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Search for exotic hadrons with the CMS experiment

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Summary. — Tetraquarks are exotic hadrons made of four quarks whose existence is predicted by Quantum Chromodynamics. Tetraquarks have been observed by several experiments, like BaBar and LHCb. However, their internal structure is not fully understood, and more experimental observations are needed. This analysis extends, for the first time, the search for tetraquarks made of four bottom quarks in final state $2\mu 2e$ ($X(bb\bar{b}\bar{b}) \to \Upsilon\Upsilon \to \mu^+\mu^-e^+e^-$), exploiting data collected in 2018 by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). They correspond to an integrated luminosity of 59.97 fb^{-1} for proton-proton collisions with a center of mass energy of $\sqrt{s} = 13\,\text{TeV}$. The main physical observable is the *di*-Υ invariant mass spectrum of the $2\mu 2e$ system whose signal distribution is expected to peak near the tetraquark mass. Results of this analysis are presented as expected limit on the process cross section as a function of tetraquark mass in the range between 17–30 GeV.

1. – Exotic hadrons and tetraquarks

According to the quark model, which classifies hadrons in terms of their valence quarks, hadrons are: mesons, quark-antiquark bound states ($q\bar{q}$), or baryons, three quarks bound states (qqq). However, the theory of strong interactions (QCD) allows the existence of more complex states called exotic hadrons, like tetraquarks ($qq\bar{q}\bar{q}$) and pentaquarks ($qqq\bar{q}\bar{q}$). The internal structure of exotic hadrons is not yet well understood, and several theoretical models have been developed to describe the structure of exotic states [1]. These models can be classified into two families, based on how quarks are related to each other within the state. According to the considered model, multiquark states can be extended objects (∼fm), like molecules of hadrons, or closely bound states, almost point-like objects (diquark model). This characteristic is due to the different binding energy between the constituents of the state. Thanks to the difference in binding energy, which is greater in the diquark models than in the molecule models, it is possible to use experimental measurements to understand the structure of exotic hadrons. The first observation of a tetraquark (TQ) happened at Belle experiment in 2003. It was labelled as $X(3874)$ and observed in final state $\pi^+\pi^- J/\Psi$ [2]. Since then, many other new states compatible with bound states of four or five quarks have been observed by different experiments, as BaBar [3, 4] and LHCb [5, 6]. In particular, in 2020 the LHCb experiment discovered the first state made of four charm quarks: $X(6900)$ [7]. This TQ has been observed as a peak in the *di*-J/Ψ invariant mass spectrum in four muons final state ($X(cc\bar{c}\bar{c}) \to J/\Psi J/\Psi \to \mu^+\mu^-\mu^+\mu^-$). The CMS experiment is investigating this sector too by searching for TQ bound states of four charm quarks or four bottom quarks in four muons final state ($X(cc\bar{c}\bar{c}) \to J/\Psi J/\Psi \to \mu^+\mu^-\mu^+\mu^-$, $X(bb\bar{b}\bar{b}) \to \Upsilon\Upsilon \to \mu^+\mu^-\mu^+\mu^-$). These searches have not shown any evidence of signal so far. Exotic hadrons observations are important from a phenomenological point of view, because the discovery of new particles would complete the picture of hadrons in nature. Moreover, the observation of new hadronic states give information about hadrons structure and strong interactions characteristics at low energy.

2. – Analysis strategy

The analysis carried on, in the context of my master thesis, with data collected by the CMS experiment in 2018 ($59.97\,\text{fb}^{-1}$) is presented. The purpose is the search for a bump in the *di*-Υ invariant mass spectrum corresponding to a TQ state made of four bottom quarks ($X(bb\bar{b}\bar{b})$). For the first time, the two muons and two electrons final state is explored (see fig. 1).

The study of this final state integrates the measure of the four muons final state and gives the great opportunity to test and use many of the recently developed tools provided by CMS to reconstruct and identify electrons at very low transverse momentum ($p_T < 5\,\text{GeV}$). As shown by the generator level Monte Carlo (MC) distribution, in fig. 2 (left), the searched process is characterized by low p_T electrons in the final state. Thanks to the reconstruction efficiency (fig. 2 (right)) of the new CMS reconstruction algorithm (*Low*-p_T) it has been possible to recover about 40% of Υ decaying in electrons. These particles would have been lost with the standard CMS reconstruction algorithm (*Particle Flow*).

The analysis strategy is based on the TQ invariant mass (m_X) reconstruction starting from final state leptons ($2\mu 2e$), done after the reconstruction of individual Υ and an accurate selection for the signal region. By using the selected events, the TQ invariant mass distribution is obtained for each signal MC sample and fitted using a Breit-Wigner convoluted with a Crystal Ball. A parametric signal model is extrapolated for different TQ signal masses in the range between 17–30 GeV (fig. 4 (left)). This model allows obtaining the shape and the efficiency of the signal for any value of TQ mass from the fit of the signal parameters, even if no MC samples have been generated for that value.

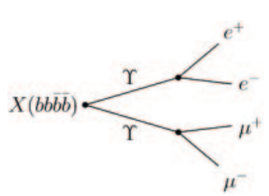

Fig. 1. – Diagram of the studied process: $X(bb\bar{b}\bar{b}) \to \Upsilon\Upsilon \to \mu^+\mu^-e^+e^-$.

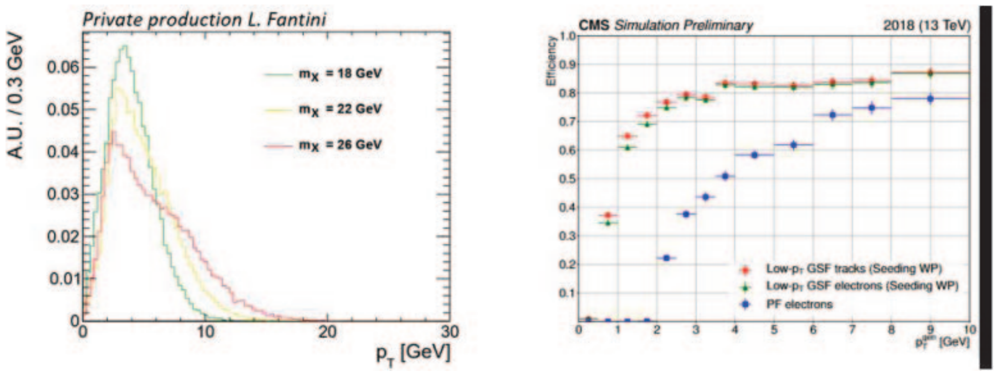

Fig. 2. – Left: electrons transverse momentum (p_T) distribution for generated MC events, corresponding to three different values of the TQ candidate mass hypothesis (m_X). Right [8]: efficiency of electrons reconstruction algorithms. Comparison between *Particle Flow* (blue) and *Low-*p_T (green) reconstruction for electrons. In red the *Low-*p_T reconstruction efficiency for generic tracks.

Thanks to this strategy, the analysis can be extended to the search of any resonance that decays in two Υ in the range of mass 17–30 GeV. Backgrounds are estimated from MC simulations (irreducible background from Single Parton Scattering (SPS) and Double Parton Scattering (DPS), fig. 3) and from a control region (CR) in data (reducible combinatorial background).

The control region is chosen by requiring high statistic, low signal contamination and good compatibility with the signal region, the latter is verified by comparing plots shapes and with statistical tests. Invariant mass distributions of all the backgrounds are independently fitted. Thus, they are included in the signal+backgrounds model used for the fit to data (fig. 4 (right)), except for DPS (negligible).

3. – Results and future perspectives

By using the signal+backgrounds model (fig. 4 (right)) a fit is performed to signal region data. This fit is performed by blinding the region in which the TQ mass is expected by theory (16–21 GeV), in order to avoid any prejudice. The fit model has been tested by performing a bias test of the model signal + CR. The obtained bias is negligible with respect to the considered systematic uncertainties. The latest result of the analysis is the expected upper limit on cross section multiplied by the branching ratio of the search process, as a function of the TQ mass. This limit evaluates the analysis sensitivity

Fig. 3. – Υ production diagrams for SPS (left) and DPS (right) irreducible backgrounds.

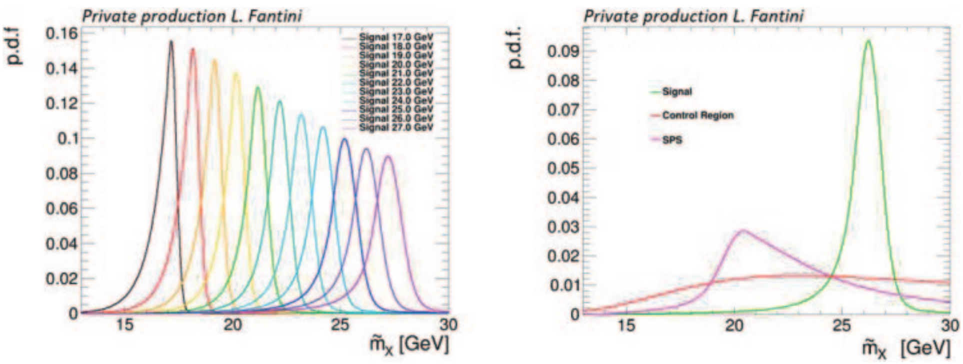

Fig. 4. – Left: signals distributions in the mass range 17–30 GeV obtained from the parametric model. Right: TQ candidate invariant mass ($\tilde{m}_X$) distributions for signal (26 GeV), CR and SPS obtained from single fits. Distributions are normalized to 1.

and shows if the experiment can exclude the signal for each nominal mass value in the studied range (17–30 GeV). This limit is obtained with the CLs method [9], a modified frequentist statistical method. The limit shows that the experiment is more sensitive to higher values of TQ mass. After the signal region unblinding, the observed limit may be computed and conclusion on the exclusion capability of the experiment may be derived.

The described analysis is a preliminary study of the $2\mu 2e$ final state at LHC. It can be completed and further developed both in Run 2 and in the next phases of LHC. The analysis can be extended by using all Run 2 data (137.6 fb^{-1}), thus also the 2016 and 2017 data. For the next Run of LHC (2022) a dedicated High Level Trigger can be developed. The trigger is the event selection step that most affects the signal efficiency, by requiring pairs of muons with $p_T > 12\,\text{GeV}$ in the event. Thus, the goal is developing a trigger with a lower p_T threshold. Moreover, the analysis can be extended to the search of TQ made of four charm quarks in the $2\mu 2e$ final state. Finally, a long-term development can be the *Mip Timing Detector* (MTD) [10] contribution in the High Luminosity Phase of LHC (2026). Thanks to the time of flight measurement provided by MTD, the impact of multiple collisions per event will be mitigated and the low-p_T leptons reconstruction improved.

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