviton resonances. We find that the process is unlikely to be observed at the Large Hadron Collider, although its presence or absence would be a potentially useful consistency check were other signals of such models seen, and the process would provide additional data to constrain the gravitational coupling 1/Λ (since this coupling is dependent upon the Kaluza-Klein graviton mass and determines the event rate, so the coupling is related to the energy scale and number of resonant events).

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