Relatório Científico

Busca por Física Além do Modelo Padrão no Canal Díbosons Vetoriais

Outorgado
José Cupertino Ruiz Vargas

Orientador
Sérgio Ferraz Novaes

Co-orientador
Thiago Tomei

Instituição:	Instituto de Física Teórica – IFT/UNESP
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1. Abstract

The Standard Model (SM) of elementary particles is the physics theory that describes the fundamental constituents of matter. The SM has been experimentally tested by a long series of high-energy experiments, amongst which the latest is the Large Hadron Collider (LHC) at CERN. No evidence of new phenomena has been observed so far. Our project involves the search for new resonances produced in proton-proton collisions, decaying into a pair of bosons WZ or ZZ. Our preliminary results are based on the analysis of data collected by the CMS experiment along 2015, corresponding to an integrated luminosity of 2.63 fb^{-1} delivered by the LHC operating at centre-of-mass energy of 13 TeV.

2. Introduction

In spite of its experimental success, the SM still presents a series of open questions. One of those questions is related to possible interpretation of gravity as a quantum field, and its relation to the structure of Standard Model. There are several models that try to address that question, and some of them predict the existence of new massive particles that decay to a pair of bosons; among these we can count the Randall-Sundrum Warped Extra Dimensions, and the Bulk Graviton model [1, 2].

This document reports the status of the search for new resonances that decay to a pair of vector bosons in the semi-leptonic final state

$$pp \to X \to VZ \to \text{jet} + \ell^+\ell^- \,, \tag{1}$$

in which at least one boson ($V = Z, W$) decays into a pair of collimated quarks, producing an experimental signature of a spray of hadrons – a hadronic jet – while the other boson decays leptonically into a pair of muons or electrons ($\ell = e, \mu$). We focus on the search for resonances with masses above 1 TeV. Since the SM does not foresee the existence of any particle in this high mass regime, our goal is to search for deviations in the data not compatible with the SM, and compare with the expectations of the Bulk Graviton model.

This project is based on the analysis of proton-proton collision data collected by the CMS experiment at the LHC. The central feature of the CMS detector is a superconducting solenoid of 6 m diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and the strip tracker, the lead tungstate crystal electromagnetic calorimeter ECAL, and the brass scintillator hadron calorimeter HCAL, each composed of a barrel and two endcap sections. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. Muons (electrons) are measured in the pseudorapidity range $|\eta| < 2.4$ (2.5). A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref.[3].

3. Data and selection criteria

The data taken by CMS, as well as simulated samples for comparison, are available for members of the CMS collaboration only. Our membership is possible through the São Paulo Research and Analysis Center (SPRACE), which is part of the Worldwide LHC Computing Grid (WLCG). In the hierarchy of the WLCG, SPRACE is a Tier-2 linked to the Fermilab Tier-1, which in turn is linked to the Tier-0 at CERN.

Our analysis requires two types of samples: real collision data (Table 1), and simulated samples (Table 2). The real data was recorded by the CMS Detector during the `Run2015C+D` era of the LHC, operating at a centre-of-mass energy of 13 TeV. The amount of data corresponds to an integrated luminosity of 2.63 fb^{-1}.

Simulated samples include the SM background with the experimental signature of interest. As mentioned in Eq. 1, the signature consists of one jet and two leptons, so the SM processes contributing to this channel are `DYJets`, `Diboson` (`WW`, `WZ`, `ZZ`), and `TTbar` production. Simulated samples also include the signal under study. For signal modelling we use Bulk Graviton samples with different mass hypotheses ranging from 0.8 to 4.0 TeV. The generation of the samples employs `MadGraph` [4] for matrix element calculations, `Pythia8` [5] for showering and hadronization, and `Geant4` [6] to simulate the interactions of the particles with the detector.

Table 1: Real collision data.

Dataset name	**Run range**	$\mathcal{L}$ [pb^{-1}]
/SingleElectron/Run2015C_25ns-16Dec2015-v1	254231-254914	15.3
/SingleElectron/Run2015D-16Dec2015-v1	256630-258750	2615.0
/SingleMuon/Run2015C_25ns-16Dec2015-v1	254231-254914	15.3
/SingleMuon/Run2015D-16Dec2015-v1	256630-258750	2615.0

Table 2: Simulated SM backgrounds and Bulk Graviton signal samples.

Sample name	**Cross section[pb]**	$\mathbf{N_{events}}$
/DYJetsToLL_M-50_HT-100to200_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/	147.40 x 1.23	2655294
/DYJetsToLL_M-50_HT-200to400_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/	40.99 x 1.23	962195
/DYJetsToLL_M-50_HT-400to600_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/	5.678 x 1.23	1069003
/DYJetsToLL_M-50_HT-600toInf_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/	2.198 x 1.23	1031103
/WW_TuneCUETP8M1_13TeV-pythia8	118.7	988418
/WZ_TuneCUETP8M1_13TeV-pythia8	66.1	1000000
/ZZ_TuneCUETP8M1_13TeV-pythia8	15.4	985600
/TT_TuneCUETP8M1_13TeV-amcatnlo-pythia8	831.76	19090400
/BulkGravToZZToZlepZhad_narrow_M-800_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-1000_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-1200_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-1400_13TeV-madgraph	1.0E03	49200
/BulkGravToZZToZlepZhad_narrow_M-1600_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-1800_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-2000_13TeV-madgraph	1.0E03	48400
/BulkGravToZZToZlepZhad_narrow_M-2500_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-3000_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-3500_13TeV-madgraph	1.0E03	50000
/BulkGravToZZToZlepZhad_narrow_M-4000_13TeV-madgraph	1.0E03	50000

After reconstruction, each event contains the four-momenta of all particles emerging after a proton-proton collision, together with a number of quantities that can be used for the identification and assessment of the reconstruction quality. Among the plethora of events in a dataset, we have to select those containing one jet plus two leptons. A single event may contain several jets and also many lepton candidates, therefore, precise selection criteria are required to avoid ambiguities and improve the particle identification. A description of the analysis selection criteria is presented in Table 3; those criteria are optimised to have a high selection efficiency for signal events, while discarding a large amount of SM background.

Table 3: Summary of the analysis selection.

Selection	**Value**	**Comments**
High Level Trigger		
Electron channel	Single electron, $E_T > 105$ GeV	
Muon channel	Single muon, $p_T > 45$ GeV, $\|\eta\| < 2.1$	
Electrons		
Electron identification	Loose working point	CMS EGamma POG [7]
Isolation	Particle-flow [8]	
Acceptance	$p_T > 115$ GeV, $\|\eta\| < 2.5$	leading electron
	$p_T > 20$ GeV, $\|\eta\| < 2.5$	second electron
Muons		
Muon identification	Tracker High p_T or High p_T	CMS Muon POG [9]
Isolation	Tracker-based isolation	
Acceptance	$p_T > 50$ GeV, $\|\eta\| < 2.1$	leading muon
	$p_T > 20$ GeV, $\|\eta\| < 2.4$	second muon
Dilepton selection		
Leptonic Z	$p_T > 170$ GeV	
	$70 < M_{\ell\ell} < 110$ GeV	
AK8 Jets		
Jet identification	PFJetID Loose	CMS JME POG [10]
Acceptance	$p_T > 170$ GeV, $\|\eta\| < 2.4$	
Pruned jet mass (signal)	$65 < m_{jet}^{pruned} < 105$ GeV	
Pruned jet mass (low-mass sideband)	$20 < m_{jet}^{pruned} < 65$ GeV	
Pruned jet mass (high-mass sideband)	$135 < m_{jet}^{pruned} < 220$ GeV	
Diboson candidate		
VZ candidate mass	$M_{VZ} > 600$ GeV	

4. Preliminary results

Any analysis inside the CMS collaboration has to be approved before proceeding to publication. The results shown in this section are preliminary, and they have to be submitted to the scrutiny of the collaboration before they are shown publicly. This internal review process is enforced even for preliminary results; on top of that, the scientific papers produced by CMS are subject to the standard peer review. This thorough process helps ensure the quality of the physics results obtained.

The kinematic variable that defines our signal region is the jet mass, since the decay products of the hadronically decaying Z boson will usually be reconstructed as a single jet. Advanced substructure techniques [11, 12] suggest the usage of the `pruned mass` as the variable to characterise V-originated jets. In a simulated sample corresponding to a 1 TeV Bulk Graviton, the distribution of the jet pruned mass is shown in Fig.1. In the initial stage of the analysis, it is common practice to blind the kinematic region containing the signal events. As shown in right plot of Fig.1, the jet pruned mass distribution in data contains a gap in the signal region $65 < m_{jet}^{pruned} < 135$ GeV.

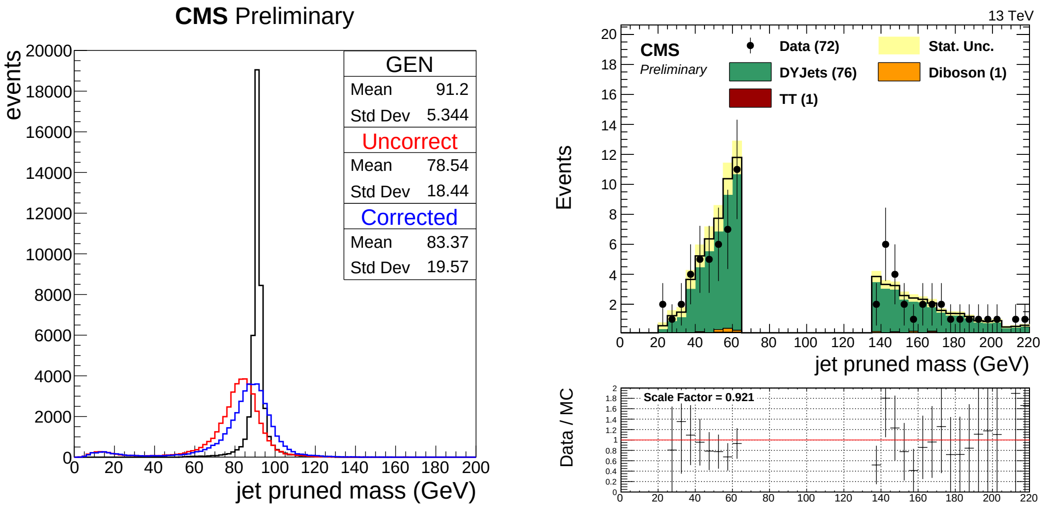

Figure 1: The jet pruned mass peaks close to the Z boson nominal mass (left-plot). In addition, jet energy corrections improve the agreement between the reconstructed jet (blue line) and the generated Z boson (black line). Due to our blinding policy, the signal region is not shown in the distribution for data (right-plot).

Leptons also play an important role in the analysis. The analysis selection involves two opposite charge muons or electrons with invariant mass $70 < M_{\ell\ell} < 110$ GeV, $\ell = e, \mu$. In addition, the transverse momentum of the dilepton pair satisfies $p_T > 170$ GeV. Distribution of the invariant mass of the dilepton pair are show in Fig.2.

The kinematic variable with most discovery potential is the invariant mass of the jet + leptons system:

$$M_{VZ} = \sqrt{E^j E^{\ell\ell} - p_T^j p_T^{\ell\ell} - p_z^j p_z^{\ell\ell}}\,, \tag{2}$$

where E, p_T, p_z, are the energy, transverse momentum, and longitudinal momentum, respectively. The index j stands for jet, and the index $\ell\ell$ stands for dilepton.

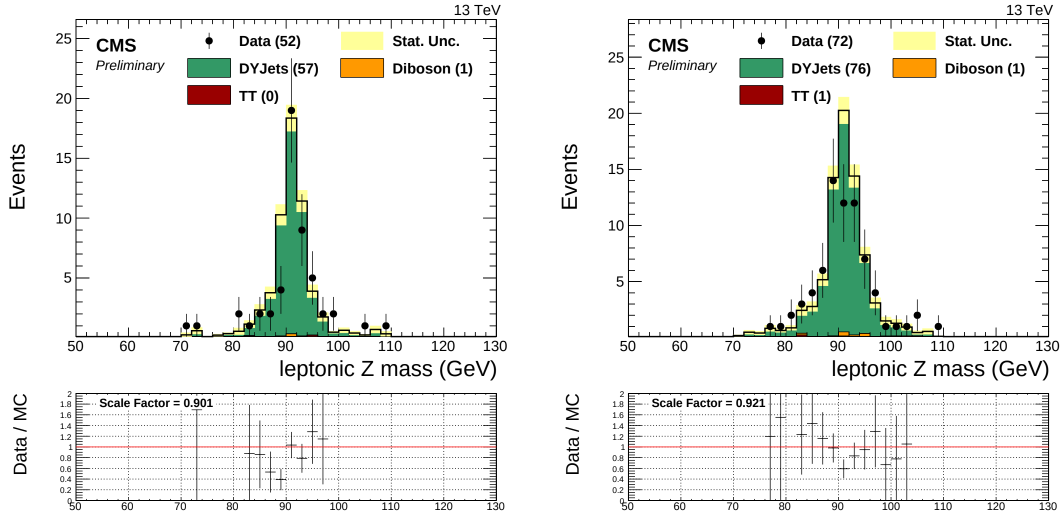

Figure 2: Invariant mass of the Z boson reconstructed from a pair of opposite sign leptons. Electron (left) and Muon channels (right) are shown.

According to the decay chain indicated in Eq.1, the invariant mass M_{VZ} corresponds to the mass of the exotic resonance. By analysing the distribution of M_{VZ} we can search for indication of new physics beyond the SM – a localised excess above the SM expectation. After unblinding, we will be able to compare the Standard Model expectation with the observation. For the time being, we show the comparison in the sideband regions; this result is shown in Fig.3 for the electron and muon channels, and is useful to validate the simulation used.

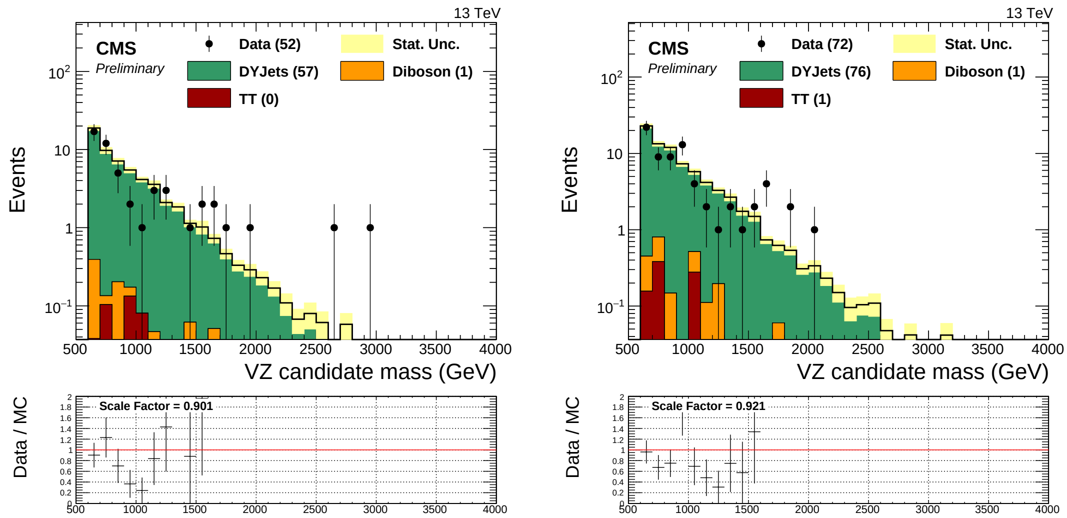

Figure 3: Invariant mass distribution reconstructed with the kinematic information of the jet + leptons system. Electron (left) and Muon channels (right) are shown.

The criteria for deciding if there is evidence for the existence of a new particle – or, conversely, if the observed data exclude the existence of such a particle – is traditionally the setting of an upper limit ata 95% confidence level (C.L.). To calculate the expected upper limit the following inputs are needed:

- signal efficiency,
- background estimation,
- systematic uncertainties,

while, for an observed limit, the observed data is also needed. Since the analysis is still blind, we cannot obtain observed limits for the moment. Fig.4 shows the 95% C.L. upper limit on the Bulk Graviton cross section times branching ratio as function of the VZ candidates mass. The expected upper limit should be compared with the observed limit; we refer to Section 7 for a tentative schedule to unblind the final result, approval of the analysis, and publication of the corresponding paper.

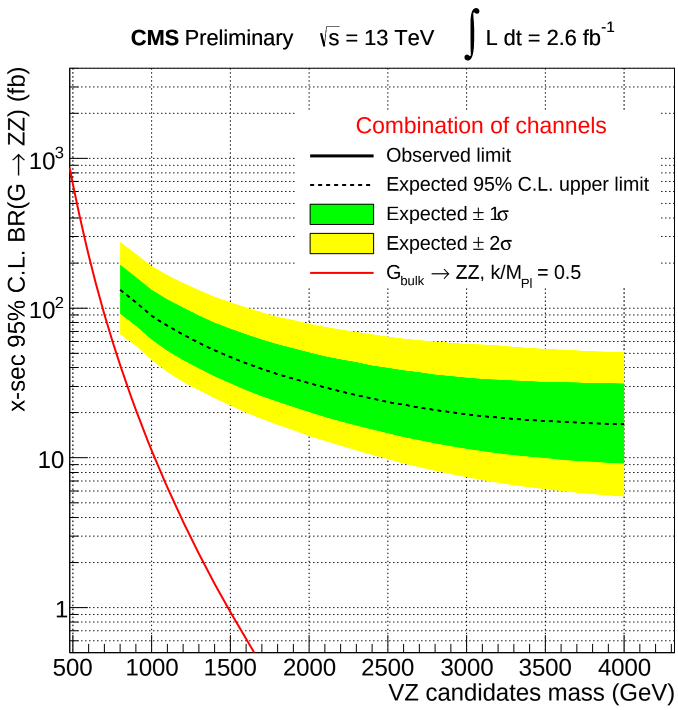

Figure 4: Expected upper limit on $\sigma(pp \rightarrow G) \times BR(G \rightarrow ZZ)$, with theoretical prediction (red line). The green (yellow) band corresponds to the 1σ (2σ) uncertainty on the expected limit (dotted line). Due to our blinding policy, the observed limit is not shown.

5. Collaborative activities

In addition to the research activities, every CMS participant has to dedicate a part of their work to the experiment's operation. For this purpose, two additional service tasks inside the CMS collaboration have been carried out. The first one consists in the validation of the High Level Trigger (HLT), a real-time system responsible for selecting events that events are interesting from the physics point of view and should be recorded for offline analysis. Another service task undertook was the monitoring of the WLCG, which is done in turns of 8 hours. The contribution to this service is one shift per month (in average).

6. Participation in events

Past events

- Search for Physics Beyond the Standard Model in the VZ channel at the CMS Experiment. **Oral presentation** at XXXVI Encontro Nacional de Física de Partículas e Campos, 14-18 de Setembro de 2015, Caxambu MG, Brasil.
- Física de Altas Energias no LHC. **Oral presentation** at II Simpósio de Física, Astronomia e Metereologia, 27-29 de Novembro de 2015, Bauru SP, Brasil.

Upcoming events

- Search for new resonances in the merged jet + dilepton final state in CMS. **Poster presentation** at 38th International Conference for High Energy Physics, ICHEP 2016, August 3 - 10, Chicago IL, United States

Weekly meetings

- Regular presentations at SPRACE weekly meeting (Table 4).

Table 4: SPRACE weekly meeting.

Date	Link to agenda
15 Apr 2016	https://indico.cern.ch/event/515939/
08 Apr 2016	https://indico.cern.ch/event/515938/
01 Apr 2016	https://indico.cern.ch/event/515937/
18 Mar 2016	https://indico.cern.ch/event/501898/
11 Mar 2016	https://indico.cern.ch/event/501897/
04 Mar 2016	https://indico.cern.ch/event/501896/
26 Feb 2016	https://indico.cern.ch/event/501895/
19 Feb 2016	https://indico.cern.ch/event/501894/
12 Feb 2016	https://indico.cern.ch/event/496662/
05 Feb 2016	https://indico.cern.ch/event/494785/
29 Jan 2016	https://indico.cern.ch/event/491876/
22 Jan 2016	https://indico.cern.ch/event/487407/
15 Jan 2016	https://indico.cern.ch/event/477852/
08 Jan 2016	https://indico.cern.ch/event/477289/
18 Dec 2015	https://indico.cern.ch/event/472673/
11 Dec 2015	https://indico.cern.ch/event/470267/
04 Dec 2015	https://indico.cern.ch/event/467409/
27 Nov 2015	https://indico.cern.ch/event/464872/
13 Nov 2015	https://indico.cern.ch/event/461777/
23 Oct 2015	https://indico.cern.ch/event/457275/
16 Oct 2015	https://indico.cern.ch/event/455445/
09 Oct 2015	https://indico.cern.ch/event/453209/
02 Oct 2015	https://indico.cern.ch/event/450954/
25 Sep 2015	https://indico.cern.ch/event/449095/
11 Sep 2015	https://indico.cern.ch/event/445784/
04 Sep 2015	https://indico.cern.ch/event/443330/
28 Aug 2015	https://indico.cern.ch/event/441880/
21 Aug 2015	https://indico.cern.ch/event/440538/
07 Aug 2015	https://indico.cern.ch/event/437709/
31 Jul 2015	https://indico.cern.ch/event/436549/
24 Jul 2015	https://indico.cern.ch/event/435405/
17 Jul 2015	https://indico.cern.ch/event/434000/
03 Jul 2015	https://indico.cern.ch/event/406536/

7. Schedule

This is the proposed schedule for the remainder of the project.

- Pre-approval of the analysis by CMS Collaboration: May 31, 2016
- Unblinding and approval by CMS Collaboration: July 15, 2016
- Writing paper for publication: August 31, 2016
- Submission of paper for publication: September 30, 2016
- Writing Ph.D. thesis: September - December, 2016
- Thesis defence: January 15, 2017

São Paulo, 10 de Maio de 2016

José Cupertino Ruiz Vargas

Dr. Sérgio Ferraz Novaes

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