Discovering True Muoniums on CMS

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Abstract

The primary focus is on meticulous data analysis of data retrieved from the CMS detector server. A series of cut flows are implemented to eliminate impurity data and refine the dataset. The culmination of these procedures results in a graph emphasizing the balance variable 'B,' revealing a remarkable symmetry concerning the y-axis. Complementing the data analysis is the creation of a Toy Monte Carlo simulation. This innovative method aims to replicate the experimental signal. Considering uncertainties in experimental data, the kinetic energy in the dimuon rest frame is systematically smeared. Additionally, the momenta of outgoing particles are subjected to variation, adhering to a normal distribution—a process termed the "experimental effect." The simulated balance spectrum is then meticulously compared with the experimental counterpart. This comparative analysis serves as the litmus test for the presence of True Muonium signals. The outcome of this project bears implications for the understanding of True Muoniums and contributes to the broader discourse in particle physics. The combination of advanced data analysis and simulation techniques enhances our ability to discern the subtleties of particle interactions, offering valuable insights into the fundamental nature of the universe.

Keywords: CMS; atomic effect; momentum smearing; Toy Monte Carlo; balance variable

1. INTRODUCTION

Electromagnetic (EM) interactions between oppositely charged particles form bound states; the most well-known are the atoms. Similar atom-like bound states of elementary particles have since been discussed, including the physical properties of positronium (a bound state of e^+e^-) theoretically [1 and 2] and its observation [3], which occurred in the same era. The prediction for muoniums (bound state of μe) was released [4] in the 1950s, and the state was discovered soon after that experimentally [5].

However, the remaining heavier QED bound states that have not yet been experimentally observed can provide unique probes that are sensitive beyond the standard model (BSM) physics. In particular, the hypothesized bound state known as true muoniums ($\mu^+\mu^-$) [6, 7] has yet to be discovered. Based on this, many phenomenological and experimental works have been conducted. A well-known insight into true muoniums was carried out in Ref. [8]. In their work, the generation of the true muonium mechanisms $e^+e^- \to (\mu^+\mu^-)$ and $e^+e^- \to \gamma(\mu^+\mu^-)$ are investigated. Given the calculation of their cross-sections, which are

$$\sigma_{e^+e^-\to(\mu^+\mu^-)} = \frac{2\pi\alpha^2\beta}{s}\left(1-\frac{\beta^2}{3}\right)S(\beta) \tag{1}$$

and

$$\sigma_{e^+e^-\to\gamma(\mu^+\mu^-)} = \frac{\pi}{2}\left[\ln\left(\frac{1+c_0}{1-c_0}\right)-c_0\right]\frac{\alpha^6}{s} \tag{2}$$

where $c_0 = \pm1$ and β is the velocity of either of the $\mu^\pm$ is the center-of-mass frame and $s \approx 2m_\mu$ is the energy in the center-of-mass frame needed to produce true muoniums as well as the SSS threshold Columb resummation factor [9, 10]

$$S(\beta) = \frac{X(\beta)}{1-\exp[X(\beta)]} \tag{3}$$

wherein

$$X(\beta) = \pi\alpha\sqrt{1-\beta^2}/\beta, \tag{4}$$

It is suggested that an experiment considering the collisions of electrons to generate true muoniums should be performed.

Besides the methodology of electron collisions, another proposal using the decay of η mesons is well developed in Ref. [11]. The first stage of the reaction involves an η meson decaying into true muoniums and photons: $\eta \to \gamma(\mu^+\mu^-)$ whose signal is comparable to dark photons [12], which is capable of being detected at LHCb. The second stage is focused on the electronic decays of the true muoniums, i.e. $(\mu^+\mu^-) \to e^+e^-$, and it is believed that true muoniums can be discovered at a cross-section of 15 fb with a signal significance larger than 5 when the final state reconstruction efficiency $\varepsilon_f > 20\%(12\%)$ for the $e^+e^-(e^+e^-\gamma)$ final state.

In our work, we lay our interests on the experiments at CMS detectors [13] of recent data, which is relevant to both the trajectories and momenta because of its high adaptability on muon detects. Based on that, we established a sequence of selection criteria (named "cut flow") to filtrate and purify the muon signals. We also released a toy Monte Carlo model to examine whether the experimental data performs as the theoreticians and phenomenologists ever expected.

The structure of this paper is arranged as follows: in section II, we simulate a decay model of η mesons and analogs using the Monte Carlo method; in section III, we turn to handle the experimental data of ROOTS [14, 15] to illustrate the behaviors of the signals of muons in the hadron collider CMS. In the last section, we give a summary and conclusion on our research as well as further work to do on this topic.

2. MONTE CARLO SIMULATION

At the very beginning, consider a η meson decays into a proton and a pair of muons, which forms the bound state of true muoniums:

$$\eta \to \gamma(\mu^+\mu^-) \tag{5}$$

where the mass of eta mesons $m_\eta \approx 0.547$GeV [16]. As in the ordinary two-body decay process

$$M \to m_1 + m_2, \tag{6}$$

in the rest frame of M, it is given from the relativity theory that the output three-dimensional momenta reads

$$|p_1| = |p_2| = \frac{\sqrt{\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)}}{2M} \tag{7}$$

By that, the momentum of the true muonium can be calculated as

$$p = \frac{m_\eta^2 - m_{TM}^2}{2m_\eta}, \tag{8}$$

where the mass of true muonium m_{TM} is the combination of the masses of two single muons minus the bounding energy between them [11]

$$m_{\mathrm{TM}} = 2m_\mu - B_{\mathrm{E}} \approx 0.211\mathrm{GeV}. \tag{9}$$

Now, suppose the input momentum of η meson is given by applying the Lorentz boost between the lab and η rest frames. In that case, we can ultimately get the final kinetics information of true muoniums in the rest frame.

The next stage is the decay of the true muoniums into two separate muon particles. However, since in Eq. (9), the mass of the true muonium in its bound state is less than the sum of masses of two muons, the reaction is kinetically forbidden in a vacuum environment. However, in reality, the true muoniums will
collide with the atoms of the beam pipe and detector on the surface, leading to extra energy given to them to push forward the dissociation of true muoniums [17, 18], which is called the atomic effect.

A. Atomic Effect

Owing that both the scale of true muoniums and atomic nuclei are relatively small, we assume that the energy interchange between them is not an evident effect, making the dissociation of the true muoniums just a little above the lower bound take place.

In that case, we assume that after the interaction of true muoniums with other atoms, it carries kinetic energy in an equivalent scale of the bounding energy in the true muonium rest frame

$$T = B_{\mathrm{E}} = 1.41\mathrm{keV} \tag{10}$$

and then dissociates into two muon leptons, which is

$$(\mu^+\mu^-) \to \mu^+\mu^-. \tag{11}$$

Such extra energy plays a role in adding the effective mass of true muoniums, i.e.,

$$m\text{effective}TM = mTM + T, \tag{12}$$

letting what is ample for muon dissociation, which results in both muons having a momentum of

$$\left|p'_+\right| = \left|p'_-\right| = \sqrt{\frac{\left(m_{TM} + T\right)^2}{4} - m_\mu^2}\ . \tag{13}$$

B. Experimental Effect

What we are concerned about most is the static variables and characteristics of the relation of motion of two muons, from which we can reconstruct the behaviors of true muoniums and determine their existence.

Since it is too idealistic and even sometimes na¨ıve to hypostasize to get an exact number for experiment measurement, we need to transform certificate numbers to random variables that follow a certain distribution, namely smearing. The most commonly used terms are Gaussian distributions, and we suppose that the output momenta of muons in the rest frame are normally distributed, with whose mean value is the momentum being boosted from the true muonium rest frame to η rest frame and then to the lab frame and the standard deviation is one present of that mean.

The quantity, namely the balance variable, defined as

$$B \equiv \frac{|p_+| - |p_-|}{p_{\mathrm{avg}}} \tag{14}$$

where

$$p_{\mathrm{avg}} = \frac{\left|p^+\right| + \left|p^-\right|}{2} \tag{15}$$

the average value of the outgoing muons in the lab frame describes the degree of muons being taken apart from each other.

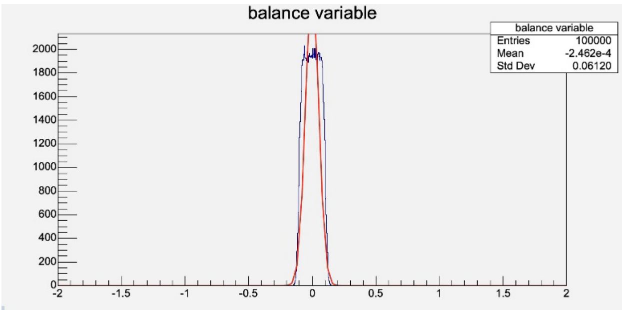

FIG. 1. The frequency of the balance variable simulated. The blue line represents the data output, and the red line represents the fitting line. The horizontal line is the value of the balance variable, while the virtual line is the number of events of a particular balance variable.

In our simulation, as shown in FIG. 1, we expect it to lie beside the zero and be symmetric with the vertical axis.

3. EXPERIMENTAL DATA

The experimental data we are dealing with is a mixture of many factors and indicators, aligning with many possible effects that may occur simultaneously along with the reactions we are considering. Given the above, we should cut off the useless data unrelated to what we do not care about. This process, terminologically called cut flow, is a series of selection criteria aiming to cut down the number of entries in our data, leaving only the useful ones in our hands.

The selection procedures are listed below:

1. We require at least two muons to take part in the action. This excludes the possibility of muon decays and other reactions with only one muon included.
2. We require at least one photon. This is to show that only the true muonium decay mode in all η decay channels is included.
3. We require that the muons have opposite charges. Since the homogenous muons with the same charges can not form a true muonium-bound state, any events related to this case are excluded.
4. We require $\chi^2 < 10$ for the dimuon vertex.

This is for the need to have the balance variable more appreciative of Gaussian distribution, as discussed.

5. We require a radial true muonium vertex position.

In the range $\sqrt{v_x^2 + v_y^2} < 3\text{cm}$, v_x and v_y represent the position of true muonium projected on the x and y axes. This is because farther vertices also carry a bigger measurement error, so only the centered ones are considered.

6. We require that the invariant mass of the $\mu\mu\gamma$ lie within the $0.52 < M_{\mu\mu\gamma} < 0.58\text{GeV}$. This is also to exclude the other possible reactions occurring at the same time.
7. We require the opening angle significance cut to be $S < 3.5$. The angle significance is demonstrated by the fraction of the opening angle of two muons in the lab frame and its standard deviation:

$$S \equiv \frac{\theta}{\sigma_\theta} \tag{17}$$

where

$$\theta \equiv \arccos \frac{p_+ \cdot p_-}{|p_+||p_-|} \tag{18}$$

This is performed considering that only the muons are close to each other and are parallel in trajectory, which could have come from the dissociation of the same true muonium.

After that, the balance variable from the experimental data is plotted as below:

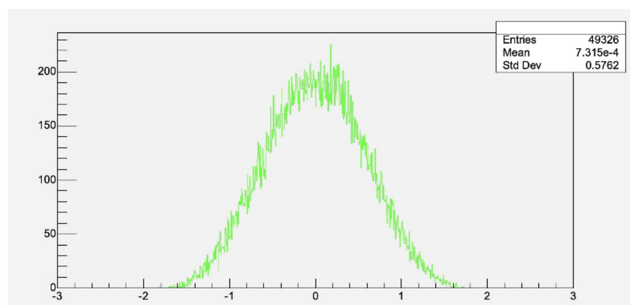

FIG. 2. The frequency of the balance variable is based on the experimental data. The horizontal line is the value of the balance variable, while the virtual line is the number of events of a particular balance variable.

The standard deviation is much bigger than 1, though they share the same symmetry property along the vertical axis. This more decentralized data shows that there might be other factors in the experiment we have not considered, and the Monte Carlo simulation method should also be improved to adapt to the more complicated reality.

4. SUMMARY AND CONCLUSION

In conclusion, in this paper, we discussed the η decay and true muonium dissociation reactions and simulated those processes in the Toy Monte Carlo model. Moreover, we analyzed the experimental data according to several selection criteria and compared the balance variable with the computer-generated one. We reveal that the basic characteristics of both methods are similar; however, the experimental data has a bigger standard deviation, requiring more investigation on this topic.

As for further research, improving the complexity of our simulation model is of interest. A background peak should be added in the figure of the balance variable, showing that the background noise in the reaction environments may cause a wider distribution in the experimental data. Besides, the selection criteria for the experimental data should also be decorated and modified. Since the main channel of η decays also generates photons with a much larger branch ratio [19], i.e.

$$\eta \rightarrow \gamma\gamma,\ \mathrm{BR} = 0.39 \tag{19}$$

and

$$\eta \rightarrow \pi^{+}\pi^{-}\gamma,\ \mathrm{BR} = 0.05 \tag{20}$$

and those photons may also generate pairs of muons. Hence, it is necessary to design a stricter flow of cuts to eliminate those contributing factors.

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