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Tesi di Dottorato

Search for heavy resonances decaying into a Z boson and a vector boson in the $\nu\nu\ q\bar{q}$ final state at CMS

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"I have no special talent. I am only passionately curious."
(A. Einstein)

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Abstract

Chapter 1

Introduction

This analysis searches for signal of heavy resonances decaying into a pair of heavy vector bosons. One Z boson is identified through its invisible decay ($\nu\nu$), while the other is required to decay hadronically into a pair of quarks. The final states probed by this analysis therefore consists in two quarks and two neutrinos, reconstructed as missing transverse energy (met). The hadronically decaying boson (Z, W) is reconstructed as a fat jet, whose mass is used to define the signal region. Two purity categories are exploited, based on the n-subjettines of the fat jet.

The search is performed by examining the distribution of the diboson reconstructed transverse mass of the resonance VZ (mtVZ) for a localized excess. The shape and normalization of the main background of the analysis (V+jets) are estimated with an hybrid approach using the distribution of data in the sidebands, corrected for a function accounting for potential differences between the signal region and the sidebands, while the minor background sources are taken from simulations.

Chapter 2

Theoretical motivation

The Standard Model (SM) of particles represents, so far, the best available description of the particles and their interactions. It is the summation of two gauge theories: the electroweak interaction, that pictures together the weak and electromagnetic interactions, and the strog interaction, or Quantum Chromodynamics (QCD). Particles, namely quarks and leptons, are described by spin 1/2 fermions, whilst interactions are embodied by spin 1 bosons. The simmetry group of the standard model is:

$$SU_C(3) \times SU_L(2) \times U_Y(1), \tag{2.1}$$

where the first factor is related to strong interactions, whose mediators are eight gluons, whilst $SU_L(2) \times U_Y(1)$ is the electroweak simmetry group, whose mediators are photons and Z-$W^{\pm}$ bosons.

In renormalizable theories, with no anomalies, all gauge bosons are expected to be massless, in contrast with our experimental knowledge (cite W-Z discovery). This kind of dilemma can be solved by introducing a new scalar particle, the Higgs boson (cite Higgs article), that can give mass to weak bosons and fermions via the spontaneous symmetry breaking mechanism.

In the last decades, Standard Model has been accurately probed by many experimental facilities (LEP, Tevatron), demonstrating an impressive agreement between theoretical predictions and experimental results. The discovery of the Higgs boson at the CERN Large Hadron Collider, measured by both CMS and ATLAS collaborations [1]- [2]- [3]- [4]- [5]- [6]- [7], represents not only an extraordinary confirmation of the model, but also the latest biggest achievement in particle physics as a whole.

2.1 Beyond Standard Model theories

Even though the Standard Model is the most complete picture of the universe of the particles, many questions are still left open by the model. From a phenomenological point of view, some experimental observations are not included in the theory:

- in SM, neutrinos are massless (whilst experimentally it has been confirmed to be non-zero, i.e. by the neutrino oscillation);
- no candidate for the dark matter is foreseen (whilst it has been observed in cosmology);

- no fields included in the SM can explain the cosmological inflation;
- SM can not justify the matter-antimatter asymmetry.

From a purely theoretical perspective, some issues are still relevant in the formulation of the model:

- *Flavour problem.*
The Standard Model has 18 free parameters: 9 fermionic masses; 3 angular parameters in Cabibbo-Kobayashi-Maskawa matrix, plus 1 phase parameter; electromagnetic coupling α; strong coupling α_{strong}; weak coupling α_{weak}; Z mass; the mass of the Higgs boson. Such a huge number of degrees of freedom is considered as weakly predictive.
- *Unification.*
There is not a "complete" unification of strong, weak and electromagnetic interactions, since each one has its own coupling constant, behaving differently at different energy scales; not to mention the fact that gravitational interaction, completely excluded from the SM.
- *Hierarchy problem.*
From Quantum Field Theory, it is known that perturbative corrections to the mass of the scalar bosons included in the theory tend to make it increase towards the energy scale at which the considered theory is valid [cite n. 4 of master thesis]. If the Standard Model is seen as a low-mass approximation of a more general theory valid uo to the Planck mass scale (i.e., $\approx 10^{19}$ GeV), a fine-tuning cancellation of the order of 1 over 10^{34} is needed in order to protect the Higgs mass at the electroweak scale (≈ 100 GeV). Such an astonishing correction is perceived as very unnatural.

Numerous Beyond Standard Model theories (BSM) have been proposed in order to overcome the limits of the Standard Model.

Grand Unified Theories (GUT) aim at extending the symmetry group of the SM (eq. 2) into largest candidates, such as $S0(10)$, $SU(5)$ and $E(6)$. At GUT scale, approximately at 10^{16} GeV, non-gravitational interactions are expected to be ruled by only one coupling constant, α_{GUT}.

Super Symmetryc (SUSY) models state that every fermion (boson) of the Standard Model has a bosonic (fermionic) superpartner, with exactly the same quantum numbers, except the spin. If SUSY is not broken, each couple of partners and superpartners should have the same masses, hypotesis easily excluded by the non-observation of the s-electron. Super Symmetry represents a very elegant solution of the hierarchy problem of the Higgs boson mass, since the perturbative corrections brought by new SUSY particles exactly cancel out the divergences caused by SM particles corrections. A particular sub-class of SUSY models, Minimal Super Symmetric Standard Models, is characterized by the introduction of a new symmetry, the R-parity, that guarantees the proton stability and also the stability of the lightest SUSY particle, a possible good candidate for dark matter.

Two other possible theoretical pictures are extensively described in sec. 2.2-2.3.

2.2 Heavy Vector Triplet

The heavy vector triplet model [8] provides a general framework aimed at studying new physics beyond the standard model, that can manifest into the appearance of new resonances.

The adopted approach is that of the simplified model, in which an effective Lagrangian is introduced, in order to describe the properties and interactions of new particles (in this case, a triplet of spin-1 bosons) by using a limited set of parameters, that can be easily linked to the physical observables at the LHC experiments. These parameters can describe many physical motivated theories (such as sequential extensions of the SM [9]- [10] or Composite Higgs [11]- [12]).

Since a simplified model is not a complete theory, its validity is restricted to the on-shell quantities related to the production and decay mechanisms of new resonances, that is the case of most of the LHC BSM searches are performed. Given these conditions, experimental results in the resonant region are sensitive to a limited number of the phenomenological Lagrangian parameters (or to a combination of those), whilst the remaining parameters tend to influence the tail of the distributions.

Limits on production cross-section times branching ratio ($\sigma\mathcal{B}$), as a function of the invariant mass spectrum of the probed resonance, can be extracted from experimental data. Given that $\sigma\mathcal{B}$ are functions of the simplified model parameters and of the parton luminosities, it is then possible to interpret the observed limits in the parameter space.

The heavy vector triplet framework assumes the existence of an additional vector triplet, V_μ^a, $a = 1, 2, 3$, in which two spin-1 particles are charged and one is neutral:

$$V_\mu^\pm = \frac{V_\mu^1 \mp i V_\mu^2}{\sqrt{2}}; \; V_\mu^0 = V_\mu^3. \tag{2.2}$$

The triplet interactions are described by a simplified Lagrangian, that is invariant under SM gauge and CP symmetry, and accidentally invariant under the custodial symmetry $SU(2)_L \times SU(2)_R$:

$$\begin{aligned}\mathcal{L}_\mathcal{V} = &-\frac{1}{4}\left(D_\mu V_\nu^a - D_\nu V_\mu^a\right)\left(D^\mu V^{\nu\, a} - D^\nu V^{\mu\, a}\right) + \frac{m_V^2}{2} V_\mu^a V^{\mu\, a} \\ &+ i g_V c_H V_\mu^a \left(H^\dagger \tau^a D^\mu H - D^\mu H^\dagger \tau^a H\right) + \frac{g^2}{g_V} c_F V_\mu^a \sum_f \bar{f}_L \gamma^\mu \tau^a f_L \\ &+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} V_\mu^a V_\nu^b \left(D^\mu V^{\nu\, c} - D^\nu V^{\mu\, c}\right) + g_v^2 c_{VVHH} V_\mu^a V^{\mu\, a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\, a} V_\mu^b V_\nu^c.\end{aligned} \tag{2.3}$$

In the first line of the formula 2.3, V mass and kinematic terms are included, described with the covariant derivative $D_\mu V_\nu^a = \partial_\mu V_\nu^a + g\epsilon^{abc} W_\mu^b V_\nu^c$, where W_μ^a are the fields of the weak interaction and g is the weak gauge coupling.

The second line describes the interaction of the triplet with the Higgs field and the SM left-handed fermions; c_H describes the vertices with the physical Higgs and the three unphysical Goldstone bosons that, for the Goldstone equivalence theorem, are connected to the longitudinal polarization of W and Z bosons at high-energy; hence, c_H is related to the bosonic decays of the resonances. c_F is the analogous parameter describing the V interaction with fermions, that can be generalized as a flavour dependent coefficent, once defined $J_F^{\mu\, a} = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$: $c_F V_\mu^a J_F^{\mu\, a} = c_\ell V_\mu^a J_\ell^{\mu\, a} + c_q V_\mu^a J_q^{\mu\, a} + c_3 V_\mu^a J_3^{\mu\, a}$.

CHE COSA C'ENTRA IL GOLDSTONE BOSON EQUIVALENCE THEOREM CON LE W-Z AD ALTA ENERGIA? APPROFONDISCI

The last part of the equation does not describe vertices of V with SM fields, hence it can be neglected while describing the LHC phenomenology, under the assumptions previously made (**NEXT SECTION...**), along with dimension four quadrilinear *V* interactions, otherwise their effects would be appreciated in electroweak precision tests and precise Higgs coupling measurements.

In Eq. (2.2) we adopted a rather peculiar parametrization of the interaction terms, with a coupling g V weighting extra insertions of V , of H and of the fermionic fields. Similarly, the insertions of W in the last line is weighted by the SU (2) L coupling g. We take g V to represent the typical strength of V interactions while the dimensionless coefficients âĂIJcâĂİ parametrize the departures from the typical size. The parametrization of the fermion couplings is an exception to this rule. In this case one extra factor of g 2 /g V 2 has been introduced. This is convenient because in all the explicit models we will be interested in, both of weakly- and strongly-coupled origin, this factor is indeed present and the c F âĂŹs, as defined in Eq. (2.2), are of order one. The other câĂŹs are typically of order one, except for c H which is of order one in the strongly-coupled scenario but can be reduced in the weakly coupled case as described in Section 4. In all cases, the câĂŹs are never parametrically larger than one, with the notable exception of the third family coupling c 3 , which could be enhanced in strongly-coupled scenarios where the top quark mass is realized by the mechanism of Partial Compositeness, see for instance [71]. The coupling g V can easily vary over one order of magnitude in different scenarios, ranging from g V âĹij g âĹij 1 in the âĂIJtypicalâĂİ weakly-coupled case up to g V ′ 4ÏĂ in the extreme strong limit. Therefore it is useful to factor it out of the operator estimate. Notice that there is no sharp separation between the weak and strong coupling regimes as nothing forbids to consider theories with a âĂIJweakâĂİ UV origin but with large g V , of the order of a few, and âĂIJstrongâĂİ models where g V is reduced by the large number of colors of the strong sector, g V = 4ÏĂ/ N c . This provides one additional motivation for our approach which interpolates between the two cases.

the simple but well-motivated example of electroweak-charged spin one resonances which are a common prediction of many New Physics scenarios. The latter can be weakly coupled, like for instance Z 0 [6, 17âĂŞ27] or W 0 [7, 8, 10, 11, 28âĂŞ32] models, or strongly coupled constructions such as Composite Higgs models [33âĂŞ39] and some variants of Technicolor [40âĂŞ48].

2.2.1 Model A

2.2.2 Model B

2.3 Warped extra dimension

Chapter 3

Data and Monte Carlo samples

Chapter 4

Physics objects

Chapter 5

Diboson candidate reconstruction

Chapter 6

Background estimation

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Chapter 8

Results

Chapter 9

Conclusions

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