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Search for new physics in dielectron final states at CMS

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Abstract

This thesis describes searches for new massive resonances that decay in an electron-positron or photon pair in the final state. Different datasets, coming from proton-proton collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV at the Large Hadron Collider (LHC) and collected by the CMS experiment in 2015 and 2016, have been analyzed. After a chapter devoted to the description of the standard model of elementary particle physics, the motivation for the introduction of new theories that go beyond the standard model are introduced and some classes of models are described. The techniques used in order to reconstruct the particles produced in the collisions are discussed afterwards, with a special emphasis on electron/positron and photon reconstructions. Two separate analyses are presented.

The first one is the search for new heavy resonances decaying in an electron-positron pair in the final state. Such resonances are predicted by a variety of models such as grand unified theories or theories that introduce extra space-like dimensions. Their signature would appear as a localised excess of events in the electron-positron invariant mass spectrum. The event selection is optimized in order to be highly efficient for high-energy electrons/positrons and to avoid loosing potential signal events. The analysis relies on simulated samples for the estimation of the main source of background, which is the standard model Drell-Yan process. Data-driven approaches are pursued for both validating the simulation of the subleading background processes with prompt electrons in the final state and the determination of the background coming from processes of quantum chromo dynamics. After having inspected the electron-positron invariant mass, no excess over the standard model expectation is observed, and 95% confidence level upper limits are set on the ratio of production cross-section times branching ratio of a new resonance to the one at the Z boson peak, using the data collected in 2016 (35.9 fb^{-1}).

The second analysis presented in this thesis is the search for new heavy resonances decaying in the diphoton final state, the existence of which is predicted by models with non-minimal scalar sectors or by theories postulating the existence of additional space-like dimensions. Their signature would appear as a localised excess of events in the diphoton invariant mass spectrum. As for the case of the dielectron analysis, the event selection has been optimized in order to be highly efficient for high-energy photons. The background estimation is completely data-driven and achieved via a parametrization of the observed diphoton invariant mass spectrum. After the inspection of the diphoton invariant mass, no excess over the standard model expectation is observed, and 95% confidence level upper limits are set on the production cross-section times branching ratio, using the data collected in the first half of 2016 (12.9 fb^{-1}). Results have also been combined with those obtained with the same analysis techniques but with different datasets collected in 2012 and 2015 by the CMS experiment.

Résumé

Cette thèse décrit les recherches de nouvelles résonances massives se décomposant en une paire électron-positron ou une paire de photons dans l'état final. Différents ensembles de données, provenant des collisions proton-proton à une énergie dans le centre de masse $\sqrt{s} = 13$ TeV au Large Hadron Collider (LHC) et enregistrés par l'expérience CMS en 2015 et 2016, ont été analysés. Après un chapitre consacré à la description du modèle standard de la physique des particules élémentaires, les motivations pour postuler de nouvelles théories qui dépassent le modèle standard sont introduites et certaines classes de modèles sont décrites. Les techniques utilisées pour reconstituer les particules produites dans les collisions sont discutées ensuite, avec un accent particulier sur la reconstruction des électrons/positrons et des photons. Deux analyses séparées sont présentées.

La première est la recherche d'une nouvelle résonance massive se désintégrant en une paire électron-positron dans l'état final. De telles résonances sont prédites par une variété de modèles tels que les théories de grande unification ou les théories introduisant des dimensions supplémentaires. Leur signature apparaîtrait comme un excès localisé d'événements dans le spectre de masse invariante des paires électron-positron. La sélection des événements est optimisée pour être très efficace pour les électrons/-positron à haute énergie et éviter de perdre des événements de signal potentiels. L'analyse repose sur des échantillons simulés pour l'estimation de la principale source de bruit de fond, qui est le processus Drell-Yan du modèle standard. Des approches basées sur les données sont poursuivies pour la validation de la simulation du bruit de fond avec des électrons/positrons produits dans l'état final et pour la détermination du bruit de fond provenant de processus de *quantum chromodynamics*. Après avoir inspecté la distribution de masse invariante des paires électron-positron, aucun excès sur la prédiction du modèle standard n'est observée, et des limites supérieures à 95% de niveau de confiance sont placées sur le rapport entre la section efficace de production multipliée par le rapport de branchement d'une nouvelle résonance et cette même quantité au pic du boson Z, avec les données prises en 2016 (35.9 fb^{-1}).

La deuxième analyse présentée dans cette thèse est la recherche d'une nouvelle résonance lourde se désintégrant en une paire de photons dans l'état final, dont l'existence est prédite par des modèles avec des secteurs scalaires non minimaux ou par des théories qui postulent l'existence de dimensions spatiales supplémentaires. Leur signature apparaîtrait comme un excès localisé d'événements dans le spectre de masse invariante des paires de photons. La sélection des événements a été optimisée afin d'être très efficace pour les photons à haute énergie et d'éviter la perte de signaux potentiels. L'estimation du bruit de fond est entièrement basée sur les données et réalisée avec une paramétrisation du spectre de masse invariante observé. Après l'inspection de la masse invariante des paires de photons, aucun excès par rapport à la prédiction du modèle standard n'est observé, et des limites supérieures à 95% de niveau de confiance sont placées sur la section efficace de production multipliée par le rapport de branchement d'une nouvelle résonance, avec les données prises jusqu'à Juillet 2016 (12.9 fb^{-1}). Les résultats ont également été combinés avec ceux obtenus par les mêmes techniques d'analyse, mais avec des ensembles de données différents enregistrées par l'expérience CMS en 2012 et 2015.

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Introduction

Where are we come from ? Does university has boundary ? What are the basic elements which construct our university ? From time to time these questions will come to my mind and make me lost in the thought, maybe also the same for you. What a lucky thing for me is I choosed the particle physics expreiment as my PhD research subject. The aim of particle physics experiment is to find the basic particles which formed the matter world, studying their properties and their interaction mechanism (or put it simply how they make the world).

There are a lot particle physics experiments over the world and can mostly be categorized in three kinds by the way of the studied particles come from. First one are the cosmic rays experiments which stduy the particles come from the universe. The advantages of this kind of experiments are easy to make the detector and cheap in the cost, while the disadvantages includes the very low count rate for very high energy particles and can only detect the long lifetime or stable particles like $e^{\pm}$, γ, $\pi^{\pm}$ and so on. For unstable or short lifetime particles it can do nonthing.

Second one are the nulcear reaction experiments which mostly study the properties of neutrino, because when the fission happens a lot of neutron will be produced and one neutron can decays to one proton, one electron and one anti-neutrino. Therefore the reactor can produce abundant neutrinos which has precise producing time and position and known to be electron anti-neutrion, therefore it can be use for studying the neutrion oscillation phenomenon. The advantage for this kind experiment is the low cost because the stable neutrino beam is the by-products of reactor and it is free. The disadvantage is it can only study the neutrino.

Third one are the collider experiments which make the collision between two accelerated high energy particles and detect the particles from the collision. The collided particles are most the electron, positron, proton and anti-proton because they are stable and easy to be accelerated. The advantages of this kind of experiment are high luminosity (means high statistic), the collision energy can be control and a lot of particles can be studyed including very short lifetime particles. For the disadvantages it includes high cost which comes from building the long accelerated tunnel and to accelerate particles and making a complicated detector which used to reconstruct the whole collision event.

What I joined is CMS experiment in LHC which is the proton proton collision experiment

Chapitre 1

The theory

This chapter introduces the standard model (SM) of particle physics which describes the family of elementary particles and their interactions.

1.1 The standard model of particle physics

1.1.1 The elementary particles

It has been long time for people try to understand what is the basic object which constitutes our world. From Demokritos (470-380 BC) who thought matter was built of discrete building blocks to John Dalton (1766-1844) who came up with the matter was made of atoms. In the early 1900's J.J. Thomson proposed a so called "plum pudding model" which assume the atom was a uniform sphere of positively charged matter in which electrons were embedded. However in 1910 Ernest Rutherford and his colleagues performed α rays scattering experiments and found that the whole mass and all positive charge of the atom were concentrated in a minute space at the centre which is called "nucleus". After the discovery of the neutron in 1932 by James Chadwick, models for a nucleus composed of protons and neutrons were quickly developed by Dmitri Ivanenko and Werner Heisenberg. Furthermore in 1968 the deep inelastic scattering experiments at the Stanford Linear Accelerator Center provided the first convincing evidence of the reality of quarks in the proton or neutron. In the standard model (SM) the quarks are the elementary particles and there are six different kinds of flavors for the quarks called up (u), down (d), charm (c), strange (s), top (t) and bottom (b), the mass, charge and spin of the quarks are shown in table 1.1, here the e means one electron's charge which equal 1.6×10^{-19}C. The quarks are categorized in there generations which will be discussed in section 1.1.2.3. Besides the quarks have another property which is called the "color charge", a quark can be "Red" or "Blue" or "Green". The reason for there are only three kinds of color charges will be discussed in section 1.1.2.3. Moreover all the quarks have its anti-quark which has opposite quantum number with regard to quark including flavor, charge and color charge quantum number. Therefore there are 6 (flavor) $\times$ 3 (color) $\times$ $2(\mathrm{anti-quark}) = 36$ kinds of quarks in the SM and all the hadrons are composed by quarks or anti-quarks, for meson it is composed by $\mathrm{q\bar{q}}$ and for baryon it is composed by qqq or $\mathrm{\bar{q}\bar{q}\bar{q}}$.

Similar with quark family there are a lepton family, the most common one is electron which exists as a cloud out of nucleus to form an atom. All the leptons are shown in table 1.2 with their charge, spin and mass, they are electron (e), electron neutrino (ν_e), muon (μ), muon neutrino (ν_μ), tau (τ) and tau neutrino (ν_τ). The leptons are also categorized into three generations and each generation has its own lepton flavor. First generation are electron flavor leptons, second generation are muon flavor leptons and third generation

Generation	Quark	Charge	Spin	Mass
First	up quark (u)	2/3 e	1/2	$2.3^{+0.7}_{-0.5}$ MeV
	down quark (d)	-1/3 e	1/2	$4.8^{+0.5}_{-0.3}$ MeV
Second	charm quark (c)	2/3 e	1/2	1.275 ± 0.025 GeV
	strange quark (s)	-1/3 e	1/2	95 ± 5 MeV
Third	top quark (t)	2/3 e	1/2	$173.21 \pm 0.51 \pm 0.71$ GeV
	bottom quark (b)	-1/3 e	1/2	4.66 ± 0.03 GeV

TABLE 1.1 – Quarks and their properties [1].

are tau flavor leptons. The reason for neutrinos have non-zero mass is because of the observation of neutrino's oscillations otherwise in SM the mass of neutrinos are zero. Similar with the quarks, all the leptons also have theirs anti-particle partners which own the opposite quantum number. While unlike the quarks, the leptons do not have color charge property. Therefore there are $6 \times 2 = 12$ kinds of leptons in SM.

Now the all the spin 1/2 (fermion) elementary particles in SM are introudced, in section 1.1.2 the interactions between these particles and the mediators will be discussed.

Generation	Lepton	Charge	Spin	Mass
First	electron (e)	-e	1/2	511 MeV
	electron neutrino (ν_{e})	0	1/2	< 2 eV
Second	muon (μ)	-e	1/2	105.67 MeV
	muon neutrino (ν_μ)	0	1/2	< 2 eV
Third	tau (τ)	-e	1/2	1776.99 MeV
	tau neutrino (ν_τ)	0	1/2	< 2 eV

TABLE 1.2 – Properties of the leptons in the three generations. Neutrinos are assumed to have zero mass in SM but by the observation of neutrino's oscillations the upper limits on their mass are set[1].

1.1.2 The fundamental interactions

It is well known there are four characteristic interactions among fundamental particles.

1. Electromagnetic interaction : it is mediated by massless photon ($\mathrm{m}_\gamma = 0$) with spin $= 1$ among charged particles. The theory to describe the electromagnetic interaction is quantum electrodynamics (QED) which is well understood. Because of the massless of photon the interacting range is infinite. QED is renormalizable for example the divergence from vacuum polarization and higher order loop contributions can be absorbed in to the physical charge of particle. The coupling constant is $\alpha = \frac{\mathrm{e}^2}{4\pi\varepsilon_0\hbar c} \simeq \frac{1}{137}$ which characterizes the strength of the coupling of charged particle with the electromagnetic field. Because of smallness of α the perturbation works well for QED. Besides we α is dependent will the energy scale of interaction but the difference is very small for wide energy scale.
2. Weak interaction : it is mediated by massive weak bosons ($\mathrm{m}_{\mathrm{W}^\pm} \cong 80.4$ GeV/c^2, $\mathrm{m}_{\mathrm{Z}} \cong 91.2$ GeV/c^2) with spin $= 1$ among quarks and leptons.
3. Strong interaction : it is mediated by massless gluons ($\mathrm{m}_{\mathrm{g}} = 0$) with spin $= 1$ among the quarks.
4. Gravitational interaction : it is mediated by massless gravitons ($\mathrm{m}_{\mathrm{G}} = 0$) with spin $= 2$ among all massive particles.

Interaction	Range	Relative strength	Mediators
Strong	10^{-15} m	1	8 gluons (g)
Electromagnetic	∞	10^{-3}	photon (γ)
Weak	10^{-18} m	10^{-14}	W^+, W^-, Z
Gravitational	∞	10^{-43}	graviton (G) ?

TABLE 1.3 – Range, relative strength with respect to the strong force, and mediators of the four fundamental interactions. The gravitational force is not included in the SM, and gravitons are hypothetical particles.

1.1.2.1 The electromagnetic interactions

1.1.2.2 The weak interactions

1.1.2.3 The strong interactions

1.1.3 The symmetries and the gauge theory

1.1.4 The effective fermi theory

1.1.5 The Drell-Yan process

1.1.6 The shortcomings of standard model of particle physics

1.2 The beyond standard model of particle physics

1.2.1 The unified ground theory

1.2.2 The super symmetry theory

Bibliography

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