A consideration of the search for graviton resonances in the diphoton decay mode at the ATLAS detector

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Standard Model & Gravity

- In the Standard model, each force has an associated force mediator gauge boson (examples)
  - EM -> photon
  - Weak -> W, Z
  - Strong -> gluons
  - Gravity -> graviton?

- Particle physics has a tradition of unifying the fundamental forces: Maxwell’s unification of electricity and magnetism into the electromagnetic force in the 1860’s, and the unification of electromagnetism and the weak interaction into the electroweak interaction a century later.

- Convinced many that a unified field theory, combining general relativity and a grand unified theory of the electroweak and strong interactions, is in our future
Randall-Sundrum Model

- Attempt to solve hierarchy problem (relative weakness of gravity)

- The 3-space+1-time dimensional world on the SM brane that exists within higher dimensional (5D) universe

- Extra dimension warped in a manner analogous to warping of spacetime near a massive object

- Graviton is the sole elementary particle capable of propagating in extra dimension; so-called ‘warp factor’ responsible for it’s weak appearance in our 4D brane.

- Graviton Kaluza-Klein spectrum has a scale: $\Lambda_\pi = M e^{-kr_c\pi}$
RS Model (II)

- Distinct from other additional dimensional theories:
  - Hierarchy between fundamental 5D scale and compactification scale $(=1/r_c)$ is order 10 rather than $(M_{Pl}/\text{TeV})^{2/n}$
  - A single extra dimension rather than $n \geq 2$
  - First KK modes are predicted at the TeV scale
  - Should be observable at colliders as spin-2 resonances capable of being reconstructed from their decay products
- Graviton has many decay modes, of which we will focus on $G^* \rightarrow \gamma \gamma$ despite having a branching ratio of $\sim 4\%$. 
Simulation

- Pythia event generator to simulate proton-proton collision
- EM energy deposited in EM calorimeter used to reconstruct 4-vector information regarding particles associated with event using Geant4
- Signal: 500, 1000, 1500, 2000, 2500 GeV
- Background: 450, 950 GeV
  - Two largest potential of background are the dijet and jet-photon, which although have a smaller probability of occurring is compensated by a cross section several orders of magnitude larger.
## Simulation Information

<table>
<thead>
<tr>
<th>Signal (GeV)</th>
<th>$N_{\text{events}}$</th>
<th>$N_{\text{matched}\gamma}$</th>
<th>Reconstruction efficiency, $\varepsilon_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>850</td>
<td>1367</td>
<td>85%</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
<td>1877</td>
<td>86%</td>
</tr>
<tr>
<td>1500</td>
<td>991</td>
<td>2014</td>
<td>87%</td>
</tr>
<tr>
<td>2000</td>
<td>838</td>
<td>1845</td>
<td>87%</td>
</tr>
<tr>
<td>2500</td>
<td>498</td>
<td>1104</td>
<td>88%</td>
</tr>
<tr>
<td>Background (GeV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>1000</td>
<td>768</td>
<td>71%</td>
</tr>
<tr>
<td>950</td>
<td>1000</td>
<td>846</td>
<td>68%</td>
</tr>
</tbody>
</table>
Computing the invariant mass…

For each collision event:

- Define a 60 GeV $P_T$ cut so as to disregard photons not energetic enough to have decayed from massive $G^*$

- All possible combinations of reconstructed photons, compute invariant mass from four-vectors of decay products, the photons

\[ W^2c^4 = (\sum \mathbf{E})^2 - (\sum \mathbf{p}c)^2, \text{ for a system of 2 particles} \]
Invariant Mass (500 GeV)

| Invariant Mass - 500 GeV |

- **Entries**: 668
- **Mean**: 5.049e+05
- **RMS**: 3.685e+04

**Mean**: 5.03736e+05

**Sigma**: 6.98805e+03
Invariant Mass (1000 GeV)

<table>
<thead>
<tr>
<th>Invariant Mass - 1000 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>hM0</td>
</tr>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

Mean: 1.00502e+06  
Sigma: 1.38183e+04
Invariant Mass (450 GeV)

Mean: 5.32050e+05
Sigma: 7.89165e+04
Reconstruction Efficiency

Why is this important?

- Limitations are inherently imposed by the success of detectors in being able to accumulate data regarding an event.
- Simulations represent the single arena where we have access to the “truth”, that is we know how particles in simulations decay to form a particular collection of products.
- Thus, simulations are the ideal method to investigate the ability of detectors to reconstruct events with vastly different particle properties.
Efficiency vs Photon Pt (500 GeV simulation data)

Efficiency as a function of Spcl_Pt

P(0): 0.524822
P(1): 0.000002
Efficiency vs Photon Pt (1000 GeV simulation data)

Efficiency as a function of Spcl_Pt

- P(0): 0.306732
- P(1): 0.000003
Efficiency vs Pseudorapidity (500 GeV Simulation Data)
Efficiency vs Pseudorapidity (1000 GeV simulation data)
Resolution = \( \frac{\text{Pt}_{\text{Gen}} - \text{Pt}_{\text{Recon}}}{\text{Pt}_{\text{Gen}}} \)

(500 GeV simulation data)
Resolution (1000 GeV simulation data)

Mean: -4.50758e-03
Sigma: -1.75518e-02
Determination of Min Luminosity (Process)

• Apply a Gaussian fit to invariant mass distribution, obtaining mean and standard deviation fit parameters
• Count the number of signal events in a 1, 2, or 3 sigma mass window.
• Applying same window invariant mass distribution of the SM background, count the number of background events
• Use the relation, Total Number of Events = \( \varepsilon \times (\sigma \times Br) \times L \), where \( \varepsilon \) represents the fraction of the entire distribution that is localized within the selected mass window, \( \sigma \) and \( Br \) are the cross section and branching ratio of the decay mode respectively, and \( L \) is the luminosity.
• Statistical error is minimized by maximizing the significance, \( S \), where

\[
S = \frac{N_{signal}}{\sqrt{N_{background}}}
\]

• Algebraic manipulation allows one to solve for the integrated luminosity as a function of the other variables, from which you can derive the minimum luminosity required to achieve a significance of 5 or larger.
## Determination of Min Luminosity (Results)

<table>
<thead>
<tr>
<th>Sigma</th>
<th>$\sigma$</th>
<th>2 $\sigma$</th>
<th>3 $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Luminosity, 500 GeV</td>
<td>4.56 pb$^{-1}$</td>
<td>4.07 pb$^{-1}$</td>
<td>5.87 pb$^{-1}$</td>
</tr>
<tr>
<td>Min. Luminosity, 1000 GeV</td>
<td>417.7 pb$^{-1}$</td>
<td>385.8 pb$^{-1}$</td>
<td>455.4 pb$^{-1}$</td>
</tr>
</tbody>
</table>
Future Work

- Angular distribution:
  - Important because by plotting the angular distribution of the signal and background, one can say with confidence that the signal is a fundamentally difference process and even claim a spin-2 resonance has been observed in the collider, consistent with RS(1) model.
  - The fact that the anomalous decay products are photons, if indeed found, would be suggestive of a graviton because of the fact that the graviton is said to couple universally, to sheer energy, while this is not the case for alternative exotic particles such as the Z', the heavy cousin of the Z boson which would not decay to a diphoton pair.

- Modify code to prevent (rare) possibility of superfluous invariant masses by including a single photon in multiple diphoton pairs. Sufficient to just take most energetic photons in this case as the most likely to have decayed from a massive graviton.

- Relatively few signal and background events simulated; would like to apply work to a larger project so as to achieve more.
Conclusions

- Able to study the effects of the detectors ability to reconstruct photons of varying energies and angles from the beam line
- Calculated the minimum required luminosity to achieve various degrees of significance
- Still exist other decay modes to examine, since $G^* \rightarrow$ diphoton represents about 4% of the decays for given 1.5 TeV gravitons
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