Search for massive resonances decaying into pairs of boosted bosons in semi-leptonic final states at \( \sqrt{s} = 8 \text{ TeV} \)

Course on Physics at the LHC

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CMS DETECTOR

- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
- Pixel (100x100 µm) ~16m² ~66M channels
- Microstrips (80x180 µm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
- Barrel: 260 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PWO₃ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
Large difference between mass of the Higgs boson and Planck scale $M_{Pl}$, where the gravitational force is expected to have the same strength as the other fundamental forces.

Some models, such as the Randall–Sundrum, extend the number of spatial dimensions and predict the existence of new resonances coupling to pairs of massive vector bosons.

Extension of this model to bulk graviton model, where only coupling to massive gauge bosons is relevant. It has two free parameters: the mass of the first mode of the KK bulk graviton, $M_G$, and the ratio $\frac{k}{M_{Pl}}$, where $k$ is the unknown curvature scale of the extra dimension, and $\overline{M_{Pl}}$ is the reduced Planck mass.
Two Feynman diagrams for the production of a generic resonance $X$ decaying to some of the final states considered in this study.
Simulation

- Bulk graviton is forced to decay to the WW and ZZ final states.
- Vector gauge bosons are predominately produced with a longitudinal polarization.
- Graviton masses considered lie in the range 600 to 2500 GeV.
- The total cross section of the process $pp \rightarrow G_{bulk}$ at $\sqrt{s} = 8$ TeV is 15.1 fb, for a graviton mass of 1 TeV and $k/M_{Pl} = 0.5$.
- At the same resonance mass, the Branching Fraction of $G_{bulk} \rightarrow WW$ is 18.7% and of $G_{bulk} \rightarrow ZZ$ is 9.5%.
Online Trigger

$l\nu + V - jet$ channel:

- Trigger requiring either one muon or one electron, no isolation requirements and loose identification criteria.
- $p_T > 40$ GeV for the muons and $p_T > 80$ GeV for the electrons.

$ll + V - jet$ channel:

- Trigger requiring either two muons or two electromagnetic energy deposits, with loose identification criteria.
- No lepton isolation requirements.
- $E_T > 33$ GeV for the electrons.
Large values of the mass of a $ZZ$ resonance

Leptons originating from the high-$p_T$ $Z$ boson are highly collimated because of the large Lorentz boost

Small values of angular separation $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$

Global muon reconstruction, which uses both the inner tracking system and the muon spectrometer, fails to very closed muons, causing the loss of one of them

In the di-lepton final state, selection requires two tracker muons (less precise reconstructed muons) of which at least one should be reconstructed and identified as a global muon.
An isolation requirement is applied in order to suppress the background from multi-jet events.

$l\nu + V - jet$ channel:
- One global muon with $p_T > 50$ GeV and $|\eta| < 2.1$.

$ll + V - jet$ channel:
- Two muons, one with $p_T > 40$ GeV and the other with $p_T > 20$ GeV, and $|\eta| < 2.4$. 
Electron candidates are reconstructed by matching energy deposits in the ECAL with reconstructed tracks and obey precise isolation criteria.

$l\nu + V − jet$ channel:
- One global muon with $p_T > 90$ GeV and $|\eta| < 2.51$.

$ll + V − jet$ channel:
- Two electrons with $p_T > 40$ GeV and $|\eta| < 2.5$. 
Jets are reconstructed using the Particle-Flow (PF) algorithm, which combines information from all sub-detector systems.

Particles not associated with the primary-event vertex are rejected.

Criteria regarding isolation and tagging is applied to the jets, that must also have $p_T > 30$ GeV and $|\eta| < 2.4$.

In the $l\nu + V − jet$ channel it is required an $E_T^{\text{miss}} > 40$ GeV for muons and $E_T^{\text{miss}} > 80$ GeV for electrons.
Bosons Reconstruction

- In the leptonic channels where there are neutrinos the missing transverse energy is associated to the system of neutrinos (one or three, depending on the lepton decay).

- The invariant masses of $ll$ and $l\nu$ have to be consistent with the boson masses associated.

- In the hadronic channels the reconstructed jet mass also has to be close to the boson masses and jet substructure analysis is performed in order to reduce background.
Final event selection and categorisation

- In the $ll + V−jet$ channel both the leptonic and the hadronic $V$-boson candidates must have a $p_T$ greater than 80 GeV, while for the $l\nu + V−jet$ channel this minimum threshold is set at 200 GeV, due to higher trigger thresholds and larger multijet background.

- Applied criteria regarding that the two $W$ bosons from the decay of a massive resonance are approximately back-to-back in the $l\nu + V−jet$ channel.

- The minimum value of $m_{VV}$ is 700 GeV for the $l\nu + V−jet$ channel and 500 GeV for the $ll + V−jet$ channel.

- Categorisation having in mind lepton flavour (muon or electron) and $V$-jet purity (one or two subjets)
Final event selection and categorisation

Hadronic $W$ $p_T$ and N-subjettiness ratio $\tau_{21}$ distributions for the combined muon and electron channels and with $65 < m_{\text{jet}} < 105$ GeV. The VV, $tt$, and single-t backgrounds are taken from simulation and are normalized to the integrated luminosity of the data sample. The $W+\text{jets}$ background is rescaled such that the total number of background events matches the number of events in data. The signal is scaled by a factor of 1600 for better visualization.
Background Modeling

Dominant background comes from SM V+Jets events and its estimation in the signal region is derived from a fit excluding this same region, while the predictions for the other minor backgrounds come from the simulation.

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<thead>
<tr>
<th></th>
<th>$\mu\mu + V$-jet HP</th>
<th>$\mu\mu + V$-jet LP</th>
<th>$ee + V$-jet HP</th>
<th>$ee + V$-jet LP</th>
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</thead>
<tbody>
<tr>
<td>Observed yield</td>
<td>575</td>
<td>338</td>
<td>360</td>
<td>233</td>
</tr>
<tr>
<td>Expected background</td>
<td>622 ± 29</td>
<td>338 ± 22</td>
<td>370 ± 22</td>
<td>207 ± 17</td>
</tr>
<tr>
<td>Bulk graviton ($k/M_{Pl} = 0.5$)</td>
<td>2.4</td>
<td>0.5</td>
<td>2.0</td>
<td>0.4</td>
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<tr>
<td>$m_G = 800$ GeV</td>
<td>0.16</td>
<td>0.04</td>
<td>0.14</td>
<td>0.035</td>
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<tr>
<td>$m_G = 1200$ GeV</td>
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<tr>
<td>Observed yield</td>
<td>1483</td>
<td>1546</td>
<td>892</td>
<td>988</td>
</tr>
<tr>
<td>Expected background</td>
<td>1434 ± 38</td>
<td>1644 ± 41</td>
<td>878 ± 30</td>
<td>978 ± 31</td>
</tr>
<tr>
<td>Bulk graviton ($k/M_{Pl} = 0.5$)</td>
<td>12.8</td>
<td>5.1</td>
<td>10.1</td>
<td>3.9</td>
</tr>
<tr>
<td>$m_G = 800$ GeV</td>
<td>0.92</td>
<td>0.43</td>
<td>0.79</td>
<td>0.37</td>
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<tr>
<td>$m_G = 1200$ GeV</td>
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Final distributions in $m_{WW}$ for data and expected backgrounds. Also shown is a hypothetical bulk graviton signal with mass of 1000 GeV and $\frac{k}{M_{Pl}} = 0.5$. The normalization of the signal distribution is scaled up by a factor of 100 for a better visualization.
Signal Modeling

- The shape of the reconstructed signal mass distribution is extracted from the bulk graviton Monte Carlo samples generated with the coupling $\frac{k}{M_{Pl}} = 0.2$.

- The natural width of the resonance is sufficiently small to be neglected when compared to the detector resolution, making the modeling of the detector effects on the signal shape independent of the model used for generating the events.

- The signal mass distribution is parametrized separately for events with electrons and muons.
Limits on a narrow-width bulk graviton model

Observed (solid) and expected (dashed) 95% CL upper limits on the product of the graviton production cross section and the branching fraction of $G_{\text{bulk}} \rightarrow WW$ and $G_{\text{bulk}} \rightarrow ZZ$
BACKUP
Observed exclusion limits at 95% CL on the number of events for a $WV \rightarrow l\nu + V - jet$ and $ZV \rightarrow ll + V - jet$