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Search for trijet resonances in the unexplored boosted dijet final state

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Summary. — A search for trijet resonances decaying to a boosted di-gluon resonance and a quark or a gluon is presented. The second resonance is assumed to be light, so its decay products are collimated and reconstructed as a single jet. The experimental signature is represented by a pair of high-energy hadronic jets. The analysis exploits the jets substructure information to divide events in categories, then the dijet mass spectra are analysed looking for a resonance peak over a smooth background. The analysis uses the sample of 137 fb^{-1} of proton-proton collisions collected by the CMS detector at a center-of-mass energy of 13 TeV. Results are interpreted in a warped extra-dimension model where the first resonance is a Kaluza-Klein (KK) gluon, the second resonance is a radion, and final-state partons are all gluons.

1. – Introduction

The presence of new physics beyond the standard model (SM) is supported by both theoretical reasons and experimental observations such as, for example, the matter-antimatter asymmetry, the large gap between the gravity and electroweak energy scales, and the presence of dark matter in the universe.

Theories beyond the SM predict the existence of new particles which can be produced at colliders at the TeV energy scale, within the reach of the CERN Large Hadron Collider (LHC), which produces proton-proton (pp) collisions with a center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$.

In particular, searches for hadronic resonances are important at the LHC as any hypothetical particle produced in pp collisions must couple and decay to quarks/gluons which hadronize to form jets. The experimental searches could have missed their observation because these resonances decay into non-standard final-state configurations, which the current strategies are not optimized for, and are not able to identify the signal in the large background from quantum chromodynamics (QCD) multijet production.

This research aims to extend the current physics program at the LHC and study a new decay channel in which a new resonance (R_1) decays into a second, new resonance (R_2) and a SM quark/gluon (P). Such cascade resonance decays are foreseen by theoretical models beyond the SM that predict the existence of heavy partners of SM quarks [1] or the existence of extra spatial dimensions [2].

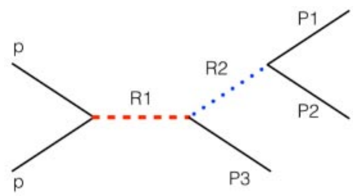

Fig. 1. – Feynam diagram of the process $pp \to R_1 \to R_2 + P_3 \to (P_1 + P_2) + P_3$.

In this analysis a systematic search for these new resonances in the allowed model parameter space is performed. The masses of R_1 and R_2 are free parameters of the theory, ranging from few hundreds GeV to several TeV.

2. – Data sample and object reconstruction

This analysis uses data collected by the Compact Muon Solenoid (CMS) experiment (detailed description in ref. [3]) in 2016–2018 from pp collisions at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $137\,\text{fb}^{-1}$. This represents an unprecedented data sample for the search of these new particles at the LHC.

Events are reconstructed using the CMS particle-flow (PF) [4] algorithm, which combines information from the CMS detector to reconstruct individual particles, which can be clustered in jets. This procedure allows to keep all the information on the jet substructure by storing all information of each jet constituent.

3. – Analysis strategy

The new physics process is $pp \to R_1 \to R_2 + P_3 \to (P_1 + P_2) + P_3$ (see fig. 1), where the three partons in the final state (P_x with $x = 1, 2, 3$) can be quarks and/or gluons depending on the model considered.

The experimental signature is defined by the mass ratio $\rho_m = M_{R_2}/M_{R_1}$, where M_{R_1} and M_{R_2} are the masses of the two resonances. In the approximation of R_1 produced at rest in the reference system of the laboratory and assuming massless P_x particles, the minimum angle between P_1 and P_2 depends only on ρ_m. The analysis here presented is focused on the case where M_{R_2} is much lighter than M_{R_1} ($\rho_m < 0.2$–0.3). Hence, R_2 is produced with large momentum and P_1 and P_2 are collimated and reconstructed as a single jet in the detector, so the final state presents only two jets: the first coming from P_3 (P_3-*jet*) and the second containing both P_1 and P_2 with mass corresponding to the R_2 resonance (R_2-*jet*). The experimental signature is a resonance peak in the distributions of both the $m_{R_2\text{-}jet}$ and the mass of the dijet system (m_{jj}).

Existing searches for dijet resonances at collider experiments (as [5]) look for bumps in the inclusive m_{jj} spectrum, so are sensitive but not optimized for this scenario. The approach described in the following exploit the jet substructure information to further suppress the QCD background compared to the dijet searches, thus improving significantly the sensitivity to new physics.

Triggers based on jet p_T are used to select events, and are fully efficient for values of m_{jj} greater than about 1.6 TeV. The events selected are required to have at least two jets with high p_T (above 100 GeV) in the central part of the detector. In order to collect the decay products of R_2, wide jets are formed using the anti-k_T algorithm [6] with distance parameter $R = 1.5$. An algorithm based on the value of the N-subjettines ratio (τ_{21}) [7] identifies R_2-*jet* as the jet with the most pronounced dipolar jet substructure. The identification of R_2-*jet* allows to disentangle the signal (characterized by one jet with

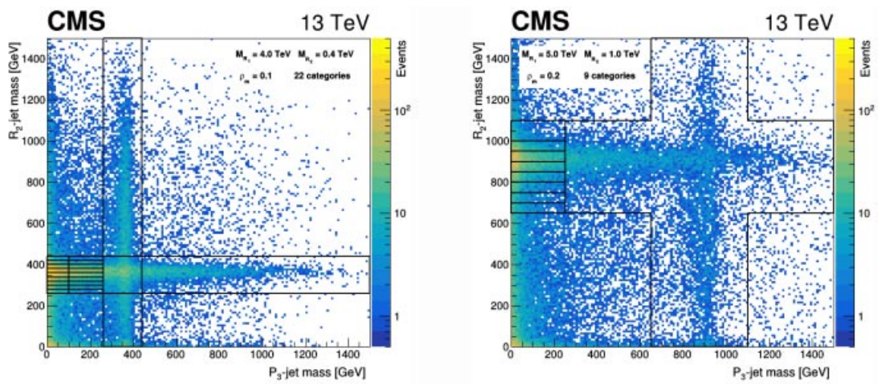

Fig. 2. – Left (Right). Simulated events in $m_{R_2\text{-}jet}$ *vs.* $m_{P_3\text{-}jet}$ plane for a signal hypothesis of $M_{G_{KK}} = M_{R_1} = 4\,\text{TeV}$ and $M_\phi = M_{R_2} = 0.4\,\text{TeV}$ ($M_{R_1} = 5$ TeV and $M_{R_2} = 1.0\,\text{TeV}$). The *cross-like* shape is approximately centered around the value of M_{R_2} for both horizontal and vertical axes. The black lines represent the 22 or 9 different categories boundaries in the two cases.

dipolar substructure) from the background of QCD multijet events. In some cases the jet substructure algorithm tags incorrectly the single jet coming from P_3 hadronization as the R_2-*jet*. Therefore, for these signal events, there is a resonance peak in the distribution of the reconstructed P_3-*jet* mass ($m_{P_3\text{-}jet}$) instead of $m_{R_2\text{-}jet}$. For this reason the scatter plot of $m_{R_2\text{-}jet}$ *vs.* $m_{P_3\text{-}jet}$, for signal events, shows a characteristic cross-like shape in the two-dimensional plane (fig. 2) centered at the value of the M_{R_2}, where the horizontal (vertical) axis of the cross represents the events with correct (incorrect) R_2-*jet* matching, while the QCD background shows a smooth pattern in the same plane.

To exploit the different pattern between signal and background, and thus improving the analysis sensitivity, events are divided in categories in the two-dimensional (2D) plane $m_{R_2\text{-}jet}$ *vs.* $m_{P_3\text{-}jet}$, as indicated by black lines in fig. 2. Following this procedure, we are able to reject events from regions outside the cross, where we expect to have a small ratio between signal (S) and background (B) events, and to divide the regions with high signal-to-background ratio (S/B) from regions with lower S/B, enhancing the analisys sensitivity to trijet signals.

The number of categories and the corresponding intervals for jet masses are optimized to reach the best sensitivity to the signal with the available statistics in data, and are different for each signal hypothesis, because the position of the signal cross-like shape in the 2D plane depends on M_{R_2}.

When testing different signal hypotheses, as the center of the "cross" formed by the categories in the $m_{R_2\text{-}jet}$ *vs.* $m_{P_3\text{-}jet}$ plane shifts to higher mass values, the m_{jj} spectrum is modified introducing turn-on effects. To mitigate this issue, a variable minimum m_{jj} threshold is applied, which depends on the mass of the signal hypothesis tested.

A simultaneous, maximum likelihood fit to the m_{jj} spectra from each category is then performed to search for a peak centered at the value of the hypotesized M_{R_1}, while the QCD background is a falling spectrum of m_{jj}. The QCD background distribution is modeled with a smooth function of m_{jj}, while the shape of the signal peak is derived from Monte Carlo (MC) simulation. The fit extracts an overall signal yield parameter in common to all categories, which is proportional to the signal cross-section. Figure 3(a) shows an example of the simultaneous background-only fit to the m_{jj} spectra for a signal hypothesis with $M_{R_1} = 3.0$ TeV and $\rho_m = 0.1$, obtained from pseudo-data from MC simulation.

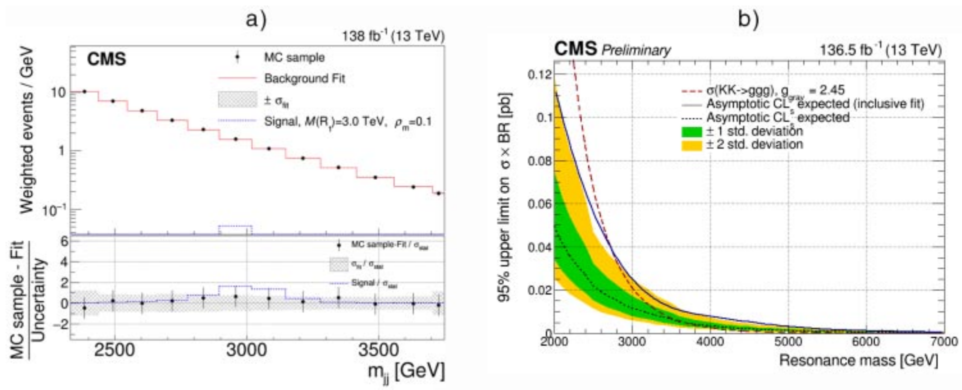

Fig. 3. – (a) Weighted sum of the m_{jj} spectra from the 22 categories for a signal with $M_{R_1} =$ 3.0 TeV and $\rho_m = 0.1$ from MC simulation. The weight of each category is equal to the $S/(S{+}B)$ value of its category. The lines represent the fitted background $\pm$ the fit uncertainty ($\sigma_{\rm fit}$) and a simulated signal sample with cross-section equal to the expected limit. The lower panel shows the difference between the data and the fit (points), the background uncertainty (hatched gray area) and the signal yield (dashed line), all divided by the stat. uncertainty ($\sigma_{\rm stat}$). (b) Expected 95% upper limit on cross-section $\sigma_{G_{KK}} \times BR(\phi + g \to 3g)[pb]$, for trijet signals with $\rho_m = 0.1$ and $M_{R_1} \in [2; 7]$ TeV, with couplings: $g_{GKK} = 3; g_{grav} = 6; g_{WKK} = 2.45; g_{AKK} = 2.7$.

4. – Results on limit cross-section

The review of this analysis is still ongoing, so it is not possible to show any result on data. In fig. 3(b) we report the expected upper limits at 95% Confidence Level (CL) on the cross-section times branching ratio. The limits are evaluated for a particular model from [2], where R_1 is a new vector boson, the Kaluza-Klein gluon (g_{KK}), R_2 is a radion (ϕ) and P_1, P_2 and P_3 are all gluons: $pp \to g_{KK} \to \varphi + g \to ggg$. These results are obtained applying the analysis on the full sample of data, for $\rho_m = 0.1$. Limits obtained by a simple inclusive fit to the m_{jj} distribution (without the event division in categories) are also represented in the plot by the solid blue line. The comparison shows that this analysis is 2–3 times more sensitive to trijet signals with respect to a standard inclusive approach.

In the final analysis, the search for new resonances will be extended to higher ρ_m values (up to 0.2–0.3), reaching an unprecedent sensitivity to trijet signals with respect to existing analyses at the LHC.

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