Probing signal characteristics of a maverick top decaying to a dark photon

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Light dark matter candidate already become a focal point for many years. Dark photon, as a dark sector mediator is favoured by researchers. Astronomical data have already gives the constrains between the dark photon mass and kinetic mixing parameter. The maverick top partners model give a new way to produce the dark photon. If the mass of dark photon is around 100 MeV, the branching ratio for decaying into e^+e^- pair is 1, giving rise to a lepton-jet signal in the detector. The particle level simulation has been done last year. This report will give a brief introduction of the target dark photon and continue the detector level analysis. By probing signal characteristics, the top quark is reconstructed. But we haven't obtained the correct dark photon signal because the overlap removal of the electron signal.

I. INTRODUCTION

In the past few decades, knowledge of the history of our universe has vastly grown. The data revealed that dark matter as well as dark energy dominant the matter component of the universe. The detection of dark matter have become a popular topic for researchers. Different dark matter candidate varies by their mass scale (Fig 1). Weakly interacting massive particle (WIMP) is

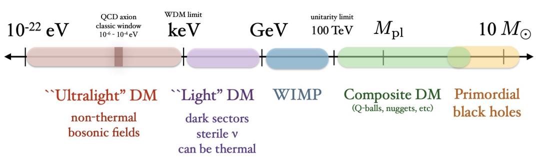

FIG. 1. Mass scale for dark matter candidates [2].

one of the most famous candidate. The thermally averaged annihilation cross section is very similar to the numerical value arrived at for a generic weak-scale interaction. In this case, if the mass scale of dark matter is of electroweak scale, the dark matter relic abundance in today's universe can be reproduced. This coincidence is called "WIMP miracle" to express the excitement of researchers. However, WIMP hasn't been discovered. As a result, more focal point was shifted to the search of light dark matter, which have a mass scale from keV to GeV [2].

In this study, dark photon which has the mass of 100 MeV detection will be discussed. The model of dark photon and the new gauge group will be introduced in section II. In section III, the production of dark photon will be discussed. Section IV and V will gives the result of the event simulation in particle level and detector level.

II. DARK PHOTON

There is few knowledge for us to know the interaction between the dark matter candidate and SM particles. In particle physics, the hypothetical interactions that connects the Standard Model particles to a dark sector of particles are called "portal". One of the most popular vector portal is dark photon which plays a role of dark force carrier leading to a new gauge group $U(1)_d$. This comes to a interesting point that although the dark matter are presumed not to have a sizable electromagnetically interaction, they can be some source of dark EM field. The consequence to this is the Maxwell equation need to be extended. One thing need to be mentioned is called kinetic mixing which means two gauge bosons (photon and dark photon) from different gauge groups ($U(1)$ and $U(1)_d$) acquire mixing terms in their kinetic energy terms in Lagrangian. This mixing occurs when there are interactions between particles that transform under different symmetries, leading to the interplay of their respective gauge fields. The kinetic mixing between EM and dark EM field given by [3].

$$\mathcal{L}_{\text{kin}} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} + \frac{\kappa}{2}\hat{F}_{\mu\nu}\hat{F}'^{\mu\nu} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu}$$

$\hat{F}'$ gives the strength tensor of dark EM field. It's worth noticing that dark photon may obtain mass from Higgs mechanism or Stueckelberg mechanism. In order to cancel the kinetic mixing term in the Lagrangian, the fields need to be redefine differently for massive or massless situation. Massive γ' case: $\hat{A} \to A + \varepsilon A'$, $\hat{A}' \to A'$ Massless γ' case: $\hat{A}' \to A' + \varepsilon A$, $\hat{A} \to A$ where A' is the dark EM field potential. The Lagrangian finally become

$$\mathcal{L} = -\frac{1}{4}FF - \frac{1}{4}F'F' + \frac{1}{2}m_{\gamma'}^2 A'A' + \mathcal{L}_{\text{int}}$$

where

$$\mathcal{L}_{\text{int}} = \begin{cases} -(A + \kappa A')\,J - A'J' & (\text{massive } \gamma' \text{ case}) \\ -(A' + \kappa A)\,J' - AJ & (\text{massless } \gamma' \text{ case}) \end{cases}$$

where $J\,(J')$ is the electromagnetic (dark) current. And finally obtain the Maxwell equation for dark photon.

$$\nabla \cdot \vec{E}' = (\rho' + \kappa\rho) - m_{\gamma'}^2 A'^0$$

$$\nabla \times \vec{B}' = \left(\vec{J}' + \kappa\vec{J}\right) - m_{\gamma'}^2 \vec{A}' + \frac{\partial \vec{E}'}{\partial t}$$

$$\nabla \cdot \vec{B}' = 0$$

$$\nabla \times \vec{E}' = -\frac{\partial \vec{B}'}{\partial t}$$

Here the existence of axion is not considered. The discussion below will only focus on the massive dark photon. The stellar observation constrains the mass of dark photon m_V and the kinetic mixing parameter κ.

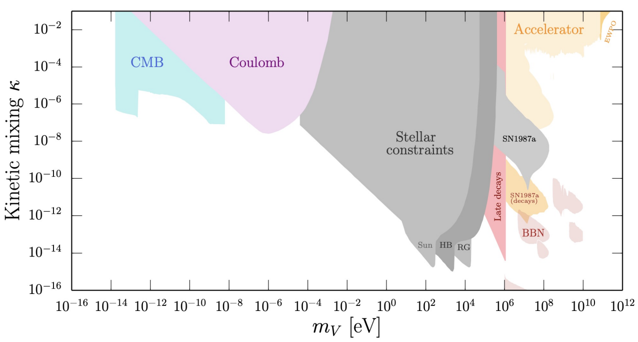

FIG. 2. Mass constrain by the astronomical data [2].

III. THE PRODUCTION OF DARK PHOTON

Different from other models, this study focus on the dark photon which is produced by another hypothetical particle vector like top partner (VLT) [1]. The production of VLT is shown in Fig 3 which can be achieved in LHC.

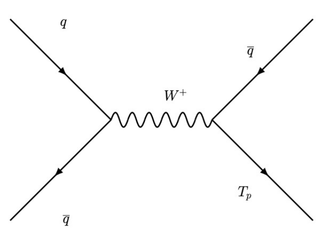

FIG. 3. The production of VLT [4].

What is important here is the decay mode of VLT (Fig 4). According to the model, the VLT can decay into one top quark and dark photon. The W boson can decay hadronically or leptonically, which will be considered separately. While dark photon decay mode will form a unusual topology known as lepton-jets due to the tiny angular separation of the electron and positron.

IV. PARTICLE LEVEL SIMULATION

Based on the previous discussion, the particle level discussion have been done last year. This level simulation

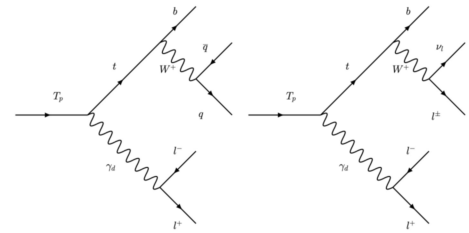

FIG. 4. The decay mode of VLT where the left panel decays leptonically and right panel decays hadronically [4].

based on the physics model and software will used to imitate the particle collision in the collider. By setting the parameter of the new physics model, one can get the expected signal of collision event. Signal events were generated using MadGraph5 interfaced with Pythia8 [5,6]. The dark photon mass was chosen to be $m_d = 100$ MeV, which makes sure the branching ratio of dark photon decay to e^+e^- to be 1. The dark kinetic mixing parameter is set to be $\kappa = 0.001$ while the the dark sector Higgs boson vaccum expected vavlue $v_d = 10$ GeV, dark Higgs boson mass $m_{H_d} = 10$ GeV. the top VLT mixing angle $sin\theta_l^t = 0.1$, the scalar mixing angle between the Higgs and dark Higgs boson, $sin\theta_S = 0.1$. Finally, all distributions below are normalised using an integrated luminosity of $300fb^{-1}$,corresponding to projected combined integrated luminosity combining LHC Run 2 and Run 3.

The signal contains a pair of high p_T e^+e^- with tiny angular separation. So electron reconstruction algorithm used in LHC experiments will mostly misreconstruct it as a single electron. So unlike standard searches, electron multiplicity is a misleading observable here. The expected signal state configuarion is showned in Fig 5 (W boson in hadronic decay) [4].

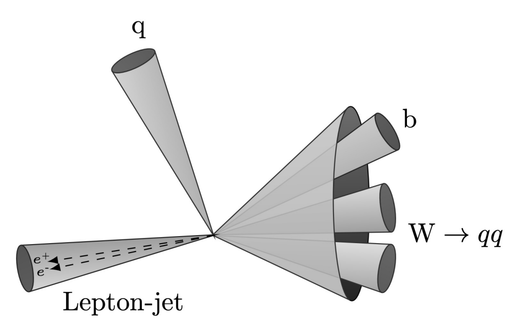

FIG. 5. Signal event final state configuarion (W boson in hadronic decay) [4].

The top left quark (or antiquark) is from the VLT generation. The large cone on the right side is a large radius jet (J10), which is expected to have a mass of top quark. This will decay into 3 small jet (J4), one of them is b-tagged. In the leptonic decay mode of the top quark, it will contain a charged lepton and corresponding neutrino, along with the b-tagged jet. The other one (bottom left) is the lepton jet candidate, which is also a small jet (J4). This e^+e^- pair is overlap with each other so it likely to get one single electron signal. So the signal events are required to have at least 1 J10 as boosted top jet, at least 1 electron as the lepton-jet candidate.

A. Top quark decaying hadronically

We expect the dark photon or saying lepton-jet candidate is the J4 closest to the leading p_T electron because the detector will misconstruct the overlapping e^+e^- to be one single electron. This can be verified by the simulation (Fig 6).

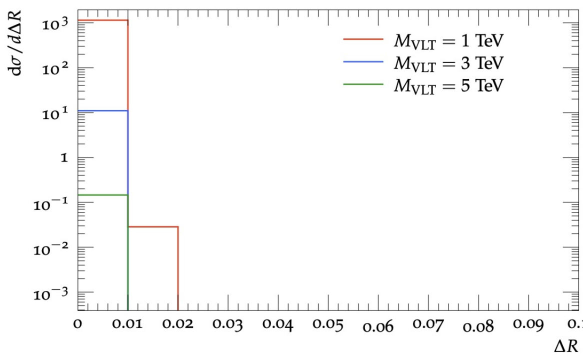

FIG. 6. Particle level simulation result. ΔR between the e^+e^- pair. For different VLT mass 1TeV, 3TeV, 5TeV [4].

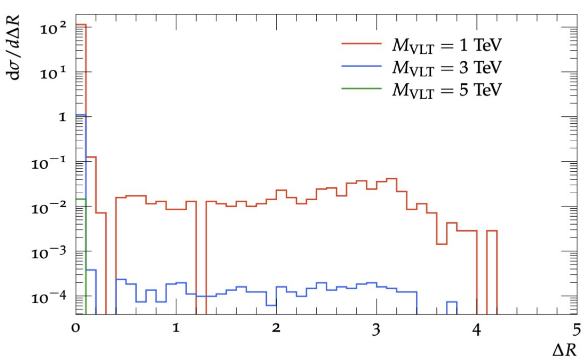

FIG. 7. ΔR between the leading p_T electron and the closest J4 (right panel). For different VLT mass 1TeV, 3TeV, 5TeV [4].

where x axis is the angular separation ΔR while the y axis the differential cross-section which gives the rate at which events are produced per unit interval of ΔR. From the plot (Fig 7), the two electron are almost in the same direction, while a jet is collinear with them which is supposed to be the dark photon. For this reason, when the top quark decays hadronically, the requirement for lepton number in the detector level will be greater or equal to 1 rather than 2.

The background of the event mainly comes from the multijet and hadronic $t\bar{t}$ background. Multijet events are multiple jets which are collimated sprays of particles resulting from the hadronization of quarks and gluons are produced in a particle collision. While $t\bar{t}$ comes from the relatively large cross section for $t\bar{t}$ production compared to many other processes at collider energies. In the collider, top quark and an antitop quark pairs are produced and subsequently decay into a variety of final states leading to the background.

In the particle level, there is no electron in the background. However, when it comes to detector level, there is a chance that a small jet is misidentified as electron. So the cut should be prepared for detector level cases. The graph of $\Delta\phi$ between the lepton jet and top jet is plotted.

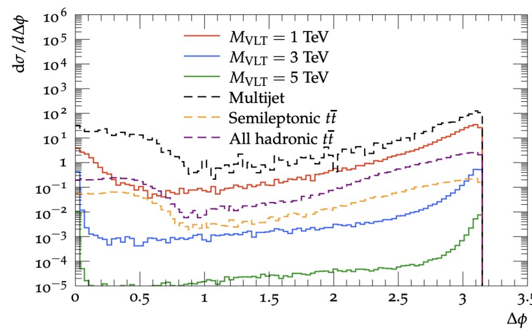

FIG. 8. $\Delta\phi$ between the lepton jet and top jet [4].

From the topology, lepton jet and top jet on the opposite site of each other.

B. Top quark decaying leptonically

In lepton decay mode, the overlapping e^+e^- will be indentified as a leading pT lepton. Besides, there should be at least 2 J4, one of them are supposed to be b-tagged.

For the muon channel, there is only e^+e^- signal and the muon signal is used to reconstruct the top quark. For the electron channel, there are 3 electrons in total. Some of the events have two b-tagged jets so we can't assume the electron which is closest to the b-tagged jet is from top quark decay. Fortunately, it was found that 99.5% of the dark photon (overlapping e^+e^- pair) have the leading p_T among the electron signal. The rest electron will be used to reconstruct the top quark. Finally the VLT mass can also be obtained.

V. RESULTS

The particle level simulation has already shown us the theoretical expectation of the observables. The next step is to get the particle level analysis and compare with the particle level plot. The graphing part is based on ROOT and the root file comes from the detector level analytical system is trained using Atlas simulated data. It's significant to aware that the y-axis of the plot in this session is frequency which is balanced by eventweight.

In order to make sure the event was successfully generated, the number of J4 is set to be greater or equal to 3 and the number of J10 can't be smaller that 1. Besides, there must be at least 1 lepton in the signal.

The lepton jet candidate or saying dark photon is considered to be the closest J4 to the leading p_T lepton. ΔR between the leading p_T lepton and its closest J4 is plotted (Fig 8).

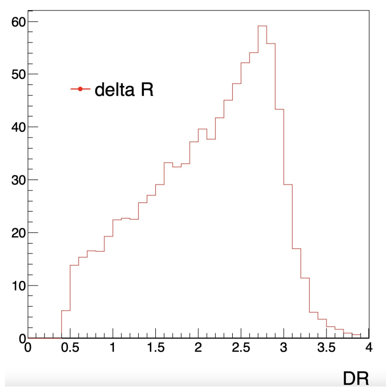

FIG. 9. ΔR between leading p_T lepton and the dark photon

The plot of ΔR in not as expected as Fig 6 which shows that the dark photon should very closed to the leading p_T electron. This is referred to as overlap removal, which for the default analysis removes jets that are within 0.2 of an electron and removes electrons that are 0.4 within a jet. The lepton jet is within 0.1 of the leading electron. This can be also seen in the figure of lepton number. As

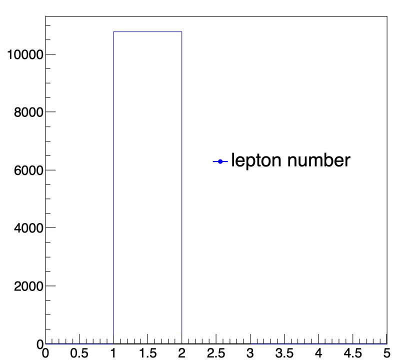

FIG. 10. Number of lepton.

shown in Fig 10, there is only one lepton signal and the others are vanished.

Differently, the number of large jet looks reasonable. The large jet J10 can be selected by its mass as top quark

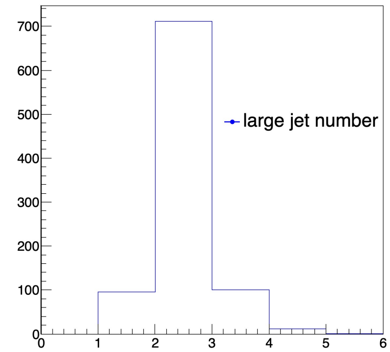

FIG. 11. Number of large jet.

candidates, in this way, the top tagged histogram can also be plotted. Top mass is expected to be 175 GeV. Using the way of top tagged, we obtain the mass (Fig 12) and p_T (Fig 13) of top quark.

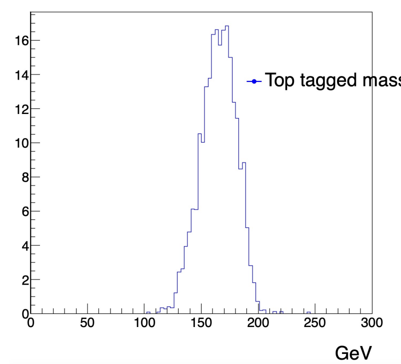

FIG. 12. Top Mass

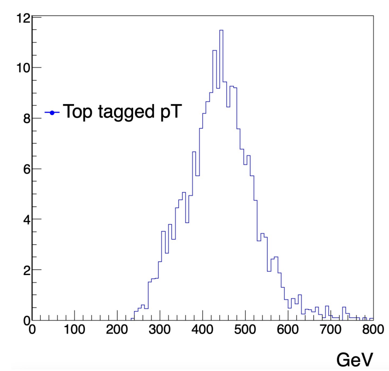

FIG. 13. Top p_T

Although we have successfully reconstructed the top mass and p_T, the dark photon is still unknown, we can't obtain the correct VLT mass.

The graph of top quark looks fine, the peak of top quark mass is closed to 175 GeV. However, some of the graphs are not consistent with what we expected in particle level, especially for the dark photon graphs. If one check the ΔR between dark photon and leading lepton carefully, anomaly large angular separation is spotted. Moreover, the expected dark photon mass and p_T are peaked at 200 MeV and 500 MeV which are not agree with the detector level plot. Besides, there is only one lepton for any event.

The problem may come from the default analysis framework removing jets which are close to electrons, which is most likely the reason why the dark photon plots look so weird and the event only have one electron. The future step to this study is to adjust the analytical system to include these electrons.

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